SEVENTH FRAMEWORK PROGRAMME

Theme 9: SPACE

<u>Space Thermoacoustic Radio-Isotopic Power System</u>

Space TRIPS

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THIRD REVIEW MEETING WITH AREA
BRUSSELS JANUARY 15 2016

Conclusion

The project concerns the design realisation and test of a prototype of a TA/MHD generator, representative as much as possible of a space prototype, but of course not completely identical due for example to the presence of gravity. On the other hand, the prototype is not optimised in terms of efficiency and mass. The objective is mainly to validate the theoretical approach, in order to be able to optimise the generator.

The main efforts of the third year were devoted to work packages 2 and 3. The work package 2 was focused on the realisation of experimentation plan and means, on the construction and on the tests of the two engines, Thermo acoustic loop and MHD generator. The construction of the two engines has begun with some delay and the tests of both have revealed difficulties producing the break of some pieces when the nominal conditions, about temperature and pressure were applied. So it was necessary to construct new elements producing a new delay about the end of the tests. The objectives are to realise the totality of the program that is expected to be finished on the end of January 2016. The work package 3 concerns the study about the space architecture, including hot and cold sources, as well as on the possibilities to stabilise the liquid/gas interface, with new very important results obtained by HZDR.

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Third periodic review report

1. Generalities

1.1: Summary description of project context and objectives

The project relates to an advanced thermal to electric conversion for radio-isotopic power systems (RPS). Indeed RPSs are a key for space exploration as the solar power is very low in deep space, notably in Jupiter orbit and beyond. These systems are also useful for exploration of Mars or other astronomical bodies where solar power availability is subject to the effects of nights or dust storms.

Thermoelectricity fits very well with small RPS (e.g.20We), and is generally suitable for the 100We range, but high efficiency conversion is desirable. Indeed, this could lead to save between 2/3 up to 3/4 of the radioisotope mass. This is of real importance in term of cost and safety. For this reason, Stirling converters are under development in the USA, but they are prone to reliability issues due to the presence of pistons (sensitive to launch vibrations and shocks, subject to wear).

A generator based on coupled thermo acoustic (TAc) and magneto hydrodynamic (MHD) engines is an innovating technology ideally free of moving parts. Unfortunately, the Technological Readiness Level is low and for this reason in ESA's programme the priority is given to Stirling engines, even if ESA has supported the first studies of TAc-MHD systems. Therefore this project is complementary with ESA's approach.

So, the objective of this Project is to raise the TRL of this technology from 2 to 3-4 and show that this option is viable for European RPSs. The approach is based on 3 axes:

– Theoretical modelling, which has been already developed but needs to be validated,
– Experimentation of a thermo acoustic engine coupled with a MHD generator,
– Design of the space RPS, equipped with this conversion system, to check if the technology is suitable for space mission.

The targets are:

– to validate the process efficiency (close to 20%),

– to justify the compatibility of the technology with space missions,

Europe has a great strong expertise in thermo acoustic and MHD. But these technologies have never been coupled. This is precisely one of the objective of the consortium involved in the project. The consortium, coordinated by the start-up company HEKYOM, associates three research organizations: CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (CNRS) in France, IPUL in Latvia and Rossendorf in Germany. The space and nuclear industries are represented by Thales Alenia Space -Italy and AREVA. Thales Alenia Space represents also the end-user in terms of space systems.

The present situation of the project is as follow:

- The global configuration has been chosen.
- The global and detailed design of the two engines have been established.
- The construction is under operation.
- The possible configuration for space is proposed.

The next and last step will be the test programmed for the last mid years of 2015. A new and ambitious objective concerns now the adaptation of the concept for the high level of power and high temperature at the hot source involving new technological development and new solution for introduction of heat inside the thermo acoustic loop involving may be the use of heat pipe.

1.2: Recall of the stucture of spaceTRIPS.

The main transfert of energies are recalled on the figure below (Fig.1). The radio isotopic elements are the hot source of the system and supply a thermo acoustic loop by conduction process. The thermo acoustic loop converts thermal energy in mechanical one and this mechanical energy is introduced inside the MHD generator to produce electricity. The residual heat that have not been transfromed in mechanical energy is transferred at the cold source and evacuated in space by radiation.

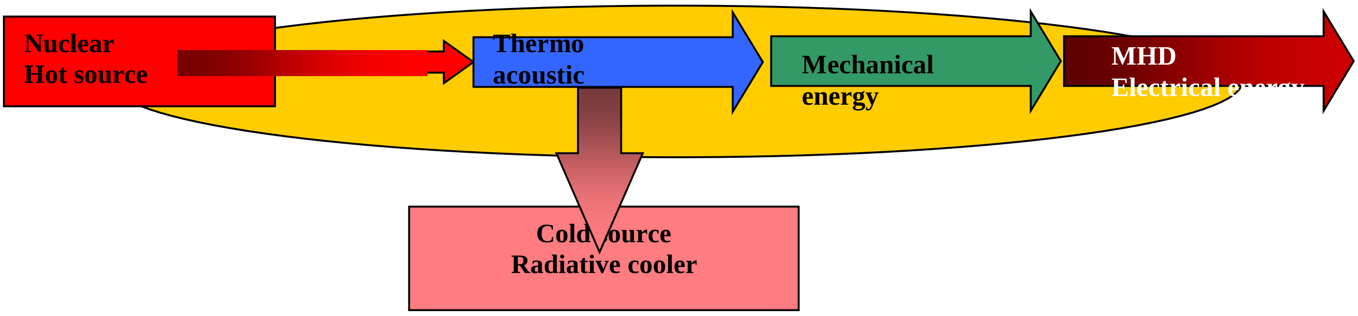

Figure 1: Energy transfert along the thermao acoustic/MHD electrical generator

The adopted configuration for the coupling between TAC engine and MHD generator is represented below (Fig. 2). The MHD generator (corresponding of the configuration 3 of the 4 possible ones presented in january 15 2015) is located in "a diameter" of a toroidal TAC loop. So when the pressure wave has maximum amplitude one one side then amplitude is minimum on the other side and reversibely according the frequency evolution of the thermo acoustic wave.

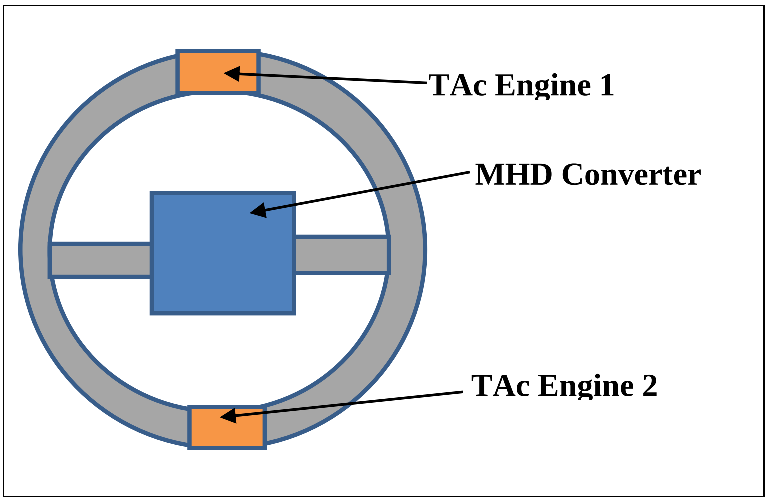

Figure 2: The adopted configuration for the TAC/MHD genrator

The working process of the MHD genrator is recalled in the following figures 3.

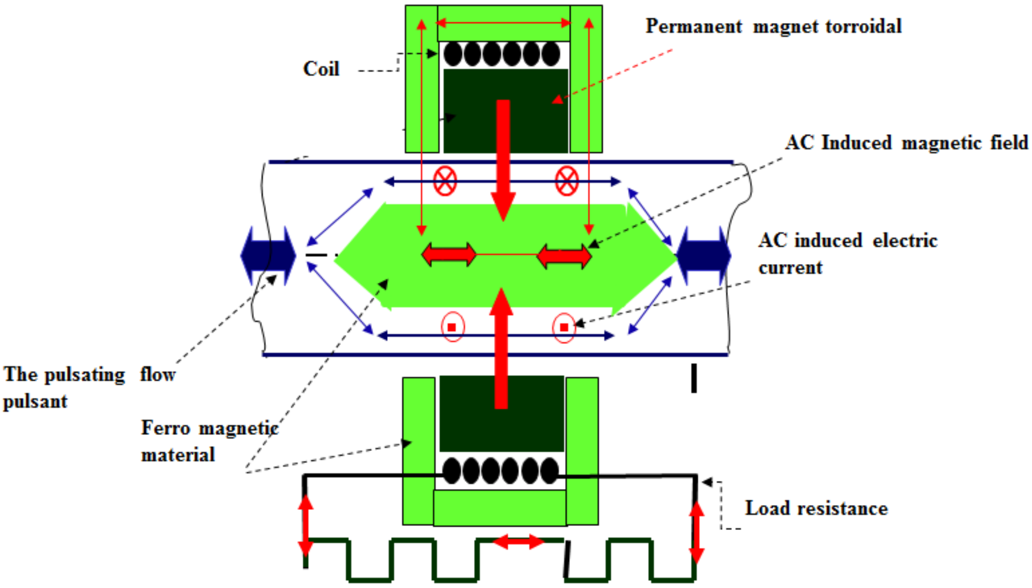

Figure 3 : Schematic representation of the principle of MHD generator

The thermo acoustic loop imposes a vibration of velocity, at large amplitude, which is transmitted to the liquid sodium in a torroidal channel. This vibration of the liquid sodium interacts with the imposed magnetic field, producing an AC electric current through the torroidal channel. This AC induced electric current produce itself and AC magnetic field, and the corresponding variation of magnetic flux produces, by induction, an electric current in the external coil connected with the load.

A Taking into account these elements, the design was done by the SERAS office. The different elements that preceded the establishment of the drawings was for the first year: the theoretical approaches of the problems that was done separately by three scientists, Armand Krauze from IPUL, Christian Chillet from the CNRS G2elab (Grenoble) and finally by Taha Mirhoseini (analytical model) from the University of Louvain in Belgium. The second year was essentially devoted to the choice of the best configuration with the Help of the society ESTER (Kees de Block) under the advising of Maurice Francois, and to design both the MHD generator and thermo acoustic engine and the coupling between both. The main tools necessary for the building of these two elements was also designed by the SERAS office, CNRS, Grenoble.

And finally the last year was devoted to the constructions and tests that was under the responsibility of IPUL in close collaboration with partners, and this phase is essentially the object of the present report.

The final design of the MHD generator is given below:

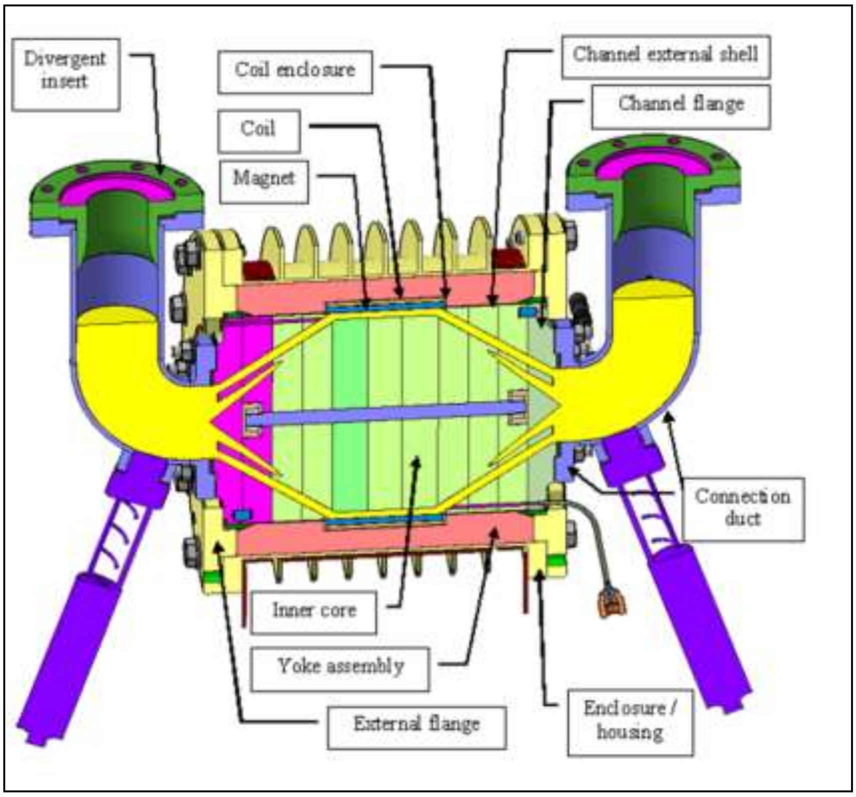

Fig. 4: view of the design of the MHD generator

And finnaly the glogal concept of thermo acoustic loop and MHD generator mounted on a special support (to absorb vibration) also designed by the CNRS SERAS Grenoble.

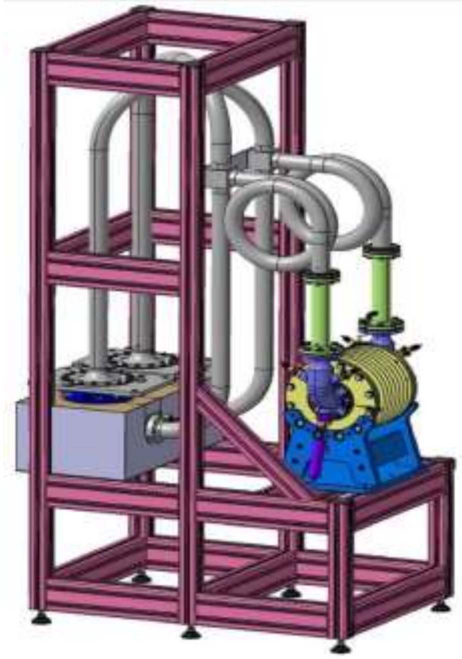

Figure 5: The global view of the design of TAC/MHD generator mounted on its support

1.3: Expected results and their potential impacts.

This project aims to demonstrate the feasibility of coupling TA with MHD to obtain a highly efficient and reliable electrical generator, and to investigate its suitability for space applications as a more efficient way of producing electricity from a radio isotopic heat source. The project is based on the modelling, design, construction and experimentation of a prototype of MHD electrical generator driven by a thermo acoustic engine. A design implementing this technology will be completed to asses the performance of a space system.

Activities are split in two “branches”: the first one is devoted to design, manufacturing and testing of a ground-based prototype, while the second one is dedicated to the conceptual design of a similar generator for space applications.

Several possible architectures have been conceived and evaluated (they have been named “Configuration 1” to Configuration 4”). One of these, namely Configuration 3, has been chosen as the reference architecture for the demonstrator (prototype to be built and tested).

Of course the prototype will take into account as much as possible the main specificities of the space technology, but it will be tested on Earth and this implies some differences with respect to the generator tailored for space applications. Moreover, the best architecture for the demonstrator has been chosen based on the simplicity of the design, considering that it will be the first engine using a combination of thermo acoustic and MHD.

The particularity of the concept comes from the fact that it does not use any moving mechanical part. It is based only on the fluid oscillations and thus it is a quasi static concept that could be a competitor with the solar cells. But potentially it has a much higher efficiency combined with a good reliability, due to the simplicity of the engine.

Furthermore, this type of generator is also particularly suitable for the exploitation of renewable energies (solar energy for example) as well as for waste recovery

.

Following the Horizon 2020 program presented in September 2014 in Roma a new program devoted to high electrical power to supply MHD thrusters in space, based on the use of a combination of Thermo acoustic loop and MHD generator have been presented in collaboration with many partners from 4 countries, French, Italy, Poland and Spain. In the new system the MHD generator is based on the use of ionised gas instead off liquid metal, supressing the problem of interface between liquid and gas

1.4: The web site.

The web site of space TRIPS (see the address below) is available and follows the evolution of constructions and tests of the TAC/MHD electrical generator.

http://space-trips.eu.seventhframework.sal.lv/

The realisation of the site was achieved by the Latvian partner, IPUL, under the umbrella of the space TRIPS coordinator.

2. General contacts and presentation of the partners of the project.

2.1: General contacts.

The scientific co-ordinator Antoine Alemany is the main contact being at the origin of the concept together with Jean Pierre Roux from AREVA TA. In the frame of the project, Antoine Alemany acts as a collaborator of the Hekyom Company which is the project leader.

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And finally for Thales Alenia Space Italy in charge with the cold source and interface stability using membrane:

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2.2: Presentation of the partners of the project.

The main partners of the project belong to 4 countries: France, Latvia, Germany, and Italy. The choice of partners was done in function of their complementarities and competences. They are

FOR FRANCE

- The firm HEKYOM, develops thermo acoustic engines, and thermo acoustic refrigerators or heat pumps. This company, which leads the project, is in charge with the management, the financial coordination, and with the sizing of the thermo acoustic engine in collaboration with IPUL.

- The CNRS, state organism, is the most important structure of research in France. This partner has double responsibilities. They concern firstly the numerical simulation of the MHD generator using a 3D model. The second aspect of is focused on the design of the two engines that composes the electrical generator, thermo acoustic loop and the MHD generator.

- The company AREVA TA is an important actor of the project having supported (especially on the financial aspect) the initial program of definition and development of the thermos acoustic/MHD electrical generator since more of 10 years in collaboration with the CNRS. In the frame of the project AREVA is mainly in charge with the hot source of the process using nuclear elements.

FOR LATVIA

- The Institute of physic of the University of Latvia (IPUL) is mainly involved in the actual construction and experimentation of the Thermo acoustic/MHD electrical generator .By this way it has to follow the evolution of the design of the engine, task under the responsibility of the CNRS Grenoble. This partner is one of the most important European research entities in the frame of magneto hydrodynamics activities since a long time. Its competence in the domain of liquid metal technologies is recognized.

FOR GERMANY

- The MHD department of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) was created during the period of East Germany, and due to the dynamism of the researchers who compose the group; the development of this department was extremely rapid. This group is in charge with the important problem of the liquid/gas interface, and of the investigating and testing the possibilities to control this interface.

FOR ITALY

- The partner, Thales Alenia Space Italy, is, within the Consortium, the only European company purely devoted to space engineering, and it has been involved because of its solid expertise in the frame of space technologies. For that reason, TAS-I is responsible for the definition of space requirements for the TA/MHD generator and the radiator for the cold source. Additionally, TAS-I has the responsability to evaluate the feasibility of another solution for the liquid-gas interface, based on the use of a moving sheet of solid metal. A workshop in Torino will be organised by this partner with most of the european companies and researchers involved with space activity at the end of space TRIPS project, september 2015.

3. Project objectives, work progress and achievements, and project management.

3.1: Project objectives.

The objectives performed in 2015 have respected the program but the work presents a delay from the forecast that was presented on January 15 2015 during the second review meeting in Brussels. The modified schedule is reported below:

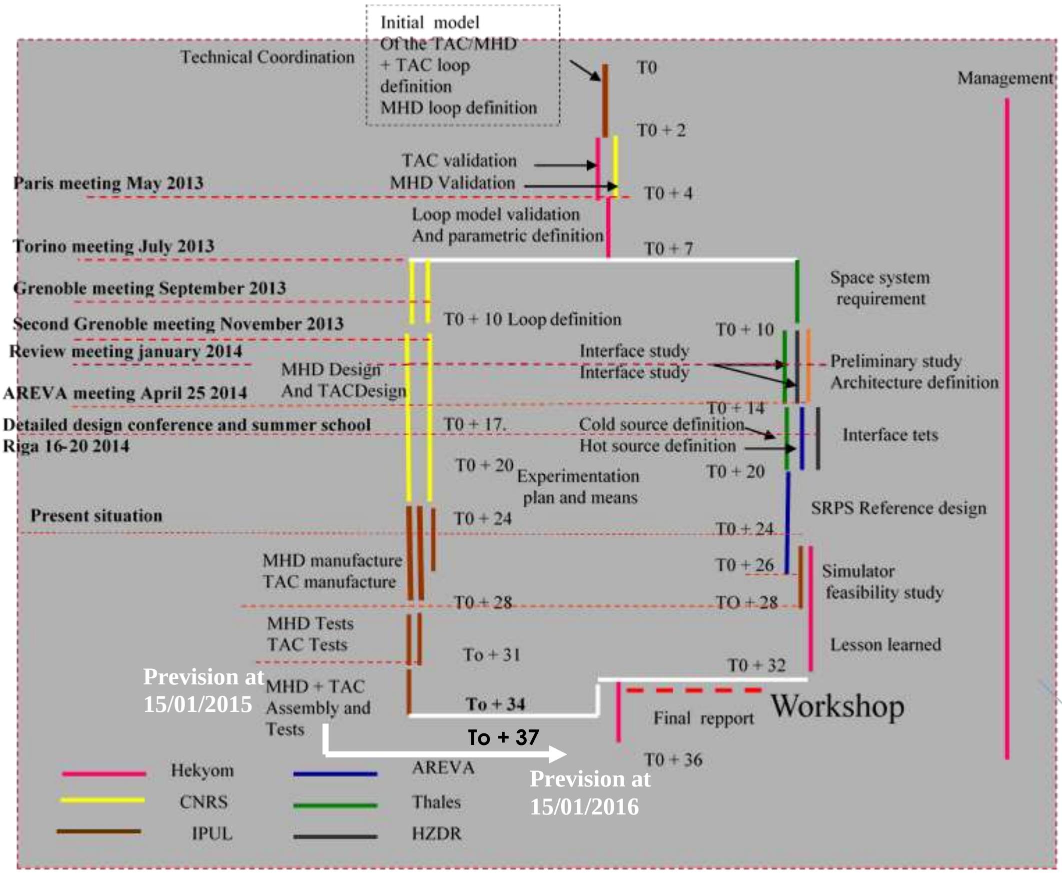


Table 1: Prevision for the spaceTRIPS conclusion

The main works was devoted to the construction of the test engines, the construction of the TAC loop and MHD generator, The acquision of the systems of measurement and finally the tests.

The main elements of these works are reported here after, it was essentially the involvement of IPUL, but of course these were achieved in close collaboration with the SERAS office in Grenoble, the design office of the CNRS in charge with the conception, with HEKYOM which moved to Latvia (IPUL offices) two times to help the Latvian scientists for the test of the thermo acoustic loop, as well as with AREVA TA and Thales Alenia space Italy. The German scientists (HZDR) have continued the interface tests and obtained good results recently.

The programme realised is in conformity with the structure of the project as it was proposed at the EU.

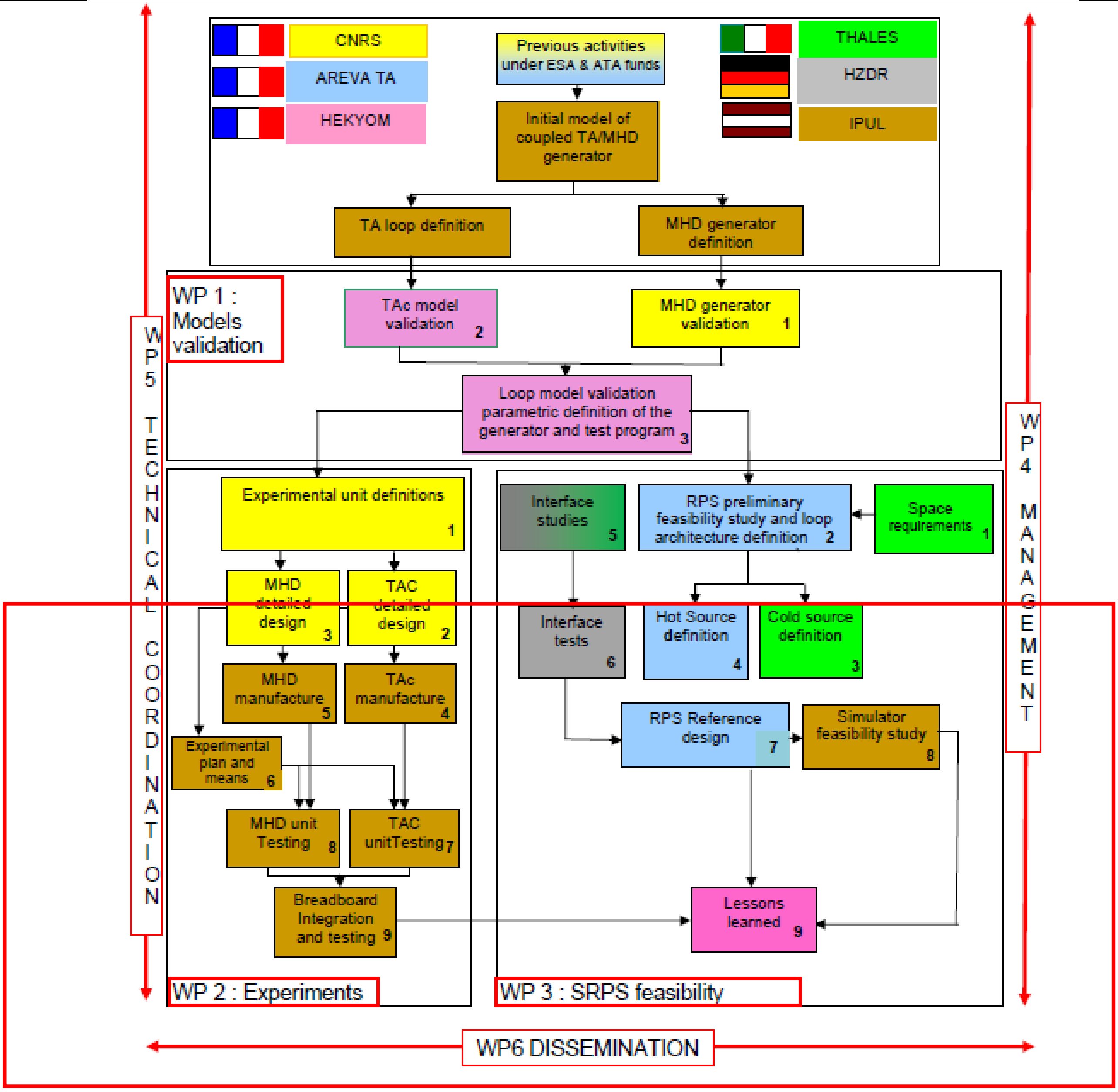


Table 2: third year work structure

3.2: Work progress and achievements during the period.

3.2.1: Detail of the objectives for Work Package 2 and 3.

The project activity during this period is in compliance with the proposed program. After the first year devoted to the precise definition of the concepts and expected performances, the evolution of the project activity was focused on the detail design of the two parts of the electrical generator (i.e. Thermo acoustic loop and MHD generator). In parallel the hot source definition and was achieved by AREVA TA, as well as the cold source definition was studied by Thales Alenia space Italy. The interface studies by Thales and HZDR was performed, in particular, an experiment was achieved by HZDR using surface tension to stabilise the liquid gas interface. The most important work realised on the third year concerns: the construction of the test means, the acquisition of the measurement systems including the construction and calibration of the electromagnetic flow meter, the construction and tests of both the thermo acoustic loop and the MHD generator.

Concerning the tests the adopted methodology consists to test separately the two engines before to test the full machine after assembly of both. The TAC/MHD electrical generator is a prototype, and difficulties was revealed in course of testing concerning the tightness and mechanical constraints producing the broken of some pieces realised in zirconium, the renewing of this material have taken a relatively long time, producing an important delay on the tests. The main elements of construction and the present situation of tests are given here after.

3.2.1.1: Works realized by IPUL for construction and tests (Work package 2).

The main work packages on which was involved IPUL this year are recalled here under.

Task 2.4 : TAc engine manufacture

Task 2.5 : MHD machine manufacture

Task 2.6 : Experimentation plan and means

Task 2.7 : Tac engine tests

Task 2.8 : MHD engine tests

Task 2.9 : Breadboard assembly and Breadboard Tests

In the following the order of presentation will be as below:

a: Experimentation plan and means
b: Measurement systems.
c: TAc engine manufacture
d: MHD machine manufacture
e: Tac engine tests
f: MHD engine tests
g: Breadboard assembly and Breadboard Tests

a: Experimentation plan and means

To test the MHD generator a structure, using two compressors able to impose a pressure pulsation at the both parts of the generator was built. The MHD generator test facility using two cylinder compressor seems to be most simple and reliable. We are building it as a first. This additional pneumatic equipment will be used for free surface stability tests and for single MHD generator tests. In the device the two cylinders compressor was used as source of pulsating pressure.

Figure 6: Compressor applied for pneumatic tests

The compressor consists of two cylinders shifted in phase by 180 degrees. For applying the compressor the upper lid of it was slightly modified and each cylinder separately connected to output pipe.

Figure 7: Compressor with the old wheel | **Figure 8: Overview of compressor**

Working principle is to create gas pressure fluctuations on free surface of MHD generator, by using compressor with two cylinders, where cylinders are phase shifted by 180 deg. Gas pressure will be adjusted by opening valves V3 and V4 and closing V1 and V2, the rest of the scheme is for starting the process

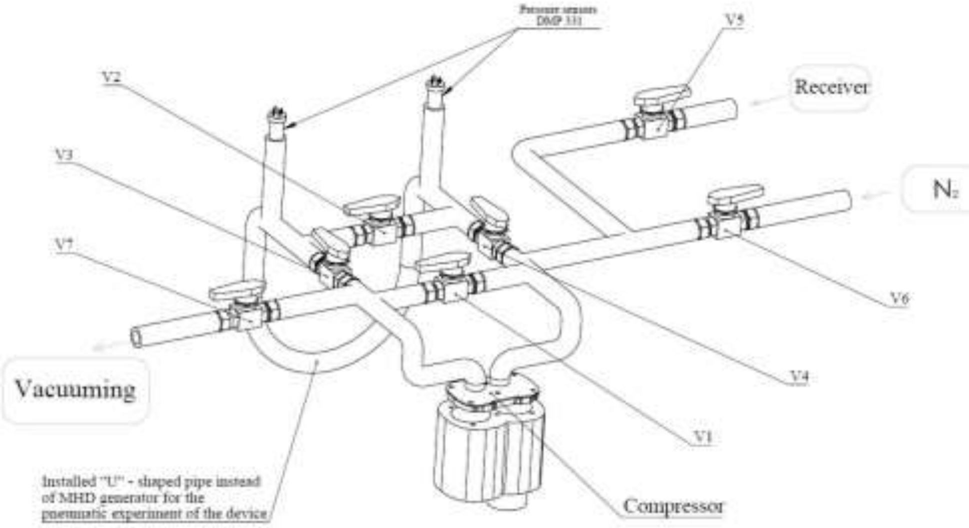


Figure 9: schematic view of the pneumatic circuit

Figure 10: Overview of the installation | **Figure 11: Compressor with changed wheel**

The wheel of compressor has been changed to the exact size of the wheel on electric motor, that we can get an exactly 3000 min^{-1} and 50 Hz frequency as we need (Fig. X). It means that the wheel is about 2 times smaller than previous one. With the frequency converter we slowly increase the rotating frequency up from 0 to 50 Hz or from 0 to 3000 min^{-1}

For compressor test there are two modes possible: calibration and full test. In calibration mode the pressure oscillation is produced by one cylinder only and applied on one side of MHD generator. From secondary pressure on another side (sensor P2) one can estimate sodium flow oscillations. In full test mode both cylinders are working for pressure difference, but flow rate should be monitored by another means.

Action	Compressor	Valves						
		1	2	3	4	5	6	7
Evacuation	off					X	X	
Filling Nitrogen	off					X		X
Level arranging	off			X	X	X	X	X
	Start up		X	X	X	X	X	X
Calibration begin	on		X	X	var		X	X
Calibration middle	on	var	X	X				X
Calibration full	on	X	X	X				X
Test begin	on		var			X	X	X
Test middle	on		X			X	X	X
Test full	on	X	X			X	X	X

Table 3: the compressor tests

There: X =valve closed, var= valve semi opened, blank=valve opened .

Working principle of testing scheme:

• Valve 5 is closed. Valve 6 is closed. All other valves are opened. The system is vacuumed. Then valve 7 is closed, valve 6 is opened to fill system with nitrogen.

• Valve 3 and 4 are closed. Valve 2 is opened to get equal pressures on both MHD generator sides. V2 then closed.

• Valve 1 is opened, valve 7 closed, valve 6 closed. Compressor has been started up to normal working regime.

• While valve 1 remains open, valve 3 and 4 together gradually are opened to increase load on compressor.

This short described sequence of closing/opening valves is used in all tests made by pneumatic.

Pneumatic test system itself is tested connecting transparent pipe instead of MHD generator. The pipe is in U shape and the same cross section as the MHD generator has. Instead of sodium will be used colored water. Level changes are monitored using video camera. Aim of this preliminary experiment is to test stability to follow level changes with electronic manometers and also to search for instability border of free surface.

Testing of MHD generator using two cylinders compressor.

Test program and design of single MHD generator compressor experiment.

Passive measurements:

a) Measurements of magnetic field in the gap between magnets and core, during assembly process.
b) Measurements of active and reactive impedance of coil before filling of sodium.
c) A measurement of active and reactive impedance of coil after channel is filled with sodium.

Experiments in the pneumatic stand (see schematic figure 1.):

1. At start and shut off the valves V3 and V4 are closed, but valve V1 is open!
2. System working in full load valves V2, V5, V6 and V7 are closed.
3. When compressor running at full speed valves V3 and V4 are gradually opened and valve V1 is gradually closed in order to achieve necessary pressure characteristics.
4. When system working at half load valve V1 is open and amplitude is regulated by valves V3 and V4.

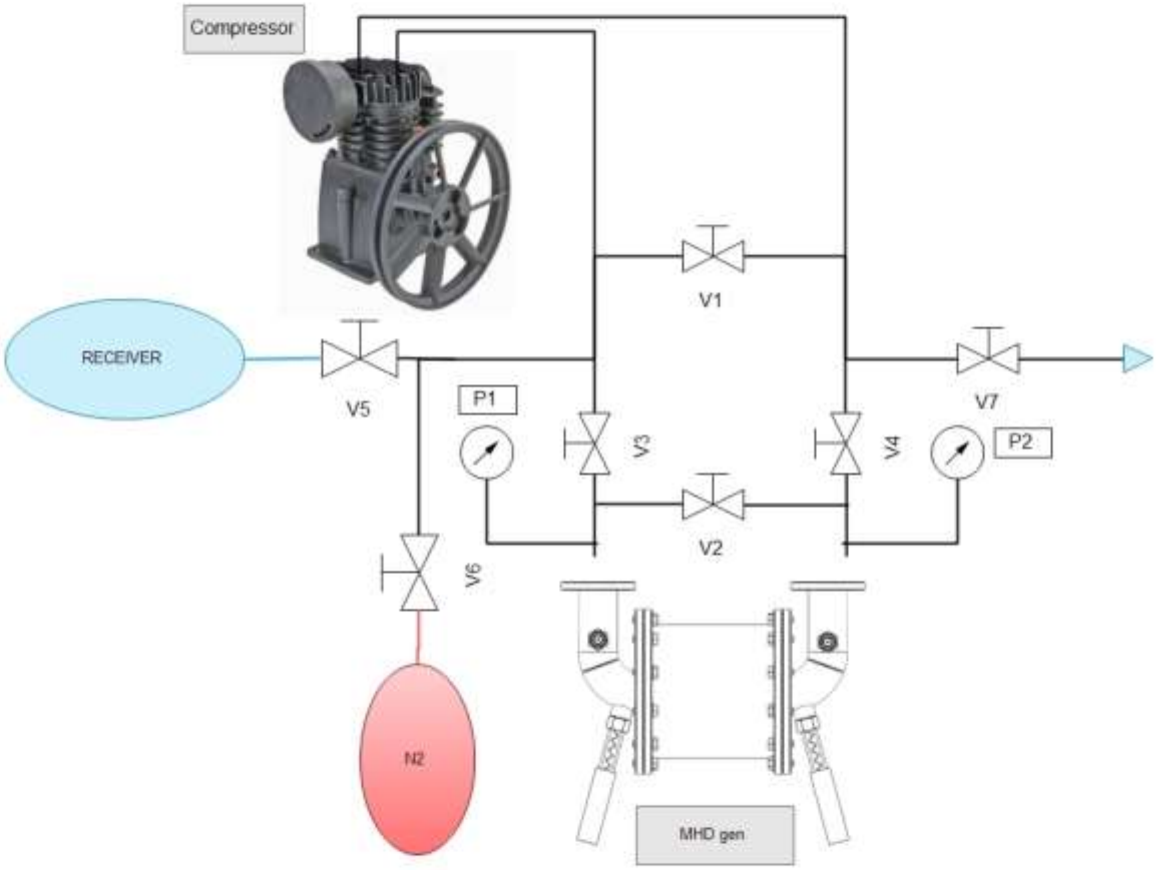


Figure 12: esting of MHD generator using two cylinders compressor (pneumatic test).

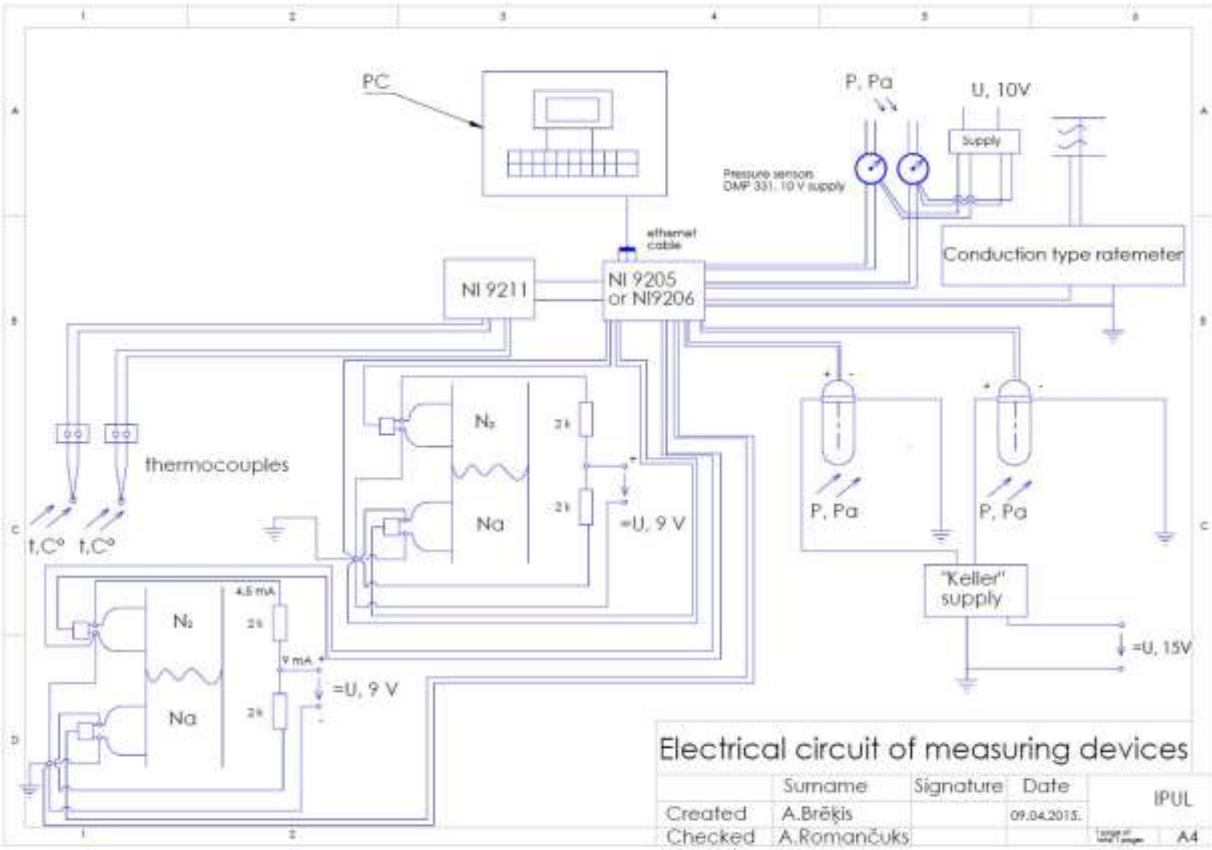


Figure 13: Electrical scheme for MHD generator test

MHD generator test in pneumatic stand:

Generator and whole stand is vacuumed, than filled with nitrogen. Heated up to T=120^{o}C. Sodium is melted and filled in the generator.

Tests start working in half load. There will be changed electric impedance from none to 100 ohm, measurements logged by pc measurement system (see Fig. 3.7.2.). Measurements are voltage, current and pressure. Also the levels and temperature are measured. Frequency is changed by compressors driving motors frequency. After experiment data is recalculated to amplitudes, power and phase angle. After successful half load experiment it is done in full load.

There had been already developed Labview programs (see Fig. 3.7.3.) for pc measurement system for pressure sensors, thermocouples for temperature measurements and sodium level sensors, which will work as a safety indicators in that case, if the sodium would go up to unexpectedly high level.

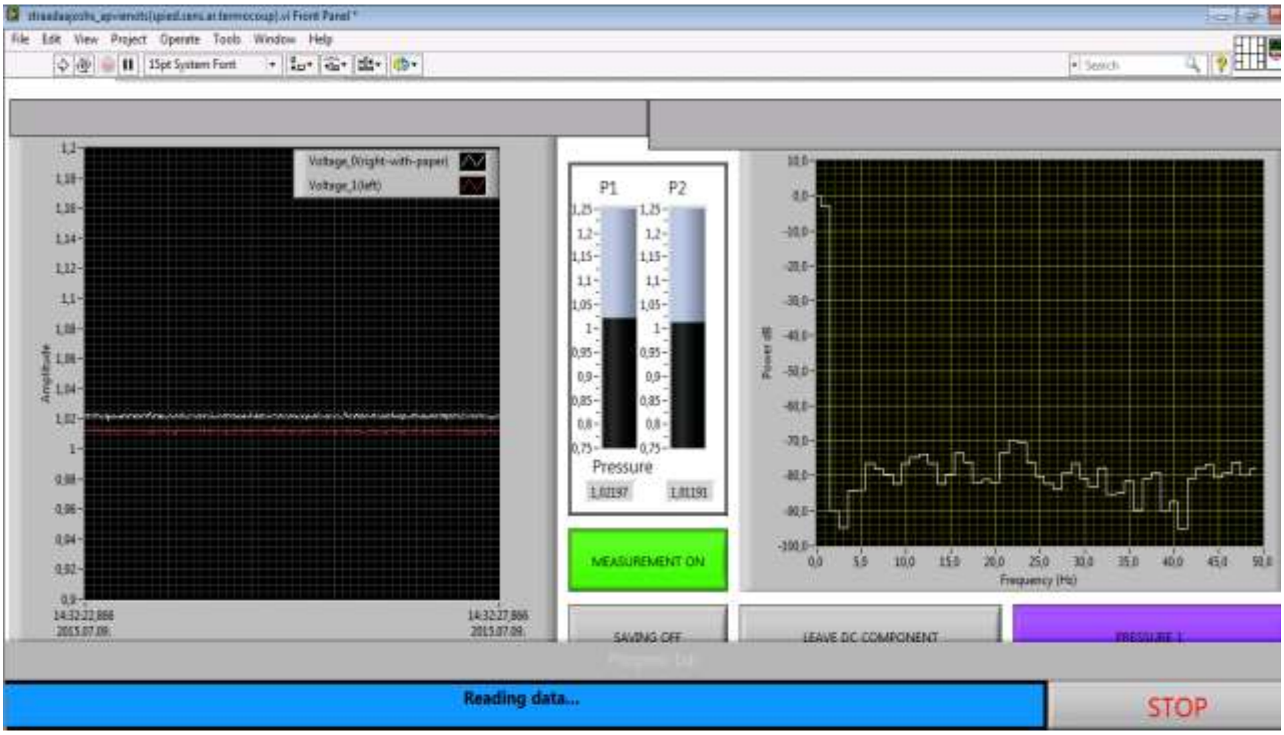


Figure 14: Measurements of the pressure sensors on the left side and indicators in the middle;frequency analysis on the right side.

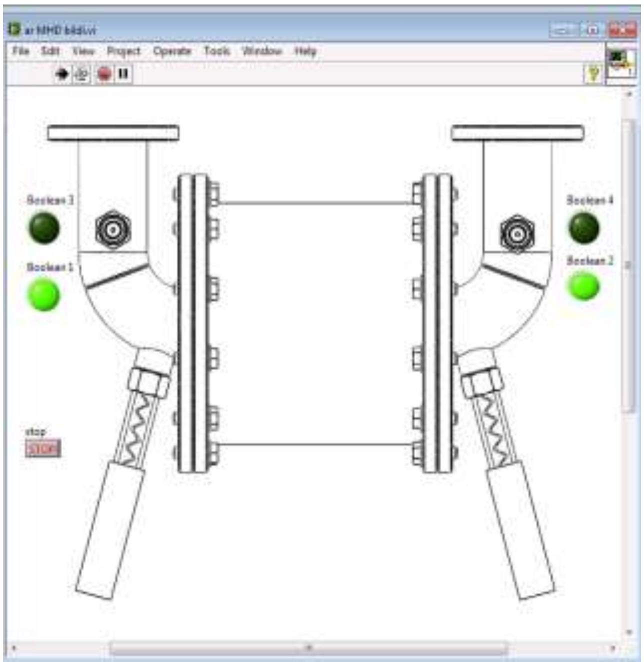


Figure 15:. Level sensor indicators

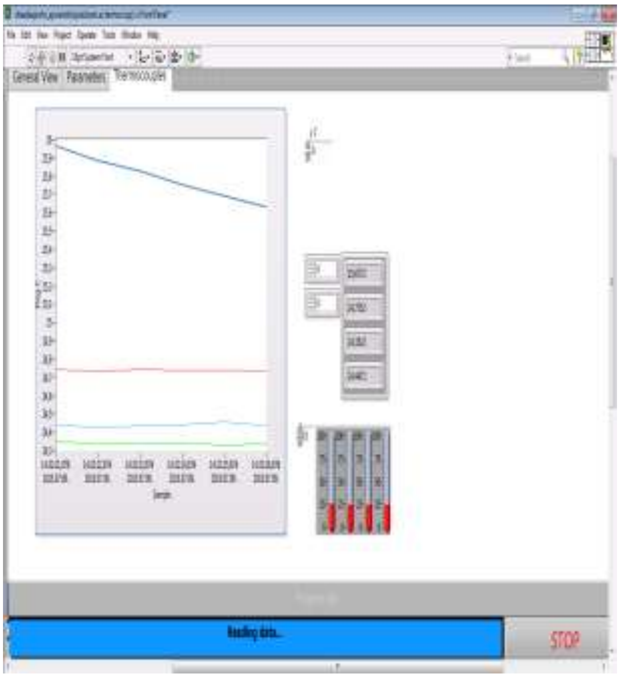


Figure 16: Temperature measurements

For testing the Thermo acoustic loop, there is no specific equipment needed to be build. The cooling system has used a water flow rate at room temperature. And the heat source, simulation of the radio isotopic elements, have been realised by electrical resistances as it was planned in the SERAS design.

The only think that was constructed and necessary for testing the thermoacoustic loop alone, is an element able to simulate more or less the MHD generator, able to dissipate the mechanical power resulting from the thermo acoustic effect. This dissipation is realised by friction by hydraulic resistances between the two tube connected with the pull push system. The impedance can be adjusted with the valve mounted on the transverse tube

.

Figure 17: Experiment with hydraulic resistance on the ends ot the TAC generator

b: Measurement systems.

The main systems of measurement used concerns, temperatures, pressure (constant and pulsating), velocity (flow rate in reality) and magnetic field.

The measuring system of both systems (MHD and TAC) consists of more than 30 measuring units.

For MHD generator there were used 2 high – pressure class sensors from ''BD sensors'' with measuring range up to 40 bars for measuring pressure oscillations in sodium,

2 low – pressure sensors from ''FGP sensors'' for measuring gas oscillations in compressor,

4 spark plugs – like an indicators for sodium level,

6 thermocouples for MHD generator for temperature monitoring on the computer and additional 5 thermocouples for thermoregulation.

Output electrical power measurements

Flowmeters flowrate measurements

For TAC generator there was used:

8 ''SensorTechnics'' pressure sensors for acoustic power measurements,

11 thermocouples for temperature monitoring and additional 2 thermocouples for heater thermoregulation.

So together more than 30 measuring units.

Measuring program was created in programming language ''Labview'' and for some measurements (for example – TAC pressure sensors) it is saving 1000 measurements per second.

Independently of the classical systems of measurement for the temperature and pressure that are common on the two engines, some specific measurement systems have to be used for each of them. For the MHD generator they concern magnetic field and velocity measurement in the liquid sodium. Some elements of these, are given here after.

- **Magnetic field measurement**

Figure 18: Magnetic induction made by magnets,measuring in the open air.

Here we can see the induction values, measured in the somalloy core, without external yoke – it's 0,155 T. We had to find a special teslameter, whith whom we could measure induction inside such a small sodium channel in diameter about 4 mm.

Teslameter sensor parameters:Length – 78 mm Width – 3,5 mm

Figure 9 Magnetic induction, measured in the somalloy core, without external yoke – 0,155 T

Here we can see the induction values, measured in the somalloy core, without external yoke – it's 0,155 T. We had to find a special teslameter, whith whom we could measure induction inside such a small sodium channel in diameter about 4 mm.

Teslameter sensor parameters: Length – 78 mmWidth – 3,5 mm

Figure 20: Magnetic induction, measured in the somalloy core, with complete external yoke – 0,295 T

It can be seen, that by completing ferromagnetic circuit, the magnetic flux had increased by almost 3 times, than it was before.

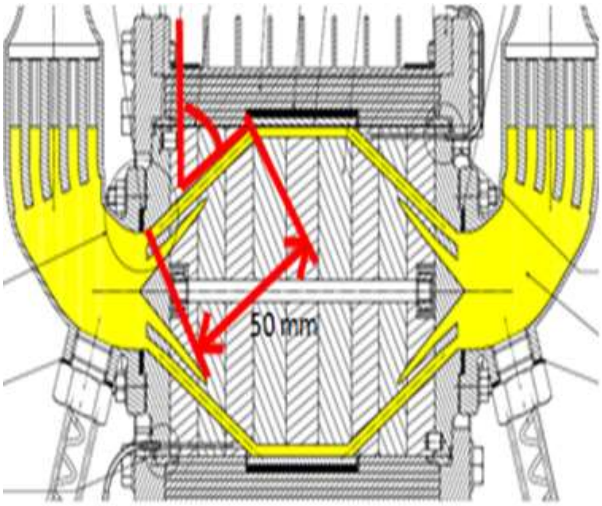


Figure 21: Using 3D drawings when recalculating induction component to the right angle, we got that the real magnetic induction that is measured in the end of channel is 0,55 T.

Here we also can see magnetic field view and the value of induction (0,28186 T) in the point, where induction was measured. So it's pretty much the same, only without calculating to the right angle.

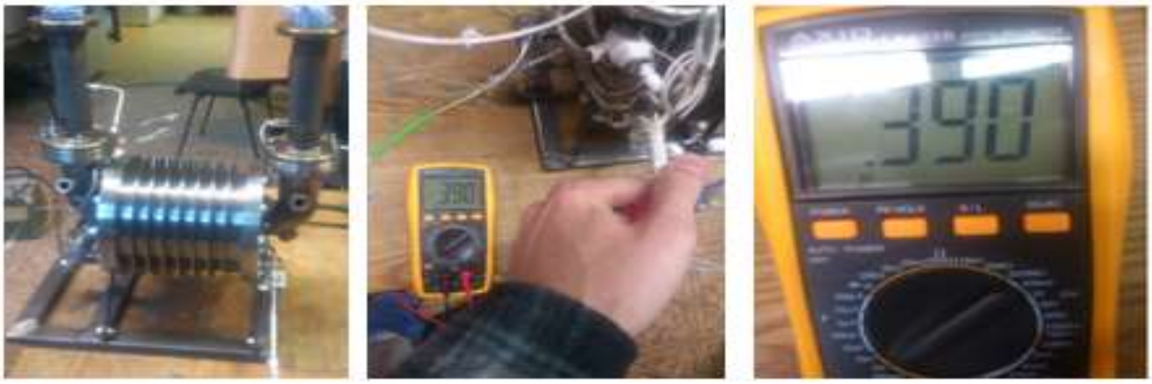
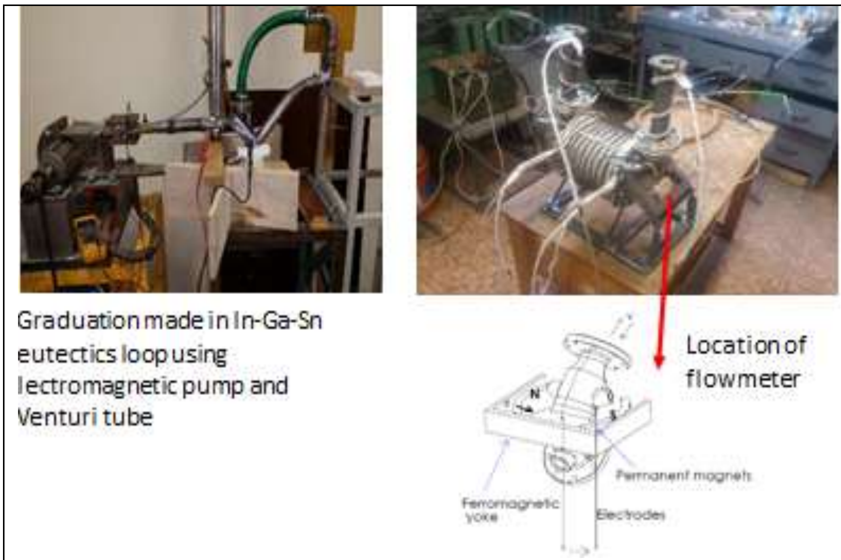


Figure 22 : inductance measurement

We have also measured an inductance of MHD generator coil. These measurements were made when MHD generator assembling were fully been finished. It can be seen that the inductance of a coil, together with the ferromagnetic yoke, are L= 0,39 H.

The measurement of velocity was made by using electromagnetic flow meter that was build and calibrated by Latvia scientists. The main elements of this system can be view in the flowing figures.

- **Flow rate measurement**

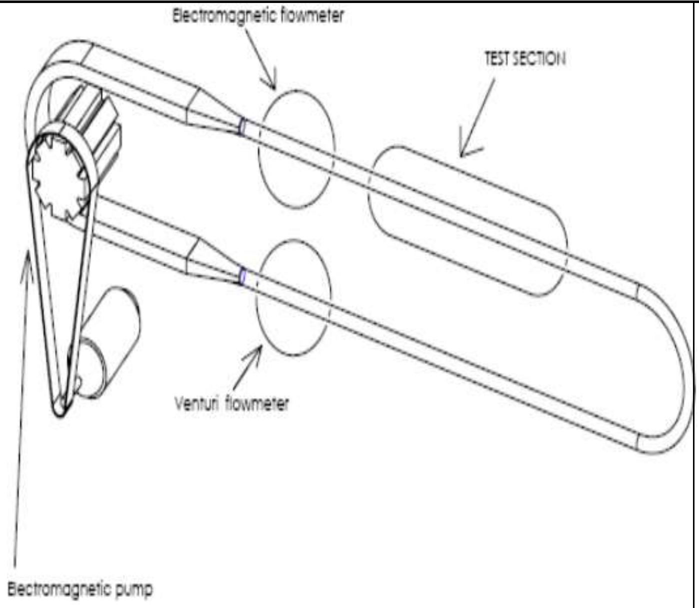


We have also made a conduction type electromagnetic flowmeter, which can measure a sodium flowrate in liters per second in the MHD generator.

Graduation of MHD generator flowmeter were made in In-Ga-Sn eutectics loop, using electromagnetic pump and Venturi tube.

Figure 23: The electromagnetic flow meter

Graduation of flowmeter have been carried out for both (forward and reverse) flow directions. At reverse flow direction the output signal of flowmeter at the same fixed pump motor rotation speed was a little lower. But from this measurement results we can not make right conclusion that at reverse direction the sensitivity of flowmeter is lower as at changing flow direction also hydraulic resistance of liquid metal In-Ga-Sn circulation loop can be different. At reverse flow direction there was no possibility to measure precisely flowrate as our reference flowmeter (Venturi tube) due to its non-symetry in geometry measures right flowrate only at forward flow direction.



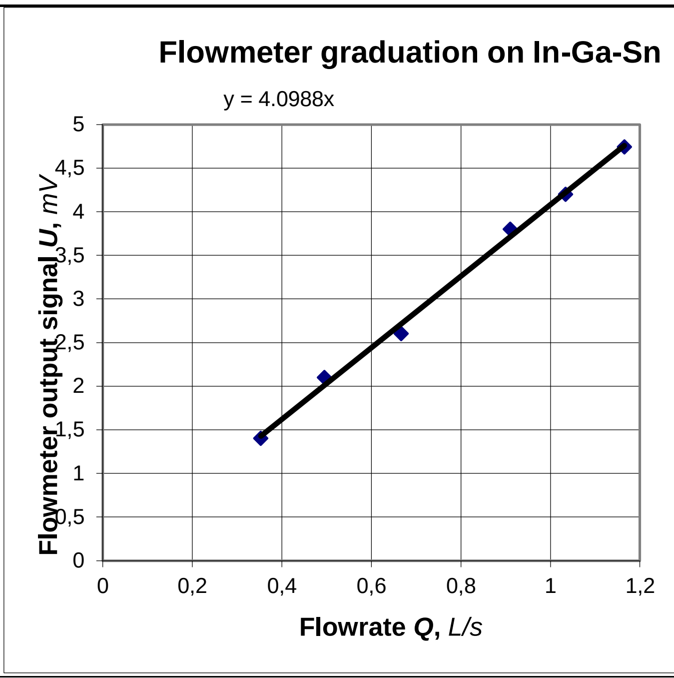
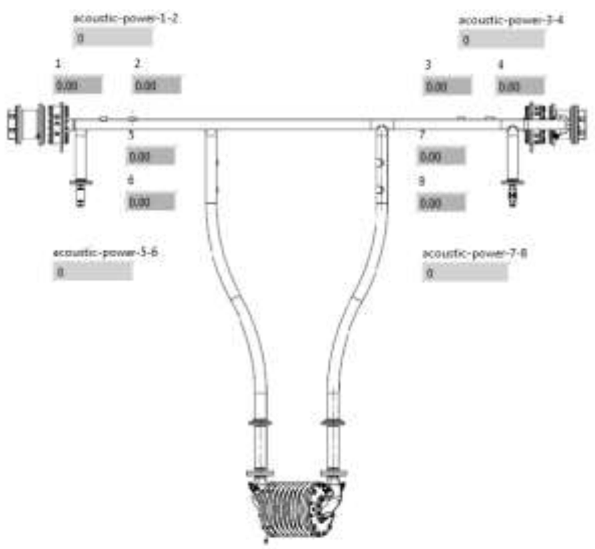


Figure 24: Calibration of the electromagnetic flow meter

The flow meter consists of two permanent magnets applied on the bent tube near the entrance in MHD generator and two electrodes welded outside on the wall. The flow meter have been calibrated on the loop with liquid at room temperature eutectic melt In-Ga-Sn and as reference flow meter the Venturi flow meter were used. The maximal flow rate of In-Ga-Sn eutectic in the loop can be reached up to 1.5 L/s. In the loop two flow meters are installed: reference Ventury flow meter and additional EM conduction flow meter. Being calibrated flow meter were incorporated in the loop in the place shown as “TEST SECTION”.

- **For thermo acoustic engine, acoustic power and pressure measurements.**

Thermoacoustic generator acoustic power measuring system was made by 8 pressure sensors coupled by 2 in 4 different places of TAC generator. This method is called 2 sensor method. It calculates acoustic power from both sensor measured gas oscillation amplitude, mean pressure, phase shift between both measurements, gas density, distance between both sensors and gas oscillation frequency.



$$P_{ac} = \frac{A}{2\cdot\rho\cdot\omega\cdot\Delta x}\cdot\left(p_{a1}\cdot p_{a2}\cdot\sin\varphi\right)$$

The TAC generator schematical measuring system is also shown below. The system consists of 4 couples of pressure sensors. This type of measuring system is called 2 sensor method. The formula below is the acoustic power calculation formula, which we used in our experiments to calculate the acoustic output power in the system, together in 4 places – 2 of couples are on the upperside of the system and 2 of them are closer to the MHD generator connection places. Like an output power indicators. The values in formula are:

A – pipe crossection area (m2)
X – distance between two sensors (m)
Rho – gas density, which is like a function of mean pressure
Fi – phase shift (radians) Omega – frequency (2*Pi*f)

Figure 25: Schematic view of the thermos acoustic measuring system.

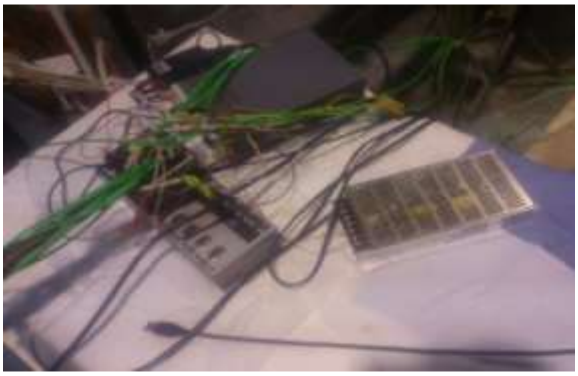
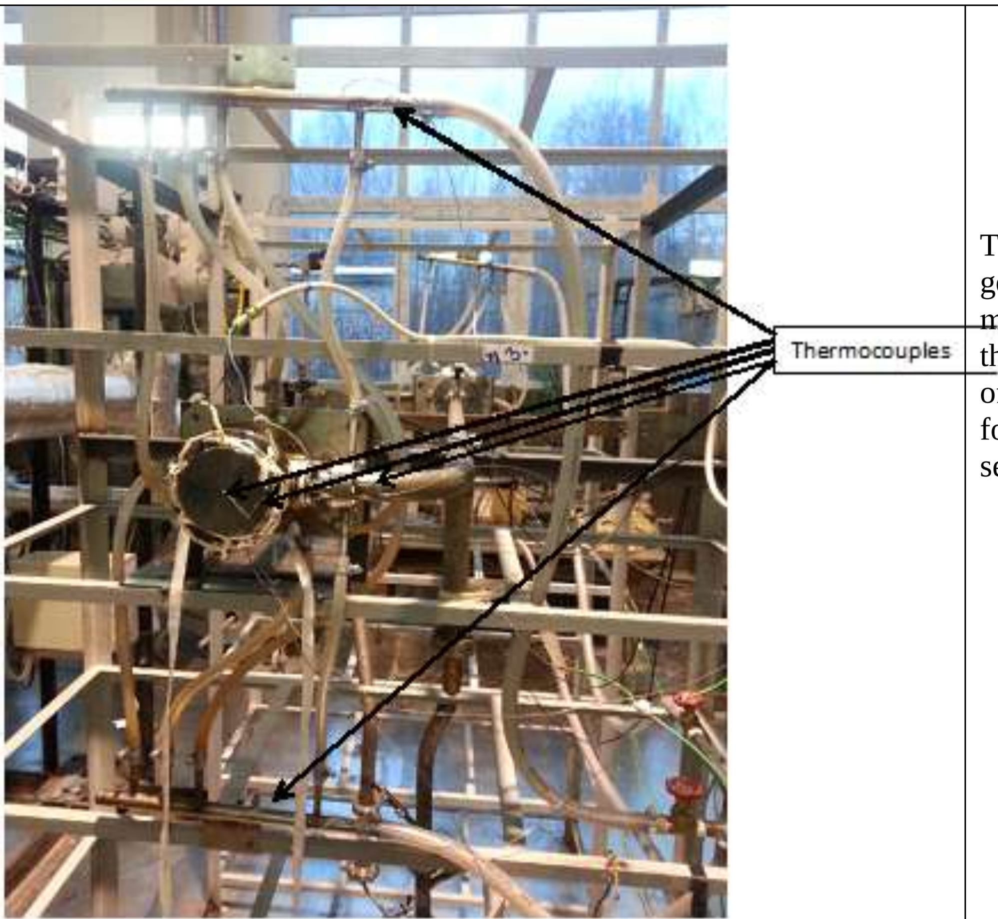


Figure 26: Elements of the thermos acoustic measuring system.

Measuring system was made by National Instruments data acquisition modules. A program for data acquisition, power calculation, saving and displaying on computer screen was written in programming language Labview. The ’’SensorTechnics’’ pressure sensors are used for pressure measurements. Measuring range of these sensors is 0-50 bar. The Labview program is measuring 1000 measurements per second, because in other case it is hard to get a good and precise phase shift and amplitude measurements. In next pictures there are samples from measuring program window.



Temperature on the TAC generator surface was measured with “K” type thermocouples. The overview of positions of thermocouples for one TAC generator can be seen in picture

Figure 27 : The thermo acoustic loop with the locations of the thermocouples

c: TAc engine manufacture

First of all it is recalled that the geometry of the Thermo acoustic engine was slightly modified from the design proposed by the SERAS office, CNRS, Grenoble in that sense that instead of to have a rolled tube for the thermoacoustic engine as it is shown on the following figures (Fig.   a) the tubes thermo acoustic are straight, with the same diameters and the same length that was initially designed. This preliminary geometry was adopted to facilitate the tests and in particular to control the more easily the interface evolutions between gas and sodium.

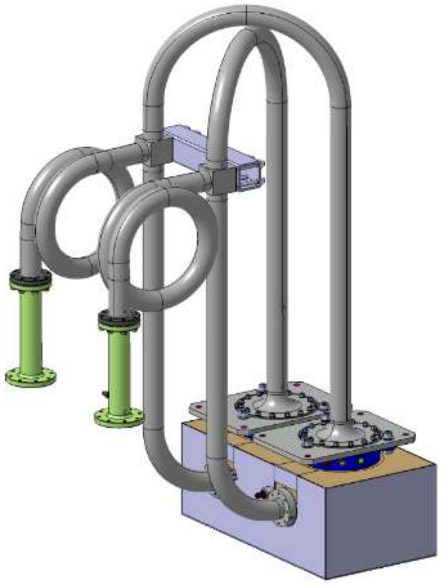


Figure 28: View of the coupling of the both engines as it was designed

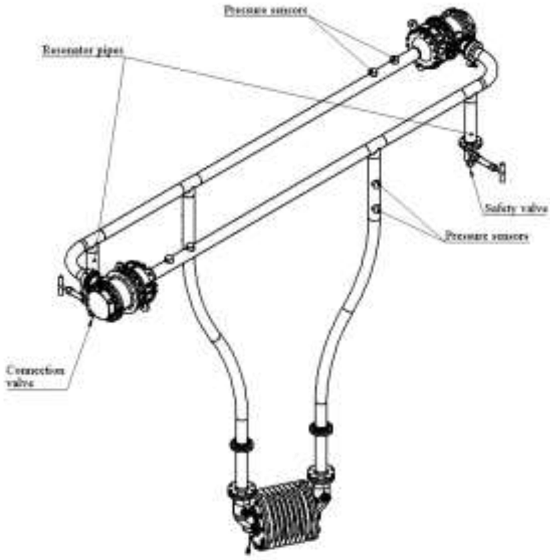


Figure 29: View of the coupling of the both engines as it was constructed

Some parts of the thermo acoustic engine was realised at the IPUL by the technician men of this laboaratory, exepted important elements that was subcontracting, zirconia flanges importation from china, Titanium flange that was operated by 3D prototyping by the society (????). The cold exchanger was and the regenerator was realised by the same French company SOREMET . The detail of the pieces constituing the thermoacoustic engine is given here after:

Figure 30: The hot exchanger

This part is made from Inconel.While experimenting, it’s being heated up to 1100°C with electrical heaters.

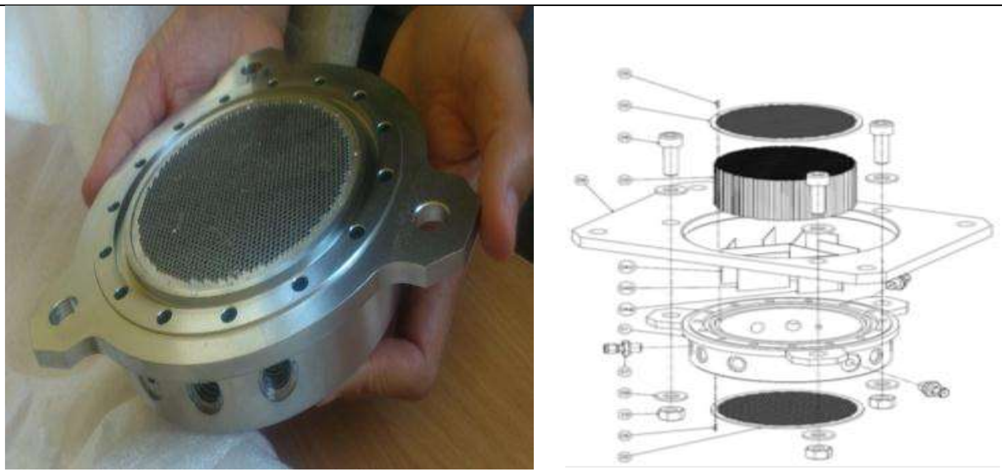


Figure 31: The cold exchanger

This part is used for cooling. Inside TAC an argon gas is oscillating and it is cooled by water flow through cold heat exchanger. It consists of many small tubes in diameter 1,7x1,0 mm and deflectors which are like separating walls. They are used to change water flow direction inside cold heat exchanger

Figure 32: Zirconium connection and Zirconium flange

This part, together with Zirconium flange, is made from a special Zirconium Oxide ceramics. Ordered and manufactured in China. Zirconium connection separates a hot part of TAC generator from feedback tubes, so heat cannot go away from TAC generator

Figure 33: Zirconium flange

Zirconium flange separates cold heat exchanger from hot heat exchanger. Inside zirconium flange there is a regenerator, which has been made by stack of steel. It consists of many steel plates, where heat can go from one plate to another.

Figure 34: Inconel shield

It's made also from Inconel steel and it serves as shield for hot heat exchanger

Figure 35: Graphite seals and O-rings

All sealings in thermoacoustic generator has been made with high pressure stainless steel graphite sealings and with O-rings made from Viton material, made for high pressure.

Connection tubes Both thermoacoustic generators are connected to each other with stainless steel connection tubes. There are also 2 connections going to MHD generator connection. When the temperature difference between hot and cold heat exchangers are reached high enough, and when pressure is raised up to 40 bars, a TAC has been started to work normally and gas pressure is oscillating. The tubes are like road where travelling acoustic wave is travelling. Some part of acoustic power is going to the MHD generator connection which can oscillate liquid sodium inside it.

Variant	CHe-Res	Res-HHe	Res (LOOP-dovn)
Original	1162	723	804
V1	1199	1424	834
Built	1060	700	1100

Table 4: Comparison of length of pipes in three variants of TAc

Original

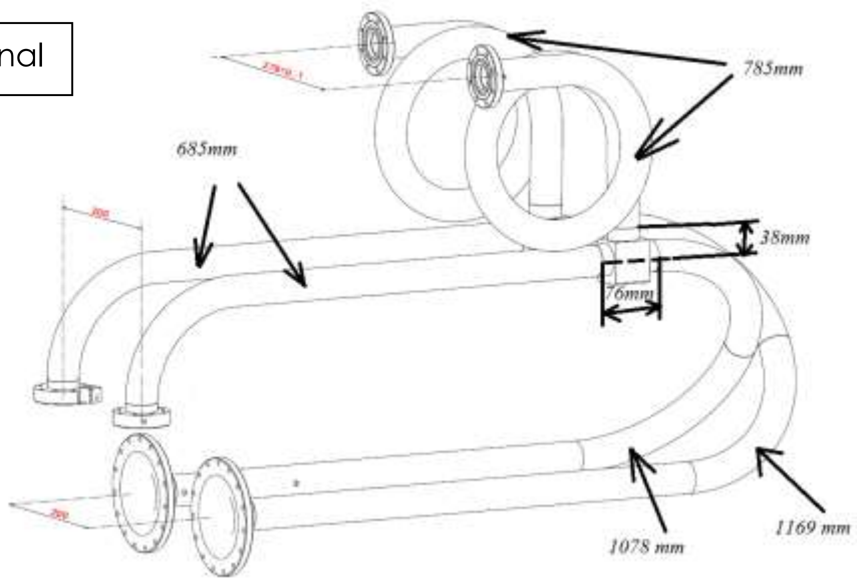
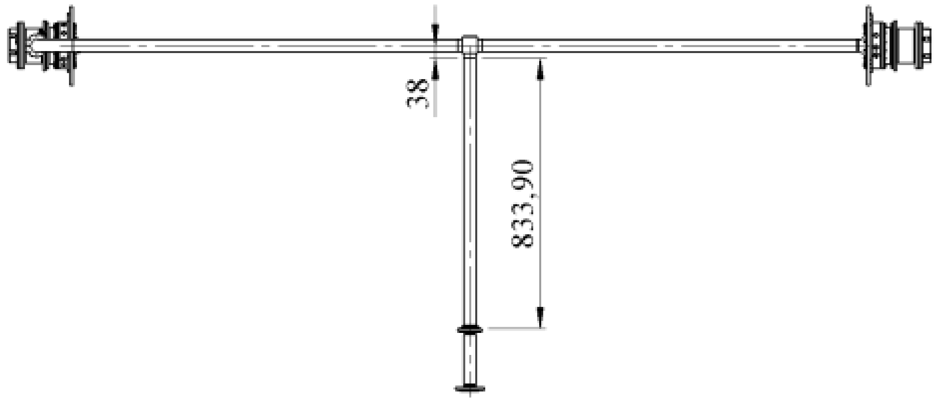


Figure 36: Original design of the Thermo acoustic loop.

V1



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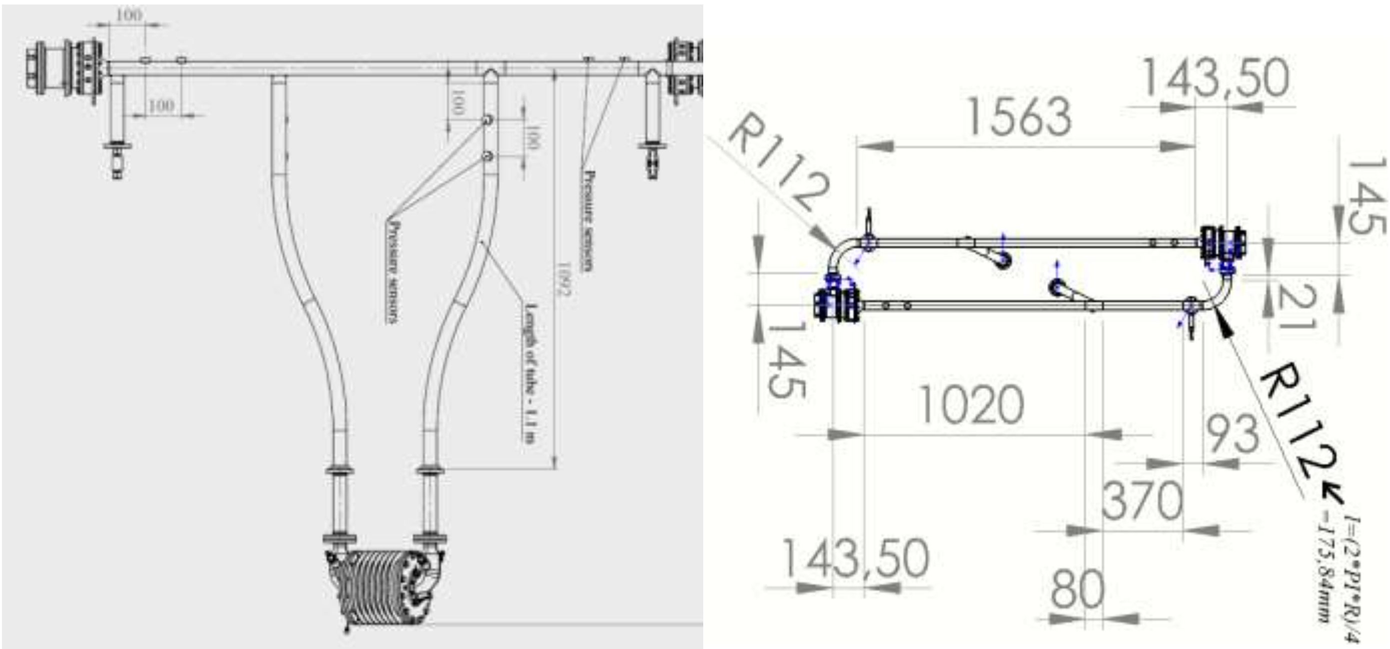


Figure 37: Modified design of the Thermo acoustic loop

Figure 38 : Photo of the constructed thermos acoustic loop

Due to the evolution of the geometry of the thermo acoustic engine, the supporting structure, made with stainless steel tubes was modified and the thermo acoustic loop was fixed on this structure. The view of the thermo acoustic engine fixed on the structure is given Below (Figure 36).

d: MHD machine manufacture

Main of the pieces were realised by IPUL, by classical machines, under the direction of both Raimonds Nikoluškins and Arturs.Brekis and under the advising of Janis Freibergs. Some parts was subcontracted.

.

For the assembly some very specific tools was machined, having been designed by the SERAS office (CNRS Grenoble).This specific tool were realised for the assembling of the magnets on the generator. This is necessary by the by the fact that is is impossible to maintain the magnets with the hand due to the extremely intense magnetic forces between the Ferro magnetic material and the magnets. Therefore, the magnets are mounted with glue on a special device (Fig. 39 a, b), and approached slowly, by screw up to the contact with the MHD generator (Fig. 39 b). When the contact is established, the screw is removed that is possible because the magnetic force is higher than the glue is able to support. So step by step, reproaching two magnets located on a diameter alternatively, all magnets was placed on the MHD generator.
After this operation the coil was wound on the magnets, (Fig. 39 c) and the ferro magnetic material used for the closure of the magnetic field, assembled externally to the coil (Fig. 39 d). Then all these elements was introduced in the external enveloppe surrounding the generator. The two tubes at the two extremities were placed for the connection with the TAC engine or with the compressor for the tests (Fig. 39 e f)

Figure 39: elements of construction of MHD generator

The heater was wound on the generator. It is used to melt the sodium prior to use and to preheat all parts of the generator (Fig.40)

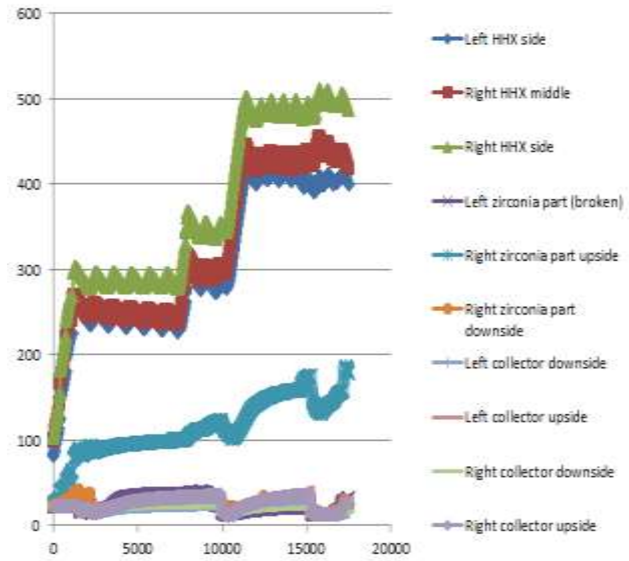
Figure 40: The MHD generator equipped with the heating elements

e : Tac engine tests

The detail of the tests will be reported in the deliverable test results. One difficulty for testing alone the thermo acoustic engine comes from the fact that without the connection with the MHD generator there is no load to absorb the mechanical energy produced and then this element, the MHD generator has to be replaced by and other load, able to dissipate the mechanical energy produced. This element that have been specifically constructed under the advising of Maurice Francois from HEKYOM, needs to have the same impedance than that the MHD generator. This was realised on the form of a friction tube giving high friction losses dissipating the mechanical energy produced but the thermo acoustic engine.

Figure 41: First elements of connection betwen the two actves parts of Thermo acoustic loop

Experiment with shortly-ended ends means, that in this experiment there were no hydraulic resistance in the ends of TAC generator – the ends were closed. To get an exact parameters of acoustic-wave that maches with this type of construction, as it was calculated for, we have made and have put inside the endings 2 metallic rods.



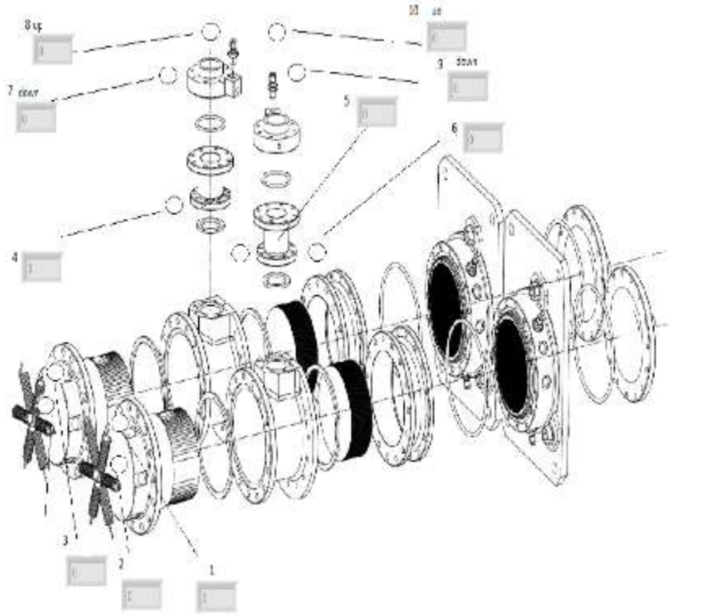
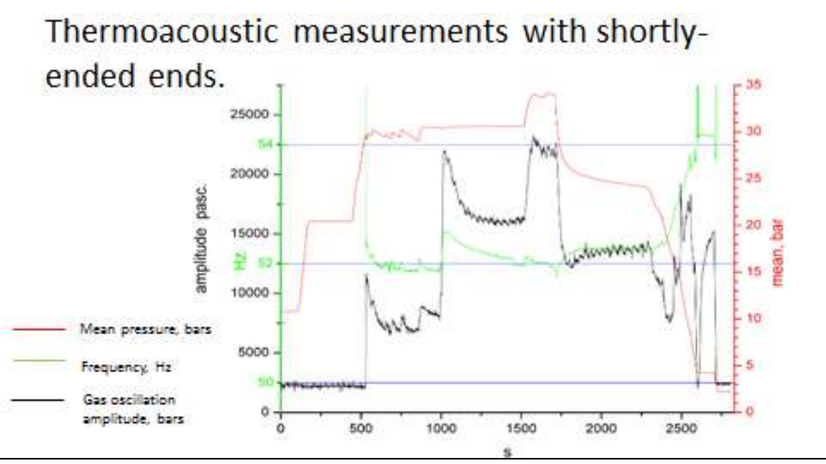


Figure 42: First test results

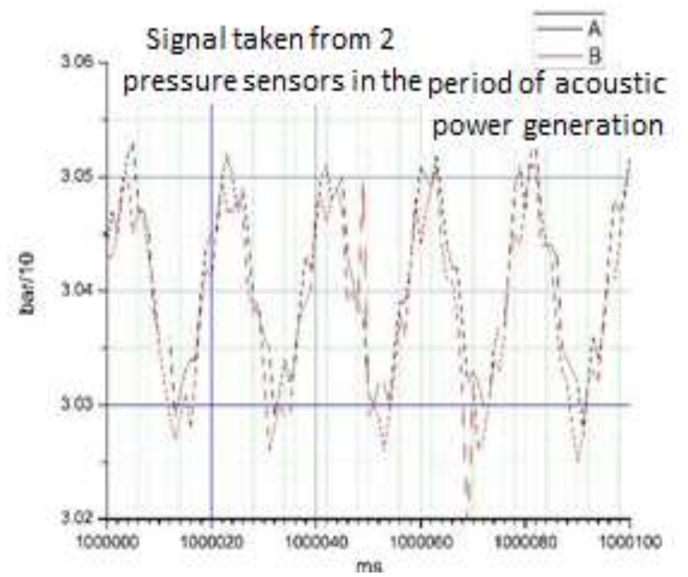
First experiments were made without any hydraulic resistance in the ends of the TAC generator in place where MHD should be. Tests are made in order to get onset of wave oscillation. It is obvious that under a very unappropriate loading, the TAC cannot develop an acoustic wave large amplitude. In the picture below there can be seen measurement results of the first try. The acoustic power generation had been started when hot temperature reached about 300°C after some 500sec heating. The amplitude rised up to 10 000 Pa, frequency – about 52 Hz. Mean pressure were rised up to 30 bars.

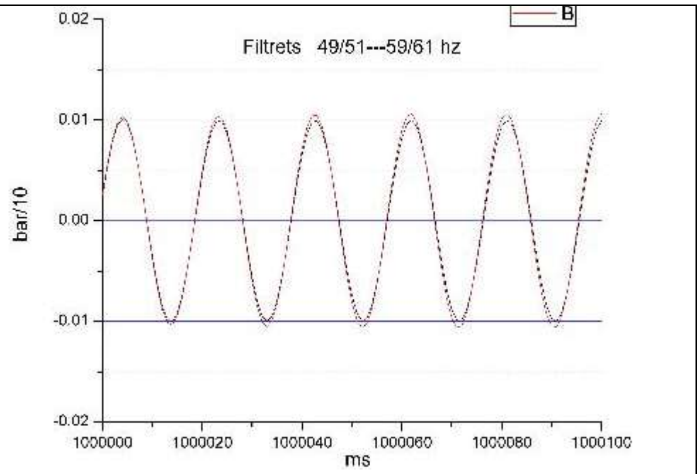
Here we also can see temperature measurements of TAC thermocouples and positions of where thermocouples are put in the TAC generators.



The written results of the argon oscillations are shown in the graph. It can be seen, that we were increasing mean (or average) pressure in the system by steps – by 10 bars, simultaneously increasing the temperature of heaters in hot heat exchangers. The acoustic power generation begins when the mean pressure has reached 30 bars. The gas oscillation amplitude in the first moment are high enough and then it starts to decrease a little bit. Then it stabilizes. The frequency measurements, as it can be seen, are allways about 52 Hz.

Figure 43: test results: dependency between mean and oscillating pressure

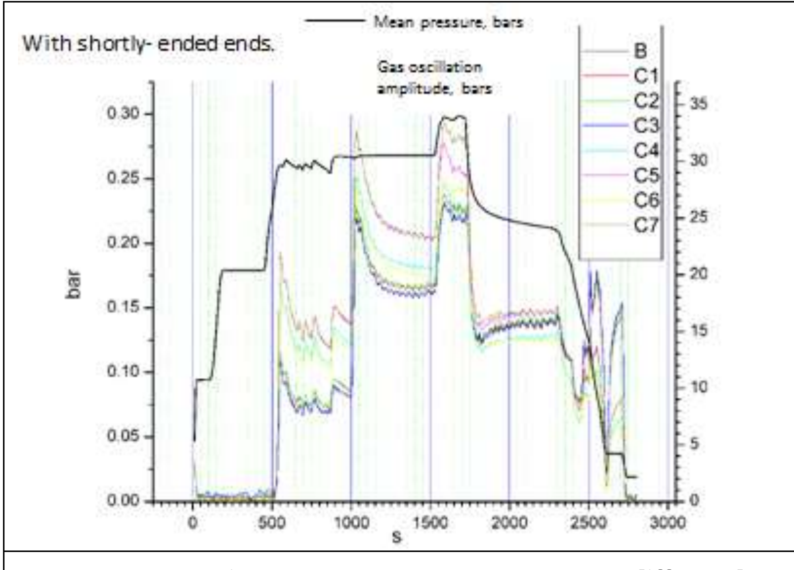




Here can be seen a part of a saved signal in the time when the acoustic power generation had been started at 30 bar mean pressure.

Here we can visually see the gas oscillations. The way we got our measurements better were mathematical filtering method.

Figure 44: Oscillating pressure before and after filtering.



The written amplitudes of all pressure sensors in TAC system, like it can be seen, are pretty much similar and there aren’t big differences in different pressure sensor measurements.

Figure 45: Pressure measurement at different locations inside the thermo acoustic loop

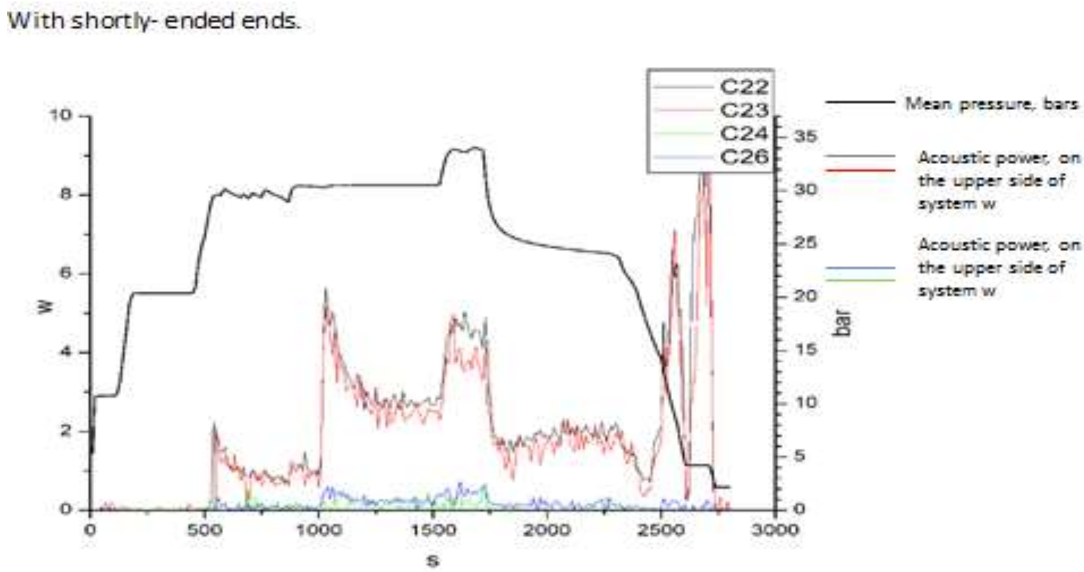


Figure 46: Acoustic power measurements.

The acoustic power measurements can be seen in the graph below. Measurements in the upper side of system are black and red curves and down side are blue and green. The acoustic power are about 5 watts in the upperside. Remind that without the designed loading (MHD engine), TAC cannot develop more acoustic energy.

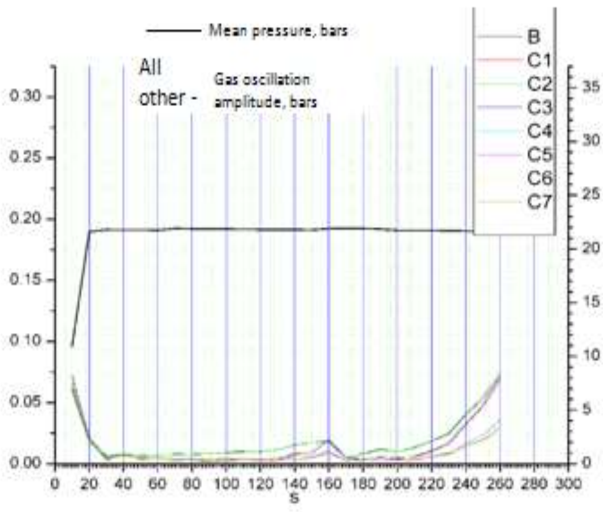


Figure 47: second system of connection between the two part of the thermo acoustic loop. The valve allows adjusting the hydraulic losses.

The purpose of this experiment was to test the possibility of making hydraulic impedance on the ends of TAC generator and to see how it makes changes on the measured values of acoustic power, frequency etc. For this, a valve had been put on the ends of TAC generator like in picture above Here we can see the amplitude measurements of the TAC generator in the position when the valve is fully closed. The acoustic power generation fully stops, and the amplitude of gas oscillations are going down to zero.

During the campaign of tests, many difficulties were encountered.

First of all the zirconium flange was broken many times. It seems that many element could explain this difficulties, one being the bade quality of the material furnished by china, and the second one can be attributed to the level of mechanical constraint due to the temperature gradient at the level of the cold exchanger higher

than expected because the level of temperature of the cooling system was lower that that was take into account in the calculation.
Secondly many likes was observed during the test when the thermo acoustic engine was operating at high pressure (it is recalled the nominal pressure is 40 bars) and at high temperature (the nominal temperature at the hot exchanger is 900 K).

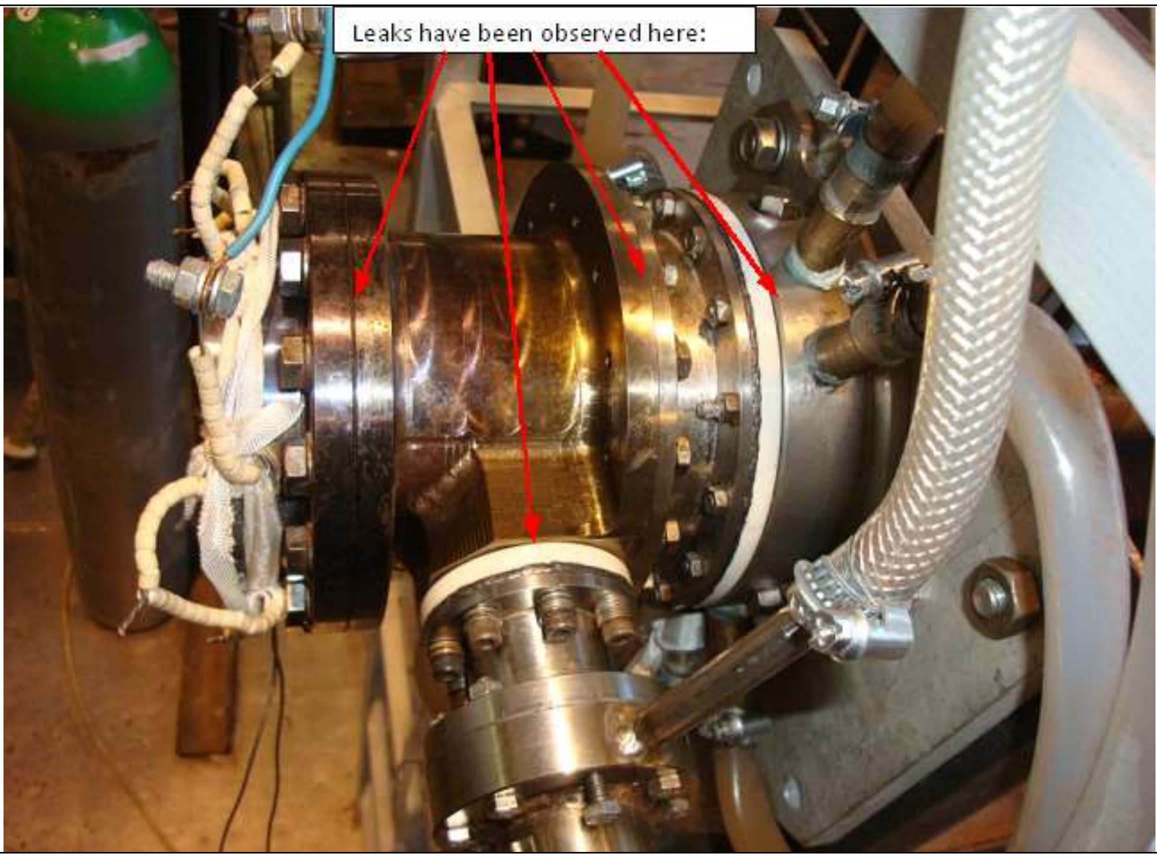


Figure 48: Location of the leaks that appear during test operations

Leaks of Argon gas from TAc generator initially were almost at all sealants. At the cold sealants (rubber Viton O-rings) in both sides of cold heat exchanger the leaks were prevented by applying high-temperature silicone sealing mail. The leaks through high temperature graphite sealant rings were not possible to prevent. The gas leakage starts at pressure more than 20 Bars and at 30 bars and more - it is so large that sometimes you can hear the sound of leakage and feel it even by hand if it is placed close to leak place. We have tried several configurations of graphite seals and tried to apply high temperature (up to 1000C) proved glue but unsuccessfully.

Figure 49: Rupture of the zirconium pieces

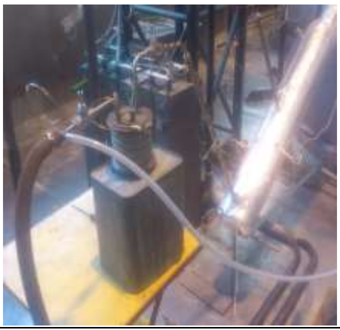
Zirconium oxide ceramic parts were crashing one by one because of the thermal reasons inside these parts. A place where it is possible to order them is a Chinese company „XIAMEN INNOVACERA ADVANCED MATERIALS". It took about 1.5 month for one part to be delivered.

f: MHD engine tests

The tests of MHD generator involve the use of liquid sodium that involves specific precautions and special equipment. In particular the operation of filling of the generator has to be done carefully. the following figures summarises the filling operation

1) before heating system mounted

3) fully assembled; with thermoisolation



2) with heating system, vacuum pump and argon bottle connected

4) Connected to MHD generator

Figure 50: Procedure for filling sodium in the MHD generator

A special tank had been manufactured like a preparation for filling sodium in the MHD generator. It has been filled up with the about 1 l of liquid sodium, so right now the tank is easy to transport from one place to another. The sodium had been warmed up to 150° to be sure that it had became liquid.

Next step was sodium tank gas/vacuum cleaning – the tank were many times vacuumed, then filled with argon to be sure that everything is ready for sodium. Control of sodium filling levels were made by spark plugs as level sensors. Temperature was controlled by thermocouples.

Measured output values:

Voltage, current (with load), frequency.

Max. alternating current: 0,034 A

Max. voltage: 3 V

With frequency – 12 Hz

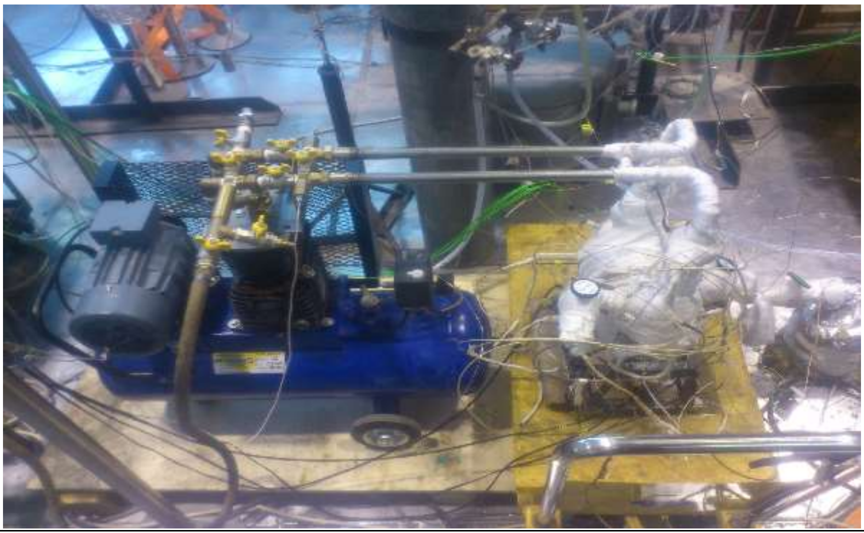


Figure 51: view of the test operation of the MHD generator actived by the compressor

Making experiments with the sodium, we saw that the maximum output voltage amplitude of the MHD generator were 3 volts, alternating current – 0,034 amperes, frequency – 12 Hz. These measurements were made by compressor rotating frequency of 14 Hz. So the registered frequency of alternating current is similar. The highest registered flowrate in all experiments with the flowmeter was 0,1 L/s. In the all next experiments, it was clearly seen, that every next try was with worse results. In the next try we saw, that the output voltage was about 1,41 V with 0,021 A current,and next one was about 0,92 V. It seems that inside the MHD generator there are some bubbles gone inside the sodium channel or some different reasons.

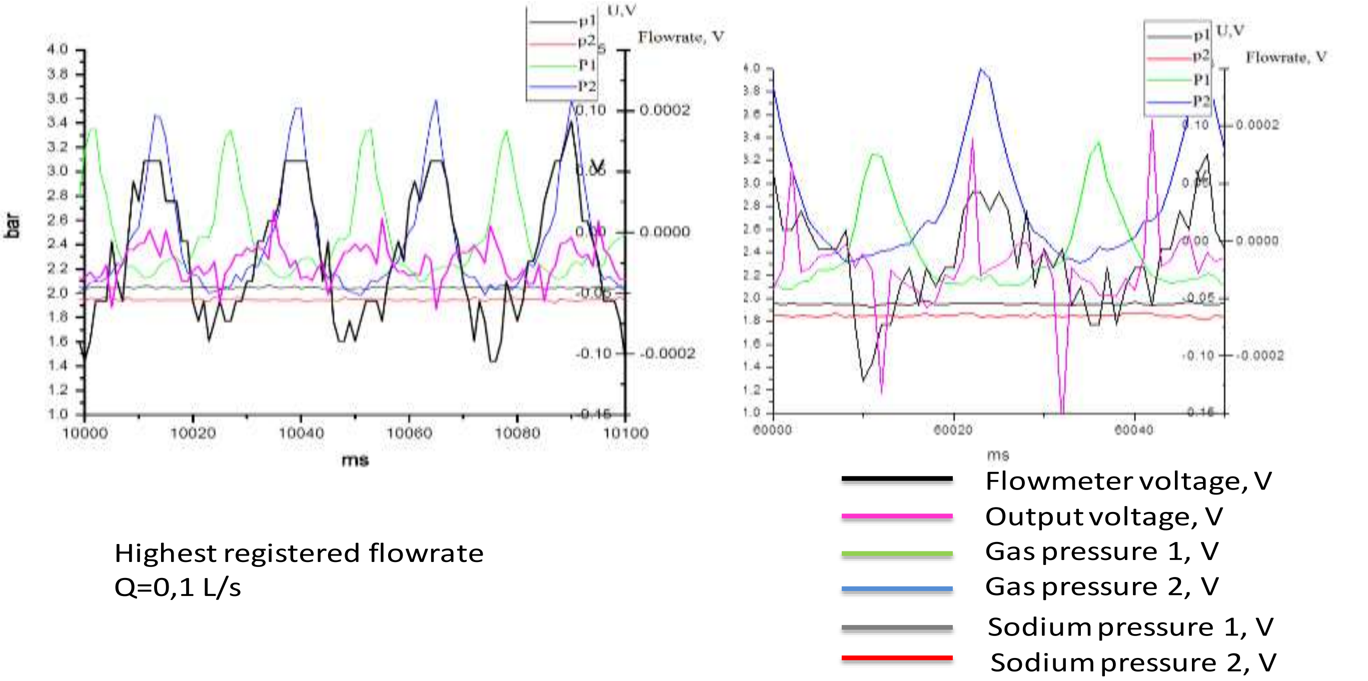


Figure 52: MHD tets results

Here we can a typical compresser-MHD generator testing curves. The black graph is flowmeter's output voltage and the pink one is output voltage. They are shown in 2 different periods of time. It can be seen that, registered small upper pressure sensor oscillations are periodical and they are in the opposite phases. The highest registered stabilized flowmeter output voltage is Q=0,1 L/s.

After the tests all the pieces have to be washed to be ready to do the new tests, the procedure of a good method for experiment have to be established carefully.

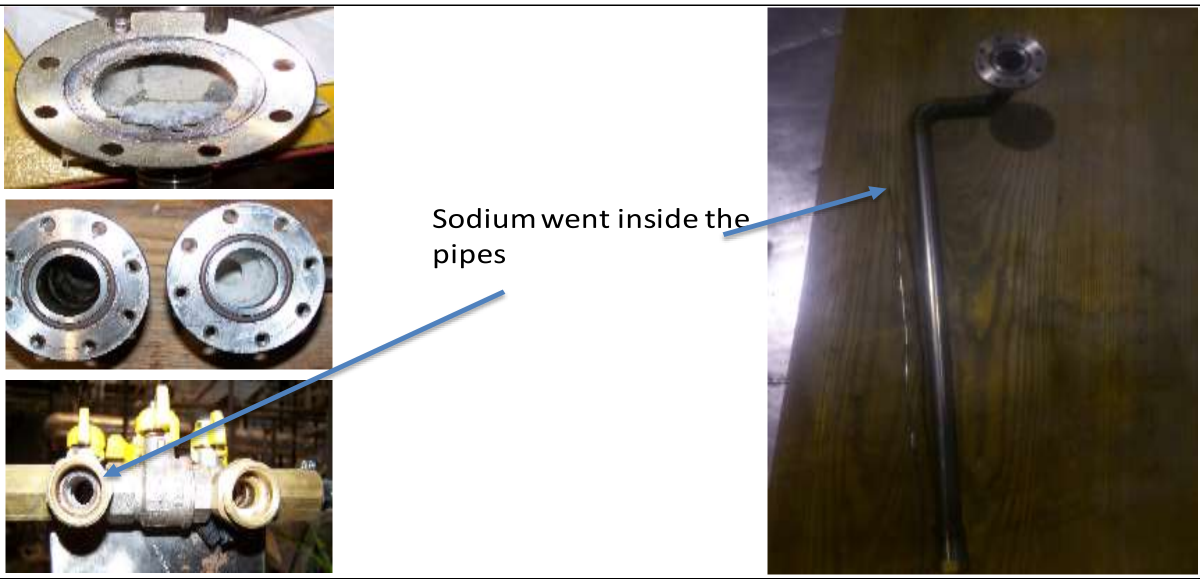


Figure 53: Cleaning of some elements after sodium testing.

After the sodium experiment in the MHD generator we found that in time of sodium oscillations, the sodium had gone inside the compresser-MHD connection pipe and stuck inside there in the distance about 15 cm from the beginning of the pipe.

g: Breadboard assembly and Breadboard Tests

The results of these tests (not realised at the present time) will be reported latter

3.2.1.2: Other Partners activities.

The various work packages of the different partners concern the following elements

WP3: SRPS reference design
WP3: Task 3.8: Simulator feasibility study
WP3: Task 3.9: Lessons learned
WP6 : Workshop
WP6 : Presentation to ESA

These works are reported in the corresponding deliverables. Some details of the works done by partners (excepted the IPUL work that was presented largely above) are reported below

HEKYOM activities

The work of HEKYOM in 2015 was finally important for several pints :

1. It was necessary to follow the TAC manufacturing whose several elements as regenerator or HHEX are very specific and hard to make according to the rule book.
   This was made by many mails and telephone calls.
2. IPUL engineers were not familar with TAC system mounting and testing. Acoutic pressure or energy measurements are indeed also specific and requiered some training period to be correctly performed. HEKYOM was in charge for such teaching and following up. IPUL engineers were visited HEKYOM and made a first training course for acoustic and thermoacoustic devices measurement and control.
3. First TAC assembling had to be carrefully checked by HEKYOM and for best success chances getting, HEKYOM (Maurice François) and ASTER (Kees de Blok) heads visits were decided twice (see below)
4. HEKYOM participates to dissemination work by presenting Space Trips in a thermoacoustic workshop and by participating to several events organised by A.Alemany inside the Space and Plasma scientific community such as CNES, CIRA (Italy), Cagliari (Sardinia Italy), CNRS, ESA..Etc.

- **First meeting: July 21-24, 2015.**

HEKYOM visit was decided to provide support to IPUL for their work on the installation of the thermoacoustic engine and setup of the test environment.Every parameter of the thermoacoustic device has been checked. Pipe lengths were controlled and show some mistakes. Two small “stub” necessary for getting right matching condition between TAC engine and MHD engine were added. A new precise drawing is provided .

A static Test (with no acoustic wave) of heating supply has been made and the result is pretty good, with a global thermal conductance of 0,5W/°C between the hot source coupled to the hot heat exchanger and the external environment. As an example, 650°C has been reached with 300Watts input. It means that the dynamic test could be performed next times. Another characteristic is the very big heat capacity (MCp –J/°C) of the heating sample composed by HHEX and its Inconel housing. The fact that the required thermal energy will be of the order of few hundred joules seems likely to make quite difficult a precise heating power measurement and suggests for looking at acoustic power and cold HEX power measurements. Thus a particular attention will be given to these last parameters. It can be also noted that in general for a thermoacoustic engine, hot temperature is a consequence of energy balance between thermal power, acoustic power, viscous dissipation and thermal losses. In our case, due to this enormous heat reservoir (HHEX+housing), hot temperature would be imposed but with a quite long time constant and thus a relative difficulty for reaching a quasi-stationary state.

Instrumentation have been carefully checked: pressure sensors (a new company much cheaper is proposed), indication for location and mounting procedure – indication for thermocouple location – flow meter for cooling system.It was also proposed to take in account these improvements for the final report given by IPUL.

A list of different operation to be performed at IPUL, before the next experimental run, is given:

1. Safety pressure test with water at 60bars must be performed
2. M5 screws used for fixing the (08) flange connecting CHEX to the next pipe must be checked because they look like too feeble. This gives opportunity for controlling all used screws
3. New lengths for acoustic circuit are provided and must be made
4. Pressure sensors adapter pieces drawing are provided
5. 4 new Tees (smooth angle) to be mounted are to be bought. The sharp angle Tees used will give a strong acoustic dissipation and lower the available acoustic power for driving MHD engine.
6. 4 Special pieces are to be made for Thermocouple connector: cooling water circuit (see photo from HEKYOM)
7. Mass flow rate sensor for cooling water circuit to be added
8. For **separated TAC tests,** a special U tube(with heating wire) filled by sodium connected to TAC engine in place of MHD device with a valve in the middle will be manufacture and mounted
9. A safety valve is to be mounted on one "stub" extremity
10. A filling valve is to be mounted on the other "stub" extremity

Concerning the critical problem of liquid gas interface:
Experiments were made with IPUL set up until 50 Hz. They used a solid separation between the two phases as shown in the IPUL report. They show some 'splash' of liquid above the solid separation.
It was noticed that the gap between this solid bloc and the wall, about 3 mm, was much too big and could explain the presence of these droplet splashes. But using such a moving piston with a small friction seems to be the right purpose.
HEKYOM suggests making some more experiments with:

1. A glass or Plexiglas tube with a nice wall and small rugosity
2. A light cylinder compatible with Sodium whose length would be tested, 1cm or 2 cm..
3. Taking new pictures

Further TESTS
It was decided that the **TAC engine test** will be made after the separated **MHD test** will has been already achieved. Then, it will be possible to make in the next visit (HEKYOM)

1. MHD test before 24 08 15
2. TAC test 24 08 15
3. Global test 26 08 15

HEKYOM, 24th of July 2015
Maurice-Xavier FRANCOIS, Kees de BLOK

- Second meeting, August 25-28, 2015.

1. Space TRIPS device (STD) : Mechanical damage

HEKYOM has been informed (25th afernoon) new problems occuring with STD during first tests. Zirconium housing of one regenerator experiences a « crack » when heated up. Another zirconium piece connecting hot heat exchanger with acoustic pipe was broken.

26/08/2015

a. HEKYOM examines carefully the two pieces. It was founded :
b. Measured holes made into Zirconium flange (regenerator housing) are not large enough and the measured difference (0,15mm) between this hole diameter and bolt diameter on one hand and the thermal dilatation of Inconel flange (0,6mm at 800°C) on the other hand could explain the « crack.
c. Zirconium fail is probably due to :
    i. Either a mounting error introducing differential forces
    ii. Or a little lenght difference between the two long acoustic tubes introducing forces at the bend part.

iii. Or a default in the manufacturing material and process (a photo will be joined to the final report)

2. Information are sent to SERAS and Antoine Alemany

3. HEKYOM proposes
    a. to enlarge the hole diameter of the zirconium flange 019 : impossible
    b. to locally reduce the bolt diameter suppressing the male thread of bolt on a short distance corresponding to the zirconium flange thickness.
    c. Agrees a proposition of Janis Frieberg for adding a bellow on each long acoustic tube for dilatation compensating
4. As already decided by IPUL, HEKYOM agrees that every zirconium piece will be temporarely replace by stainsteel equivalent piece.

27/08/2015

Modifications were made 26/08 by IPUL workshop. All bolts were modified as suggested. Noting that one regenerator housing is still in zirconium and the other in stainsteel, when heat was supplied, the stainless steel housing is of course about sixty degrees lower than the Zirconium one with more or less the same electric power applied. But this was not a big problem.

The measurement system was carefully updated and calibrated to provide the correct sensor signals.

Because the MHD generator was not present, the frequency was sligthly different, the impedance seen by the thermoacoustic engine was strongly modified deviated from the design impedance, inhibited oscillations. As a workaround insert rods were placed inside the transformer tubes. This was sufficient to get oscillations started.

Argon gas and heat was carefully supplied. But at the first run, a leak appears for 25 bars into the 0-ring seal at the safety valve. It was repared.In a next test, increasing again Argon pressure gas and heat supply, up to 30 bars and 400°C wall temperature, gas oscillations occur at an amplitude of 15kPa at a frequency of 52,4 Hz.In conclusion, the IPUL modified acoustic configurations are good and allow the system working.

Further experiments are to be performed by IPUL up to 800°C and 40 bars. Carefull measurements have to be made and complete energy balances will be provided.Of course, maximum acoustic power will not be available because of too small loading. Data will be sent to HEKYOM and assistance for analysis and understanding will be provided

CNRS Activities

After sizing and designing the ground prototype, year 2015 was dedicated to manufacturing, integrating and testing the ground prototype. Those activities were carried by IPUL as illustrated in the work breakdown given in table 4. In 2015, CNRS activities were organised around technical support to IPUL, calculations, and dissemination.

CNRS Activities

Task 2.1 Experimental unit definitions

Task 2.2 TAc engine detailed design

Task 2.3 MHD machine detailed design

2014

IPUL Activities

Task 2.4 TAc engine Manufacture

Task 2.5 MHD Machine Manufacture

Task 2.6 Experimentation plan and means

Task 2.7 TAc Engine tests

Task 2.8 MHD engine tests

Task 2.9 Breadboard assembly and Breadbords Tests

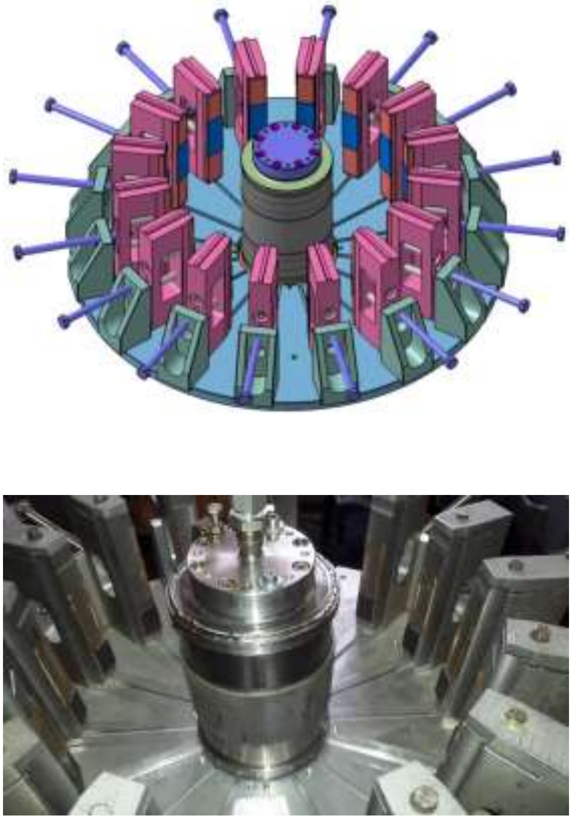
2015

Table 4: activities breakdown for the WP2

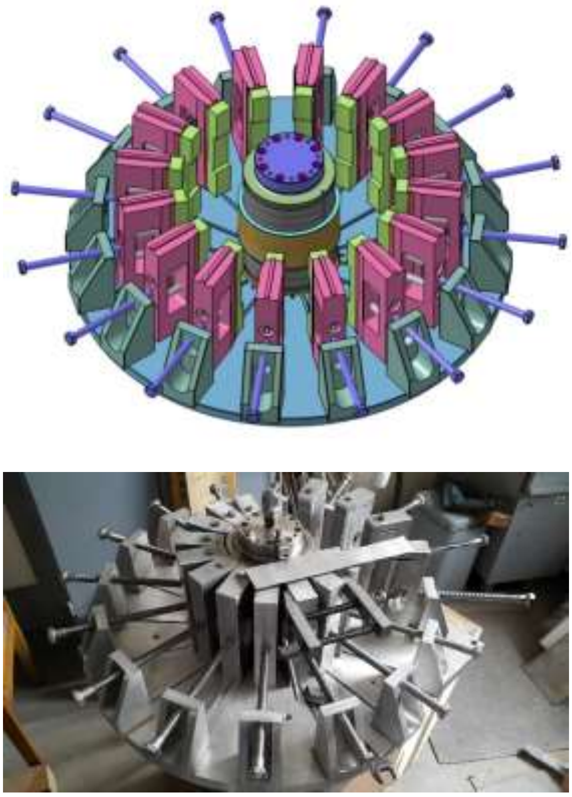
Technical support

For the phase of manufacturing, CNRS try to assist IPUL work in several ways:

- For **the sub-contracting activities**, CNRS-SERAS provides quote price and potential subcontractors able to perform the machining activities.
- To deal with the **modifications between designed and as built prototype**, CNRS proposed a document to track changes and evaluate their impact. The template is given in annex 1.
- For the magnet assembly and the yoke assembly procedure, CNRS **designed tooling** devices adopted by our partner (ref. figure 2).



a: Module MHD partially mounted: core and titanium shell



b: Module MHD partially mounted: yoke element positioned onto the magnets and the coils

Figure 54: designed and manufactured tooling for the assembly of the magnets with the ferromagnetic yoke

For **the testing phase**, testing reports template has been proposed for MHD, TAc engine and the prototype. Files are given in annex 2.

- **Calculations**

Finite element calculations were carried out for specific and critical parts.
Furthermore, vibration behaviour was calculated using Samcef software.

In addition, SERAS has spent a lot of time for preparing and writing the technical report part of the justification file. These reports are included in the following deliverable D2.1 Tac / MHD Design File and D3.3 Simulator feasibility study (sensitivity of the prototype to vibration).

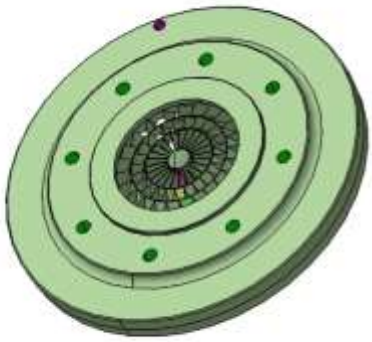
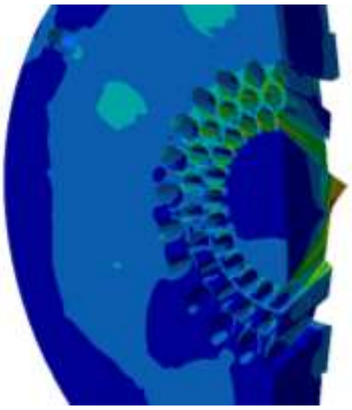
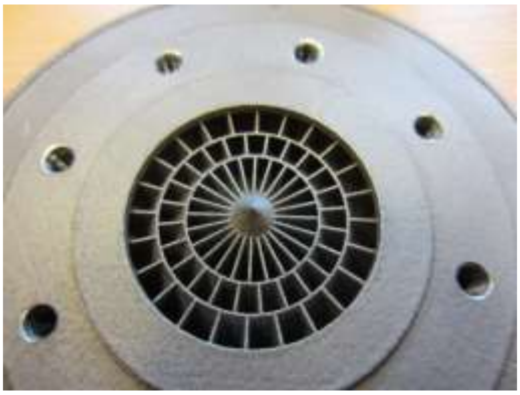


Figure 55: titanium flange of the MHD module (part of the sodium channel) - CAD model



a: (part of the sodium channel) - Von Mises equivalent stress



b: (part of the sodium channel) - realized by 3D prototyping technology

Figure 56: titanium flange of the MHD module

AREVA TA activities

The SRPS reference design. This work package, detailed in the deliverable D3.2,was realised under the responsibility of AREVA TA. It concerns the establishement of a space concept using the evolution of the differents elements discussed all along the project. The detail of the evolution of the concept is given below as it is reported in the deliverable D3.3 Simulator feasibility study

At the beginning of the study, based on a TAc input needed power of 440Wth for each TAc engine, a preliminary size of the space hot source was calculated. This hot source was made of 8 Heat Source Modules, delivering a total power of 1160 Wth. A first architecture was suggested by the TAc specialists

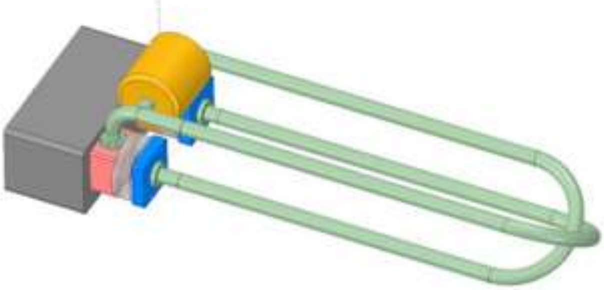


Figure 57: First architecture

Taking into account this architecture it was suggested rolling the tubes in order to lower the needed volume. On this basis a global architecture of the space system was drawn up as follow:

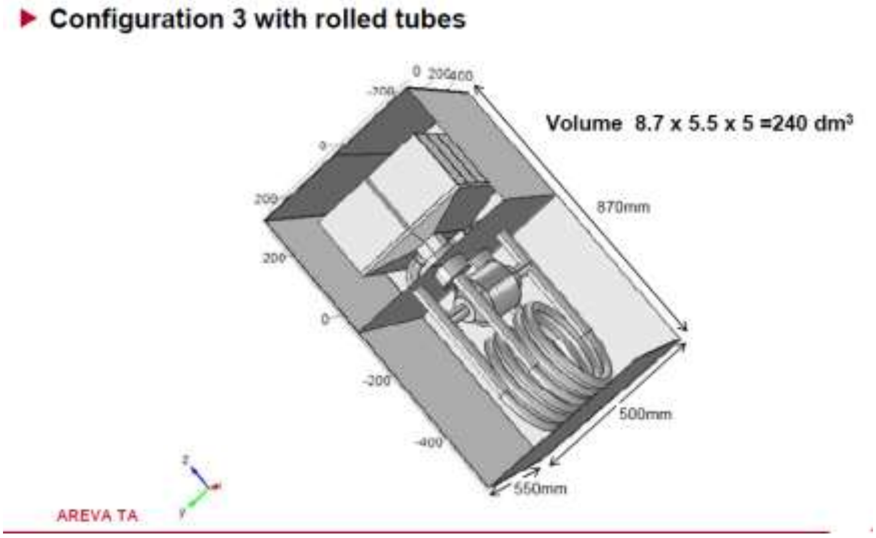
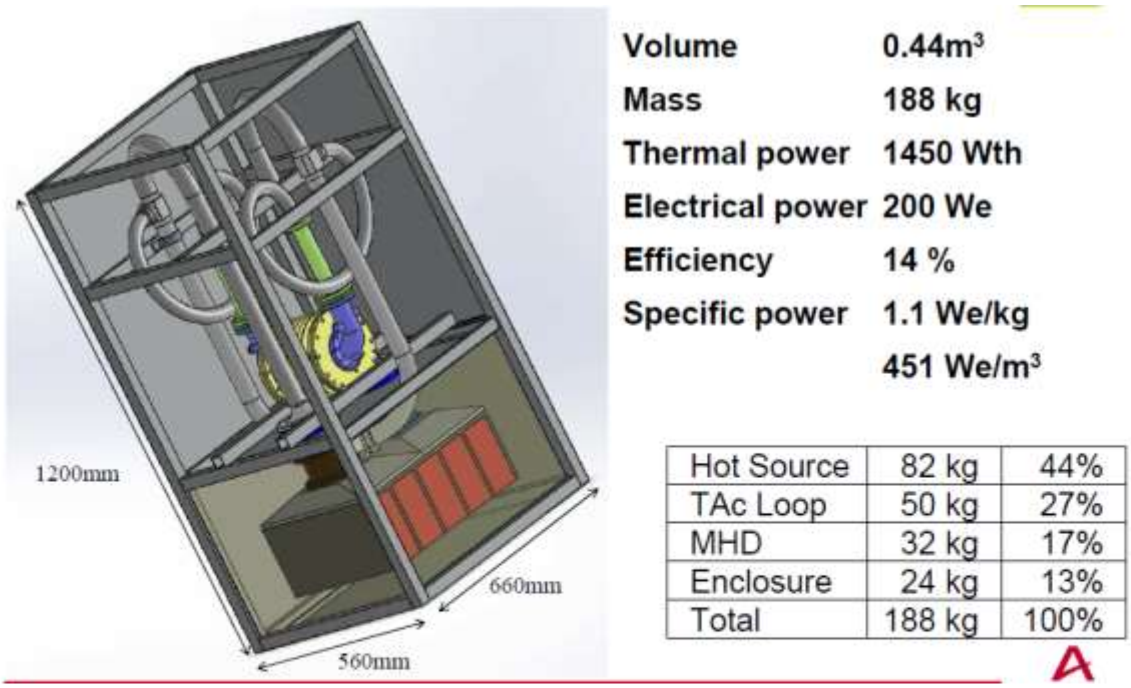


Figure 58: Second architecture

Later on, it was shown that the needed power at the TAc input was higher than previously expected. Consequently two additional heat source modules were added in order to reach the required thermal power (1450 Wth). At the same time, the size of the TAc's pipes was settled. This led us especially to modify the length of pipes connected to the MHD converter as well as the starting position of these pipes in order to optimise the power transfer from the TAc engine to the MHD converter.

A view of the corresponding preliminary space system design and the main characteristics reached are shown below.



Hot Source	82 kg	44%
TAc Loop	50 kg	27%
MHD	32 kg	17%
Enclosure	24 kg	13%
Total	188 kg	100%

Figure 59: Preliminary space system architecture

Once again, in order to lower the volume and the mass of the space system it was decided, with the agreement of the TAc engine specialists, to modify the shape of the pipes keeping their respective length and diameter.This allowed us reducing the height of the space system from 1200 mm to 700mm. Saving at the same time more than 20 kg especially on the enclosure part.
A view of this last design is shown below:

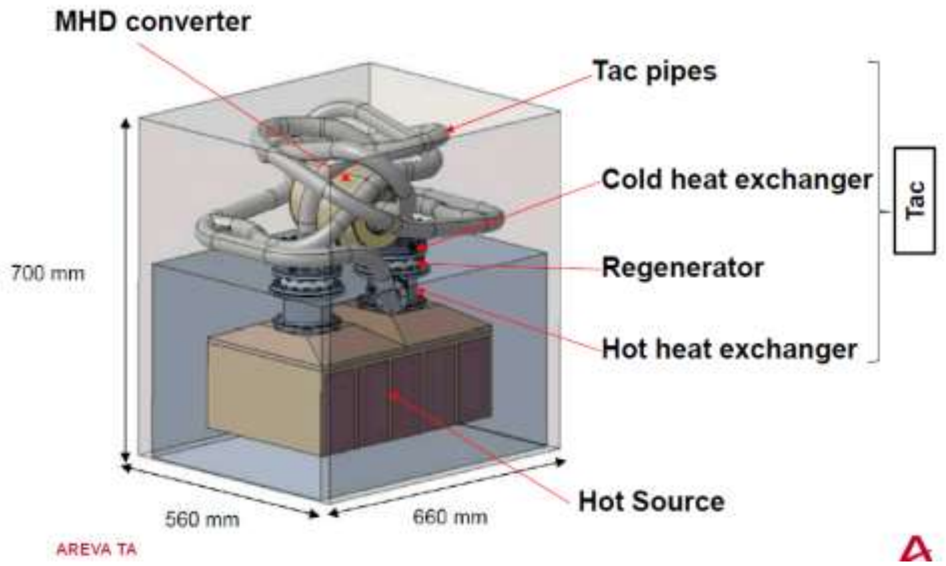


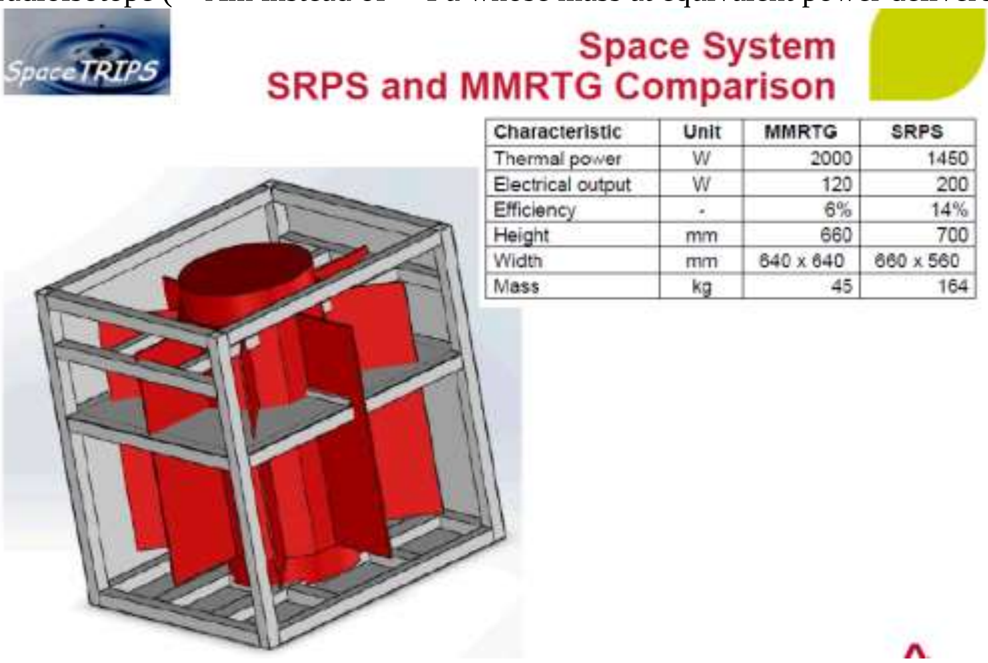
Figure 60: Final space system architecture

One of the most important requirements from a nuclear safety point of view is that the Heat Source modules must be freely released in case of inadvertent re-entry.That is why the heat spreader is not a closed box. In order to maintain each Heat Source module in its housing, a rod attached to the main housing and pushing the Heat Source module is foreseen. This rod includes a spring to insure that the pressure will remain even in case of small bending. In case of inadvertent re-entry, the structure quickly burns, the rods are released and consequently the heat source modules are released in turn. Another important consequence of this choice is that the insulation material is not supporting the weight of the Hot Source.

This last design was compared to the MMRTG (RTG currently used on Mars) regarding the electrical power delivered, the efficiency, the volume and the mass.

We can see, as shown on the figure below, that:

- The two volumes are quite similar,
- The electrical power delivered is a little higher
- The expected efficiency is more than twice the efficiency of the MMRTG,
- The mass is significantly higher than the one of the MMRTG, but this is mainly due to the choice of the radioisotope (^{241}Am instead of ^{238}Pu whose mass at equivalent power delivered is 5 times higher).



Characteristic	Unit	MMRTG	SRPS
Thermal power	W	2000	1450
Electrical output	W	120	200
Efficiency	-	6%	14%
Height	mm	660	700
Width	mm	640 x 640	660 x 560
Mass	kg	45	164

Figure 61: Comparison with SRPS and MMRTG

The last WP under the responsibility of AREVA TA concerns the ESA workshop with the objective to follow up of the project. This event has taken place at ESTEC on December 8 2015. It is reported in the deliverable D6.4. Here under is the schedule of the meeting. All the details including a copy of the presentation are given in the portal of participant.

The minute of the meeting is given here after

9h30 9h40 Welcome address
9h40 10h00 General introduction and present position of the project (A ALEMANY)
10h20 10h50 TAc - MHD electrical generator (A ALEMANY – M FRANÇOIS)
10h20 10h50 TAc - MHD coupling and sizing of the ground prototype (E ROY – Ph JEANTET)
10h50 11h20 Prototyping and experiments (J FREIBERGS)
11h20 11h40 Space applications (E ZEMINIANI – G POLI)
11h40 12h00 Phase separation issues (E ZEMINIANI - S ECKERT)
12h00 12h30 Conclusion

FORESEEN PARTICIPANTS:

ESA : K. STEPHENSON, H. SCHROEVEN-DECEUNINCK, H. BARDE, A. OWENS, D. FEILI.

HEKYOM M. FRANÇOIS, A. ALEMANY,
TAS-I E. ZEMINIANI
HZDR S. ECKERT
CNRS E. ROY, PH. JEANTET
IPUL J. FREIBERGS, A. BRĒĶIS
AREVA TA : G. POLI

1. PRESENTATIONS

1.1 MHD Converter (HEKYOM)

After a reminder of the project objectives, A ALEMANY has presented the main elements of the process with a special focus on the MHD convertor.

1.2 Thermoacoustic system (HEKYOM)

After a reminder of thermo-acoustic properties, M FRANCOIS presented the various architecture options analysed in the frame of the project and a sizing example of the chosen architecture. This architecture was chosen because it allows self-starting operations.

1.3 ground prototype Design (CNRS)

After a short description of the prototype as designed and its main characteristics, E ROY highlighted the critical points which have been addressed during the design of the prototype:

- Hot temperature (≈1100 K on the Hot Heat Exchanger),
- high temperature gradient (ΔT≈700 K over some centimes length) and low thermal losses,
- Sodium channel design (from a circular section to a ring section keeping area constant),
- Instrumentation

Some of the several numerical simulations performed in order to improve the design were presented too.

1.4 Prototyping and experiments (IPUL)

Several control tests have been performed during the manufacture of the part of the system and especially during MHD convertor manufacture (magnetic field, coil inductance, coil resistance, ..). It has to be noticed that the measurements show that the measured values are pretty close to the calculated one.

A. BRĒĶIS presented the various tools and devices manufactured in order to

- Fill the MHD convertor with sodium,
- Measure the liquid sodium flow during experiments
- Test separately the Thermo-Acoustic system and the MHD convertor.

Measurements performed on the thermos-acoustic system and MHD convertor were presented as well.

The results of experiments performed on MHD convertor with sodium let think that gas bubbles, due to instability at the sodium/gas interface, were trapped in the active part of the MHD convertor, during the tests.

For the test of generator alone, the quantity of sodium will be increased to avoid the bubble introduction inside then generator

1.5 Space System (AREVA TA)

After a reminder of the characteristics of the Heat Source Module designed previously under ESA contract, G POLI has presented the sizing of the hot Source and the way chosen to drive the thermal power from the hot source to the Hot Heat Exchanger which is the inlet of the Themo-Acoustic system.
On this basis and according to the design hypothesis, the heat distribution in the hot part of the system was presented.
The resulting Space Design was compared to the Radioisotope Power System currently used on Mars mission.

The insulation material is a kind of foam not a multi-layers insulation material in order to be used even on planet with atmosphere. This material is only surrounding the hot parts of the system. It is not used to support the hot source. The Hot source is supported thanks to rods, including springs, which wedge the hot source between two parts of the structure.

The static load calculation was made with a simplified model assuming that the MHD converter is a rigid device and that the mass of the hot source was split half on the support bars at the basis of the structure and half on the support bars of the cold plate which support the Cold Heat Exchanger.

1.6 Space application and phase separation (TAS-I

After a reminder of mission's characteristics and space requirements, E ZEMINIANNI presented the cold sink analysis and the phase separation studied by TAS-I on the basis of a solid device.

1.7 Liquid Metal-Gas Interface (HZDR)

After a presentation of the theoretical approach of the liquid metal/gas interface, S ECKERT presented the experimental tests performed in HZDR premises. These tests confirmed the theoretical approach and show that the use of a "honeycomb" (d≈1mm) allows stabilising the motion of the liquid column in the conditions similar to the one of the ground prototype.
It was underlined that dirty surface at the liquid/gas interface, significantly decreases surface's tension which is the driving parameter for surface stability.

2. CONCLUSION≈

The liquid metal / gas interface remains a major issue for space application, even if significant improvements have been done during the project.

A question regarding the use of NaK instead of Sodium was raised, in order to lower the cold sink temperature. In fact, the cold sink temperature is due to the reasonably reachable temperature for a space system. This temperature (around 400 K) is the temperature taken into account for the cold source of the US space power systems. Moreover Sodium is easiest to manipulate than NaK.

The expected efficiency of the SRPS (~14%) is more than twice the efficiency of a RTG (~6%)

The expected specific power of the SRPS (1.2 We/kg) is 35% higher than the expected specific power of a RTG (50We, 0.9 We/kg) based on the same radioisotope (^{241}Am).

Thales Alenia space activities.

Independently on the close collaboration with AREVA TA about the relations between hot and cold source as it can be view on the final space architecture, that was very important for the reduction of volume of the space system, one important work performed by Thales Alenia space was the organization of a workshop that taken place in the frame of the important symposium about aerospace. A mini symposium was devoted to space TRIPS. The schedule of this mini symposia is given here after:

9 November 2015: Space TRIPS workshop and meeting (MS10 and R9)

The workshop will take place from 14h30 to 17h15 in room Aerospace at Oval Lingotto Fiere Via Nizza 294 - 10126 Torino – Italia. The meeting will take place in the same venue from 17h30 to 18h30

List of attendees:

HEKYOM: A. Alemany
CNRS: E. Roy
IPUL: J. Freibergs, A. Brekis
AREVA: G. Poli
TAS-I: E. Zeminiani, S. De Palo, F. Massobrio, E. Gaia
UNICA: A. Montisci

workshop: 14h30

1- Welcome address 5 mn ADM/TAS-I
2-General introduction and present position of the project 10 mn A. Alemany
3-TA - MHD electrical generator 15 mn A. Alemany
4-TA - MHD coupling and sizing of the ground prototype 15 mn E. Roy
5-Prototyping and experiments 25 mn J. Freibergs A. Brekis
15h40 15 mn break **15h55**
6-Space application and nuclear power source 10 mn G. Poli
7-Space application and phase separation issues 10 mn E. Zeminiani
8- FET OPEN Prometheus (TA-MHD) 15mn A. Montisci
9-The plasma magnetic sail, as space thruster 15 mn A. Alemany
10-Round table, Q&A 30 mn All

17h15 15 mn break

17h30
11-SpaceTRIPS meeting R9 (status of experiments and ESA meeting) 60 mn All
18h30 End of the activities

The minutes of the meeting is reported here after, all the presentations are reported in the deliverable D6.3: “Workshop”.

MINUTES OF THE SPACE TRIPS WORKSHOP
TORINO, NOVEMBER 19, 2015.

THE WORKSHOP STARTS AT 14 H 30.

01 WELCOME ADDRESS - ZEMINIANI

The workshop begins with an introduction by E. Zeminiani regarding the generalities of the SpaceTRIPS project. The introduction also lists reference e-mails for future questions or contacts.The pdf presentation with such information is given to some participants (loaded on their USB drives), after they requested it in order to have contact information easily available.

02 - 03 GENERAL INTRODUCTION AND TA-MHD GENERATOR - ALEMANY

The discussion follows with an explanation by A. Alemany regarding the overall framework of the project and details on how the concept works.In particular, the presentation focuses on explanation of physics, TA engine, MHD engine, TA-MHD coupling, status of testing,space version and comparison with ground prototype.

The discussion also include answers to some questions (reason behind the choice ofsodium; explanation of the fact that electricity is produced at the same frequency of motion of the sodium mass).

04 DETAILED DESIGN - ROY

The following presentation is done by E. Roy, who gives an overview of CNRS involvement in SpaceTRIPS and describes details of TA and MHD solution. This presentation focuses on critical technical / technological issues and design challenges. It also gives an overview of analysis performed: static, thermal, dynamic.

The conclusions include remarks about critical aspects of the design and how they influenced the development of SpaceTRIPS activities (iterations, assumptions, risks). A question is proposed about increasing the efficiency of the system by lowering sink temperature, which is unfortunately not feasible as the SpaceTRIPS converter works with liquid sodium and has to stay above its melting point.

05 PROTOTYPING AND EXPERIMENTS - FREIBERGS BREKIS

The next speech is presented by J. Freibergs and continued by A. Brekis. It presents the entire timeline of integration and testing activities, giving interesting details on how each step has been conducted (including issues and main results). The presentation includes:

· Tests with water in the MHD section to predict how the fluid will behave and study possible countermeasures to interface control problems.
· Schematics of pneumatic test.
· Experiments with compressor and water fluctuations.
· Data from pressure sensors.
· Process of filling sodium tank and proper cleaning of the tank.
· Procedure for the graduation of the flowmeter (max flow 0.1 l/s 0.5 mV).
· Presentation of experiments with liquid sodium.
· Problems with bubbles inside the MHD generator (best tests were in themorning, then the following ones were worse and worse, then the day after everything was fine again).
· MHD results at high frequency are worse (best is achieved at 12-16 Hz, then worse at 45 hz and 50 hz).
· Problems with sodium plugging the cross sectional area.
· Measurements of magnetic induction in the generator with or without Somalloy and with geometrical corrections.
· Measurements of inductance and active resistance in coils.
· Description of measuring systems: type and number of sensors and Labview acquisition system (high sampling rate).
· TA measurement results with short-circuited ends to see the inset of TA phenomenon.
· TA measurements were at first influenced by electromagnetic noise,interferences.
· Experiment with valve (pneumatic resistance) at the TA output.
· Step-by-step manufacturing: pictures.

As foreseen this presentation is the one to capture more interest and a god discussion is started. It deals with several points, among which the most relevant are:

· Relevance of position of pressure sensors in the loop, because in some areas sound wave is amplified and in some areas it is not.

· Strong interest to compare good tests at 12-16 Hz with theoretical results at the same frequency.

· No test done with floats on liquid sodium: would the system work implementing a solution similar to the one adopted with water? Is it feasible?

· Future test timeframes.

BREAK

During the first break, the discussion continues.

06 SPACE APPLICATION AND NUCLEAR POWER SOURCE - POLI

After the break, the first presentation is done by G. Poli. It explains the heritage of the nuclear fuel modules, and the architecture of the hot source (modules - spreader – insulation).

It also explains some broader concepts on the intrinsic efficiency of the hot source (parasitic losses) and shows how it is located and works in the space system concept. The presentation closes showing that the SpaceTRIPS system is comparable in size with the MMRTG, even if mass and figure of merit are strongly influenced by the European choice of using Americium in the nuclear modules (this is not negotiable).

The presentation stirs questions on two fronts:

· Possible upscaling (maximum power, temperature levels, moving from radioisotope modules to actual reactors such as in MEGAHIT or DEMOCRITOS).

· Advantages and disadvantages in using heat pipes to convey heat from the nuclear modules to the TA hot heat exchangers (with the current module geometry and size, and with the current thermal chain including radiative coupling, using heat pipes instead of a solid pyramidal spreader would not lead to big improvements).

07 SPACE ISSUES AND PHASE SEPARATION - ZEMINIANI

The last SpaceTRIPS presentation is done by E. Zeminiani and concerns space applications.It presents reference mission, system requirements, advantages of the SpaceTRIPS generator over other static conversion systems. This presentation also depicts how the space concept evolved over the three years of activities, and how it could be integrated on a real space system (comparison with existing RPGs).

The discussion touches again some points on the possible usage of heat pipes, scaling of the system and usage in systems at much higher power levels (e.g. MEGAHIT). The following two presentations are "guest projects" which have technologies and challenges in common with SpaceTRIPS and could be part of the evolution roadmap.

08 FET OPEN PROMETHEUS TA-MHD - MONTISCI

The first guest speech is given by A. Montisci, from University of Cagliari. He introduces the Prometheus project.

This project studies a possible thermal to electrical power converter which exploits a different working principle: using a TA machine plus a ionizing system (the MHD part does not need a conducting fluid, but works by separating charge carriers within the medium which takes part in the TA motion). The presentation explains that there is a charge confinement problem to be solved, but the system is interesting because energy (spark) is theoretically needed just once at the beginning of the process to ionize the gas, and then the machine works electrostatically.

No more power has to be provided because the charges are separated and confined and the medium does not recombine in its original form (no power consumption to keep
the charges segregated). The challenges are: to choose the gas, produce the electrical discharge, design the,plates, design the TA, design the core, make the device appealing to different applications.

The presentation also covers the Consortium and work breakdown (4 year project), plus the management scheme. While explaining the management structure, Prof. Montisci issues a call for expression of interest: if any company, institution or agency is interested in acting as external advisor or being part of the technology transfer panel, it would be welcome.

09 SOLAR SAIL - ALEMANY

The second guest speech is given by A. Alemany on behalf of a Consortium studying a
Plasma Magnetic Sail.

The presentation introduces the Consortium and the physics behind this study.It gives some details about solar wind, plasma hydrogen VS photon wind, two different solutions for the magnetic sail (coil VS plasma). The objective of the study will be to test the concept in plasma tunnel (plasma of air, not hydrogen). It will be a much bigger scale than previous experiments. At the moment the study is just at the beginning of simulations, which are extremely sensitive to geometrical disturbances and therefore very difficult to be carried out with commercial software.

10 BREAK

During the second break, the discussion continues (Q&A) and goes directly into the review meeting.

11 REVIEW MEETING

The coordinator summarizes the activities still to be completes (see attached presentation), then the discussion focuses on experimental aspects. In particular, the following points are debated:

· Possible change in the MHD testing rig: increase the level of sodium and impose the oscillations with pistons to suppress the presence of gas and verify results against theory

· Magnetic field measurement : a single big coil with very low resistance can be used to measure the magnetic field by measuring the voltage at open ends (with no resistance). It can be the same prototype coil but without the applied load.

· Suggestions of a tentative solution for the floating piston, but IPUL is sceptical because gaps are left around the piston and bubbles are entrained nonetheless.

The proposals will be collected by the Coordinator and sent to IPUL via e-mail.

CONCLUSION

The workshop shows good coherence of the work performed by the different Partners,
and good advancement of the activities. Some difficulties have been encountered during manufacturing, assembly and testing, which is normal due to the very challenging technology. There are possible collaborations and overlapping areas with other EC funded projects.

HZDR activities

Many experiments were performed about the stability of the interface between gas and liquid metal under high frequency high amplitude pulsating motion. The facility was mainly what was presented in the previous reports but the tests were focused on the use of honey combs. Using classical honey comb do not permit to reach the high frequencies because the level of power required over pass the possibility of the generator. So the solution was to reduce to one unique element, one tube of 1 mm of diameter; the number of mesh. In this case it was possible to reach the full frequency even if the amplitude of the motion were less than expected on the TAC/MHD generator. But any perturbation of the free surface was observed in this condition confirming the theoretical approach.

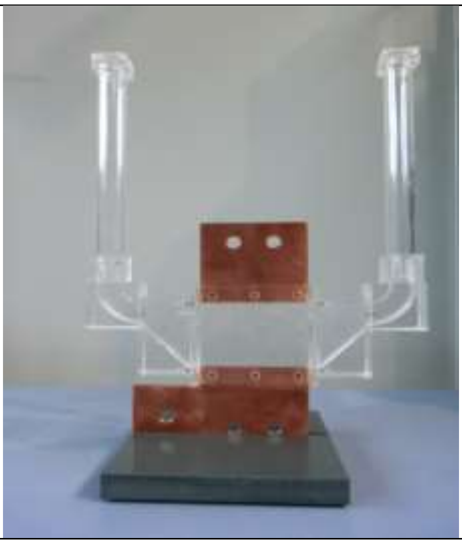


Figure 60: Photographs showing the experimental configuration:

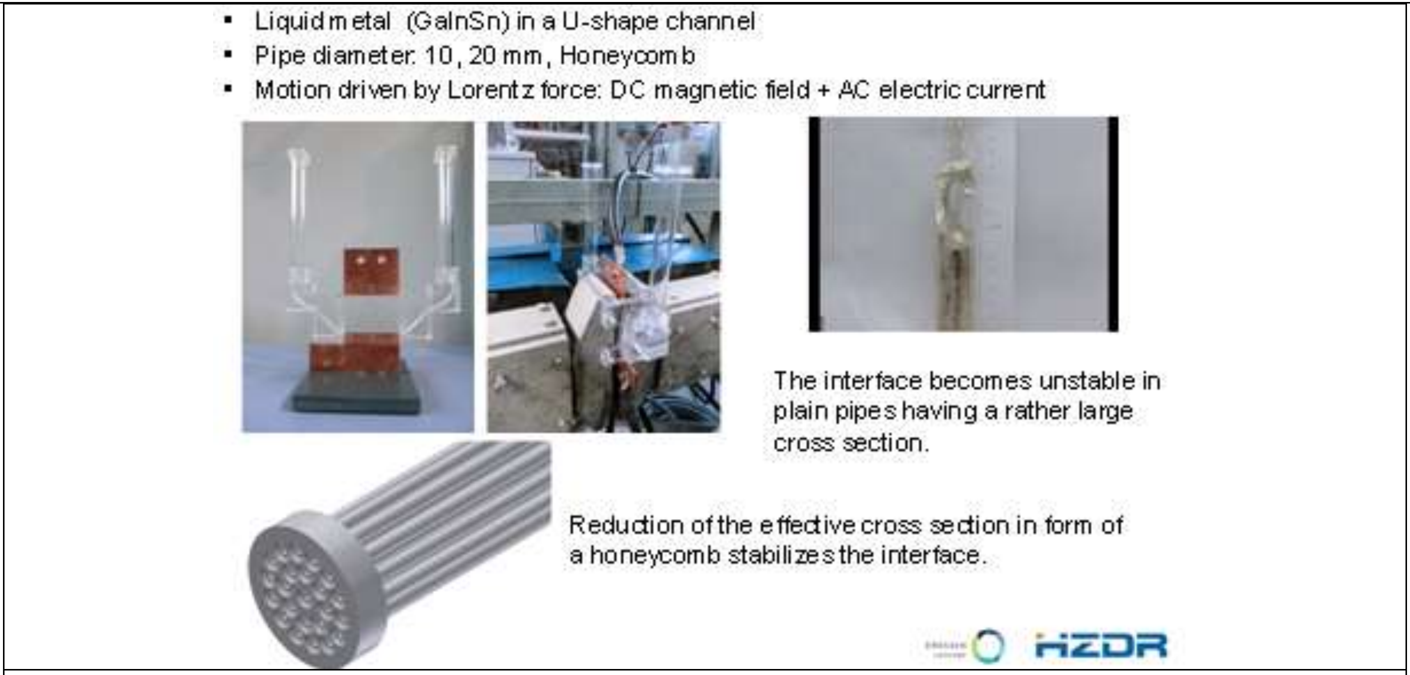


Figure 61: Model experiments on interface stability

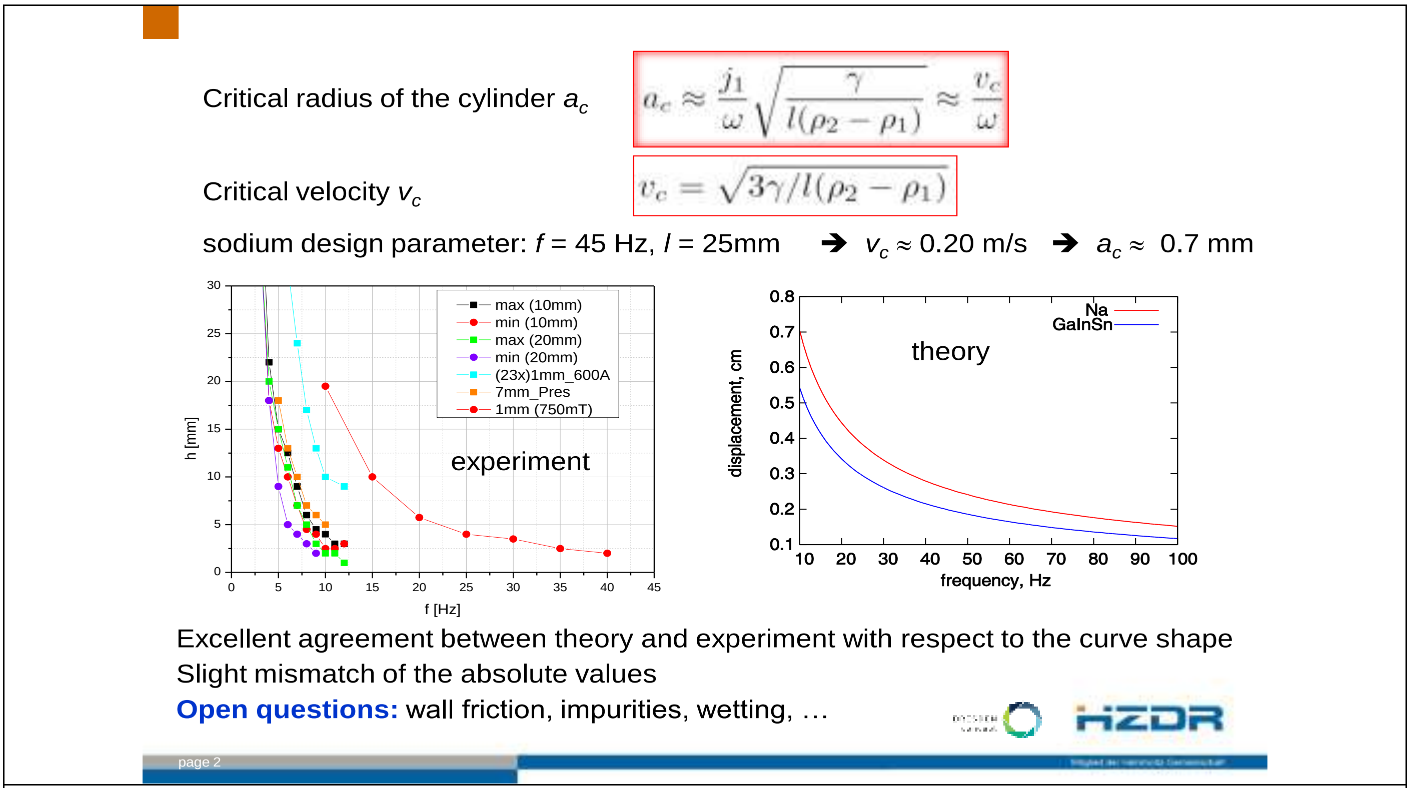


Figure 62: Influence of the radius on the onset of instability

3.2.1.3: Work package 4.

a- Objectives

To manage the project in terms of administrative, legal and financial issues. This work package includes:

- All reporting activity towards EC and interface between the different partners and the REA administration.
- Project management (finance, time schedule, reviews and meetings…). The last point includes in particular, the preparation of each meeting the time table location and meeting chair...
- Coordination of the exchanges between partners about the evolution of the projects
- Maintaining of the consorsium agreement and resolution of the disputes.
- Information about the day to day request and reorganization if it need to the work plan

b- Mains results

All the activities reported in the objectives of this work package were respected. In particular

Four reports were written submersing the activities of the partners during the second year that concern:

D3.2 Space system requirement: SRPS reference design
D3.3: Simulator feasibility study
D3.4: Lesson learned **(Draft)**
D6.3: Workshop
D6.4 Presentation to ESA and
Third review meeting To + 36

The finance management was achieved and all the meetings reported in the DOW were organised with new ones necessary for the progression of the construction and tests. In particular two meetings were necessary to launch the test program of thermo acoustic loop, in the offices of IPUL, at which have contributed HEKYOM (Maurice Francois) and ASTER (Kees de Block). Video conferences were also necessary during the test phase. They have taken places in the design offices CNRS Grenoble. The details of the meeting, dates and locations, are given latter in the report (see page 50). All these meetings were programmed by the coordinator.

The coordination of exchanges was organised with the help of the partner's correspondants. The main exchanges were comprehensive cordial and focussed on the good advancement of the program. No dispute appeared necessitating resolution by the general assembly.

A delay for the achievement of the program is necessary. It is reported on table 1. The timetable is modified but the objective is always to realise the integrality of the program as it is mentioned in the DOW.

3.2.1.4: Work package 5, Scientific and Technical coordination.

The WP5 task is focused on technical coordination of the project. It is a fundamental aspect for many reasons:

1- Inside the work package WP2 there are several activities that was needed to be coordinate as:
The construction of the two engines under the responsibility of IPUL required the coordination with the designer (CNRS) and the specialist of Thermo acoustic (HK). The tests that are very difficult,have involved (and involve again) the contribution of several partners and in particular the counsels of HK for the thermo acoustic loop

2- the coordination between AREVA TA and Thales Alenia space Italy was really very efficient for the space preliminary feasibility study of the TAC/MHD electrical generator

3- Generally speaking the project is articulated around two parallel activities, one for the loop demonstration that is tested in Latvia and which has as partners HEKYOM, CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE and LATVIJAS UNIVERSITATES AGENTURA LATVIJAS UNIVERSITATES FIZIKAS INSTITUTS and one for space architecture which has as main partners AREVA, THALES ALENIA SPACE ITALIA and HELMHOLTZ-ZENTRUM DRESDEN-ROSSENDORF.

The both activities have been developed in close coordination for the adaptation of the project to space development. The participation of partners at the technical coordination have taken the form:

a-Follow up of the evolution of the technical aspects of the project including the participation at the two reports (middle and final reports), meetings and teleconferences:

b- HEKYOM has assumed the responsibility to verify regularly the technical coordination of the project to organize the meetings and teleconferences.

c- The role of THALES ALENIA SPACE ITALIA and AREVA was focused on the space applications. This activity including dissemination (connection with CNES and ESA) necessitated also technical coordination. That will be mentioned in the deliverable D5.2, on the form of a report.

To conclude, the main activities this year were devoted to coordinate the work packages WP2 corresponding to the construction and tests of the two engines. Specific meetings was necessary frstly in Latvia (IPUL) to launch the tests and secondly by the way of video conferences organised by the SERAS Grenoble. Other partners was also invited and participated to these meetings in particular AREVA and Thales in charge with the global design for space application.

3.2.1.5: Work package 6, dissemination of knowledge.

a- Objectives

- For the publications the partners will take advantage of the international journal Magneto Hydro Dynamics which is under the responsibility of the LATVIJAS UNIVERSITATES AGENTURA LATVIJAS UNIVERSITATES FIZIKAS INSTITUTS (partner 3).

- Two main events was organised this year under the responsibility of Thales Alenia space and AREVA TA They concern the organisation of a workshop that taken place in Torino on November 19 in the frame of aerospace symposium. The other one was organised at the ESA offices in December 8. All the elements of these two events are reported on the (paragraph **3.2.1.2**).

- Other contributions in the dissemination were achieved by the partners of spaceTRIPS consisting in oral presentation in international conferences. In particular two papers were accepted for oral presentation at the”3th International workshop on Thermo acoustics Enschede, October 26-28, 2015”.

- Also some seminars were given especially at the CNES office in Paris focused on the main principles of thermo acoustic and its coupling with MHD generators. another one in Italy in the CIRA offices where the program was explained in the frame of a proposal of cooperation for a new project focused on the solar sail submitted to the EU program H2020, FETOPEN.

b- Mains results

The selection of the best papers presented at the pamir 2014 conference have been published in international Latvian journal Magneto Hydrodynamics in August 2015. This important works, especially in the selection of papers and printing, was realised by the partnership of spaceTRIPS, the edition of the two special (number 52 and 53) issues having been done by the Latvian partner.

An other very important results obtained by this effort about the dissemination concerns the submission of a new project devoted to the use of a combination of thermo acoustic and MHD, “Prometheus”, acronym of Plasma-based Research On Magnetogasdynamics Effected by THermoacoustics for Electrical Unmoving generatorS, based on the use of an ionised gas that allows, if the feasibility will be verified, to suppress the interface liquid and gas that could be an important improvement for space application; This project was submitted in the frame of H2020, FET OPEN.

3.2.2: Work progress achievements.

a: Progress achievement

The construction of thermo acoustic loop and MHD generator was delicate but was realised in agreement with the timetable devoted to the project. But the phase tests was not so easy for several reasons:

For the thermo acoustic loop. Firstly one piece was broken when the pressure and temperature have reached the nominal value (40 b and 900 K). The origin of this problem is difficult to analyse and can be due at a bad quality of the Chinese material or at a value of the temperature gradient higher than that was taken into account by the calculation. On the other hand the physical properties of the zirconium is not well known at high temperature and was extrapolated taking into account the values at low temperature. After many ruptures of this element and many new commands at the Chinese supplier, introducing some months of delay, a new composition of this piece was adopted consisting to build this element partially in zirconium and partially in stainless steel. This new element is not so efficient regarding the thermal losses but many times more resistant regarding the mechanical constraints. That does not means that a full zirconium piece must be abandoned in the future but the choice of the supplier and the test of material at high temperature have to be done to be able to design with security this element.

The new element is able to withstand the stresses but when working under nominal conditions some leaks appear on the thermo acoustic loop that have involved new modifications. Instead of continuing to try tinkering over the existing installation, it was decided to change by the technical analysis, the sealing problem. Finaly this element will be build in metal even if the thermal losses will be increased.

For the MHD generator. Some problem about the coil was detected necessitating the disassembling of the generator. This operation was delicate because the coil is located at the periphery of the assembly of magnets. During disassembling some magnets were broken and were replaced, the coil was also replaced.

MHD generator was repaired. This operation is delicate by the reason of the use of the sodium as liquid metal for the MHD generator, and consequently safety precautions need to be used for intervention.
Nevertheless some tests was realised and are summarised on the paragraph (3.2.1.1 f) of the present report. The objective now is to finish the tests of the two engine separately and to connect them, to end the program. It can be noticed that, the duration of the construction and of the tests, does not over pass that was expected. The delay on the evolution of the project comes of the phase shift of the previous work packages.

3.2.3: Deviations and impact on tasks and resources.

There is no deviation about the objectives of space TRIPS. The deviation that is mentioned here after concerns the time table to reach the main objectives. At the present time it is expected to finish the tests at To + 37, one moth after the theoretical end of the project. This results of many difficulties that appear along the tests, rupture of some elements of Thermo acoustic loop and MHD generator that have necessitated some modification in the design of some pieces and the establishment of new plan of tests. To conclude even if the project presents some delay, the totality of the program is expected to be respected.

3.2.4: Use of the resources.

3.2.4.1: Work package 1 Lead partner CNRS.

	Partner1 HEKYOM	Partner2 CNRS	Partner 3 IPUL	Partner 4 ATA	Partner 5 (TAS-I)	Partner 6 HZDR
Proposed mm	9	5	1	1	1	0.5
Realised mm	10.5	5.7	2	0.34	1.9	0.5

Table 10 : Recapitulation of the man month for WP1

3.2.4.2: Work Package 2 Lead partner IPUL.

Although unexpected but probably quite normal, 2015 year was a busy for Thermoacoustic engineers at HEKYOM. It must be notice that even if all manufacturing took place in Latvia, Latvia engineers were absolutely not prepared neither for official acceptance of work nor for mounting knowledge and specific precautions for use. Due to that, HEKYOM engineer and CTO, the most specialists for thermo acoustic devices had had to work very close from IPUL and receive IPUL engineers for some training courses or visit them for working on TAC. This explains why it was considered by HEKYOM that its engineers involved in this TAC work should be attributed to WP2. It have to be noticed that the total MM cost for the whole project will be quite close the expected and accepted corresponding budget.

	Partner1 HEKYOM	Partner2 CNRS	Partner 3 IPUL	Partner 4 ATA	Partner 5 (TAS-I)	Partner 6 HZDR
Proposed mm	4	21	40		4	3
Realised mm	12.65	22.6	40		3.92	3

Table 11 : Recapitulation of the man month for WP2

3.2.4.3: Work Package 3 Lead partner ATA.

	Partner1 HEKYOM	Partner2 CNRS	Partner 3 IPUL	Partner 4 ATA	Partner 5 (TAS-I)	Partner 6 HZDR
Proposed mm	4	2	6		16	12
Realised mm	5.5	2.5	6		15.10	12

Table 12: Recapitulation of the man month for WP3

3.2.4.4 Work Package 4 Lead partner HK.

	Partner1 HEKYOM	Partner2 CNRS	Partner 3 IPUL		Partner 5 (TAS-I)	Partner 6 HZDR
Proposed mm	4.5	0.5	0.5		0.5	0.5
Realised mm	6.5	0,7	0.5		0.63	0.5

Table 13 : Recapitulation of the man month for WP4

3.2.4.5 Work Package 5 Lead partner: HK.

	Partner1 HEKYOM	Partner2 CNRS	Partner 3 IPUL	Partner 4 ATA	Partner 5 (TAS-I)	Partner 6 HZDR
Proposed mm	4	1	1		1	0.5
Realised mm	6.73	0,8 mm	1		0.8	0.5

Synthesis, Table 14 : Recapitulation of the man month for WP5, status at the 30/12/2014

3.2.4.6: Work Package 6 Lead partner: HK.

	Partner1 HEKYOM	Partner2 CNRS	Partner 3 IPUL	Partner 4 ATA	Partner 5 (TAS-I)	Partner 6 HZDR
Proposed mm	3	1	3		1	1
Realised mm	7.5	1.2	2.8		1.2	1

Table 15 : Recapitulation of the man month for WP6

WP6 : note a big effort made by HEKYOM for communicating in several international conferences or internal seminar of Group as Airbus or CNES, the promising results of our TA+MHD engine

3.2.4.7: lists of the theoretical efforts for the 36 months against the actual effort .

	Partner1		Partner2		Partner3		Partner 4		Partner 5		Partner 6	
	Theor.	Actual	Theor.	Actual	Theor.	Actual	Theor.	Actual	Theor.	Actual	Theor.	Actual
WP1	9	10	5	5,7	1	2	1		1	1.90	0.5	0.5
WP2	4	12.65	21	22.6	40	40	4		4	3.92	3	3
WP3	4	5.5	2	2.5	6	6	16		16	15.10	12	12
WP4	4,5	6.5	0.5	0,7	0,5	0.5	0.5		0.5	0.63	0.5	0.5
WP5	4	6.73	1	0,8	1	1	0		1	0.8	0.5	0.5
WP6	3	7.5	1	1.2	3	3	1		1	1.24	1	1

Table 16: lists of the theoretical efforts for the whole project against the actual effort for the 36 months

3.2.4.8: Deviations and impact on tasks and resources.

The deviation concerns a delay for the finishing of the work (To+37) and for the writing of the conclusion and technical synthesis of the project. The small subcontracting justified last year does not affect the resources and the total budget. The Partner 1, the co-ordinator, has strongly increased the number of men months what was necessary absolutely because of the technical difficulties encountered during the development phase and the machine tests. However, the total cost of the project is not affected it is a little lower than was planned, because the reduction of the CNRS budget.

3.2.5: Problems occurred and applied solutions.

During the test some parts of the TAC generator was broken when the nominal value of paramaters was applied (high temperature and high pressure) So new materials were ordered many times and finnaly new design structure was adopted. Moreover, the problems of tightness, delayed tests. to avoid the "DIY", new provisions have recently been taken and are being implemented. The entire program will be implemented with a reasonable delay.

3.2.6: Changes in the consortium.

No change

3.2.7: List meetings, dates, venues and participants

Kind of Meeting	Location	Date	Participants
Kickoff	Brussels	18 01 2013	1-2-3-4-5-6
Teleconference		13 02 2013	1-2-4-5
Model validation/milestone	ORSAY (Paris)	14 05 2013	1-2-3-4-5-6
Mid term review	Torino	10 07 2013	1-2-3-4-5-6
Technical meeting	Grenoble/SERAS	26 09 2013	1-2-3-6
Technical meeting	Grenoble/SERAS	14 11 2013	1-2-3-4-6
Pre review meeting	Brussels	08 01 2013	1-2-3-4-5-6
First review meeting	Brussels	08 to 09 01 2014	1-2-3-4-5-6
Specific meeting on sodium technology	Cadarache	14 04 2014	2
Progress meeting	Aix en Provence	25 04 2014	1-2-3-4-5-6
PAMIR conference & summer school	Riga (LV)	16/20 06 2014	1-2-3-4-5-6
Specific meeting on WP2 : Design evolution	Grenoble	10 07 2014	1-2-3
WP2 Design review for information	Grenoble	09 09 2014	1-2-3
Final design review	Grenoble (FR)	01 10 2014	1-2-3-4-5-6
R8 Experiment readiness	Riga	26-28 05 2015	1-2-3-4-5
Test procedures meeting	Riga	21-24 07 2015	1-3
Test procedures meeting	Riga	25-28 08 2015	1-3
Visio conference	Grenoble	25 11 2015	1-2-3-4
R9 Meeting about the final results and Workshop	Torino	19 11 2015	1-2-3-4-5
ESA meeting	ESTEC	08 12 2015	1-2-3-4-5-6
Visio conference	Grenoble	22 12 2015	1-2-3
Visio conference	Grenoble	05 01 2016	1-2-3
Last review meeting	Brussels	15 01 2016	1-2-3-4-5-6
Specifig meeting for tests of MHD generator	Riga	22-25 02 2016	1-3
Specific meeting for tests of thermos acoustic loop	Riga	13-16 03 2016	1-3
Video conf.: tests .evolution	Grenoble	5 02 2016	1-2-3-4
Video conf;: tests .evolution	Grenoble	12 2 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	19 2 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	4 03 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	11 03 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	29 03 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	1 04 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	8 04 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	15 04 2016	1-2-3-4
Video conf.: tests .evolution	Grenoble	22 04 2016	1-2-3-4

Table 16 : List, date and location of the meetings

3.2.8: Project planning and status.

The program which presents a resonable delay to finish the tests of the TAc/MHD generator, will be concluded at the beginning of 2016 (End of January).

3.2.9: Changes to the legal status of beneficiaries.

No change of the legal statutes of beneficiaries

3.2.10: Dissemination & Development of the project Website.

-The dissemination of results is a very important problem, carefully considered by the partners of Space Trips.

-The selection of 48 papers, presented at the international conference pamir 2014 (June) have been published in the international Journal Magneto Hydro dynamics, august 2015.

-SpaceTRIPS was presented at the international conference 3th International workshop on Thermoacoustics Enschede, October 26-28, 2015, and on the form of a seminar (CNES), by Maurice Francois and Antoine Alemany, HEKYOM.

-This year and in agreement with the spaceTRIPS project, a workshop has been organised in Torino November 19 by Thales Alenia Space Italy.

The meeting with ESA was organised by Gerard Poli at ESTEC on December 8 2015.

3.3: Deliverables and Milestones.

Below is reported the list of deliverables and, in red rectangles, those the already sent the last year, The deliverables D2.6: Tests report, D4.1: Final report, D5.2 Technical synthesis of the project results, will be send latter after the end of the tests .

WT2:
List of Deliverables

Project Number [1]	312639	Project Acronym [2]	Space TRIPS

List of Deliverables - to be submitted for review to EC

Deliverable Number **	Deliverable Title	WP number **	Lead beneficiary number	Estimated indicative person-months	Nature **	Dissemination level **	Delivery date **
D1.1	Validated model	1	1	14.00	R	RE	8
D1.2	Parametric definition of the loop	1	1	3.50	R	CO	8
D2.1	TAc/MHD design file	2	2	26.00	R	RE	18
D2.2	Tac loop and MHD machine hardware	2	3	26.00	O	RE	26
D2.3	Experimental plan	2	3	3.00	R	PP	26
D2.4	Test means hardware	2	3	5.00	O	PP	26
D2.5	Tests Reports	2	3	17.00	R	PP	33
D3.1	Space system requirements	3	5	2.00	R	PU	12
D3.2	SRPS reference design	3	4	37.00	R	PU	24
D3.3	Simulator feasibility study	3	3	11.00	R	PU	28
D3.4	Lesson learned	3	1	5.00	R	PU	33
D4.1	Final report	4	1	7.00	R	CO	36
D5.1	Mid term report	5	1	0.50	R	PU	7
D5.2	Technical synthesis of the project results	5	1	7.00	R	CO	36
D6.1	pamir conference/ summer school Proceedings	6	3	8.50	O	PU	18
D6.2	Proposed plan for dissemination and use of results	6	4	0.50	R	PU	18
D6.3	Workshop	6	5	0.50	O	PU	33
D6.4	Presentation to ESA	6	4	0.50	O	PU	36
			Total	174.00			

The list of milestones is given below with identification of the already realised ones in red rectangle

WT4:
List of Milestones

Project Number [1]	312639	Project Acronym [2]	Space TRIPS

List and Schedule of Milestones

Milestone number [59]	Milestone name	WP number [53]	Lead beneficiary number	Delivery date from Annex I [60]	Comments
MS1	Review models validation	WP1	1	5	
MS2	Validation by partners of the global concept	WP1	1	8	
MS3	Preliminary definition: First Periodic Review Meeting	WP2, WP3	2	12	Periodic Review Meeting with the REA
MS4	Space system feasibility study	WP3	4	15	
MS5	Experiment detailed design	WP2	4	18	
MS6	Conference and summer school	WP6	3	18	The event could be organised in June 2014 in Latvia corresponding to the middle of the project.
MS7	Space system components review	WP3	4	21	
MS8	SRPS feasibility, loops manufacture:Second periodic review	WP2, WP3	3	24	Periodic Review Meeting with the REA
MS9	Experiment readiness review	WP2, WP3	4	29	
MS10	Global results analysis/workshop	WP2, WP6	3	33	Workshop will be under the responsability of TAS-I
MS11	Third Periodic Review and final meeting/Technical coordination synthesis and final report	WP4, WP5	1	36	Periodic Review Meeting with the REA

3.4:Breadboard assembly and breadboard tets: Last tests results

According to the last review meeting a new series of tests was realised. For that a completely new system of interface control was studied constructed and tested. This new system is composed essentially by a floating piston which is described here after.

3.4.1 Floating pistons.

After the last review meeting that taken place at the REA offices in Brussels, January 15, it was decided to test another possibility of control of the interface. In close collaboration with the SERAS offices of the CNRS Grenoble, the society Hekyom together with Aster society, and with the participation of AREVA TA, a concept of floating piston was propose designed and tested in a specific loop using water instead of sodium and Plexiglas tube to visualise the interface evolution. The principle is to ask a hollow floating piston, 0.2 mm thick, and very lightweight about 16 g (see figure 62), on the free surface between the argon of thermo acoustic loop and the liquid sodium. The piston then penetrates about 1 cm in the sodium. Therefore it perfectly follows the evolution of the free surface since all abruption in relation to this surface created a vacuum that effectively pick the piston on the interface. So the system reduces almost completely the free surface perturbations. On the other hand to equilibrate the pressure inside and outside the floating piston, a tube was welded on the top of the piston allowing this necessary equilibrium. Of course because the system presents two identical interfaces (free surfaces) two identical pistons were realised (see figure 62-63)

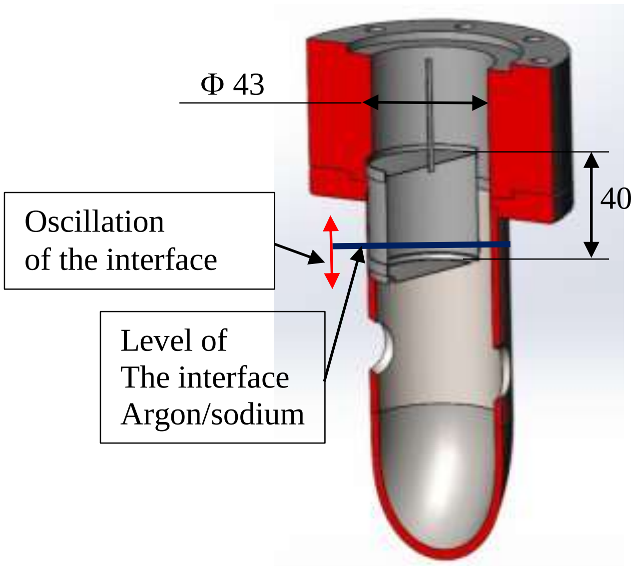


Figure 62: Schematic view of the system proposed, using floating piston to stabilise the interface argon/sodium

Figure 63 : view of the piston two floating piston that was realised to stabilise the interface

To view the operation, an installation in Plexiglas full with water was machined and tested with the floating piston, under 1 bar of amplitude of oscillating pressure and frequency of 45 Hz (See figure 64), the oscillation being provided by the experimental installation IPUL using a compressor.

The results have been very interesting and have shown that, under amplitude of oscillation around 10 mm, the piston is continuously in contact with the water. So the system have been sufficiently convincing to adopt this solution to perform the tests in the sodium installation after coupling of the two engines; MHD generator and thermos acoustic loop.

This system gives good results but nevertheless a small quantity of water was introduced inside the floating piston. To obvious that, the small tube at the top was curved as it can be show on the figure below 66. So it is expected that using this artifice no introduction of liquid will results about the exploitation of the system.

The first type of floating piston (see figure 63) was used in a first series of tests with sodium when in the second series of tests the new type of piston with curved small tube as the top will be used. In this report, only the first series of test are reported (floating piston fig.63).

Figure 64 :View of the experimental device used to test the floating piston with water and Plexiglas tube

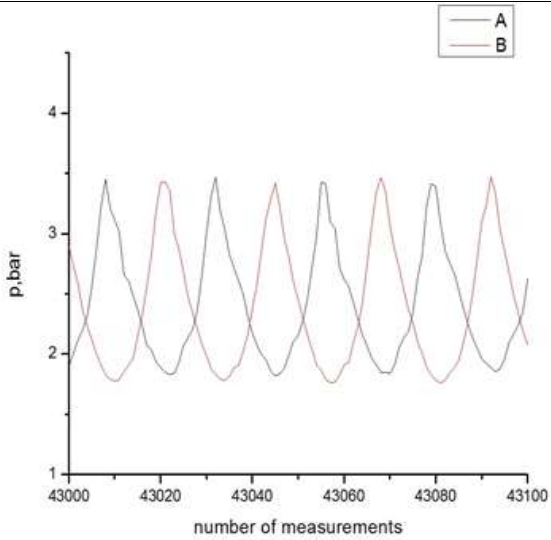


Figure 65 : Graph of the pressure oscillation imposed on both side of the water/Plexiglas equipment

Figure 66: New type of floating piston with curved tube at the top.

3.4.2: The tests results.

The figure below , figure 69, gives the schematic view and a photograph , figure 70, of the two engines coupled and the location of the sensors that were used for analysis of the experimental results.

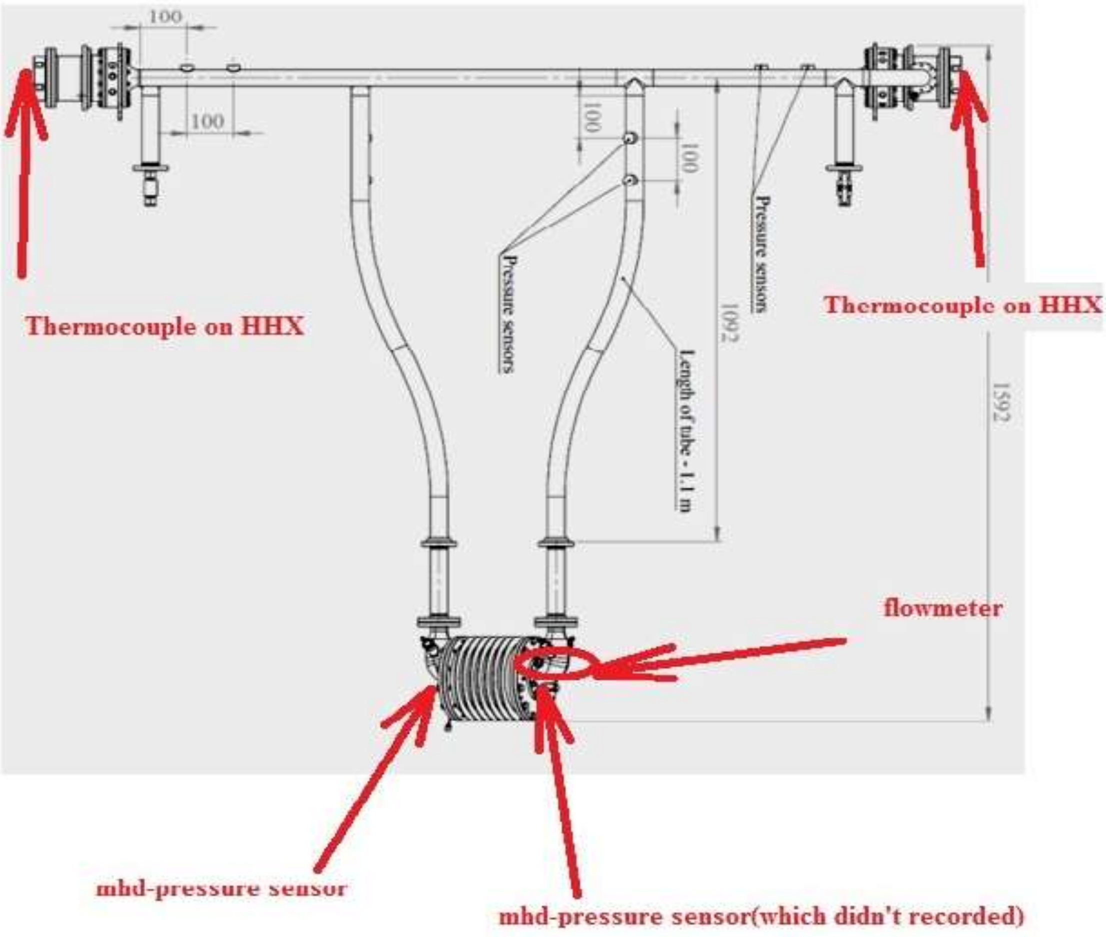


Figure 69: The measurements system applied on the electrical generator.

The figure 70 is a photograph of the MHD generator and Themo acoustic loop after assembly, with all the system used for measurement and registration of Data.

Figure 70: The facility after assembly of TAC loop and MHD generator

As it can been seen on the figure 69, the measurement system concerns the temperature at the hot source, the temperature at the cold source, the pressure at the both parts of the MHD generator and the flow rate of sodium. Independently of these parameters the phase shift, φ, between pressure and flow rate play a very important role in the interpretation of results. Taking into account this information the mechanical energy introduced in the system write:

$W_{mechanics} = P.Q\ cos\varphi$
In this expression, P designs the amplitude of the oscillating pressure and Q the volumic flow rate. In the form expressed above, the level of energy corresponds to the sum of mechanical energy exerted on the two faces of the generator. The following table summirises the experimental results obtained in a first series of test.

What is important in the results is:
- The mechanical energy introduced at the interface with the sodium
- The thermal energy introduced in the system.
- The electrical energy extracted from the load resistance
- So the main results with this first series of tests can be summirised by the following tables.
-

Mean pressure: 25 b	Resistance 1	Resistance 2	Resistance3	Resistance 4	Resistance 5
	50	100	150	340	7,58
Thermal energy	300 W	300 W	300 W	300 W	300 W
Oscillating pressure (b)	0.486	0,498	0,503	0,5198	0,476
Flow rate (l/s)	0,293	0,302	0,296	0,3023	0,281
cos φ	0,761	0,753	0,748	0,735	0,769
Current (A)	0,331	0,214	0,156	0,076	0,63
Voltage (V)	16,729	21,224	23,415	26,1	4,82
Electrical energy W	2,77	2,266	1,82	0,997	3,724
Mechanical energy	10,84	11,32	11,16	11,55	10,289
Coil energy (R~9.2 Ω)	1,006	0,42	0,22	0,054	1,534
Total electrical efficiency	0,348	0,237	0,183	0,091	0,511

Table 17 : Main perforamce of the MHD generator for mean pressure of 25 b

Mean pressure: 30 b	Resistance 1	Resistance 2	Resistance3	Resistance 4	Resistance 5
	50	100	150	340	7,58
Thermal energy					
Oscillating pressure (b)	0,863	0,876	0,908	0,999	0,821
Flow rate (l/s)	0,538	0,536	0,55	0,55	0,517
cos φ	0,638	0,637	0,634	0,626	0,641
Current (A)	0,507	0,33	0,24	0,119	0,989
Voltage (V)	25,77	32,63	36,06	40,47	7,48
Electrical energy W	6,54	5,38	4,32	2,404	3,701
Mechanical energy	29,65	29,897	31,747	34,48	27,26
Coil energy (R~9.2 Ω)	2,37	1,002	0,529	0,13	9,01
Total electrical efficiency	0,3	0,214	0,153	0,077	0,474

Table 18 : Main perforamce of the MHD generator for mean pressure of 30 b

Mean pressure 40 b	Resistance 1	Resistance 2	Resistance3	Resistance 4	Resistance 5
	50	100	150	340	7,58
Thermal energy					
Oscillating pressure (b)	0,845	0,85	0,85	0,85	0,825
Flow rate (l/s)	0,493	0,499	0,472	0,503	0,482
cos φ	0,69	0,68	0,675	0,65	0,719
Current (A)	0,458	0,3	0,22	0,11	0,846
Voltage (V)	23,26	30,055	32,36	37,51	6,44
Electrical energy W	5,33	4,55	3,48	2,07	2,726
Mechanical energy	28,72	28,84	27,085	27,78	28,62
Coil energy (R~9.2 Ω)	1,93	0,84	0,43	0,11	6,596
Total electrical efficiency	0,25	0,19	0,144	0,079	0,33

Table 19 : Main perforamce of the MHD generator for mean pressure of 40 b

The evolution of the efficiency versus the load resistance is plotted below. As it can be seen the optimum value seems better for the low value of the mean pressure, but the in parallel the level of power is higher for high value of the mean pressure.

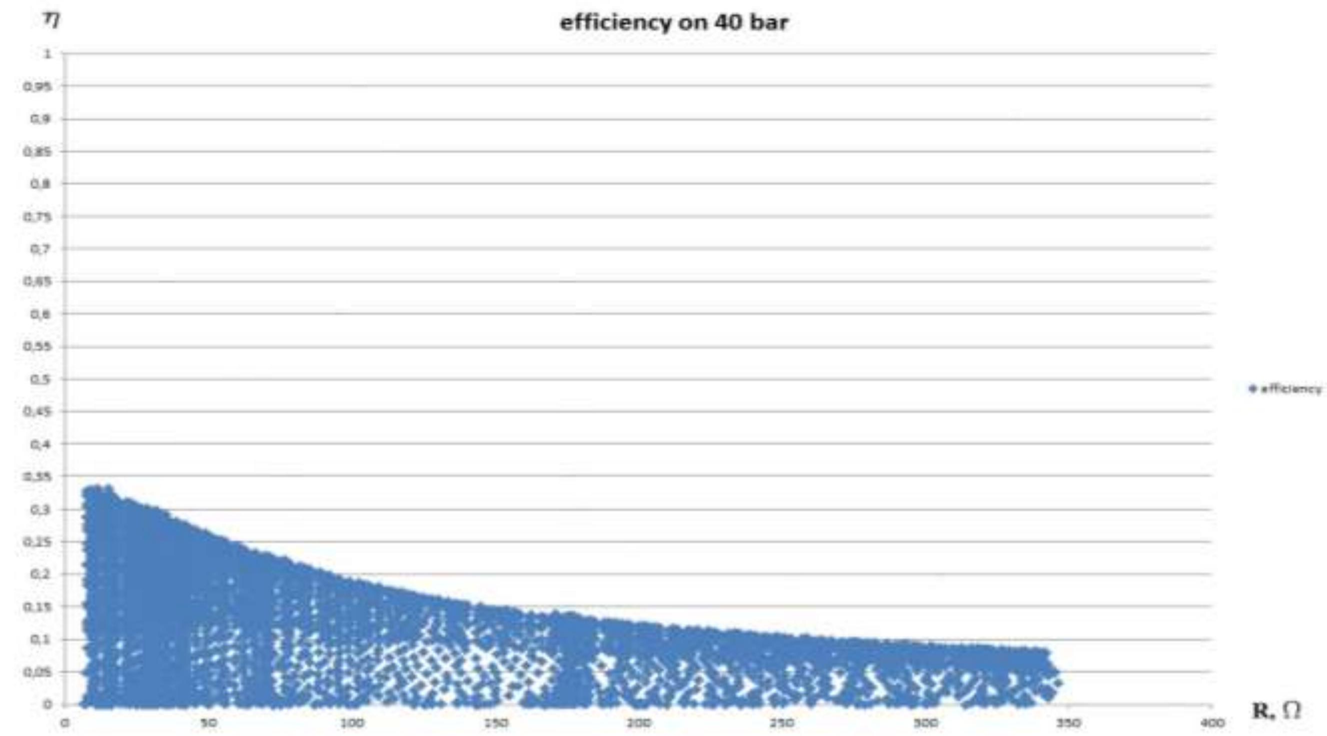


Figure 71: evolution of the efficiency, for a mean pressure of 40 b, versus the variation of the load resistance

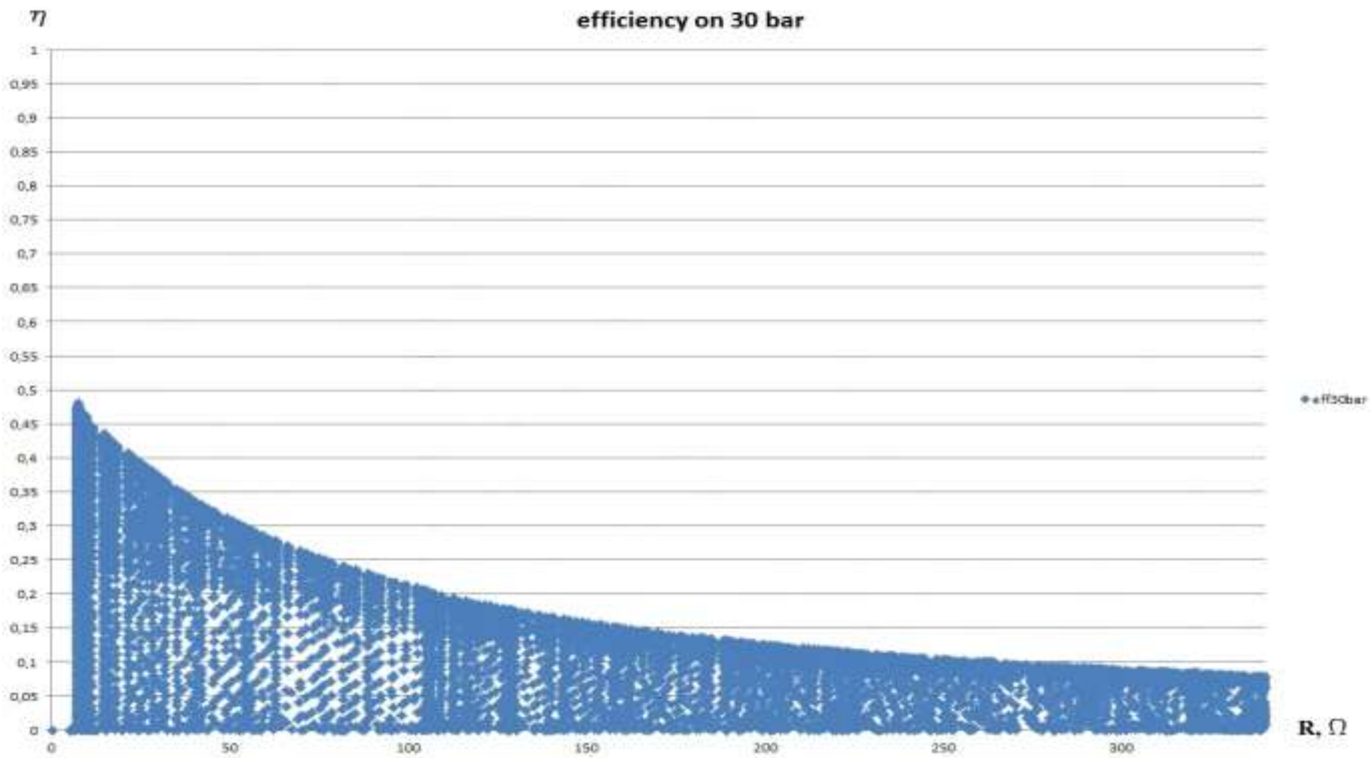


Figure 72: Evolution of the efficiency, for a mean pressure of 30 b, versus the variation of the load resistance

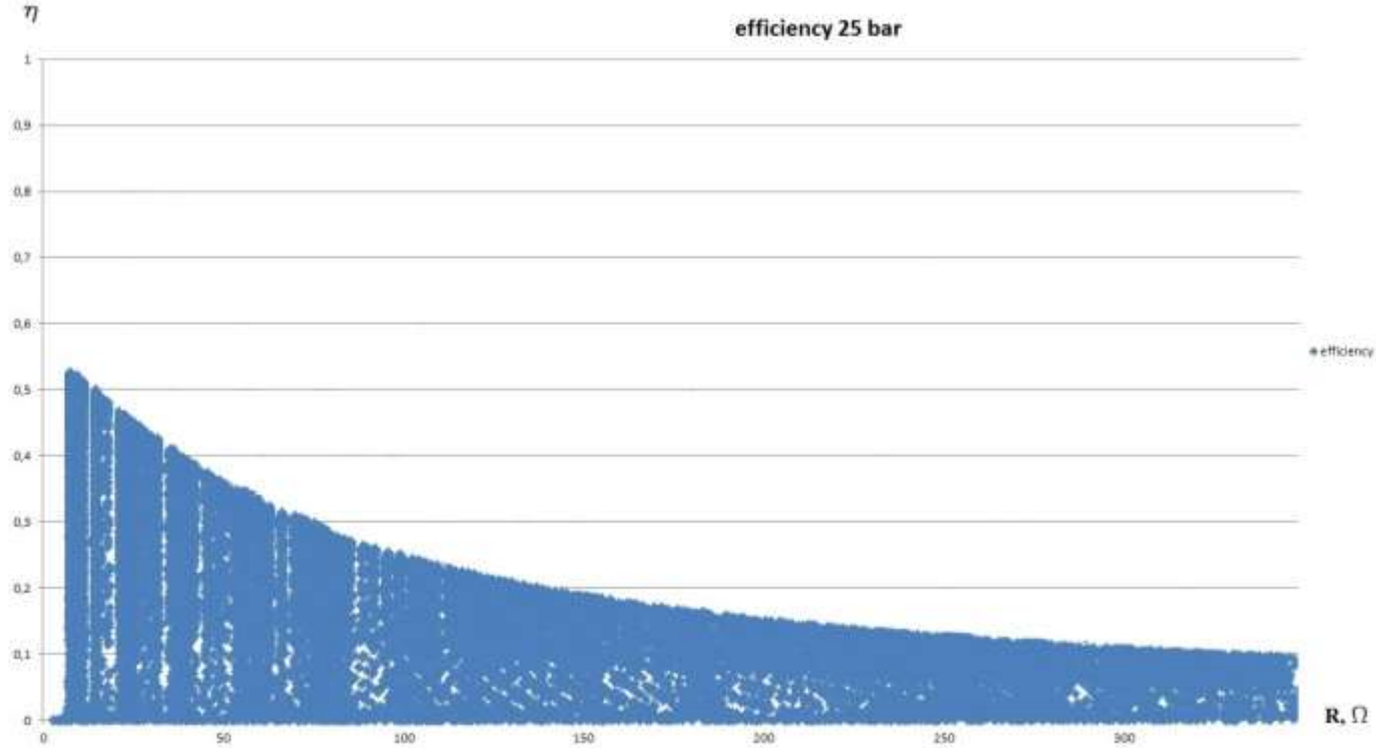


Figure 73: Evolution of the efficiency, for a mean pressure of 25 b, versus the variation of the load resistance

The results given above correspond to the MHD generator efficiencies. The obtained Electrical power transmitted to the load resistance is at list 10 times lower than expected. The reason is simple, it is due to the fact that the Thermal level introduced inside the Thermo acoustic loop is much lower that it needs to obtain a full power functioning of the system, and for example as it can be seen below, the temperature at the hot source (see figure 74) is almost 3 times lower than it is necessary to obtain full power. This lower level of the hot source is partially compensated by a lower value of the temperature at the cold source (see figure 75) and so the gradient of temperature is sufficiently large to obtain the thermos acoustic effect. However, this gradient is not large enough for obtaining great level of power. Due to that, the efficiency of the thermos acoustic loop alone is lower than 10%. That justify the realisation of a new series of tests.

This first series of tests was stopped because a dysfunctioning of a mechanical valve. Consequently, the facility was disassembled. A new series of tests will be done after cleaning of each pieces and after cleaning of sodium. This operation will take some time and the news results will be introduced in the final report latter.

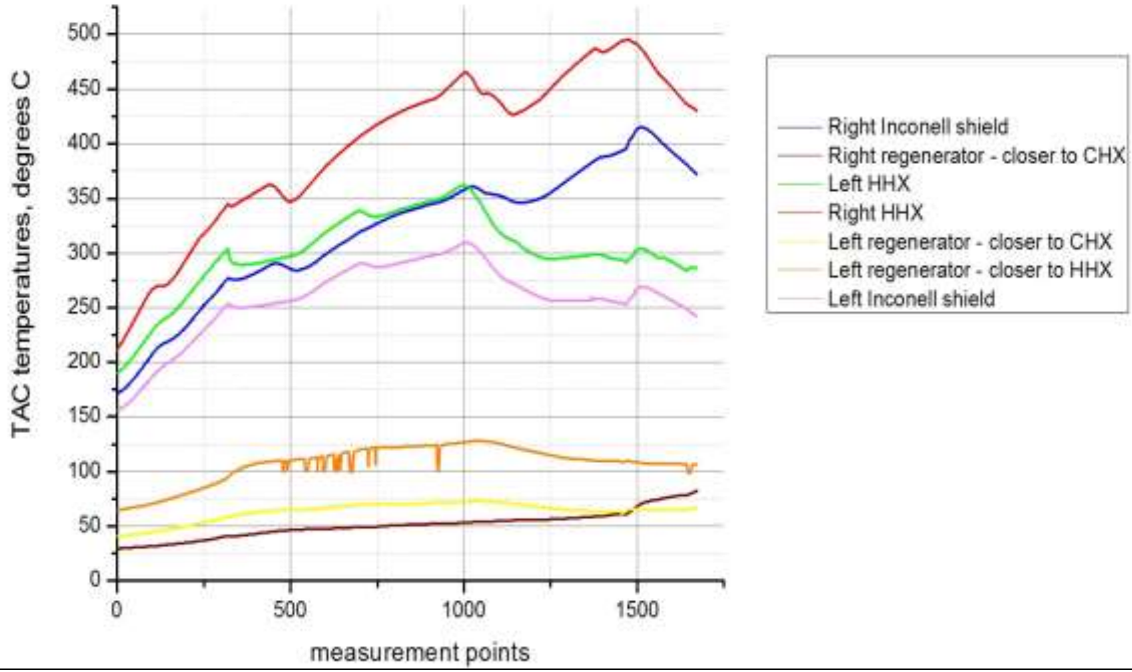


Figure 74: Evolution of the temperature level at the two hot sources in green and pink.

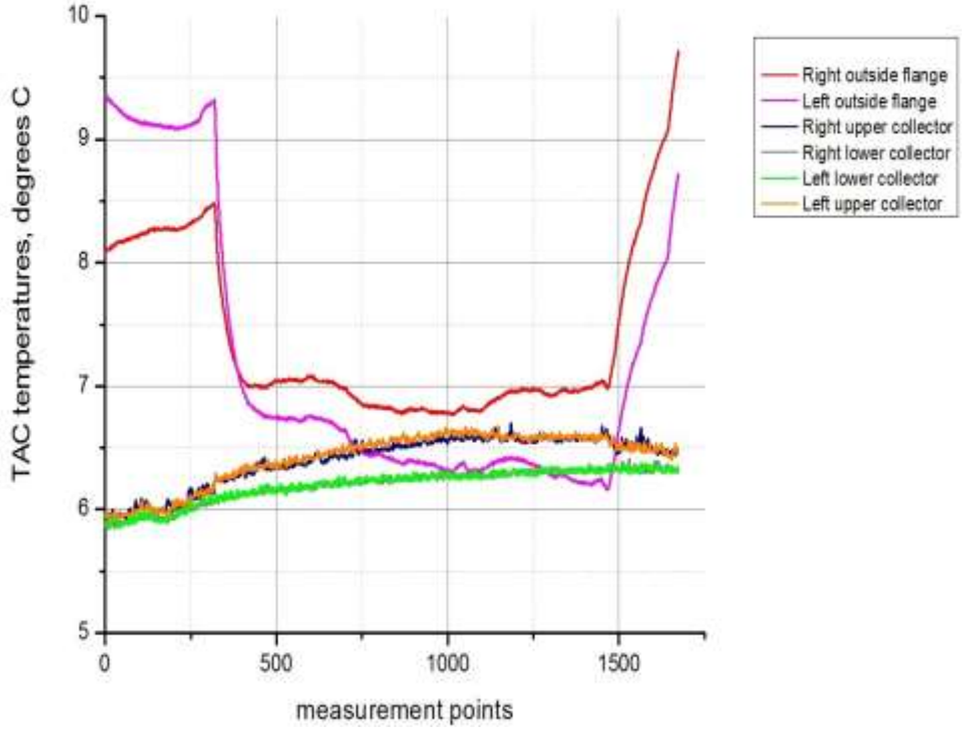


Figure 75: Evolution of the temperature level at the two hot sources in green and pink.

Even if this series of test are too much lower in term of power obtained, they are very logical in term of interpretation. It can been seen also in the figure 16.6 below that a good quality of signal have been obtained both for the pressure and electrical current evolution. The good connection between MHD generator and Thermos acoustic loop have been also demonstrated.

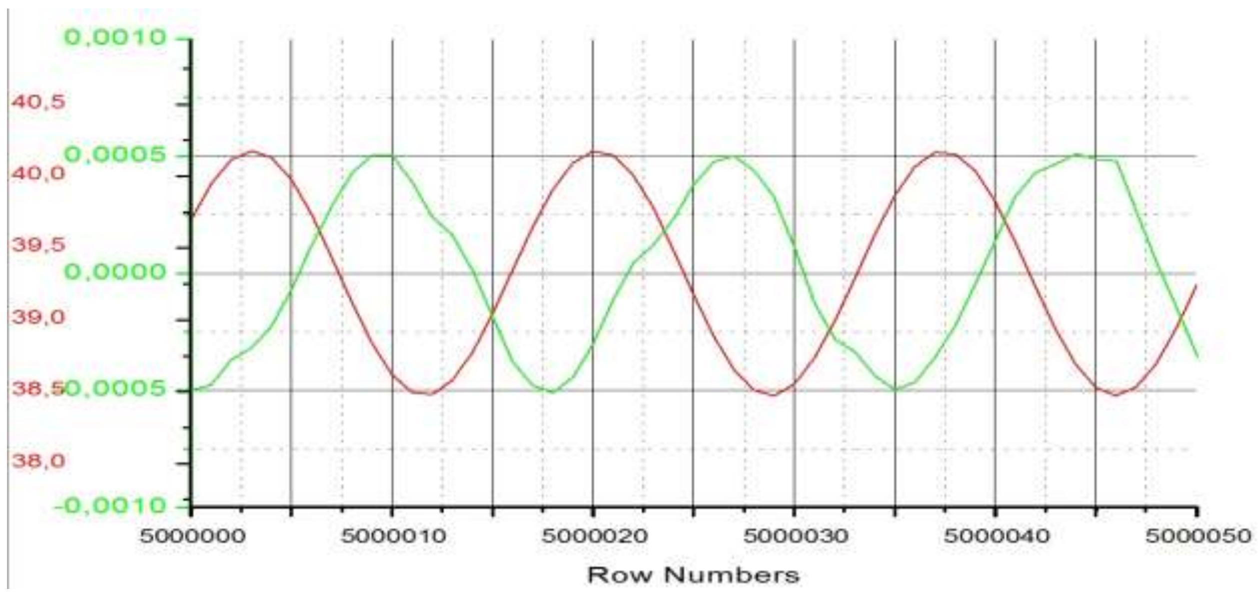


Figure 77: Time evolution of the pressure in red and the flow rate in green.

taking into account the cross section of the sodium flow, which is1458 mm² the amplitude of velocity obtained is around 0. 34 m/s, That is again at list 10 time lower than it need to a full power.

4. Conclusion

The project concerns the design realisation and test of a prototype of a TA/MHD generator, representative as much as possible of a space prototype, but of course not completely identical due for example to the presence of gravity. On the other hand, the prototype is not optimised in terms of efficiency and mass. The objective is mainly to validate the theoretical approach, in order to be able to optimise the generator.

The main efforts of the third year were devoted to work packages 2 and 3. The work package 2 was focused on the realisation of experimentation plan and means, on the construction and on the tests of the two engines, Thermo acoustic loop and MHD generator. The construction of the two engines has begun with some delay and the tests of both have revealed difficulties producing the break of some pieces when the nominal conditions, about temperature and pressure were applied. So it was necessary to construct new elements producing a new delay about the end of the tests. The objectives are to realise the totality of the program that is expected to be finished on the end of January 2016. The work package 3 concerns the study about the space architecture, including hot and cold sources, as well as on the possibilities to stabilise the liquid/gas interface, with new very important results obtained by HZDR.