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MAX Project Final Report

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On behalf of all project partners

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[MAX]

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Distribution list

This report will be distributed to all the participants of the MAX project.

It will also be specifically distributed to the following members of the SCK•CEN and/or MYRRHA management:

- Eric van Walle
- Hamid Aït Abderrahim
- Peter Baeten
- Marc Schyns

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1. Introduction

The MYRRHA project, “Multi-purpose hYbrid Research Reactor for High-tech Applications”, is to be considered as a major milestone in the endeavour to develop a sustainable solution to the nuclear waste problem based on efficient transmutation of minor actinides. It aims at demonstrating the Accelerator Driven System (ADS) concept at a relevant power level, and also at providing an efficient fast spectrum neutron irradiation facility. Its liquid lead-bismuth cooled reactor would be a highly significant prototype of one of the Generation IV options, namely the Lead Fast Reactor. By simultaneously addressing outstanding R&D needs in the fields of future reactor technology and of fundamental nuclear science, MYRRHA is nominated on both the ESNII roadmap [1] and the ESFRI list [2]. A description of MYRRHA may be found in [3] and references therein.

The object of the “MYRRHA Accelerator eXperiment” (MAX) collaborative project, as described in the Annex B of its proposal [4], in its first Deliverable 1.1 [5] or in its public web-site [6], is to pursue the R&D on ADS-type driver accelerators and deliver an updated consolidated reference layout of the MYRRHA proton linac (linear accelerator). This accelerator has to satisfy a list of criteria that have been defined by the reactor design team in accordance with the accelerator design team [7,8]. They primarily concern the particle type, energy, beam current and beam delivery time structure. They constrain the operational tolerances on the parameters. Finally they fix a beam reliability goal, expressed as a tolerance to beam trip frequencies according to beam trip durations. These tolerances may be translated to values of Mean Time Between Failures (MTBF). The MYRRHA accelerator main beam requirements are presented in Table 1.

Table 1: MYRRHA driver accelerator main beam requirements

Particle		protons	
Beam energy		600	MeV
Peak beam current		0.1 — 4	mA
Beam duty factor		10^{-4} — 1	
Time structure	(microstructure)	CW	
	(nominal macrostructure)	200 µs beam holes	(at 1 — 250 Hz)
Beam power stability		± 2%	(100 ms integration time)
Footprint on target		circular ø 85 mm	
Footprint stability		± 10%	1 s integration time
Beam trip tolerance	$\tau > 3$ s	10	per 100 day period
	$0.1 \text{ s} < \tau < 3 \text{ s}$	100	per day
	$\tau < 0.1$ s	∞	
Corresponding MTBF	$\tau > 3$ s	250	hours

It must be stressed that the beam trip tolerance criterium is particularly stringent in view of present day operational data from existing accelerators with comparable performance in terms of beam power. This fact was already fully acknowledged during the FP5 project PDS-XADS [9], where it led to the fundamental choice of proposing a SuperConducting (SC) linac as the driver machine in the ADS context. Thus the Spallation National Source (SNS) linac [10] is particularly relevant: a comparison of the MYRRHA request with SNS experimental beam trip data is enlightening (see Figure 1) and perfectly underlines that a strong focus is still needed to improve the reliability of present accelerators and reach the ADS goal. Therefore, even if today the SC linac choice is entirely corroborated for the ADS purpose, it is more obvious than ever that its implementation needs extensive R&D efforts to be undertaken and proper prototyping to be pursued. This statement is doubtlessly reinforced by considering the borderline position of MYRRHA in today's accelerator landscape (see Figure 2).

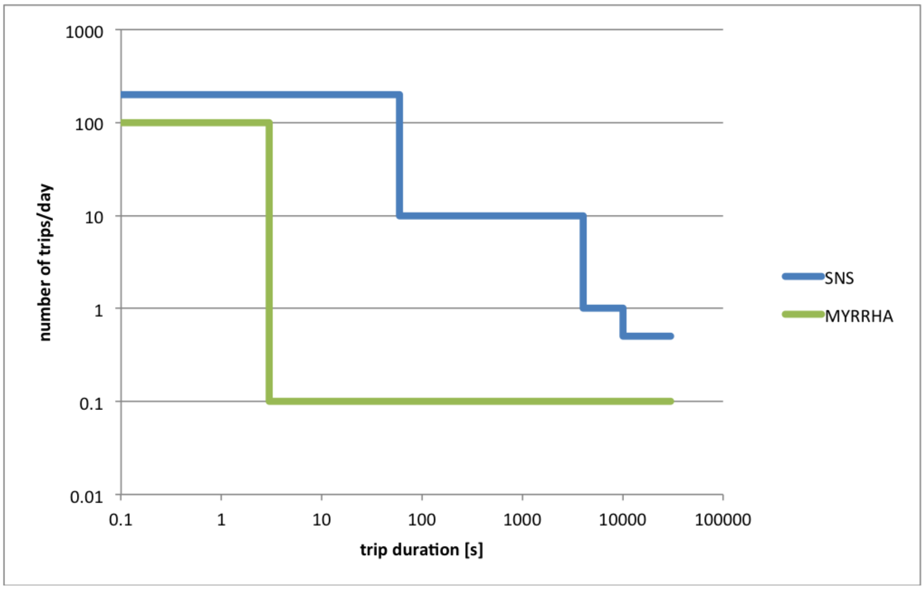

Figure 1: Comparison of beam trip rates: the MYRRHA goal against the SNS experience [11].

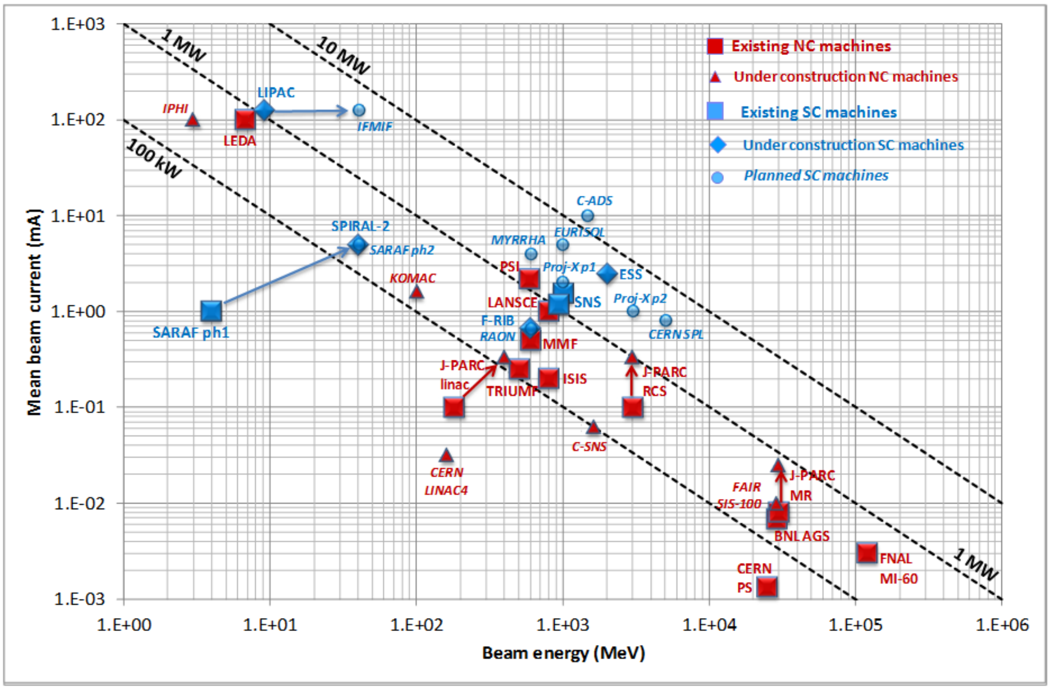

Figure 2: Present high-power hadron accelerator landscape in a beam current vs. beam energy plot: existing, under construction and planned machines [12].

2. Goals and overview

In general terms, the goals of the MAX project may be itemized as follows.

- Obtain a consolidated concept of the entire MYRRHA linac (MLA).
- Build selected engineering design files.
- Perform selected experiments that have been defined earlier within the preliminary concept.
- Gather and interpret return on experience data.

At its start, the definition of the MAX project mainly built upon the preliminary MLA concept generated by Work Package 1.3 of the FP6 Integrated Project EUROTRANS. More information can be found in the associated reports and especially the final WP 1.3 Deliverable [13]. Moreover, an open question raised at the very end of EUROTRANS regarding the choice of the RF frequency in the injector section, and more generally, the urgent need for an international design review was felt in order to gain adequate confidence in the choices that had been made and obtain relevant feedback for the further developments.

From these considerations, the project was built with 11 partners from national research institutes, universities or industries (see Table 2), and subdivided in 4 main technical Work Packages, namely:

- WP1: Global coherence
- WP2: Injector developments
- WP3: Main linac developments
- WP4: System optimization

Table 2: List of MAX partners

Partner #	Partner short name	Partner long name
1	CNRS	Centre National de la Recherche Scientifique – France
2	ACS	Accelerators and Cryogenic Systems – France
3	ADEX	Adaptive Predictive Expert Control – Spain
4	CEA	Commissariat à l’Energie Atomique – France
5	EA	Empresarios Agrupados Internacional – Spain
6	FE-UCP	Catholic University of Portugal, Faculty of Engineering – Portugal
7	IAP	Institut für Angewandte Physik, Goethe Universität Frankfurt – Germany
8	INFN	Istituto Nazionale di Fisica Nucleare – Italy
9	KUL	Katholieke Universiteit Leuven – Belgium
10	SCK•CEN	Nuclear Research Center – Belgium
11	TED	Thales Electron Devices – France

Even if the goal was obviously to keep an as complete work programme as possible, some topics were discarded from the MAX activities in regard of limited resources. It was in particular considered that “Controls and Diagnostics” were bearing a reduced priority in view of the MAX goals, and that the design of the reactor interface and of its high-energy beam line was adequately dealt with in the FP7 CDT project [14]. Also, a thorough revision of the accelerator budget was not explicitly included.

The withheld MAX topics may then be assigned to 5 main categories. Table 3 presents the resulting overview of activities. For each of them it refers to the relevant MAX deliverables containing the detailed descriptions/data/calculations/design/analyses.

Table 3: Overview of the MAX topics, assigned to 5 main categories

Category	Topic	Deliverable(s)
Global design and coherence	Definition of the MYRRHA linac consolidated concept	**D1.2**, D1.4
	Advanced beam optics simulations for fault tolerance	**D1.4**, D1.2
	MYRRHA linac reliability modelling	**D4.4**
	Cryogenic working temperature assessment	**D4.1**
	Buildings and infrastructures	**D1.3**
Injector layout	LEBT design	**D1.2**
	Choice of frequency & injector concept	**D2.1**
	Simulation codes benchmarking and optimal optical solution	**D1.4**, D1.2
Construction readiness design files	Spoke cavity and cryomodule engineering design	**D3.3**
	Room-temperature CH cavity engineering design	**D2.3**
	4-rod RFQ engineering design	**D2.4**
Experiments	Operation & reliability assessment of an elliptical cryomodule	**D3.1**, D3.4
	Assessment of the ADEX cavity tuner control loop with LLRF	**D3.2**, D3.1
	Fabrication & cryogenic test of a superconducting CH cavity	**D2.2**
	RFQ thermal mock-up evaluation and test	**D2.4**
	704 MHz SS RF amplifier module development and test	**D4.5**
Return on experience	Reliability analysis of the SNS linac	**D4.2**
	Accelerator operation in the GUINEVERE experience	**D4.3**

The aim of this final MAX project report, Deliverable 1.5, is (i) to give a summarizing overview of these different MAX activities and (ii) to present in a rather condensed way a new up-to-date consolidated concept with adequate recommendations which will later constitute the basis for further developments in the MYRRHA linac development program.

The following sections of this Deliverable 1.5 are organized in the following way.

- Section 3 "***MAX topics & main achievements***" is structured according to the contents of Table 3, summarizing each of the activities and highlighting its main results and outcome.
- Section 4 "***International Design Review***" gives a short description and interpretation of this event.
- Section 5 "***Outlook***" gives an executive summary of the main project outputs, positions MAX in the broader context of other research programs and proposes future activities and the contents of a potential follow-up project within Horizon 2020.

3. MAX topics & main achievements

3.1 Global design and coherence

3.1.1 Definition of the MYRRHA linac consolidated concept

Based on previous conceptual design studies [9,13,15], a consolidated reference design of the MYRRHA linear accelerator has been settled during the project. It includes for the first time a rather detailed description of all the different parts of the machine with extensive beam optics simulations, from the source to the target. It also includes the definition of the different envisaged scenarios to be applied for machine reconfiguration in case of faults during operation and the strategy to be used for a reliable and accurate control of the beam power sent into the MYRRHA reactor [16]. The main different parts of this consolidated MYRRHA linac design are briefly described here after.

- The 17 MeV MYRRHA injector line [17] is designed to provide optimal acceleration efficiency with a minimized number of components. To increase the reliability, the philosophy consists in doubling the whole 17 MeV injector, providing a hot stand-by spare one able to quickly resume beam operation in case of any failure in the main one. The fault-recovery procedure is based on the use of a switching dipole magnet connecting the two injectors through a 'double-branch' Medium Energy Beam Transport (MEBT) line (see Figure 3). Each branch of the injector is composed with the following elements:
  - a 30 kV ECR proton source followed by its 2 metres long Low Energy Beam Transport (LEBT) magnetic line,
  - a 4 metres long 176.1 MHz 4-rod RFQ accelerating the beam to 1.5 MeV and operating with very conservative inter-vane voltage (30 kV),
  - a 15 metres long booster composed with a matching section followed by 7 room-temperature multi-cell CH cavities up to 5.9 MeV and by 5 superconducting ones.

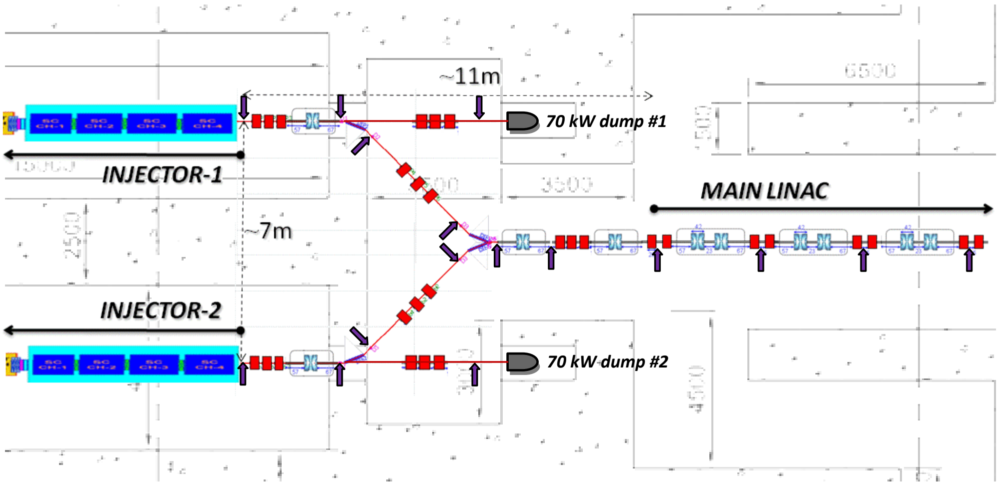

Figure 3: General scheme of the MYRRHA MEBT, superimposed on a preliminary building layout. (red squares: quadrupoles, blue elements: Spoke SRF cavities, purple arrows: Beam Position Monitors)

- The MYRRHA main superconducting linac then brings the beam from 17 MeV to its final energy 600 MeV over about 240 metres [18]. It is composed of a periodic array of independently-powered superconducting cavities with moderate energy gain per cavity and regular focusing lattices. Three distinct cavity families are used to cover the full energy range: the first section uses 352.2 MHz Spoke 2-gap cavities (β_{opt}=0.37), while the two following sections use 704.4 MHz elliptical 5-cells cavities (β_{opt}=0.51 & 0.70). The linac is designed to increase as much as possible the tuning flexibility and ensure a very large beam acceptance so as to provide sufficient margins for the implementation of a fault-tolerance capability by serial redundancy, where a missing element's functionality can be replaced by retuning other elements with nearly identical functionalities. The present adopted strategy is to use a local compensation method to compensate RF failures (cavities and their associated control and power systems): the faulty cavity (respectively cryomodule) is compensated by acting on the RF gradient and the phase of the 4 nearest neighbouring cavities (respectively cryomodules) operating de-rated (i.e. not already used for compensation). This retuning scheme can be achieved by providing significant RF power and gradient overhead throughout the 3 superconducting sections. In the present design, this operation margin in terms of acceleration capability was chosen to about 30%.

- A final High Energy Beam Transport (HEBT) line finally injects the proton beam onto the spallation target located inside the reactor [19]. This beam line is composed of four 45° bending magnets going up from the linac tunnel, and then down through the reactor hall to the sub-critical core. It has achromatic and telescopic optics in order to guarantee the beam stability on target and to ease the tuning, and houses AC magnets to scan the beam on target with the specified donut shape. A full power beam dump is also foreseen in the alignment of the linac for the commissioning purposes. Specific room has also be reserved in this HEBT to insert a fast beam kicker so as to keep the possibility to send a small part of the MYRRRHA beam to an ISOL facility, taking advantage of the 200 µs beam interruptions to be regularly produced for the on-line monitoring of the core sub-criticality.

Much more details can be found in Deliverable 1.2 [8], issued on August 26, 2013, which describes over 80 pages the design of this reference accelerator. Complementary details are also available in Deliverable 1.4 [20], in particular on the final injector design which has been improved very recently (see section 3.2.3).

3.1.2 Advanced beam optics simulations for fault-tolerance

Several advanced beam optics simulations have been performed during the project to check the robustness of the linac architecture submitted to typical errors, mismatches, imperfections and to further assess the feasibility of the fault-tolerance concept [21,22] in the main superconducting linac. These studies have been performed in 3 steps.

- Preliminary sensitivity analyses have been performed on the different parts of the machine by assessing the impact of typical errors on the beam behavior. These results are gathered inside Deliverable 1.2 [8] and led to the conclusion that the overall design described in this report was robust and acceptant enough, except for the injector part which needed to be reworked and improved.

- New simulation studies [23,24] have been carried out to further evaluate the feasibility and the limits of the local failure-compensation method in the main superconducting linac. These results, summarized in Deliverable 1.2 [8], showed that the fault recovery scheme is a priori feasible everywhere in the MYRRHA main linac to compensate for the loss of a single cavity or of even a full cryomodule. It has been also showed that it should be possible, to a certain extent, to compensate multiple RF failures simultaneously.

- Start-to-end massive beam dynamics simulations have been performed, followed by Monte-Carlo statistical error studies. The goal was to estimate in different operation conditions (nominal, fault compensation case…) the robustness of the MYRRHA linac architecture submitted to typical errors and imperfections, tracking the induced beam losses probability. To be able to estimate accurately the losses occurring in the accelerator, the simulations need to be as closed as possible to the real machine operation. This especially implies to define a realistic correction scheme, and to perform simulations with a huge number of particles and linac error configurations. The results, presented in Deliverable 1.4 [20], are very positive, but also indicate some necessary improvements.
  - ✓ Longitudinal acceptance is the key point concerning the control of the beam losses along the structure.
  - ✓ The most logical and more comfortable way to improve the situation should be to provide a new RFQ optical design with a smaller longitudinal output emittance as main objective (in place of the usual beam transmission). Such a work has been already started and an improved design is existing (see section 3.2.3).
  - ✓ Using the present envisaged compensation scheme, the loss of a full cryomodule is not so easy to manage in terms of longitudinal acceptance: in some cases, the associated beam losses are approaching the limits (see Figure 4). The settings of the compensating cavities should be generally less aggressive, including more cavities if possible and using a tuning model taking into account a new acceptance criterion, which remains to be developed.
  - ✓ Finally, the MEBT should be further optimized in terms of achromat and collimation.

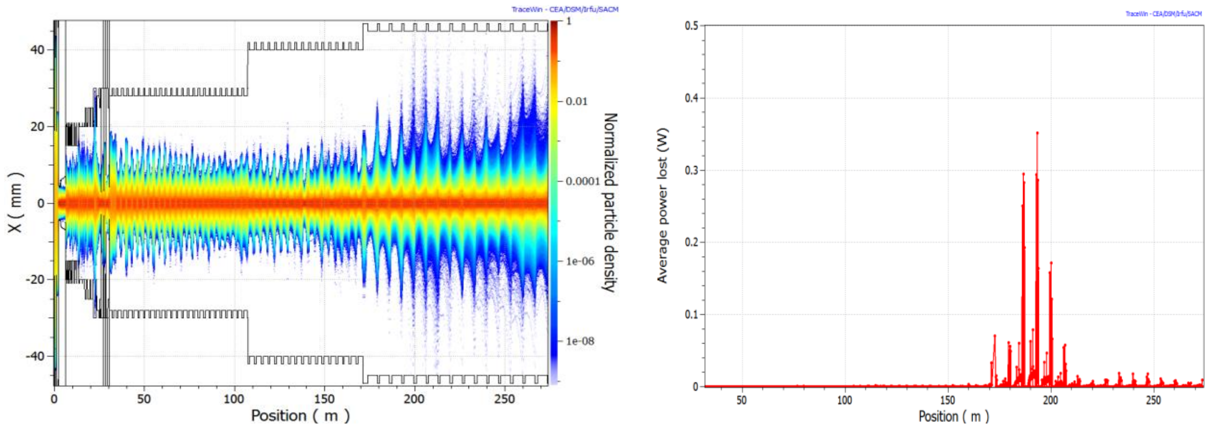

Figure 4: Results from a statistical error study in the case a fault compensation case with several simultaneous faults (1 full cryomodule + 2 single cavities); the reached cumulative statistics is 3.10^9 particles.
(Left) Superposition of all beam horizontal transverse densities.
(Right) Average beam losses in the superconducting part of the linac.

3.1.3 MYRRHA linac reliability modelling

Based on the analysis of the SNS linac (see section 3.5.1), the modelling work applied to the MYRRHA case has been performed. In particular, the 3 main reliability-oriented features of the MYRRHA linac design have been included as extensively as possible: injector switch procedure, SC cavity failure compensation function, specificities of the solid-state amplifiers architecture. The detailed analysis of the MYRRHA reliability model is described in Deliverable 4.4 [25]. The main outputs and conclusions are summarized here under.

The MYRRHA linac Risk Spectrum model allows to obtain two fundamental reliability-related characteristics related to the Top Event of the fault tree, which is “MYRRHA accelerator down”.

1. The Mean Unavailability.
2. The Frequency.

It is important to acknowledge that a “standard” MYRRHA-type linac without redundancy and/or fault compensation exhibits a Mean Availability of 70% and a Frequency of 550 trips/year. These figures are obtained if SNS input parameters are used, and they may be considered as initial values for the optimisation.
Another initial piece of information is given by the main causes of unavailability in SNS.

1. The Superconducting section (RF, cavities, cooling, vacuum).
2. Diagnostics and Controls.
3. Front End.

These findings suggest that, indeed, redundancy (front end) and fault compensation (SC section) have a high reliability-increasing potential. The optimisation studies confirm this potential. However, a first major conclusion is that the Diagnostics and Controls systems of MYRRHA must be designed with significantly increased reliability (to the 10^{-3} failure level) for the fault compensation to be effective. It reflects the fact that any compensation scheme is very heavily relying on the quality of the controls. It is remarkable that, this being achieved, the failure rate of the compensation mechanism itself becomes a rather weak optimisation parameter.

A second global conclusion is the fact that the optimal effectiveness of a compensation scheme, expressed as the generated reduction of the number of linac trips, is around 100/year. This figure appears to be roughly independent from the initial trip frequency. It is subdivided in 50 trips/year gained by doubling the injector, 50 trips/year gained by fault compensation in the superconducting linac. Two important consequences are:

1. The MYRRHA goal of 40 trips/year (10 per 3-months period) implies an initial trip frequency (bare linac without injector doubling and without fault compensation) of 140 trips/year. This figure has to be obtained through a systematic improvement of single system MTBF values — the Deliverable 4.4 provides detailed tables.
2. During a 3-month operational period the number of compensation events is, on average, roughly limited to 13. This figure determines the amount of RF power overhead that the compensation scheme requires. It appears to be significantly inferior to the presently assumed number of 30%.

It is clear that the underlying results are preliminary and that they need much further refinement. However, there is no doubt about the validity of its main message: global fault compensation turns out to be a very effective mean for boosting both availability and top-level fault frequency if and only if it is supported by an underlying basic linac that already has an intrinsic optimized reliability. This reliability must be based on a careful control of single failures through adequate MTBF and/or MTTR values. The reliability model has an essential role in the determination of these design values. Under these conditions the MYRRHA reliability goal appears to be achievable.

3.1.4 Cryogenic working temperature assessment

The cryogenic system needed to cool the 156 cavities of the MYRRHA superconducting linear accelerator has been assessed [26]. The detailed results of the analysis can be found in Deliverable 4.1 [27]. The main outputs are summarized here after.

- *Technical comparison of 2K and 4K solutions*. A detailed analysis of the thermal losses at the different temperature levels has been performed, based on the most recent inputs (operation of different types of SC cavities, static and dynamic losses, coupler losses, refrigerator performances and efficiency). It leads to propose a full 2K scheme for all SC cavities all the MYRRHA linac. The power capacity of the refrigerator is estimated to an equivalent 13.1 kW @ 4.5 K (corresponding to 4.75 kW @ 2.1K, 1.1 kW @ 5K and 13.6 kW @ 40 K). These values include an uncertainty factor of 1.25 and an overcapacity factor of 1.5.

- *Reliability related aspects of cryogenic plant*. Several existing cryogenic plants have been analysed, including HERA in Hamburg which is now stopped but has registered failure statistics during 16 years. Also the LEP, J-Lab, SNS and preliminary operating results with the LHC units were analysed. This shows that the cryogenic refrigeration system can reach very high availability figures and that short interruptions are not relevant due to the long thermal time constants. Some control systems related failures (sensors, electronics, cabling, software) must be analysed in more detail and eventually propose more redundancy and robust design.

- *Preliminary layout and cost of cryogenic plant*. Comparing the estimated power for MYRRHA with the existing or planned cryogenic plants, it appears to be close to one LHC unit (equivalent 17 kW @ 4.5 K). Based on the LHC unit as installed in CERN, it allows to evaluate preliminary needs for buildings and infrastructure and to propose a budget for components of 21 M€ and associated manpower cost of 7 M€.

3.1.5 Buildings and infrastructures

The work on this task has been performed from the data coming from the MYRRHA project team and from the CDT (Central Design Team) FP7 project [28]. Using this information as a basis, different general layouts for the MYRRHA buildings have been proposed during the course of the MAX project, including cost-related aspects.

Several alternatives for the linac tunnel and the linac annexed buildings arrangement inside the general plant layout have been analysed, including the study of the personal and equipment flow to the linac, the access roads to the different buildings and the road connection with the existing SCK•CEN track network. The interconnection between the linac and the RF gallery has been especially analysed considering the interference with the cryogenic connection and the definition of the different linac exit galleries. Preliminary access and safety requirements for the different linac auxiliary buildings have also been defined.

Details are given into Deliverable 1.3 [29], issued on June 3rd, 2014. This report includes the plant layout drawings, based on the preliminary size of the buildings defined in previous EURATOM Framework Programmes, as the CDT, or proposed during the course of the MAX project as the cryogenic buildings and the injector building.

3.2 Injector layout

3.2.1 LEBT design

The 30 keV Low Energy Beam Transport (LEBT) line for MYRRHA has been designed during the first phase of the MAX project. The details of its conceptual design are available in Deliverable 1.2 [8]. Its layout is based on a short magnetic solution and is designed to maximize the proton beam transmission from the proton source to the RFQ by considering the space-charge compensation effects of the beam. The overall length of the line, from the plasma chamber extraction hole to the RFQ rods, is around 2.8 metres. The beam transport and focusing is ensured by a couple of solenoid magnets with integrated dipole steerers. Collimation slits, located in the middle of the LEBT, are used for halo cleaning to improve the RFQ transmission, and several beam diagnostics can be inserted, allowing for interceptive beam current, profile and transverse emittance measurements. Before the RFQ injection flange, a short RFQ interface section hosts a slow electrostatic beam chopper, adopted to give a precise time structure to the beam delivery towards the future MYRRHA reactor.

From this conceptual design, performed within the MAX project, the engineering design and construction of this beam line has been started and is presently on-going by CNRS/LPSC and SCK•CEN on their own resources. Associated to its ion source, this LEBT will be used in the near future to perform low-energy beam physics experiments on the space-charge compensation phenomenon and, once fully characterized and operational, as the first stage of the future MYRRHA injector prototype (see section 5.3). A complete picture of the ion source, LEBT and RFQ interface is shown in Figure 5 [30], together with associated beam simulation results.

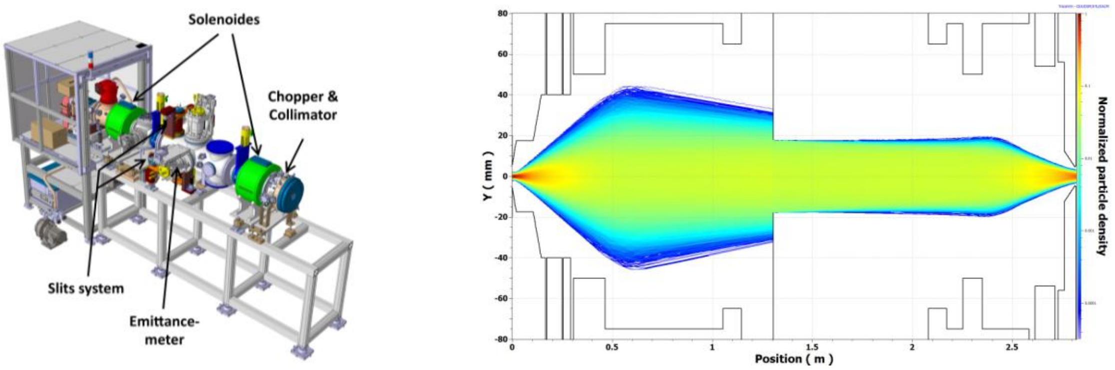

Figure 5: (Left) 3D model of the MYRRHA ion source, LEBT, RFQ interface (courtesy of CNRS/LPSC & SCK•CEN). (Right) LEBT multiparticle tracking and aperture model in the vertical plane.

3.2.2 Choice of frequency & injector concept

The baseline frequency of the superconducting linac is 352.2 MHz. The spoke section (17 – 81 MeV) uses this fundamental and the elliptical section (81 – 600 MeV) applies double this frequency, i.e. 704.4 MHz. At the start of the MAX program the layout of the injector (30 keV – 17 MeV) was not yet fixed, with these alternatives: (i) 352.2 MHz with a 3 MeV 4-vane RFQ, (ii) 176.1 MHz with a 1.5 MeV 4-rod RFQ. Alternative #2 was becoming realistic due to the reduced beam intensity requirement of MAX (5 mA) with respect to EUROTRANS (up to 30 mA for the EFIT option [31]). The main expected benefit of alternative #2 over #1 was lying in its reduced cost: less RF power and less construction cost of the RFQ. However, the beam dynamics of the entire injector, up to 17 MeV and featuring CH-type cavities, had to be confirmed.

This issue was investigated at the very beginning of the MAX project. The outcome is clearly in favour of the 176.1 MHz solution:

- safer and more reliable CW operation parameters, thanks to an improved RFQ shunt impedance and a significant reduction of RF power consumption per unit length;
- reduced costs, thanks to the use of a more flexible and cost-saving 4-rod RFQ structure instead of the originally proposed 4-vane one;
- still good beam performance, with lower RFQ output energy.

A new 176.1 MHz injector was therefore designed for MAX [32].The detailed design and simulation results as well as the comparative analyses with the previous 352 MHz EUROTRANS injector [33] are gathered in the MAX Deliverable 2.1 [34], issued on January 31st, 2012.

3.2.3 Simulation codes benchmarking and optimal optical solution

All along the MAX project, several specific beam dynamics simulation activities dedicated to the injector part (RFQ + CH booster) have been performed in order to crosscheck the results obtained using different beam simulation codes and improve and optimize the design of this low-energy part of the machine, that is crucial to ensure good beam quality in the subsequent higher energy sections of the accelerator. The main steps of the activity have been as follows.

- Benchmarking activities between beam simulation codes (Parmteqm/Toutatis for the RFQ & Lorasr/TraceWin for the CH booster) have been successfully completed [35]. Details are available in Deliverable 1.2 [8].

- Following the findings of Deliverable 1.2 on the preliminary beam dynamics sensitivity analyses to errors and the first start-to-end simulation results (see section 3.1.2), and in agreement with the recommendations of the international design review (see section 4), it was decided to rework and optimize the CH booster part of the injector to replace the very aggressive KONUS-type optical design by a safer and more conservative design based on conventional negative synchronous phase laws for acceleration.

- After several intermediate designs, a new MYRRHA injector layout has been settled (see Figure 6), with very robust beam dynamics, low emittance growth rates and a smooth output particle distribution [17]. Compared to the previous design, sufficient drift space also provides plenty room for diagnostic elements. Behind the 4-rod RFQ and a pair of two-gap QWR rebunchers, the 1.5 MeV protons are matched into the CH cavity section. A focusing triplet between the rebunchers ensures an ideal transversal matching into the doublet lattice. Each of the 7 RT CH structures has a constant phase profile and doesn't exceed thermal losses of 25 kW/m. The transition to the 5 SC CH cavities with constant beta profile is at 5.9 MeV. For a safe operation of the niobium resonators the electric and magnetic peak fields are defined below 25 MV/m and 57 mT respectively. The details of this new CH booster design, that has been used for the error studies presented in section 3.1.2, are provided into Deliverable 1.4 [20].

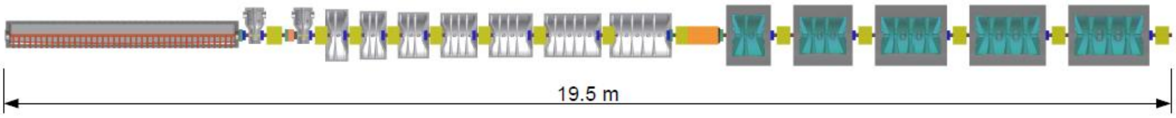

Figure 6: Global view of the consolidated MYRRHA injector, including from left to right: 4-rod RFQ, QWR-based matching section, room-temperature CH-based linac, superconducting CH-based linac.

- Finally, on the basis of the MYRRHA RFQ reference design defined in Deliverable 1.2 (and also used for the error studies presented in section 3.1.2), further improvements with respect to electrode aperture, emittance growths and output distributions have been performed very recently, following the conclusions of Deliverable 1.4 [20]. A new design for the MYRRHA RFQ accelerator has been thus proposed [36] with 10% higher inter-vane voltage and 24-cell longer pre-bunching. The average mid-cell electrode aperture is 6.5% bigger, which will be helpful for easy tuning and power-consumption reduction. The output longitudinal emittance is 40% smaller, which will provide a better starting point for the MYRRHA accelerator and contribute to a more reliable operation of the whole facility. This new design will be used as a basis for future RFQ activities (see section 5.3).

3.3 Construction readiness design files

3.3.1 Spoke cavity and cryomodule engineering design

Spoke-type superconducting accelerating cavities are the baseline elements of the 17 – 81 MeV energy section of the MYRRHA main linac. During the MAX project, a detailed engineering design of a spoke cavity accelerating module [37] suited to the MYRRHA machine has been performed, including detailed drawings to be used to order and manufacture a first prototypical module when associated funds are available. All these drawings are included in the MAX Deliverable 3.3 [38], released on June 30th 2014, which gathers all the details of this cryomodule engineering design.

The main steps of this design study have been the following.

- The operating temperatures as well as the static thermal losses specifications have been fixed in close relation with the cryogenic system design work (see section 3.1.4).
- The MYRRHA Spoke cavity (352.2 MHz, beta=0.37) design has been performed, with optimised RF and mechanical characteristics and including helium tank. The technical drawings of the cavity have been produced and 2 real-scale prototypes have been launched in fabrication (from CNRS/IPNO own resources) for future tests in 2015/16 (see section 5.3).
- Auxiliary components (power coupler, cold tuning system, magnetic shielding) have been designed on the basis of existing components.
- Engineering design of the full cryomodule completely equipped (incl. cavities and their auxiliary components, main vessel, thermal shields, frame, cryogenic circuitry, pressure security, vacuum, assembly and alignment procedures…) has been completely achieved and a first preliminary implementation inside the MYRRHA linac tunnel, with one valve box per cryomodule, has been settled. The associated CAD model of the module (see Figure 7) and the technical drawings of all sub-components have been produced.

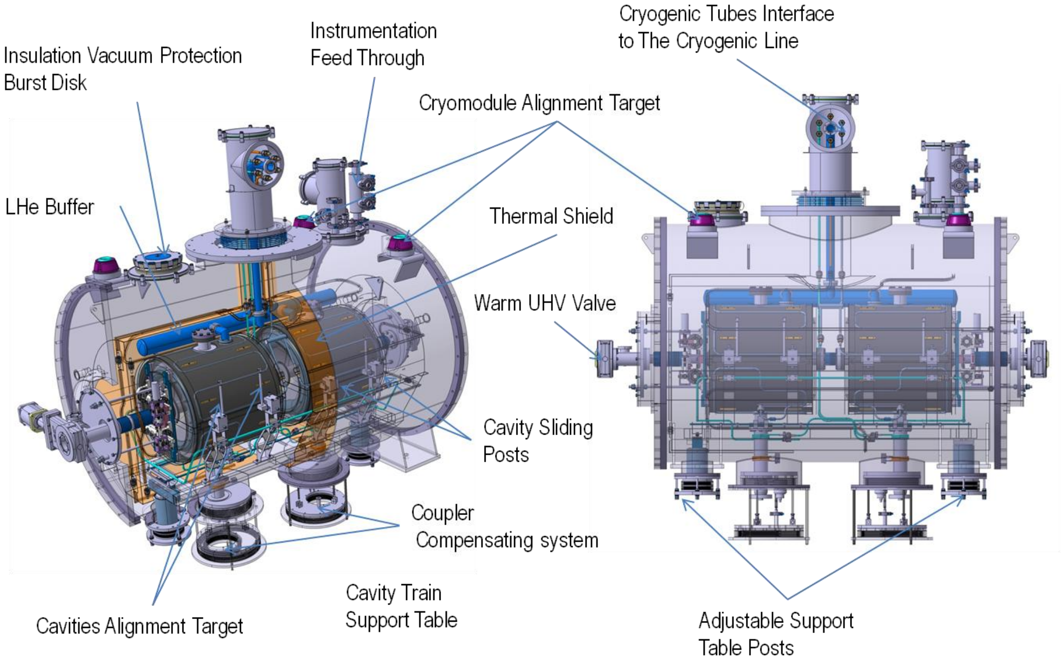

Figure 7: Views of the MYRRHA spoke cryomodule.

3.3.2 *Room-temperature CH cavity engineering design*

Room temperature CH-cavities will cover the energy between 1.5 MeV and 5.9 MeV in the MYRRHA injector. During the MAX project, a room temperature 175 MHz CH-cavity prototype has been developed including detailed engineering design. This 5-cell cavity requires 11 kW RF power for an effective voltage of 500 kV within 28 cm. Special attention to the RF optimisation, to the tuning procedure and to the cooling capabilities since CW operation leads to high average thermal load in room-temperature cavities.

A prototype of this cavity has been built, from third-party funds (see Figure 8). All preliminary low power RF measurements have shown excellent agreement with the simulations. Presently the cavity is prepared for copper plating and will then be tested at high RF power to check that the cavity can sustain a specific power of at least 40 kW/m. The tuner system as well as the power coupler have been also designed and constructed and in 2015, beam tests with a 2 mA proton beam at 2 MeV are planned to provide valuable information about the performance and reliability of the MYRRHA room-temperature injector under realistic operational conditions. More detailed information is given in Deliverable 2.3 [39].

Figure 8: (Left) 3D plot of the complete CH-prototype cavity.
(Right) Photograph of the manufactured CH-cavity before copper plating.

3.3.3 4-rod RFQ engineering design

The first accelerating stage of the MYRRHA linac is a 176.1 MHz 4-Rod-RFQ with a final energy of 1.5 MeV. The 4-Rod RFQ has been identified as the most promising candidate for a 176 MHz cw operated RFQ for MYRRHA with respect to capital costs, access, maintenance and technological risk (see section 3.2.2).

A detailed design of the MYRRHA RFQ has been performed during the MAX project. Details are given in Deliverable 2.4 [40]. The main conclusions are given here under.

- The beam dynamics simulations give a robust design with high transmission. On the basis of the first reference design used for the simulations in [8] and [20], further improvements with respect to electrode aperture, emittance growths and output distributions have been performed (see section 3.2.3) [36].

- One main concern is the cw operation of the RFQ with a thermal load of 25 kW/m. With the experience from the SARAF project, the geometry, the RF contacts and in particular the cooling system have significantly been improved [41]. New technologies as thick layer copper plating have been introduced.

- The full scale 1.5 MeV MYRRHA RFQ will have a length of about 4 m (see Figure 9). The design produced within MAX will be taken as a basis for the future construction of the actual MYRRHA RFQ (see section 5.3). There will be some additional modifications based on the recent experience with the prototype module (see section 3.4.4) and on the latest simulation results. In particular, the main goal will be to reduce the height of the tuning plates. This will result in lower power densities on the stems and in a reduced dipole component.

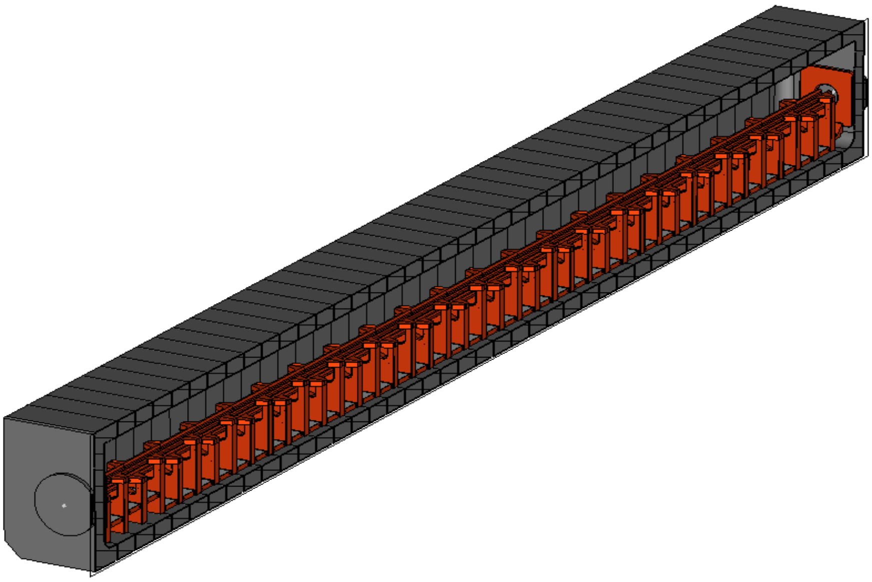

Figure 9: 3D plot of the full-scale MYRRHA RFQ.

3.4 Experiments

3.4.1 Operation & reliability assessment of an elliptical cryomodule

In the continuation of the work initiated within the FP6 EUROTRANS programme, a prototypical cryomodule of the medium-energy section of the MYRRHA proton linac has been developed, built and fully tested in “accelerator-like” configuration [42,43]. This module includes: a MYRRHA-type β=0.5 elliptical superconducting cavity, a slow mechanical Cold Tuning System (CTS), a fast piezo-based CTS, a high-power coupler, a 80 kW IOT operating at 700 MHz, a digital Low Level RF (LLRF) feedback system coupled to the CTS control loop, and all cryogenic circuits (2K, 4K, coupler supercritical loop).

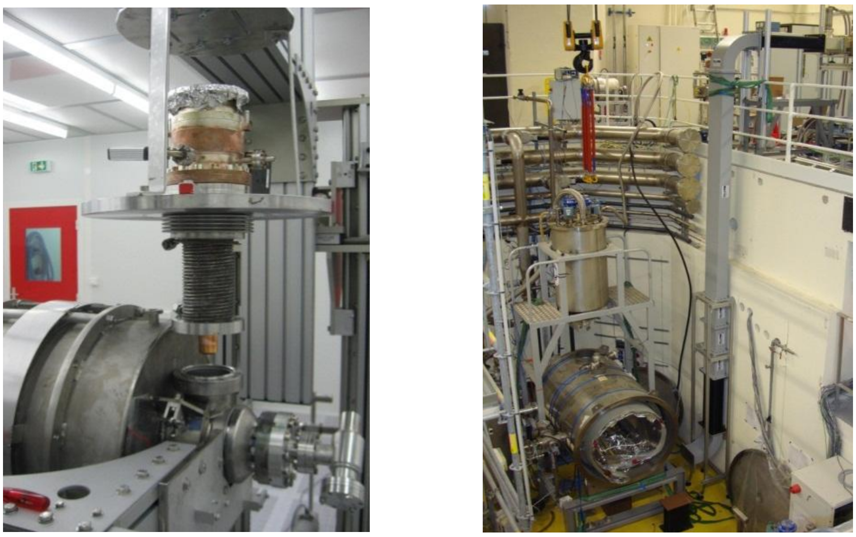

Figure 10: (Left) Superconducting cavity being connected to its RF power coupler in clean room. (Right) Overview of the cryomodule test stand at IPN Orsay.

All details and results obtained during the different experimental test campaigns can be found in Deliverable 3.1 [44]. The main lessons learned are the following.

- Several problems have been encountered and solved (linked to cryogenic operation, instrumentation, power coupler conditioning process, coupler supercritical cooling loop…), underlining that particular care needs to be taken during the design and implementation phases of such a complex system.

- In the end, the whole system has been fully characterized and successfully operated at 2K and high RF power. The cryogenic properties of the cryostat have been analyzed and the operation of the RF chain has been validated. The performance of the cavity has been measured, with a maximal accelerating field of about 14 MV/m at 2K, together with its relevant characteristics (sensitivity to pressure, Lorentz detuning, microphonics…).

- Electron multipacting activity observed in the cavity and couplers has been specifically analysed and compared with models and simulations, showing that measurements, scaling laws and calculations are in rather good agreement. This analysis is the subject of a dedicated report, Deliverable 3.4 [45], issued on July 8th 2014.

- The performance of the LLRF and of the cold tuning system regulation loops have also been assessed, and a few experimental tests have been successfully performed to demonstrate the main sequences of the fault-recovery scenario that is foreseen for MYRRHA. In particular, fast detuning of the cavity has been demonstrated using piezo-capability of the tuner, and field set-point fast changes have been also successfully achieved (up to 3 MV/m) using ramps to ensure optimal stability.

- Nevertheless, at higher field levels, stable operation was unsuccesfull, due to very high and fast microphonics partly linked to Lorentz force dynamic detuning. This limitation can be clearly explained by the very high mechanical softness of this very low-beta elliptical cavity, which is extremely sensitive to all perturbations (pressure variations, vibrations, Lorentz forces, field flatness degradation…), leading to severe difficulties to achieve its stable and reliable operation at high RF fields and relatively low bandwidths.

- It is recommended in the future to:
  - ✓ Design and develop the different MYRRHA cryomodules taking into account the different lessons learned during this MAX experiment; reliability still needs to be improved on several key points (e.g. power coupler cooling).
  - ✓ Improve the design of the elliptical low-beta cavity to make it much less sensitive to mechanical perturbations, or even consider to use an alternative cavity type with better mechanical performance (e.g. Spoke) for this 100-200 MeV energy range.
  - ✓ Pursue the development of the LLRF+CTS coupled control systems and the on-going assessment of the fault-recovery procedures; the results obtained up to now are very promising but there is still room for improvement, in particular for the compensation of high frequency microphonics. It is also recommended to try to pursue these control activities using a more “reasonable” cavity on the mechanical point of view.

3.4.2 *Assessment of the ADEX cavity tuner control loop with LLRF*

In the frame of the prototypical cryomodule test described here before, a dedicated experimental activity has been developed in order to thoroughly evaluate the control performance of both the standard (PID) and ADEX technologies applied to the piezo-based fast Cold Tuning System (CTS) of the 700 MHz superconducting cavity in RF operation.

The ADEX controller algorithm is embedded in a Delfino board that is coupled to a Cyclone III FPGA board that is used for filtering. In parallel, a dsPIC board is used for driving the piezo actuators. After several tests on different experimental set-ups and on the 700 MHz cryomodule in “accelerator-like” conditions, the main conclusions are:

- The evaluation of the performance of the CTS control system, both under PID and ADEX control was satisfactory in simulation and in the real application with Phase Lock Loop (PLL) RF operation.
- The evaluation of the CTS control system in the real application, working together with the digital LLRF control system at fixed frequency, was also reasonable under the circumstances, given the cavity´s narrow bandwidth and high sensitivity to microphonics (see section 3.4.1).

- The ADEX system enhanced the stability and control precision of the CTS loop and demonstrated to be a reliable control system under unforeseen perturbations that resulted in the PID control system losing control of the cavity´s variables.
- Although the test campaign was short, the knowledge acquired during the development of this task, and the results obtained, confirmed that there is much room for improvement, both in the design of the cavity and the hardware + software setup of the CTS control system.
- The ADEX control system can be improved through a more powerful hardware + software setup that will make it more efficient (and possibly fast) in execution and transparency for interpretation of results, as well as an improved configuration.

All details and results obtained during the different experimental test campaigns can be found in Deliverable 3.2 [46], issued on July 28th, 2014.

3.4.3 Fabrication & cryogenic test of a superconducting CH cavity

Superconducting CH-cavities are foreseen for the 176.1 MHz MYRRHA injector to cover the energy between 5.9 and 17 MeV. Such accelerating structures are efficient low and medium energy drift tube cavities for protons and ions. The RF operation mode is a TE_{211} mode. They combine the advantages of superconducting operation and multi-cell cavities with large energy gain per unit.

During the MAX project, a 325 MHz CH-cavity has been built from third party funds and tested to demonstrate this promising emerging technology. The main results are the following.

- An important goal was the achievement of the frequency at operational conditions (evacuated, cryogenic) while keeping a good field distribution. Using a sophisticated tuning procedure to tune the cavity during manufacturing, the design frequency could be reached at cryogenic conditions with the bandwidth of the tuner.

- The cavity has been successfully tested with gradients of up to more than 12 MV/m at 2K in vertical cryostat [47], as shown in Figure 11. This result is a world premiere. The reached gradients and Q-values are more than a factor of 3 higher than required for MYRRHA.

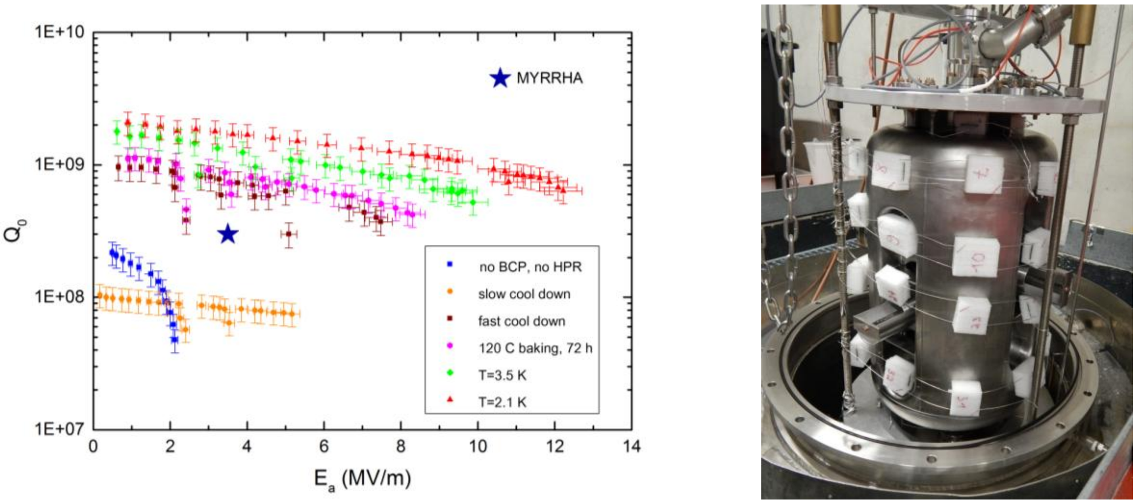

Figure 11: (Left) Measured Q versus E_{acc} curves for different cases at 4K (no surface preparation, Q-disease, without Q-disease, baking), 3.5K and 2K. (Right) Cryogenic test preparation of the SC CH-cavity.

- Power couplers and tuner systems have been also developed and are ready to use. A horizontal cryomodule has been developed and is in the final stage of production. This cryomodule will be used in the near future to test the cavity in accelerator-like conditions. It is also designed to be able to be tested with beam (see section 5.3).

The details of these experimental developments can be found in Deliverable 2.2 [48]. They show the large potential of this technology from which the MYRRHA project can profit significantly.

3.4.4 RFQ thermal mock-up evaluation and test

The design goal of the MYRRHA RFQ is an increased performance with respect to cw power levels compared to existing 4-Rod structures (see section 3.3.3). During the MAX project, a dedicated RFQ short prototype section has been built for demonstration [49] and successfully tested. Details are given in Deliverable 2.4 [40]. The main outputs of this activity are given here below.

- During the design phase, the cooling of electrodes and stems has been improved significantly compared to existing similar structures. This is important to minimize the frequency shift during operation and the geometrical distortions due to inhomogeneous heating, respectively. Another important topic was the design of the RF contacts between tuning plates and stems, using massive silver plates instead of usual RF spring contacts.

- The short prototype section is shown on Figure 12. After several low level RF measurements (e.g. shunt impedance), this prototype has been tested with power coupler and tuning system at high RF power, up to power levels exceeding 115 kW/m in cw operation, which is more than a factor of 4.5 higher than required for MYRRHA. The power level is also 2.5 times higher than the old record for a 4-Rod RFQ. This shows that the optimization of the cooling system and the overall layout of the RFQ are working excellent. There is a huge safety margin between achieved and required performance.

Figure 12: Real RF structure of the MYRRHA-RFQ prototype.

3.4.5 704 MHz solid-state RF amplifier module development and test

The RF systems of the MYRRHA accelerator in the 700 MHz high-energy sections represent the most costly part of the machine and one of the most challenging sub-systems as far as reliability is concerned. During the MAX project, special focus has been put on the study and development of a suitable optimized SSPA (Solid State Power Amplifier) solution, which could be very promising as far as reliability is concerned and therefore very suitable for MYRRHA.

The detailed results of the study and of the experimental developments can be found in Deliverable 4.5 [50], released on July 07th, 2014. The main outputs are summarized here after.

- Comparative analysis of possible architectures for the MYRRHA 700 MHz RF system has been achieved, and the Solid State Power Amplifier (SSPA) has been identified as the optimal choice.
- A conceptual design of a SSPA suite for the MYRRHA needs has been performed, based on a single 15 kW RF cabinet concept. These cabinets are using parallelized low power elementary RF modules, bringing huge redundancy and extensive fail-safe capabilities. They can be coupled to achieve the final desire power depending on the cavity. It is underlined that a special care must be attached to the power supplies in order to avoid that single failure of one of them generates a cabinet fault.
- A 850 W mock-up elementary module has been fabricated to demonstrate the performance of the technology. The transistor type has first been selected (LDMOS) and two cw RF base module have been built and extensively tested. They have then been successfully combined into a 850 W water-cooled amplifier block using 3dB micro-strip prototype couplers, with very satisfactory results in CW operation. This mock-up has demonstrated that such a SSPA solution is possible for the MYRRHA project.

3.5 Return on experience

3.5.1 *Reliability analysis of the SNS linac*

The SNS (Spallation Neutron Source) at ORNL (Oak Ridge National Laboratory) [10] has been selected at the very start of the MAX project as the existing accelerator to be used for developing a relevant reliability modelling methodology to be applied to the MYRRHA linac case. The main steps of the work and the lessons learned [51] are as follows.

- A complete structure of the SNS linac fault tree reliability model has been developed, reviewed and validated. Continuous contact has been maintained with George Dodson (SNS) who provided valuable information on the SNS design and operation.
- The results obtained running this SNS risk spectrum model have been analysed and compared with the SNS Logbook data registered during beam operation over the period Oct. 2011 – Aug. 2012 in ORNL.
- Simulation results give an overall availability of the SNS linac of about 73% and show that the most affected systems are :
    - ✓ SC linac, injector, diagnostics & controls,
    - ✓ RF systems (especially the SCL RF system),
    - ✓ Power Supplies and associated controllers.
- These results are in line with the SNS operation log-book records, giving a good confidence in the validity of the method to be used in the case of the MYRRHA linac (see section 3.1.3).
- Reliability could be improved in an SNS-type linac by including redundancy in the most affected system and components, e.g. implementing intelligent fail-over redundancy in controllers for compensation purposes, based on suited and reliable diagnostics.

Details of this analysis can be found in Deliverable 4.2 [52], issued on November 26, 2012.

3.5.2 *Accelerator operation in the GUINEVERE experience*

The GUINEVERE experiment [53] on the SCK•CEN site couples a sub-critical fast reactor core with an accelerator, generating neutrons by bombarding a tritium target with a pulsed, DC, or DC with programmable interruptions deuteron beam. This accelerator-coupled experiment (see Figure 13) represents a unique platform to study ADS reliability and system optimisation.

A detailed analysis of the GUINEVERE machine with respect to operation reliability, interfaces, data recording/logging, safety/licensing aspects and beam monitoring has been performed. The main problems encountered during the last 4 years of commissioning and operation have especially been thoroughly analysed. The lessons learned which could apply to improve the MYRRHA linac operation reliability have then be derived. The main ones are the following.

- Relations with safety authorities had a huge impact on the facility commissioning and operation; this will need to be anticipated as much as possible for MYRRHA.
- DC mode was not as successfully in Guinevere compared to pulsed mode, especially because this operational mode was never commissioned properly due to planning constraints. It is recommended for MYRRHA to perform extensive beam commissioning to fully understand and master the beam operation before any standard operation of the facility.

- The too few on-line beam diagnostics appeared to be a limitation in Guinevere to be able to anticipate problems; it is suggested to foresee numerous beam diagnostics for MYRRHA, both invasive and non invasive, able to operate in all beam modes.
- An excellent level of communication between the accelerator and the reactor teams is mandatory since the design phase of the facility.

All results and conclusions have been gathered inside Deliverable 4.3 [54], issued on November 29, 2013. Significant progress in machine performances and reliability has been accomplished during the 2 years of coupled operation of the facility.

Figure 13: (Left) Upper level of the accelerator during beam line handling: the vertical line is being inserted in the reactor bunker while the magnet is retracted. (Right) Vertical beam line inserted into the reactor core.

4. International Design Review

The confrontation of the current MYRRHA linac design and of its R&D program with the criticism of an international panel of experts was one main goal of the MAX project. This review was to be held around the mid-term of the project, i.e. around month 18. An "International Design Review of the MYRRHA accelerator" was therefore organized in the SCK•CEN headquarters in Brussels on November 12 and 13, 2012. The list of reviewers was the following.

- Dan BERKOVITS (SOREQ, Tel Aviv, Israël)
- Robin FERDINAND (GANIL, Caen, France)
- John GALAMBOS (ORNL, Oak Ridge, USA)
- Roger GARBIL (EURATOM, Brussels, Belgium – observer)
- Andreas JANSSON (ESS, Lünd, Sweden)
- Alban MOSNIER (F4E & CEA, Garching, Germany – president)
- Andrea PISENT (INFN, Legnaro, Italy)
- Peter OSTROUMOV (ANL, Argonne, USA)
- Maurizio VRETENAR (CERN, Geneva, Switzerland)

A set of 4 charge questions were submitted to the reviewers.

1. May the adopted general philosophy and methodology lead to the design of a highly reliable accelerator?
2. Are the different design choices appropriate for such a machine?
3. Is the R&D programme coherent, adequately focused and efficient at this stage of the project?
4. In a more global view, what should be the essential points of concern for the MYRRHA project team in the two following years (2013-2014) to prepare for the accelerator construction?

The evaluation report from the review team [55] was issued on December 20th, 2012. It formulates answers to the 4 charge questions and additional recommendations regarding all the subsystems. This report was then commented by the MAX team and re-issued on February 4th, 2013. It is added to this report in Appendix 1.

Globally the review team was positive about the MAX project itself and about the quality of the work that was presented, but emphasized the fact that the concept needed to be further improved. The reviewers stressed the need for extensive R&D activities around all the critical components. Taking these caveats:

- the answer to question #1 is positive; the reviewers especially appreciated the approach to reliability modelling (see sections 3.1.3. and 3.5.1).
- The answer to question #2 suggests to strive for enhanced coherence and uniformity.
- In the answer to question #3 there is special emphasis on the need for testing the entire injector up to its final energy.
- Besides stressing the R&D needs again, the answer to question #4 highlights the too aggressive schedule of the MYRRHA project and the lack of a strong central accelerator team in SCK•CEN.

The main recommendations on the different systems are summarized here after (see Appendix 1 for details). Most of them have been obviously taken into account during the last phase of the MAX project.

- Regarding the injector, the 4-rod RFQ was considered as a reasonable option with a convincing design. It was suggested to carefully assess the choice of applying CH-type cavities in place of more common half-wave resonators. The Review Committee expressed a special concern about the KONUS beam dynamics scheme by considering it to be an unjustified choice in the context of a high reliability machine. As explained in section 3.2.3, a new, optimized beam optics scheme has now been designed for the injector in response to this point of criticism.

- Regarding the superconducting linac, the comments mainly concerned the intermediate energy section in which the β=0.47 elliptical cavities may be unsuitable due to lack of stiffness. As suggested by the MAX team, spoke cavities (especially double spoke) may be preferred. This option was supported by the reviewers but they recommended to also investigate single and triple spoke cavities. Today the results reported in section 3.4.1 fully confirm the concerns about the low-β elliptical cavities and the need for an alternate (spoke-based) solution.

- Regarding the high-energy beam delivery line to the reactor the recommendations stress the need for further detailed investigations in view of obtaining very high reliability in all relevant domains, but also in view of providing all the necessary diagnostics for commissioning. Concerning the latter issue a straight line beam dump (low power) will be mandatory.

- Regarding fault-recovery procedures, the recommendations aim at more elaborate error simulations and a highly detailed 3 second fault-recovery scenario. Moreover the Committee recommends to consider a non-local recovery system by making use of some spare cavities kept at full voltage in non-accelerating mode. Today, substantial work has been done on these topics, as described in section 3.1.2. Additionally, the Committee fully supports the use of solid state RF amplifiers.

- Regarding instrumentation the main comment concerns the need for redundancy in the critical devices that belong to the Machine Protection System. The crucial role of the near-target monitor is highlighted.

- Regarding cryogenics the reviewers emit a warning on obtaining a realistic estimation of the overall heat load. They suggest to revisit the “full 2K” operational model in view of actual 4K tests of the future MYRRHA spoke cavities and of a possible increase of the spoke contribution to the total linac.

5. Outlook

5.1 Main project conclusions

5.1.1 *MAX project in brief*

MAX has been the follow-up of the EUROTRANS Work Package 1.3. It has been a 3.5-year collaborative project with a global budget of 5 M€ and an EC contribution of 2.93 M€. The success of MAX is expressed by the fact that all but one[1] of its initially defined milestones have been fully reached and that the corresponding performance indicators are green.

The list of performance indicators is given in Appendix 2.

This fact clearly points to the value of the collaboration and to the high level of motivation of each of the 11 partners. Besides the production of the 18 scientific MAX Deliverables, the quality of the work produced in the frame of the MAX project is also underlined by the following list of achievements.

- More than 40 publications (in journals or international conference proceedings).
- More than 40 oral presentations in cross-projects collaboration workshops.
- More than 50 contributions to seminars and lectures (including the 2-day MAX accelerator training school, organized in Frankfurt on October 1st & 2nd, 2013).
- More than 60 internal MAX project meetings (incl. Governing Council, Project Coordination Committee, Project, WP and specific tasks meetings).
- Training of several students through internships, PhD or post-doc positions directly related to the MAX project.
- Development of a dedicated web site [6] to ensure the public communication of the project and, through its secured private section, the exchange of internal working documents between the MAX partners.

A complete list of publications, seminars, schools and meetings can be found in the 3 MAX activity reports (Deliverables 5.3 [56], 5.4 [57], 5.5 [58]).

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[1] *It had been planned to test the superconducting CH cavity (Task 2.2) in a horizontal cryomodule during the MAX project. Unfortunately there were delays in the call for tender and at the manufacturing company of the module. It has been agreed and decided during the last MAX Governing Council (Orsay, July 4th 2014) that the activity will be continued after the end of the MAX project, in order to achieve the test of the CH cavity in its horizontal cryostat as foreseen and communicate the results to the MAX partners when available (estimation: summer 2015).*

5.1.2 MAX scientific outputs: executive summary

With respect to the EUROTRANS outputs [13] a very significant progress has been made on the path towards the accelerator for MYRRHA. From the very start, MAX has been organized around the actual needs of the MYRRHA linac and thereby it has been able to focus on the well defined requirements of this machine. As detailed in section 3 of the present report, this has led to a number of achievements that are all fundamental in view of the reliability goal.

- A fully reliability-oriented overall consolidated concept of the accelerator.
- A set of benchmarked modelling tools allowing for start-to-end beam simulations.
- An operational reliability model based on the SNS experience.
- An adequate and realistic injector design.
- A detailed engineering design of a few critical elements.

Specific experiments, matched to particular aspects of an ADS-accelerator, have supported some of these achievements or provide valuable information for future and further developments.

- Cooling performance tests of the 4-rod RFQ model cavity in real CW RF operation.
- Investigation of the behaviour of a low-β elliptical superconducting (SC) cavity in accelerator-like conditions (2K, high RF power).
- Assessment of a SC cavity fault-recovery scenario using a digital low level RF feedback system and featuring an ADEX (adaptative) tuner controller.
- RF test of a superconducting CH cavity at 4K and 2K in vertical cryostat.
- Performance of a 704 MHz solid state RF amplifier module and associated power combiner.

A particularly strong achievement of the results generated by the MAX programme and of the outcome of the International Design Review is the global level of confidence, in the concept on the one hand, and in the feasibility of its components on the other hand. This level of confidence is coherent with the fact that MAX has now brought us to the first major milestone on the road towards the realisation of the MYRRHA linac. The milestone may be labelled *"ready for prototyping"*. It is the starting point of a new set of mandatory R&D activities where the emphasis should lie on experimental optimisation. It must be acknowledged that in this phase, the full exploitation of synergies with similar projects may be particularly awarding.

Finally, MAX has brought many answers but has obviously also initiated some specific new questions, the main ones being, among others:

- Which is the optimal type of superconducting cavity for the energy section 80 – 180 MeV, low-beta elliptical or multi-gap spoke? *(→ from the conclusions of section 3.4.1, ESS-type spoke [59] might be the good choice)*
- What should be the optimized field and RF power margins to efficiently ensure the local fault-compensation scheme in the main superconducting linac? *(→ from the conclusions of sections 3.1.2 and 3.1.3, the present 30% value might be actually too much)*
- Are the reliability targets achievable in reality, in particular in the Diagnostics & Controls area? *(→ from the conclusions of section 3.1.3, a dedicated R&D programme is clearly required on this topic)*

5.2 Recommendations

By combining the R&D results generated by MAX and the comments formulated by the members of the International Design Review, it is now possible to emit certain recommendations with respect to a potential pursuing of MYRRHA linac related R&D activities.

5.2.1 Regarding the global linac design

The present conceptual design is convincing and satisfies (is able to satisfy) all the requirements. This statement is obviously largely based on simulation results. This calls for 2 important observations.

1. The link with reality has to be ensured through experiments.
2. Further optimisation has to be pursued in a persistent way, by taking into account new input data or by applying updated boundary conditions and by improving the existing models.

In this way it should be foreseen in the following phase of the activities to review and further optimize:

- the global linac layout,
- the redundancy configuration,
- the detailed design of the injector.

Certain global accelerator items had been omitted in the MAX project definition. In particular, diagnostics and controls were missing. Given the fact that both diagnostics (in general, not being restricted to beam diagnostics alone) and controls (the entire 3-tier control system) have an essential role to play in the extreme reliability scenario, it is now mandatory to include these items in an upcoming R&D program. The time has also come for an overall updated cost evaluation and cost optimisation – the latter being strongly connected to the above observation #2.

5.2.2 Regarding specific future R&D activities

Besides considering the global aspects which are mentioned in the preceding section, it is adequate to highlight some topics that have to be addressed in priority. There are two principal lines: prototyping and modelling.

- Correct (i.e. conform to reality) initial beam data are of fundamental importance in all beam dynamics simulation tools. Making use of the platform consisting of the ECR ion source and the LEBT that is presently under construction, an experimental campaign for fully characterizing the emerging beam (beam entering into the RFQ) should be launched.

- The injector has to be investigated in detail, in a step-by-step approach allowing for testing with beam. The logical first step is thus the construction of the 4-rod RFQ that has been designed in MAX (keeping in mind that the output longitudinal beam emittance needs to be minimized) and coupling it to the source-LEBT assembly presently under construction. This obviously implies the procurement of all the auxiliary equipment. The solid state RF power amplifier and the digital LLRF will themselves be prototype items.

- Since the superconducting linac is highly modular, thorough prototyping is very efficient. The MYRRHA-type spoke cryomodule has been fully designed in MAX and should now be constructed and tested. More generally, concerning SC cavities cryomodules, significant synergies is potentially existing with the ESS project [60] and, to a lesser extent, with the CERN SPL project [61]. A later series production could be discussed with potential manufacturers.

- The effort around the reliability modelling tool put in place by MAX should be pursued with vigour so as to obtain confidence and predictability. This tool is indispensable for the optimisation task.

- A virtual accelerator, performing on-line machine modelling with real-time machine data, will be a powerful and essential operational tool in the high reliability context. It is challenging, though, both from the simulation and from the control system point of view. The injector tests should serve such a development.

5.2.3 Regarding the connections with other projects or R&D programmes

The Superconducting Linacs for High Power Proton beams (SLHiPP) series of workshops [62], managed by CERN and ESS with a participation from SCK•CEN (MYRRHA), is a very useful forum for the exchange of engineering design information and of test results. MAX has been actively present in these meetings and its continuation should be supported.

However, in order to exploit the synergies that obviously exist between the different high power hadron accelerator projects, a network of bilateral collaboration agreements is required. From the MYRRHA side such MoU's are already available with CNRS/IN2P3, SPIRAL-2 at GANIL [63] and CERN; the agreement with ESS is missing. Especially in view of cryomodule prototyping, the relevant collaborations may reveal their usefulness and should be activated. Note that a MYRRHA-type elliptical cryomodule design is up-to-now inexistent and that a close collaboration with (for instance) the CERN/SPL or the ESS cryomodule development activities would be highly valuable.

Within the European Framework Program FP7, synergies between MAX and EUCARD-2 [64] have been clearly identified during a common workshop on ADS accelerators [65]. Practical possibilities of future collaboration between EUCARD-2 and a potential follow-up of MAX lie in the joint organisation of topical workshops on subjects of common interest.

More generally, the R&D topics oriented on accelerator availability and reliability, that have been specifically explored within MAX, should be actively pursued in the following years. Besides the ADS application and the MYRRHA project, these developments will indeed bring substantial impact for all emerging and future accelerator projects featuring high power proton beams.

5.3 Future plans

Largely inspired by the recommendations of section 5.2, a proposal is being formulated for an Accelerator Work Package within a new MYRRHA-related project EC proposal, called MYRTE (MYRRHA Research and Transmutation Endeavour). The related call is: EURATOM FISSION NFRP-2014-2015; Section "Cross-cutting aspects for nuclear fission and radiation protection"; Topic NFRP 9 - 2015 "Transmutation of minor actinides" (deadline date: 2014-09-17).

The structure of this proposal is presented in Table 4. The Accelerator Work Package of this 4-year project, to be led by CNRS IPN Orsay, is expected to have a size that closely matches MAX's size, both in budget (4 M€ EC contribution) and in number of participants (14). Most of the MAX partners would join this Horizon 2020 project – remarkable new participants would be IBA, CERN and Cosylab. In this proposal a strong emphasis is put on the deployment of the first part of the injector (LEBT and RFQ), as illustrated in Table 4. It is foreseen that even this short accelerating section, together with all its ancillaries and equipped with a complete 3-tier control system, might become a relevant test platform for the whole MYRRHA linear accelerator.

Table 4: Present state of the MYRTE WP2 "Accelerator" H2020 proposal, led by CNRS / IPN Orsay.

Task #	Task description	Task leader
1	Realisation of a full-size MYRRHA-type RFQ demonstrator	IAP
2	Construction of a prototype Solid State RF power amplifier	SCK•CEN
3	Digital LLRF development	CNRS
4	Beam diagnostics development	CEA
5	Control system development in a highly reliable accelerator context	Cosylab
6	Beam simulation code development, global coherence	CEA
7	Injector commissioning	SCK•CEN
8	Space-charge experiments	CNRS
9	LINAC4 reliability analysis	CERN
10	MYRRHA SRF spoke R&D	CNRS
11	SRF CH demonstration with beam	IAP
12	MYRRHA linac cost estimation	SCK•CEN

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- ✓ SLHiPP-3, 17-18 April 2013, Louvain-La-Neuve, Belgium.
- ✓ SLHiPP-4, 15-16 May 2014, Geneva, Switzerland.

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