The 600 MeV EUROTRANS Proton Driver Linac

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Abstract. Accelerator Driven Systems (ADS) for nuclear waste transmutation require proton drivers with energies between 600 and 800 MeV and beam currents of several mA for demonstrators and up to 25 mA for a large industrial systems. The required operation is continuous wave (cw) which prefers superconducting cavity technology. One major issue of these accelerators is reliability and fault tolerance to reduce the number of unwanted beam trips. Additionally, beam losses have to be minimized to avoid activation of the machine. The European activities are focused in the EUROTRANS project. The EUROTRANS driver linac has to deliver a 600 MeV proton beam with a maximum beam current of 4 mA but it is capable to accelerate up to 25 mA. In order to improve the overall reliability two 17 MeV, 352 MHz injectors are foreseen. Each injector consists of a 3 MeV RFQ, two room temperature (rt) CH-cavities and four superconducting (sc) CH cavities. The intermediate energy section (17-100 MeV) consists of independently phased superconducting spoke cavities. It is followed by a high energy section with two groups of superconducting elliptical 5-cell cavities (704 MHz). The paper describes the present status of the reference design with respect to beam dynamics issues, prototype development and fault tolerance.

1. Introduction

In Europe about 35% of the electric power is generated in 145 nuclear fission reactors. The total amount of produced electrical energy is 850 TWh leading to 2500 tons of spent fuel [1]. A small fraction of this nuclear waste i.e. long lived fission fragments and minor actinides are considered to be very problematic because of the long decay times and their high radio toxicity. It is well known that the quest of minimizing the long term environmental impact of this nuclear waste inventory is one of the most challenging scientific subjects in nuclear energy research. In principle, there are two different options to deal with it, long term storage in geologically stable caves or reducing the amount of waste by using appropriate partitioning and transmutation technologies. Transmutation of nuclear waste based on Accelerator Driven Systems (ADS) is one of the most promising concepts to reduce radio toxicity and life time [2].

The solution is based on two main components: a sub-critical reactor ($k<1$) and an intense neutron source that provides additional neutrons with a broad energy spectrum to maintain the nuclear reactions. The key component of the neutron source is a high power proton accelerator. The spallation target hit by the proton beam consists usually of a heavy liquid metal like lead or lead-bismuth-eutectic. The neutrons are created by spallation reactions. The beam energy as well as the beam current has an impact on the transmutation rate. While the number of created neutrons is proportional to the beam current the neutrons created per proton depends on the beam energy. The proton energy should be several 100 MeV up to 1 GeV and the beam current is between a few mA and several 10 mA, respectively.

During the last several years a strong research programme has been carried out to facilitate the construction of an eXperimental facility demonstrating the technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS). This EUROTRANS called research programme is funded by the European Union within the 6^{th} Framework Programme involving 31 partners between research agencies and nuclear industries with the contribution of 16 universities. The main objective is to work toward a European Transmutation Demonstrator (ETD) using a two-step approach aiming for:

- Providing an advanced design of all components of a XT-ADS system at significant power levels (30-100 MWth), driven by conventional MOX fuel, in order to allow its realization short term (10 years).
- Providing a conceptual design of a European Facility for Industrial Transmutation (EFIT) with power levels of several 100 MWth and operated with fuel loaded with reprocessed waste. The EFIT is the long term objective of the programme.

2. Requirements for the EUROTRANS Proton Driver Linac

Nuclear Waste Transmutation based on an Accelerator Driven System requires a proton beam with very high duty cycle up to continuous wave (cw) operation. The overall efficiency with respect to the plug power of the system should be as high as possible. This makes the use of a superconducting proton linac favourable because the RF losses are reduced significantly compared with a room temperature option. Additionally, in case of cw operation capital and operational costs are lower for a superconducting machine. This is even true by taking the cryogenic system into account. The needed power amplifiers are much smaller than for room temperature operation. In principle only the power added to the beam has to be provided because the RF losses are negligible compared to the beam power. A cw superconducting linac can be operated at significant higher accelerating gradients which reduces the linac length and therefore the costs.

The goal of XT-ADS is to demonstrate the feasibility of transmutation using an Accelerator Driven System. It must be a compromise between cost considerations and the necessity to be as realistic as possible with respect to a future EFIT. Therefore the beam energy has been fixed to 600 MeV and the nominal beam current to 2.5 mA which can be increased to 4 mA during the burning process of the fuel. This is required to keep the thermal power of the reactor core constant. The beam power is between 1.5 and 2.4 MW depending on the beam current. The favoured operation mode is cw because it reduces the peak current and avoids problems in the superconducting cavities due to Lorenz force detuning.

With an average beam power in the MW range the EUROTRANS linac belongs to the group of high power proton accelerators. One major issue of these machines are beam losses which could lead to local heating and thermal break down of the superconducting state or in the worst case to damaging of accelerator components. Beam losses could also lead to an unwanted activation of the accelerator. To provide hands-on maintenance of the accelerator these losses have to be minimized. In general, fast and reliable beam diagnostics devices have to be used to detect extensive beam losses due to component failure or halo formation. This must be associated with fast interlock systems for emergency shut down.

An ADS accelerator is constraints by additional requirements concerning the reliability and availability. Failure of accelerator components can potentially lead to beam interruptions on the target. Interruptions with duration longer than 1 second will result thermal stress and thermal fatigue in the neutron target, fuel assembly and reactor cooling system. To avoid this problems and to increase the availability of the whole system the number of these unwanted beam trips (t>1s) should not exceed a few per year. Very short interruptions (t<<1s) are not critical because of the large thermal inertia of the structural components. It is estimated that beam trips between 0.1 and 1s can be tolerated up to a number of several hundreds to several thousands per year. However, the EUROTRANS proton driver linac asks for an extreme reliability which is far away from existing machines. To make sure that the required reliability can be reached the design strategy relies on over-design, redundancy and fault-tolerance.

3. The EUROTRANS Proton Driver Linac

3.1. Reference Design

The present reference design for the EUROTRANS proton driver linac is shown in Figure 1. It is optimized with respect to high reliability and to high efficiency. As shown two identical front ends are foreseen delivering a proton beam of 17 MeV. This low energy part of the accelerator is the most complex section with respect to beam dynamics issues and reliability. Presently it seems to be questionable that the required reliability can be fulfilled with only one injector. Therefore it has been decided to build two front ends. Both front ends are in operation with the nominal beam current. But only one injector delivers the beam to the main linac. In case of a beam trip in this injector which can not be handled within a given time (t<1s) the second injector will deliver the beam.

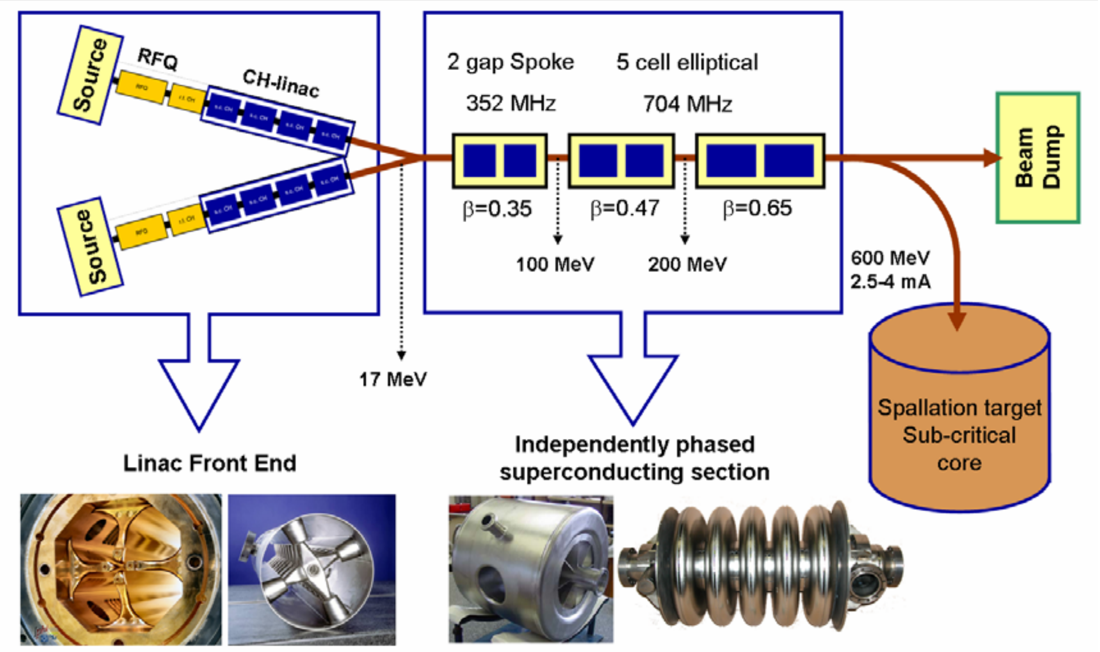

FIG.1. Schematic overview of the 600 MeV EUROTRANS proton driver linac.

The main linac consists of independently phased superconducting cavities. The intermediate energy part from 17 to about100 MeV consists of 352 MHz spoke-type 2-gap cavities. They provide sufficient large voltage gain per cavity with a broad velocity acceptance. Therefore only one type of cavities is required to cover this energy range. It could be shown that this linac section is tolerant against the fault of a cavity by adjusting the field levels and RF phases in neighbouring cavities (see section 4).

About 85% of the total voltage will be provided by 704 MHz elliptical 5-cell cavities. These cavities have been originally developed for electron accelerators. Now they are considered to be the standard solution for superconducting proton or even heavy ion linacs for energies above 100 MeV. They are two sections of elliptical cavities, optimized for β=0.47 and β=0.65.

3.2. Low Energy Section

The front end of the EUROTRANS proton driver linac consists of an ECRIS (Electron Cyclotron Resonance Ion Source), an RFQ accelerator (Radio Frequency Quadrupole), two short rt CH-(Crossbar H-mode)-cavities and four sc CH-cavities providing 17 MeV total energy gain. Figure 2 shows the schematic layout of this injector.
Presently an ECR source with an extraction voltage of 50 kV is foreseen. At CEA Saclay the SILHI source showed reliable operation with beam currents exceeding 100 mA [3]. In principle it is also possible to use volume sources which provide typically beams with smaller emittance.

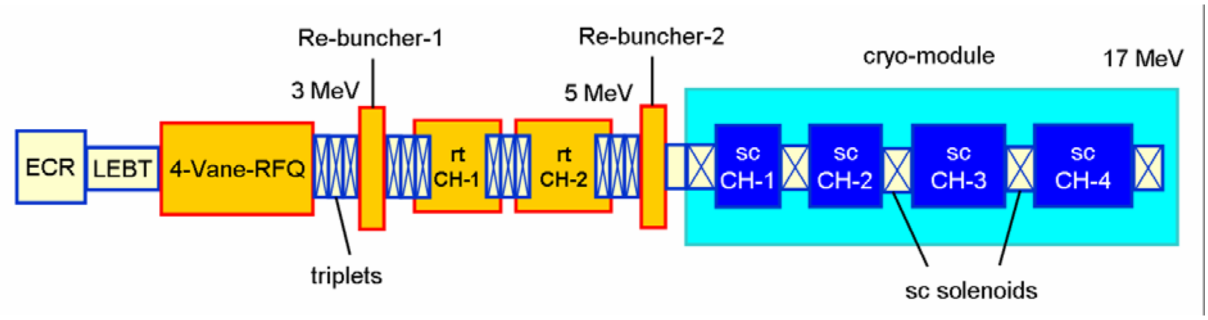

FIG.2. Schematic overview of the 17 MeV EUROTRANS front end.

The first accelerating structure is an RFQ accelerator operated at 352 MHz. As RF structure a 4-vane RFQ has been chosen because this structure seems to best suited for cw operation at this frequency. Presently a 3 MeV, 100 mA prototype RFQ is under construction [4]. Figure 3 shows the first section of this RFQ which will be tested with beam from the SILHI source. In principle the EUROTRANS RFQ will be similar to the IPHI RFQ but the design beam current has been reduced and optimized to the XT-ADS requirements. The smaller beam current of 4 mA (XT-ADS) and 20 mA (EFIT), respectively lead to lower power consumption and a shorter length. The right side of figure shows the parameters of the EUROTRANS RFQ.

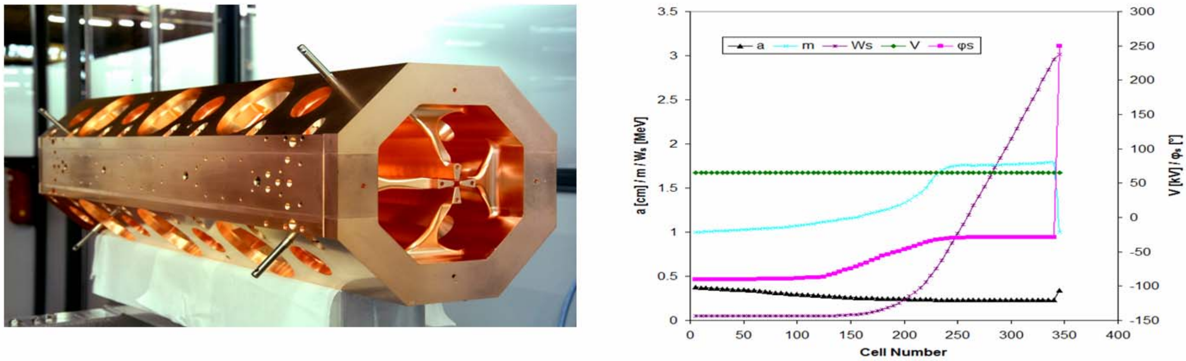

FIG.3. First section of the IPHI-RFQ (left), parameter plot of the EUROTRANS 3 MeV RFQ (right).

The RFQ is followed a rebuncher cavity to match the beam longitudinally into the drift tube cavities. The first two drift tube structures are room temperature CH-cavities. CH-cavities are very efficient RF structures for the low and medium energy range [5]. They belong to the family of H-mode structures which means that the exited wave pattern is an H-mode. Each cavity provides about 1 MV of effective voltage and will require an RF power of about 35 kW.

The main acceleration of the front end will be provided by four superconducting CH-cavities. A superconducting CH-prototype cavity has been developed and tested successfully in Frankfurt [6]. This 19-cell cavity is optimized for a relative particle velocity of β=0.1. Effective accelerating gradients of 7 MV/m have been achieved based on the so called βλ-definition [7]. The design goal for EUROTRANS is 4 MV/m with a Q-value of $2\cdot10^8$. These values have been exceeded with a large safety margin. Figure 4 shows the sc CH-prototype cavity and the experimental results.

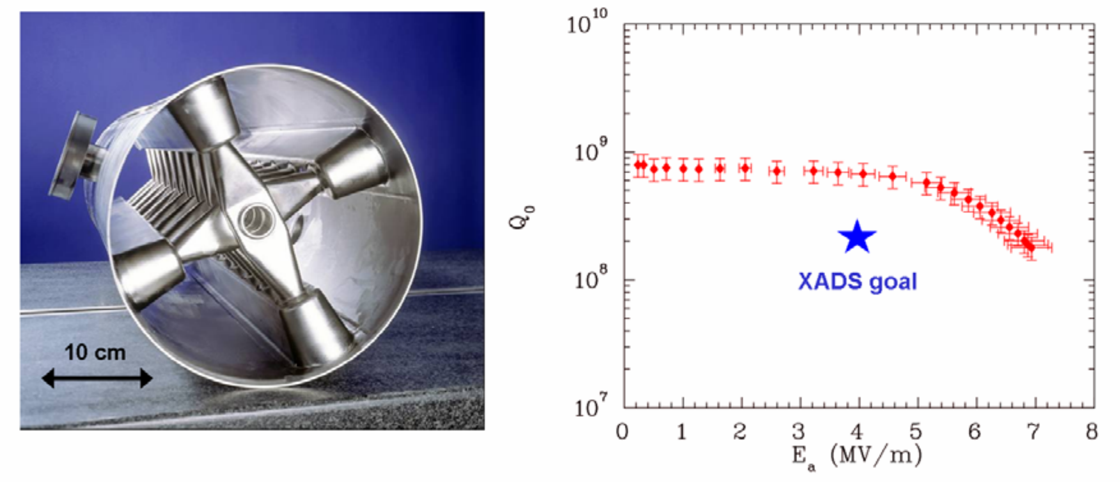

FIG.4. Superconducting CH-prototype cavity (left), measured Q-value as function of the accelerating field (right).

3.3. Intermediate Energy Section

The intermediate section covers the beam energy between 17 MeV and about 100 MeV. It consists of independently phased superconducting 2-gap spoke-type cavities developed at IPN Orsay. Because of the broad velocity acceptance, i.e. transit time factor it is possible to use identical cavities for this section. They are optimized for a relative particle velocity of β=0.35. This β gives a sufficient large accelerating length and therefore a large voltage gain per cavity. A superconducting prototype cavity has been developed and tested with great success. Effective accelerating gradients of above 12 MV/m have been reached based on the βλ-definition [8]. Figure 5 shows the superconducting spoke cavity and experimental results. There is also a large safety margin with respect to the design goal aiming for a gradient of 8.5 MV/m with a Q-value of $4\cdot10^8$.

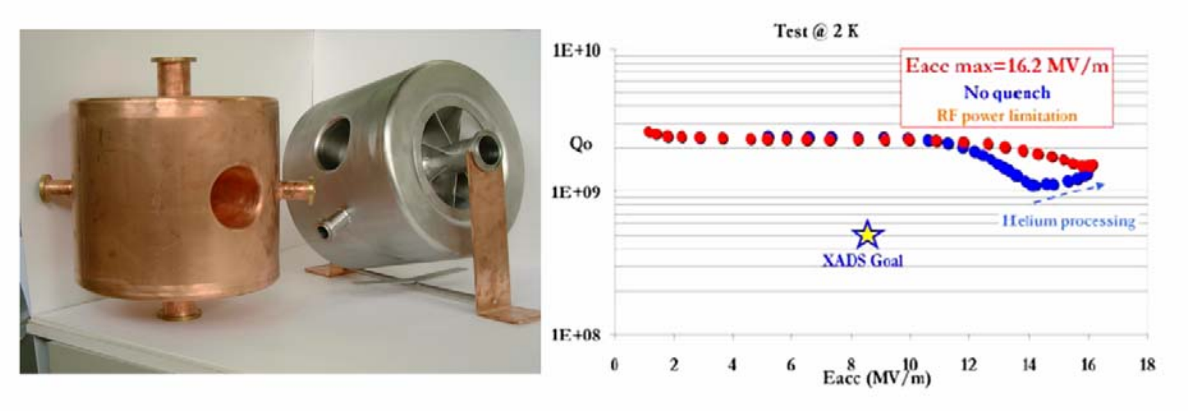

FIG.5. Superconducting β=0.35 spoke-prototype cavity (left), measured Q-value as function of the accelerating field. The gradient shown is based on the active length of the cavity (right).

3.4. High Energy Section

The main part of the required acceleration voltage of 600 MeV will be provided by superconducting elliptical 5-cell cavities operated at 704 MHz [9]. There are two groups of these cavities, optimized for β=0.47 and β=0.62. Two β=0.47 cavities have been developed successfully at INFN Milano. Gradients of 17 MV/m have been obtained which is more than twice the required value of 8.5 MV/m. Figure 6 shows a β=0.47 cavity and the layout of the cryo module housing this cavity. It is planned to test the cavity fully equipped with high power in the cryo module.

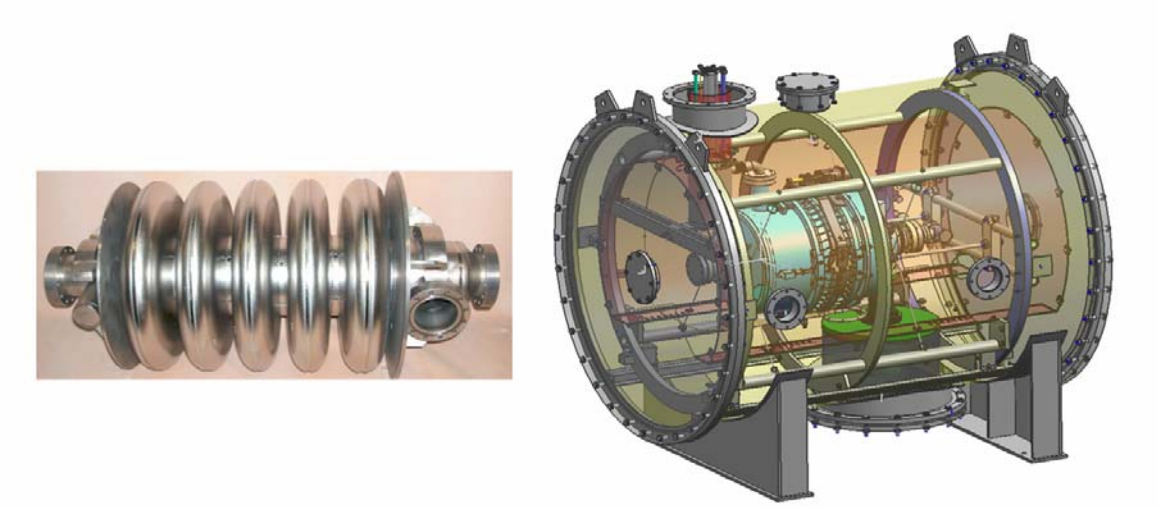

FIG.6. Superconducting elliptical β=0.47 cavity (left), schematic view of the cryo module for the elliptical cavities (right).

4 Fault Tolerance

In order to achieve the required reliability and availability of the EUROTRANS linac it is necessary to reduce the number of faults of different accelerator components. One method to extend the time between failures is “over design”. This means that different components like cavities, RF amplifiers, magnets and power supplies are operated far below their limits. In case of the superconducting RF cavities it could be shown that they reached a performance which is about twice the required value.

Another approach is redundancy. If it is questionable that a single device can guaranty the reliability it can be doubled. Therefore it has been decided to use two front ends up to 17 MeV. But it is also possible to have backup power supplies or RF control systems to keep single accelerator modules running. The third method to increase the reliability is the fault tolerance of the linac itself [10]. The main linac above 17 MeV consists of short superconducting cavities. After cavity fault has been detected it is possible to change the RF phase and RF power in neighbouring cavities to maintain the beam. This means that sufficient RF power, i.e. up to 80% is available to increase the accelerating voltage in the remaining cavities. Figure 7 shows the principle of maintaining the beam after a cavity fault by changing phase and amplitude. This principle has been proven experimentally in the proton accelerator of the Spallation Neutron Source (SNS) [11]. But it is important that the cavities with increased fields are still well below their limits to avoid additional cavity faults.

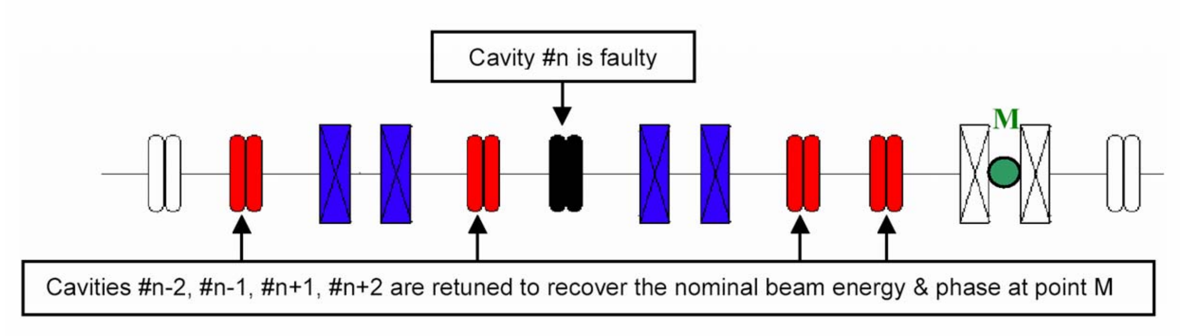

FIG.7. Principle of fault tolerance in the superconducting spoke linac.

5. Summary

Transmutation based on an Accelerator Driven System is an attractive option to reduce the long term environmental impact of nuclear waste. One of the key elements of such a system is a high power proton accelerator which should be superconducting because of the required cw operation. A reference design of a 600 MeV linac for EUROTRANS has been presented with emphasis on efficiency and reliability. It is planned that the design will be frozen until 2010. A possible construction could start between 2012 and 2015.

6. Acknowledgements

This work has been supported by Gesellschaft für Schwerionenforschung (GSI), BMBF contr. No. 06F134I. and EU contr. No 516520-FI6W. We acknowledge also the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395) and EU contr. No. EFDA/99-507ERB5005 CT990061 between EURATOM/FZ Karlsruhe IAP-FU. The work was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors would like to thank the company ACCEL (RI Research Instruments) for the excellent work on technical drawings as well as in the fabrication of the superconducting prototype cavity.

7. References

[1] The European Roadmap for Developing ADS for Nuclear Waste Incineration, European Technical Working Group, ISBN 88-8286-008-6, ENEA 2001

[2] C. Rubbia, A High Gain Energy Amplifier Operated with Fast Neutrons, Proc. of the International Conference on Accelerator Driven Transmutation Technologies and Applications, AIP Conf. Proc. 346, 1994

[3] R. Hollinger, W. Barth, L.A. Dahl, M. Galonska, L. Groening, P.S. Spaedtke, R. Gobin, P.-A. Leroy, O. Meusel, High-Current Proton Beam Investigations at the SILHI-LEBT at CEA/Saclay, Proc. of the Linear Accelerator Conference 2006, 232-236

[4] P.-Y. Beauvais, R. Duperrier, R. Gobin, Installation of the French High Intensity Proton Injector at Saclay, Proc. of the Linear Accelerator Conference 2006, 153-155

[5] H. Podlech, Development of Room Temperature and Superconducting CH-Structures, Proc. of the Linear Accelerator Conference 2004, 28-32

[6] H. Podlech, Ch. Commenda, H. Klein, H. Liebermann, U. Ratzinger, Superconducting CH-Structure, Phys. Rev. Special Topic Accelerators and Beams, 10, 080101(2007)

[7] H. Podlech, Entwicklung von Normalleitenden und Supraleitenden CH-Strukturen zur Effizienten Beschleunigung von Protonen und Ionen, Habilitationsschrift, Universität Frankfurt, 2008

[8] G. Olry, J.-L. Biarrotte, S. Blivet, S. Bousson, F. Chatelet, D. Gardes, T. Junquera, N. Hammoudi, J. Lesrel, C. Mielot, A.C. Mueller, D. Ruffier, H. Saugnac, P. Szott, J.P. Thermeau, Recent Developments on Superconducting β035 and β015 Spoke Cavities at IPN for Low and Medium Energy Sections of Proton Linear Accelerators, Proc. of the European Accelerator Conference 2004, 1003-1005

[9] A. Bossoti, C. Pagani, P. Pierini, J.P. Charrier, B. Visentin, G. Ciovati, P. Kneisel, RF Tests of the beta=0.5 Five Cell TRASCO Cavities, Proc. of the European Accelerator Conference 2004, 1024-1026

[10] J.-L. Biarrotte, D. Uriot, Dynamic Compensation of an RF Cavity Failure in a Superconducting Linac, Phys. Rev. Special Topic Accelerators and Beams, 11, 072803(2008)

[11] J. Galambos, S. Henderson, A. Shishlo, Y. Zhang, Operational Experience of a Superconducting Cavity Fault Recovery System at the Spallation Neutron source, Proc. of the Conference on Utilisation and Reliability of High Power Proton Accelerators 2007, 161-170