Superconducting Proton Linac for Waste Transmutation

H. Safa, CEA Saclay, DSM/DAPNIA/SEA, 91191 Gif-sur-Yvette, France

Abstract

In Europe, and specially in France, great concern is given for solving the issue of high level radioactive waste generated by nuclear power plants. A promising option is the use of a proton accelerator driving a subcritical assembly containing the undesired elements. In France, an R&D program has started to study the different parts of this hybrid reactor concentrating on some basic technological points. This four-year R&D phase should lead to a European proposal for building a "demonstrator" having a relatively low thermal power (one hundred MW). This paper describes the main parameters required for the accelerator driver, highlighting the use of niobium superconducting cavities in the high-energy section, reducing the overall length to less than 300 m. A first estimation of the total investment cost of the accelerator is also given.

1 - INTRODUCTION

In the frame of the 1991 French law on nuclear waste management, one axis of research has been dedicated to evaluate the separation and transmutation of highly radioactive long-lived nuclear waste. One promising option for transmutation is the hybrid reactor combining a high power proton accelerator to a subcritical target-blanket assembly. Each proton hitting a high Z material target will produce many (around 20) neutrons. These neutrons will multiply inside the blanket core and will eventually be captured by a long-lived radioactive element to form a short lived or even stable element. Specific R&D programs have started in many countries worldwide [**1**] converging towards the design and study of a linear accelerator using in its high energy section the superconducting cavity technology. Moreover, many other projects are now seriously considering similar accelerator-type machines like the spallation neutron sources, neutrino factories or radioactive beams.

2 - ACCELERATOR REQUIREMENTS

The waste transmutation accelerator requires a very robust operation as the target/blanket will suffer thermal shocks if the beam trips. Consequently, the design parameters should take in account additional safety margin to ensure a very high reliability. An extremely low level of beam induced radioactivity in the accelerator structures is also required to allow for hands-on maintenance.

The beam power specification is directly related to the thermal power of the hybrid. For a full scale prototype of 1000 MWth, the beam should deliver 32 MW. But a first step would be the construction of a "demonstrator" having a thermal power less than 100 MW in the core which implies a beam power of 9 MW. In all the following, the accelerator for the demonstrator project will only be discussed.

3 - ACCELERATOR LAYOUT

Knowing the beam power, an optimization of the total accelerator cost for a given transmutation capability leads to choose a current beam of 20 mA for a maximum proton energy of 450 MeV. The linac is divided in three parts. The first one is the injector, starting from the proton source up to an energy of about 10 MeV. The second part is called the "intermediate" part and accelerates the beam from 10 to 85 MeV. The high-energy part is the third and longest one and brings the proton energy up to its final energy. The important choice here concerns the use of superconducting radiofrequency (SCRF) cavities for this latter part which offers many advantages over the more classical room temperature copper one. The main parameters are summarized in table I and an overall scheme of the accelerator is shown in figure 1.

		Normal Part	SCRF Part	Total
Accelerator Length	(m)	100	193	293
Maximum Energy	(MeV)	85	450	450
Maximum Current	(mA)	20	20	20
Beam Power	(MW)	1.7	9.0	9.0
Electrical Power	(MVA)	10	21	31
RF Sources	*(MVA)*	*10*	*18*	*28*
Cryogenics	*(MVA)*		*3*	*3*

Table I - Main parameters of the superconducting linac.

4 - ADVANTAGES OF SUPERCONDUCTING CAVITIES

The first obvious advantage is the very high RF to beam efficiency. While on copper structures the efficiency is around 50%, half of the power being dissipated in the wall, it is almost 100% for SCRF cavities. For input power levels of hundreds of kilowatts, only a few Watts are lost. Although these are dissipated at the liquid helium temperature, even taking in account Carnot efficiency, AC losses are still negligible when compared to room temperature structures. Consequently, a very significant part of the operating cost is saved, especially in continuous wave (CW) accelerators. Moreover, less RF power is needed to feed the RF structures, making additional savings upon the investment costs. Besides these definite economical advantages, technical issues equally favor the superconducting option. Large beam tube openings, not achievable in normal conducting cavities, help to dramatically reduce the threat of activation induced by beam halo. As a matter of fact, almost zero beam loss is expected when using SCRF structures, even for high current beam [**2**]. Secondly, the length of the high-energy part is tremendously shortened (reduced by a factor of 3!), due to the very high electrical gradients that new progress on SCRF cavities have demonstrated [**3**] (Accelerating fields of 10 MeV/m are easily achieved in SCRF cavities as compared to 1.6 MeV/m for copper cavities). Finally, the use of superconducting cavities will allow more flexibility in the use of the accelerator, making it easier to change the beam power level while maintaining a fairly high overall efficiency. The only drawback of superconducting cavities is the use of cryogenics, but this technology has already proven to be quite well mastered on several large machines worldwide.

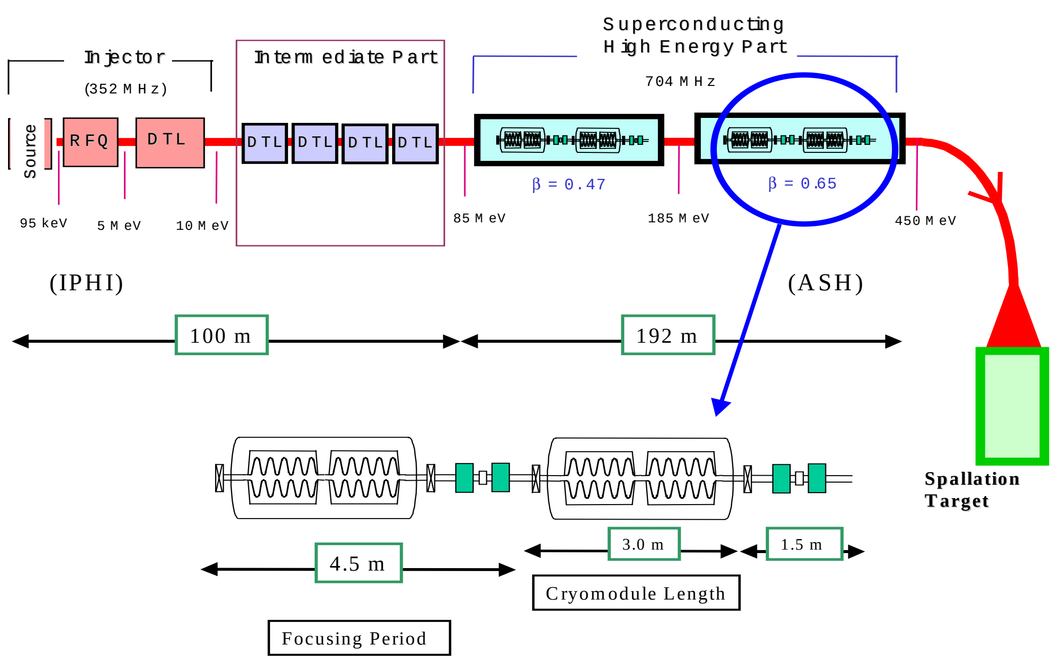


Figure 1 - Layout of the superconducting linear accelerator for waste transmutation studies.

5 - INJECTOR

The injector covers a proton source at 95 keV followed by a Radiofrequency Quadrupole (RFQ) bunching and accelerating the beam to 5 MeV, then a small Drift Tube Linac (DTL) that brings up the energy to 10 MeV.

5 - 1 . The IPHI Project

The IPHI (Injector for Protons with High Intensity) project aim at building this 10 MeV CW injector for currents up to 100 mA [**4**]. The total investment for the IPHI prototype is 50 MFF and the CEA/CNRS-IN2P3 team amount to 45 men.year/year. Figure 2 shows the layout and highlights the key goals of the project.

5 - 2 . The Source

The first stage is the High-Intensity Light-Ion Source SILHI designed to produce a high-intensity proton or deuteron beam at 95 kV. This 2.45 GHz ECR source is already built [**5**] and runs now at a high performance level (see Table II). An availability of 99.96% has been obtained during one week long test run.

5 - 3 . RFQ

A final technical design review of the RFQ was held at CEA/Saclay in June 1999 defining the main parameters (Table II). A high transmission beam is expected despite the relatively low electric fields. Beam dynamics optimization has been done using codes developed at Saclay, LANL (PARMTEQ) and MRTI (LIDOS) [**6**]. The thermo-mechanical analysis of the cavity and the study of the RFQ vacuum system progress successfully. The fabrication bid has already been awarded last September. After a 1 m length prototype, the full 8 m structure should be installed and tested in 2002.

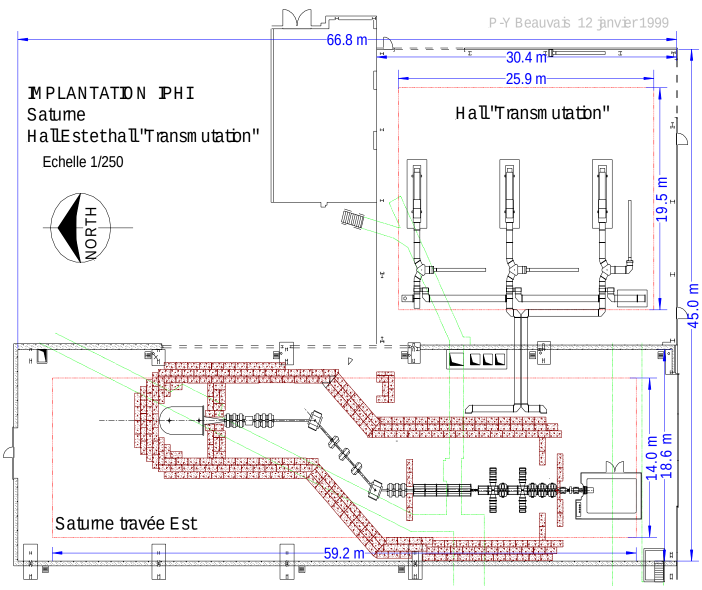
5 - 4 . DTL

A complete 3D magnetic analysis of the low energy quadrupoles (around 5 MeV) has been done. The field non-linearities have been calculated taking into account the surrounding quadrupoles. A short tank (4 cells) for high-power testing will be built and, if funding is available, the complete 10 MeV tank should run by 2003.

SOURCE	Nominal Φ 10 mm	Status Φ 8 mm	Status Φ 10 mm
Proton current (mA)	100	91	98
Duty cycle (%)	100	100	100
Extraction voltage (kV)	95	95	92
Total current (mA)	~ 110	108	122.5
Proton fraction (%)	> 90	84	80
Plasma density (mA/cm2)	140	215	156
RF power (W)	1 200	1 100	1 200
Hydrogen mass flow (sccm)	< 10	2	3
Beam current noise (%)	± 1	± 2	NA
Norm. rms emittance (π mm mrad)	0.20	0.17 @ 80 mA	0.21 @ 97 mA

RFQ		
Length	8.0	m
Vane voltage	87.34 to 122.82	kV
R_0 (mean aperture)	3.69 to 5.27	mm
(ρ/R_0)	0.85	
Min. Aperture a	3.56 to 4.41	mm
Modulation m	1.0 to 1.735	
Input trans. Emittance	0.25 (rms norm)	π mm mrad
Output trans. Emittance	0.25 (rms norm)	π mm mrad
Output long. Emittance	0.18 (rms norm)	MeV.deg
Transmission	99.4% for 1.8 Kp	@ 100 mA

Table II - Source measured performance and RFQ calculated parameters.



Source / LEBT		
	Test the matching conditions to the RFQ	1999
RFQ		
	Tests of RF systems	06-12 / 2001
	Tuning of the RFQ cavity	01-06 / 2002
	Low beam current tests	06-12 / 2002
	Nominal beam	01 / 2003
Diagnostic Line		
	Beam measurements at reduced power	06 / 2002
	Beam measurements at nominal power	01 / 2003
DTL		
	Short tank hot RF tests	04-08 / 2000
	Start a 10 MeV tank	01 / 2001

Figure 2 - General layout and schedule of the IPHI project.

6 - THE INTERMEDIATE PART

The basic option for the intermediate part will be the use of classical DTL copper structures assembled in tanks. Each tank will be around 25 m long and will roughly increase the kinetic proton energy by 25 MeV. One basically needs three of these tanks for this part but an additional tank might be added to adapt the beam before injection into the first superconducting cryomodule. An alternative option could be the use of superconducting structures. But for these low $\beta = v/c$ proton velocities, non-elliptical superconducting cavities will require additional effort and time for development. Although this option is not discarded, focusing effort is mainly directed towards the high-energy part, where the expected gain is much more valuable.

7 - SUPERCONDUCTING PART

The high energy part of the accelerator will be using superconducting bulk niobium cavities at the second harmonic frequency of 704 MHz working in the superfluid helium temperature at 2 K. This choice enables running at high accelerating fields (Eacc > 10 MeV/m) while keeping very low RF losses (Quality factors Q_0 above 10^{10} are achievable). A single power coupler will feed each cavity. A string of two cavities with their main coupler will be assembled and evacuated inside a clean room then inserted in a cryomodule. Beam focusing will be following a doublet scheme having a lattice period of

4.5 meters and using standard coils in between two cryomodules. The superconducting part is divided in two sections, each section corresponding to a different geometric β value (β = 0.47 and β = 0.65). Table III summarizes the main parameters of the superconducting part.

Superconducting Part		Demonstrator		
Beam Current	(mA)	20		
Sections		β=0.47	β=0.65	Total
Starting Energy	(MeV)	85	185	85
Ending Energy	(MeV)	185	450	450
Real Length	(m)	76	117	193
Number of Cavities		36	52	88
Number of Cryomodules		18	26	44
Max. Accelerating Field	(MeV/m)	8.6	9.1	9.1
Max. Magnetic Peak Field	(mT)	50	50	50
Max. Input Power/Coupler	(kW)	75	110	110

Table III - Main parameters of the superconducting high energy part for the demonstrator.

7-1. Cavities

The superconducting cavities are of standard elliptical shape used for electron machines, but squeezed to take in account the non-relativistic velocity of the protons. Consequently, the ratio of the surface magnetic field to the accelerating field (B_{peak}/E_{acc}) is enhanced in comparison with a β = 1 cavity by almost a factor of 2. Hence, considering the margins required for reliability, the performance aimed at (B_{peak} = 80 mT) is of the same order than for high gradient machines. This definitely imposes the use of bulk niobium cavities at 704 MHz and rules out other choices. The cryogenic losses, although only weighing about 10% of the total AC losses, have to be reduced for cost savings during operation. First results obtained at Saclay on a β = 0.65 single-cell cavity are very promising [**7**]. Excellent performances have been achieved, exceeding the design point with enough margins, and justifying the above choices (figure 3). Optimised 5-cell cavities will be fabricated and tested for both β values in the next coming year.

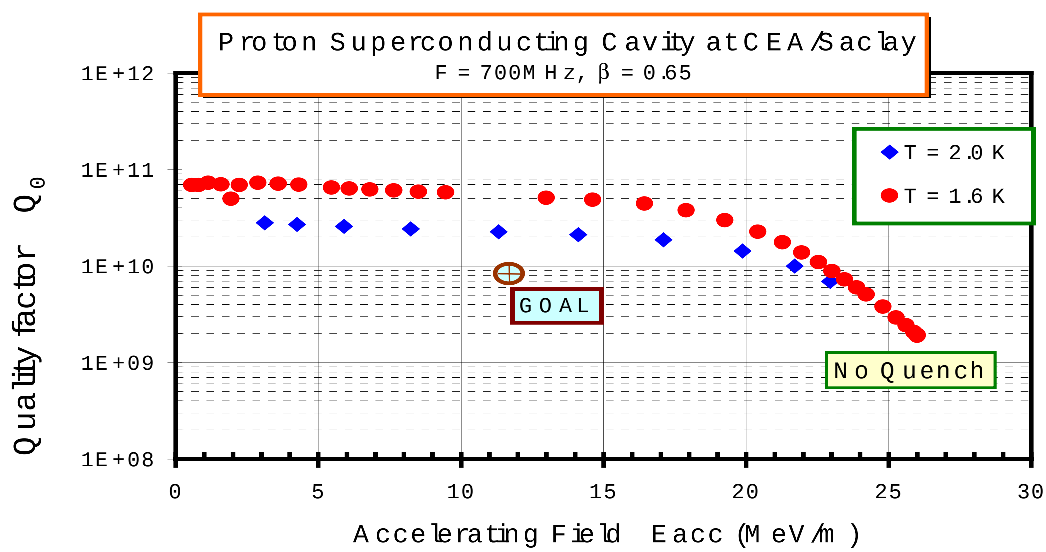


Figure 3 - Q_0 vs. E_{acc} plot for a single-cell niobium cavity for proton. Note that the obtained performance by far exceeds the design goal.

7-2. Couplers

The main power coupler has to deliver 150 kW of continuous RF power from the RF source at room temperature down to the cavity at cryogenic temperature. It is a very delicate part to design, bearing in mind the desired reliability and robustness. Although recent progress in most laboratories have been achieved in high power handling on superconducting machines (KEK in Japan [**8**], CERN in Europe and Cornell in US have demonstrated more than 300 kW CW), the design of such a coupler is still a challenge. Work has been started at CEA/Saclay, in collaboration with the Los Alamos National Laboratory (USA) which has achieved 1 MW on a warm test bench [**9**]. The goal is to design and build a

300 kW power coupler at a frequency of 700 MHz within three years.

7 - 3 . Cryomodule

Integration of cavities and power couplers in a cryomodule is a rather skilled operation. It requires complete mechanical and thermal calculations, as well as magnetic shielding, cryogenic cold box and vacuum system designs. Furthermore, if mounting is not done properly following careful assembly procedure in a clean room, cavity performance might be completely ruined. Integrated cryogenic cooling schemes of the different parts (cavities, couplers and thermal shield) have to be optimized taking in account the cryogenic plant.

7 - 4 . The ASH Project

A 5-year R&D plan for developing superconducting cavities for proton accelerators is starting in FY2000 at CEA/Saclay in collaboration with CNRS/Orsay and INFN/Milano. The ASH (Superconducting Accelerator for Hybrid) project will aim at building and testing a fully equipped cryomodule at 704 MHz, including the design and construction of multicell cavities and power couplers. If the cryogenic tests are successful in terms of accelerating field, power handling and cryogenic losses, the know-how should be transferred to European industrials for future production.

The issue of this R&D work should be a fully evaluated (technical and cost) proposal for a waste transmutation accelerator which will be submitted to the French National Parliament in 2005.

8 - COST ESTIMATION

A preliminary cost evaluation is shown in table IV for the demonstrator option. The total investment cost amount to 150 MEuros, including the buildings. A realistic time schedule would aim at eight years from the starting point (4 years of R&D + 4 years of construction). This would enable commissioning the hybrid in 2008 and beginning the transmutation experiments in 2010. This machine would certainly open a lot of opportunities for physics science based on neutron and look very promising for future both basic and applied science.

	Cost (in MEuros)
Injector & DTL	30.0
Injector	*6.1*
DTL	*22.9*
Others	*1.0*
Cryomodule	33.5
Cavity	*6.7*
Cryostat	*6.7*
Manpower	*13.4*
Others	*6.7*
Radiofrequency	27.4
RF Source	*21.7*
Power Supply	*5.7*
Cryogenics	8.8
Plant	*5.6*
Cryoline	*2.7*
Others	*0.5*
Infrastructures	46.5
Tunnel	*4.1*
Hall	*16.8*
Buildings	*20.5*
Others	*5.1*
Miscellaneous	4.2
TOTAL	150

Table IV - Preliminary cost estimation of the linear accelerator for the demonstrator project.

9 - REFERENCES

1 KCD Chan & al., "Review of Superconducting RF Technology for High Power Proton Linacs", 9th Workshop on RF Superconductivity, Santa Fe, USA, these proceedings [1999]

2 G. Lawrence and T. Wangler, "Integrated NC/SC high power proton linac for the APT project", PAC97 proc., p. 1156, Vancouver, Canada [1997]

3 H. Safa, "High gradients in SCRF cavities", Particle Accelerators, Vol. 60, p. 219 [1998]

4 J.M. Lagniel & al., "IPHI, the Saclay high-intensity proton injector project", PAC 97 proc. , p. 1120, Vancouver, Canada [1997]

5 R. Gobin et al., "New performances of the CW high-intensity light-ion source SILHI", EPAC98 proc., Sweden [1998]

6 B. Bondarev et al., "CW RFQ designing using the LIDOS.RFQ Codes", Linac 98, Chicago (USA) [1998]

7 J.L. Biarrotte & al., "704 MHz Superconducting Cavity for a High-Intensity Proton Accelerator", 9th Workshop on RF Superconductivity, Santa Fe, USA, these proceedings [1999]

8 S. Mitsunobo & al., "High Power Input Coupler for KEKB SC Cavity", 9th Workshop on RF Superconductivity, Santa Fe, USA, these proceedings [1999]

9 E. Schmierer & al., "Thermal and Mechanical Testing Status of the SCRF Power Coupler for the APT Accelerator", 9th Workshop on RF Superconductivity, Santa Fe, USA, these proceedings [1999]