HIGH-INTENSITY LINAC STUDIES IN FRANCE

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Abstract

Teams from different French research agencies are working on high-intensity high-duty factor proton, H^- and deuteron linear accelerators for several applications (waste transmutation, spallation neutron sources, tritium production, materials irradiation facilities...). The conceptual design of the TRISPAL project achieved by the CEA for tritium production is presented. A separate R&D program undertaken by a CEA-CNRS (IN2P3) collaboration is also discussed. This program includes both the construction of a high intensity (100 mA), cw (continuous wave), 10 MeV, prototype linac (IPHI) and the fabrication and test of $\beta < 1$ superconducting cavities.

1 OVERVIEW OF THE HIGH-INTENSITY LINAC ACTIVITIES IN FRANCE

Proton and deuteron accelerators with average beam power greater than 1 MW are being studied all over the world for numerous applications (see [1-2] for reviews), mainly because they are increasingly considered as ideal sources of neutrons (high flux, broad energy spectra, cw or pulsed mode, safety associated with fast shut-down...).

In France, the CEA (Commissariat à l'Energie Atomique) started the study of the TRISPAL project for tritium production in 1992. In this project, a high-intensity cw proton beam is used to produce a high neutron flux through spallation process in a heavy metal target. These neutrons are then used to transmute ^{6}Li into tritium. The TRISPAL conceptual design is now complete [3]. The 24 MW beam power linac (40 mA, 600 MeV, cw, protons) designed by a team from CEA-Bruyères-le-Châtel, CEA-Saclay and Thomson-CSF-Airsys is described in section 2.

The CEA-Saclay team is also involved for the last several years in the IFMIF project (International Fusion Material Irradiation Facility). The aim of this IEA (International Energy Agency) activity is the design of a high-flux neutron source with an energy spectrum peaked near 14 MeV for research and development of materials for the next generation of fusion reactors. The IFMIF team has the distinction to have a broad community of scientists from different fields (accelerator, Li-target, test facility, users, design integration) and from different countries e.g. the European Union (EU), Japan and the United States of America, along with the Russian Federation as an associate member. The EU contribution in the accelerator field is done by a Frankfurt University - CEA-Saclay collaboration thanks to a support of the European Commission. The confrontation of ideas with scientists from different labs is very fruitful and the work with our European, Japanese, American and Russian colleagues has been and is still highly appreciated. The IFMIF design is based on two 125 mA, 35-40 MeV, cw deuteron linacs. A full description of the work done during the IFMIF Conceptual Design Activity (CDA, 1995 and 1996) can be found in ref. [4]. The project is now in the Conceptual Design Evaluation (CDE) phase. The CEA-Saclay team is working on the ion source, high-power 175 MHz RF systems (in collaboration with Thomson-Tubes-Electronics) and beam loss.

The CEA is also involved in the 5 MW European Spallation Source (ESS) project [5]. CEA-Saclay will participate in the R&D program for the linac (1.33 GeV, 107 mA H^- peak current, 6% duty cycle). R&D studies are being contemplated in the development of H^- ion source, the beam diagnostics and the design of the accelerating structures including the evaluation of a superconducting cavity option for the high energy part of the linac.

Two French research agencies, CEA and CNRS-IN2P3 (Centre National de la Recherche Scientifique - Institut National de Physique Nucléaire et de Physique des Particules), have started an evaluation program for the accelerator driven transmutation of waste (ADTW) technology. In such a system, spallation neutrons are used to transmute long lived nuclei with high radio-toxicity into short lived or stable nuclei. The accelerator is coupled to a sub-critical target where minor actinides and/or fission products for transmutation are located [6-7]. A beam power of 20 - 40 MW or more is needed. For this, 20 - 60 mA cw proton beam will be accelerated by a linac up to an energy range 600 - 1200 MeV. The choice of beam intensity and energy must result from a complex optimization process of the whole system and the design must take into account the severe constraints on the accelerator availability and beam losses [7-8].

A significant R&D program has been undertaken by the CEA-CNRS (IN2P3) collaboration in order to optimize the design of such a high-power proton linac which could be also used for the next generation of radioactive ion beam facilities and for muon colliders. The program includes the construction of a high intensity (up to 100 mA), cw, 10 MeV prototype (IPHI, section 3) and the fabrication and test of $\beta < 1$ superconducting RF (SRF) cavities (section 4).

2 THE TRISPAL PROJECT

TRISPAL is the CEA project for tritium production using spallation neutrons. The accelerator parameters have been optimized to produce the requested quantity of tritium per year. Optimization process has taken into account the fluctuation in the cost of electricity during the year (electricity in France is ten times more expensive during the winter). The process has lead to the choice of a beam power of 24 MW delivered by a 600 MeV 40 mA cw proton linac [3].

The main directive to the TRISPAL design team was to be as conservative as possible for the choice of the technology and parameters. This accelerator based tritium production system compete directly with the process based on a conventional nuclear reactor. Thus, the linac must be built as part of an industrial facility. The major considerations that went into the design of the accelerator are :

- limit beam losses to an extremely low level ($\sim\Delta I/I < 10^{-9}$) in order to allow hands-on maintenance.
- achieve a high reliability/availability (greater than 90%) and minimize the number of abrupt beam interruptions to limit the stress in the target. It has been calculated that the TRISPAL target (including the window) can accept up to 10000 abrupt beam stops (longer than 100 ms) per year. This approximately corresponds to a mean value of one stop per hour which seems to be realistic.
- Minimize the total cost of the machine (construction and operation) without compromising the two previous items.

Figure 1 shows the layout of the TRISPAL linac. The 24 MW proton beam is produced using 4 types of RF cavities, all operating at the same frequency (352 MHz). This minimizes bunch compression which is always a source of mismatch and halo formation. The front end is composed of an 95 kV ECR source, a low energy beam transport line with two solenoids and a 5 MeV RFQ. The main parameters of the RFQ are listed in Table 1. The maximum electric field is limited to 1.5 Kilpatrick to reduce the sparking rate. The price for this choice is a relatively low transmission.

Table 1, TRISPAL RFQ main parameters

Length	8 m (578 cells)
Vane voltage	88.5 kV (1.5 Kp)
R_0 (mean aperture)	4.38 mm (min a = 2.8 mm)
ρ (vane radius)	3.72 mm (ρ/R_0 = 0.85)
Input trans. Emit.	0.25 π mm mrad (rms norm)
Output trans. Emit.	0.23 π mm mrad (rms norm)
Output long. Emit.	0.12 MeV deg (rms norm)
Transmission	93% (for 50 mA input current)

The high output energy of the RFQ is achieved in a 8 m long structure thanks to the segmented coupled RFQ concept developed at LANL [9]. This capability of pushing up the RFQ energy is very useful because as β = v/c increases, the first cells of the DTL become long enough (~ 8 cm) to accommodate electromagnetic quadrupoles. The front end cavities can then operate at a relatively high RF frequency allowing the construction of a high energy machine without a frequency jump (352 MHz for the TRISPAL basic design), or only with a jump of a factor of two if 704 MHz SRF cavities are used in the high energy part. This is an important point to facilitate the beam matching in the accelerator, to avoid halo formation, and unacceptable beam losses.

The medium energy part of the TRISPAL linac is made up of an RFQ to DTL matching section, a 29 MeV DTL and SDTL cavities up to 85 MeV. The beam matching between the RFQ and the DTL is done in a ~ 80 cm section using four quadrupoles and two 352 MHz bunchers. The phase advances per unit length are kept constant from the last cells of the RFQ to the first cells of the DTL and the beam envelope modulations are minimized as much as possible in order to obtain an intensity independent matching and to minimize emittance growth. The transmission through the 29 MeV DTL is 100% ; a full beam dynamics study including errors on both the beam and accelerator parameters has been completed to determine tolerances [10]. The DTL has two tanks, each fed by an 1.3 MW RF system similar to those used in LEP or ESRF accelerators. A SDTL (Segmented DTL), mechanically simpler to build than a standard DTL, is chosen for acceleration from 29 to 85 MeV. The SDTL is composed of short DTL cavities (5-7 cells) with simple drift tubes, the transverse focusing being provided by the quadrupoles located outside the cavities.

LEP-type CCL copper cavities (see figure 2) take the beam to the final energy (600 MeV). The beam dynamics beyond the DTL has been studied using a simplified linear model ; more accurate simulations using multiparticle codes (including error analysis) may lead to an adjustment of the transition energies. In the present TRISPAL design, each SDTL and CCL cavity is fed by couplers capable of maximum power of 125 kW (a conservative value). The RF power is supplied by 49 1.3 MW RF systems. A quadrupole doublet focusing lattice is chosen. The SDTL uses seven β families in a total of 40 cavities with beam apertures ranging from Φ 50 to 30 mm and effective shunt impedance ranging from 44 to 34 MΩ/m (80% SUPERFISH). The CCL uses twelve β families in a total of 344 cavities with beam apertures ranging from Φ 30 to 60 mm and effective shunt impedance of ~30 MΩ/m. An option using superconducting RF cavities is also presented in addition to this basic conservative design.

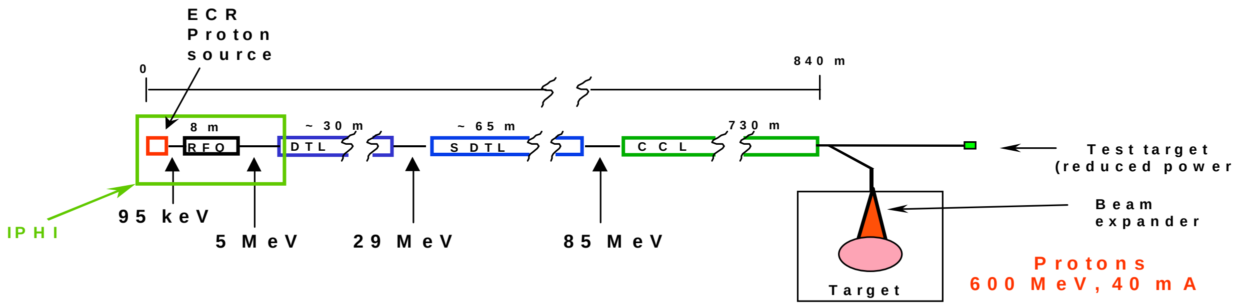

Figure 1 : TRISPAL layout

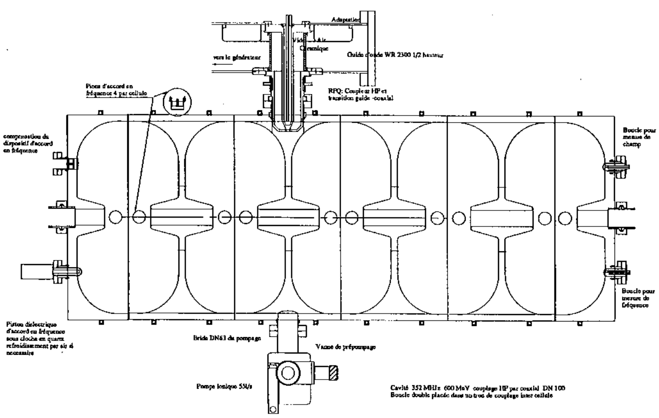

Figure 2 : TRISPAL CCL high-energy copper cavity

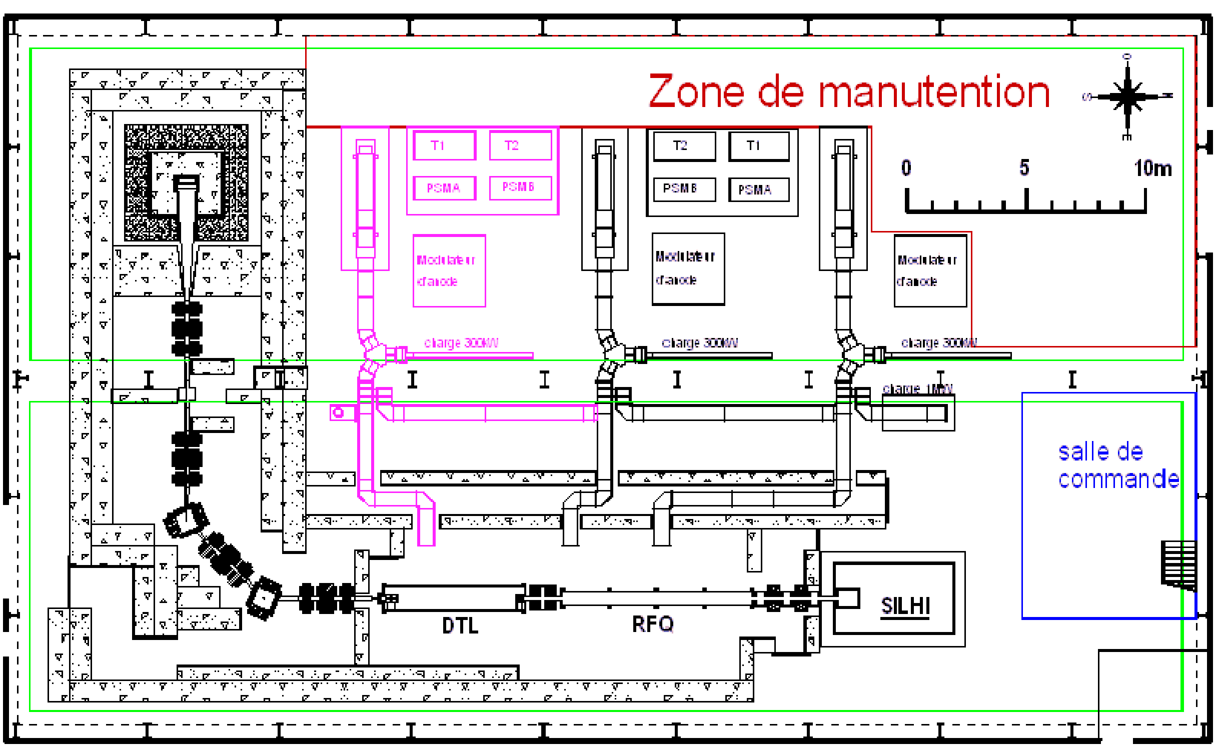

Figure 3 : General layout of the IPHI project

3 IPHI

IPHI (Injecteur de Protons Haute Intensité) is the name of the CEA-CNRS R&D program undertaken in 1997 for the front end of a typical high-power linac. The objective is to gain experience in this difficult part of the accelerator in order to optimize the whole machine in terms of performances, cost, reliability and availability. To summarize, the IPHI objectives are :

- validation of the beam dynamics codes in the low-energy sections where space-charge effects are dominant,
- knowledge of the beam distribution at an energy where halo considerations are crucial,
- demonstration of the merit of technological choices and adequacy of design codes,
- acquisition of data on reliability and availability, reality check on the cost of the components and ability of the manufacturers to build them.

The project goal is to build a 10 MeV "Injector for Protons with High Intensity" (up to 100 mA) and duty cycle up to 100%. The first stage is a High-Intensity Light-Ion Source, SILHI, designed to produce high-intensity proton or deuteron beams at 95 kV. This 2.45 GHz ECR source is now at a high performance level [11]. Table 2 shows the current performance data (consistent values except when specified) for two values of extraction diameter.

Table 2, status of the SILHI source

	Objective	Achieved	
Extraction Diameter (mm)	10	8	10
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/cm^2)	140	215	156
RF power (W)	1200	1100	1200
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

A first uninterrupted operation was done at the end of 1997 to measure the availability of the source. It was operated continuously for 100 hours (~5 days) at 100 mA cw. An availability of 96% was obtained with 1 h 45 mn for the Mean Time Between Failures and 4 mn 44 s for the Mean Time To Repair. Most of the beam interruptions occurred during the first day. When this conditioning period is not taken into account in the statistics, the source availability reach 99% (MTBF = 5 h 33 mn). EMC improvements made after this test and incorporation of an automatic restart controlled by computer is expected to improve these already high performance statistics.

No damage to the new HV extraction electrodes was observed after more than 300 hrs of cw operation at 100 mA. The stability and reproducibility of the beam are excellent. A non-interceptive emittance measurement system based on measurement of beam profiles with a CCD camera has been successfully tested recently [12].

The key parameters of the 5 MeV RFQ are now almost fixed. Table 3 shows that our objective to achieve a very high beam transmissions with a relatively low maximum electric field is at hand. The optimization of the beam dynamics has been done using a large set of codes developed at Saclay, LANL (PARMTEQM) and MRTI (LIDOS) [13]. An in-depth analysis of the different models used in these codes is underway [14].

Table 3 : IPHI RFQ main parameters

Length	8 m
Vane voltage	87.34 to 122.82 kV (1.7 Kp)
R_0 (mean aperture)	3.69 to 5.27 mm
ρ/R_0	0.85
A	3.56 to 4.41 mm
M	1.0 to 1.735
Input trans. Emit.	0.25 π mm mrad (rms norm)
Output trans. Emit.	0.25 π mm mrad (rms norm)
Output long. Emit.	0.18 MeV deg (rms norm)
Transmission (100 mA input current)	99.4% for 1.8 Kp 99.3% for 1.7 Kp 97.3% for 1.6 Kp

The thermo-mechanical analysis of the cavity and the study of the RFQ vacuum system has been successfully completed. Several prototypes will be built before the end of this year to validate the fabrication process. Financial commitment for the high-power RF system will be made in 1999 (klystrons, windows and circulators).

To optimize the geometry of the DTL, a full 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 effect of surrounding quadrupoles. The construction of a short tank (4 cells) for high-power tests will start at the end of this year. A affirmative decision for the construction of a 10 MeV tank is expected in 1999. Total investment for the IPHI prototype is ~8 M ECU (equipment only) and the CEA - CNRS-IN2P3 team consist of around 45 men-year/year. The key dates are :

Source / LEBT :

Test the matching conditions to the RFQ 1999

RFQ :

Tests of the 2 RF systems 01-06/2001
Tuning of the RFQ cavity 06-12/2001
Low beam current tests 01-06/2002
Nominal beam 06/2002

Diagnostic Line :

Beam measurements at nominal power 09-12/2002

DTL :

Short tank hot RF tests 04-08/2000

Start a 10 MeV tank 01/2001 (not yet funded)

4 SRF CAVITY STUDIES

A strong R&D effort on $\beta < 1$ SRF cavities is justified by the fact that this technology brings important advantages, the most obvious one being economy. In fact, the high RF to beam power efficiency (almost 100%) significantly reduces the operation cost. In addition, the investment cost can also be slightly reduced through length reduction. Standard copper RF cavities typically provide ~1.5 MeV/m with a shunt impedance ~35 MΩ/m. A 1 GeV linac is then ~ 670 m long and ~43 MW of RF power is lost in the copper (~ 70 MW from the plug).

An important know-how for the SRF cavity has been obtained by the CEA - CNRS-IN2P3 collaboration (CEA-Saclay, IPN-Orsay and LAL) and by the French industry (CERCA...) thanks to several studies and constructions done for the TESLA-TTF electron linac. This expertise is obviously very useful in the high-power proton linac field for which $\beta < 1$ SRF cavities must be developed. The first studies done in 1996 by a LANL - CEA-Saclay team demonstrated that beam losses as high as 10^{16} protons/cm^2/s do not affect the superconducting properties of niobium cavities [15-16]. In 1997, four 700 MHz single-cell cavities (β = 0.48 and 0.64) were successfully built and tested at LANL with participation of CEA-Saclay [17-18-19]. Several single cell 704 MHz β = 0.6 Nb cavities have been made by CERCA for CEA-Saclay ; low power RF tests will start very soon. Studies are also underway for the development of high-power RF couplers. "CRYHOLAB", the horizontal cryostat being built by CEA and CNRS, will be available in 1999 to test multicell cavities.

In the near future, a full study for the best choice of the RF frequency (352 vs 704 MHz) in terms of cost, beam dynamics and reliability-availability will be done. A new R&D programme called "ASH" (Accélérateur Supraconducteur pour Hybrides) [20] has also been proposed for high-power RF tests. The aim is to design a cryomodule fully equipped with high field cavities, high-power couplers and cryogenic connections, to measure the real cryogenic losses of the system. The ultimate objective of this proposal (1999-2002) is to transfer technology to the industry.

Together with the SRF cavity technology development, beam dynamics studies including errors on both beam and accelerator parameters need to be done. This would answer several basic questions such as - Are the long focusing periods due to the use of room temperature quadrupoles lead to acceptable beam losses ? - Must we limit the accelerating field to avoid emittance growth due to a strong transverse-longitudinal coupling ? - Must we use superconducting quadrupoles to shorten the focusing periods ? - What is the best choice for the beam aperture ? - Is 100 MeV the right energy to start SRF cavities ? An answer to the last question is definitely needed before starting the R&D on $\beta \sim 0.5$ SRF cavities. Analysis and improvement of the codes to achieve high precision for these beam dynamics calculations are an important part of the current effort [21-22]. For this, as well as for the development of the SRF cavity technology, a strong and productive collaboration is in place with several laboratories around the world, particularly with LANL (USA) and INFN (Italy).

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