THE SUPERCONDUCTING PROTOTYPE LINAC FOR IFMIF

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Abstract

The development of the IFMIF accelerator prototype is in progress within the framework of the EVEDA phase (Engineering Validation and Engineering Design Activities). This prototype will be installed at Rokkasho (Japan) and will allow testing the key systems. The first warm section composed of the deuteron source, beam lines and RFQ will prepare the beam for the cryomodule (CW 125mA at 5 MeV). The 8 HWR superconducting cavities equipped with a 200kW power coupler will accelerate the beam up to the maximum energy of 9 MeV. The design of the IFMIF/EVEDA accelerator prototype is briefly presented, and the general layout of the cryomodule is detailed.

INTRODUCTION

The IFMIF-EVEDA phase has been launched in June 2007 in the framework of the EU-JA Agreement for the Broader approach for Fusion. The two objectives of this EVEDA phase are the validation of the technical options with the construction of a prototype accelerator, and the delivery of the detailed integrated design of the future IFMIF accelerator (including complete layout, safety analysis, cost and planning).

The 250mA deuteron beam is delivered to the lithium target by two identical superconducting LINACs, each delivering half of the beam current. The prototype accelerator is identical to the final IFMIF one from the deuteron source to the first low beta cryomodule (Figure 1). It delivers a full current (125mA) deuteron beam at 9MeV. Each final IFMIF accelerator includes 3 additional cryomodules in the high energy portion that increase the energy of the beam up to 40MeV.

The prototype accelerator will be installed and commissioned at Rokkasho (Japan).

The components of the prototype accelerator are provided by European institutions (CEA, INFN, CIEMAT): the injector, the RFQ, the transport line to the 1.2 MW beam dump, the 175 MHz RF systems, the matching section and the cryomodule, the local control systems and the beam instrumentation, required for tuning, commissioning and operation of the accelerator. The building constructed at Rokkasho site, the supervision of the accelerator control system, as well as the RFQ couplers, are provided by JAEA.

The first part of this paper gives a brief overview of the layout of the EVEDA prototype accelerator. More details about the accelerator can be found in previous papers [1,2,3]. The second part of this paper describes the cryomodule design and presents the status of its development.

THE PROTOTYPE ACCELERATOR

As described above, the design of the IFMIF superconducting LINAC is based on 4 cryomodules (CM) with 2 beta families of half wave resonators (HWR). It has to accelerate the beam from 5 MeV to the final energy 40 MeV. The optimization of the LINAC configuration led to the following sequence [4]:

- 1st CM: 8 periods of 1 solenoid + 1HWR β=0.094
- 2nd CM: 5 periods of 1 solenoid + 2 HWR β=0.094
- 3rd and 4th CM: 4 periods of 1 solenoid + 3 HWR β=0.166

The EVEDA prototype accelerator that will be tested at Rokkasho will deliver the full beam current at 9MeV. It will be identical to the final IFMIF accelerator from the deuteron source to the first low beta cryomodule (Figure 1).

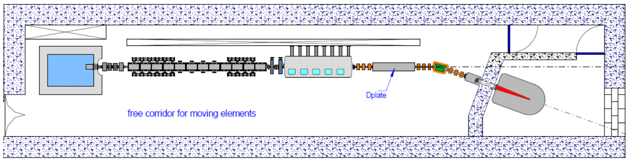

Figure 1: Layout of the prototype accelerator in the vault at Rokkasho.

The injector (Figure 2) is composed of an ECR (Electron Cyclotron Resonance) ion source and a Low Energy Beam Transport line (LEBT). It shall deliver a 140 mA low emittance deuteron beam with high reliability at 100keV [5, 6].

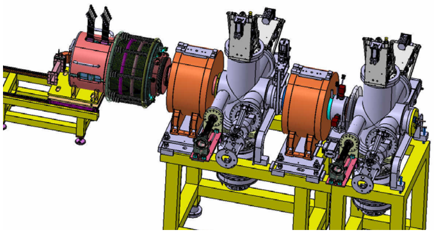

Figure 2: The mechanical assembly of the injector. The total length is 2.05m.

The development of the ion source is based on the SILHI source previously developed at CEA-Saclay.

The injector will be integrated at Saclay and the beam tests will start in April 2010 in a dedicated test stand already built.

The RFQ is a four vane structure at 175MHz developed by INFN [7]. It has to bunch the dc beam from the injector at 100 keV and to accelerate it up to 5 MeV. The total RF power required is about 1.6 MW and will be delivered by eight 200 kW RF power sources.

The optimisation of the RFQ resulted in a structure composed by 9 modules of 1.1 m long each (Figure 3).

The brazing procedure was chosen for the assembling of the different modules.

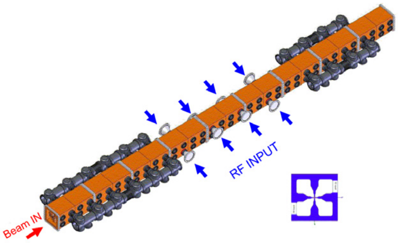

Figure 3: Overall view of the RFQ.

As activation of the RFQ cavity is of main concern for maintenance, extensive multi-particle simulations have been performed to evaluate the loss of particles along the RFQ. The transmission is about 98.5% and the losses above 1 MeV are kept at a very low level.

The RF power system is developed by CIEMAT in collaboration with CEA and SCK-CEN [8]. All power units of the IFMIF accelerators are tetrodes: 18 units of 105 kW and 24 units of 220 kW (Figure 4).

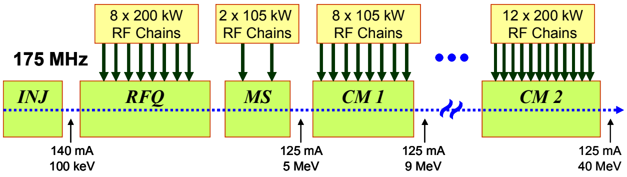

Figure 4: Identical RF power stations for the accelerator.

At the exit of the cryomodule the beam is transported to the beam dump with the required beam spot (rms size of 40 mm rms divergence of 16 mrad) into the High Energy Beam Transport line [9].

The EVEDA beam dump [10] has to stop deuteron beams with a maximum power of 1.125 MW. While the profile of the beam power deposition depends on the geometry of the cartridge, the choice of the beam facing materials should take into account the neutron production and activation level, as well as the thermal stresses.

THE CRYOMODULE

General Layout of the Cryomodule

The cryomodule (Figure 5) is developed by CEA in collaboration with CIEMAT. The alternation of the cavities and the solenoids inside the cryomodule results in 8 lattices. The length of each lattice was minimized to 580 mm (solenoid package: 400mm - cavity: 180mm). The total length of the cryomodule is about 5 m. The inner cavity vacuum and the insulating vacuum are separated. The cold mass is cooled by liquid helium at 4.4 K. A copper thermal shield maintained at 77 K by liquid nitrogen protects the cold mass from the 300 K radiations. Each cavity is equipped with a power coupler designed for the final IFMIF accelerator requirement of 200kW. The maximum power for the EVEDA accelerator prototype is 70kW.

Choice has been made to put the couplers in vertical position in order to limit the risks of breaking the ceramic window during transportation to Japan. As a consequence the HWR cavities are horizontal. This position is not optimum for the helium cooling efficiency, but the analysis we made showed that the risk of limiting the cavity performances due to a poor cooling is negligible.

The vertical power couplers are below the cavities, letting a large volume available above the cavity for the cryogenic helium phases separator, and for the mechanisms of the tuning systems.

This configuration of the cold mass allows using a cylindrical vacuum tank 1.5 m in diameter. The total mass is about 10 tons.

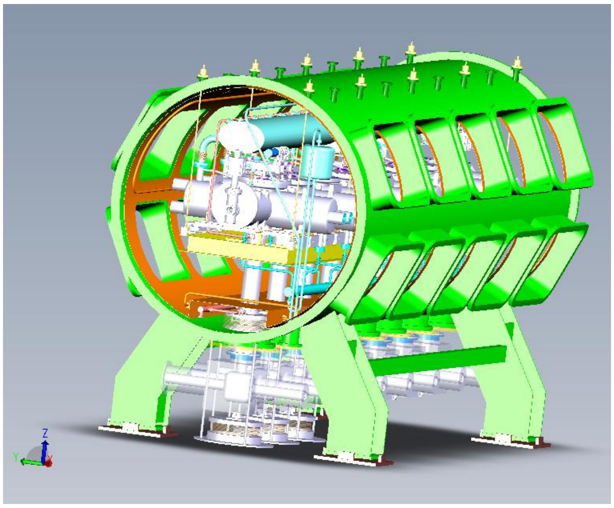

Figure 5: the cryomodule of IFMIF-EVEDA prototype LINAC.

Cavity and Tuning System

The nominal gradient for the IFMIF accelerator is quite conservative: 4.5 MV/m. The optimization of the HWR cavity design and of the plunger tuner (Figure 6) is detailed in [11].

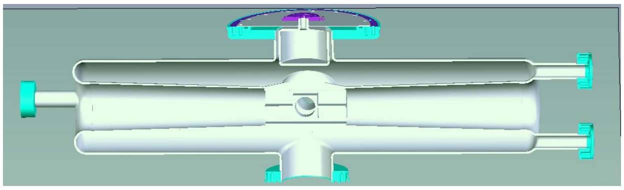

Figure 6: view of the IFMIF-EVEDA cavity equipped with the plunger tuner (upper port).

Epk / Eacc and Bpk / Eacc are respectively 4.42 and 10.12 mT/(MV/m). Due to the very low Q_{ext} value of the power coupler ($5.7\ 10^4$) the band width of the cavity is about 3 kHz. As a consequence, the detuning effects due to helium pressure variations (~ 0.04 Hz/mb), to the Lorentz force detuning ($1.1\ \mathrm{Hz/(MV/m)^2}$), and to the microphonics can be considered as negligible.

The helium vessel is made out of titanium. Two additional ports on both extremities of the cavity allow the chemical BCP treatment and high pressure rinsing. All the NbTi alloy flanges are tightened by Helicoflex gaskets.

The diameter of the cavity cylinder is 180mm. There are 4 large ports in the electric region of the accelerating gaps (Figure 6): the 2 beam ports (40 mm), the power coupler port (98 mm), and the capacitive tuner port (110 mm).

The standard way to tune the cavity by mechanical deformation was not chosen because of the lack of space along the beam axe inside the cryomodule. A mechanism strong enough to deform the very stiff cavity would have been too big.

The alternative solution we developed is based on the capacitive tuner already tested at Legnaro [12]. The plunger of the IFMIF cavity tuner (Figure 7) is a niobium cylindrical box. The geometry of the plunger tuner was optimized [11] in order to:

1. maximize the tuning range (without plastic deformation)
2. minimize the risk of multipacting
3. minimize the RF dissipations.

A flexible niobium sheet welded on the plunger allows for a large tuning range without plastic deformation (± 50MHz at 4K). This flexible sheet separates the cavity vacuum from the insulating vacuum. It is not welded on the cavity. It is mounted with a flange that allows dismounting it in order to change the geometry in case the previous one doesn't work as foreseen. 3D multipacting simulation has been performed to optimize the geometry and limit the risk of multipacting in this volume. The plunger itself is maintained at 4 K by liquid helium filling it. The niobium sheet is cooled by thermal conduction. The driving mechanism of the plunger is a double lever with a screw-nut system acted by a stepper motor with a gear box. It runs inside the vacuum tank and at 4K.

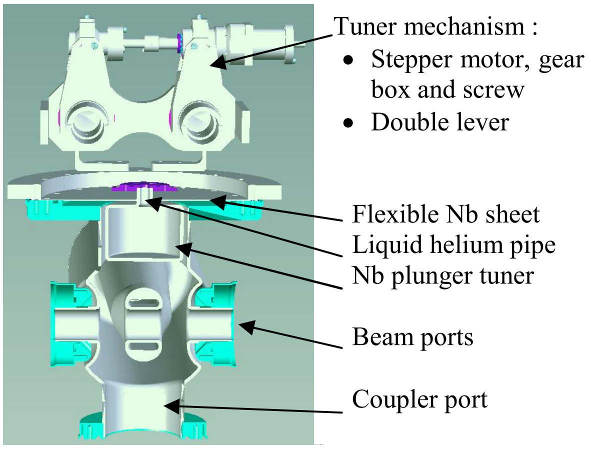

Figure 7: View of the cavity with the tuner.

Power Couplers

All the power couplers of the final IFMIF cryomodules [13] will be identical. They have to allow transferring a maximum RF power of 200 kW in CW to the beam loaded cavities (Figure 8).

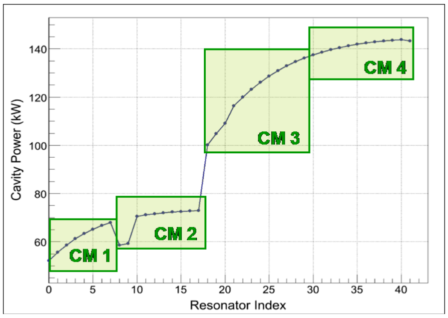

Figure 8: RF power transferred to the beam along the 4 IFMIF cryomodules.

The layout of the coupler is based on a ceramic disc coaxial window working at 300K and equipped with a copper antenna cooled by water circulating inside it. Polarisation of the antenna is not foreseen within the EVEDA phase, but is envisaged for the final IFMIF couplers. The diameter of the outer conductor is 98 mm, and that of the antenna is 42.6 mm is order to have the 50 Ω impedance. The rather low frequency allows an easy optimization of the ceramic window geometry in order to minimize the S_{11} parameter: $S_{11} < -50$ dB over a large frequency range from 0 to 230 MHz, and it is minimum at 175 MHz (Figure 9).

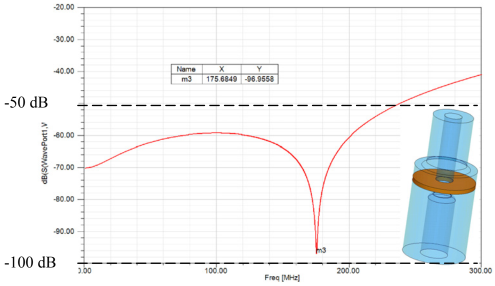

Figure 9: S_{11} parameter of the ceramic window.

The distance between the ceramic window and the cavity is an important parameter that allows minimizing the RF dissipations inside the ceramic in case of reflected power, and also minimizing the multipacting risks. Due to surrounding constraints the optimum distance (883 mm) is too long, and a compromise was chosen at 670 mm. Calculations showed the ceramic window placed at 670 mm from the cavity is free from multipactor for power values lower than 120 kW in transmitted waves.

The temperature gradient of the outer conductor is controlled by a helium gas flow circulating in a double wall chicane. This helium gas is injected at 4 K at the cavity flange and flows out at 300 K at the opposite extremity of the tube. If necessary, dry air at 300 K may be blown on the external surfaces of the ceramic in order to evacuate the heat due to RF dissipation inside it.

A T transition is mounted between the external coupler flange and the RF coaxial lines in order to allow the connexion of the water pipes cooling the antenna (Figure 10).

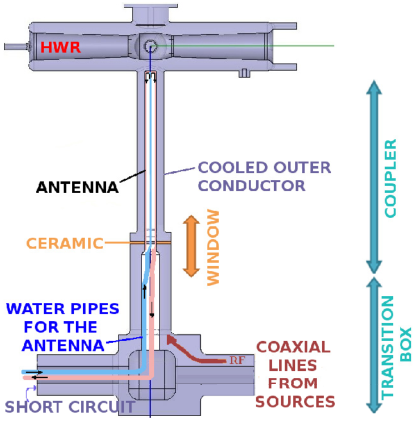

Figure 10: cavity – coupler – T transition assembly.

The Q_{ext} value is 5.7 10^4 for the EVEDA prototype accelerator.

Before being mounted on the cryomodule, all couplers will be conditioned up to a maximum power of 200kW on the test bench developed by CIEMAT.

Alignment Considerations

The cold mass is supported on a stainless steel frame fixed inside the vacuum tank by a series of rods (Figure 11).

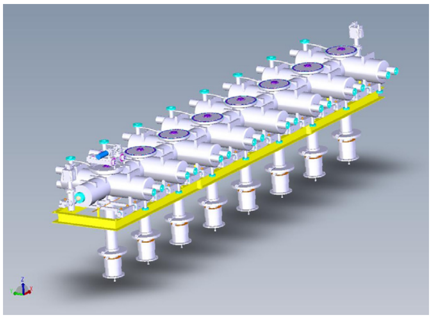

Figure 11: Cavities and solenoids on the support frame at the end of the assembling in clean room.

This support frame allows mounting the cavities and solenoids packages on it directly inside the clean room. Precise alignment of the cavities and of the solenoids packages as referenced to the frame can be performed during the clean room assembly. As the assembly will be definitely fixed on its support frame, only small adjustments of the component position are foreseen once the assembly is put out of the clean room.

The connexions between the components (cavities and solenoids) and the support frame are sliding systems that allow precise positioning. Two INVAR rods fixe the axial position of each cavity and solenoid during the cooling down. The principle of this system is comparable to the XFEL one. It lets the support frame to shrink by about 15 mm during cool down or warming up, while it minimizes the axial displacement of the power couplers.

Solenoid Package

The solenoid package (Figure 12) includes a superconducting solenoid for beam focusing, a normal conducting steerer (vertical + horizontal), a BPM, and microlosses detectors. This component is developed by CIEMAT. One of the main constraints is the axial length limited to 400 mm. The technical specifications are the following:

- Integrated on-axis field (solenoid): 1 T.m
- Steerers dipole field : 5 T
- Aperture: 50 mm
- Length (flange-to-flange): 400mm
- Fringe field at cavity flange: 20 mT
- Working temperature: 4.4K

The nominal current is 350A for the solenoid and 100A for the steerer. A passive shielding is foreseen.

Frozen flux that can appear during the ramp up and down of the solenoid current may cause significant reduction of the cavities performances. One has to take into account the experience of TRIUMF/ISAC [14] in order to reduce to the impact of this phenomenon.

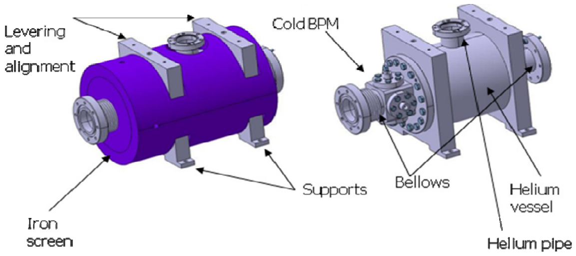

Figure 12: The solenoid package.

Cryogenic System

The cavities and the superconducting solenoids are cooled by liquid helium at 4.4 K and 0.12 MPa. Separated tanks around each cavity and each solenoid package allow an easy assembly and reduce the helium inventory.

The main coupler jackets (outer conductor) need a dedicated 4-300 K cooling circuit to absorb the RF heat losses between 4.4 K and 300 K,

The current leads of the solenoids are vapour cooled between 4.4 K and 300 K,

No cold valve is located inside the cryomodule. A permanent circulation of liquid is maintained inside the cavity helium tank during the nominal operation to insure a constant level of liquid in the upper phase separator. This principle limits the number of circuit inside the cryostat. However it needs small phase separator at the entrance of liquid helium in the cryostat able to recover the gas created during the path of liquid in the main transfer line between the LHe Dewar and the cryostat. This cold gas is exhausted from the cryostat and its flow is regulated to maintain a constant level of liquid in this separator; the liquid coming from the low part of this separator is sent to the inlet pipe of the cold mass.

Cavities and solenoids will be cooled by two different circuits. This option allows cooling down or warming up the cavities and the solenoids independently. This configuration is needed to allow minimizing the effect of the frozen flux [14].

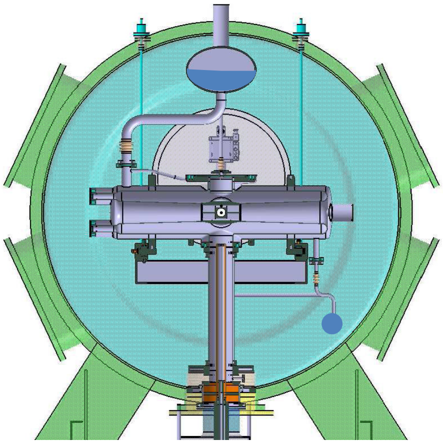

Figure 13: cross view of the cavity and of the main phase separator.

The estimated static losses are 18 W at 4.4 K, and dynamic losses are about 55 W (~7 W per cavity at 4.5 MV/m).

RF Power Tests at Saclay

A dedicated RF test stand is going to be installed at Saclay. It will be equipped with a RF power system (P_{max}=230kW in CW) and the liquefier of the SupraTech area is able to deliver 100W of liquid helium at 4K.

Future Plan

The order of two cavities has been launched. These cavities will be delivered in May 2010. Tests will be performed in vertical cryostat with and without the plunger tuner in order to validate the cavity design and that of the innovating tuning system before launching the series of cavities. The mechanical study of the equipments for performing the chemical treatment and the High Pressure Rinsing in clean room is in progress.

The order for the study and the manufacturing of the power couplers is going to be launched. Due to the tight schedule of the EVEDA project, the series of power couplers will be manufactured before the first two couplers are conditioned at CIEMAT.

The complete cryomodule will be tested at Saclay before being sent to Rokkasho in 2013.

CONCLUSION

After all components are validated in the different laboratories in Europe, they will be sent to Japan and the prototype accelerator will begin to be installed in the vault of the Rokkasho building (Figure 1) in 2013 in order to operate the commissioning with deuteron beam in December 2013.

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