DEVELOPMENT OF THE IFMIF/EVEDA ACCELERATOR

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Abstract

With the aim of producing an intense flux of 14 MeV neutrons, the International Fusion Materials Irradiation Facility (IFMIF) relies on two high power CW accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV to a common lithium target. The Engineering Validation and Engineering Design Activities (EVEDA) phase of IFMIF, which has been launched in the middle of 2007, has two major objectives: to produce the detailed design of the entire IFMIF facility and to build and test the key systems, in particular the prototype of a high-intensity CW deuteron accelerator (125 mA @ 9 MeV). The design of the IFMIF accelerator, as well as the design of the prototype to be installed in Rokkasho (Japan) are presented.

INTRODUCTION

The IFMIF accelerator consists of two high power linacs, each delivering 125 mA deuteron beams at the energy of 40 MeV to the common lithium target. The Engineering Validation and Engineering Design Activities (EVEDA), launched in the framework of a bilateral agreement between Euratom and the Government of Japan in the middle of 2007 aims at producing the detailed design file enabling the further construction of IFMIF, as well as the construction and test at full current of the low energy part of one accelerator at Rokkasho in Japan. The components of the prototype accelerator are provided by European institutions (CEA, INFN, CIEMAT, SCK-CEN): the injector, the RFQ, the transport line to the 1.2 MW beam dump, the 175 MHz RF systems, the matching section and the DTL, the local control systems and the beam instrumentation. The building constructed at Rokkasho Broader Approach site (Japan), the supervision of the accelerator control system, as well as the RFQ couplers, are provided by JAEA. From the IFMIF Conceptual Design Report [1], technical updates have been brought in order to optimise the design of the entire linac [2]: in addition to the RFQ, which looks now shorter, the major change is the switch from the room temperature DTL to superconducting technology for the high energy portion of the linac, resulting in a complete redesign of the RF system.

INJECTOR

The injector has to deliver a 140 mA, low emittance deuteron beam with high reliability. An ECR type (Electron Cyclotron Resonance) ion source has been selected owing to its intrinsic high efficiency, high availability and limitless lifetime. Starting from the SILHI source, developed at CEA-Saclay, with a frequency of 2.45 GHz at 875 Gauss, the extracted energy has been increased from 95 keV to 100 keV and the extracted intensity from 150 mA to 175 mA in order to meet the 140 mA deuteron current requirement (26 mA D_2^+, 9 mA D_3^+). Simulations have been carried out to optimize the electrode number, electrode shape, aperture diameter and to minimize the electric field which has been has been kept around 100 kV/cm. The design of the Low Energy Beam Transport (LEBT) is based on a dual solenoid focusing scheme. The total length was minimized to about 2 m in order to restrain the beam emittance growth. Figure 1 shows the injection cone at the LEBT-RFQ interface including an electron repeller in order to extend the compensation zone up to the RFQ entrance.

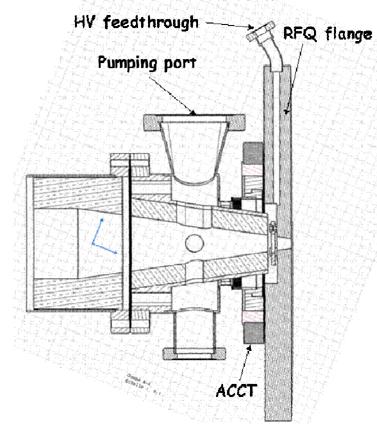

Figure 1: Injection cone at the LEBT-RFQ interface.

In order to assess properly the local space charge compensation of the beam induced by the ionisation of the residual gas, a 3D particle-in-cell code (SOLMAXP) has been developed. Back and forth calculations between the TRACEWIN code and the SOLMAXP code [3] were then carried out to optimize the LEBT parameters. The emittance at the RFQ entrance could meet the requirement (0.25 π.mm.mrad for the total current of 175 mA) provided that krypton gas is injected in addition to deuterium in order to better compensate the space charge effect (P_{D2} = 1.10^{-5} hPa, P_{Kr} = 4.10^{-5} hPa). The beam matching conditions (Twiss parameters) to the RFQ entrance could also be achieved and correspond to the maximal beam transmission through the RFQ. The beam transport from the ion source to the RFQ entrance is shown on Figure 2. The two solenoids (in red) and the electron repeller are also drawn.

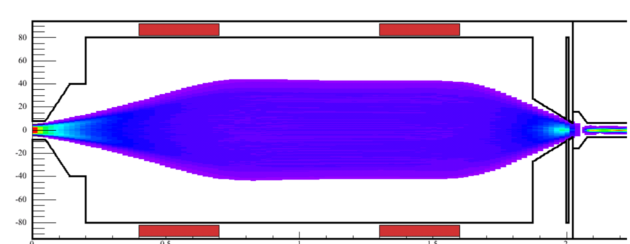

Figure 2: Beam density plot from the ion source (plasma electrode) to the RFQ entrance (first cells).

RADIOFREQUENCY QUADRUPOLE

The RFQ has to bunch the dc beam from the injector and to accelerate the beam from 100 keV to 5 MeV. It is a four vane structure and is developed by INFN. The optimisation of the 175 MHz RFQ [4] resulted in reduced length (9.8 m) and power consumption, with minimal beam losses at high energy (above 1 MeV).

Table 1: Main RFQ parameters.

Particles	D+	
Frequency	175	MHz
Input current	130	mA
Input emittance	0.25	π.mm.mrad
Max Surface field	25.6	MV/m
Length	9.78	m
Voltage min/max	79/132	kV
R0 min/max	4.1/7.1	mm
Transmission (Gaussian)	96	%
Power dissipation in Cu	< 650	kW

The use of an analytic law for the voltage V(z) resulted in a smooth increase of the voltage in the accelerator section and a continuous cut-off frequency range. A minimal physical aperture "a" at the end of the gentle buncher plays the role of beam collimator, thus scraping the particles not well bunched and close to the vane tips, while the parameters are left unchanged in the accelerator section, thus avoiding losses at high energy. The peak surface electric field is limited to the reasonable value of 1.8 x Kilpatrick's criterion. The resulting parameters, modulation, vane voltage, average aperture and physical aperture along the RFQ are plotted in Figure 3.

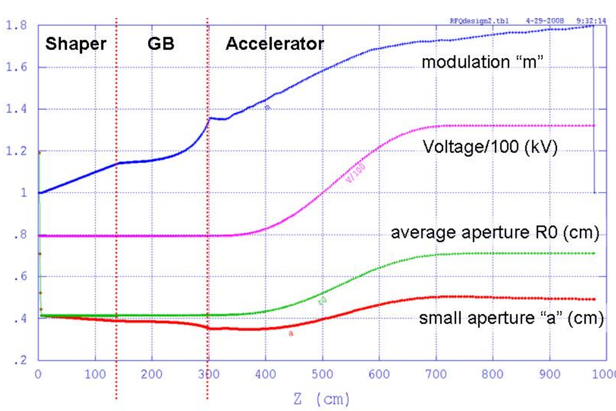

Figure 3: Main parameters along the RFQ.

As activation of the RFQ cavity is of main concern for maintenance, extensive multi-particle simulations [4] have been performed to evaluate the loss of particles along the RFQ. Assuming an input beam of 0.25 π.mm.mrad rms emittance with waterbag distribution, the transmission is about 98.5% and the losses above 1 MeV are kept at a very low level. Any deviation from these ideal conditions will increase the losses in the RFQ and spoil the emittance. If one consider for example an input beam, of Gaussian distribution and 20% larger in emittance, the transmission drops to 92%, still acceptable. The Figure 4 shows for example the effects of input beam current on transmission and loss for two different beam distribution (waterbag and Gaussian). The transmission is nearly 100 % up to 50 mA and is still above 90 % up to 160 mA input beam current.

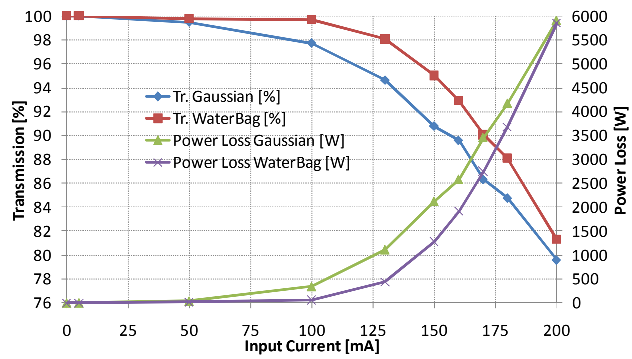

Figure 4: RFQ transmission and power loss as a function of input current for waterbag and Gaussian distributions.

An overall view of the RFQ with the location of the RF couplers and vacuum ports is shown in Figure 5. Although it offers a lower stiffness under vacuum, a square transversal section instead of circular shape was chosen because it presents some advantages, as a lower total amount of required RF power, large free surfaces for the positioning of all vacuum lines and tuning plungers, reduced request of raw material to obtain the final shape of the components. The structure is made of 9 modules of 1.1 m each. The brazing technique has been chosen for the assembling of the different modules [5]. The total RF power required is about 1.6 MW and will be delivered by eight 200 kW RF power sources. Field stability should be provided by segmentation and finger dipole correctors. However, since simulations do not show a large gain from segmentation, the tuning algorithms will be tested on a full scale cold model in aluminium, for both segmented and un-segmented resonators.

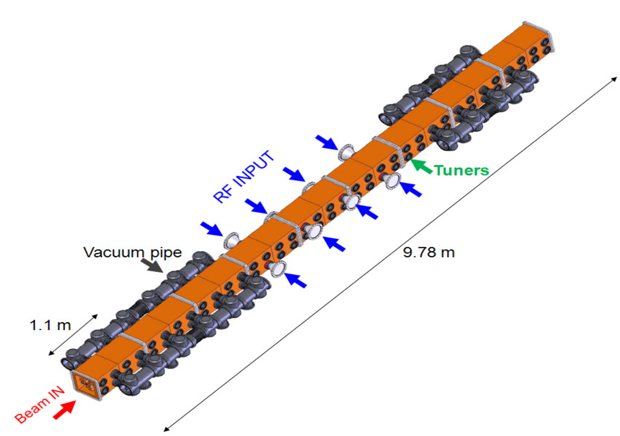

Figure 5: Schematic view of the RFQ.

DRIFT TUBE LINAC

The proposal, based on Half Wave Resonators (HWR) and close to existing and widely used technology, was finally selected for the EVEDA phase in 2008. The baseline design is the result of a conservative approach for both resonators and focusing lattice. Four cryomodules for an overall length of 22 m housing a total of 42 resonators are used to cover the acceleration from 5 MeV to the final energy 40 MeV. Table 2 lists the main parameters of the HWR Linac and Figure 6 shows an overview of the present EVEDA cryomodule design.

Table 2: Main parameters of the HWR Linac.

Cryomodule	1	2	3 & 4
Cavity geometric β	0.094	0.094	0.166
Cavity length (mm)	180	180	280
Beam aperture (mm)	40	40	48
Nb cavities / period	1	2	3
Nb cavities / cryostat	1 x 8	2 x 5	3 x 4
Nb solenoids	8	5	4
Cryostat length (mm)	4.64	4.30	6.03
Output energy (MeV)	9	14.5	26 – 40

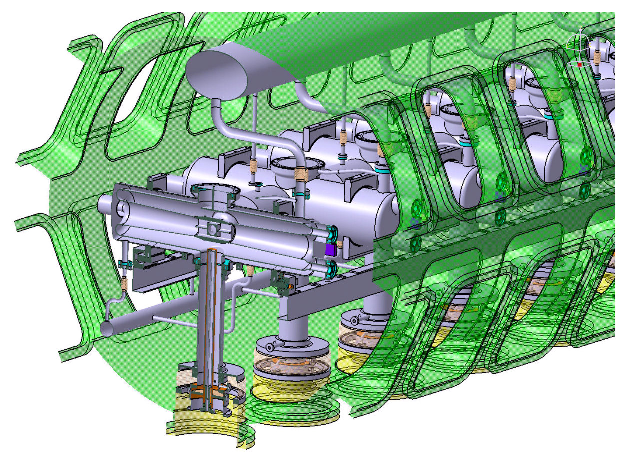

Figure 6: Overview of the EVEDA cryomodule.

Beam dynamics results

Particle tracking simulations [2] have shown that the HWR scheme can sustain very conservative alignment and field errors, up to 1 mm misalignment and 10 mrad solenoid tilt while keeping a large safety margin between the beam occupancy and the pipe aperture. The beam orbit correction relies on beam position monitors and steering coils located at the solenoid package. A new design of the MEBT, composed of 2 buncher cavities and 5 quadrupoles enabled a much better matching of the beam coming from the RFQ to the entrance of the HWR-Linac. Numerical simulations [6] with real 3D field maps (for solenoid and cavity), including this new Matching Section were then carried out on the overall HWR-Linac in order to optimise the global focusing scheme and the matching between sections. The beam phase space distribution at the exit of the linac is shown in Figure 7. Simulations with conservative errors over 200 linacs showed that the beam occupancy, ratio of the beam external edge to the vacuum chamber size, keeps a reasonable safety margin of 70 % (Figure 8).

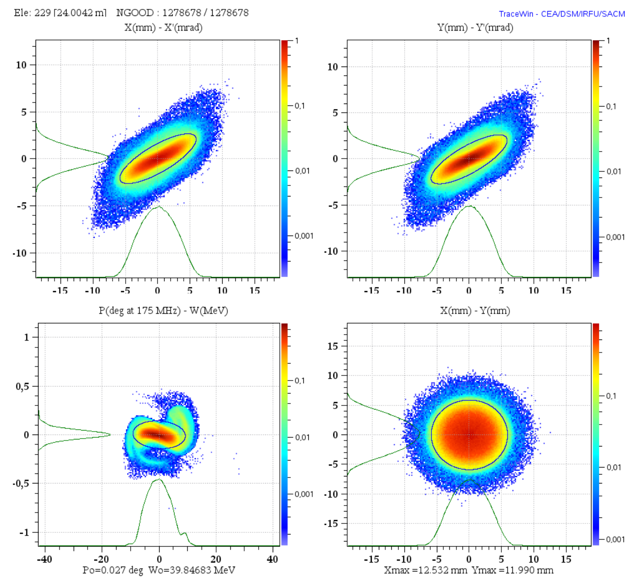

Figure 7: Beam space phase distribution at linac exit.

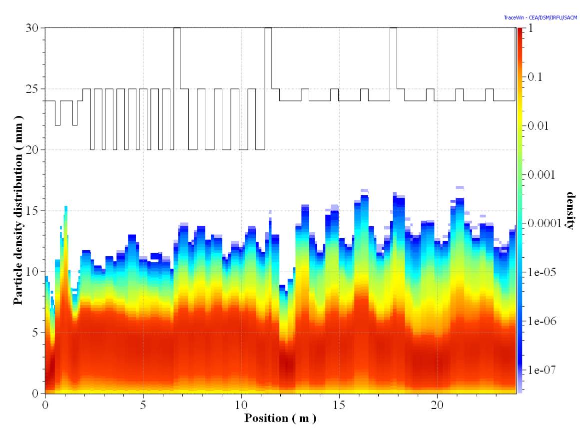

Figure 8: Probability density of beam occupancy calculated over 200 linacs with errors.

Cavity and coupler RF design

The peak surface electrical and magnetic fields have been first minimized [7]. For the first cavity family, the peak surface fields obtained after optimisation are low Epk/Eacc < 4.4, Bpk/Eacc < 10.1 mT/(MV/m). The cavity structural design also minimizes the resonant frequency dependence to external pressure fluctuations. Concerning the cavity frequency tuning system, few options were investigated [7]. The capacitive tuner, opposite to the coupler port, was finally selected since the required frequency tuning range (±0.05 MHz) can be easily achieved, without significant increase of Epk/Eacc.

The power couplers are designed for a capability of 200 kW in continuous wave (only 70 kW in EVEDA case). The position of the coupler is proposed to be vertical; thus the risk of window breaking due to strong forces applied to the junction antenna-window is minimized. In ordert to achieve the required Qext = 5.7x10^4, the coupler is at the beam gap level. The inner conductor will be cooled by water while the external conductor (warm part) will be cooled with forced air to reduce the temperature gradient in the ceramic. The cooling to 4 K will be provided by the circulation of LHe in a double wall cylinder.

RF POWER SYSTEM

Following the change from normal to superconducting DTL, the RF Power System of IFMIF [8] is now based on smaller and conventional power units using tetrodes: 18 units of 105 kW and 24 units of 220 kW. As a positive side effect, these 220 kW units will also be used for the RFQ, standardizing the whole accelerator. In addition, the same RF chain is used for all power sources, only the high voltage power supply changes: one 400 kW HVPS feeds one 220 kW RF amplifier or two 105 kW RF amplifiers. The RF needs for the IFMIF/EVEDA accelerator, which includes only one cryomodule is shown on Figure 9.

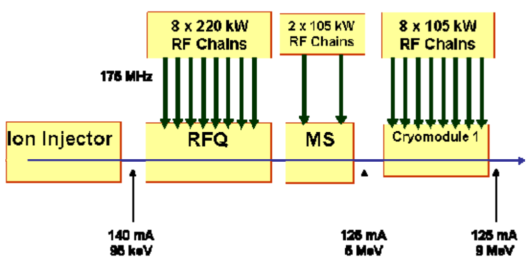

Figure 9: RF power stations for the prototype accelerator.

Though the CW mode will be the normal operation, the start-up and commissioning phases foresee the pulsed operation, beginning with low power and low duty factor and finally switching to CW by extending the pulse length (repetition rate from 1 to 100 Hz, pulse width from 100µs to CW). The stability requirement are 1 % in amplitude and ± 1° in phase. The switch off time should be lower than 10 µs on interlock request. The Low Level RF system will be based on digital technology embedded on a cPCI board. In order to optimize space, maintenance and availability, a symmetric modular system, composed of removable modules with 2 complete RF chains each, is under study (Figure 10).

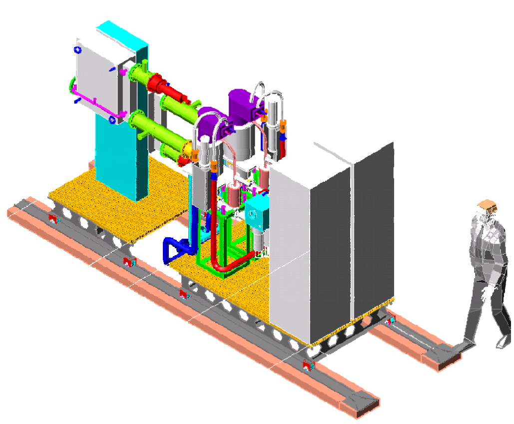

Figure 10: Removable RF power module.

PROTOTYPE ACCELERATOR

In order to test and to validate the technical options, the prototype accelerator is identical to one IFMIF accelerator running at full beam current (125 mA) but the high energy portion includes only the first cryomodule, resulting in the lower output energy of 9 MeV. It will comprise the ion source and LEBT, the RFQ, the matching section and the DTL, the transport line to a 1.2 MW beam dump, as well as the 175 MHz RF system and the beam instrumentation, required for the tuning, commissioning, operation. The layout of the prototype accelerator integrated in the IFMIF/EVEDA accelerator building of the Rokkasho BA site is shown in Figure 11. The figure shows also the implementation of the high voltage power supplies and RF amplifiers of the RF Power system, the cryogenic plant and the water cooling circuits.

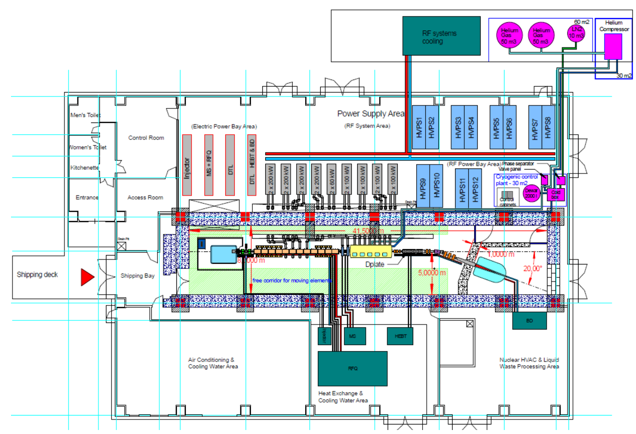

Figure 11: Layout of the prototype accelerator in the IFMIF/EVEDA accelerator building.

HEBT and beam dump

The High Energy Beam Transport [9] of the prototype accelerator has to transfer the beam to the beam dump with the required beam spot (rms size of 40 mm rms divergence of 16 mrad) while enabling the full beam characterization by means of the so-called Diagnostics Plate (Figure 12). A first triplet focuses the beam through the 3 m diagnostics plate; a doublet is able to compensate the variations of the first triplet during the emittance measurement with the quad-scan method; a bending magnet (angle 20°) prevents neutron from streaming back into the accelerator and can be used as spectrometer for the energy spread measurement; the last triplet expands the beam towards the downstream beam dump.

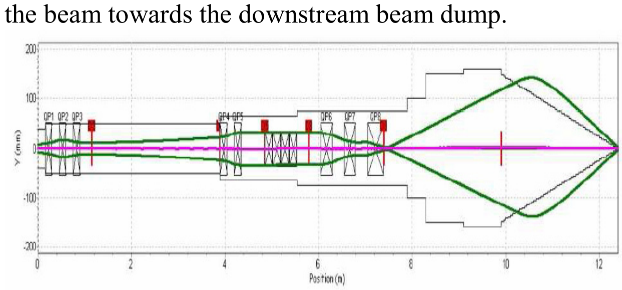

Figure 12: Layout of the HEBT of the P.A.

The EVEDA beam dump has to stop deuteron beams with a maximum power of 1.125 MW. Figure 13 shows the profile of the beam power deposition on the wall facing material. The conceptual design for the IFMIF-EVEDA accelerator beam dump (Figure 14) is based on a conical beam stop (2.5 m length, 30 cm diameter) plus a cylindrical beam scraper. The cooling system is based on an axial high velocity flow of water. The choices of material (Cu) and thickness (5 mm) result from thermo-mechanical optimisation [10].

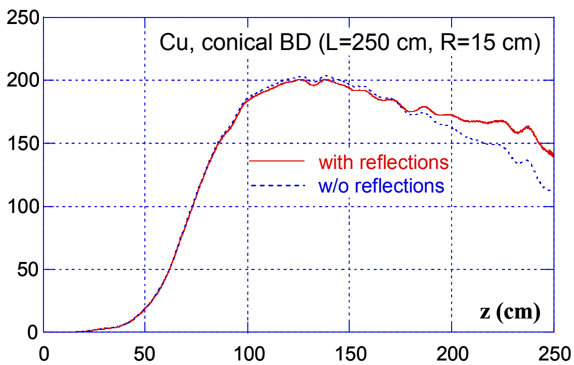

Figure 13: Power density at BD surface (W/cm^2).

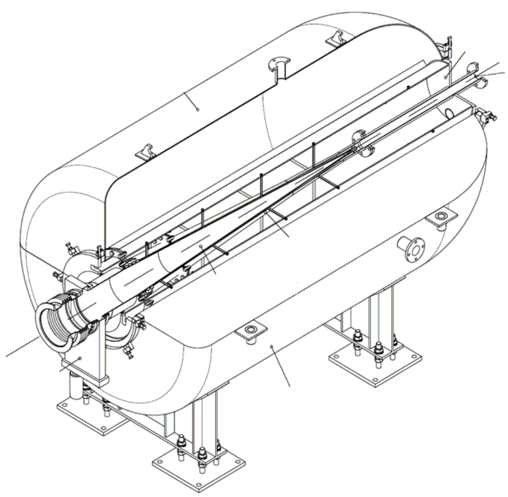

Figure 14: Mechanical design of the beam dump.

Diagnostics

Beam instrumentation is essential to tune the linac and monitor the beam from the ion source to the beam dump, to minimize the beam loss and to characterize the beam properties [11]. A complete set of diagnostics will be also implemented at the exit of the HWR Linac on the Diagnostics Plate, for the measurement of the main beam parameters [12]: current, phase, position, transverse profile, energy, transverse halo, transverse emittance and longitudinal profile. Non interceptive transverse profile monitors, based on fluorescence and ionization of the residual gas, are specially developed for the prototype accelerator [13] and will be the first step towards the IFMIF diagnostics, required for the beam profile monitoring in front of the IFMIF target.

CONCLUSION

One year after the start of the project, substantial technical updates have been brought in order to optimise the design of the entire linac. The beam dynamics studies, even if they are far from being completed (next steps: end-to-end simulations with errors, beam tuning strategy, analysis of the IFMIF HEBT line, etc), have shown that the full beam can be accelerated at the final energy with reasonable emittance growth and beam loss.

In addition to the RFQ, which looks now shorter and less prone to beam loss, the major change is the switch from the room temperature DTL to superconducting technology for the high energy portion of the linac and a linked complete redesign of the RF system. In addition, preliminary designs of most of the components of the prototype accelerator have been drawn up (the injector, the RFQ, the cryomodule, the beam dump, and part of the RF power system) and will enter very soon into the manufacturing phase.

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