BEAM DYNAMICS DESIGN OF ESS WARM LINAC

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Abstract

In the present design of the European Spallation Source (ESS) accelerator, the Warm Linac will accelerate a pulsed proton beam of 50 mA peak current from source at 0.075 MeV up to 80 MeV. Such Linac is designed to operate at 352.2 MHz, with a duty cycle of 4% (3 ms pulse length, 14 Hz repetition period). In this paper the main design choices and the beam dynamics studies for the source up to the end of DTL are shown.

INTRODUCTION

The ESS, going to be built at Lund, will require a high current linac to accelerate protons for the spallation process on which high flux of pulsed neutrons will be generated. The accelerator is 5 MW superconducting proton linac delivering beams of 2.5 GeV to the target in pulses of 2.86 ms long with a repetition rate of 14 Hz [1]. Beam current is 50 mA, 4% duty cycle, which at 352.21 MHz is equivalent to ~ 9×10^8 protons per bunch.

Both hands on maintenance and machine protection set a strict limit on beam losses and have been a concern in every high power linac: Therefore it is crucial, especially for high power accelerators, to design a linac which does not excite particles to beam halo and also minimizes emittance growth. The ESS linac is carefully designed to minimize such effects all along the linac and transfer lines.

In this paper the physical design of ESS warm linac is shown.

SOURCE AND LEBT

ESS requirements for proton source are quite restrictive, the current required for the ESS facility in the baseline configuration can be satisfied by means of conventional Microwave Discharge Ion Source (MDIS), based on the plasma direct absorption of the pumping electromagnetic waves through the Electron Cyclotron Resonance mechanism.

Considering the experience gained with the already designed and optimized sources at INFN-LNS, the needs of the initial phase of the facility will be fulfilled by using a "conservative" approach, based on a standard MDIS configuration. The second phase requirements are more stringent in terms of currents (up to 90 mA or more), but possible solutions for the source upgrading have been considered already in the design phase, by proposing a new flexible magnetic system. More standard solutions for performance optimization (which do not require any ab-initio design modification) will be implemented, as the alumina tubes introduced into the plasma chamber. Therefore we will not only take care about currents, emittance, efficiency and reliability requirements, but also to a continuous MDIS development [2].

In low energy beam transport of high intensity beams the self-generated repulsion between charged particles can generate a large and irreversible emittance growth, while the optimum matching with the RFQ requires high focussing and low emittance. To reduce this negative effect the space charge neutralization of the beam charge can be done by ionizing the residual gas. Such space charge compensation regime has many similarities to plasma but the electric field produced for example by the pre-chopper introduces many significant variations especially in the transition regimes. In order to preserve the compensation regime from the high electric field located in the extraction system and inside RFQ, a repelling electrode was inserted in the extraction system and in the RFQ collimator. Then, to reduce the longitudinal dimension of the LEBT and to keep free space for the installation of diagnostics, we designed the chopper chamber coupled to the Turbo molecular Pump (TMP) as shown in Fig. 1.

The extraction system has been simulated with AXCEL and the emittance parameters at the position z = 0.14 m has been used as input for the simulation of the LEBT by using the TraceWin code. This software has been chosen because it is able to take into account of space charge along the LEBT and it is able to perform the optimization of the optical element parameters so that we may achieve the RFQ Twiss parameters. Figure 2 shows the beam density obtained in the LEBT by using a space charge compensation value of 98% [3].

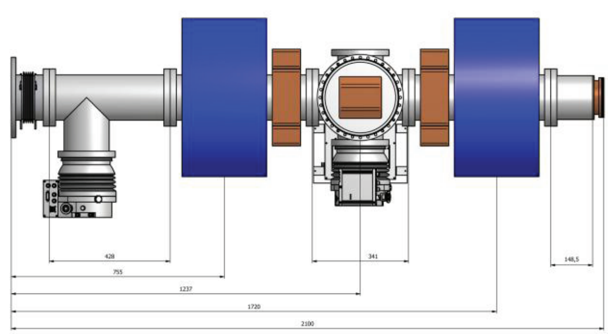

Figure 1: LEBT layout.

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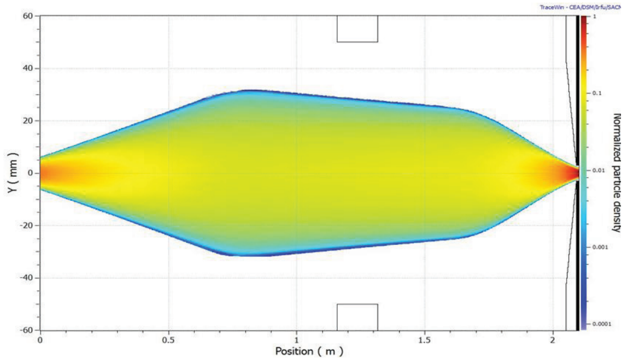

Figure 2: Beam density in the Y plane along the LEBT.

RFQ

In the linac front-end the RFQ will bunch, focus and accelerate the beam from 75 keV to 3 MeV. The design is with a 4-vane RFQ composed of 4 segments of 1 m each.

In the RFQ the limit on low energy particle losses, less than 3 MeV, is relaxed and the halo development and beam loss in the high energy linac section traceable to the RFQ are minimized. The RFQ is without tails in the longitudinal phase space as they are known to translate into transverse halo. The initial and final phase advances per meter are matched to adjacent linac sections. The accelerated particles are in the order of 98%, with an RMS longitudinal emittance of 0.13 degMeV [4].

The evolution of several parameters within the RFQ is shown in Fig. 3. The longitudinal phase space at the RFQ exit is shown in Fig. 4.

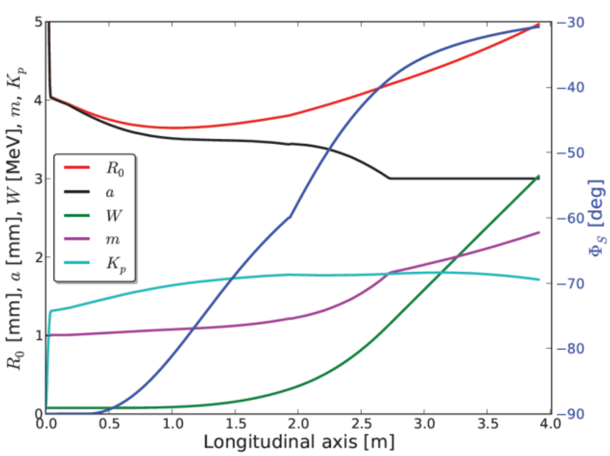

Figure 3: Main parameters evolution within the RFQ.

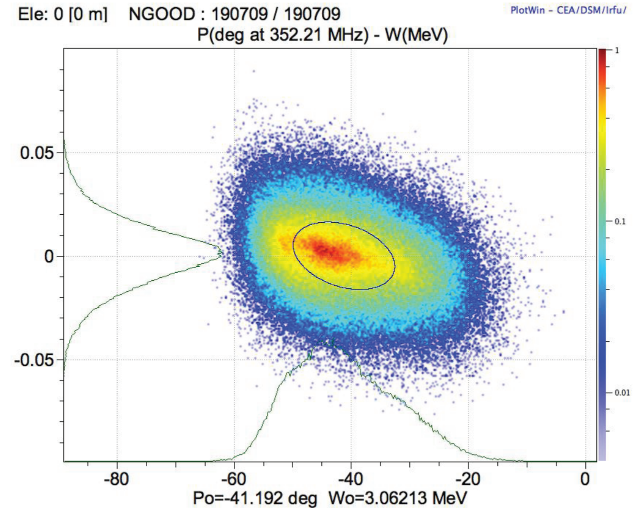

Figure 4: Longitudinal phase space at the RFQ exit.

MEBT

The major challenge of this part of the accelerator is to maintain the beam quality, low emittance and minimized halo, to limit the beam losses downstream the linac and maximize the ESS reliability. The considered versatile MEBT is designed to contain a chopper and its correspondent beam dump that could serve in the commissioning as well as in the ramp up phases, in the MEBT it is necessary also to measure the beam phase and profile between the RFQ and the DTL, along with other beam properties. The main goal of the MEBT is to match the RFQ output beam to the DTL in all the three planes. For this purpose, a set of ten quadrupoles is used to match the beam characteristics transversally, combined with three 352.21 MHz buncher cavities, which are used to adjust the beam in order to fulfil the required longitudinal parameters. With these objectives in the May 2012 baseline, the MEBT was extended from ~1.2 m to ~3.5 m (Fig. 5).

Due to concern with the shape of the output properties distribution, the MEBT has been modified and the configuration with better beam dynamics property was found. It was seen that the modified MEBT improves the beam dynamics throughout the linac.

Following the SNS experience, the MEBT collimation scheme has been studied. It is observed that the collimators could reduce the halo throughout the linac but their influence on the loss in the SC section hasn't been clarified yet. Due to the strong space charge force, the collimators do not work efficiently and the locations of the collimators must be determined by observing the evolution of the beam distribution in a great detail. Because the ideal locations highly depend on beam dynamics in the MEBT, upon making a decision of the final layout, a study must be done with a more realistic beam distribution going into the MEBT, based on a realistic estimation of the beam distribution coming out of the ion source [5].

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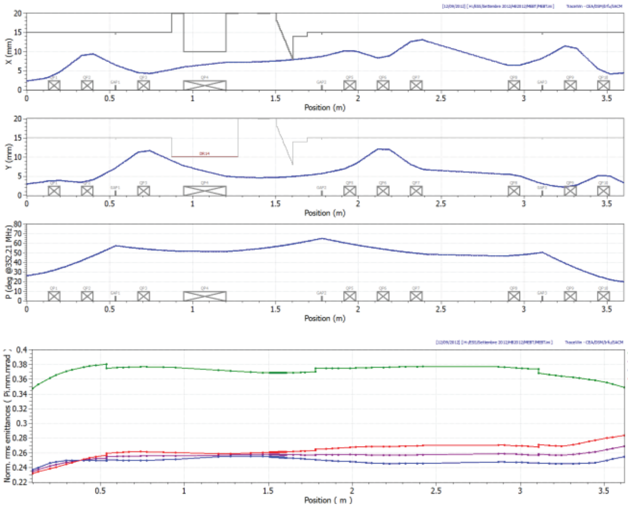

Figure 5: MEBT Layout and emittance evolution.

DTL

The design is done by respecting practical technology limits and by avoiding losses along the DTL structure. The maximum RF power per tank is fixed at 2.15 MW. The surface electric field limit is 1.4 Kilpatrick, to avoid sparking, especially at the first DTL cells, due to the contemporaneity presence of electric and static magnetic fields, see Fig. 6.

The tank length is limited at 8 meters (9.3 λ), to avoid stability problem on the voltage RF design. The total number of tanks is 4, to reduce the global RF power needed. The DTL beam bore radius is increased along the DTL to avoid losses; the main parameters are reported in table 1. The optimized solution has been found by using GenDTL, from the CEA suit of codes.

A FODO channel using Permanent Magnet Quadrupoles is used for transverse focusing, i.e., with half of the drift tubes with empty space, in this way it is possible to allocate diagnostics and steeres inside the empty drift tubes. The values of the magnets permit an equipartitioned beam evolution as reported in Fig. 7, and a good phase advance matching with the RFQ at low energy and with the SC linac at high energy. The magnets range is from 70 to 30 T/m. The particles density in the DTL is shown in Fig. 8, and the layout of the DTL in Fig. 9 [6].

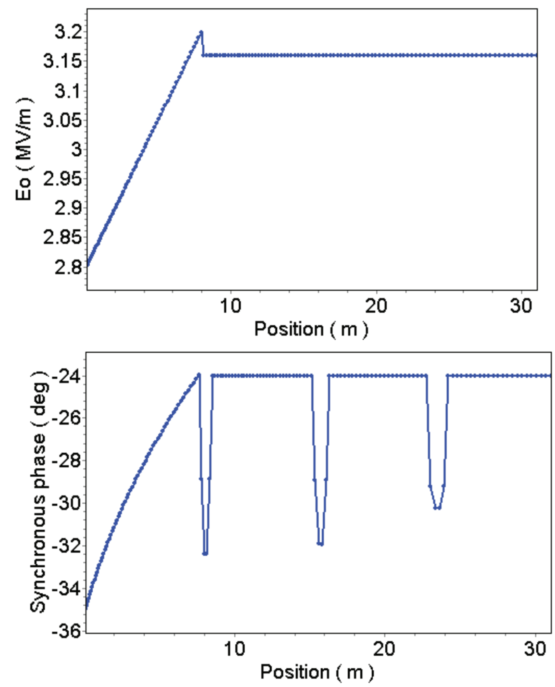

Figure 6: Design E0 and synchronous phase, along the DTL.

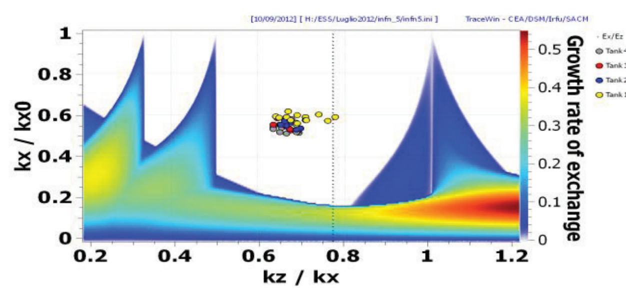

Figure 7: Stability plot for the DTL.

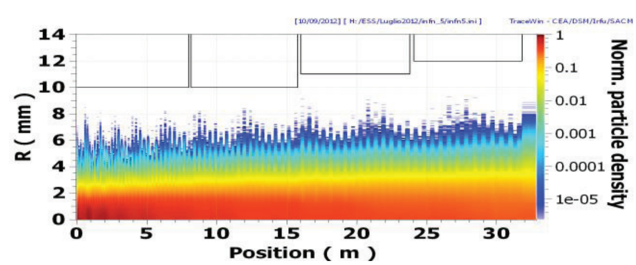

Figure 8: Particles density along the DTL.

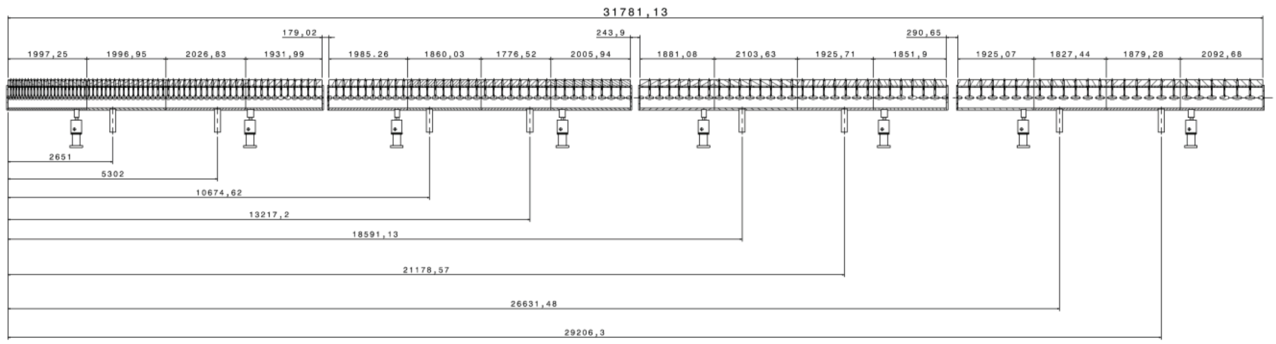

Figure 9: DTL overview.

Table 1: Summary of DTL Tank Properties

Parameter/Tank	1	2	3	4
Cells	66	36	29	25
E0 [MV/m]	2.8, 3.2	3.16	3.16	3.16
E_{Max}/Ek	1.4	1.43	1.39	1.37
ϕs [deg]	-35, -24	-24	-24	-24
L_{Tank} [m]	7.95	7.62	7.76	7.72
Bore Radius (mm)	10	10	11	12
Post Couplers	22	23	28	24
Tuning [MHz]	±0.5	±0.5	±0.5	±0.5
Tuners	24	24	24	24
Q0 (SF)	53000	56000	55000	55000
Modules	4	4	4	4
Peak P_{cu} [MW]	0.91	0.91	0.92	0.95
E_{OUT} [MeV]	21.4	41.0	60.0	77.7
P_{TOT} [MW]	2.06	2.12	2.10	2.07

CONCLUSION

Integrating the beam dynamics design of the warm linac, as one structure, have significantly improved the beam quality along the linac. The general rules used are:

- Smooth variation of the phase advance between sections.
- Equipartitioning law in the DTL, to avoid emittance exchange phenomena.
- Check the Halo formation and development from the RFQ up to the target.
- Use of collimators in the MEBT.
- Avoid tune depression below 0.4.

By using these laws, the design is more robust and less sensitive to any source of errors.

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