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PRELIMINARY STUDY ON THE POSSIBLE USE OF SUPERCONDUCTING HALF-WAVE RESONATORS IN THE IFMIF LINAC

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Abstract

The driver of the International Fusion Materials Irradiation Facility (IFMIF) consists of two 125 mA, 40 MeV cw deuteron linacs, providing a total of 10 MW beam power to the liquid lithium target. A superconducting (SC) solution for the 5 to 40 MeV accelerator portion could offer some advantages compared with the copper Alvarez-type Drift Tube Linac reference design: linac length reduction and significant plug power saving. A SC scheme, based on multi-gap CH-structures has been proposed by IAP in Frankfurt [1]. Another SC scheme, using half-wave resonators (HWR), which are in an advanced stage of development at different places [2,3,4], would allow a shorter focusing lattice, resulting in a safe beam transportation with minimal beam loss. In order to investigate the feasibility of the superconducting HWR option, faced with the very high space charge regime of the IFMIF linac, beam dynamics calculations have been performed. This paper presents an optimized linac layout, together with extensive multi-particle simulations including various field and alignment errors.

INTRODUCTION

New projects of high intensity radioactive beam facilities, at design stage or under construction [5,6] have chosen superconducting low-β coaxial-type resonators. Though the space charge forces are not as strong as in the IFMIF linacs, these projects aim at accelerating relatively high beam currents, of the order of a few mA. The goal of this study is to assess the capability of such superconducting linacs to accelerate deuteron beams at much higher currents, as high as the 125 mA design value of IFMIF. In that case, as only deuteron beams are required, the property of such independetly phased 2-gap resonators to accelerate different ion species and charge-to-mass ratios, due to their large velocity acceptance, is not really used. However, as these 2-gap cavities allow short focusing lattices, they could potentially accelerate ion beams of high intensity without phase space distortion or beam loss. Though they provide a lower real-estate accelerating gradient than multi-gap cavities, like the CH-structures [1], the plug power saving is about the same.

For this preliminary feasibility study, the selected coaxial-type structure was the HWR instead of the QWR for the following reasons:

- Unlike the QWR, they do not present a beam steering effect thanks to a better field symmetry in the beam axis region;
- the implementation of a coupler, with a strong cavity-coupling and able to transfer a very high rf power, should be easier;
- the beam aperture in the drift tube should be larger while keeping a moderate electric field.

LINAC LAYOUT

The linac consists of a sequence of 176 MHz HWR resonators and focusing magnets.

Resonators

The acceleration of high-intensity beams push for both large beam pipe aperture and conservative accelerating field, in order to prevent any beam loss and to restrict the demands on the rf power of the input coupler. It is worth noting that a bigger aperture leads to a larger peak-to-accelerating fields ratio and then inclines to decrease the accelerating gradient as well, in order to keep the peak surface field at an acceptable magnitude.

Instead of typical 30 mm aperture and 5-6 MV/m gradient for this type of resonator, a lower gradient at 4.5 MV/m and larger apertures in the 40-50 mm range (depending on the cavity-β) were chosen. As a result, the peak surface fields are much lower than the ones that can be achieved today (Epk < 40 MV/m, Bpk < 80 mT) without too much effort by using well-tried methods developed in the last ten years, such as high-pressure rinsing, high-purity niobium and clean conditions. Two resonator families, with different geometric β-values, are enough to cover the acceleration from the RFQ exit (5 MeV) to the final energy (40 MeV).

Focusing magnets

The focussing is ensured by solenoids instead of quadrupoles because a smaller peak beam envelope can be achieved with minimum overall dimensions and the sensitivity to misalignments is weaker. However, care must be paid to the tilt of the solenoids, which gives randoms transverse kicks to the particles. The axial field is kept low enough (lower than 6 T) in order to use the classical NbTi technology for the superconducting coils.

Linac layout optimisation

Once accelerating gradients and realistic component dimensions and spacings are given, the SC linac is then optimised in order to achieve the shortest linac while meeting the IFMIF requirements. A numerical code has been developed to find the optimal set of geometric cavity β-values, transition energies between the cavity families and number of resonators per period.

Two essential rules must be respected to avoid dilution and beam loss: the phase advance per lattice period must be lower than 90° and the beam must be carefully matched in all planes (longitudinal and transverse) between tanks. This statement favours a large number of resonators per tank and led to choose 12 resonators per cryostat. As a result, the SC linac needs a total of four 12-resonator cryomodules:

- the first two cryomodules contain β=0.094 resonators with 1 solenoid every 2 resonators.
- the last two cryomodules contain β=0.164 resonators with 1 solenoid every 3 resonators.

The lattice of the first cryomodule is shown in Fig. 1. Of course, the final dimensions, in particular the spacing between components, will be precisely determined after further mechanical studies.

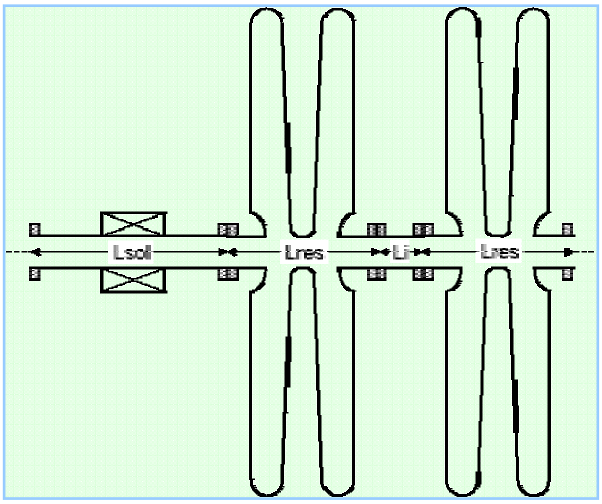

Figure 1: Lattice of the 1st cryomodule (one solenoid package and one pair of HWRs) Lsol=400mm; Lres=160mm; Li=100mm.

The solenoid package includes

- bucking coils in order to cancel the fringe field at the cavity location;
- steering coils, associated with button-type beam positions monitors (BPM) for orbit correction.

Assuming an inter-tank spacing of 20 cm, the total SC linac length amounts to 22 m, longer than the CH-structure option (13 m) but shorter than the n.c. Alvarez DTL reference design (~30 m). Table 1 summarises the parameters of the cryomodules.

Table 1: Energy gain in the resonators.

Cryomodules	**1 & 2**	**3 & 4**
Cavity β	0.094	0.164
Cavity length (mm)	160	280
Beam aperture (mm)	40	48
Nb cavities / period	2	3
Nb cavities / cryostat	2 x 6	3 x 4
Cryostat length (mm)	4.92	5.76
Output energy (MeV)	9 / 16	28 / 42

The design of the linac lattice has been made "safe", in particular with a large longitudinal acceptance and without any structure instability. These features ensure minimum beam halo and no loss that could be induced by machine imperfections or beam mismatch. The accelerating fields and synchronous phases are shown in Fig. 2 and 3:

- at low energy, where the phase extension of the bunches is still large, the synchronous phase has been set to large negative values (-50°) while letting grow linearly with the beam energy;
- the longitudinal phase advance, given by the expression (1), can be rather high at low energy and trigger the structure instability; the field is then reduced to lower the phase advance below 90° per period.

$$k_s = \left[\frac{-\omega q E_0 T \sin\varphi_s}{mc^3\beta_s^3\gamma_s^3}\right]^{1/2} \qquad (1)$$

The resulting energy gain provided by the resonators is shown in Fig. 4. Given the beam intensity of 125 mA, the maximum rf power per cavity is 80 kW for the first resonator family and 150 kW for the second family (Fig. 5).

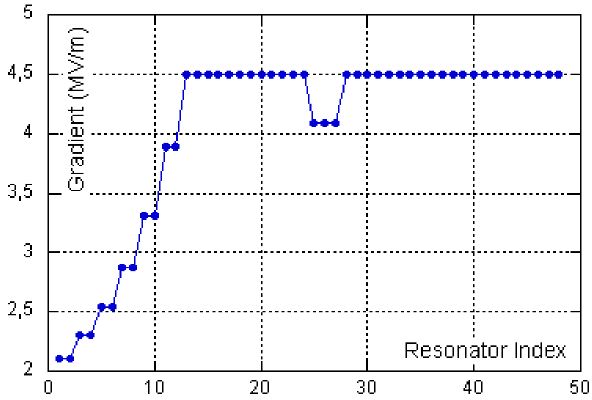

Figure 2: Amplitude of the accelerating field.

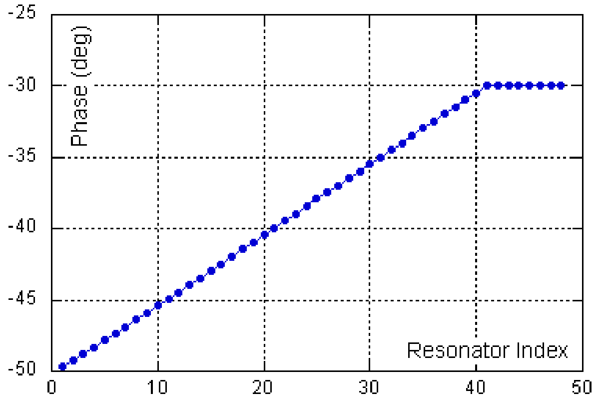

Figure 3: Synchronous phase in the resonators.

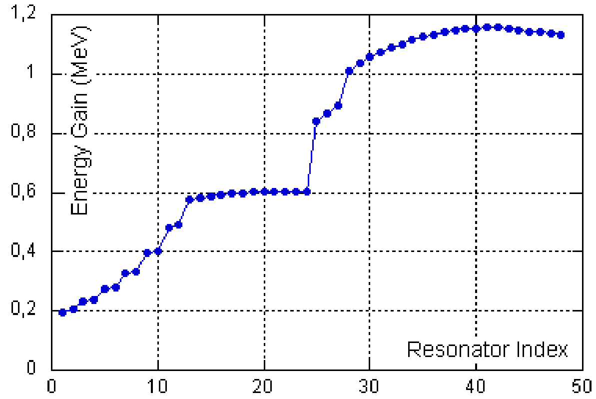

Figure 4: Energy gain in the resonators.

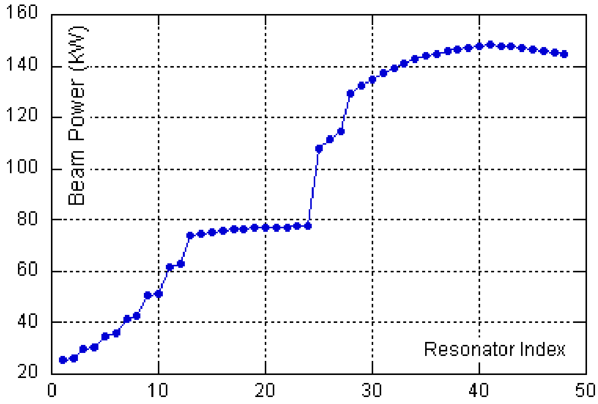

Figure 5: Power transferred to the beam.

BEAM DYNAMICS

Intensive beam dynamics studies and simulations have been carried out to probe the linac design. Prior to use their real computed field-maps, the resonators were modelled by the theoretical field on axis, based on a Bessel development taking into account the drift tube apertures. For instance, the resulting field map of the first resonator family is shown in Fig. 6.

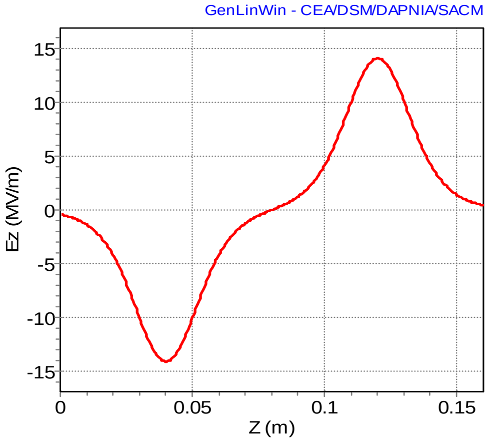

Figure 6: Field on axis (β =0.094)

Numerical simulations have been performed with *Toutatis* for the RFQ and with the package *TraceWin-Partran* for the DTL, both of them have been benchmarked with other tracking codes used in the community for simulations of high-intensity linacs [7].

The initial beam distribution at the Matching Section is the output distribution coming from the CEA-Saclay RFQ design simulated using *Toutatis* with 1,000,000 macro-particles. These simulations will have of course to be done with the final INFN-LNL RFQ design, but should not change the significantly the conclusions. The Matching Section between the RFQ and the SC linac (Figure 7) includes 2 buncher cavities and 3 quadrupoles.

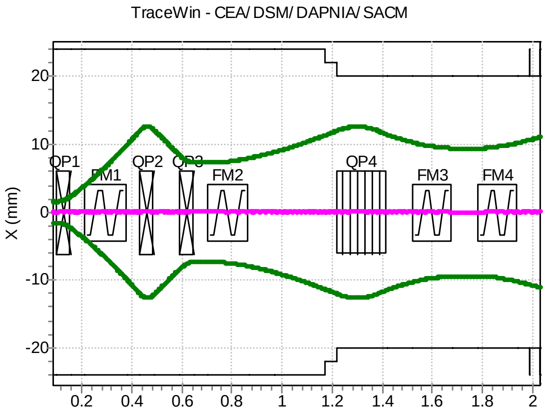

Figure 7: Matching line between RFQ (left) and SC linac (starting at 1.1 m).

Fig. 8 shows the beam envelope at 3 times the rms size through the 4 cryomodules of the SC linac. The bore radius to beam radius ratio shows a comfortable safety margin. The smoothness of the envelopes show correct matchings between the cryomodules.

The emittance growths are 43% and 26% in the transverse and longitudinal planes, respectively (Fig. 9).

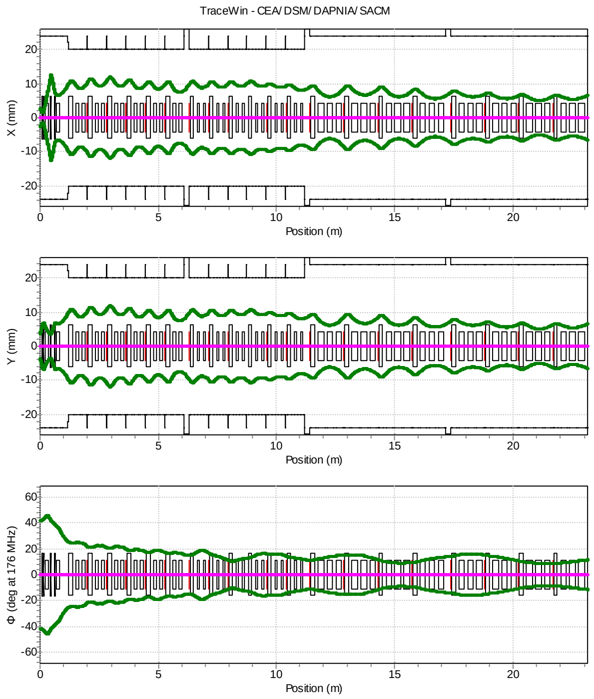

Figure 8: 3 rms beam envelopes.

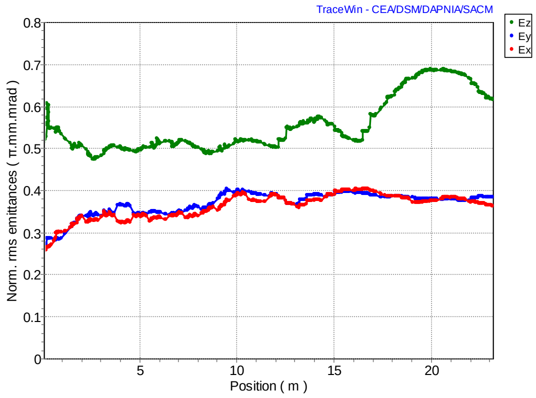

Figure 9: rms emittances (green: longitudinal; red and blue: horizontal and vertical)

Fig. 10 shows the beam phase space at the exit of the linac. The beam transmission is equal to 100% and no beam loss is observed with the 10^6 particle beam distribution. The full beam envelope stays far from the bore radius as we can see on Fig. 11 which shows the particle density with contour lines encircling 90% to 100% of particles. The safety margin, measured by the bore-to-beam radius ratio, is higher in the HWR scheme than in the Alvarez reference DTL[8] or in the CH-structure scheme [9].

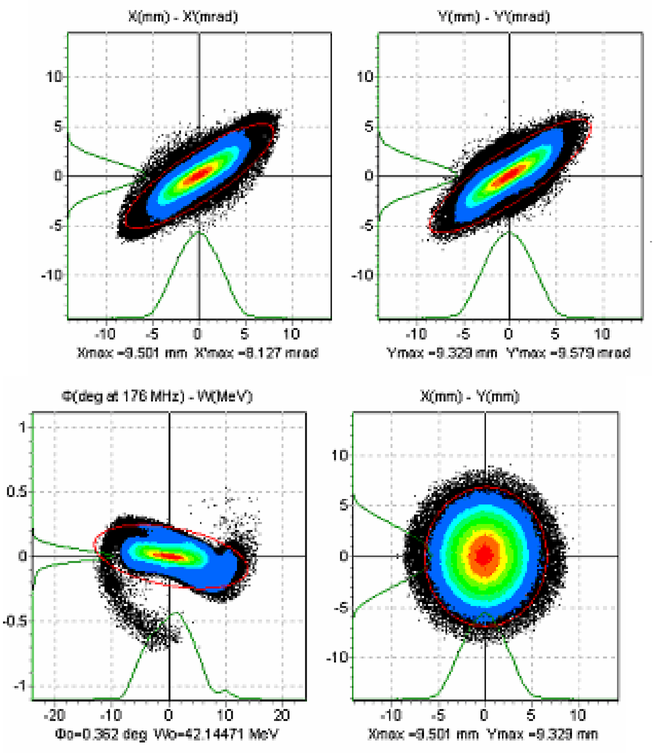

Figure 10: The beam phase space at the linac exit.

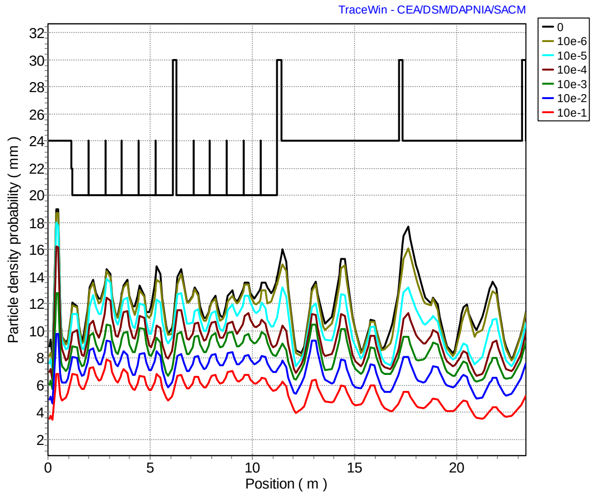

Figure 11: particle density plot with contour lines encircling 90% to 100% of particles (without errors).

Last, a relevant parameter to appraise the quality of the longitudinal transport in a linac is the longitudinal acceptance. Fig. 12 gives the longitudinal acceptance (grey area), calculated without space charge, as well as the beam phase space at the linac entrance for comparison. The available space looks wide enough compared to the space occupied by the beam.

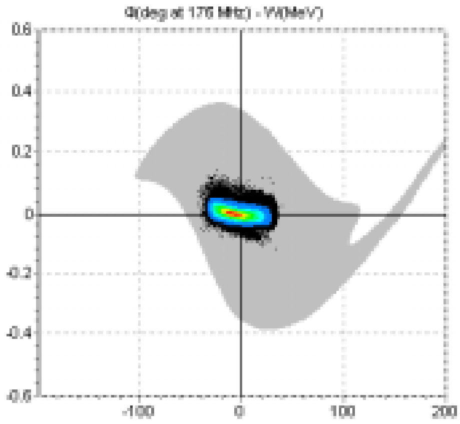

Figure 12: Longitudinal acceptance (grey area).

ERROR ANALYSIS

In order to study the effect of random errors along the linac, the simulation Monte-Carlo method has been carried out by tracking 10^6 particles through 100 different linacs, each with a different seeding of the random errors. The errors are uniformly distributed in the given ranges (Table 2).

Table 2: Error distributions.

Error type	Error range
Resonator	
Misalignment [x,y]	1.0 mm
Field amplitude (static)	1 %
Field phase (static)	1 deg
Solenoid	
Misalignment [x,y]	1.0 mm
Magnet tilt	10 mrad
Field amplitude	1 %
Beam **P**osition **M**onitor	
Measurement accuracy	0.25 mm

The range of the errors (1 mm misalignment) has been intentionally chosen very conservative since the alignment of SC components in cryostats cannot be accurately guaranteed. The beam orbit spoiling stems mainly from the solenoid tilts. The correction scheme relies on the steering coil (H and V) associated with the downstream beam position monitor (H and V) located at every solenoid package. This simple one-to-one correction scheme limits the rms beam displacement maintained below 0.6 mm (Fig. 13) while keeping the maximum deviation below 2 mm from the beam axis. The solenoid rotation or misalignment could be also easily compensated by beam-based correction: whereas the current of each solenoid is varied, the corrector is adjusted until the beam displacement, measured at the next downstream BPM is cancelled.

The particle density, calculated with these very loose tolerances, is shown on Fig. 14. The contour lines look very similar to the ones simulated without errors (see Fig. 11), giving a large safety margin between the beam occupancy and the pipe aperture.

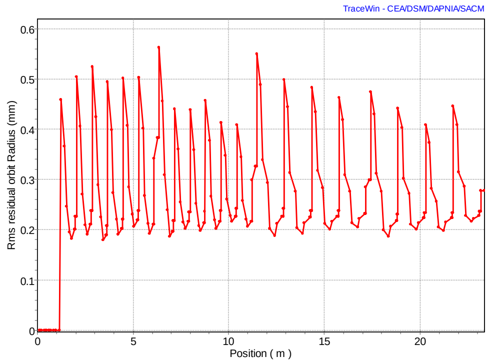

Figure 13: rms beam displacement with correction.

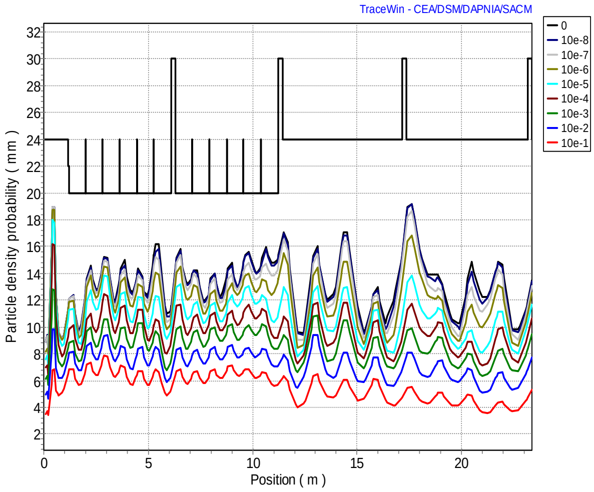

Figure 14: particle density plot with contour lines encircling 90% to 100% of particles (with errors).

CONCLUSIONS

Half-wave resonators can safely accelerate high-intensity beams, as the 125 mA deuteron beam of the IFMIF linac up to 40 MeV. Besides, the present lattice design looks very robust and very conservative. In case the length is a strong criterion, the number of resonators and the linac length could be reduced (4 x 10-resonator cryomodules resulting in a linac length of about 18 m) at the expense of higher rf power required from the input couplers. Within the EVEDA-phase of IFMIF, it is planned to build and test the accelerator prototype with full beam current, from the ion source to the first tank of the DTL. In order to test a SC solution, an alternative could consist in replacing the Alvarez DTL by the first 4.9 m long cryomodule to achieve the 9-10 MeV energy.

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