FRONT END DESIGN OF A MULTI-GeV H-MINUS LINAC*

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Abstract

The proposed 8-GeV driver at FNAL [1] is based on ~430 independently phased SC resonators. Significant cost savings are expected by using an rf power fan-out from high-power klystrons to multiple cavities. Successful development of superconducting (SC) multi-spoke resonators operating at ~345-350 MHz provides a strong basis for their application in the front end of multi-GeV linear accelerators. Such a front-end operating at 325 MHz would enable direct transition to high-gradient 1300 MHz SC TESLA-style cavities at ~400 MeV. The proposed front end consists of 5 sections: a conventional RFQ, room-temperature (RT) cross-bar H-type (CH) cavities, single-, double- and triple-spoke superconducting resonators. It is effective to use short RT CH-cavities between the RFQ and SC sections in the energy range 3-10 MeV as is discussed below.

INTRODUCTION

SC cavities operating at 1300 MHz and originally developed for the electron-positron linear collider (ILC) can be directly applied for acceleration of H^- or proton beams above ~1.2 GeV. Squeezed ILC-style cavities designed for β_G=0.81 can be used in the energy range from ~400 MeV to 1.2 GeV. Preliminary engineering studies show that the most cost-effective design of the linac can be achieved by rf power fan-out from one klystron to multiple cavities. The front end of the 8-GeV linac is defined as a section operating at 4^{th} sub-harmonic of the ILC frequency. There are several reasons to choose 325 MHz:

- Multi-spoke SC cavities have been developed and demonstrated excellent performance at 345-352 MHz [2,3] and can be easily modified to 325 MHz;
- A front end operating at 325 MHz requires 30% fewer of cavities compared to 433 MHz option;
- Klystrons are available from J-PARC;
- Triple-spoke cavities can be applied for acceleration up to ~400 MeV. The frequency jump by the factor of 4 at relatively high energy is favorable for beam dynamics in longitudinal phase space.

FRONT END DESIGN

The design of the 8-GeV linac utilizes rf power fan-out from high-power klystrons to multiple cavities. This technology can also be effectively applied both for SC and RT cavities in the front end. The proposed front end uses both RT and SC short cavities alternating with focusing elements. The RT section includes ion source, RFQ, MEBT and 15 five-cell RT cross-bar CH-type cavities [4]. The SC section consist of single-, double- and triple-spoke resonators (SSR, DSR and TSR) and accelerates H^- ion beam up to 410 MeV. The total length of the front end is 115 m. Advantages of single-frequency medium energy proton linac based on multi-spoke cavities have been discussed elsewhere [5]. The H^- ion source and RFQ will be similar to those at J-PARC and SNS except that the beam exiting RFQ will be axial-symmetric. Focusing by SC solenoids provides compact lattice, shortens focusing period and facilitates using high accelerating gradients offered by SSRs and DSRs. In addition, axial-symmetric beam optics in the MEBT mitigates halo forming which can take place due to weak asymmetric focusing [6]. However, to avoid excessive stripping of the H^- beam in the fringe fields of solenoids, the focusing above ~110 MeV which is the transition energy between DSRs and TSRs will be provided by quadrupoles. Beam matching between the cryostats will be provided by adjusting parameters of outermost elements in the cryostats.

It is difficult to avoid several different lattice structures in a SC linac. To minimize the effect of the lattice transitions on beam parameters, the wave numbers of betatron and synchrotron oscillations k_{x0} and k_{z0} are adiabatically varied along the whole linac. However, use of adiabatic matching in the longitudinal phase space at the frequency transition 1:4 results in ineffective use of the available accelerating gradients therefore the matching is provided by 90° “bunch rotation”. This matching technique may require retuning of the phases of the cavities located near the transition region for appropriate matching of beams at different currents.

Focusing Lattice

Table 1 shows main parameters of the focusing lattice.

Table 1: Focusing Lattice. S-solenoid; C-cavity; F, D – quadrupoles, L_P-length of the Focusing Period; L_E – Effective Length of the Focusing Element

Section	**CH**	**SSR**	**DSR**	**TSR**
Focusing	SC	SC	SCC	FCDC
L_P, m	0.4-0.6	0.6	1.5	3.0
L_E, m	0.1	0.1	0.20	0.20
B (T), G* (T/m)	≤6.0	≤6.0	≤5.4	≤7.5*

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Transition from solenoid focusing to quadrupole lattice requires an extra quadrupole. Currently we are investigating doublet focusing instead of FODO (or FCDC). The doublet focusing could have some advantages in cryostat design and can eliminate beam matching requirements in the inter-cryostat transitions.

Room Temperature Section

The front end consists of RT and SC sections. The RT section includes ion source, RFQ, MEBT and 15 five-cell RT resonators operating at π–mode. The mechanical design of the RFQ resonator can be based on J-PARC 324 MHz RFQ [7].

There is a MEBT between the RFQ and RT section of the linac. The beam optics in the MEBT should provide a drift space to accommodate a fast chopper. A major function of the chopper is to form 800 ns abort gaps in beam structure for the extraction kicker in the FNAL main injector. A possibility of beam matching with the 53 MHz rf structure of the main injector by chopping away every 7th bunch is being investigated. The traveling-wave chopper should provide ~2.5 nsec rise/fall time of the deflecting voltage. The most stringent MEBT design requirement is preserving of beam quality from the RFQ to the DTL and avoiding beam halo formation. Numerical simulations confirmed that axial-symmetric focusing by SC solenoids makes the MEBT beam optics space-charge independent.

To provide adiabatic variation of the k_{z0}, the real-estate accelerating gradient has to change from ~0.75 MV/m which is valid at the RFQ end to ~2 MV/m that can be achieved using SSRs incorporated into solenoidal focusing lattice. The transition energy ~10 MeV between the RT and SC structures provides adiabatic ramp of the accelerating field. The length of each drift tube in the 5-gap RT structures will be designed to provide synchronous motion as in a standard DTL. Our preliminary studies show that the best RT accelerating structure in the energy range 3-10 MeV is a cross-bar H-type (CH) cavity [4] operating at 325 MHz. Figure 1 shows 5-gap CH structure designed for acceleration of 3 MeV proton beam. The shunt impedance of the CH cavities varies from 80 MOhm/m to 60 MOhm/m in the energy range from 3 to 10 MeV. Further optimization of the CH-cavities is being investigated to enhance its shunt impedance. 15 cavities are required for acceleration up to 10 MeV with total power consumption of 290 kW. An additional 182 kW is necessary to compensate 26-mA beam loading. The CH-cavity can be incorporated into a vacuum tank together with SC solenoids as is seen from Fig. 1.

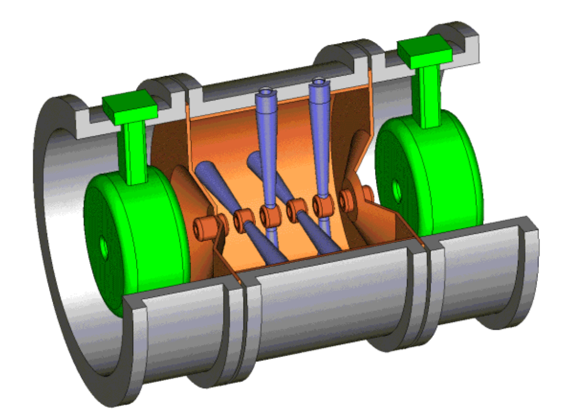

Figure 1: Cut-away view of the RT section of the linac comprising 5-gap CH cavity and two SC solenoids.

Superconducting Section

The superconducting section of the front end is based on spoke cavities. Main parameters of the spoke cavities are based on proven performance [2,3] and given in Table 1. The ratio of the peak surface field E_{peak} to the accelerating field E_{acc} is assumed to be 3.0 for all cavities for the given effective length. Preliminary studies indicate that this parameter can be reduced by optimization of the cavity internal shape. The rf coupler power in Table 2 is given for 26 mA beam current averaged along the pulse.

Table 2: Main Parameters of the SC Resonators

Parameter	**SSR**	**DSR**	TSR
Energy range, MeV	10-33	33-110	110-410
Beta geometrical	0.22	0.40	0.61
Aperture diameter, cm	3.0	3.0	4.0
Number of resonators	22	28	42
E_{peak}, MV/m	32	32	32
Voltage, MV	1.34	3.49	9.16
Effective length, cm	13.0	36.9	85.6
Coupler power, kW	26	102	238

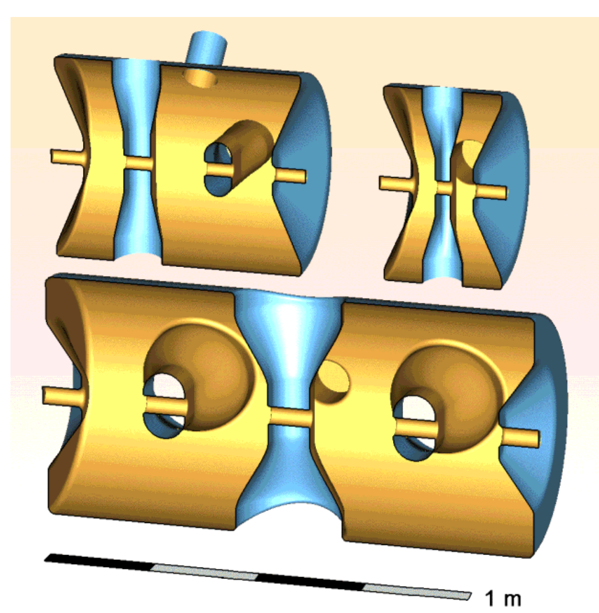

Figure 2: Cut-away view of the spoke cavities.

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Beam Dynamics

The lattice design has been optimized to maintain adiabatic change of wave-numbers of betatron and synchrotron oscillations k_{x0} and k_{z0} along the linac as seen in Fig. 3. Prior to the beam dynamics simulations a careful matching of the 28-mA beam Twiss parameters in the lattice and inter-cryostat transitions has been provided. For this purpose the codes TRACE3D [8] and TRACK [9] have been applied. The code TRACK tracks particles in realistic 3D fields in all accelerator elements therefore the TRACE3D results have been iterated to obtain acceptable matching. The simulation starts with 30 mA H^- dc beam at the entrance of the RFQ with initial water-bag distribution represented by $2{\cdot}10^5$ particles. About 7% of the beam injected into the RFQ is not accelerated and intercepted by the RFQ vanes and MEBT collimators. Figure 4 shows rms and total envelopes of the beam accelerated from 65 keV to 410 MeV. The ratio of the aperture to the rms beam size is higher than 12 in all SC sections. Figure 5 shows acceptable emittance growth in all three phase planes both for rms emittance and emittance containing 99.5% of particles. The emittance growth is given with respect to the beam emittances at the RFQ exit.

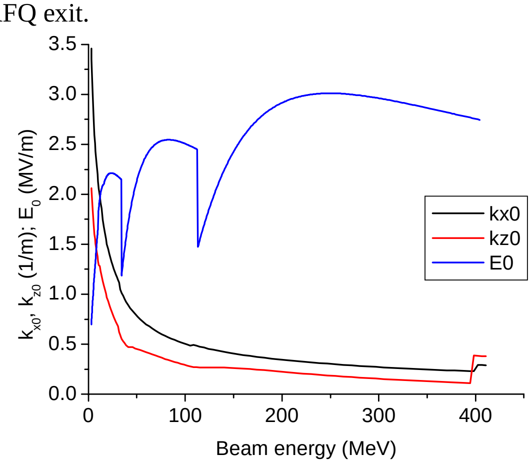

Figure 3: Wave numbers of betatron (kx0) and synchrotron (kz0) oscillations, real-estate accelerating gradient (E0) along the front end.

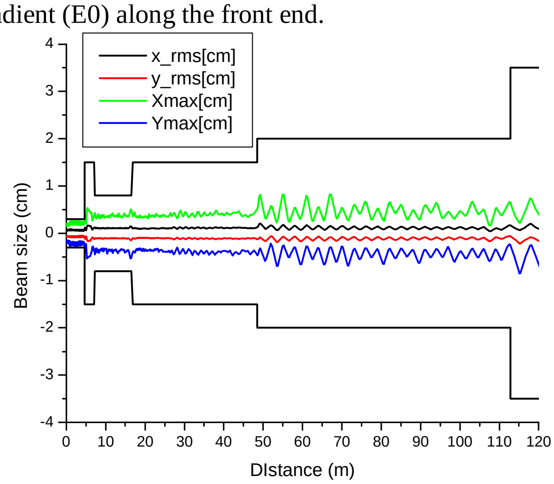

Figure 4: Transverse envelopes of 28 mA beam along the front end. The black solid line shows the aperture.

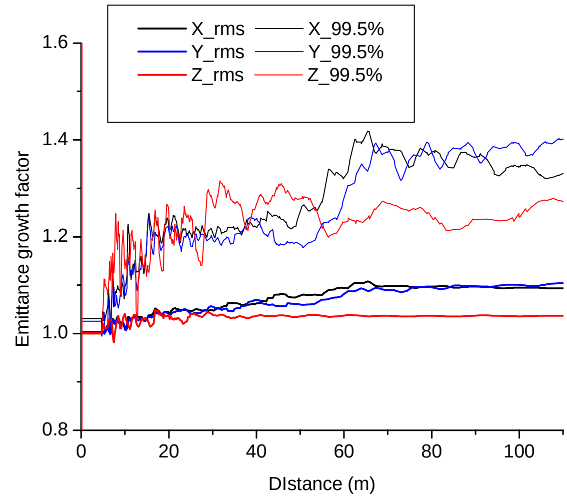

Figure 5: Emittance growth factor of the 28 mA beam along the front end.

To provide 90° bunch rotation prior to the frequency jump, the synchronous phase in the last four TSRs is set to -60°. This causes an abrupt change of the k_{z0} at 400 MeV required for matching to the 1300 MHz section of the linac (see Fig. 3).

CONCLUSION

The front end of the 8-GeV linac is based on single-frequency multi-spoke SC cavities. Using short normal conducting resonators up to ~10 MeV reduces the number of different types of SC cavities and provides adiabatic beam matching. Focusing by SC solenoids results in a compact lattice, shortens focusing period and facilitates using high accelerating gradients offered by SSRs and DSRs. The frequency transition 1:4 above 400 MeV facilitates beam quality preservation in the high energy section.

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