AN ELECTRON FRONT END FOR THE FERMILAB MULTI-SPECIES 8 GEV SCRF LINAC

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Abstract

Fermilab is considering a 8 GeV superconducting linac whose primary mission is to serve as an intense H^- injector for the main injector. This accelerator is also planned to be used for accelerating various other species (e.g. electrons, protons and muons). In the present paper we investigate the possibility of such a linac to accelerate high-brightness electron beam up to $\sim$ 7 GeV. We propose a design for the electron front end based on a photoinjector and consider the electron beam dynamics along the linac. Start-to-end simulations of the full accelerator for electrons are presented. Finally the potential applications of such an electron beam are outlined.

INTRODUCTION

The proposed superconducting radio-frequency (SCRF) 8 GeV linac is to serve as a single-stage H^- injector to prepare 2 MW "Super-Beams" for Neutrino experiments using the Fermilab Main Injector (MI). The required frequency for H^- injection, 0.67 Hz, corresponds to the cycling frequency of the MI (8 GeV→120 GeV→8 GeV). Because of the resulting low duty cycle operation of the SCRF linac, it has been suggested [1] to also use the linac to accelerate other species (e.g. $e-$, p). Such a proposal would require the linac rf-system to rapidly change the linac SRF cavities phases and amplitudes accordingly to the specie being accelerated. To address this issue, an R&D program aimed toward the development of fast ferrite-based phase shifter is on-going at Fermilab. The SCRF linac will consist of six sections composed of (1) conventional RFQ, (2) single, (3) double and (4) triple spoke resonators, (5) squeezed TESLA cavities (β=0.81) and (6) standard TESLA cavities.

In the next Sections we concentrate on studying what would be needed to produce and accelerate electron bunches with beam parameters in order to enable state-of-art applications such as advanced accelerator studies, or short wavelength, single-pass, free-electron lasers. An overview of the considered facility is depicted in Fig. 1. Since the primary mission of the linac is to provide H^- to the MI, the proposed $e-$ injector has to be off-axis of the main linac (the $\beta = 1$ linac section is henceforth refer to as "main linac"). Furthermore, the impact on the main linac design should be minimized. In the following we do not consider the use of the $\beta = 0.81$ section of the SCRF linac to accelerate e^- [1], and we actually foreseen to fit the $e-$ injector in the service building located above the $\beta < 1$ linac sections (see Fig. 1).

OFF-AXIS INJECTION OF E^- BEAM

The requirement of an off-axis injection into the main linac, along with the fact the photo-injector axis has to be parallel to the main linac axis impose the use of a "dog-leg" $-$ a dispersion-less translating section $-$. The dog-leg bending angle should be as large as possible (to minimize the associated real estate) while maintaining energy spread and associated bending-plane transverse emittance dilution, e.g., due to coherent synchrotron radiation (CSR) as low as possible. On another hand the non closure of high order dispersion of such system results in (chromatic) emittance growth, when a large fractional energy spread beam is considered. Based on numerical simulations, we infer DL1 bending angle should be less than $10°$. Assuming an elevation difference between the injector and main linac beamlines of 5 m, a $\sim$30 m length dogleg would result in a $\simeq 9.5°$ bending angle. Using this nominal bending angle we present in Fig. 2 the expected vertical emittance dilution versus incoming fractional momentum spread (chromatic emittance dilution) and incoming rms bunch length (CSR-induced emittance dilution). The results of these calculations indicate we should limit the incoming fractional momentum spread and bunch length to σ_δ <0.2% and $\sigma_z > 0.5$ mm.

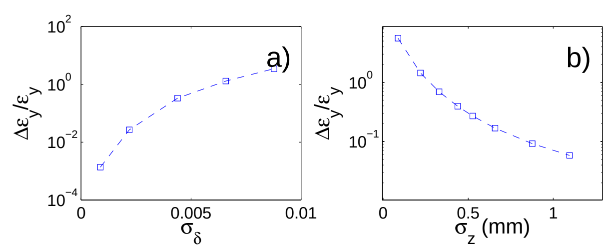

Figure 2: Tolerance of dogleg DL1 to incoming fractional momentum spread **a)** and rms bunch length **b)**.

THE FNPL FACILITY AS AN INJECTOR

The FermiLab/NICCAD photoinjector laboratory (FNPL) [3], presently under operation at Fermilab, could

[1]because of phase slippage this would introduce some complications on the electron beam dynamics.

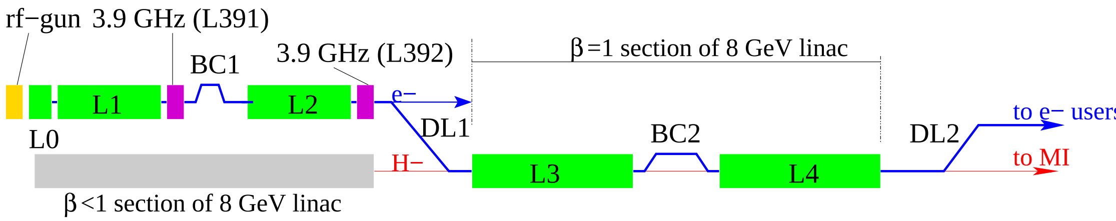

Figure 1: Overview of the multi-species linac project at FNAL, with element associated to electron transport. Legends: BC1, BC2 are bunch compressors, L0,...,L4 are 1.3 GHz SCRF linac sections, and DL1, DL2 are injection/ejection doglegs.

serve as an electron injector (see Fig. 1). After its forthcoming energy upgrade this L-band photoinjector ($f = 1.3$ GHz) will consist of an rf-gun followed by two TESLA cavities (L0) (respectively operated at an average gradient of 12.5 and 25 MV/m). FNPL would thereby produce a 40 to 50 MeV electron beam. Therefore we hereafter consider FNPL to be used as an injector to produce and prepare the e^- beam before injection in a subsequent TESLA accelerating module. Based on previous work [2] the injector operating point was optimized to produce a low transverse emittance 1 nC bunch downstream of the FNPL section. The beam is then injected in a standard TESLA accelerating module operated off-crest to impart the proper time-energy correlation for subsequent bunch compression in a magnetic chicane (BC1) with momentum compaction $R_{56} = -104.4$ mm. A third order frequency section (L391) located upstream of BC1 enables the correction of longitudinal phase space nonlinearities [2]. Finally the beam is once more accelerated with one TESLA accelerating module (L2) and then passed through a second third order frequency section (L392) operated at zero-crossing for removal of correlated energy spread before injection in the (narrow energy bandwidth) dogleg (DL1). The evolution of the beam transverse emittances, envelopes and energy spread from the photocathode up to the dogleg exit (i.e. the main linac entrance matching section) are depicted in Fig. 3. The optimized operating point for the rf components and the resulting beam parameters downstream of DL1 are gathered in Table 1. The numerical calculations were performed using the programs ASTRA [4] (for the electron bunch generation and low energy transport) and ELEGANT [5] starting from the magnetic chicane BC1. The beam downstream of the injector reaches a total energy of approximately ~ 400 MeV.

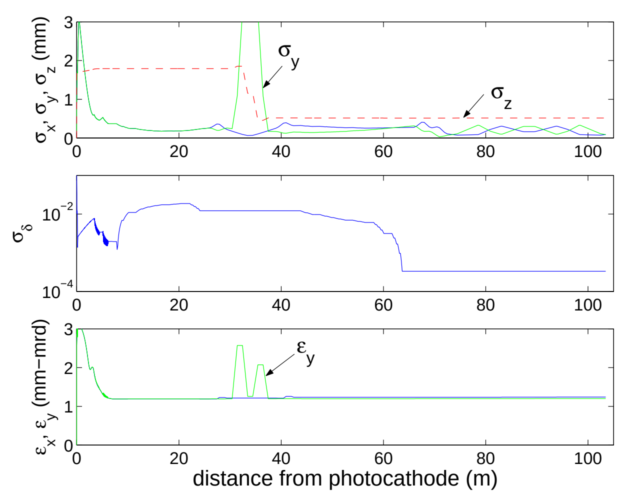

Figure 3: Evolution of beam transverse envelopes and bunch length (top), fractional momentum spread (middle) and transverse emittance (bottom) along the injector transport line up to DL1 exit. BC1 extension is from $\sim 30 < z < 37$ m, DL1 starts at $z \simeq 73$ m.

MODIFICATION OF THE MAIN LINAC

Downstream of DL1, the beamline in the main linac consists of a set of five pulsed quadrupoles providing a matching section for the e^- beam into the linac FODO lattice. In the present design we assume the linac optics to be tuned as a FODO lattice but we have not considered whether this optics would be optimum for the H^- beam, or whether we could rapidly vary the quadrupoles strength depending which specie is being accelerated.

One of our goal is to produce high peak current electron bunch $\hat{I} \simeq$1-5 kA, which results in a requirement for the bunch duration of $\sigma_t = Q/(\sqrt{2\pi}\hat{I}) \simeq 100-500$ fs. We do not foreseen to generate such a short bunch directly out of the injector principally because the transport of short bunch in DL1 would result in large emittance dilution. Instead we plan to insert in the main linac a magnetic chicane (BC2 in Fig. 1) with pulsed dipoles. The required real estate for the magnetic chicane insertion (that is magnetic chicane, and two matching sections) is approximately 40 m, Two matching telescopes upstream and downstream of the chicane are inserted to provide a transition from/to the FODO lattice and a knob for optimizing the lattice functions within the BC2 area. BC2 has a momentum compaction of $R_{56} = -45.8$ mm, and is presently located at $E \simeq$813 MeV requiring the upstream linac (L3) to be operated approximately 57 off-crest. The downstream linac (L4) is operated on-crest. Presently both L3 and L4 are operated with an accelerating gradient of 20 MV/m

parameter	value	units
laser injection phase	44	rf-deg
laser radius on cathode	0.75	mm
laser flat top length	20	ps
laser rise time	2	ps
E-peak on cathode	60	MV/m
L0 accelerating voltage	12.5+25	MV
L0 phase	0 (on-crest)	rf-deg
L1 accelerating voltage	200	MV
L1 phase	-26 off-crest	rf-deg
L391 accelerating voltage	28.4	MV
L391 phase	+155 off-crest	rf-deg
L2 accelerating voltage	200	MV/m
L2 phase	0 (on-crest)	rf-deg
L392 accelerating voltage	28.0	MV
L392 phase	90 (0-crossing)	rf-deg
reduced energy γ	782.5	-
charge Q	1	nC
bunch length σ_z	516	μm
frac. energy spread σ_δ	3.3×10^{-4}	-
norm. emit. $\tilde{\varepsilon}_x$	1.24	mm-mrd
norm. emit. $\tilde{\varepsilon}_y$	1.20	mm-mrd

Table 1: Nominal settings for the rf elements and photocathode drive laser, and beam parameters downstream of DL1 (bottom part of table)

resulting in total energy upstream of DL2 of $E \simeq 6$ GeV for the simulation results presented hereafter.

In our preliminary tracking simulations (only 50000 macroparticles), we found the peak current could easily reach ~3 kA (see Fig. 4 and 5). The slice transverse emittances along the bunch (Fig. 5) can reach value close to 1 mm-mrad while maintaining slice current of about 2-3 kA. Such low emittances high peak current values support the possibility to use the SCRF linac to drive a free-electron laser (as proposed in Reference [1]).

SUMMARY

The tracking studies of the previous Sections indicate that using the $\beta = 1$ section of the proposed SCRF linac could provide electron bunches with parameters comparable to those foreseen in e.g. short wavelength FELs, or other linacs dedicated for advanced accelerator physics. In addition, the e^- injector could be operated in a straight ahead mode thereby providing beam for low energy (~400 MeV) beam physics applications or for a superconducting module or linear collider test facility [6]. More studies to refine, optimize and investigate the performance of the herein proposed design are on-going.

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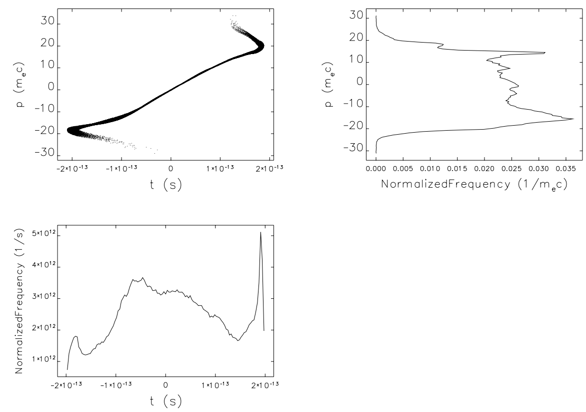

Figure 4: Longitudinal phase space, energy spread profile and bunch distribution upstream of DL2. Time $t > 0$ corresponds to bunch tail.

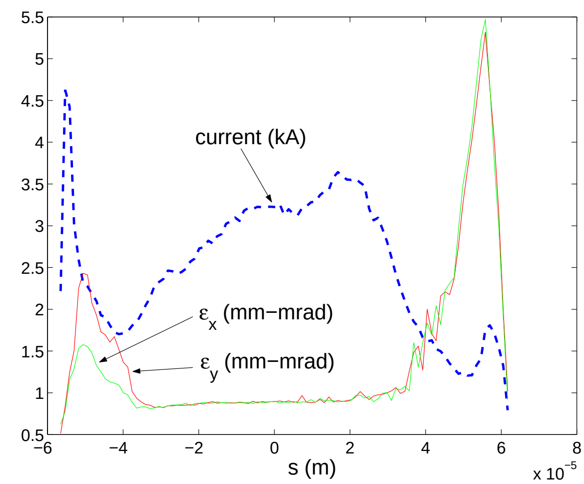

Figure 5: Slice parameters along the bunch: transverse emittances and peak current. Coordinate $s > 0$ corresponds to bunch tail.

REFERENCES

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[5] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000

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