DESIGN OF THE PROJECT X CW LINAC*

N.Solyak, J-P.Carneiro, V.Lebedev, S.Nagaitsev, N.Perunov, J-F.Ostiguy, A.Vostrikov,
V.Yakovlev, FNAL, Batavia,IL 60510, U.S.A.

Abstract

Project X proposes high-intensity H- accelerator complex that could provide high intensity beam for a variety of physics projects: neutrino-, kaon- and muon-based precision experiments. In the current proposal 3MW CW linac would contains few types of superconducting cavities and focusing elements to accelerate beam from 2.5 MeV up to 3 GeV. The paper presents the status of the 3GeV x 1mA CW linac, including design and testing of the linac components, lattice design and results of beam dynamics studies. Few alternative designs without ILC cavities are described and analysed.

INTRODUCTION

The Project-X, a multi-MW proton source, is under development at Fermilab [1]. It enables world-class precise experiments in neutrino, kaon and muon physics. The proposed facility is based on 3-GeV 1-mA CW superconducting linac. In the second stage of about 5-9% of the H^- beam is accelerated in a SRF pulse linac or RCS for injection to Recycler/Main Injector to create multi-MW high intensity beams for neutrino and muon experiments. The main portion of H^- beam from 3GeV linac is directed to three different experiments.

GENERAL

The CW 3 GeV linac of the Project-X provides H^- beam with average current of 1 mA and has a special time structure [1] in order to satisfy the requirements of the experiments. The pulse current for 325 MHz bunch sequence option is up to 10 mA. The schematic of baseline configuration of linac is shown in Figure 1. It includes (i) ion source, (ii) RFQ, (iii) medium energy beam transport (MEBT), (iv) three sections based on 325 MHz Single-Spoke Resonators (SSR), two sections of 650 MHz elliptical cavities, and (v) final section of 1.3 GHz ILC-type cavities.

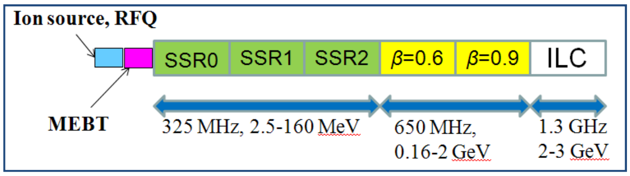

Figure 1: Baseline CW 3GeV linac schematic.

Front-end

The ion source provides 10 mA of H^- that is accelerated in the RFQ operating at 325 MHz (other option is 162.5 MHz). RFQ provides 2.5 MeV beam with transverse normalized emittance of $\sim 2.5\cdot 10^{-7}$m and longitudinal emittantce of ~1.5 keV*nsec.

In the room temperature MEBT section, the beam is chopped by the high-bandwidth bunch-selective chopper in order to get the time structure necessary for the experiments. Almost 90% of the beam is chopped out. MEBT contains chopper section, matching sections to match beam in and out of chopper and necessary diagnostics. Chopping section has 4 periods in it each chopper is 0.5m long with the gap 15mm and applied voltages on the plate ±375V. A 325 MHz bunching cavities are used to support the beam longitudinal dynamics, and triplets provide the beam focusing. This scheme provides high chopping efficiency, thus transmitted fraction of the chopped beam is $<10^{-4}$ [2]. Figure 2 show results of PARTRAN tracking for un-chopped and chopped beams and fraction of lost particles in each diaphragm.

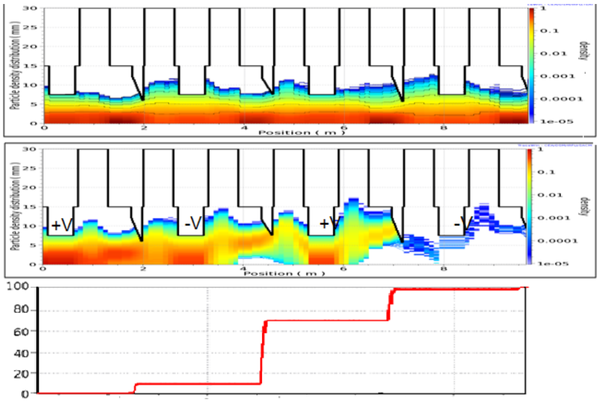

Figure 2: Proposal for lattice design for MEBT. Picture shows X-envelopes of the un-chopped beam (upper), chopped beam (middle) and losses of the chopped beam.

Superconducting Linac

Further acceleration of the beam takes place in SC linac. Low-energy part of the linac consists of three single-spoke resonator (SSR) sections, working at 325 Status of the spoke cavities design and prototyping and tests are presented here [3,4]. The focusing in these sections is provided by superconducting solenoids to minimize focusing period.

High-energy part of the linac consists of two sections, based on two families of elliptical cavities (beta=0.61 and 0.9) operating at 650 MHz [5,6], and section containing 1.3 GHz ILC-type cavity. The focusing in 650 MHz sections is provided by superconducting doublets. In ILC section is based on ILC type cryomodule with the quadrupole in the middle. Break points between sections, number and type of components are shown in Table 1. Transition energy between cavities was optimized to

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*Work supported by the U.S. DOE
#solyak@fnal.gov

achieve good accelerating efficiency and maximal beam acceptance.

Working gradient at the cavities was chosen to provide the peak surface magnetic field that allows operation below high-filed Q-slope [7], which gives more reliable cavity performance and minimize power losses in the cavity walls. The maximum surface field was chosen is 60mT for 325 MHz; 70 mT for 650 MHz and 1.3 GHz. For another hand, peak surface electric field is to be lower than 40 MV/m in order to avoid strong field emission. It was one of consideration for the cavity design.

Table 1: Transition Energy and Number of Components

Cavity type	**Freq MHz**	**Energy MeV**	**cav/mag/ CM**	**Element type: cavity, magnet**
SSR0	325	2.5-10	26/ 26/ 1	Single-spoke, Solenoid
SSR1	325	10-32	18/ 18/ 2	Single-spoke, Solenoid
SSR2	325	32-160	44/ 24/ 4	Single-spoke, Solenoid
LB650	650	160-520	42/ 21/ 7	5-cell cavity Doublet
HB650	650	520-2000	96/12 /12	5-cell cavity, Doublet
ILC	1300	2000 3000	64/ 8/ 8	9-cell cavity Quad

Status of the Component Development

One of the challenges is development of the SRF cavities and magnets. Some of the components required for Project X is already designed and tested in the frame of HINS program, which has goal to demonstrate front-end of the proton driver. Two prototypes of SSR1 single-spoke cavity were built and tested. The results are very encouraging. Two types of required solenoids are also designed and tested. Significant progress was achieved in developing of 1.3 GHz cavities and cryomodules in frame of ILC program. Today Fermilab has completed electromagnetic design for all cavities, described above. The mechanical design is under development or ongoing.

RF Power

Power requirements for the cavities are described in paper [8]. Solid-state amplifiers a considered for the front- end. For 650 MHz and 1300 MHz sections IOT or solid-state amplifier (if available) will be used. On can see that because of small current load the cavity Q_{etx} is considerably high, and special efforts to reduce microphonics are necessary. However, L's they consider operation of SC cavities at Q_{Load} up to 10^8 using special system of the amplitude and phase stabilizing [9].

The RF couplers for all the cavities are under development. The couplers have to allow assemble and seal cavities in a clean room. Sealed cavity is to be installed in cryomodule. 1.3 GHz coupler has to match existing ILC-type cavity and ILC type-4 cryomodule. 325 MHz coupler should match existing SSR1 cavity. We need to feed 6 types of the cavity at three different frequencies. Nevertheless, couplers components have to be universal as much as possible, simple, reliable, and cheaper.

Cryomodules and Cryo-Segmentation

In baseline lattice all crymodules in low-energy part of the linac (325 MHz) are separated by short RT sections in order to provide (i) ma maintenance and reliability, (ii) beam profile diagnostics in RT drifts, (iii) possible dump (reduction of aperture) for halo cleaning in accelerator. High energy sections (650 MHz β=0.61 and β=0.9, and 1.3 GHz ILC) are assembled in cryo-strings with warm inter-connections between sections. Each string contains ~6-8 cryomodules with short ~ 1-2 m warm insertions between available for beam profile measurements and diaphragms for halo cleaning. Starting from HE650 it is possible to use even longer warm sections without disturbing longitudinal beam dynamics. In example of cryo-segmentation shown in Figure 3, we assume ~12m warm sections inside HE650 section and between HE650 and ILC section. Longitudinal matching was done by changing the phase and amplitude of cavities before and after warm insertion. For transverse matching a RT doublets (or quads) in the warm section are used.

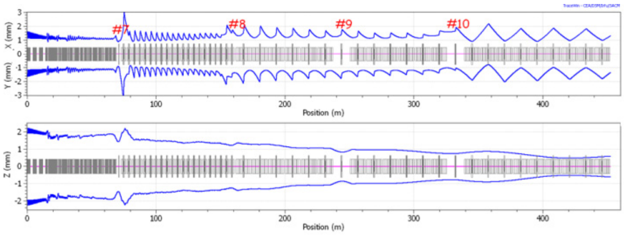


Figure 3: Transverse (above: X-positive, Y-negative) and longitudinal sigma envelopes for the case of 12m long warm insertions in between of cryogenic strings.

Note that the empty space is used between the cavities in the beta=0.61 section in order to keep constant focusing period with 6 cavities and 3 doublets in each cryomodule. In 1.3 GHz ILC section a standard ILC type-4 cryomodule will be used that contains 8 cavities and one quad in the center, the focusing system in this section is FODO cells. The number of cryomodules is shown in the Table1. The cryomodules in high energy part of the linac are assembled into cryo-strings, containing 6-8 cryomodules per string with the warm interconnection between strings. Total number of the strings is 4: one in low-beta 650 MHz, two in high-beta 650 MHz and one in ILC section. Note that the empty space is used between the cavities in the beta=0.61 section in order to keep constant focusing period with 6 cavities and 3 doublets in each cryomodule. In 1.3 GHz ILC section a standard ILC type-4 cryomodule.

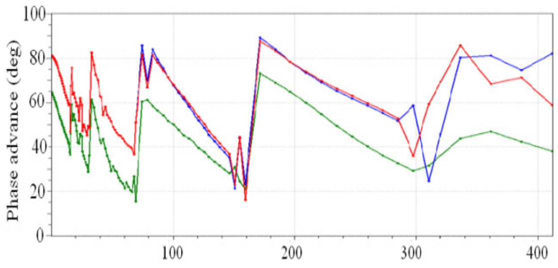
LATTICE DESIGN AND BEAM DYNAMICS

The beam optics is based on the following principles. The wavenumbers of transverse and longitudinal particle oscillations changes adiabatically along the linac. This feature minimizes the potential for mismatches and helps to assure a current-independent lattice. Derivative of zero-current longitudinal phase advance along lattice is minimized to reduce halo excitation. One should avoid the n=1 parametric resonance (zero current) between the transverse and longitudinal motion. One should avoid also energy exchange between the transverse and longitudinal planes via space-charge resonances either by providing beam equi-partitioning or by avoiding unstable areas in Hofmann's stability charts. For that the ration of longitudinal to transverse phase advances for zero-current is typically kept in range ~0.6-0.8. Proper matching in the lattice transitions is provided to avoid appreciable halo formation. In the perfect "current-independent" design, matching in the transitions is provided automatically if the beam emittance does not grow for higher currents. The length of the focusing period must be short, especially in the front end. Beam matching between the cryostats is achieved: adjust parameters of outermost elements (solenoid fields, rf phase). In the frequency transition at, the longitudinal matching is provided by 90° "bunch rotation", or bunch compression. The beam dynamics in the linac is considered in details in [8,10].

Baseline Design

For lattice design and beam physics studies a few simulation codes have been used: TRACKv39 [11], GenLinWin/TraceWin/PARTRAN and ASTRA. Result received in one code was cross-check with others. All simulations were done for 10 mA peak current. Initial normalized transverse/longitudinal emittances at the entrance of linac (after RFQ) of ~π·(0.25/0.5) mm*mrad. The transverse and longitudinal phase advances depicted in Figure 4(on the top) present some strong but unavoidable jumps due to changing length of the focusing periods at transitions between different types of cavities. The transverse and longitudinal phase advances are kept below 90°. The smooth evolution of the transverse and longitudinal wavenumbers shown in Figure 4(bottom) is achieved by properly selecting the length of the focusing periods and adequately adjusting the synchronous phase and amplitude of each cavity.

Beam tracking simulation done by TRACK and PARTRAN does not show emittance growth in transverse direction and about 10% growth in longitudinal. Codes predict moderate tune depression (0.6-0.8) along the linac, therefore, space charge driven resonances are not a concern for this design. Analysis of Hofmann's stability chart at peak current of 10 mA with a longitudinal to transverse emittance ratio of $\varepsilon_L/\varepsilon_T=2$ does not predict stability problems in the linac.



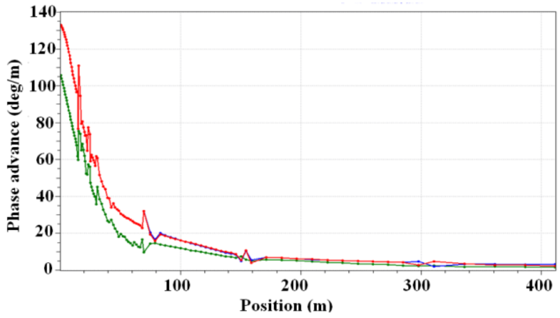


Figure 4: Transverse (red and blue) and longitudinal (green) phase advances (top) and wavenumbers (bottom).

Alternative Designs

The accelerating efficiency of the ILC 9-cell cavities (β=), used to accelerate beam from 2 to 3 GeV in baseline design, is still lower than efficiency of 5-cell 650 MHz (β=0.9) cavities, as shown in Figure 5.

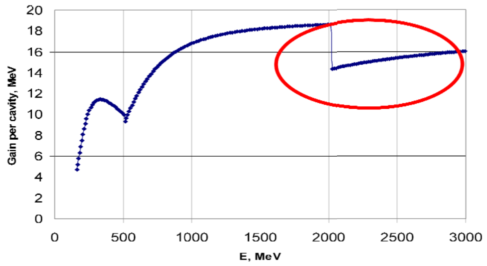


Figure 5: Energy gain per cavity vs. beam energy in two 650 MHz sections and ILC section.

To increase accelerating efficiency it was proposed to avoid ILC section in the linac and use HE650 cavities up to 3 GeV to save number of cavities and RF sources. This schematic is presented in Figure 6. The additional benefits of that are: i) 2-fold frequency jump instead of 4-fold which provides easier transition, ii) smaller beam losses, because of larger aperture; iii) less effect of cavity focusing (scaled as frequency). The trade-offs of such a solution are: i) more serious problem with microphonics in 650MHz cavity; ii) higher cost per cavity.

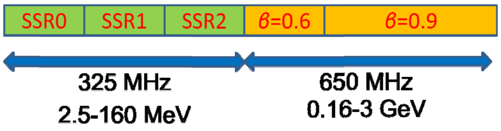


Figure 6: Alternative (without 1.3 GHz section) CW 3GeV linac schematic.

Three possible configurations of alternative designs were developed, according the following assumptions:

- Version.1: ILC section was replaced with HE650 section. No any other modifications.
- Version 2: We are not assuming utilization of ILC type cryomodule for LE650 and HE650 sections. Instead we optimized layout of cryomodule for each section for higher efficiency. Thus in LE650 cryomodule we are using 3cavities per period (CM configuration is

$MR^3MR^3MR^2$, where M-doublet, R-cavity) instead of 2cavities in baseline lattice. Last cavity at the end of cryomodule was omitted to compensate extra-length needed for inter-connection of two cryomodules.

- Version 3: In this lattice all cryomodules are separated by ~2m long room temperature drifts with warm doublets in it as shown in Figure 7. In LE650 cryomodes there are two superconducting doublets and 9 cavities. HE650 cryomodule contains 8 cavities only.

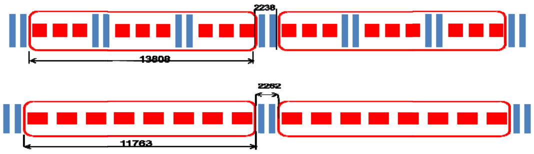


Figure 7: Configuration of Cryomodules for LE650 (above) and HE650 (below) Sections. Cavities are Shown in Red, Doublets in Blue.

Number of components (cavities/cryomodules) in high energy part of the linac and total linac length for baseline and three alternative designs are shown in Table 2. As one can see the utilization of 650 MHz β=0.9 cavities instead of ILC cavities allows to save ~30 cavities and ~40 m of linac length.

Table 2: Transition Energy and Number of Components

Lattice	LE650	HE 650	ILC	Total	Length
Base line	42/7	96/12	72/9	298/35	424
Ver.1	30 /5	152/19	0	270 / 31	374
Ver.2	36 /4	144 / 18	0	268 /29	383
Ver.3	36 /4	144 / 18	0	268 / 29	381

Cavity voltage (gain for particle on-crest) for alternative version 3 design is shown in Figure 8. From picture is clear that 650 MHz cavity perform very well up to final energy 3 GeV.

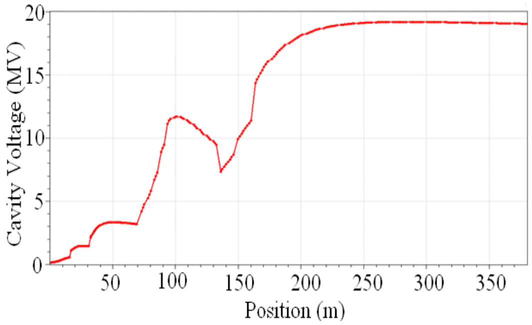


Figure 8: Cavity voltage along the linac.

The required RF power is not exceeded 20kW per cavity and the estimated cryogenic losses are below 27 W/cavity, similar to baseline lattice. The magnetic gradient in doublets is moderate < 10 T/m, the quad aperture of ~100 mm. Beam dynamics simulations done for alternative designs show similar or even better performances compared to baseline design.

Effect of Misalignment Errors and RF Jitter

Effect of misalignment of the beamline components and jitter in phase and amplitude of the cavity field was studied for baseline lattice using TRACKv39 code. Preliminary benchmarking TRACK and ASTRA codes for misalignments errors and RF jitter demonstrated good agreement in simulated losses, including pattern and quantity. It gives us confidence that result presented in Table 3 is correct. One can see that alignment tolerances for magnets should be less than 300 microns, otherwise beam correction are needed. From these studies we observed that beam start loose particles when transverse beam centroid off-set exceeds ~10mm.

Table 3: Effect of Alignment Errors and RF Jitter

Error Type	Limit	Lossy runs out of 400
Solenoid X&Y	300 μm	3
Solenoid θ_x	2 mrad	2
Quad X&Y	300 μm	3
Quad θ_x	>10 mrad	0
Cavity X&Y	> 1 mm	0
Cavity θ_x	10 mrad	6
RF phase jitter	1 deg	20
RF field jitter	1 %	3
RF phase+field	1deg+1%	56

In Project X linac we assume that each magnet has X&Y corrector and has attached (or built-in) BPM with resolution ~30 micron or better. To study alignment correction schemes, we first misaligned all elements, including BMP's, by ±1 mm. RF jitter of 0.5 deg x 0.5 % in the front-end and 1 deg x 1% in the high-energy part was also implemented. Without any corrections the losses are very big, well above 100 W/m. With correction (so called 1-to-1 correction scheme) no beam losses were observed. This correction algorithm, implemented in TRACK, allows control the beam centroid off-set at the level of ±1mm (limited by BPM misalignment). The transverse emittance increases after correction is below 20%. The result of simulations for 100 seeds (each seed represents different machine) and 1 million macro-particles per seed is plotted in Figure 9.

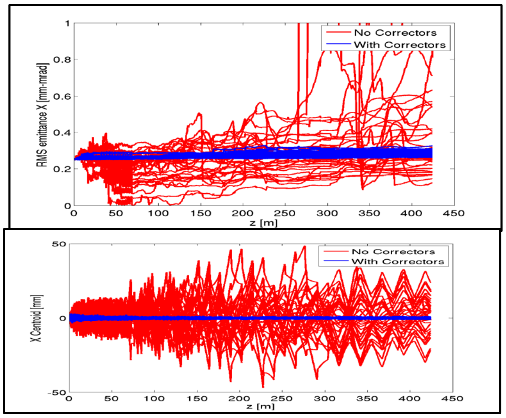


Figure 9: Top: RMS transverse emittance before (red) and after (blue) correction. Bottom: Beam centroid off-set before (red) and after (blue) correction.

Losses due to H^- Stripping

There are few sources and mechanisms of H^- stripping in the linac: residual gas, blackbody radiation, magnetic and electric fields from magnets and cavities and intra-beam stripping. Intra-beam stripping, described in paper [12] was one of our concern for Project-X multi-megawatt beam. The estimations of beam losses due to stripping for baseline and alternative designs were discussed at FNAL Project X collaboration meeting, September 8-9, 2010 [13,14]. The results of studies can be summarized as follow:

- Losses due to residual gas stripping are below 0.1 W/m if pressure in linac is below 10^{-8} Torr at 300 °K (10^{-10} at 3°K). We assume gas contains 25% N, 25%O and 50% H.
- Stripping from magnetic field of solenoids and quads is well below 0.1 W/m even for unrealistically large ~5mm beam offset. Estimations for stripping from cavity RF fields, previously done for Fermilab 8-GeV Proton Driver does not indicate problems from this side.
- Stripping on black body radiation is not an issue for SC linac, though it may give significant contrition in transfer line from Linac to injector.
- Intra-beam stripping was simulated for all designs. From results, shown in Figure 9, one can concludes that contribution from this source is ~0.1 W/m for baseline design and a little bit lower for alternative designs. This level of losses is manageable but nevertheless remains a concern, especially in view of the uncertainties and possible increases for real machine with errors, misalignments and mismatches.

Based on these studies we can conclude that beam losses due to H^- stripping in Project X linac is not severe problem.

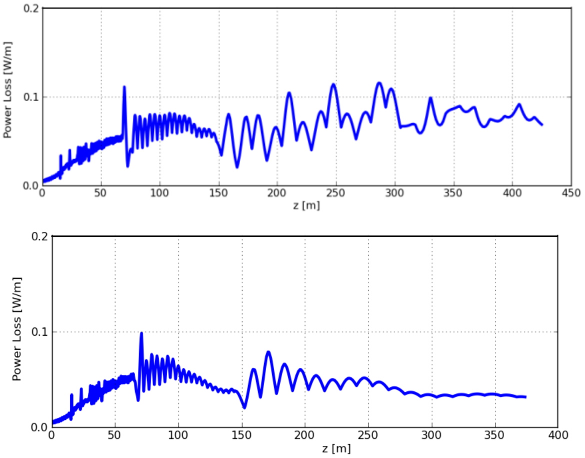


Figure 10: Beam losses due to intra-beam H^- stripping in the baseline design with ILC 1.3 GHz cavity (above) and for alternative design without ILC cavity Ibelow).

SUMMARY

The conceptual design of the CW superconducting H^- linac for 3GeV, 1mA beam, proposed for Project X, looks feasible. Alternative design without 9-cell ILC cavity has some advantages. Further studies are needed to finalize design and make a choice for optimal and reliable configuration of the CW 3 MW linac.

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