THE CONCEPT DESIGN OF THE CW LINAC OF THE PROJECT-X*

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Abstract

The concept design of the 3 GeV superconducting CW linac of the Project X is discussed. The linac structure and break points for different cavity families are described. The results of the RF system optimization are presented as well as the lattice design and beam dynamics analysis.

INTRODUCTION

The Project-X, a multi-MW proton source, is under development at Fermilab [1]. It enables a world-class Long Baseline Neutrino Experiment (LBNE) via a new beam line pointed to DUSEL in Lead, South Dakota, and a broad suite of rare decay experiments. The 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. 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 linac schematic 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.

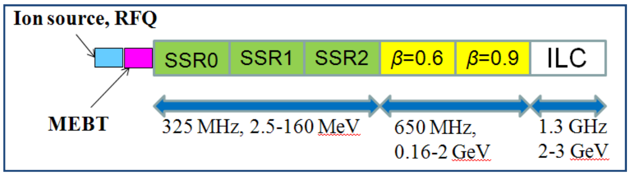

Figure 1: CW 3GeV linac schematic.

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.

MEBT with Beam Chopper

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 (see Figure 2), 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. The cavity voltage is below 160 kV, and the power dissipation not exceeds 5 kW. The chopped out bunches are dumped in the four targets. This scheme provides high chopping efficiency, thus transmitted fraction of the chopped beam is $<10^{-4}$ [3].

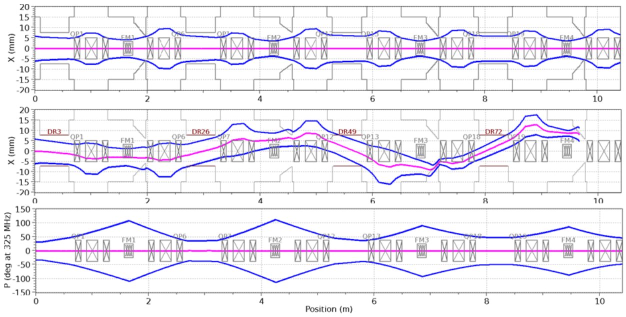

Figure 2: Proposal for lattice design for MEBT. Picture shows X-envelopes of the un-chopped beam (upper), chopped beam (middle) and longitudinal envelope.

Superconducting Cavities

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 MHz: SSR0 (beta=0.12), SSR1 (beta=0.22) and SSR2 (beta=0.4). Status of the spoke cavities design and prototyping and tests are presented here [2]. 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, 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.

Working gradient at the cavities was chosen to provide the peak surface magnetic field that allows operation below high-filed Q-slope [4], 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.

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Table 1: Parameters of the linac sections

Section	Freq MHz	Energy MeV	# Cavity/ Focusing /CM	Element Type
SSR0 beta=0.11	325	2.5-10	26/ 26/ 1	Single-spoke, Solenoid
SSR1 beta=0.22	325	10-32	18/ 18/ 2	Single-spoke, Solenoid
SSR1 beta=0.4	325	32-160	44/ 24/ 4	Single-spoke SR, Solenoid
LB 650 beta=0.61	650	160-520	42/ 21/ 7	5-cell cavity Doublet
HB 650 beta=0.9	650	520-2000	96/12 /12	5-cell cavity, Doublet
ILC beta=1	1300	2000-3000	64/ 8/ 8	9-cell cavity Quad

Transition from the front-end operating at 325 MHz based on single-spoke cavities [2] to 650 MHz section based on elliptical cavities is chosen at the energy of H$^-$ of 160 MeV, because for lower energy elliptical cavities are not efficient. In order to achieve good efficiency two families of 650 MHz cavities may be used. Optimization was made for the transition energy between the two families and their geometrical betas (Figure 3). In simulation we assume 5-cell elliptical cavity. Optimal geometrical betas for both sections are in the range of 0.61-0.64 and 0.87-0.93 respectively (upper figure). Optimal transition energy is ~460 MeV (lower figure), where the gain per cavity is equal in both sections. Initial synchronous phase is -30°, and it increases with the energy as a square root. More exact simulations taking into account realistic enhancement factors show betas of 0.61 and 0.9.

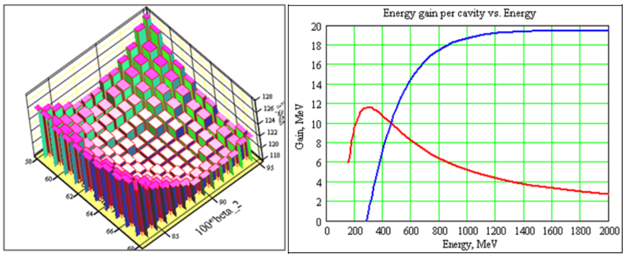
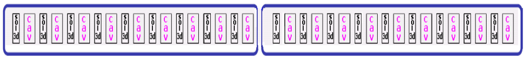


Figure 3: Number of cavities versus betas in the first and second sections (left). Gain per cavity versus the particle energy in both sections.

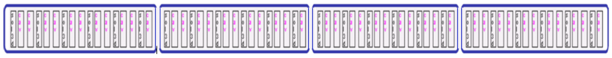
Cryomodules and Cryo-segmentations

All crymodules in Low-Energy (325 MHz) part of the linac are separated by short RT sections in order to provide (i) maintenance and reliability, (ii) beam profile diagnostics in RT drifts, (iii) possible dump (reduction of aperture) for halo cleaning in accelerator. High Energy (HE) 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. Beam profile measurements available between in warm sections. Halo cleaning in warm sections is also assumed.

1 CM SSR0: 26 cavities, length of CM is 11-16 m;



2 CM SSR1, 9 cavities, length of CM is 7.2 m



4 CM SSR2, 11 cavities, length of CM is 9.6 m

Figure 4: Segmentation of the 325 MHz linac front end.

Cryomodule segmentation in the 325 MHz front end is shown in Figure 4. For SSR2 section we use two cavities per period, except the end of cryomodule, where only one cavity is used to provide quasi periodic structure for transverse beam dynamics. The length of the warm sections is to be minimized. An idea of the warm section between SSR0 and SSR1 is shown in Figure 5. The cryomodule configuration in the high-energy part is shown in Figure 6. For 650 MHz section a modified ILC cryomodule is considered, with the three slots, available for doublets, see Figure 7.

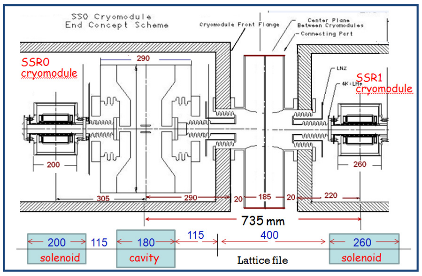


Figure 5: Concept of the warm section between SSR0 and SSR1.

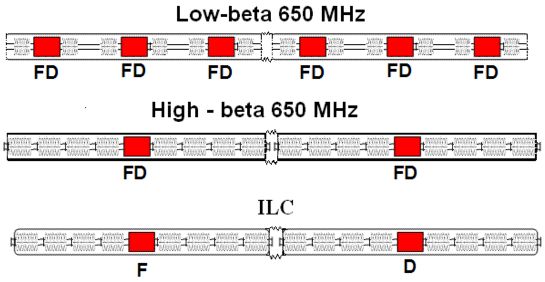


Figure 6: Cryomodule segmentation for high-energy part of the linac

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 HE linac is assembly into cryo-strings, containing 6-8 cryomodules per string with the arm intewrconnection 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

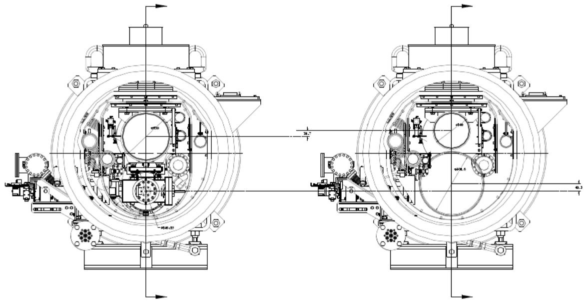


Figure 7: Modified cryomodule for 650 MHz (left) compared to a standard typ-4 ILC cryomodule (right).

RF Power

Power requirements for the cavities are shown in the Table 2. 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, in ERL's they consider operation of SC cavities at Q_{Load} up to 10^8 using special system of the amplitude and phase stabilizing [5].

Table 2: Power requirements for the linac cavities.

Cavity type	Freq MHz	Power +25%	RF kW	Q_{ext}	Bandwidh Hz
SSR0	325	0.63	5	6.5e6	50
SSR1	325	1.9	5	6.5e6	50
SSR2	325	4.0	5	1.e7	33
LB-650	650	14	25	3.3e7	20
HB-650	650	23	25	3.4e7	19
ILC	1300	20	25	1.7e7	76

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 cheap. Example of the coupler for 1.3 GHz section is shown in Figure 8.

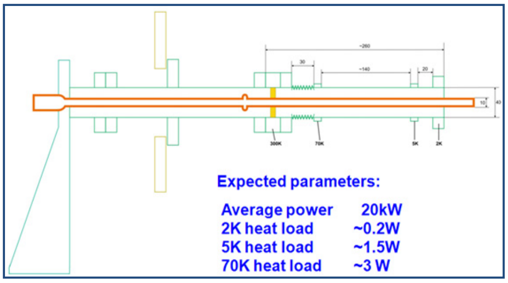


Figure 8: Possible configuration of 1.3 GHz coupler. Coupler has the same connections as TTF-III coupler.

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.

Lattice Design

The beam optics are 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 [6].

Summary

The conceptual design of the CW superconducting H^- linac for 3GeV, 1mA beam, proposed for Project X, looks feasible.

REFERENCES

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