UPDATE OF BEAM OPTICS AND SRF CAVITIES FOR PROJECT X*

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Abstract

The Project X staging [1] requires reconsideration of the beam optics and thus, the SRF system for the 3 GeV Project X CW linac. The revised beam optics, a new concept of the linac segmentation and an update on the cavities are presented in the paper. The new versions for the Project X cryo-modules for the SSR2 section, low-beta 650 MHz section and high-beta 650 MHz section are discussed. The beam separation scheme at 1 GeV is also discussed.

UPDATE OF THE BEAM OPTICS AND LINAC CONFIGURATION

The unique feature of the Project X [1] is a capability of delivering a MW-range proton beam to several experiments quasi-simultaneously with a beam structure that can be adjusted to each experiment's needs. A structure of CW superconducting linac is presented in Figure 1.

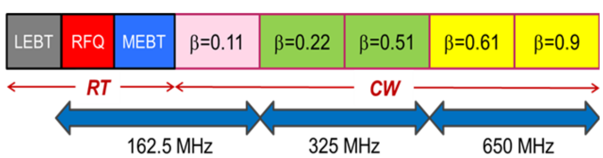

Figure 1: Structure of the CW 3 GeV linac.

Table 1: The Project X SRF cavities and cryomodules

Section	Freq MHz	Trans. Energy (MeV)	Cavity /magn /CM	Gain MV	Q_0 10^{10}	CM conf
MEBT	162.5	2.1	3/10/	0.1	n/a	n/a
HWR	162.5	9.13	8/8/1	1.7	0.5	8^{x}(sc)#
SSR1	325	32.44	16/8/2	2.4	0.8	4^{x}(csc)
SSR2	325	155.8	35/21/7	5.0	1	scscscsc
LB650	650	487.8	36/12/6	11.5	2	cccdccc
HB650[1]	650	1000	42/7**/7	17.5	2	6^{x}(c)
HB650[2]	650	3000	120/15**/15	17.5	2	8^{x}(c)

**warm doublets, # s – solenoid, c-cavity, d – doublet.

An acceleration to 2.1 MeV and formation of the required bunch structure is provided by room temperature sections (~15 m) consisting of LEBT, RFQ and MEBT [2]. The full scale model of Project X frontend (PXIE) [3,4] will address the most challenging issues in this part of the linac. In recently proposed staging scenario [5] the whole 3-GeV linac is divided into two parts connected by 180° arc to reduce the cost and tunnelling for Stage I. Second part of the linac will accelerate the beam from 1 to 3 GeV and will use only one type of cryomodule with 650 MHz 5-cell β = 0.9 cavities in configuration shown in the last row of Table.1.

Since last presentation of the Project X linac configuration and beam dynamics simulations [6,7] a several changes were implemented recently. The major changes are:

- LEBT was modified to implement un-neutralized section from LEBT chopper to RFQ to eliminate optics changes due to ion accumulation at transition from "Beam OFF" to "Beam ON". As a drawback we have larger emittance growth in this section due to space-charge. It still is acceptable for the linac.
- Introduction of the RF splitter and achromatic/ isochronous 180° arc (~100 m) after 1 GeV part of the linac. It will allow having 1 MW beam for experimental program at 1 GeV and support staging scenario of the Project X [8].
- New design of the SSR2 spoke cavity with β = 0.51 and aperture 50 mm to replace the previously considered β = 0.47 cavity with 40mm aperture. This decision was made to get an advantage of collaboration between Project X (FNAL) and RISP (South Korea). The common design will be beneficial for both projects and will save R&D time and cost.
- The above item resulted in a new proposal for SSR2 cryomodule design. Compared to the previous proposal the new design will be shorter (6.5 m vs. 8.2 m) and will contain 5cavities and 3 solenoids (vs. 9 cavities and 5 solenoids.)
- A new design of the 650 MHz elliptical 5-cell high beta (geometrical β = 0.92) cavity was proposed to address monopole HOM excitation issues for the future high beam current upgrades of Project X. This cavity has a larger aperture of 120 mm and its cell shapes are optimized for lower surface electric and magnetic field enhancements. The cavity is free from trapped monopole HOMs and, thus, it has less probability of HOMs excitation, which reduces a technical risk for the project. In particular it allows us to eliminate a chance of significant cryogenic losses and longitudinal emittance growth [9]. This cavity can be also used application such as ADS linacs developed by India and China creating an attractive subject for collaborations [10,11].
- Number of cavities in higher energy cryostat used in the first stage was reduced from 8 to 6 to reduce

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focusing period at a relatively low energy. In 1-3 GeV linac we assume using a cryomodules with 8 cavities as it was in the previous proposal.

- After acceleration in 3 GeV linac a fraction of the beam (~5%) will be directed to the pulsed 3-to-8 GeV linac for further acceleration and subsequent injection into the Recycler/MI for the neutrino experimental program. The optics between CW and pulse linacs includes RF splitting section and quite long achromatic/isochronous 180° arc (~300 m) optimized for 3 GeV beam. The same as 1 GeV arc the 3 GeV arc contributes to the emittance growth related to the space charge effects in the course of beam transport.

All described above changes were incorporated in the optics and the first set of optimizations and beam dynamics studies was completed. This design is currently used as a basis for the baseline proposal described in more details in Project X RDR [1]. The 1σ transverse and longitudinal beam envelopes along entire linac, including both arcs, are shown in Figure 2.

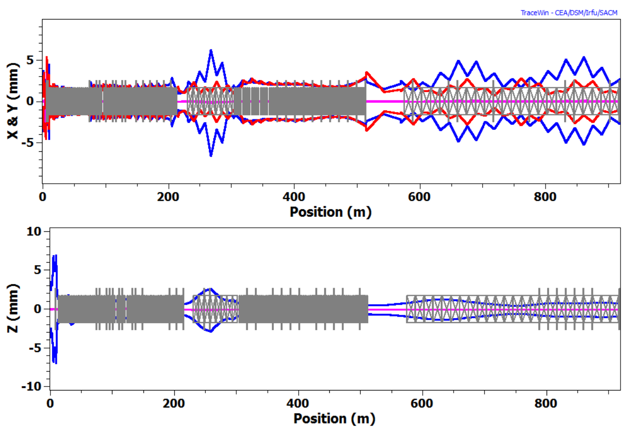

Figure 2: 1σ beam envelopes (transverse *X/Y* above and longitudinal *Z* below) in the 3 GeV CW linac.

SSR2 SECTION

SSR2 cavity design has been changed significantly. It resulted in changes of the main parameters such as the optimal beta and the beam tube aperture. The beta was increased from 0.47 to 0.51 and the beam pipe diameter from 40 mm to 50 mm. This cavity is capable of delivering a 5.3 MeV maximum energy gain (for a particle with optimal beta and 0 synchronous phase) at the surface peak magnetic field of 70 mT, [12]. One of the known issues with SSR2 cavity is the transverse field asymmetry which leads to an asymmetric transverse focusing for accelerated particles [13,14].

If uncompensated, an absence of symmetric focusing induces a beam envelope beating in otherwise axial symmetric transport supported by solenoidal focusing. Two ways of addressing this problem have been developed. The first solution was suggested in [13], and it implies a rotation of nearby cavities by 90° around the axis. The second solution relies on a quadrupole correction provided by correctors located inside solenoids. The field asymmetry in the cavity originates from asymmetry of the inner conductor (spoke) which breaks the azimuthal symmetry. It introduces different transverse fields for components along and transverse to the spoke axis. Both magnetic and electric fields contribute to this asymmetric focusing. The magnetic component is not negligible for SSR2 cavities, due to the particle beta having medium-high values [14]. The new SSR2 design shows a higher kick asymmetry, especially in the first part of the beta domain (see Figure 3). However it is still well within strength delivered by the quadrupole corrector placed in the SSR2 section.

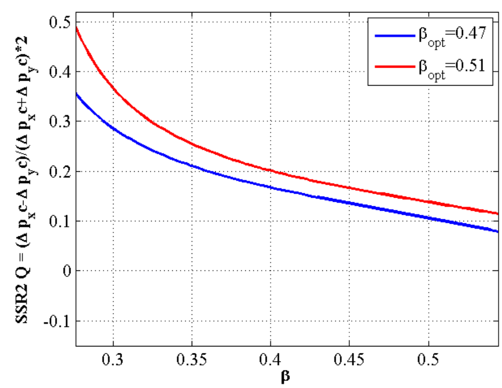

Figure 3: Asymmetry parameter Q (ratio between the quadrupole amplitude and an averaged radial kick) vs. particle β.

The new SSR2 cryomodule is shorter than in the earlier version (~6.5m vs. 8.2m), but spacing between cavities is increased. RISP is planning to use 8 cavities in CM. Project X need more focusing, therefore every third cavity is replaced by SC solenoid. Finally cryomodule has 5 cavities and 3 solenoids with the configuration shown in Table 1. In contrast, the previously proposed cryomodule contained 9 cavities and 5 solenoids with shorter period (distance from solenoid to solenoid)

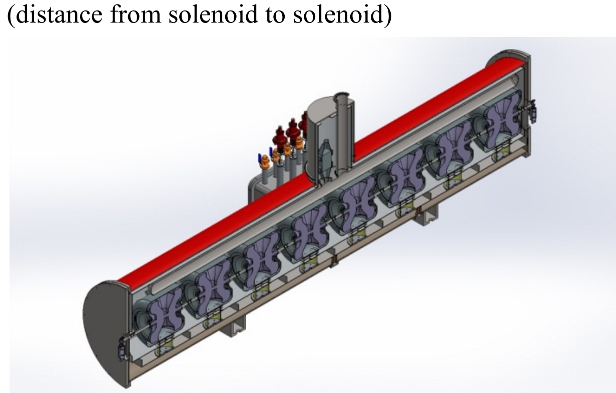

Figure 4: SSR2 cryomodule with 8 cavities (RISP).

HIGH BETA SECTION

The base design of the β=0.9 cavity for Project X is optimized for 1mA beam current and a low bunch charge. It completely satisfies the baseline Project X specifications. Unfortunately this design has a weak coupling of the 5[th] monopole passband with the beam pipe (see Figure 5) resulting in trapped monopole modes with high Q_{ext}. It potentially could compromise the beam emittance and increase the cryogenic losses at the high beam current operation. There are two possible ways to correct it: a) by changing the cell length (geometrical beta) and b) by changing the beam pipe aperture. Increasing geometrical beta has an advantage because it provides the cell shape with lower surface fields. A large cell aperture has following evident advantages: a) higher cell to cell coupling and a better field flatness; b) lower possible beam losses for a high beam current operation; c) better coupling with operating mode and reduced coupler antenna penetration; d) lower HOMs quality factors and, thus, reduced potential of cryogenic losses.

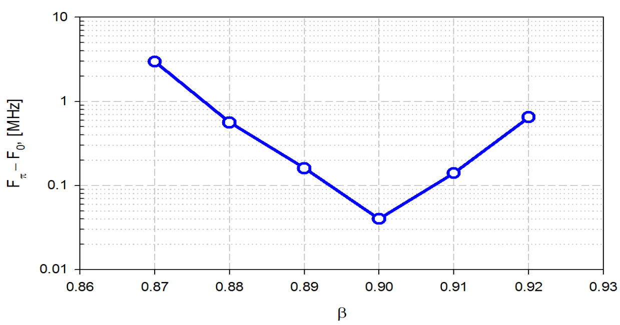

Figure 5: The width of the 5th monopole band vs beta for the base design of the β=0.9 cavity.

Simulations predict only ~2.5% surface magnetic field enhancement if we would increase both the cell aperture to 120 mm and the cell period to β_{geom} = 0.92. Thus, we decided to propose these parameters as an alternative for the Project X high beta cavity. Finally we analyzed the entire geometry of the 5-cell accelerating structure and compared it with the present design. The results of the comparison are shown in Table 2.

Table 2: Parameters of old (blue) and new (red) 5-cell accelerating structures

Quantity	Old	New
G, Ω	256	260
R_{sh}/Q_0 max, Ω	638	609
β_{opt}	0.95	0.97
E_{surf}/E_{acc}*	2.08	2.04
B_{surf}/E_{acc}*, mT/MV/m	3.81	3.85
K_{couple}, %	0.75	1.29
Monopole HOM Q_{ext}	10^{10}	10^6

* $E_{acc} = E_{cav}/L_{cav}$, where L_{cav} = 1044 mm for both cavities

The major advantage of the proposed cavity is that the quality factors Q_{ext} of the monopole HOMs are suppressed below 10^6. At the same time both structures have similar RF losses and acceleration efficiency and, thus, it is possible to keep the same layout of the high-energy part of the linac.

The proposed alternative cavity shape allows to suppress high-Q monopole HOMs completely and, thus, to mitigate the large cryo-losses problem and to limit the beam longitudinal emittance growth by factor of two maximum. [9].

The 6-cavity HB650 cryomodule design proposed for 1 GeV linac is shown in Figure 6. The flange-to-flange length is 9.479 m. The distance between cryomodules is 1.6 m. It includes a room temperature doublet (0.8 m) and space for beam diagnostics and collimators. The cryomodule for 1-3 GeV linac has the same design, but is longer to accommodate 8 cavities.

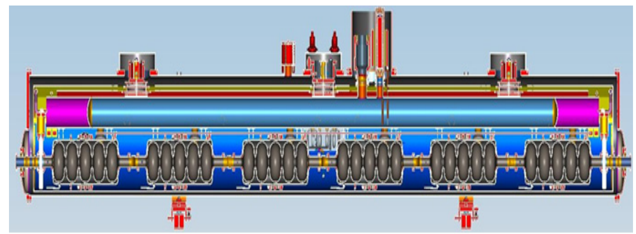

Figure 6: Layout of the HB650 cryomodule with 6 cavities for 1 GeV section.

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