650 MHz OPTION FOR HIGH-ENERGY PART OF THE PROJECT X LINAC*

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Abstract

650 MHz option for the high energy part of the 3 GeV, CW Project X linac is discussed. It may give significant benefits compared to current 1.3 GHz option based on the utilization of ILC-type beta=1 cavities. Results of the break point optimization for linac stages and cavity optimization are presented. Possible reduction in the number of cryomodules and linac length compared to the current linac project version is discussed. Cryogenic losses are analyzed also.

INTRODUCTION

The initial proposal for the Project–X 2 MW H$^-$ - source (ICD-1) was based on 8-GeV pulsed SC linac [1], which conceptually was close to the earlier proposed design for Proton Driver [2]. In this document the high–energy part of the SC linac consisted of two sections: S-ILC section based on beta=0.81squeezed elliptical cavities for the acceleration from ~400 MeV to 1.2 GeV, and ILC section, based on the 9-cell, beta=1 ILC-type cavities for acceleration up to 8 GeV. However, recent design of Project-X, ICD-2 [3] demands 3 MW, CW linac, which should deliver 3 GeV H$^-$ beam with the average current of 1 mA. At this energy range the ILC cavity does not work effectively, because the transit time factor depends strongly on beam beta, and for the H$^-$ of 1.2 GeV it is only ~60% of maximal, as shown in Fig. 1.

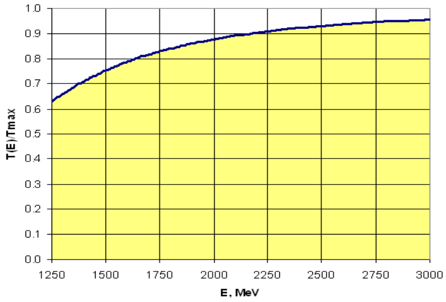

Figure 1: Transit time factor versus the H energy for the 1.3 GHz, ILC-type cavity.

The transit time factor dependence on beam velocity (β) is shown in Fig. 2 for different number of cells in a cavity. One can see that in order to improve the transit time factor, and thus, increase the acceleration gradient at given RF fields in the cavity, one should use the cavities containing smaller number of cells. Another way is to use a family of cavities with different geometrical beta, which is unacceptable. If one uses 5–cell cavity, it gives the possibility to improve the transit time factor and, thus, reduce the number of the cavities significantly.

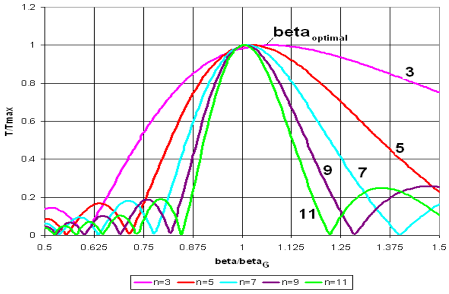

Figure 2: Transit time factor versus the the ratio of the beta to the geometrical beta for different number of cells in a cavity *n*. Geometrical beta is a ratio of the cavity period to the half-wavelength (the cavity operates in CW π-mode).

In order to keep about the same length as for ILC cavity, the same energy gain per cavity and the same power requirements, one should use two times lower frequency, or 650 MHz. Utilization of the lower frequency gives the following benefits:

- It simplifies the beam dynamics; Project-X front end operates at 325 MHz, and 2-fold frequency jump at transition to the high energy stage for 650 MHz is easier than 4-fold for 1.3 GHz.
- Lower frequency allows larger aperture that is essential for proton linacs (because of activation, the losses should be smaller than 1 W/m).
- Losses caused by intra-beam stripping will be smaller for lower frequency as well.
- Also the effect of acceleration cavities focusing will be smaller at lower frequencies.
- HOM impedances (transverse and longitudinal) are smaller at lower frequency, and it may in principle allow to get rid of HOM dampers, which may be a source of many problems for proton accelerators (multipactoring, RF leak, etc).
- 650 MHz concept is similar to SNS, SPL and ESS, that allows use their experience

However, there is a trade-off of lower frequency application:

- More serious problem with microphonics, but still may be manageable.
- Cavities for 650 MHz are more expensive (more niobium), but increase in price is compensated by smaller number of the cavities and RF sources.

Note that the cryogenic losses for lower frequency option may be about the same because of smaller number of the cavities.

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GENERAL

Working gradient was chosen to provide the peak surface magnetic field that allows operation below high-filed Q-slope, see Fig.3 taken from [4]. For the frequency of 650 MHz the peak magnetic field should be not greater than ~70 mT. For another hand, peak surface electric field is to be lower than 40 MV/m [5] in order to avoid probability to get strong field emission.

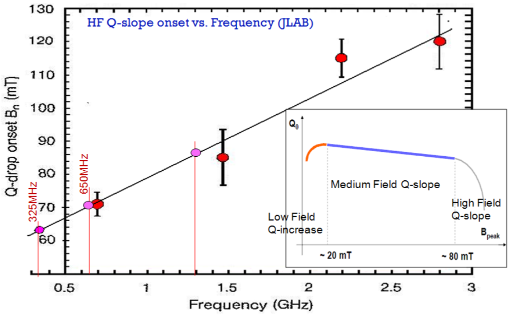

Figure 3: High field Q-slope level versus frequency.

Transition from the front-end operating at 325 MHz based on single-spoke cavities [6] 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. For H^- acceleration above 2 GeV 1300 MHz, beta=1 ILC-type cavities may be used, because the transit time factor for these energies is already high enough. It is inefficient to accelerate H^- from 160 MeV to 2 GeV using the same type of a cavity. In order to achieve good efficiency two families of 650 MHz cavities may be used.

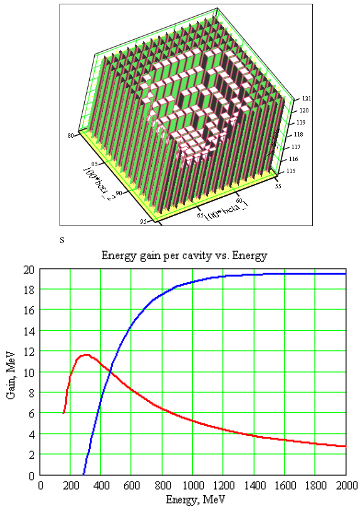

Figure 4: Number of cavities versus betas in the first and second sections (upper and middle figures). Gain per cavity versus the particle energy in both sections.

Optimization was made for the transition energy between the two families and their geometrical betas supposing the linear dependence of the field enhancement factors versus beta [7], see Fig. 4. Optimal geometrical betas for both sections are 0.64 and 0.9 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. Thus, the entire linac schematic is as shown in Fig.5, 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.

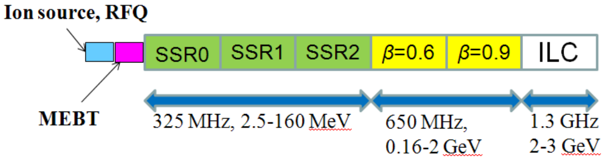

Figure 5: 3 GeV CW Project linac schematic.

Cavity Design

The goal of the cavity shape optimization was to decrease the field enhancement factors (magnetic and electric) to improve the interaction between the beam and the cavities. In order to do this, the cavity aperture should be as small as possible. One has the following limitations for the cavity aperture: (i) field flatness, (ii) beam losses, (iii) mechanical stability, (iv) reliable surface processing. For given relative error in the frequencies of the cavity cells field flatness is determined mainly by the distance between the operating frequency and the frequency of the neighbouring mode $\pi(n-1)/n$, as follows from the linear perturbation theory [8], or by the coupling k between the cavity cells and the number of cells:

$$\delta E/E \sim f_\pi/|f_\pi - f_{\pi(n-1)/n}| \equiv f_\pi/\delta f \approx 1/kn^2.$$

Thus, for required field flatness $k \sim 1/n^2$, and the cavity with smaller number of cells allows smaller coupling k. For 9-cell ILC cavity one has $\delta f/f_\pi$ of 6e-4 (k=1.87%). For 5-cell cavity one can take the same $\delta f/f_\pi$ at least, that gives k > 0.6%. For comparison, the cavity aperture for 805 MHz high-energy part of SNS proton linac that is close to Project-X linac in average current is 83 mm for low-beta part, and 100 mm in high-beta part. Thus, it is possible to use about the same apertures that allow the same beam losses. It looks like these apertures allow relevant surface processing. However, 650 MHz cavities require the walls thicker than for 1.3 GHz. In Fig.6 the results are shown of the simulation of the cavity sag caused by it's weight. Maximal sag of the ILC cavity is 120 µm for 2.8 mm wall thickness. In order to have the same sag for 650 MHz cavity having 100 mm aperture, the wall thickness is to be ~4 mm. Note that small cavity wall slope gives more freedom to decrease the field enhancement factors. However, the slop is limited by surface processing and mechanical stability requirements. For beta=0.9 we selected the slope of 5°. For beta=0.61 it is a problem to get considerably low field enhancement factor for this slope, and we reduced it to 2°, that looks still acceptable. Basing on constrains mentioned above, optimization of the cavities for both beta values, 0.9 and 0.61, was made.

In the Figure 7 layout of the cavities is shown. Parameters are shown in Tables 1 and 2. Cryogenic losses in the cavities are determined by R/Q value, G-factor and surface resistance that in turn is a sum of residual resistance and BCS resistance.

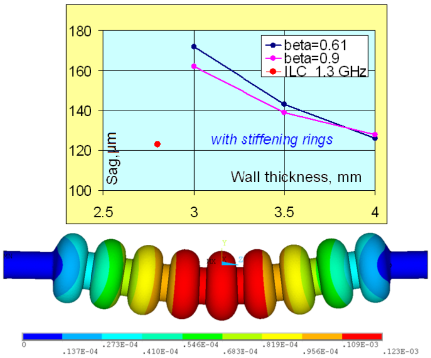

Figure 6: The cavity sag versus the wall thickness.

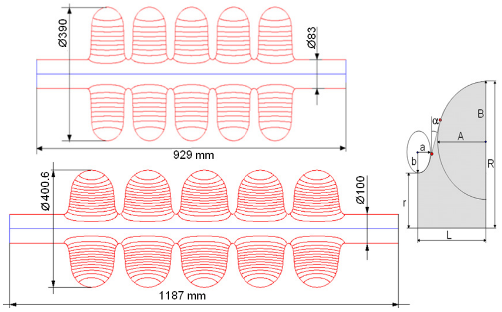

Figure 7: Layout of 650 MHz cavities. Beta=0.61(top) and beta=0.9 (bottom).

Table 1: Dimensions of the 650 MHz Cavities

Dimension	Beta=0.61		Beta=0.9	
	Regular cell	End cell	Regular cell	End cell
r, mm	41.5	41.5	50	50
R, mm	195	195	200.3	200.3
L, mm	70.3	71.4	103.8	107.0
A, mm	54	54	82.5	82.5
B, mm	58	58	84	84.5
a, mm	14	14	18	20
b, mm	25	25	38	39.5
α,°	2	2.7	5.2	7

Table 2: RF Parameters of the 650 MHz Cavities

Beta	0.61	0.9
R/Q, Ohm	378	638
G-factor, Ohm	191	255
Max. gain per cavity, MeV(on crest)	11.7	19.3
Gradient, MeV/m	16.6	18.7
Max. Surfae electric field, MV/m	37.5	37.3
E_{pk}/E_{acc}	2.26	2
Max surf magnetic field, mT	70	70
B_{pk}/E_{acc}	4.21	3.75

Modern surface processing technology may provide a residual resistance of ~5 nΩ (see, for example, [9]). BCS resistance at a function of the frequency f and temperature T may be estimated using formula

$$R_{BCS} = 2.10^{-4}\frac{1}{T}\left(\frac{f}{1.5}\right)^2 e^{-17.67/T}$$

that gives some average value of the resistance among the the results achieved for different cavities. For 650 MHz one has ~3 nΩ for BCS and, thus, ~8 nΩ total.

Table 3: Parameters of the Linac Sections

Section	Freq, MHz	Energy MeV	# of C/FE/CM	component type
SSR0 beta=0.11	325	2.5-10	26/26/1	Single-spoke cavity, Solenoid
SSR1 beta=0.22	325	10-32	18/18/2	Single Spoke cavity, Solenoid
SSR2 beta=0.4	325	32-160	44/24/4	Single Spoke cavity, Solenoid
LB 650 beta=0.61	650	160-520	42/21/7	5-cell cavity, doublet
HB 650 beta=0.61	650	520-2000	96/12/12	5-cell cavity, doublet
ILC beta=1	1300	2000-3000	64/8/8	9-cell cavity, quad

Assuming medium field Q-slope at the peak field of 70 mT is about 30% that gives the target for Q value of the 650 MHz cavity of ~2e10 [9], and losses at the operating gradient of ~30 W/cavity, or <250 W/cryomodule. The beam dynamics were optimized in the 650 MHz sections [10], and in Table 3 the number of cavity (C), focusing elements (FE) and cryomodules (CM) in each section is shown.

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