SRF CAVITIES FOR CW OPTION OF PROJECT X LINAC

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Abstract

Alternative option of Project X is based on the CW SC 2GeV Linac with the average current 1mA. Possible option of the CW Linac considered in the paper includes low energy part consisted of a few families SC Spoke cavities (from 2.5 MeV to 466 MeV) and high energy part consisted of 2 types of elliptical cavities (v/c=0.81 and v/c=1). Requirements and designed parameters of cavities are considered.

INTRODUCTION

An alternative scheme [1] of the Project X proton source is based on the 2 GeV CW superconducting linac that accelerates H^- beam with the current of 1 mA, see Figure 1.

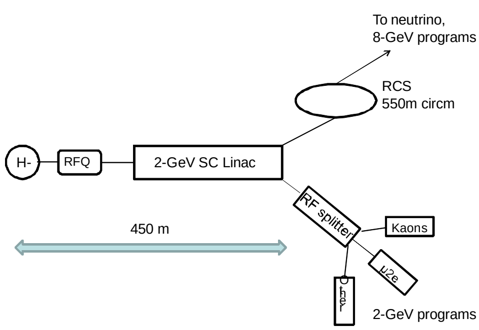


Figure 1: Layout of the 2 GeV proton source.

The beam originates from a DC H^- source. The beam is then bunched and accelerated by a CW normal-conducting RFQ to 2.5 MeV and the bunches are formatted by a chopper following a pre-programmed timeline. From 2.5 MeV to 2 GeV the H^- bunches are accelerated by a CW super-conductive linac. A present concept of the linac is based on the 8 GeV pulse linac design [2], including designs of cavities, cryomodules and beam optics (to the extent possible). The CW, 2-GeV linac has an average current (over few microseconds) of 1 mA, with a pulsed current of up to 10 mA. Since the pulsed 8-GeV Project X linac (ICD-1) has a well developed optics operating at this current range, it is possible to use the same structure of the linac and same break points as in the pulsed linac with the necessary modifications to operate in a CW regime.

GENERAL

The CW linac (see Figure 2) consists of a low-energy 325 MHz SCRF section (2.5 - 450 MeV) containing three different families of single-spoke resonators (SSR0, SSR1, SSR2) and one family of a triple-spoke resonator (TSR), and the high energy 1.3-GHz SCRF section (450 MeV – 2 GeV) containing squeezed elliptical β_G =0.81cavities (S-ILC), and ILC-type β_G=1 cavities.

The major modification in the low energy (325-MHz) part of the initial pulse linac design [3] necessary for CW operation includes replacing buncher cavities and 16 room temperature cross-bar cavities with the SC spoke cavities. The break points between sections containing the cavities of different types are shown in Table 1. The bunching cavities together with focusing solenoids are presented. The number of focusing elements and cryomodules are also shown.

Table 1: Break points between the sections in the low-energy part of the linac β_G is cavity geometrical phase velocity.

Section	Energy range MeV	β	Number of cavities/ lenses/CM	Type of cavities and focusing element	Power/cavity, kW (I_{av}=1 mA)
Bunching SSR0 (β_G=0.11)	2.5	0.073	2/3/2	Single spoke cavity, Solenoid	0.5
SSR0 (β_G=0.11)	2.5-10	0.073-0.146	16/16/2	Single spoke cavity, Solenoid	0.5
SSR1 (β_G=0.22)	10-32	0.146-0.261	18/18/2	Single spoke cavity, Solenoid	1.3
SSR2 (β_G=0.4)	32-117	0.261-0.5	33/17/3	Single spoke cavity, Solenoid	4.1
TSR (β_G=0.6)	117-466	0.5-0.744	48/48/8	Triple spoke cavity, quads	8.5

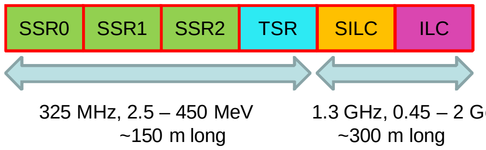


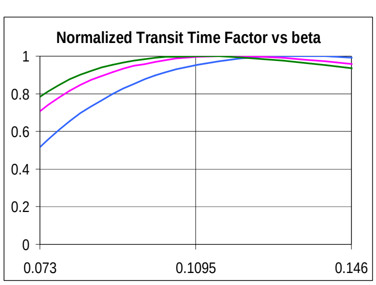
Figure 2: The schematic of the CW linac (2.5 MeV – 2 GeV).

2.5-10 MeV: a single family of CW Spoke (SSR0) SC cavities may be used for acceleration for the beam energy from 2.5 MeV to 10 MeV. The SSR0 cavity for beta =0.073-0.146 was optimized, and the results of optimization are shown in Table 2.

Table 2: SSR0 cavity parameters.

Operating frequency	325	MHz
β_G	0.117	
Cavity diameter	200	mm
R/Q	120	Ω
Average transit time factor (TTF)	0.94	
Electric field enhancement factor, $(E_{max}/E_{acc})/(E_{max}/E_{acc*})$	5.5/5.85	
Magnetic field enhancement factor, $(H_{max}/E_{acc})/(H_{max}/E_{acc*})$	6.5/6.9	[mT/MV/m]
Cavity effective length, $D_{eff} = 2*\beta\lambda/2$	108	mm

Here $E_{acc*}=E_{acc}(\beta_G)\times TTF$ and TTF is the transit-time factor. The transit time factor versus beta and the field pattern are shown in Figure 3. Experience with SSR1-02 cavity at Fermilab shows that it is possible to achieve the maximum gradient of 25 MeV/m at 4°K, and 33 MeV/m at 2°K, see Figure 4. The gradient of E_{acc}= 15 MeV/m looks reasonable for CW operation. It corresponds to the maximum surface electric field $E_{max}\approx$ 40 MV/m and magnetic field $H_{max}\approx$ 60 mT. For fixed H_{max}= 60 mT the energy gain vs. beta is shown in Figure 3a. The green curve corresponds to the gain per cavity for the RT cavities of the ICD-I 8 GeV pulsed linac. One can see that the chosen design can provide the required gain per cavity.



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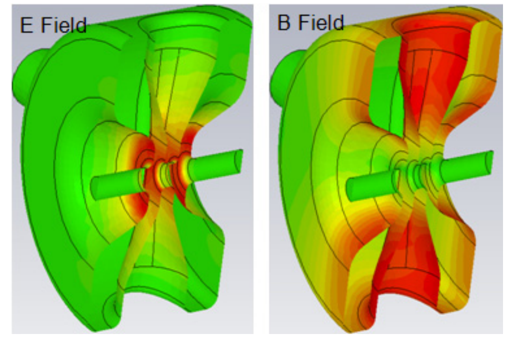


b) c)

Figure 3: The transit time factor vs. proton beta (a) and cavity layout with field pattern (b,c). One can see (figure c) that the surface magnetic field is distributed homogeneously on the spoke surface.

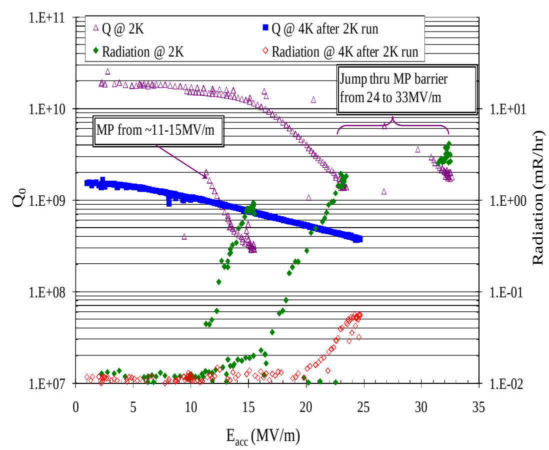


Figure 4: Q_0 vs. acceleration gradient E_{acc} from the first cold test of SSR1-02 single-spoke cavity (beta = 0.22). In pink the quality factor versus the gradient is shown on different stages of the cavity conditioning at 2 K. In blue the quality vs the gradient is shown at 4 K after 2K run. Maximal E_{acc}= 25 MeV/m @4K; 33MeV/m@2K.

10-466 MeV: Other parts of 325 MHz SC linac are the same (SSR1, SSR2, TSR) as in the ICD-I 8 GeV linac. Parameters of the cavities are shown in Table 3. Single spoke 325 MHz cavity SSR1 having β_G =0.22 was designed and built for the HINS project. The cavity layout is shown in Figure 5. Results of the cavity tests are shown in Figure 4, see above. The surface resistance dependence on the temperature is shown in Figure 6. One can see that the resistance at 4 K, and thus, quality factor, are more than 10 times higher than at 2 K. Conversion factor for cryogenics for 2 K is 700 W/W versus 200 W/W for 4 K, thus, the ratio is 3.5 (see also Table 4). It means that from efficiency point of view it is preferable to work at 2 K. In addition, at 2 K the level of microphonics is much smaller. However, average RF power requirements for CW operation are higher, and the coupler should be redesigned.

Table 3: Parameters of the spoke cavities.

cavity type	F [MHz]	E_{acc} [MV/m]	L_{eff}, mm	Ep/E_{acc}	B_p/E_{acc} mT/(MV/m)	R/Q Ω	G Ω	$Q_{0,2K}$ $\times10^9$	$Q_{0,4K}$ $\times10^9$	P_{2K} [W]	P_{4K} [W]
SSR0	325	8.7	72	4.1	4.6	120	57	9.5	0.7	0.34	4.67
SSR1	325	10.8	135	2.62	3.87	242	84	14.0	1.0	0.63	8.78
SSR2	325	13.6	246	2.42	3.95	322	112	18.0	1.3	1.93	26.74
TSR	325	9.75	943	3.22	6.85	554	117	19.0	1.4	8.03	108.99

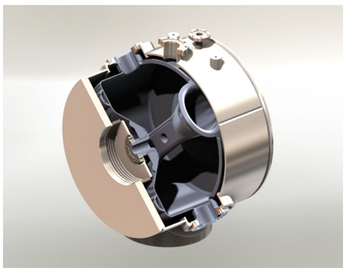


Figure 5: SSR1 cavity layout.

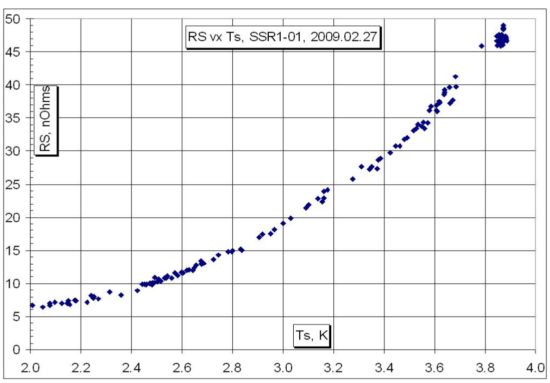


Figure 6: Temperature dependence of the surface resistance for SSR1 cavity.

A single spoke 325 MHz cavity SSR2 having β_G =0.4 was developed for the HINS project as well. The cavity layout is shown in the Figure 7. The EM optimization as well as mechanical design was completed including a piezo tuner and a Helium vessel. The triple-spoke cavity TSR operating at 325 MHz was also developed, see Figure 8.

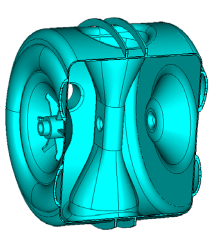


Figure 7: SSR2 cavity layout.

Each cavity of SSR0, SSR1, SSR2 and TSR types may be powered by separate RF source: IOT or solid state amplifier are feasible for the required power consumption at 325 MHz.

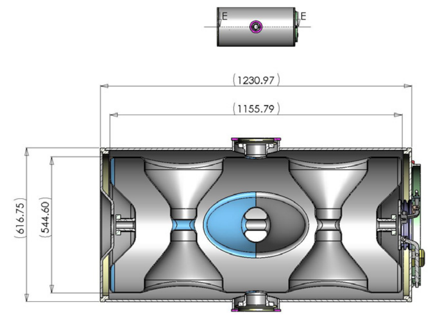


Figure 8: Layout of TSR.

466-2000 MeV: The acceleration from 466eV to 2 GeV may be provided at 1300 MHz using the same configuration as developed for the ICD-I 8-GeV pulsed linac. This configuration contains two sections, S-ILC and ILC. S-ILC section is based on the elliptical squeezed cavity with β_G =0.81. In the ILC section standard β_G =1 ILC cavities are used. The same type-4 ILC cryomodule is used in both sections. In this case, in order to use the cryomodule space effectively, 11-cell β_G =0.81 squeezed cavity was suggested. The cavity layout is shown in Figure 9 as well as its parameters and cell dimensions.

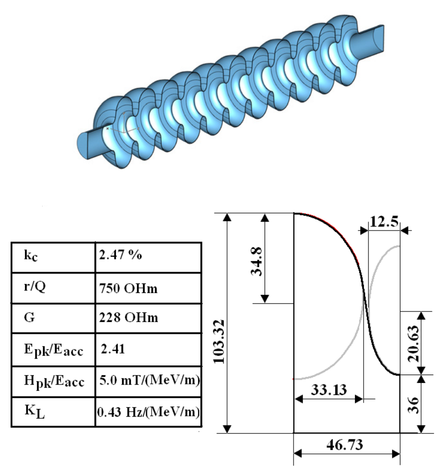


Figure 9: 11-cell β_G =0.81 cavity layout, parameters, and cell dimensions. Note that the coupling coefficient k_c is increased to 2.47% compared 1.87% for the TESLA cavity, in order to provide the same field flatness for large number of cells. It leads to the surface field (electric and magnetic) enhancement factor increase. However, 11-cell cavity provides higher energy gain per cavity than the cavities with smaller number of cells, see [4].

The gradient for this section was chosen to be 16.4 MeV/m. It corresponds to the surface magnetic field of 82 mT (see Table 4 and Figure 9). This magnetic field corresponds in turn to the gradient of 19 MeV/m for a standard ILC section, that should be acceptable for CW regime.

Table 4: Parameters for the cavities of the high-energy sections, SILC and ILC.

cavity type	F [MHz]	E_{acc} [MV/m]	L_{eff}, mm	Ep/E_{acc}	B_p/E_{acc} mT/(MV/m)	R/Q Ω	G Ω	$Q_{0,2K}$ $\times10^9$	$Q_{0,4K}$ $\times10^9$	P_{2K} [W]	P_{4K} [W]
11-cell, β=0.81	1300	16.4	1028	2.41	5	750	228	12.7	n/a	29.92	n/a
9-cell, ILC	1300	18	1038	2	4.26	1036	270	15.0	n/a	22.46	n/a

For this gradient, the Q-factor for ILC cavity is not smaller than 1.5×10^{10}, see [5], where the test results for different TESLA structures are summarized. For S-ILC structure the Q-factor will be about 1.3×10^{10} taking into account that for this case G-factor is 228 Ohm versus 270 OHm for ILC structure, see Figure 9. The RF losses are about 30 W/cavity, see Table 4. The number of cavities (preliminary) necessary in this section is 66, or 11 cryomodules - see Figure 10 where the modified Type-4 CM schematics is shown: each cryomodule in the S-ILC section contains 6 squeezed elliptical cavities and 3 quads.

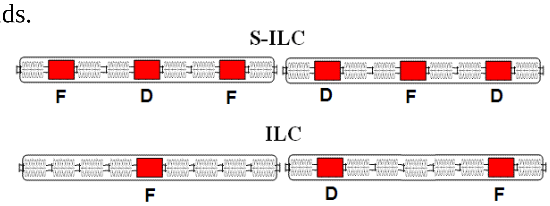


Figure 10: Modified Type-4 ILC cryomodule schematics. The cryomodule in S-ILC section contains three quads in the positions of 2nd, 5th, and 8th cavities, and six 11-cell cavities. The ILC cryomodule has the two different quad locations: in 5th position, and in 2nd and 8th positions.

Acceleration from 1.2 MeV to 2 GeV may be provided by section with 68 standard well-tested β_G =1 ILC cavities, or 9 cryomodules (see Figure 11). The gradient is 18 MeV/m. Maximal surface magnetic field is about the same as in the S-ILC section, 77 mT. The RF losses are about 22.5 W/cavity, see Table 4.

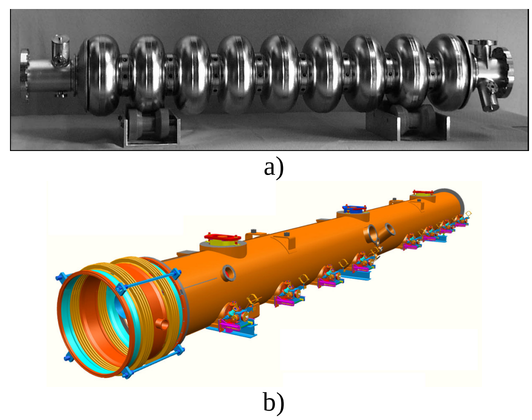


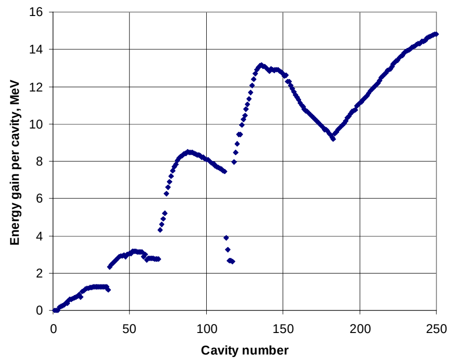
Figure 11: A standard 1.3 GHz, β_G =1 TESLA structure (a) and Type-4 ILC cryomodule (b).

There are two types of the ILC cryomodules following one after another as shown in Figure 10, so that the pair of cryomodules contains 15 ILC-type 9-cell cavities, and 3 quads. Note that the ILC-type cavity is not optimal for acceleration from 1.2 to 2 GeV (the beta range from 0.9 to 0.95), but it is well-developed, and there is a long-term experience of the cavity operation at DESY. The parameters of the sections including the number of quads, cavities and cryomodules are presented in Table 5.

Table 5: Break point between the sections in the high-energy part of the linac.

Section	Energy range MeV	β	Number of cavities/ quads/CMs	Type	Max Power/cavity (on crest), kW (I_{av}=1 mA)
S-ILC(β_G=0.81)	466-1200	0.744-0.9	66 / 42/ 11	Squeezed elliptical	13
ILC (β_G=1)	1200-2000	0.9-0.95	68 / 13 / 9	9-cell ILC	15

Figure 12a presents the average energy gain per cavity along the linac. The equilibrium phases are shown in the Figure 12b



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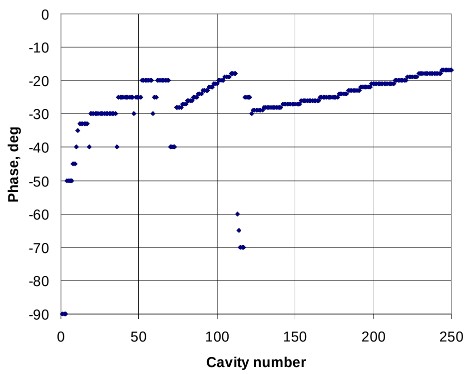

b)

Figure 12: The energy gain per cavity (a) and equilibrium phases (b). Cavities 1-117 are 325 MHz, 118-251 are 1.3 GHz. One can see that the last five cavities (112-117) in the 325 MHz section have very big (60-70°) equilibrium phase and, thus, small energy gain (<4 MeV/cavity), in order to match the beam longitudinal dynamics to the 1.3 GHz section.

Maximal required average power per cavity in the high-energy section is no more than ~20 kW. The IOT with this power are available at 1300 MHz, thus RF distribution system is simple and similar to SNS SC linac; one RF source per cavity.

RF splitter. RF splitter directs (i) two quarters of the beam to one user (Mu2e), (ii) one quarter to another user (Kaon), and (iii) one quarter to the third (unidentified) user (see Figure 1). The natural way is to use a SC structure with the deflecting TM_{110} mode operating at the frequency $f_0(m\pm1/4)$,where f_0 is the bunch sequence frequency (f_0=325 MHz). Operating the structure in CW regime at 406.25 MHz (m=1) with a deflection $\Delta p_{\perp}c$ of ~15 MeV, it is possible to achieve a required total deflection angle of ±5 mrad. Cavity layout is shown Figure 13, parameters are shown in Table 6. In order to achieve the kick of 15 MeV one needs 4 cavities. Te kick per cavity is 3.75 MeV. The surface magnetic field is 72 mT, that is smaller than in ILC1 section (76 mT). The length of the cavity + power coupler + HOM couplers is about 1 m. The total length of the deflecting RF structure is ~4.5 m. Transverse size is about ~1 m. The power requirements are determined mainly by microphonics, it is 20 kW/cavity, or 80 kW total. In this case Q_{load}~1.3e7. Total cryogenic losses are ~1 kW at 4.2 K. The lowest monopole mode should be damped to Q_{load}~4.e5, the parasitic dipole modes should have Q_{load} < 1.e7. The parasitic mode couplers shown in Figure provide this damping. The monopole mode damper has a notch filter to reject the operating frequency.

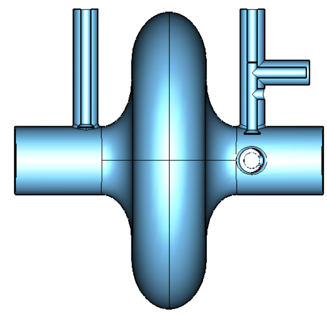

Figure 13: Layout of the RF splitter. Main couler and parasitic mode couplers are shown.

Table 6: RF splitter parameters.

Parameters	
Esp/Vkick , (MV/m)/MeV	7.8
Bsp /Vkick , mT/MeV	19.2*
R/Q*(Ohm)	27
Longitudinal size (mm)	440
Vertical size (mm)	865
Horizontal size (mm)	962

*R/Q=$Vkick^2/(2\omega W)$

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