SRF LINAC TECHNOLOGY DEVELOPMENT AT FERMILAB*

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Abstract

Superconducting linear accelerators are being developed for different applications: for fundamental research at the high-energy and high-intensity frontiers, in nuclear physics, for spallation neutron sources, for synchrotron radiation sources, etc. The linac applications dictate the requirements for the superconducting acceleration system, and, thus, for SRF technology. Fermilab is currently involved in two projects: ILC and Project X, both based on SRF technology. For high-intensity frontier investigations, Project X – a multi-experiment facility – is being developed based by a wide collaboration of US National and Indian Laboratories. In the CW H$^-$ linac several families of SC cavities are used: half-wave resonators (162.5 MHz); single-spoke cavities, SSR1 and SSR2 (325 MHz); elliptical 5-cell beta=0.61 and beta=0.9 cavities (650 MHz). The pulsed 3-8 GeV linac is based on 9-cell 1.3 GHz cavities. In this paper the basic requirements for the CW superconducting Project X linac are considered as well as its specific technology challenges.

INTRODUCTION

The application of SRF technology to electron and hadron linacs has a long – almost 50 years long – and successful history. Superconducting RF cavities are now widely used and are planned to be used in linear accelerators for different applications, for example: (i) high-energy physics (SPL [1], ILC [2]) and the high-intensity frontier (Project X [3]); (ii) new X-ray free electron lasers (XFEL [4], NGLS [5], Cornell ERL [6]), (iii) spallation neutron sources (SNS [7], ESS [8]), (iv) nuclear physics and rare isotope production (ATLAS [9], ISAC-II [10], CEBAF [11], SARAF [12], SPIRAL –II [13]), (v) ADS accelerators (MYRRHA [14], Indian ADS [15], China ADS [16]). The recent progress in development of superconducting acceleration cavities was achieved substantially in connection with the ILC project, see Fig 1, where a sketch of the ILC is presented. For such a long machine, high acceleration gradient is essential: 35 MeV/m with a duty factor of 0.5%. The 9-cell ILC cavity (see Fig. 2) operates at 1.3 GHz. The ILC collaboration [2], which includes Fermilab, achieved impressive results in the development of cavity processing (which includes electro-polishing and 120°C baking, see Fig. 3) and clean assembly techniques. These developments allowed the achievement of cavity gradients at quite high and gradually increasing production yields, see Fig. 4 [17]. At Fermilab, the work on building ILC-type cavities and cryo-modules is continuing.

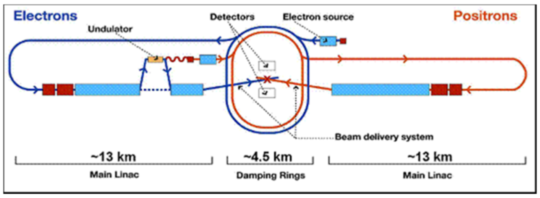

Figure 1: The ILC project sketch (2007 Reference Design).

The new large accelerator facility which is under development at Fermilab, Project X [18], is based on a CW H$^-$ superconducting linac, which has requirements very different from what is suitable for ILC, creating new problems and new challenges.

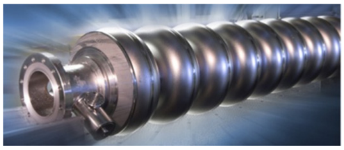

Figure 2: Photo of the ILC 1.3 GHz 9-cell SC cavity [Fermilab Visual Media Services].

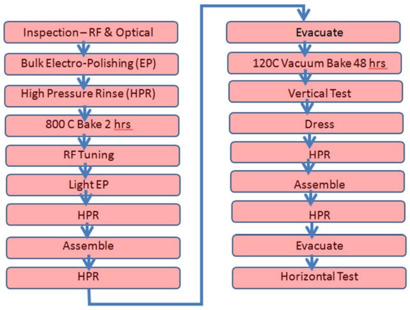

Figure 3: ILC Cavity Processing Basic Recipe.

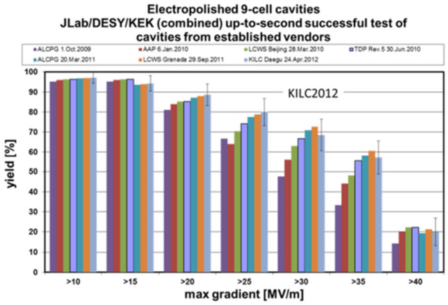

Figure 4: ILC gradient yield. ILC cavities reach 35 MV/m in vertical test more than half the time after one or two processing cycles.

DISCUSSION

Project-X, a multi-MW proton source, is under development at Fermilab. The Project X configuration is shown in Fig. 5. It enables a world-leading program in neutrino physics, and a broad suite of rare decay experiments. The facility is based on 3-GeV 1-mA CW

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superconducting linac [19]. In the second stage, about 5-9% of the H^- beam is accelerated up to 8 GeV in a SRF pulsed linac to the Recycler/Main Injector. The beam from the CW linac is directed to the 8 GeV linac for further acceleration in the Main Injector up to 120 GeV, for the long baseline neutrino program.

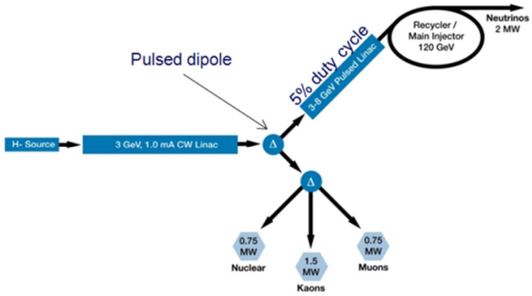


Figure 5: Project X configuration.

The 3-GeV CW linac of the Project X, see Fig. 6, contains (i) a front end with a room-temperature injection system having an H^- source, a Low-Energy Transport Line (LEBT), a 162.5 MHz RFQ, a Medium-Energy Transport Line (MEBT) with a beam chopper, (ii) a low-energy section based on 162.5 MHz Half-Wave Resonators (HWR) and 325 MHz Single-Spoke Resonators (SSR), and (iii) a high-energy section based on 650 MHz 5-cell elliptical cavities. The accelerator details for each SRF section are summarized in Table 1.

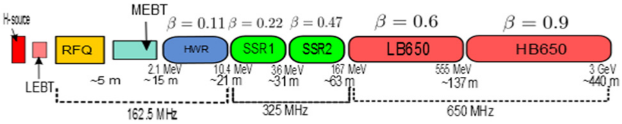


Figure 6: 3-GeV CW linac of the Project X.

Table 1: Accelerator details of the linac sections. CM: Cryomodule; D: Doublet, S: Solenoid, R: Resonator, R^n: n-Resonators Sequence.

Section	**f[MHz]**	**Cav/mag/CML$_{CM}$[m]**		**Cell**
HWR	162.5	8/8/1	5.26	S-R
SSR1	325	16/8/2	4.76	R-S-R
SSR2	325	36/20/4	7.77	S-R^2
LB650	650	42/17/7	7.1	R^3-D
HB650	650	152/19/19	11.21	D-R^8

The cavity design parameters for the low-energy sections and high-energy sections are shown in Tables 2 and 3, respectively. The HWR cryo-modules are developed by ANL [20]. The layout of the HWR cavity is shown in Fig. 6. SSR1 cavities [21], see Fig. 7, are designed by Fermilab and have been built by Zanon and Roark/Niowave. Two of them have been processed and tested showing performance consistent with design parameters. The helium vessel and tuners (coarse and fine) are also designed. The SSR2 cavity design is in progress [22]. Fermilab designed two 5-cell 650 MHz elliptical cavities for the high-energy section, at beta=0.61 (LE650) and beta=0.90 (HE650) [23]. JLAB has also developed a version of the LE650 cavity [24] with increased aperture, 100 mm versus 88 mm for FNAL design. JLAB has built and tested two single-cell cavities, see Fig. 9. One of them, #2, met Project X specifications (Q_0=2e10 at the nominal gradient).

Table 2: Cavity design parameters for the Project X low-energy section

Section	**beta**	**Aper-ture, mm**	**Gain MeV**	**E$_{peak}$** MV/m	**B$_{peak}$** mT	**R/Q** Ohm	**G** Ohm
HWR	0.11	33	1.8	40	62	225	48
SSR1	0.21	30	2.0	28	70	242	84
SSR2	0.47	40	3.3	32	60	292	109

Table 3: Cavity design parameters for the 5-cell elliptical cavities of the Project X high-energy section (FNAL design)

Section	**beta**	**Grad MeV/m**	**Gain MeV**	**E$_{peak}$** MV/m	**B$_{peak}$** mT	**R/Q** Ohm	**G** Ohm
LE650	0.61	16.6	11.7	37.5	70	378	191
HE650	0.90	17	17.7	34	61.5	638	255

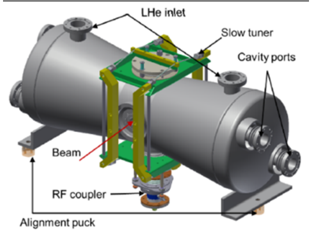


Figure 7: 3D model of HWR cavity (ANL)

Figure 8: SSR1 cavity, bare (left) and dressed (right).

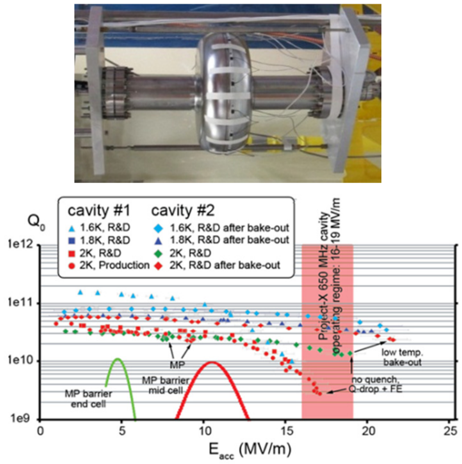


Figure 9: JLAB LE650 1-cell cavity and test results.

A HE650 single-cell cavity was designed by Fermilab, and six were built by AES, see Fig. 10. The tests are expected in October. A 3D model of the HE650 5-cell cavity is shown in Fig. 11.

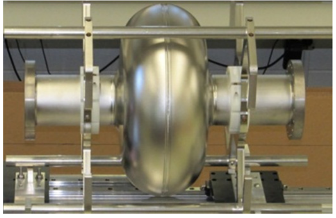


Figure 10: HE650 single-cell cavity.

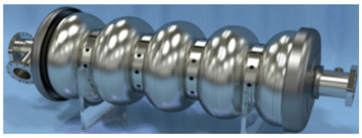
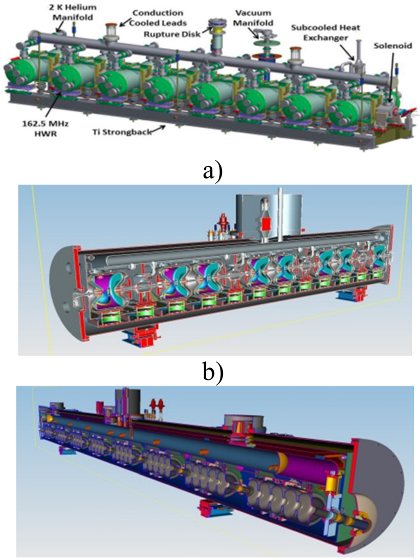


Figure 11: 3D model of HE650 5-cell cavity.

Cryo-modules for the HWR, SSR1 and high-beta 650 MHz cavities, see Fig. 12, are being designed [22,23].



a)

b)

c)

Figure 12: Cryo-module design for a) HWR (ANL), b) SSR1 (FNAL) and c) HE650 MHz (FNAL).

The cryo-modules of Project X have substantial operational differences compared to the ILC: 100% and 0.5 % duty cycle, respectively, and thus, a big difference in RF load: ~200 W/CM at 17 MeV/m and ~5 W/CM at 35 MeV/m, respectively. Thus, achieving high gradients is not an issue for the Project X cavities, but low RF load, or high Q_0, is. RF load in the CW regime determines the power consumption of the cryogenic system, which, in turn, determines (i) the capital cost of the cryogenic system (cost of a cryogenic system is proportional to (RF load)$^{0.6} \propto Q_0^{-0.6}$ for big machines [25]) and thus the cost of the entire project (cost of the cryogenic system is about 15% of the cost of a big machine); and (ii) operation cost, which is proportional to RF load, or Q_0^{-1} . Note that higher Q_0 also allows somewhat higher gradient, which may reduce the linac civil construction costs. The influence of RF load on the capital and operational cost of the Project X cryogenic system was analysed in [26]. The RF load was estimated using the averaged data on BCS resistance (the total surface resistance which determines Q_0 is the sum of residual resistance and BCS resistance) for ILC cavities [27] and Halbritter's model [28] for its gradient dependence (parameter γ=1 was taken based on these data). The cryogenic efficiency, i.e., the coefficient of performance (COP), was taken to be 890 W/W at 1.9 K, which corresponds to a modern level of cryogenic techniques [26]. In Fig. 13 a normalized capital cost of a cryogenic plant is shown versus the cavity operating temperature for two values of surface residual resistance, 5 nOhm and 10 nOhm. One can see that reduction of the residual resistance by a factor two decreases the cost by 30%. Note that the plant cost is about 75% of the total cost of the cryogenic system.

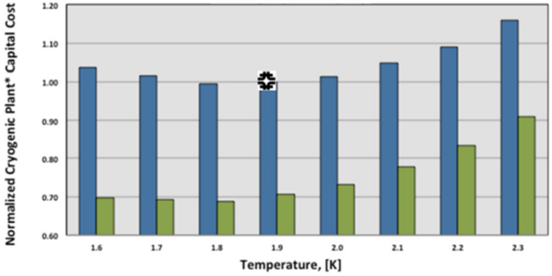


Figure 13: Normalized cryogenic plant cost versus operating temperature for different residual resistances: 10 nOhm (blue) and 5 nOhm (green).

Different approaches to reduce Q_0 are under development now. One of them is cavity processing in a nitrogen atmosphere, which creates a bulk layer of NbN on the cavity surface. NbN is a superconductor having a critical temperature of up to 16K compared to 9.2K for Nb, which gives the potential for lower surface resistance. The very first experiment [29] demonstrated the record $Q_0 \approx 7.5e10$ at 2K for a large-grain 1.3 GHz single – cell cavity (Fig 14). Another approach is hydrofluoric acid (HF) rinse of a cavity, with which one experiment [30] demonstrated a 35% increase in Q_0 at B_{peak} =70 mT for a 1.3 GHz fine-grain cavity, see Fig. 15. High-temperature baking (1400° C) is a third approach, which demonstrates $Q_0 \sim 4.5e10$ at B_{peak} =90 mT [31] also for 1.3 GHz, see Fig. 16. B_{peak}/E_{acc} =4.26 mT/MeV/m for all three of these cavities. Note that a Q_0 increase is demanded for any large CW superconducting accelerator, such as NGLS or ADS accelerators.

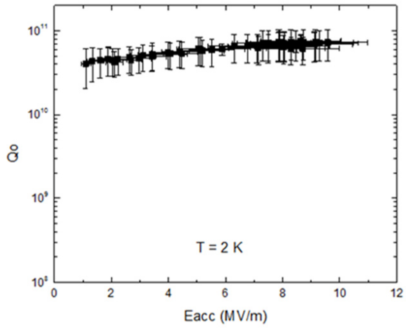


Figure 14: Q_0 versus E_{acc} for a NbN experiment.

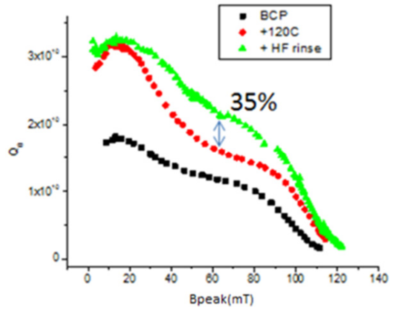


Figure 15: Q_0 versus B_{peak} for HF treatment.

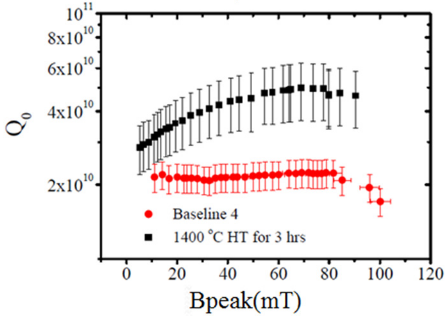


Figure 16: Q_0 versus B_{peak} for high-temperature baking.

Another critical issue for Project X and other large SC accelerators with modest beam current, e.g., NGLS, is small beam loading. Optimal coupling to the planned 1mA beam current at Project X would require relatively narrow cavity bandwidths. SC RF cavities are made from Nb sheet and the walls of the cavities are deliberately kept thin to maximize heat transfer to the surrounding superfluid helium bath. The thin walls of the cavities and the narrow operating bandwidths make them susceptible to detuning due to variations of the helium bath pressure or to mechanical vibrations (microphonics). Typically, the main source of vibration is helium pressure fluctuations [32]. As the cavities detune, additional RF power is required to maintain the accelerating gradient. If sufficient reserve RF power is not available to maintain the gradient, the beam can be lost. Sufficient reserve RF power must be provided to compensate for the peak detuning levels expected, not just for the average detuning. For narrow bandwidth cavities, providing sufficient reserve RF power can significantly increase both the acquisition cost and the operational cost of the machine. For the high-energy part of Project X, the bandwidth is about 23 Hz. In this case, a maximal detuning of 20 Hz requires an RF power overhead of 43% [33].

Microphonics can be mitigated by using the following approaches, or a combination of them: (i) providing sufficient reserve of RF power to compensate detuning; (ii) reducing the sensitivity of the cavity resonant frequency *f* to the helium bath pressure (*P)* fluctuation (*df/dP*), i.e., passive damping; (iii) actively damping microphonics using a fast tuner controlled by feedback from measurements of the cavity resonant frequency; (iv) decreasing the helium bath pressure fluctuations. To minimize *df/dP*, a number of approaches are used. A "self-compensating" scheme [34] was suggested for a triple spoke cavity, see Fig. 17. In this case, the cavity and helium vessel geometry are optimized such that a change in the stored energy of the electric field in the cavity is close to the change of stored energy of the magnetic field. Another approach is mechanical coupling of the cavity and the helium vessel, which improves the system stiffness [21], see Fig. 18. A third approach [35] exploits the idea of using a special element coupled to the cavity and separated from the helium vessel by a bellows which stretches the cavity in case of excess pressure, compensating the frequency changes caused by the cavity walls being squeezed. In SSR1 we use all these approaches to reduce *df/dP* to an acceptable level [21]. Active damping of microphonics for high – Q0 cavities was pioneered at Cornell [36]. Active piezo feedback reduces the microphonics amplitude by 70 %, see Fig. 19, and allows cavity operation with loaded Q up to 1e8. At Fermilab, an active microphonics compensation system was successfully developed and tested [37] for the SSR1 cavity at 4 K. The system allows a reduction in the r.m.s. detuning to 0.45 Hz, and peak detuning to 1.46 Hz, see Fig, 20. The system provides a very narrow peak without any evidence of long tails, which could cause rare trips. (Note that the Project X requirement is < 1 trip in 500 hours.) This approach for microphonics compensation satisfies Project X requirements, and may be useful for other large CW accelerators.

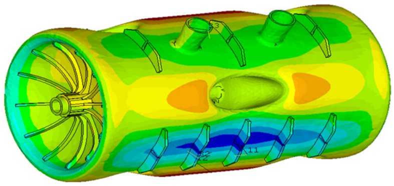


Figure 17: Self-compensating scheme for a triple-spoke cavity. Final adjustment of *df/dP* is reached by cutting the stiffening ribs on the He vessel walls.

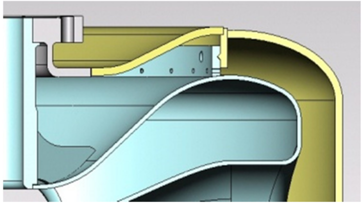


Figure 18: Mechanical coupling of the cavity and He vessel in order to improve the system stiffness.

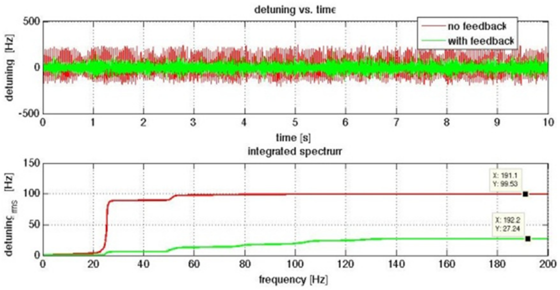


Figure 19. Active microphonics compensation in the Cornell ERL injector.

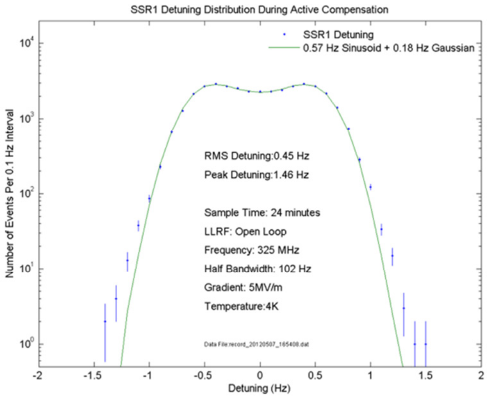


Figure 20: SSR1 active microphonics control.

CONCLUSIONS

Fermilab is proceeding with SRF activity connected to ILC and Project X. SRF for ILC is well-developed, and the international team has made good progress in achieving high accelerating gradient. New large CW linacs such as Project X, NGLS, ADS projects, ERL's, etc., need not high gradient, but high Q_0 at modest gradient. New SC material research concentrates on the achievement of high Q_0. Another critical issue for new CW projects is microphonics. Dedicated research is ongoing to develop both passive and active means for microphonics compensation suitable for large SC linacs with low beam loading.

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