STATUS OF SRF DEVELOPMENT FOR PROJECT X*

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Abstract

Project X is a high intensity proton facility being developed to support a world-leading program of Intensity Frontier physics over the next two decades at Fermilab. The superconducting RF (SRF) portion of this facility consists of two linacs: a continuous wave (CW) linac to accelerate beam from 2.1 MeV to 3 GeV and a pulsed linac to accelerate 5% of the beam up to 8 GeV. In the CW linac, five families of superconducting (SC) cavities are used: half-wave resonators (162.5 MHz), single-spoke cavities (SSR1 and SSR2 at 325 MHz), and elliptical 5-cell β=0.6 and β=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 and the status of development of the SC accelerating cavities, auxiliaries (couplers, tuners, etc.) and cryomodules are presented as well as some of the technological design challenges.

INTRODUCTION

Fermilab is pursuing advanced R&D towards Project X [1] which is a proposed high intensity proton facility capable of supporting many experiments simultaneously. The current plan calls for building Project X in stages. Each stage is associated with compelling scientific programs and maintains synergy with existing Fermilab infrastructure. After several iterations, the current "un-folded paper-clip" configuration was adopted as a baseline for the reference design report (see Fig. 1).

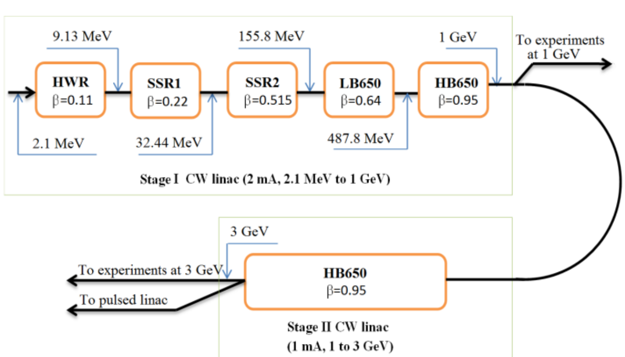

Figure 1: Acceleration scheme for the first two stages.

Stage 1 involves the construction of a 1 GeV, 1 mA (average) CW linac providing beams to the existing Booster synchrotron, to a new muon campus (under construction), and to a new 1 GeV experimental facility. Stage 2 doubles the average current in the 1 GeV linac and provides acceleration for half of the beam to 3 GeV in a second linac, with the 3 GeV beam aimed at a new high power muon and kaon campus located in the area enclosed by the old Tevatron. Stage 3 further accelerates a small fraction of the 3 GeV beam up to 8 GeV in a pulsed superconducting linac for injection and accumulation into the existing Recycler ring. Further acceleration will be provided after transfer into the Main Injector synchrotron. Project X enables a world-leading program in neutrino physics and a broad suite of rare decay and nuclear physics experiments. Note that technology of the Project X CW linac is well suited for Accelerator Driven Systems (ADS) applications. ADS projects in India [2] and China [3] are based on the Project X concept.

The CW linac of Project X 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 section are summarized in Table 1. HWR cavities and cryomodule are under development at Argonne National Lab (ANL) in the framework of a Fermilab-ANL collaboration [4].

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
HWR*	162.5	9.13	8/8/1	1.7	0.5	8×(sc)#
SSR1	325	32.44	16/8/2	2.05	0.5	4×(csc)
SSR2	325	155.8	35/21/7	5.3	1.2	scscscsc
LB650	650	487.8	36/12/6	11.5	1.5	cccdccc
HB650[1]	650	1000	42/7**/7	17.6	2	6×(c)
HB650[2]	650	3000	120/15**/15	17.6	2	8×(c)

*HWR cavity and cryomodule developed by ANL [4]
**warm doublets, # s – solenoid, c-cavity, d – doublet.
[1]Stage I CW linac.
[2]Stage II CW linac.

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325 MHZ SPOKE CAVITIES

Initially, SSR1 was developed at Fermilab for acceleration of proton/H^- beams in the HINS pulsed accelerator [5]. Switching to CW operation and 2 K operating temperature required a design change for the SSR1 cavity. The bare cavity and the He vessel are shown in Figure 2. The first SSR1 cavity prototype was manufactured by ZANON, the cavity was tested at our Vertical Test Stand (VTS) and outfitted with a helium vessel. The second prototype was manufactured by ROARK, tested and showed acceptable performance [6]. Subsequently, ten other SSR1 cavities were manufactured and delivered to Fermilab.

Table 2: Cavity parameters for Project X

Parameter	Value				
Cavity	HWR	SSR1	SSR2	LB6 50	HB650
Cavity type	Half-wave	Spoke	Spoke	Ell.	Ell.
Frequency, MHz	162.5	325	325	650	650
Operating temp,K	2	2	2	2	2
Optimal beta, β_{opt}	0.11	0.22	0.515	0.64	0.95
$L_{eff}= \beta_{opt}\lambda$, cm	20.7	20.5	47.5	70	104
Aperture, mm	33	30	50	83	100
Accel. gradient, MeV/m	8.2	10.0	11.1	16.4	16.9
E_{peak}/E_{acc}	4.7	3.84	3.53	2.27	2.07
B_{peak}/E_{acc}, mT/(MV/m)	5.0	5.81	6.25	4.25	3.78
$G = Q_0R_s$, Ω	48	84	118	191	255
R/Q_0, Ω	272	242	275	387	638

The cavity design parameters for the low-energy sections and high-energy sections are shown in Table 2.

The measured performance [7] of these cavities tested at 2 K is displayed in Figure 3. Note that the cavities are made of niobium, which is not certified for high-gradient operation and demonstrated higher losses than material from certified vendors. However, all seven tested cavities show a $Q_0 > 0.7\times10^{10}$ at 2 K at the operating gradient of 10 MeV/m, which is well above the required value of $Q_0 > 0.5\times10^{10}$. Note that the first two cavities made of certified material demonstrated a $Q_0 = 1.1\times10^{10}$ at 2 K at the operating gradient.

A new design for the helium vessel, shown in Figure 4, was developed for these resonators with the main goal of reducing the frequency sensitivity of the resonator to variations in helium pressure [8], which is critical for the Project X cavities because of their narrow bandwidth.

Figure 2: SSR1 cavity, bare (left) and dressed (right).

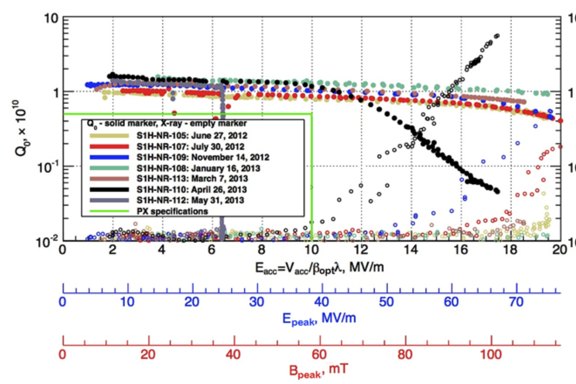

Figure 3: Test results for SSR1 bare cavities at 2 K.

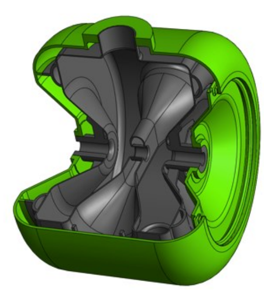

Figure 4: The mechanical design of the new SSR1 He vessel (3rd generation).

A transition ring couples the SSR1 niobium cavity wall to the steel vessel wall and can be seen on the left side of the cavity in Figure 4. The bellows is visible on the right.

The first prototype of the new vessel has been manufactured [9]; see Figure 2, on the right. Tests were performed at room temperature with the cavity free to move at the tuning interface and also with a dummy-tuning device which simulated a tuner having a rigidity of 30 kN/mm. The sensitivities measured in both conditions were ~10 Hz/Torr for a free interface and ~ 4 Hz/Torr for an engaged interface. This provides the maximal frequency detune of < 1 Hz at the expected maximal value of He pressure fluctuation of ~0.1 mbar (0.07 Torr),

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which is well below the required design value of 20 Hz [1].

A new tuner was developed despite the good results of the first prototype due to the different behavior of the resonator in the new helium vessel (Fig. 5). Other aspects of the tuning system were improved such as access to the tuner motor and piezoelectric actuators from outside the cryomodule [10].

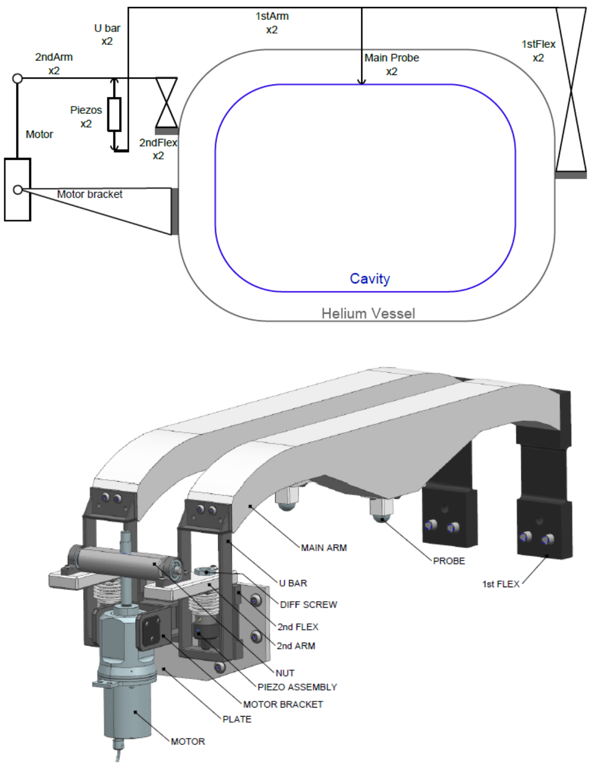

Figure 5: SSR1 tuner scheme (top) The mechanical advantages are about 2:1 between piezos and probes, and about 3:1 between motor and piezos. Actuating elements of the tuning system (bottom).

The SSR1 cryomodule [11] contains 8 cavities and 4 focusing solenoids (Fig. 6). The length of the cryomodule is 5.2 m. The overall design is very far along, although the detailed design of individual components and assemblies has just started. We have drawings for the strong-back, support posts, and vacuum vessel, three of the major components, but there is a lot of detailed design work to complete and many drawings to make. It is worth mentioning that new approach to setting requirements for the allowed magnetic field generated inside a cryomodule after cooling down was established and verified by a series of special tests. Using this approach resulted in significant relaxation of requirements for the local magnetic shielding, and for the SSR1 cryomodule allowed complete elimination of the local shielding [12].

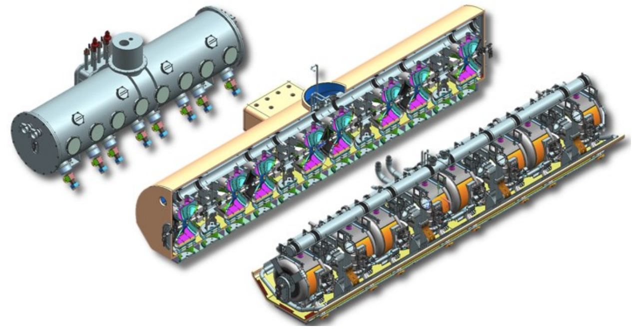

Figure 6: SSR1 cryomodule design.

The electro-magnetic and conceptual mechanical design of the SSR2 cavity is complete as shown in Figure 7 and based on the SSR1 cavity design [13, 14]. The design of the He vessel for the SSR2 resonator has been optimized in order to achieve a near zero *df/dp* for the system. The main elements that affect this performance have been introduced and optimized. The optimal design of the He vessel with the ideal combination of the bellows diameter and tuner passive stiffness has been determined.

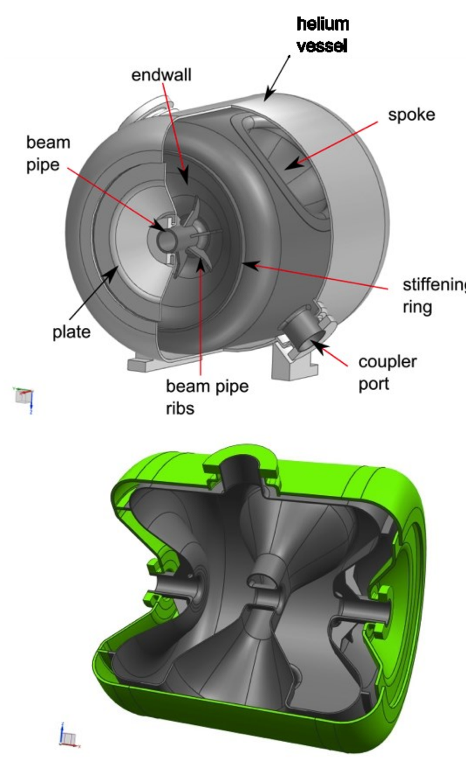

Figure 7: Design of the SSR2 cavity. Major components (top) and a sectioned view (bottom).

The SSR2 cryomodule contains 5 cavities and 3 solenoids, see Figure 8. The length of the cryomodule is 6.5 m.

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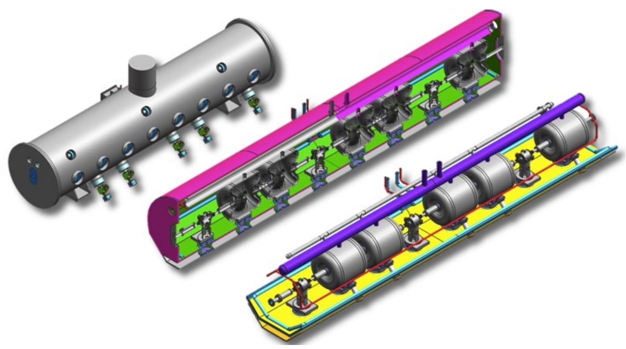

Figure 8: SSR2 cryomodule design.

Both SSR1 and SSR2 cavities will use the same input coupler, see Figure 9. The coupler is designed for 30 kW traveling wave (TW) at full reflection [15]. The input impedance is 50 Ω; the output impedance is 105 Ω. The coupler is not adjustable. DC bias is utilized in order to suppress multipactoring. For SSR2 cavities the coupler will be air-cooled. Three couplers are ordered and expected to be manufactured in this fall. The test stand is ready, see Figure 10.

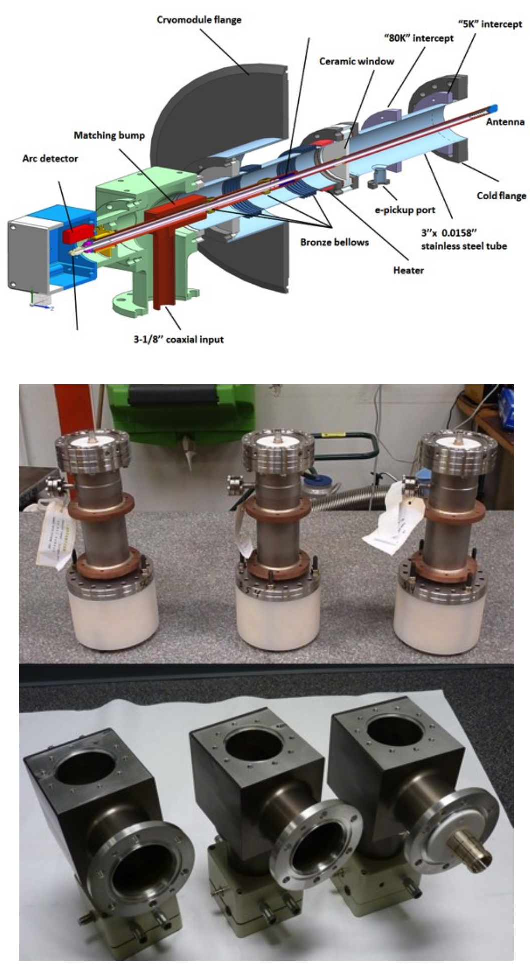

Figure 9: The 325 MHz input coupler for SSR1 and SSR2 cavities (top) and the coupler parts (bottom).

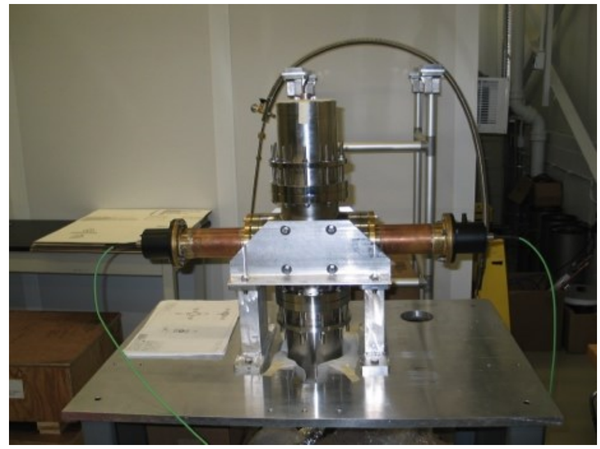

Figure 10: The coupler test stand with dummy couplers.

650 MHZ ELLIPTICAL CAVITIES

A HB650 single-cell cavity was designed at Fermilab, and six were built by AES, see Figure 11. The tests results for two of them are shown in Figure 12 [16]. The Q_0 at operating gradient of ~17 MeV/m well exceeds requirements, which gives assurance that the designed value of 2×10^{10} will be achieved in a cryomodule.

Four 5-cell HB650 cavities were recently manufactured by AES, see Figure 13. RF measurements demonstrated the field flatness of the operating mode to be within ±10% even without tuning. High-order modes have been measured. The cavities will be tuned, processed and tested at VTS this year.

The 2nd generation of HB650 cavity was designed having much lower *df/dP* and better tunability [17] compared to the 1st generation of HB650 cavity mentioned in Table 2. In addition, this cavity has no trapped higher order modes (HOMs) which allows it to operate at high beam current. The cavity has an increased aperture of 118 mm. The conceptual design of the cavity, helium vessel and tuner are shown in Figure 14 [18].

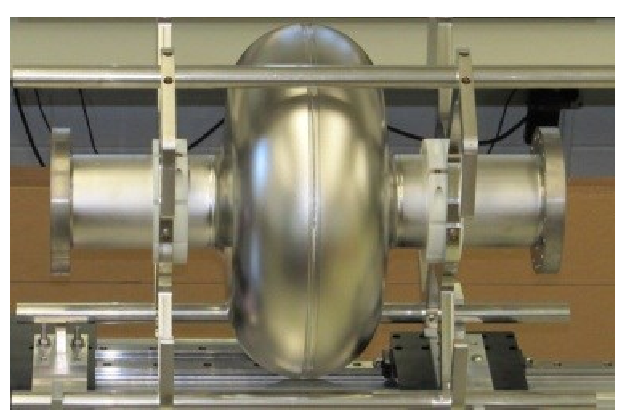

Figure 11: HB650 single-cell cavity.

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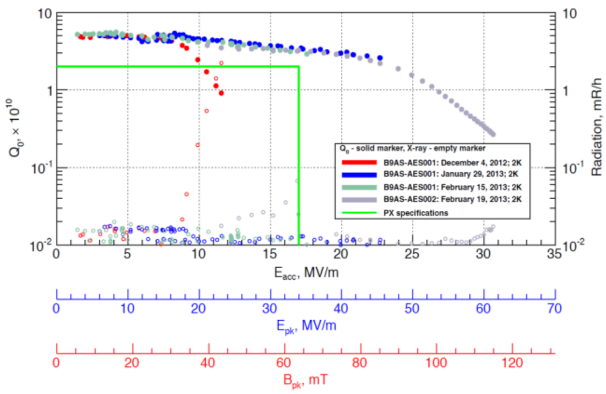

Figure 12: Test results of the HB650 single-cell cavities at 2 K.

Figure 13: HB650 five –cell cavities fabricated by AES.

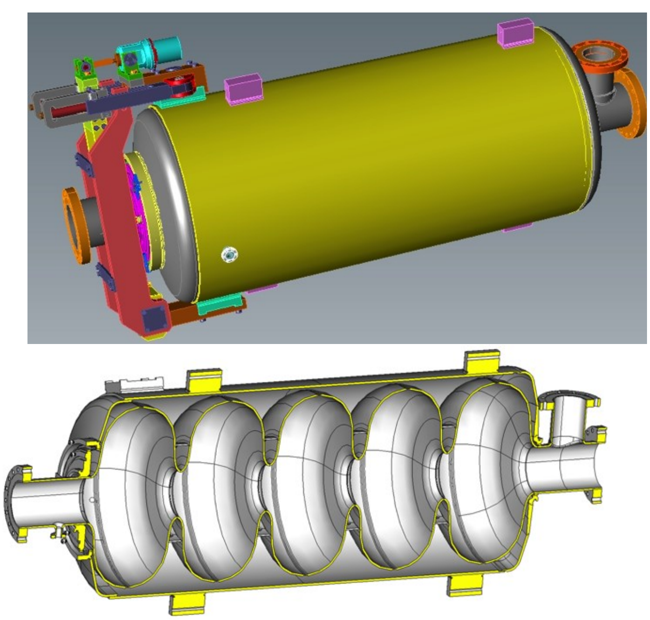

Figure 14: Conceptual design of the 2[d] generation HB650 cavity and He vessel (top) and tuner (bottom).

The cryomodule concept for the HB650 cavities is shown in Figure 15 [19]. For the 1 GeV section it contains six cavities and no focusing elements. We have a conceptual design of the cryomodule that includes placement of the cavities in the vacuum vessel, a concept for a support system and some rudimentary piping.

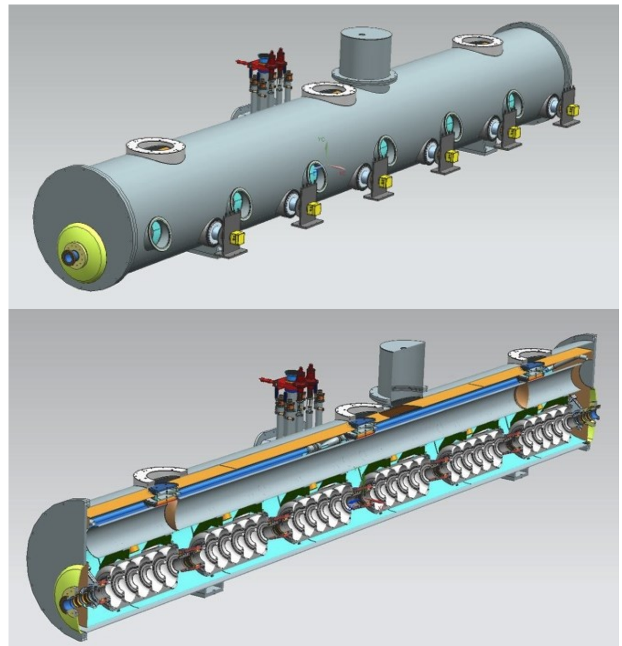

Figure 15: Cryomodule design for HB650 cavities.

The cryomodules for Project X have substantial operational features: 100% duty cycle, and thus, a high RF load of ~200 W/CM at 17 MeV/m. Achieving high gradients is not an issue for the Project X cavities, but achieving low RF load, or high Q_0 is a technical challenge. RF load in the CW regime determines the power consumption of the cryogenic system, which is a major cost driver for the project. The capital cost of a cryogenic system is proportional to $(\text{RF load})^{0.6} \propto Q_0^{-0.6}$ for big machines [20]. Thus, the cost of the entire project (cost of the cryogenic system is about 15% of the cost of a big machine) is a strong function of Q_0. Operational costs are proportional to RF load, or Q_0^{-1}.

Different approaches to increase Q_0 are under development at Fermilab [21]. One of them is interstitial doping of different gas species into the SRF surface layer in order to decrease the mean free path of Cooper paired electrons and therefore lower the BCS resistance at the SRF surface. Recent experiments [21] have demonstrated Q_0 as high as 7.5×10^{10} at 2 K for a large grain 1.3 GHz TESLA shaped single cell cavity (Figure 16). The next natural step is to introduce the successful R&D results into the cavity production stream.

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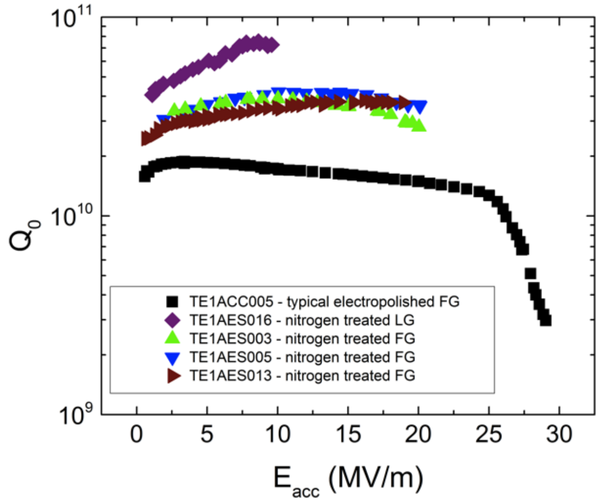

Figure 16: Q_0 versus E_{acc} for a NbN experiments at 2 K.

SUMMARY

For a staged concept of Project X, the current "un-folded paper-clip" configuration of the accelerator was adopted as a baseline described in the reference design report. The types of cavities, frequencies and transition points have been selected. Development of SRF cavities for the Project X CW linac - 325 MHz spoke cavities SSR1 and SSR2, and 650 MHz elliptical cavities HB650 - is in progress as well as cryomodule design. The research program for Q_0 improvement is developing successfully at Fermilab, demonstrating breakthroughs in physics understanding and optimizing the cavity processing recipe.

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