DESIGN, FABRICATION AND TESTING OF MEDIUM-BETA 650 MHZ SRF CAVITY PROTOTYPES FOR PROJECT-X*

F. Marhauser[#], W. Clemens, J. Henry, P. Kneisel, R. Martin, R.A. Rimmer, G. Slack, L. Turlington, S. Williams, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.

Abstract

A new type of superconducting radio frequency (SRF) cavity shape with a shallow equator dome to reduce electron impact energies for suppressing multipacting barriers has been proposed. The shape is in consideration for the first time in the framework of Project-X to design a potential multi-cell cavity candidate for the medium-beta section of the SRF proton CW linac operating at 650 MHz. Rationales covering the design of the multi-cell cavity, the manufacture, post-processing and high power testing of two single-cell prototypes are presented.

INTRODUCTION

Project-X is a multi-MW proton accelerator complex proposed for construction at the Fermi National Accelerator Laboratory (FNAL) based on an H^- linac utilizing superconducting RF (SRF) cavity technology operated in continuous-wave (CW). Project-X is currently in its early design stage supported by a concerted effort of major national laboratories led by FNAL in collaboration with international partners from Indian, European and Asian institutions. As outlined in [1], the initial design criteria for the high intensity proton beam have been provided by the High Energy Physics Advisory Panel's P5 report. The presently considered layout is a 3 GeV CW linac followed by a 8 GeV rapid cycling synchrotron or SRF linac, both of which use FNAL's existing recycler and main injector rings to accumulate the beams and boost the beam energies to a range of 60-120 GeV. The CW linac under design comprises a DC H^- ion source, a radio-frequency quadrupole (RFQ), a medium energy beam transport section, three families of 325 MHz spoke resonators (2.5-160 MeV), two families ($\beta = 0.61$ and $\beta = 0.9$) of 650 MHz SRF five-cell cavities (160 - 2000 MeV). The final acceleration from 3 to 8 GeV is proposed to be a pulsed SRF linac consisting of ILC type 1.3 GHz nine-cell cavities. The functional requirements of the medium-beta ($\beta = 0.61$) 650 MHz cavities for Project X are given in [2].

DESIGN CONSIDERATIONS

Jefferson Laboratory (JLab) has proposed a multi-cell cavity design for the medium-beta section [3]. The cavity shape (Fig. 1) is based on a cell profile optimized for $\beta = 1$ high average current (HC) applications in excess of 10mA[4]. With encouraging results [5], a five-cell at 748.5 MHz and two more previously built cavities of same shape scaled to 1497 MHz have been tested at theJLab vertical test area (VTA). The cavity walls are flat and relatively large iris apertures are used. The flat walls have been found to allow practical chemical cleaning, i.e. removingall chemical residues that mitigate the RF performance. Conceptual layouts of scaled versions for proton driver applications at lower betas have been presented previously as well[6]. For Project-X, in contrast to a merely scaled design, the shape has been further optimized changing both the iris and equator profiles. This targeted somewhat lower field enhancement factors$E_{peak}/E_{acc}$and $B_{peak}/E_{acc}$with the compromise to achieve a relatively high R/Q·G-value at the same time as a figure of merit for the cavity dynamic losses.

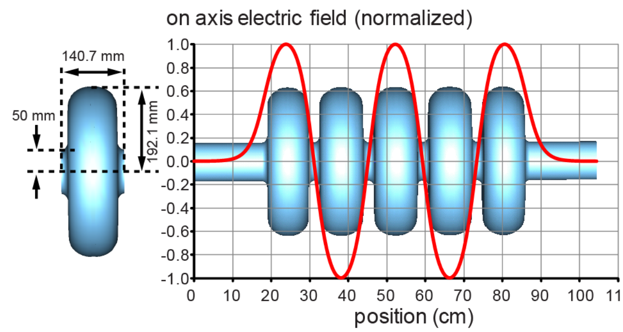

Figure 1: Medium-beta ($\beta = 0.61$) 650 MHz cavity mid cell layout (left) and five-cell cavity design (right).

Theproposed cavity has a beam tube ID of 100 mm, which is identical with the dimension chosen for the $\beta = 0.9$ cavity sectionproposed at FNAL, though it is less aggressive than FNAL's alternative $\beta = 0.61$ cavity design using an ID of 83 mm[7].A comparison of the RF parameters for both designs is given in Table 1.

Table1: Comparison between the proposed JLab and FNAL five-cell, $\beta = 0.61$ cavity design for Project X

Parameter	Unit	JLab	FNAL
β		0.61	0.61
number of cells		5	5
frequency	MHz	650	650
equator diameter E	mm	380.4	389.9
iris aperture A	mm	100	83
E/A		3.83	4.70
active length	mm	694	705
cell-to-cell coupling	%	1.4	0.75
E_{peak}/ E_{acc}		2.71	2.26
B_{peak}/ E_{acc}	mT/(MV/m)	4.78	4.21
R/Q	Ω	297	378
G	Ω	190	191
R/Q·G	Ω^2	56430	72198

*Work authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
[#]now at Muons, Inc., e-mail: frank@muonsinc.com

Table 2on the other hand reveals that even with a large iris aperture improved RF parameters have been achieved when compared to the existing medium-beta 805 MHz cavityat the Spallation Neutron Source (SNS) at ORNL.

Table 2: Parameters of the proposed cell shape compared to the SNS shape (inner cells only)

Parameter	Unit	Project-X	SNS
β		0.61	0.61
frequency	MHz	650	805
equator diameter E	mm	380.4	327.5
iris aperture A	mm	100	86
E/A		3.84	3.81
cell-to-cell coupling	%	1.40	1.53
E_{peak}/E_{acc}		2.71	2.72
B_{peak}/E_{acc}	mT/(MV/m)	4.78	5.81
R/Q	Ω	58.7	49.2
cell length	mm	140.7	113.6
G	Ω	193	176
R/Q·G	Ω^2	11310	8652

While a larger iris aperture increases E_{peak}/E_{acc} andB_{peak}/E_{acc}, it yet has several benefits by improving

- the ability for chemical etching (BCP and/or EP) at the cell equators (electron beam welded "heat-affected" zone) and a more uniform surface removal
- the mechanical stability with respect to cell deformations including a reduction of microphonics and the Lorentz-force detuning coefficient
- the cell-to-cell coupling, which in turn reduces the
  - sensitivityof fundamental field flatness to cell imperfections
  - amount of required post-production bench tuning

A large aperture is also beneficial forreducingparasitic beam losses and related effects, e.g. activation as a known concern at SNS. Furthermorefewer trapped/tilted HOMs will exist below the related beam tube cutoff frequency with less HOM power deposited in the cavity surface at cryogenic temperatures. It should be mentioned, though, that FNAL presently does not see a necessity for HOM couplers based onbeam dynamics simulation.Analyzing the mechanical stability of the cavity was not part of this work, but need to be addressed at a later stage. We believe cavity stiffening is mandatory independent of the aperture size, e.g. considering the elevated microphonics that have recently been experienced at JLab in CEBAF upgrade style cryomodules with cavities that were left unstiffened by design.

At an envisaged 12 MV effective voltage (E_{acc} = 17.3 MV/m) one can estimate B_{peak} = 83 mT and E_{peak} = 47 MV/m respectively. The 28 Watts dynamic losses per cavity at an assumed unloaded quality factor Q_0 ~ 1.7e10 and operation at 2 Kelvin is below the targeted Project-X functional requirement of < 35 Watts per cavity(250 W allowance per cryomodule).

A crucial role may be multipacting (MP) barriers particularly in the operational regime. Suppressing MP within the cavity has been addressed as part of the design process. It has been shown by numerical analysis using the code Fishpact [8] that a shallow equator with a flat dome is beneficial for reducing electron impact energies for any resonant cavity inner-cell MP condition. This is illustrated in Fig. 2 for the optimized cell profile (red curve) exhibiting significantly lowered electron impact energies compared toexisting designs. The 20eV barrier (peak value) is therefore a comparably "soft" barrier. Moreover, the barrier is shifted well below the envisaged operational regime of 16-19 MV/m (vertical bar).

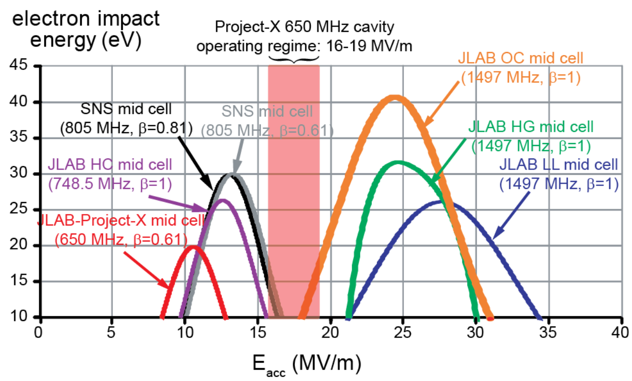

Figure 2: Electron impact energy for stable multipacting trajectories in various inner cavity cells.

PROTOTYPE FABRICATION

In order to evaluate the suitability of the proposed β = 0.61 cavity design, two single-cell cavities were fabricated at JLab in early 2011by standard deep drawing and electron beam welding (EBW) techniques, see Fig. 3.

Figure 3: Medium-beta 650 MHz SRF cavities.

Both cavities have been produced from fine grain niobium 4 mm sheets with RRR > 250, which were available at JLab (cavity #1) and received from FNAL (cavity #2) respectively, both originating from ATI Wah Chang. The beam tubes have been produced by rolling and EBW of seams using4mm reactor grade niobium. This low RRR material is routinely used for high power prototyping, whenbeam tubes can befully immersed in Helium in a vertical dewar. Hereby sufficient heat conduction is guaranteed, while the impact on the achievable $Q_0$is insignificant due to the low magnetic fields in the tubes. Although fabrication tolerances/errors may not play a crucial role for these first R&D single-cell prototypes, precisionfabrication rationaleshave been adoptedsimilar to the most recent series fabrication at JLabconducted in 2010 comprising eight multi-cell cavitiesinstalled in the cryomodule "*R100*"[9].These rationales have been compiled rigorously as lessons learned to counteract significant and prevalent error sources in past production years [10]. The cavity end flanges were built conform to the FNAL convention, and as such FNAL supplied the NbTi material for the end flanges and round AlMg gaskets from Wepek (hexagonal cross-section) to provide ultra high vacuum tightness. The gaskets are squeezed between the cavities' NbTi flanges and stainless steel blank-offs each including a port for an antenna RF vacuum feedthrough and one blank-off an additional vacuum pumping port.

HIGH POWER TESTING

Both cavities have been high power tested in JLab's VTA after routine post-processing, which includes bulk BCP aimed to remove approximately 250 µm at the cell equator (cross-checked by ultrasonic gauge wall thickness measurements before and after BCP), heat treatment for hydrogen degassing (typically 600ºC for 10 hrs), ultrasonic degreasing in a detergent (micro-90) followed by antenna probe calibration in air, a final light BCP (~30 µm), subsequent hot and cold ultrapure water and high pressure water rinsing. The cavities have been left in a class 10 clean room for overnight drying (~12 hrs) prior to the final assembly of the antennaRF vacuum feedthroughsand vacuum pumping portcomponents.All assembled partshave been blown particulate-free in nitrogen gaswitnessed by a particle counter.

Several high power tests have been carried out for both cavity #1 and #2 as described previously [11] with the results presented in Fig.4.

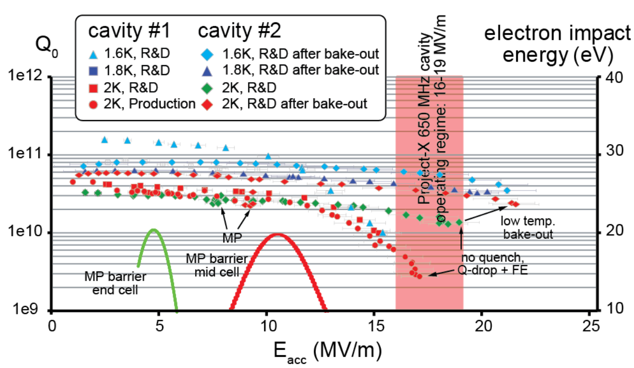

Figure 4: Unloaded quality factor versus effective accelerating field for cavity #1 and #2 respectively.

The performance limit of both cavities was field emission (FE) reaching $E_{acc} \sim 17$ MV for cavity#1 and $E_{acc} \sim 19$ MV/m for cavity#2 respectively, but without quenching. A routine measure to mitigate FE while improving Q_0 is an in-situ low temperature bake. At the time of writing this could only be performed for cavity#2 (120ºC for 24 hrs.). The cavity performance indeed improved significantly such that cavity #2 has exceededthe required performance criteria at 2 K, i.e. Q_0 >1.7e10 within 16-19 MV/m.The operational temperature of the Project X cavities is not yet determined, but within the range of 1.8-2.1 K.For both cavities Q_0-values have been measured as a function of temperature to evaluate the residual resistance. This revealed values aslow as ≤ 1.5 nΩ for cavity #1 and ≤ 3nΩ for cavity #2 respectively. The Q_0-values for cavity #1 exceeding 10^{11} at 1.6 K at lower fields are therefore among the highest ever achieved Q_0-values in niobium cavities. The high power tests have been carried out initially with JLab's "R&D" RF system and - to double-check the excellent Q_0-values - with the "SNS 805 MHz Production" RF system that verified the results within error bars.

For both cavities MP barriers were observed and processed at levels of 7-8 MV/m. The numerically predicted MP barriers plotted in Fig.4 peaks around 10 MV/m for mid cell contours (red curve), whereas the cavities' end cells (with beam tube) exhibit a barrier shifted to lower field levels around 5 MV/m (green curve). The MP barrier at the observed field value can be explained by the fact that the as-built single cell cavities differ from the multi-cell design (equator region) to re-tune the frequency. Moreover, the spring-back effect has been counteracted by making the equators longer than specified on drawings to achieve frequencies close to 650 MHz at 2 K.

DISCUSSION

A five-cell medium-beta 650 MHz SRF cavity design with rather large beam tube aperture has been proposed at JLab for Project-X considering a shallow equator dome to suppress cavity interior multipacting effects that have been shifted away from the operational regime at the same time. Two single-cell cavities have been fabricated to scrutinize the RF performance and suitability of the conceptual design for Project X. The results are encouraging. For both cavities extremely low surface resistances have been achieved yielding among the highest low-field Q_0-values ever measured in niobium cavities. Since both cavities are field emission limited, better cleaning and assembly could push the field emission to higher limits. Applying a final bake-out for cavity #1 is one of the next steps to boost its performance beyond project specifications as verified for cavity #2.

REFERENCES

[1] Project-X: The Accelerator, Fermilab, December 6, 2010, http://www.fnal.gov/pub/projectx/pdfs/ProjectX.sHolmes.v2.pdf.
[2] http://projectx-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=915.
[3] F. Marhauser, JLab-TN-10-043, 2010.
[4] H. Wang et al., Proc. PAC 2005 TPPT086.
[5] R.A. Rimmer et al., PAC 2009, WE5PFP056.
[6] R.A. Rimmer at al., IPAC 2010, WEPEC076.
[7] S. Yakovlev, FNAL – JLabProject Meeting, May 4th, 2011.
[8] G. Wu, http://www.jlab.org/~genfa/fishpact/.
[9] F. Marhauser, these proceedings, MOPC113.
[10] F. Marhauser, these proceedings, MOPC115.
[11] P. Kneisel, F. Marhauser, A. Burrill, P. Kushnick, R.A. Rimmer, Proceedings of SRF 2011, MOPO070.