Hot Topic: Processing and testing of large elliptical cavities (<1 GHz) for hadron linacs

TESLA Technology Collaboration Meeting

4 - 7th February 2020

TTC Meeting Scientific Program Committee:

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Geneva, Switzerland
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COLLABORATION

Asia

- CEPC – Contributed by P. Sha
- CiADS – Contributed by T. Tan
- CSNS– Contributed by F. He

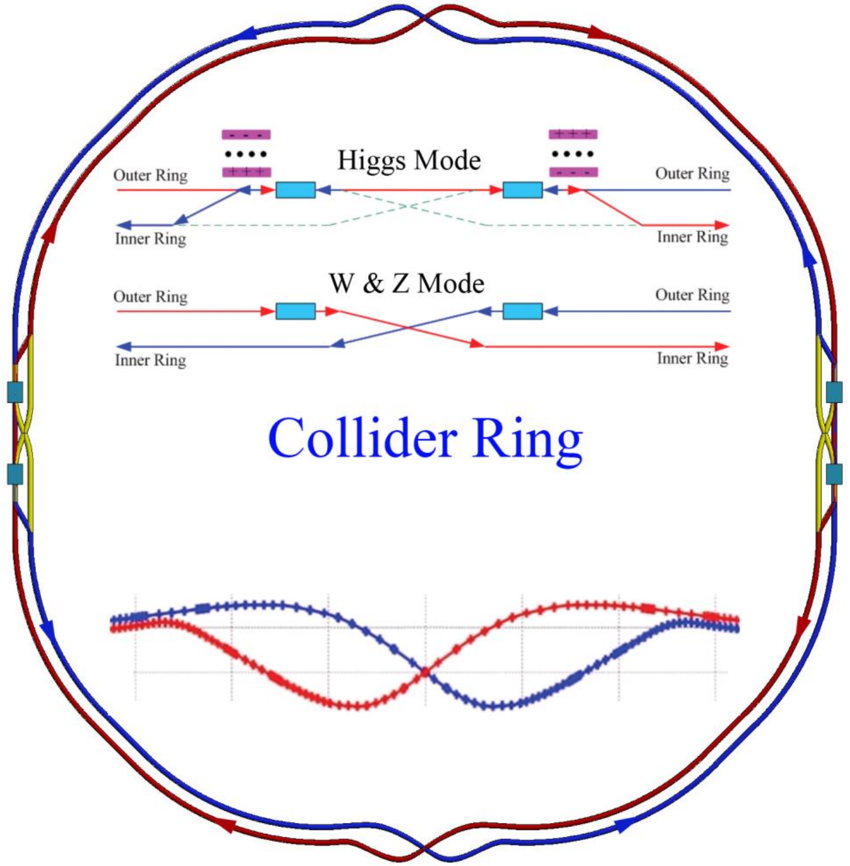
Americas

- BNL/eRHIC – Contributed by W. Xu
- MSU/FRIB – Contributed by K. McGee
- SNS – Contributed by C. Reece
- FNAL/PIP-II – Contributed by M. Martinello
- Jlab– Contributed by R. Rimmer

650 MHz cavity for CEPC

Peng Sha, IHEP CAS.

CEPC SRF System



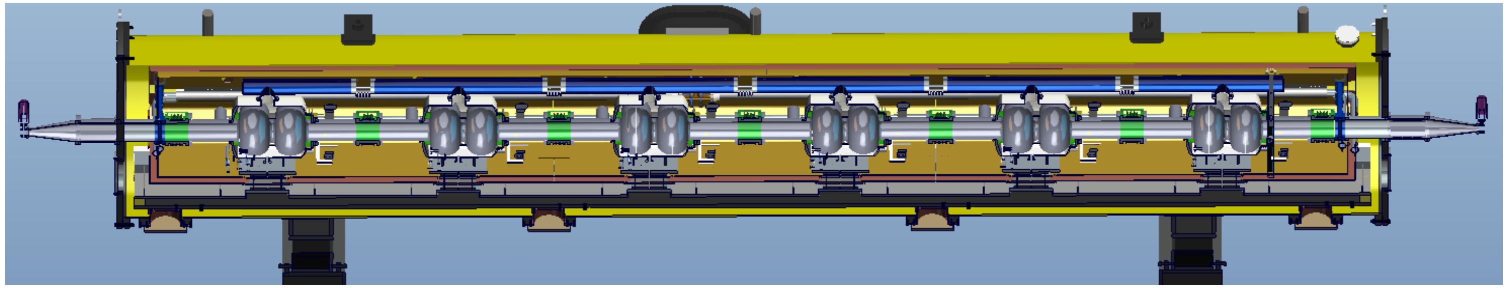
100 km CEPC Collider. Common H cavities and separate W/Z cavities for the two collider rings. One-time full installation of all the same cavities for H, W, Z. Use part of the Higgs cavities for W and Z.

High Q high gradient in high power ring accelerator.

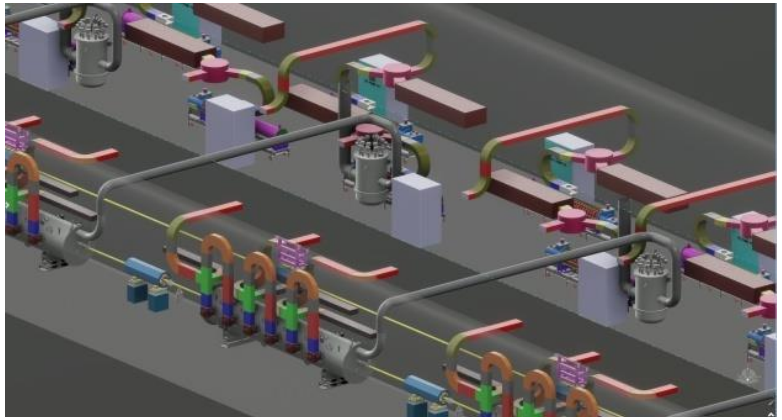
	H	W	Z
Collider Ring	**650 MHz 2-cell cavity**		
Lumi. / IP (10^{34} $cm^{-2}s^{-1}$)	2.93	10.1	16.6 / 32.1
RF voltage (GV)	2.17	0.47	0.1
Beam current (mA)	17.4 x 2	87.7	460
SR power / beam (MW)	30	30	16.5
Cavity number	240	108 x 2	60 x 2
Q_0 at max gradient	4E10 @ 22 MV/m (vertical test) 1.5E10 @ 20 MV/m (long term operation)		
2 K cavity wall loss (kW)	6.1	1.3	0.1
Booster Ring (extraction)	**1.3 GHz 9-cell cavity**		
RF voltage (GV)	1.97	0.585	0.287
Beam current (mA) peak	0.52	2.63	6.91
Cavity number	96	64	32
Q_0 at max gradient	3E10 @ 24 MV/m (vertical test) 1E10 @ 20 MV/m (long term operation)		

CEPC SRF

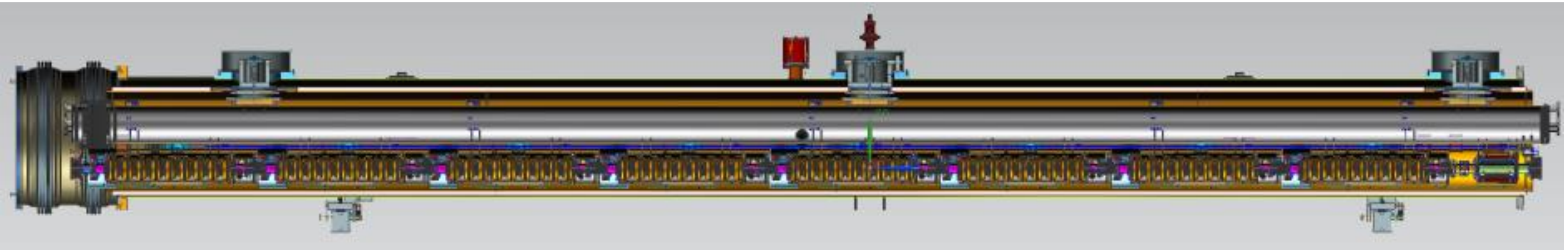
◆**CEPC Superconducting Radio Frequency (SRF) System consists of 240 650 MHz 2-cell cavities for collider and 96 1.3GHz 9-cell cavities for booster, which are evenly distributed in two SRF Station.**



Collider 650 MHz Cryomodule (6x2-cell, 10 m)

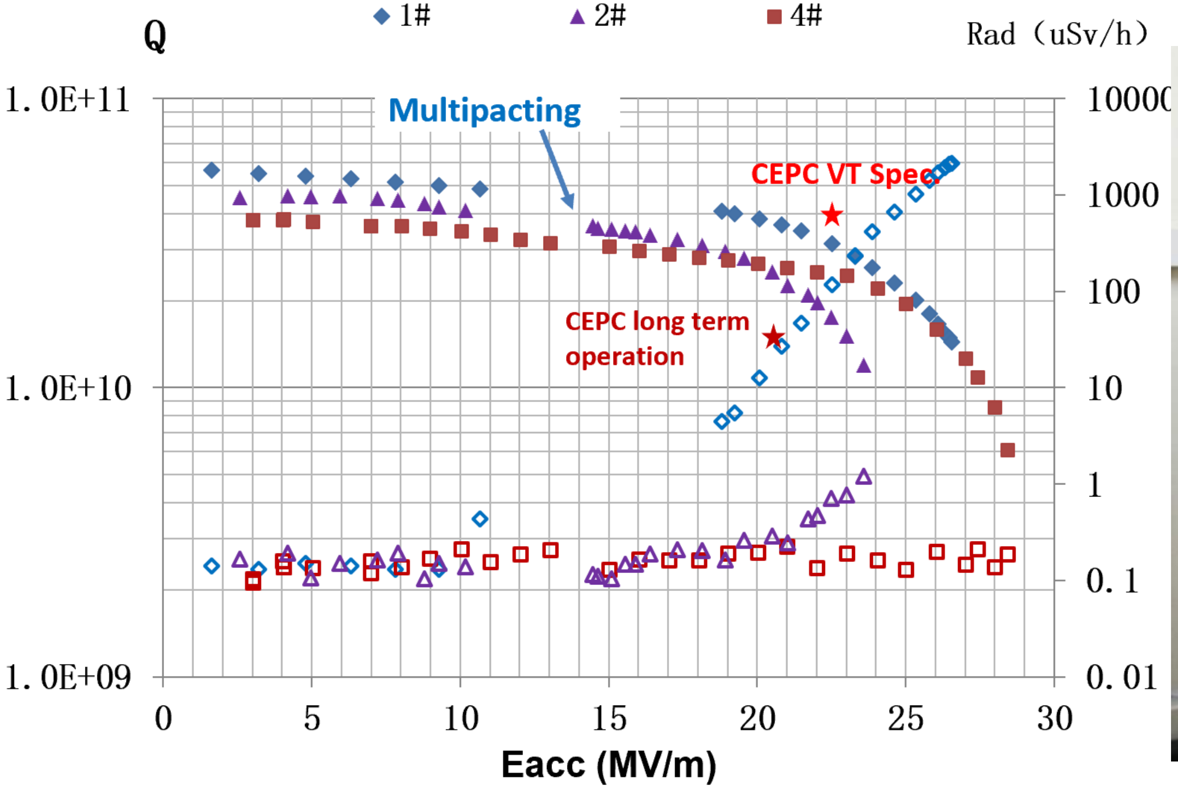


SRF Session of collider



Booster 1.3 GHz Cryomodule (8x9-cell, 12 m)

650 MHz 2-cell cavity for CEPC

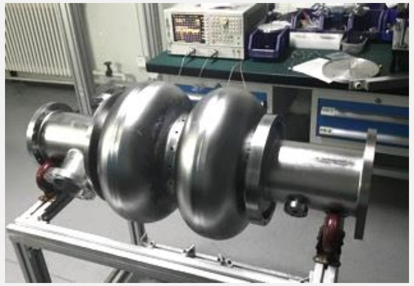


BCP

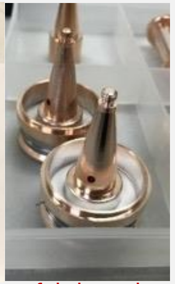
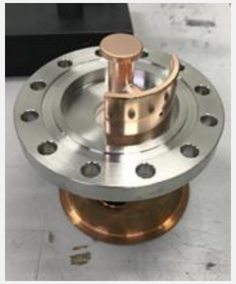
HPR

- All cavities received BCP and 120C baking before vertical test.

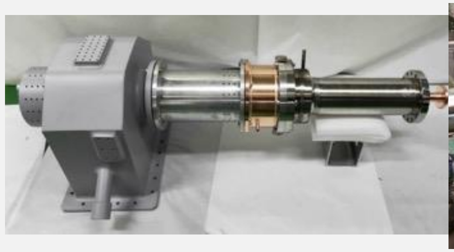
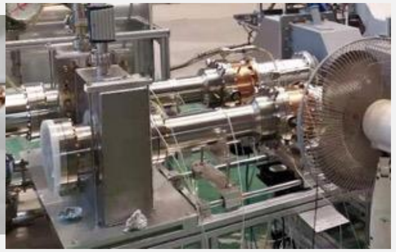
Prototypes of CEPC 650 MHz SRF System



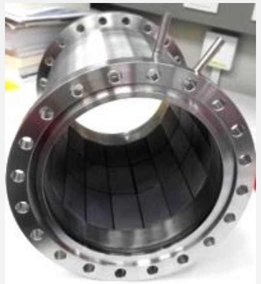

Three fine grain 650 MHz 2-cell cavities fabricated and processed (BCP). Vertical test and helium vessel weld with magnetic shield inside soon. Two for module horizontal test and beam test. Tuner fabrication completed and will test in a stand.

Four high power HOM couplers fabricated and low power tested with cavity. Three will mount on the 2-cell cavities. Vertical test soon with the cavity to verify the notch properties. High power test (1 kW) at RT and 2 K planned with special rigid coaxial line.

High power test of one 650 MHz fixed coupling input coupler reached 150 kW SW (corresponding to 400 kW TW at the window). Another coupler's window broke due to excess ceramic heating. New window and two variable couplers in fabrication.

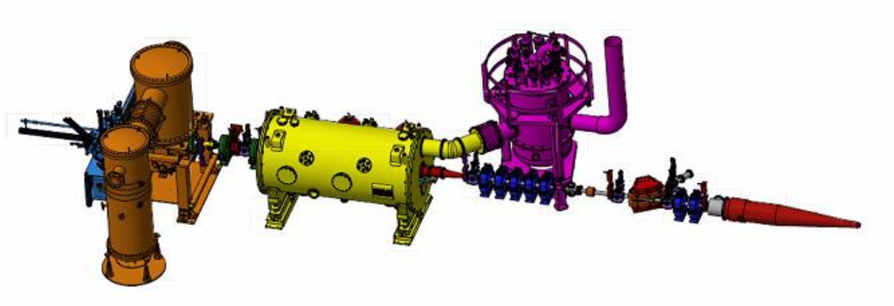


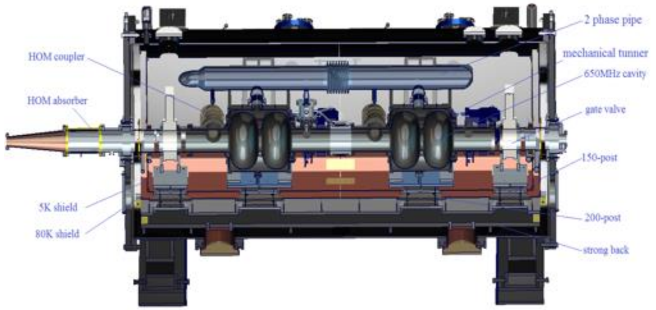
Wideband high power room temperature HOM absorber with SiC+AlN material. 5 kW high power test planned.

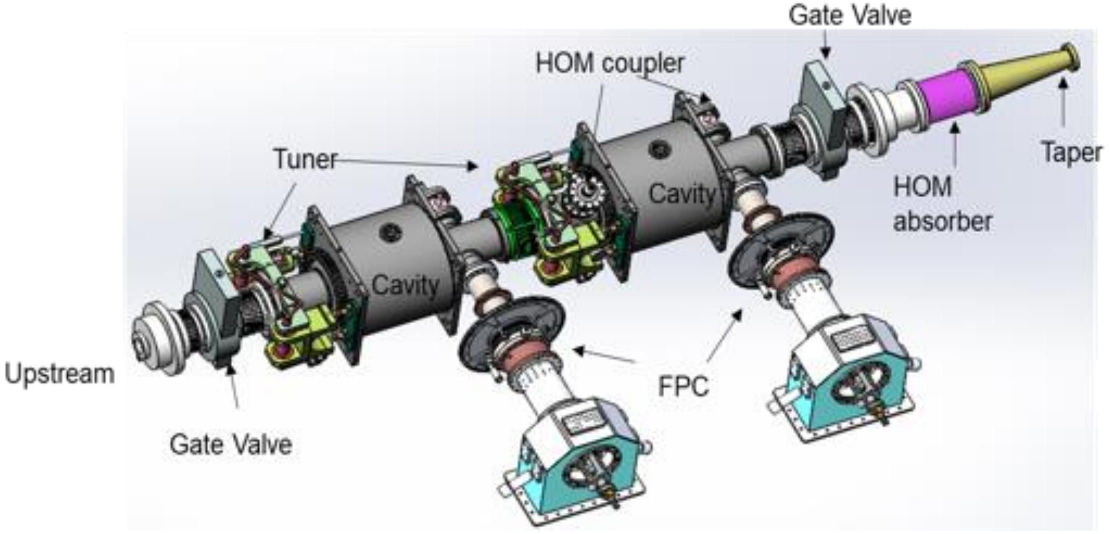
Cryomodule and valve box for two 650 MHz 2-cell cavities etc. Module assembly and beam test at PAPS in 2020.

CEPC 650 MHz Test Cryomodule

- Two 650 MHz 2-cell cavities with input couplers, HOM couplers and absorbers, tuners etc.
- Module assembly and 15 MeV beam test with 1 ~ 10 mA from DC photo-cathode gun in 2020.
- Demonstrate system integration and performance of high Q 650 MHz cavity (but with low input power and HOM power) for the Collider Ring.



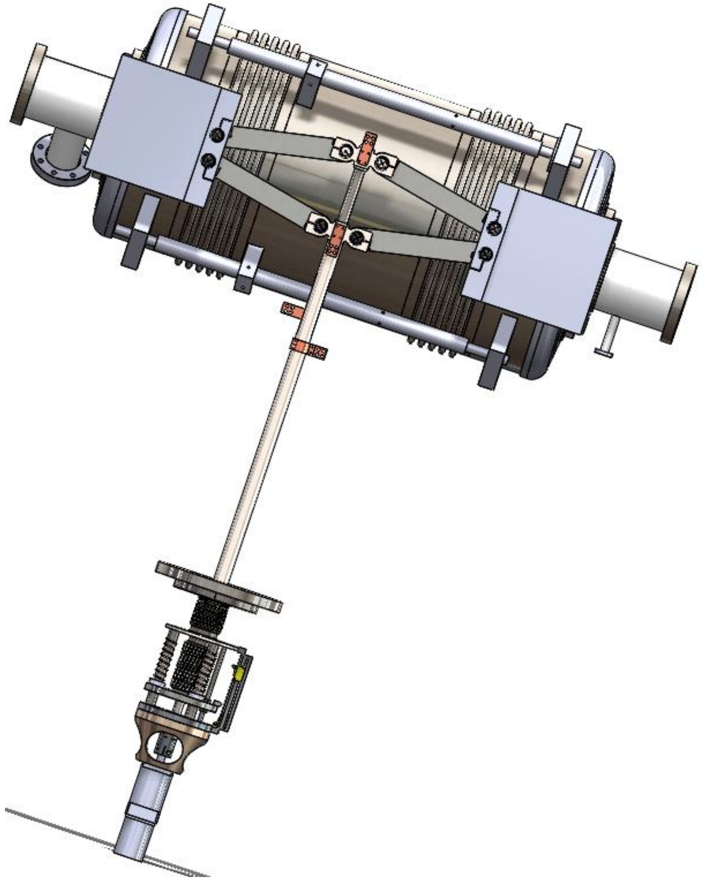


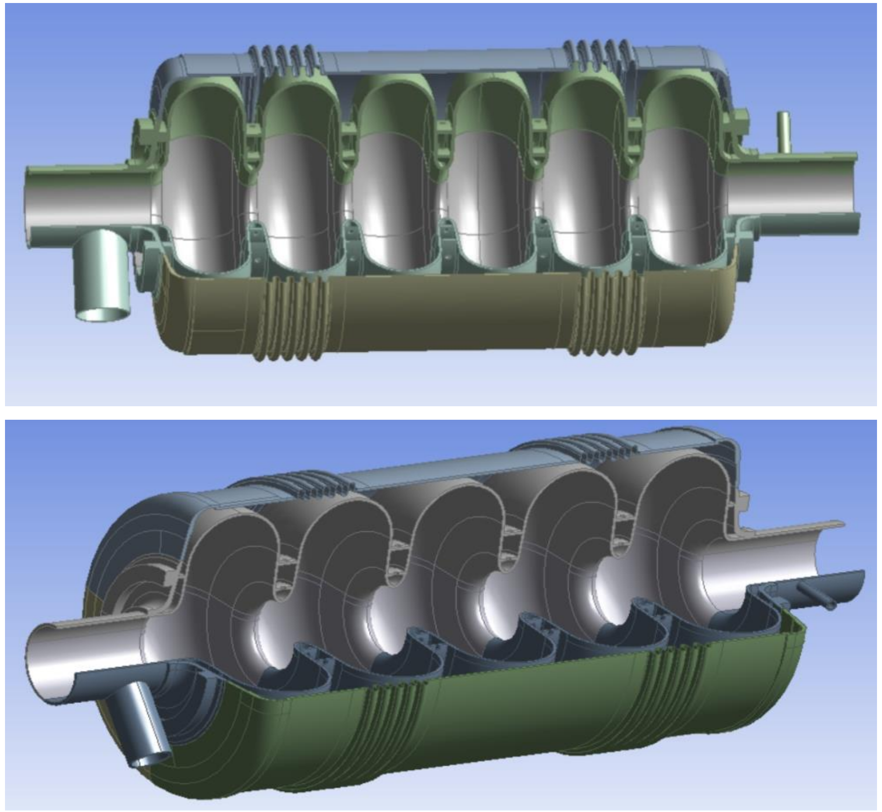


650 MHz cavity for CiADS

Teng Tan, IMP CAS.

650 MHz 5-cell cavity for CiADS





650 MHz 5-cell cavity for CiADS

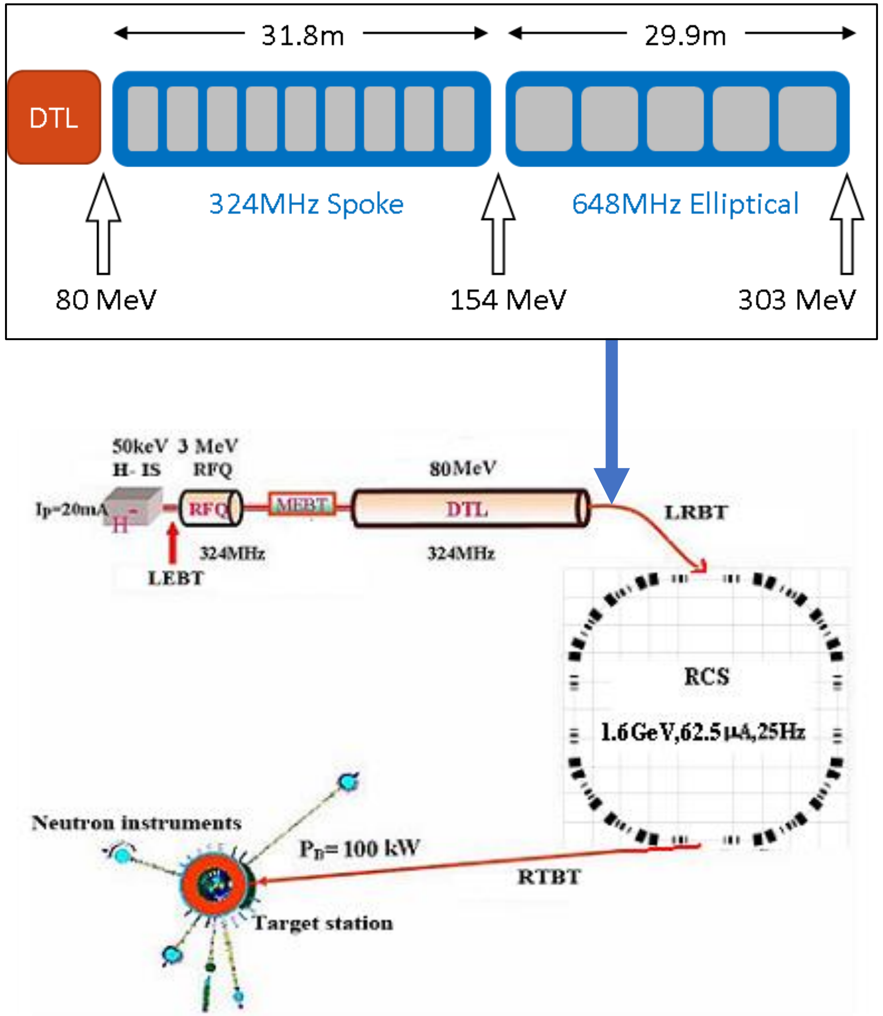
SC Cavity		Elliptical062-6cell	Elliptical082-5cell
Optimum Beta		0.62	0.82
Frequency	MHz	650.00	650.00
Beam Aperture	mm	100.00	100.00
Leff	m	0.821	0.896
L_{ftof}(flange to flange)	m	1.2200	1.2200
Ep1(operation)	MV/m	29.00	29.00
Bp @Ep1	mT	50.38	54.61
Veff @Ep1	[MV]	8.56	12.15
Eacc@Ep1	[MV/m]	10.43	13.55
G	Ohm	188.00	229.00
R/Q	Ohm	330.00	501.00
Rs	nOhm	17.57	17.57
Q0		1.06E+10	1.30E+10
Ploss[2K] @Ep1	W	20.77	22.59
Stress on Cavity	MPa	<50	<50
df/dp	Hz/mbar	<abs(20)	<abs(20)
dp	(mbar)	±0.1	±0.1
LFD coefficient	Hz/(MV/m)^2	<abs(-1)	<abs(-1)
df_LFD @Ep operation	Hz	<abs(91)	<abs(145)
Tuning sensitivity	Hz/mm	209	214
Cavity stiffness	kN/mm	2.6	5
Tuner stiffness	kN/mm	>30	>30

650 MHz cavity for CSNS Upgrade

Feisi He, IHEP CAS.

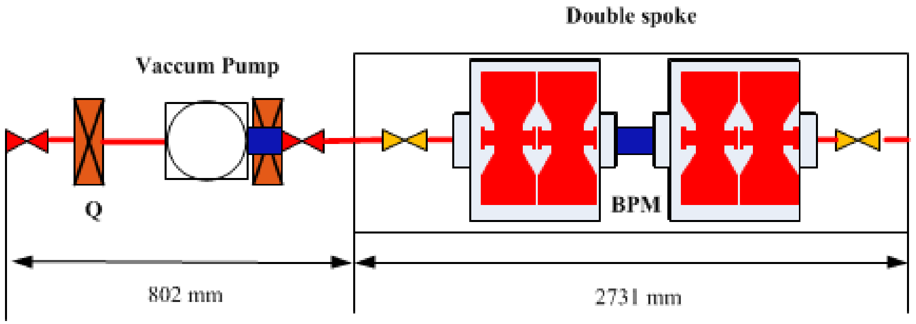
CSNS Upgrade

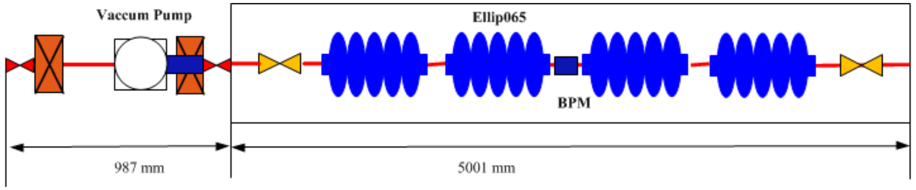
- Target of the CSNS upgrade:
- Beam power 500kW (1.6GeV)
- Linac length <85m
- Peak current 40mA
- Pulse width 1.25ms
- Repetition rate 25Hz
- Beam energy at exit of linac >300MeV (the higher, the less space charge effect)

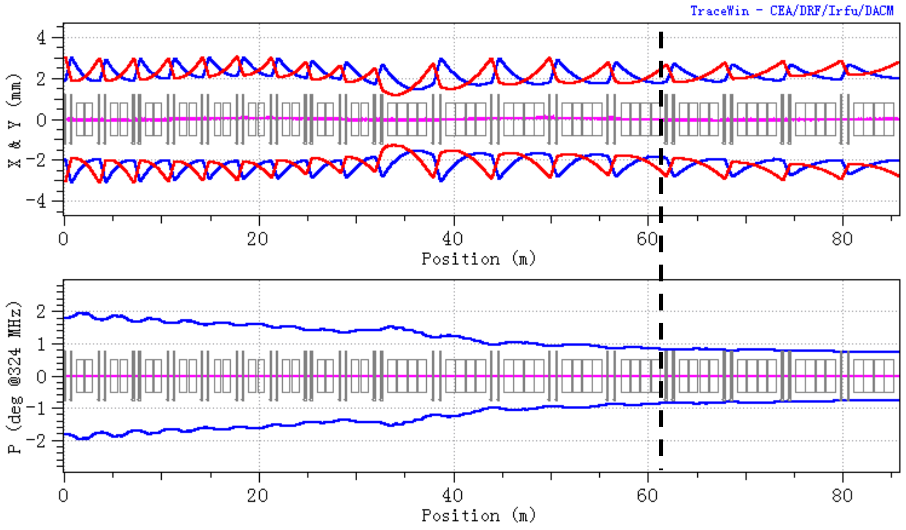


Linac design

- Double-spoke(β_0=0.50) + 5-cell elliptical (β_0=0.65) + RT quadrupole
- 38 SRF cavities, linac 61.7m + matching 2m, 303MeV at exit
- Spoke period 3.5m, 9 periods
- Elliptical period 6.0m, 5 periods
- Spoke cavity Ep<25MV/m, Eacc < 7.3MV/m
- Elliptical cavity Ep<35MV/m, Eacc<12.5V/m

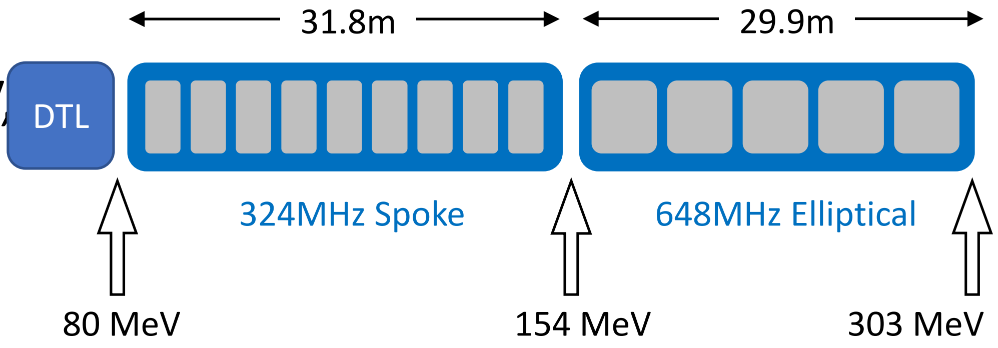


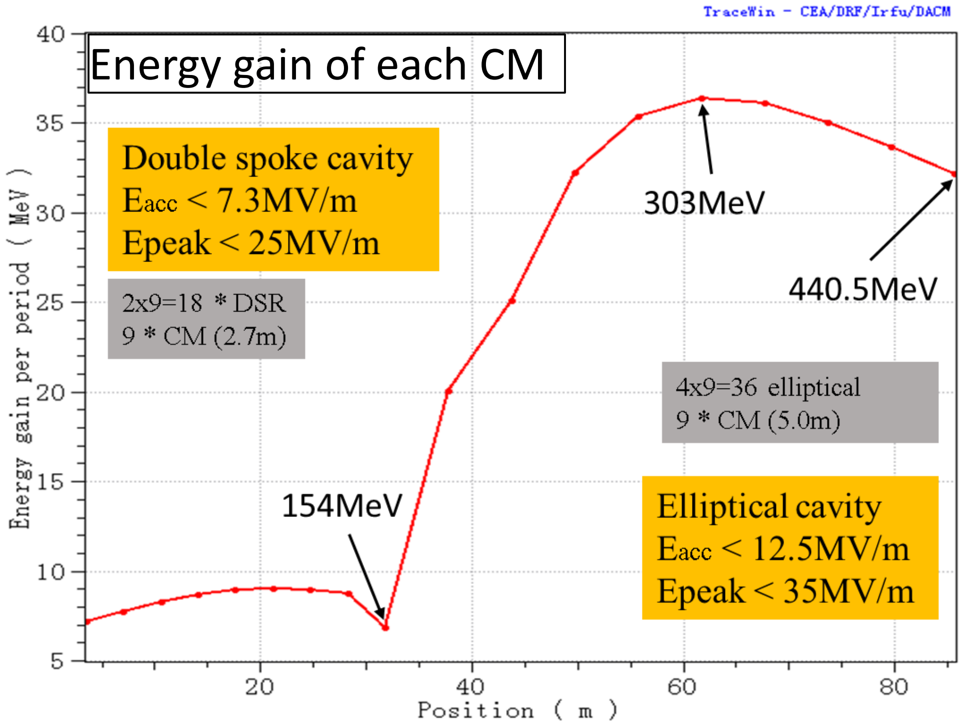




Linac design (2)

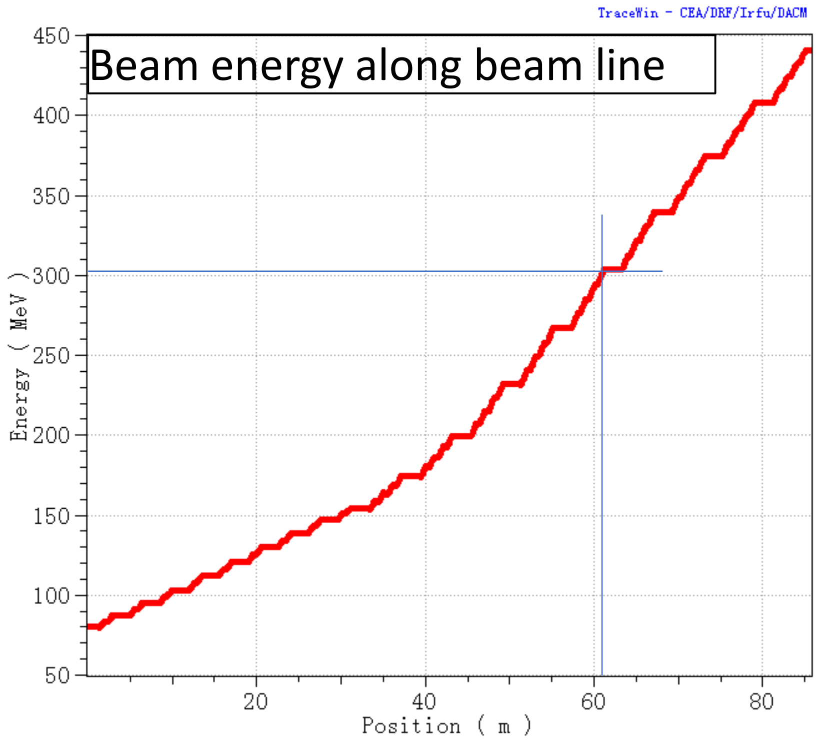
- Spoke section, two cavities in a CM of 2.73m, energy gain 7-9 MeV, Pf=136~184kW ;
- Elliptical section, 4 cavities in a CM of 5.00m, energy gain 20-36MeV, Pf=183~370kW ;
- Safety margin:
  - Spoke: it's safe to increase Ep from 25 to 31MV/m, i.e. 24%
  - Elliptical: safe to increase Ep from 35 to 40MV/m, i.e. 14%
  - With adaqute forward power, max beam energy is 366MeV
  - With 10% more forward power, max beam energy is 315MeV

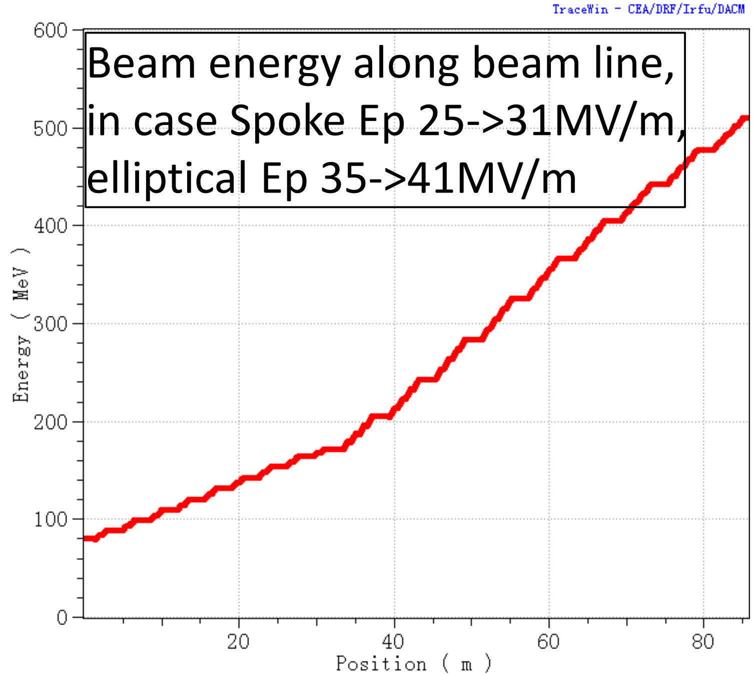




Further upgrade:

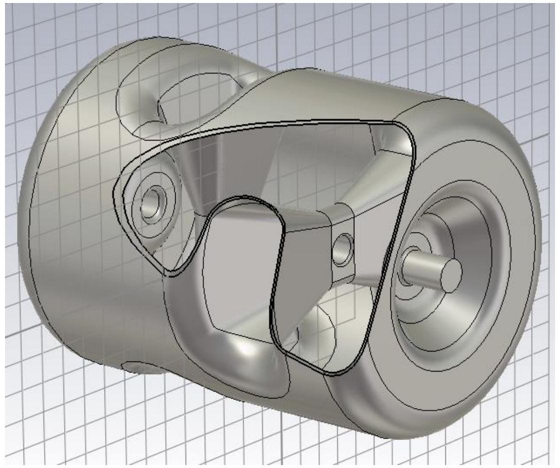
- 4 more CMs (16 elliptical cavities)
- 54 SRF cavities, linac 85.7m + matching 2m, 440.5MeV at exit.
- Using all safety margin in cavity gradient, max beam energy is 510MeV
- With 10% more forward power, max beam energy is 458MeV

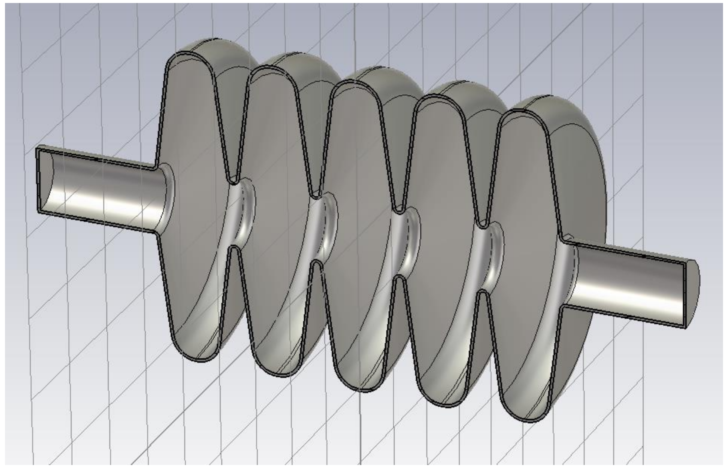




SRF cavity design

- 324MHz β_0=0.50 double-spoke cavity, beam aperture 50mm
- 648MHz-5cell β_0=0.65 elliptical cavity, beam aperture 80mm
- Operation target: spoke Ep<25~31.5MV/m; elliptical Ep<35~40MV/m ; Bp<80mT.
- Design goal is to minimize Ep/Ea, to suppress field emmission (FE)





	Double -spoke	**5-cell elliptical**
Aperture diameter[mm]	50	80
Ep/Ea	3.4	2.8
Bp/Ea [mT/(MV/m)]	8.87	4.4
Geometry factor [Ω]	125.8	183
R_a/Q_0 [Ω]	413.0	347

BNL eRHIC/EIC

650 MHz fabrication, processing and test experiences:

- Most existing SRF cavity fabrication processing and handling infrastructure is for 1.3 and 1.5 GHz cavities.
- All of the BNL EIC cavities need larger more robust facilities and equipment.
- Fabrication:
  - Our large cavity geometries and thick walls (4.5 mm) necessitate different niobium forming procedures. We started developing these techniques with our 650 MHz 5-cell cavity.
- Processing:
  - Chemistry tooling to fit our large SRF cavities needs to expand.
  - Many of the BNL EIC cavities require larger high vacuum ovens for processing.
  - In the past we modified our cavity to fit existing infrastructure. We cannot do this for the BNL EIC.
- Vertical test
  - Large, especially long, cavity may be close to the dimension limit of the vertical dewar, thus, limits the test progress.
- Other concerns
  - Large diameter beampipe with matching large gasket requires development for both RF seal and leak tight operation.

The cavity reached 18.2 MV in the preliminary vertical test at BNL, which was limited by the field emission.

FRIB400: 644 MHz β = 0.65 elliptical cavities for the FRIB hadron linac

TTC Hot Topic Session: Processing and Testing of Large Elliptical cavities (<1GHz) for hadron linacs

K.E. McGee, S.H. Kim, P.N. Ostroumov on behalf of
Facility for Rare Isotope Beams/Michigan State University

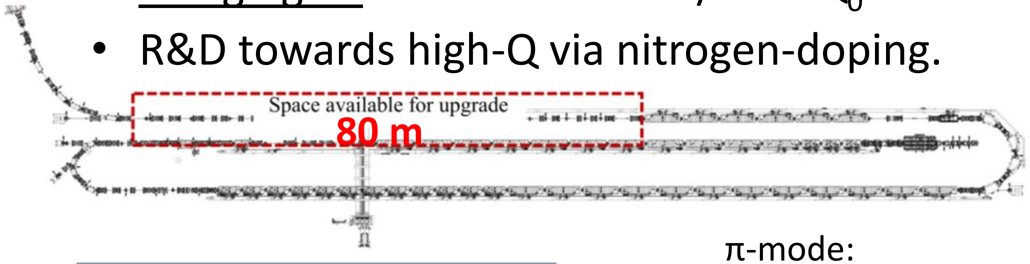
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

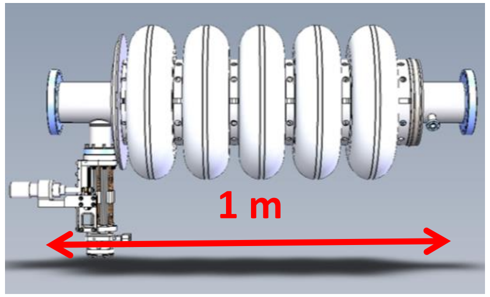
FRIB Energy Upgrade, FRIB400

β_{opt}=0.65 5-cell 644 MHz Elliptical Cavity

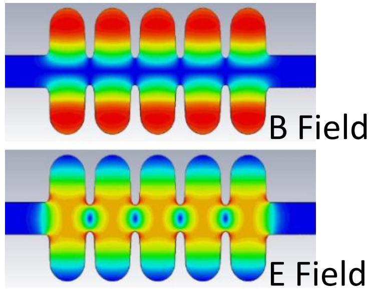
- 5-cell SC Nb elliptical cavity
  - Meets energy goal while minimizing heat load, number of cavities (55) and cryomodules (11).
  - Large longitudinal acceptance, robust accelerator operation/reduced beam losses.
- Two fabricated in industry (RI)
- Design goal: Eacc of 17.5 MV/m at $Q_0 \geq 2\text{x}10^{10}$
- R&D towards high-Q via nitrogen-doping.

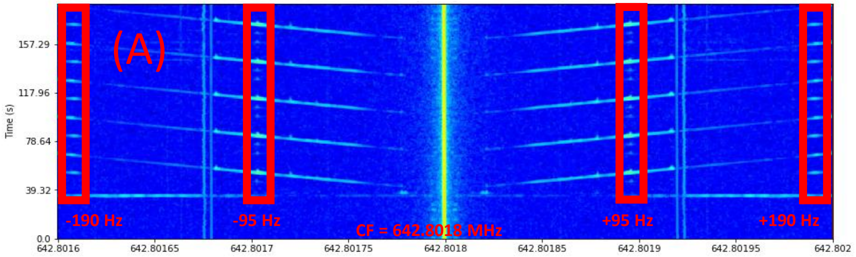
Parameter	Value	Units
Frequency	644	MHz
Geometrical β	0.61	
Optimal β	0.65	
Aperture diameter	83	mm
Effective length, L_{eff}	71.0	cm
Number of cells	5	
Geometric shunt impedance, R/Q	368	Ω
Geometry factor, G	188	Ω
E_{peak}	40	MV/m
B_{peak}	77.5	mT
Acc. gradient E_{acc}	17.5	MV/m
E_{peak}/E_{acc}	2.28	
B_{peak}/E_{acc}	4.42	mT/(MV/m)

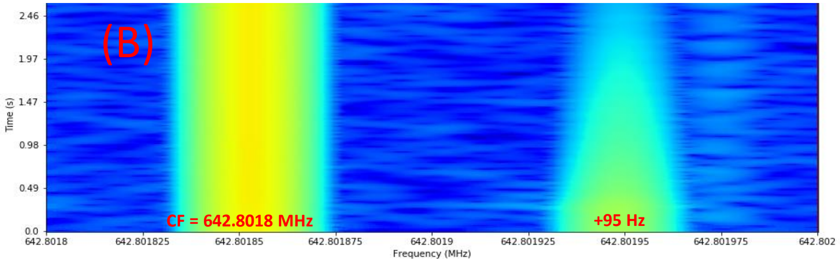




π-mode:



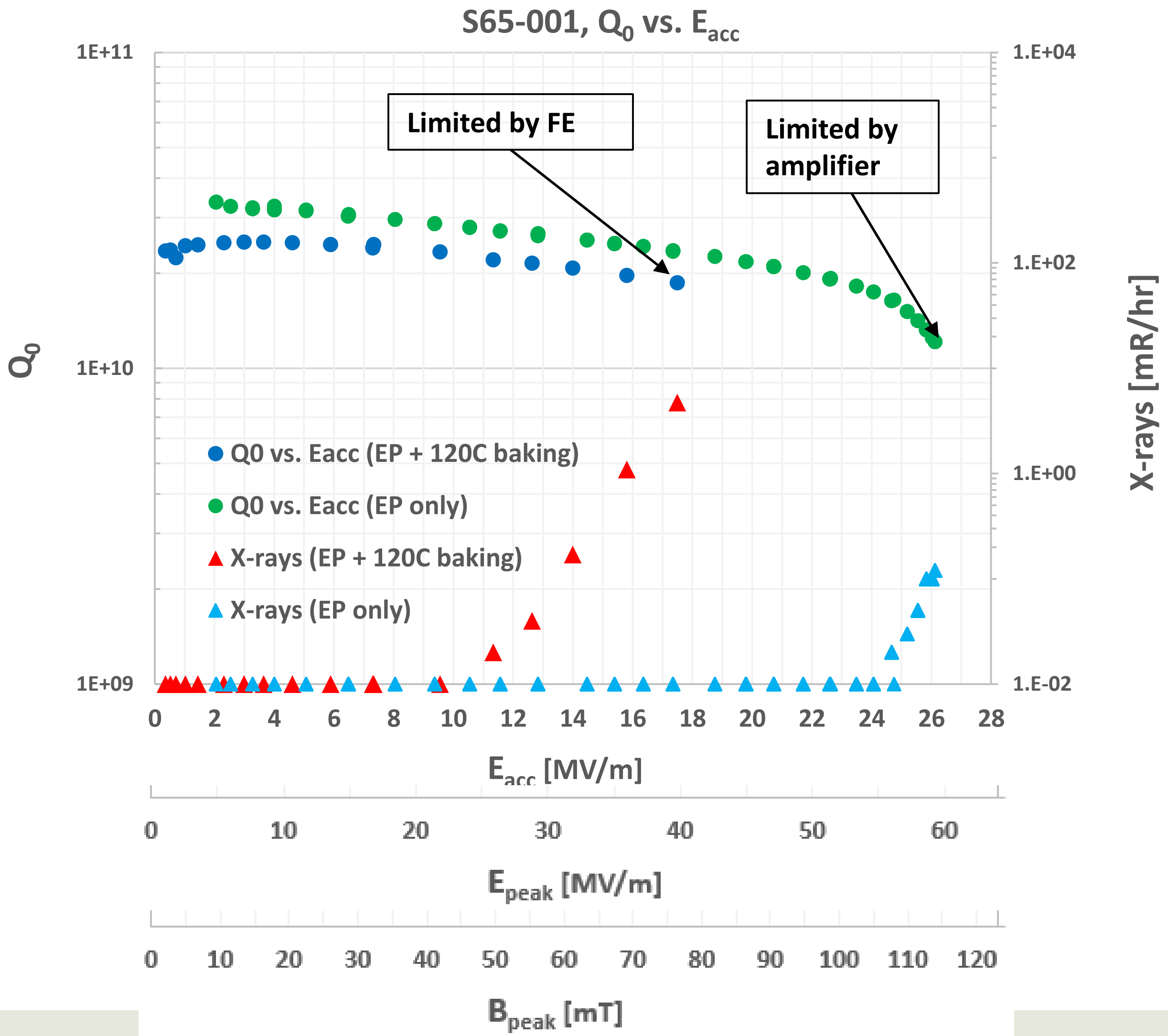




- Mechanical mode scans (A) and decay measurement (B) found the only mode within 200Hz is the accordion/bellows mode at 95Hz, with a Q of ~185.

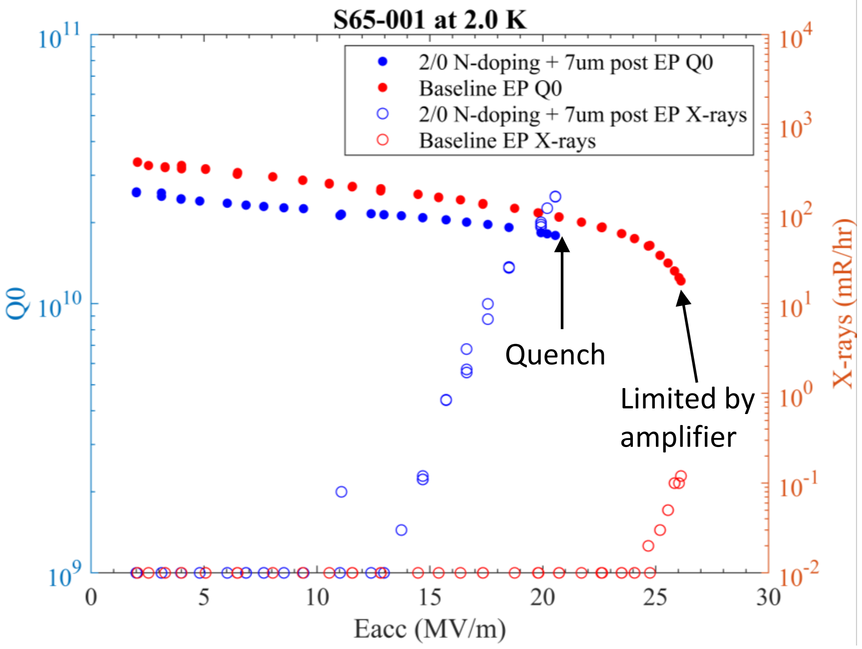
Multi-cell Cavity Performance with EP

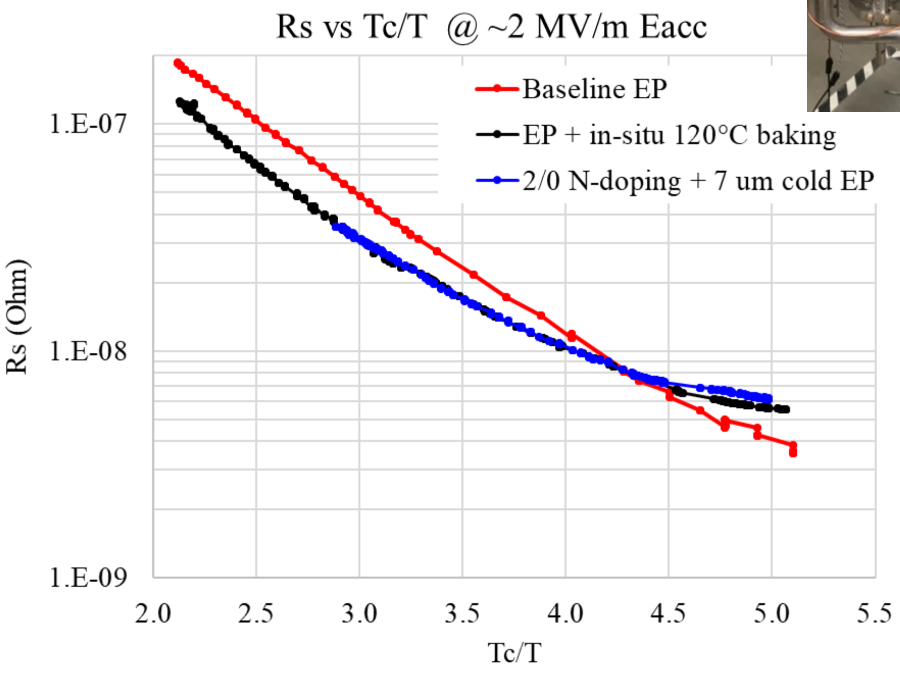
- Test 1: Standard ILC EP recipe, with baking
  - » 150 μm bulk EP at Argonne National Laboratory [ANL],
  - » 600º C baking for 10h,
  - » 20 μm light EP [ANL],
  - » 120º C for 48h in-situ baking
- Test 2: EP only
  - » 10 μm EP + 10 μm cold EP [ANL]
- No improvements in Q0 with in-situ 120º C baking



First N-doping of Medium-β Multi-cell Cavity

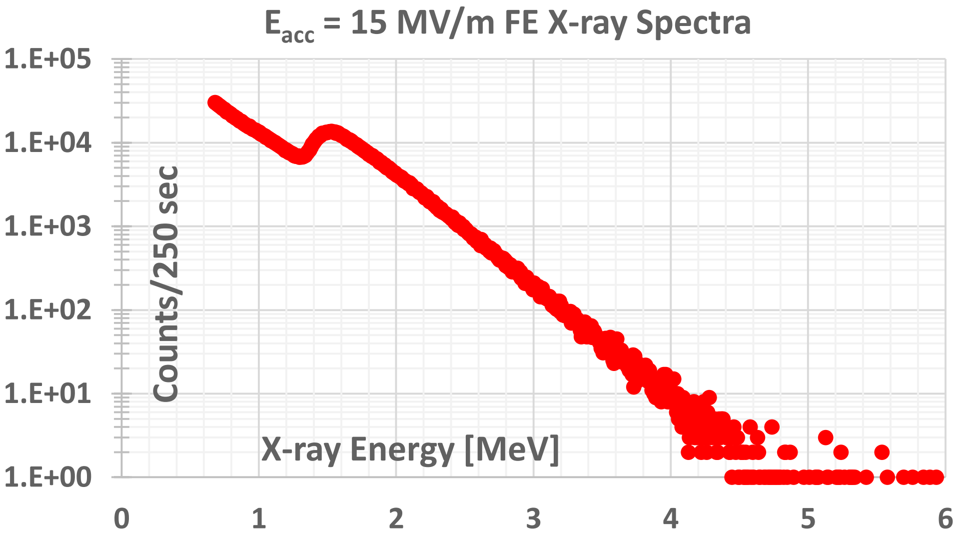
- 2/0 N-doping at FNAL, 7 um Cold EP at ANL, tested at FRIB
- First results:
  - » Higher residual resistance than the baseline
  - » First attempt of higher-ΔT cooldown gave a worse residual resistance; it is necessary to electrically insulate the titanium fixture rods for 'fast' cooldown.

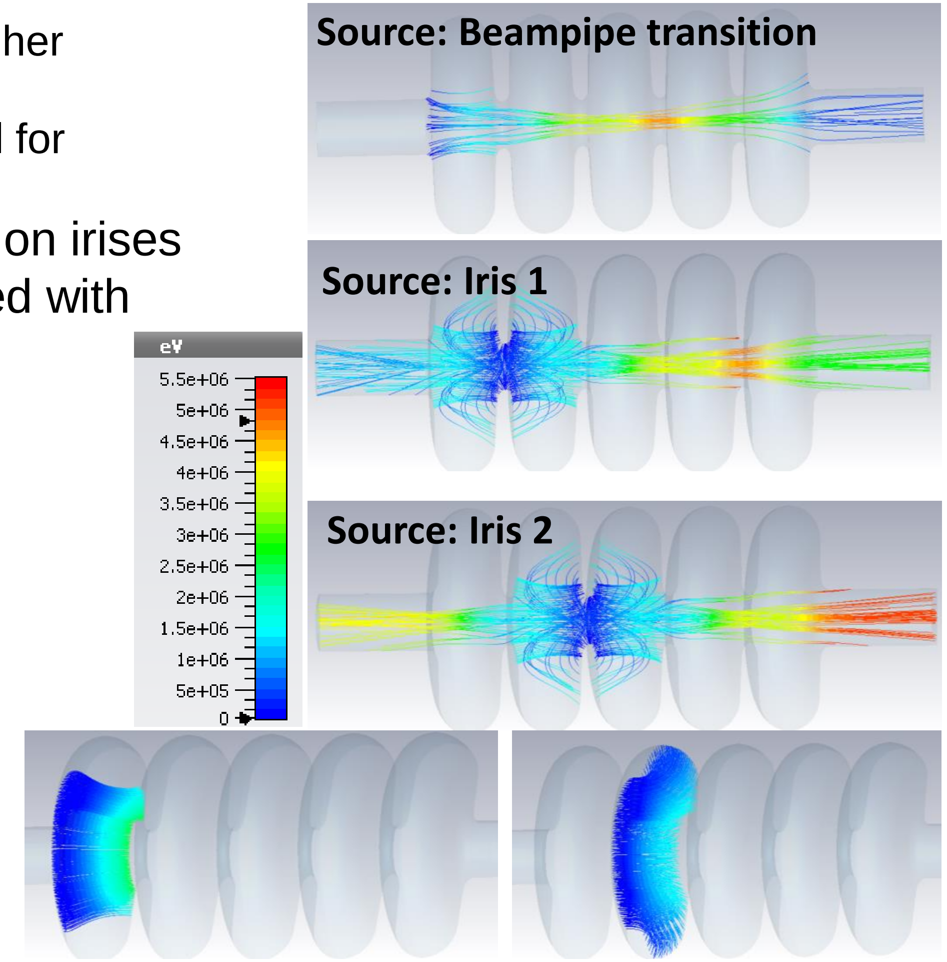




Field-emission is the main field-limiting factor

- Improving HPR and clean assembly
  - » Reduce HPR nozzle from 12 holes to 3 for higher velocity
  - » Reconfigure vacuum line to minimize potential for particulate contamination
- X-ray spectra indicate emission point likely on irises
- Coupler MP excited with strong FE, resolved with 100 V DC bias on coupler inner conductor





- Sidewalls do not produce high-E electrons

Beware of "Electro-etching" Nb cavities

An experiment you shouldn't repeat – even by accident

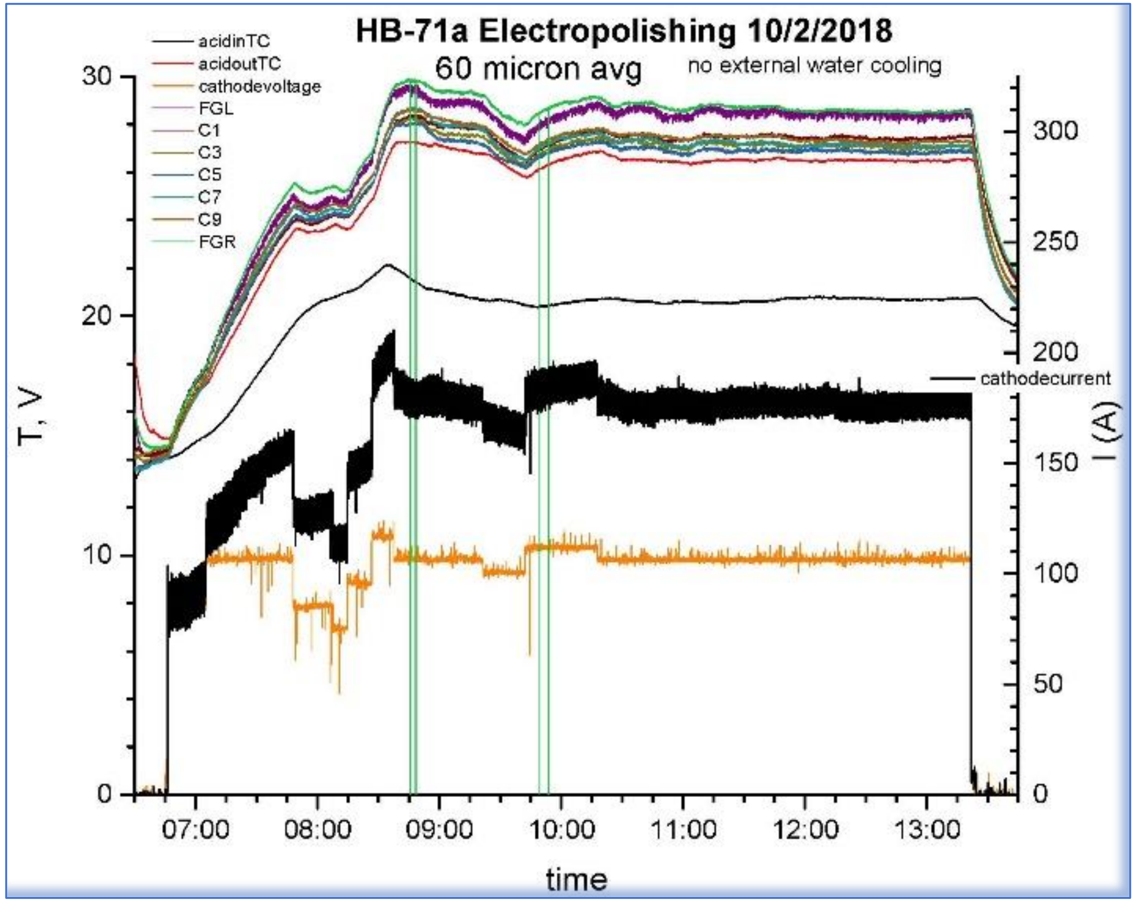
C. E. Reece

TTC Meeting

CERN 2020

Beware of “Electro-etching” Nb cavities

- If you want to polish the *beampipe* of a cavity while roughening the **surface** in the *equator* region, and simultaneously **load the cavity with hydrogen** to create a “Q-disease” condition – *do this*.

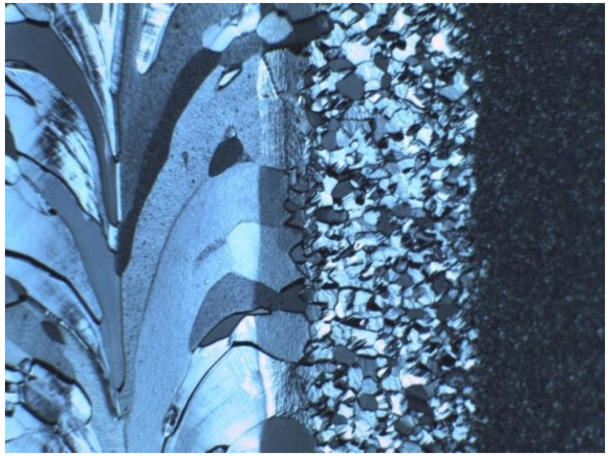


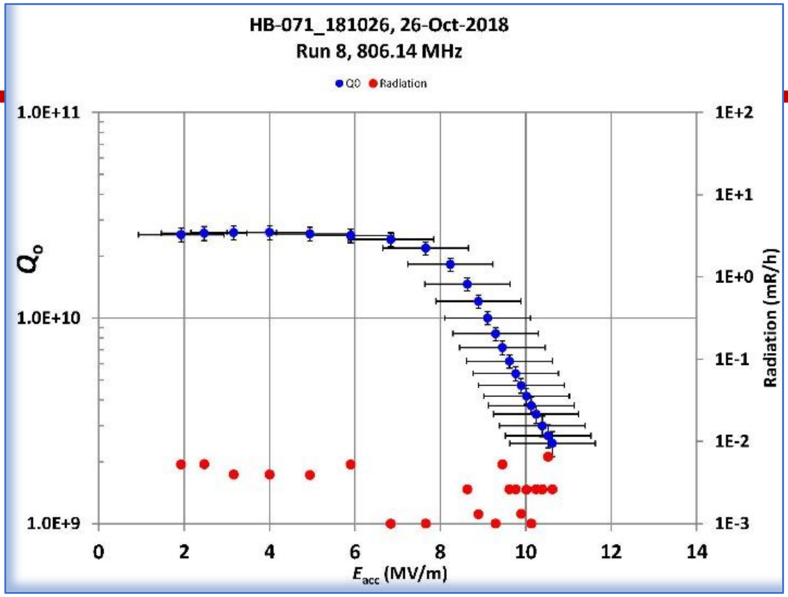
- Large cavity surface area
- 27 °C cavity surface temperature
- 10 V applied “EP” potential

- High current density on cathode leaves inadequate polarization to anodize the equator.
- No continuous anodization >> etching and hydrogen loading into bare Nb

AN EXPERIMENTAL ANALYSIS OF EFFECTIVE EP PARAMETERS FOR LOW-FREQUENCY CYLINDRICAL Nb CAVITIES
http://accelconf.web.cern.ch/AccelConf/srf2019/papers/tup029.pdf

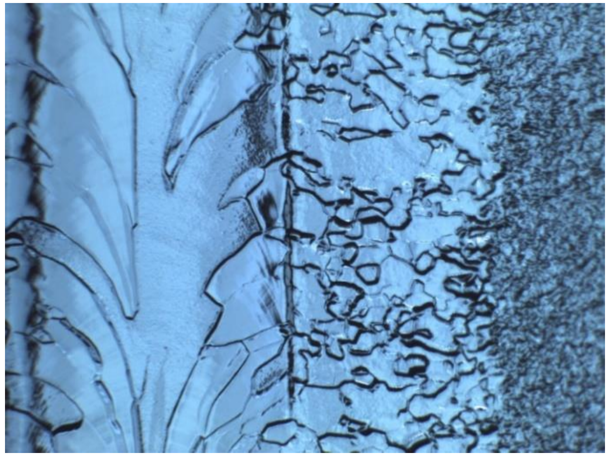
Beware of “Electro-etching” Nb cavities

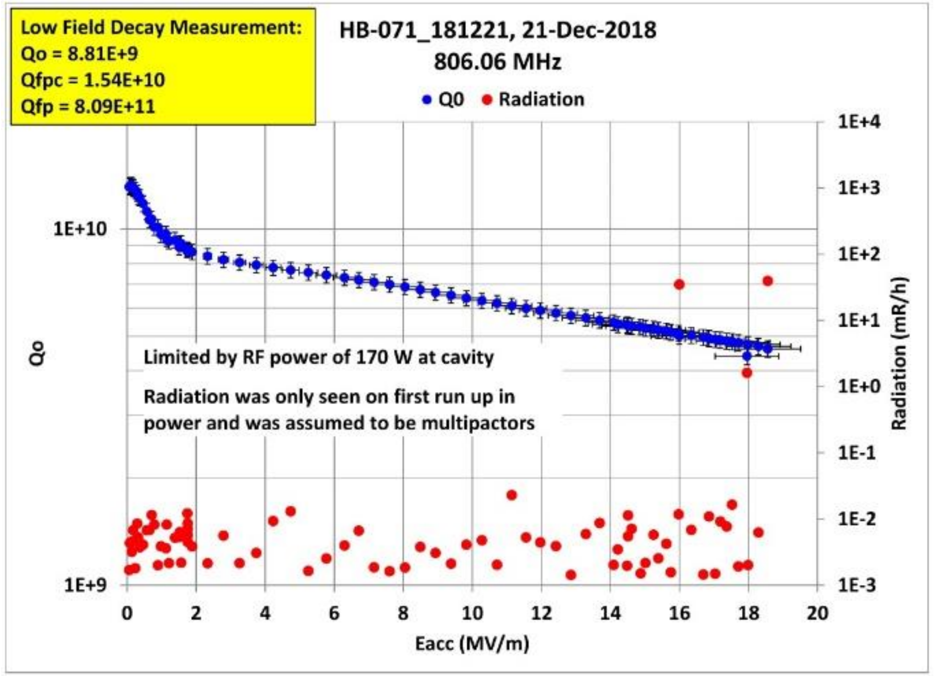




- **Rough, faceted surface normal RF test >> low field Q-drop**

+ ~50 µm“good” EP





- **Partially recovered polish, but with slow cooldown >> Q-disease**

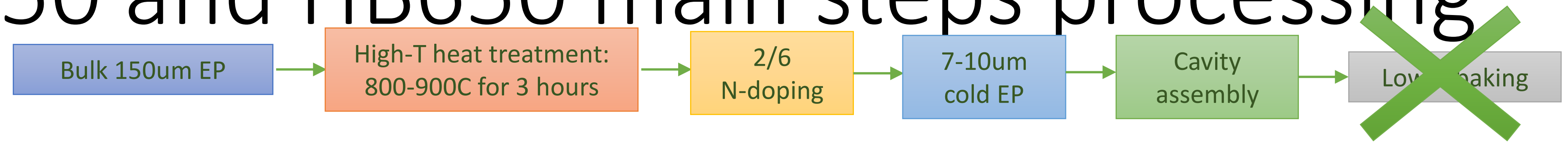
FNAL processing procedure for 650MHz cavities for PIP-II

Martina Martinello

Hot Topic (Processing and testing of large elliptical cavities (<1 GHz) for hadron linacs) – TTC 2020, CERN

6 Feb, 2020

LB650 and HB650 main steps processing



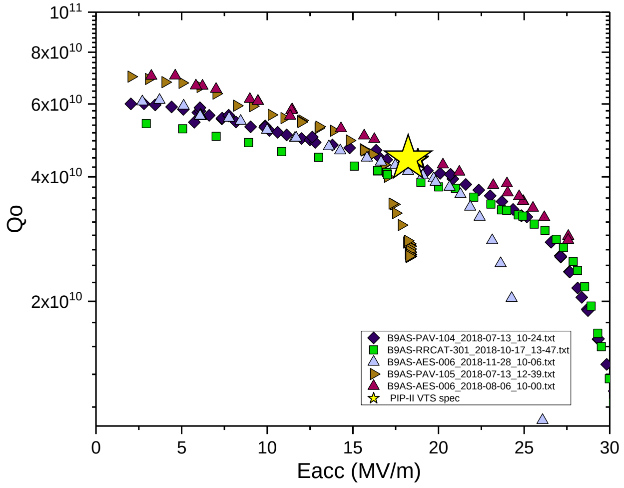
- 650 MHz cavities are bulk EP'ed. 150um are removed to be sure there is no damage layer left on the cavity surface.
- Cavities are heat treated at 800-900C for 3 hours, and the process is followed by N-doping (2min w 25mTorr of N_2 at 800C + 6min w/o N_2 at 800C).
- Between 7 and 10um are then removed via cold EP to assure slow and uniform post-doping removal. This has been found to be essential to improve quench field after N-doping.

➢ Extensive studies in single-cell and 5-cell cavities were carried out to optimize the surface treatment in HB650 cavities

All test done in compensated magnetic field

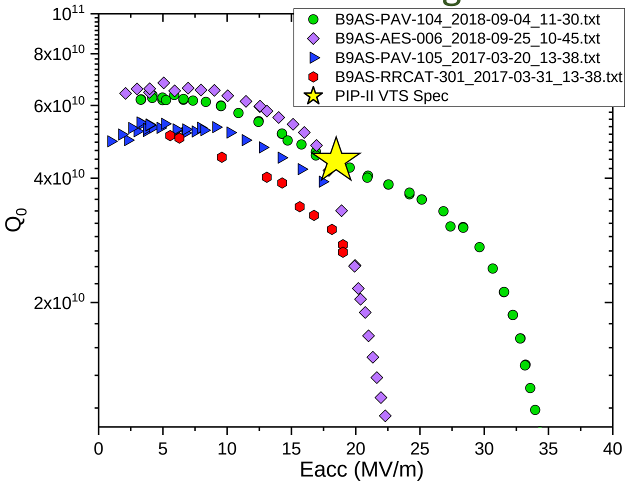
HB650 single-cell surface treatments comparison

EP



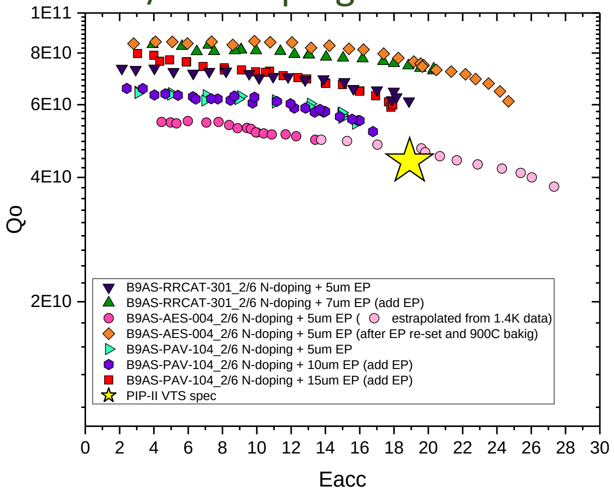
- Quench field between 17 and 30 MV/m
- HFQS onset starting from 16 MV/m to 27 MV/m

Low-T baking



- Quench field between 18 and 35 MV/m
- HFQS onset starting from 17 MV/m to 27 MV/m

2/6 N-doping + 5-15um EP

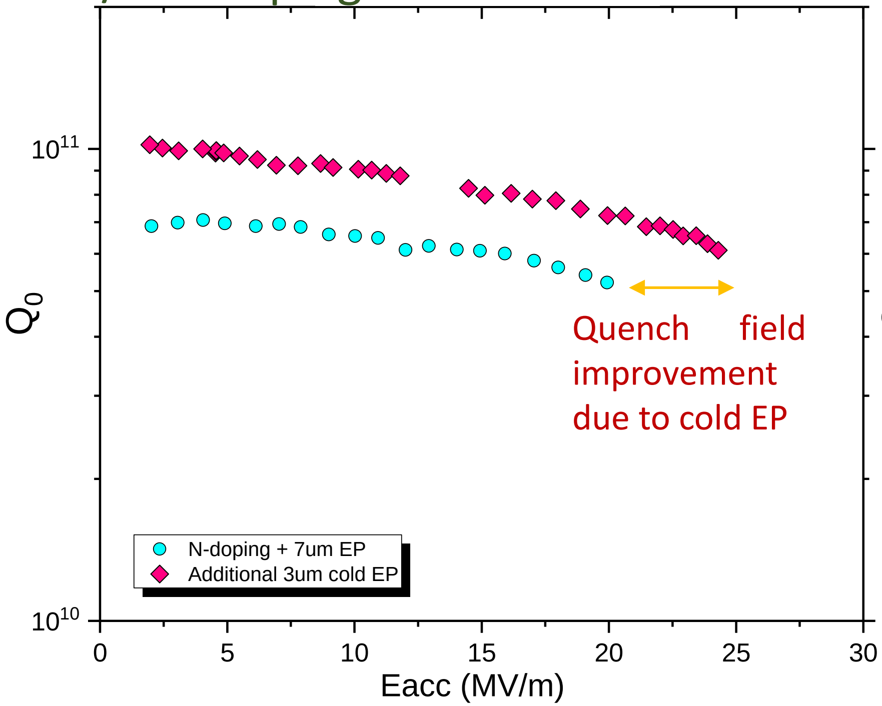


- Quench field between 16 and 28 MV/m
- No HFQS

- Q-factor considerably higher when N-doping is applied.
- In some cases, for all these treatments, early quench and/or HFQS is observed. These gradient limitations seem to be related to defects in the cavities, not to fundamental limitations.

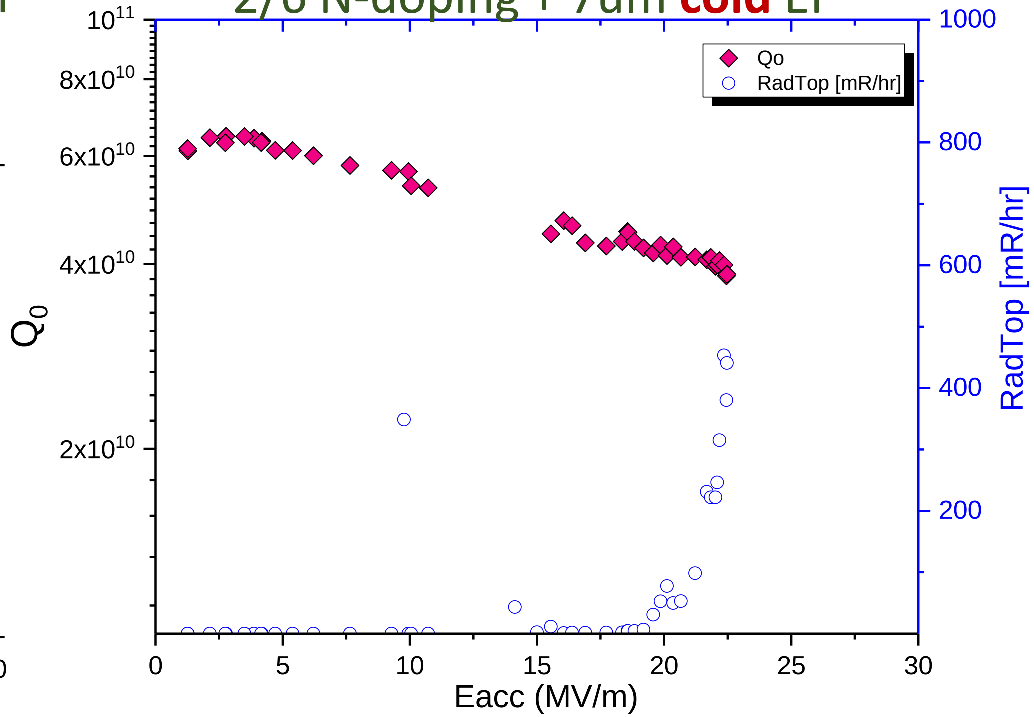
Quench field improvement in HB650 5-cell cavities after cold EP

2/6 N-doping + 7um EP + 3um **cold** EP



Quench field improved from 20 to 24 MV/m by adding 3um of cold EP

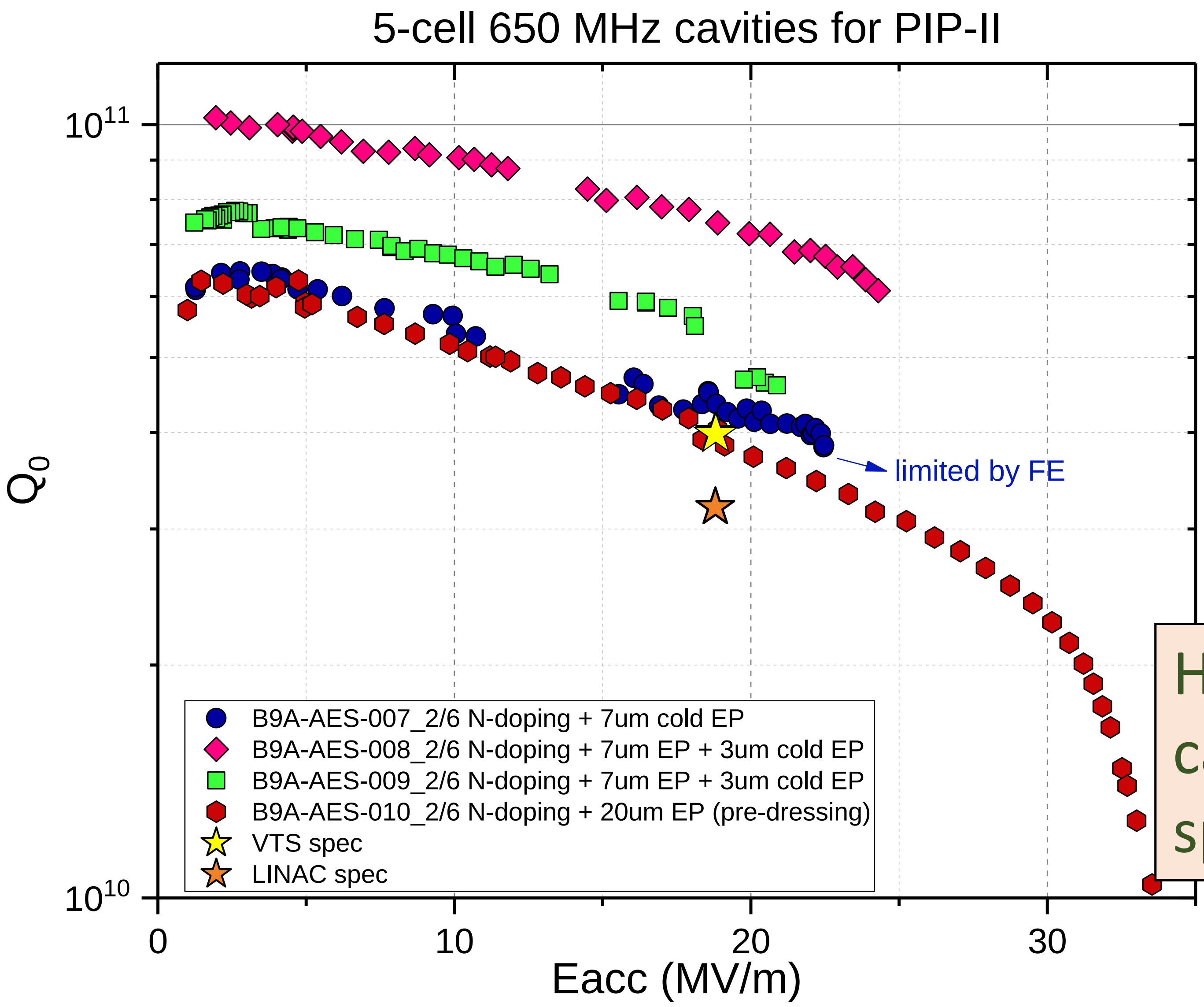
2/6 N-doping + 7um **cold** EP



Cavity limited by FE at ~23MV/m, quench field may be higher

N-doped cavities are no longer limited by early quench when **cold EP** is applied post-doping

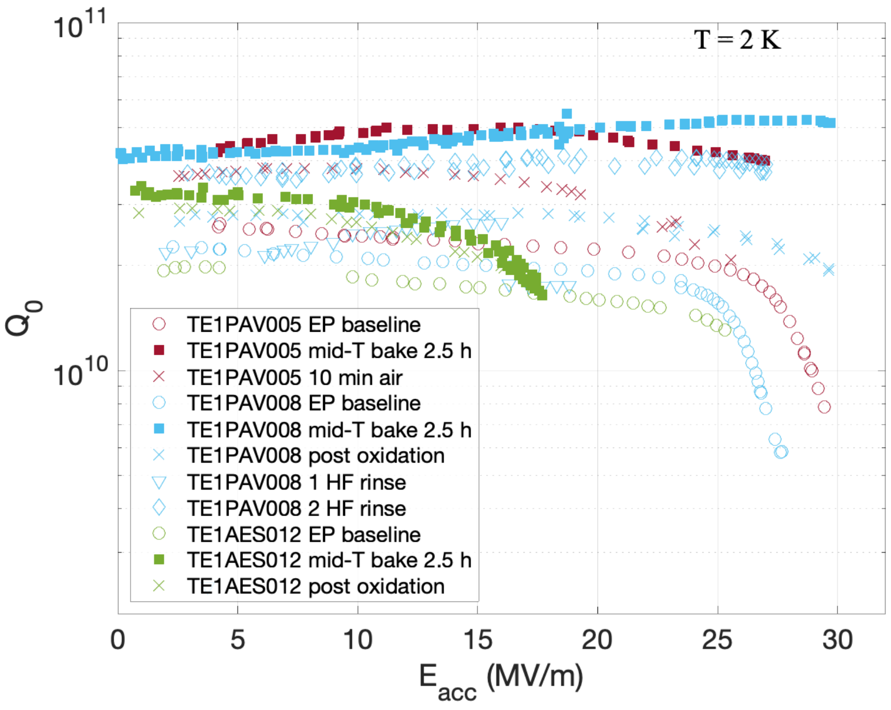
Summary results of doping on HB650 5-cell cavities

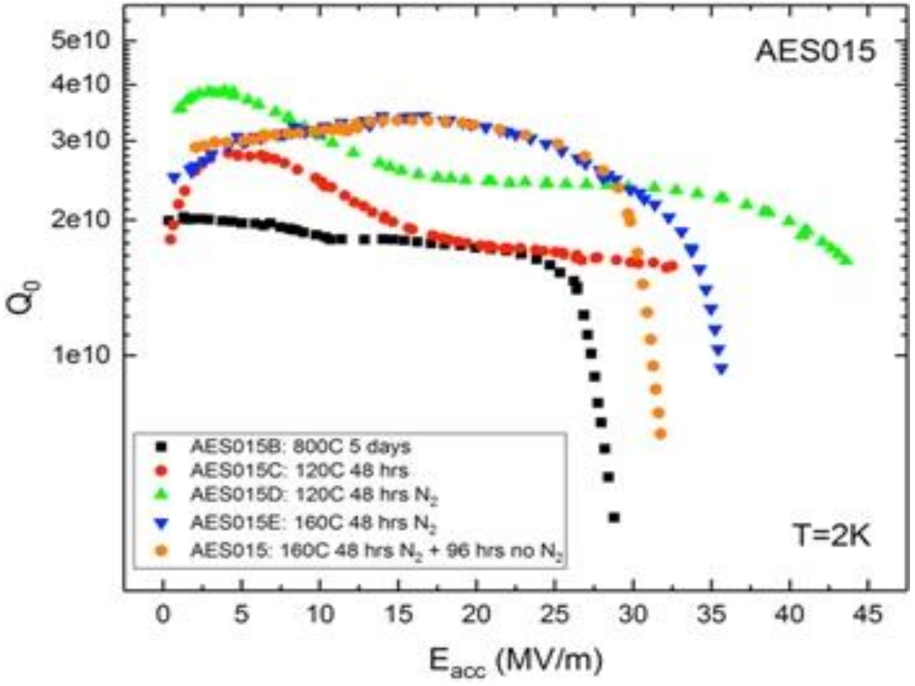


HB650 5-cell cavities meet VTS specifications.

Other promising directions for 650 MHz cavities

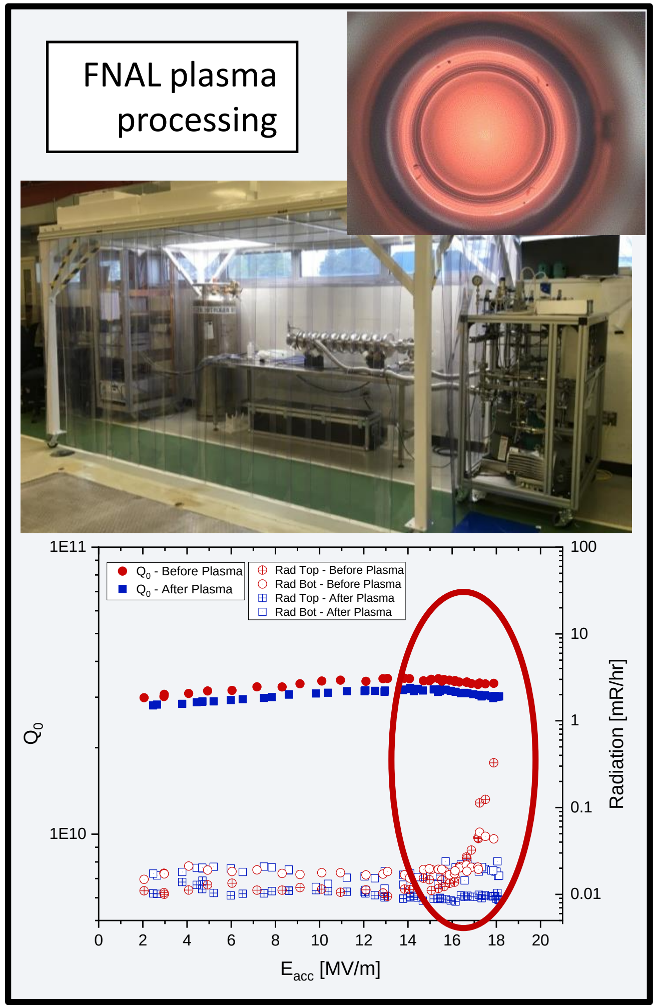
- N-doping have been successfully applied in 650 MHz cavities, and other treatments may show good results as well
  - **Mid-T baking** or **N-infusion** for high-Q high-gradients



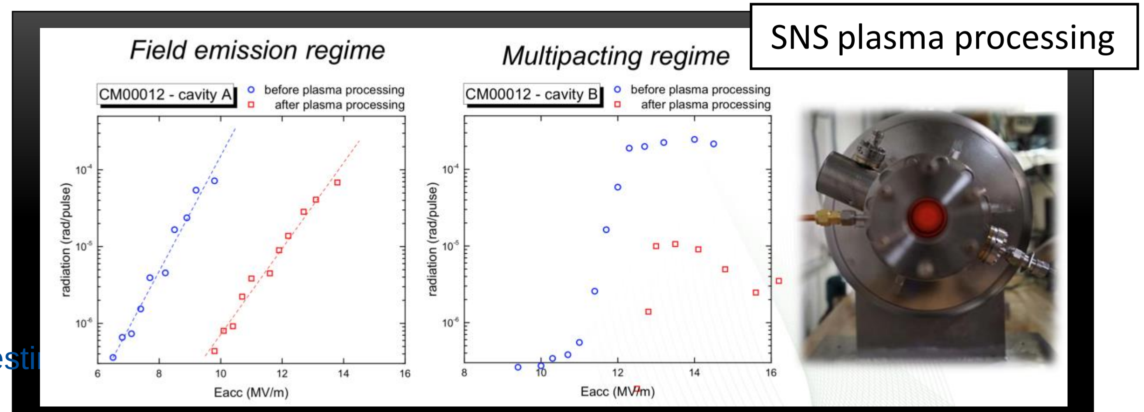


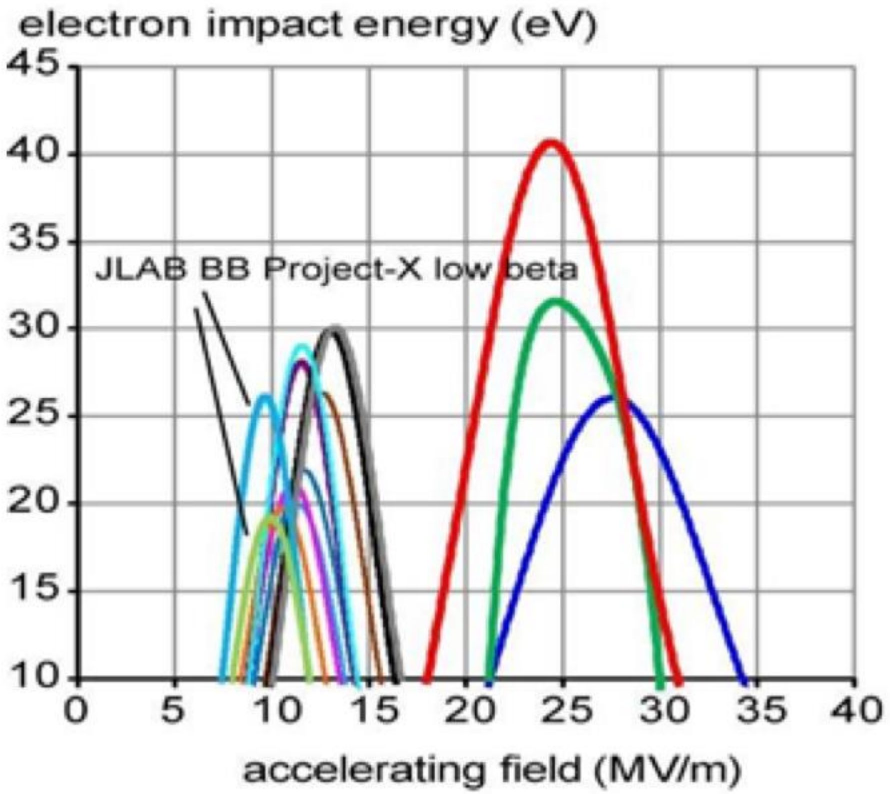
Other promising directions for 650 MHz cavities

- FNAL successfully developed **plasma processing** for LCLS-II cavities using HOM for plasma ignition. Could plasma processing be applied also in 650 MHz cavities?
  - No possibility of using HOM couplers, but SNS had successful experience in similar cavities using fundamental pass band modes
  - Abatement of field emission must be considered as of primary importance for these cavities for medium/high-gradient applications



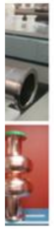
- Possibility of MP reduction via plasma processing may also be extremely beneficial





studies

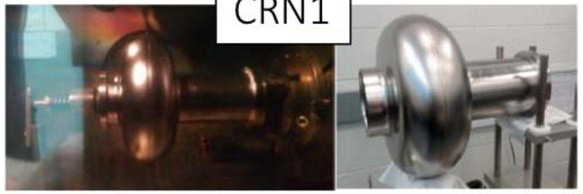
ental



Electron Beam Welding

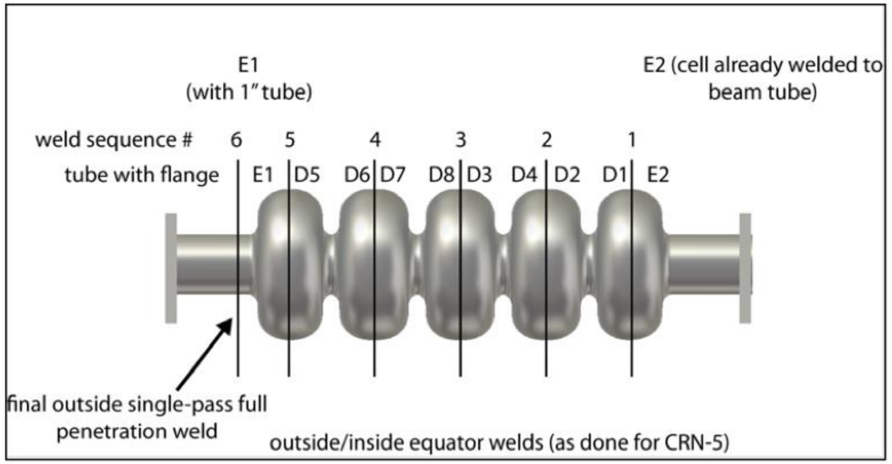
- Single-pass outside and inside partially (60-70%) penetrating equator welds, 3 mm weld preps

CRN1



CRN5

field flatness = ~85 %
as built (before tuning)



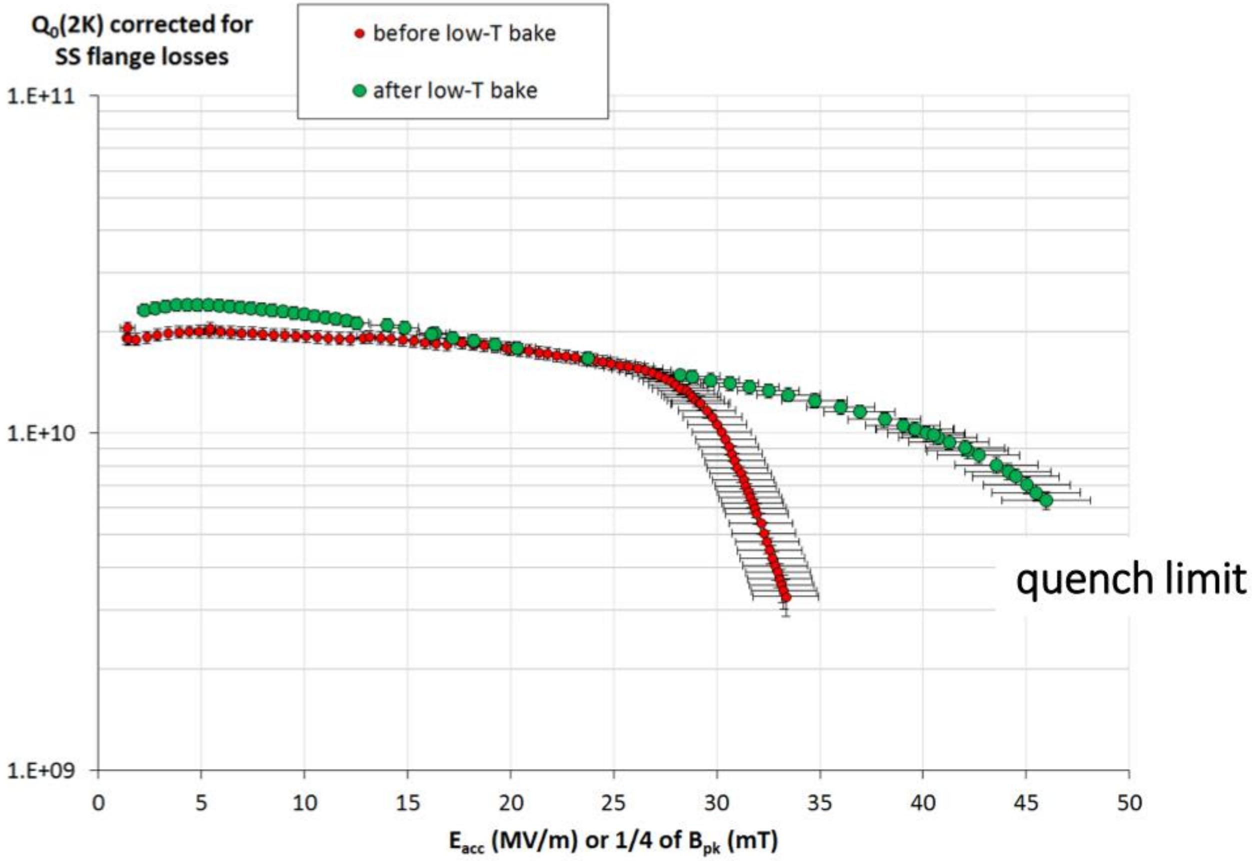
EIC5

field flatness = ~90 %
as built (before tuning)

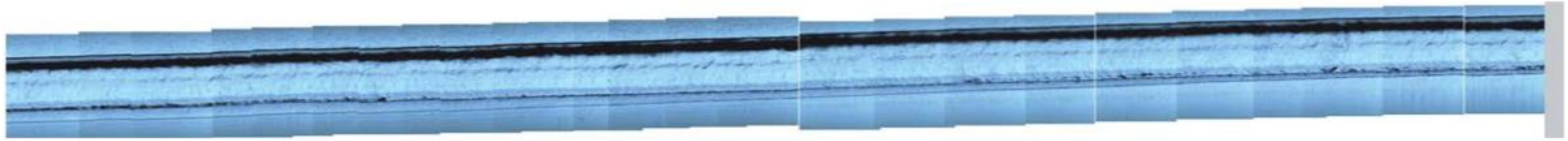
Jefferson Lab

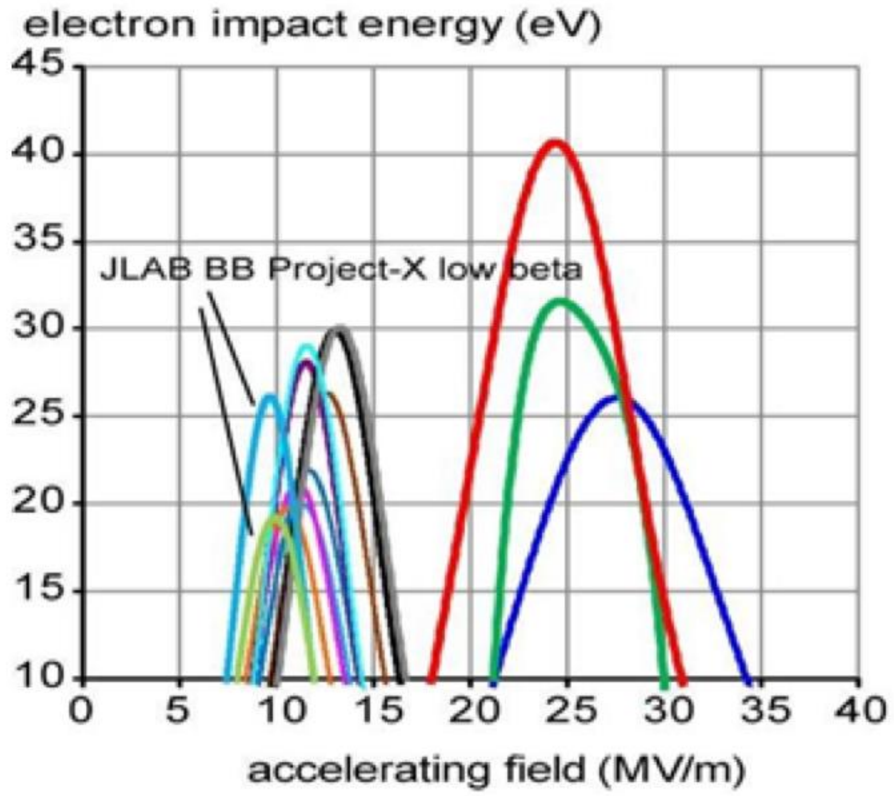
Weld Quality Matters

- RF test of **953 MHz** of 1-cell (*EIC1*) cavity



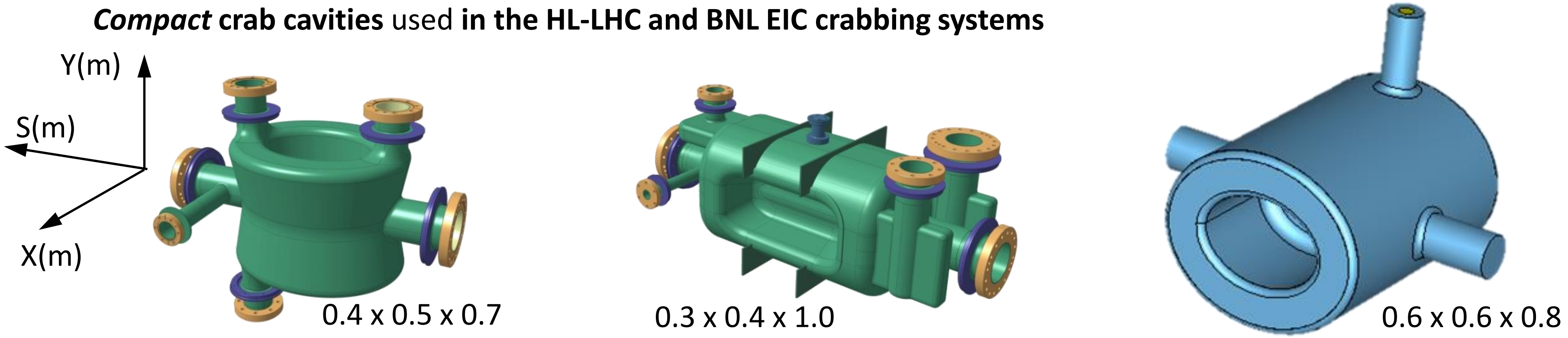
EIC1




electron impact energy (eV)
45
40
35
30
25
20
15
10
JLAB BB Project-X low beta
0
5
10
15
20
25
30
35
40
accelerating field (MV/m)

Crabs: large dimension and complex shape (incl. ports)

***Compact* crab cavities** used **in the HL-LHC and BNL EIC crabbing systems**



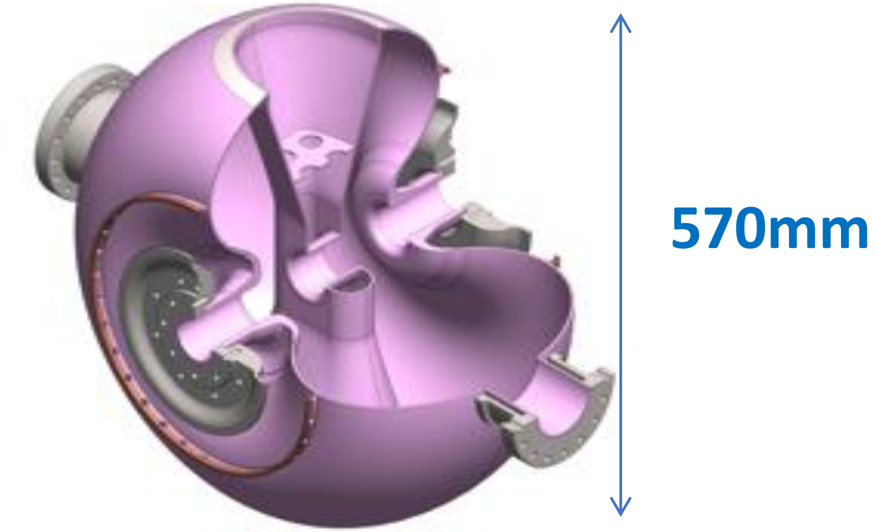
HL-LHC 400 MHz DQW | HL-LHC 400 MHz RFD | BNL EIC 200 MHz RFD

Experience from HL-LHC crabs (CERN, BNL, JLab and SLAC within the US LARP, Niowave, UK-STFC), valuable for the 200 MHz BNL EIC crab:

- *Fabrication*
  - Complex shapes, port openings motivate considering fab. from bulk, 3D print despite size
  - Large aspect ratio shapes: challenging deep-drawing is assisted by simulations which help optimize process to reduce stress and avoid excessive thinning
  - Non-circular welds and no easy line sight: 3D program in 5-axis machine
- *Buffered Chemical Polishing*
  - Several iterations and configurations to guarantee uniform removal:
    - Vertical bench at JLab (2 conf.)
    - Horizontal bench at CERN (2 conf.)
    - Rotational bench at ANL
  - Fluid dynamics simulations to study thickness removal rate and homogeneity for different configurations + measurements for each orientation (CERN / UK-STFC)
  - Surfaces looking downwards experience slower thickness removal rate (UK-STFC)
- *Vertical Testing*
  - Short ports require RF-seal gaskets and Nb-coated SS flanges to reduce heat load // copper disks also used

Balloon SSR

- Balloon Concept
- Fabricated from two elliptical reentrant shells
- 570mm diameter
- Issues
  - Requires precise forming
  - Large pieces to handle and weld
- Spoke welding to completed body is challenging



Shells in Nb

Shells

Stack-

Handling/testing frame