SRF R&D: Highlights and Impact on PIP-II

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Fermilab Institutional Review

11 Feb 2015

Outline

- Recent achievements of SRF R&D
- PIP-II SRF – progress highlights
- Application of R&D breakthroughs to PIP-II

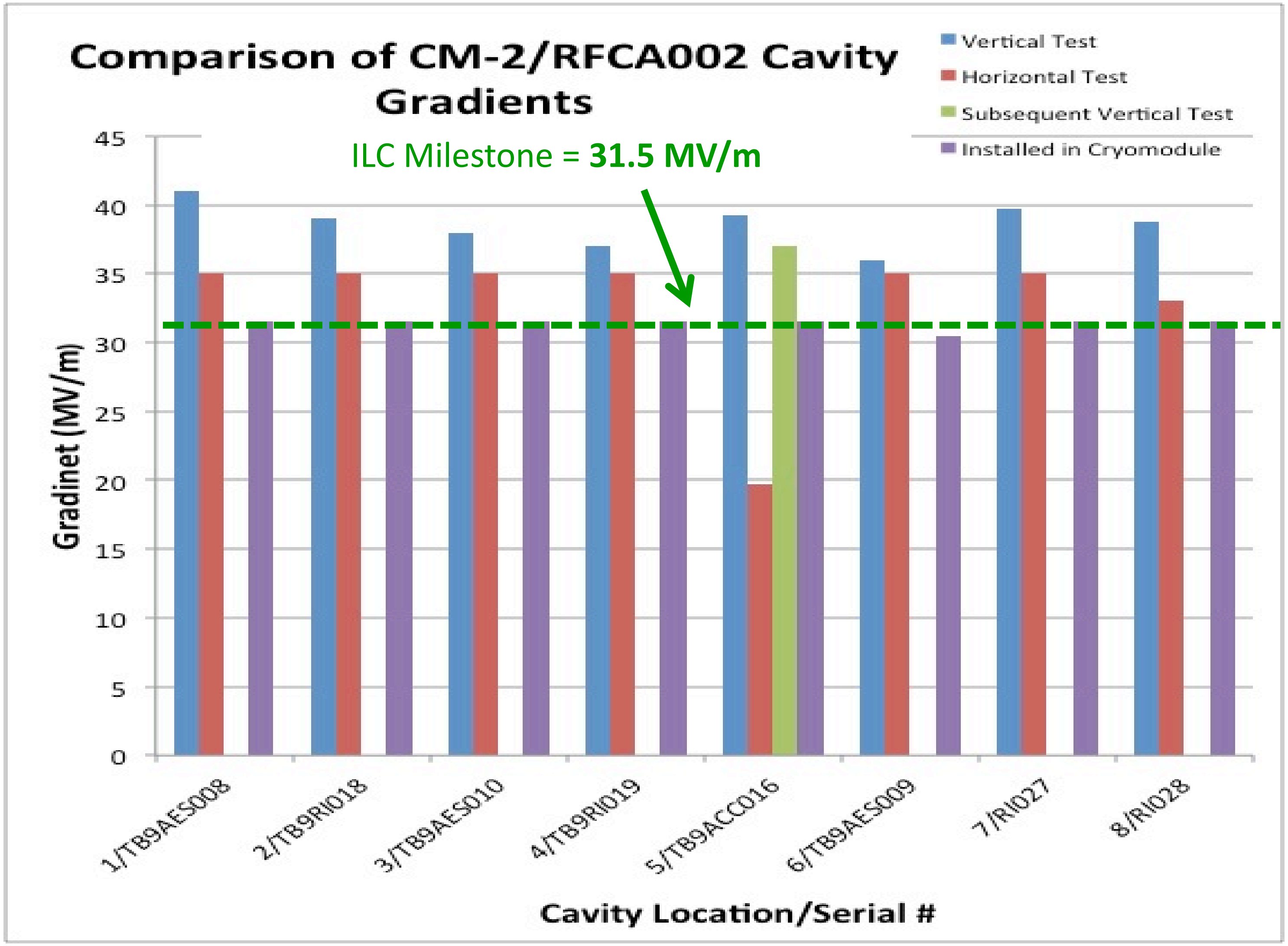
Recent Fermilab SRF R&D Achievements

- Highest gradient ILC SRF cryomodule at FNAL
  - 31.5 MV/m – culmination of SRF development activities at FNAL
- Ultra-high Q via nitrogen doping
  - Cut cryogenic capital and operational costs by a factor of > 2
  - Current baseline for LCLS-II which is a CW SRF-based upgrade for LCLS facility at SLAC
    - >~50M$ in capital savings, 10s of M$ in operational costs
- Discovery of efficient expulsion of ambient magnetic field from cavity walls leading to record low residual resistances => even higher Q
  - World record Q>2e11 up to ~20MV/m demonstrated combining N doping and efficient flux expulsion
- Development of SRF structure chain for PIP-II
  - Integration of PIP-II and SRF R&D

CM#2

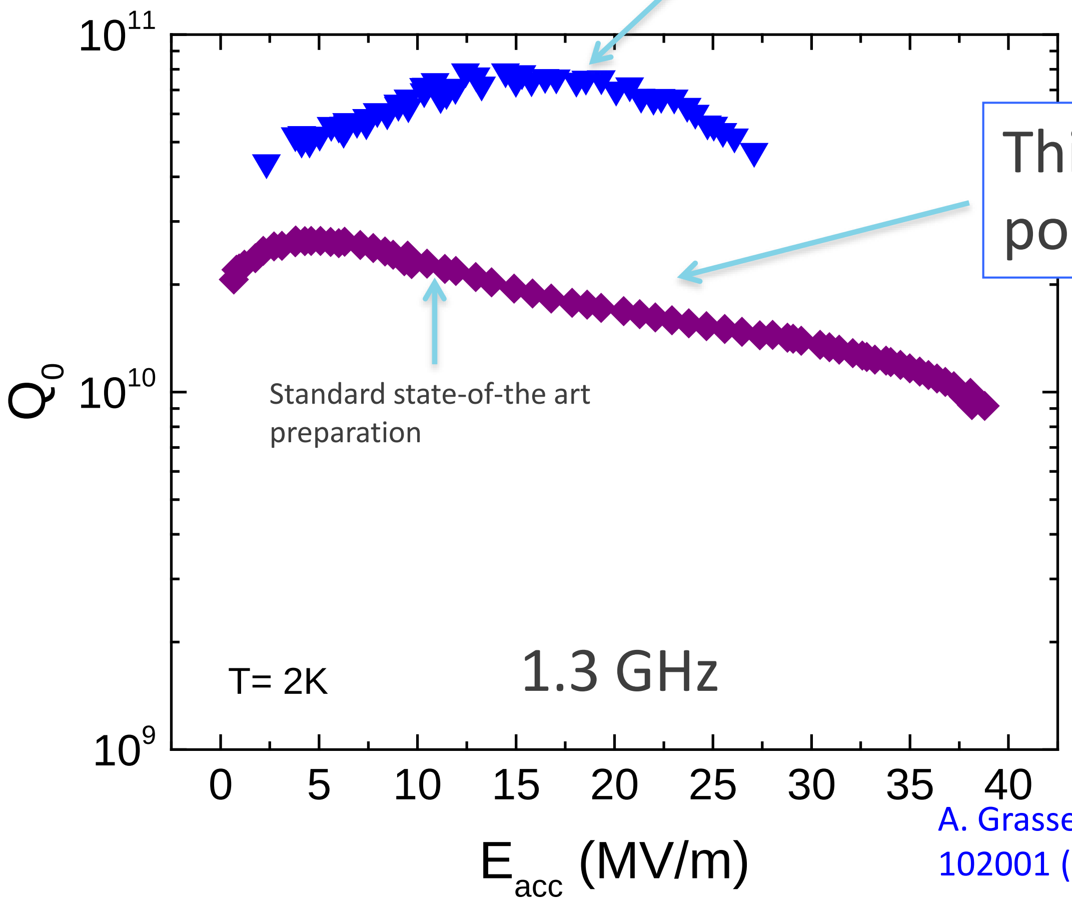
World Record Performance of ILC SRF Cryomodule

Fermilab CM2 -> Highest Gradient ILC–Cryomodule



Nitrogen doping: a breakthrough in Q

Record after nitrogen doping – up to 4 times higher Q!

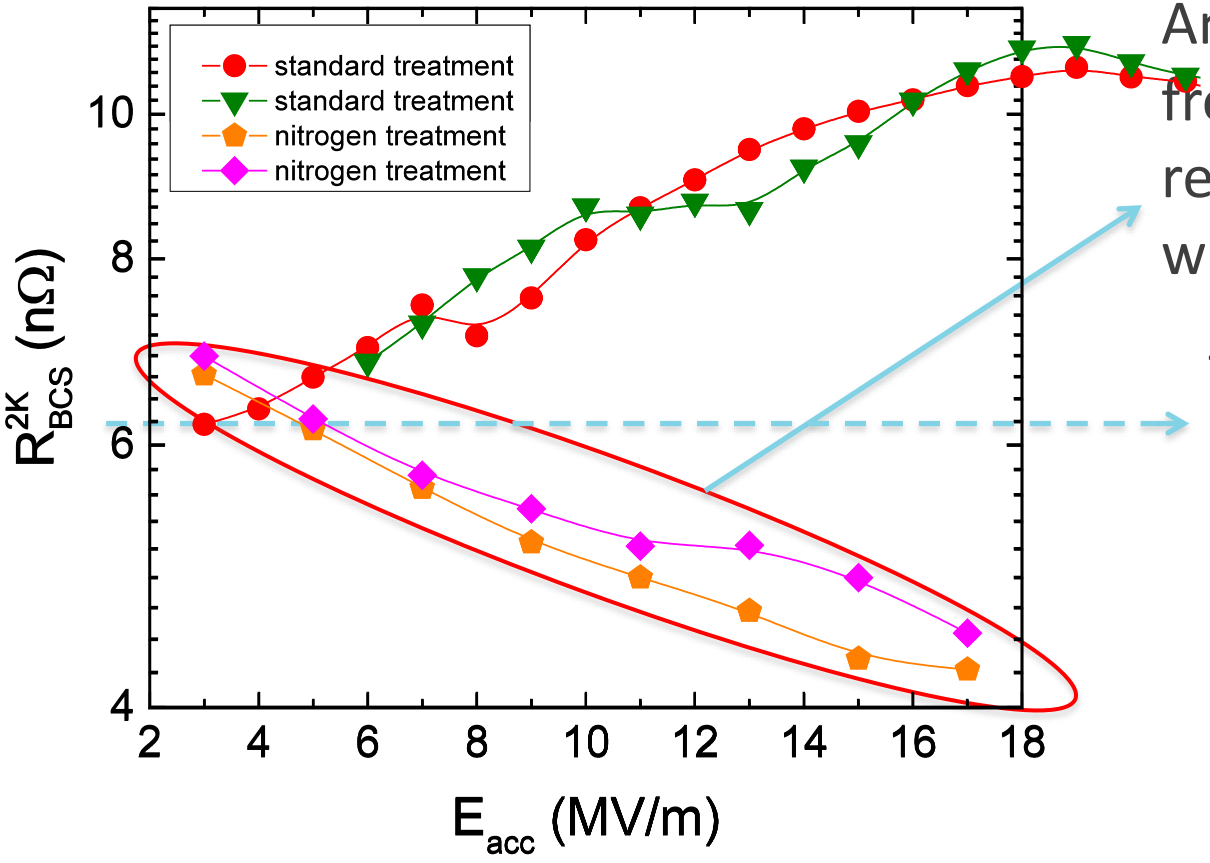


This was the highest Q possible up to 2012

Standard state-of-the art preparation

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication) – highlights of 2013

Physics – perceived BCS limit has been overcome



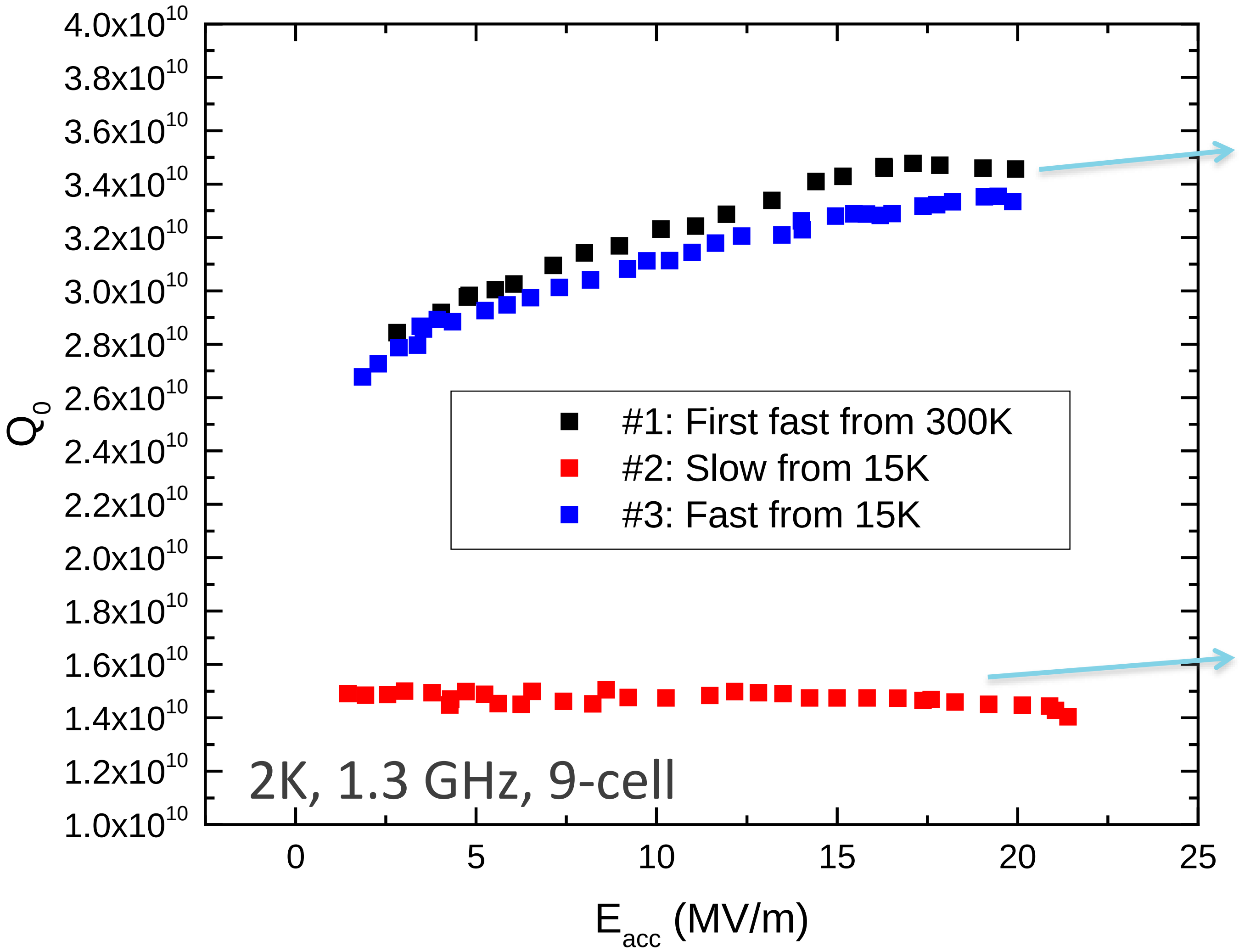
Anti-Q-slope emerges from the BCS surface resistance decreasing with field

This is what BCS theory predicted to be the lowest possible surface resistance

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)
A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

Minimizing residual resistance (maximize Q) by avoiding the ambient magnetic flux to be trapped

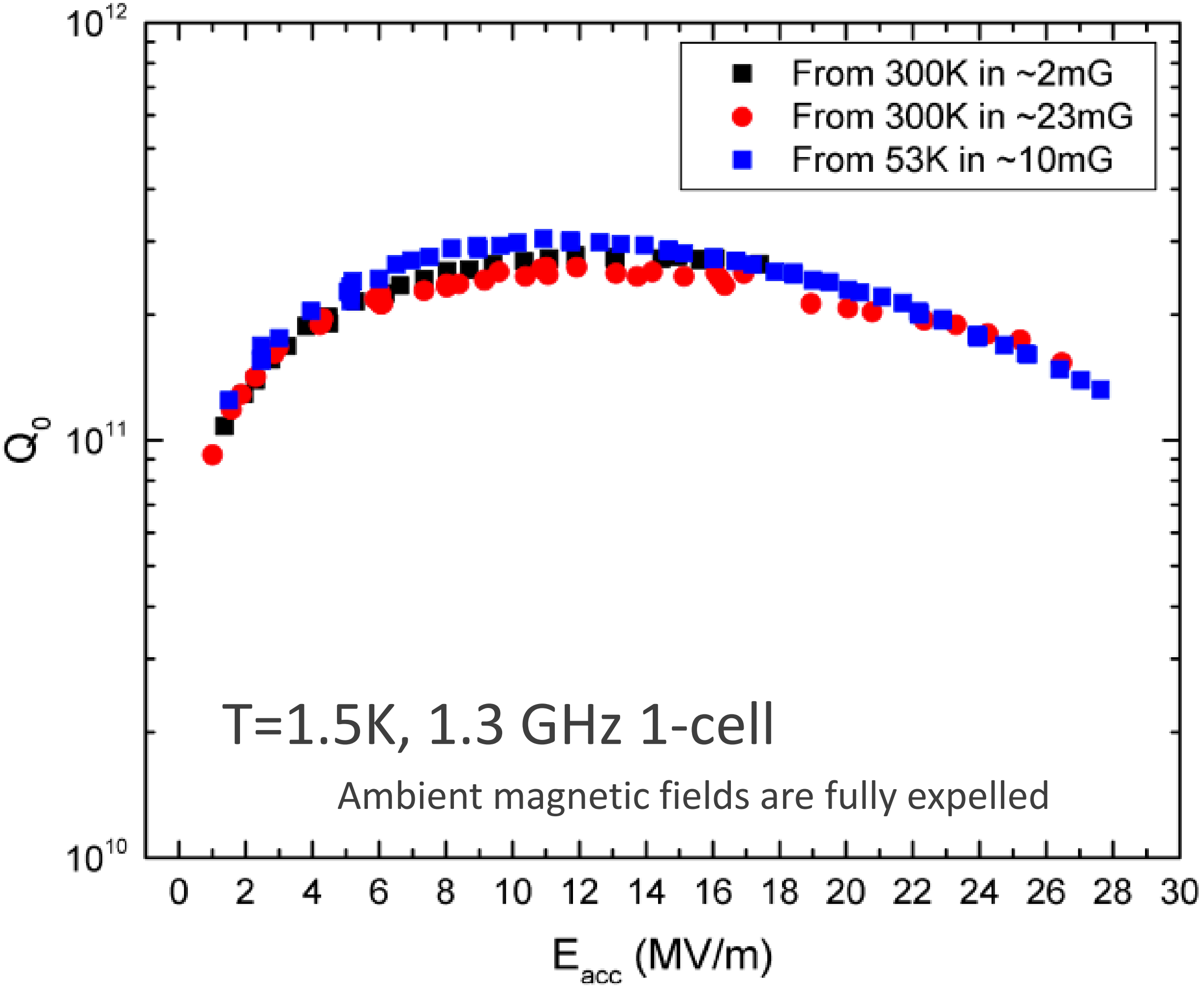
Same cavity, just cooled differently through 9.2K



Flux expelled efficiently

Flux mostly trapped

Utilizing new physics for record high Qs



T=1.5K, 1.3 GHz 1-cell

Ambient magnetic fields are fully expelled

Combination of nitrogen doping and efficient flux expulsion =>
Record high Q >1e11 up to 28 MV/m in SRF cavities

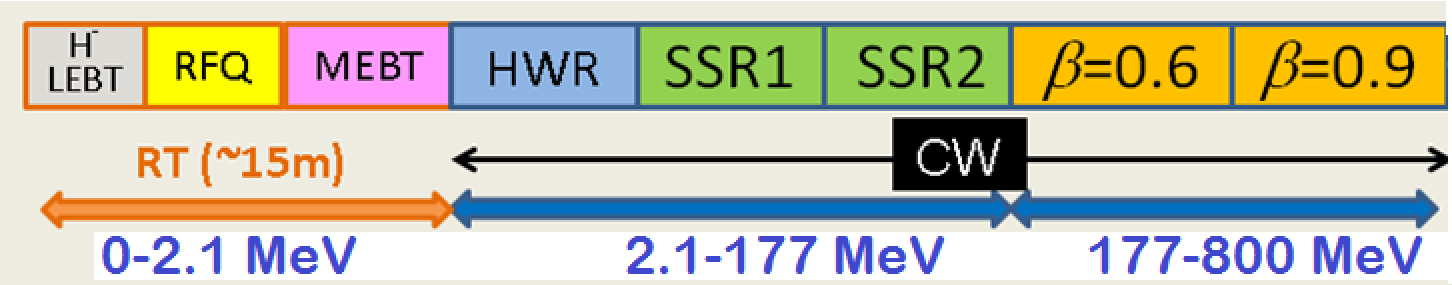
A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk, Appl. Phys. Lett. **105**, 234103 (2014)

PIP-II and SRF R&D

- Development of cavities and cryomodules
  - 162.5 MHz -> at ANL
  - 325, 650 MHz -> FNAL
- High Q to enable high duty factor
  - Mu2e – up to 100% duty factor is desirable

PIP II

SRF Linac Technology Map



SRF Cavity Type	Freq, MHz	Energy (MeV)	Cav/mag/CM	CM type, length
HWR (β_G=0.11)	162.5	2.1-11	8 /8/1	scscscscscscscsc, 5.3m
SSR1 (β_G=0.22)	325	11-38	16 /8/ 2	csccsccsccsc, 4.8m
SSR2 (β_G=0.47)	325	38-177	35 /21/ 7	sccsccsc, 6.5m
LB 650 (β_G=0.61)	650	177-480	30 /12/10	ccc, 7.1m
HB 650 (β_G=0.9)	650	480-800	24 /6/ 4	cccccc, 9.5m

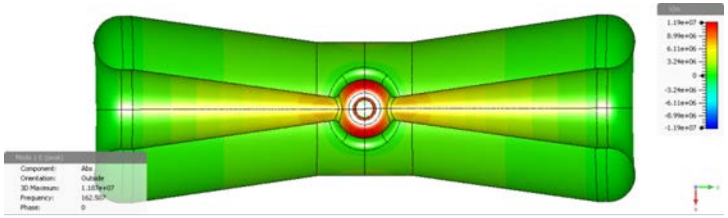
ANL work

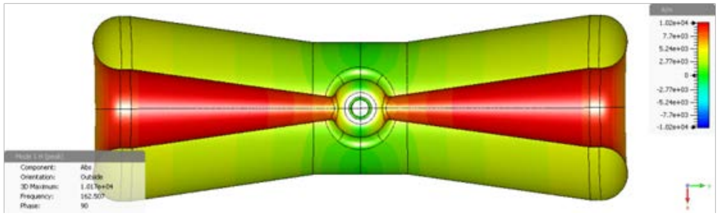
162.5 MHz Half Wave Resonators (beta=0.11)

Z.A. Conway, A. Barcikowski, S. Gerbick,
M.P. Kelly, M. Kedzie, S. Kim, R. Murphy, P.N. Ostroumov and T. Reid

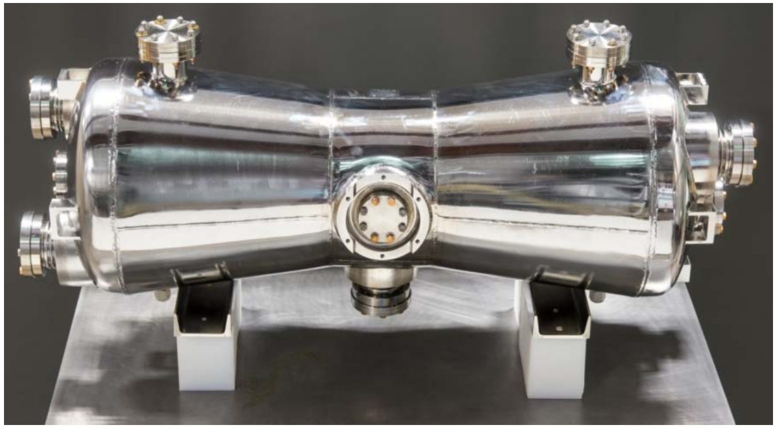
Design Parameters

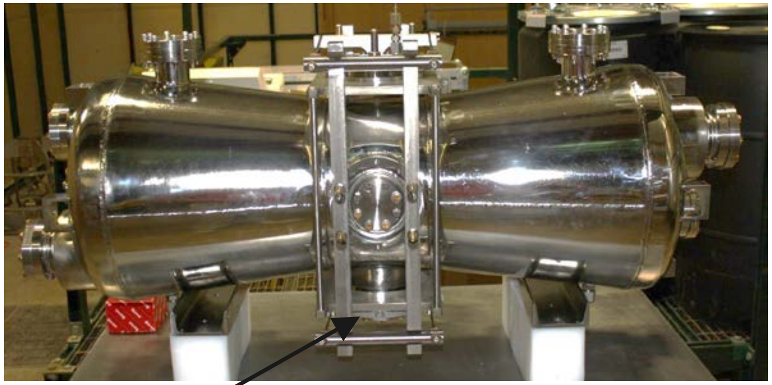
Parameter	Value
Optimal beta	0.112
E_{PEAK}/E_{ACC}	4.6
B_{PEAK}/E_{ACC}, mT/[MV/m]	5.0
R/Q, Ω	271
G, Ω	48


E-field


B-field

Fabrication of 2 prototype cavities is finished



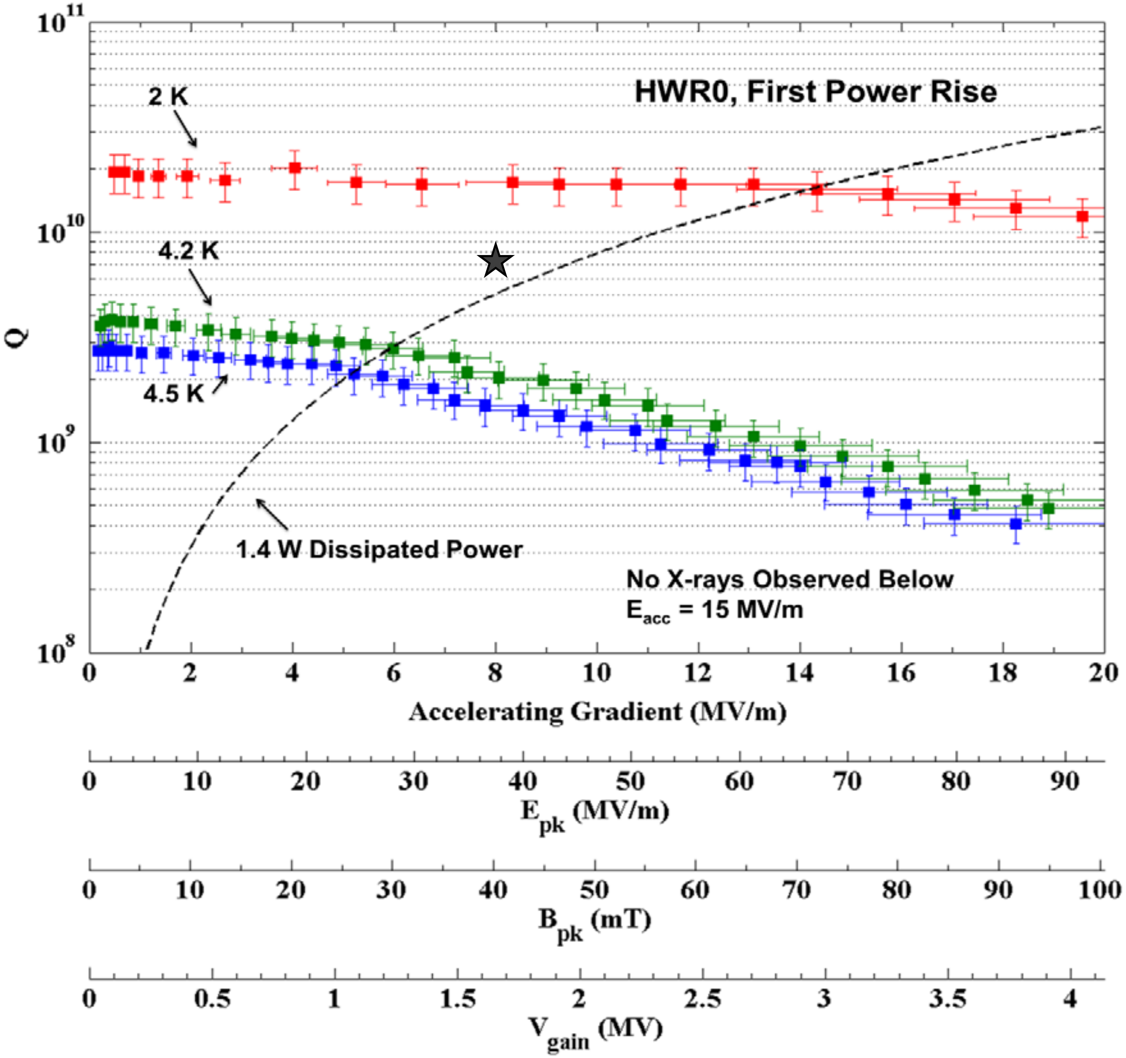

Pneumatic slow tuner

ANL work

The First HWR0 Cold/RF Testing

Z.A. Conway, A. Barcikowski, S. Gerbick,
M.P. Kelly, M. Kedzie, S. Kim, R. Murphy, P.N. Ostroumov and T. Reid

- Performance sets a new world record in TEM-class cavities
- The star is the design specification
- Testing was done with adjustable coupler at critical coupling
- Residual resistance is 2.6 nΩ up to 14 MV/m
- Design field is 8 MV/m, $Q_0=7\times10^9$
- No X-rays observed below 15 MV/m
- Second cavity (HWR1) tested as well



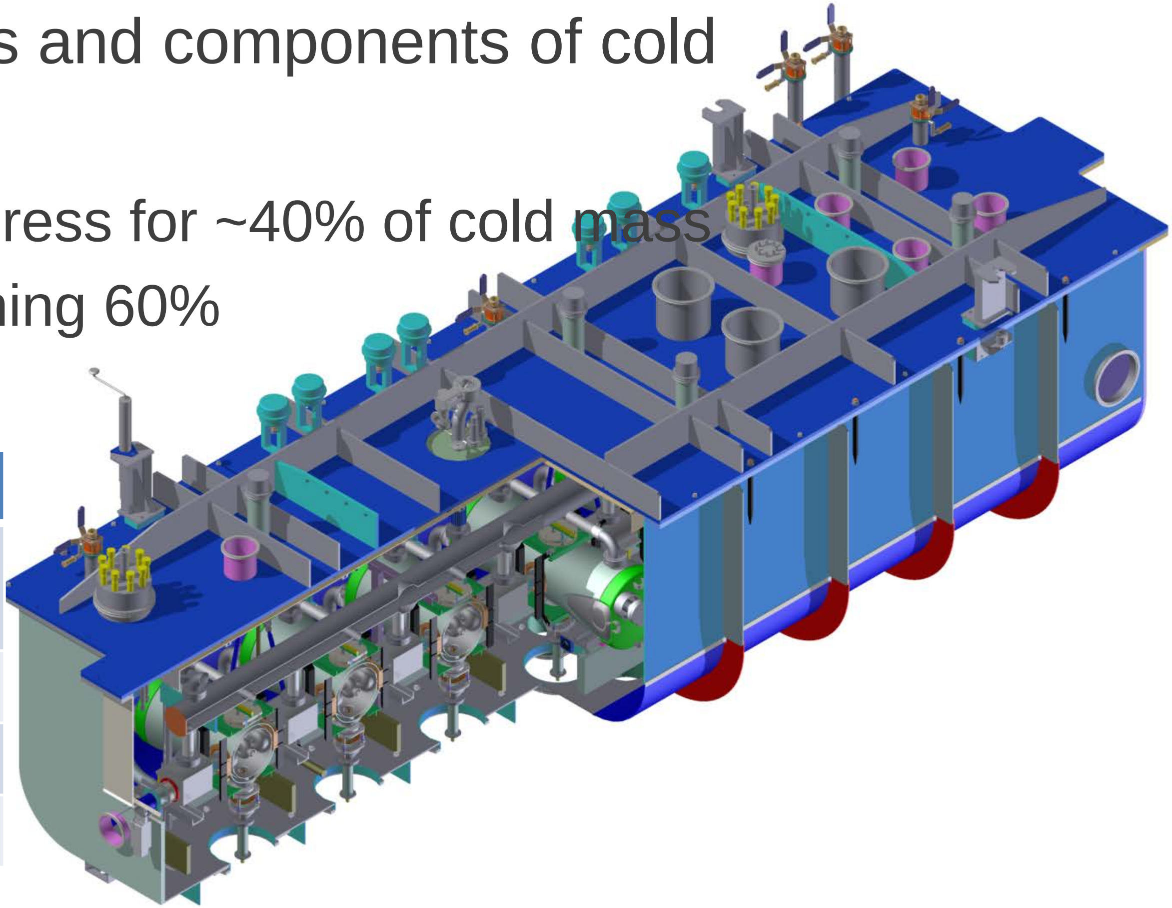
ANL work

HWR Cryomodule

Z.A. Conway, A. Barcikowski, S. Gerbick,
M.P. Kelly, M. Kedzie, S. Kim, R. Murphy, P.N. Ostroumov and T. Reid

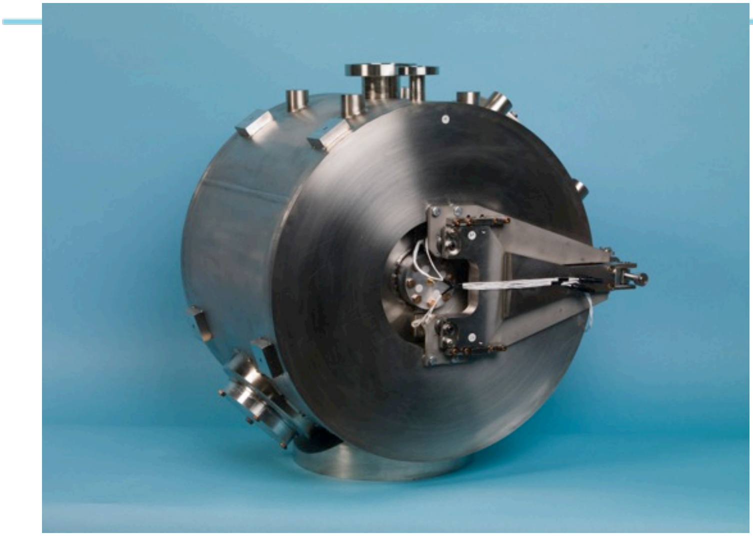
- The vacuum vessel, thermal and magnetic shield are being fabricated
- Design of sub-systems and components of cold mass is complete
  - Fabrication is in progress for ~40% of cold mass
  - Fabrication of remaining 60% is limited by funding

Parameter	Value
Length (beam ports)	5.93 m
Length (overall)	6.3 m
Width	2.1 m
Height	2.2 m



SSR1 (beta=0.22) development

L. Ristori – D. Passarelli



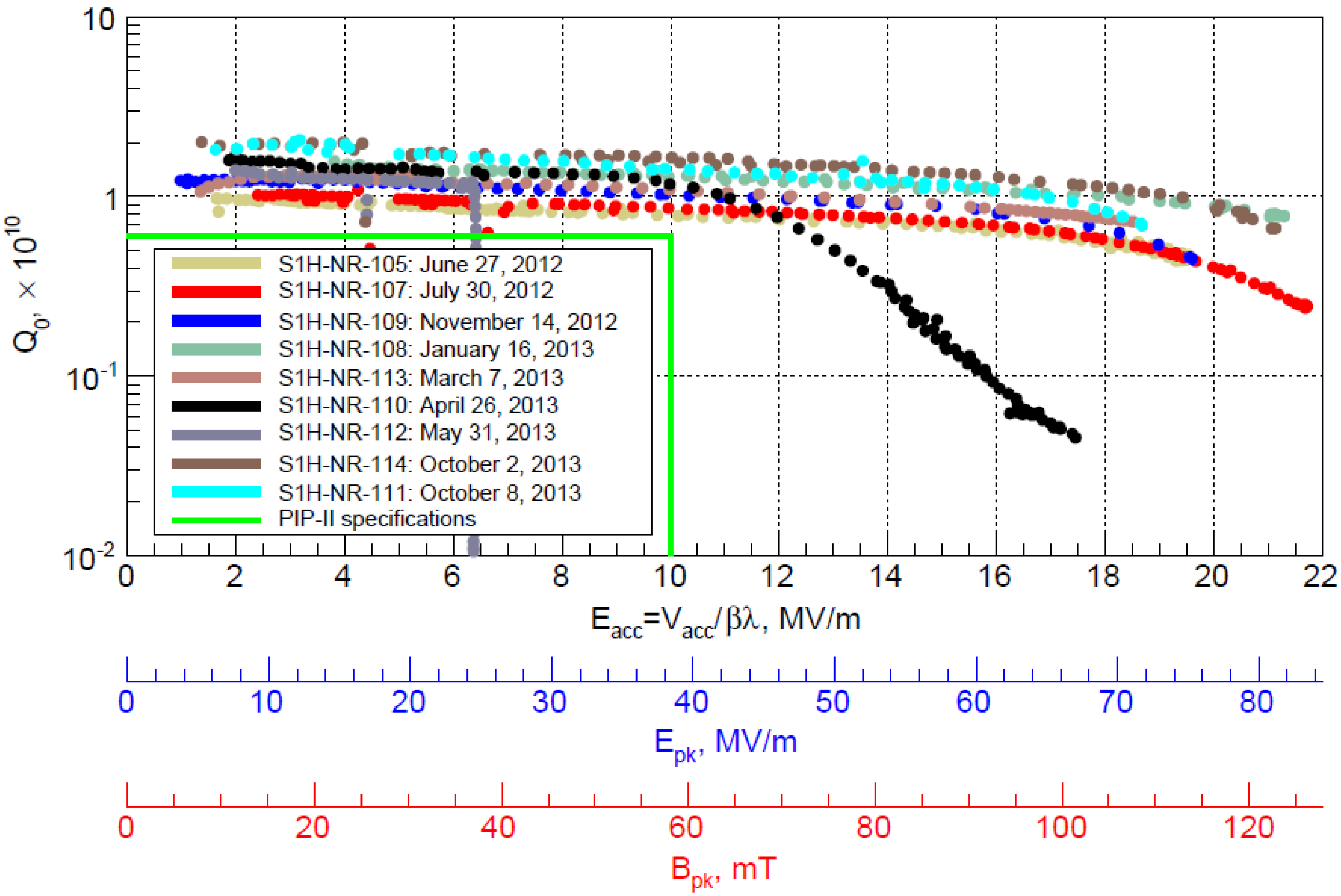
First jacketed SSR1 prototype with prototype tuner for HINS (2010)

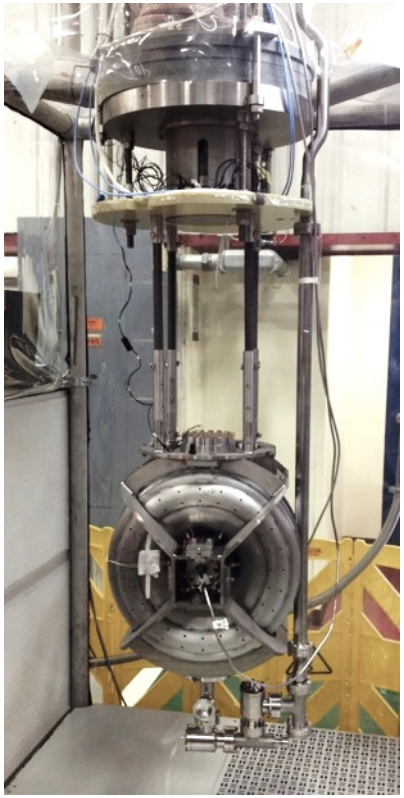
New generation SSR1 for PXIE (2013)

The new Double-Lever tuner (left) and piezo encapsulations (right)

Vertical Test Stand (VTS) results of SSR1

All 8 cavities for PXIE cryomodule are qualified



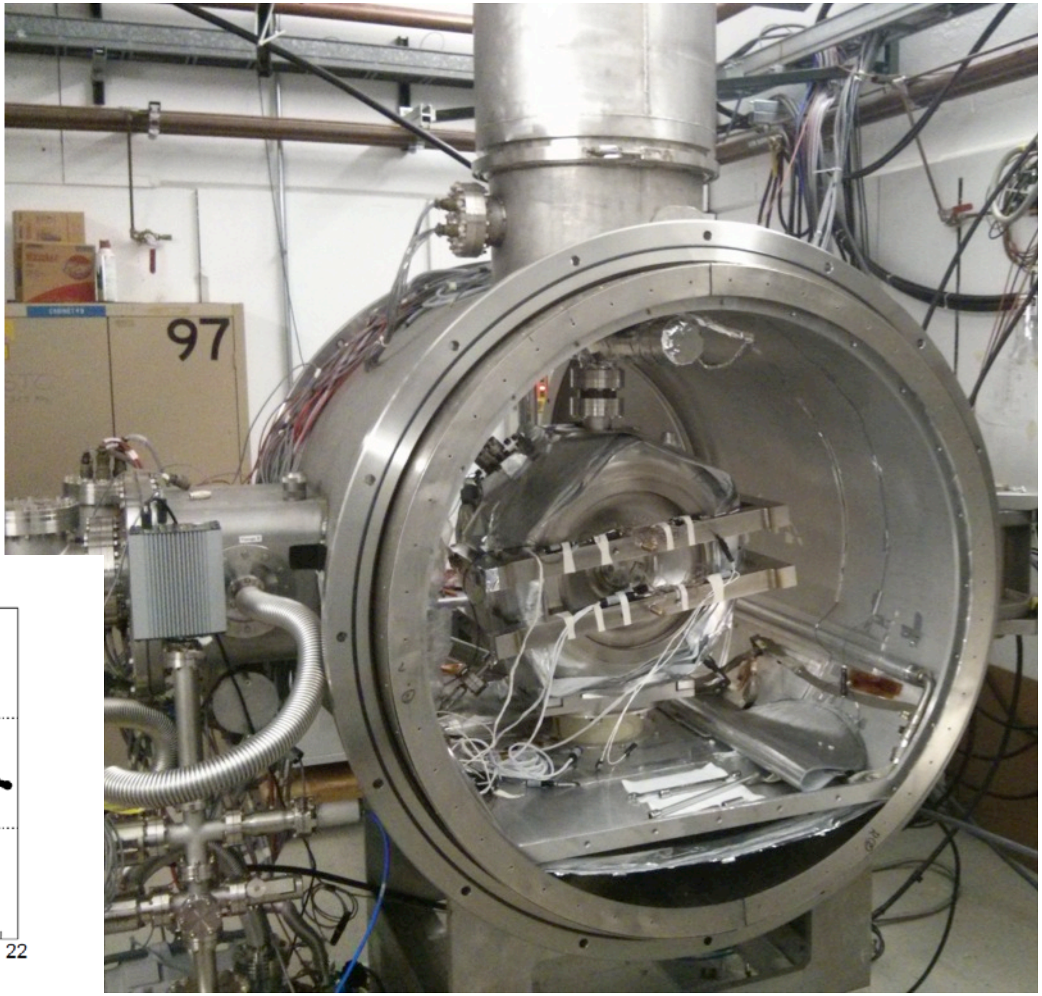


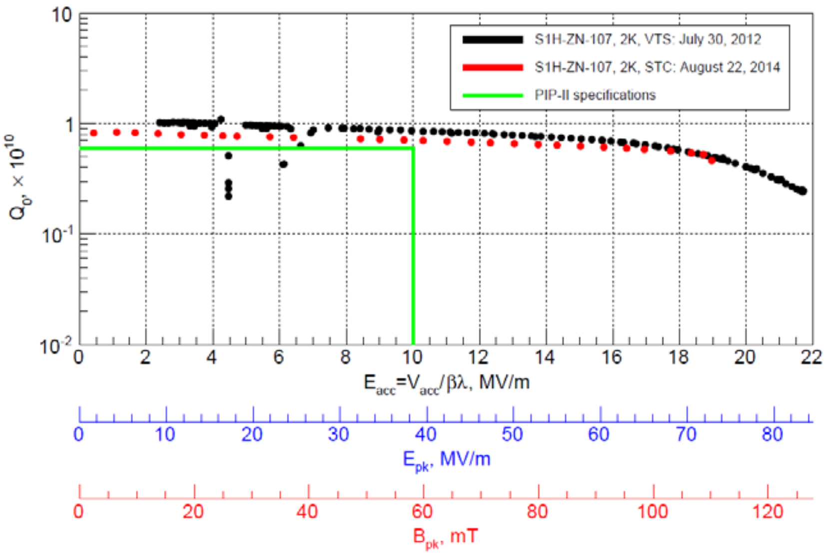
Spoke Test-Cryostat (STC) results of SSR1

L. Ristori – D. Passarelli

Sep-Oct 2014

Successful cold tests of first production SSR1 (S107) and piezo encapsulations

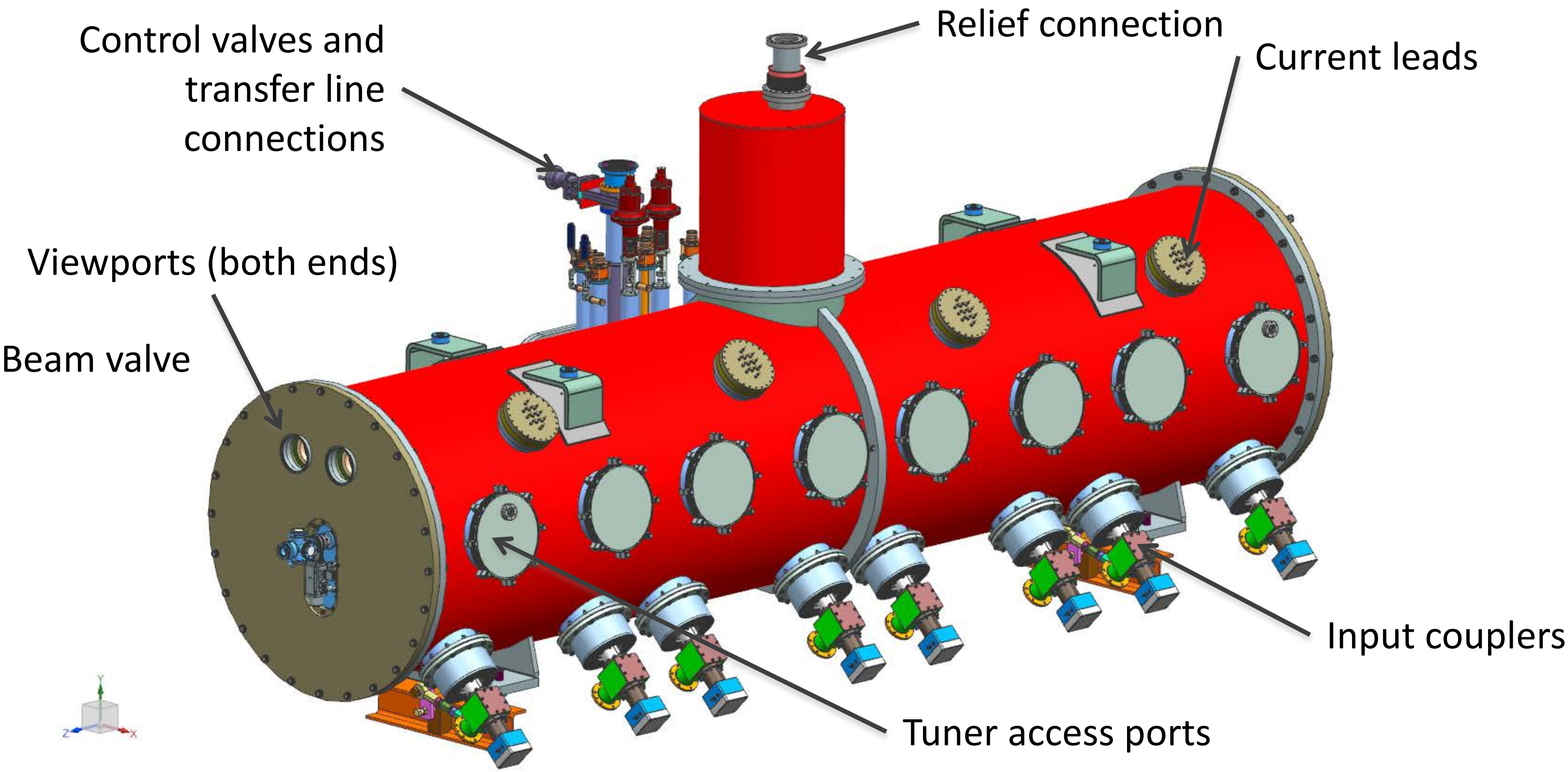




Tests courtesy of A. Sukhanov

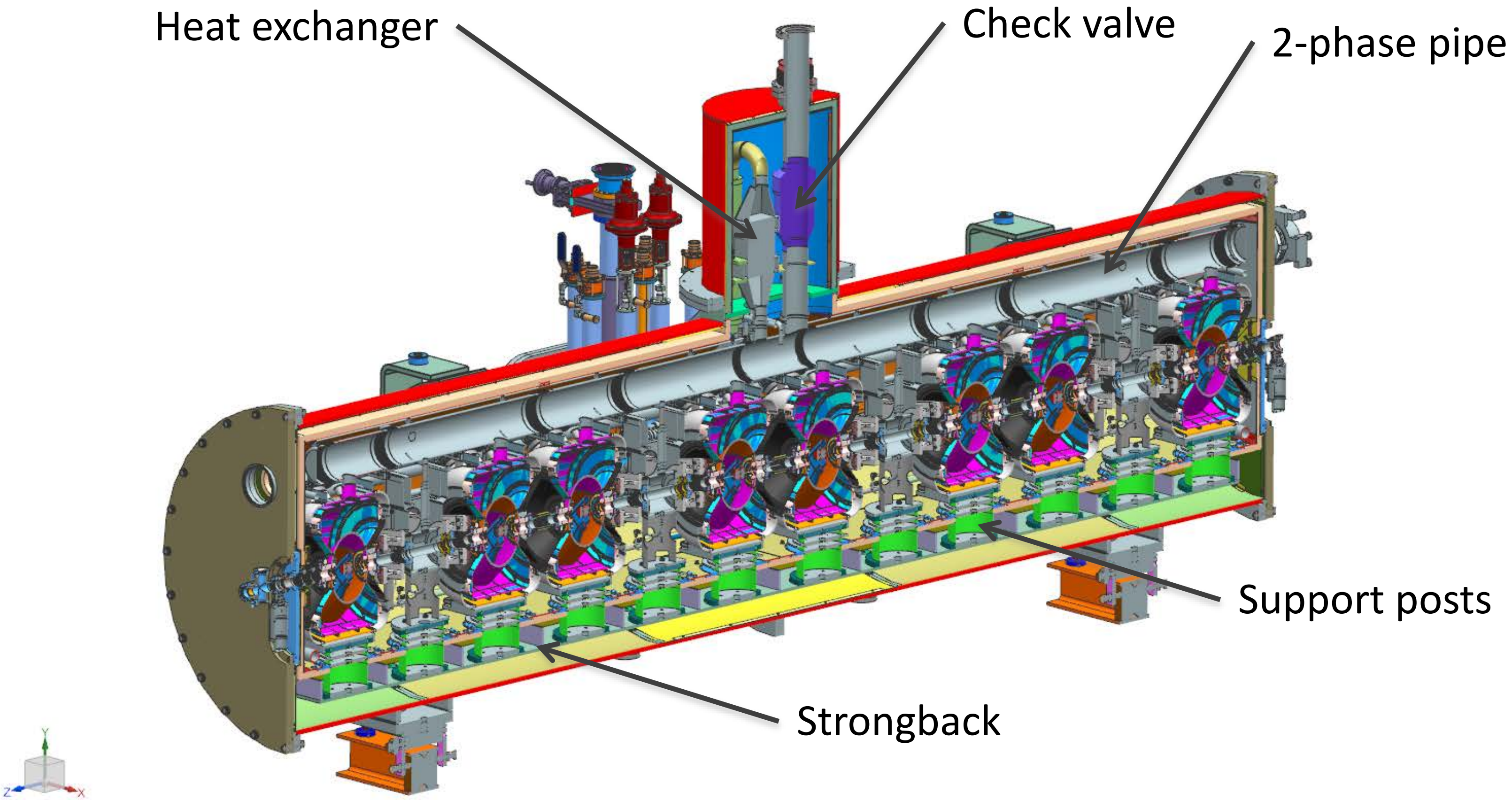
SSR1 Cryomodule for PXIE (aisle side)

T. Nicol



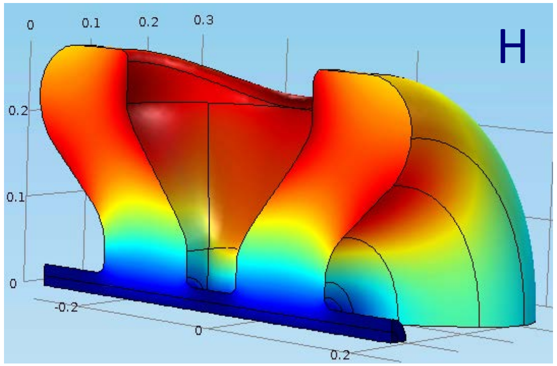
SSR1 Cryomodule for PXIE (aisle side)

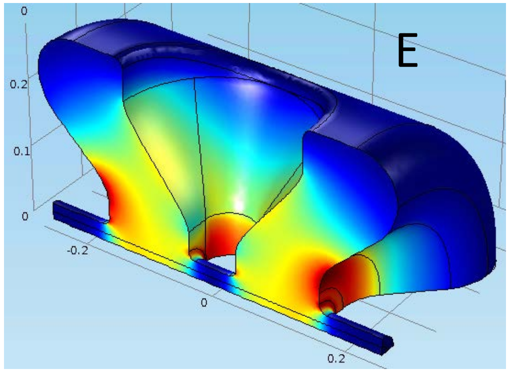
T. Nicol

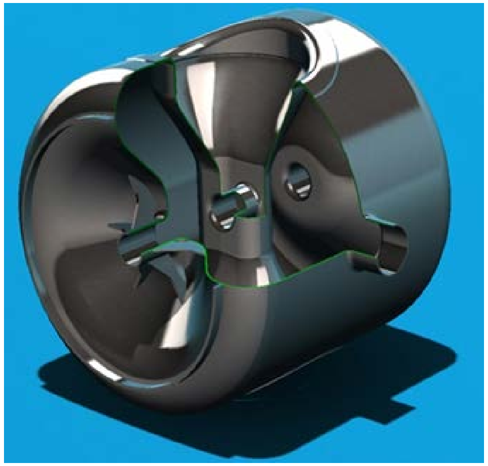


SSR2 (beta=0.47): Design ongoing

- SSR2 EM and mechanical design is be based on the SSR1 design.
- SSR1 test results will be taken into account;
- Preliminary EM design is finished (including MP mitigation),
- Preliminary mechanical design is in progress.





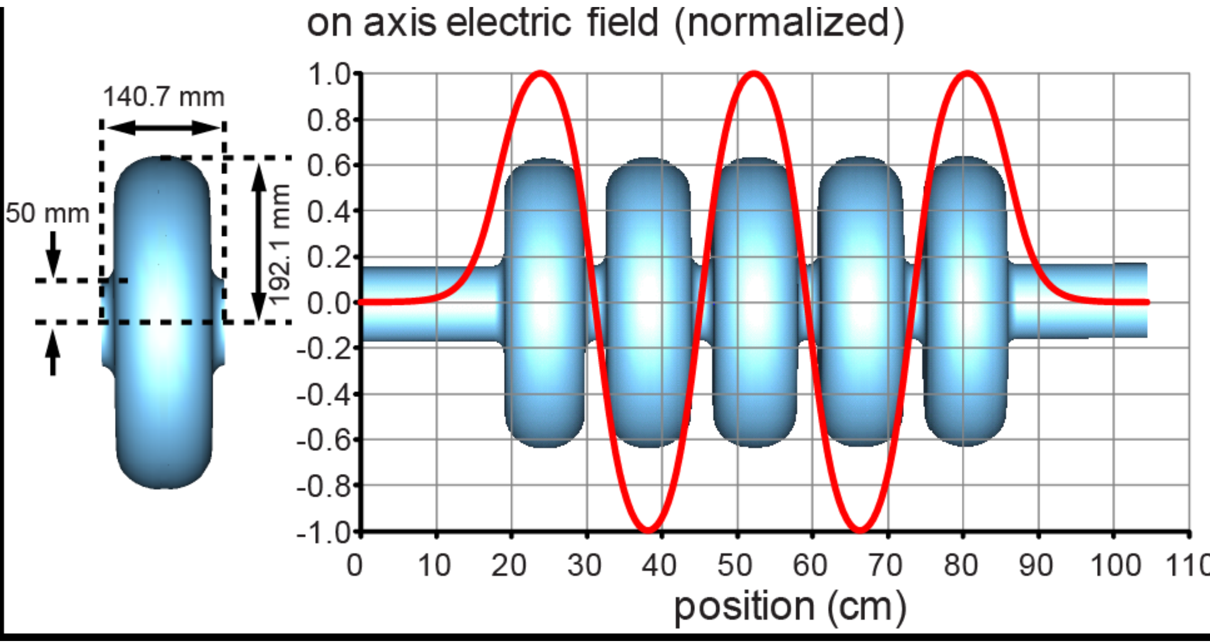


JLAB version of the 650 MHz (beta=0.61) cavity for PIP II

Cavity #2 is above the spec:

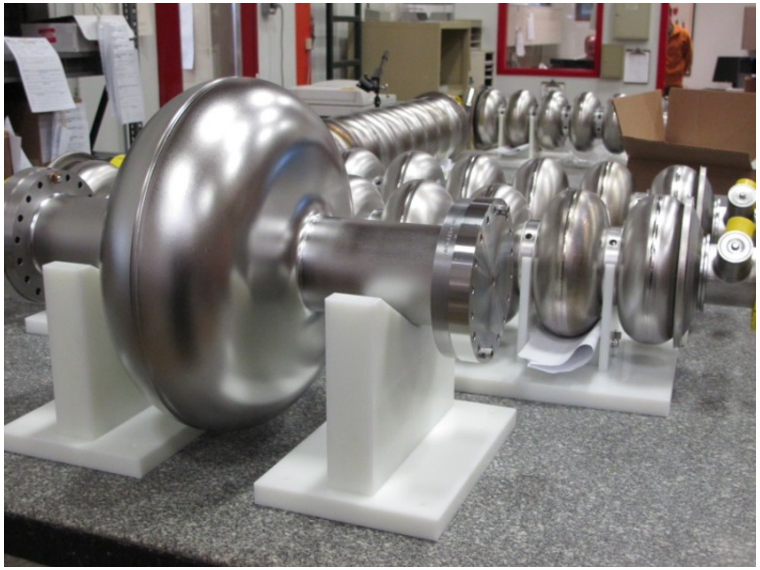
Q_0 >4e10 @17MeV/m

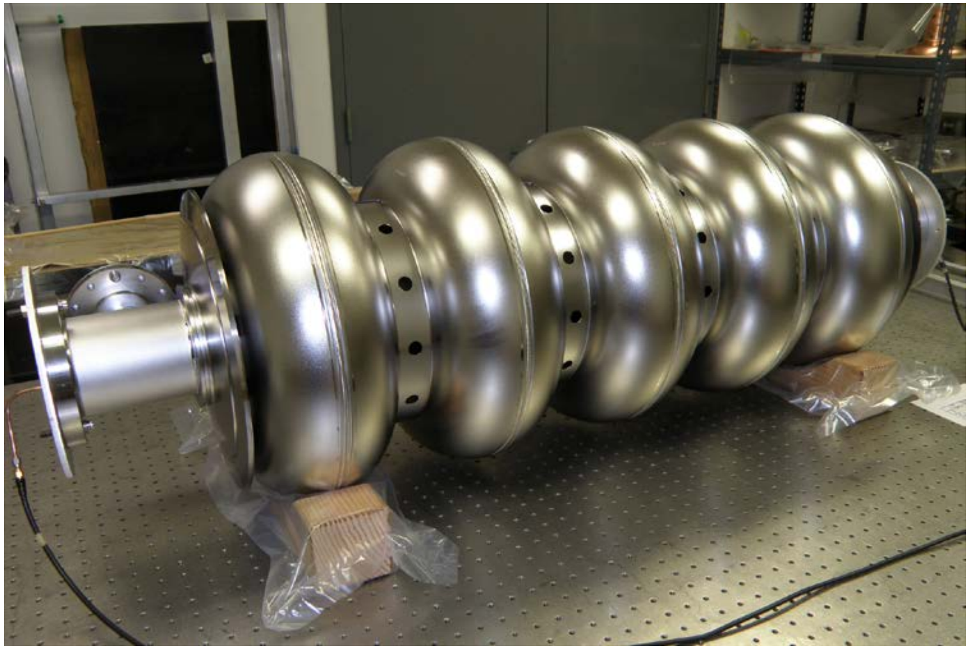
cavity #1



650 MHz (beta=0.9) cavities

Currently Available Cavities:





1-Cell 650 MHz

6 from AES

6 from PAVAC

5-Cell 650 MHz

4 from AES

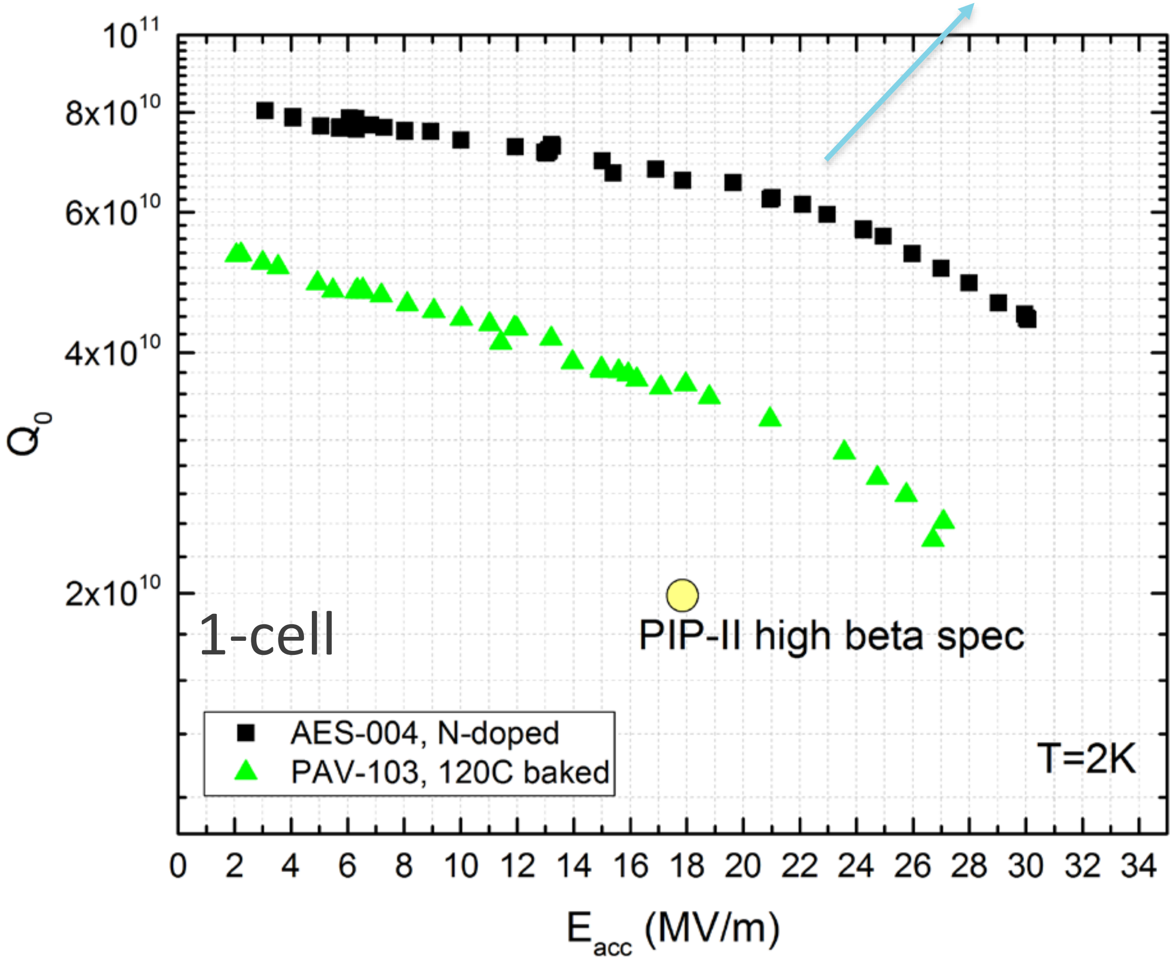
5 from PAVAC

Integration of SRF R&D and PIP-II

- First impact of high Q

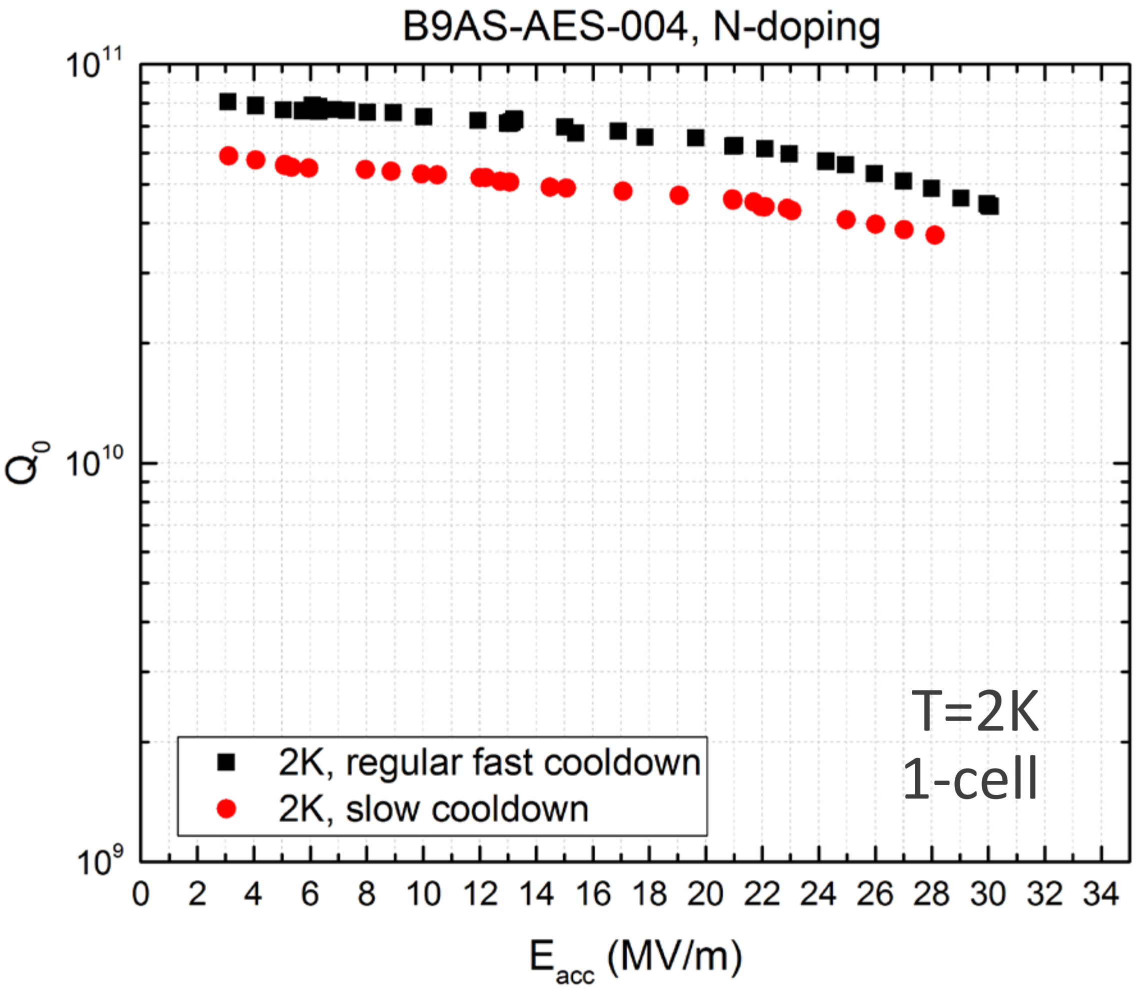
Results – highlights – 120C bake vs N doping – 7e10 at 2K, 17 MV/m – world record!

Applying N doping to 650 MHz (beta=0.9) leads to Q far exceeding specs



High duty factor operation may be possible even with the existing (limited) capacity cryoplant

Results – cooling studies – fast vs slow cooling

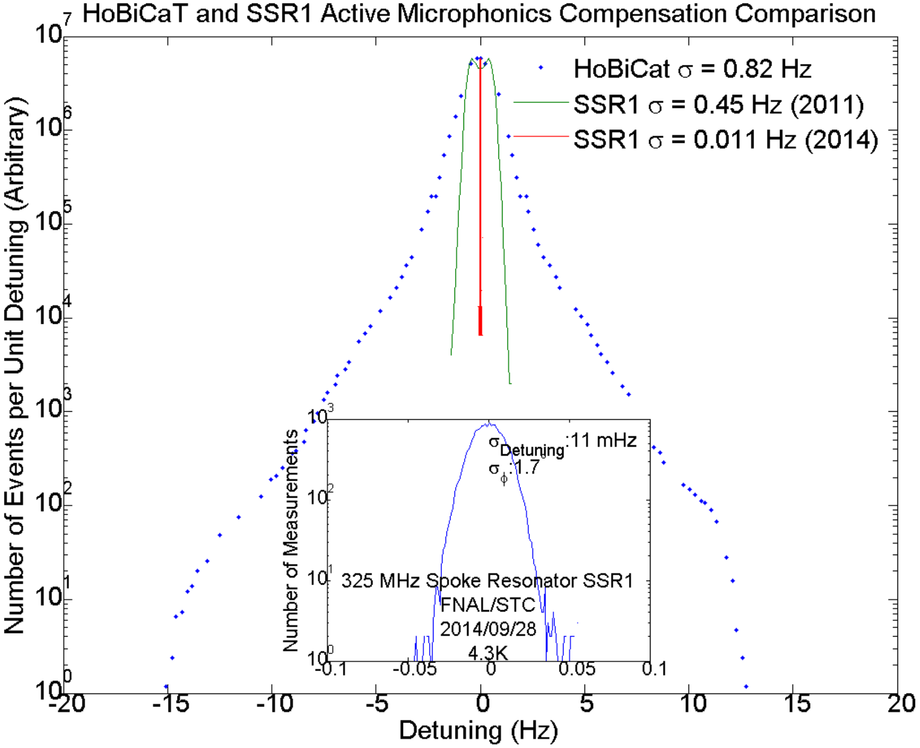


Good news: 650 MHz cavities appear to be less sensitive to fast/slow cooldown impact on trapped flux

Full cryomodule implementation of high Q cavities should be less challenging than for LCLS-II

Microphonics Compensation at Fermilab

- Narrow bandwidth SRF cavities susceptible to detuning by mechanical vibrations (microphonics).
- Active resonance stabilization critical to operation of next generation of SRF accelerators: LCLS-II, PIP-II , ERLs, etc.
- Advanced compensation techniques being developed and tested in FNAL HTS and STC test stands.
- Full stabilized SSR1 cavity in STC
  - Feed-forward LFD compensation
  - Fast feed-back on forward/probe phase
  - Slow feedback on detuning
  - Synchronous down-conversion
- Almost two orders of magnitude improvement compared with best previously published results
  - $\sigma_{\mathrm{Detuning}}$=11 mHz



Courtesy of W. Schappert

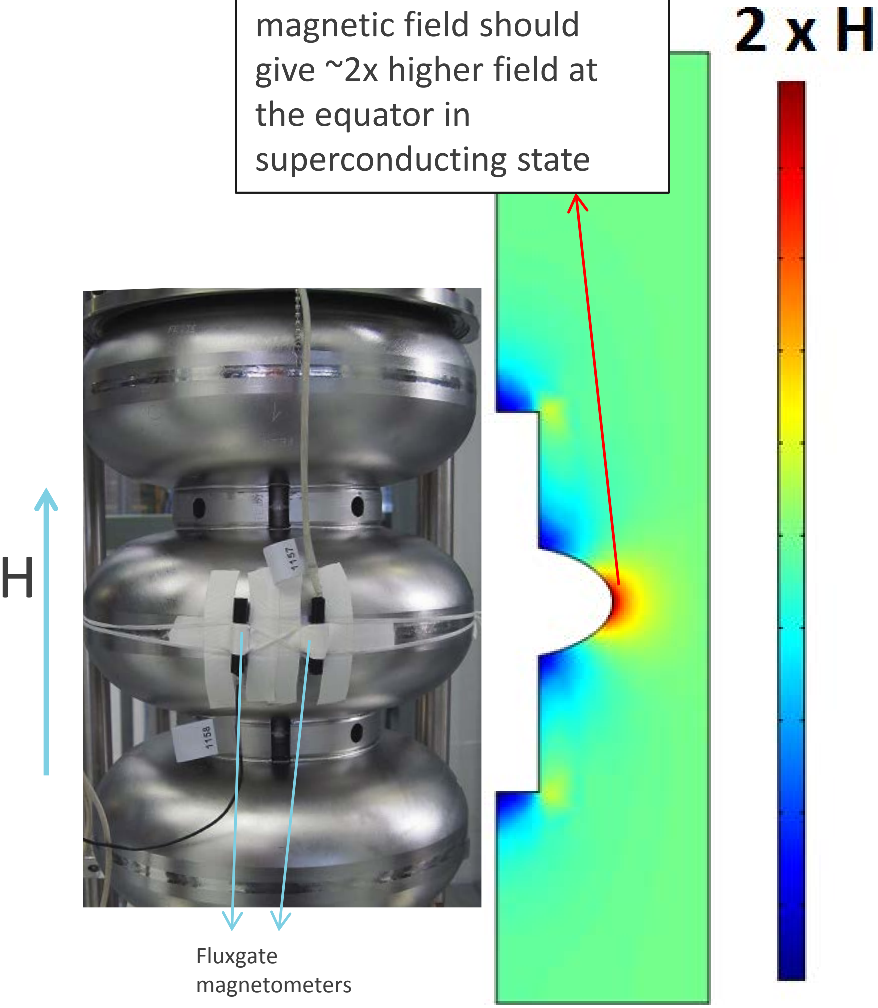
Summary

- Vibrant SRF R&D program with recent discoveries of major impact
  - Nitrogen doping
  - Efficient magnetic flux expulsion
- Immediate implementation of findings for projects
  - LCLS-II
    - Save >$50M in capital costs, ~4MW of power in operational costs
  - PIP-II
    - Potential to enable 30% duty factor for Mu2E without extending cryocapacity
- PIP-II
  - Cavities, cryomodules design and development is successfully progressing
  - High Q achievements are coupled in

BACKUP SLIDES

Magnetic probes reveal the new physics

Full expulsion of the magnetic field should give ~2x higher field at the equator in superconducting state



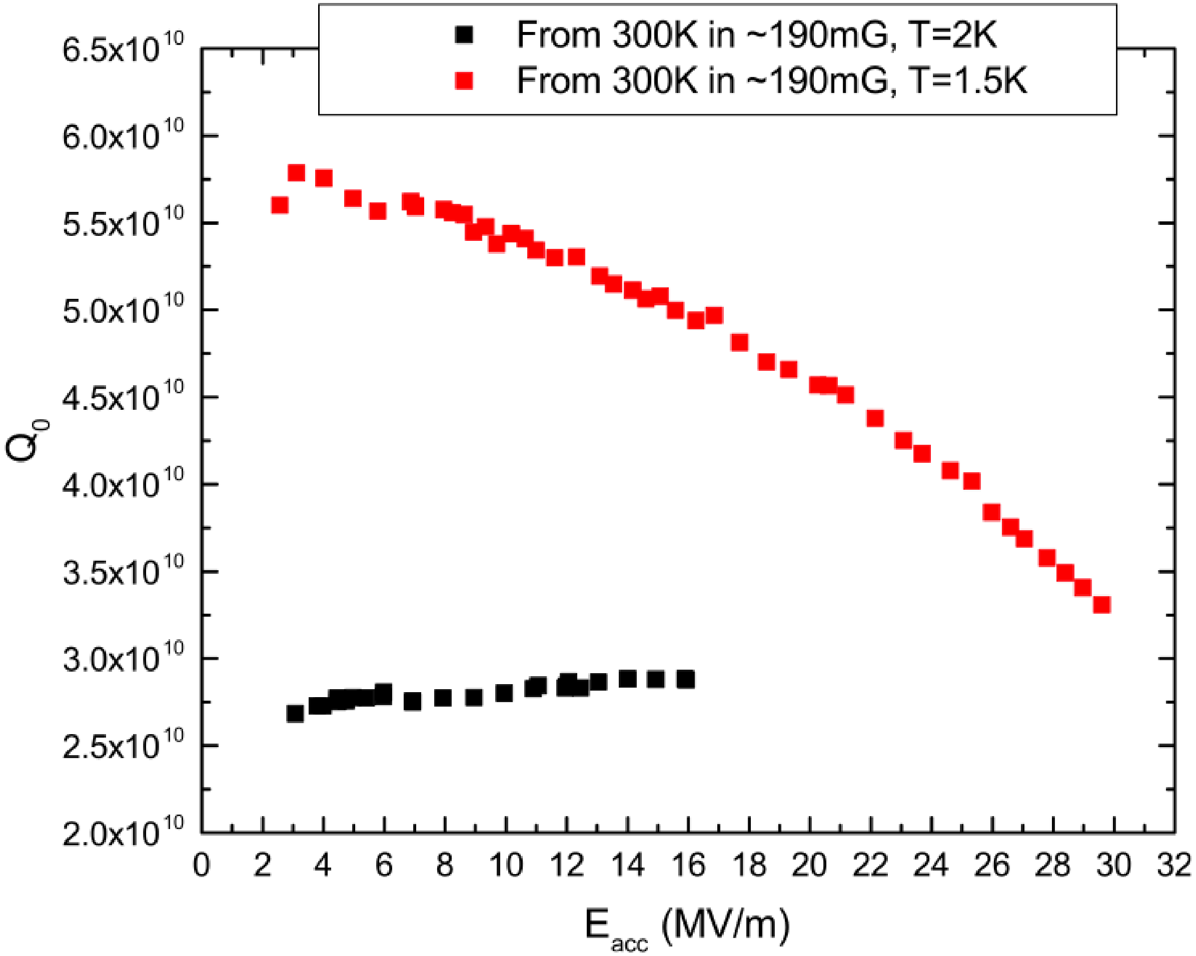
It turns out the expulsion efficiency can be controlled by the cooldown procedure (fast/slow, uniform or not)

Efficient flux expulsion

Poor flux expulsion

A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. **115**, 184903 (2014)

Record high Qs in high ambient magnetic fields



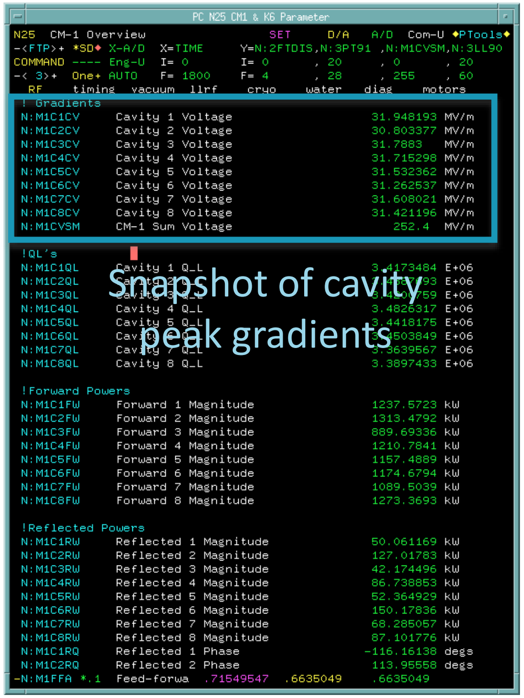
Very high Qs even in 190 mG if efficient cooling through Tc is implemented

Means that stringent magnetic shielding requirements for SRF accelerators may be potentially relaxed

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk, Appl. Phys. Lett. **105**, 234103 (2014)

CM2 Performance – All Cavities ON

- CM-2 achieved an average cavity gradient of 31.5 MV/m this past Friday (3 October) with all 8 cavities powered simultaneously
- 1.6 millisecond pulse width, 5 Hz repetition rate
- Lorentz Force Detuning Compensation (LFDC) on and ‘adapting’
- Peak accelerating voltage = 252 MV



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PC N25 CM1 & K6 Parameter
N25  CM-1 Overview               SET     D/A    A/D   Com-U ♦PTools♦
-<FTP>+ *SD♦ X-A/D  X=TIME      Y=N:2FTDIS,N:3PT91 ,N:M1CVSM,N:3LL90
COMMAND ---- Eng-U  I= 0        I= 0      , 20      , 0       , 20
-< 3>+  One+ AUTO   F= 1800     F= 4      , 28      , 255     , 60
  RF     timing  vacuum  llrf    cryo    water   diag    motors
 ! Gradients
 N:M1C1CV     Cavity 1 Voltage                          31.948193 MV/m
 N:M1C2CV     Cavity 2 Voltage                          30.803377 MV/m
 N:M1C3CV     Cavity 3 Voltage                          31.7883   MV/m
 N:M1C4CV     Cavity 4 Voltage                          31.715298 MV/m
 N:M1C5CV     Cavity 5 Voltage                          31.532362 MV/m
 N:M1C6CV     Cavity 6 Voltage                          31.262537 MV/m
 N:M1C7CV     Cavity 7 Voltage                          31.608021 MV/m
 N:M1C8CV     Cavity 8 Voltage                          31.421196 MV/m
 N:M1CVSM     CM-1 Sum Voltage                              252.4   MV/m

 !QL's
 N:M1C1QL     Cavity 1 Q_L                              3.4173484 E+06
 N:M1C2QL     Cavity 2 Q_L                              [illegible] E+06
 N:M1C3QL     Cavity 3 Q_L                              3.4200759 E+06
 N:M1C4QL     Cavity 4 Q_L                              3.4826317 E+06
 N:M1C5QL     Cavity 5 Q_L                              3.4418175 E+06
 N:M1C6QL     Cavity 6 Q_L                              3.4503849 E+06
 N:M1C7QL     Cavity 7 Q_L                              3.3639567 E+06
 N:M1C8QL     Cavity 8 Q_L                              3.3897433 E+06

 !Forward Powers
 N:M1C1FW     Forward 1 Magnitude                       1237.5723 kW
 N:M1C2FW     Forward 2 Magnitude                       1313.4792 kW
 N:M1C3FW     Forward 3 Magnitude                       889.69336 kW
 N:M1C4FW     Forward 4 Magnitude                       1210.7841 kW
 N:M1C5FW     Forward 5 Magnitude                       1157.4889 kW
 N:M1C6FW     Forward 6 Magnitude                       1174.6794 kW
 N:M1C7FW     Forward 7 Magnitude                       1089.5039 kW
 N:M1C8FW     Forward 8 Magnitude                       1273.3693 kW

 !Reflected Powers
 N:M1C1RW     Reflected 1 Magnitude                     50.061169 kW
 N:M1C2RW     Reflected 2 Magnitude                     127.01783 kW
 N:M1C3RW     Reflected 3 Magnitude                     42.174496 kW
 N:M1C4RW     Reflected 4 Magnitude                     86.738853 kW
 N:M1C5RW     Reflected 5 Magnitude                     52.364929 kW
 N:M1C6RW     Reflected 6 Magnitude                     150.17836 kW
 N:M1C7RW     Reflected 7 Magnitude                     68.285057 kW
 N:M1C8RW     Reflected 8 Magnitude                     87.101776 kW
 N:M1C1RQ     Reflected 1 Phase                        -116.16138 degs
 N:M1C2RQ     Reflected 2 Phase                         113.95558 degs
-N:M1FFA *.1  Feed-forwa .71549547  .6635049            .6635049
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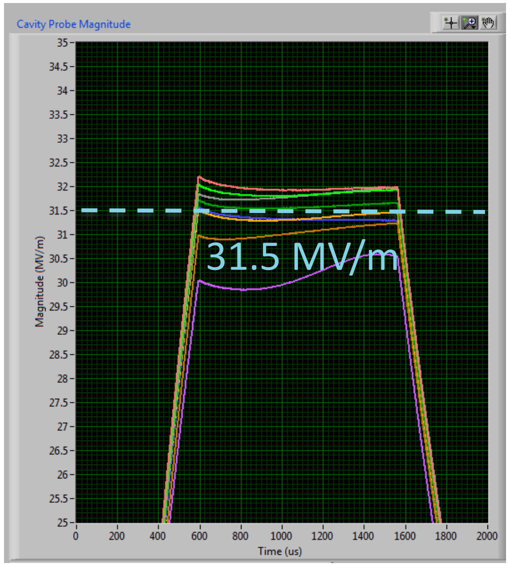
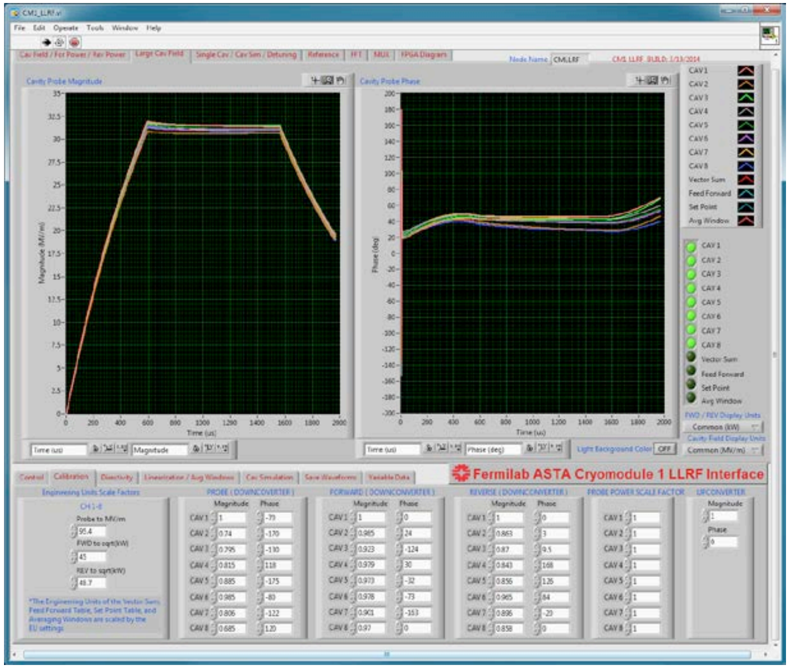
Snapshot of cavity peak gradients



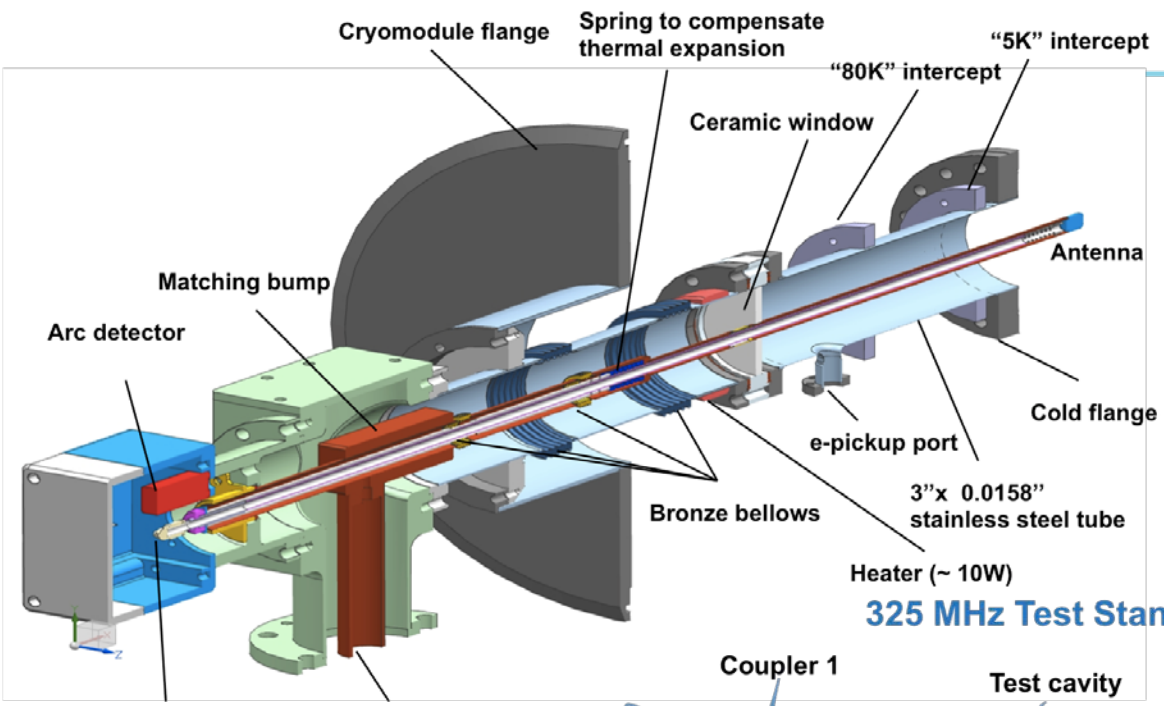
31.5 MV/m

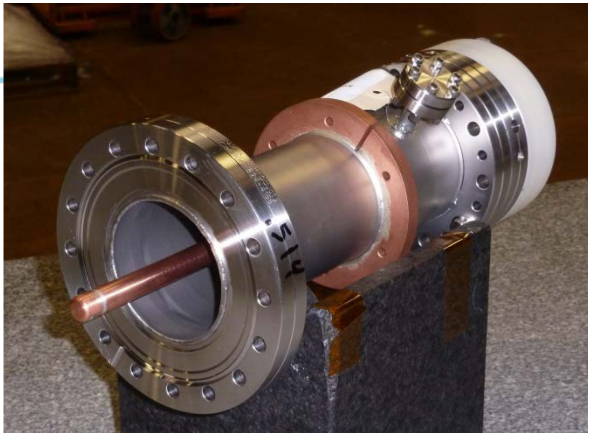


CM2 Amplitude (MV/m, left) & Phase (right)

325 MHz coupler anatomy

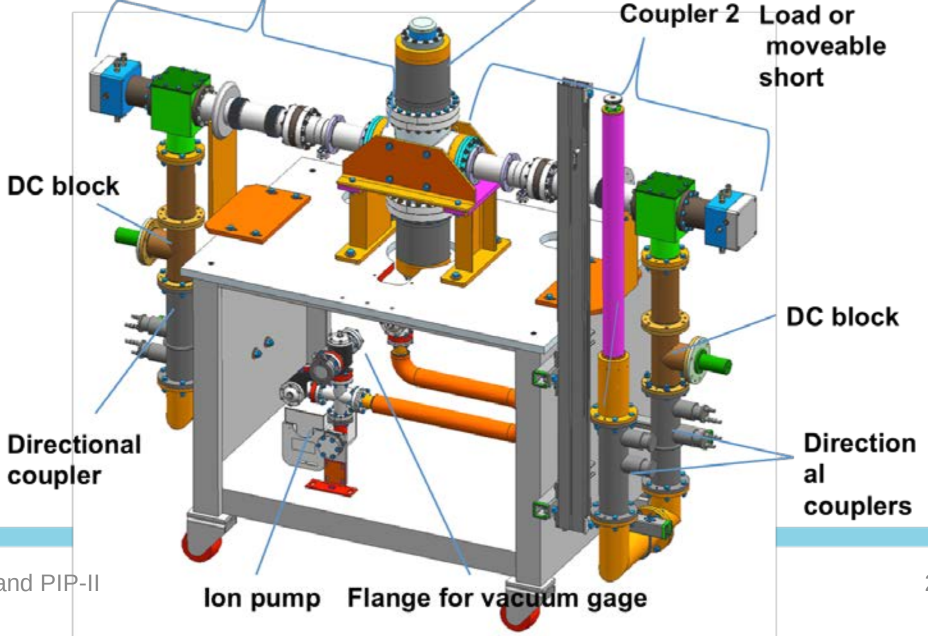
S. Kazakov – O. Pronitchev

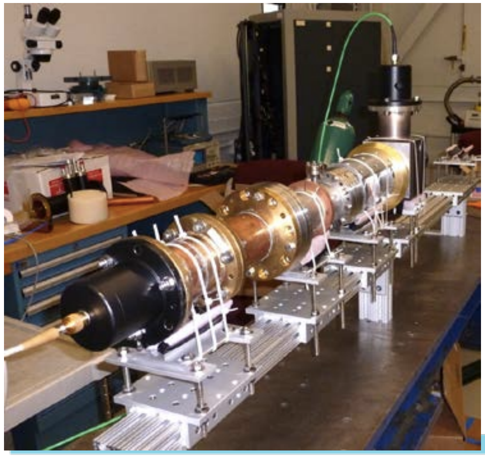


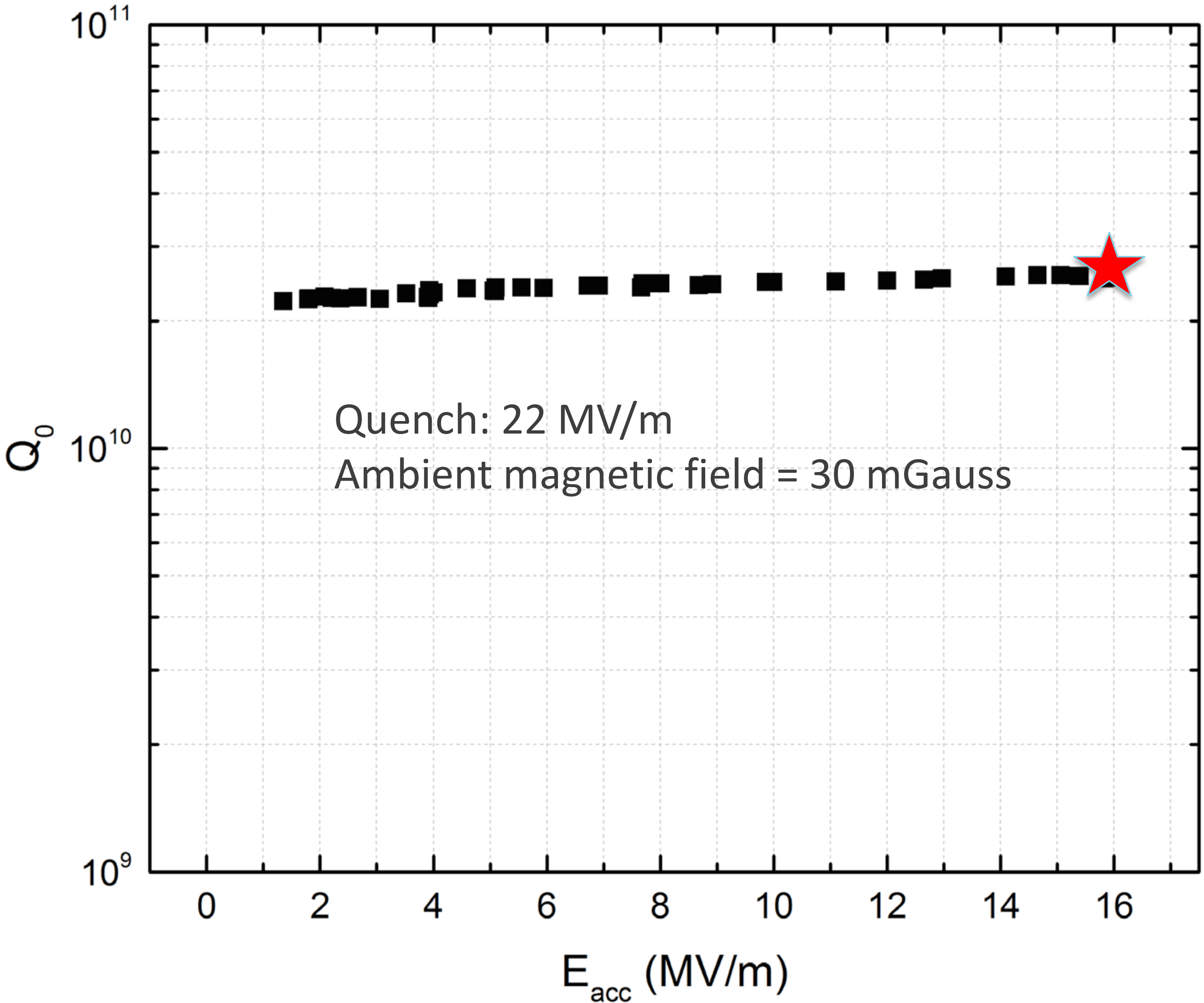


- **325 MHz couplers work well up to 7.8 kW CW inTW mode.**

325 MHz Test Stand







Quench: 22 MV/m

Ambient magnetic field = 30 mGauss