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SRF Accelerators Flourish In a Golden Age

Past, Present and Future Success of SRF

Hasan Padamsee/Fermilab

Formerly: Cornell

7th May 2015

Outline

- 50 Years of Advances in SRF science
  => New inventions, new technology
- SRF accelerator success stories
  => Present Status
- Further advances in SRF science and technology
- Prospects for future SRF success stories

Advances in the “Golden Age of Athens”

- What is a Golden Age?
- A period when a skill, or activity is at its peak.
- Example: During the Golden Age of Athens
  - Plato’s Academy Philosophers Raised Basic Questions
  - Greek Architects Raised Technical Masterpieces

Advances of the "Golden Age of Athens"

Basic Questions Raised at Plato's Academy

- What is matter?
- What are the elementary constituents of matter?
- Is matter continuous or discrete?
- What is the shape of the world?

Pompei Mosaic

Technical Accomplishments of the Golden Age

Temple Complex at Acropolis

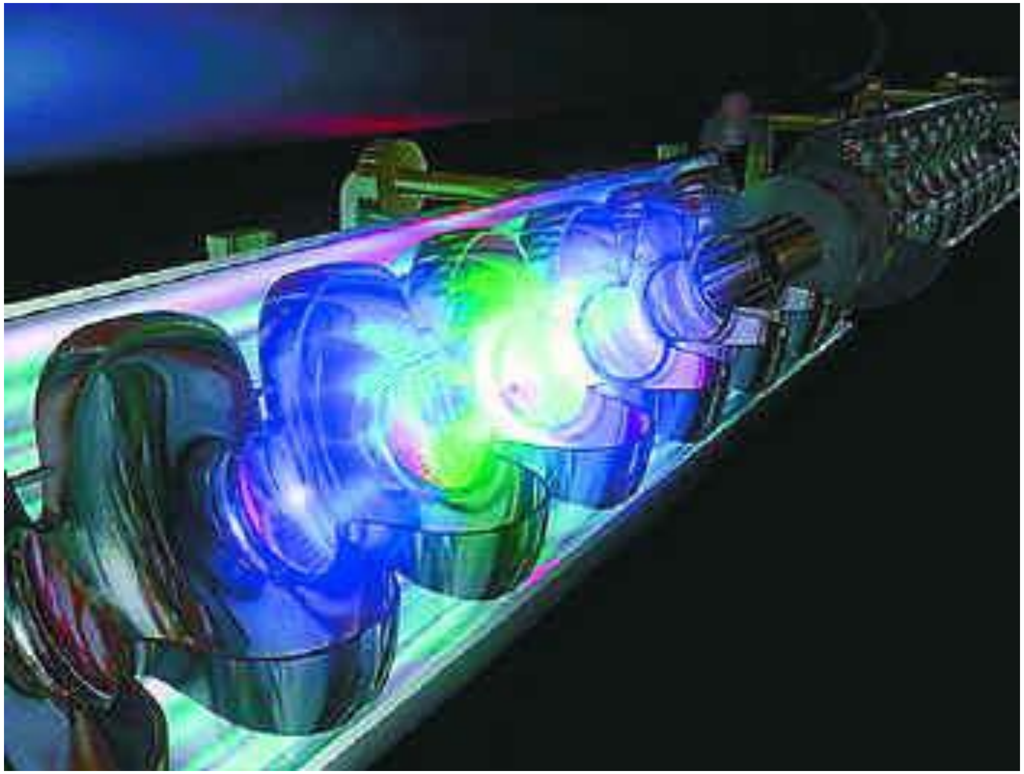
Our own SRF "Philosophers" and SRF Questions

- What is multipacting?
- What is thermal breakdown (quench)?
- What is field emission?
- Why does Q mysteriously fall above 25 MV/m?
- What are the fundamental limits to gradient?
- What are the fundamental limits to the Q?




Technological Advances

- How can we raise gradients?
- How can we raise Q?
- What accelerators can we build with SRF cavity advantages?

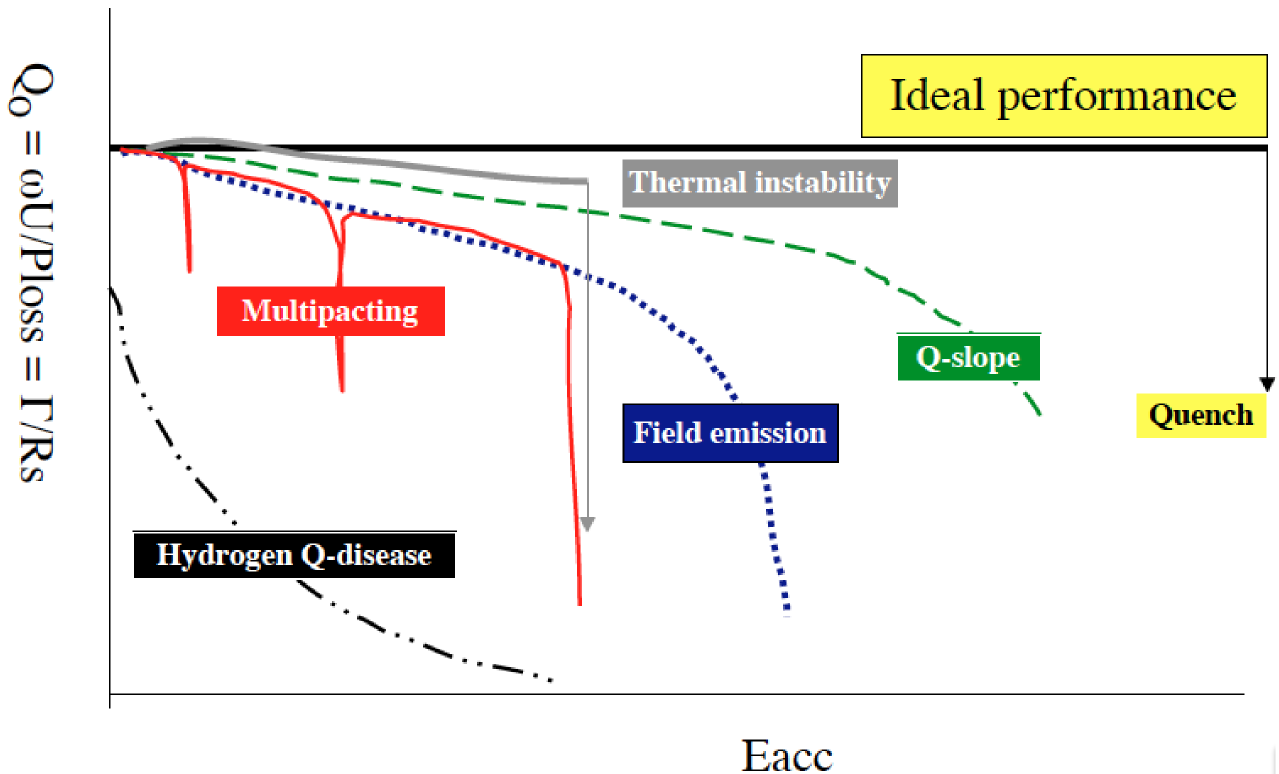


Fundamental Understanding

Drives Technological Advances

Drives Accelerator Applications

Real SRF Cavity Performance



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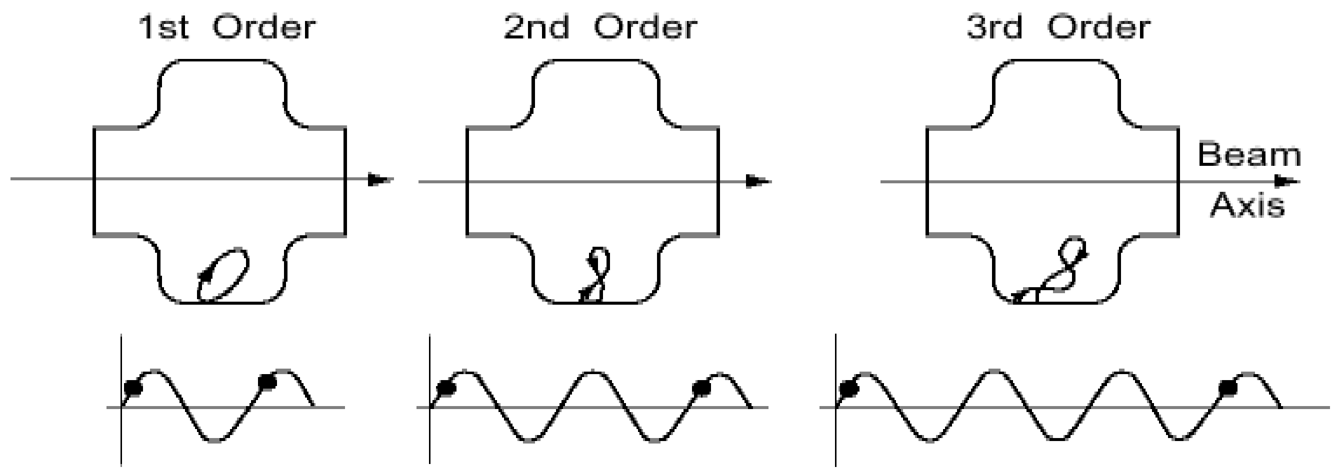
Multipacting & Thermal Breakdown (Quench)

- Limiting gradients 2 - 4 MV/m
- Understanding
- Solutions => 6 – 8 MV/m
- Technological advances =>
- Accelerator applications

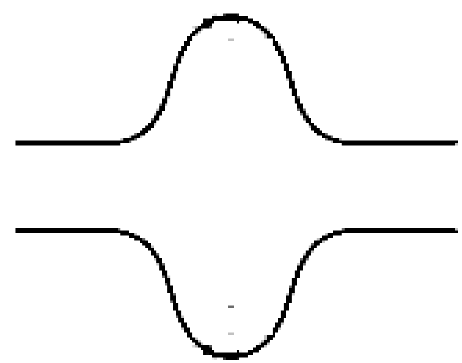
1970's: Multipacting

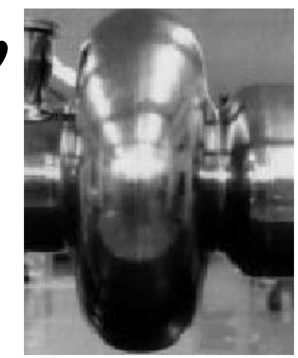
Understanding:
Electron avalanche
Resonant
mulitiplication due
to secondary
emission



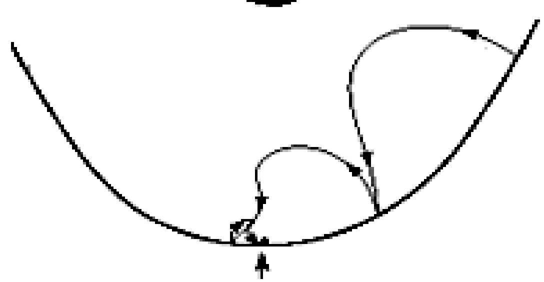
High Field

Solution: Spherical/
elliptical cavity shape



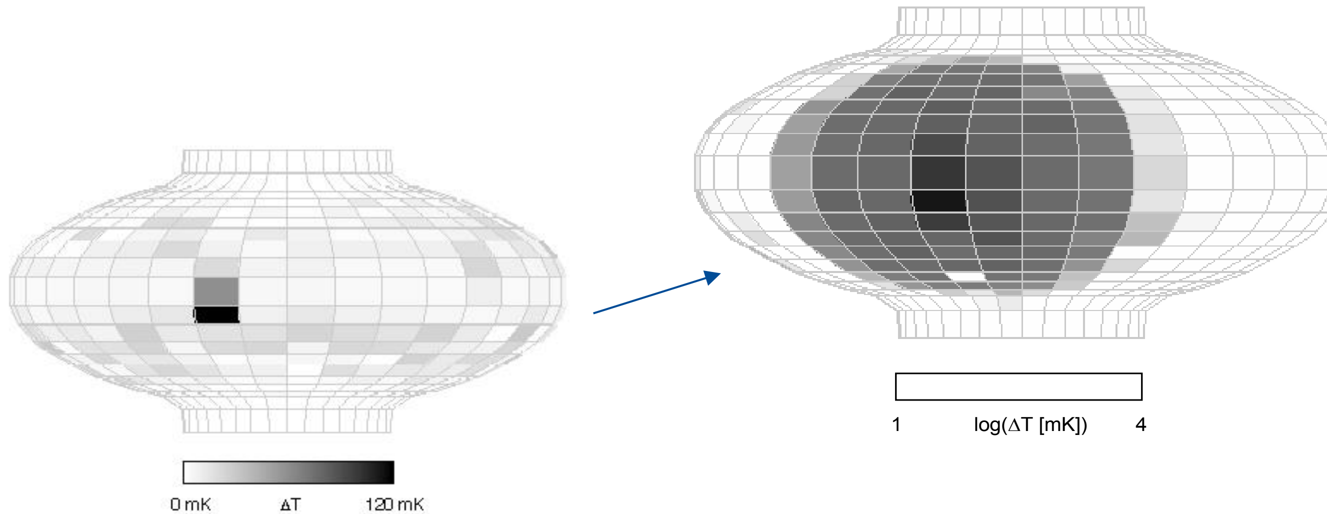


1980: Gradients rise
From 2-3 MV/m => 5 – 6 MV/m

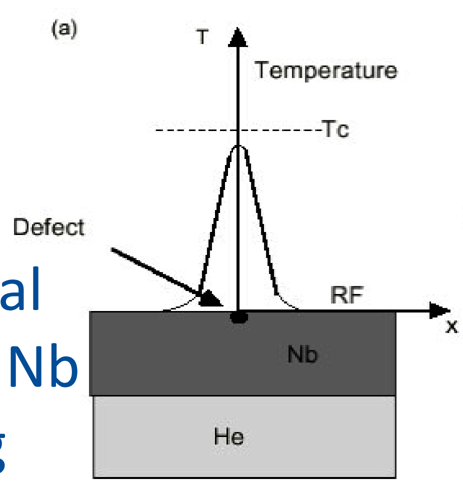


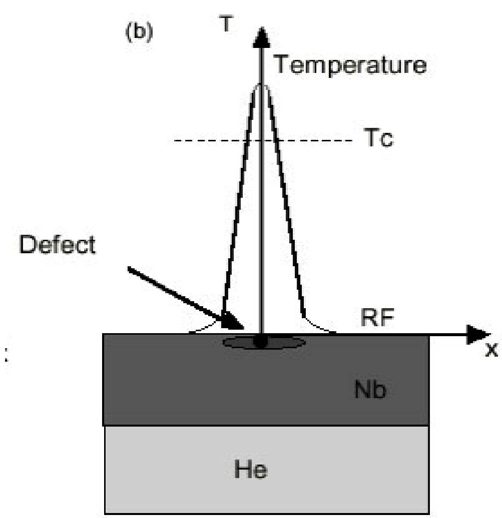
1980’s Understanding Thermal Breakdown - Quench

Resistive imperfection leads to heating above Tc, and quench

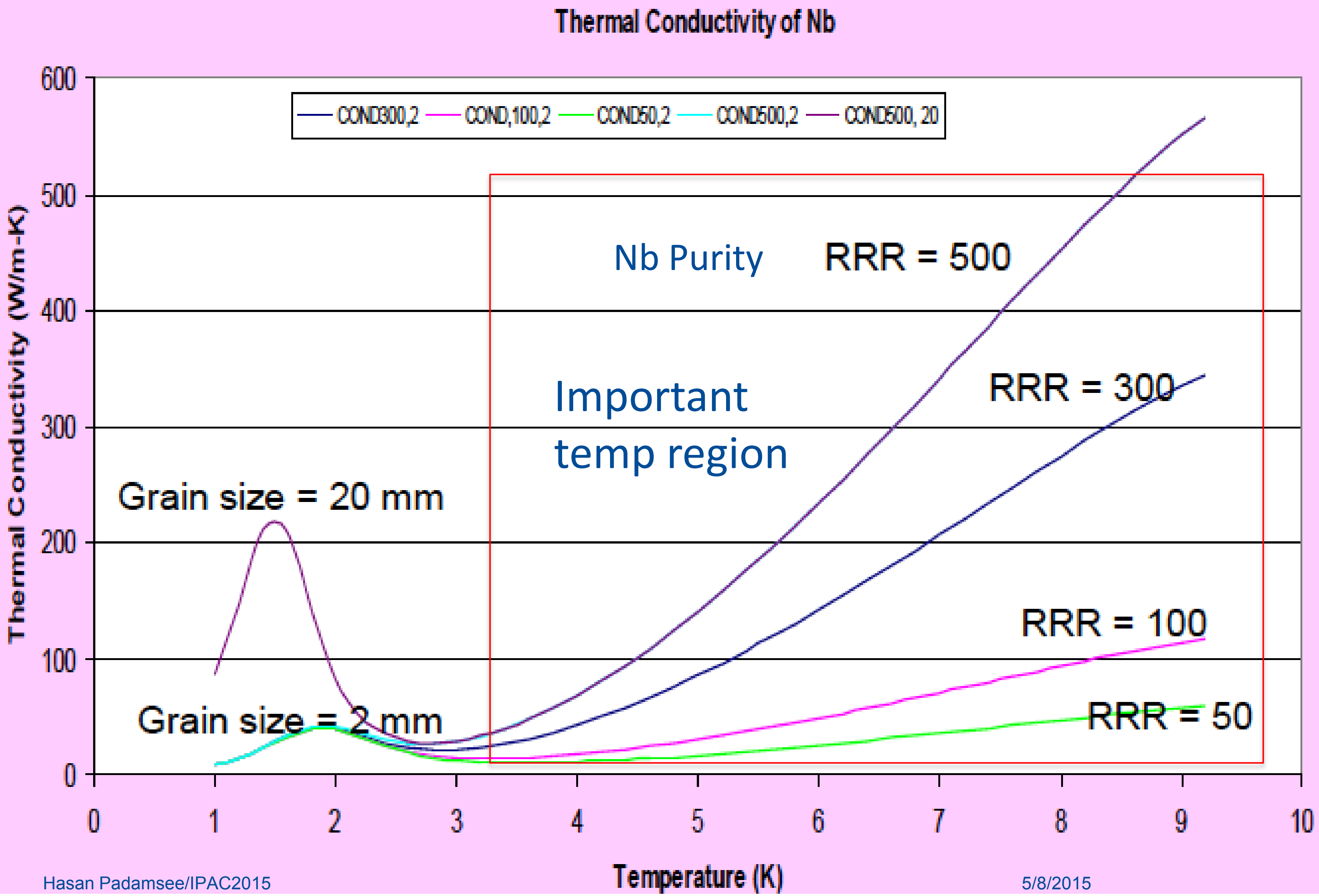


Solution:
Increase thermal conductivity of Nb
Reduce heating



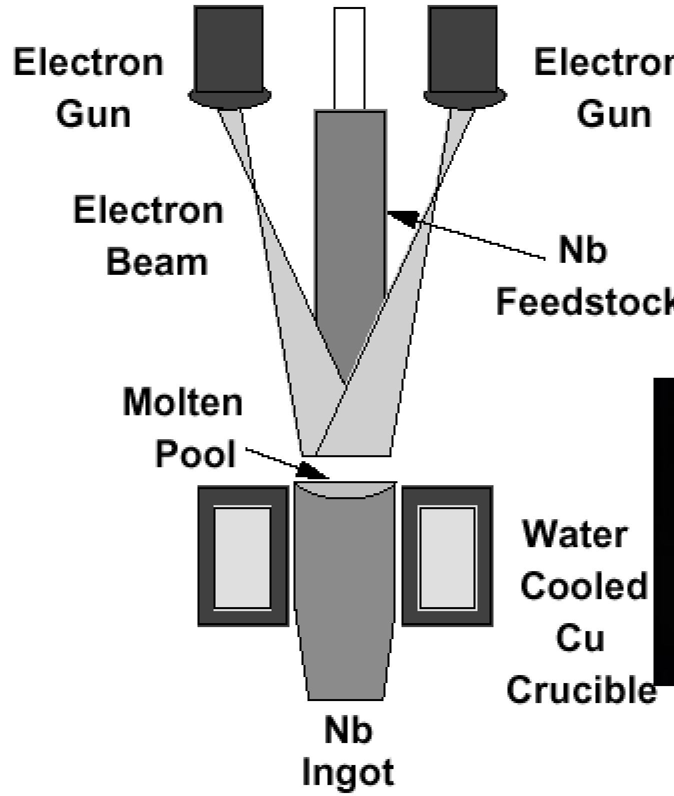


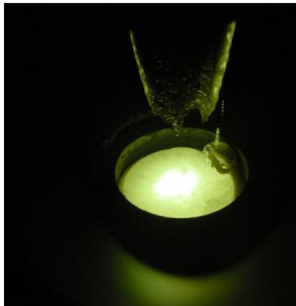
Increase Thermal Conductivity at T> 4.20 K By Increasing Purity



Nb Purification by Electron Beam Melting

Co-operation with Worldwide Industries Wah Chang, Tokyo Denkai, Heraeus…





Interstitial O, N and C are the major impurities limiting Nb RRR (purity)

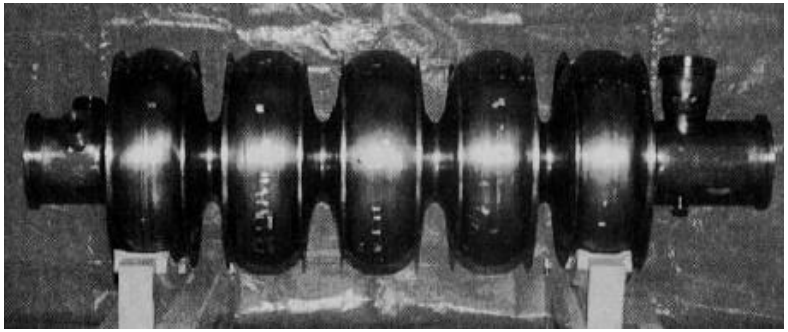
Need to bring down total < 10 ppm

1980 – 2000: Gradients Rise to 6 – 8 MV/m

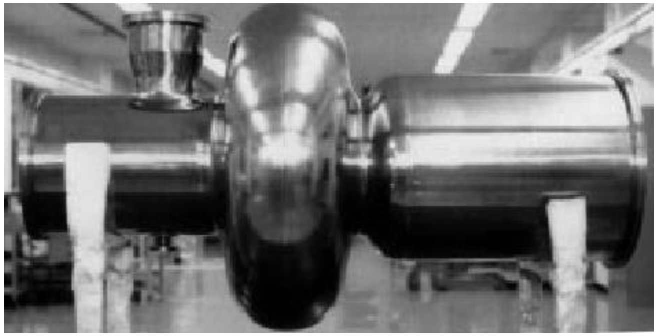
=> Accelerator Applications of SRF: 7 GeV Installed (500 cavities)

- **Nuclear Physics**
  - Ions (total > 1 GeV installed voltage)
    - Low Energy
    - Nuclear Astrophysics
    - ATLAS, ISAC, ALPI….
- **High Energy Physics-** Energy and Luminosity Frontiers
  - Electrons (total 12 GeV installed voltage)
    - TRISTAN, HERA, LEP-II, CESR, KEK-B, BEPC
  - Protons
    - LHC
- **Light Sources**
  - Electron Storage Rings
    - CESR, DIAMOND, CANADIAN-LS, TAIWAN-LS, ESRF, SOLEIL, POHANG
  - Free Electron Lasers (FELs)
    - JLAB-FEL, JAERI

Spherical Cavities For TRISTAN, HERA, LEP, CEBAF, CESR, KEK-B

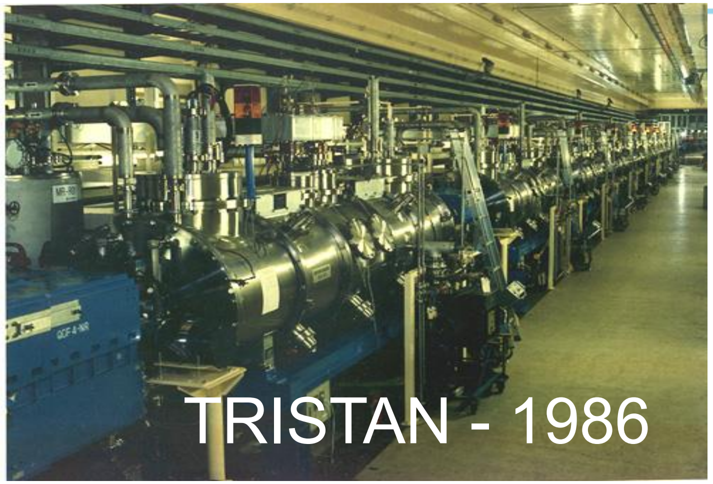


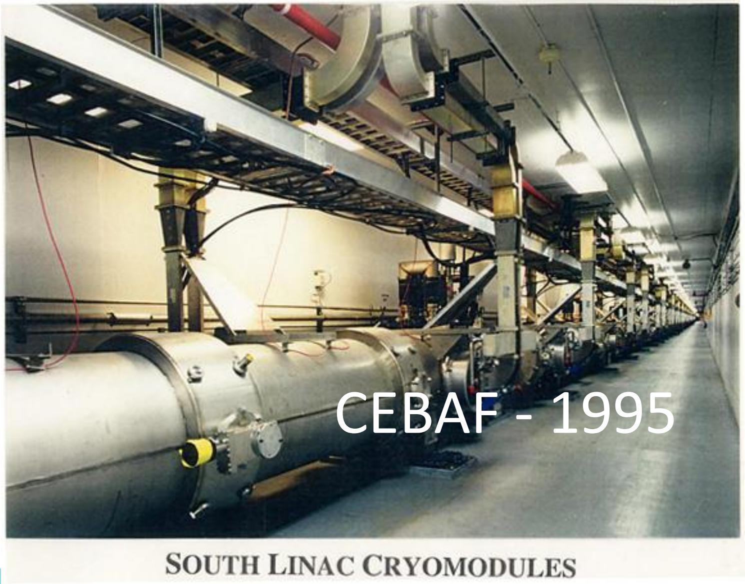
TRISTAN - KEK

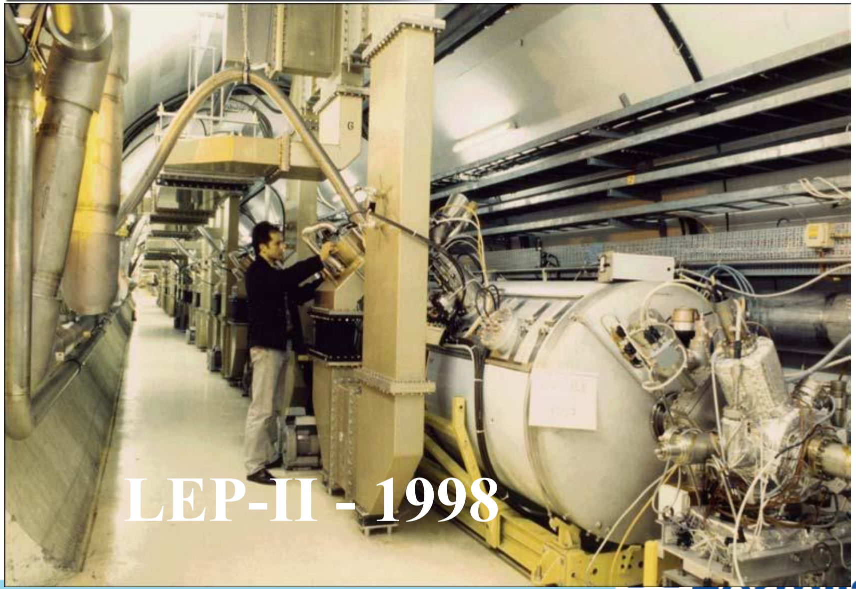


KEK-B

Installed Cryomodules

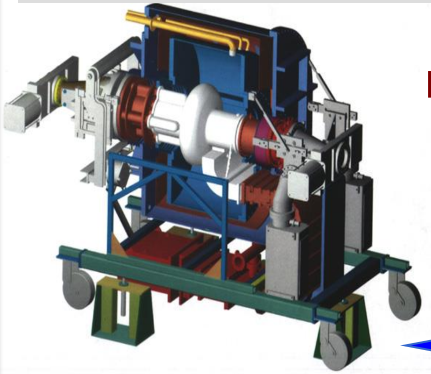






CESR and Light Sources Around the World

CESR Technology Transfer to Industry



Technology transfer

ACCEL

CESR-c

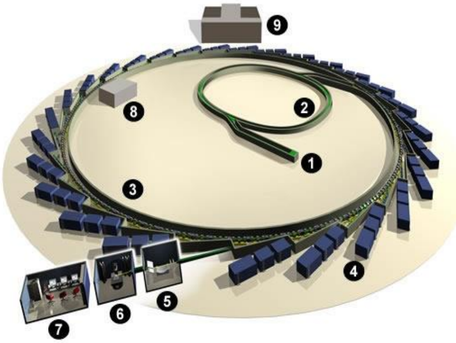
Taiwan Light Source

NSRRC National Synchrotron Radiation Research Center

Canadian Light Source Inc.

diamond

Shangai Light Source



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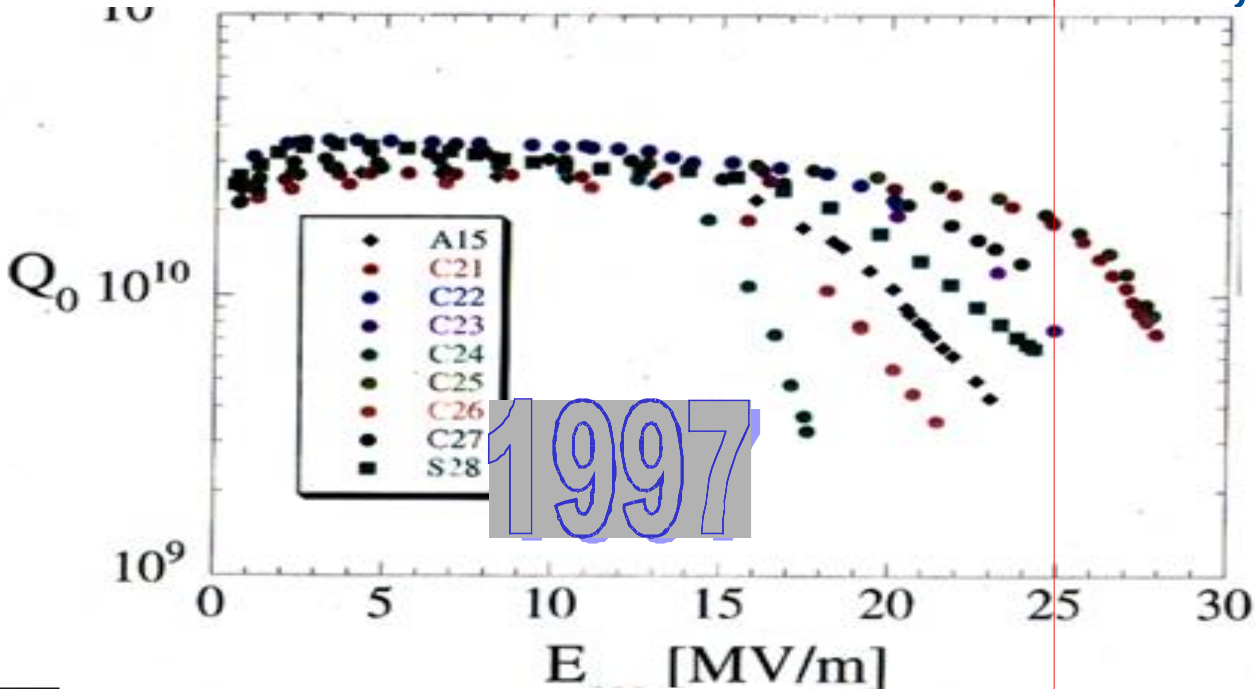
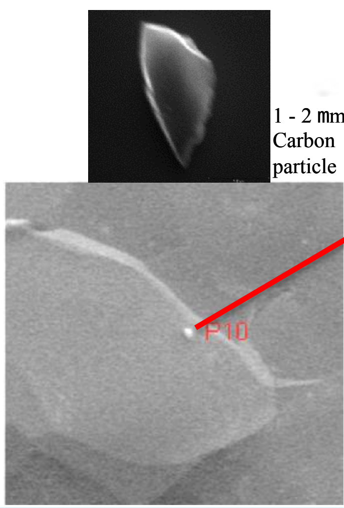
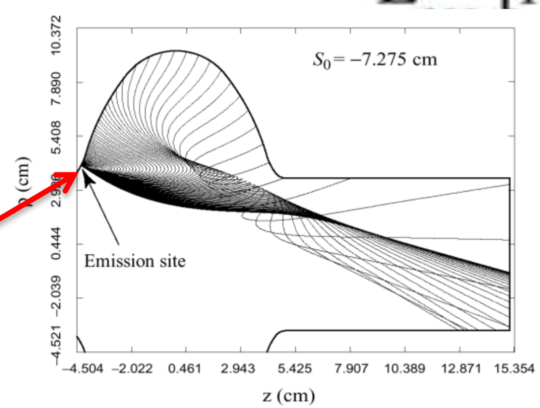
1990- 2000: Above 10 MV/m => Field Emission, Q Falls

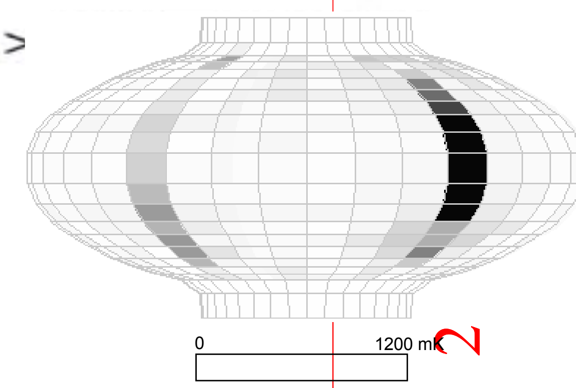
Understanding Field Emission



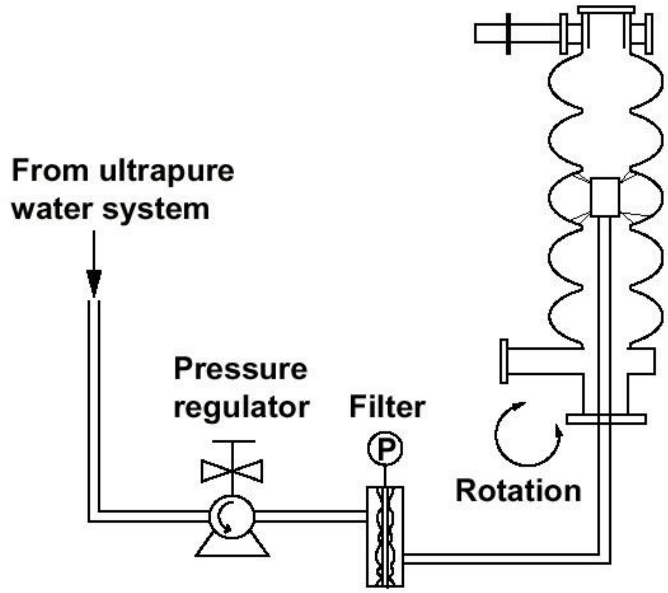


1 - 2 mm, Carbon particle





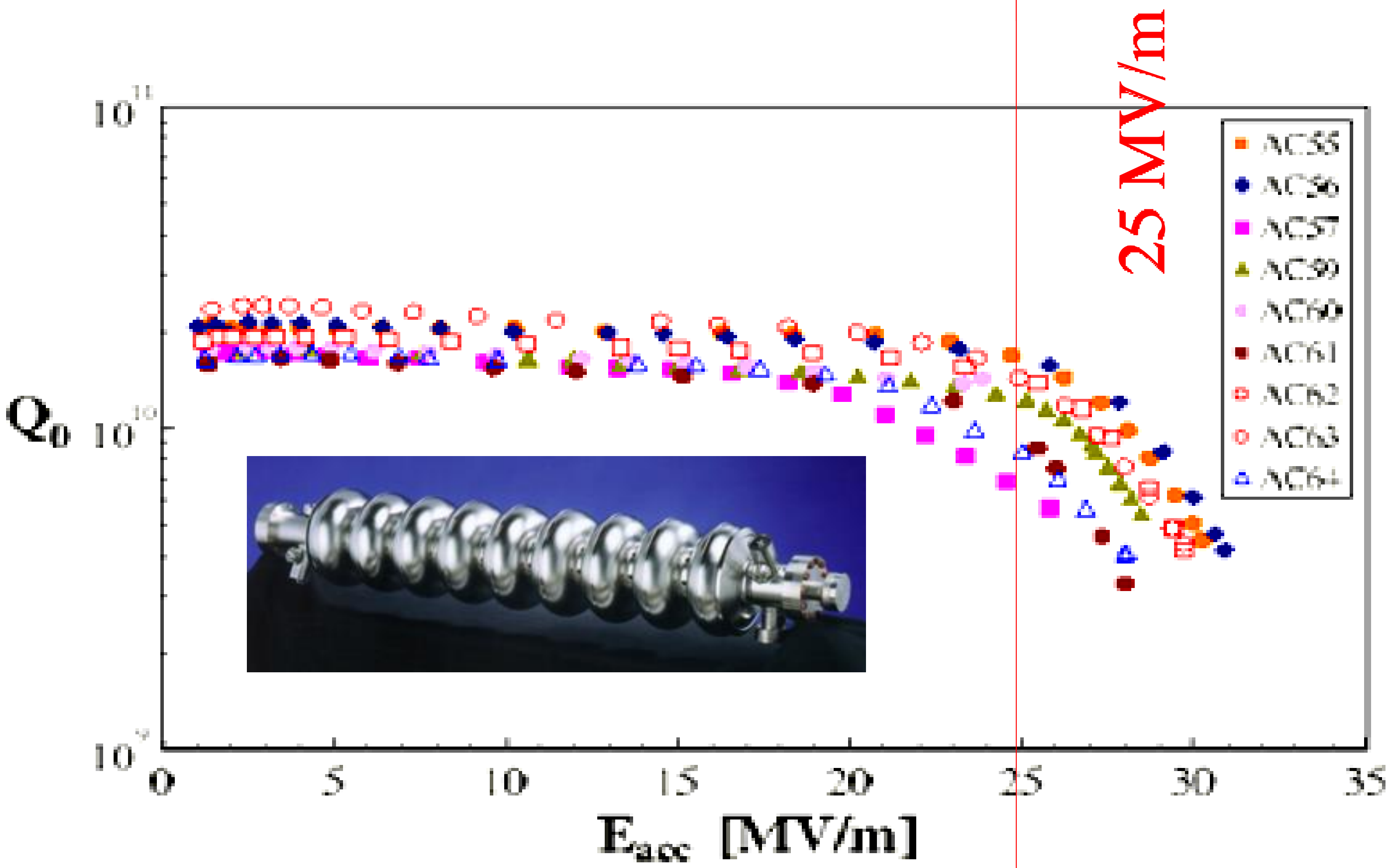
Solution to Field Emission:
Eliminate Surface Contaminants and Dust



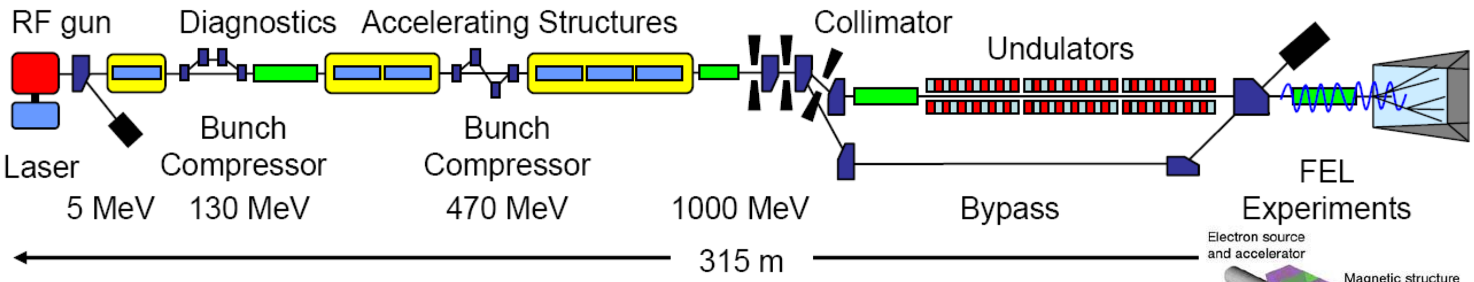
High Pressure (100 bar) Water Rinsing

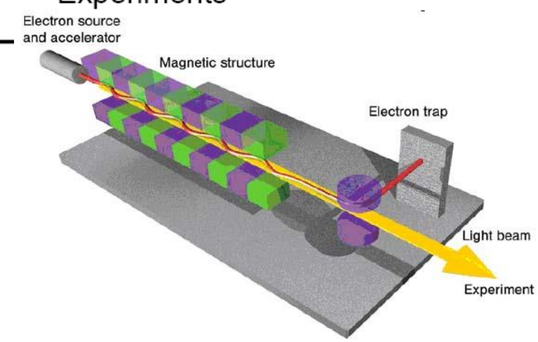
Clean Room Assembly

2000: Gradients and Q Rise, 20 to 25 MV/m Followed by "High Field Q-Slope"

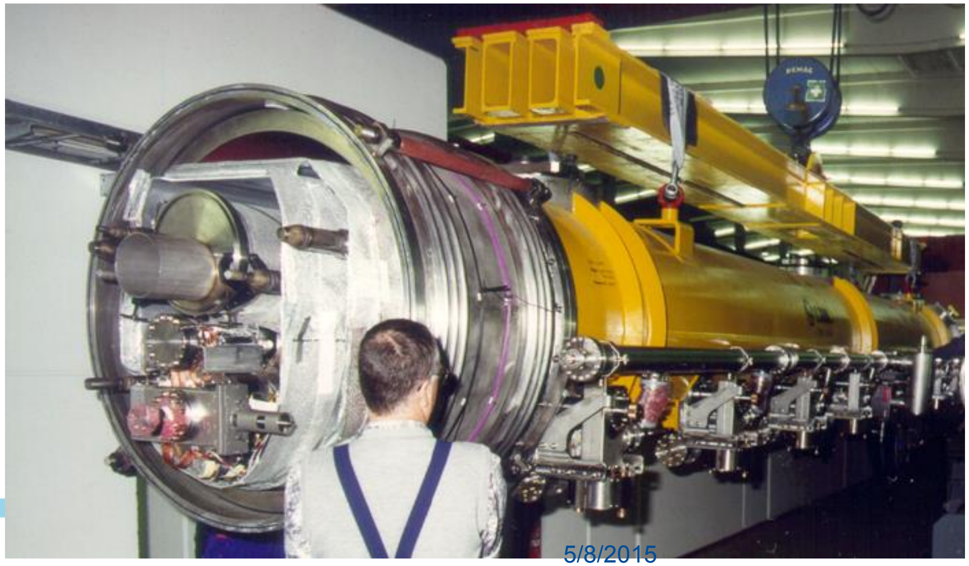


FLASH at DESY in Hamburg, Gradient 15 – 20 MV/m



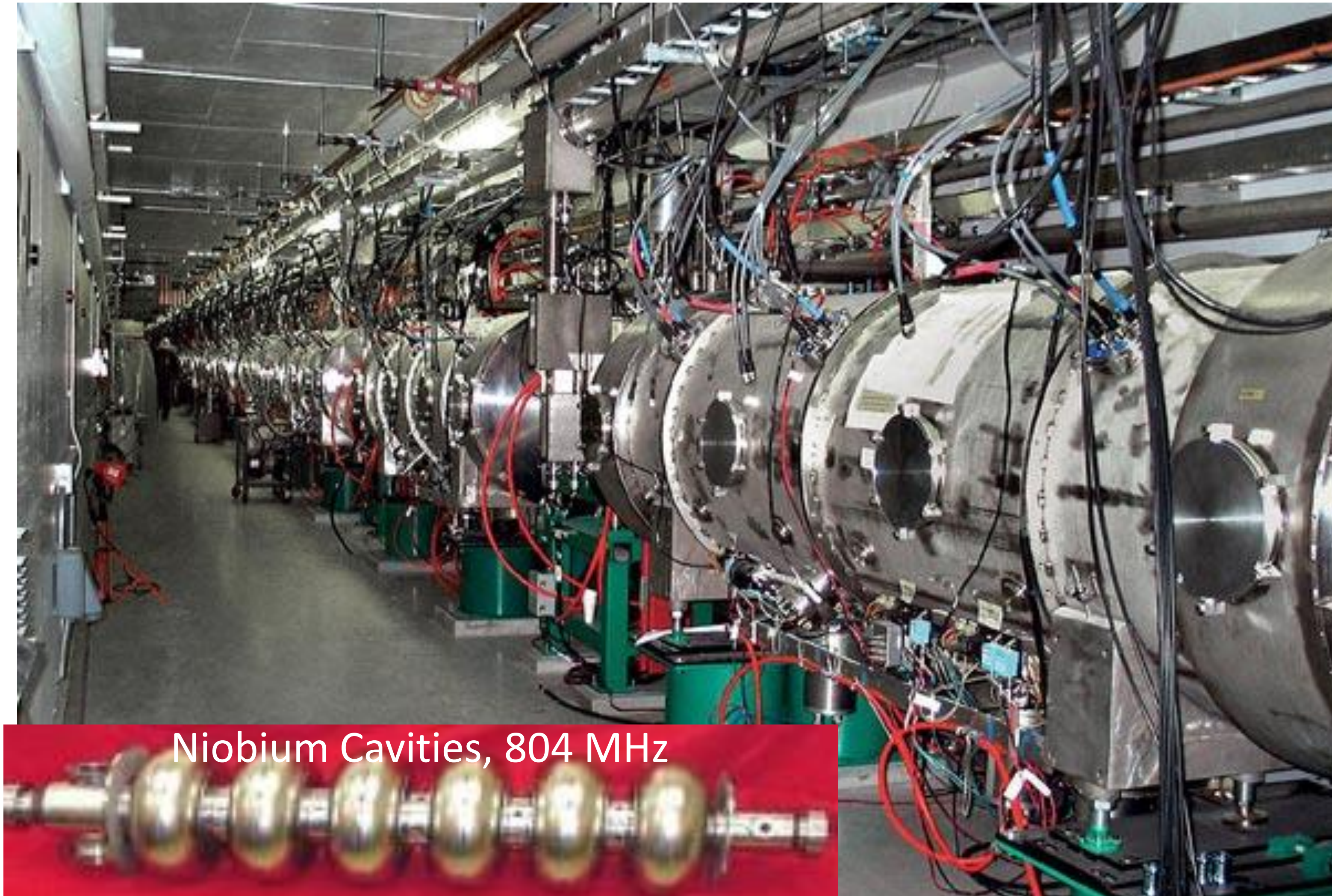


- 56 cavities in 7 modules provide >1 GeV beam:
- UV Laser: Lasing at 6.5 nm, now 2.5 nm



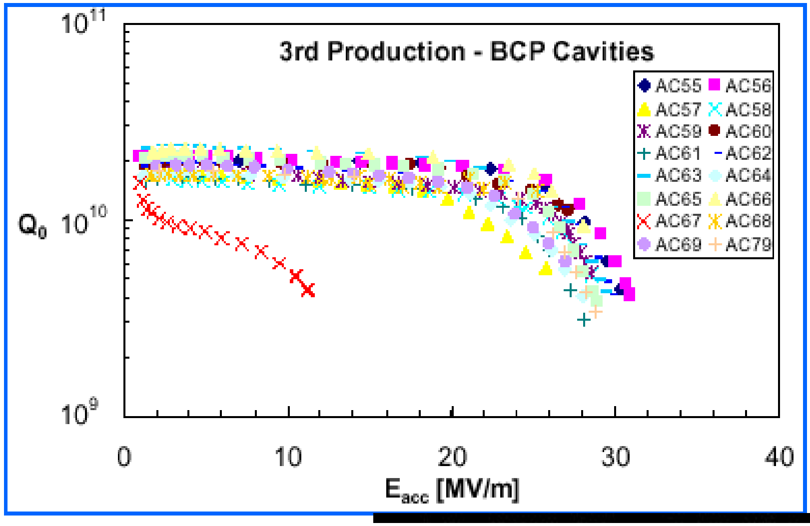
SNS (1 GeV protons, > 1 MW Beam Power)

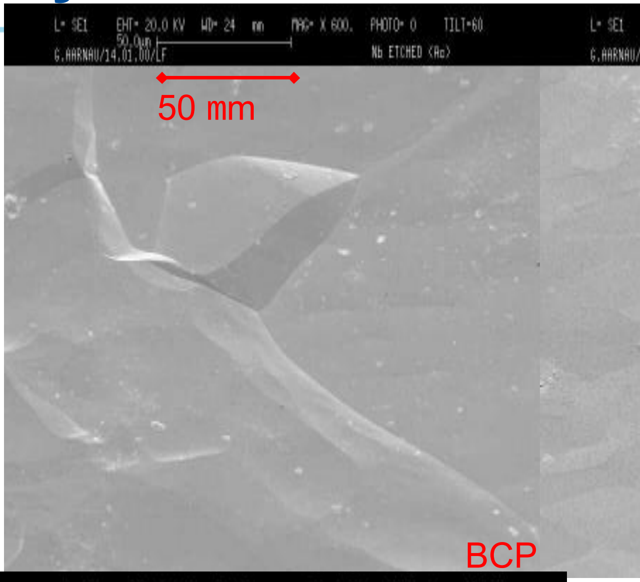
~ 100 Cavities, Gradients: 15 MV/m



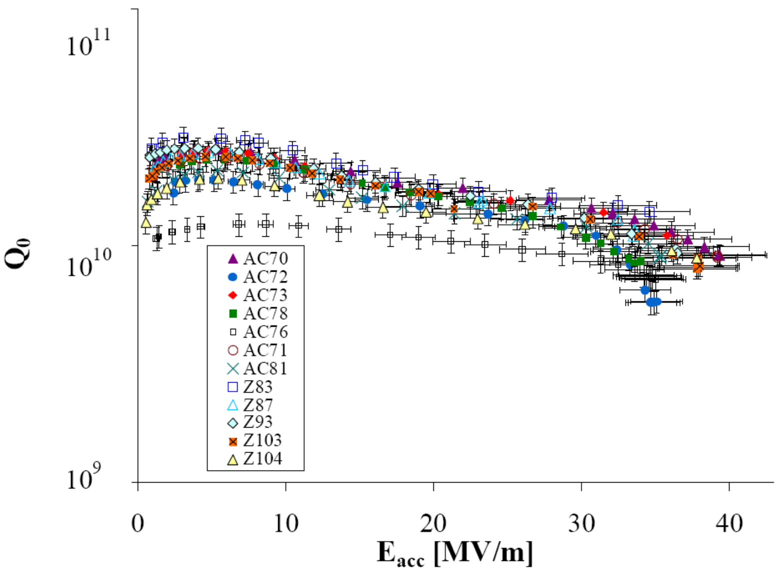
High Field Q-Slope Solved! But Not Yet Fully Understood!!

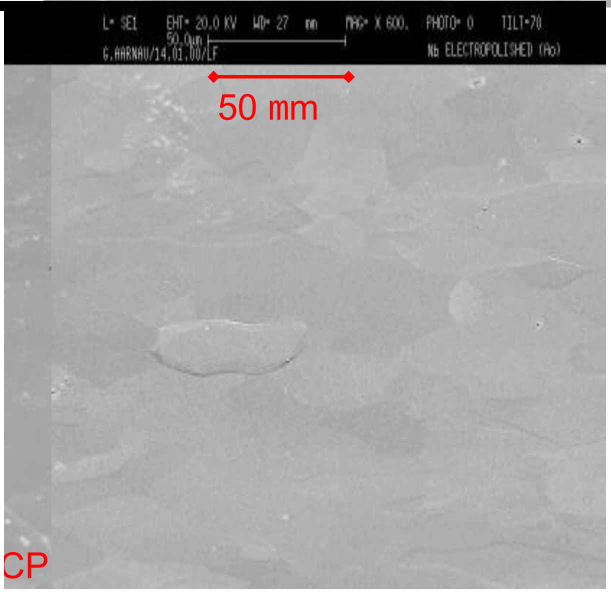
Understanding: BCP Chemistry gives rough surface





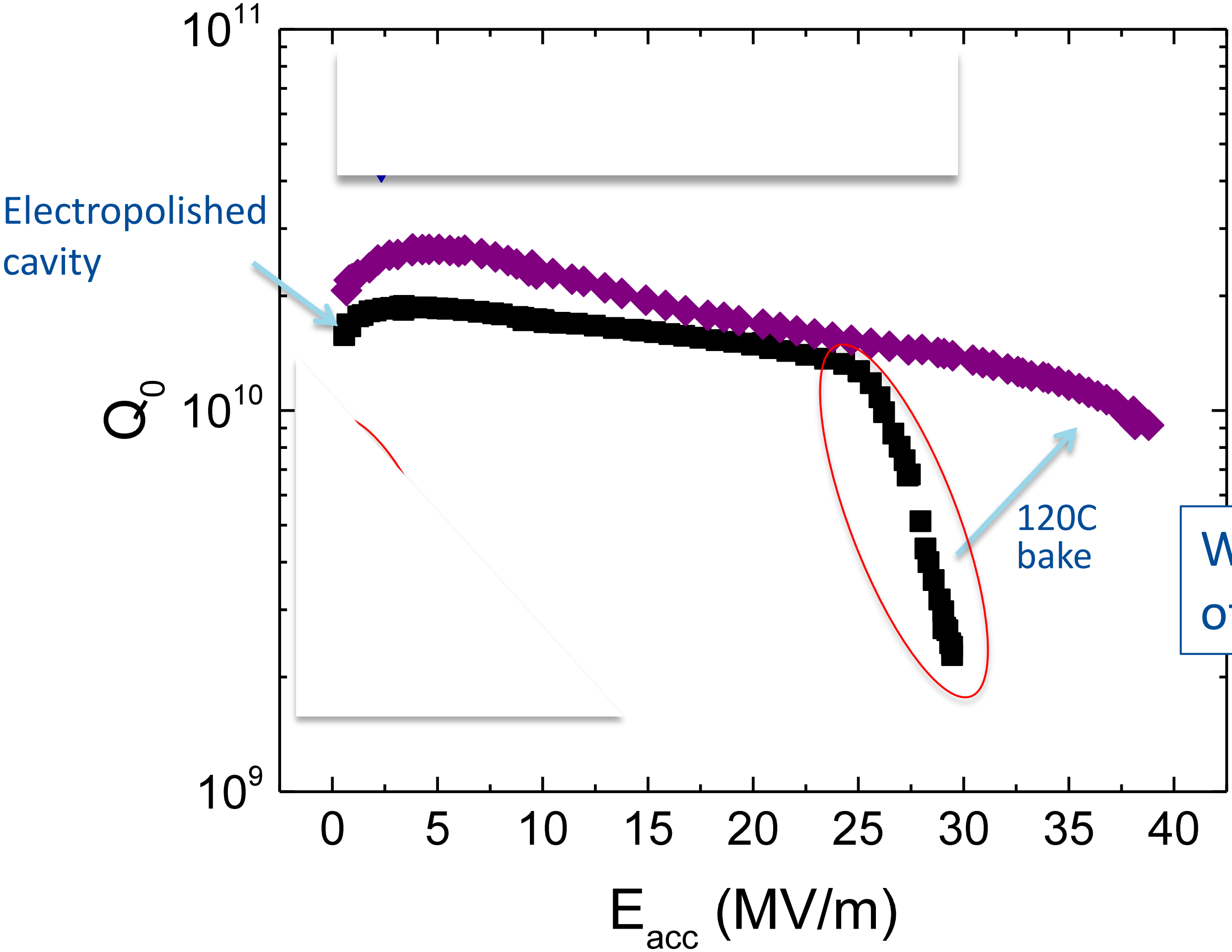
Electropolishing provides smooth surface Plus 120 baking for 24 – 48 hours





CP

120 C Bake Heals the Q-Slope



What is the mechanism of the “120C baking”?

> 2010: Dawn of a New Age: Accelerators Under Construction

≈ 2000 Nb Cavities, Installed Voltage will rise from 7 GeV => 25 GeV

- CEBAF Upgrade - JLAB (80 cavities)
  - Upgrade 6.5 GeV => 12 GeV electrons
- XFEL – Hamburg (840 cavities)
  - 18 GeV electrons – for Xray Free Electron Laser – Pulsed)
- LCLS-II – SLAC (300 cavities)
  - 4 GeV electrons –CW XFEL (Xray Free Electron Laser)
- ARIEL – TRIUMF
- SPIRAL-II – France (28 cavities)
  - 30 MeV, 5 mA protons -> Heavy Ions
- FRIB – MSU (340 cavities)
  - 500 kW, heavy ion beams for nuclear astrophysics
- ESS – Sweden (150 cavities)
  - 1 – 2 GeV, 5 MW Neutron Source ESS - pulsed
- PIP-II – Fermilab – 800 MV (115 cavities)
  - High Intensity Proton Linac for Neutrino Beams

Electrons for Nuclear Physics Research – CEBAF, Virginia
Add 80 High Voltage Cavities to 320 (original) Cavities

- CEBAF Upgrades 6 GeV to 12 GeV
- Each cryomodule provides 100 + MV
- New cavities 20 MV/m vs existing 7 MV/m

Each cryomodule contains a string of **eight 7-cell low-loss SRF 1497 MHz cavities**

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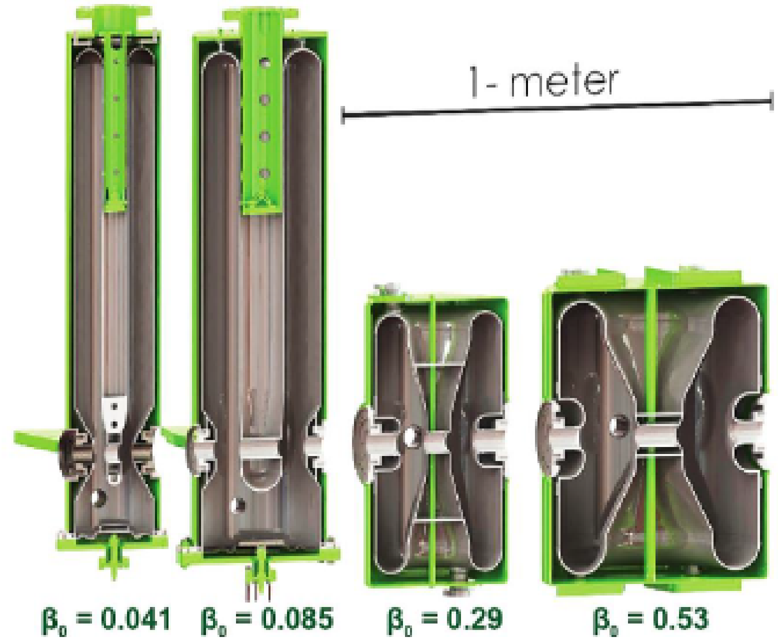
FRIB SRF Scope

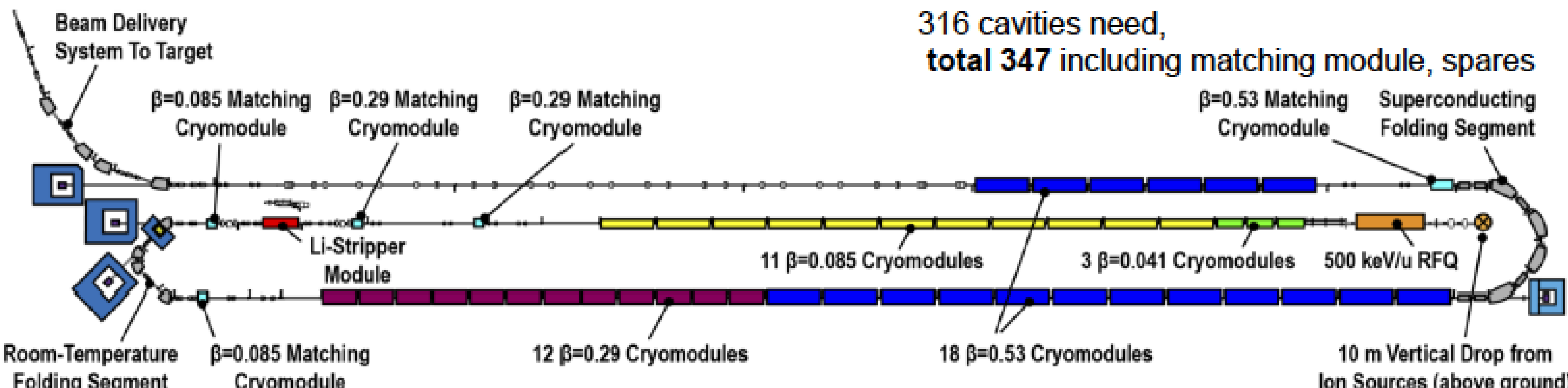
Challenge: All SRF from low β(0.041) to middle β(0.53)

Michigan State University
340 cavities



N = 12 88 72 144

316 cavities need,
total 347 including matching module, spares



XFEL (18 GeV) ….X-ray Laser

The biggest SRF application to date

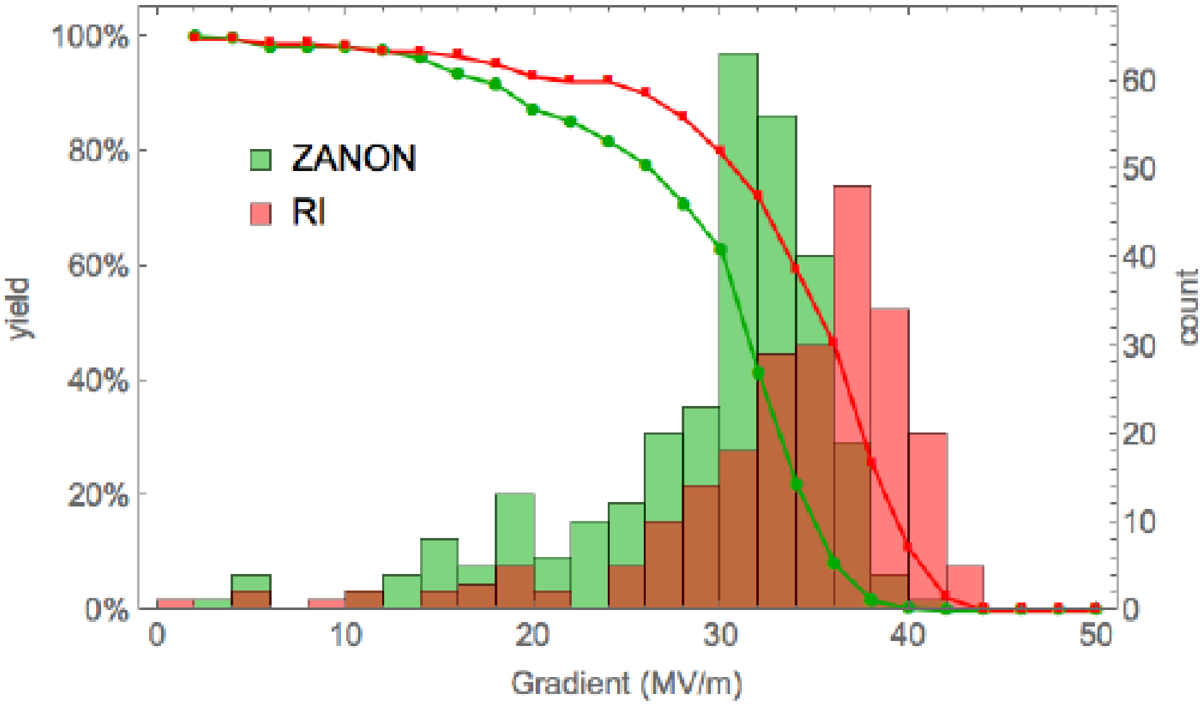
840 cavities , 24 MV/m, 18 GeV

840 Nb Cavities

Cavity preparation area

Cavity Testing at DESY

Test results: MAX GRADIENT



Cavities	522	(88%)
Tests	522	(63%)

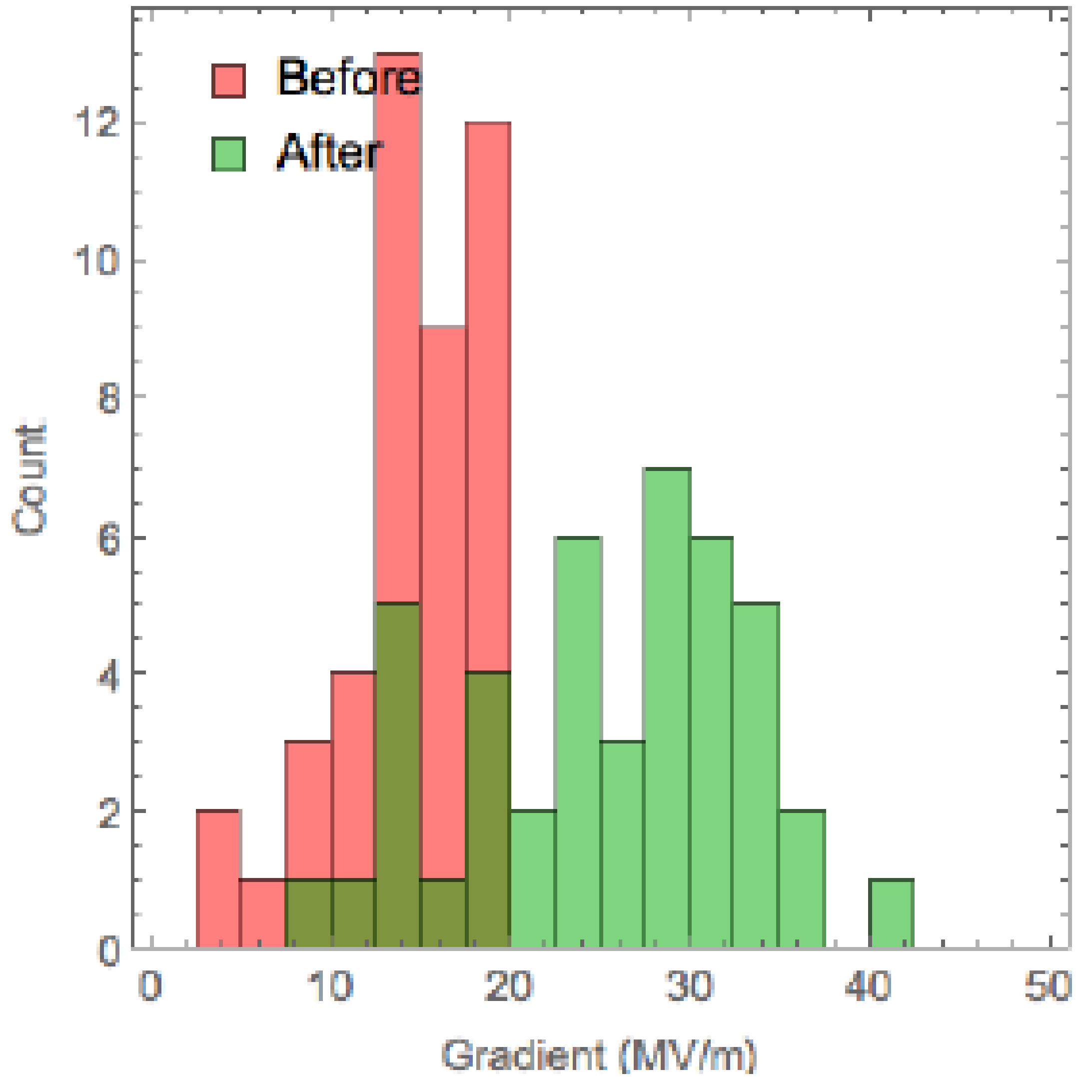
"As received" test

Average 31 MV/m

Clearly see the difference between Final EP and Final Flash BCP

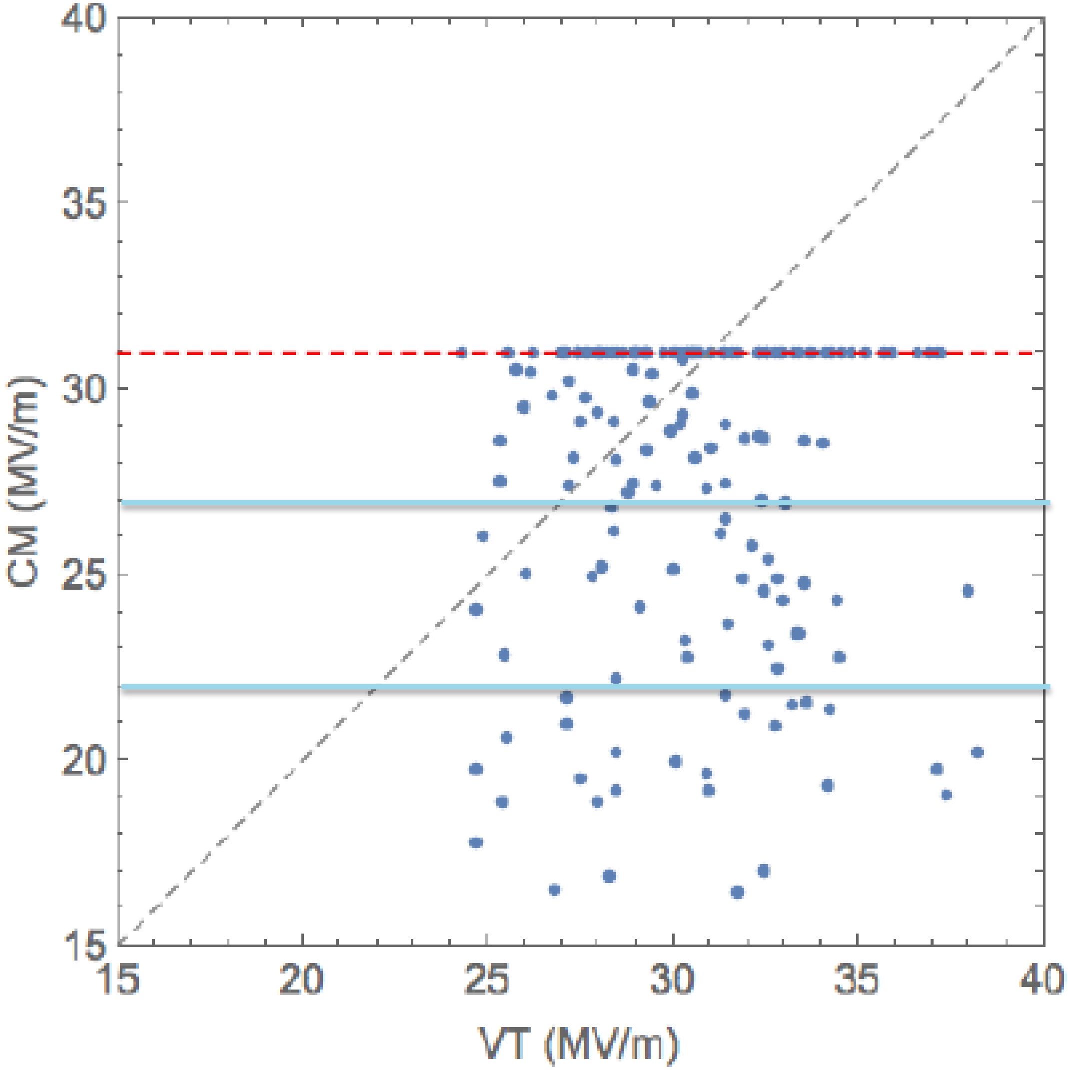
	Tests	Average	RMS	Yield@20	Yield@26	Yield@28
ZANON	291	29.3	6.8	87%	78%	71%
RI	231	33.6	7.	93%	90%	86%
All	522	31.2	7.2	90%	83%	77%

Recovery: Simple Re-treatment (HPR) of Low Gradient Cavities at DESY



103 Cryomodules – Assembled at Saclay

CM vs Vertical Test Gradients



Administrative Limit

Average CM Gradient
27 MV/m

Design Gradient for CM

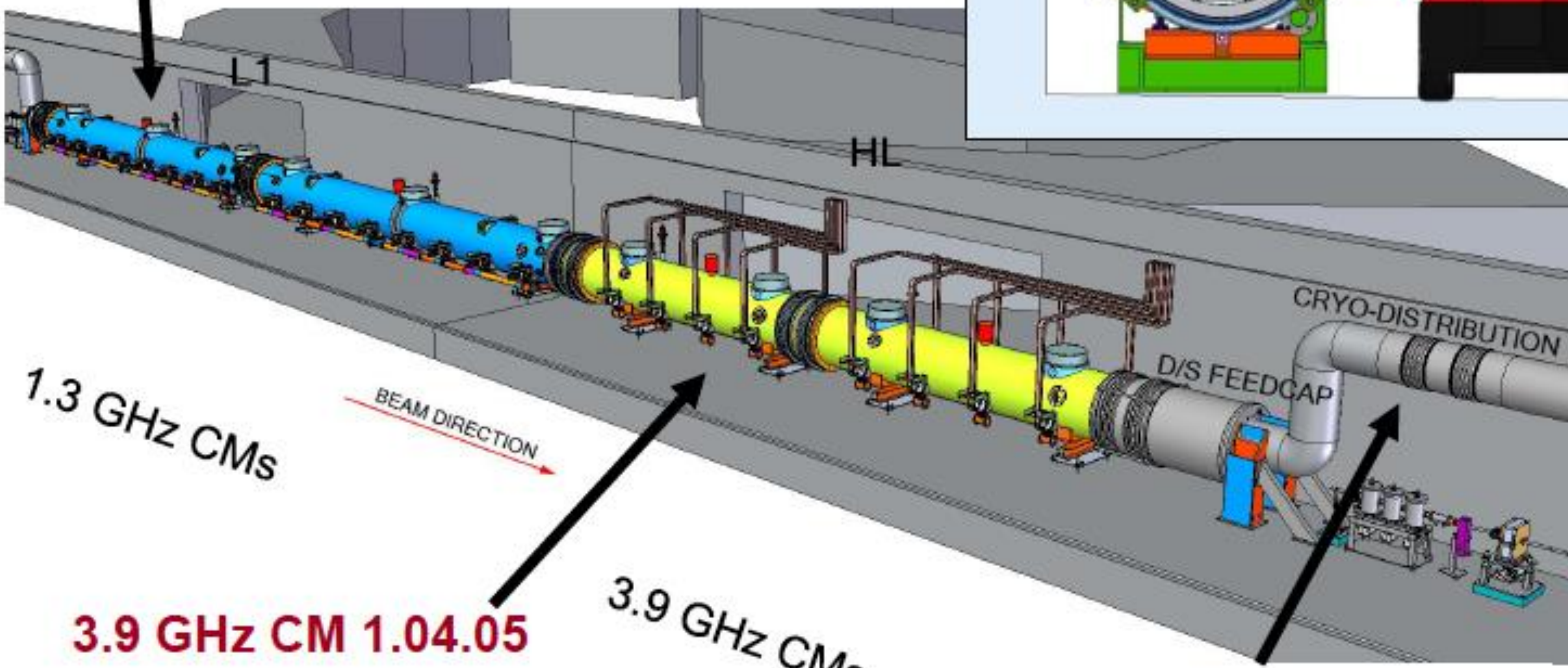
Cryomodules Installed in XFEL Tunnel

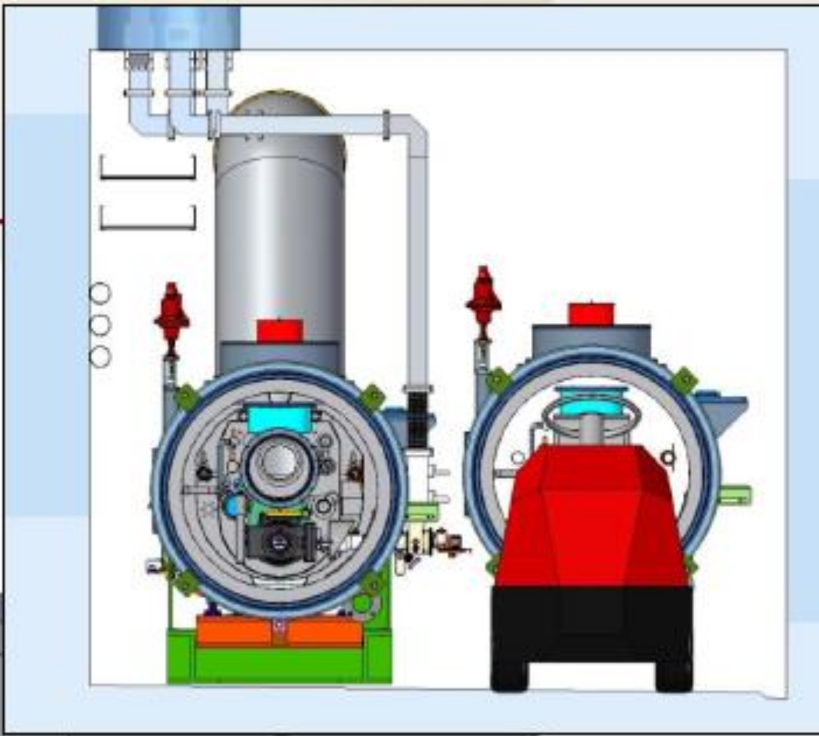
LCLS-II at SLAC

- SRF Linac based on XFEL/ILC technology
  - but 100% duty cycle
- High gradient (16 MV/m) in CW regime:
- High dynamic heat loads in CM
- High Q0 needed to reduce cryogenic loads

Tunnel Layout and Cross-section

1.3 GHz Modules 1.04.05/ 1.04.06 (Fermilab/JLab)





3.9 GHz CM 1.04.05

ESS - European Spallation Source – Lund

> 150 Cavities

EUROPEAN SPALLATION SOURCE

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Fermilab Proton Improvement Plan-II (115 Cavities)

IS	LEBT	RFQ	MEBT	β=0.11	β=0.22	β=0.51	β=0.61	β=0.9

162.5 MHz
0.03-11 MeV

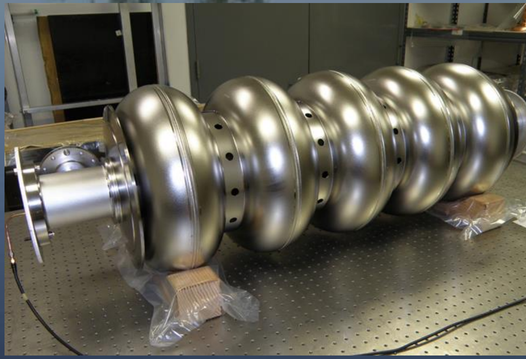
325 MHz
11-177 MeV

650 MHz
177-800 MeV

Half Wave

Spokes

Medium-Beta Elliptical Cavities

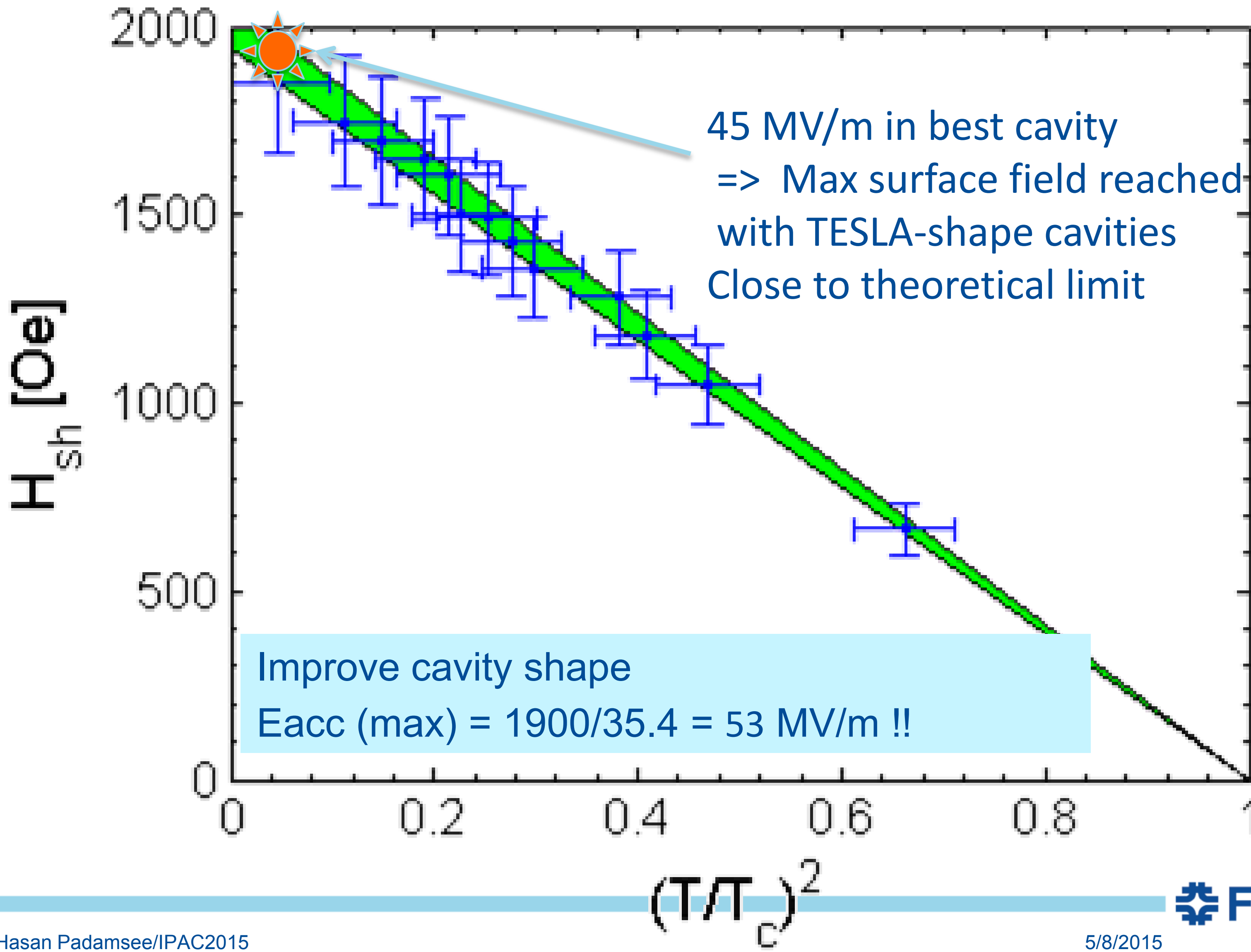


High-Beta Elliptical Cavities

Questions for…

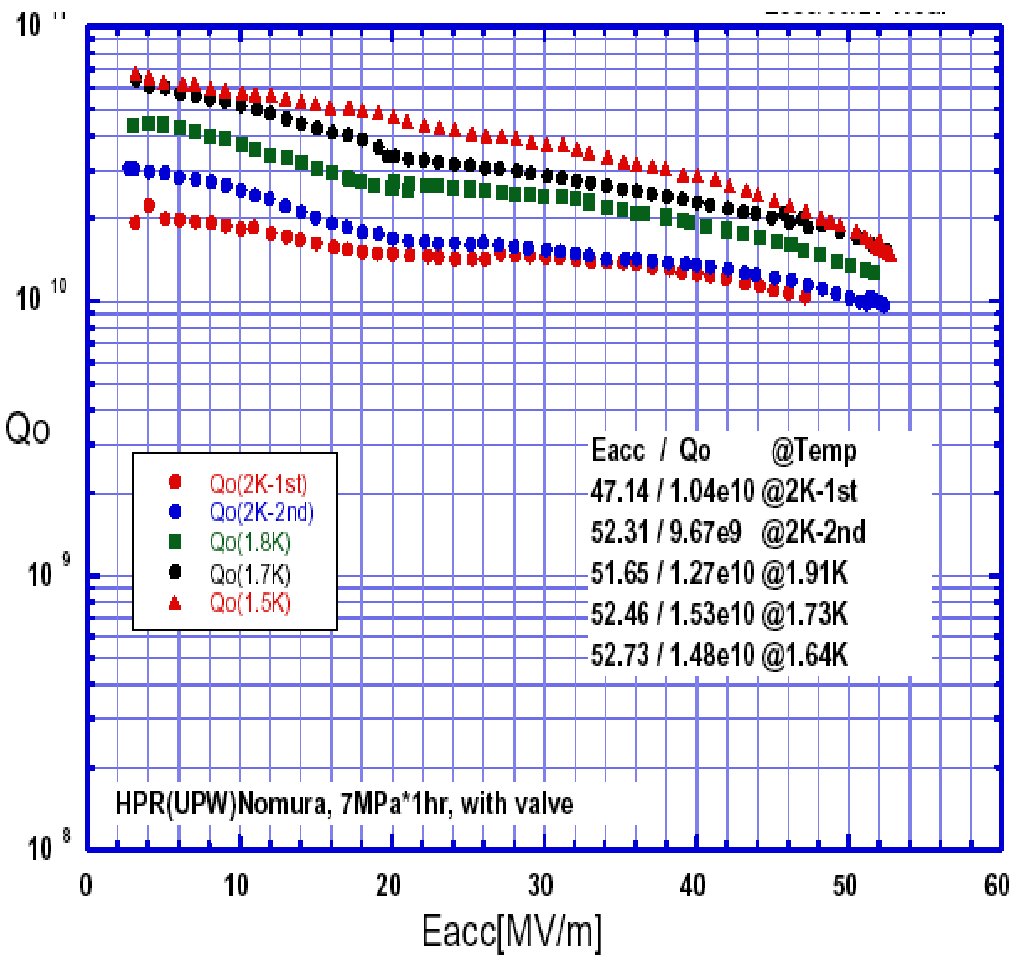
What are the prospects for higher gradient?
From 35 => 50 MV/m => 100 MV/m?

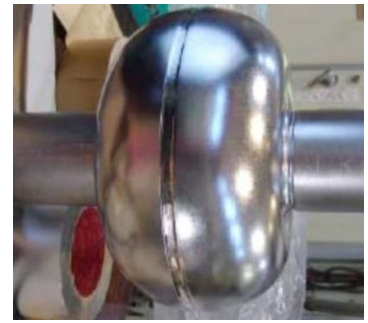
Fundamental RF Critical Field (Hsuperheating) Measurement

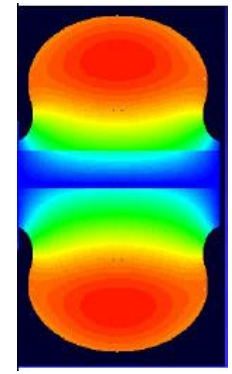


Low-Loss and Re-entrant Shapes Exceed 50 MV/m in Single Cells !

With Lower Surface Magnetic Field & RF Lower Losses

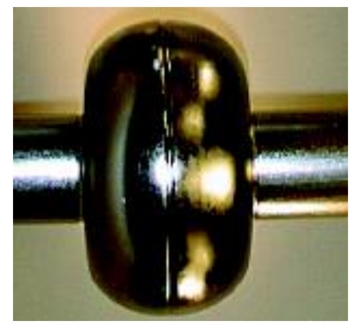


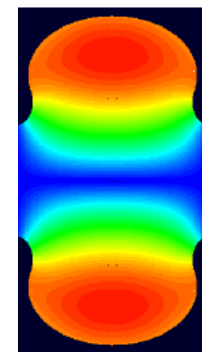




60 mm Re-entrant

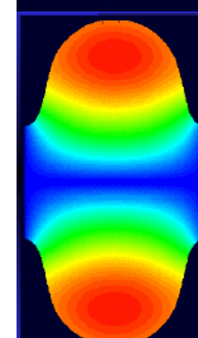
Cornell KEK





70 mm Re-entrant

Cornell KEK

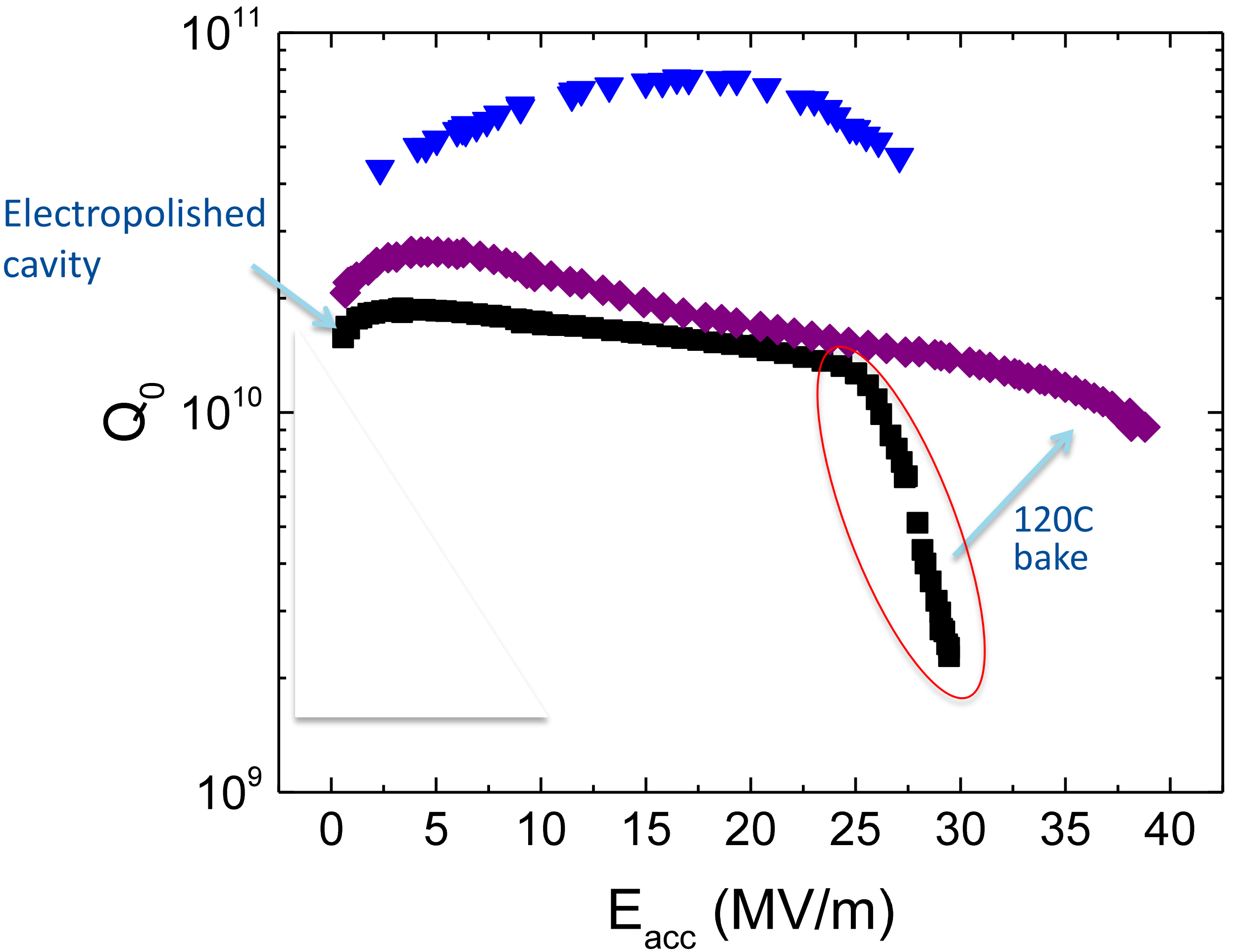


70 mm Tesla Shape

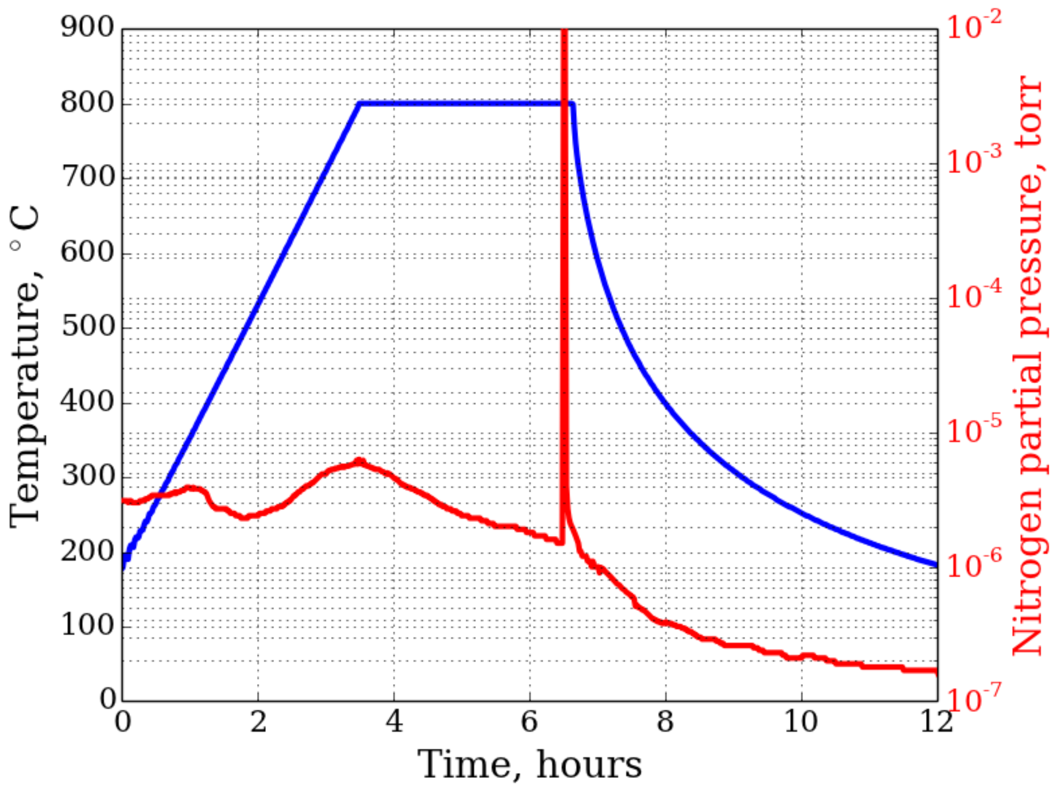
What the are prospects for higher Q?

Major finding: N doping drastically increases Q - FNAL

First Step: for Medium Fields

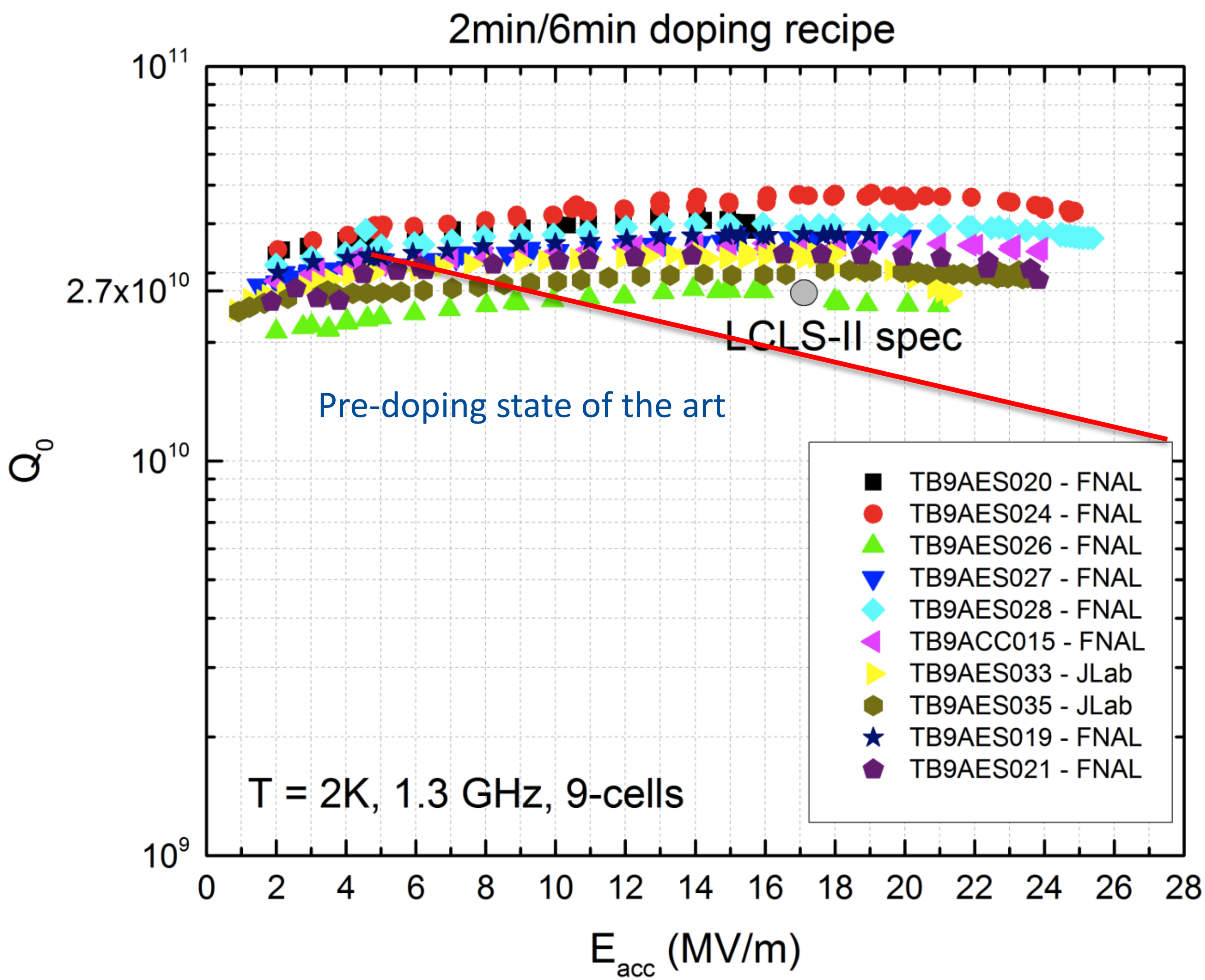


N doping: infusing the cavity surface with a small concentration of nitrogen (about 50 ppm)



Injection of small nitrogen partial pressure at the end of 800C degassing-> drastic increase in Q

Q values obtained by N-Doping doping repeatedly on multicells for LCLS-II



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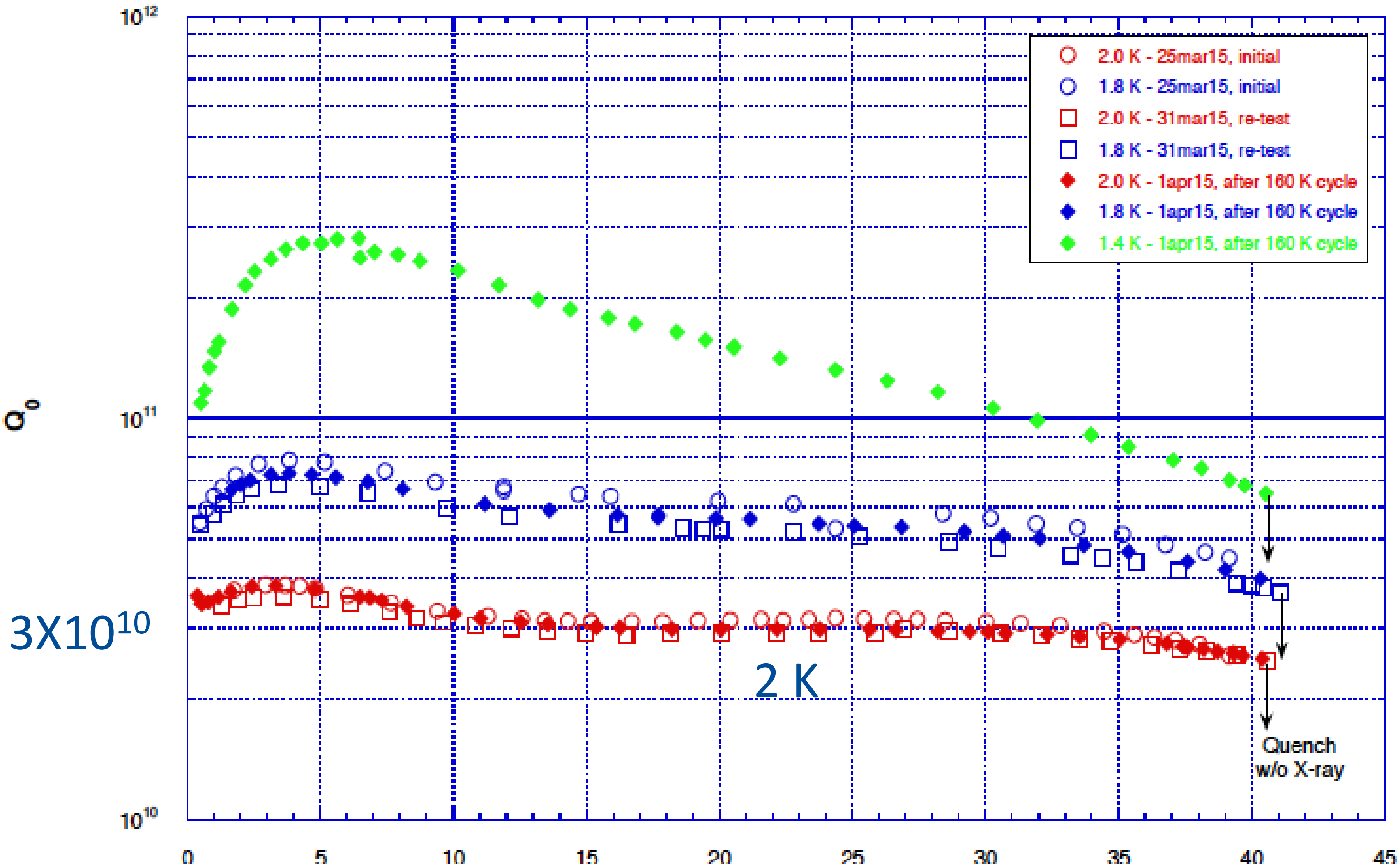
Is High Q Extendable to High Fields? Yes - JLAB



What are the prospects for new materials?

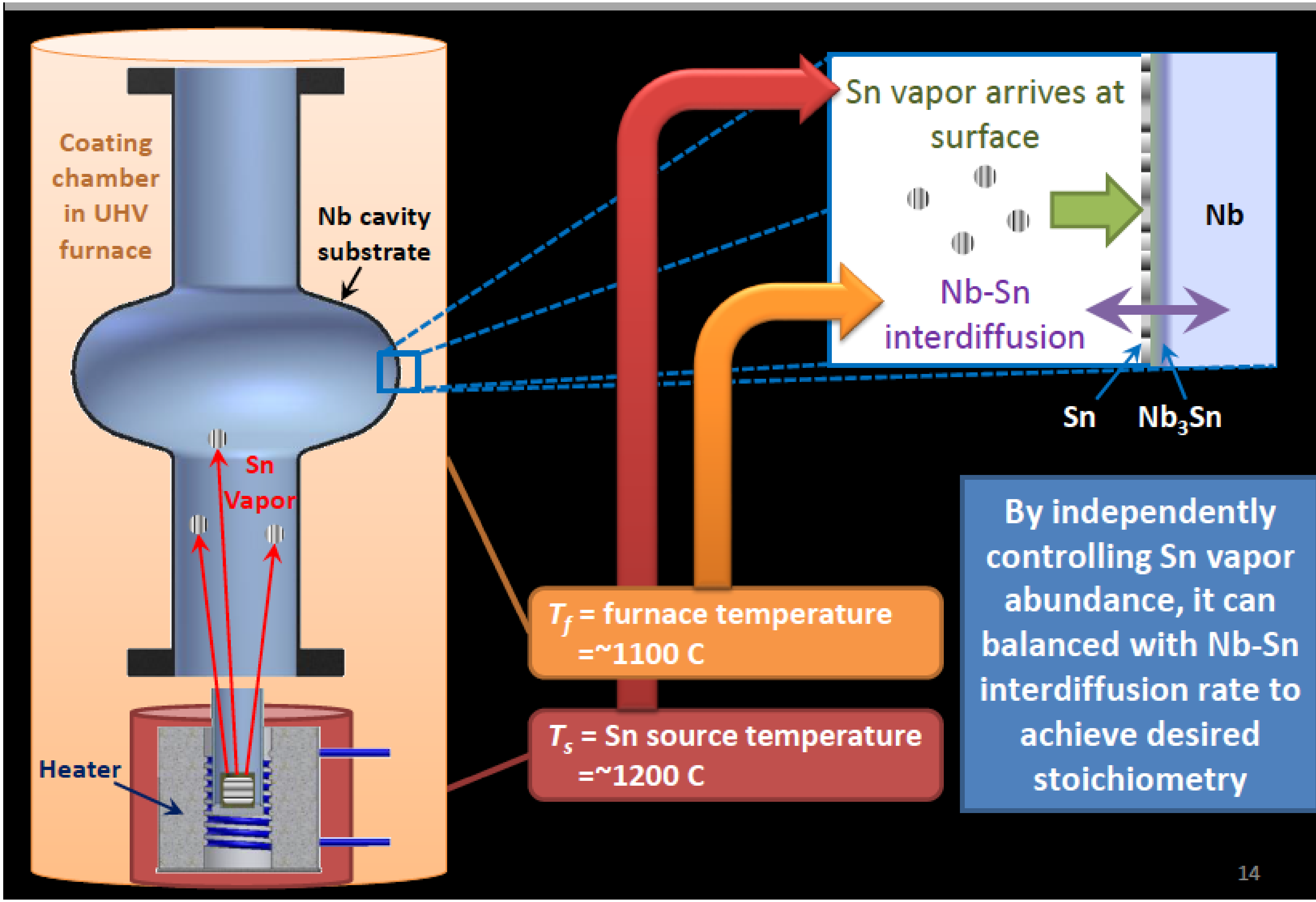
Experimental Properties of Promising Materials

NA PAC '13

Material	λ(0) [nm]	ξ(0) [nm]	B_{sh} [mT]	T_c [K]	$\rho_n(0)$ [μΩcm]
Nb	50	22	210	9.2	2
Nb_3Sn	111	4.2	410	18	8
MgB_2	185	4.9	210	40	0.1
NbN	375	2.9	160	16	144

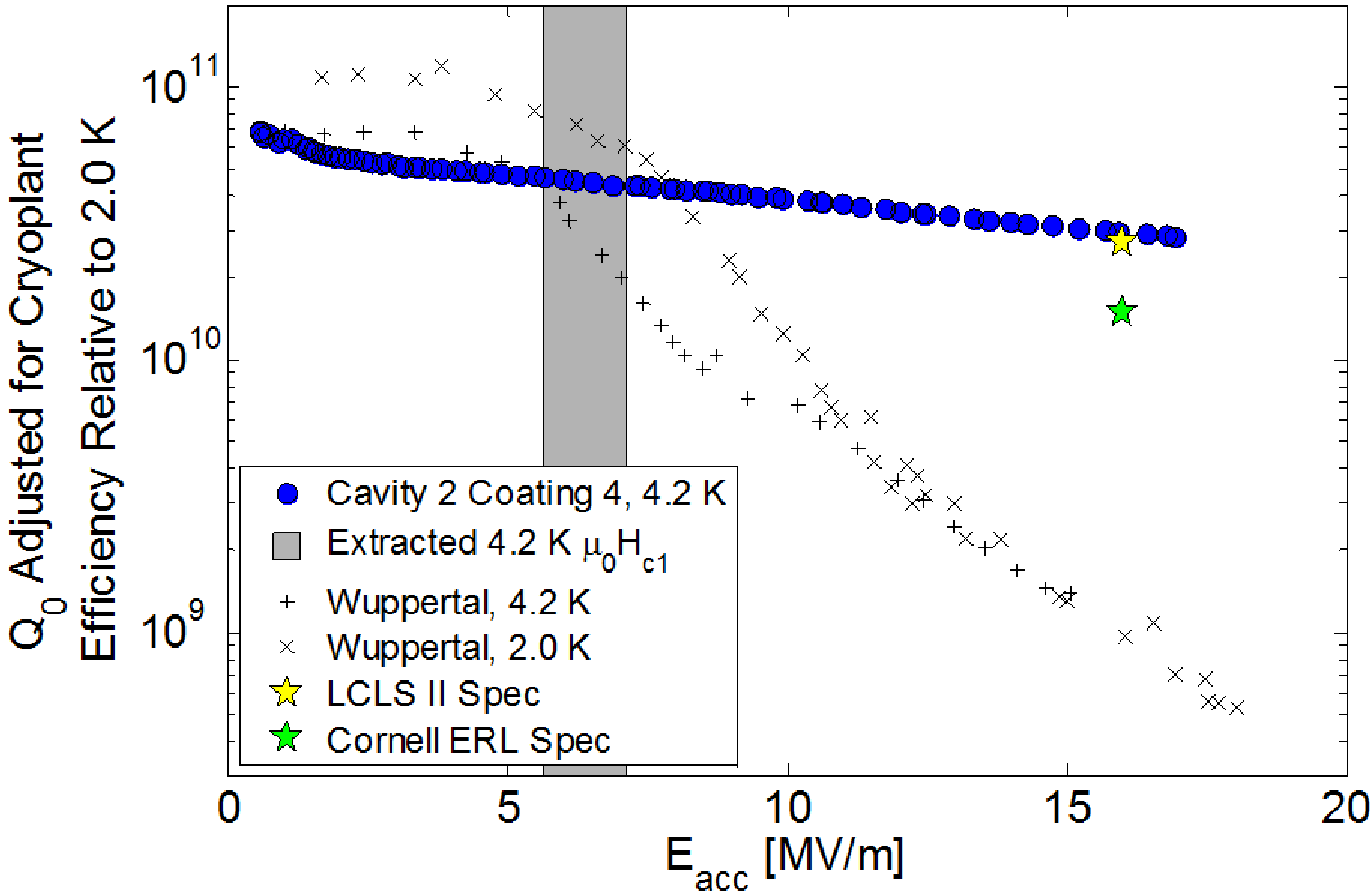
- Nb3Sn, Tc = 18K
- Higher Q at higher operating T
- Higher ultimate field possible

Nb3Sn Fabrication/Cornell



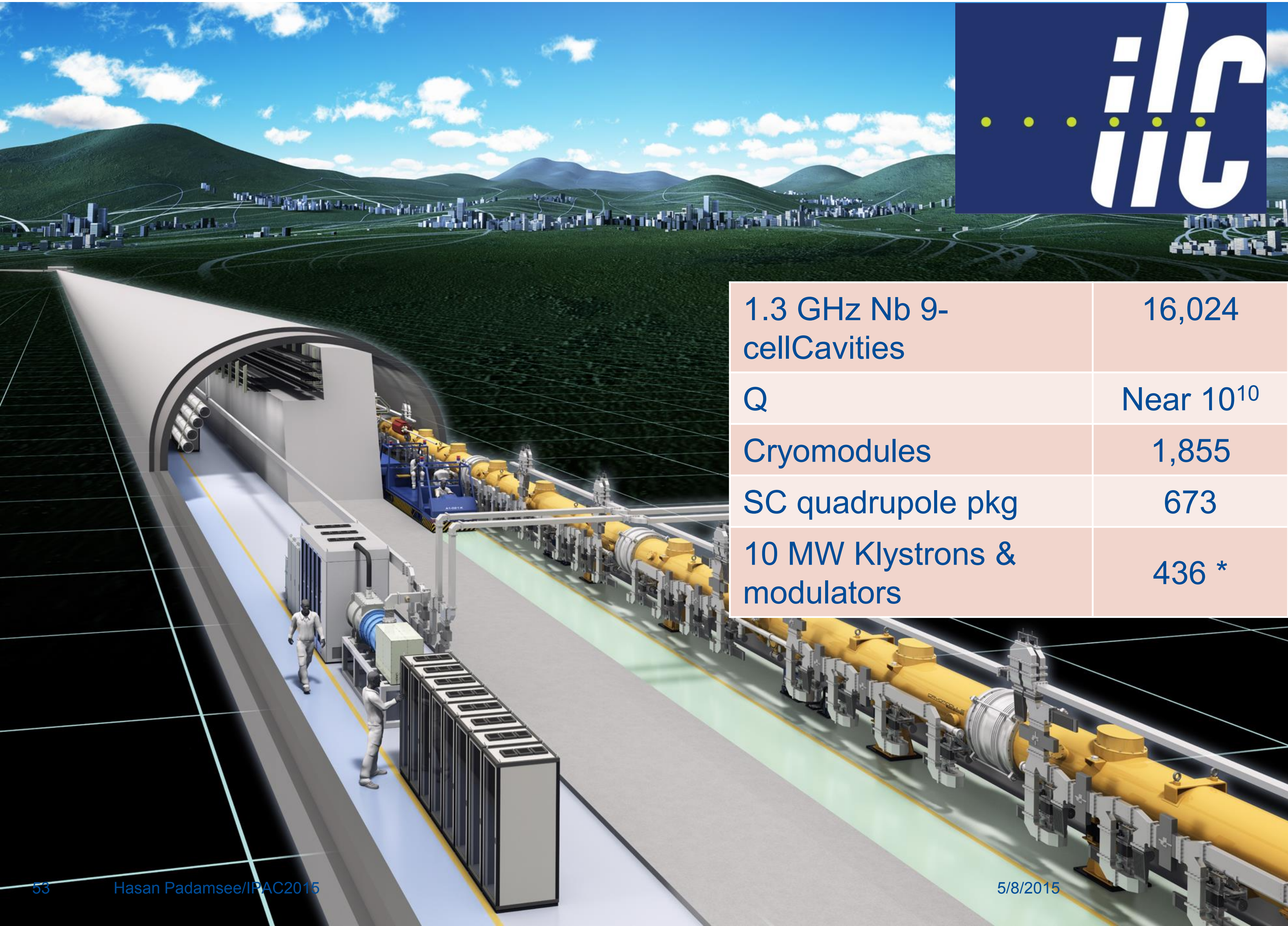
Fermilab

Best Nb3Sn Result - Cornell



SRF Based Accelerators for Future Decades?
World-Wide Expansion of SRF

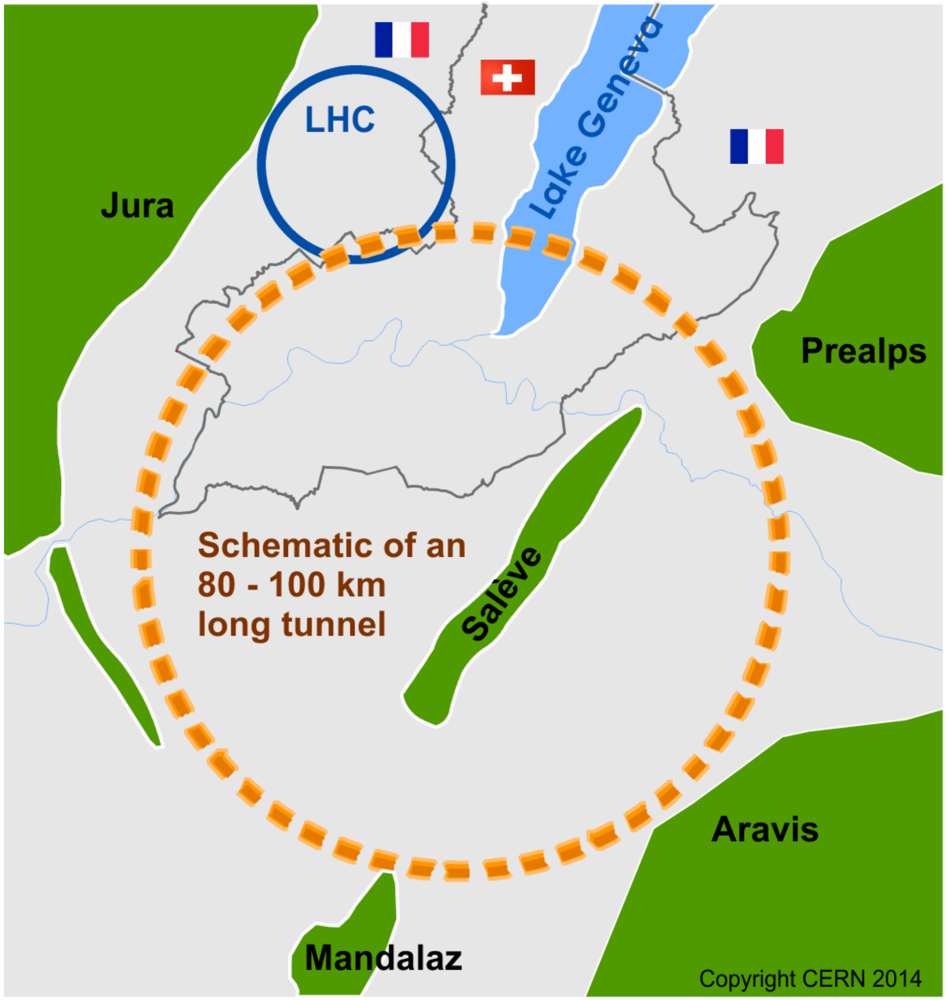
- USA/Europe => Asia
- ILC Could be built in Japan by World Collaboration
- Korea – RAON, 600 MeV, 400 kW (like FRIB) – 360 cavities
- ADS (Accelerator Driven Systems) For
  - Transmutation of Nuclear Waste
  - Energy Generation from Thorium
  - Sub-critical Nuclear Power Station
- China ADS
- India
  - I-SNS – 1 GeV, 2 mA
  - ADS – 1 GeV – 30 mA
- Future Circular Collider (post LHC)
  - CERN and/or China



1.3 GHz Nb 9-cellCavities	16,024
Q	Near 10^{10}
Cryomodules	1,855
SC quadrupole pkg	673
10 MW Klystrons & modulators	436 *

Future Circular Collider Dreams (FCC)

- 1st Stage - Higgs Factory
- e+ e- collider
  - 650 cavities, 400 – 800 MHz
  - 250 GeV –> 350 GeV
  - CERN 80 –> 100 km ring
  - China 50 –> 70 km ring
- 2nd Stage pp collider to follow LHC



Vision for Continuous Growth!

"Moore's" Law for SRF 50 Yr-Growth of Installed Voltage

for v/c=1 Accelerators