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Title:	Introduction to Superconducting RF Structures and the Effect of High Pressure Rinsing
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Introduction to Superconducting RF Structures and the Effect of High Pressure Rinsing

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Accelerator Operations & Technology Division

A seminar at AFRL, 29 June 2016

LA-UR-16-XXXXX

Outline

- **Introduction**
  - What is RF superconductivity
  - How SRF accelerating structures work
- **Brief history of the advances in the last 50 years**
  - 105 years after superconductivity was discovered in 1911, and 55 years since SRF accelerator was proposed in 1961
- **History on field emission research for SRF cavities and HPR**
- **HPR of the Air Force Research Lab (AFRL) samples**

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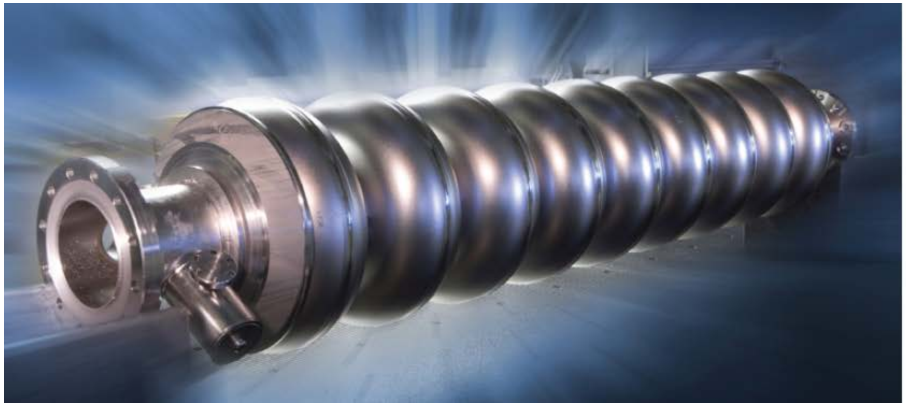
What is radio-frequency (RF) superconductivity? What is SRF structures (a.k.a. cavities)?

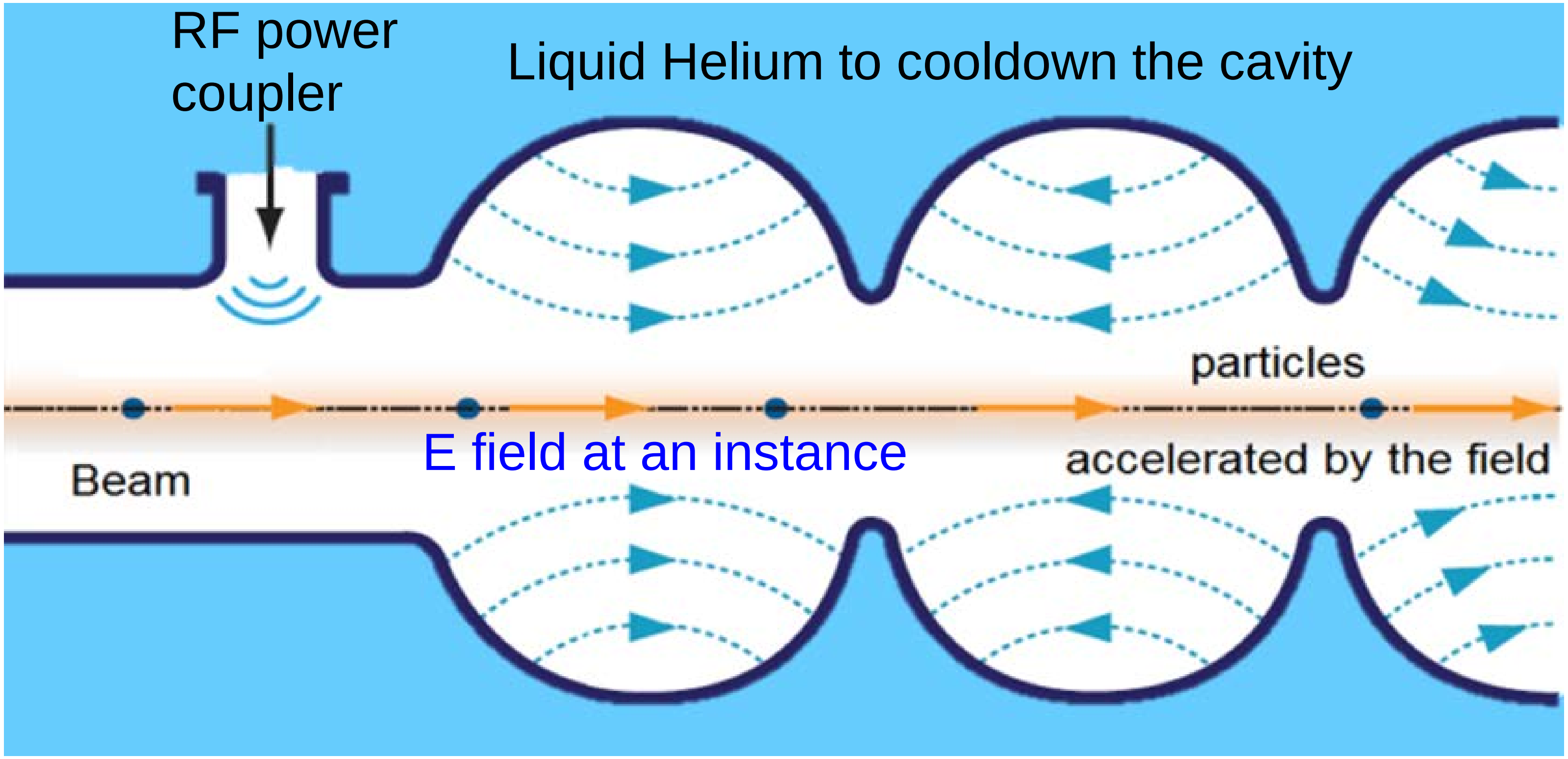
- **RF is a rate of oscillation in the range of 3 kHz to 300 GHz [Wikipedia]**
- **RF superconductivity is explained in Wikipedia as "Superconducting radio frequency (SRF)" authored by a Cornell University group.**
  - "SRF science and technology involves the application of electrical superconductors to radio frequency devices."
  - Niobium SRF resonant structures (a.k.a. cavities) used on particle accelerators are one of the most successful applications of the RF superconductivity in the last couple of decades.



- ~8" diameter cells
- ~50" long
- Made of ~1/8" thick high-purity (RRR~300) Nb

9-cell niobum cavity to be used in European XFEL at DESY and the future ILC. [3]

How the SRF structure works. An example of a simple multi-cell elliptical π-mode cavity.



Electric fields change their direction at half the resonant frequency (RF cycle), e.g., 0.5 ns with 1 GHz cavity, in a synchronized fashion so that the beam bunches always feel accelerated.

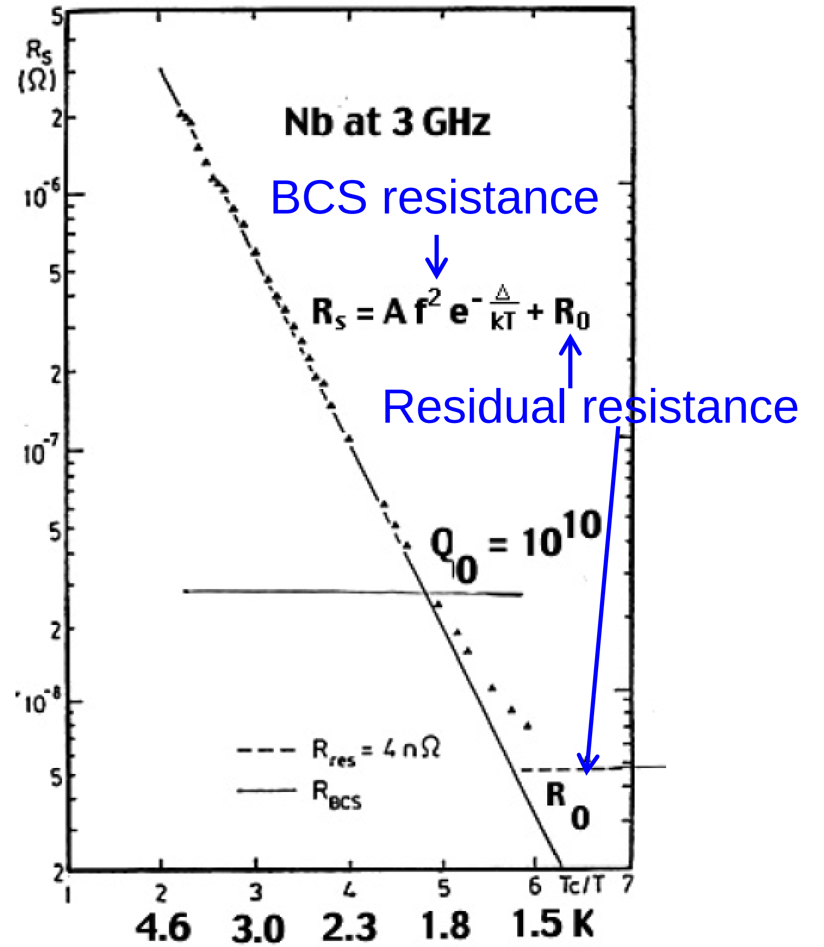
SRF structures are ~x100 efficient compared to normal conducting structures

- **RF surface resistance (R_s) is not zero, but very very small compared to typical normal conducting metals**
  - e,g,. 2 mΩ vs. ~7 nΩ at 1.5 K at 3 GHz.

    >x10⁵ less loss !!

Even with ~x10³ AC power needed for refrigeration (e.g. for ~1 kW system), ~x10² efficient than copper structures.

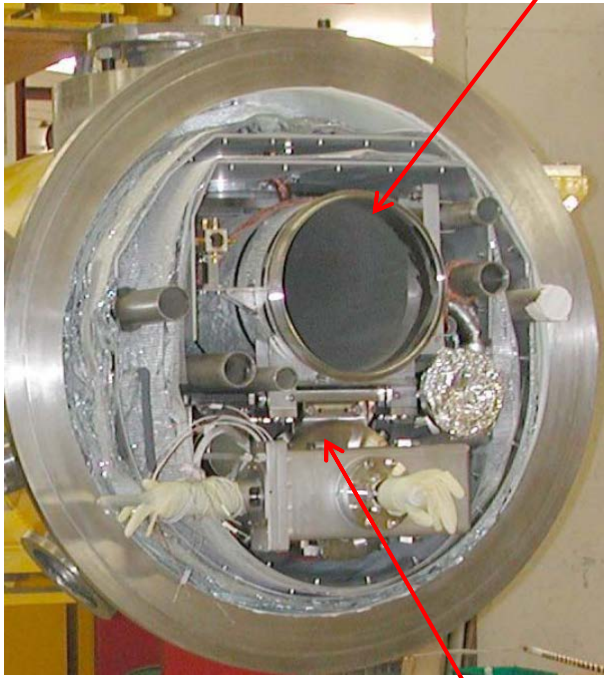
Strong temperature dependence

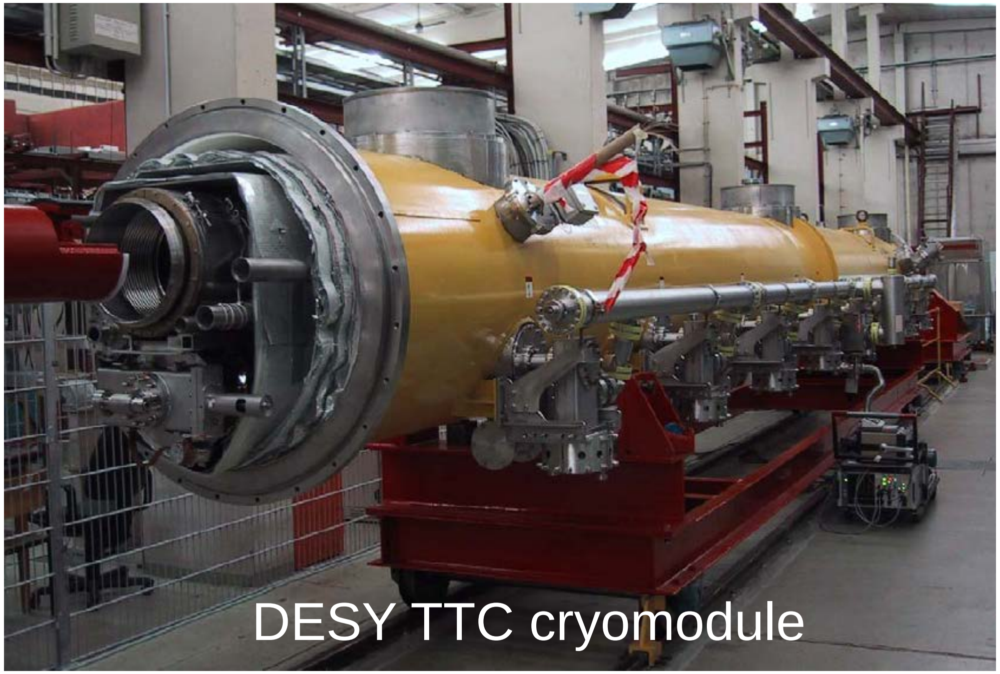


Cavities are connected in a class-10 clean room and installed as a string in a horizontal cryostat (module)

He gas return pipe

~12 m long cryomodule





Behind the gate valve is a 1.3 GHz 9-cell cavity

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First generation large-scale SRF accelerator installations for high-energy and nuclear physics

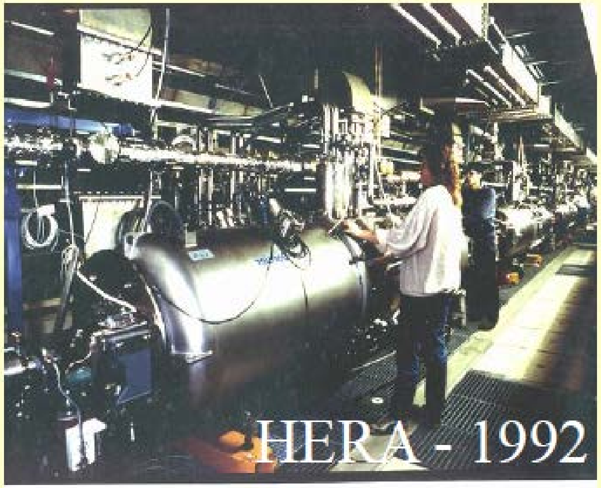
32
508 MHz
5-cell

KEK, Japan

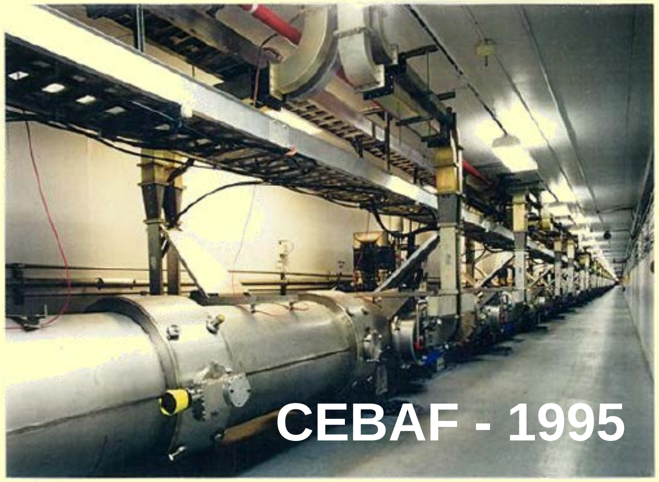
CERN, EU

288
352.5 MHz
4-cell

16
500 MHz
5-cell



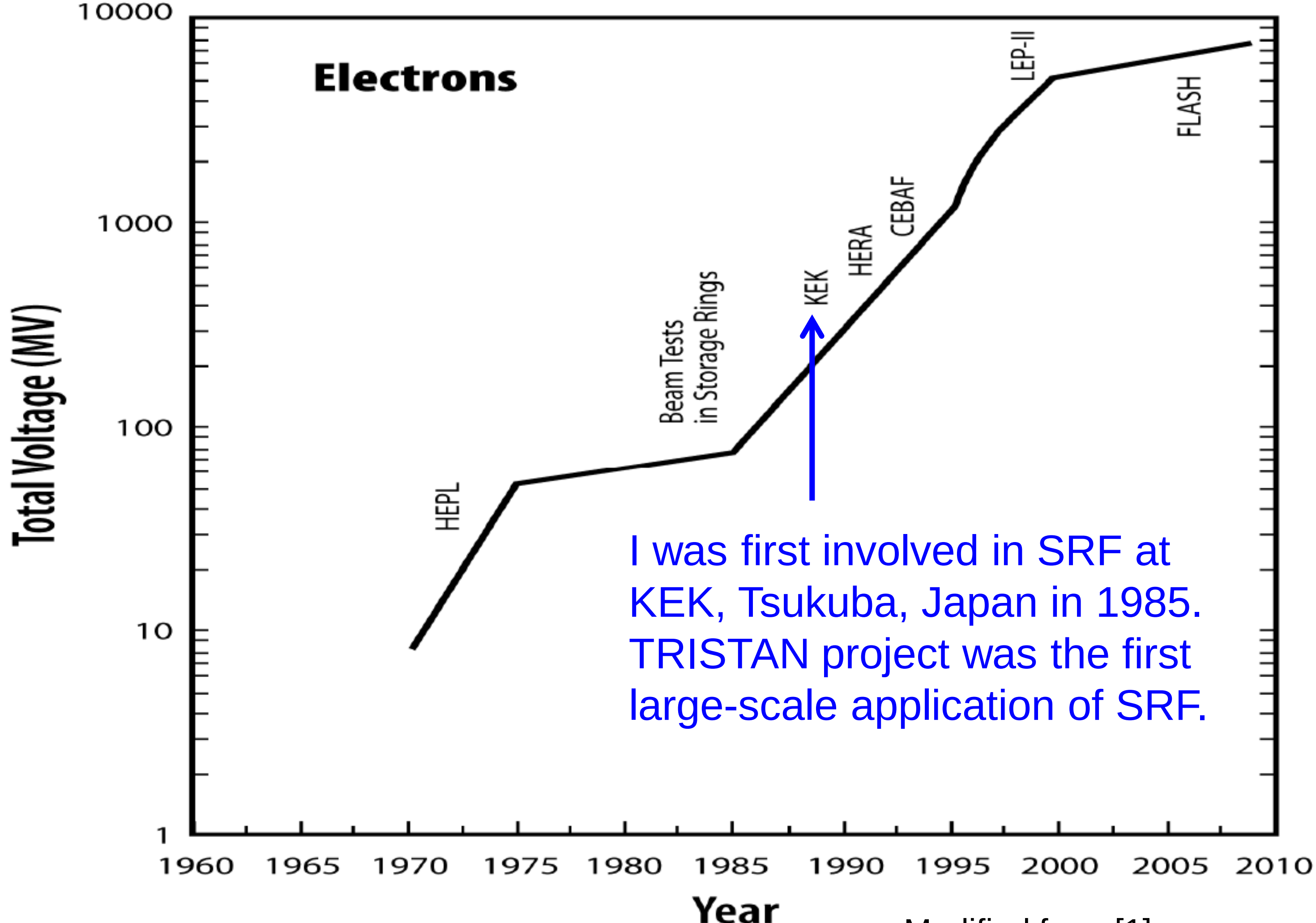
DESY, Germany



Jefferson Lab, USA

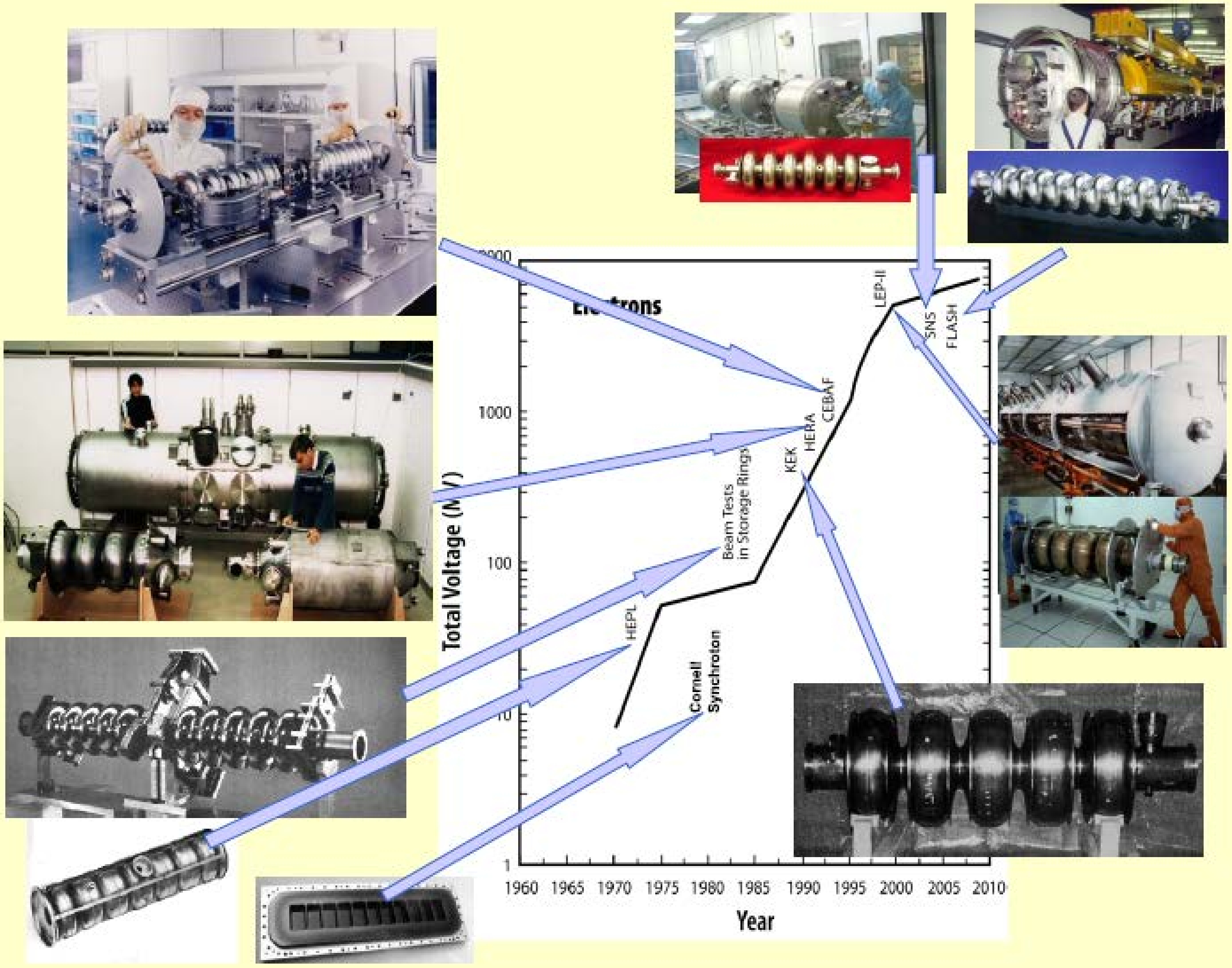
338
1.5 GHz
5-cell

50 Yr-Growth of Installed Voltage for *v/c = 1* Accelerators

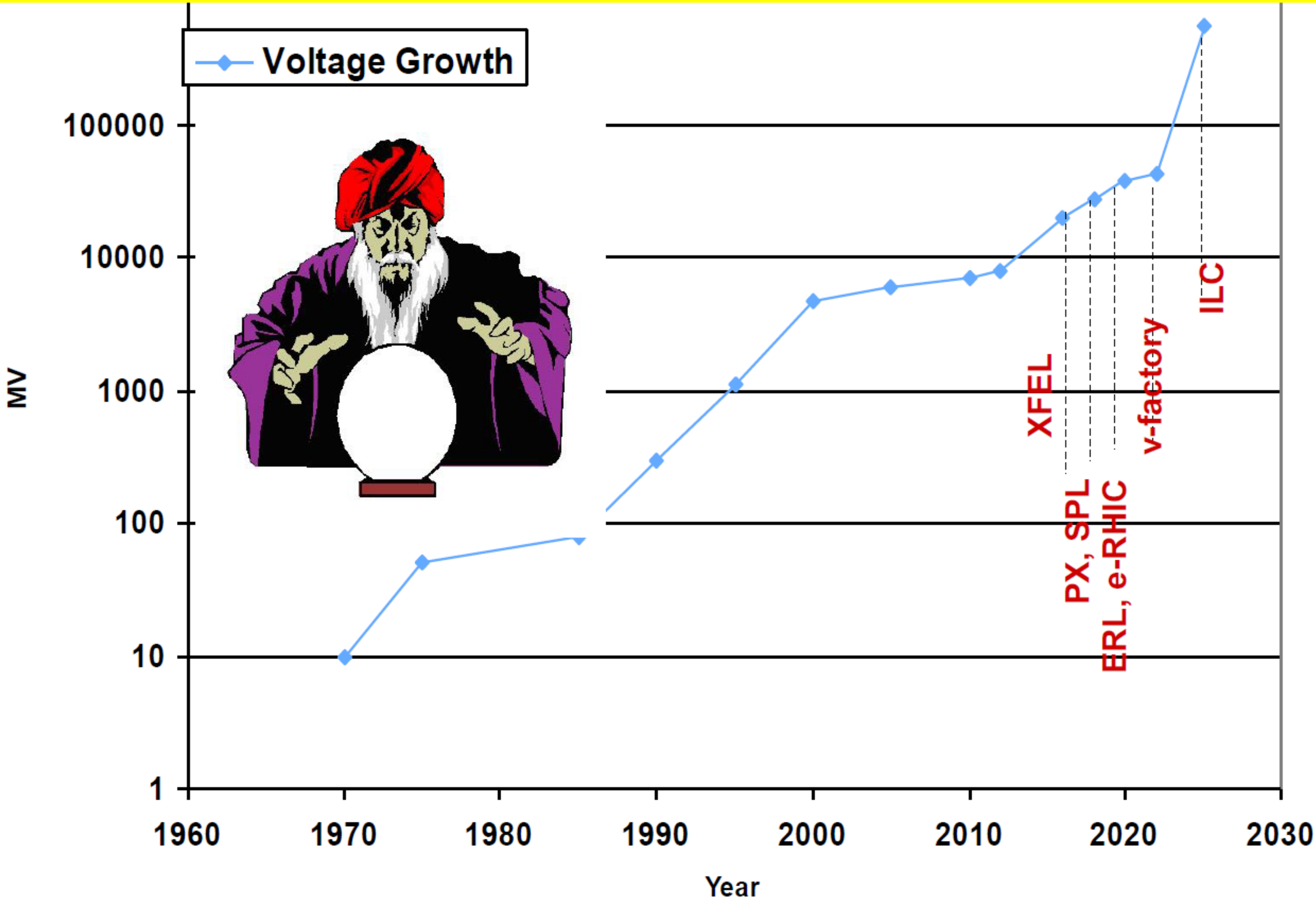


Modified from [1]

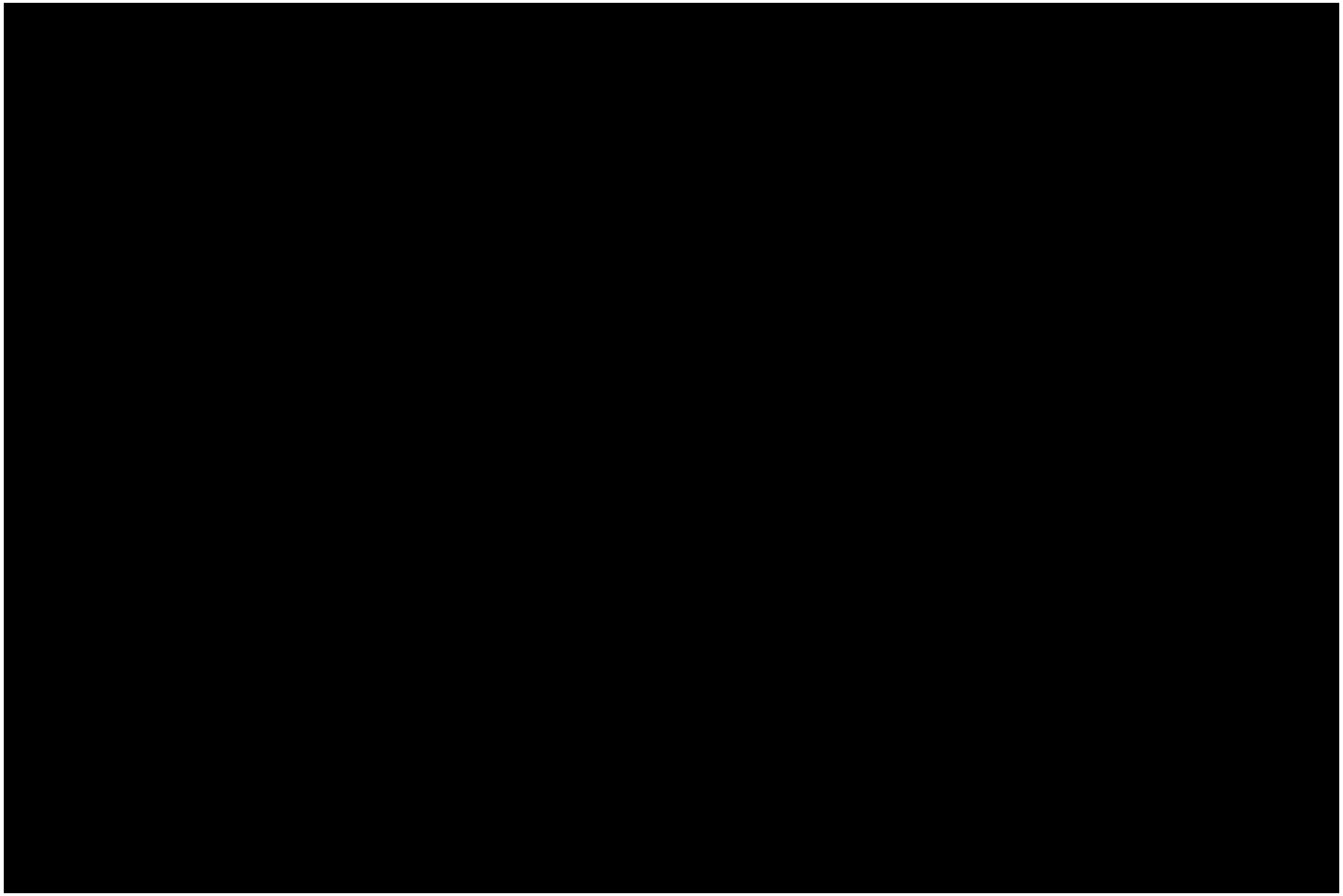
Total Installation > 1000 m, > 7 GV Until 2010 [2]



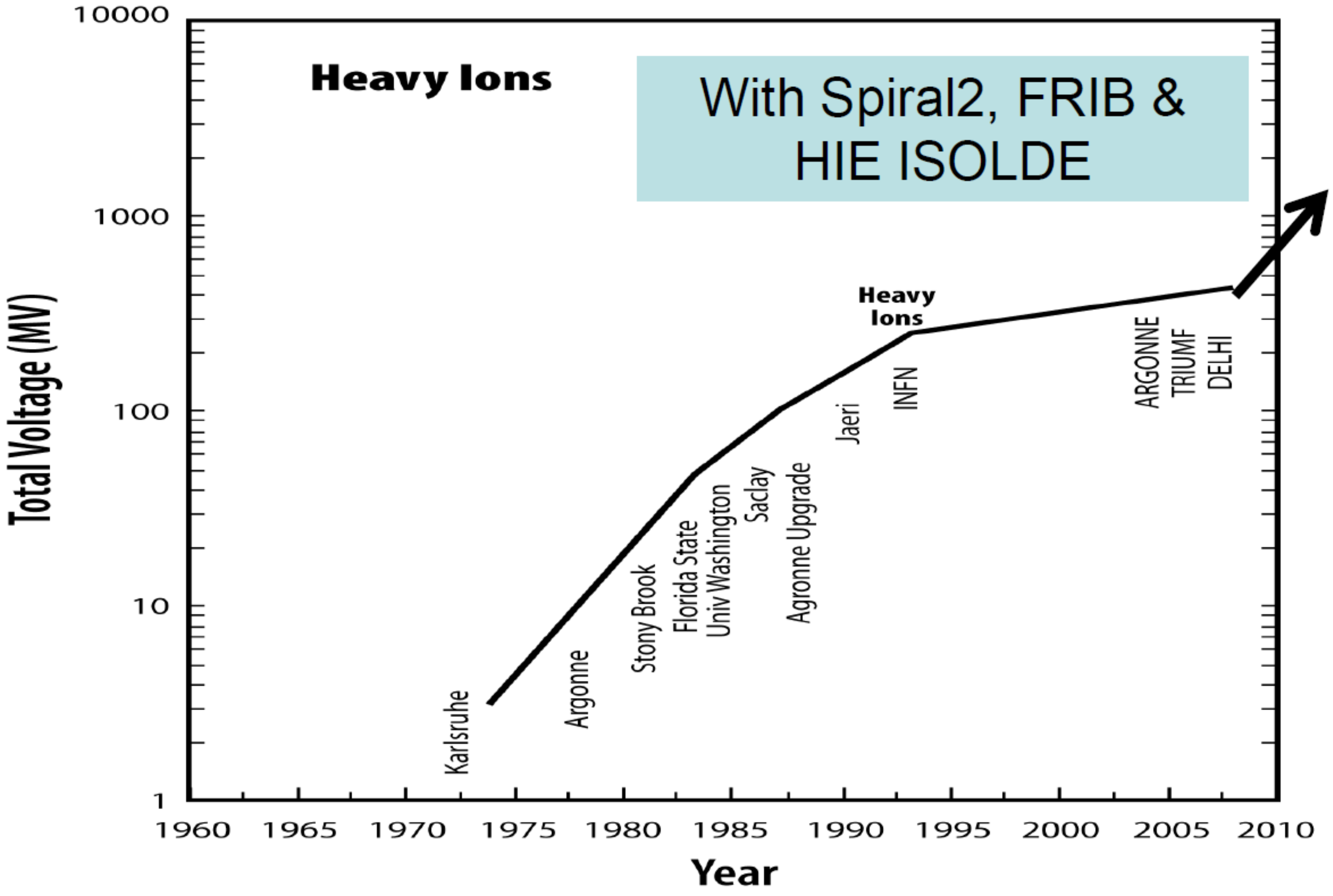
Far Future: Keep Dreaming Big [1]



The International Linear Collider (ILC) will use ~16,000 SRF cavities with ~2,000 cryomodules to get 500 GeV e^+/e^- colliding energy [animation at www.linearcollider.org]

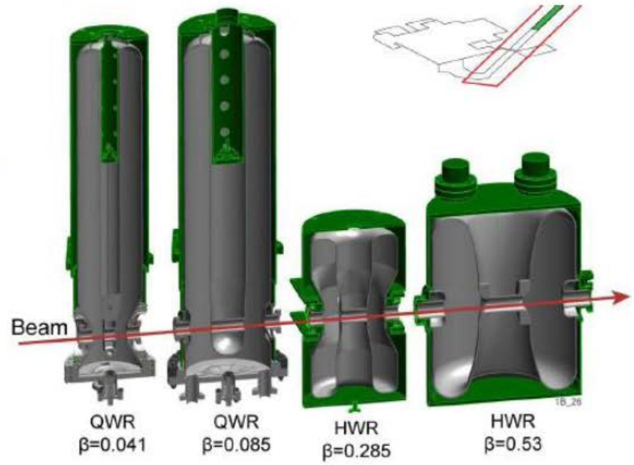


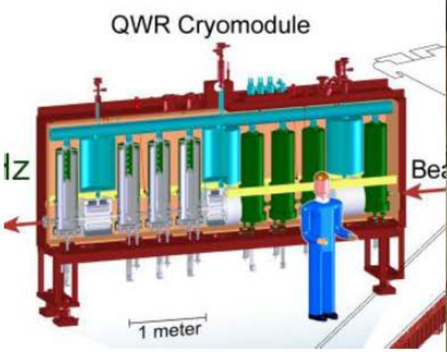
Total installed voltage with heavy ion SRF accelerators [1]

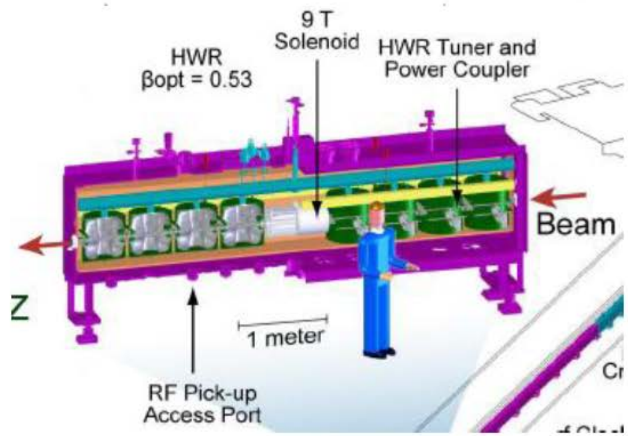


Facility for Rare Isotope Beams (FRIB) at MSU under construction [1] (slower particles need different structures than elliptical cavities)

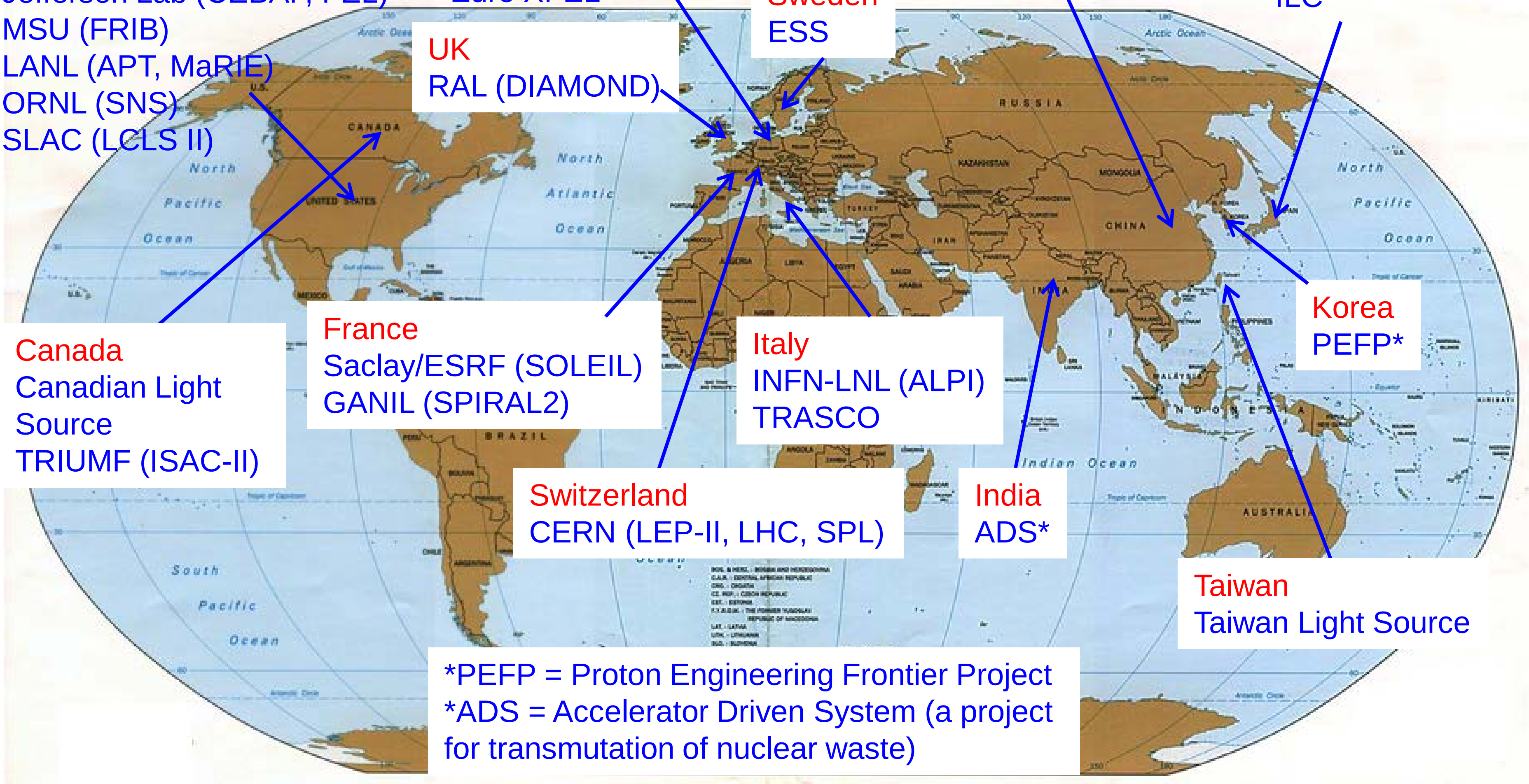
- FRIB will allow major advances in nuclear science and nuclear astro-physics
- 336 Resonators QWR and HWR







SRF-based Accelerators in the World (past, present & future machines/projects)



USA
ANL (ATLAS)
BNL (eRHIC)
Cornell (CESR, ERL)
FNAL (Project X, PIP)
Jefferson Lab (CEBAF, FEL)
MSU (FRIB)
LANL (APT, MaRIE)
ORNL (SNS)
SLAC (LCLS II)

Germany
DESY (HERA, FLASH)
Darmstadt (S-DALINAC)
Rossendorf (ELBE)
Euro XFEL

China
IHEP (BEPC, CSNS, ADS)
Shanghai Light Source
IMP (ADS)

Japan
KEK (TRISTAN,
KEKB, c-ERL)
JAEA (FEL)
ILC

Sweden
ESS

UK
RAL (DIAMOND)

Korea
PEFP*

Canada
Canadian Light
Source
TRIUMF (ISAC-II)

France
Saclay/ESRF (SOLEIL)
GANIL (SPIRAL2)

Italy
INFN-LNL (ALPI)
TRASCO

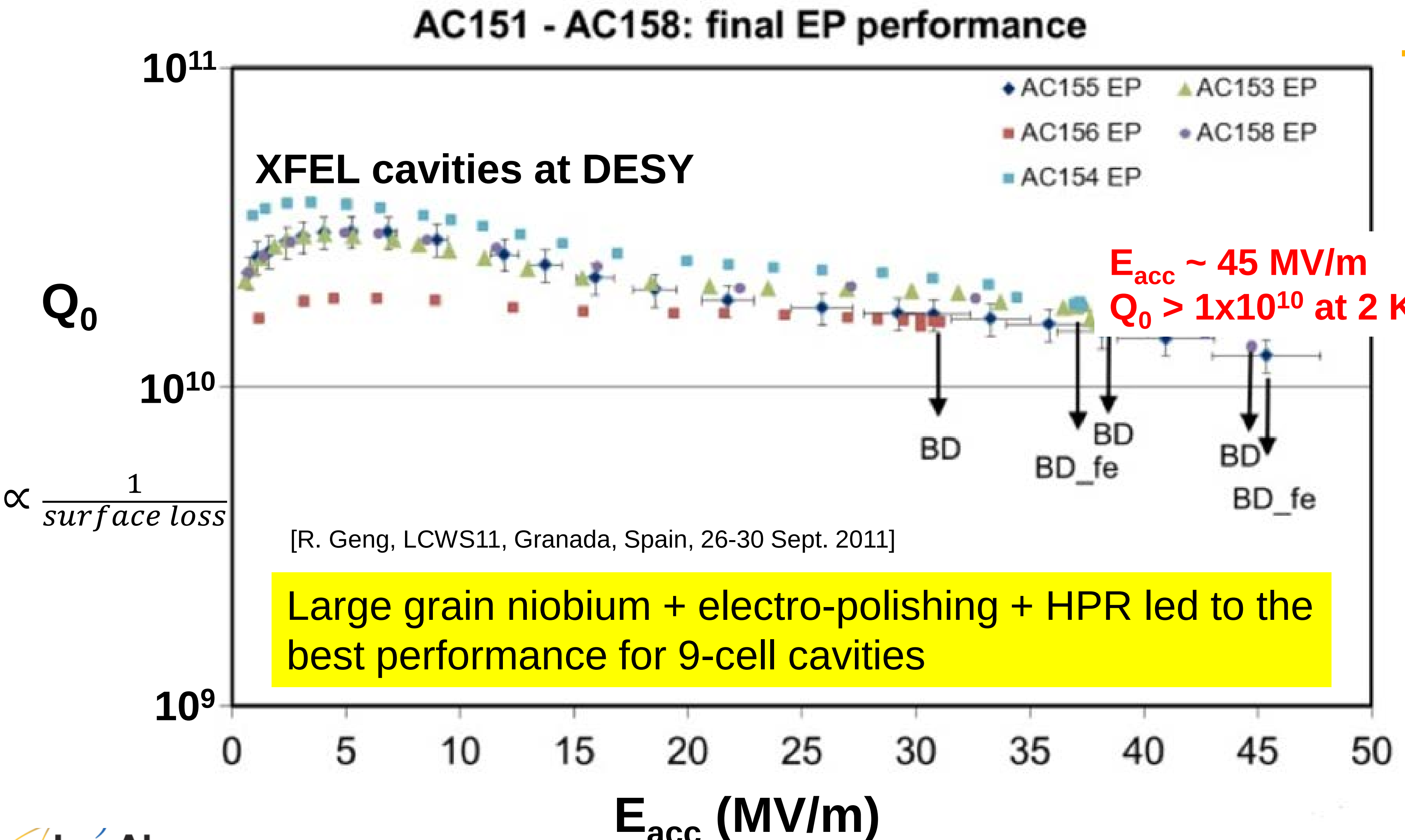
Switzerland
CERN (LEP-II, LHC, SPL)

India
ADS*

Taiwan
Taiwan Light Source

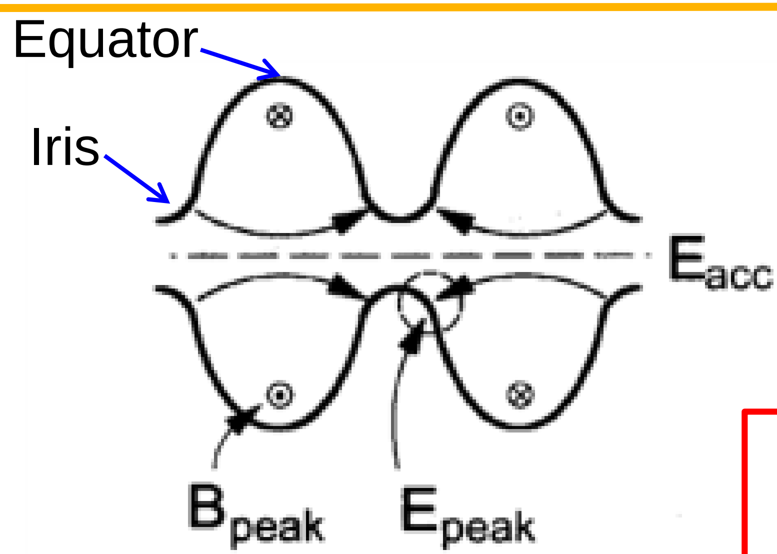
*PEFP = Proton Engineering Frontier Project
*ADS = Accelerator Driven System (a project for transmutation of nuclear waste)

Cavity performance is described as a plot of quality factor (Q_0) as a function of accelerating gradient (E_{acc})



Large grain niobium + electro-polishing + HPR led to the best performance for 9-cell cavities

Theoretical limitation of Nb cavity performance: Fundamental limit is peak surface magnetic field B_{peak}



$$E_{peak} \simeq 2 \cdot E_{acc}$$

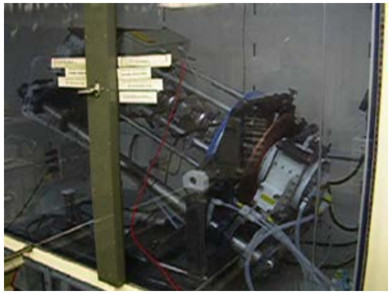
$$\frac{B_{peak}}{E_{acc}} \simeq \frac{4\ \text{mT}}{\text{MV/m}}$$

$$\text{Nb:} \quad B_c \simeq 200\ \text{mT}$$

$$\Rightarrow \quad \max E_{acc} \simeq 50\ \text{MV/m}$$

- **Bulk Nb has been the most popular material so far.**
- **Nb is a Type II superconductor with B_{c1} ~ 170 mT, B_c ~ 200 mT and B_{c2} ~ 240 mT for high RRR Nb.**
- **Surface electric field sometimes becomes a practical problem causing field emission, but it can be controlled by surface treatment.**

Electropolishing of a 1.5 GHz 9-cell cavity at Jefferson Lab in Virginia (video clips taken on 16 August 2006)

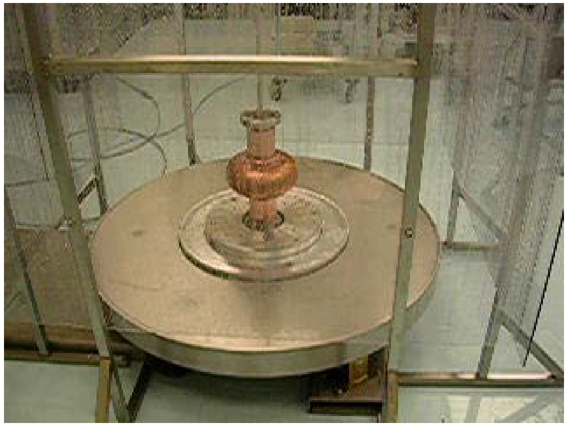


Electropolishing of a 1.3 GHz 9-cell cavity at Cornell University in Ithaca, NY (a video clip taken on 11 April 2007)

Vertical EP. Not so popular, but cheap.

High-pressure ultra-pure water rinsing of a 1.3 GHz 9-cell Nb cavity and a single-cell Nb/Cu cavity at LANL (video clips taken on 02 October 2008 and 26 July 2012)

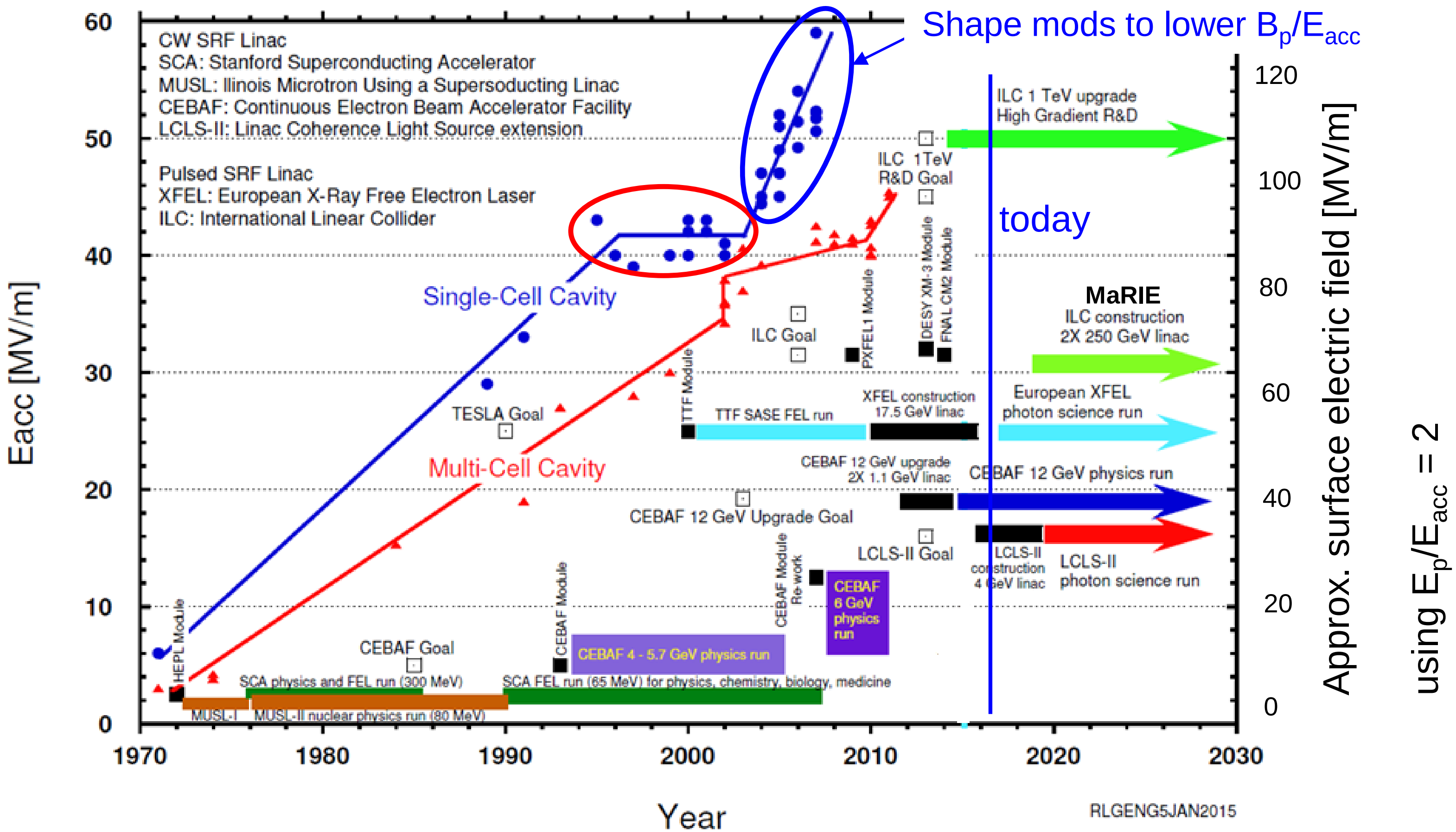
02 October 2008



26 July 2012

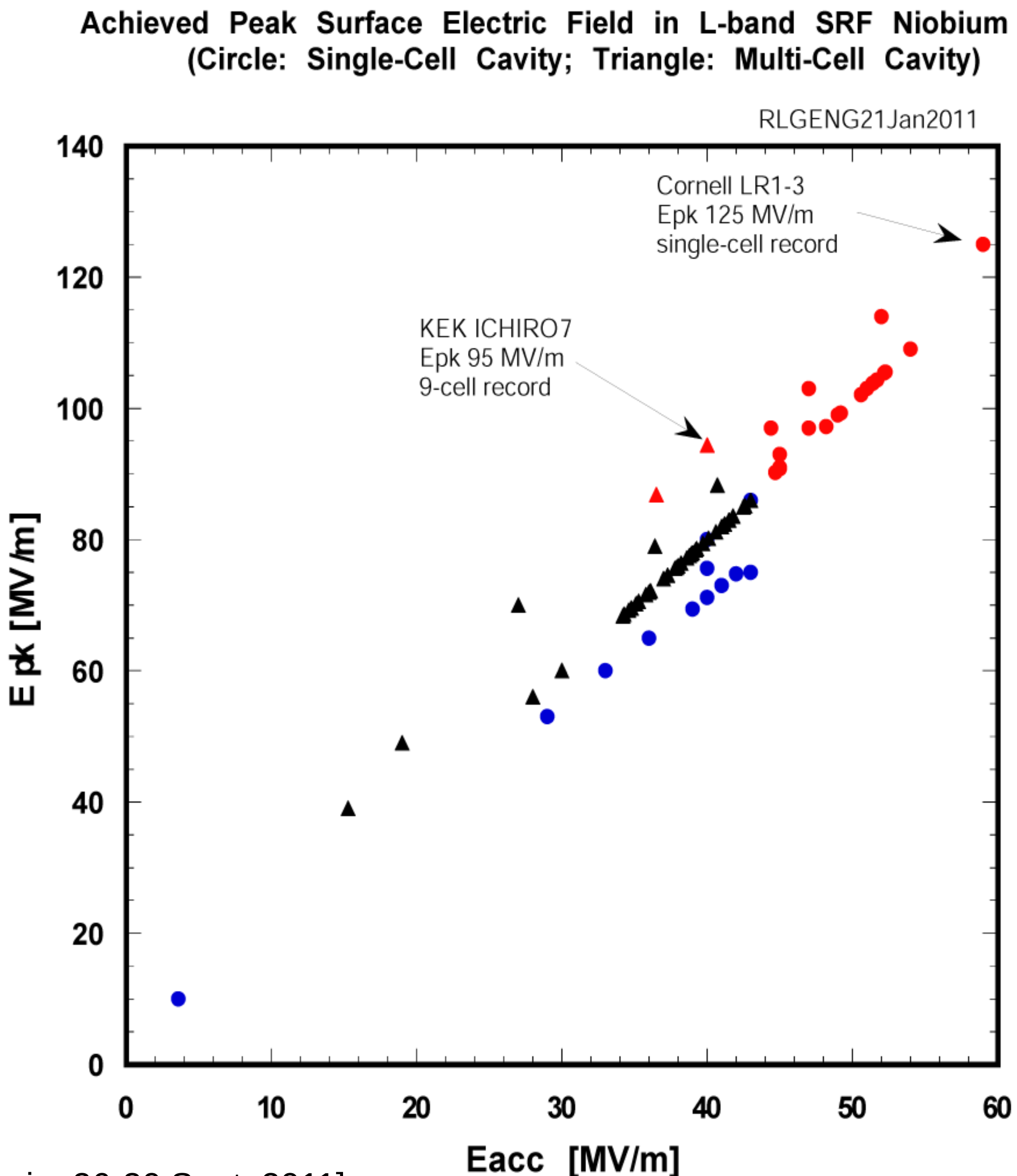
We believe that the achievement of 40-44 MV/m since ~1995 is partly due to the elimination of field emission with HPR (red oval)

L-band SRF Linear Accelerator Technology and Impact to Nuclear, Elementary Particle, and Photon Sciences



[R.L. Geng et al., IPAC2015, p. 3518]

Peak surface electric field (E_{pk}) up to 125 MV/m (1250 kV/cm) has been achieved on a 1-cell cavity



[R. Geng, LCWS11, Granada, Spain, 26-30 Sept. 2011]

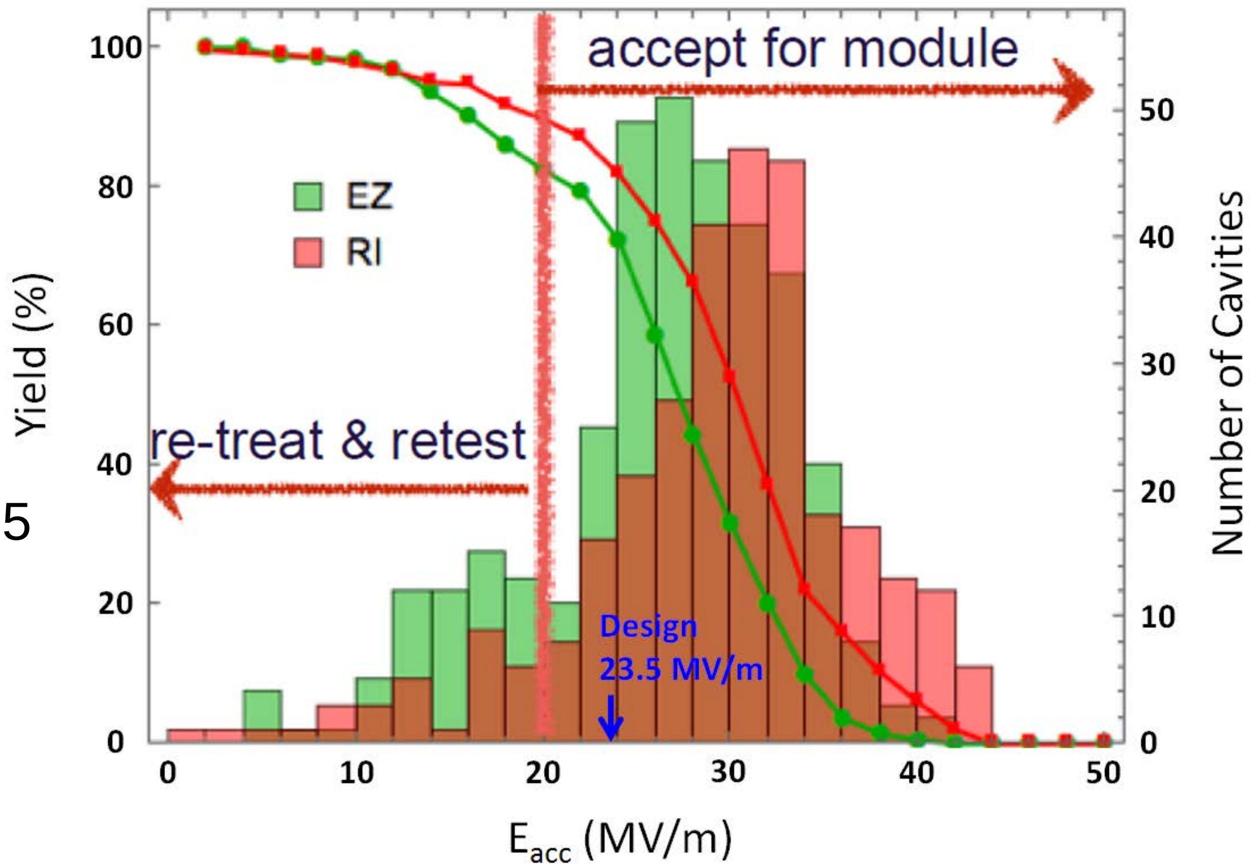
State of the art cavity production in industry [8] : SRF cavities for European X-ray FEL project under construction

Two best qualified companies

EZ (an Italian company)

RI (a German company)

Data until September 2015



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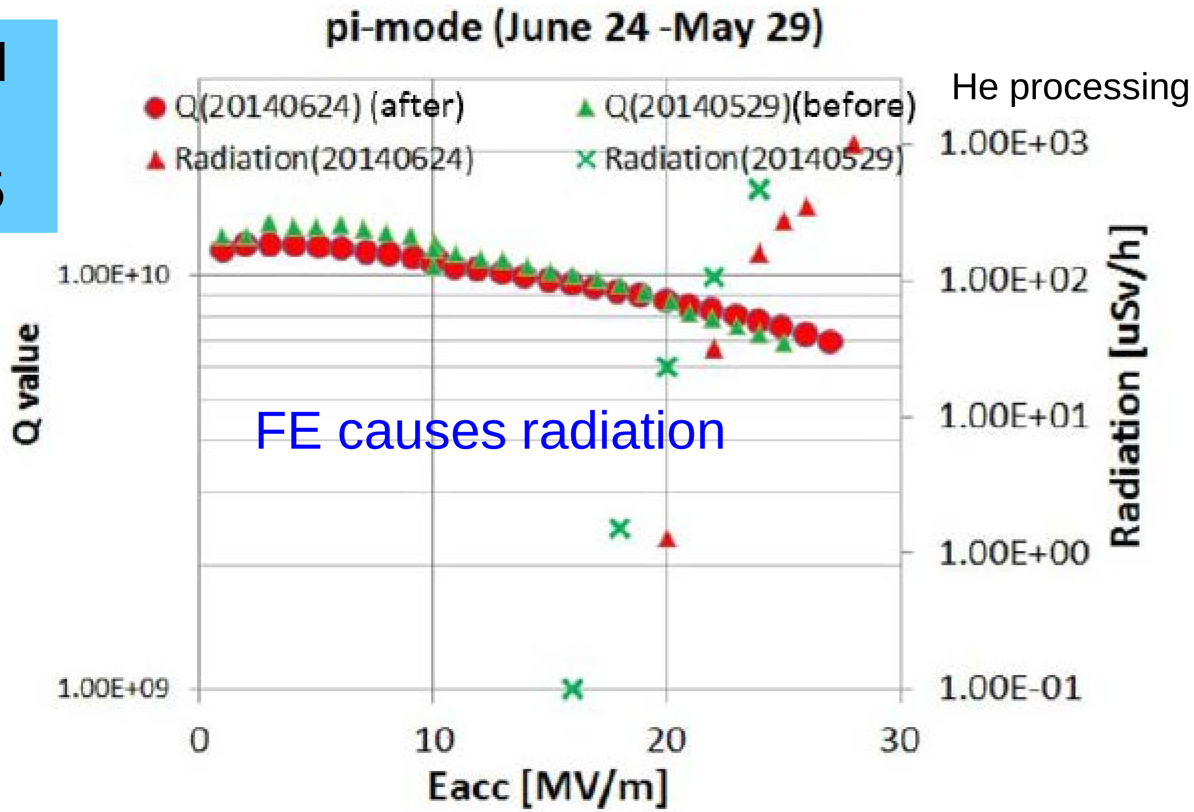
Field emission control was (and still is) a very important practical issue for SRF cavity development [7]

- A lot of research was done in the 1990s and until ~2010
- HPR has been a routine final cleaning process of SRF cavities

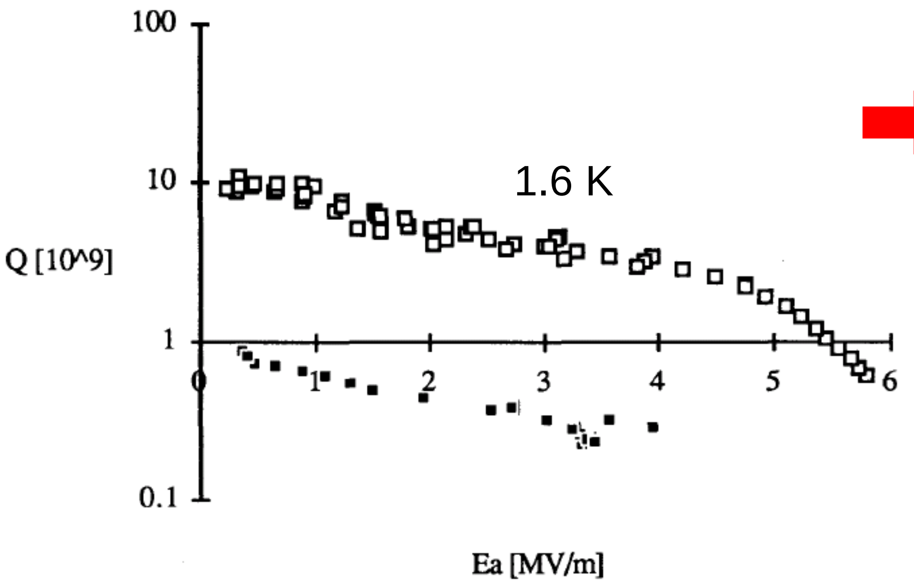
1.3 GHz 9-cell cavity at KEK, Japan in 2015



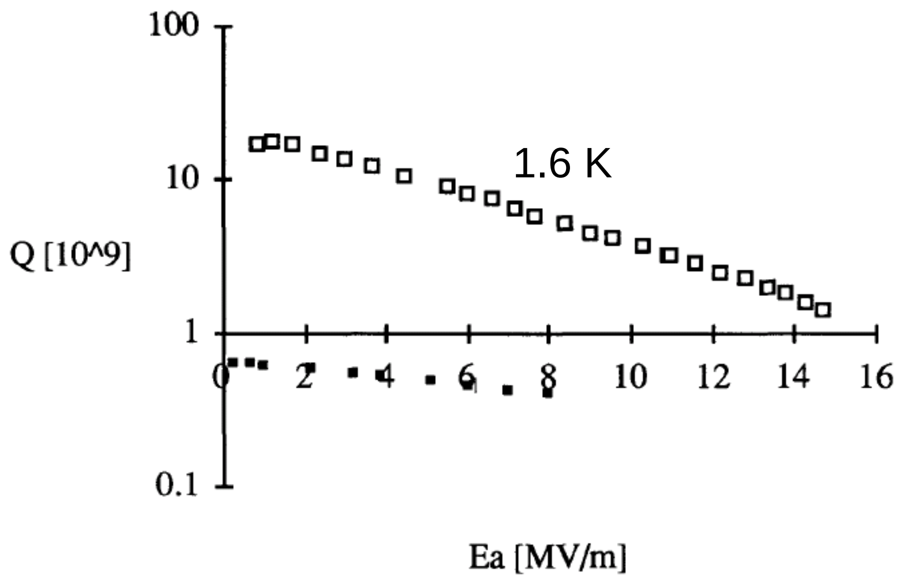
A result from CERN surprised us in 1991 that showed a significant improvement in E_{acc} after HPR [6]

E_{acc} improved by a factor of >2 to E_{acc} >14 MV/m

(in 1990s, the design E_{acc} was only 5-7 MV/m)



After HPR

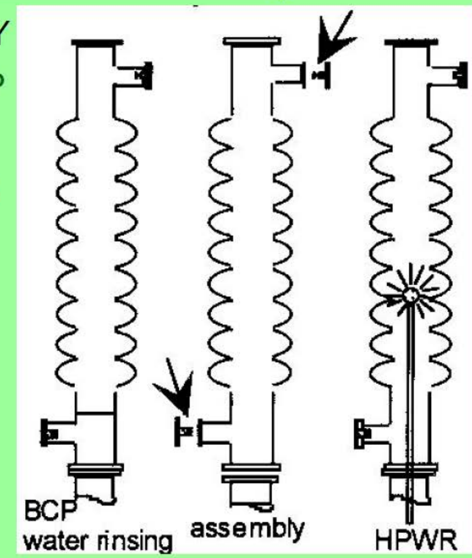


1.5 GHz 1-cell cavity

The most advanced studies on FE for SRF cavities have been done at University of Wuppertal in Germany

Preparation techniques for Nb samples

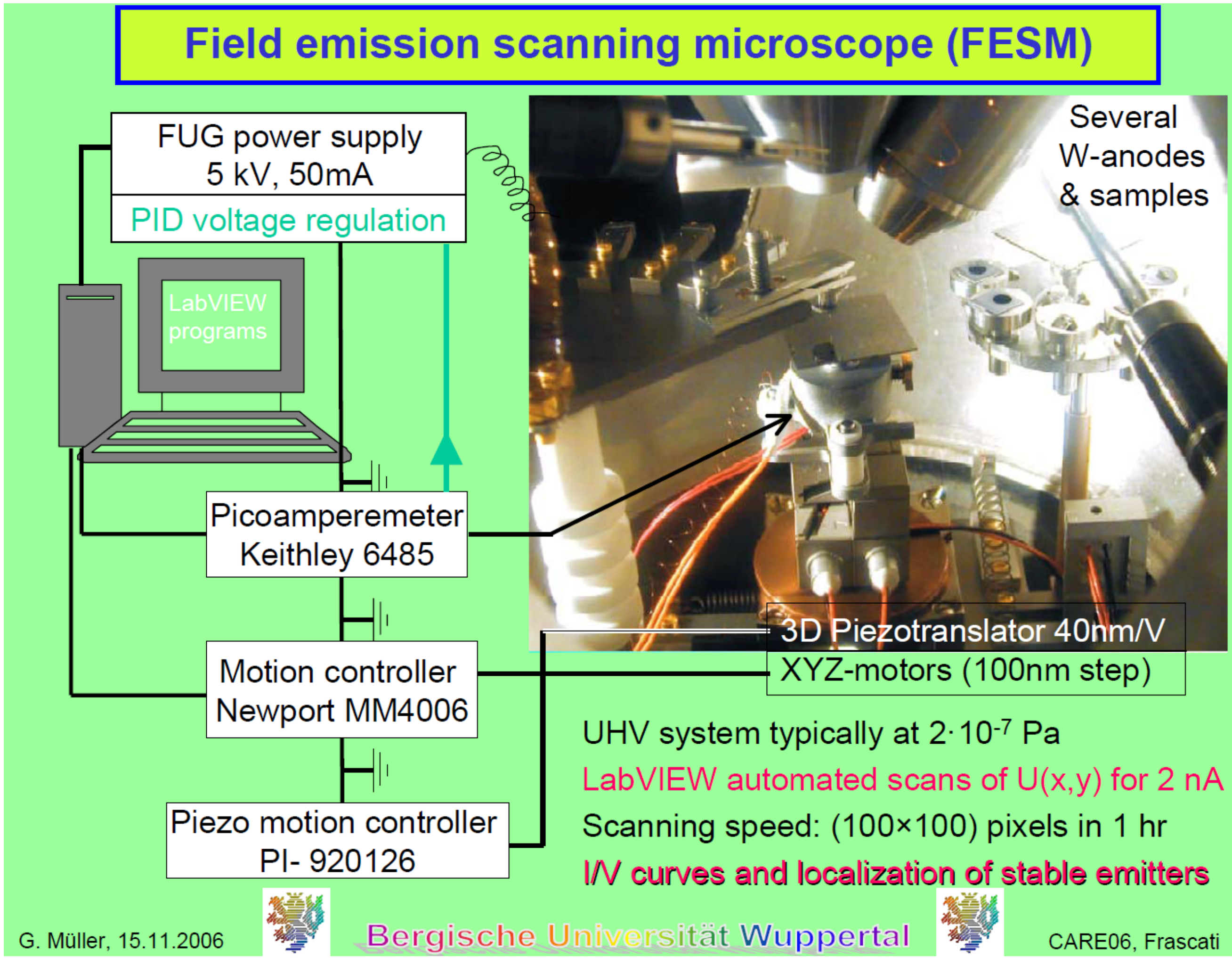
Nb samples prepared like cavities at DESY
Buffered chem. BCP or electropolished EP
and **high pressure rinsed HPR** with water
mostly in single cells, few in 9-cell cavities



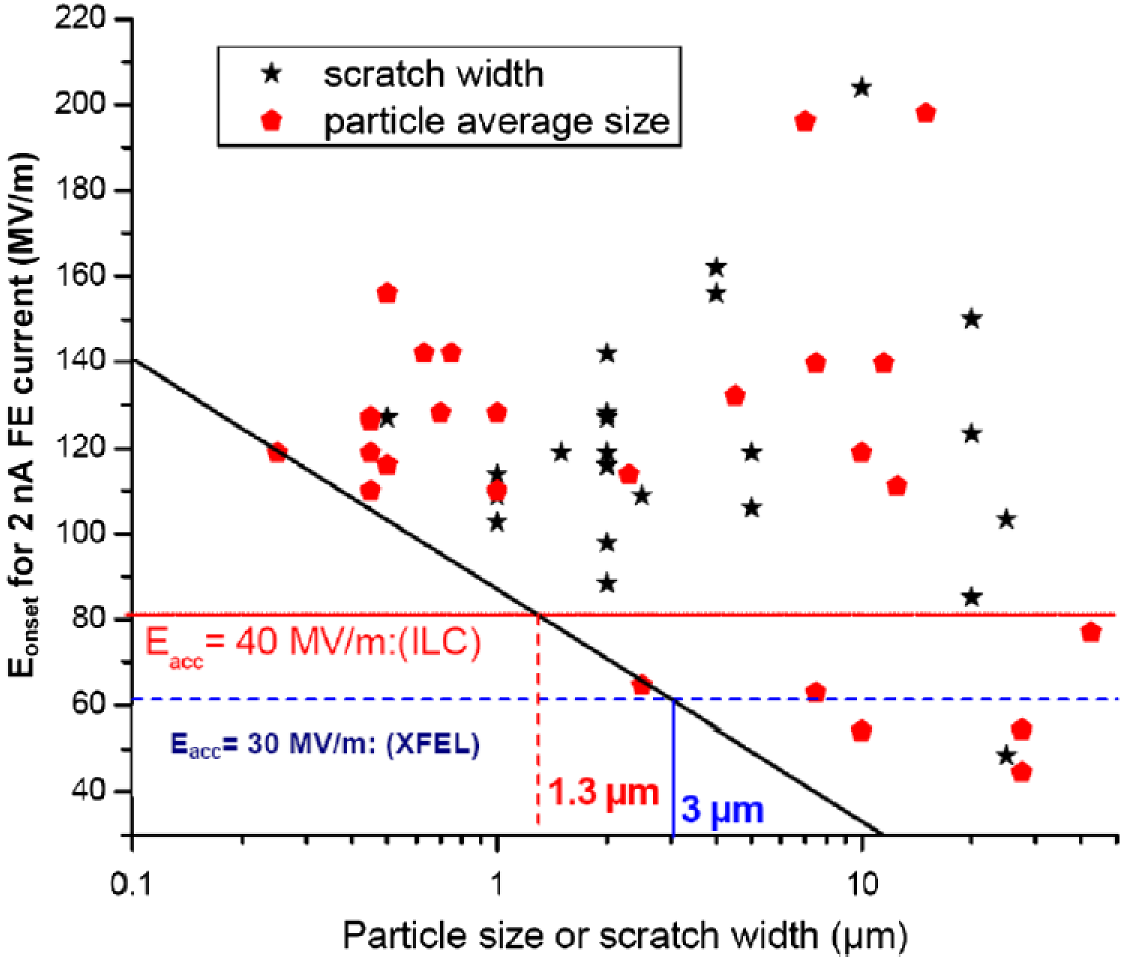
Ultra pure water	ρ > 18MΩcm
Water flow	7 - 20 l/min
Water pressure	80-150 bar
Rotation speed	4-5 rpm

G. Müller, 15.11.2006 Bergische Universität Wuppertal CARE06, Frascati

Emission characteristics were studied with field emission scanning microscope (FESM)



DC field emission study on Nb has shown up to >200 MV/m (2000 kV/cm) on particle/defect-free surfaces [4]



Peter Kneisel of JLAB stated in 1995 that HPR led to a high reproducibility of high-performance cavities [5]

5. SUMMARY OF EXPERIENCE WITH HIGH PRESSURE ULTRAPURE WATER RINSING

From the experience gained during the last three years involving more than 200 separate tests on niobium and Nb_3Sn cavities, the follwing conclusions can be drawn:

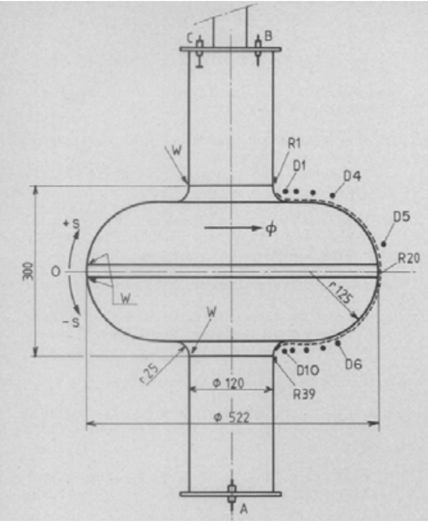
a. High pressure ultrapure water rinsing (HPR) as a final cleaning step after chemical surface treatment resulted in consistant performance of single and multi-cell superconducting cavities.
b. After successive steps of chemical material removal the reproducibility of cavity performance is quite remarkable with only a small spread in data.
c. Application of the same surface treatment procedure to different cavities with subsequent HPR resulted in reliable cavity performance. An estimated > 80% of the cavity tests showed satisfactory performance and no or only insignificant field emission loading for peak surface electric fields $E_{peak} \leq 45$ MV/m.
d. Rinsing of the cavities with reagent grade methanol after HPR and subsequent assembly in a class 100 clean room does not seem to re-contaminate the cavity surfaces.
e. Usually there is no or only very short (≈ min) rf–processing required to achieve the highest fields in a given cavity, indicating a rather "clean" surface.
f. The application of high pressure rinsing resulted not only in reduced field emission loading, but also low residual surface resistances were achieved consistantly.

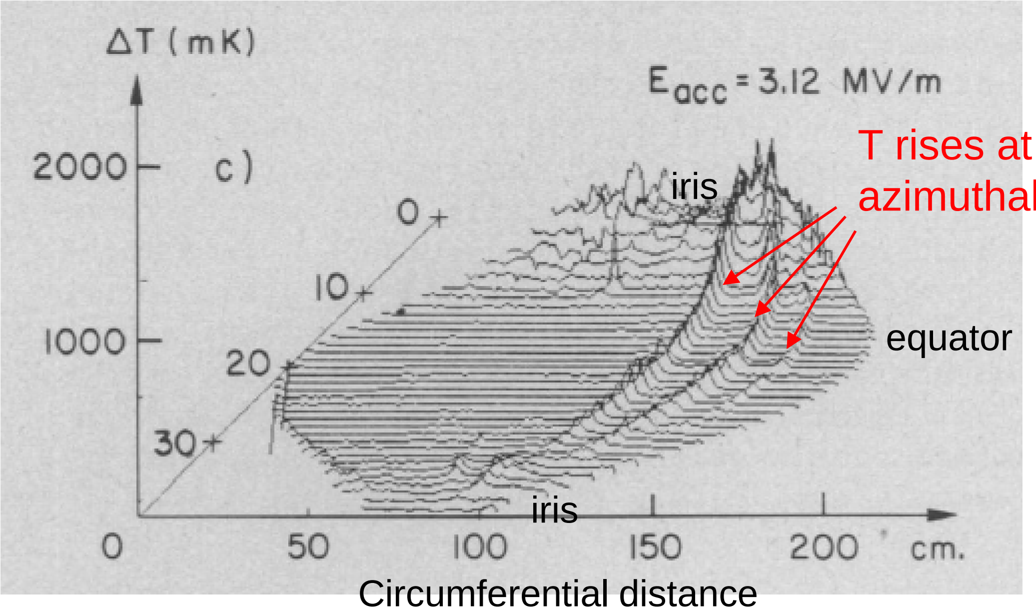
Causes of field emission

- **Particles**
  - Found to be a major cause of FE
  - Removal of particles improved the cavity performance significantly
- **Surface irregularities**
  - These increase the field enhancement factor, which was confirmed by the study at Wuppertal
- **Adsorbates on the surface**
  - These such as hydrocarbons reduce the work function of the metal, thereby reducing the breakdown field (Fowler-Nordheim theory)
  - Removing hydrocarbons from the surface with plasma processing has been successful in improving the performance of degraded SRF cavities with FE in the recent years at the Spallation Neutron Source (SNS) accelerator at ORNL.

Detection of field emission inside the SRF cavity

- **Difficult to insert a probe in the cavity since it disrupts the E-M field**
- **Mostly indirect measurement**
  - Detect the temperature rise of the outside surface caused by the bombardment of emitted electrons, e.g. [9] shown below
  - Detect Bremsstrahlung x-rays from the metal surface hit with emitted and accelerated electrons using arrays of x-ray detectors (photo diodes)





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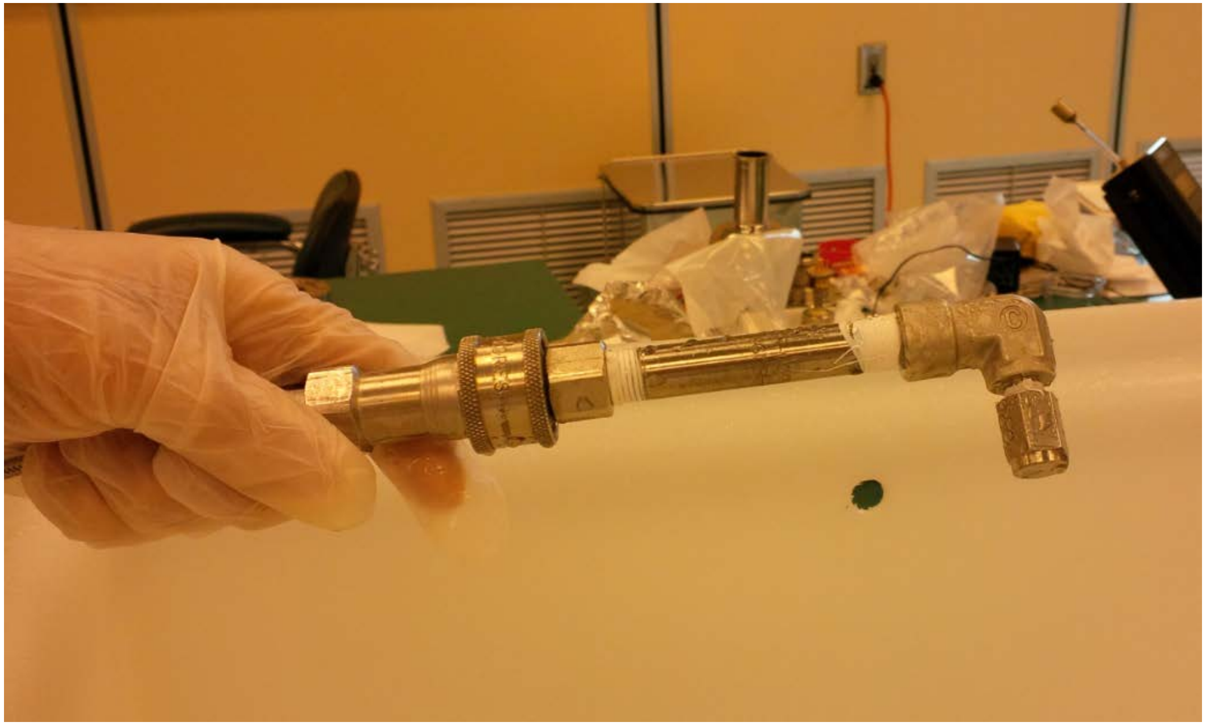
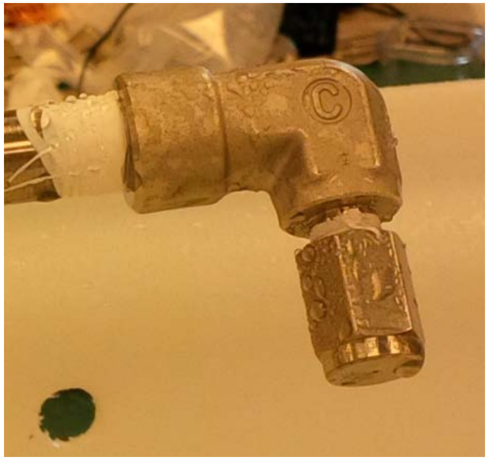
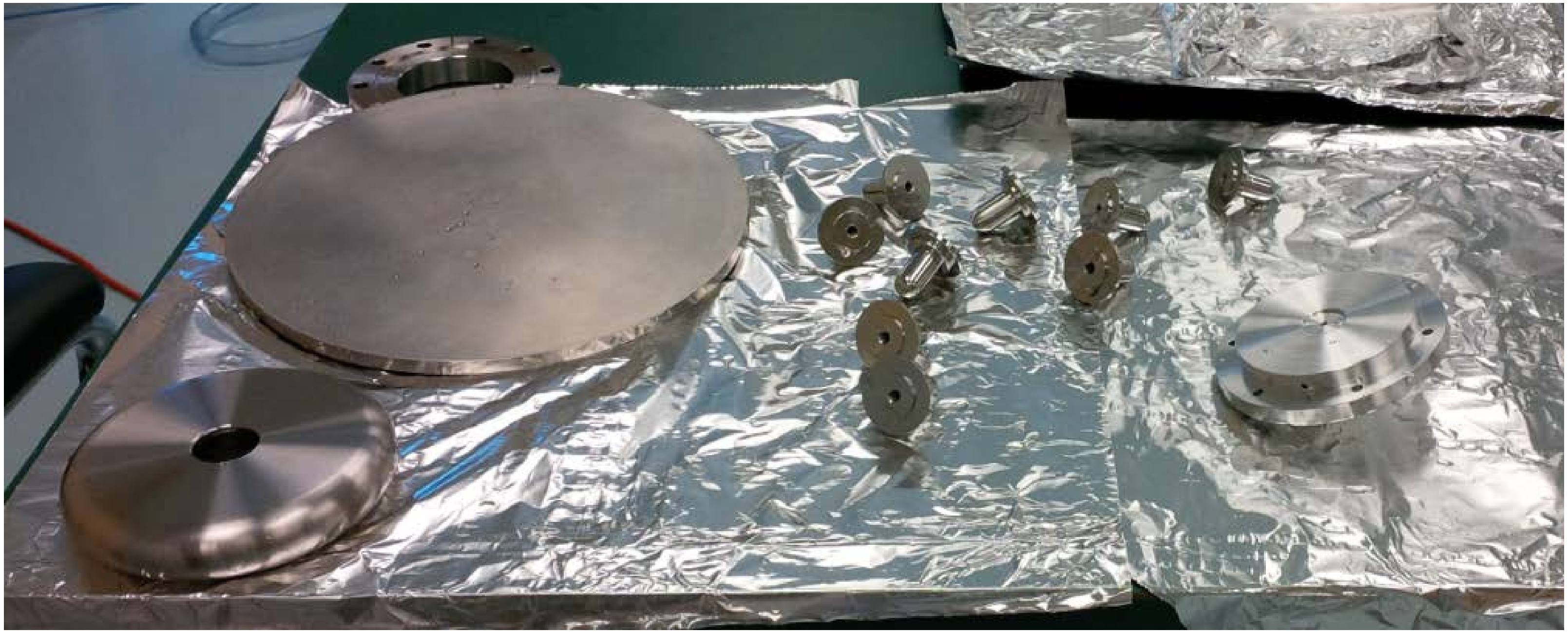
Frist day of Chris Leach and Tom Ellis of AFRL inside the LANL class-100 clean room on 01 July 2015

The spray nozzle used to clean the parts
The water pressure was 500-700 psi at the pump





Parts cleaned on 01 July 2015



Procedure

- Ensure the cleanliness of the work area using a portable particle counter (0 particle of >0.3 micron size)
- If there is any oily contamination on the sample, wipe it off with Ethanol and pre-clean it before HPR
- Start HPR system and set the pressure to 500-700 psi. (The ultra-pure water system is outside the clean room and running all the time at >17 MΩ·cm. Several use points in the clean room.)
- Clean parts with high pressure water (2-5 min per part)
- Leave the parts on a clean bench overnight to dry
- Ensure no particles on the samples and bags to be used with a portable particle counter and double bag the parts to transport to outside the clean room

Chris Leach has presented encouraging results from ongoing HV breakdown tests. Here are things that I suggest to do for the improvement of HPM devices

- **Continue tests on the effect of HPR and clean assembly using samples with different materials (Cu, Al) and parameters**
- **Design and build a simple HPR system, maybe starting with pure water (5-10 MΩ·cm) with <0.2 um filter to reduce the cost. (a liquid particle counter is a good investment to quantify the quality of the water)**
- **Clean samples with the new system and test them**
- **If good results are obtained, design nozzle(s) that can clean target HPM device(s) effectively**
- **Test the HPM devices cleaned with HPR and assembled in a clean environment**

References

[1] Hasan Padamsee, "50 Years of RF Superconductivity – A Perspective," Talk at CERN, 2011, http://indico.cern.ch/getFile.py/access?contribId=8&resId=1&materialId=slides&confId=161849

[2] Hasan Padamsee, "RF Superconductivity 2010: Science, Technology and Applications," http://lepp.cornell.edu/Research/AP/SRF/rsrc/LEPP/Research/AP/SRF/AboutSrf/RF_Superconductivity_2010.pdf

[3] Hasan Padamsee, "RF Superconductivity Companion 2010," http://lepp.cornell.edu/Research/AP/SRF/rsrc/LEPP/Research/AP/SRF/AboutSrf/RF_Superconductivity_Companion.pdf

[4] A. Dangwal et al., Phys. Rev. ST-AB 12 (2009) 023501

[5] P. Kneisel and B. Lewis, Proc. SRF1995, p. 322

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[6] Ph. Bernard et al., Proc. SRF1991, p. 487.

[7] H. Sakai et al., Proc. SRF2015, p. 1019.

[8] D. Reschke, Proc. SRF2015, p. 14.

[9] H. Lengeler, IEEE Trans. Nucl. Sci. 28 (1981) 3217