SRF technology challenge and development

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Outlook

- SRF technology status
- What can we count on?
- What's new since the last couple of years
- Future perspectives

Virtues and challenges of srf

- Virtues:
  - Low overall rf losses:
    - energy saving, Reduced rf system cost, efficient operation at high field and in cw
  - Large aperture:
    - lower beam losses, lower wakefields, lower tolerances
  - The only possible choice in some cases, e.g. Energy Recovery Linacs
- Challenges:
  - High gradient and high Q
    - Surface quality, material quality, rf geometry, assembly procedures...
  - <u>Operation</u> at high gradient and high Q
    - Rf power coupling, Phase and amplitude lock, cooling,...
  - Cavities reliability
    - Performance scattering, performance degradation, ancillaries failures,...
  - Keeping cavity cost competitive
    - Mechanical and rf design, construction and treatment techniques...

Overview of <u>main</u> SRF cavity types in operation (or ready for)

- Elliptical cavities (~0.6≤β≤1)
- Quarter-Wave Resonators (QWR) (~0.02≤β≤0.16)
  - 2gap, 4 gap
- Half-Wave Resonators (HWR) (~0.09≤β≤0.5)
  - Coaxial, Spoke
- CH Resonators
  - Multigap CH , Multi gap Spoke
- Split ring (low-β, now being replaced by QWRs)
- SCRFQ
- CRAB/deflecting cavities
- (SRF guns: special cavities, not treated here)


Multi-cell elliptical

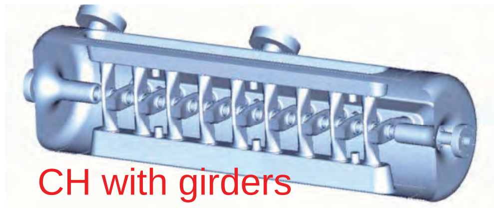

Single-cell elliptical


QWR

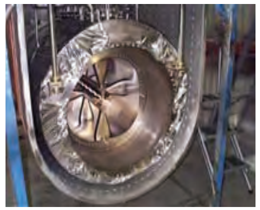
HWR coaxial


HWR spoke

CH multi-spoke


CH with girders


Split ring


SCRFQ


CRAB

An “ideal” SC resonator...

- Works at high gradient, up to the fundamental limits of physics
- Has a high Q, as above
- Does not have multipacting
- Has a resonant frequency which is stable and determined only by the tuner position
- Only one resonant mode can be excited
- Even very high power can be coupled to it without changing its properties
- Its field distribution has a perfect axial symmetry (or planar for deflecting cavities)

Main ingredients to high Q and high E_a (well established recipes)

- High Residual Resistivity Ratio (RRR) material
  - Good thermal conductivity at low T
- Clean, pure and smooth rf surface
  - No dust and no inclusions which give NC rf losses, enhanced field emission, increased SEY enhancing multipacting and quench
  - (however some O atoms diffused near the surface within the skin depth seem to be beneficial to reduce Q slope)
  - Smooth surface to avoid surface field enhancement, overheating and quench
- No Hydrogen in the bulk
  - No Q-disease, caused by H precipitation around 100K
- Good magnetic shielding
  - To avoid trapped magnetic flux creating NC areas

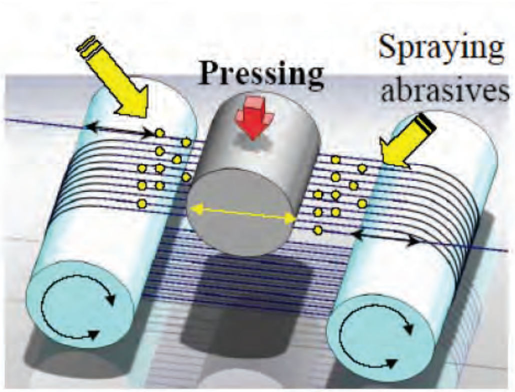
And, of course,

- Good rf geometry with low E_p/E_a, low B_p/E_a, high R_{sh}
- Good thermodynamical and mechanical design

State of the art in Nb material

- High RRR (thus high thermal conductivity) fine grain material commercially available.
- RRR=300 is a standard, RRR>300 is available.
- Sheets, rods, tubes, disks of very pure material
- Post-purification can be done in HV furnace with Ti
- Large grain (LG) material is available too:
  - sheets and rods from crystals of tens of cm size
  - Sheets are sliced, not rolled several times: potentially lower cost, pure material
  - Smoother surface: less treatments required
  - Less grain boundary extension: lower risk of foreign material in the Nb (and of magnetic flux trapping)
  - More homogeneous material: better thermal stability, better cooling
  - It is difficult to make large sheets: LG is used mostly in elliptical resonator until now
- Several vendors providing excellent material from US, Europe, Japan, China

Large grain sheet, cut from ingot



Slicing ingots to produce single grain disks (proposal) (K. Saito et al., proc. SRF2009, p. 467)

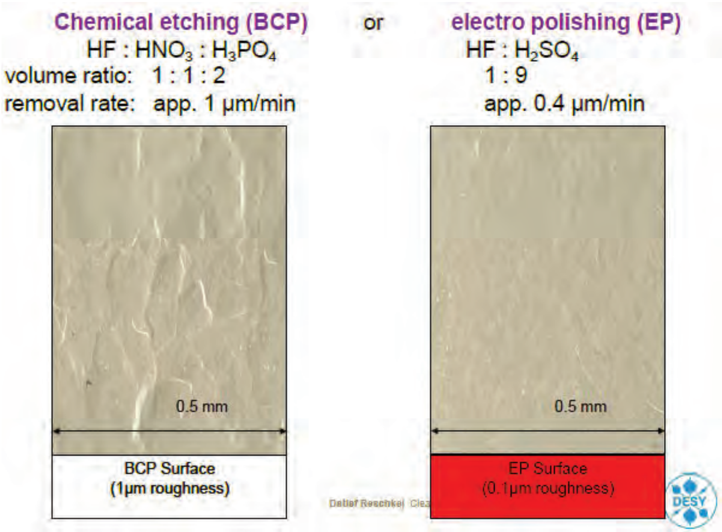
State of the art in surface preparation

"Standard" procedure main steps after mechanical construction:

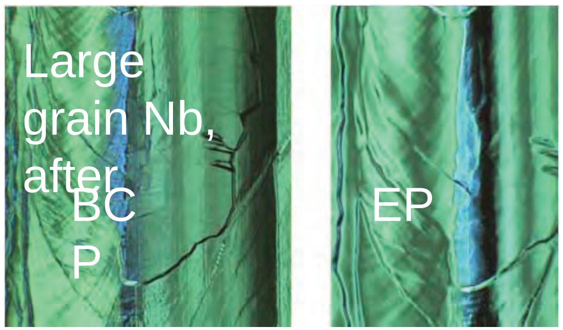
- Degreasing and ultrasound cleaning
- Removal of the "dirty" Nb layer (~150 μm) from the rf surface:
  - (Surface smoothing with grinding, tumbling, CBP...)
  - BCP (Buffered Chemical Polishing), or
  - EP (ElectroPolishing), for better surface smoothness
- Thermal treatment in high vacuum
  - 600-800 °C for H removal from Nb to cure Q-disease
- ("light" BCP or EP ~20 μm to remove contamination from furnace)
- 120 °C baking to increase Q at high field (esp. at 4.2K)
- HPR high pressure water rinsing for final particulate removal from rf surface

(several variations of the main recipe exist)

Surface smoothing: BCP vs. EP



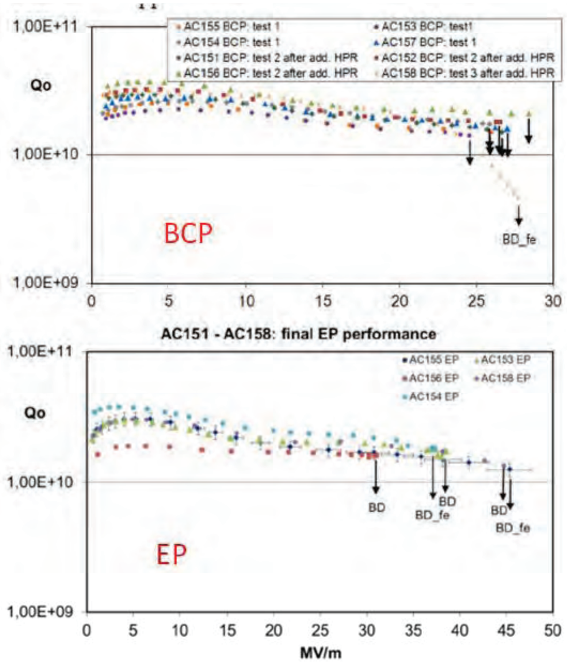
From D. Reschke, SRF11 Tutorial



From S. Aderhold, Proc. Of SRF11

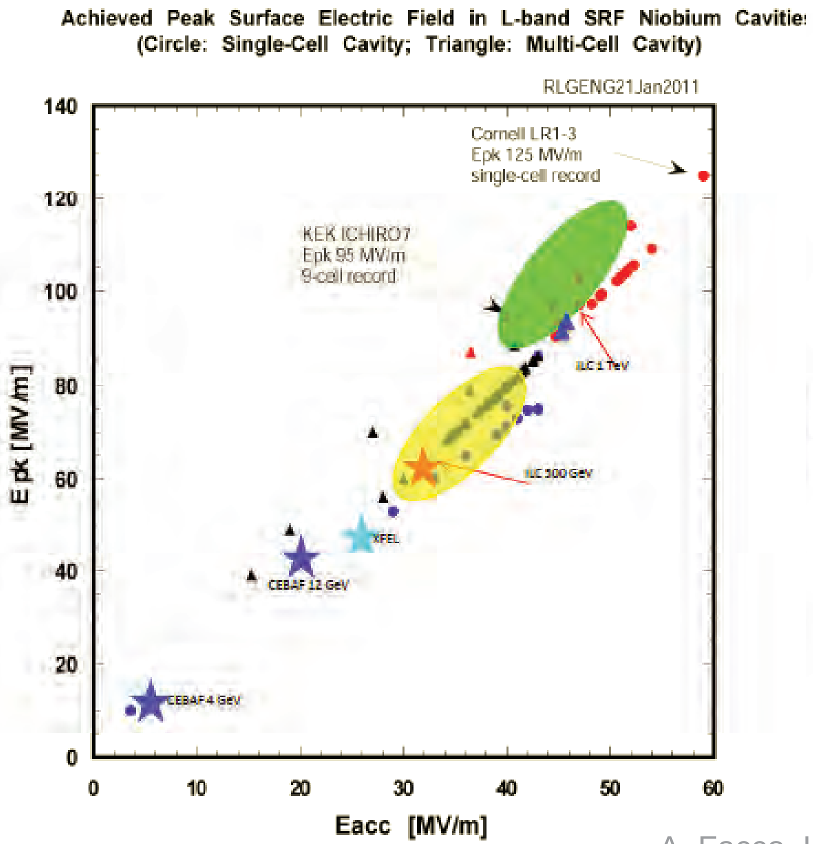
- 10 times smoother surface with EP (right) compared to BCP (left).
- This is especially clear at grain boundaries of Large Grain material
- EP tends to move quench to higher fields, at least in ILC type elliptical cavities

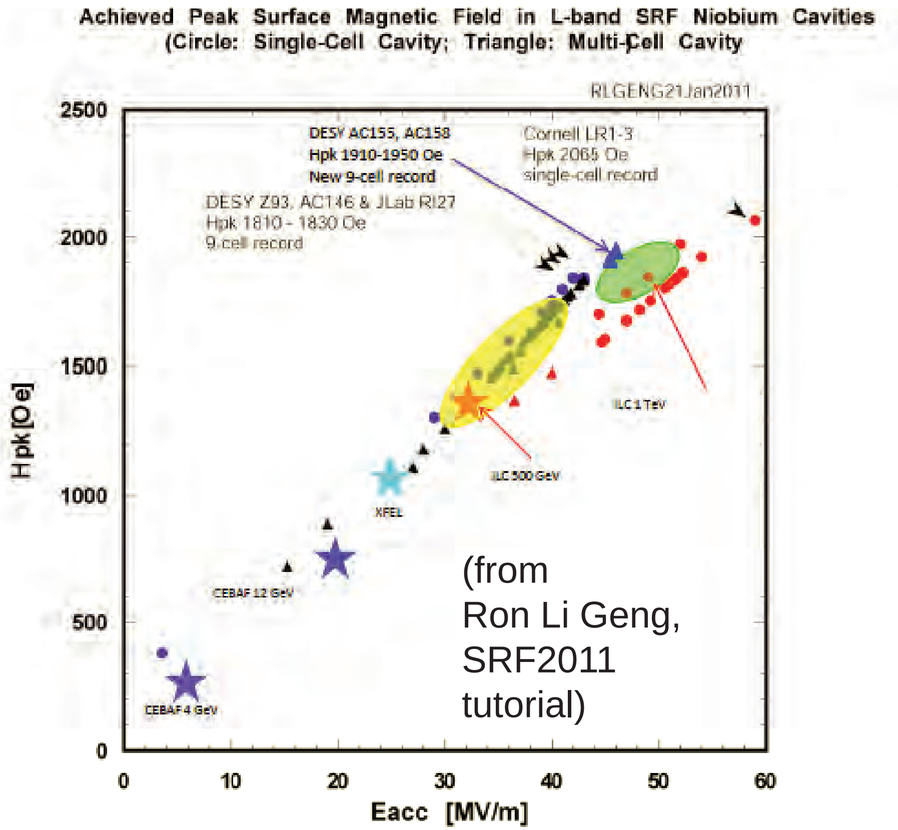
Large Grain Nb, 9-cell ILC type cavities after BCP (top) and EP at DESY (D. Reschke et al., SRF2011)



Record peak fields in ILC type 1.3 GHz cavities

- **Maximum accelerating gradient is determined by achievable peak fields E_p and B_p** through the geometrical factors E_p/E_a , B_p/E_a
- **Ep>120 MV/m and Bp>200 mT achieved in single cell ILC type cavities**

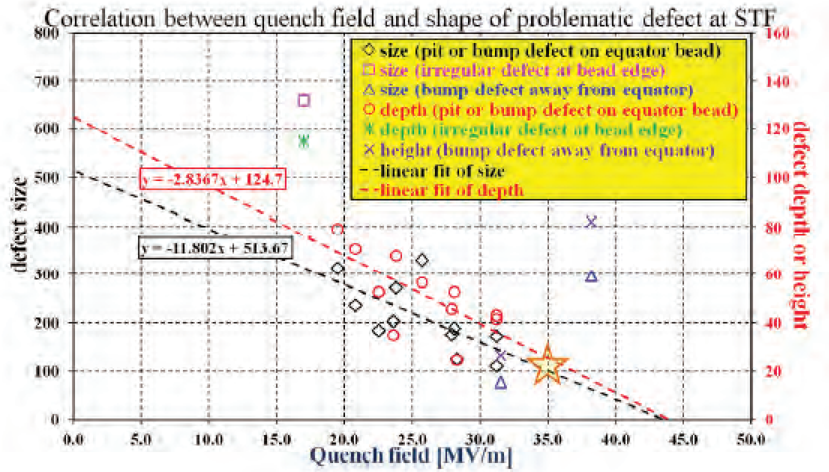




(from
Ron Li Geng,
SRF2011
tutorial)

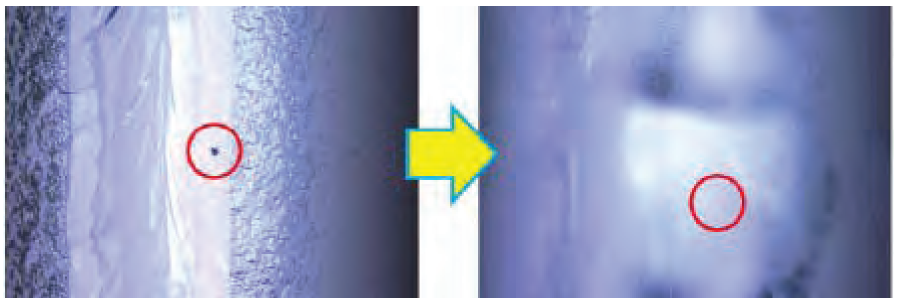
Role of surface defects

- Quench field and defect shape and size can be numerically correlated
- Cavity gradient can be increased reducing defect size
- Good diagnostics has been developed to find the defects
- local grinding (or other means like laser or eb melting) for single or few defects removal
- Global surface processing if numerous defects are present
- **Bad cavities can be repaired and reach record performance**

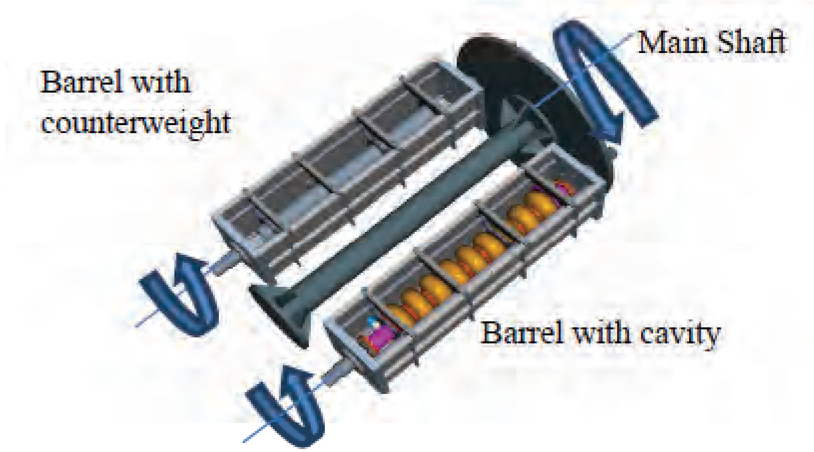


Correlation between quench field and defect shape (Y. Yamamoto et al., proc. of IPAC 2012, p. 2235)

Defect before and after removal by local grinding



Surface smoothing by barrel polishing



Barrel polishing schematic

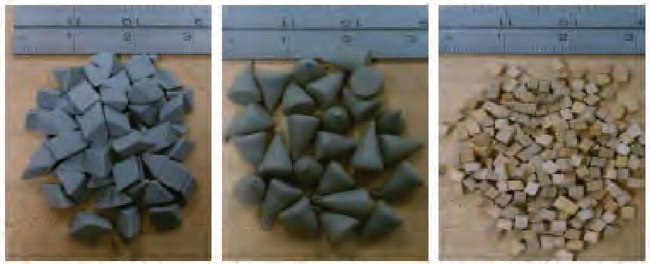
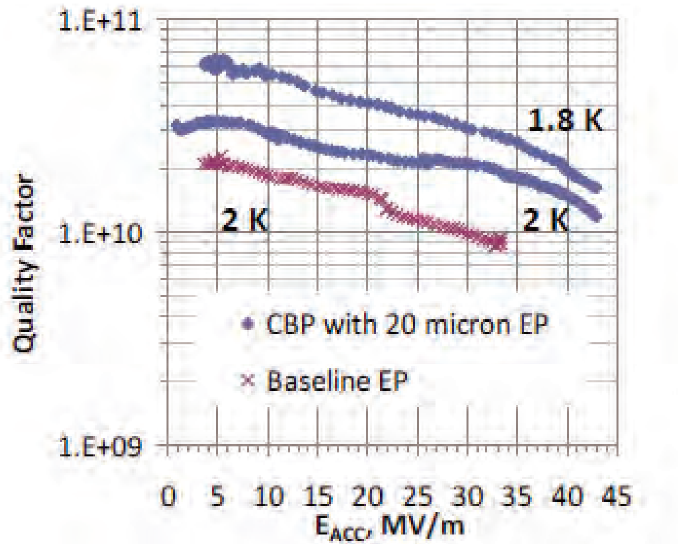


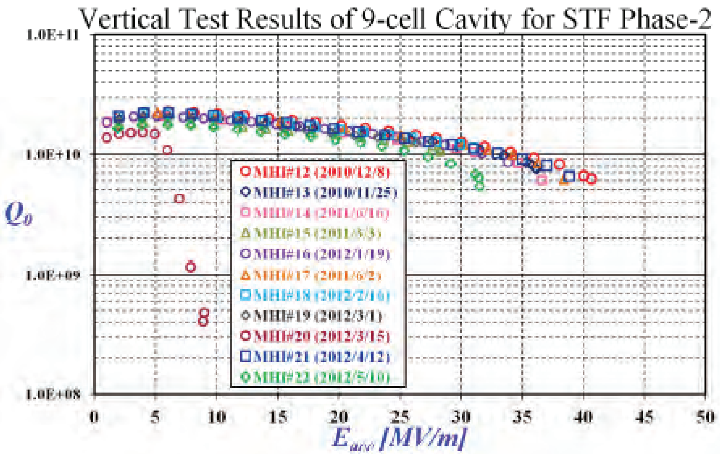
Figure 2: Picture of some of the media used for CBP of cavities at Fermilab to achieve a mirror like finish on the inside of cavities.

(From C. Cooper, Proc. of SRF11, p. 571)

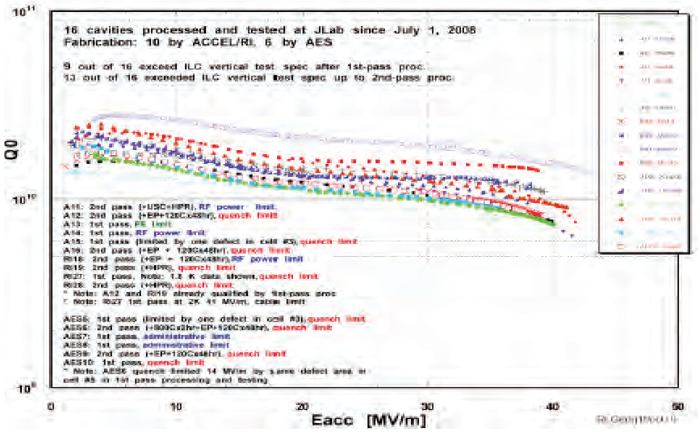
- Mechanical rf surface smoothing techniques (grinding, centrifugal barrel polishing) can further improve results, even in cavities treated with EP



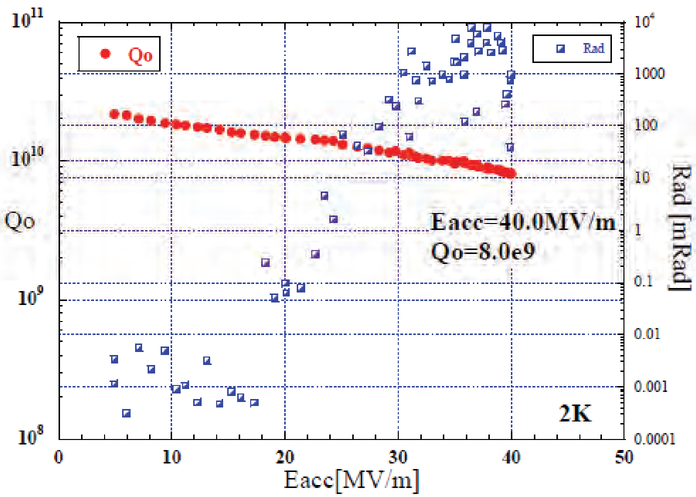
Some of the 9-cell, 1.3 GHz best results



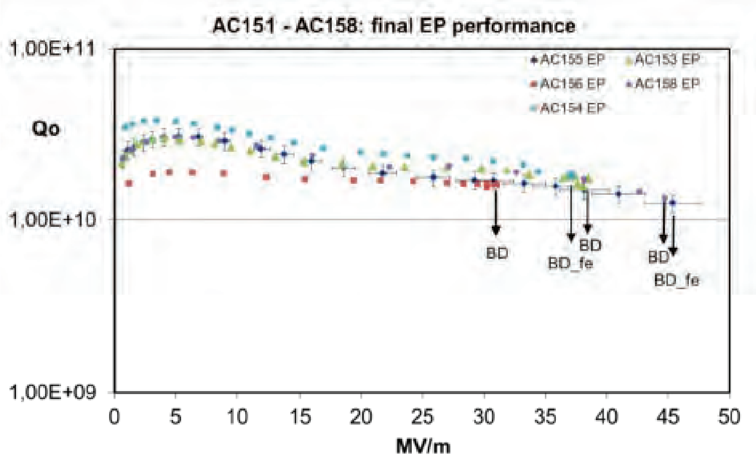
KEK 9-cell (Y. Yamamoto et al., IPAC 2012)



9-cell produced by industry (R.L. Geng, SRF2011)



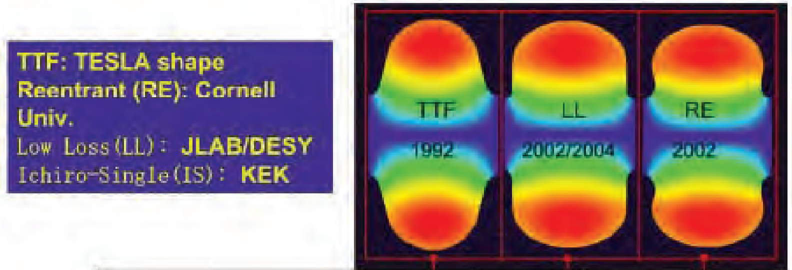
KEK -Jlab 9-cell ICHIRO (F. Furuta et al., SRF2011)



DESY 9-cell LG Nb (D. Reschke et al., SRF2011)

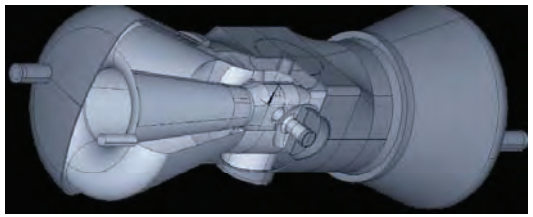
Geometrical issues

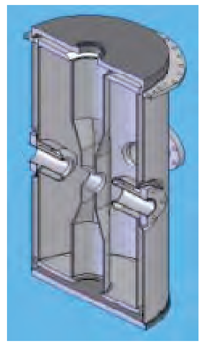
- Cavity geometry is critical for
  - peak fields
  - rf efficiency
  - field distribution quality
- Optimization rather mature in elliptical cavities
- still room for improvement in low beta (TEM) ones
  - new proposals are coming
- The limit in refining geometrical optimization of cavities (and in their cost) should come from a global cost evaluation of the project



	TESLA	LL	RE	IS
Diameter [mm]	70	60	66	61
Ep/Eacc	2.0	2.36	2.21	2.02
Hp/Eacc [Oe/MV/m]	42.6	36.1	37.6	35.6
R/Q [W]	113.8	133.7	126.8	138
G[W]	271	284	277	285
Eacc max	41.1	48.5	46.5	49.2

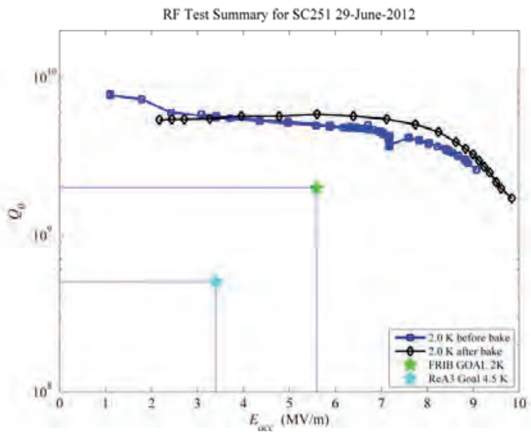
High gradient cavity shape for ILC (from J. Sekutowicz, SRF2011 tutorial)





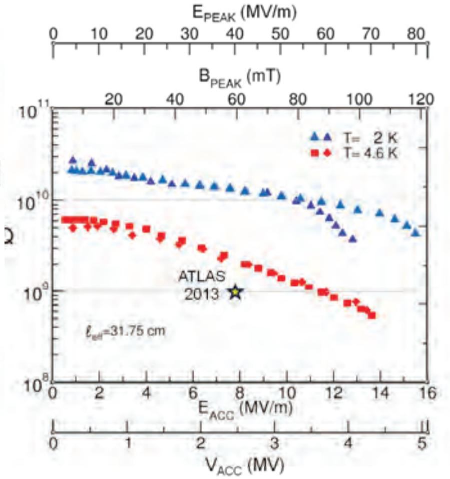
Recent version of Bi-conical HWR (E. Zaplatin and A. Kanareykin, SRF2011). Right: cilindrical HWR (INFN-LNL, 2002)

QWR examples: minimum cost vs. maximum E_a



MSU 80.5 MHz
ReA3 FRIB

ANL ATLAS
72.7 MHz



low cost QWRs			Highest E_a QWR
MSU ReA3	MSU FRIB		ANL tapered
6.2	5.9	Ep/Ea (MV/m)	5.2
13.9	12.5	Bp/Ea (mT/(MV/m))	7.6
60	Not yet tested	max Ep (MV/m)	80
135	Not yet tested	max Bp (mT)	120
BCP	BCP	Surface treatment	EP
0.73	1.0	Rsh (GΩ) (@Rs=10 nΩ)	1.5

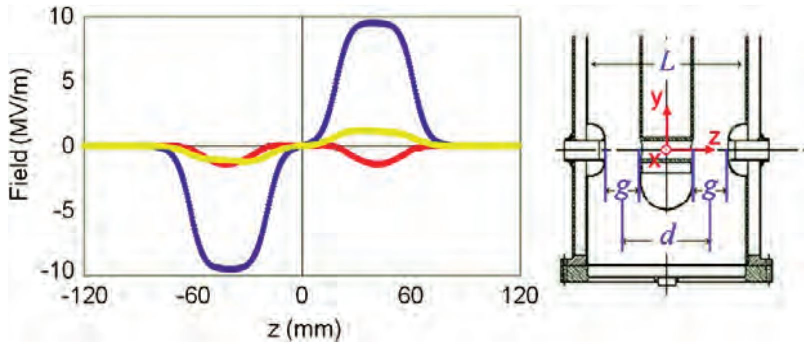
- In both cases, high Q and peak fields, largely above specifications
- Different accelerators optimization led to different cavity geometries

Beam steering in QW cavities

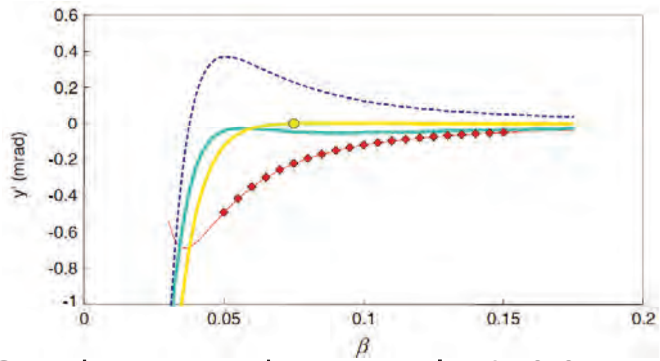
- QWRs give beam steering
- The problem is well understood and prevents β_0 >0.2 in QWRs and their operation at $\beta << \beta_0$
- Correction techniques work well up to about β_0 <0.15 :
  - Cavity **vertical displacement** from axis (using rf defocusing)
  - **Beam port shaping** (using E_y to correct B_x)
- Useful analytical formula :

$$\Delta y'(E_a, \phi, \beta, y) = \frac{qeE_aL\sin\phi}{Am_oc^2T_{Ez}(\beta_0)}\left\{D_{Bx}(\beta) + \sum_{J=1}^{n} D_{Eyj}(\beta) + D_{rf}(\beta, y)\right\}$$

(A. Facco and V. Zvyagintsev, PRST-AB 14, 070101 (2011))



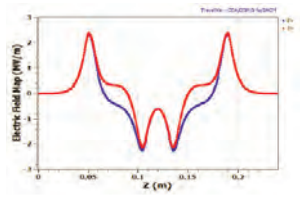
On-axis field components in a QWR. E_z (blue), cB_x (yellow) and E_y (red, ×10).

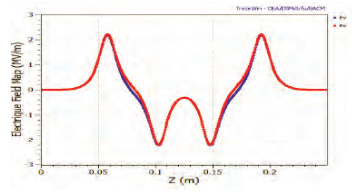


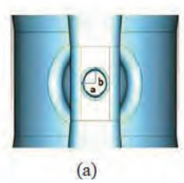
Steering correction example: β=0.07 TRIUMF QWR at 1 MV/m. Red : normal QWR steering; blue: after cavity optimum displacement; yellow: after beam ports shaping.

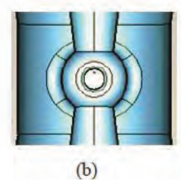
High order field components in low-β SC cavities

- quadrupolar field components in HWRs and QWRs are now being considered as potential problems too
- Significant effects only in high intensity beams
- Cancellation of electric field asymmetry can be obtained by proper shaping of beam pipes
- Cancellation of magnetic field asymmetry would require a more sophisticated shaping: correction can be obtained in the lattice design



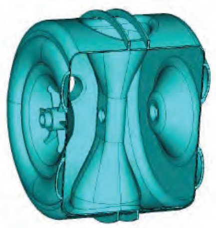


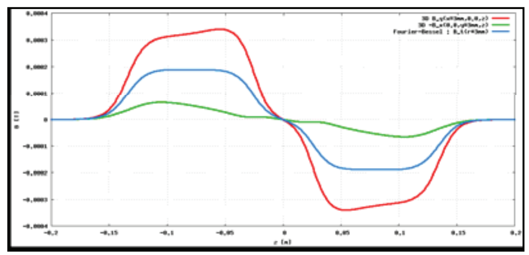




(P. Berrutti et al., IPAC 2012)

(J-F. Ostiguy , N. Solyak, IPAC 2011)





FNAL 325 MHz Spoke cavity and B_x (green) and B_y (red) field components near the beam axis

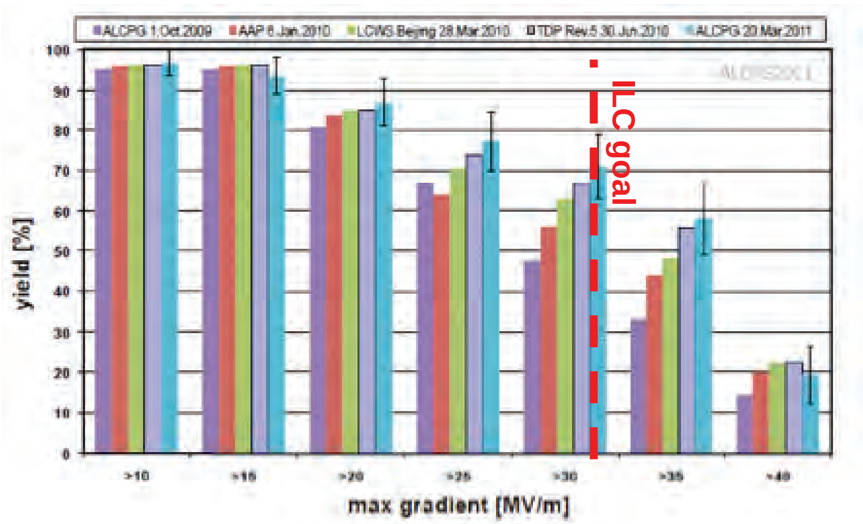
Other factors limiting operation at high gradient

- Mechanical stability
  - **SC cavities with high Q have small rf bandwidth $\delta f \sim f/Q_L$** , in some cases a few tens of Hz
  - Allowed detuning is < $\delta f/2$ to maintain phase and amplitude lock
  - **Microphonics, Helium pressure fluctuations and Lorentz Force Detuning (LFD)$\propto E_a^2$ can give detuning >> $\delta f/2$**
    - Example: FRIB QWR. $\delta f/2$ =20 Hz; $df/dE_a^2 \sim 3$ Hz/(MV/m)^2 , Ea=5.6 MV/m, LFD ~100 Hz
  - Mechanical stability, overcoupling, suitable tuning systems and stable amplitude lock are required
- Rf couplers, HOM couplers
  - Overheating, high field MP...
- Cryogenic load
- E_a and ϕ stability with pulsed beam loading

Challenges are not only in gradient and Q

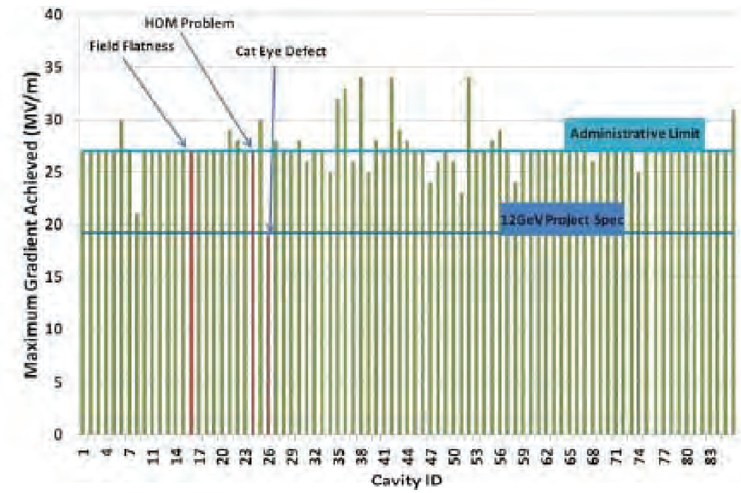
High gradient: realistic goals

- Realistic operation gradients are increasing in SC cavities, but still require a large safety margin (around 40 ÷ 50 % of the maximum achievable field)
- Present realistic peak field specifications in operation: E_p~35÷45 MV/m (ILC: 60) , B_p~70÷90 mT (ILC:110)



Maximum gradient evolution of ILC nine-cell cavites built by industry for DESY, Cornell, Jlab, KEK and FNAL

(A. Yamamoto et al., SRF 2011)

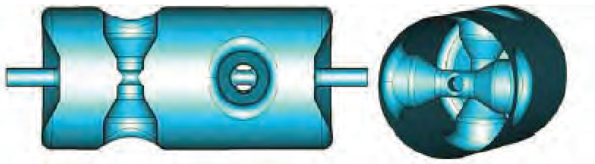


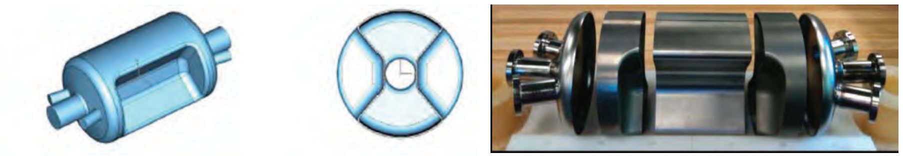
Performance of the 86 cavities built for the 12 GeV C100 upgrade at Jlab

(A. Burrill et al., IPAC 2012)

Some new entries…

ODU-Niowave 700 MHz, β=1 multispoke cavity for electrons
(B. Hall et al., IPAC 2012)





ODU-Jlab 499 MHz Deflecting /400 MHz crabbing cavity (S. U. De Silva, J. R. Delayen, IPAC 2012)

Tunable 28 MHZ SC “folded QWR” for RHIC
(C. H. Boulware et al., IPAC 2012)

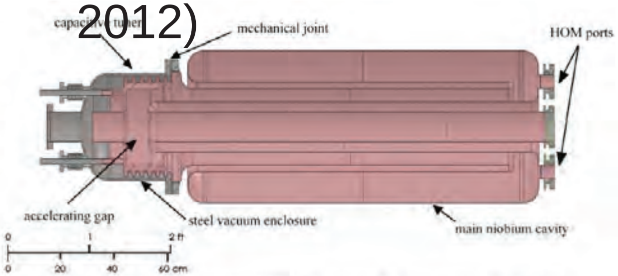


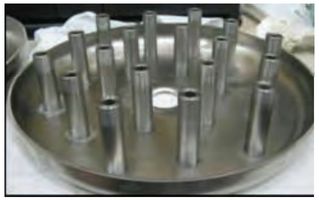
Figure 1: The folded quarter-wave cavity structure with the proposed capacitive tuner.

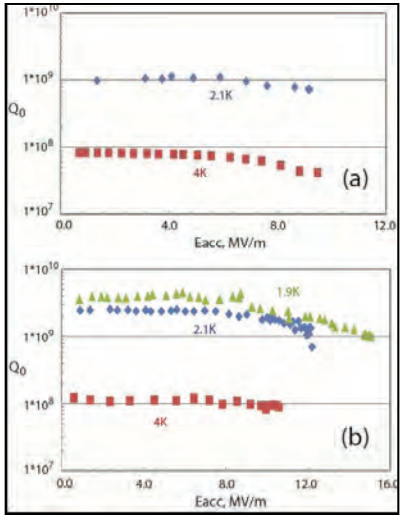
Figure 6: Interlaced rods during wire EDM of the baseplate from Nb ingot.

400 MHz, 4-rod crabbing cavity for the LHC upgrade (B. Hall et al., IPAC 2012)

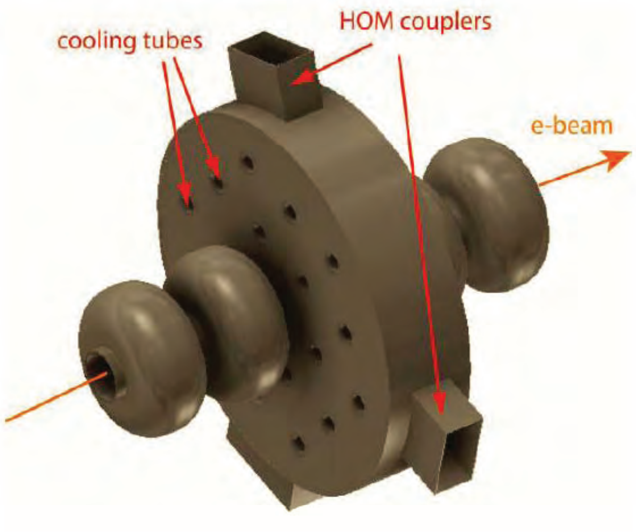
Out of the main stream: SC Photonic Band Gap

- 2.1 GHz SC Photonic Band Gap resonators, proposed 20 years ago, now tested at high gradient:
  - Excellent filters for HOMs while keeping high accelerator gradient if integrated in a multicell cavity
  - Allowing higher frequency for electron linacs, higher gradient, lower charge per beam bunch
- 15 MV/m capability recently demonstrated





Q vs. E_a of the two prototypes



Conceptual design of a multicell resonator with integrated PBG

(Evgenya I. Simakov et al., IPAC 2012)

Future perspectives in high gradients

Main goals of present R&D:

1. Improve Nb **bulk and rf surface quality** (purity, crystal size, roughness...)
   - Improving techniques or developing new ones
2. **Increase critical magnetic field** of the SC material to move quench to higher gradients
   - Developing high Tc materials deposition techniques on Cu or on Nb
   - Using thin films of high T_c materials over Nb to shield it from the rf magnetic field
3. **Decrease surface resistance** R_s of Niobium to reduce cryogenic load
   - Developing high T_c materials deposition techniques on Cu or on Nb
   - Depositing, or creating by chemical reactions, thin films of high T_c materials in the Nb rf surface to reduce the BCS surface resistance
4. Further **improve geometries**

Recent development:
Heat treatment with induction furnace

- Cavity heated by Joule effect of rf currents produced by an outside induction coil
- No heaters and no contaminants in the vacuum chamber, high temperature only at the cavity, no chemical polishing needed after treatment
- Possible performance improvement and cost reduction

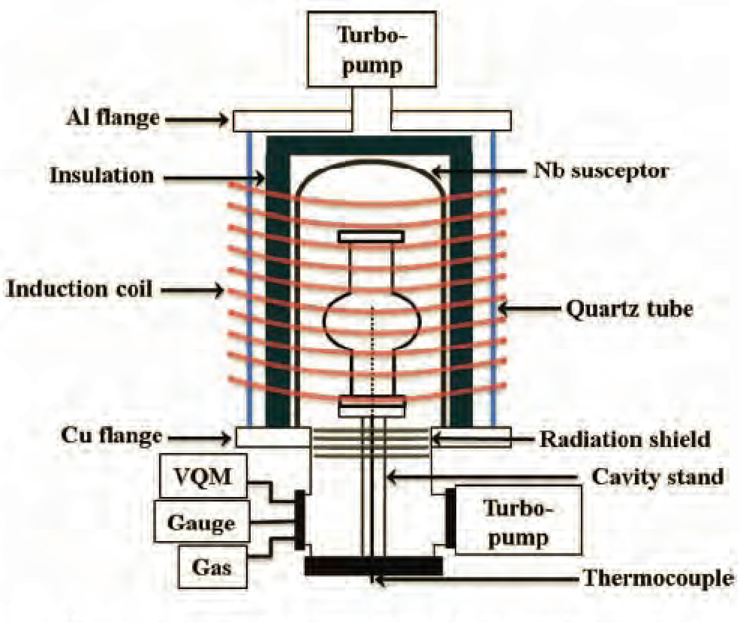


FIG. 1. The schematic diagram of the induction heating system.

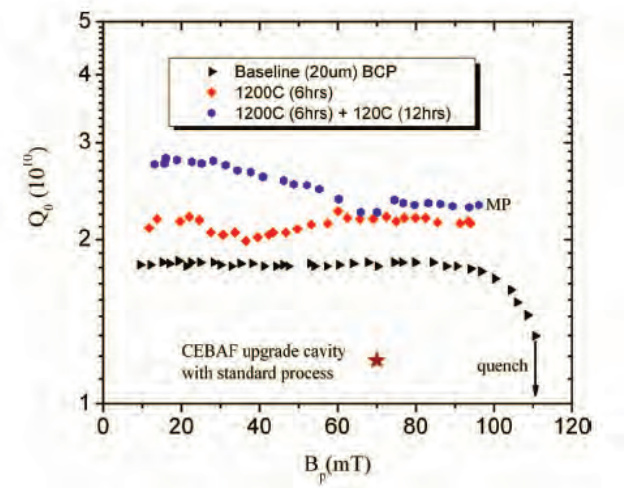


FIG. 7. Summary of Q_0 (B_p) measurements at 2 K. Also shown is the average values of Q_0 at 2 K form Jefferson Lab 12 GeV upgrade 7-cell fine-grain cavities subjected to the standard fabrication process.

P.i Dhakal et al., REV. SCI. INSTRUM. **83, 065105 (2012)**

Recent development: NbN layers in a Nb cavity

- 6 GHz Nb cavity heated to 2000 °C in an induction furnace in the presence of N gas
- A layer of high NbN (T_c =16.2 K, B_c=230 mT) is created on the cavity rf surface
- **Very high Q** at 4.2K
- Still present problem: quench at low field and maximum gradient still low, probably due to poor thermal contact of NbN on Nb
- <u>Recent success up to 20 MV/m in a 1.3 GHz cavity at FNAL (A. Grassellino et al., LINAC 2012)</u>

Figure 1: – A Nb 6 GHz cavity heated at a temperature close to 2000°C.

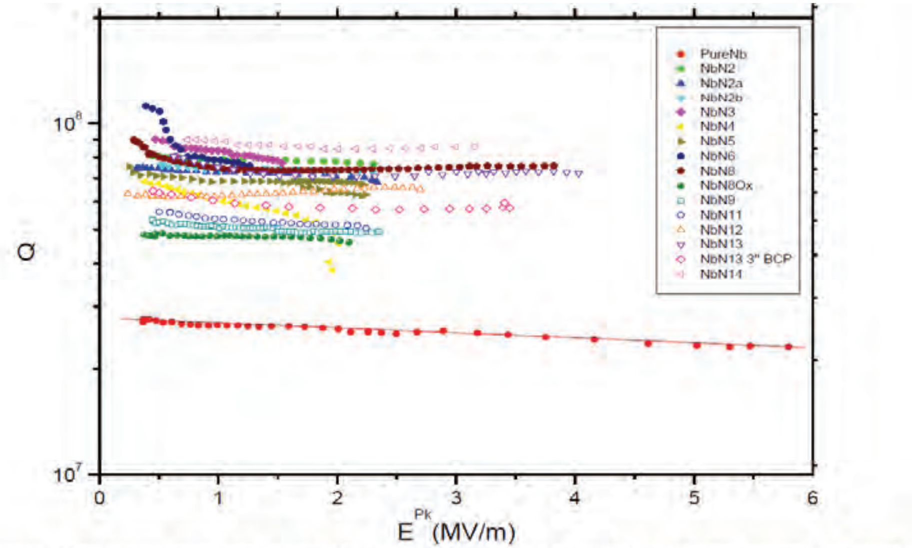
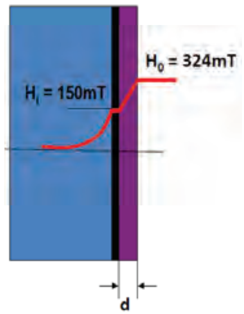


Figure 3: The Q-factor versus peak electric field for the 14 different Nitrided 6 GHz Niobium cavities. The lowest curve (Red dots) refers to the pure Niobium, while all the others are nitrided cavities at temperatures over 2000°C. All curves refer to 4.2 K.

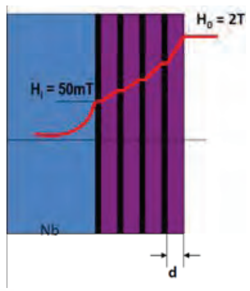
V. Palmieri et al., Proc. of SRF2011

SIS layers: possible way to higher E_a

- Main physical limitation to high gradient: critical magnetic field H_c
- Thin ($d \ll \lambda$) layers of superconductor with thickness *d* and London penetration depth λ, have $\mathbf{H_{c1} \propto \ln(d/\xi)/d^2}$ instead of $\mathbf{H_{c1} \propto \ln(\lambda/\xi)/\lambda^2}$
- If a Nb cavity is coated with *N* such layers of SC material, separated by thin layers of insulator, the magnetic field at the rf surface is attenuated by $e^{-(Nd/\lambda)}$ when it reaches the Nb surface (**A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006).**)
- First experiments of have already started, breakthroughs might be possible in the next future

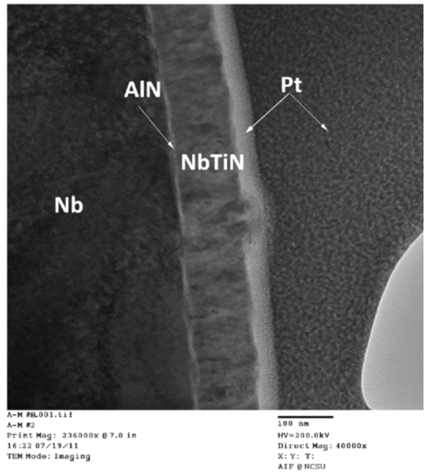


Example:
1 layer of Nb_3Sn
d=50 nm, λ=65 nm, $H_{c1}(d,\xi)$=1.4T
A cavity could now double its maximum field!



Many more layers, much higher gradient before reaching magnetic quench limit...
(however the cavity might quench much earlier due to field emission)

((From T. Tajima -SRF2011 tutorial)



Example of SIS layer deposition (A.-M. Valente-Feliciano et al., Proc. SRF2011)

Conclusions

- Several large accelerator projects are based on SRF technology, which looks robust, reliable, and highly performing
- Knowledge in SRF and cavity performance are steadily increasing, many of the past problems have been solved, but there are still fundamental phenomena to be fully understood
- Reliable operation gradient is is still much below the best experimental results; a big effort is being done to reduce the large scattering in the performance of production cavities
- The present technology is growing fast and could approach its physical limits of gradient in one decade
- Future breakthroughs might come from the use of high T_c materials and the use of thin film technology