

Latest Developments in Superconducting RF Structures for $\beta=1$ Particle Acceleration

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Outline

- Challenges of SRF Technology
- Design Criteria for Superconducting Cavities
- Update on Developments

General Remarks(1)

- The recommendation of the ITRP in 2004 to use SRF technology in favor of “warm” technology for the ILC gave a big boost to superconducting rf activities around the world, adding to existing activities on the implementation of the XFEL, SNS and developments for ERL’s (Cornell, FZ Rossendorf, 4GLS, BESSY, Jlab) and Upgrades such as e.g. for CEBAF
- The enthusiasm for ILC has led to a large set of meetings, workshops and conferences, resulting among other things in an International Organization (GDE) and a Baseline Conceptual Design (BCD) with heavy reliance on the TESLA/XFEL developments.
- However, also a recognition of the technological challenges has slowly set in and mainly the “newcomers” to SRF technology have realized, that many areas of R&D need to be explored, before as large a machine as the ILC can be realized

General Remarks(2)

- SRF technology is a difficult technology and it is not very forgiving, if mistakes are being made.
- After all it involves many areas of physics and technology such as: Surface science, vacuum technology, metallurgy, chemistry, rf engineering, cryogenics, clean room technology, contamination control, cleaning technology, quality control...
- The ILC design goals are close to the fundamental limit of the material properties (in this case niobium) and this is the first proposed project to my knowledge, where the design goals only been achieved in a few rare cases have and a solid technological baseline has not yet been established
- Other projects such as ERL's, Neutron and Light sources, or Upgrades of existing machines such as the CEBAF Upgrade are more modest in their goals for cavity losses and gradients – the challenges here are in the areas of cw operation and management of high currents/ damping of higher order modes

General Remarks(3)

- It is one thing to achieve good performance of cavities in a laboratory environment (vertical or horizontal Dewar tests, ILC goals are $E_{acc} \sim 35$ MV/m at a Q-value of $Q \sim 8 \times 10^9$ at 2K) and another to consistently and reliably produce in an production environment over several years app. 20 km of cavity strings with the design parameters.
- The installation of the X-FEL at DESY starting next year with somewhat reduced requirements for the superconducting cavities, will be a good demonstration project to see the difficulties of the implementation of a very large scale SRF accelerator.

What are the challenges?
What are the limitations?

Critical Magnetic Field

- Superconducting properties are lost, when the critical magnetic field of the superconducting material is reached and the material “quenches”
- For niobium, this is a field of $H_{\text{crit}} \sim 190 \text{ mT}$, which, in an optimal cavity design, can lead to accelerating gradients of $E_{\text{acc}} \sim 50 \text{ MV/m}$ by a reduced H_p/E_{acc} –ratio (LL and RE shapes)
- Typically, “quench fields” are lower because of **defects** in the material, even for **high purity Nb**
- Pre-selection of “defect-free” material sheets is done by eddy current or squid scanning developed at DESY [W. Singer et al.]



Field Emission

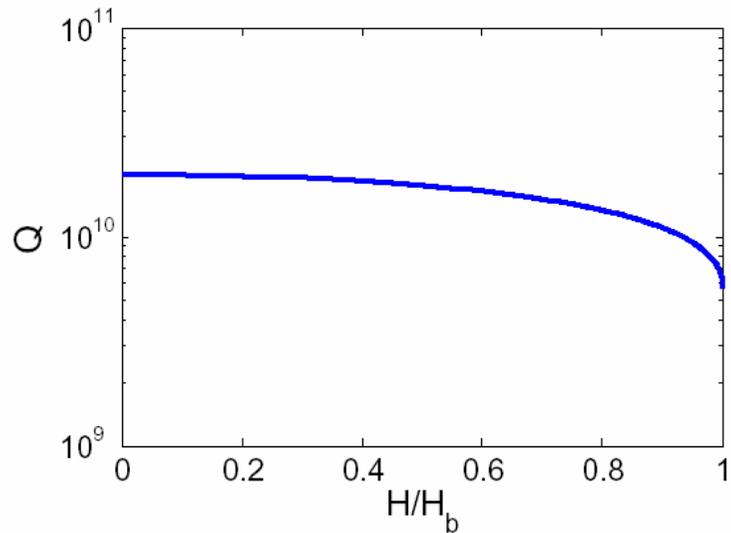
- Typically, superconducting multi-cell cavities are limited in surface electric fields to $50 \text{ MV/m} \leq E_{\text{peak}} \leq 70 \text{ MV/m}$ by the onset of field emission (FE)
- Higher surface fields have occasionally been established, more frequently in smaller assemblies.
- FE leads to an exponential increase in dark currents (and X-radiation) and an exponential increase in cavity losses.
- FE is caused by contamination of the sensitive superconducting surfaces
- Remedies are strict **contamination control**:
 - Clean Processing and Assembly: Clean room, High pressure ultrapure water rinsing for extended periods of time is used
 - Prevention of re-contamination: oil-free pumping systems, particulate-free hardware, clever procedures...

Field dependence of Q-value: “Q-drop”

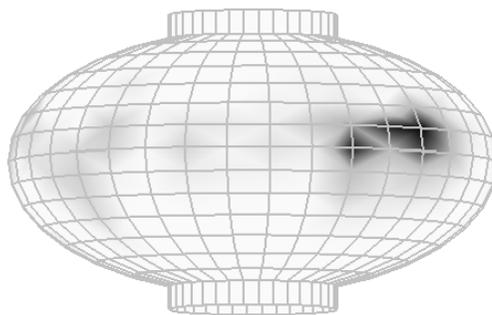
- Cavities made from high purity niobium (RRR>200) typically show a degradation of the Q-value at $E_{\text{acc}} > 24 \text{ MV/m}$ ($H_{\text{peak}} > 100 \text{ mT}$) in the absence of field emission
- “In situ” baking at $\sim 120 \text{ C}$ for extended periods of time ($\geq 12 \text{ hrs}$) causes the disappearance of the “Q-drop”; baking is more effective on electropolished surfaces than on surfaces treated by chemical polishing
- The physical effect causing this Q-degradation is not yet well understood, but here are indications that a re-distribution of the oxygen concentration in the penetration depth plays a role
- Temperature maps of cavities in superfluid helium have shown, that “hot spots” are responsible for the “Q-drop” and models have been developed (e.g. A. Gurevich)

“Q – drop”

Theoretical Dependence [A. Gurevich]



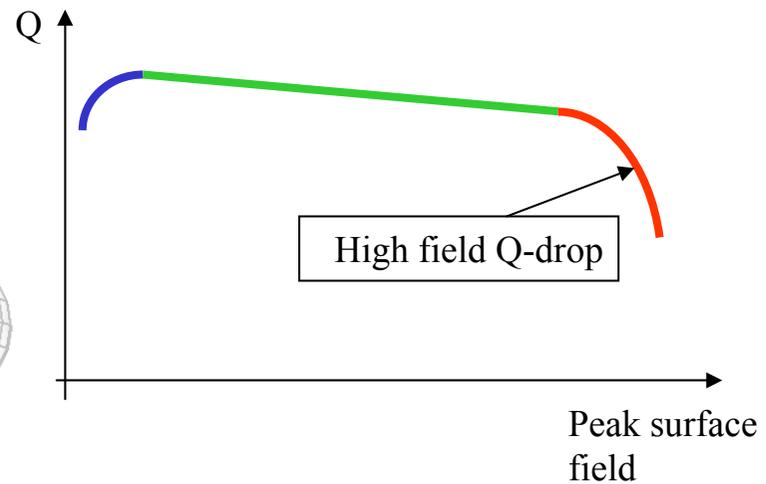
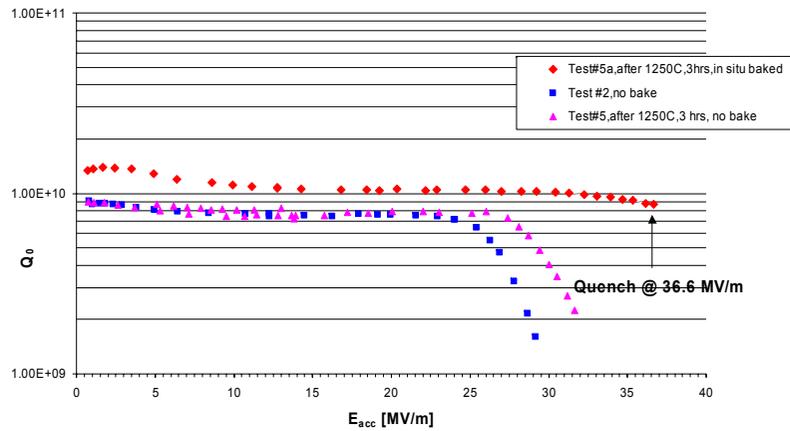
Linear BCS Resistance, $T=2.2K, \Delta/kT_c=1.85$



G. Ciovati, Jlab

Experimental

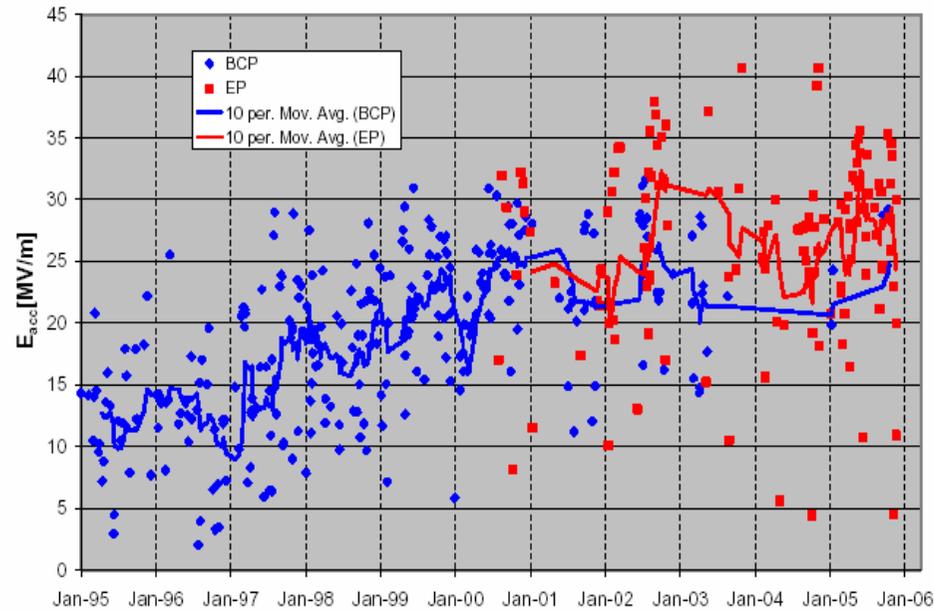
CEBAF Single cell Chinese Large Grain
 Q_0 vs. E_{acc}



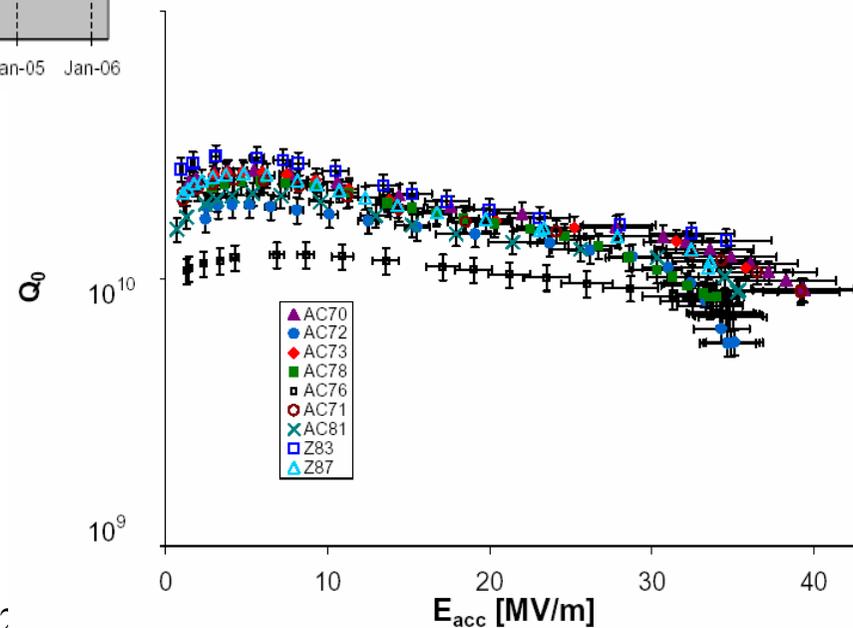
Reproducibility and Reliability(1)

- This is mainly a concern for large projects such as the XFEL or the planned ILC
- The ambitious goals for ILC call for are a gradient of (35 MV/m \pm 5%) and a Q-value of $\sim 8 \times 10^9$
- The huge data base/experience at DESY for the last decade indicates, that the technology is not yet there to produce the above requirements, even though in a few cases the design goals have been achieved or exceeded.
- Within the ILC community there are plans for more R&D under way to understand and solve these problems, which seem to be connected to the large number (> 50) of preparation steps: only a flawless execution gives the desired result
- A “streamlining” of procedures might improve the situation

Reproducibility and Reliability(2)



Courtesy of L. Lilje,
DESY



June 28, 2006

EPAC 2

Cost Reduction (specific for ILC)

- **Alternative Material**
 - large grain/single crystal vs polycrystalline
 - “streamlining” of procedures
- **Optimization of cavity shape considering material limitations**
 - TESLA shape vs Low Loss, Re-entrant shapes
 - reaching the magnetic field limit of niobium
- **Increasing the real estate gradient**
 - superstructure
 - reduction in length, reduction in # of components

Design Criteria for Superconducting Cavities

Design Considerations(1)

- There is no universal design for a superconducting cavity
- Each design has to be tailored to its specific application
- One has to clarify, whether the cavity will used for
 - High gradient or high current acceleration
 - Needs to be optimized for maximum gradient or minimum cryogenic losses
 - Will be used in a CW mode or a pulsed mode
- One also has to make a judgment about the **achievability of the design goals**

Design Considerations(2)

For a “standard” elliptical cavity a design has to consider the following parameters:

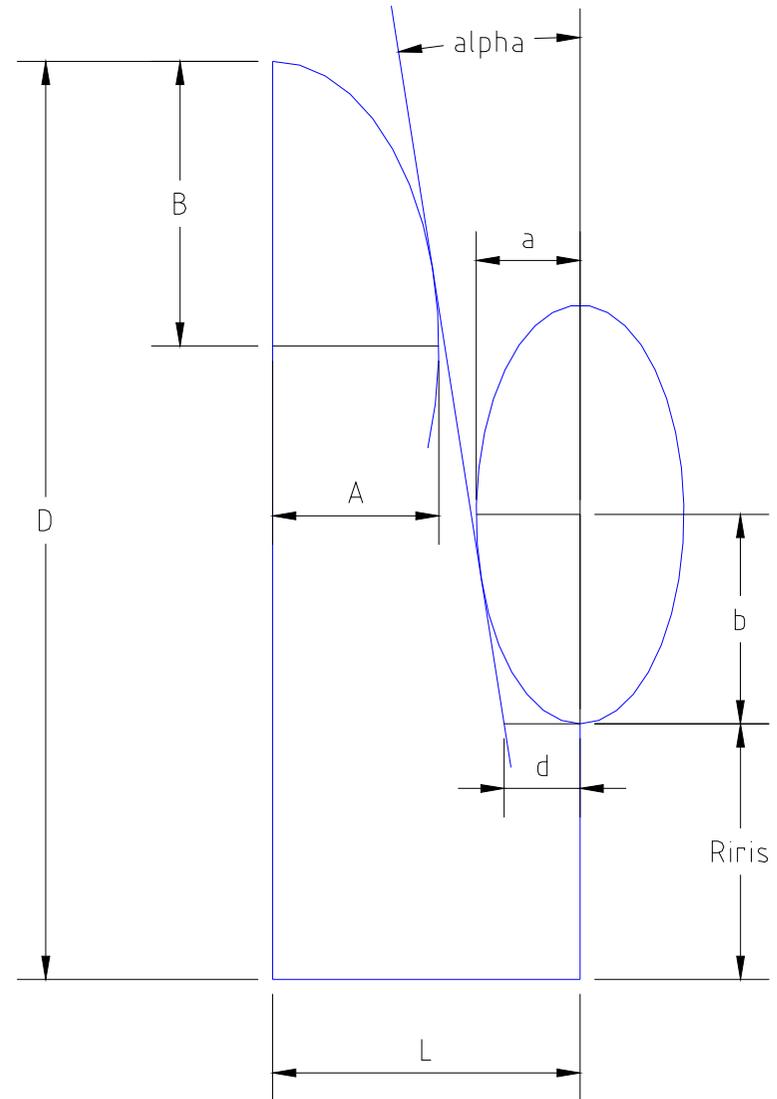
- E_{peak} and H_{peak} at a given E_{acc}
- (R/Q) and $G \times (R/Q)$: is measure of power dissipation
- Cell number N and k_{CC} : field flatness $a_{\text{ff}} = N^2 / \beta k_{\text{cc}}$
 $a_{\text{ff}} \sim 5000$ still manageable
- Side wall slope angle α : stability and cleaning
- Lorentz force detuning k_{L} : material thickness, stiffeners?
- HOM damping: loss factors k_{\parallel} and k_{\perp} of dangerous modes
also modes between cavities
- Q_{ext} of input coupler: size of beam pipe, location, penetration
- Helium vessel: material (Nb55Ti, Ti, SS), stiffness, microphonics noise, mechanics of cold tuners
- Multipacting

Cavity Design / Cell Shape

Full parametric model of the cavity in terms of 7 meaningful geometrical parameters:

- ✓ Ellipse ratio at the equator ($R=B/A$)
ruled by mechanics, magnetic volume
- ✓ Ellipse ratio at the iris ($r=b/a$)
 E_{peak}
- ✓ Side wall inclination (α)
and position (d)
 E_{peak} vs. B_{peak} tradeoff and coupling k
- ✓ Cavity iris radius R_{iris}
coupling k , peak fields, (R/Q)
- ✓ Cavity Length L
 β
- ✓ Cavity radius D
used for frequency tuning

[C. Pagani et al.; "Design Criteria for Elliptical Cavities" , 10th Workshop on RF Superconductivity, Tsukuba, Japan (2001)]



Design Considerations (courtesy of J. Sekutowicz)

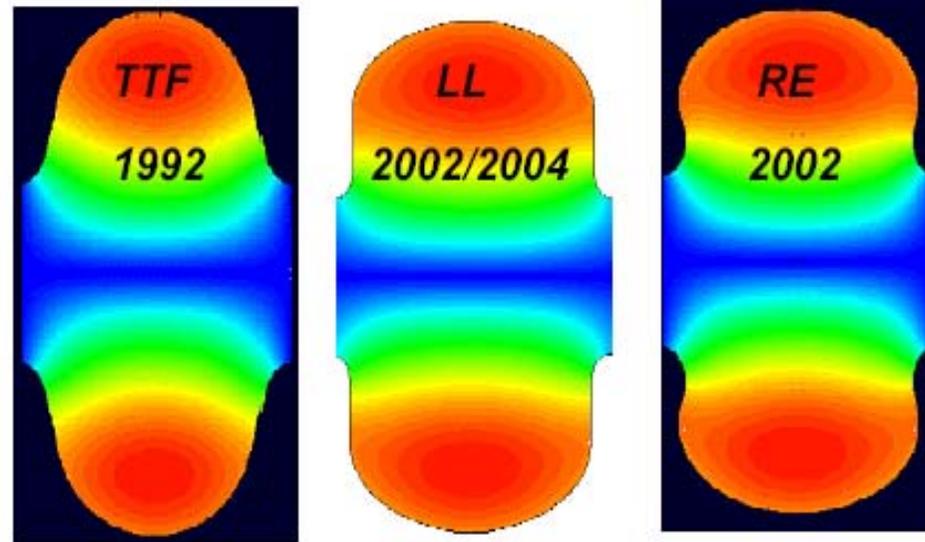
<i>Criteria</i>	<i>RF-parameter</i>	<i>Improves when</i>	<i>Cavity examples</i>
<i>Operation at high gradient</i>	E_{peak}/E_{acc} ↓ B_{peak}/E_{acc} ↓	R_{iris} ↓ <i>Iris, Equator shape</i>	<i>TESLA,</i> <i>HG CEBAF-12 GeV</i>
<i>Low cryogenic losses</i>	$(R/Q) \cdot G$ ↑	R_{iris} ↓ <i>Equator shape</i>	<i>LL CEBAF-12 GeV</i> <i>LL- ILC cavity</i>
<i>High I_{beam} ↔</i> <i>Low HOM impedance</i>	k_{\perp}, k_{\parallel} ↓	R_{iris} ↑	<i>B-Factory</i> <i>RHIC cooling</i> <i>ERL/FEL</i>

R_{iris} = iris diameter , is a very “powerful variable” to trim the RF-parameters of a cavity.

New Cavity Shapes

- In 2002 J. Sekutowicz optimized a cavity for the CEBAF Upgrade with respect to cryogenic losses (LL shape, CW operation)
- This cavity shape has been chosen for the CEBAF Upgrade
- In 2003 K. Saito proposed to increase the effectiveness of an accelerating structure by optimizing it with respect to the ratio of $H_{\text{peak}}/E_{\text{acc}}$ rather than to $E_{\text{peak}}/E_{\text{acc}}$, arguing that FE is not a fundamental limit, but H_{crit} is.
- This can be accomplished by increasing the magnetic field volume of the cavity (slope change0 and closing the iris.
- Unfortunately, the peak electric fields are increasing, the cell-to-cell coupling is decreasing and the loss factors for HOM's are going up.
- As a result, two new cavity shapes have been proposed and prototyped

New Cavity Shapes for ILC (courtesy of J. Sekutowicz)



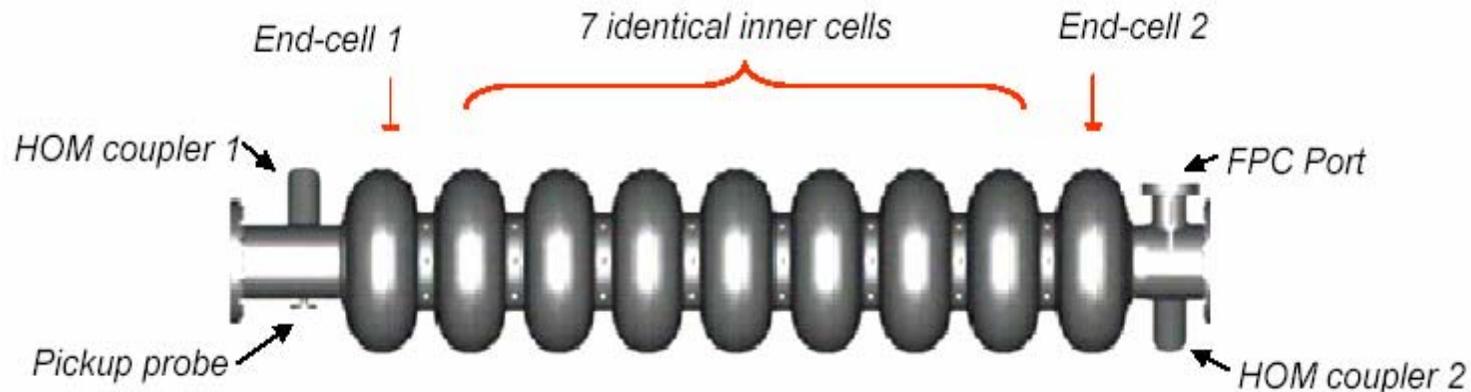
RE shape: Shemelin,
Padamsee, Geng,
Nim A 496(2003), 1-
7

r_{iris}	[mm]	35	30	33
k_{cc}	[%]	1.9	1.52	1.8
E_{peak}/E_{acc}	-	1.98	2.36	2.21
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76
R/Q	[Ω]	113.8	133.7	126.8
G	[Ω]	271	284	277
$R/Q * G$	[$\Omega * \Omega$]	30840	37970	35123

Update on Developments

Cavities for High Gradient/Low Loss (1)

- The TESLA cavity design (1992) has been adopted as baseline for the ILC and is the “standard” for many ERL – applications such as the 4GLS, Elbe, BESSY ERL, the Cornell ERL and the KEK planned ERL at KEK , with some slight modifications
- Gradients of ≥ 35 M V/m have been measured on several cavities and a cavity string/cryomodule will be assembled in the near future
- This cavity is available “off the shelf” for the ERL projects



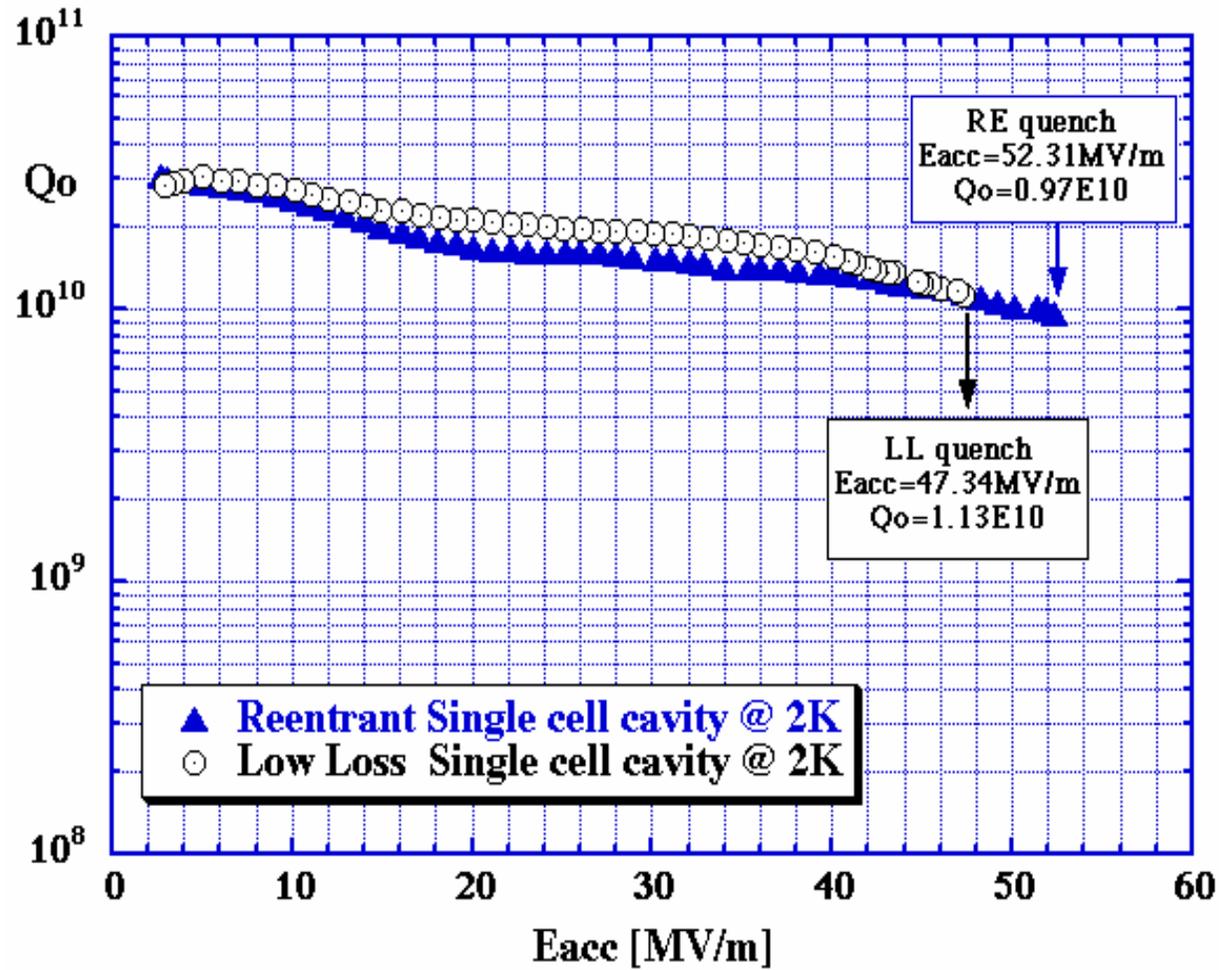
Cavities for High Gradient/Low Loss (2)

- The RE and LL/Ichiro cavity shapes have been prototyped as single cell and 9-cell cavities.
- Both at Cornell University and at KEK record performances have been achieved in the vicinity of $E_{acc} = 50 \text{ MV/m}$ (190 mT) on single cell cavities
- At KEK four 9-cell “Ichiro” cavities have been fabricated and testing has started.
- Gradients up to 30 MV/m have been reached, limited until now by multipacting in the beam pipes (K. Ko, SLAC)



Cavities for High Gradient/Low Loss (3)

K. Saito, KEK



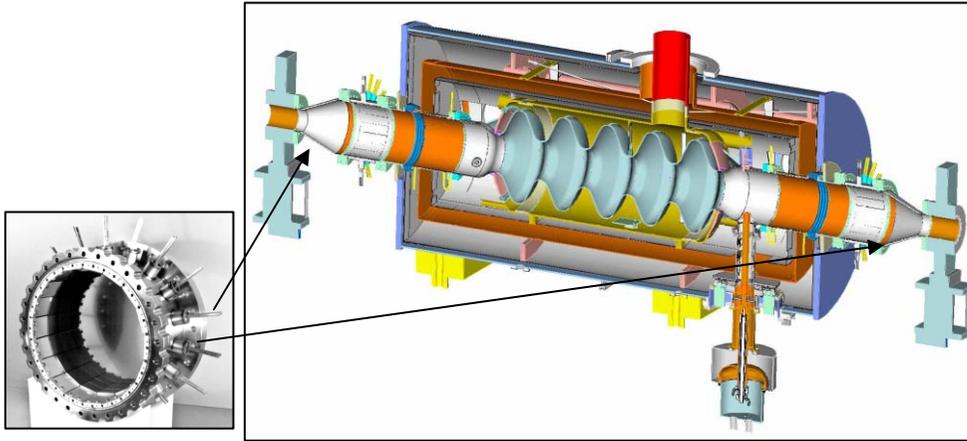
Cavities for High Current(1)

- These cavities are designed for “moderate” gradients and Q – values: $E_{\text{acc}} \leq 20 \text{ MV/m}$, $Q \sim 8 \times 10^9$ at 2K
- The challenge here is the appropriate damping of HOM’s and absorption of the HOM power in room temperature loads
- **BNL**: 5-cell cavity for electron cooling experiment, large aperture, ferrite absorbers in beam line
- **Cornell ERL**: 8 coax HOM couplers on modified TESLA cavity + ferrite rings in beam pipe at 80K
- **Jlab 1 MW ERL/FEL**: six waveguides/cavity, RT absorber
- **KEK ERL**: radial line HOM absorbers on TESLA cavity
- **MSU (Thesis)**: circular waveguide in TE_{11} – mode, all HOM’s propagate to RT load

Cavities for High Current(2)

BNL [see TUZBPA01]

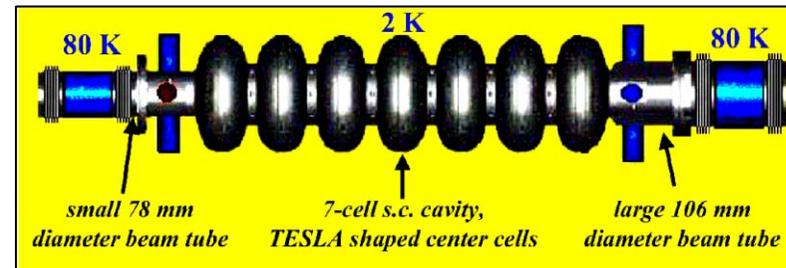
Cornell (R.Geng)



Injector: 5 cavities needed for ERL injector; prototype reached 21 MV/m; at 15 MV/m, $Q \sim 10^{10}$

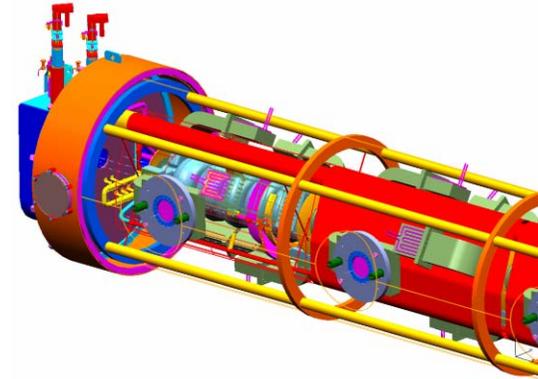
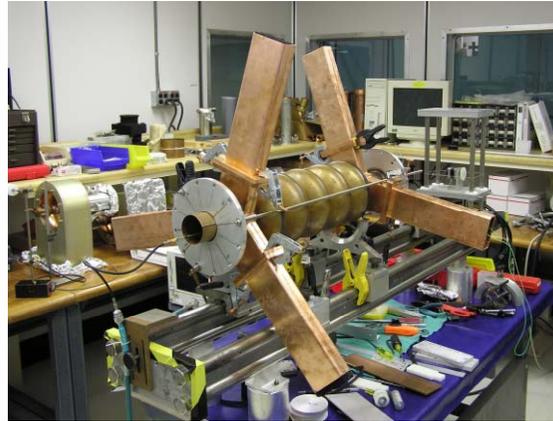
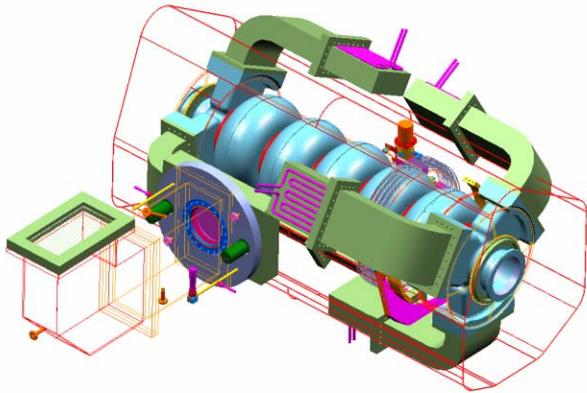


Cavity is being processed and tested at Jlab



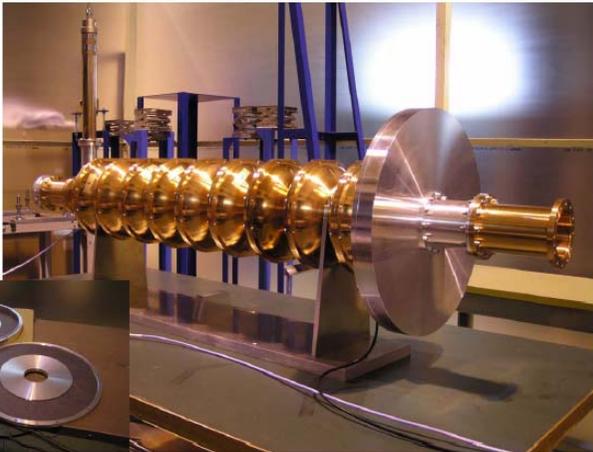
Cavities for High Current(3)

Jlab 1 MW FEL[MOPCH182]



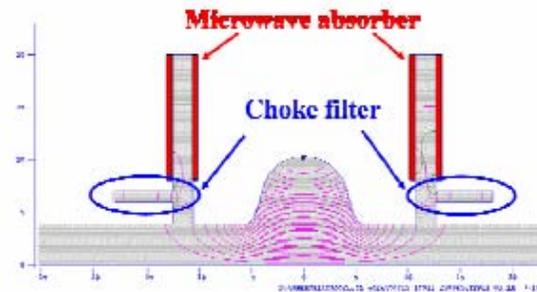
KEK ERL [K. Umemori, et. al.,
proceedings PAC'05]

TESLA type
cavity fitted
with a radial
HOM
absorber



June 28, 2006

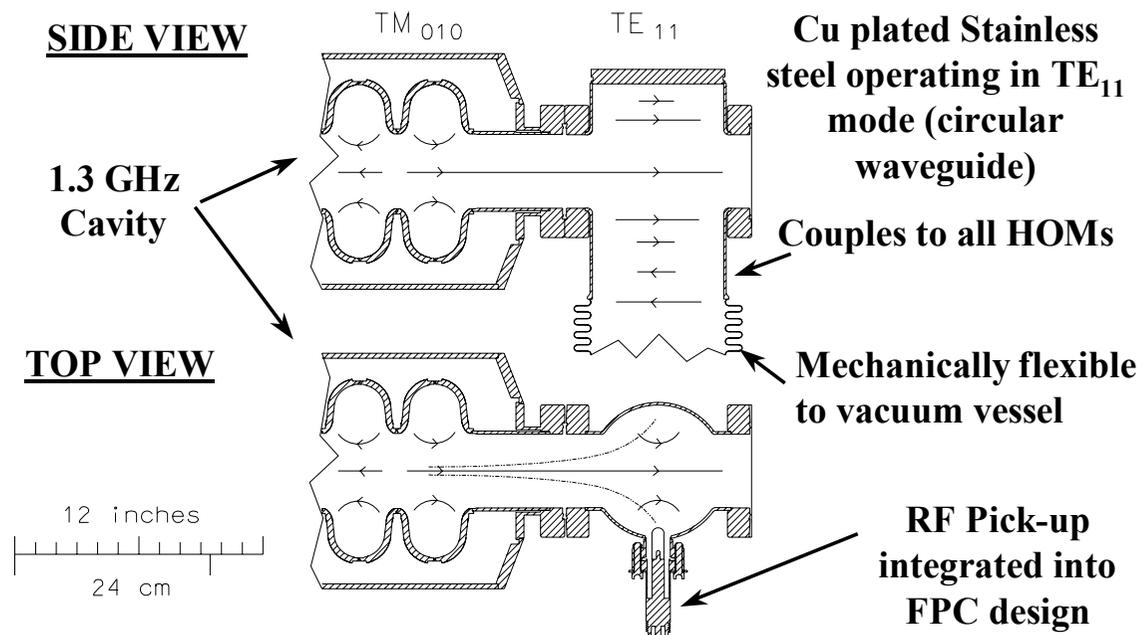
EPAC 2006, Edinburgh



Higher-Order-Mode Damping
of L-band Superconducting
Cavity Using a Radial-line
HOM Damper

Cavities for High Current(4)

- **Large aperture (thesis, *D. Meidlinger*)**
 - HOMs above cutoff in beam pipe $f_{\text{HOM}} \geq 2f_{\text{RF}}$
 - HOMs propagate to room temperature loads
- **Ampere beam currents possible in multi-cell cavities**

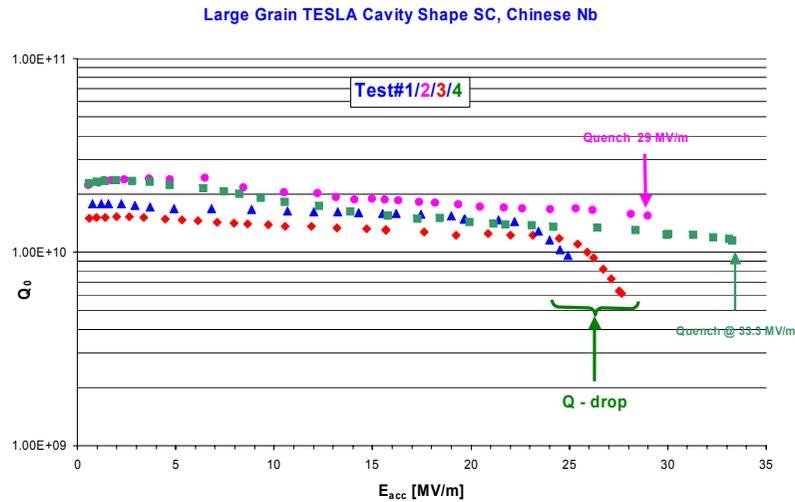


Other Developments: large grain/single crystal niobium(1)

- Initially large grain and single crystal niobium cavities from CBMM material were manufactured and tested at Jlab with encouraging results
- Several niobium manufacturers (W.C.Heraeus, Ningxia) offer large grain material now and other labs (Cornell, DESY) have manufactured and tested single cell cavities.
- At DESY single cell cavities gave gradients in the vicinity of 40 MV/m after horizontal EP.
- At Cornell a gradient of 30 MV/m was achieved after vertical EP
- At Jlab material from the 3 vendors was evaluated and gradients between $31 \text{ MV/m} \leq E_{\text{acc}} \leq 34.5 \text{ MV/m}$ were measured after BCP only
- At DESY a 9-cell cavity from large grain niobium has been accepted from ACCEL, two more cavities are in fabrication
- At Jlab two 9-cell TESLA cavities are being manufactured; anticipated completion and testing after BCP is in August/September

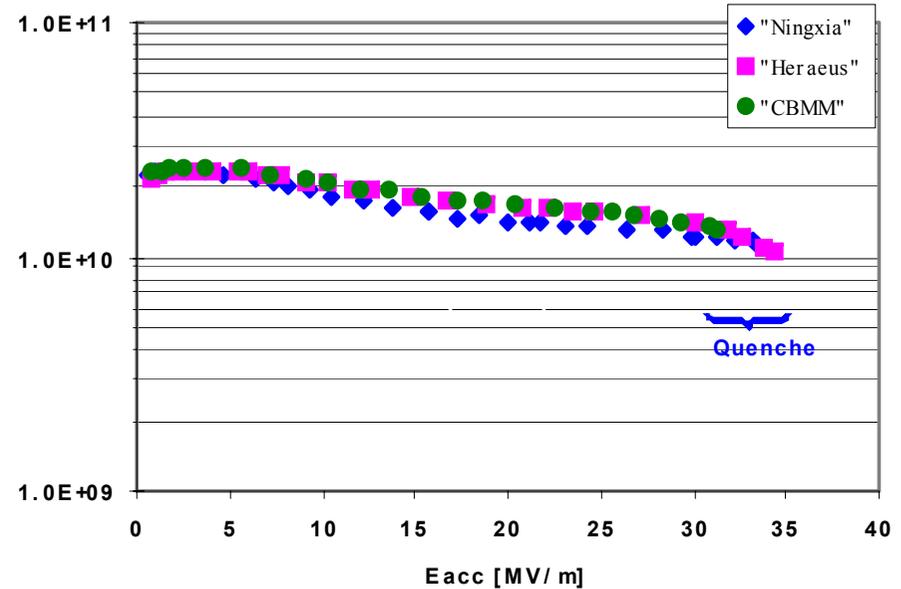
Other Developments: large grain/single crystal niobium(2)

Test results from recent tests at Jlab



Potential benefits:

- lower costs at comparable performance
- very smooth surfaces with bcp, no EP
- streamlining of procedures/QA
- less spread in data?



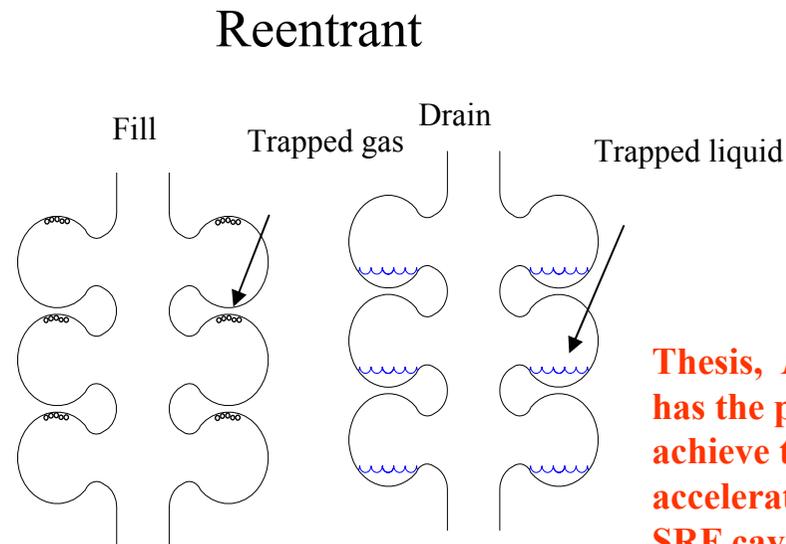
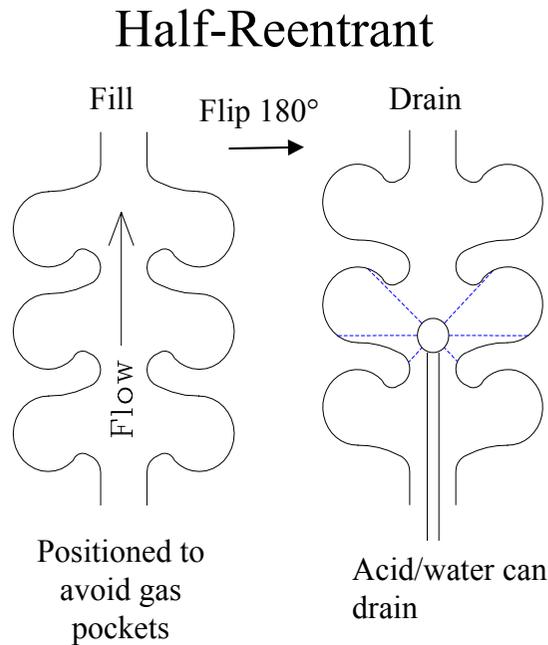
Three 9-cell cavities from large grain Nb are in fabrication (Fa. ACCEL) (courtesy of W. Singer)



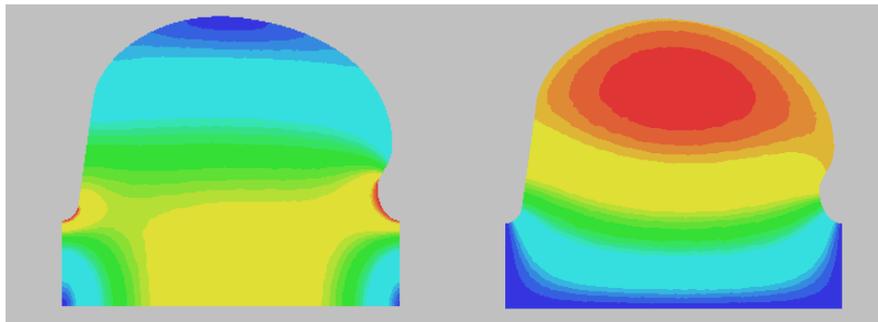
The surface is more shiny after BCP. The steps at grain boundaries are more pronounced as in polycrystalline material



High Gradient: Half-Reentrant Cavity



Thesis, M. Meidlinger has the potential to achieve the highest accelerating gradient in SRF cavities >50 MV/m



Electric field contours

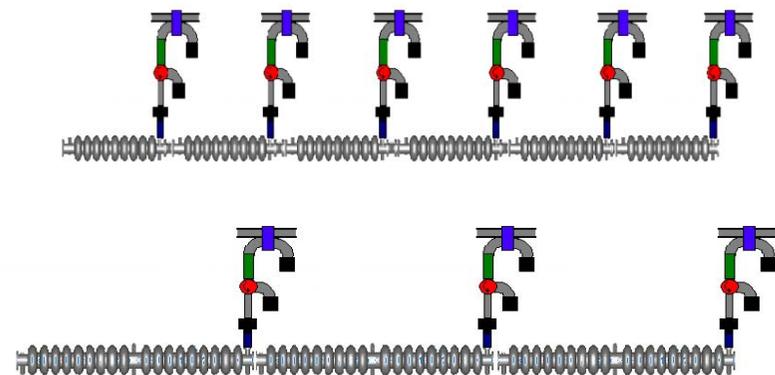
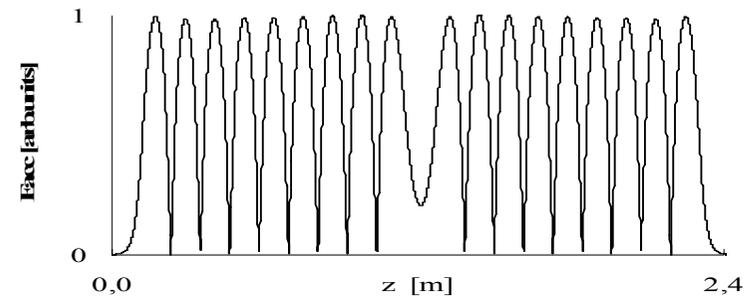
Magnetic field contours

	TESLA	Reentrant	Half-Reentrant
k_c (%)	1.87	1.57	1.52
B_p/E_a [mT/(MV/m)]	4.26	3.55	3.51
E_p/E_a	2.0	2.26	2.40
$R/Q \times G$ (Ω^2)	30510	38350	39363

Superstructure: cost savings

Superstructure idea developed by J. Sekutowicz at DESY (Phys.Rev.STAB 1993)

- Two 9-cell cavities are connected by a larger diameter beam pipe of $\lambda/2$ length to form a weakly- coupled 18-cell structure
- 2 HOM couplers at the interconnecting pipe and one at each cavity end provide sufficient HOM damping below BBU limit
- Each sub-unit has integrated He – vessel and tuner
- Major cost reduction due to shorter length and much less components (couplers)
- Concept successfully tested at DESY
- Development of sc joint between cavities underway



SUMMARY

- SRF technology has developed to a point ,were “moderate” performance levels of $15 \text{ MV/m} < E_{\text{acc}} \leq 20 \text{ MV/m}$ for CW application (ERL, FEL...) are achievable
- For these devises – especially for **higher currents** – the main issues are sufficient HOM damping
- For **high gradient** applications such as the XFEL and ILC the main issues are **reliability** and **reproducibility** of high performance, mainly limited by contamination control issues
- The use of **large grain** or **single crystal niobium** is potentially an alternative to present technology and in combination with a super-structure configuration could **reduce the cost** of a machine such as the ILC significantly

ACKNOWLEDGEMENT

I would like to thank my colleagues for providing me with information for this review: L. Lilje, D. Reschke, J. Sekutowicz, W. Singer, R. Geng, T. Grimm, D. Meidlinger, R. Rimmer, G. Ciovati, K. Saito, K. Ko.