# Overview of ongoing Research on RF Superconductivity limits

hedwards, ANL 9-24-04

# Motivation for talk

- Where are we putting effort now,
- Do we have enough emphasis on most important areas? And enough collaboration?
- Is there reasonable balance in the overall program? (basic understanding vs observational)
- Background for this morning>s discussion

Talk includes material provided- has overlap with some of the other presentations, but not necessarily balanced relative to all we have heard (and some overlap with summary talks)

# Information provided by:
## (What they thought important)

- Saito
- Campisi
- Ben-Zvi
- Calatroni
- Claire, Visentin
- Grimm
- Kneisel, Wu
- Padamsee
- Shepard
- Tajima
- Bauer/Lee
- Proch
- Palamieri

# Topics, categories

- Toward Higher Effective Acceleration or Beam current
  - Different cavity shapes
  - Packing factor
- Basic understanding
- Measurements of properties
- Surface characterization
- Process optimization
- Films and materials other than Nb
- Nb-plus cavity development
- Programatic R&D

1. Toward Higher Effective Acceleration or Beam current

Different cavity shapes

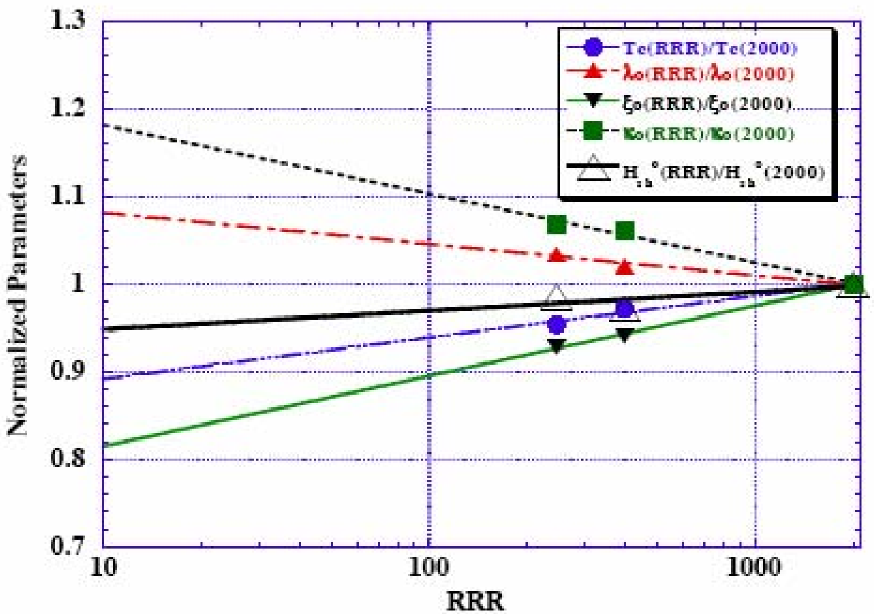
Packing factor

- Sekutowiczet
- Saito
- Padamsee
- Ben Zvi

Saito

# Cure for the high gradient : Eacc~50MV/m

**NO hope in the further material improvement**




**The hope only for the new cavity shape with smaller Hp/Eacc ratio**
**Hp/Eacc ~ 35 Oe/(MV/m) for Eacc=50MV/m**
**e.g Pill box cavity without beam tube**
**Hp/Eacc = 30.5 Oe/(MV/m) , Eacc= 57.4 MV/m**

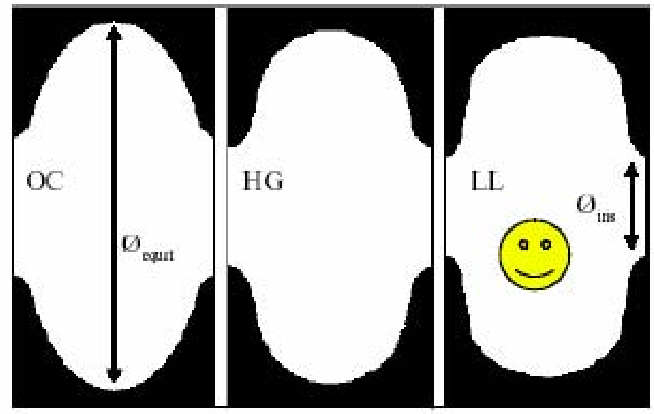



Figure 1: Geometry of three inner cells.

Table 1. Parameters of inner cells

| Parameter | | OC | HG | LL |
|---|---|---|---|---|
| $Ø_{equator}$ | [mm] | 187.0 | 180.5 | 174.0 |
| $Ø_{iris}$ | [mm] | 70.0 | 61.4 | 53.0 |
| $k_{cc}$ | [%] | 3.29 | 1.72 | 1.49 |
| $E_{peak}/E_{acc}$ | [-] | 2.56 | 1.89 | 2.17 |
| Hp/Eacc | [Oe/(MV/m)] | 45.6 | 42.6 | 37.4 |
| R/Q | [Ω] | 96.5 | 111.9 | 128.8 |
| G | [Ω] | 273.8 | 265.5 | 280.3 |
| R/Q·G | [Ω·Ω] | 26422 | 29709 | 36103 |

byJ.Sekutowiczet al.

JLAB LL shape is expected 47MV/m as a realistic cavity shape.

Saito

# 8-cell structure and Superstructure

If keep the same field error as the current TESLA 9-cell cavity, the number of cells is 8 as following:

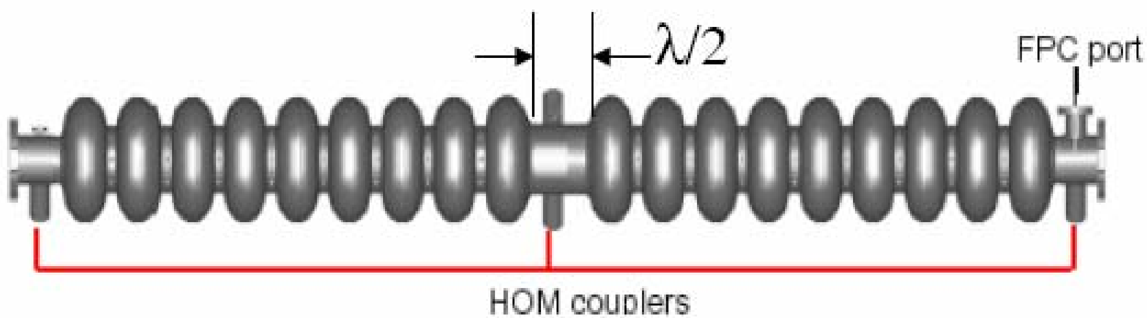
$$\frac{9^2}{1.87}\cdot\delta f = \frac{N_c^2}{1.49}\cdot\delta f \Rightarrow N_c = 9\cdot\sqrt{\frac{1.49}{1.87}} = 8.03 \cong 8$$

However, the shorter structure losses the fill factor and resulted in lower energy reach.

2 x 8-cell superstructure can solve this problem.

**Example:**

**In a 18-cell structure, field error is serious by a factor 4 than a 9-cell. However, if one connects the two 9-cell structure through one beam pipe of a λ/2 wave length, the problem is reduced much.**



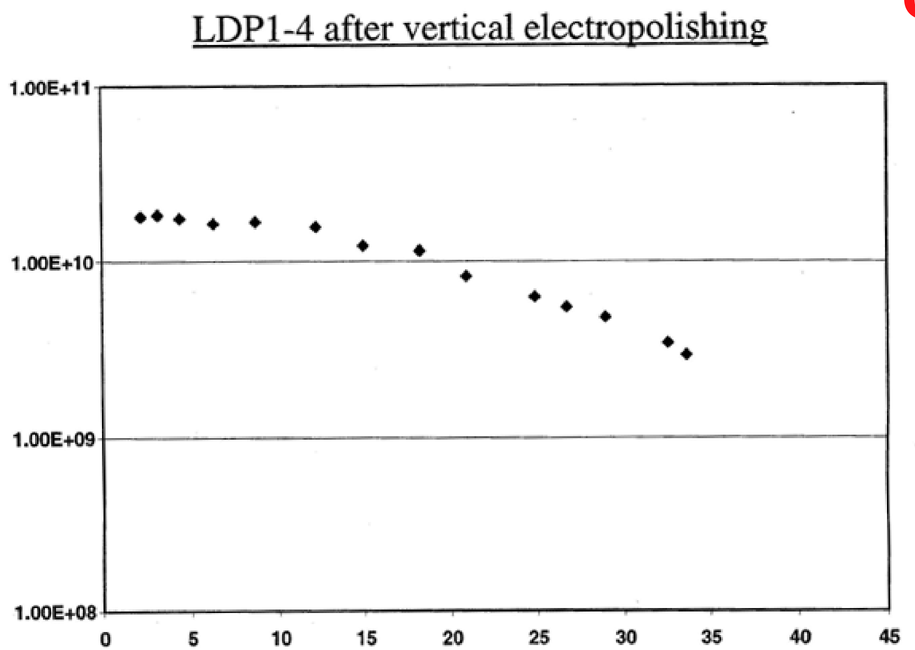

2x9-cell superstructure proposed for the TESLA800

# Cornell Future R&D Program on Hi Grad

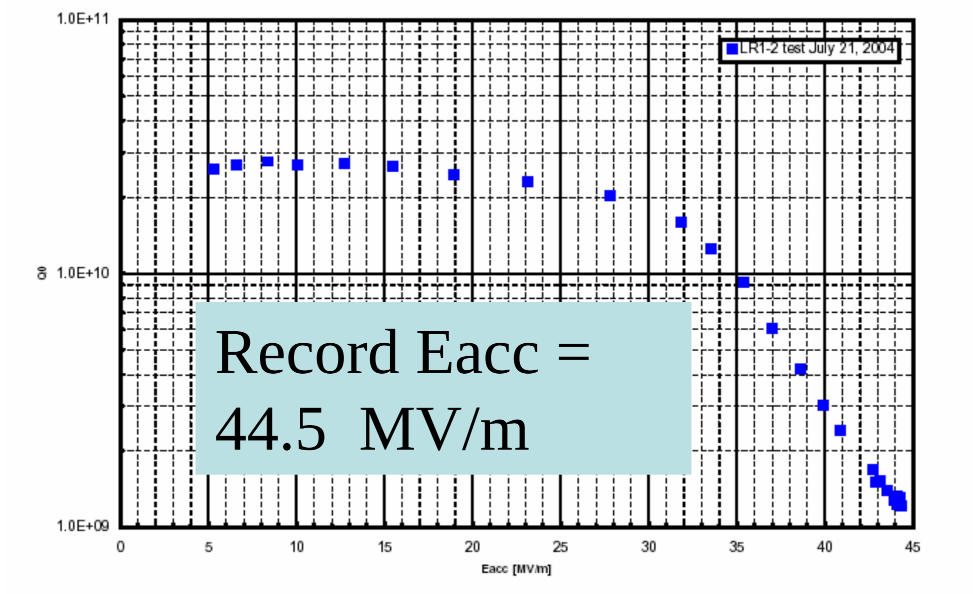
Explore new cavity geometry/new operating mode

- Push for higher Eacc by reducing surface magnetic field which sets the ultimate limit for Nb
- Record Eacc reached

# Cornell First Results

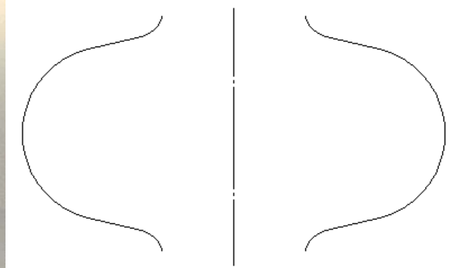



10 20 30 40 MV/m

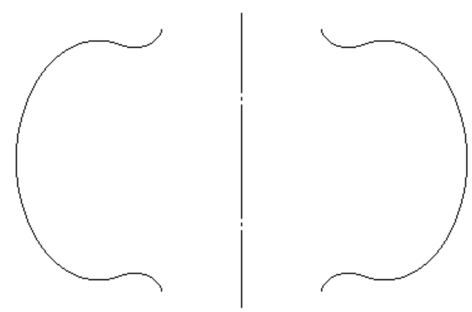



Record Eacc = 44.5 MV/m

TESLA shape



New shape

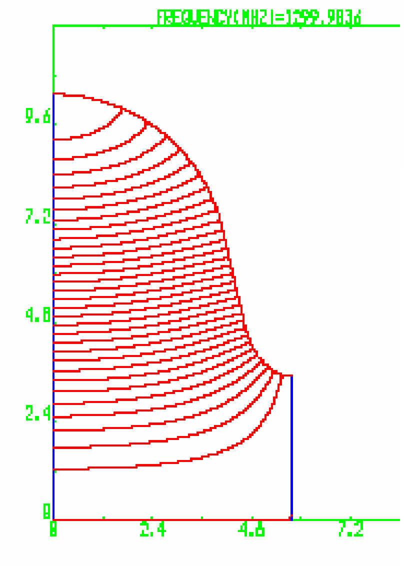


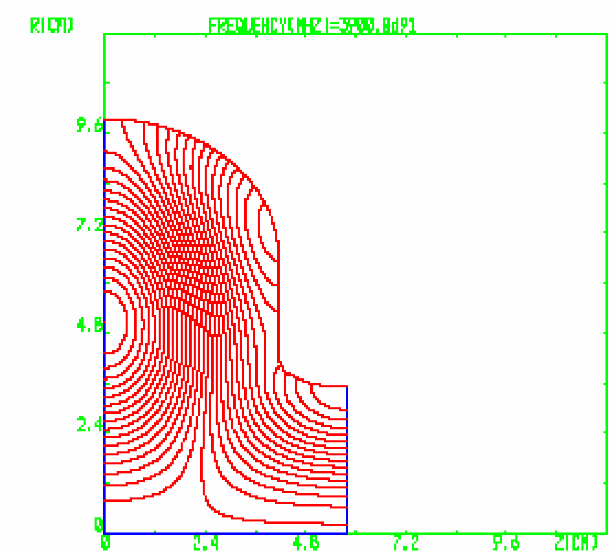
New Idea

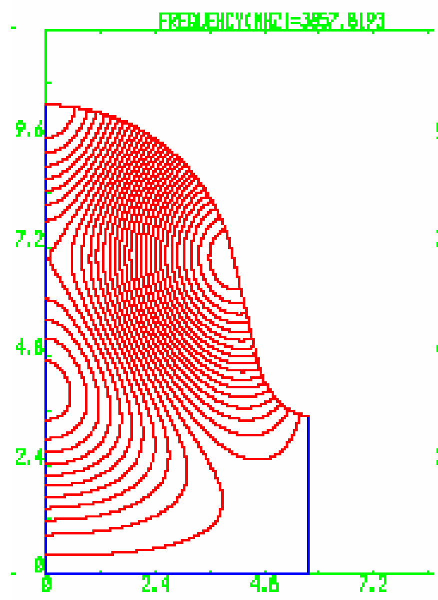
# HOW TO INCREASE TESLA'S ACCELERATING RATE AT LEAST BY 30%

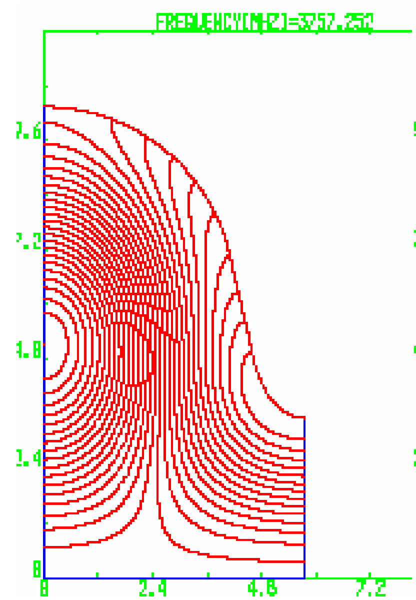
Cornell

Valery Shemelin









Idea in very early stage !

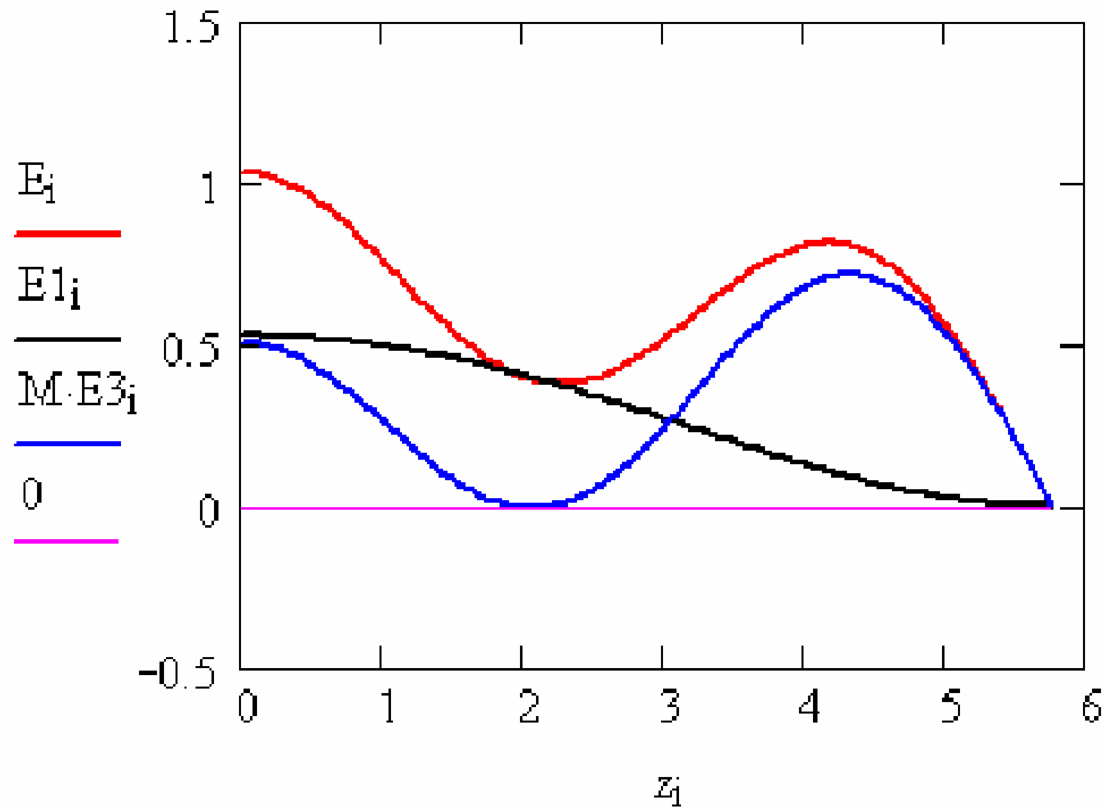


Fig. 4: Fields on the axis.

## 2 mode cavity

$$E = E_1 \cos\theta + M\, E_3 \cos 3\theta$$

$$H = H_1 \sin\theta + M\, H_3 \sin 3\theta$$

$$H_{max} = H_{max\text{-}tesla}$$

$$E_{max} = E_{max\text{-}tesla}$$

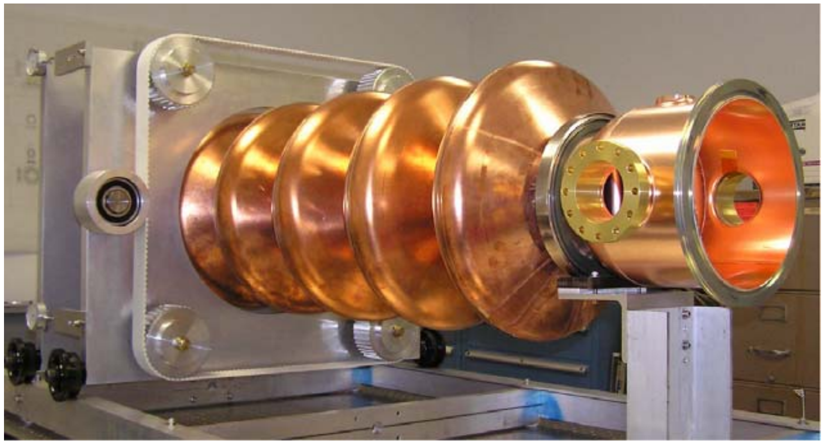
$$E_{acc} = 1.30\, E_{acc\text{-}tesla}$$

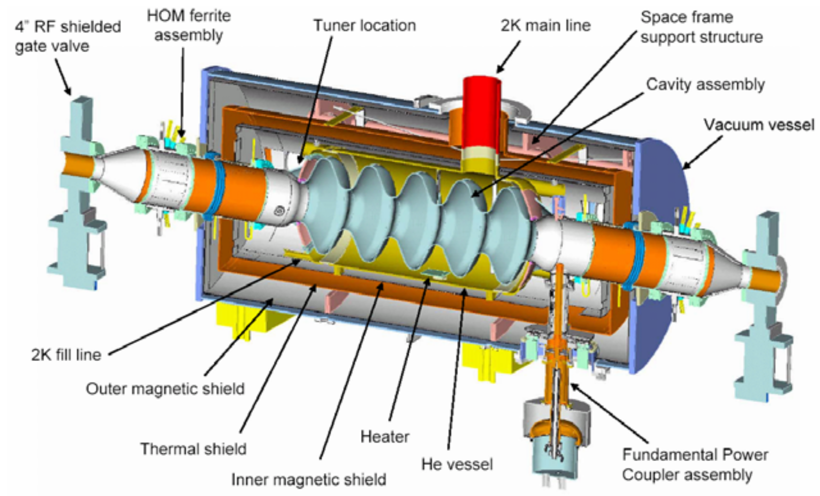
# Many Challenges Remain
# Is 30% payoff enough?

- Does 3rd harmonic multipactor?
- End-cell tuning needed
- Need two active (independent) tuners
- Must have good phase control of 2 modes
- Need RF source of two frequencies
- Higher frequency mode components (about 50%) will have more losses
- Need to study effect of 3rd harmonic on bunch emittance and energy spread.

# Ampere-Class ERL Cavity

## Ben Zvi BNL






**Objectives:**

1. Low loss factor
2. High BBU threshold

**Principles:**

1. Low frequency elliptical cavity
2. Large iris (17 cm diameter)
3. Huge beam tube (24 cm dia.)
4. External ferrite HOM dampers

**Cryomodule is under construction, in collaboration with AES and JLAB.**

## 2. Basic understanding

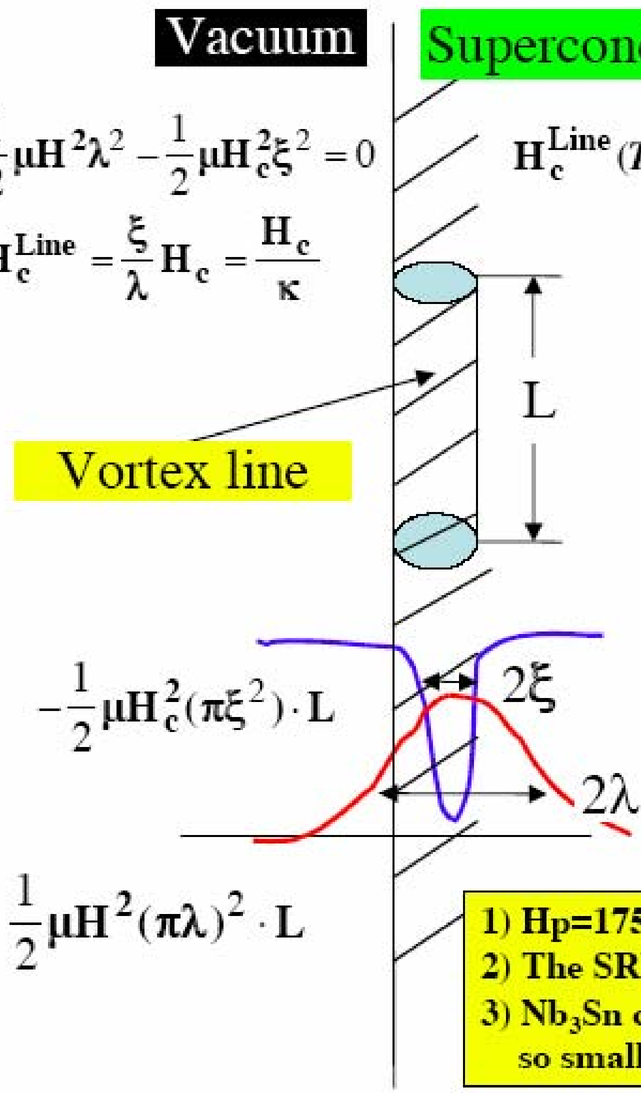
- Overview, Gurevich
- Vortex line nucleation, Saito
- (Q slopes, in summary)

Saito

# Field limitation of vortex line nucleation

$$\frac{1}{2}\mu H^2\lambda^2 - \frac{1}{2}\mu H_c^2\xi^2 = 0$$

$$H_c^{Line} = \frac{\xi}{\lambda}H_c = \frac{H_c}{\kappa}$$

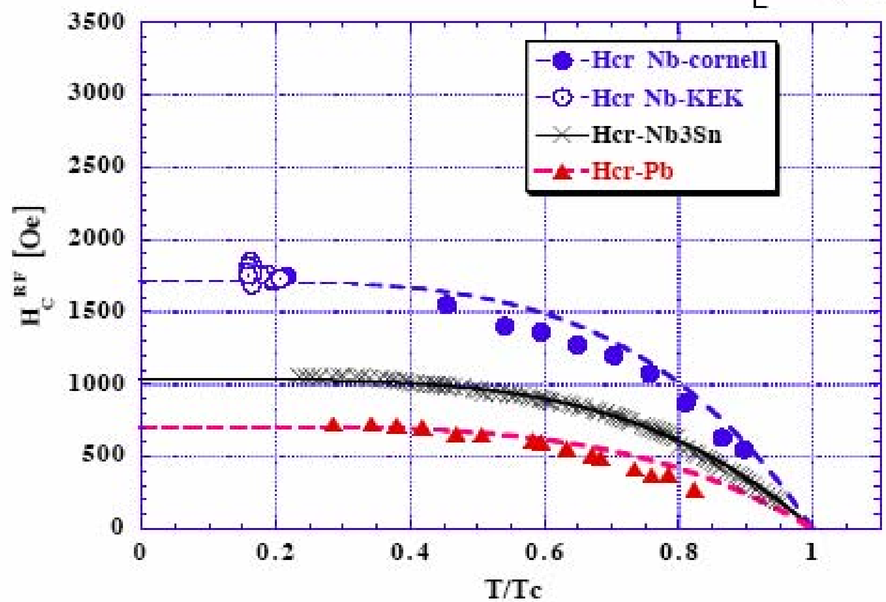



$$-\frac{1}{2}\mu H_c^2(\pi\xi^2)\cdot L$$

$$\frac{1}{2}\mu H^2(\pi\lambda)^2\cdot L$$

Effective field strength

$$H_c^{Line}(T) = \frac{\xi(T)}{\lambda(T)}\cdot\sqrt{2}H_c(T) = \frac{\sqrt{2}H_c(T)}{\kappa(T)} = \sqrt{2}\frac{H_c(0)}{\kappa(0)}\cdot\left[1-\left(\frac{T}{T_c}\right)^4\right]$$

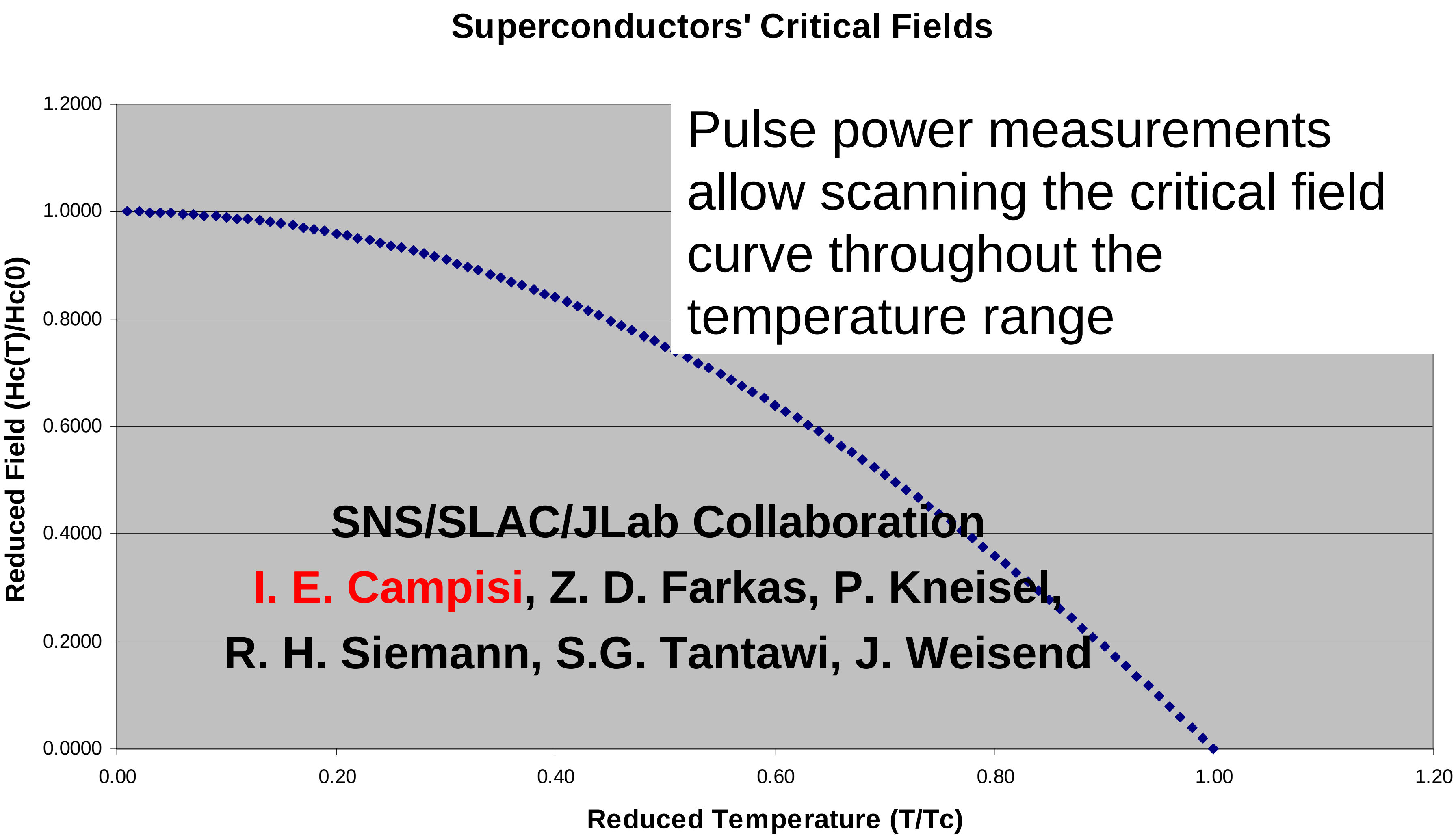



1) Hp=1750±50 Oe with Nb cavity → Eacc ~ 40MV/m
2) The SRF technology is meeting the theoretical limit.
3) $Nb_3Sn$ cavity has a very larger k(0), therefore the critical field is so small.

## 3. Measurements of SRF properties

- Campisi,
- Kneisel

# Limiting RF fields in Superconductors at X-band



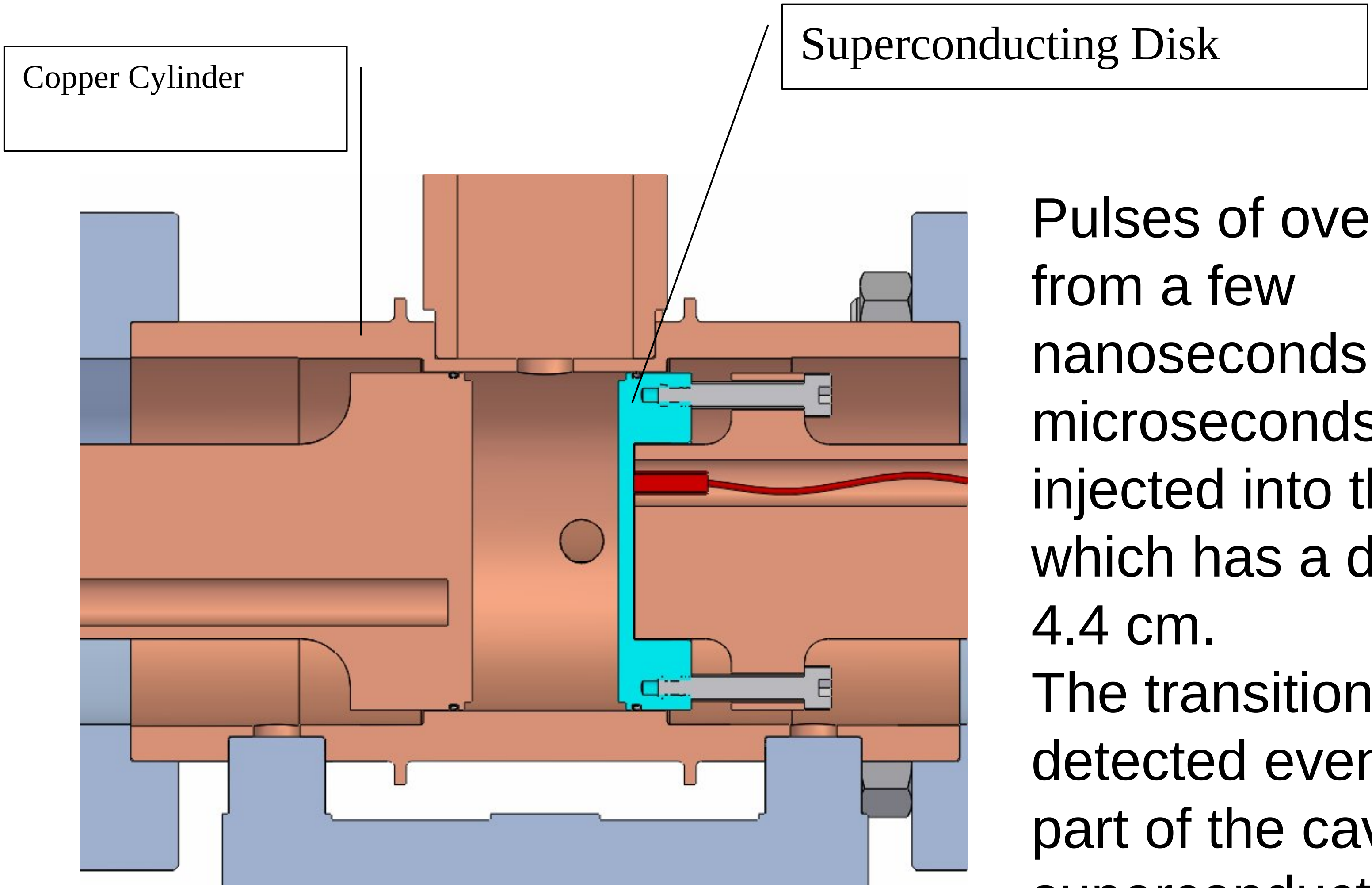

Pulse power measurements allow scanning the critical field curve throughout the temperature range

**SNS/SLAC/JLab Collaboration**

**I. E. Campisi, Z. D. Farkas, P. Kneisel,**
**R. H. Siemann, S.G. Tantawi, J. Weisend**

Campisi

# Modified Copper TE011 cavity




Pulses of over 100 MW from a few nanoseconds to a few microseconds can be injected into the cavity, which has a diameter of 4.4 cm.

The transition can be detected even if only part of the cavity is superconducting.

# R&D Activities at JLAB(1) Kneisel

- Investigation of baking effect on single cell cavity
  - Material parameters ($\Delta/kT_c$ , *l*, $R_{res}$, $\lambda_0$) and Q-drop behavior as a function of baking temperature (G. Ciovati,Journ.Appl.Phys, Vol. 93(3), p.1591)
- Investigation of high field Q-drop and Q-slopes on single cell cavity in <u>$TE_{011}$ and $TM_{010}$ modes</u>
  - Evidence of Q-drop in TE mode at higher fields than TM mode and recovery after baking
  - Addition of fast T-mapping system in near future
- Influence of Ta content in Nb on cavity performance ( cost savings)
  - Single cell cavities prepared with BCP, no quench up to $B_{peak}$=133mT for Ta ~ 1200 wtppm

## 4. Surface characterization

- Kneisel
- Claire/ Visentin
- Lee/ Bauer

# R&D Activities at JLAB(2)

Kneisel

- Surface studies on Nb surfaces using SIMS
  - Develop new method to study oxide composition
- Material studies on Nb ( mechanical properties under various conditions)
  - Influence of impurities (O, H) on mechanical properties
  - Develop new methods in collaboration with NIST, Uva
- (Thin Nb film energetic deposition- see later)
  - Good crystallographic and SC properties ($T_c$, RRR) on samples
- Photo-cathodes in SC cavities (not relevant in the context of this workshop)
  - Develop photocathode (Pb, diamond) integrated in SC Nb cavity in collaboration with BNL, DESY

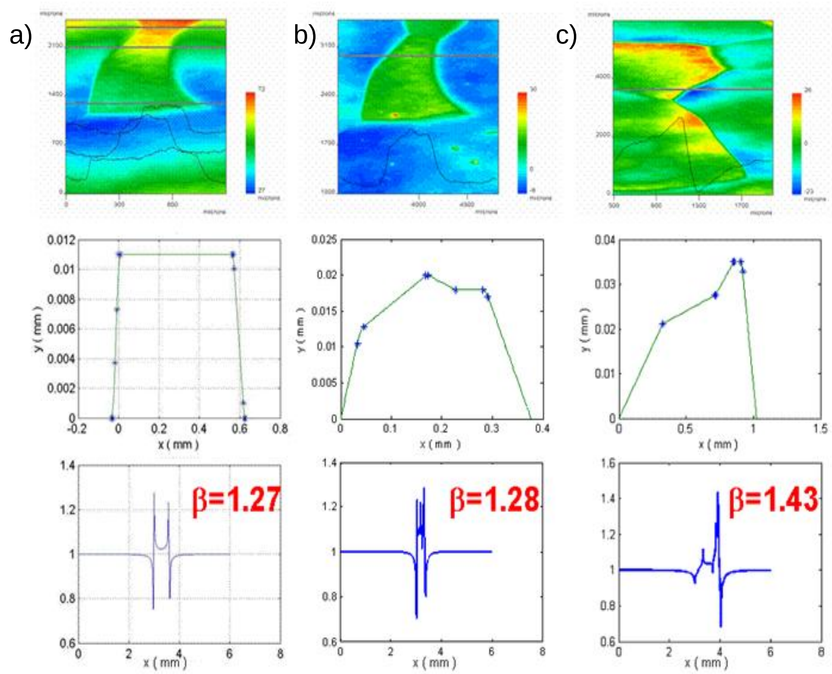
# R & D Activities at CEA-Saclay

Grading X-ray diffraction

Antoine

- <u>PhD collaboration with Stuttgart MPI</u>
- First experiments on mono crystal : signature of the deformation of the Nb lattice by interstitial O. Profiling has been done.

Replica at the quench site




*Contour line of replicas, modelling of the edge profile and β (field enhancement factor) for :*

*a) first quench site,*

*b) same area after 20 µm and quench site @ a new location*

*c) new quench location.*

Local morphology seems to play an important role in the triggering of the quench.

# Collaboration Fnal – ASC/UW on SRF Material Research

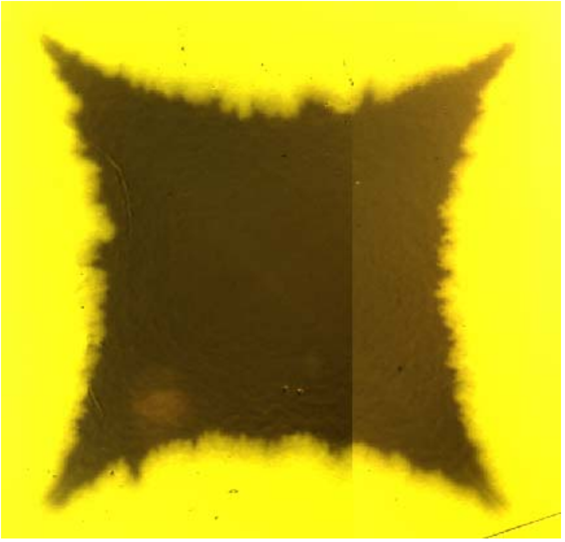
Lee/Bauer

**GOALS:**

- Characterize and investigate state of the art high purity Nb
- Contribute to better understanding of RF surface resistance contribution of grain boundaries

**METHODS:**

- SEM, AES, XPS, profilometry
- Magnetization, transport (RRR, Ic), magneto-optics, cp



Example of magneto-optical image of 5x5 $mm^2$ BCP etched and heat treated sample in 80 mT field (6 K)

P. Lee / P. Bauer – Report on UW-FNAL Collaboration on SRF Materials Research (Thursday afternoon, session II)

-1- Microscopy and Surface Analysis, -2- DC magnetization, -3- Magneto-optics

## 5. Process optimization

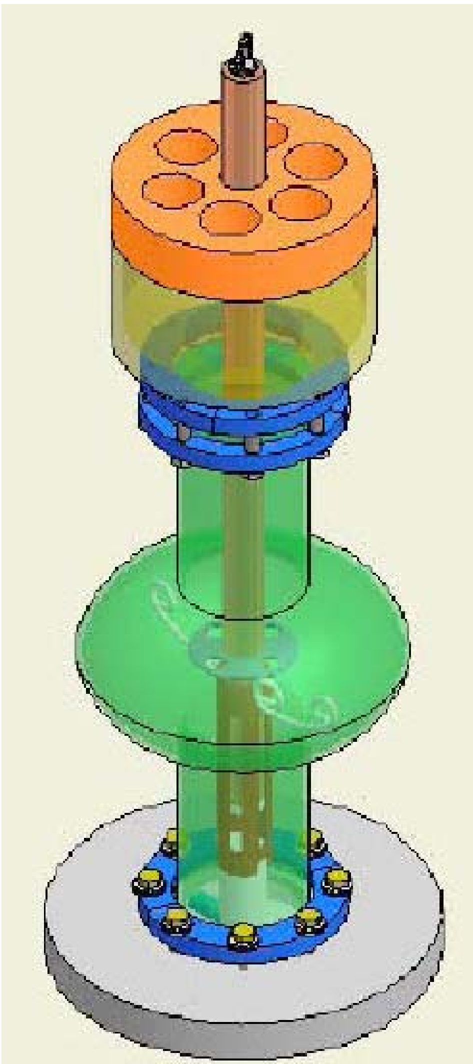
- Padamsee  Vertical EP
- Claire/Visentin- EP realistic sample holder

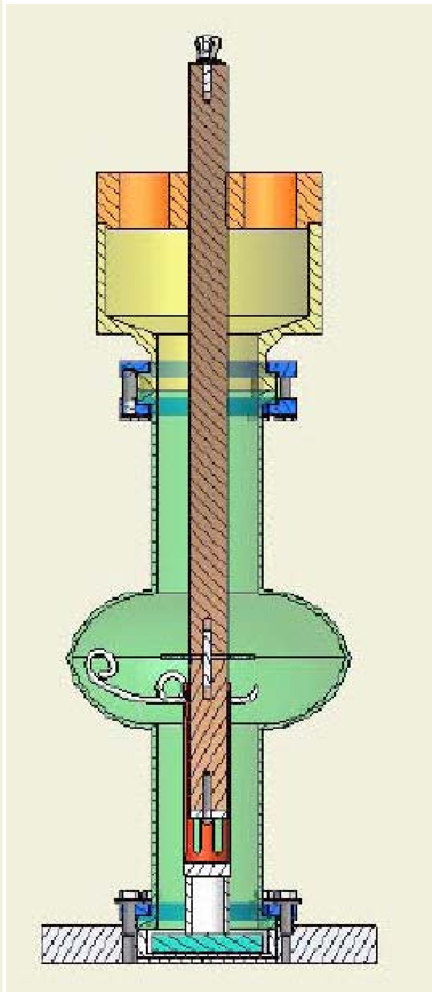
# Cornell Future R&D Program on High Gradient

- 1) Develop vertical electropolishing for multi-cells
  - Less technical complexity?
  - but failed in the past

- 2) Continue Q-slope studies on BCP/EP cavities and companion Auger/SIMS studies

# Cornell- Develop Electropolishing in Vertical Orientation





- Technically less complex than horizontal orientation used at other labs
- Previous attempts failed due to improper stirring
- Special stirrer geometry developed

Reached 35 - 40 MV/m accelerating with single cells, so far…extending to multicells

# R & D Activities at CEA-Saclay

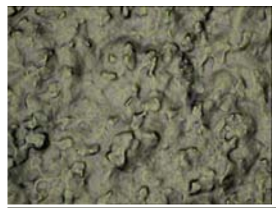
Antoine

## Optimizing EP on samples (rotating sample holder)

@ 16 V :

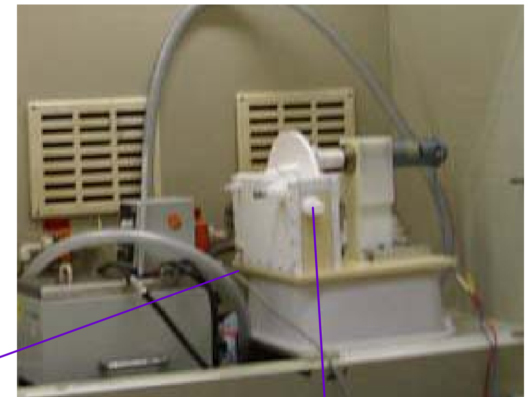
• t = 470mn, $d_{A-C}$ =22 mm, Rem.Thick. = 160 µm

• t = 470mn, $d_{A-C}$ = 92 mm, Rem.Thick. = 80 µm



• t = 300mn, $d_{A-C}$ = 2.2 mm, Rem.Thick. = 157 µm
• *Standard sample holder*

*EP bath*



*Rotating sample holder: (reproduces cavity geometry, exposure to air, rotation….)*

• Rotating anode: surface state differ considerably from what usually found on samples => better tool to estimate optimal conditions on cavities
•Near future:EP optimization with rotating anode with “design of experiments” and mounting of EP facility, transfer optimization from samples to cavities

# R & D Activities at CEA-Saclay

## Grain Boundary and RRR Measurements

- Very low level 4-wires measurement : a lot of trouble with noise
  ( Need further confirmation )
- Indications of non-uniformity of the niobium in depth and lateral

## Q-Slopes and Baking

- Research on Alternative methods to modify Q-Slopes
- Baking studies under atmospheric air
- Integrated System for cavity baking in clean room

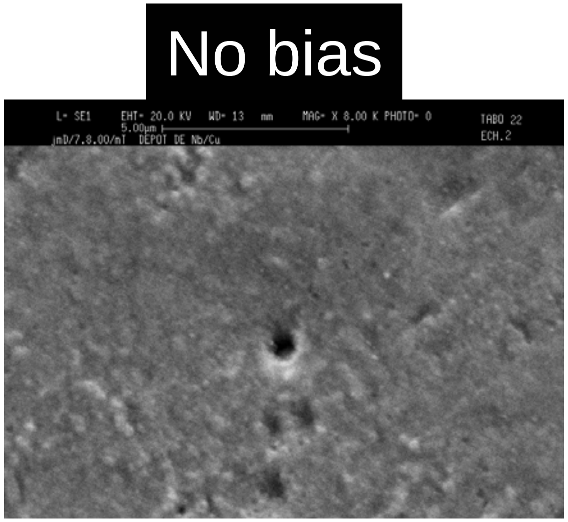
# 6. Films and materials other than Nb

- Calatroni,
- Palmieri
- Genta Wu,
- Tajima

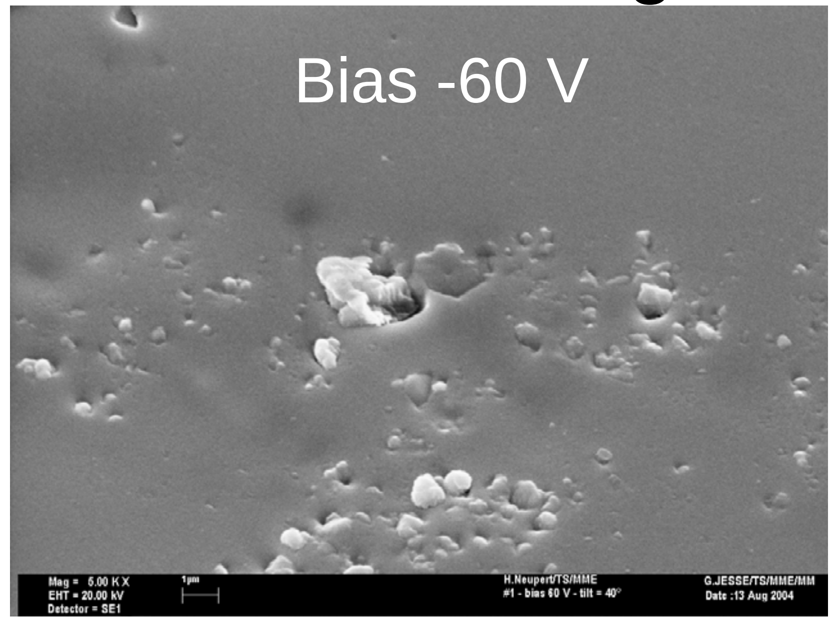
# Research lines at CERN

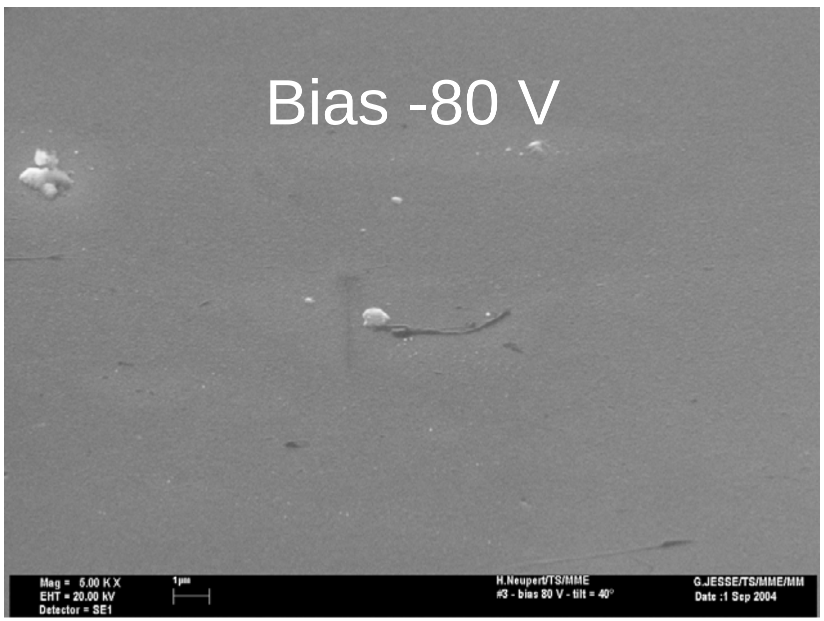
- Effect of roughness
  - Optimisation of substrate preparation – EP: this work is considered as completed, although implementing EP requires a continuous and careful monitoring of all the chemistry parameters
- Film structure – defects
  - In order give more energy to the growing film, and thus more surface mobility to niobium atoms, a bias electrode has been added to the standard sputtering configuration. This should reduce the voids and dislocation density
  - The bias allows noble gas bombardment at energies ~-80V of the growing film, thus removing also those Nb atoms that are loosely bound (typically in non-correct crystal locations). This is also relevant for reducing the roughness
- Oxidation state
  - Surface effects: $Al_2O_3$ cap layers should prevent oxygen and sub-oxides contamination of the Nb film, and at grain boundaries close to the surface

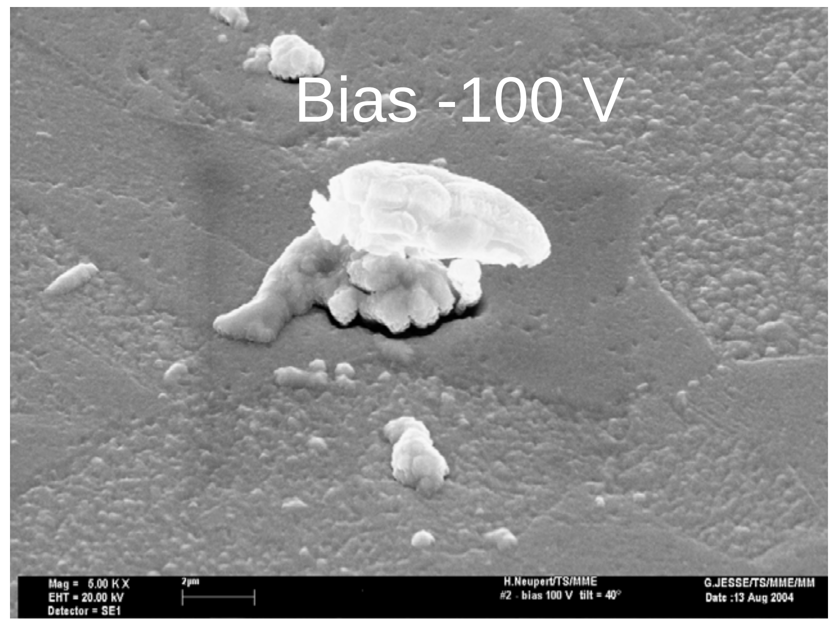
# CERN Bias deposition – First SEM images




5 µm

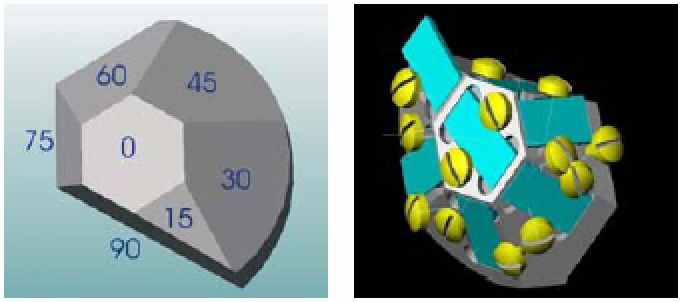


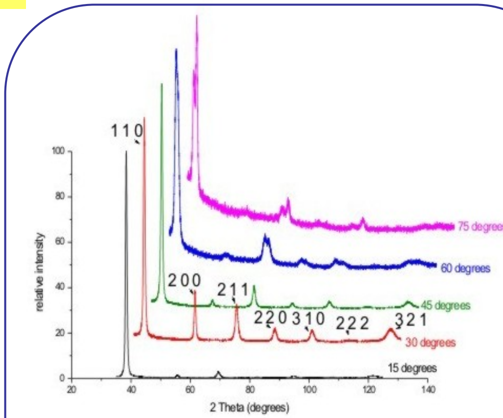



# LNL research on Nb film: investigation of the role of the target substrate orientation on film properties and morphology

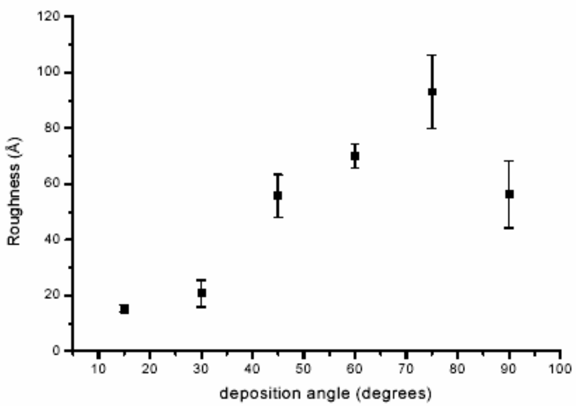
Palmieri



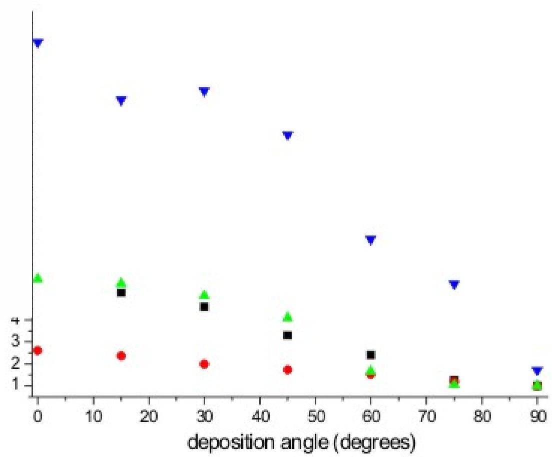

. Multi-angle substrate holders (faces at 0°, 15°, 30°, 45°, 60°, 75°, 90°)

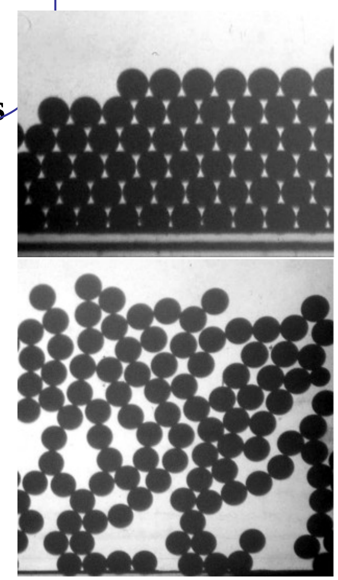



**Normalized X-ray diffraction spectra at various deposition angles**



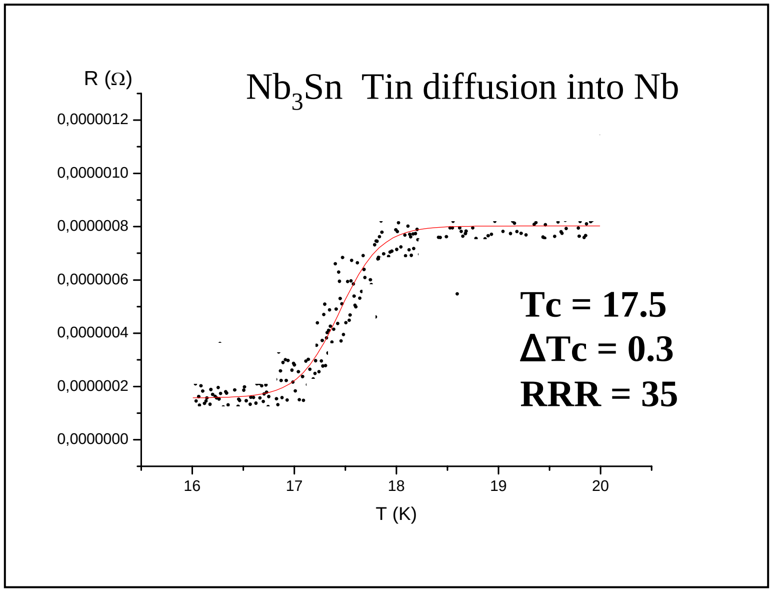

**Average roughness vs. deposition angle**



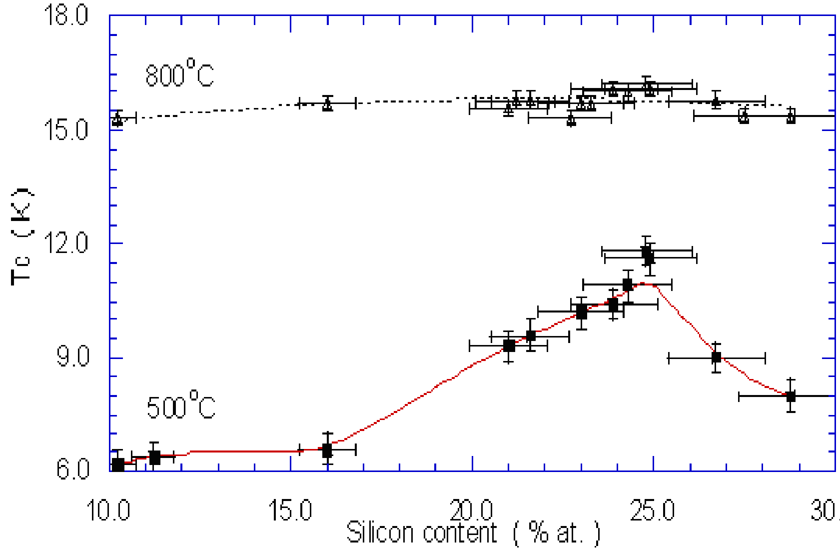
**Growth simulation at 0 and 45 degrees**

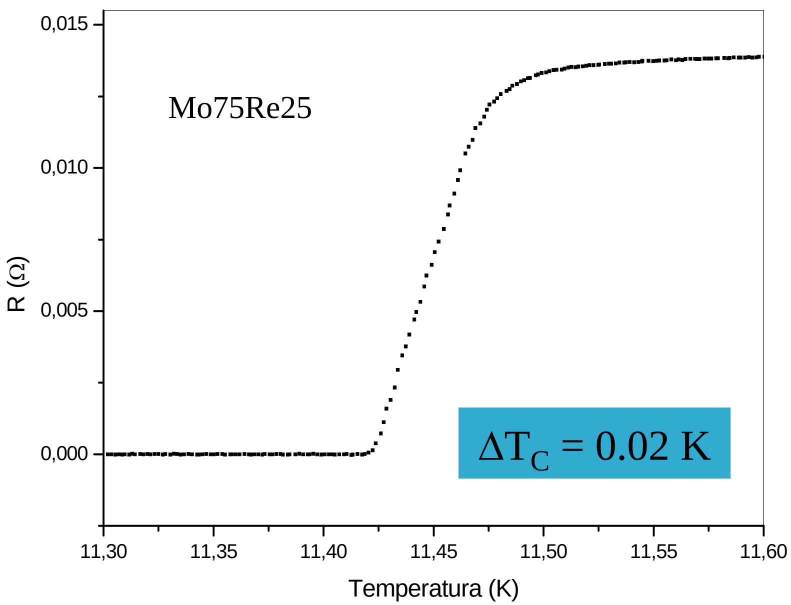
# LNL activity on Superconductors with Tc higher than the one of Nb




Palmieri

*Tc vs Si content for sputtered films before and after in situ post-annealing in SiH4 atmosphere*

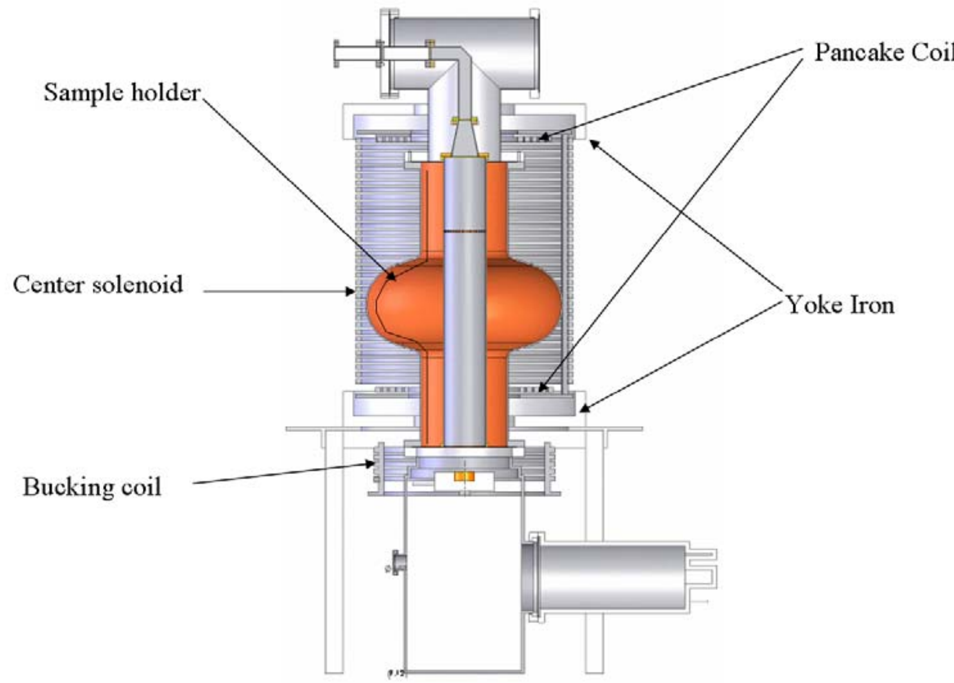


# JLAB thin film related R&D

Based on the result from energetic niobium thin film deposition, three different energetic deposition processes have been pursued in JLAB.

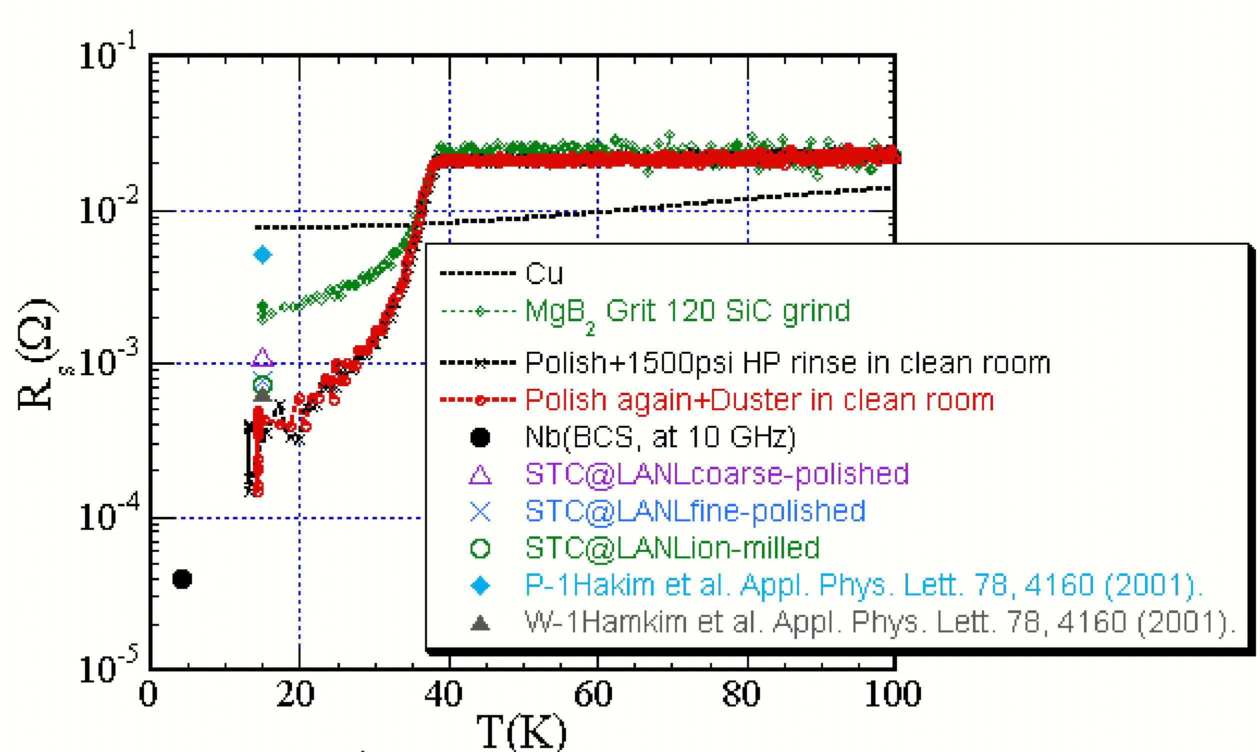
- A prototype ECR cavity deposition system
- A vacuum arc deposition system for single cell
- A pulsed ion deposition process is being used to produce small niobium samples.



# Research at LANL Tajima

- Magnesium diboride ($MgB_2$) has been evaluated as a new material for SRF cavities.

RF Surface Resistance Measurement of HIPped bulk $MgB_2$ at LANSCE of LANL: Results converted to 10 GHz



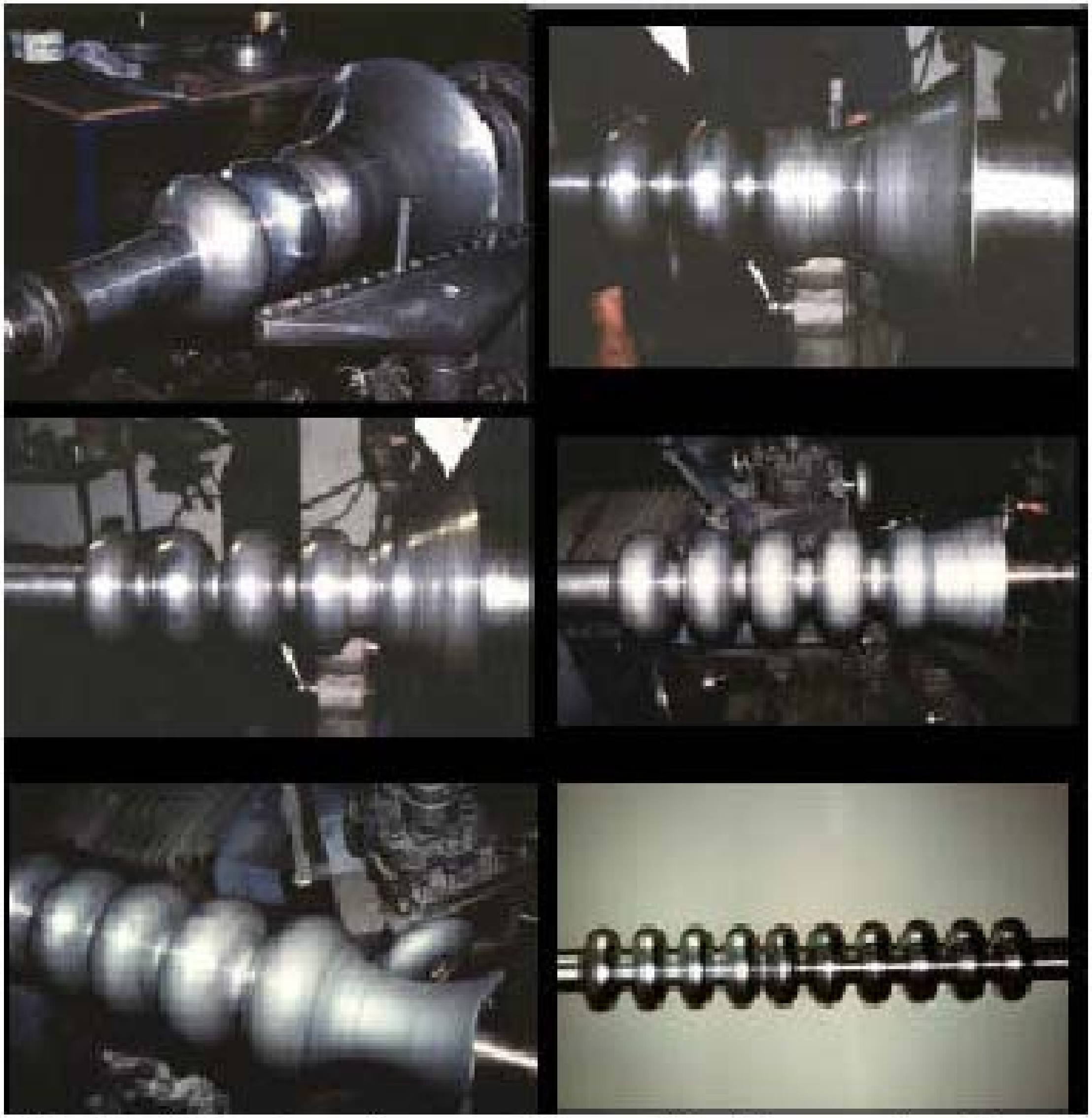

T. Tajima, J. Liu et al., 6th European Conference of Applied Superconductivity, Sorrento, September 14-18

## 7. Nb-plus cavity Developments

- Spinning - Palmieri
- Nb/Cu - Singer, Saito

Palmieri

# Seamless cavity spinning at LNL

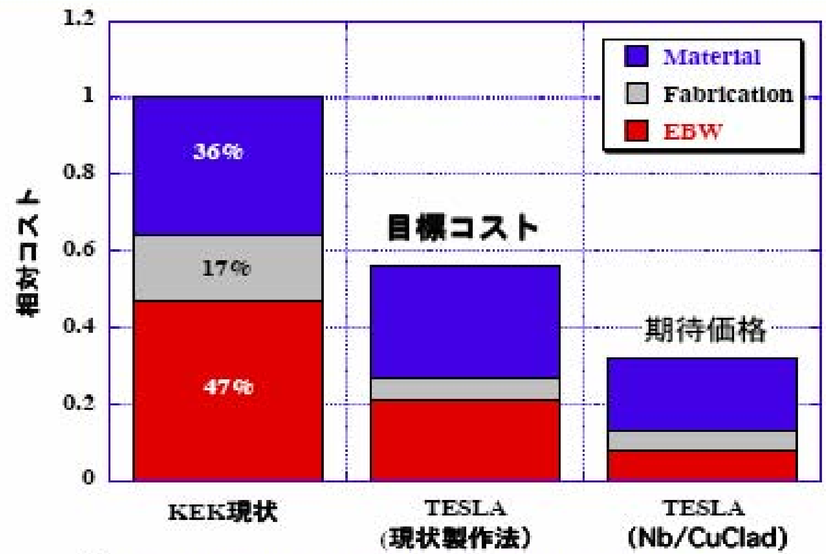


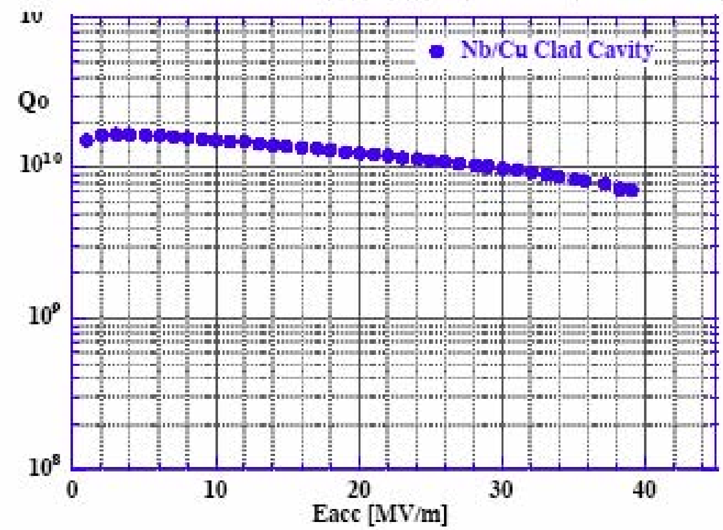
**Cold forming of a multicell resonator from a planar circular blank**

# Japanese Initiative in the Cold LC

Saito

**Cost effective & Reliable cavity performance : Nb/Cu clad seamless cavity**



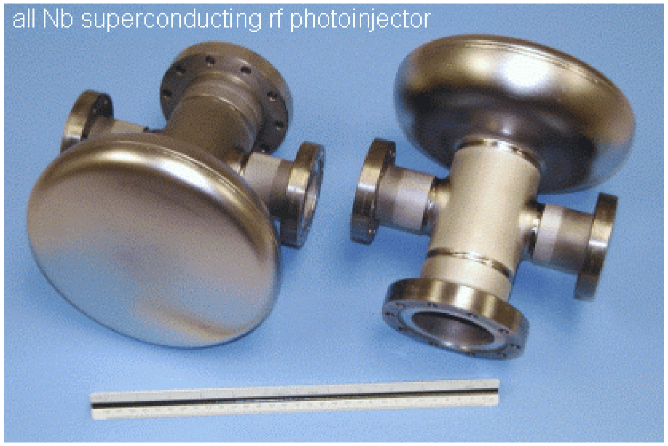
# 8. Programatic R&D

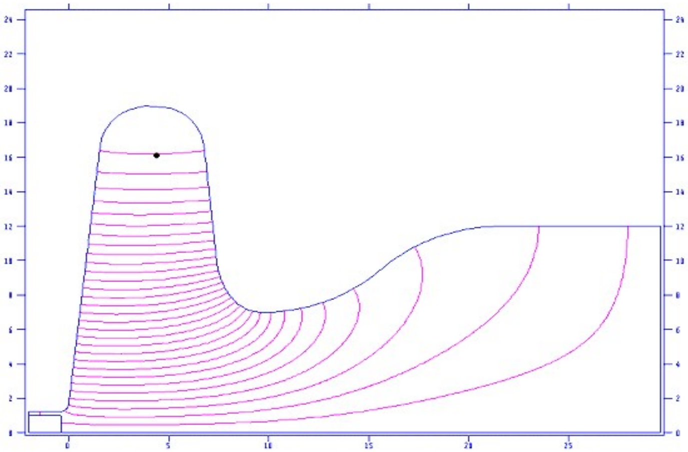
- BenZvi (Gun & cathode)
- Palmieri- low beta
- Grimm "
- Shepard "

# The electron gun

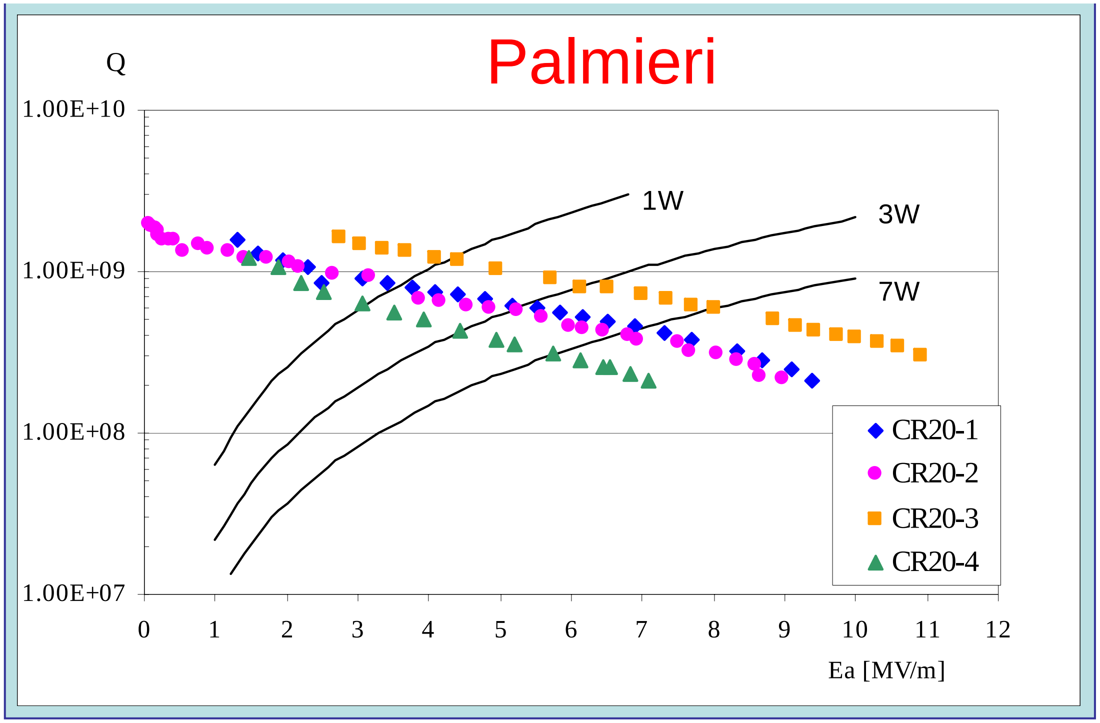
Ben Zvi

- We have an operational 1.3 GHz SRF gun. Initial results gave 0.5 nC pulses. Currently running with a mode-locked laser.
- Design work is done towards a 703.75 MHz, ampere class gun.
- R&D towards SRF compatible photocathode with diamond - secondary emission assisted .



# High β section: ALPI sputtered Nb/Cu resonators

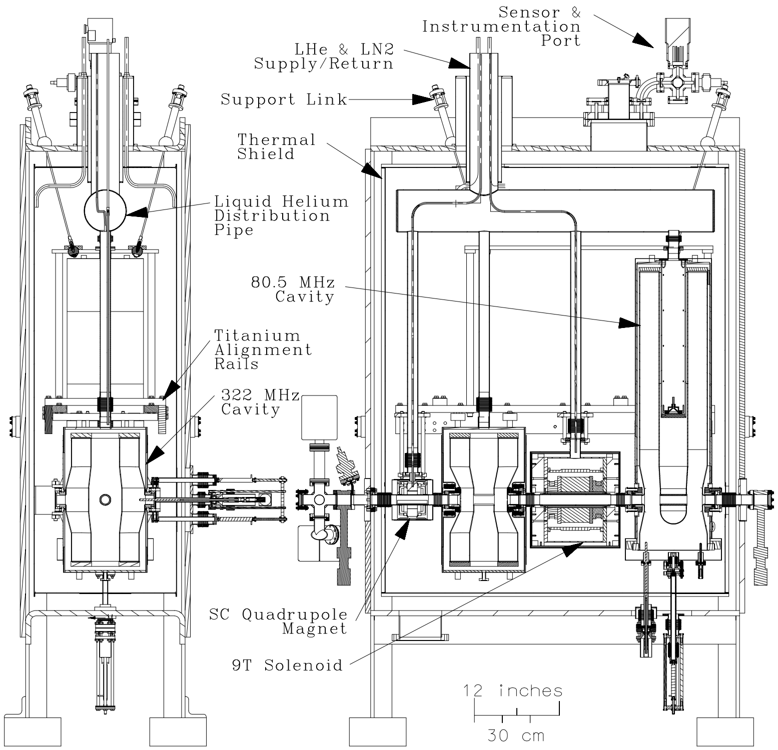


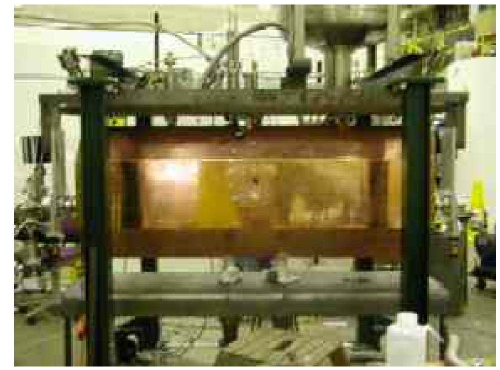

**48 Resonators installed at LNL:**

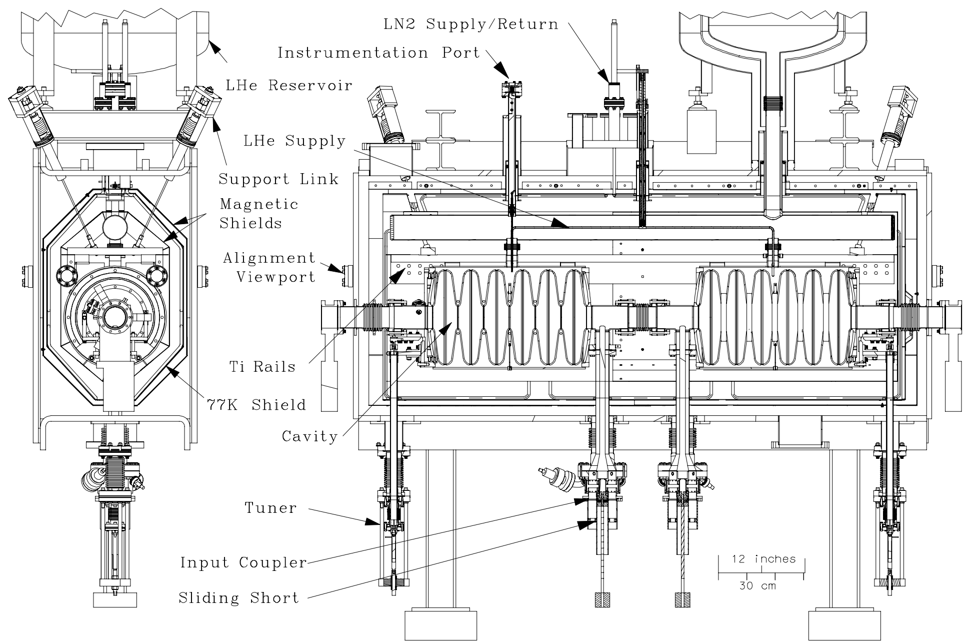
- High termal stability
- Performance improvement with operation time
- No microphonics

Grimm

# Prototype Cryomodules @ MSU [3]





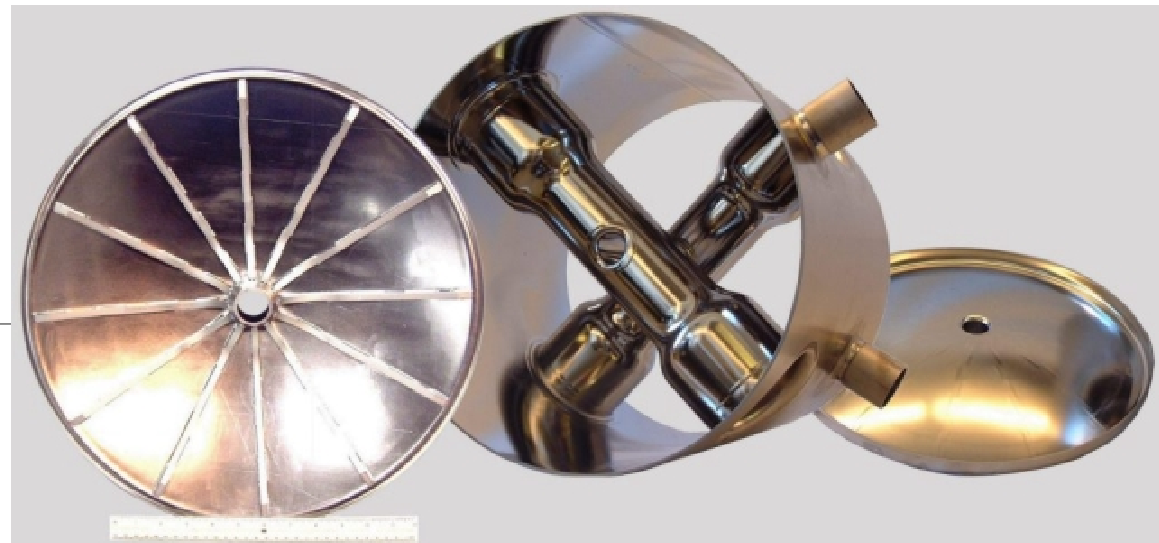
# SRF Techniques Developed @ MSU [4]

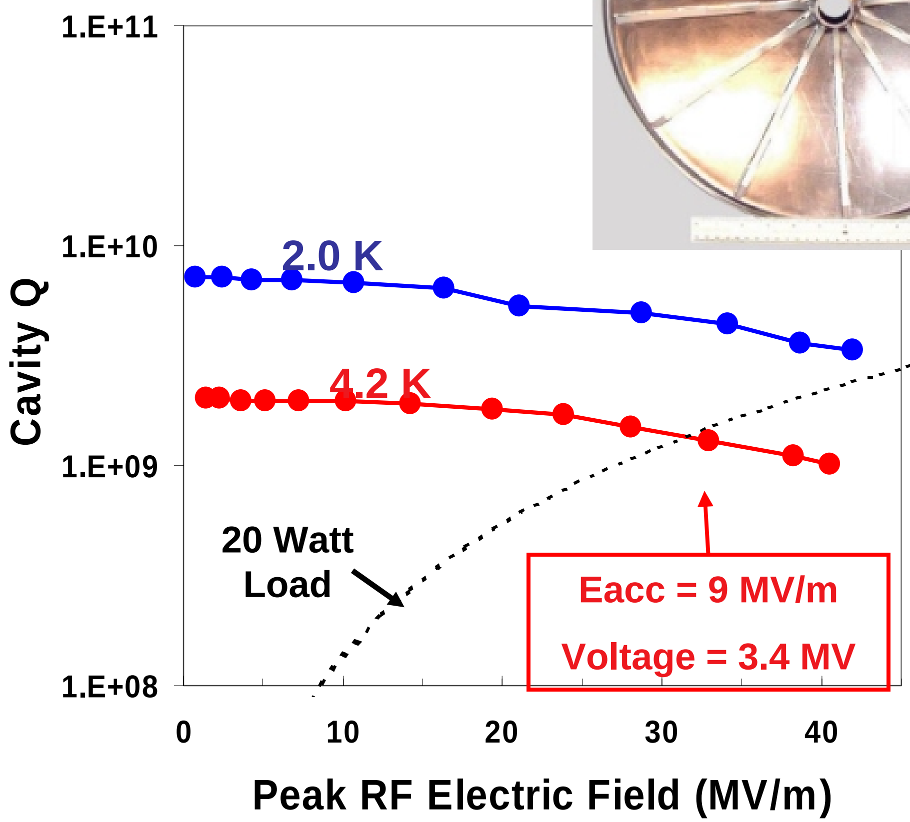
- **Microphonics control in high loaded-Q cavities**
- **Materials Science**
  - **Niobium formability & weld properties**
  - **Improved Nb-helium heat transfer studies**
    - Increased Bpeak
- **Diagnostics of cavity performance**
  - **X-ray tomography**
  - **Boiling helium camera**

# Electropolished, HPR-cleaned TEM cavities exhibit small ‘Q-droop’ at 4.2 K

Shepard ANL

**345 MHz β 0.4 double spoke cavity after electropolishing and before the closure welds**






**Cold-test results after high-pressure water rinse and clean assembly into the test cryostat**

Pioneering Science and Technology

# SRF related R&D at DESY Proch

- **TTF linac:**
  - New cavities (30) and couplers (40)
    - High gradient module (EP), spare modules
- **EC supported R&D (CARE)**
  - Improved components for TTF
    - Cavities, EP, preparation, couplers, tuners, LLRF
- **EC supported R&D (EUROFEL)**
  - Industrialization of modules, new rf source
- **Preparatory R&D for X-FEL**
  - Module test stand, industrialization of major linac components
- **Participation of DESY at ILC** (international linear collider)
  - First meeting at mid Sept., KEK, towards establishing the "Central Design team", WG5: High gradient cavities

More from Dieter

# Stop

# Misc

- Reliability- tuners
- Critical developments- SC flange
- Toward basic understanding of what is important
- Understanding toward efficient cost to produce- what is important
-

# Field Limits in SRF Cavities

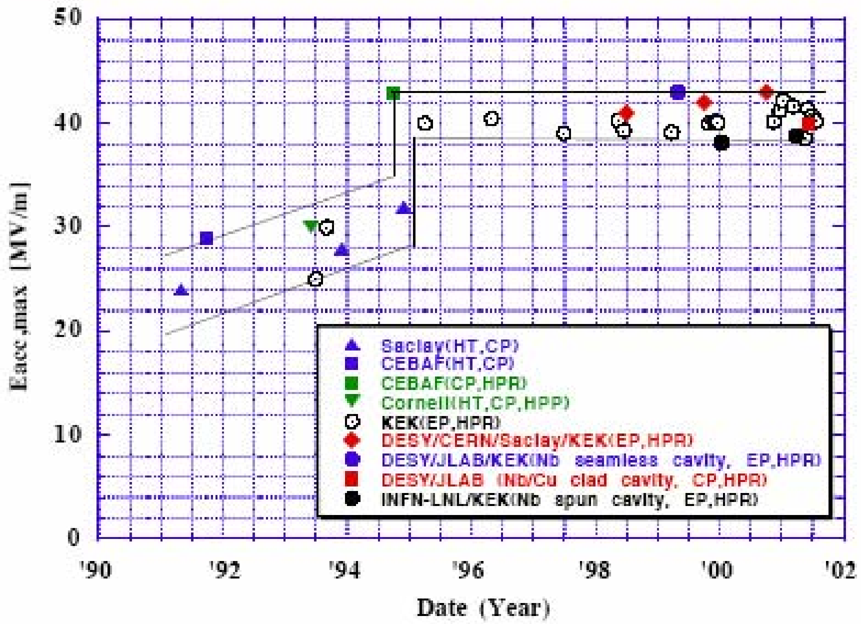



Fig.1 : History of High gradient n L-band Nb single cell cavities

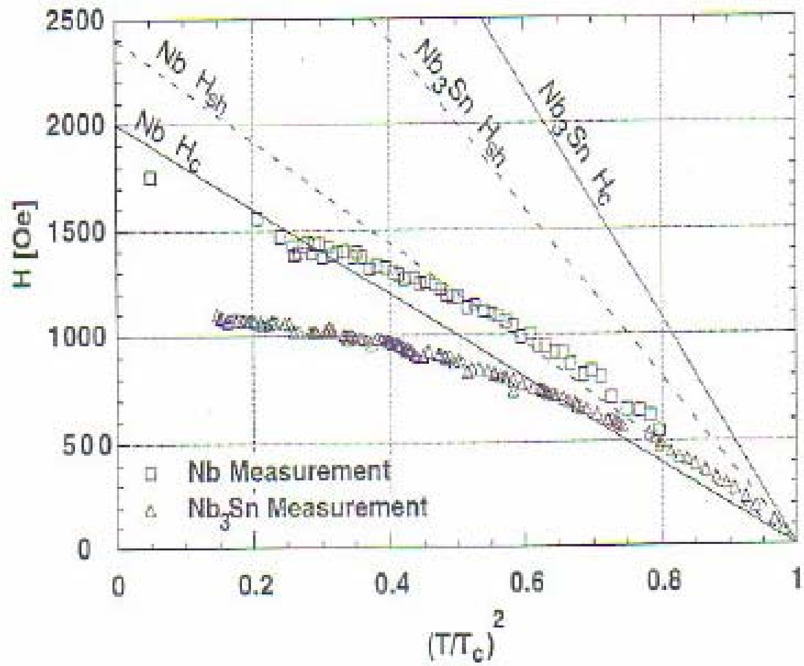
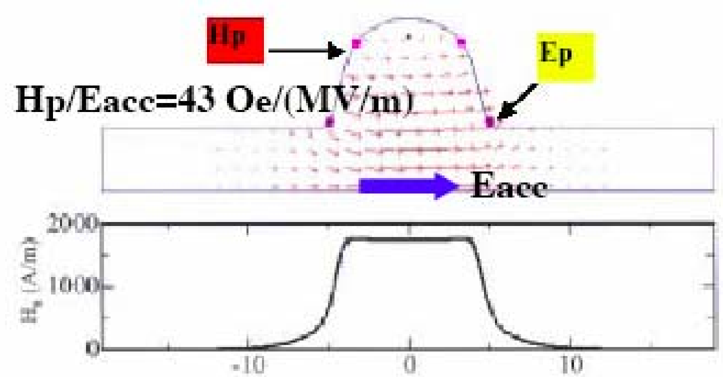



Fig.2 : Critical RF magnetic field by pulse measurement (Cornell U.)

1) Saturation around 40MV/m in gradient (CW)
   Hp = 43.8 x 40 ~ 1752 Oe
2) Hp ~ 1750 Oe with the critical field measurement by pulse
3) Conventional superheating model does not fit the T-dependence of the experimental critical field
4) Why $Nb_3Sn$ cavity has such a small crtical field ?



# The proposed 1-TeV SCSL

Saito

| Energy Reach [GeV] | Gradient [MV/m] | Main LINAC effective length [km] | Main LINAC total length [km] | Tunnel length [km] |
|---|---|---|---|---|
| TESLA500 (510) (1752 17m cryomodules) | 23.4 | 21.8 | 29.78 | 33 |
| TESLA800 (810) (1596 17.6m cryomodules) | 35.0 2 x 9-cell SST | 25.45 | 28.09 | 33 |
| US SCLC 500 (510) (1462 17m cryomodule) | 28.0 | 18.22 | 24.85 | 46.8 |
| US SCLC1000(1020) (2340 17m cryomodules) | 35.0 | 28.590 | 39.78 | 46.8 |
| SCLC500 (510) (1170 17m cryomodules) | 35.0 | 14.58 | 19.89 | 33 |
| SCLC1000(1018) (1752 17m cryomodules) | 45.0 2 x 8-cell SST | 22.64 | 29.53 | 33 |

Our proposals:

1st step, 35MV/m operation, 33km long tunnel,
Save the cost of the first 500GeV SCLC construction.

2nd step, 45MV/m operation used new cavity shape and STT
Re-install new SST modules in the existing 33km tunnel for energy upgrade in future.