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500MHz SCRF Cavity Development for Accelerating Muons

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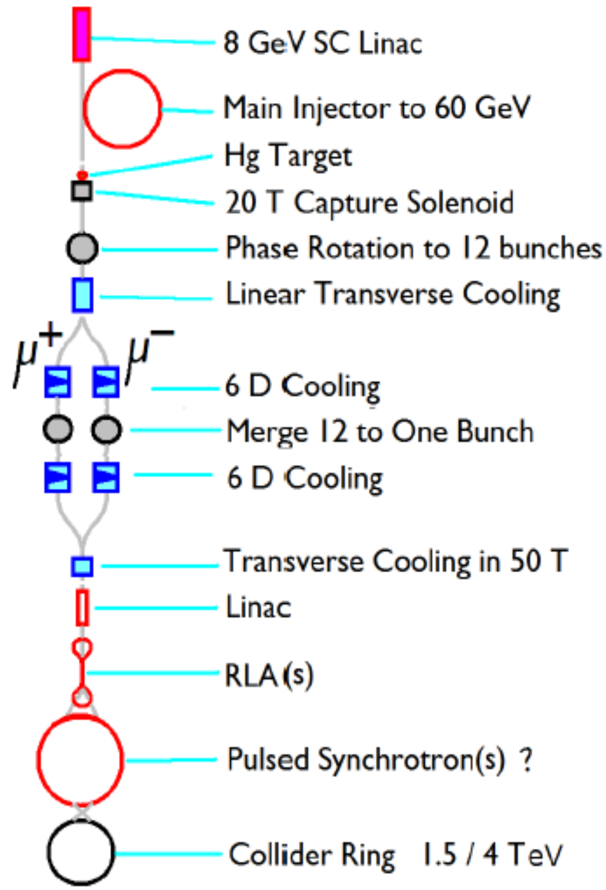
Muon Collider Ingredients

- **Muon Collider comprises these sections (similar to NF)**
  - **Proton Driver**
    - primary beam on production target
  - **Target, Capture, and Decay**
    - create π; decay into $\mu \Rightarrow$ MERIT
  - **Bunching and Phase Rotation**
    - reduce ΔE of bunch
  - **Cooling**
    - reduce long. and transverse emittance
      $\Rightarrow$ MICE $\rightarrow$ 6D experiment
  - **Acceleration**
    - 130 MeV $\rightarrow$ ~1 TeV
      with RLAs, FFAGs or RCSs
  - **Collider Ring**
    - store for 500 turns



Much of Muon Collider R&D is common with Neutrino Factory R&D

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Acceleration Requirements

- **The highest possible Eacc to minimize muon decay**
- **Large transverse and longitudinal acceptances**

Both requirements favor the choice of SRF

- SRF cavities have a high Q_0 $P_d = E_{acc}^2/((R/Q)Q_0)$
- SRF can achieve high gradients with modest RF power
- SRF cavities accommodate a larger aperture without a large penalty for the low R/Q
- Chose low frequency because of beam size
- Chose low frequency to have high stored energy (bunch current)

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History of 200 MHz Program

- Collaboration formed in late 2000 to produce and test two 200 MHz Superconducting Cavities based on a CERN design
- Two cavities were produced and tested
- One cavity performed well: E_{acc} > 11 MV/m
- Second cavity was limited by field emission at < 3 MV/m
- Second cavity demonstrated performance in $H_{ext} \leq 1200$ Oe
- To save costs decided to move to 500 MHz with parallel effort to improve Nb sputter coatings and to fabricate cavities from explosion bonded and hot isostatic pressure bonded 1 mm thick Nb on 4 mm thick Cu
- Program was terminated in the fall of 2006 with the explosion bonded cavity awaiting final finishing

200 MHz Program Collaborators

H. Padamsee
R. Geng – now at JLAB
P. Barnes
J. Sears
V.Shemelin
J. Kaufman

R. Losito
E. Chiaveri
H. Preis
S. Calatroni
E. Palmieri - INFN
M. Pekelar - ACCEL
G. Wu – JLAB – now at FNAL

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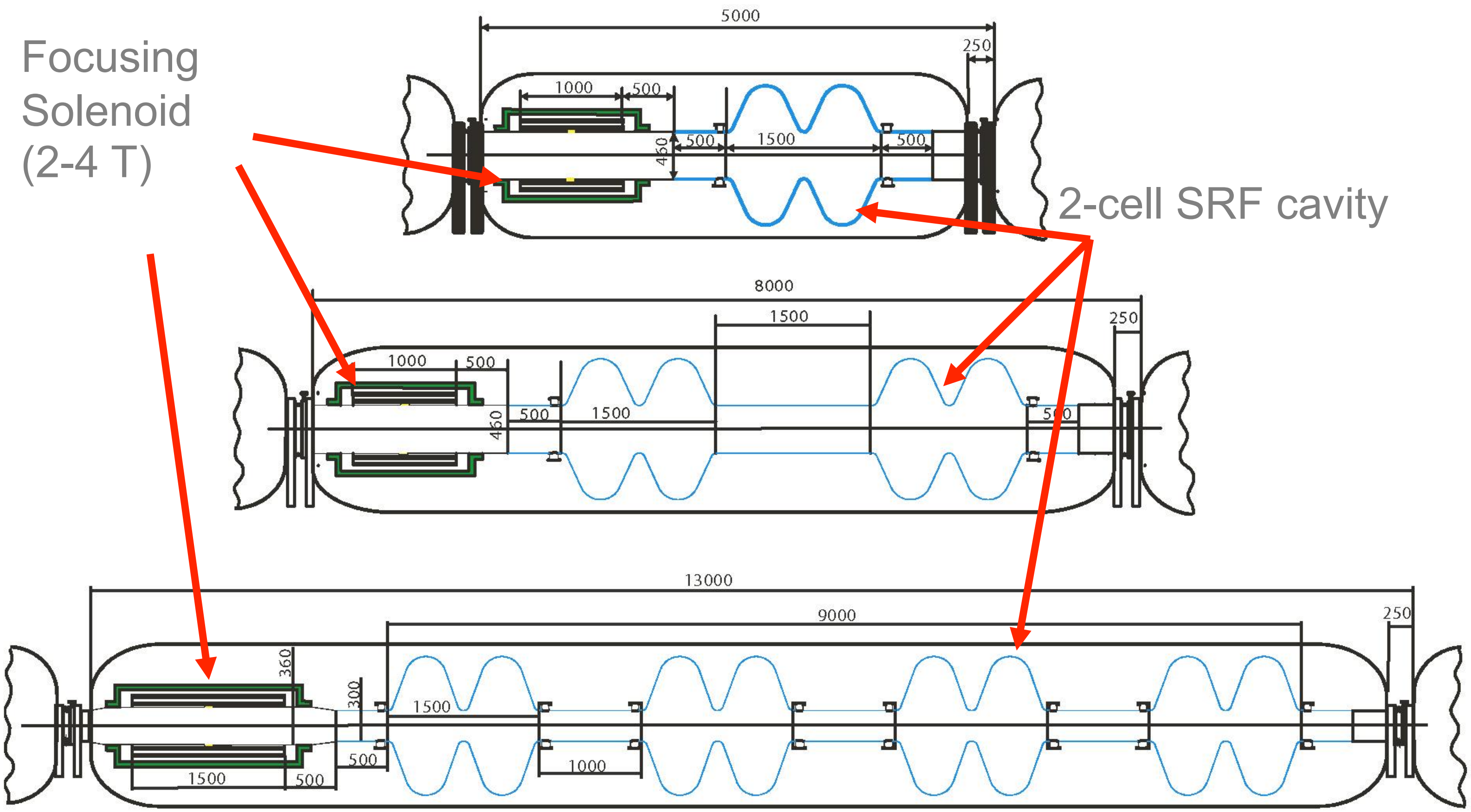
Linac and RLA Cavity Layout



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200MHz SRF parameter list

Linac

2-cell, 460 mm-aperture cavity parameters.

RF freq (MHz)	201.25
No. of cells per cavity	2
Active cavity length (m)	1.5
No. of cavities	43
aperture diameter (mm)	460
E_{acc} (MV/m)	15
Energy gain per cavity (MV)	22.5
Stored energy per cavity (J)	1932
R/Q (Ω/cavity)	208
E_p/E_{acc}	1.54
H_p/E_{acc} (Oe/MV/m)	44
E_{pk} at 10 MV/m (MV/m)	23.1
H_{pk} at 10 MV/m (Oe)	660
Q_0	6×10^9
Bandwidth (Hz)	200
Input power per cavity (kW)	980
RF on-time (ms)	3
RF duty factor (%)	4.5
Dynamic heat load per cavity (watt)	18.3
Operating temperature (K)	2.5
Q_L	10^6
Microphonics detuning tolerable (Hz)	40

RLA

2-cell, 300 mm-diameter cavity parameters.

RF freq (MHz)	201.25
No. of cells per cavity	2
Active cavity length (m)	1.5
No. of cavities	256
Linac	76
RLA	180
Aperture diameter (mm)	300
E_{acc} (MV/m)	17
Energy gain per cavity (MV)	25.5
Stored energy per cavity (J)	2008
R/Q (Ω/cavity)	258
E_p/E_{acc}	1.43
H_p/E_{acc} (Oe/MV/m)	38
E_{pk} at 15 MV/m (MV/m)	24.3
H_{pk} at 15 MV/m (Oe)	646
Q_0	6×10^9
Bandwidth (Hz)	200
Input power per cavity (kW)	1016
RF on-time (ms)	3
RF duty factor (%)	4.5
Dynamic heat load per cavity (W)	18.9
Operating temperature (K)	2.5
Q_L	10^6
Microphonics detuning tolerable (Hz)	40
Wall thickness (mm)	8
Lorentz force detuning at 15 MV/m (Hz)	128

300 high gradient 200MHz cavities needed

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Why Nb-Cu cavities?

- **Save material cost**
- **May save cost on magnetic field shielding (Rs of sputtered Nb may be less sensitive to residual magnetic field than bulk Nb)**
- **May save cost on LHe inventory by pipe cooling (Brazing Cu pipe to Cu outer surface of cavity)**

1.5GHz bulk Nb cavity (3mm) material cost: ~ $ 2k/cell
200MHz: X $(1500/200)^2 = 56 \rightarrow$ $ 112k/cell
Thicker material (8mm) needed: X 2.7 → $300k/cell
Nb Material (bulk Nb version) cost for 600 cells : 180M$
Cu (OF) Material (sputter substrate) is x 40 cheaper: 5M$
Nb-Cu Bonded Material: < 50 M$

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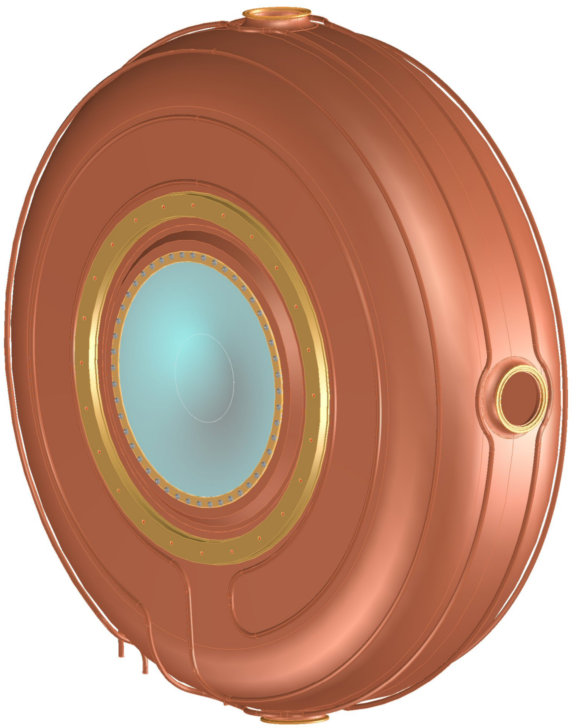
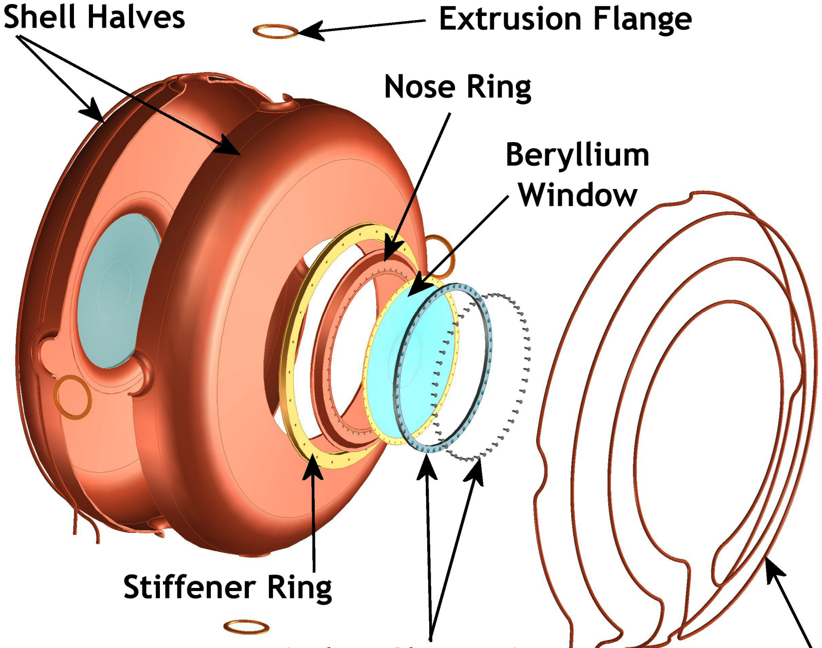
Example of Pipe Cooling





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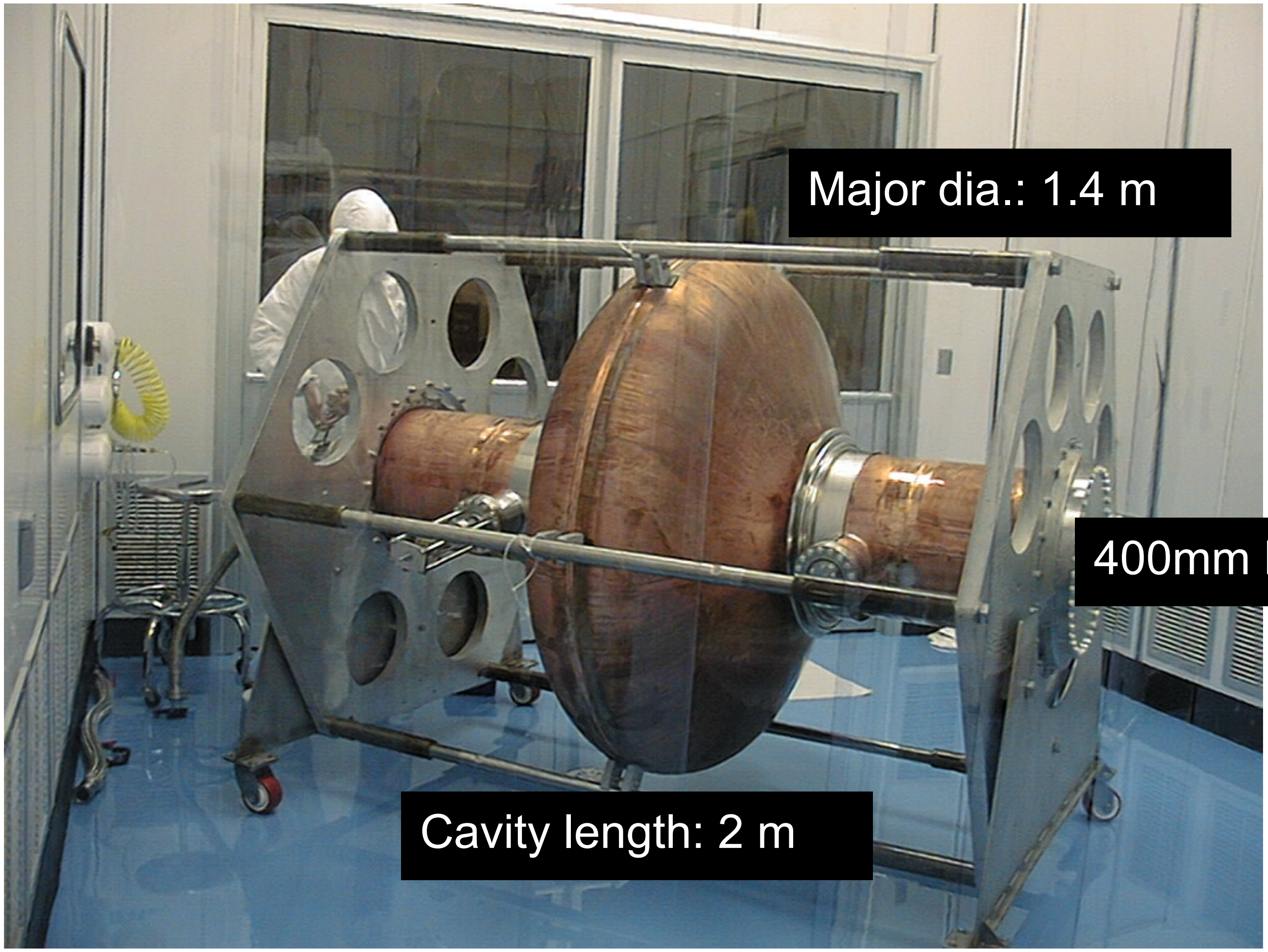
First 200MHz Nb-Cu cavity



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Fabrication at CERN

Electro-polished half cell

- DC voltage: 400-650 V
- Gas pressure: 2 mTorr
- Substrate T: 100 °C
- RRR = 11
- Tc = 9.5 K

Magnetron Nb film (1-2 μm) sputtering

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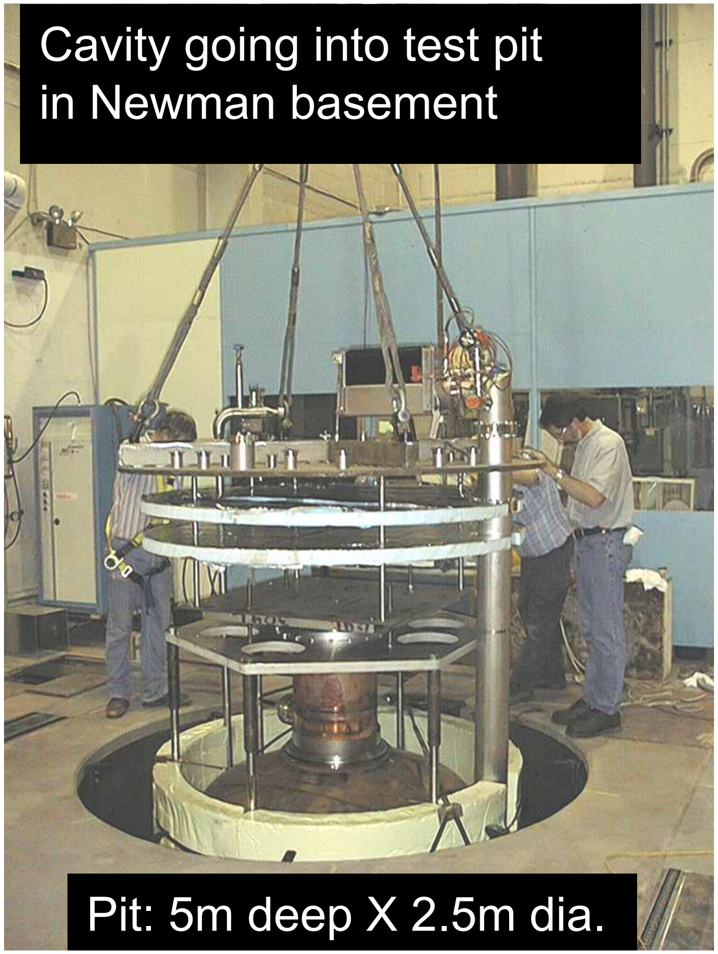
First RF test at Cornell



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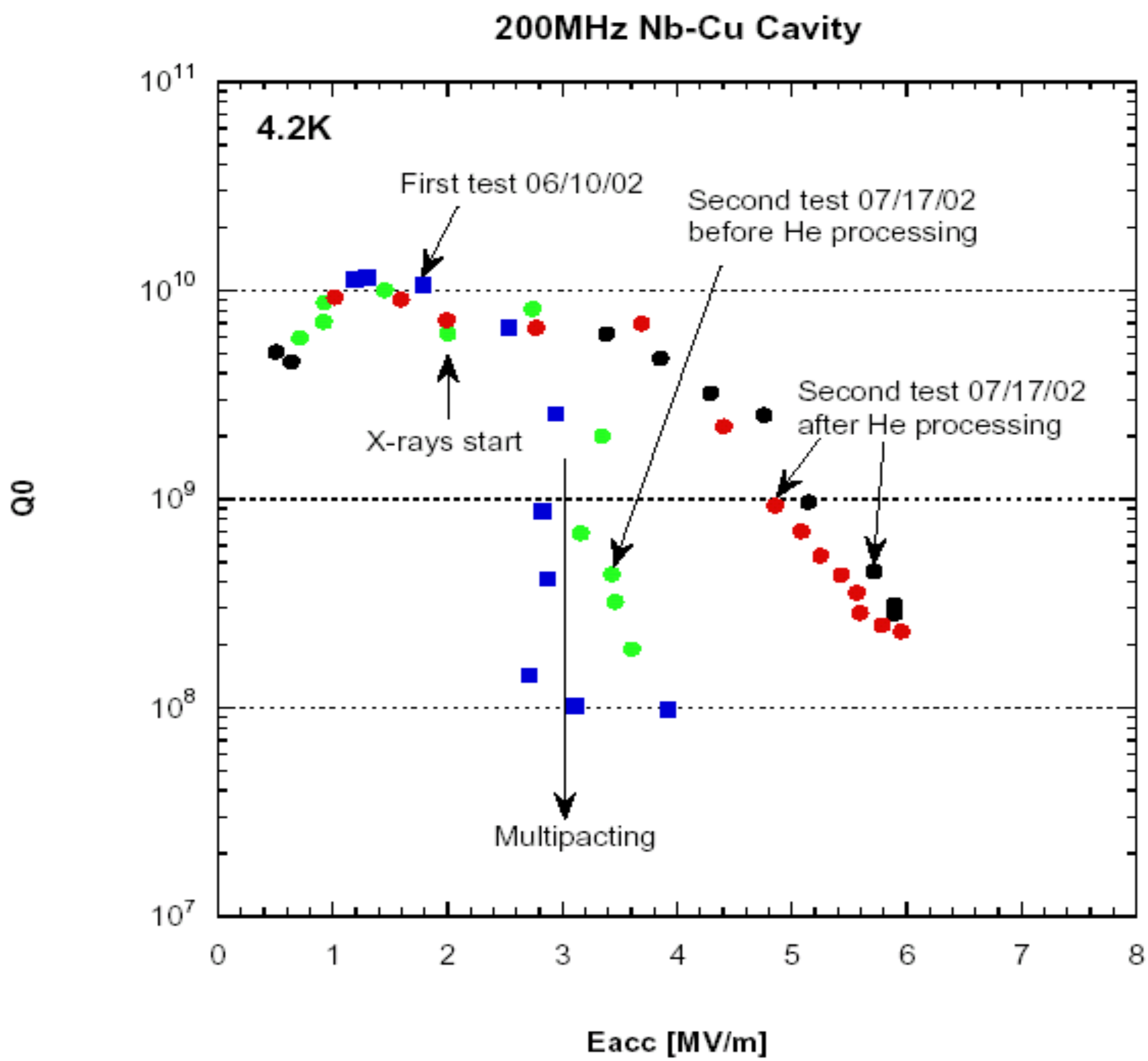
First Cavity Test Results



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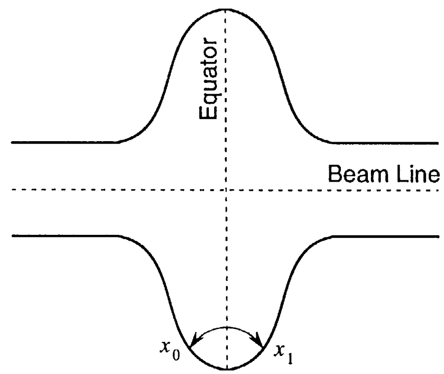
Two-point Multipacting



- Two points symmetric about equator are involved
- Spontaneously emitted electrons arrive at opposite point after T/2
- Accelerated electrons impact surface and release secondary electrons
- Secondary electrons are in turn accelerated by RF field and impact again
- The process will go on until the number of electrons are saturated

MP electrons drain RF power → a sharp Q drop

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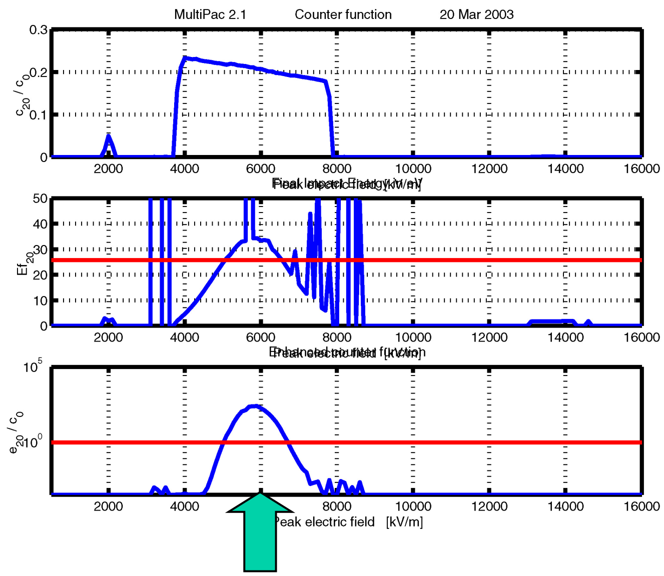
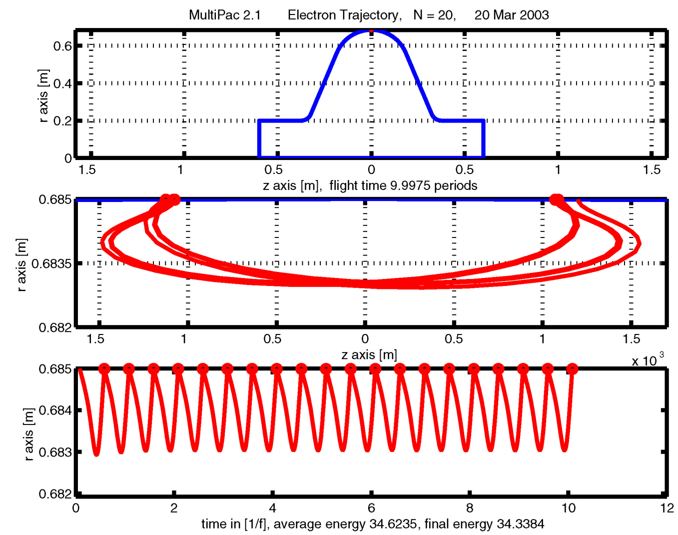
Two-point MP at 3 MV/m



MULTIPAC simulation confirmed exp. observation



Resonant trajectory of MP electrons

It was possible to process through MP barrier

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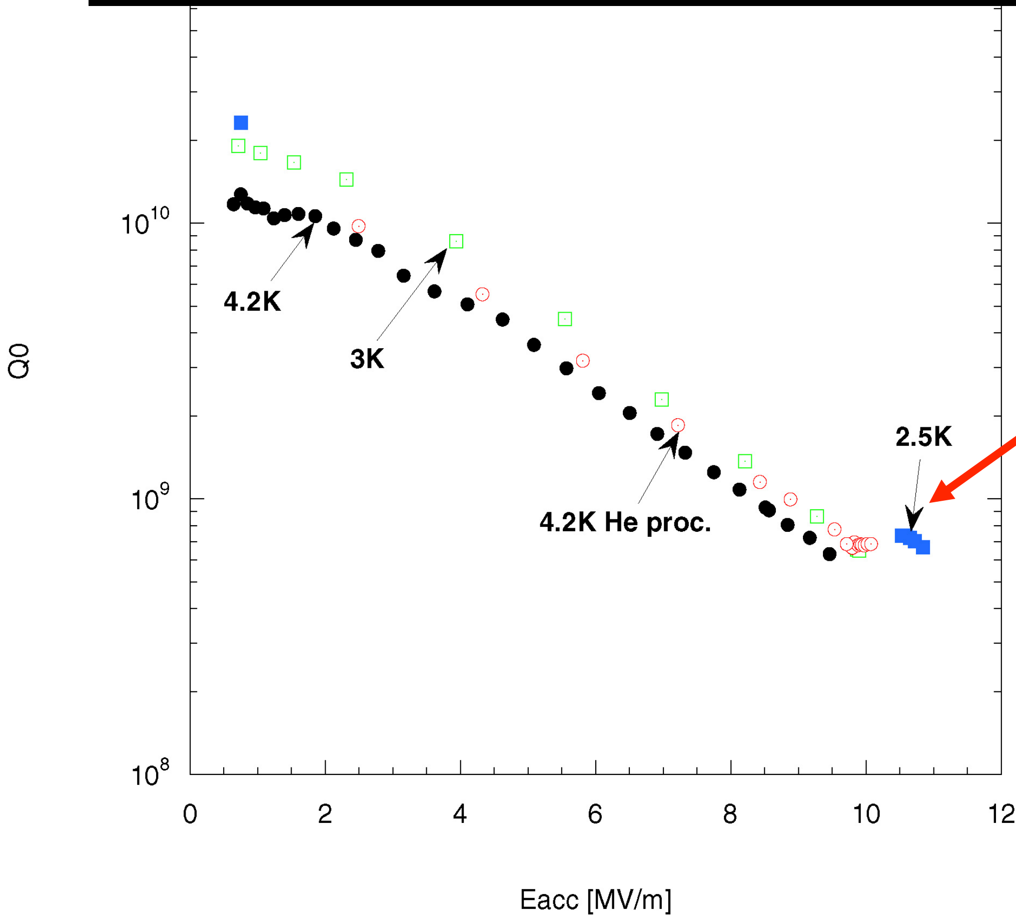
Third Cavity Test

Q(Eacc) after combined RF and Helium processing



- Eacc = 11MV/m
- Low field Q = 2E10

Limited by RF coupler

- 75% goal E_{acc} achieved
- Q-slope larger than expected

Q improves with lower T
→ FE not dominant

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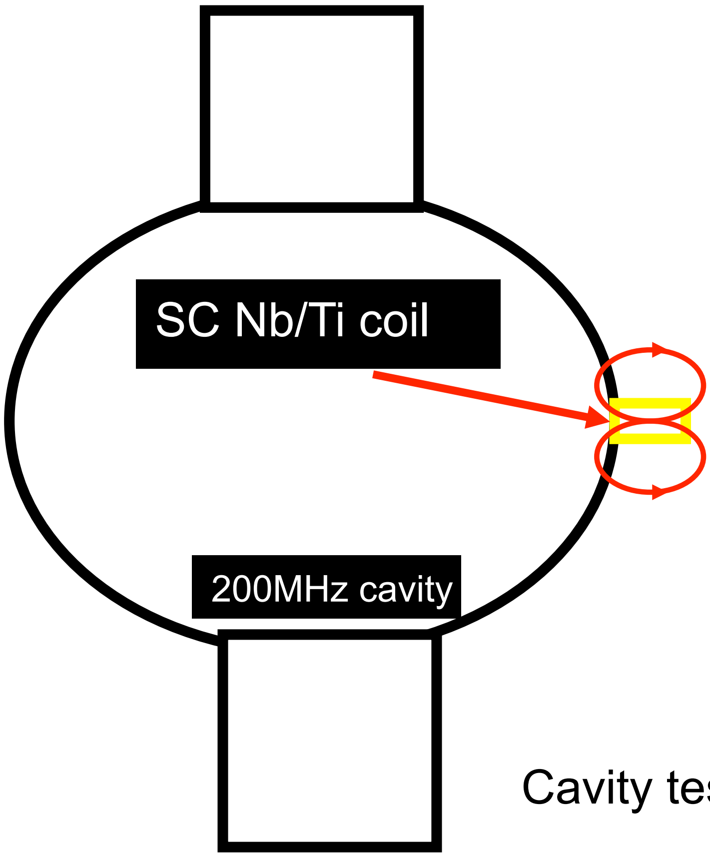
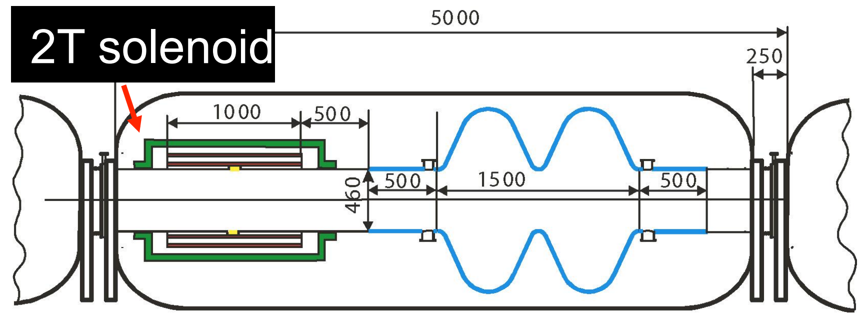
H_{ext} effect on cavity setup





Layout of Linear Accelerator for ν source

- 2T solenoid needed for tight focusing
- Solenoid and cavity fitted in one cryostat
- Large aperture (460 mm)
- Q: Will cavity still work $H_{ext} >_0$?

Cavity test in the presence of an H_{ext}

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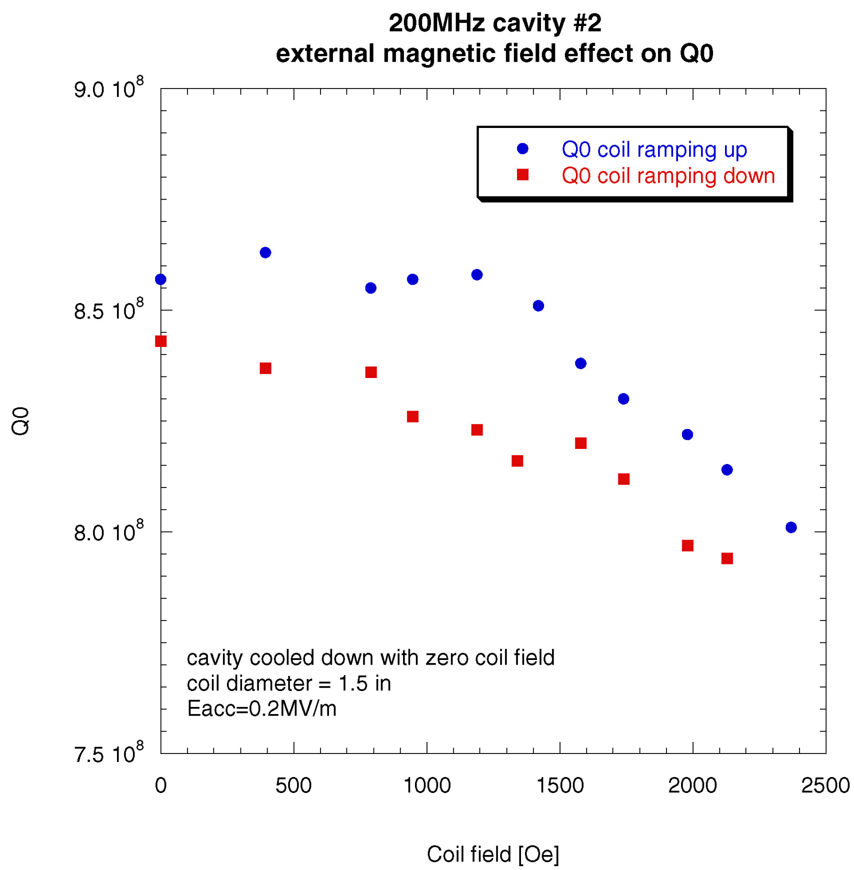
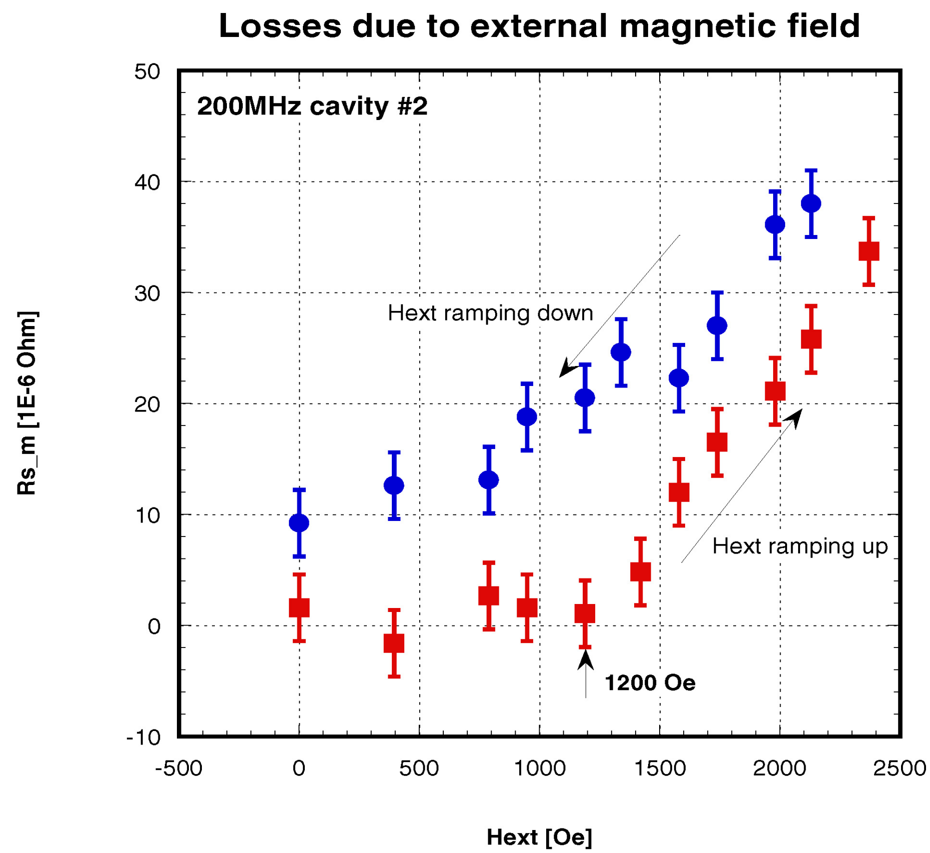
H_{ext} effect on 2^{nd} cavity





Cavity Q stays intact up to Hext = 1200 Oe

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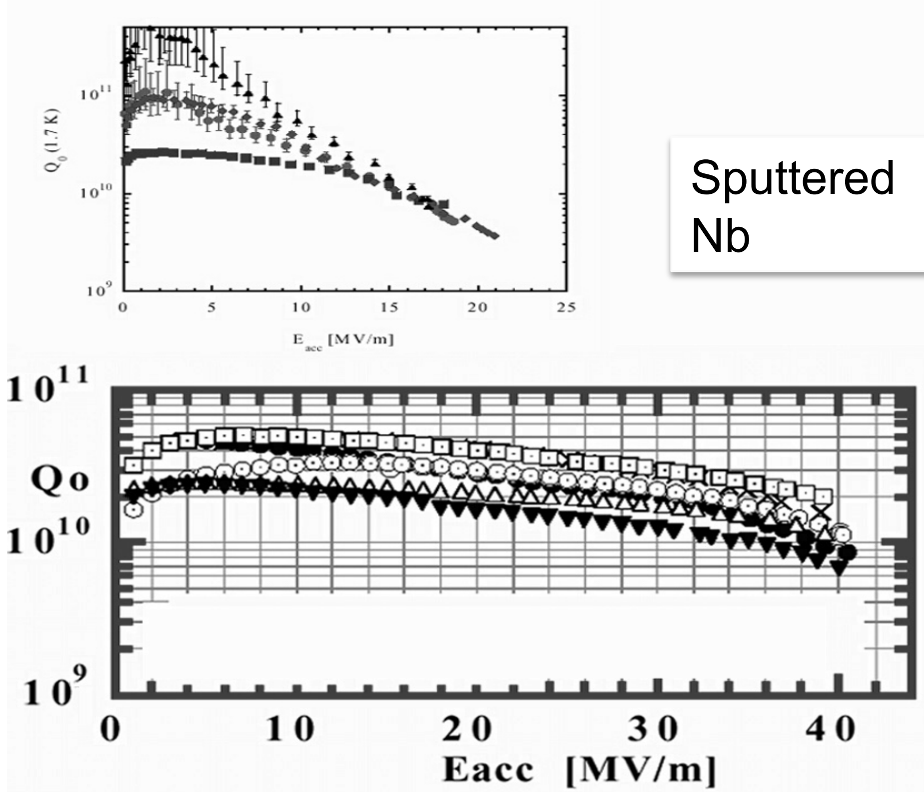
Q-slope of sputtered film Nb cavities

- Q-slope is a result of material properties of film Nb
- The Cu substrate (surface) has some influence
- The exact Q-slope mechanism is not fully understood



Sputtered Nb

Bulk Nb

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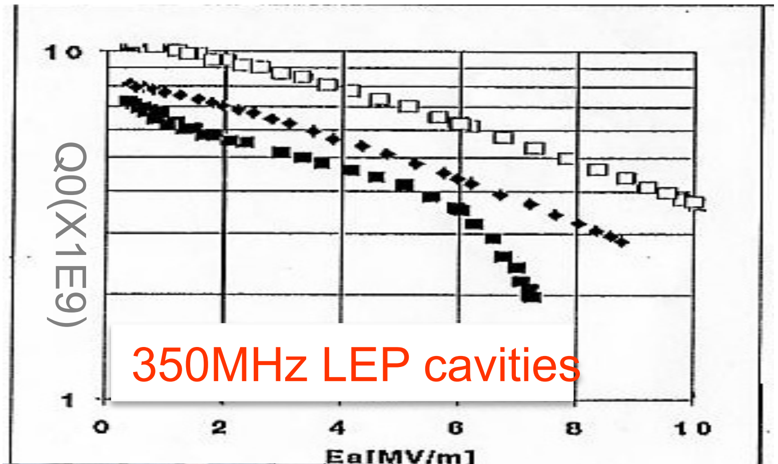
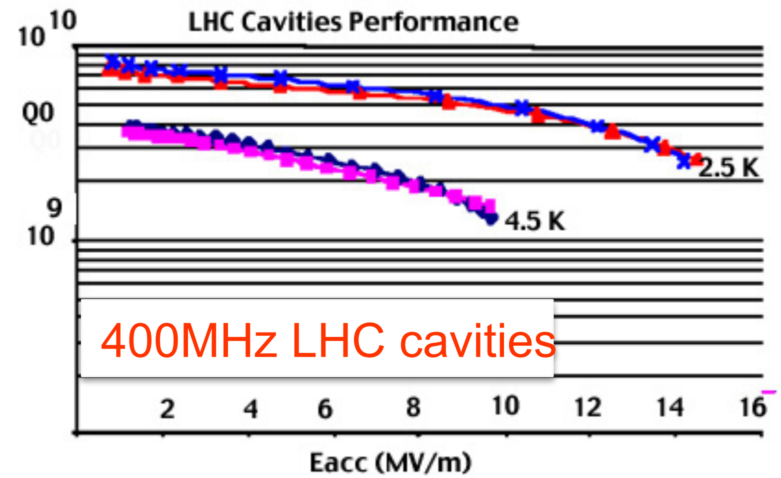
Sputtered Nb-Cu cavities





Despite Q-slope, sputtered Nb-Cu cavities have achieved a 15MV/m Eacc at 400MHz

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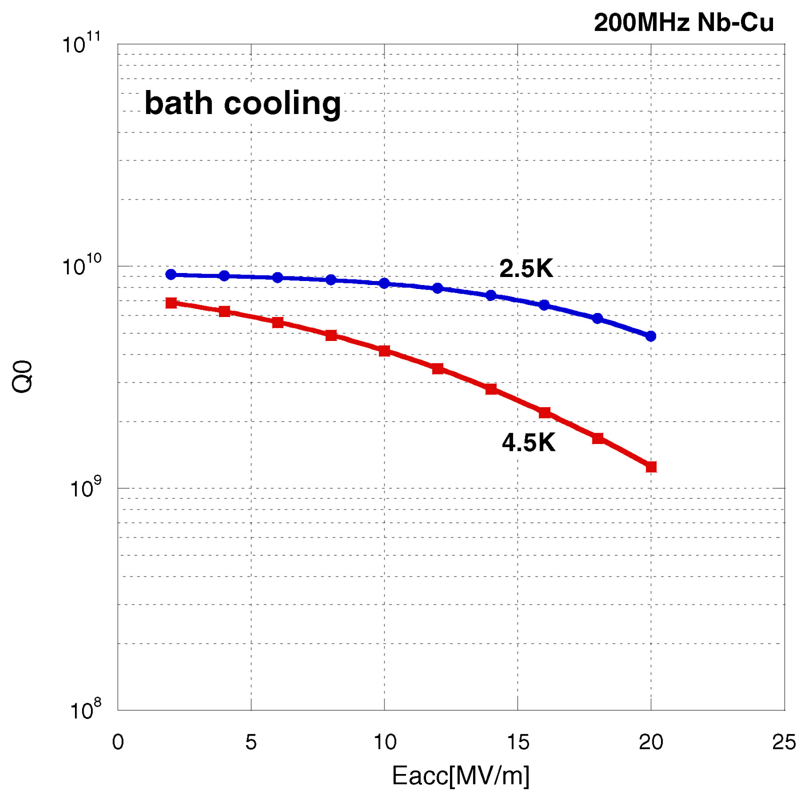
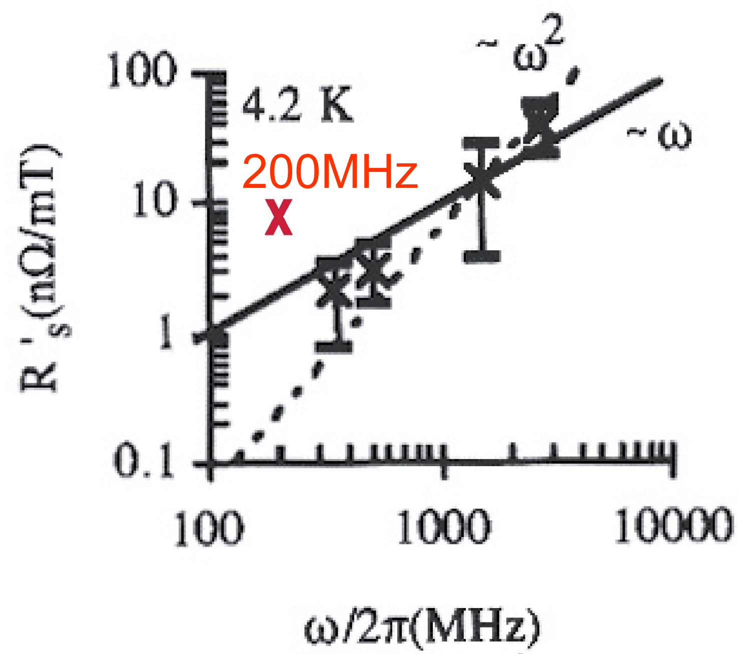
Expected performance

Projecting LHC 400MHz to 200MHz





Empirical frequency dependence of Q-slope

Measured Q-slope of 200MHz cavity is 10 times steeper than expected

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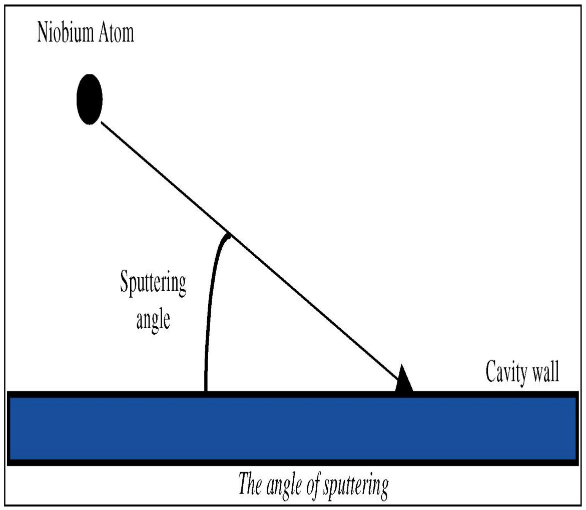
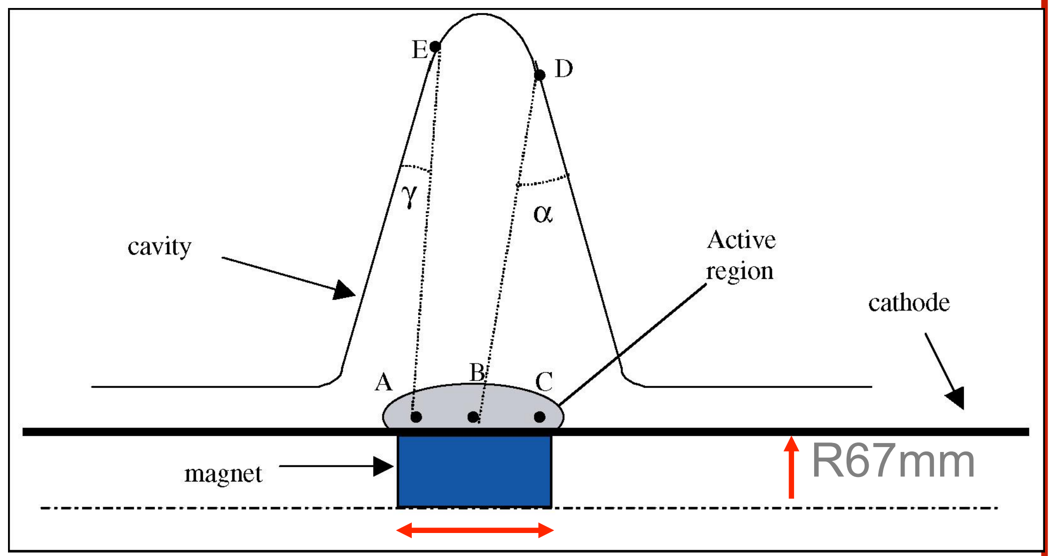
Q-slope: impact angle effect



Impact angle of Nb atom: γ



100mm

- CERN explored low β = (v/c) 350MHz cavities
- With the same cathode geometry, lower $\beta \rightarrow$ low γ

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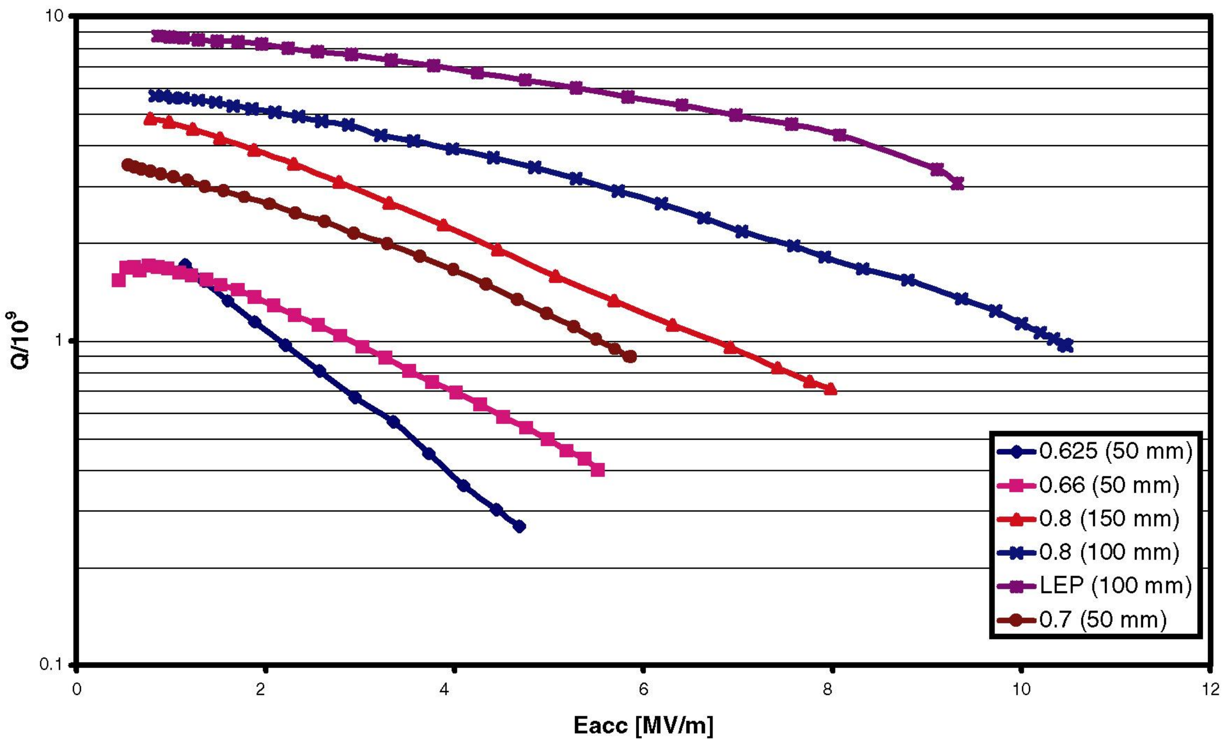
Q-slope: impact angle effect



Correlation: lower β → lower γ → steeper Q-slope
→Need a more robust approach to maintain high Q needed for economy

Reducing Q-Slope

- **It is clear from the LEP cavity production that there is significant variation in Q slope and it is always present in magnetron sputtered Nb cavities.**
- **To limit power requirements, both RF and cryogenic, Q slope must be reduced to a minimum.**
- **Different sputtering techniques other than magnetron sputtering may yield better results.**
- **The sputtered surface will always be a delicate feature.**
- **Reproducibility will always be a problem.**
- **Because of diffusion of Cu into Nb layer, low temperature bake know to help in solid Nb cavities is not possible.**

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Other techniques for Nb film deposition

- Bias sputtering
- Energetic deposition in vacuum
- Vacuum arc deposition
- Electron cyclotron resonance sputtering
- Prototypes of these techniques were developed but none were mature enough to produce a cavity.
- Bond 1 mm thick Nb to 4 mm thick Cu by hot isostatic bonding or explosion bonding.
- With all the challenges of Nb sputter coating decide to concentrate on using bonded Nb material.
- Bonded Nb permits a low temperature bake.

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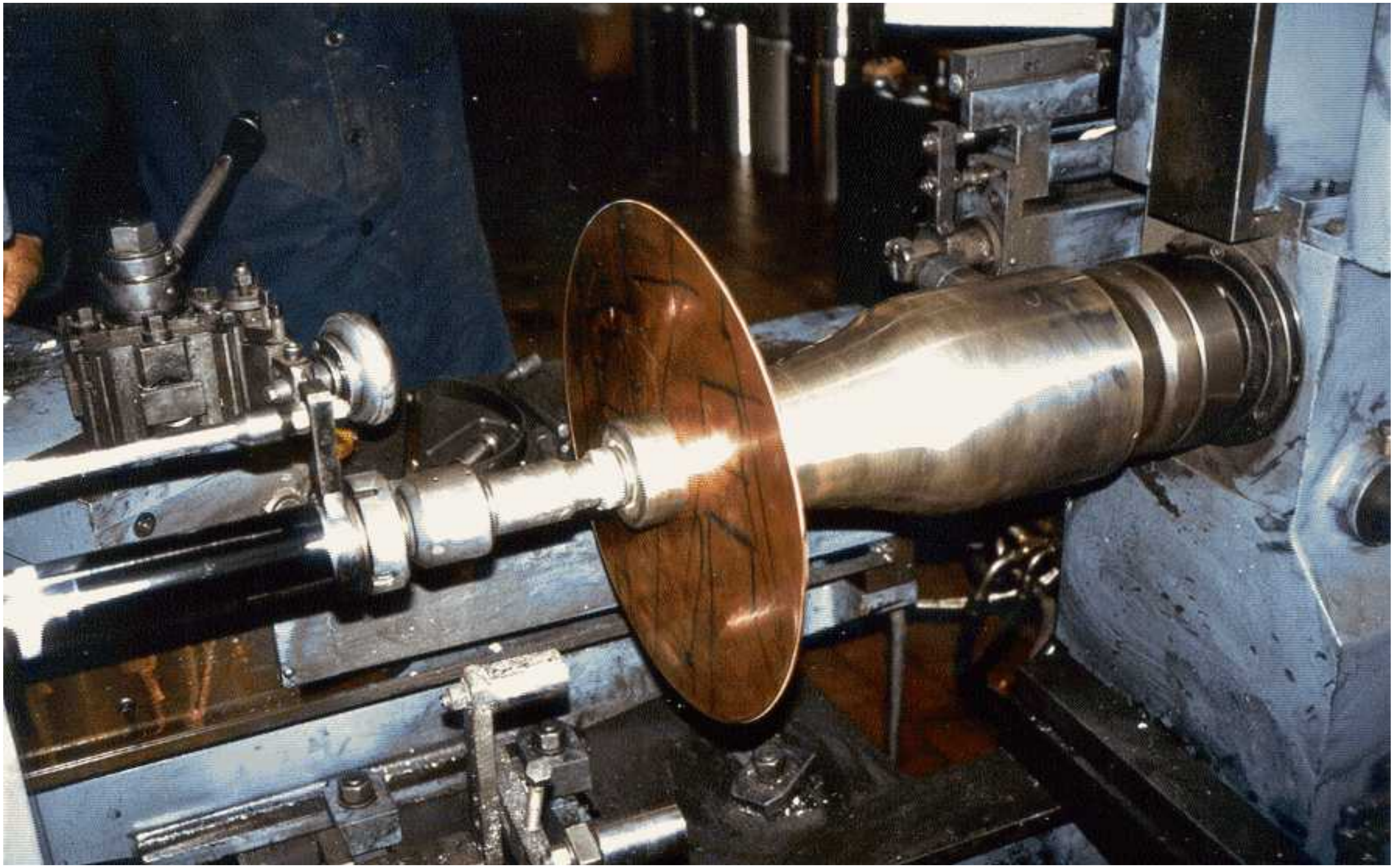
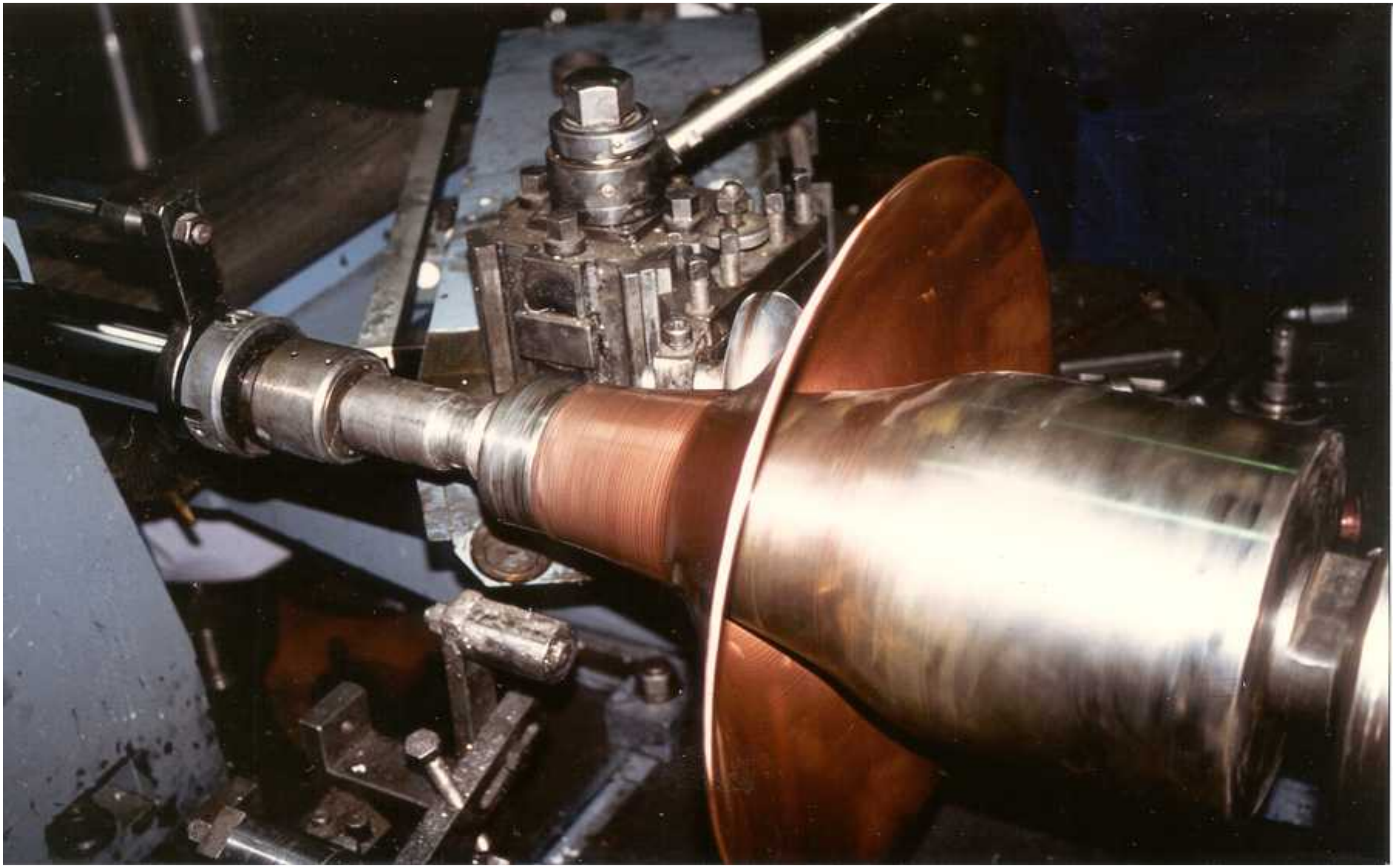
Spinning Cavities

- **A few slides illustrating the spinning process**





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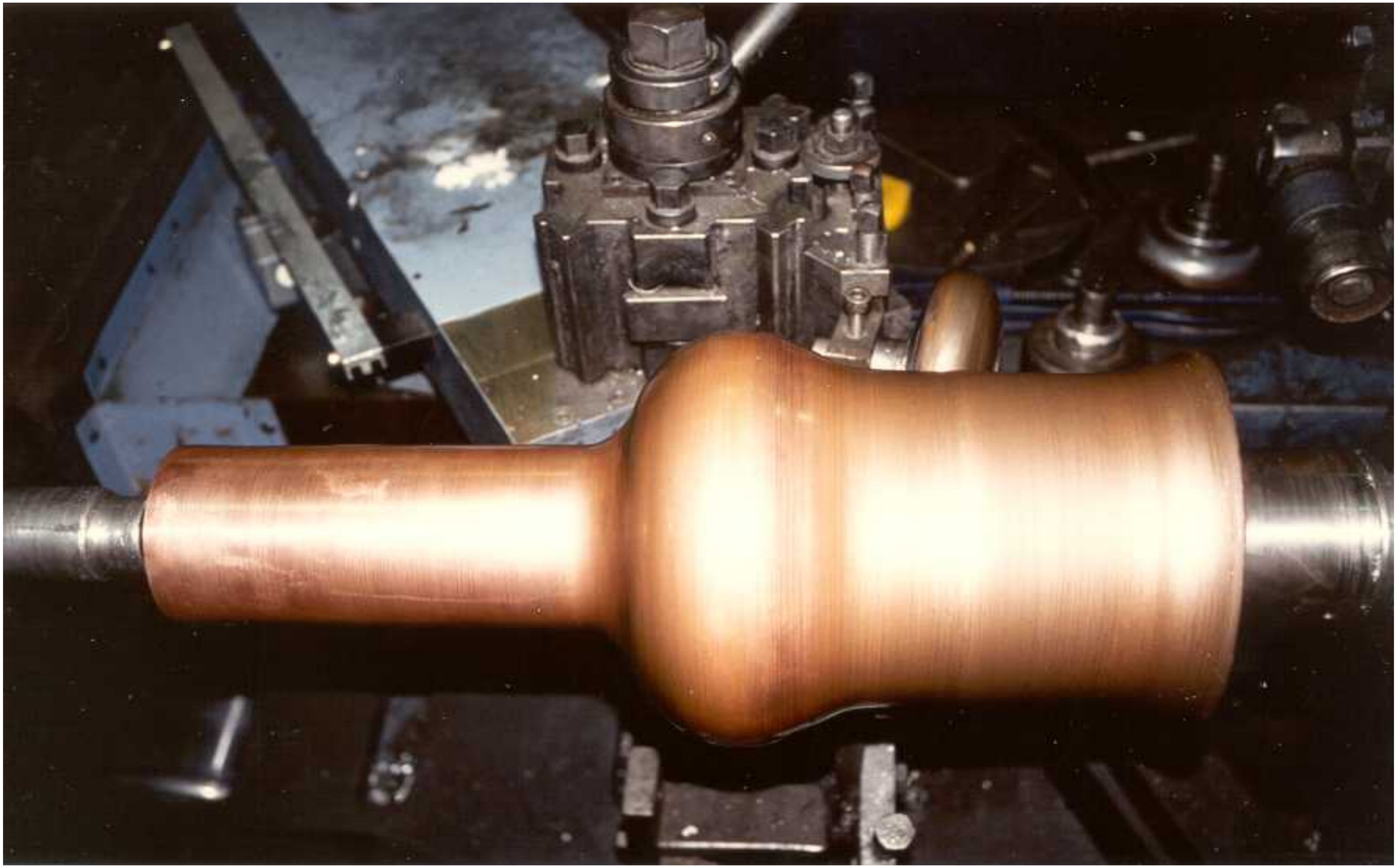

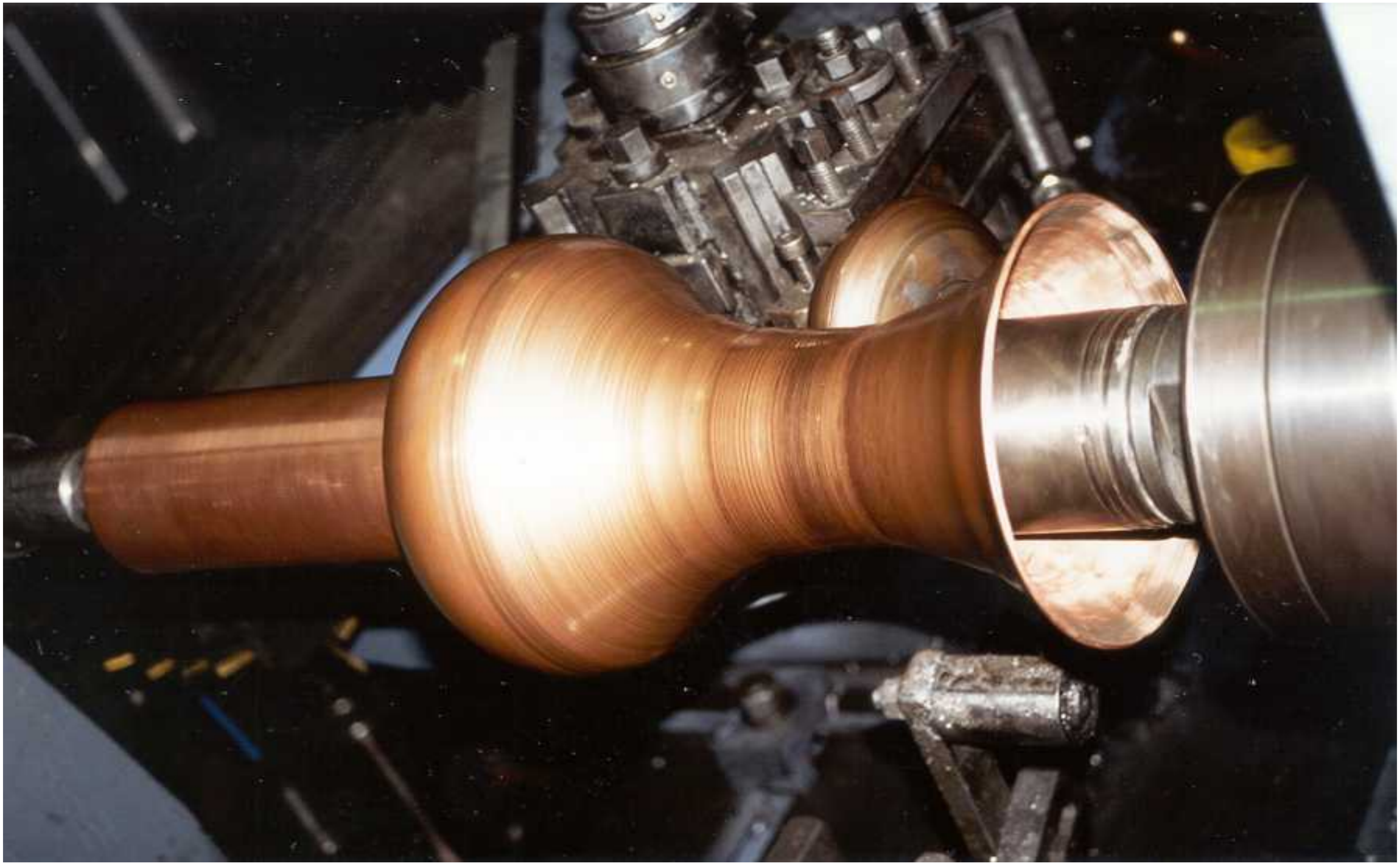

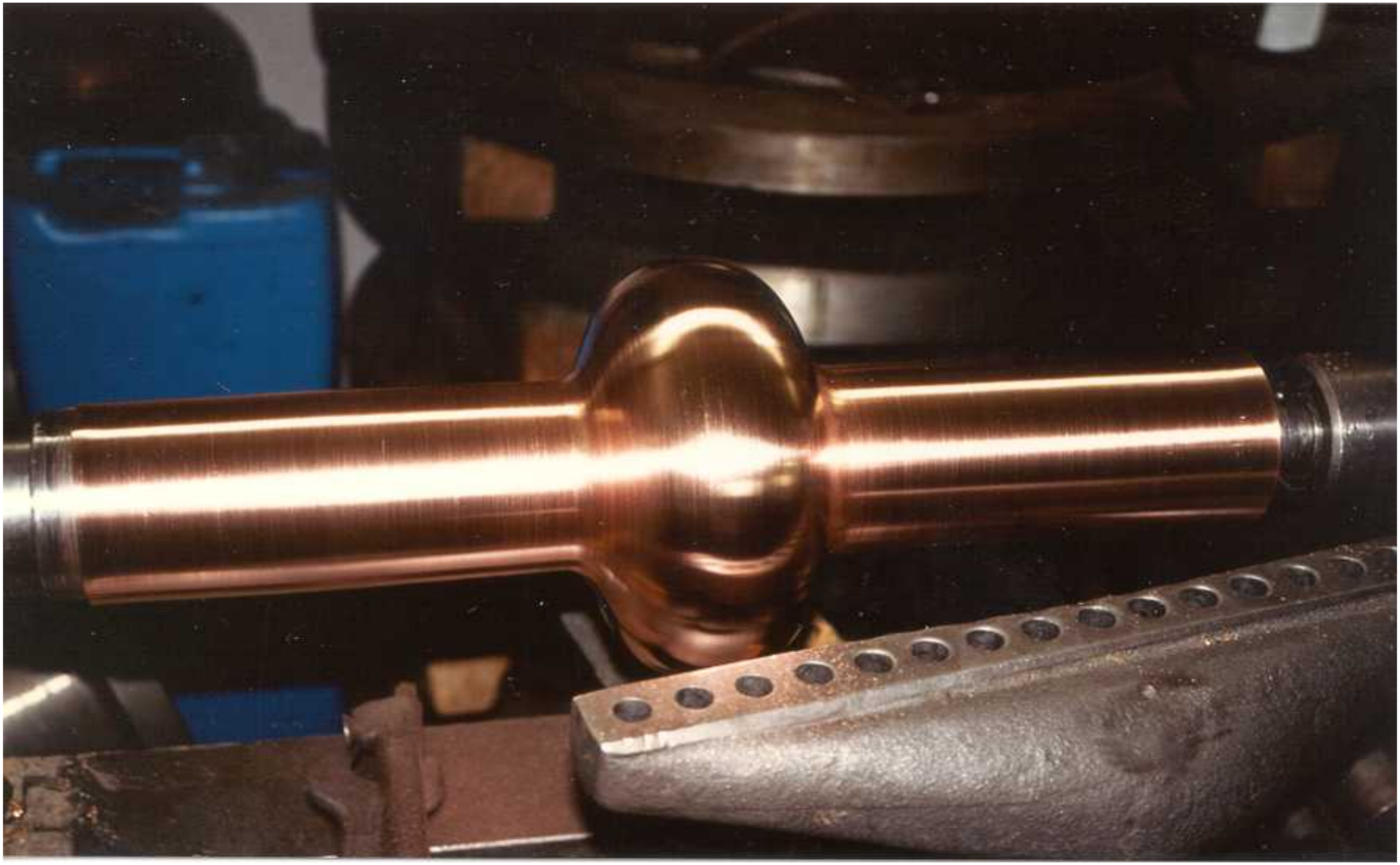

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Spinning of Bonded Nb-Cu

- Both a hot isostatic pressure bonded (hipped) Nb-Cu and an explosion bonded Nb-Cu plate were spun into 500 MHz cavities.
- The hipped material appeared to yield an excellent Nb inner surface after initial spinning. After annealing at 250 ^{o}C, several small bubbles (10 mm^2) appeared indicating de-lamination of Nb from Cu.
- Minor surface cracks were apparent in the cavity spun from the explosion bonded material.
- With very light grinding and subsequent surface chemistry the cavity from explosion bonded material is likely to yield a cavity capable of > 17 MV/m accelerating gradient. The hipped cavity cannot be used because it would be thermally unstable in the bubble regions.
- A single cell 1300 MHz cavity spun from the explosion bonded material has achieved a 40 MV/m accelerating gradient.

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Summary of Original Program

- The first 200MHz SC cavities have been constructed.
- Test results for the first cavity were Eacc = 11 MV/m with Q_0 = 2E10 at low field.
- MP barriers were present and could be processed through.
- Cavity performance was not affected by Hext < 1200 Oe.
- Some progress was made on the understanding of the Q-slope in sputtered cavities.
- Currently a low temperature bake ~ 100 ^{o}C seems to significantly reduce the Q slope in solid Nb cavities. This is not suitable for sputter coated cavities because of the diffusion of Cu into the Nb layer. OK for the bonded material since Nb is 1 mm thick and diffusion rates are low.

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Summary of Original Program

- **A 500 MHz cavity coated at ACCEL was assembled and tested twice to 4 MV/m with heavy field emission and quench. A second cavity reached 10 MV/m with large Q slope on its second test.**
- **Recoated 200 MHz cavity #1 at CERN in 3/04 – peeling observed – recoated again, still bad – recoat again and retested with heavy field emission and quench – both cavities shipped back to CERN to avoid paying duty.**
- **Used Auger surface analysis system and SIMS to further characterize sputtered Nb surfaces. Found that the oxygen level near the surface is an important player.**
- **Spun cavities from bonded material were sent to ACCEL for flange installation.**

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Summary of Original Program

- **Cost of 1 mm Nb bonded to 4 mm of Cu is <1/3 that of 5 mm RRR 300 Nb sheet in small quantities for both hip and explosion bonded material.**
- **Program was terminated in the Fall of 2006.**

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Proposed Development Program

- Finish the explosion bonded cavity presently at Research Instruments (formerly ACCEL).
- Carry out surface preparation, chemistry and high pressure rinsing.
- Test the cavity taking advantage of the new helium recovery system and the new diagnostic technique based on second sound. This may be particularly interesting since these cavities have no equator weld zone.
- Check sensitivity to external DC magnetic field.
- Spin a new cavity from one of the two remaining explosion bonded sheets at INFN. Pay particular attention to the annealing procedure to see if this influences the minor surface cracking.
- Add flanges to the new cavity at Research Instruments.
- Carry out surface preparation, chemistry and high pressure rinsing.
- Test the cavity.

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Proposed Development Program

- Order two sheets of explosion bonded material with thicker Nb (1.5 to 2 mm) on 4 mm of Cu.
- Spin a new cavity from the thicker material at INFN.
- The thicker material may be less prone to minor surface cracking and if not, it provides more material to work with.
- Add flanges at Research Instruments.
- Carry out surface preparation, chemistry and high pressure rinsing.
- Test the cavity.
- Check the sensitivity to external DC magnetic field.
- Assuming success of the 500 MHz program, develop a proposal to construct and test a 200 MHz cavity using these same techniques.