200MHz Nb-Cu Cavity for Muon Acceleration

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This work is a collaboration between Cornell and CERN with participation of the following

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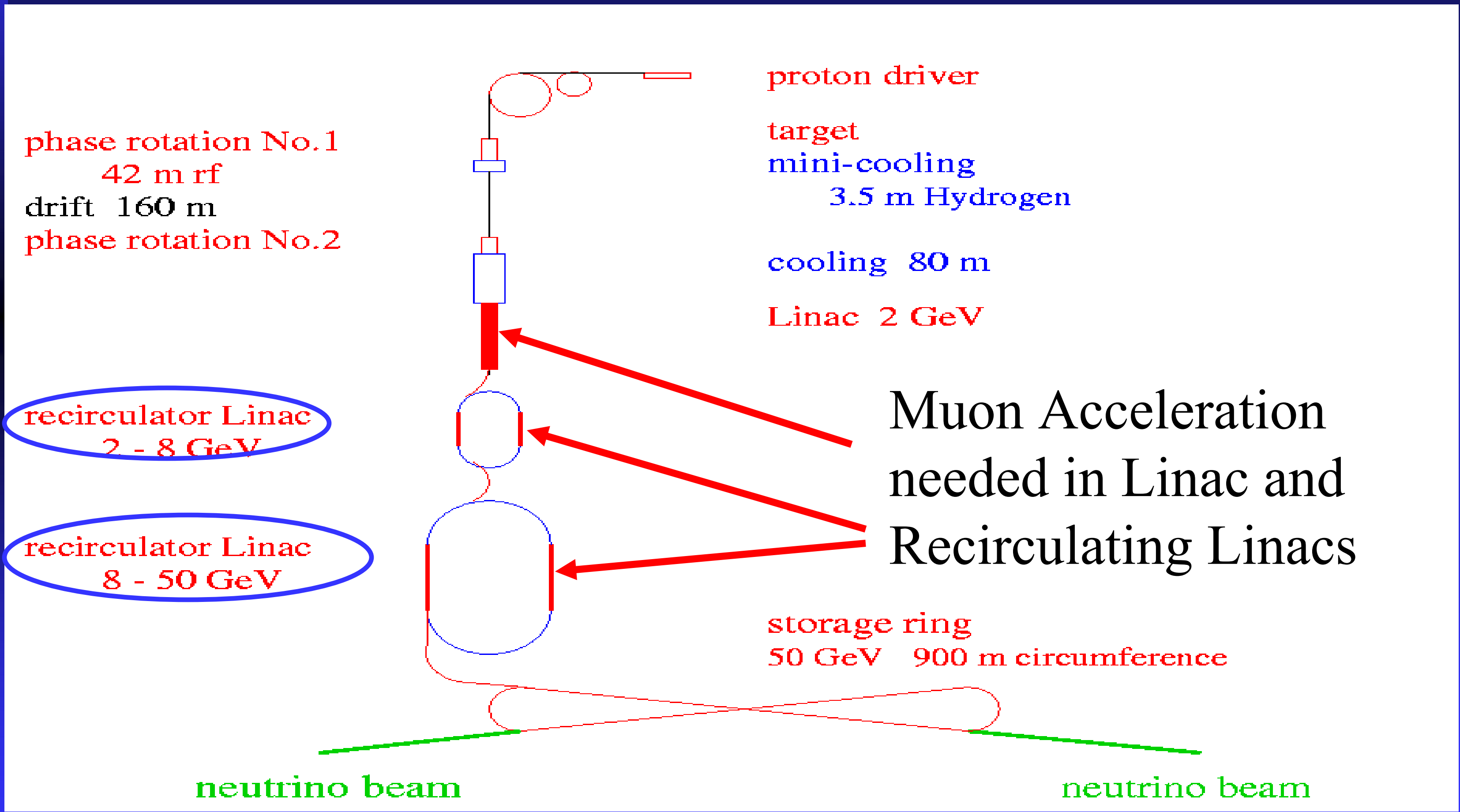
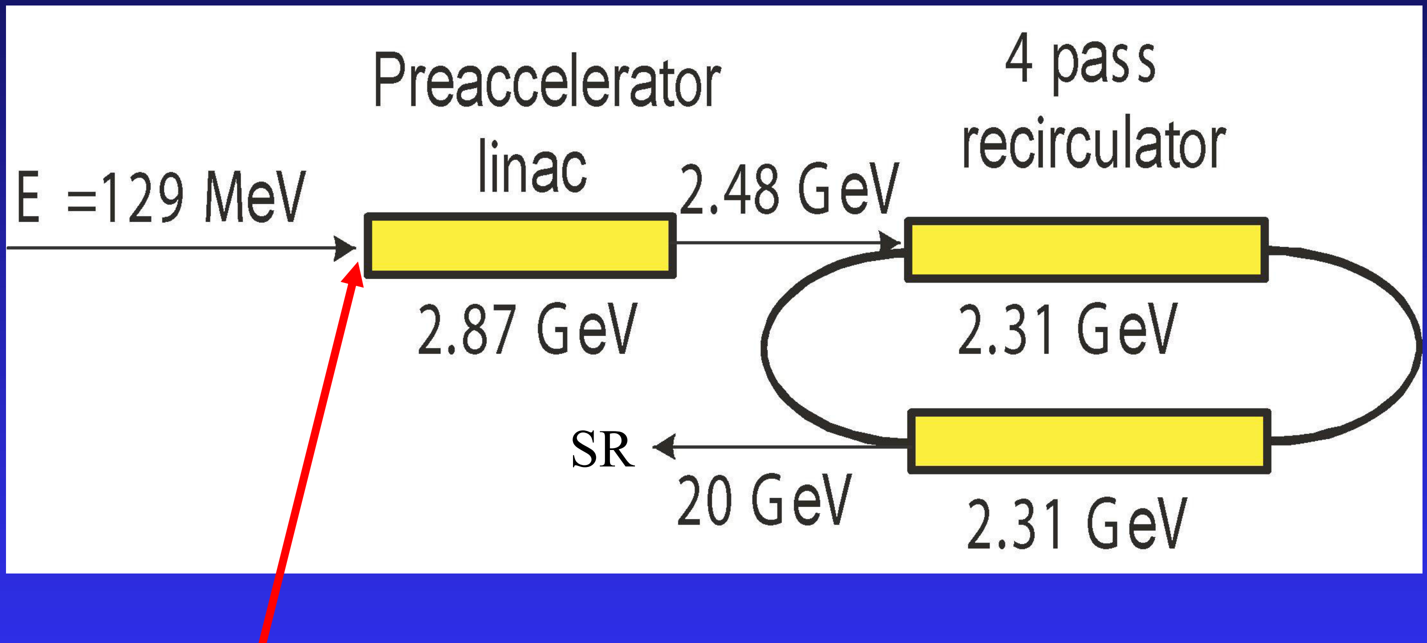
Contents

- Muon acceleration for NF and MC
- Cavity fabrication and RF tests
- Cavity performance: Eacc and Q and MP
- Q-slope
- Performance when $H_{ext} \neq 0$
- Conclusion

Muon-based neutrino source



Accelerator driver layout



- RMS emittance: 2.4 mm-rad
- Momentum spread: +/- 0.21
- Total bunch length: 814 mm

} Large phase space volume

Requirements to acceleration

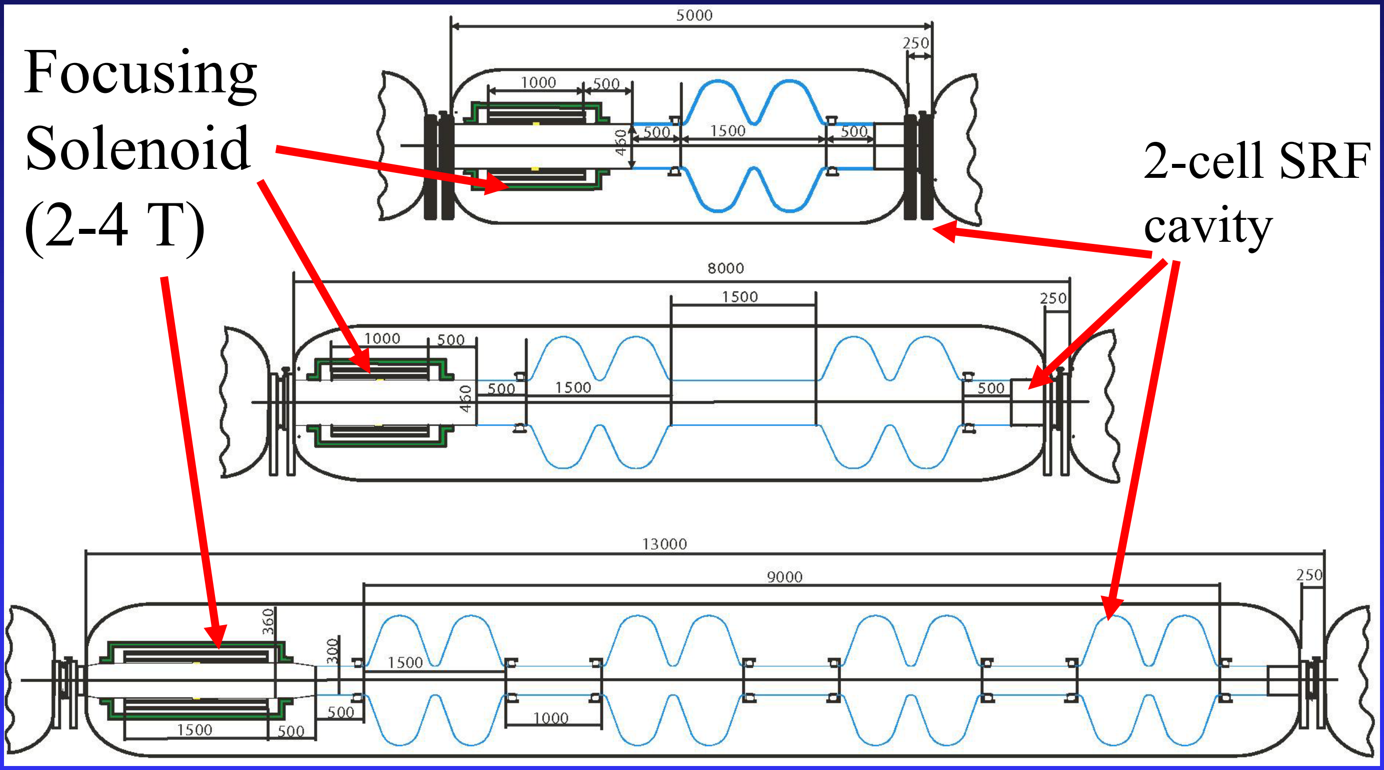
Requirements imposed by the nature of muon beams:
short life time and large emittance

- The highest possible Eacc to minimize muon decay
- Very large transverse and longitudinal acceptances

Both requirements favor the choice of SRF

- High gradients with modest RF power
- Larger aperture

200MHz SRF layout for Linac



Tight focusing need requires to operate a strong solenoid in the vicinity of SRF cavities

200MHz SRF parameter list

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

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

Challenges to SRF cavity

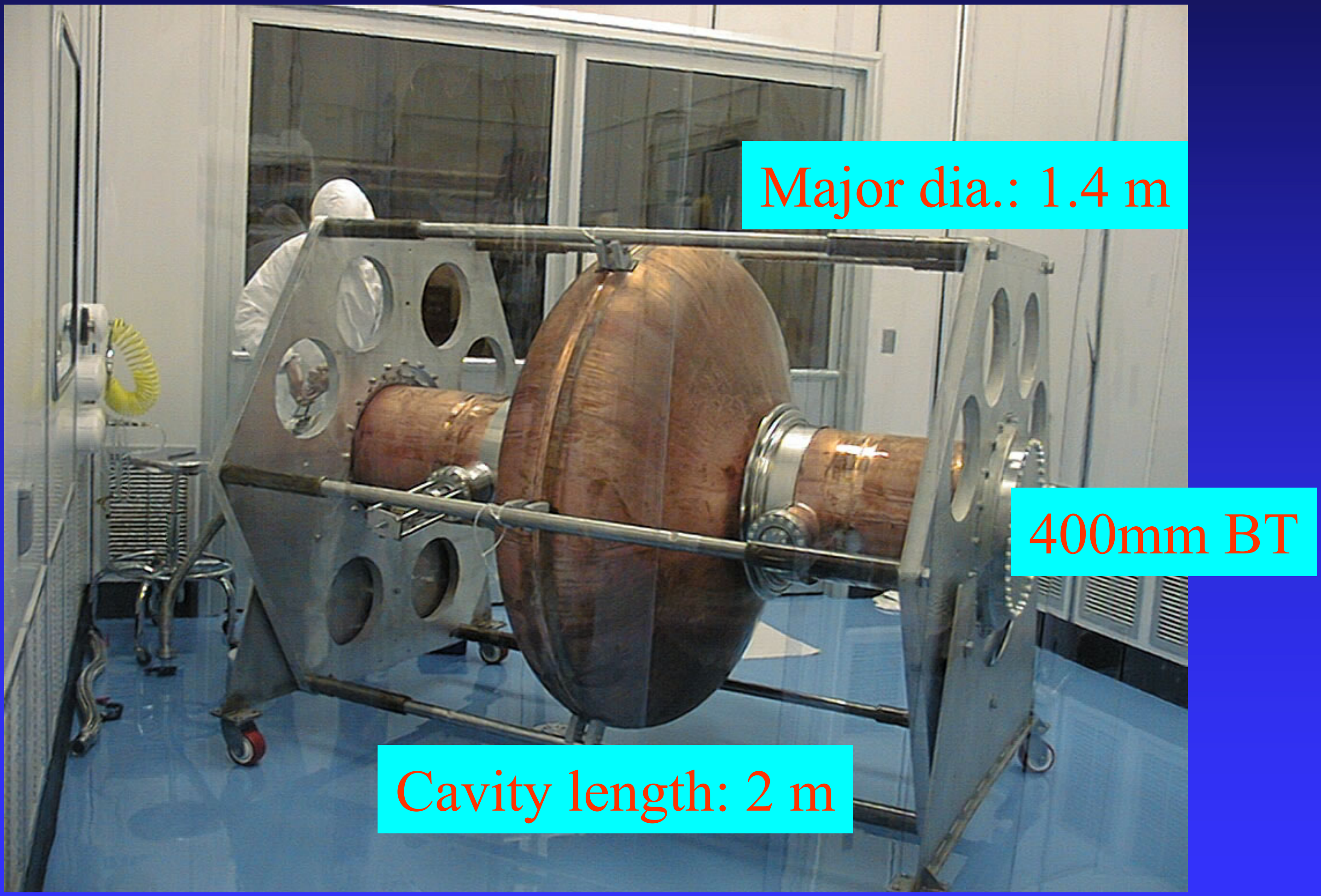
- Fabrication challenge: High Q at 200 MHz requires to attain defect-free superconducting material over large area
- Preparation challenge: Low radiation background requires to maintain low field emission over large RF surface
- Operation challenge: Operate SRF cavity near a strong solenoidal magnetic field

A joint collaboration between Cornell and CERN is formed to address these challenges

Why Nb-Cu cavity?

- Save material cost
- Increased quench protection by virtue of good thermal conductivity of Copper: at 200MHz, huge stored energy needs to be dissipated when quench occurs
- Save cost on magnetic field shielding: Nb-Cu less sensitive to residual magnetic field
- Further cost saving in LHe possible by using pipe cooling

First 200MHz Nb-Cu cavity



200MHz cavity size in comparison

Fabrication at CERN

Electro-polished half cell

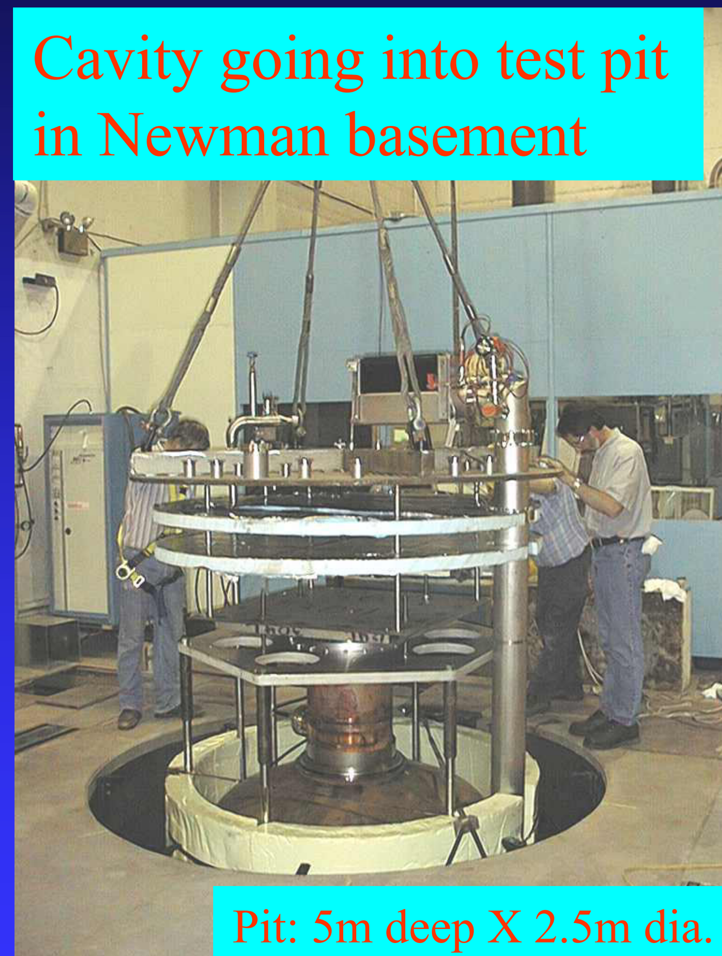
Magnetron Nb film (1-2 μm) sputtering

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

Cavity EBW done by ACCEL

RF test at Cornell

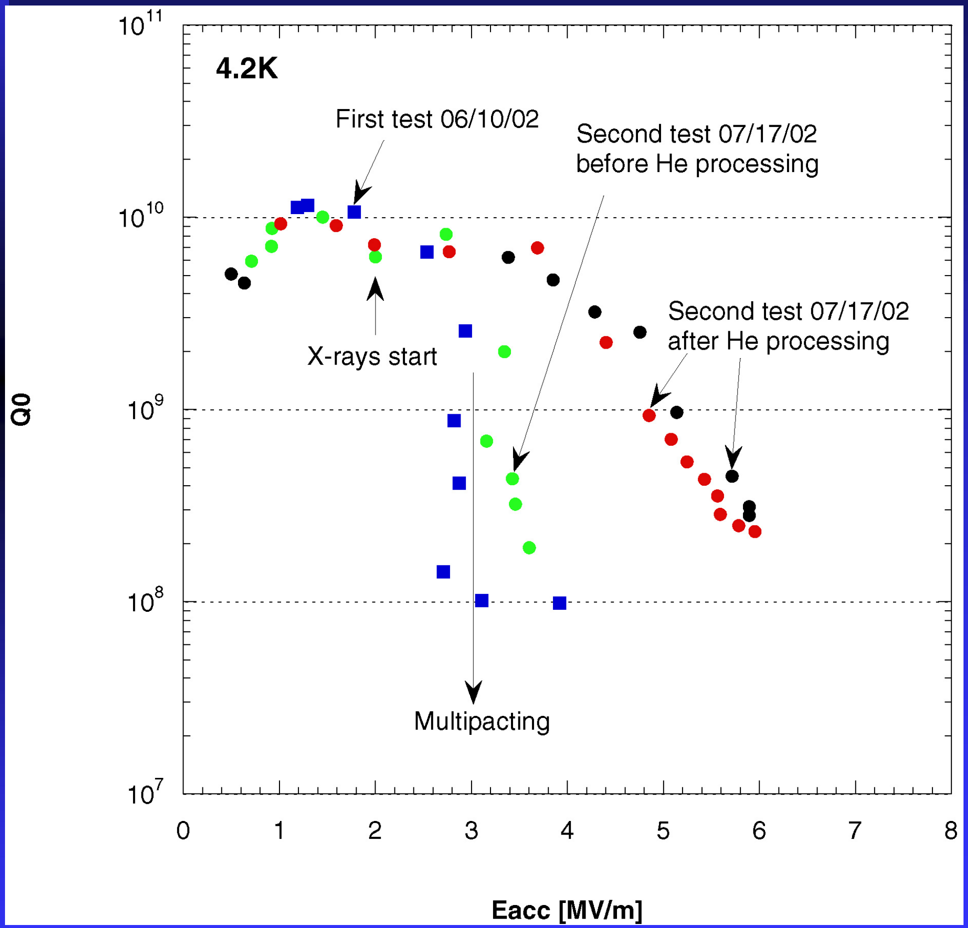
Cavity on test stand



Cavity going into test pit in Newman basement

Pit: 5m deep X 2.5m dia.

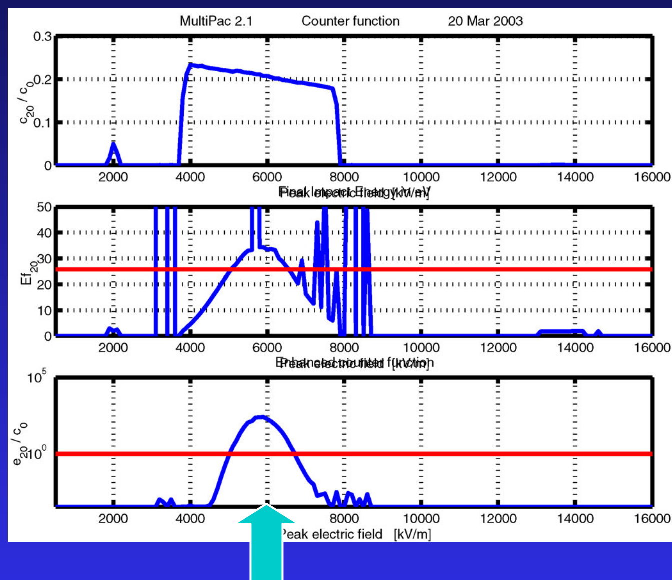
First test result



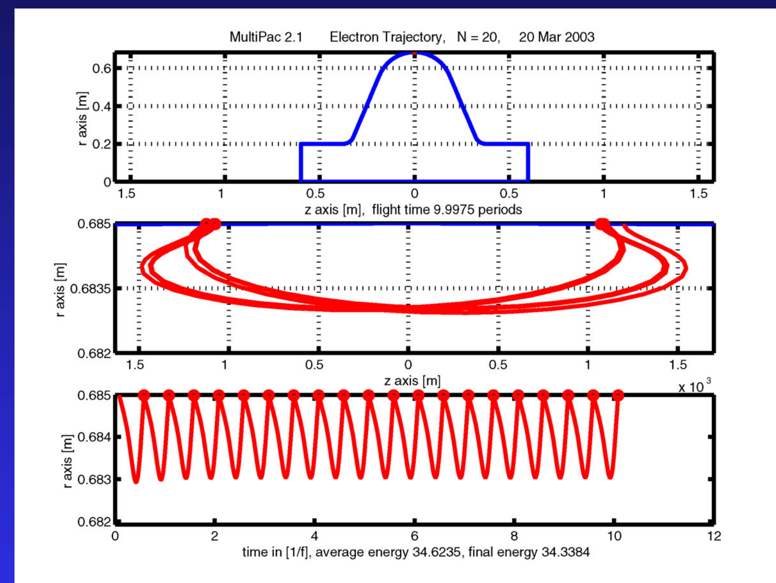
- A high Q at low filed
- Multipacting at 3MV/m
- MP breakthrough by processing
- Limited by strong FE

Cavity sent back to CERN and re-rinsed

DESY/Helsinki MP code sim.



MULTIPAC simulation
confirmed exp. observation

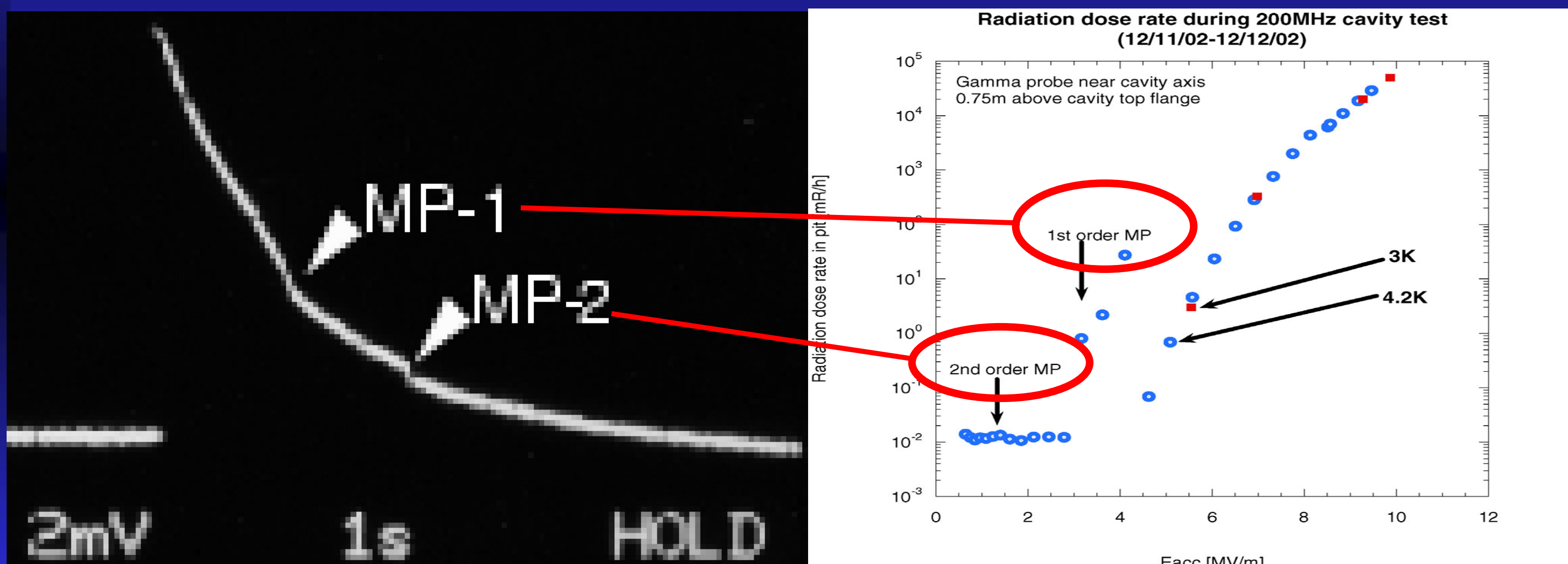


Resonant trajectory of MP electrons

It was possible to process through MP barrier

Two-point MP: 1st & 2nd order

- Two switches in reflected signal → two MP barriers
- Each MP barrier is accompanied by a γ-ray burst

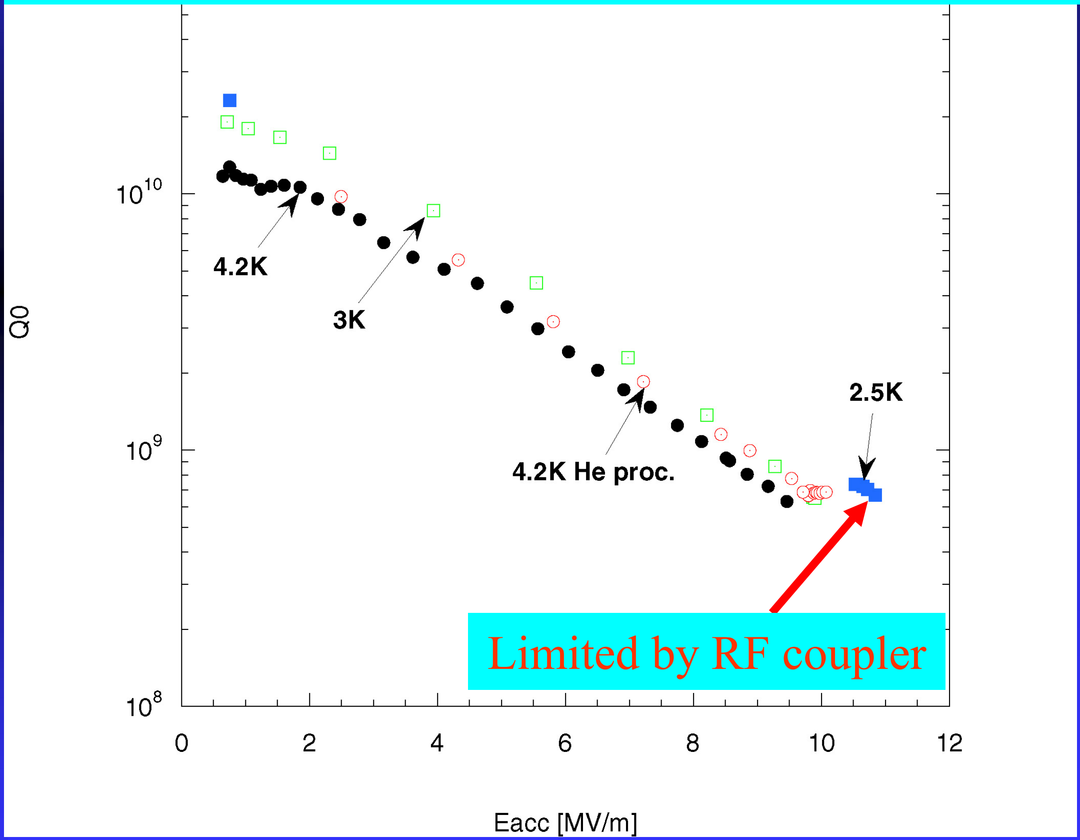


1st order MP: flight time between impact = T/2

2nd order MP: flight time between impact = 3T/2

Performance at 4K and 2.5K

After re-rinse, combined RF and Helium processing



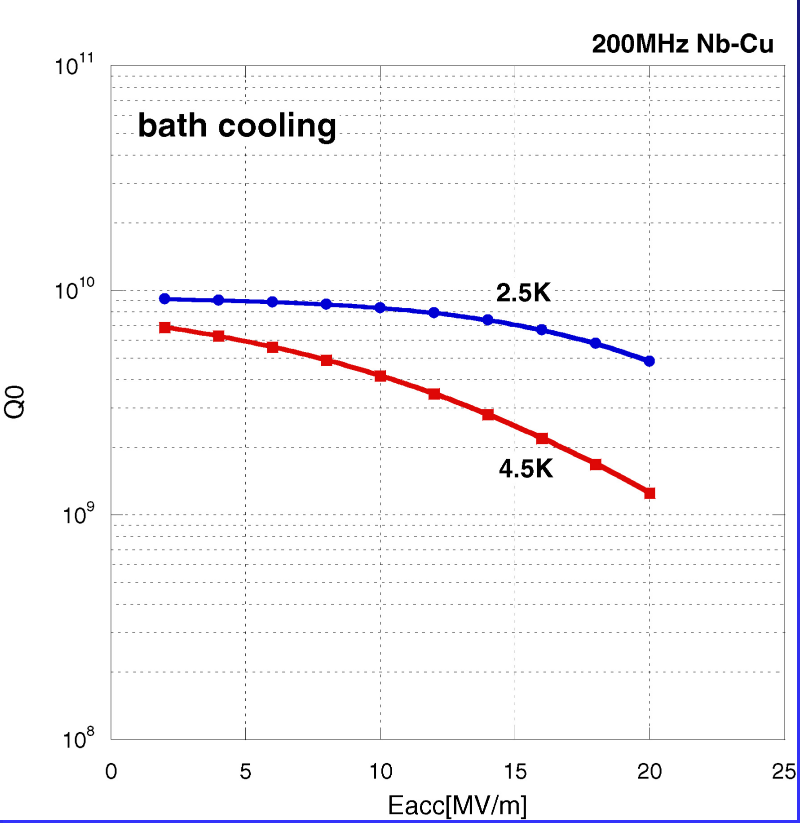
- Eacc = 11MV/m
- Low field Q = 2E10

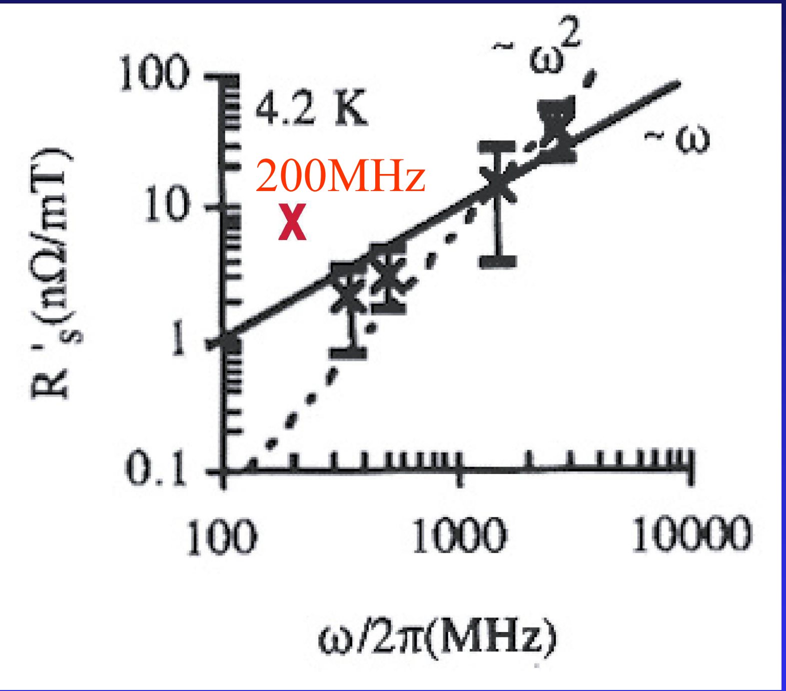
- 75% goal E_{acc} achieved
- Q-slope out of expectation

Q improves at lower T
→ FE not dominating

Expected performance

Projecting LHC 400MHz to 200MHz



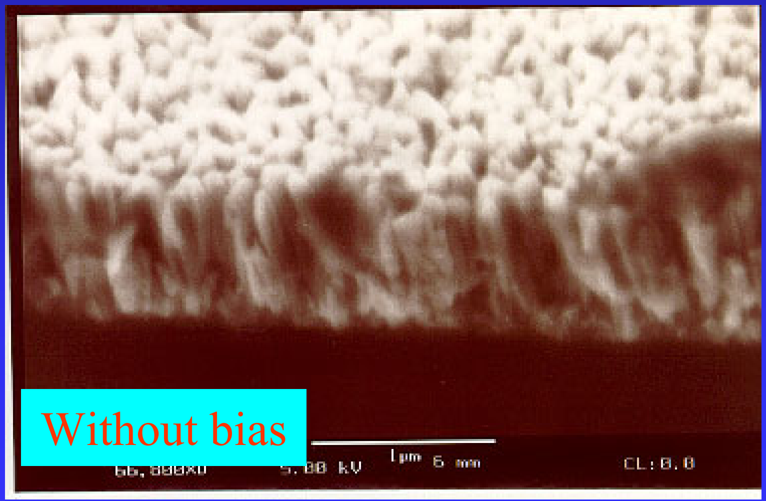


Empirical frequency dependence of Q-slope

Measured Q-slope of 200MHz cavity is 10 times too steep than projected

Q-slope improvement

- Why Q-slope of 200 MHz cavity too steep?
- What can be done to improve?
- Optimization of sputtering configuration (current apparatus optimized for 350 MHz LEP2 cavities)
- Bias sputtering



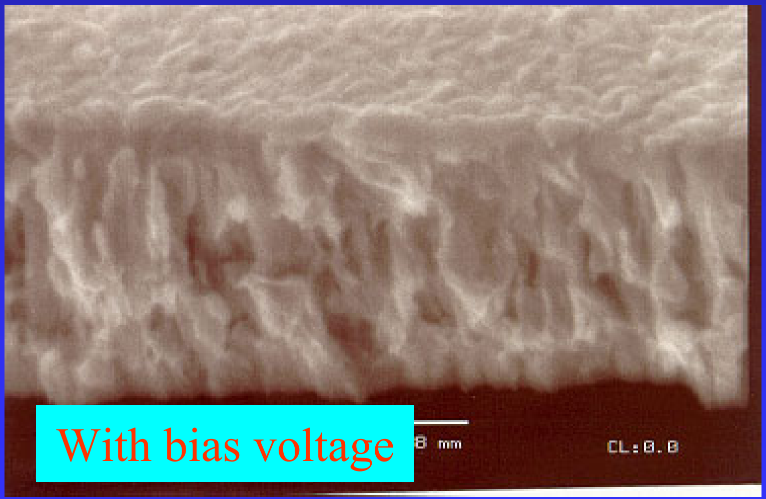
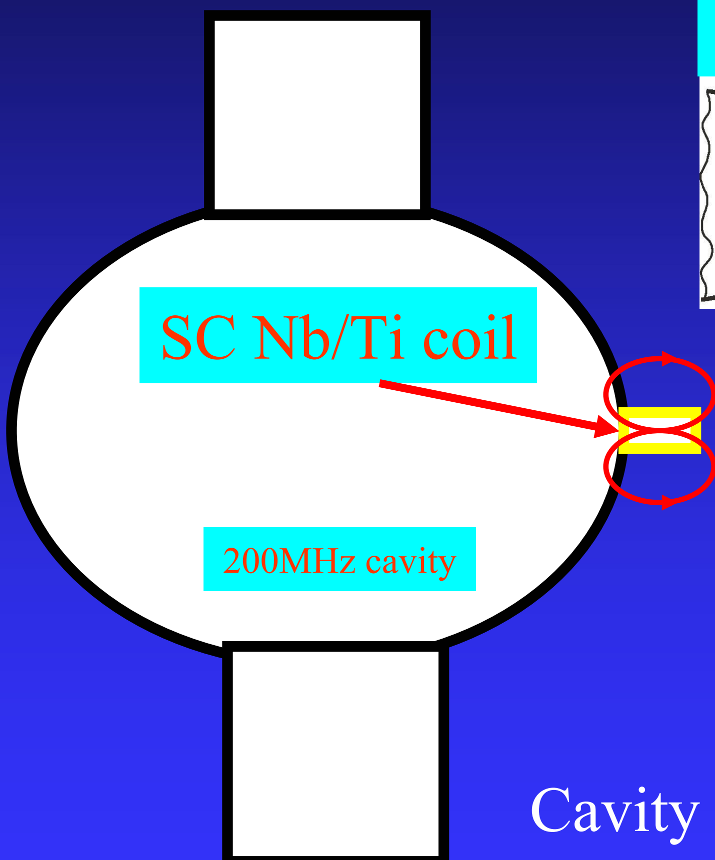


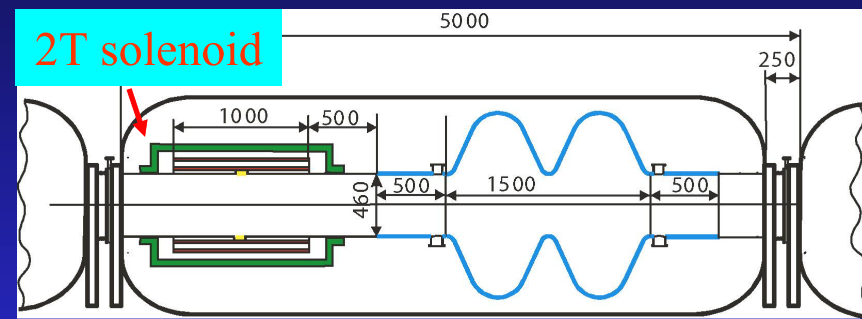
Photo credit: K. Zhao et al., PKU

Film studies at 500 MHz

- LHe consumption for RF test 200 MHz cavity is expensive
- We aim to study Nb film at 500MHz with existing B-cell SRF infrastructure
- Seamless 500MHz copper cavities from INFN
- Bias sputtering test at ACCEL

H_{ext} effect on cavity



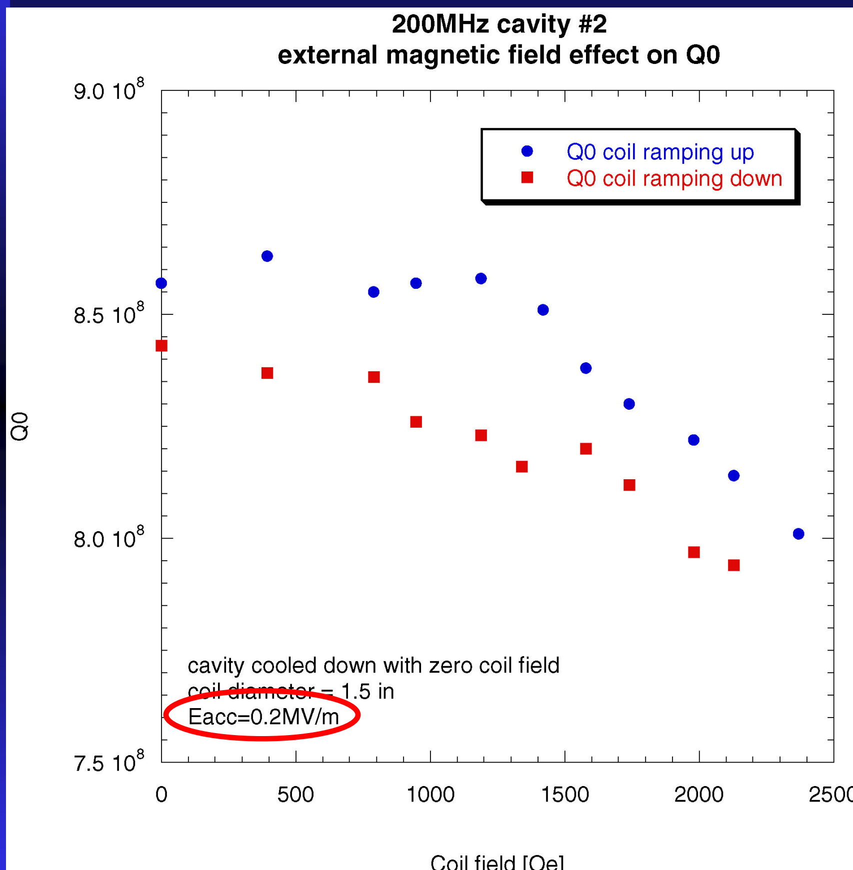


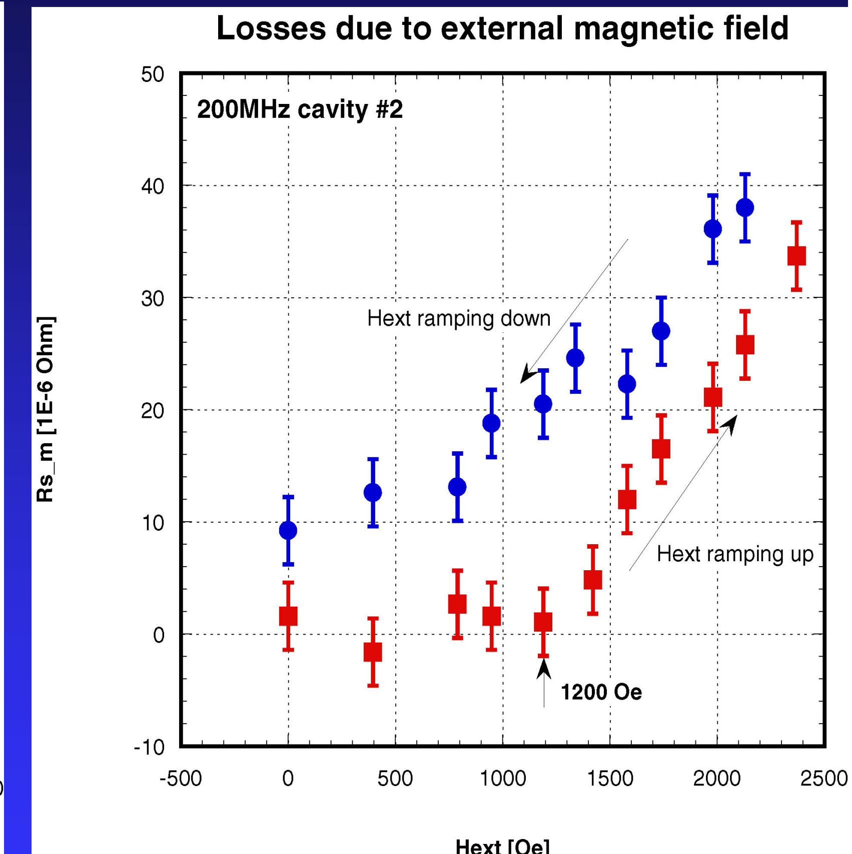
Layout of Linear Accelerator for ν source

- 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}

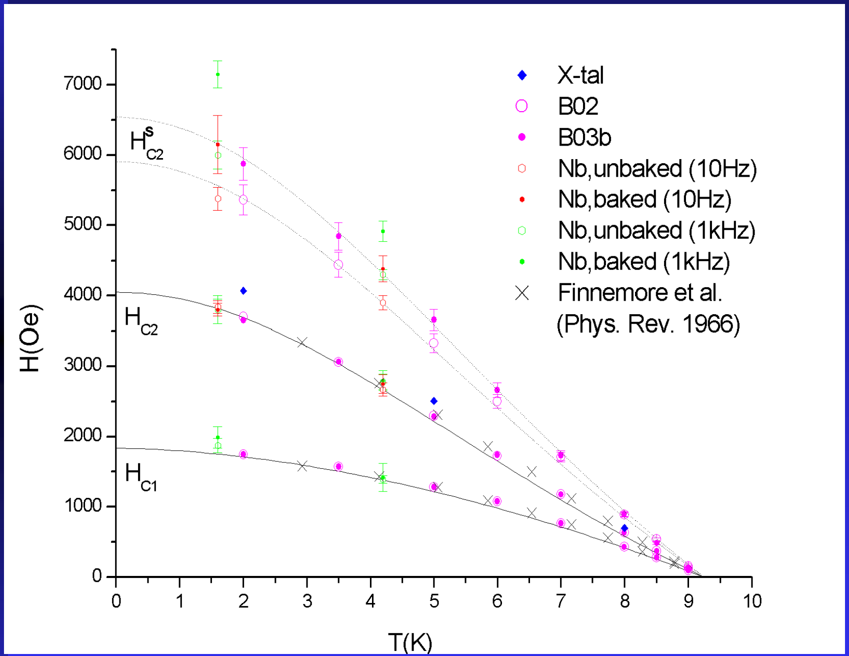
H_{ext} effect (preliminary)





Cavity stays intact up to Hext = 1200 Oe

Hext effect cont.



- Nb is a type-II SC
- Mixed state above Hc1
- Magnetic flux penetration
- Normal core causes Rs ↑

- Onset H_{ext} for loss increase consistent with Hc1 of Nb
- Measurements at higher Eacc needed to examine the effect of combined $H_{ext} + H_{RF}$ (resistive flux flow)

Exploring new cavity shapes

Q: Is the elliptical cavity the best choice for muon acceleration ?

Driven by the special need for muon beams and based on the lessons learned from 200 MHz cavities so far, it is worth well to explore other cavity shapes like,

- Spoke cavity:

  Smaller size

  Larger longitudinal acceptance

- Pill-box cavity:

  Uniform sputtering over high-magnetic surface

  Reduced Hpk/Eacc to mitigate Q-slope

  But MP may limit – MULTIPAC simulation will answer

Conclusion

- First ever 200MHz cavity completed successfully
- First results achieved Eacc = 11 MV/m and Q_0 = 2E10 at low field
- MP barriers can be processed through
- Cavity not affected by Hext < 1200 Oe
- Further work needed to reduce Q-slope
- Measurements on Hext effect at higher Eacc needed
- Exploration of new cavity shapes desired