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 $\pi$; decay into $\mu \Rightarrow$ MERIT
  - Bunching and Phase Rotation
    - reduce $\Delta E$ of bunch
  - Cooling
    - reduce long. and transverse emittance
      $\Rightarrow$ MICE $\rightarrow$ 6D experiment
  - Acceleration
    - 130 MeV $\rightarrow$ $\sim$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
Acceleration Requirements

- The highest possible $E_{acc}$ 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)
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: $E_{\text{acc}} > 11 \text{ MV/m}$
- Second cavity was limited by field emission at $< 3 \text{ MV/m}$
- Second cavity demonstrated performance in $H_{\text{ext}} < 1200 \text{ Oe}$
- 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
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
Linac and RLA Cavity Layout

Focusing Solenoid (2-4 T)

2-cell SRF cavity
## 200MHz SRF parameter list

### Linac

2-cell, 460 mm-aperture cavity parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>RF freq (MHz)</td>
<td>201.25</td>
</tr>
<tr>
<td>No. of cells per cavity</td>
<td>2</td>
</tr>
<tr>
<td>Active cavity length (m)</td>
<td>1.5</td>
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<tr>
<td>No. of cavities</td>
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<tr>
<td>Aperture diameter (mm)</td>
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<tr>
<td>$E_{acc}$ (MV/m)</td>
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<td>Energy gain per cavity (MV)</td>
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<tr>
<td>Stored energy per cavity (J)</td>
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<tr>
<td>$R/Q$ (Ω/cavity)</td>
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<tr>
<td>$E_p/E_{acc}$</td>
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<td>$H_p/E_{acc}$ (Oe/MV/m)</td>
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<td>$E_{pk}$ at 10 MV/m (MV/m)</td>
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<td>$H_{pk}$ at 10 MV/m (Oe)</td>
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<td>Bandwidth (Hz)</td>
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<td>RF on-time (ms)</td>
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<tr>
<td>RF duty factor (%)</td>
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<tr>
<td>Dynamic heat load per cavity (watt)</td>
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<tr>
<td>Operating temperature (K)</td>
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<tr>
<td>$Q_L$</td>
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<tr>
<td>Microphonics detuning tolerable (Hz)</td>
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</table>

### RLA

2-cell, 300 mm-diameter cavity parameters.

<table>
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<th>Parameter</th>
<th>Value</th>
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<td>No. of cells per cavity</td>
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<td>RLA</td>
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<td>Aperture diameter (mm)</td>
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<td>$E_{acc}$ (MV/m)</td>
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<td>Energy gain per cavity (MV)</td>
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<tr>
<td>Stored energy per cavity (J)</td>
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<tr>
<td>$R/Q$ (Ω/cavity)</td>
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<td>$E_p/E_{acc}$</td>
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<td>$H_p/E_{acc}$ (Oe/MV/m)</td>
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<td>$E_{pk}$ at 15 MV/m (MV/m)</td>
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<tr>
<td>$H_{pk}$ at 15 MV/m (Oe)</td>
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<tr>
<td>$Q_0$</td>
<td>$6 \times 10^9$</td>
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<tr>
<td>Bandwidth (Hz)</td>
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<tr>
<td>Input power per cavity (kW)</td>
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<td>RF on-time (ms)</td>
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<td>RF duty factor (%)</td>
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<tr>
<td>Dynamic heat load per cavity (W)</td>
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<td>Operating temperature (K)</td>
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<tr>
<td>$Q_L$</td>
<td>$10^6$</td>
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<td>Microphonics detuning tolerable (Hz)</td>
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<td>Wall thickness (mm)</td>
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<td>Lorentz force detuning at 15 MV/m (Hz)</td>
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300 high gradient 200MHz cavities needed
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 → $ 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$
Example of Pipe Cooling

- Cavity Shell Halves
- Extrusion Flange
- Nose Ring
- Beryllium Window
- Stiffener Ring
- Window Clamp Ring and Fasteners
- Cavity Cooling Tube
First 200MHz Nb-Cu cavity

Major dia.: 1.4 m

Cavity length: 2 m

400mm BT
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
First RF test at Cornell

Cavity on test stand

Cavity going into test pit in Newman basement

Pit: 5m deep X 2.5m dia.
First Cavity Test Results

200MHz Nb-Cu Cavity

4.2K

First test 06/10/02
Second test 07/17/02 before He processing
X-rays start
Second test 07/17/02 after He processing
Multipacting

Q0

Eacc [MV/m]

Don Hartill  NFMCC meeting  January 15, 2010
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
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
Third Cavity Test

- $E_{acc} = 11 \text{MV/m}$
- Low field $Q = 2 \times 10^{10}$

Limited by RF coupler

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

$Q$ improves with lower $T$ → FE not dominant
**H_{ext} effect on cavity setup**

- SC Nb/Ti coil
- 200MHz cavity
- 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 on 2^{nd} cavity**

Cavity Q stays intact up to H_{ext} = 1200 Oe
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
Despite Q-slope, sputtered Nb-Cu cavities have achieved a 15MV/m $E_{acc}$ at 400MHz.
Expected performance

Empirical frequency dependence of Q-slope

Measured Q-slope of 200MHz cavity is 10 times steeper than expected
CERN explored low $\beta = (v/c)$ 350MHz cavities.
With the same cathode geometry, lower $\beta \rightarrow$ low $\gamma$. 

Impact angle of Nb atom: $\gamma$
Correlation: lower $\beta \rightarrow$ lower $\gamma \rightarrow$ steeper Q-slope
$\rightarrow$ 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.
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.
• A few slides illustrating the spinning process
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 °C, several small bubbles (10 mm²) appeared indicating delamination 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.
The first 200MHz SC cavities have been constructed.

Test results for the first cavity were $E_{acc} = 11$ MV/m with $Q_0 = 2\times10^9$ at low field.

MP barriers were present and could be processed through.

Cavity performance was not affected by $H_{ext} < 1200$ Oe.

Some progress was made on the understanding of the Q-slope in sputtered cavities.

Currently a low temperature bake ~ 100 °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.
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.
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.
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.
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.