200MHz SCRF cavity development

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Contents

- Fabrication and RF tests
- Performance: $E_{acc}$ and $Q$
- Performance when $H_{ext} \neq 0$
- Status and what we hope to finish
- Conclusions
Acceleration Requirements

- The highest possible $E_{\text{acc}}$ to minimize muon decay
- Large transverse and longitudinal acceptances

Both requirements favor the choice of SRF

- SRF cavities have a high $Q_0$
- SRF can achieve high gradients with modest RF power
- SRF cavities accommodate a larger aperture without a large penalty for the low $R/Q$

$$P_d = \frac{E_{\text{acc}}^2}{(R/Q)Q_0}$$
Linac and RLA Cavity Layout

Focusing Solenoid (2-4 T)

2-cell SRF cavity
200MHz SRF parameter list

2-cell, 460 mm-aperture cavity parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</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>
</tr>
<tr>
<td>No. of cavities</td>
<td>43</td>
</tr>
<tr>
<td>Aperture diameter (mm)</td>
<td>460</td>
</tr>
<tr>
<td>$E_{acc}$ (MV/m)</td>
<td>15</td>
</tr>
<tr>
<td>Energy gain per cavity (MV)</td>
<td>22.5</td>
</tr>
<tr>
<td>Stored energy per cavity (J)</td>
<td>1932</td>
</tr>
<tr>
<td>$R/Q$ (Ω/cavity)</td>
<td>208</td>
</tr>
<tr>
<td>$E_{p}/E_{acc}$</td>
<td>1.54</td>
</tr>
<tr>
<td>$H_{p}/E_{acc}$ (Oe/MV/m)</td>
<td>44</td>
</tr>
<tr>
<td>$E_{pk}$ at 10 MV/m (MV/m)</td>
<td>23.1</td>
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<tr>
<td>$H_{pk}$ at 10 MV/m (Oe)</td>
<td>660</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>
<td>200</td>
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<tr>
<td>Input power per cavity (kW)</td>
<td>980</td>
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<tr>
<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>
<td>$10^6$</td>
</tr>
<tr>
<td>Microphonics detuning tolerable (Hz)</td>
<td>40</td>
</tr>
</tbody>
</table>

2-cell, 300 mm-diameter cavity parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>RF freq (MHz)</td>
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<tr>
<td>No. of cells per cavity</td>
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<td>Active cavity length (m)</td>
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<tr>
<td>No. of cavities</td>
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<tr>
<td>Linac</td>
<td>76</td>
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<tr>
<td>RLA</td>
<td>180</td>
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<td>Aperture diameter (mm)</td>
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<tr>
<td>$E_{acc}$ (MV/m)</td>
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<tr>
<td>Energy gain per cavity (MV)</td>
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<tr>
<td>Stored energy per cavity (J)</td>
<td>2008</td>
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<tr>
<td>$R/Q$ (Ω/cavity)</td>
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<tr>
<td>$E_{p}/E_{acc}$</td>
<td>1.43</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>
<td>24.3</td>
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<tr>
<td>$H_{pk}$ at 15 MV/m (Oe)</td>
<td>646</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>
<td>200</td>
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<tr>
<td>Input power per cavity (kW)</td>
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<tr>
<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 (W)</td>
<td>18.9</td>
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<tr>
<td>Operating temperature (K)</td>
<td>2.5</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Microphonics detuning tolerable (Hz)</td>
<td>40</td>
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<td>Wall thickness (mm)</td>
<td>8</td>
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<tr>
<td>Lorentz force detuning at 15 MV/m (Hz)</td>
<td>128</td>
</tr>
</tbody>
</table>

300 high gradient 200MHz cavities needed
Why Nb-Cu cavities?

- Save material cost
- May save cost on magnetic field shielding (Rs of Nb-Cu less sensitive to residual mag. field)
- May save cost on LHe inventory by pipe cooling (Brazing Cu pipe to Cu 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 cost for 600 cells: 180M$
Cu (OF) is X 40 cheaper: 5M$
Nb-Cu Bonded Material: < 50 M$
First 200MHz Nb-Cu cavity

Cavity length: 2 m

Major dia.: 1.4 m

400mm BT
Fabrication at CERN

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

Cavity on test stand

Cavity going into test pit in Newman basement

Pit: 5m deep X 2.5m dia.
Performance of the cavity

- 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
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

$\text{MP electrons drain RF power} \rightarrow \text{A sharp Q drop}$
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
$H_{\text{ext}}$ effect on cavity

- SC Nb/Ti coil
- 2T solenoid
- 200MHz cavity
- 2T solenoid needed for tight focusing
- Solenoid and cavity fitted in one cryostat
- Large aperture (460 mm)
- Q: Will cavity still work $H_{\text{ext}} > 0$?

Cavity test in the presence of an $H_{\text{ext}}$
H_{ext} effect on cavity

Cavity stays intact up to H_{ext} = 1200 Oe
Hext effect on cavity

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

- Onset $H_{ext}$ for loss increase consistent with Hc1 of Nb
- Msmts at higher Eacc needed: $H_{ext} + H_{RF}$; resistive flux flow
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 Eacc at 400MHz
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
Q-slope: impact angle effect

• CERN explored low $\beta$ 350MHz cavities
• With the same cathode geometry, lower $\beta \rightarrow$ low $\gamma$
Q-slope: impact angle effect

Correlation: lower $\beta \rightarrow$ lower $\gamma \rightarrow$ steeper Q-slope
Other techniques for Nb film deposition

- Bias sputtering
- Energetic deposition in vacuum
- Vacuum arc deposition
- Electron cyclotron resonance sputtering
- Bonding of 1 mm Nb to Cu substrate by hot isostatic pressyre or by explosion bonding
Nb Sputtering Variation

- Standard films have rod like form
- Avoid oxide formation
- More uniform and larger grains
Reducing Q-Slope

- Study Nb film with 500MHz cavities (less LHe) with existing LEPP infrastructure developed for CESR SRF
- Seamless Cu cavities to simplify fabrication (Italy)
500 MHz

ACCEL Sputtering Setup
500 MHz Progress

ACCEL Nb Coated Cavity before Final Water Rinse
500MHz Sputtered Nb on Spun Cu Cavity

R.L. Geng

- 10^{10}
- 10^{9}

- 10^{8}
- 4.2K
- RF limit

- Quench

Q0, SC500-1, March 2, 2004
Q0, SC500-1, September 10, 2004, recoated
Q0, SC500-3, April 14, 2005
Q0, SC500-3, March 2, 2005

Eacc [MV/m]
Film Nb/Cu cavity Q-slope rate

\[ R'_s (\text{n}\Omega/\text{mT}) \]

\[ \omega / 2\pi \text{(MHz)} \]

- 200MHz
- 495MHz

4.2 K

\[ \sim \omega^2 \]

\[ \sim \omega \]

April 15, 2005
Summary of Recent Program

- 500 MHz cavity from ACCEL, assembled and tested twice to 4MV/m with heavy field emission and quench. Second cavity reached 10 MV/m with large Q slope on 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 - cavities shipped back to CERN to avoid paying duty.
- Continued using Auger surface analysis system and SIMS to further characterize Nb sputtered surfaces.
- Explored effectiveness of Atomic Force Microscopy in characterizing good Nb RF surfaces.
Near term Program

• Electron Cyclotron Resonance Coating R&D work at JLAB under way - nearly ready to coat first cavity.
• Have spun two 500 MHz cavities from explosion bonded Nb-Cu sheet (1 mm Nb on 4 mm Cu). Single cell 1300 MHz cavity spun from this material has achieved 40 MV/m accelerating gradient.
• Have spun two 500 MHz cavities from hot isostatic pressure bonded Nb-Cu sheet (1 mm Nb on 4 mm Cu).
• Nearly ready to Bias Sputter coat a spun Cu single cell 500 MHz cavity at ACCEL and at INFN in Italy.
• Spun cavities of bonded Nb-Cu to ACCEL for flange installation soon. Expect them at Cornell early summer.
Improve Films with Energetic Deposition

Energetic Condensation (Deposition)

- Evaporation
- Sputtering
- Arcing, plasma
- Back-sputtering occurs
- Implantation

Energy in eV

0.0  0.1  1   10  100  1000 10000
INFN/Roma and Andrzej Soltan Institute

Cathodic Arc Deposition

- No working gas (UHV)
- Ionized niobium (up to 95%)
- High ion energy (10-100eV)
- Excellent adhesion
- High purity
- Possible to apply bias and magnetic field
- Chemical process capable (i.e. NbN)

Linear, Planar arc systems

Macro particle filters
RRR 20-100
SC transition width comparable to bulk
Low field Rs no worse than bulk
Columnar growth but densely packed.

Q measurement implying Rs.

SEM pictures of film surface with/without macro particle filter
SEM pictures of film structure
Energy-Controlled ECR Plasma

- Niobium Ion Energy is around 63 eV, and controllable.
- Deposition Energy of 114 eV yields better film quality for sapphire substrate.
- Epitaxial growth of niobium on sapphire
- Bias voltage affects Nb film crystal orientation
The AFM picture shows a flat, densely packed, niobium thin film on a sapphire substrate with 80 nm grain sizes.
Nb sputtered films
(in collaboration with Cornell University)
Biased Magnetron Sputtering
Biased Magnetron Sputtering
Biased Magnetron Sputtering
Biased Magnetron Sputtering
Biased Magnetron Sputtering
Biased Magnetron Sputtering
Biased Magnetron Sputtering
Thin Film Coatings for RF Superconductivity

Jefferson Lab/Cornell

- No working gas like argon
- High vacuum means reduced impurities
- Controllable “single” deposition energy,
- Near 90-degree deposition angle
- Excellent bonding
- No macro particles
- Faster rate (Conditional)
- Smooth surface (also shown in Cu hyperthermal deposition)
Recent developments for JLAB's next generation cavities, couplers and cryomodules
Recent developments for JLAB's next generation cavities, couplers and cryomodules

1. 14kW rod-fed E-gun
2. 9000 l/s cryopump system
3. bucking coil for E-gun
4. top and bottom iron yokes (outer iron shield is removed for illustration)
5. center coils
6. Nb grid tube
7. bias insulator
8. WR284 waveguide E-bend and horn to the grid tube
9. “T” vacuum chamber
10. top pancake coil
11. Cu cavity
12. bottom pancake coil.
Recent developments for JLAB’s next generation cavities, couplers and cryomodules

Inside

E-gun chamber
Recent developments for JLAB's next generation cavities, couplers and cryomodules
Spinning of Bonded Nb-Cu

- Both hot isostatic pressure bonded (hipped) Nb-Cu and explosion bonded Nb-Cu plates have been 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 de-lamination of Nb from Cu.

- Small surface cracks are apparent in the cavities spun from the explosion bonded material.

- With modest grinding and subsequent surface chemistry the cavities from explosion bonded material are likely to yield cavities capable of > 17 MV/m accelerating gradient. The hipped cavities can not be used because they would be thermally unstable in the bubble regions.

- These bonded materials combined with spinning are likely to be the most promising path to a successful superconducting accelerating system for a muon storage ring.
Conclusions

- The first 200MHz SC cavities have been constructed.
- Test results for the first cavity are $E_{acc} = 11$ MV/m with $Q_0 = 2 \times 10^{10}$ at low field.
- MP barriers are present and can be processed through.
- Cavity performance is not affected by $H_{ext} < 1200$ Oe.
- Making good progress on understanding the Q-slope.
- Confident that we can build 200 MHz SCRF cavities with $E_{acc} > 17$ MV/m.
Conclusions

- Currently a low temperature bake ~ 100 °C seems to significantly reduce the Q slope. Because of diffusion of Cu into Nb, bonded Nb sheet to copper is an attractive path to high accelerating gradients.
- 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 bonding.
- Spinning of the bonded material is straightforward. Three 500 MHz cavities have been spun with the fourth nearly finished.
- Hope to test the two 500 MHz Nb-Cu explosion bonded cavities by the end of the summer.
- Plan some continuing effort in developing suitable superconducting cavities for muon acceleration after the end of the current extended NSF muon contract (9/1/06).