R & D in RF Superconductivity at Michigan State University

W. Hartung

National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, Michigan

FNAL Accelerator Physics & Technology Seminar
14 September 2006
Introduction

Michigan State University (MSU): ∼400 km from Fermilab.

National Superconducting Cyclotron Laboratory (NSCL): basic research in nuclear physics and nuclear astrophysics.

NSCL Coupled Cyclotron Facility: user facility for experiments with heavy ions.

Nuclear physics community agrees: a new facility is needed for the next generation of experiments with heavy ion beams.

The new facility should be a heavy ion linac. Design work ongoing for several years (Argonne, Berkeley, CEBAF, Oak Ridge, NSCL, et al.).
Introduction

- Michigan State University (MSU): ~ 400 km from Fermilab.
- National Superconducting Cyclotron Laboratory (NSCL): basic research in nuclear physics and nuclear astrophysics.
- NSCL Coupled Cyclotron Facility: user facility for experiments with heavy ions.
- Nuclear physics community agrees: a new facility is needed for the next generation of experiments with heavy ion beams.
- The new facility should be a heavy ion linac. Design work ongoing for several years (Argonne, Berkeley, CEBAF, Oak Ridge, NSCL, et al.).
The heavy ion linac should operate in CW and make use of superconducting radio-frequency (SRF) cavities.

There are several existing SRF linacs for heavy ions, e.g. at Argonne, INFN-Legnaro, JAERI, etc.

Existing heavy ion SRF linacs generally use quarter-wave resonators (QWRs) and variants thereof.

A next-generation linac would use QWRs, half-wave resonators (HWRs), and elliptical cavities.

NSCL began R & D work in SRF in the year 2000, with help from CEBAF, INFN-Legnaro, and other collaborators.

SRF facilities at MSU: fabrication, chemistry, clean room, RF testing.
The heavy ion linac should operate in CW and make use of superconducting radio-frequency (SRF) cavities.

There are several existing SRF linacs for heavy ions, e.g. at Argonne, INFN-Legnaro, JAERI, etc.

Existing heavy ion SRF linacs generally use quarter-wave resonators (QWRs) and variants thereof.

A next-generation linac would use QWRs, half-wave resonators (HWRs), and elliptical cavities.

NSCL began R & D work in SRF in the year 2000, with help from CEBAF, INFN-Legnaro, and other collaborators.

SRF facilities at MSU: fabrication, chemistry, clean room, RF testing.
Cavity Design and Prototyping

QWRs, HWRs, and elliptical cavities were prototyped by NSCL in collaboration with CEBAF and Legnaro. Design work was done by INFN-Milano, INFN-Legnaro, CEBAF, and NSCL.
QWRs, HWRs, and elliptical cavities were prototyped by NSCL in collaboration with CEBAF and Legnaro.

Design work was done by INFN-Milano, INFN-Legnaro, CEBAF, and NSCL.
Cavity parameters for a heavy ion linac example: 400 MeV/nucleon, 400 kW beam power

<table>
<thead>
<tr>
<th>Type</th>
<th>$\lambda/4$</th>
<th>$\lambda/2$</th>
<th>6-cell elliptical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{opt}$</td>
<td>0.041</td>
<td>0.085</td>
<td>0.285</td>
</tr>
<tr>
<td>$f$ (MHz)</td>
<td>80.5</td>
<td>322</td>
<td>805</td>
</tr>
<tr>
<td>$V_a$ (MV)</td>
<td>0.46</td>
<td>1.18</td>
<td>1.58</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>4.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$5 \cdot 10^8$</td>
<td>$5 \cdot 10^9$</td>
<td>$7 \cdot 10^9$</td>
</tr>
<tr>
<td>$P_0$ (W)</td>
<td>1.0</td>
<td>6.7</td>
<td>2.5</td>
</tr>
<tr>
<td>$R/Q$ ($\Omega$)</td>
<td>424</td>
<td>416</td>
<td>199</td>
</tr>
<tr>
<td>$G$ ($\Omega$)</td>
<td>15.7</td>
<td>19.0</td>
<td>61.0</td>
</tr>
<tr>
<td>$Rs$ ($n\Omega$)</td>
<td>31.4</td>
<td>38.0</td>
<td>12.2</td>
</tr>
<tr>
<td>$E_p$ (MV/m)</td>
<td>16.5</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>$B_p$ (mT)</td>
<td>28.2</td>
<td>46.5</td>
<td>68.6</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>30</td>
<td>77</td>
<td>86</td>
</tr>
<tr>
<td>Magnets</td>
<td>NbTi solenoids</td>
<td>Cu quads</td>
<td></td>
</tr>
<tr>
<td># cavities</td>
<td>18</td>
<td>104</td>
<td>208</td>
</tr>
<tr>
<td># cryo-modules</td>
<td>2</td>
<td>13</td>
<td>26</td>
</tr>
</tbody>
</table>
Cavities for heavy ion acceleration

- **Legnaro**
  - $\beta_{\text{opt}} = 0.041$
  - 80.5 MHz

- **MSU**
  - $\beta_{\text{opt}} = 0.085$
  - 80.5 MHz

- **MSU**
  - $\beta_{\text{opt}} = 0.285$
  - 322 MHz

- **MSU**
  - $\beta_{\text{opt}} = 0.49$
  - 805 MHz
  - MSU/JLAB

- **MSU**
  - $\beta_{\text{opt}} = 0.63$
  - 805 MHz
  - SNS

- **MSU**
  - $\beta_{\text{opt}} = 0.83$
  - 805 MHz
  - SNS

50 cm
Cavities for heavy ion acceleration
RF tests of 6-cell $\beta_g = 0.47$ cavities at 2 K
RF test results for the $\beta_g = 0.29$ HWR.
RF test results for the $\beta_g = 0.085$ QWR
Cryomodule Design and Prototyping

- Rectangular box cryomodule design for all cavity types.
- Prototype medium-β cryomodule: 2 elliptical cavities
- Prototype low-β cryomodule: 1 QWR, 1 HWR, 2 focussing magnets
Cryomodule Design and Prototyping

- Rectangular box cryomodule design for all cavity types.
- Prototype medium-\(\beta\) cryomodule: 2 elliptical cavities
- Prototype low-\(\beta\) cryomodule: 1 QWR, 1 HWR, 2 focussing magnets
Cryomodule design for 80.5 MHz QWRs
Cryomodule design for 805 MHz elliptical cavities
Prototype Medium-β Cryomodule
## Medium-β cryomodule design parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Prototype</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavities</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Length</td>
<td>2.1 m</td>
<td>4.0 m</td>
</tr>
<tr>
<td>2 K cold mass</td>
<td>210 kg</td>
<td>460 kg</td>
</tr>
<tr>
<td>Total mass</td>
<td>2200 kg</td>
<td>3600 kg</td>
</tr>
<tr>
<td>Bayonets</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Support links</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>77 K heat load</td>
<td>&lt; 50 W</td>
<td>&lt; 100 W</td>
</tr>
<tr>
<td><strong>2 K Heat Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input coupler</td>
<td>1.6 W (each)</td>
<td></td>
</tr>
<tr>
<td>Tuner</td>
<td>0.8 W (each)</td>
<td></td>
</tr>
<tr>
<td>Total (RF off)</td>
<td>9 W</td>
<td>15 W</td>
</tr>
<tr>
<td>Total (RF on)</td>
<td>53 W</td>
<td>103 W</td>
</tr>
</tbody>
</table>
RF input coupler for medium-$\beta$ cryomodule

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance</td>
<td>50 $\Omega$</td>
</tr>
<tr>
<td>Type</td>
<td>Planar Coax (KEK/SNS)</td>
</tr>
<tr>
<td>Cooling</td>
<td>conduction</td>
</tr>
<tr>
<td>$Q_{ext}$</td>
<td>$2 \cdot 10^7$</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>40 Hz</td>
</tr>
<tr>
<td>Design power</td>
<td>5 kW</td>
</tr>
<tr>
<td>Max power</td>
<td>100 kW</td>
</tr>
</tbody>
</table>
Medium-$\beta$ prototype cryomodule components
Construction of medium-$\beta$ cryomodule
(completed February 2004)
Experimental results: medium-$\beta$ cryomodule
Experimental results: medium-$\beta$ cryomodule

<table>
<thead>
<tr>
<th>Item</th>
<th>Measured</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cavity #1</td>
<td>Cavity #2</td>
</tr>
<tr>
<td>Fixed $Q_{ext}$</td>
<td>1.4 · 10^7</td>
<td>1.3 · 10^7</td>
</tr>
<tr>
<td>Variable $Q_{ext}$</td>
<td>6 · 10^4 to 6 · 10^9</td>
<td></td>
</tr>
<tr>
<td>$\frac{df}{dP}$ (kHz/torr)</td>
<td>0.36</td>
<td>0.46</td>
</tr>
<tr>
<td>$\frac{df}{dE_a^2}$ [Hz/(MV/m)^2]</td>
<td>-16</td>
<td></td>
</tr>
<tr>
<td>Static load at 4.3 K</td>
<td>9 W</td>
<td></td>
</tr>
<tr>
<td>Static load at 2 K</td>
<td>10–11 W</td>
<td>9 W</td>
</tr>
</tbody>
</table>

Variable $Q_{ext} = \text{standing wave in input coupler}$

Measured static load includes the liquid He reservoir
Tuner with actuator at room temperature
## Tuner with actuator at room temperature

<table>
<thead>
<tr>
<th>Item</th>
<th>Design</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>±250 kHz</td>
<td>±500 kHz</td>
</tr>
<tr>
<td>Tuning coefficient</td>
<td>&gt; 200 kHz/mm</td>
<td>208 kHz/mm</td>
</tr>
<tr>
<td>Cavity spring constant</td>
<td>&lt; 1750 N/mm</td>
<td>1910 N/mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>1 Hz</td>
<td></td>
</tr>
<tr>
<td>Compliance</td>
<td>0.7 (rigid)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Prototype low-\(\beta\) cryomodule design parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Quadrupole</th>
<th>Solenoid (Dipole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective length</td>
<td>50 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Aperture</td>
<td>40 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Strength</td>
<td>31 T/m</td>
<td>9 T (0.01 T(\cdot)m)</td>
</tr>
<tr>
<td>Turns</td>
<td>78</td>
<td>16 813 (40)</td>
</tr>
<tr>
<td>Current</td>
<td>63 A</td>
<td>68 A (50 A)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat Load to Liquid He</th>
<th>QWR</th>
<th>HWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input coupler</td>
<td>0.40 W</td>
<td>0.60 W</td>
</tr>
<tr>
<td>Tuner</td>
<td>0.63 W</td>
<td>0.38 W</td>
</tr>
<tr>
<td>Total/RF off</td>
<td>6 W</td>
<td></td>
</tr>
<tr>
<td>Total/RF on</td>
<td>15.2 W</td>
<td></td>
</tr>
</tbody>
</table>
Prototype low-\(\beta\) cryomodule design parameters

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryomodule</td>
<td></td>
</tr>
<tr>
<td>77 K shield load</td>
<td>&lt; 100 W</td>
</tr>
<tr>
<td>Length</td>
<td>1.54 m</td>
</tr>
<tr>
<td>Cold mass</td>
<td>310 kg</td>
</tr>
<tr>
<td>Total mass</td>
<td>2000 kg</td>
</tr>
</tbody>
</table>
Cryogenics for the low-β cryomodule
Cold box for the low-$\beta$ cryomodule
RF Couplers for the low-β cryomodule conditioned to 1.1 kW (QWR) and 2 kW (HWR)
Tuners for low-$\beta$ cryomodule with actuators at room temperature
HWR + Solenoid  
HWR + Quadrupole  

Vertical tests: low-$\beta$ cavities and magnets
Vertical tests: low-\( \beta \) cavities and magnets
Construction of low-\(\beta\) cryomodule
Proton Driver Cavity Development Effort

Collaboration with Fermilab and CEBAF on development of cavities for the Proton Driver Linac began in 2005.

Elliptical cavity for $\beta = 0.81$ is being designed and prototyped.

Four single-cell cavities (1.3 GHz) have been fabricated: 2 fine grain, 2 large grain. RF testing in progress.

Two 7-cell cavities are being fabricated.
Proton Driver Cavity Development Effort

- Collaboration with Fermilab and CEBAF on development of cavities for the Proton Driver Linac began in 2005.
- Elliptical cavity for $\beta_g = 0.81$ is being designed and prototyped.
- Four single-cell cavities (1.3 GHz) have been fabricated: 2 fine grain, 2 large grain. RF testing in progress.
- Two 7-cell cavities are being fabricated.
0.5 MW Initial 8 GeV Linac
11 Klystrons (2 types)
470 Cavities
53 Cryomodules

β<1 TESLA LINAC
1300 MHz 0.1-1.2 GeV
2 Klystrons
96 Elliptical Cavities
12 Cryomodules

TESLA LINAC 1300 MHz β=1
8 Klystrons
288 Cavities in 36 Cryomodules

Layout for the Proton Driver baseline Linac
Cavity Design

Selected cavity parameters and comparison with SNS and TTF cavities

<table>
<thead>
<tr>
<th>Cavity</th>
<th>TTF 9-cell</th>
<th>SNS 6-cell</th>
<th>Proton Driver 7-cell</th>
<th>Proton Driver 1-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_g$</td>
<td>1</td>
<td>0.81</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>wall inclination</td>
<td>13.3°</td>
<td>7°</td>
<td>7°</td>
<td>7°</td>
</tr>
<tr>
<td>$E_p/E_a$</td>
<td>2.0</td>
<td>2.19</td>
<td>2.19</td>
<td>2.18</td>
</tr>
<tr>
<td>$cB_p/E_a$</td>
<td>1.28</td>
<td>1.44</td>
<td>1.41</td>
<td>1.58</td>
</tr>
<tr>
<td>cell-to-cell coupling</td>
<td>1.8%</td>
<td>1.5%</td>
<td>1.6%</td>
<td>-</td>
</tr>
<tr>
<td>$R/Q$ per cell</td>
<td>115 Ω</td>
<td>80.8 Ω</td>
<td>79.1 Ω</td>
<td>62.3 Ω</td>
</tr>
<tr>
<td>Geometry factor</td>
<td>270 Ω</td>
<td>233 Ω</td>
<td>227 Ω</td>
<td>229 Ω</td>
</tr>
</tbody>
</table>

Values for Proton Driver cavity were calculated with SUPERFISH
7-Cell $\beta_g = 0.81$ Cavity

Electric field lines from SUPERFISH
Cavity Fabrication and Preparation

- Sheet Nb of thickness 2.8 mm was used.
- Forming done at MSU and in local area; electron beam welding by industry.
- Nb-Ti flanges with knife edges were electron-beam welded to the beam tubes.

Fine Grain Cavities

- Nb sheet of \( \text{RRR} \geq 260 \) was rolled.
- Cu gasket knife edge seal.
- Not fired in vacuum furnace.
- c. 180 \( \mu \text{m} \) etch (BCP); 30 to 50 \( \mu \text{m} \) for repeat etching.
- High-pressure rinse with ultra-pure water for 45 to 120 minutes.
- Second cavity was baked out under vacuum for 12 hrs 20 min at 120\(^\circ\)C after the first RF test.
Large Grain Cavities

- Nb sheet was cut via wire EDM from an ingot with RRR $\sim 280$ and Ta content $\sim 800$ ppm.
- After iris weld, half-cells were mechanically polished to smooth off grain boundaries.
- Knife edges were machined off and In seals were used.
- Fired in vacuum at $600^\circ$C for 10 hours for H degassing.
- $50 \ \mu$m etch (BCP) before firing, another $50 \ \mu$m after firing.
- High-pressure rinse with ultra-pure water for 60 minutes (HPWR).

<table>
<thead>
<tr>
<th>RF Test</th>
<th>Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>see above, no additional heat treatment</td>
</tr>
<tr>
<td># 2</td>
<td>vacuum bake-out for 12 hours at $120^\circ$C</td>
</tr>
<tr>
<td># 3</td>
<td>2 hour Ti treatment at $1250^\circ$C, $50 \ \mu$m etch, HPWR</td>
</tr>
<tr>
<td># 4</td>
<td>vacuum bake-out for 12 hours at $120^\circ$C</td>
</tr>
</tbody>
</table>
Dies for deep drawing of half-cells
Fine grain (left) and large grain (right) half-cells
Etching and rinsing of fine grain cavity
Single-cell $\beta_g = 0.81$ cavity

Fine grain cavity on insert
Fine grain cavity RF testing at 2 K (no thermal treatment)
Second fine grain cavity RF testing: 120°C bake-out
First large grain cavity RF testing at 2 K
Second large grain cavity RF testing at 2 K
Parts for $\beta_g = 0.81$ large-grain 7-cell cavity
SRF Research

- x-ray imaging of SRF cavities
- Heat transfer studies for SRF cavities
- Material properties characterisation, surface texture studies
- Alternative cavity designs
- Alternative cavity fabrication techniques
- SRF electron sources
- Liquid-filled cavities
SRF Research

- x-ray imaging of SRF cavities
- Heat transfer studies for SRF cavities
- Material properties characterisation, surface texture studies
- Alternative cavity designs
- Alternative cavity fabrication techniques
- SRF electron sources
- Liquid-filled cavities
Graduate students in accelerator physics at MSU

From left to right, top: Yingjie Li (Physics), Susan Musser (Physics), Dave Meidlinger (Physics), Derek Baars (MSE), Hairong Jiang (MSE) bottom: Nathan Usher (EE), Ahmad Aizaz (ME), Mandi Meidlinger (Physics), Jonathan Delauter (Physics)
PhD research: S. Musser

In-situ x-ray imaging of superconducting cavities
Thermal conductivity of Nb at 2 K depends on internal stress, as well as purity; heat treatment of Nb affects both.

\[
T_s = T_\infty + \Delta T_h + \Delta T_k
\]

\[
P = \frac{1}{2} R_e \left( \frac{B_e}{\mu_0} \right)^2
\]

Increasing strain

\[
P = k \frac{\Delta T_k}{\Delta X}
\]

\[
P = h \frac{\Delta T_h}{\Delta X}
\]
PhD research: H. Jiang, D. Baars

Studies of material and surface properties
High-current cavity (PhD research: D. Meidlinger)
High gradient cavity (PhD research: M. Meidlinger)
Alternative forming methods for superconducting cavities

**TIG welding:** alternative to electron beam welding?

**Hydroforming:** alternative to deep drawing for seamless cavity?

- Guide rods
- Niobium cavity
- Hydraulic pressure tap
- Sliding clam-shell dies

Prototype copper cavities hydro-formed in US Industry
Liquid-Helium-Filled Cavities
Ionisation Cooling
Ionisation Cooling
Ionisation Cooling
Ionisation Cooling

**Diagram:**
- Absorber
- RF Cavity
- Solenoid
Ionisation Cooling
Ionisation Cooling
Cooling channel: Liquid hydrogen cells and RF cavities
Cooling channel: Liquid hydrogen cells and RF cavities

Cooling channel: RF cavities filled with hydrogen gas
Vacuum-filled SRF cavity
Vacuum-filled SRF cavity

Liquid-filled SRF cavity
Properties of Liquid He: Literature

DC: dielectric constant vs temperature: known (e.g. Donnelly & Barenghi 1998).

DC: dielectric strength: studied (e.g. Gerhold 1998):
  ▶ Dust particles can produce discharges (field emission).
  ▶ Breakdown field = 40 to 100 MV/m possible under well-controlled conditions (short times, small gaps, polished electrodes, no particulates, ...).
  ▶ Breakdown fields for pressurised liquid can be as much as twice those of saturated liquid.

RF: Prediction: $\tan \delta \sim 10^{-25}$ at 3 GHz (Allen et al 1969).

RF: X-band measurements in superfluid, TE_{011} mode: $\tan \delta < 10^{-11}$ (SLAC Quarterly Report 1970).
2.45 GHz single-cell Nb cavity: vacuum-filled test
2.45 GHz single-cell Nb cavity: liquid-filled test
Low-field measurements: vacuum-filled vs liquid-filled
Frequency shift with temperature during pump-down

\( f_0 = 2300 \text{ MHz}; \) vacuum: \( \Delta f \approx 70 \text{ kHz}; \) liquid: \( \Delta f \approx 10 \text{ MHz} \)
Permittivity of liquid helium inferred from the frequency
CW measurements: vacuum-filled
CW measurements: vacuum-filled vs liquid-filled
Peeking inside a liquid-filled cavity
Video images looking inside the liquid-filled cavity
Black & White video camera
Conclusion

MSU has developed capabilities and facilities for design, fabrication, and testing of SRF cavities and cryomodules. SRF research at MSU is underway, with the primary motivation being for heavy ion accelerators. MSU is also helping with other projects (e.g., FNAL Proton Driver) and is open to new possibilities.
Conclusion

- MSU has developed capabilities and facilities for design, fabrication, and testing of SRF cavities and cryomodules
- SRF research at MSU is underway
- Primary motivation is for heavy ion accelerators
- MSU is also helping with other projects (e.g. FNAL Proton Driver) and is open to new possibilities
People

NSCL Staff

MSU Graduate Students
A. Aizaz, D. Baars, H. Jiang, D. Meidlinger, M. Meidlinger, S. Musser

Collaborators
T. Bieler, L. Kempel, *et al.* (MSU Engineering)
G. Ciovati, P. Kneisel, *et al.* (CEBAF)
A. Facco *et al.* (INFN Legnaro)
V. Yarba, P. Bauer, *et al.* (Fermilab)