High-Performance SC Cryomodules for CW Ion Accelerators

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Physics Division

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Contributors and Outline

Outline

1. A few of the significant developments worldwide
2. ANL approach to CW SC Cryomodule

Thank you

- Bob Laxdal – TRIUMF
- Amichay Perry – SARAF
- Alberto Facco – INFN Legnaro
- Thomas Nicol, Ivan Gonin – FNAL
- Evgeny Zaplatin – Jülich/IFMIF
- Walter Hartung - MSU
SC Ion Accelerators Around the Globe

TRIUMF
Argonne
Stony Brook
FSU
MSU
Ganil
Legnaro
SARAF
IUAC
TIFR
JAERI
Sao Paulo
ANU
### SC Ion Accelerators Around the Globe

<table>
<thead>
<tr>
<th>Location</th>
<th>Cavity Type</th>
<th>Frequency (MHz)</th>
<th>Beta (v/c)</th>
<th># Cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral-2/Ganil</td>
<td>QWR</td>
<td>88</td>
<td>0.07-0.12</td>
<td>26</td>
</tr>
<tr>
<td>MSU/ReA3</td>
<td>QWR</td>
<td>80.5</td>
<td>0.04, 0.085</td>
<td>15</td>
</tr>
<tr>
<td>SARAF/Soreq</td>
<td>HWR</td>
<td>176</td>
<td>0.09</td>
<td>6</td>
</tr>
<tr>
<td>Triumf</td>
<td>QWR</td>
<td>80</td>
<td>0.06-0.07</td>
<td>40</td>
</tr>
<tr>
<td>New Delhi</td>
<td>QWR</td>
<td>97</td>
<td>0.08</td>
<td>14</td>
</tr>
<tr>
<td>Canberra</td>
<td>Split-ring, QWR</td>
<td>150.4</td>
<td>0.09-0.11</td>
<td>14</td>
</tr>
<tr>
<td>INFN Legnaro</td>
<td>QWR</td>
<td>80, 160</td>
<td>0.05-0.13</td>
<td>74</td>
</tr>
<tr>
<td>Kansas State</td>
<td>Split-ring</td>
<td>96, 97</td>
<td>0.06-0.1</td>
<td>14</td>
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<tr>
<td>JAERI</td>
<td>QWR</td>
<td>130, 260</td>
<td>0.1</td>
<td>46</td>
</tr>
<tr>
<td>U. Washington</td>
<td>QWR</td>
<td>150</td>
<td>0.1-0.2</td>
<td>36</td>
</tr>
<tr>
<td>Florida State</td>
<td>Split-ring</td>
<td>97</td>
<td>0.07-0.1</td>
<td>15</td>
</tr>
<tr>
<td>Stony Brook</td>
<td>Split-ring, QWR</td>
<td>150.4</td>
<td>0.07-0.1</td>
<td>40</td>
</tr>
<tr>
<td>Argonne</td>
<td>Split-ring, QWR</td>
<td>48, 72, 97</td>
<td>0.01-0.10</td>
<td>64</td>
</tr>
</tbody>
</table>

- **Operations & Upgrades**: Under construction
- **Under construction**: Under construction
- **No longer operating**: No longer operating
<table>
<thead>
<tr>
<th>Applications</th>
<th>Frequency (MHz)</th>
<th>Beta (v/c)</th>
<th>Particle type</th>
<th># Cavities (total cavities)</th>
<th>Duty Factor</th>
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</thead>
<tbody>
<tr>
<td>CERN Rex-Isolde</td>
<td>101</td>
<td>0.063, 0.103</td>
<td>Heavy-ion</td>
<td>32</td>
<td>CW</td>
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<tr>
<td>MSU FRIB</td>
<td>322 (HWR)</td>
<td>0.285, 0.52</td>
<td>Proton to Heavy-Ion</td>
<td>336</td>
<td>CW</td>
</tr>
<tr>
<td>Project X</td>
<td>325 (Spoke)</td>
<td>0.2-0.6</td>
<td>Proton</td>
<td>88</td>
<td>CW</td>
</tr>
<tr>
<td>ESS</td>
<td>352 (Spoke)</td>
<td>0.45</td>
<td>Proton</td>
<td>42</td>
<td>Pulsed</td>
</tr>
<tr>
<td>EURISOL</td>
<td>176, 352</td>
<td>0.09-0.36</td>
<td>Proton, Light ion</td>
<td>108</td>
<td>CW</td>
</tr>
<tr>
<td>IFMIF</td>
<td>175 (HWR)</td>
<td>0.094, 0.17</td>
<td>Deuteron</td>
<td>42</td>
<td>CW</td>
</tr>
</tbody>
</table>

**SC Ion Accelerators Around the Globe**

Planned
Modern low-beta TEM, a.k.a “drift-tube”, cavities

- Operated in lowest TEM-like mode
- \( \frac{\lambda}{4} \) or \( \frac{\lambda}{2} \) structures
- Physical dimensions \( 0.1 < \lambda < 1 \) meter
- Frequencies 50-800 MHz
- 4 Kelvin operation (Future 2 K @ \( f \sim 325 \) MHz and above?)
Clean techniques for low-\(\beta\) SRF cavity 10 years ago

Dramatic performance increase from HPR consistent and repeatable if cavity kept clean.
Eight cryomodules containing 40 quarter-wave cavities providing $V_{\text{ACC}} \sim 1 \text{ MV/cavity}$

Clean room assembly of the complete cryomodule
1 Cryomodule, seven $\beta=0.15$ quarter-wave cavities added to the ATLAS heavy ion linac

- Separate cavity vacuum space

- Maximum voltages of **3.75 MV per cavity** have been achieved ($E_{\text{PEAK}} = 48 \text{ MV/m}, B_{\text{PEAK}} = 88 \text{ mT}$)

- Real gradient for operational cavities of **14.5 MV in 4.6 m module length**; new standard for low-beta SC linacs
SARAF at Soreq

- Six 176 MHz \( \beta=0.09 \) **half-wave cavities** fabricated in industry by Accel (now RI); first TEM \( \lambda/2 \) structures for beam acceleration
- **CW 1 mA proton beams** accelerated to 3.7 MeV
INFN Legnaro: ALPI-PIAVE low-beta section upgrade

- Aim: Double energy gain at minimum cost by cooling rf couplers
- Status: 1 cryostat successfully upgraded and operated at 6 MV/m
- Before: $V_{\text{ACC}}=11$ MV, 20 QWR’s,
- After (goal): $V_{\text{ACC}}=21-25$ MV, 24 QWR’s
Prototypes under design/construction

IFMIF
- 8 HWR's 175 MHz $\beta=0.094$
- ~70 kW RF power per cavity!

Project X
- 3 single-spoke 325 MHz $\beta=0.2$
  cavities/4 SC solenoids
Part II. ANL approach to CW SC Cryomodule
ANL Design for a Low-Beta SC Cavity
(72.75 MHz, $\beta=0.077$)

- **Electromagnetic Design**
  - Minimize surface fields consistent with fabrication/processing/cleaning
  - Steering corrected drift-tube face to eliminate beam steering

- **Mechanical Design**
  - Below niobium yield cold for all normal conditions
  - 4 K system, moderate beam loading
    - *Null helium pressure sensitivity*
    - Increase pendulum mode frequency with modest stiffening

$E_p/E_{acc} = 3.25$
$L_{eff} = 20 \text{ cm}$

$B_p = 4.8 \text{ mT}$
$\frac{E_p}{E_{acc}} = \frac{4.8}{\text{ MV/m}}$

$\Delta f/\Delta p \approx 1.6 \text{ Hz/Torr}$

He Press. load

Slow tuner load

AES/ANL
ANL Design for a Low-Beta SC Cavity

- Niobium is hydroformed or deep drawn all with blended transitions
- Stainless steel helium vessel assembled around the e-beam welded niobium cavity

Complete Assembly
ANL Processing for a Low-Beta SC Cavity

- Final electropolishing on complete jacketed cavity
  - Similar to ILC 9-cell EP
  - Direct water cooling built in
- Why not BCP?
  - EP demonstrated statistically better for niobium approaching rf limits
  - EP can be repeated without making surface progressively rougher
Minimize parts required inside the clean room:
- Cavities
- Solenoids
- Cold Section of Coupler (4 kW E-field)
- Vacuum lines and valves
Assemble remaining components outside clean room:

- Cryogenics (4.5 K helium, 150 Watts, 15 W static load)
- Tuners (30 kHz pneumatic slow tuner, fast piezo electric)
- Cryostat lid
Angled end walls for beam valves; also used for FRIB, Rex-Isolde

Main features
- Long (5 m) cryomodule, high packing factor
- Top loading; easy access to cavities
- 80 K Copper, magnetic shields, multi-layer insulation permanent in lower section of cryomodule
- **Goal:** 2.5 MV/cavity, 17.5 MV in 5 meters
Into the tunnel...

Mock Assembly - January 23, 2009

Final Assembly - March 13, 2009

Into the tunnel - June 1, 2009

Carbon beam - July 3, 2009
Summary

- Major improvements in SRF technology for ion linacs in the last decade
  - Sophisticated designs
  - Clean room techniques
  - Improved cavity performance

- New directions for SC ion linacs
  - Upgrades and new machines for basic science
  - Very high intensity CW light ion drivers for medicine, national security, and accelerator driven systems

- The ANL approach
  - Low frequency optimized cavities
  - Large voltage gain per cavity, high quality factor (Q)
  - High real estate gradient for cryomodules

- New high performance SC cryomodules well positioned for next generation of high-current CW ion linacs