Heavy Ion Superconducting Linacs: Status and Upgrade Projects

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Content

- New Projects and Upgrades
  - GSI (Germany)
  - LRF (Huelva University, Spain): new!
  - RISP (Korea): new!
  - HIAF (IMP, China): new!

- ATLAS Upgrades

- CW RFQ for SC heavy-ion linacs

- SC Technology at ANL
  - Main steps for cavity construction
  - Cavity sub-systems
  - Performance: accelerating gradients and residual resistance

- Realistic design parameters for new SC linacs

- Application to SARAF Phase II

- Summary
GSI Upgrade: SC CW Linac

- Primary motivation is research in the field of Super Heavy Elements
- $q/A = 1/6$, 1 mA ion beam, output energy is 7.5 MeV/u, variable from 3.5 MeV/u
- Multi-gap CH cavities, focusing by SC solenoids

Injector:
1.4 MeV/u, RFQ and IH
LINAC Research Facility (LRF-Huelva)

- RESEARCH & APPLICATION PROGRAM
  - Basic nuclear physics: reactions & structure, astrophysics, superheavies; exotic isotopes (IGISOL)
  - Materials for Fusion and Fission energy
  - Aerospace
  - Medical applications: Radioisotopes & Proton therapy

- Wide range of heavy ions
  - Wide range of energies, from keV/u to ~15 MeV/u
  - Maximum intensity for HI (~100uA, 40Ar)
  - Protons up to 30 MeV (~1 mA); up to 70 MeV (nA)
## LRF Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Species</td>
<td>Heavy ions, protons</td>
<td></td>
<td>ECR ion source</td>
</tr>
<tr>
<td>Current Range</td>
<td>~1-2 mA (protons) ~ 500μA – 10 uA HI</td>
<td></td>
<td>HI intensities depends strongly on Q/A</td>
</tr>
<tr>
<td>PHASE 1</td>
<td>20 MeV protons 9 MeV/u HI</td>
<td>~3 years</td>
<td>Auxilliary, Cryogenics, Ion source, LEBT, RFQ, 2 x cryomodules (7 x SC), 2 beam lines</td>
</tr>
<tr>
<td>PHASE 2</td>
<td>55 MeV protons 15 MeV/u HI</td>
<td>2 years</td>
<td>2 x Cryomodule, Ext. Cryogenics, full experimental hall, IGISOL</td>
</tr>
<tr>
<td>PHASE 3</td>
<td>72 MeV protons 18 MeV/u HI</td>
<td>1 year</td>
<td>1 x Cryomodule, proton therapy line</td>
</tr>
</tbody>
</table>

### Table 5. Main parameters of the Linac

<table>
<thead>
<tr>
<th>Linac</th>
<th>Frequency, MHz</th>
<th>β_{opt}</th>
<th>Number of cavities</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHB*</td>
<td>36.375 (the 1st harmonic)</td>
<td>N/A</td>
<td>1</td>
<td>Based on ANL 60.625 MHz RFQ</td>
</tr>
<tr>
<td>RFQ</td>
<td>72.75</td>
<td>N/A</td>
<td>1</td>
<td>Design is available as ANL/ATLAS upgrade cryomodule</td>
</tr>
<tr>
<td>QWR1</td>
<td>72.75</td>
<td>0.077</td>
<td>7</td>
<td>Design is available as ANL/ATLAS upgrade cryomodule</td>
</tr>
<tr>
<td>QWR2</td>
<td>109.125</td>
<td>0.15</td>
<td>7</td>
<td>Design is available as ANL/ATLAS upgrade cryomodule</td>
</tr>
<tr>
<td>HWR</td>
<td>181.875</td>
<td>0.25</td>
<td>14</td>
<td>Prototype cavity (f=170 MHz) was demonstrated at ANL</td>
</tr>
</tbody>
</table>
Civil Construction Already Started
Accelerator Complex for RISP (Korea)

- SC Driver Linac 200MeV/u for $^{238}$U, 600 MeV for p, 400 kW beam power
  - Isotope Facility
  - High power ISOL driver
- Cavities: QWR, HWR and 2 types of SSR, fundamental frequency is 81.25 MHz
- Focusing by quadrupole doublets
**Heavy-Ion Accelerator Facility (HIAF) at IMP, China**

- **SC-LINAC**
  - 18O\(^{6+}\): 150 MeV/u, 1.0 pmA
  - U\(^{34+}\): 50 MeV/u, 0.04-0.4 pmA
  - U\(^{76+}\): 150 MeV/u, 0.008-0.08 pmA

**Scope**
1. Production of r/a ions
2. High pulse current for injection into synchrotron

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P.N. Ostroumov  SC Heavy-Ion Linacs  HIAT-12  

June 21, 2012
SC Linacs: Beam Physics

- High intensity heavy ion beams: multiple charge state acceleration
  - Form extremely low longitudinal emittance by using MHB and RFQ
  - Avoid effective emittance growth of multi-q beams
  - Form time and transverse focus on the stripper
  - Multi-q isopath transport after stripping
  - High-quality of accelerating and focusing fields
    - QWRs with steering compensation
    - Axial symmetric fields in TEM-class SC resonators
  - Moderate tolerances for RF errors: phase 0.5 rms, amplitude 0.5% rms
  - Alignment of cold cavity-solenoid strings
    - Cold BPMs and dipole coils in the solenoids
  - Small transverse beam size on the fragmentation target
  - Quick turn around for tuning to different q/A

- High intensity light ion beams
  - Space charge in the front end
  - A section with adiabatic transition for beam dynamics is required between RFQ and high-gradient SC linac
Transition Energy from RFQ to SC Linacs

![Graph showing energy transition from RFQ to SC Linacs]

- **SARAF**
- **SARAF-IL**
- **PIAVE**
- **SPIRAL2**
- **FRIB**
- **ATLAS**
- **Project X**
SC technology is the most critical technology for CW ion accelerators

- Main parameters of SC accelerating cavities for CW operation:
  - Accelerating gradient (cavity voltage, peak fields, design $E_{\text{ACC}}$): real-estate
  - Cavity voltage and surface resistance: cryoplant size
  - For given surface resistance there is an optimal cost (capital + operation) of the Linac as a function of cavity voltages
    - Simple for e-linacs
    - More complicated for heavy-ion linacs due to several cavity types

- 2K operation is more economic than 4K
- Cost per voltage is proportional to cavity $(\beta_{\text{OPT}})^{-k}$
- Cost of the accelerator is roughly proportional to cavity count
ATLAS Efficiency and Intensity Upgrade - Funded Projects

- Currently includes 10 cryomodules, 60 cavities
- New cryomodule and LHe distribution system upgrade
- RFQ: October 2013
- Cryomodule: April-June 2013
- EBIS-CB: 2014
ATLAS Energy Upgrade Cryomodule in Operation Since July 2009

- 7 QWRs, 1 SC solenoid
- Total accelerating voltage is 14.5 MV, 2.1 MV/cavity
- All 7 cavities perform as designed
- One cavity provides 40% higher voltage
ATLAS Beam Intensities After Upgrades

- **Funded**
  - Intensity is limited by the ECR
  - For light ions intensity is limited by shielding

- **Expected funding**
  - VENUS type ECR
  - Accelerator Shielding
  - Infrastructure improvement
ATLAS CW RFQ

P.N. Ostroumov  SC Heavy-Ion Linacs

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ANL RFQ Highlights

- Highly coupled EM structure
  - “flat” field distribution, non-operational modes are separated more than by 10 MHz
  - “bead-pull” tuning is not required
- Conservative design, peak field is 1.5 Kilpatrick
- Trapezoidal modulation
  - Increases shunt impedance by 60%
- A short output radial matcher to form axially-symmetric beam
- Fabrication: 2-step brazing in a high temperature furnace
- No “cold model” – was directly built from CST MWS geometry
- Measured Q-factor is ~93% of the MWS calculated Q for annealed OFHC copper
Acceptance

- Current PII
- The first SC cavity
  - $\beta = 0.009$
  - Aperture = $\phi 12$ mm

- With new RFQ
New Cryomodule, Project Started on 9/01/2009

- Cryomodules
  - Long cryomodules containing seven 72.75 MHz cavities ($\beta_{opt}=0.077$) and 4 SC solenoids
  - Separate cavity and isolation vacuum
  - Vertically loaded, clean room work is minimized

- Length – 5 meters, design voltage 17.5 MV; 2.5 MV/cavity

- Available voltage ~4 MV with very low res. resistance

- Replaces 3 existing cryomodules with split-rings

- Beam commissioning is in 2013
SC Cavity Performance

- EM design and mechanical design
- Fabrication technology
- RF surface processing

First step: EM design
- Reduce $E_{\text{PEAK}} / E_{\text{ACC}}$, $B_{\text{PEAK}} / E_{\text{ACC}}$
  - Conical center and outer conductor
  - Triple spokes: conical spokes
- Maximize $R_{\text{sh}} G$
- Beam aperture is defined from application; for Heavy Ion Driver accelerators it is in the range from 30 mm to 40 mm
Accelerating Field Quality

- **QWR**: beam center steering, quadrupole component of the E-field
  - Shaping of the drift tubes to compensate magnetic force with electric force
  - Displacement of the cavity axis: works well for fixed velocity profile

- **HWR**: quadrupole component of E-field
  - Elliptical aperture
  - “Donut” shape of the drift tube (higher shunt impedance)
Mechanical design and Engineering Analysis

- **Compact** mechanical design to maintain a high real estate accelerating gradient;
- Provide coupling ports enabling **advanced RF surface processing** techniques (electropolishing and high pressure water rinsing);
- Integrate a coupling port for a **RF coupler**;
- Facilitate the **integration** of several cavities and their sub-systems (RF coupler and tuners) into the **cryomodule**;
- Provide a means for cavity **alignment** in the cryomodule;
- Ensure that the **stresses** in the niobium and the stainless steel parts are below the maximum allowable limits;
- Satisfy **pressure vessel** requirements according to the ASME code
- **Minimize the sensitivity of the resonant frequency to fluctuations in helium pressure**
- Ensure that the **slow tuner** operation provides a sufficient tuning range and that the correlated cavity deformations remain well below the plastic limit;
- If necessary, integrate a **fast tuner** with a required tuning window;
- Create a complete set of **fabrication drawings**.
Fabrication

- Niobium sheet forming
- Wire EDM
- Brazed Nb-SS transitions
- Electron Beam Welding
  - BCP weld preparation
  - Pre-weld manual HPR on weld surfaces, class 1000 bag; un-bag in chamber
- SS vessel installation
Electropolishing at ANL
72 MHz QWR

- Outstanding test results

Cavity #1

Cavity #2

P.N. Ostroumov  SC Heavy-Ion Linacs

HIAT-12
Sub-Systems: RF Coupler, Slow and Fast Tuners

4 K-to-80 K, 7 cm variable bellows

80 K RF window
80 K-to-300 K RF transition
300 K RF window

Tested at 4 kW, 72 MHz

Piezoelectric tuner

Pneumatic Slow Tuner

Beam
## Design Parameters for a CW Heavy Ion Linac

- Realistic design parameters for future SC linacs

<table>
<thead>
<tr>
<th>Year</th>
<th>1999</th>
<th>2003</th>
<th>2012</th>
<th>2012 Demo</th>
<th>201X</th>
<th>ILC pulsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{PEAK}}, \text{MV/m}$</td>
<td>21</td>
<td>27.5</td>
<td>40</td>
<td>117</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>$B_{\text{PEAK}}, \text{mT}$</td>
<td>75</td>
<td>80</td>
<td>80</td>
<td>165</td>
<td>100</td>
<td>140</td>
</tr>
<tr>
<td>Operational T, K</td>
<td>4</td>
<td>4 &amp; 2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Residual Resistance, nΩ</td>
<td>25</td>
<td>25 &amp; 10</td>
<td>4-10</td>
<td>high</td>
<td>4-10</td>
<td>4.7</td>
</tr>
</tbody>
</table>
Phase II of SARAF at SNRC (Israel), 200 kW beam

- Particles: protons and deuterons
- Beam current – 5 mA
- Beam total energy – 40 MeV
- Highly optimized HWRs

<table>
<thead>
<tr>
<th>Cavity Parameters</th>
<th>Type I</th>
<th>Type I I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, MHz</td>
<td>176</td>
<td>176</td>
</tr>
<tr>
<td>$\beta_{OPT}$</td>
<td>0.089</td>
<td>0.16</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td>Aperture, mm</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>$L_{eff}$, cm</td>
<td>15.2</td>
<td>27.3</td>
</tr>
<tr>
<td>$E_p/E_a$,</td>
<td>5.3</td>
<td>4.6</td>
</tr>
<tr>
<td>$B_p/E_a$, mT/MV/m</td>
<td>5.7</td>
<td>5.6</td>
</tr>
<tr>
<td>$R/Q$, $\Omega$</td>
<td>231</td>
<td>291</td>
</tr>
<tr>
<td>$G$, $\Omega$</td>
<td>40</td>
<td>60</td>
</tr>
</tbody>
</table>
176 MHz HWRs for SARAF

- Design voltage per high-beta cavity is 2.1 MV
- Expected voltage is ~4 MV
SARAF Cryomodule Design Highlights

- Titanium strongback
- Compact SC solenoid (35 mm aperture)
  - Dipole coils for H and V steering
  - Return coils to dramatically reduce edge field
- Cleanable BPM
- Alignments system
  - Predictable displacement during the cool-down
  - Tolerances ±250 μm
Summary

- Since HIAT-09
  - Several new HI accelerators received funding
  - Several substantial upgrades of existing facilitates were funded
  - Advanced proposals for new HI facilities were developed

- We observe substantial progress in technology of CW heavy-ion accelerators

- These technologies are in demand for
  - Multi-purpose high-power ion & proton linacs (science and applications)
  - CW proton (H-minus) accelerators for fundamental science
  - Accelerator Driven Systems
  - Isotope production for medicine
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