Status of Superconducting Electron Linac Driver for Rare Ion Beam Production at TRIUMF

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Outline

• ARIEL Project
  – E-Linac Specification

• E-Linac design
  – Major components

• Status and commissioning results

• Future plans
ARIEL and the e-Linac
ARIEL Project (2010-2020)

• ISAC: World class ISOL facility for the production and acceleration of rare isotope beams (RIB)

• Presently utilize one driver beam at 500MeV and 50kW to create RIBs for ISAC

• Now adding ARIEL to allow up to three simultaneous RIB beams

• Add e-Linac (50MeV 10mA cw - 1.3GHz SC linac) as a second driver to create RIBs via photofission

• Add a second driver beam from the cyclotron
Why electrons? Why 50MeV?

- the electron linac is a strong complement to the existing proton cyclotron
  - Photofission yields high production of many neutron rich species but with relatively low isobaric contamination with respect to proton induced spallation
  - An energy of 50MeV is sufficient to saturate photo-fission production – fits the site footprint and project budget

Calculated in-target production for 10 µA, 500 MeV protons incident on a 25 g/cm² UCx target

Calculated in-target production for 10 mA, 50 MeV electrons incident on a Hg converter and 15 g/cm² UCx target
E-Linac Specifications

- The ARIEL E-Linac specification – dominated by rf beam loading
  - 10mA cw at 50MeV - 0.5 MW of beam power
  - Choose five cavities 100kW of beam loaded rf power per cavity
  - two couplers per cavity each rated for 50kW operation
  - Means 10MV energy gain per cavity
- Linac divided into three cryomodules
  - one Injector cryomodule (ICM) with one cavity
  - two Accelerator cryomodules (ACM1, ACM2) with two cavities each
  - Installation is staged - Phase I – includes ICM and ACM1 for a required 25MeV/100kW demonstration by end of 2014
The ARIEL e-Linac as a recirculator

- The linac is configured to eventually allow a recirculating ring for a multi-pass `energy doubler' mode or to operate as an energy recovery linac for accelerator studies and applications.
E-Linac Design
Electron Gun

- Thermionic 300kV DC gun – cathode has a grid with DC suppressing voltage and rf modulation that produces electron bunches at rf frequency
- Gun installed inside an SF6 vessel
- Rf delivered to the grid via a ceramic waveguide

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>RF frequency</td>
<td>650MHz</td>
</tr>
<tr>
<td>Pulse length</td>
<td>$\pm 16^0$ (137ps)</td>
</tr>
<tr>
<td>Average current</td>
<td>10mA</td>
</tr>
<tr>
<td>Charge/bunch</td>
<td>15.4pC</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>300keV</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>5µm</td>
</tr>
<tr>
<td>Duty factor</td>
<td>0.01 to 100%</td>
</tr>
</tbody>
</table>
The ARIEL cavities

- 1.3GHz nine-cell cavities
- End groups modified to accommodate two 50kW couplers and to reduce trapped modes
- Large (90mm) single chimney sufficient for cw operation up to 50W

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active length (m)</td>
<td>1.038</td>
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<tr>
<td>RF frequency</td>
<td>1.3e9</td>
</tr>
<tr>
<td>R/Q (Ohms)</td>
<td>1000</td>
</tr>
<tr>
<td>Q₀</td>
<td>1e10</td>
</tr>
<tr>
<td>Eₐ (MV/m)</td>
<td>10</td>
</tr>
<tr>
<td>Pₖav (W)</td>
<td>10</td>
</tr>
<tr>
<td>P₉beam (kW)</td>
<td>100</td>
</tr>
<tr>
<td>Qₑxt</td>
<td>1e6</td>
</tr>
<tr>
<td>Qₗ*Rₙ/Q of HOM</td>
<td>&lt;1e6</td>
</tr>
</tbody>
</table>
Injector Cryomodule

**Houses**
- one nine-cell 1.3GHz cavity
- Two 50kW power couplers

**Features**
- 4K/2K heat exchanger with JT valve on board
- Scissor tuner with warm motor
- LN2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal
- WPM alignment system
The ACM uses same basic design as ICM but with two 1.3GHz nine cell cavities each with two 50kW power couplers.

There is one 4k/2k insert identical to the ICM.

Physical dimensions:
- \( L \times H \times W = 3.9 \times 1.4 \times 1.3 \) m
- 9 tons
• 4K liquid at 1.3 Bar delivered in parallel to cryomodules from supply dewar

• 4K levels are regulated by LHe supply valve

• 2K levels are regulated by JT valve in each CM

• 2K pressure is regulated by 2K exhaust valve on each CM and trunk valve upstream of SA pumps
• For Phase I we specify two 300kW klystrons – one for each cryomodule

• In the future one 300kW klystron will drive ACM2

• we are looking for a cost effective 1.3GHz power source at ~150kW for the ICM
Status and Commissioning
Progress

- Progress in the last year
  - Cryogenics acceptance tests complete
  - E-Gun and LEBT installed and commissioned – MEBT installed
  - Two klystrons and HV supplies installed and commissioned
  - ICM assembled, installed and commissioned
  - ACM assembled and installed

January 2014

MOIOC01 - Laxdal - TRIUMF e-Linac
Electron Gun Status

- The electron gun and LEBT were installed in February/March 2014
- Bias voltage of 325kV achieved
- 10mA cw achieved at 300kV
- Rf modulation with the ceramic waveguide a success
  - Macro pulsing demonstrated over a broad range
  - 100Hz-10kHz rep rates with duty factors from 0.01-100%
- Transverse and longitudinal phase space measured in LEBT
LEBT Diagnostics

- LEBT includes an analyzing leg and diagnostics to characterize the gun emittance and set the matching for the ICM.

- TM110 deflecting mode cavity and high power emittance rig.

Screen images downstream of rf deflector show manipulation of longitudinal emittance with the buncher cavity at different voltages.

E-Gun transverse and longitudinal emittance measurements

See THIOC02
Cryogenics installation

- **4K system**
  - ALAT LL Cold Box, KAESER (FSD571SFC) main compressor (112g/s), Cryotherm - distribution
  - Acceptance tests (with LN2 pre-cooling) exceed all specifications with comfortable margins

- **Sub-atmospheric pumping**
  - Four Busch combi DS3010-He pumping units specified and installed (1.4g/s @ 24mBar each)

### Refrigeration (W)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Contract</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction</td>
<td>288 L/hr</td>
<td>367 L/hr</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>600 W</td>
<td>837 W</td>
</tr>
</tbody>
</table>

Cryo load at 14MV/m and 150% of estimated static load
High Power RF Installation

- Now installed
  - Two CPI 290kW cw 1.3GHz klystrons
  - Two 600kW 65kV klystron power supplies from Ampegon
- Each klystron reaches specification at the factory
- At TRIUMF – tests were limited by available load or circulator – one was operated to 250kW cw the other to 150kW cw
- Delivered a peak power of 25kW into a cold cavity at low duty factor
Power coupler conditioning

- Condition two couplers at once at room temperature using 30kW IOT
- Two 50kW CPI couplers installed on waveguide box and power transmitted to a dummy load

- Preparation involves extended bakeout (five days) at 100°C with N2 flowing

- RF conditioning in both TW (18kW cw) and SW mode (10kW pulsed) with adjustable short (five days)
<table>
<thead>
<tr>
<th>Cavity</th>
<th>Preparation</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIEL1</td>
<td>BCP120, Degas at FNAL</td>
<td>Installed in ICM1</td>
</tr>
<tr>
<td>ARIEL2</td>
<td>BCP, Degas at FNAL, 120Bake, HF rinse</td>
<td>Installed in ACMuno</td>
</tr>
<tr>
<td>ARIEL3</td>
<td>120micron BCP</td>
<td>Vertical test</td>
</tr>
</tbody>
</table>
• Cavity vertical cold tests in ISAC-II before and after re-process
• Both cavities reach the specified gradient of 10MV/m but at Q₀=6e9
• For Phase I we have lots of cryogenic power so derate specification to Q₀=5e9
• Strategy is to utilize ARIEL1 and ARIEL2 to characterize the cryo-engineering of the cryomodules and use ARIEL3 to optimize the process.
Cryomodule strategy

- Jacket and install ARIEL1 in ICM
- Jacket and install ARIEL2 and install in ACM together with a dummy cavity
  - We call the single cavity ACM configuration ACMuno
- ACMuno
  - Dummy cavity has all interface features including helium jacket and DC heater
  - All helium piping and beamline interconnects will be final
  - ACMuno allows a full cryogenics engineering test plus two cavity beam acceleration to 25MeV
- The goal is to install the cryomodules for a combined beam test in Sept. 2014 – cryogenic engineering and funding milestone
ICM Assembly

- Mock-up assembly of ICM used to test parts and procedures
- Final assembly (aided by lessons learned from mock-up) - completed in <1 month

ICM mock-up – 2013

Cavity hermetic unit (March 14, 2014)

ICM top assembly

Top assembly into tank

ICM unit Complete (April 9, 2014)
ICM Cold test

- ICM delivered to cryogenic test area
- Established cool-down protocol, vacuum integrity and cryogenic performance
- Tested thermal syphon parameters
- Tuned couplers to $Q_{ext} \sim 3 \times 10^6$
- Established cold alignment
On April 28 the ICM was moved from the clean room, craned over ISAC-II hall, carted over to proton hall loading bay, craned down to e-hall and finally craned into position, six weeks after completion of the hermetic unit.
10MeV beam test was an integration test to validate cryogenics, HLRF, LLRF, e-Gun, LEBT, ICM engineering and synchronization.

The MEBT 10MeV analysing leg served as the destination for the accelerated beam.
Cold test results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>4K static load (no syphon)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4K static load with syphon</td>
<td>6</td>
<td>6.5</td>
</tr>
<tr>
<td>2K static load</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>77K static load</td>
<td>100</td>
<td>&lt;130</td>
</tr>
<tr>
<td>2K production efficiency</td>
<td>82%</td>
<td>86%</td>
</tr>
</tbody>
</table>

Syphon loop performance characterized – optimized in off-line cryostat tests

Early result – burst disk works!
ICM System Performance & Acceleration

- All systems functional
  - HLRF, LLRF, tuner, power couplers
  - Cavity phase lock is stable – couplers balance – rf protection in place
  - Confirmed tuning range – 400kHz

- Measured microphonics – very stable

- Successful acceleration achieved – confirms rf integration and calibration

Microphonics detuning spectra
ICM Cavity Performance

- $Q_0$ matches vertical test so magnetic field suppression is ok – fundamental is not loaded by the HOM dampers
- but …..
- gradient limited due to strong field emission
- Detective work ensued
• Radiation measurements as a function of monitor position and rf set-point

• Results indicate that coupler end of the cavity is the most active by a factor of 5-10

• Further
  • Measurements of 7/9 and 8/9 fundamental modes suggest that quench is in the end groups
  • Temperature sensors on coupler side indicate some heating during quench
Took ICM off line for inspection

Inspection revealed that the SS damper tube that fits inside the cavity at the coupler end touched down on the Nb cavity causing scoring and creating particulate

Re-etched cavity and assembled with added support for HOM sub-assembly

ICM is now in re-assembly and due on line in two weeks
ACMuno assembly proceeds through June/July.

ACMuno – ready for cooldown!
Future
ARIEL e-Linac Completion

• **Present to Dec. 2014**
  – Continue beam tests at 25MeV up to 100kW

• **Early 2015**
  – Assemble a second ICM with ARIEL3 and test in e-Hall as part of a collaboration with VECC
  – Remove ACMuno and complete with ARIEL4

• **2018 – funding dependent**
  – Complete second accelerating module (ACM2) to complete e-Linac
  – Fabricate, process and test two more cavities
  – Install 150kW RF system for ICM
Summary

• The ARIEL e-Linac initial phase is nearing completion
  • Cryogenic, rf and service installations complete

• The 300kV E-Gun has met specification
  • being used presently to commission the LEBT and MEBT

• The ICM initial cold tests demonstrated the cryo-engineering matches specifications
  • a problem with the coupler side damper tube reduced performance

• The ACMuno is on-line and cryogenic tests will begin this week
  • The second cavity will be added after the cryo-engineering is confirmed and initial beam commissioning with ICM and ACM is complete
Thanks, Merci
ICM / ACM Cryogenic Circuits

- 4K/2K insert designed to fit in a separate test cryostat prior to cryomodule assembly
- One 4K circuit feeds the heat exchanger and JT valve for 2K supply
- One 4K circuit feeds the bottom of the cold mass through a cooldown valve for initial cooling
- One 4K circuit cools thermal intercepts via a self regulating thermal syphon circuit – flow is governed by the heat load and the LHe level in the 4K reservoir
Syphon loop

• Demonstrated that the loop turns on and off depending on head pressure and heat load – self regulating

• Existence of flow is diagnosed by a temperature sensor on the return column

• Demonstrated that the heat load to 2K is effectively intercepted by syphon loop cooling

• Lesson learned – beware of creating convection in the 4K reservoir – heat source
RF Protection

- Need fast protection to kill the rf in case of rf transient
  - PMTs on couplers
  - Quench detection circuit

- Developed transient model for quench
  - COMSOL – quench zone analysis
  - Mathematica model used to study rf transients
  - Conclude that for all beam duty factors the cavity gradient gives the cleanest indication of a quench

Typical operating regime

\[ I = 10\text{mA}, \ E_a = 10\text{MV/m}, \ P_{\text{beam}} = 100\text{kW}, \ P_{\text{cav}} = 10\text{W} \]

\[ b = \frac{P_{\text{beam}}}{P_{\text{cav}}} = 10000 \quad \text{and at } \varphi = 0 \beta_{\text{opt}} \approx b = 10000 \]

so \[ Q_{\text{ext (opt)}} = \frac{Q_0}{\beta_{\text{opt}}} = 1\times10^6 \]

Quench estimation: assume 25% of one cell (ie \(\frac{1}{40}\) of cavity) goes normal.

So \[ P_{\text{quench zone}} \bigg|_{SC} = \frac{10\text{W}}{40} = 0.25\text{W} \]

\[ \rightarrow P_{\text{quench zone}} \bigg|_{\text{Normal}} = 0.25\text{W} \times \frac{10\text{m}\Omega}{20\text{n}\Omega} = 100\text{kW} \]

\(Q_0\) will go from \(1\times10^6\) to \(1\times10^6\)

ie: The cavity will be matched (100J/msec)