The 30MeV Stage of the ARIEL e-Linac


July 17, 2017

Contribution MOXA03
• 500MeV cyclotron since 1974
  – ~300µA distributed to multiple beamlines
TRIUMF – in stages

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  - Radioactive ion beam (RIB) facility
  - Driven by 500MeV protons from cyclotron
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    • Will drive RIB production in new ARIEL target area (e-line in progress)
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    • Will drive RIB production in new ARIEL target area (e-line in progress)
  – BL4N proton line
    • Will drive second ARIEL RIB production target
• ARIEL will triple the lab’s RIB production by adding two new target stations resulting in up to three simultaneous ion beams

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  • ARIEL-I
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  - E-Linac demonstration at 23MeV (2 cavities) - 2014
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    • Complete e-Linac to 30-35MeV – third rf cavity added – 2017
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    • Install electron target station (AETE) and RIB lines - 2019
    • Install BL4N proton beamline, proton target station (APTW) and RIB lines - 2022
1.3GHz SRF Electron Linac (baseline 50MeV/10mA)

- Base-line design - five nine-cell cavities housed in three cryomodules – each cavity adds 10MeV (100kW)
- 23 MeV demonstrated from two cavities in 2014 with only one cavity in ACM1 - `ACMuno configuration’
- Install 30MeV capability in mid 2017 – in commissioning - ramp to 10kW in 2018 – limited by dump
- Bunch structure – 650MHz – macro-pulse established with e-gun rf – rep-rate is selectable from 0.1% to 100%
The ARIEL e-Linac as a recirculator

The linac is configured to allow a recirculating linac (RLA) for a multi-pass `energy doubler’ mode or to operate as an energy recovery linac (ERL) for accelerator studies and applications.
Accelerator Vault - existing configuration

- Klystron Gallery
- Cold Box
- E-Gun HV Supply
- ACM1
- MEBT
- ICM
- LEBT
- E-Gun Vessel
e-Linac Design and Status
• Thermionic 300kV DC gun – cathode has a grid with DC supressing voltage and rf modulation that produces electron bunches at 650MHz
• 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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</thead>
<tbody>
<tr>
<td>RF frequency</td>
<td>650MHz</td>
</tr>
<tr>
<td>Pulse length</td>
<td>±16° (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>
• 1.3GHz nine-cell elliptical cavities
• End groups modified to accommodate two 50kW couplers and to reduce trapped modes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active length (m)</td>
<td>1.038</td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.3e9</td>
</tr>
<tr>
<td>R/Q (Ohms)</td>
<td>1000</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>1e10</td>
</tr>
<tr>
<td>$E_a$ (MV/m)</td>
<td>10</td>
</tr>
<tr>
<td>$P_{cav}$ (W)</td>
<td>10</td>
</tr>
<tr>
<td>$P_{beam}$ (kW)</td>
<td>100</td>
</tr>
<tr>
<td>$Q_{ext}$</td>
<td>1e6</td>
</tr>
<tr>
<td>$Q_L * R_d / Q$ of HOM</td>
<td>&lt;1e6</td>
</tr>
</tbody>
</table>

To allow for a future ERL upgrade, BBU criteria set limits on the HOM dipole shunt impedance ($R_d/Q*Q_L$)

Assuming a threshold current of 20 mA, beam dynamics calculations set a limit on dipole mode shunt impedance values of $R_d/Q*Q_L < 10^7 \Omega$

Estimation of fabrication errors combine to set a lower limit of $R_d/Q*Q_L < 10^6 \Omega$

CESIC and SS passive coaxial dampers used to suppress HOMs to <BBU limit up to 4GHz
Houses
• One/two nine-cell 1.3GHz cavity
• Two/four 50kW power couplers
• HOM coaxial dampers

Features
• 4K/2K heat exchanger with JT valve on board – allows standard 4K cold box
• Scissor tuner with warm motor
• LN2 thermal shield – 4K thermal intercepts via syphon
• Two layers of mu-metal
• WPM alignment system
• Demonstration configuration
  • Installed one cavity in ICM and one cavity in ACM - `ACMuno’ configuration
  • A dummy cavity is placed in the second position
• ACMuno
  • ACMuno allows a full cryogenics engineering test plus two cavity beam acceleration to 23MeV
  • cryogenic engineering and funding milestone
• Aug. 2016 – ACMuno → ACMduo initiated
Initiated swap from ACMuno to ACM duo in Aug. 2016

Cryomodule moved to ISAC-II assembly area and disassembled

Third cavity prepared and the hermetic unit cleaned, and re-assembled in the clean room in Dec. 2016
Hermetic unit re-installed on cold mass top assembly and the cryomodule (now ACMduo) was moved to the e-hall March 2017 for installation in April 2017.
Cryomodule Cold test results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ICM</th>
<th>ACMduo</th>
</tr>
</thead>
<tbody>
<tr>
<td>4K static load</td>
<td>6.5</td>
<td>8.5</td>
</tr>
<tr>
<td>2K static load</td>
<td>5.5</td>
<td>11</td>
</tr>
<tr>
<td>2K efficiency</td>
<td>86%</td>
<td>86%</td>
</tr>
</tbody>
</table>

- Cavities meet specification
- Cryogenic engineering matches design expectations
- 2K production efficiency 86%
- Syphon loop performance characterized

MOPB105 Thermosyphon Cooling Loops for ARIEL Cryomodules – Y. Ma

July 17, 2017
• The RF system for the e-Linac utilizes two 300kW klystrons – each source driving one module

• A power divider is used to divide the power to each cavity and to power each cavity independently during start-up
• TRIUMF has a history of using self-excited loop for LLRF – one source per cavity

• In SEL mode there is no frequency seeking required as the SEL tracks the resonant frequency - \( \pi \)-mode is selected using a band pass filter and an adjustable delay line.

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• ACMduo – two cavities – two tuners – one source – stable SEL demonstrated in Vector Sum
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Developing Adaptive Feed Forward for compensation of beam loading in when beam is pulsed.

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**Diagram Description**

- **Tuner Loop 1**
  - $\phi_{t1}$
- **Tuner Loop 2**
  - $\phi_{t2}$
- **Cavity 1**
  - $\phi_{c1} \sim 0$
- **Cavity 2**
  - $\phi_{c2} \sim 0$
- **Power Divider**
- **Amp**
- **2\pi n**
- **Vector Sum**
- **Att**
- **$\phi_{A}$**
- **$\phi_{D}$**
- **$\phi_{E}$**
e-Linac with re-circulation
Beyond 2020 – proposing a ring to operate as a recirculating linac (RLA) (energy doubler) or as an energy recovery linac (ERL) for accelerator studies and applications

RLA applications:
• Increase energy for RIB production

ERL Applications:
• Infra-red and Ultra-violet Free Electron Lasers
• Intense THz radiation source (FEL and/or Coherent Synchrotron Radiation (CSR))
• Compton backscattering source of X-rays
ERL

- Dual-use possible with two interleaved bunch trains into 1.3GHz buckets
- 650MHz pulse train - single pass acceleration for RIB production – low brightness
- 650MHz/n pulse train for ERL – high brightness
- 650MHz rf separator used to separate the beams
Simultaneous beam delivery to both RIB production and an ERL/FEL requires RF separation of interleaved bunches

- 650 MHz SRF deflecting mode cavity
- Operates at 4 K
- Provides 0.3 – 0.6 MV deflection
- Shunt impedance of 625 Ω
- Peak fields < 10 MV/m, 12 mT
- 0.35 W power dissipation
• Damping of Higher Order Modes is important due to high current CW beam

• Two types of HOM dampers used:
  – HOM Coupler: antenna with 650 MHz filter
  – HOM Damper: resistive coaxial beam pipe insert, cooled by LN2

• Modes damped to below goal imposed by multi-pass Beam Break-Up

\[
\begin{align*}
\text{Deflecting Mode Shunt Impedances} & \\
\log_{10} R/Q_L & \text{[Ω]} \\
\text{frequency, [MHz]} & \\
\text{Horizontal Mode} & \\
\text{Vertical Mode} & \\
\text{BBU Limit} & \\
\text{BBU Goal} &
\end{align*}
\]
Due to low performance specs, fabrication methods include some alternative techniques:

- Machining from bulk *reactor grade* Niobium
  - RRR of 45 compared to usual ~300
- Tungsten Inert Gas (TIG) welding
  - Developed as an alternative to electron beam welding
• E-Linac first operation
  – Commission linac at 30-35MeV (summer of 2017)
  – Ramp power to 10kW – 2018
  – First beam on ARIEL target 2019

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MOPB042  The TRIUMF/VECC Injector Cryomodule Performance – Y. Ma
MOPB105  Thermosyphon Cooling Loops for ARIEL Cryomodules – Y. Ma
TUPB063  Fabrication and Test Results of a SRF Deflecting Cavity for the ARIEL eLinac – D.W. Storey
TUPB064  Operating Experience on Cavity Performance of ISAC-II Superconducting Heavy Ion Linac, Z. Yao
TUPB065  Design of Multi-frequency Coaxial Test Resonators – Z. Yao
WEXA05  Dirty layers, Bi-layers and Multi-layers: Insights from Muon Spin Rotation Experiments – T. Junginger
THXA02  Fabrication and Testing of Balloon Single Spoke Resonator – Z. Yao
Clint Laforge – SRF Cryomodule Technician and long time TRIUMF colleague and friend passed away last week after a prolonged illness.

We are thinking of Clint today.
Thank you!
Merci!