ERL Upgrade Plans for the ARIEL e-Linac

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Contribution THICCC004
• 500MeV cyclotron since 1974
  – ~300µA distributed to multiple beamlines

• ISAC since 1995
  – Radioactive ion beam (RIB) facility
  – Driven by 500MeV protons from cyclotron

• ARIEL in progress (2010-2023)
  – e-Linac being commissioned – demonstrator beam in 2014
    • 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

• ARIEL is staged
  • ARIEL-I
    • E-Linac demonstration at 23MeV (2 cavities) - 2014
  • ARIEL1.5
    • Complete e-Linac to 30-35MeV – third rf cavity added – 2017
    • Complete e-beamline – 2018
  • ARIEL-II
    • 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 (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
- Install 30MeV capability in mid 2017 – in commissioning - ramp to 100kW in 2018
- 50MeV (10mA) capability foreseen pending funding (500kW)
- 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

- E-Gun HV Supply
- Cold Box
- Klystron Gallery
- 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>
</tr>
</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>
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<tr>
<td>Normalized emittance</td>
<td>5μm</td>
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<tr>
<td>Duty factor</td>
<td>0.01 to 100%</td>
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</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>
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<tbody>
<tr>
<td>Active length (m)</td>
<td>1.038</td>
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<tr>
<td>RF frequency</td>
<td>1.3e9</td>
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<tr>
<td>R/Q (Ohms)</td>
<td>1000</td>
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<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>Pₚbeam (kW)</td>
<td>100</td>
</tr>
<tr>
<td>Qₑxt</td>
<td>1e6</td>
</tr>
<tr>
<td>Qₘ * Rₕ/Q of HOM</td>
<td>&lt;1e6</td>
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</table>

To allow for a future ERL upgrade, BBU criteria set limits on the HOM dipole shunt impedance \( \frac{R_d}{Q^2 Q_L} \).

Assuming a threshold current of 20 mA, beam dynamics calculations set a limit on dipole mode shunt impedance values of \( \frac{R_d}{Q^2 Q_L} < 10^7 \Omega \).

Estimation of fabrication errors combine to set a lower limit of \( \frac{R_d}{Q^2 Q_L} < 10^6 \Omega \).

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
### Cryomodule Cold Test Results

<table>
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<tr>
<th>Parameter</th>
<th>ICM</th>
<th>ACM</th>
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</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>77K static load</td>
<td>&lt;130</td>
<td>&lt;130</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
• There are two 300kW CPI klystrons – one for each cryomodule
• ACM1 – two cavities (two tuners) driven by one rf source in Vector Sum – stable operation demonstrated
• Each cavity turned on and tuned separately with SEL then combined in a single loop
• Working on Adaptive Feed Forward for compensation of beam loading in pulsed mode
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
Recirculating modes

**RLA**
- Single user mode only
- Doubles beam loading so limits maximum beam intensity

**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
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
Merger and Separator Optics

Merger
10MeV injected
30-50 MeV circulating

ACM1
ring
injector
ICM

a) RF separator cavity, b) dipole magnet, c) quadrupole, and d) septum
Electron Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy</td>
<td>MeV</td>
<td>30-50</td>
</tr>
<tr>
<td>RF frequency</td>
<td>GHz</td>
<td>1.3</td>
</tr>
<tr>
<td>Average current</td>
<td>mA</td>
<td>10</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>pC</td>
<td>77</td>
</tr>
<tr>
<td>Bunch rep freq.</td>
<td>MHz</td>
<td>130</td>
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<tr>
<td>Bunch length (rms)</td>
<td>ps</td>
<td>1</td>
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<tr>
<td>Energy spread (rms)</td>
<td>%</td>
<td>0.1</td>
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Output Light Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tbody>
<tr>
<td>Wavelength range</td>
<td>µm</td>
<td>1-20</td>
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<tr>
<td>Micropulse energy</td>
<td>µJ</td>
<td>30</td>
</tr>
<tr>
<td>Laser power</td>
<td>kW</td>
<td>3-5</td>
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E-Linac Applications

- THz radiation (0.3 to 20 THz), at the interface of electronics and photonics, is a frontier area for research in the physical sciences, biology, medicine.
- Accelerator-based THz sources with high peak and average power enable new applications.
- Two possibilities for linac-based THz sources:
  - Free Electron Lasers (FELs) => narrow-band THz
  - Coherent Synchrotron Radiation sources => broad-band THz
- Require a high brightness photo-injector for the e-Linac
**Electron beam parameters**

<table>
<thead>
<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>Energy</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>13 mA</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>100 pC</td>
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<tr>
<td>Norm. emittance (rms)</td>
<td>1 mm-mrad</td>
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<tr>
<td>Beam size</td>
<td>30 µm</td>
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**Laser**

<table>
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<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy</td>
<td>1.8 µJ, 1064 nm, 3 ps</td>
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<tr>
<td>Spot size</td>
<td>60 µm</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>130 MHz</td>
</tr>
<tr>
<td>Cavity gain</td>
<td>3000</td>
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X-ray beam energy: $E \sim 40$ keV

X-ray flux: $N_x \sim 2.7 \times 10^{13}$ photons per second
ERL applications require a high brightness photo-gun – RIB production favours a low brightness beam
  - Will be difficult to find space for two guns
  - Can we produce low emittance and high emittance beams from the same gun

Need to engage a user community to prioritize applications

Need to optimize final parameter set – then detail budget and effort required
• **E-Linac first operation**
  – Commission linac at 30-35MeV (summer of 2017)
  – Ramp power to 100kW – 2018
  – First beam on ARIEL target 2019

• **TRIUMF is now in the planning phase for the next five year funding cycle starting in 2020**

• **Projects being discussed include a second accelerating module to complete the linac to the original specification and the addition of a circulation ring to enable ERL R&D and applications**
Thank you!

Merci!
The electron linac driver complements the existing proton cyclotron driver

- Photofission yields high production of many neutron rich species with less isobaric contamination than spallation
- An energy of 50 MeV is sufficient to saturate photo-fission production
- Electron photofission is used at ALTO (IPN Orsay) - much lower intensity – ARIEL is cutting edge