Status of the Phase I of the SARAF Linac

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LINAC 2010, Tsukuba, Japan
September 15, 2010
Presentation Outline

- Overview
- SARAF Linac Phase I components
  - ECR ion source + LEBT
  - RFQ
  - Prototype Superconducting Module (PSM)
- Beam operation experience
- Outlook
SARAF LINAC Layout

Phase I
2009

RFQ
1.5 MeV/u

PSM
p: 4 MeV, d: 5 MeV

EIS
20 keV/u

Phase II
2015

5 × SC Modules

40 MeV

Thermal neutron radiography
Thermal neutron diffraction
Nuclear Astrophysics
Radioactive beams
Radio Pharmaceuticals

Accelerator Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions</td>
<td>p / d</td>
</tr>
<tr>
<td>Energy</td>
<td>5 – 40 MeV</td>
</tr>
<tr>
<td>Current</td>
<td>0.04 – 2 mA</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Hands-On</td>
</tr>
</tbody>
</table>

- Current upgradeable to 4 mA
ECR/LEBT

Build by RI (ACCEL)
K. Dunkel PAC 2007
See poster TUP74
L. Weissman et al.

5 mA proton beam optics
Large beam minimize space charge (TRACK)

ECRIS
8 mA p/d
DC/pulsed

ECR/LEBT
LEBT aperture

Manipulating beam size, current and emittance using the LEBT aperture
<table>
<thead>
<tr>
<th>RFQ Beam Properties</th>
<th>Protons</th>
<th>Deuterons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Parameter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>1.5 (1.5)</td>
<td>3.0 (3.0)</td>
</tr>
<tr>
<td>Maximal current [mA]</td>
<td>4.0 (CW) (4.0)</td>
<td>2.5 ($10^{-2}$) (4.0)</td>
</tr>
<tr>
<td>Transverse emittance, r.m.s., normalized, 100% [$\pi\cdot\text{mm}\cdot\text{mrad}$] (0.5 mA, closed LEBT aperture)</td>
<td>0.17 (0.30)</td>
<td>0.16 (0.30)</td>
</tr>
<tr>
<td>(4.0 mA, open LEBT aperture)</td>
<td>0.25 / 0.29 (0.30)</td>
<td>NM</td>
</tr>
<tr>
<td>Longitudinal emittance, r.m.s., [π·keV·deg/u] (3.0 mA/0.4 mA)</td>
<td>90 (120)</td>
<td>200 (120)</td>
</tr>
<tr>
<td>Transmission [%] (0.5 mA)</td>
<td>80 (90)</td>
<td>NM</td>
</tr>
<tr>
<td>(2.0 mA)</td>
<td>70 (90)</td>
<td>NM</td>
</tr>
<tr>
<td>(4.0 mA)</td>
<td>65 (90)</td>
<td>70 (90)</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>RF Conditioning Status</th>
<th>Input Power [kW]</th>
<th>Duration [hrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>190 (CW)</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>210 (CW)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>240 (CW)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>260 (DC = 80%)</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Deuteron CW operation requires conditioning up to **260 kW** (65 kV)

Power density: average ~ **25 W/cm²**
RFQ conditioning campaigns

The objective of the RFQ conditioning (260 kW CW) has not been achieved yet.

Example: campaign end 2009

RFQ issues which prevented reaching deuteron CW power:
Arching from back side of rods
Melted tuning plates
Melted plungers
Broken RF fingers
Warming of end flanges
Burning O-rings

See poster TUP095 J. Rodnizki et al.
Discharge between the rods and stems

Non-linearity of voltage response, High x-ray background

Discharge between back of the rods and stems

In spring 2009 the rods were modified locally to reduce the parasitic fields.

This solved the problem of discharge.

However, field realignment was required (later in the talk).
Contact springs of tuning plates were burned twice

**New design:**
- Massive silver plate for better current and thermal conductivity,
- Mechanical contact with stems by a splint system
The low-energy plunger electrode has been melted. It was verified that this was not due to a resonance phenomenon.

New design:
   plunger was reduced by size (twice less thermal load),
   cooling capacity was improved (the plunger and cooling shaft made from one block)
Plungers RF sliding contacts

Broken and deformed RF fingers of the plunger sliding contacts. The sign analysis of the finger surface showed melting signs.

New design:
- New type of RF contact with more rigid fingers
- Shafts plated by rhodium to avoid cold welding
- Rigid alignment of the plunger providing uniform contact pressure
Heating of end flanges

Heating of RFQ end flanges (not water cooled).
Coloration of flanges was observed.

**New design:**
efficient water cooling
improved RF contact between the flanges and the base plate
Failure of vacuum seals

Several times vacuum failure occurs during conditioning.

Damaged vacuum or water o-rings

This probably happens due to discharges of RF field leaked along cooling tubes.
RF mapping of cooling channels

RF hot spots were observed by mapping RF fields (200 W) on the cooling channels. In many cases these positions corresponded to the failed o-rings.

Solutions for better RF contact, not implemented yet.
RFQ stability/availability

Stability as a function of the duty cycle

Temperatures

RF power 200 kW

Duty cycle (%)

Stability

Trips/hour

Availability (%)

20°C

DC 25%  DC 30%  DC 35%  DC 40%  DC 45%  DC 50%  DC 55%

6 hours

25°C

RF power 200 kW

25°C

25°C

RF power 200 kW

25°C

25°C

RF power 200 kW

25°C

25°C

RF power 200 kW

25°C

25°C
RFQ Conditioning Summary

The objective to condition RFQ to CW deuteron operation powers is NOT achieved yet

Next steps to improve RF performance

- Redesign and replace water flanges to solve the vacuum seals problem
- Improve vacuum systems: additional pumps, centralized oil free backing
- Further improvement of the RFQ cooling
- Additional diagnostics for RF conditioning (more vacuum gauges, RGA, x-ray mapping, etc.)
Observed strong dependence of the overall transmission and beam profiles on the RFQ forward power.

Such strong effects were not observed before the modifications made in the RFQ in the first half of 2009.
March 2010:

RFQ field homogeneity

Shim

Tuning block

Stem no

Field U0 [%]

Nov-2009 Apr-2010

Beam
After improving field homogeneity observe much smaller RFQ power effects

We plan further improvements of rods alignment (with help of our colleagues from the optics department)
Prototype Superconductive Module

- The cryomodule houses six SC HWR cavities and three SC solenoids
- Separate beam and insulation vacuum
- Operating temperature 4.2°K
- six 2 kW solid state amplifiers
- Designed to accelerate 2 mA protons or deuterons beams

### HWR Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>176 MHz</td>
</tr>
<tr>
<td>Optimal $\beta$ (protons)</td>
<td>0.09</td>
</tr>
<tr>
<td>$L_{\text{acc}}=\beta \lambda$</td>
<td>0.15 m</td>
</tr>
<tr>
<td>$\Delta V \ @ \ E_{\text{peak}}$</td>
<td>840 kV @ 25 MV/m</td>
</tr>
<tr>
<td>$Q_0@E_{\text{peak}}$</td>
<td>&gt;$4.7 \times 10^8$</td>
</tr>
<tr>
<td>Cryogenic load</td>
<td>&lt; 70 W</td>
</tr>
<tr>
<td>$Q_{\text{ext}}$</td>
<td>~$1.3 \times 10^6$</td>
</tr>
<tr>
<td>Loaded BW</td>
<td>~130 Hz</td>
</tr>
</tbody>
</table>

Build by RI (ACCEL)

M. Pekeler, LINAC 2006
PSM commissioning

Helium processing: 99.9999% purity, 4 \times 10^{-5} \text{ mbar}
up to 43 \text{ MV/m} 10\% \text{ DC}

Reduced field emission from the cavities and allowed stable operation at the nominal fields.

However, simultaneous operation of all cavities at the nominal field was not achieved for long period.

A. Perry, SRF2009
HWR Microphonics measurements*

HWRs are extremely sensitive to LHe pressure fluctuations (60 Hz/mbar)
Detuning signal is dominated by the Helium pressure drift
Detuning sometimes exceeds +/-200 Hz (~ +/-2 BW).

* Performed in collaboration with J.Delayen and K. Davis (JLab)
HWR Tune*

**Stepper motor** is used for coarse tuning. Stepper motor movement induces instabilities and is therefore disabled during RF operation.

**Piezoelectric actuator** provides fine tuning of the resonance frequency.

Range reduction of the piezoelectric elements were subsequently replaced.

Response of the fine tuner is highly non-linear.

* Performed in collaboration with J. Delayen and K. Davis (JLab)
During operation significant heating of coupler #4 was observed.

Operation of cavity 4 is therefore limited to ~500 kV to avoid overheating.
PSM Status

- Reached stable long-term only at 60-70% of nominal gradients:
  - high-sensitivity to helium pressure fluctuations
  - problems with tuner response
  - warming up of some couplers

- Work on implementing a new tuner control algorithm on a NI – CRIO FPGA core – improve the response time and account for the hard nonlinearities.

- Upgrade of 2 kW amplifiers to 4.0 kW to provide additional RF power required for high current field stabilization.
Phasing cavities for pulsed beams

Example of phasing cavities for proton beam
Use low beam DC (10^{-2} \%) RFQ - 100 \% (protons), a few \% (deuterons)

Measure energy of the protons scattered on a 0.3 mg/cm^2 gold foil as a function of the cavities voltages/ phases

Final settings for 3.1 MeV

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Set Voltag</th>
<th>Real Voltage</th>
<th>Set Phase</th>
<th>Sync Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWR1</td>
<td>120 kV</td>
<td>150 kV</td>
<td>80</td>
<td>-95</td>
</tr>
<tr>
<td>HWR2</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>off</td>
</tr>
<tr>
<td>HWR3</td>
<td>430 kV</td>
<td>600 kV</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>HWR4</td>
<td>490 kV</td>
<td>500 kV</td>
<td>-170</td>
<td>-35</td>
</tr>
<tr>
<td>HWR5</td>
<td>400 kV</td>
<td>500 kV</td>
<td>-50</td>
<td>-30</td>
</tr>
<tr>
<td>HWR6</td>
<td>660 kV</td>
<td>500 kV</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

Beam Dynamics calculations J. Rodnizki

The highest beam energies for low DC beam:
Protons – 3.7 MeV
Deuterons – 4.3 MeV
RFQ Longitudinal emittance measurement

Example: Deuteron beam
RFQ + 1st cavity
The cavity was set to -90° (bunching mode) and its voltage is varied
Evaluation of longitudinal emittance via measuring energy width of the peak as a function of the cavity voltage

- **RFQ 227 kW**

- **RFQ 237 kW**
  - Long. Emittance: 210 π deg keV/u

- **RFQ 249 kW**
  - Long. Emittance: 365 π deg keV/u

See poster TUP091, J. Rodnizki et al
CW beam: vacuum/cryogenics effects

First attempts to conduct ~ mA CW strong effects in the PSM vacuum and in the cryogenics

In this example 1 mA beam is conducted through the cryomodule without acceleration and some optics parameters were varied (RFQ power, MEBT steers).
CW beam (continued)

Otimizing RFQ power and MEBT steering to minimize beam-induced effects
Managed to achieve stable operation for CW beam

In this example, 1-1.3 mA 1.5 MeV drifted through the cryomodule.
Operation was stable for longer than 6.5 hours and
Operation was repeated during the two consequent days

There are still effects on cryogenics but operation is stable
The effects of vary RFQ power on vacuum in the accelerator are observed.
In this example:

Operation of ~1 mA, ~3 MeV accelerated proton beam.
Operation was stable for more than 9 hours.
Only one RFQ trip. Return to operation within minutes.
Effect on cryogenics is similar to 1.5 MeV beam.

So, probably, the loss of 2-3 μA happens at the entrance of the cryomodule.
Plan to introduce a beam scrapper in MEBT
## Phase I Beam Operation Summary

<table>
<thead>
<tr>
<th>HWR #</th>
<th>Low DC Proton 3.7 MeV</th>
<th>Low DC Deuteron 4.3 MeV</th>
<th>CW (1 mA) Proton 3.1 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage [kV]</td>
<td>$E_{\text{acc}}$ [MV/m]</td>
<td>Voltage [kV]</td>
</tr>
<tr>
<td>1</td>
<td>150</td>
<td>1</td>
<td>290</td>
</tr>
<tr>
<td>3</td>
<td>630</td>
<td>4</td>
<td>590</td>
</tr>
<tr>
<td>4</td>
<td>550</td>
<td>3.7</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>550</td>
<td>3.7</td>
<td>500</td>
</tr>
<tr>
<td>6</td>
<td>900</td>
<td>5.9</td>
<td>500</td>
</tr>
</tbody>
</table>

\[ L_{\text{acc}} = \beta \lambda \]

Nominal voltage: 840 kV

- Cavities 1 is used for bunching; cavity 2 is used as a drift
- Operation at higher gradients is still limited by instabilities
- Beam induced effects
Summary and Outlook

First proton and deuteron beams were accelerated by a HWR based SC Linac

Proton and Deuteron **low duty cycle** beams were accelerated up to **3.7 MeV** and **4.3 MeV**

Protons **CW ~1 mA** beams accelerated up to **3.1 MeV**

Phase I is still in its commissioning stage.

1. Actions to improve beam operation:
   - RFQ alignment
   - MEBT scrapper
   - Upgrade of tuners control and cavities amplifiers
2. CW Deuteron operation has not been achieved yet

Design of Phase II is underway
Temporary beam line is being commissioned in the accelerator tunnel

Pilot project. Several beam lines will be built for the Phase II

The first experiments in material science and astrophysics

The first experiments should take place until the end of the year
People involved


Red font: persons who joined recently

RI&Varian / (former ACCEL): H. Vogel, Ch. Piel, K. Dunkel, P. Von Stain, M. Pekeler, F. Kremer, D. Trompetter, many mechanical and electrical engineers and technicians

Cryoelectra: B. Aminov, N. Pupeter, …

NTG/ Frankfurt Univ: A. Bechtold, Ph. Fischer, A. Schempp, J. Hauser