linac lattice in 2006 and today

1.5 MeV/u

1.3 MeV/u

25 m

SC linac status: N. Pichoff (MOPOYO53)
SC HWR physical design: G. Ferrand (MOPRC025)
SC HWR mechanical design: N. Misiara (MOPRC026)
NC MEBT rebuncher: B. Kaizer (MOPLRO050)
SARAF Phase-I Accelerator

Commissioning

A. Nagler, Linac 2006
K. Dunkel, PAC 2007
C. Piel, PAC 2007
C. Piel, EPAC 2008
A. Nagler, Linac 2008
J. Rodnizki, EPAC 2008
J. Rodnizki, HB 2008
I. Mardor, PAC 2009
A. Perry, SRF 2009
I. Mardor, SRF 2009
L. Weissman, DIPAC 2009
L. Weissman, Linac 2010

Operation

D. Berkovits, Linac 2012
L. Weissman, RuPAC 2012
A. Kreisel, Linac 2014
L. Weissman, WAO 2014
L. Weissman, JINST 2014
L. Weissman, JINST 2015

<table>
<thead>
<tr>
<th></th>
<th>MeV</th>
<th>mA</th>
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<tbody>
<tr>
<td>p</td>
<td>4</td>
<td>1 CW</td>
</tr>
<tr>
<td>p</td>
<td>2</td>
<td>2 CW</td>
</tr>
<tr>
<td>d</td>
<td>5.6</td>
<td>1*10%</td>
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### CW 4-rod RFQ - design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection/output energy</td>
<td>20 / 1500 keV/u</td>
</tr>
<tr>
<td>Isotope</td>
<td>deuterium</td>
</tr>
<tr>
<td>Frequency</td>
<td>176 MHz</td>
</tr>
<tr>
<td>Electrode voltage</td>
<td>65 kV</td>
</tr>
<tr>
<td>RFQ length</td>
<td>3.8 m</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>280 mm</td>
</tr>
<tr>
<td>Min. aperture</td>
<td>2.7 mm</td>
</tr>
<tr>
<td>Max. modulation</td>
<td>2.7</td>
</tr>
<tr>
<td>Power consumption</td>
<td>250 kW</td>
</tr>
<tr>
<td>Input emittance $\epsilon_{x,y}$</td>
<td>160 $\pi$ mm mrad</td>
</tr>
<tr>
<td>$a / b$</td>
<td>0.85 / 0.28 mm mrad$^{-1}$</td>
</tr>
<tr>
<td>Number of cells</td>
<td>199</td>
</tr>
<tr>
<td>Number of stems</td>
<td>40</td>
</tr>
<tr>
<td>Long. output emittance $\epsilon_l$</td>
<td>75 $\pi$ deg. keV/u</td>
</tr>
<tr>
<td>Transmission 0 / 5 mA</td>
<td>98 / 96 %</td>
</tr>
</tbody>
</table>

- P. Fischer, A. Schempp
  Linac 2006

![Diagram of CW 4-rod RFQ](image)
The SARAF 4-rod RFQ coupler

- The RFQ includes one coupler with an antenna loop to supply the 260 kW needed to accelerate 5 mA CW deuteron beam
Recent years main limitations

• Following conditioning campaigns the RFQ was capable to reach 200 kW CW dissipated power for few times
• During RFQ operation we faced deteriorations of the RFQ performance
• The RFQ coupler was found to be the bottleneck that prevented long term CW operation at high dissipated power.
2015 RFQ RF splitting roadmap

- Splitting the RFQ RF line to two couplers to reduce the RF load on each coupler
- Improve the coupler design to eliminate potential failures
- Couplers loop design and matching
- Conditioning the RFQ to find the available CW dissipated power to reach long term stable operation in the new configuration with reduced fields and dissipated power in the range of 170-200 kW
- RFQ deuteron beam operation test
- An accomplished step will be a design of new rods modulation with reduced fields and dissipated power to gain a long term CW RFQ operation.
Splitting the RFQ RF line to two couplers to reduce the RF load on each coupler
RF design for operation with two couplers

- LLRF control scheme is not effected
- Fixed phasing line to reach RF loops synchronization
- The 3dB splitter avoids cross talk
- Coupling is reached during the installation stage
- Directional couplers pickup output is presented and recorded
- Reflected power goes back to the amplifier.
The synchronization phase between the ports

- The eigenmode magnetic field change sign between adjacent RF cells
- The synchronized RF phase between the couplers ports is 180° due to even # of cells between the ports
- 1° deviation in phase at 176 MHz ~5 mm deviation in the fixed phasing line length →

\[
A \cos(wt - \alpha/2) + A\cos(wt + \alpha/2) = 2A \cos(wt)\cos(\alpha/2)
\]

\[
\frac{Pf_{synchronised}}{Pf} = \cos^2 \left(\frac{\alpha}{2}\right) = 0.9999
\]

where \( H_1 = A \cos(wt + \alpha/2) \) and

\( H_2 = A \cos(wt - \alpha/2) \)

\( \alpha = 1° \)

If the fixed rigid line is not matched properly that will result in additional reflected power. However for phase deviation of 1°, the additional reflected power is negligible.
Splitting the RFQ RF line with the new designed couplers
Improve the coupler design to eliminate potential failures
New coupler design

Former design  New design

Grooves for canted springs

Perpendicular drilled holes for antenna length adjustment and brazing

Drilled holes to avoid virtual leaks

Designed sealing surfaces for vacuum o-ring insulation

Brown – copper
Blue - ceramic
Gray – SS or aluminum

Long alignment contact surface
Couplers loop design and matching
Antenna design

• One loop antenna advantages:
  – Lower coupling is required, due to the installation of 2 couplers
  – Simplifies the manufacturing procedure
  – Improving the antenna reliability
  – Enable the separation between in\out water tubes (no silver brazing)

Simulation the existing RFQ coupler coupling to $Q_{\text{ext}}=4000$

Derive the required configuration to reach $Q_{\text{ext}}=8000$ (for two couplers)
One loop Antenna design

• Loop geometry considerations
  – Antenna tuning by rotation or by bending
  – Adequate coupling
  – Antenna reliability

Vertical configuration

parallel configuration

Adequate coupling was achieved only with a “parallel” (to the rods) configuration
Critical coupling with one antenna is reached by insertion of the antenna between stems

For $S_{11}<-40$ dB the $Q_{load}$ is evaluated with a network analyser. At this configuration $Q_{ex}=Q_0=2\ Q_{load}$

Each antenna is cut further to reach $Q'_{load}=(4/3)Q_{load}$

Since: $1/Q'_{load}=1/(Q'_{ex})+1/\ Q_0$  
$Q'_{ex}=2Q_{ex}$

Assembling both together, critical coupling is reached by fine tuning; $Q''_{ex}=Q_{ex}$

The former antenna reflected $S_{11}$ and pickup $S_{21}$ power as function of the forward power

The new antenna reflected $S_{11}$ and pickup $S_{21}$ power as function of the forward power
Conditioning the RFQ to find the available CW dissipated power
RFQ pre conditioning steps

• The chamber was cleaned, rods polished with tissue socked by alcohol
• Diagnostics devices were mounted:
  – a few CCD cameras at the viewports in front of couplers and rods
  – a few x-rays detectors in front of the viewports for monitoring x-ray
  – several thermocouples attached to- tank, water feedthroughs and RF lines
• Chamber was pumped for one week to avoid partial virtual leaks
Vacuum development along the first week

When cooling water were cycled vacuum level was improved due to lower surface degassing rate.

Now the base vacuum level is $2 \times 10^{-7}$ mBar.
RFQ pickup voltage as function of the forward power

- Linear dependence between the square RFQ pickup voltage to the forward power
- Max deviation 4%
RFQ conditioning campaign

- The conditioning was performed most of the time at CW mode.
- The forward power was increased at low rate to achieve a quasi static thermal behavior of the RFQ, inspected by the thermocouples output temperatures.
- The vacuum level in RFQ RF breaks usually did not increase above $10^{-5}$ to $10^{-6}$ mbar.
- Stable and long term operation were systematically demonstrated at 200 kW CW forward power, with 0.2% reflected power and 98% availability.
- Above 200 kW CW forward power, onset of forward and reflected power oscillations initiated. Other 4 rods RFQ projects report on mechanical vibration of the rods at high loads:

- 50-80% duty cycle were demonstrated at 250 kW incident forward power (the required dissipated power for a deuteron beam operation).
RFQ deuteron beam test
Beam diagnostics along the test
The deuteron beam TOF

The Time Of Flight measurement between the MEBT BPMs confirmed that the deuteron energy downstream the MEBT is $1.5 \pm 0.1$ MeV/u
The deuteron Energy distribution RBS measurement

RBS measurements of deuteron energy distribution verified that the mean beam energy is $1.50 \pm 0.01$ MeV/u

The measurement method is described in L. Weissman et al. DIPAC 2009
BPM 1 (blue) and BPM 2 (red) amplitude as function of RFQ power for 8.5 mA LEBT injected deuteron current
RFQ transmission as function of injected current for a proton and a deuteron beam

- LEBT current is LEBT FC minus RFQ entrance collimator current (0.05-0.15 mA)
- MEBT current measured without suppression and corrected assuming 20% secondary electrons yield
RMS emittance measurements for 3.6 mA deuterons at the beam dump downstream the D-Plate (5.9mA at the LEBT FC)

<table>
<thead>
<tr>
<th>Em x n</th>
<th>alpha</th>
<th>beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm mrad</td>
<td>mm/mrad</td>
<td></td>
</tr>
<tr>
<td>0.136</td>
<td>-0.701</td>
<td>9.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Em y n</th>
<th>alpha</th>
<th>beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm mrad</td>
<td>mm/mrad</td>
<td></td>
</tr>
<tr>
<td>0.162</td>
<td>1.18</td>
<td>2.73</td>
</tr>
</tbody>
</table>
Summary

- New two couplers configuration was proposed, designed, and implemented at SARAF 4-rod RFQ.
- The RFQ reached systematically up to 200 kW dissipated power, with long-term stability.
- Operation of up to 5.5 mA Deuteron pulsed beam was demonstrated.
- The preliminary results of 0.15 mm-mrad RMS normalized transverse emittance measured at the D-Plate downstream the PSM for a 3.6 mA deuteron beam are very encouraging.
- The accomplished step is a design of new rods modulation in the range of 200 kW dissipated power with 1.3 MeV/u beam energy.
- This pioneer study may contribute to other projects which intend to run CW beams with high power dissipation like FRANZ and MYRRHA 4-rod RFQ.
END

Acknowledgement:
Mr. L. Dadon for the couplers brazing works
Dr. A. Kreisel for his assistance in the beam emittance analysis.
The SARAF team for their support during the work on this project
Personnel of the Soreq workshop for their assistance during manufacturing and installations phases