SARAF PHASE II P/D
40 MEV LINAC DESIGN STUDIES

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SARAF Accelerator (2003 design view)

PSM – Prototype Superconducting Module

B. Bazak et al., linac 2010

Phase I of SARAF includes (Ion source, RFQ and one cryomodule housing 6 HWRs 176 MHz ) delivering:
- 3.6 MeV 1mA p beam
- 4.7 MeV low duty cycle 0.3 mA d beam

SARAF Phase II CW linac is planned to produce:
- variable energy (5-40) MeV p&d
- beam currents (0.04-5) mA
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B. Bazak et al., linac 2010
Outline: SARAF Phase II conceptual study

Two linac options: 176 MHz HWR & 109 MHz QWR lattices downstream a 20 keV/u - 1.3 MeV/u RFQ. Both options were studied for Phase II:

- Design of CW RFQs according to engineering and beam dynamics guidelines
- Matching the LEBT beam to the RFQ
- MEBT design
- SC cavity main EM parameters
- EM optimization of both QWRs and HWRs
- Engineering and beam physics design of the linac and its cryomodules
- Detailed beam dynamics simulations with realistic fields and machine errors.
Design of CW RFQs guidelines

- Reliable CW protons and deuterons operation
- Beam formation with extremely low longitudinal halo
- Moderate peak fields to avoid any possible breakdowns and avoid long conditioning of the resonator. In particular, the peak electric fields should be below $1.8E_K$ ($E_K$=Kilpatrick criterion)
- High acceleration efficiency (>97%) for 5 mA
- No transverse rms emittance growth through the RFQ
The 4 vanes 176 & 109 MHz CW RFQ

4-vane structure was chosen to reduce RF power as compared to 4-rod or even 4-vane structure with “windows”
# 176 MHz CW RFQ: Beam Dynamics Optimized Design

<table>
<thead>
<tr>
<th>Beam</th>
<th>Proton</th>
<th>Deuteron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input transverse emittance, rms, norm, mm·mrad</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Input Twiss $\alpha$</td>
<td>0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>Input Twiss $\beta$, cm/rad</td>
<td>3.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Transmission, %</td>
<td>99.7</td>
<td>99.9</td>
</tr>
<tr>
<td>Output longitudinal emittance, rms, keV/u·deg</td>
<td>36.6</td>
<td>36.3</td>
</tr>
<tr>
<td>Transverse rms emittance growth, %</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transverse 99% emittance growth, %</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Particle loss inside the RFQ</td>
<td>$3 \cdot 10^{-3}$</td>
<td>$1 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Two Important Design Features
- Approaches 100% transmission
- Input matcher to reduce emittance growth
A Smooth Two-Step Input Matcher

LEBT with RFQ original 6 cell input matcher: $\alpha \sim 1.5$

LEBT with RFQ special 15 cell input matcher: $\alpha \sim 0.25$
MEBT primary functions

- Match either a proton or a deuteron beam into the 6D acceptance of the SC linac;
- Avoid emittance growth and formation of beam halo;
- Provide space for beam diagnostics and cold trap

Matching of the RFQ beam to the SC acceptance is not a trivial task

- The available accelerating gradient of the SC structures is appreciably higher than that of the RFQs;
- The MEBT forms a radial beam for injection into the SC linac;
176 MHz Room Temperature Buncher

- Aperture diameter 30 mm
- Voltage – up to 160 kV
- RF power 3kW
SC cavity main EM parameters Selection

- Based on the demonstrated performance of TEM-class cavities at ANL.

  [M.P. Kelly et al, MOPB073 these proceedings]

- Weighted toward maintaining $E_{\text{PEAK}}$ at or below 36 MV/m.

- These parameters were demonstrated in operation for the past 3 years. Off-line cold test of NEW 72 MHz cavities demonstrated >70 MV/m in all 4 tested cavities.
EM optimization of HWRs

Three steps optimization to the Race-Track center conductor design to reduce magnetic field and the transverse beam asymmetry:

- Elliptical aperture.
- Intermediate round loft.
- Change the geometry to “donut” shape.
Elliptical aperture

The elliptical aperture reduces the quadrupole effect caused by the asymmetric geometry.

The required elliptical aperture is 33-36 mm for the low-β and 36-40 mm for the high-β.

[B. Mustapha et al, HIAT-2012]
HWR EM fields optimization

Intermediate round loft

Change the geometry

to donut shape

- The intermediate round loft reduces the peak magnetic field

[B. Mustapha et al, IPAC-2012]

Race-Track versus Round Loft in the Center Conductor

- The donut-shaped cavity has a slightly higher E-peak, a much lower B-peak, and a higher shunt impedance.

[CST MWS]
The final donut shape CST EM fields

CST EM Fields

Donut-Shaped vs. Race Track design: Shunt Impedance

$R/Q = V^2/\omega U$, $\omega U$ is the same in MW-Studio $\rightarrow R/Q \propto V^2$

- The Donut-Shaped has a 32% higher shunt impedance due to the narrower acceleration gaps (a better transient time factor)
- The donut-shaped cavity is capable of delivering 2.1 MV at 36 MV/m and 43 mT or 3.4 MV at 59 MV/m and 70 mT
Final designs of the 109-MHz QWRs

Geometries and dimensions for the low-\(\beta\) (left) and the high-\(\beta\) (right) cavities

The steering correction is achieved by introducing a drift tube face tilt angle to compensate the QWR non-symmetric magnetic component.
Physics design of high-intensity linacs

- The transverse and longitudinal wave numbers, $\kappa_{T0}$ and $\kappa_{L0}$, for zero beam current must change adiabatically along the linac.
- This feature minimizes the potential for mismatches and helps to assure a current-independent lattice and its tune.
- The wave numbers of particle oscillations are expressed as $\kappa_{T0}=\sigma_{T0}/L_f$, $\kappa_{L0}=\sigma_{L0}/L_f$, where $\sigma_{T0}$ and $\sigma_{L0}$ are the zero-current transverse and longitudinal phase advances per focusing period of length $L_f$.
- An adiabatic change of the real-estate accelerating gradients and focusing fields is required to fulfill these conditions. Fulfillment of these conditions results in a current-independent tune of the SC linac section.
- In the proposed lattice design for both frequency options we follow this concept very closely with a focus on minimizing the number of cavities and solenoids for cost efficiency.
176 MHz Cryomodule Design

• First low-\(\beta\) cryomodule: BPM, Solenoid, Cavity per focusing period

• High-\(\beta\) cryomodule: 3 focusing periods, 2 HWRs each, and 1 HWR in the 4\(^{th}\) period.

[Z. Conway et al, TUPB068 these proceedings]
The 109 MHz SC modules

low-β (top) and high-β (bottom) lattice design
109 MHz Linac vs. 176 MHz linac

- 109 MHz requires one cryomodule less but a new RFQ
- Apertures can be made larger
- Higher shunt impedance
- Requires new RF system
- 176 MHz is a more familiar frequency; the RF system can be made domestically
- In terms of beam dynamics they are very similar
176 MHz Lattice Beam Dynamics & Errors Study

- A 5 mA proton/deuteron beam reaches 40 MeV with 28 HWRs
- The normalized rms emittance growth for a typical run, is a few percent
- No losses were found in 100 runs with errors and 100k macro particles

**Applied Errors:**

- Cavity & Solenoid Misalignments: 500 μ
- Cavity Phase: 0.5 deg
- Cavity Field: 0.5 %

Centroid motion along the linac before (Red) and after (Blue) correction. The correction uses only 2 correctors and 2 monitors per cryomodule.
INTEGRATING SARAF PSM IN SARAF PHASE II LATTICE

- The existing SARAF Phase-I prototype SC module (PSM) can be used as a second low-β cryostat in Phase II.
- The PSM cavities were set at 600 kV, 70% of their original design voltage.
- The result is an additional 5 MeV energy gain for deuteron
- 3 MeV are gained at the PSM
- 2 additional MeV are the result of a better velocity matching downstream of the PSM
The ion source and LEBT are in the original position.
New RFQ, MEBT, and superconducting linac.
PSM included.
Analysis of the PSM coupler

- RF thermal co-simulation analysis of the PSM HWR coupler cold window temperature rise during 4kW beam operation is essential for integrating the PSM in Phase II
Summary

• Two linac options based on 109 MHz QWRs and 176 MHz HWRs capable to deliver 5 mA, 40 MeV proton and deuteron beams have been studied.

• Extensive end-to-end beam dynamics simulations iterated with the engineering design show that both options can hold the hands-on maintenance criterion which is vital for a high intensity machine.

• As there are only slight differences between both options, the SARAF project adopted the 176 MHz HWR linac since it will be a smooth transition from phase I.

• Furthermore, with some modifications, the current SARAF PSM can be included in the Phase II lattice