SARAF PHASE II P/D 40 MeV LINAC DESIGN STUDIES*

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Abstract

The Soreq NRC initiated the establishment of SARAF – Soreq Applied Research Accelerator Facility [1]. SARAF will be a multi-user facility for basic research, e.g., nuclear astrophysics, radioactive beams, medical and biological research; neutron based non-destructive testing (using a thermal neutron camera and a neutron diffractometer) and radio-pharmaceuticals research, development and production. The SARAF continuous wave (CW) accelerator is planned to produce variable energy (5-40 MeV) proton and deuteron beam currents (0.04-5 mA). Phase I of SARAF (ion source, radio-frequency quadrupole (RFQ), and one cryomodule housing 6 half-wave resonators (HWR)) was installed and is operating at Soreq NRC delivering CW 1mA 3.5 MeV proton beams and low-duty cycle (10^{-4}) 0.3 mA 4.7 MeV deuteron beams [2]. SARAF is designed to enable hands-on maintenance, which implies very low beam losses for the entire accelerator. This paper presents the physics design of two options to subsequently develop a conceptual design for extending the SARAF Phase I linac to its planned Phase-II beam parameters (40 MeV, 5 mA protons and deuterons).

INTRODUCTION

We present the physics design of two options for a CW linac capable of delivering 200-kW beams of 40-MeV, 5-mA protons and deuterons [3, 4]. The two options analyzed are (1) a linac based on superconducting (SC) halfwave resonators (HWRs) operating at a fundamental frequency of 176 MHz; and (2) a linac based on SC quarter-wave resonators (QWRs) operating at a fundamental frequency of 109 MHz. Both options include a CW radio frequency quadrupole (RFQ) designed for acceleration of protons or deuterons from 20 keV/u to 1.3 MeV/u.

The main SC cavity parameters are based on recent Argonne National Laboratory (ANL) experience with a performance margin. These parameters are used to develop baseline designs of the SC linacs. The ANL approach for CW RFQs for both options is described. Significant effort was devoted to the electromagnetic (EM) optimization of both QWRs and HWRs. The concepts for the engineering and beam physics design of the linac and its cryomodules are discussed. The results of detailed beam dynamics simulations with realistic fields and machine errors are presented.

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CHOICE OF SC CAVITY PARAMETERS

The choice of SC cavity parameters for SARAF Phase II is based on the demonstrated performance of TEM-class cavities at ANL. The horizontal bands in Fig. 1 show the proposed operating regions for each of the two pairs of 109-MHz QWRs and 176-MHz HWRs. The critical point is that in all cases there is a performance margin with respect to demonstrated Argonne cavity performance in the ATLAS energy upgrade cryomodule [5]. Overall, the choice of operating parameters is weighted toward maintaining E_{PEAK} at or below 36 MV/m because the performance margin with respect to B_{PEAK} is relatively larger. Based on the most recent ANL experience with the development of new 72 MHz QWRs for the ATLAS efficiency and intensity upgrade [6], it is most likely that the margin in both electric and magnetic fields will be increased up to 100% [7].

Generally, the proposed quarter-wave option has a modestly larger margin due to the lower value of B_{PEAK} for a given value of E_{PEAK} in QWR geometries versus HWR geometries.

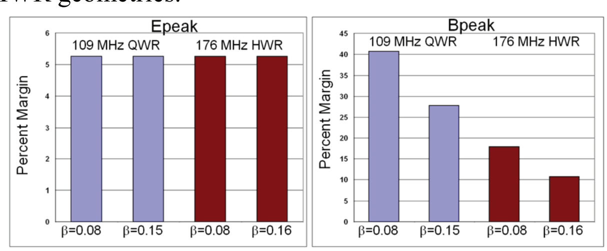

Figure 1: Operating margin with respect to already demonstrated performance in ATLAS.

RFQ BEAM AND EM DESIGN

To maintain a high level of operational reliability, we recommend the development and fabrication of a new 1.3-MeV/u RFQ with reduced RF power losses relative to the existing SARAF Phase-I 4-rod RFQ. The new RFQ would be based on a 4-vane structure. The main requirements for the RFQ for the high-intensity SARAF linac are as follows:

- Absolutely reliable CW operation for both protons and deuterons.
- Formation of a beam with extremely low halo in the longitudinal phase space.
- Moderate peak fields to avoid any possible breakdowns and avoid long conditioning of the resonator. In particular, the peak electric fields should be below 1.8EK where EK is the Kilpatrick limiting field.

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- High acceleration efficiency (>97%) for the design beam current of 5 mA.
- No transverse rms emittance growth through the RFQ.

The output beam energy of the RFQ is a compromise between the complexity and cost of the RFQ resonator and the low-beta SC cavities. As a result of past experience and a detailed analysis of both the RFQ and the SC structures, a 1.3-MeV/u transition energy is adequate for the SARAF proton and deuteron accelerator. A beam energy that is too high increases the RFQ length and the required RF power.

A conventional 4-vane structure is proposed for the 176-MHz RFQ to provide the highest possible shunt impedance and to keep the required RF power below 120 kW. The main parameters of the RFQ are listed in Table 1. High transverse phase advance per period (>33^{o}) along the RFQ provides strong transverse focusing that maintains a low transverse emittance and a low sensitivity to possible fabrication and tuning errors. Appropriate variation of RFQ parameters such as synchronous phase and modulation factor along the RFQ are applied in order to form the low longitudinal emittance of the halo-less beam in the longitudinal phase space. The transmission through the RFQ is very high, greater than 99.9% for both protons and deuterons. The acceleration efficiency is 98.5%. Relative losses of the deuteron beam inside the RFQ are below 10^{-4}, while the similar value for protons is higher, 1.5 x 10^{-3} due to the stronger space charge effects.

Fig. 2 shows the relative number of particles located outside a given longitudinal emittance obtained by simulation of 200k particles with an input current of 5.5 mA. The total longitudinal emittance is well below the acceptance of the SC linac.

An exploded view of the 4-segment 4-vane RFQ is shown in Fig. 3. The main advantage of the 4-vane structure over a 4-rod structure is a significantly lower RF power consumption, just 110 kW for deuterons based on MWS [8] simulations.

It is well known that in a long 4-vane structure the frequencies of neighbouring dipole modes are close to the operational frequency. The length of the proposed 176 MHz RFQ is just 2.2 λ, where λ is the wavelength of the operational mode, and frequencies of dipole modes are more than 3 MHz away from the operational frequency. Simple techniques have been developed and used in the past to control the frequencies of the non-operational modes. In particular, the frequency spectrum of the non-operational modes can be efficiently adjusted using four plug tuners installed on the end-plates of the RFQ.

The success of a CW RFQ and long-term reliable performance is primarily defined by the fabrication technology. Past experience confirms that highly reliable, high duty cycle normal conducting accelerating structures can be built using 100% oxygen free electronic (OFE) copper structures brazed in a high-temperature hydrogen atmosphere furnace. Usually, a brazed copper cavity is an integral vacuum and structural vessel.

The SARAF RFQ will be fabricated from OFE copper. Each part of the segments will be machined to the required tolerances, ~25 μm, and brazed in a high-temperature furnace in a hydrogen atmosphere. This technology has been successfully applied to CW RFQs such as the RIA prototype RFQ [9] and the ANL ATLAS Upgrade RFQ [6] which was successfully commissioned with beam recently. The dimensions of the 176-MHz RFQ segments are similar to those for the ATLAS Upgrade RFQ. This ensures that the fabrication technology developed for this RFQ can be directly applied to the SARAF RFQ.

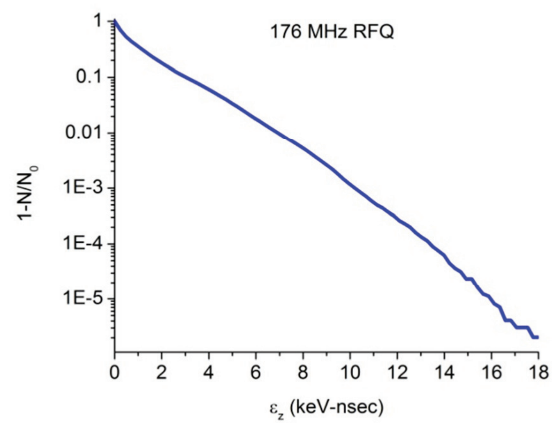

Figure 2: The relative number of particles located outside a given longitudinal emittance obtained by simulation of 200k particles with an input current of 5.5 mA.

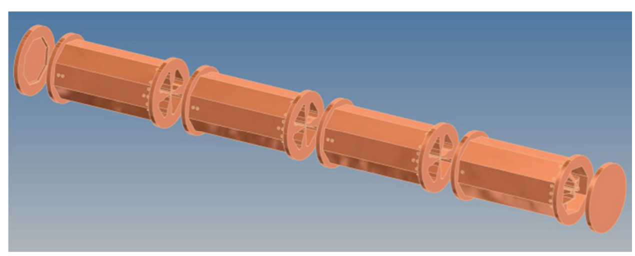

Figure 3: Engineering model of the 4-segment 4-vane RFQ.

The main parameters of the 176 MHz and 109 MHz RFQs are listed in Table 1. The 109 MHz RFQ provides very similar beam properties as the 176 MHz RFQ.

Two possible electromagnetic structures for the 109-MHz RFQ have been investigated: (1) a 4-vane structure with windows similar to the 60-MHz RFQ developed at Argonne for the ATLAS upgrade and (2) a conventional 4-vane structure. The smaller transverse dimension of the 4-vane structure with windows compared to the conventional 4-vane structure is an advantage. Indeed, the transverse dimension of the 109-MHz structure can be matched to the exact dimensions of the Argonne 60-MHz RFQ so that the fabrication technology (fixtures and tooling) of the Argonne RFQ structure can be directly applied to the SARAF RFQ. However, the introduction of windows increases the RF power losses to 145 kW versus 79 kW for the 4-vane structure. Therefore, we propose to

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use the conventional 4-vane structure for the 109-MHz SARAF RFQ.

Table 1: Main Parameters of the 176 & 109MHz RFQs

Parameter	Value	Value
Frequency, MHz	176	109
Charge to mass ratio	1, ½	1, ½
Input energy, keV/u	20	20
Output energy, keV/u	1318	1314
Design beam current, mA	5.0	5.0
Inter-vane voltage, kV	75	85
Maximum field at vane surface, kV/cm	232	209
Maximum field at vane surface, Kilpatrick units	1.57	1.79
Average radius, mm	4.4	6.0
Modulation factor, max	2.0	2.0
Minimal aperture, mm	2.93	3.93
Minimal transverse phase advance, degree	33.0	40.3
Transverse acceptance, normalized, mm-mrad	2.5	4.3
Number of cells	257	195/50
RFQ length, m	3.8	4.5
Deuteron beam (I = 0 mA) longitudinal rms emittance, keV/u deg	56	58
Deuteron beam (I = 5 mA) longitudinal rms emittance, keV/u deg	36	35.3
RF power losses in the RFQ (MWS data), kW	110	79

LEBT AND MEBT

The existing LEBT is able to deliver and match both proton and deuteron beams into the RFQ acceptance. The RFQ consists of a conventional entrance radial matching section and a short output matching section that transforms the transverse phase space into a double-waist beam at the exit of the RFQ and facilitates matching to the MEBT. The MEBT's primary functions are as follows:

- 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 a space for beam diagnostic devices;
- Provide efficient isolation of cold vacuum from warm vacuum by using a short cold trap upstream of the cryomodule.

Several options for MEBTs have been studied to satisfy these requirements. Matching of the RFQ beam to the SC linac acceptance is not a trivial task for the following reasons:

- The available accelerating gradient of the SC structures is appreciably higher than that of the RFQs;
- The MEBT must form an axially symmetric beam for injection into the SC linac;
- Emittance growth in the transverse and longitudinal phase space planes must be avoided.

Focusing in the SC section is provided by SC solenoids. We have explored several options of MEBTs differentiated by the number of focusing quadrupoles and re-bunchers. The best option for the MEBT that satisfies all mentioned requirements is the MEBT shown in Fig. 4. Extensive studies of beam dynamics for both frequency options and for both proton and deuteron beams showed that the proposed version of the MEBT is capable of matching proton and deuteron beams into the SC linac for a wide range of beam currents from 0 to 5 mA without any emittance growth.

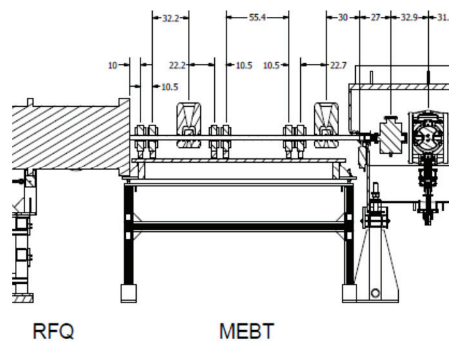

Figure 4: Medium energy beam transport (MEBT).

SC LINAC LAYOUT

A linac lattice design has been iterated between the beam dynamics and engineering designs [10,11]. The main goal of the beam dynamics design is to minimize emittance growth and halo formation within the constraints defined by the mechanical arrangement of cavities, SC solenoids, beam diagnostics and cryomodules. The concept of the physics design of high-intensity linacs based on RFQ and SC cavities is well established (see, for example, ref. [12]). One of the most important general concepts for high-intensity linac design is that the transverse and longitudinal wave numbers, κ_{T0} and κ_{L0}, for zero beam current must change adiabatically along the linac. This feature minimizes potential mismatches and helps 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 σ_{T0} and σ_{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 fulfil these conditions which 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 effectiveness.

The beam dynamics design and optimization starts with the proton beam for which the beam dynamics is more sensitive to high accelerating gradients than the deuteron beam dynamics due to the higher accelerating voltage per nucleon. In addition, space charge effects for the proton beam are stronger than for deuterons. The most critical part of the linac is the initial section downstream of the RFQ, which provides acceleration to 5–8 MeV. In the SARAF linac, this section consists of low-β SC cavities and solenoids in both frequency options. As it follows from the detailed proton beam dynamics simulations, the highest available voltages of low-β SC cavities cannot be applied for acceleration in the first several periods of the accelerating and focusing structure. High accelerating gradients in the low-velocity range produce strong nonlinear motion in the longitudinal phase space along with notable emittance growth and halo formation. These studies resulted in a better beam quality in a focusing period composed of a cavity and a solenoid in contrast to the current SARAF Prototype Superconducting Module (PSM), which has two cavities per focusing period.

176-MHz OPTION LAYOUT AND BEAM DYNAMICS

The 176-MHz SC linac is composed of four cryomodules: one low-β and three high-β cryomodules. The low-β cryomodule contains seven SC cavities and seven solenoid-steering magnet packages. The high-β cryomodules each contain seven SC cavities and four SC solenoid-steering magnet packages. Fig. 5 shows the low-β cryomodule layout.

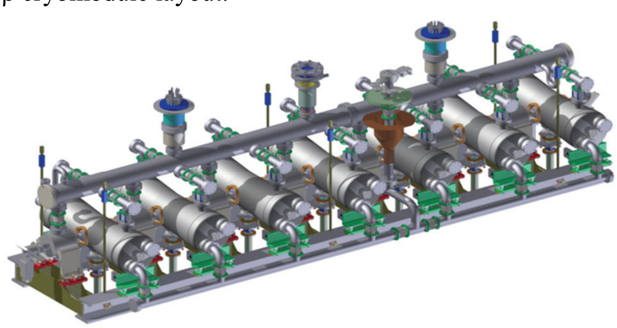

Figure 5: 3D engineering model of the cavity-solenoid string attached to the cryostat lid. 176 HWR option.

The HWR lattice beam dynamics study shows that a 5 mA proton/deuteron beam reaches 40 MeV with 28 HWRs. The rms emittance growth along the linac for a nominal run is a few percent. In the simulations with the TRACK code [13], no losses were found for 100 runs including errors based on realistic dynamic and static error ranges, and using 100k macro particles each (Fig. 6).

A COMPACT HWR LATTICE

The real-estate gradient of the 176-MHz baseline lattice [3] may be increased further by reducing the solenoid magnet length used therein. In the pre conceptual design study we used, for simplicity, the same solenoids for both the low-β and the high-β cryomodules for both accelerator options: the 176-MHz HWRs and the 109-MHz QWRs. In both options the low-β cryomodule solenoid length may be reduced which will result in shorter focusing periods in the low-β cryomodules thus allowing higher real-estate accelerating gradients. Table 2 compares the compact solenoid option for the entire SC section to the baseline option. These results demonstrate that the shorter solenoids improve the beam dynamics relative to the original lattice design. Notice that the shorter solenoids reduce the emittance growth and enable an energy gain that is slightly larger than the energy gain in the baseline lattice.

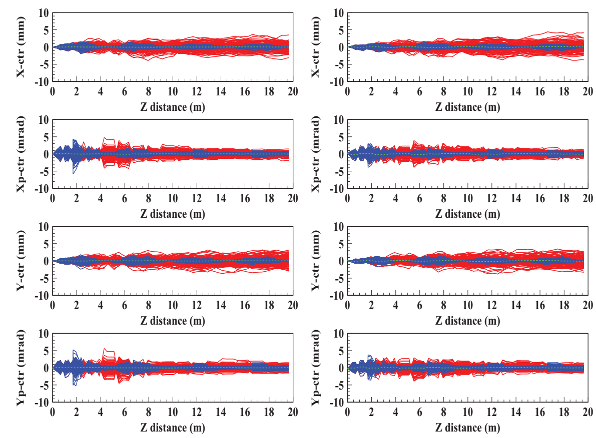

Figure 6: 176-MHz linac beam centroid motion- x,x',y,y' along the linac for 100 error simulations of 5-mA proton (left) and deuteron (right) beams simulated with 10^5 particles each, blue curves- with monitors and corrections scheme.

Table 2: 176 MHz Linac Parameters for the Compact Solenoid Compared to the Long Solenoid Lattices

Emittance growth	Protons		Deuterons	
Lattice	Compact	Baseline	Compact	Baseline
Energy, MeV	37.9	37.7	40.5	40.1
x_rms, %	4	7	1	3
x_0.99, %	30	40	12	22
y_rms, %	5	7	2	3
y_0.99, %	27	30	9	12
z_rms, %	8	12	3	3
z_0.99, %	2	23	10	14

109-MHz OPTION LAYOUT AND BEAM DYNAMICS

The 109-MHz SC linac consists of three cryomodules: one low-β cryomodule and two high-β cryomodules. The low-β cryomodule contains six SC cavities and solenoid-steering magnet packages. The high-β cryomodules each contain seven SC cavities and four SC solenoid-steering magnet packages. Fig. 7 shows the low-β cryomodule and the high-β cryomodules layout. The effect of QWR non-symmetric magnetic field component on beam center

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steering is compensated to the order of 0.1 mrad by a drift tube face tilt angle [14].

Beam dynamics studies for 5 mA proton and deuteron beams were carried out in the QWR's lattice. The rms emittance growth along the linac for a nominal run is a few percent. Beam dynamics simulations of 100k macro particles each in 100 runs with errors showed no losses. In general, beam parameters in the 109 MHz option are less sensitive to the errors than in the 176 MHz option.

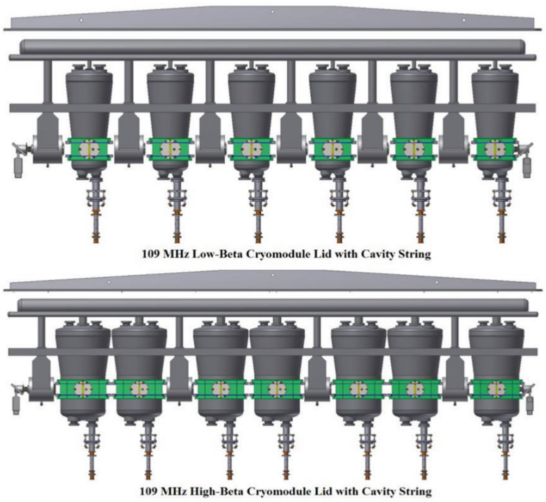

Figure 7: The 109 MHz superconducting modules, low-β (top) and high β (bottom) lattice design.

INTEGRATING SARAF PSM INTO SARAF PHASE II LATTICE

The existing SARAF Phase-I prototype SC module (PSM) can be used as a second cryostat in Phase II. To verify the beam dynamics of the Phase II with the PSM, we have performed simulations for a 5 mA deuteron beam. The integrated beam dynamics lattice includes the required space around the PSM for beam diagnostics boxes. The PSM cavities were set at 600 kV, 70% of its nominal original design voltage. The result is an additional 5 MeV deuteron energy gain (3 MeV are gained at the PSM and 2 additional MeV are a result of a better velocity matching downstream of the PSM, table 3). Modifications of the PSM cavity stiffness to reduce df/dP (now it is 50 Hz/mBar) and the RF input couplers to transmit 4kW are desirable for integration into Phase II.

Table 3: Phase II Beam Energies Before and After Including the PSM.

	Phase II [MeV/u]	Phase II with the PSM [MeV/u]
RFQ	1.32	1.32
Module 1	3.92	3.92
PSM		5.59
Module 2	8.51	11.10
Module 3	14.70	17.31
Module 4	20.65	23.09

SUMMARY

Two linac options based on 109 MHz QWRs and 176 HWRs capable of delivering 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. With some modifications, the current SARAF PSM can be included in the Phase II lattice.

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