

## OPERATIONAL EXPERIENCE AND FUTURE GOALS OF THE SARAF PROTON / DEUTERON LINAC

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### Abstract

The Soreq Applied Research Accelerator Facility (SARAF) is built as a user facility. An intense fast neutrons source, a thermal neutrons source and apparatuses for production of isotopes for basic and applied research will be available at the end of construction, foreseen in several years. SARAF is based on a high intensity CW proton / deuteron RF superconducting linear accelerator. Several novel technologies are used in order to build this demanding linac. To reduce technological risks, the construction was divided in two Phases. Phase-I was constructed in order to test and characterize the novel technologies and is in routine operation since 2010. SARAF phase-I, with its single 6 half-wave resonators separated vacuum cryomodule, is the first high current, superconducting low-beta linac in operation and it is presently delivering CW mA proton beams for target developments. Phase-II of this linac will allow acceleration up to 40 MeV and 5 mA CW proton and deuteron beams. Phase-II is now under conceptual redesign. The project status, the operational experience and the future goals of SARAF are described and discussed in this paper.

### INTRUDUCTION

#### System Requirements

The goals of the Soreq Applied Research Accelerator Facility (SARAF) are: 1) to enlarge the experimental nuclear science infrastructure and promote research in Israel, 2) to develop and produce radioisotopes for biomedical applications and 3) to modernize the source of neutrons at Soreq and extend neutron based research and applications [1,2]. SARAF, when it fulfils its goals, is intended to replace the aging research reactor in Soreq. These goals define the requirements from the accelerator. The requirements were optimized to fulfil all of the above goals, within domestic cost constraints. Production of isotopes for radiopharmaceuticals is mainly done by tens of MeV protons, so this is a basic requirement. Variable energy protons allow optimizing the production yield, while minimizing parasitic isotopes production. Deuterons have two main advantages in isotopes production; the production yield in the (d,2n) reaction is significantly higher than the (p,n) reaction for several targets with mass higher than 100 a.m.u [3]. In addition, at tens of MeV, the neutron yield of deuterons is

significantly higher than of protons bombarding the same target [4].

Although linac based neutrons sources are usually based on high energy proton based spallation reactions [5], for tens of MeVs projectiles the neutron yield of deuterons on light element targets is higher by more than a factor of 3 with respect to spallation.

For example, while using a beryllium target, deuterons of 2 mA at 40 MeV, or 5 mA at 25 MeV, are enough to generate a thermal neutron flux that is equivalent to the flux available at the image plane of the neutron radiography apparatus at the Soreq IRR1 5 MW reactor [6].

Tens of MeV deuterons on light element targets generate fast neutrons with a forward flux and neutron energy peaked around the beam energy divided by 2.5 [4]. Such a spectrum is ideal to produce isotopes using (n,2n), (n,p), (n, $\alpha$ ) and (n,f) reactions and therefore open new and interesting opportunities for basic and applied research. These reactions are the basis for niche intense radioactive beams at SARAF Phase-II [7,8]. For these reactions, the total amount of fast neutrons is two orders of magnitudes lower than in the spallation reaction. However, the neutron flux in the relevant range for these reactions (5-25 MeV) is higher by an order of magnitude (Fig. 1). The sources of this advantage are the low energy deuteron range in the target, which is shorter than spallation protons by an order of magnitude and the forward peaked structure of the stripping reaction.

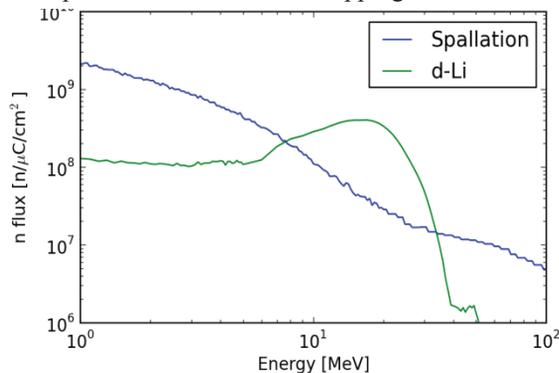


Figure 1: Forward neutron spectra comparison between 40 MeV deuterons on lithium (SARAF/IFMIF [9] like) and spallation 1400 MeV protons on tungsten (ISOLDE [10]). The spectra were measured and simulated 8 cm downstream the targets at zero degrees.

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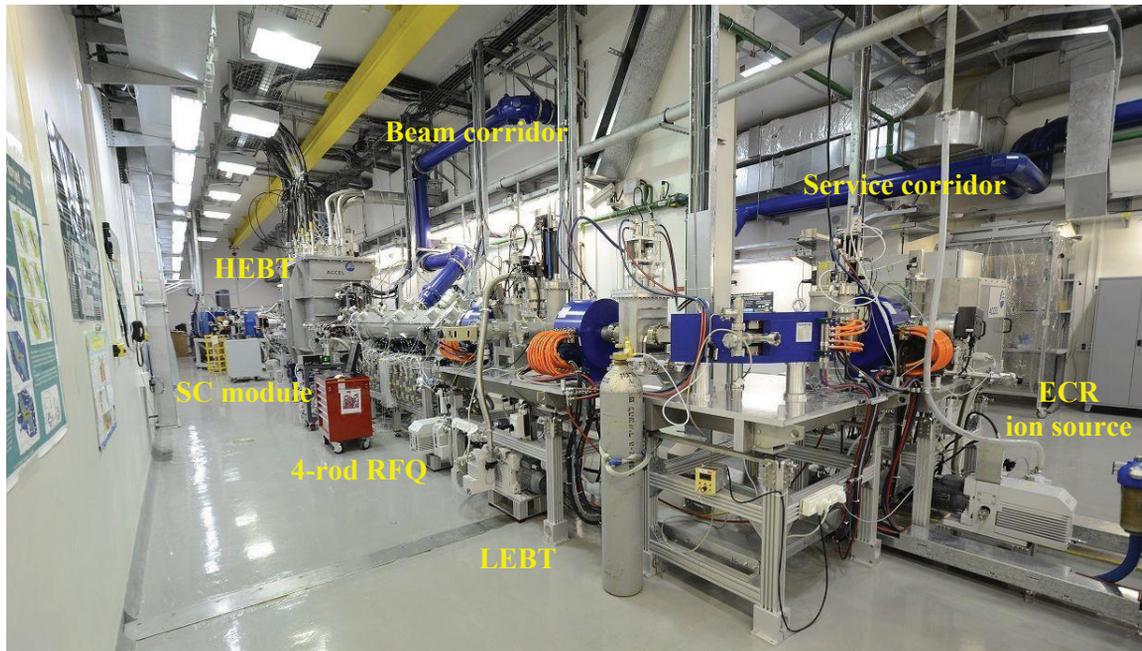


Figure 2: Phase-I 4 MeV protons and 5 MeV deuterons linac in the 4.5 m W, 5 m H and 25 m long beam corridor.

The range of tens of MeVs protons or deuterons in matter is several millimetres, so the power density developed in a tens-of-kW irradiation target is significantly higher than in a MW spallation target. This requires development of new types of targets, based on both solid [11, 12] and liquid metal [13, 14], and force the linac to deliver CW beams in order to avoid a high thermal load in the targets. It also requires developing special beam and target diagnostics and a procedure to slowly ramp the beam intensity on the targets.

### System Specifications

The beam specifications that cover all the above requirements are summarized in Table 1.

Table 1: SARAF Linac Top-level-requirements

Parameter	Value	Comment
Ion Species	Protons/Deuterons	$M/q \leq 2$
Energy Range	5 – 40 MeV	Variable energy
Current Range	0.04 – 5 mA	CW (and pulsed)
Operation	6000 hours/year	
Maintenance	Hands-On	Low beam loss

The demands for variable energy, proton and deuteron currents in the mA range and low beam loss that meets the definition of a hands-on maintenance are met only by a superconducting RF linear accelerator. Independently phased cavities are needed in order to allow variable energy at the exit of the linac and efficient acceleration of more than one ion species. Superconducting cavities are needed for large beam apertures that moderate beam loss.

Phase-I of the SARAF linac (Fig. 2) is composed of a 20 keV/u, 7 mA,  $0.2 \pi$  mm mrad norm. rms emittance ECR ion source + LEBT [15], a 176 MHz, 4 m long, 250 kW, 4-rod RFQ [16,17,18], a 65 cm long MEBT and a 4.5 K 2.5 m long superconducting module housing 6  $\beta_0=0.09$

bulk Nb HWRs, 0.85 MV each and 3 6T solenoids in separated vacuum [19, 20, 21, 22]. The Phase-I linac routinely accelerates 1 mA CW protons up to 4 MeV and 10% duty factor deuterons up to 5 MeV. The design and commissioning of the acceleration components and the operation of the entire machine [23, 24] and the 13 m long HEBT line [25] were published in recent years. The next section describes in detail additional beam tuning issues and technical challenges.

### BEAM OPERATION

Several beam-on-target experiments were performed last year with proton and deuteron beams of various energies and intensities. Proton beams at the highest available energy of  $\sim 3.9$  MeV were mainly used for the tests of thin ( $\sim 25\mu\text{m}$ ) foil targets cooled by liquid metal [11, 12]. The thin foil targets are delicate and there were several incidents of targets being damaged. Following the insight gained from the first experiments, numerous improvements of the target arrangement and beam diagnostics quality were implemented. Initial tuning is performed a  $10^{-4}$  duty cycle pulsed beam on a quartz viewer. Next, the duty cycle is increased to  $10^{-2}$  and the beam position is verified on a thin Tantalum foil. Then, the first solenoid at the LEBT is defocused and the LEBT aperture is closed in order to moderate the CW beam current. The CW beam intensity is ramped up by two orders of magnitude by refocusing this solenoid and reopening the aperture. We found that it is important to ramp the beam intensity without moving its centre on target and without changing the beam distribution shape. To first order, such a ramping procedure does not change the beam distribution on the target. The target surface temperature is tracked using a pyrometer and an infrared (IR) camera. It was found that, in these targets, the

transverse spatial variation of the temperature is in the order of a square mm, so the beam tune and temperature measurements are performed with mm resolutions.

For 1 mA beam tests, we use beam dump that consists of a 250 micron tungsten sheet fused to a water cooled cooper plate. A tungsten beam dump is chosen for Phase-I since up to 10 MeV, no activation is induced and moderated neutron radiation is expected. After a few irradiation hours of a 3 MeV 1 mA proton beam, the tungsten surface blisters (Fig. 3). The protons beam (hydrogen) implementation depth is  $\sim 30 \mu\text{m}$  inside the tungsten. The hydrogen pressure blows up the tungsten surface and a hydrogen pressure peak is measured in a nearby residual gas analyser (RGA).

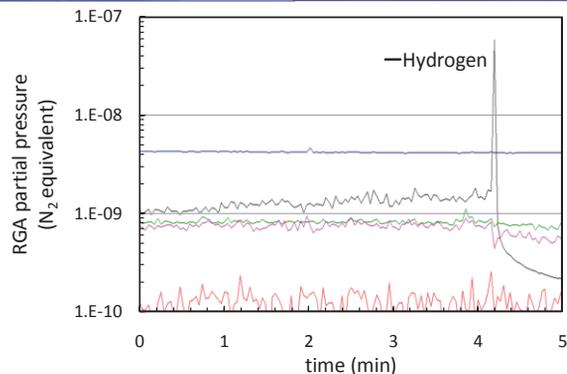


Figure 3: Top - Two 150 mm diameter Tungsten beam dumps after 8 hours of irradiation by 1 mA CW protons at 3 MeV. Bottom - Hydrogen blistering is well presented and detected using a residual gas analyser.

## BEAM CURRENT TECHNICAL LIMITATIONS

There were, and still are, a few technical issues that limit the beam current below the design value of 2 mA. The cavity sensitivity to helium pressure, calculated to be 16 Hz/mbar, was measured to be 56 Hz/mbar [20]. Three sub-components; the RF coupler, the RF amplifier and the tuner are affected.

### Piezo Tuners Upgrade

The cryogenic system  $\pm 1.5$  mbar pressure variation is manifested by frequency detuning that easily exceeds the cavities loaded bandwidth of 130 Hz. This detuning brings forth challenging demands on the cavities' tuners.

The tuners include a coarse tuning stepper motor and a fine tuning piezo electric actuator (Pst150 [26]). In 2009, a dramatic reduction of the actuators range was observed, leading to the replacement of the actuators by modified ones [22]. In 2011 the piezo actuators suffered again from significant reduction of the tuning ranges (Fig. 4). During the winter maintenance period, the tuners were replaced by high voltage piezo actuators (Pst1000 [26]), which operate at 800 V and have superior mechanical strength. A smaller deterioration slope of the tuning range has been observed (Fig. 4) after this modification.

### RF High Power Amplifiers (HPA) Upgrade

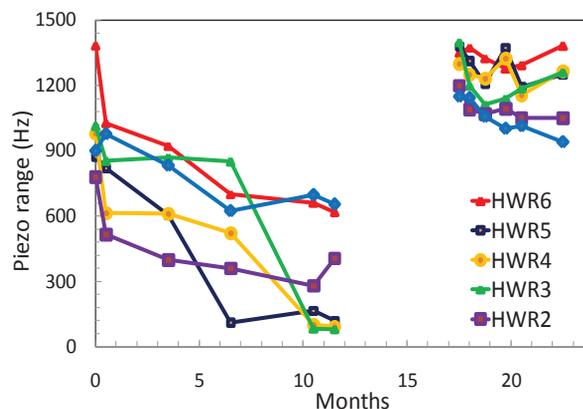


Figure 4: Piezo fast tuners dynamic range since January 2011. At the end of 2011 the piezo actuators were upgraded from low voltage to high voltage.

When the cavity is detuned, the LLRF control system [27] draws extra power from the HPA, in order to keep the cavity at its nominal accelerating voltage. Most of this power is reflected. In order to accelerate a 2 mA beam with maximal energy gain of 0.845 MV, we need 4 kW HPAs. In 2011, the original 2 kW solid state HPAs [28] were replaced by 4 kW HPAs designed and manufactured at SoreqNRC [29]. The operation of the cavities with the new power amplifiers has proven to be more stable.

### RF Coupler Warming

After improving the tuners and RF amplifiers, warming of the RF couplers (Fig. 5) has become the main limiting factor in operating the linac at high fields. The capacitive coupler was designed for 4 kW [19]. The coupler enters the cryomodule from the top flange and turns to a middle plane HWR port (Figs. 6-7). The couplers warming phenomena has been recognized already at the commissioning stage [18]. A cooling copper strip line was added between the cold window and the 70 K thermal shield. This helped but not solved the problem. Thus, we are compelled to reduce the field in the 2<sup>nd</sup>, 3<sup>rd</sup> and 6<sup>th</sup> cavities in order to keep the external coupler's temperature below 120 K during long operation (Fig. 5). It is noteworthy that no significant warming is observed at the 5<sup>th</sup> cavity coupler. This cavity could be operated at a nominal voltage value, just before onset of X-ray emission. In the near future we plan to improve the

couplers cooling, by replacing the copper strip with a more massive one.

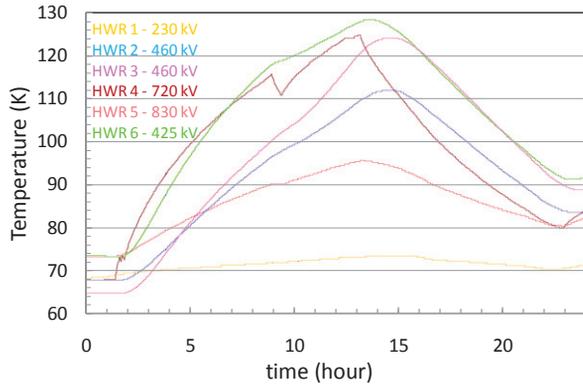


Figure 5: Couplers temperature, measured in the vicinity of the cold window, during beam operation. The RF voltage was turned on at 1h, closed at 9h for 20 min and turned off again at 13h. Beam intensity was ramped between 1h and 13h to 0.2 mA.

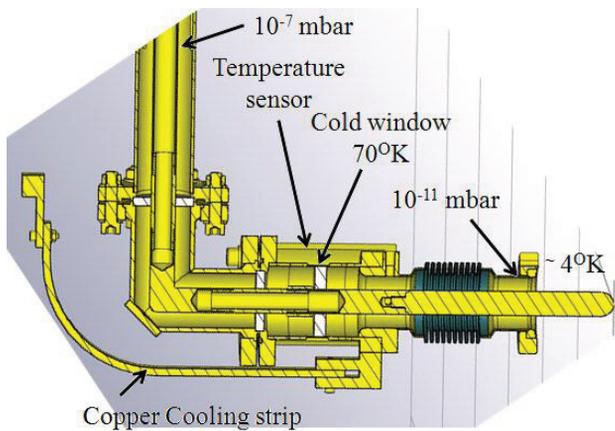


Figure 6: Drawing of the 4 kW RF coupler elbow section around the 70 K window.

At a later stage we will try adding He gas cooling around the window [30]. The cavity sensitivity to vibrations and pressure causes extra reflected power that can heat the coupler. Multipacting can also heat the



Figure 7: Coupler elbow section (Fig. 6) photo with the cooling strip connected to the 70 K thermal shield.

coupler. A common method of suppressing multipacting is to apply a DC voltage to the coupler inner conductor. Solving the couplers warming problem will allow comfortable operation of the PSM at beam energies of 4.5 and 5.5 MeV for protons and deuterons, respectively, and an increase of the CW beam current to 2 mA.

### PHASE-II RE-DESIGN

The goal of Phase-II is to complete the existing linac to 40 MeV and 5 mA. Novel technologies were explored for the completion of the linac. The main question was whether QWR dipole steering compensation methods are robust enough and can safely lead to a hands-on maintenance QWR proton linac. It was shown, by the Argonne National Laboratory (ANL) Linac Development department, that by using the drift tube face tilting correction method, cold BPM diagnostics and steerer correction after each QWR, the dipole steering is reduced to a negligible value [31]. The comparison between the 176 MHz HWR option and a 109 MHz QWR option showed only slight differences between the options, so for SARAF we opted for a 176 MHz HWR linac, since it enables a smoother transition from Phase-I.

A new conceptual design of a 176 MHz HWR linac was performed by the ANL group for SARAF. All Phase-I limits were addressed and solutions were found.

A MEBT that includes 2 re-bunchers was designed. Extensive simulations proved that it is possible to match proton and deuteron beams into the SC linac at beam currents from 0 to 5 mA, with no need to modify the linac tune design [31].

Varying the depth of the flat dish located in the opposite side to the RF coupler port found to be a good way for minimizing the cavity frequency sensitivity to fluctuations of the helium pressure in the novel design for Phase-II: . The results of sensitivity analyses showed that the flat dish reduces the sensitivity to 2 Hz/mbar in the low beta cavities [32] and 3.5 Hz/mbar for the high beta cavities. This is an improvement of an order of magnitude with respect to the existing Phase-I HWRs.

The HWR internal conductor was designed in a donut shape, in order to reduce the quadrupole effect and to minimize emittance growth [33].

A short 15 kW coupler was designed [34]. It enters the cryomodule from the bottom in order to keep the coupler environment clean throughout the operation life cycle. This forces the orientation of the cavities to be horizontal. A DC bias to the inner conductor is planned, to minimize multipacting, if needed. The simulated total heat load of this coupler at 4.2 K is 1.6 W.

For such a heavy loaded cavity, a dedicated fast tuner is not needed. A pneumatically actuated mechanical tuner, which compresses the cavity along the beam axis, is attached to the SS flanges outside of the helium vessel. The design of the pneumatic tuner is based upon the tuner design used since 2009 in the ANL ATLAS energy upgrade cryomodule. This tuner dynamic range at 2000 lb is 90 kHz, enough to replace both the slow step motor mechanical tuner and the dynamic piezo tuner [32].

The cryomodules that were designed for SARAF by ANL are based on the ANL experience gained in ANL in recent ATLAS upgrade projects. Special care is taken to simplify assembly, maintenance, alignment, resonator cleanliness, operating and auxiliaries system interfacing, without interfering with beam dynamics optimization [35]. The low (high)  $\beta$  module is 4.8 m (4.6 m) long and hosts 7 HWRs and 7 (4) solenoids. Each SC solenoid unit includes X-Y steerers and a cold BPM. The modules design fits into the existing SARAF beam corridor and leaves enough space to insert and extract modules alongside the linac.

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