THE SARAF CW 40 MEV PROTON/DEUTERON ACCELERATOR

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Abstract

The Soreq Applied Research Accelerator Facility, (SARAF) is currently under construction at Soreq NRC. SARAF will be a multi-user facility for basic research, medical and biological research, neutron based non-destructive testing and radio-pharmaceuticals research, development and production. SARAF is based on a continuous wave (CW), proton/deuteron RF superconducting linear accelerator with variable energy (5–40 MeV) and current (0.04-2 mA). The accelerator is designed to enable hands-on maintenance, which implies beam loss below 10^{-5} for the entire accelerator. Phase I of SARAF consists of a 20 keV/u ECR ion source, a low energy beam transport section, a 4-rod RFQ, a medium energy (1.5 MeV/u) beam transport section, a superconducting module housing 6 half-wave resonators and 3 superconducting solenoids, a diagnostic plate and a beam dump. Phase II will include 5 additional superconducting modules. The ECR source is in routine operation since 2006 and the RFQ has been operated with ions and is currently under characterization. The superconducting module is installed in the beam line and its RF performance is being characterized. Phase I commissioning results, their comparison to beam dynamics simulations and beam dynamics simulations of Phase II are presented.

SARAF OVERVIEW

SARAF is currently under construction at Soreq NRC [1]. It will consist of a medium energy (up to 40 MeV) high current (up to 2 mA) RF superconducting linac of protons and deuterons, beam lines and a target hall with several irradiation stations for the abovementioned applications.

The facility schematic layout, its required parameters and a technical description of its components are given in Ref. 2. For a review of its operation concept and control system see Ref. 3.

Due to the technical novelty in the accelerator, the project has been divided to two phases. Phase I includes the ECR ion source, the RFQ, a prototype superconducting module (PSM), the design of the full accelerator (based on beam dynamics simulations [4]) and the design and risk reduction of the foreseen applications. Phase II includes construction of rest of the accelerator and its applications.

This paper presents recent commissioning results of phase I, including comparison to beam dynamics simulations [5], selected results of simulations for Phase II and a calculation of the expected residual activation due to beam loss in Phase II.

PHASE I COMMISSIONING

The SARAF accelerator is designed, manufactured, installed and commissioned by Accel Instruments GmbH [6], in close collaboration with Soreq NRC personnel.

Phase I is fully installed on site, as is shown from 2 views in Figs. 1 and 2.

Figure 1: Upstream view of Phase I as installed on site at Soreq NRC. From right to left: ECR ion source (EIS), Low energy beam transport (LEBT), RFQ and Prototype Superconducting Module (PSM).

Figure 2: Downstream view of Phase I of SARAF. From right to left: PSM, Diagnostic plate (D-Plate), low power (Beam dump 1, copper, 6 kW) and high power (Beam dump 2, tungsten, 20 kW) beam dumps.

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In the following sub-sections we describe the commissioning status of each main component.

Ion Source and LEBT

The SARAF ion source is of type ECR, to ensure stable high quality performance and minimal maintenance. The ECR frequency is 2.45 GHz and the plasma is confined via two electromagnetic solenoids.

The ion source is followed by a low energy beam transport line (LEBT) which consists of three focusing solenoids, steerers, a bending magnet, which acts as an ion filter and beam diagnostics, which include two Faraday cups and a slit-wire system for emittance measurement

In Table 1 we show the commissioning results for the ion source. Proton, deuteron and H_2^+ beams in the specified range of 0.04 – 5.0 mA have been successfully generated. The emittance of all ion beams in both the X and Y planes was measured by a slit and wire system in the LEBT. Results for protons and deuterons are within the specified value, $\varepsilon_{rms_norm_100\%} = 0.2\ \pi\cdot$mm·mrad. For the H_2^+ beam, the emittance is higher.

Table 1: Ion source measured rms, normalized, 100% emittance at both planes for all ions. Emittance for H_2^+ at 0.04 mA was not measured.

Beam current	ε Protons (X/Y)	ε H_2^+ (X/Y)	ε Deuterons (X/Y)
[mA]	r.m.s, normalized, 100% [π·mm·mrad]		
5.0	0.20 / 0.17	0.34 / 0.36	0.13 / 0.12
2.0	0.13 / 0.13	0.30 / 0.34	0.14 / 0.13
0.04	0.18 / 0.19	NA	0.05 / 0.05

Possible reasons for the reduced performance for H_2^+ are poor ionization efficiency for molecular hydrogen, due to optimization for protons and deuterons, and molecular breakup and ion neutralization of the hydrogen molecules in the beam line's residual gas (5×10^{-6} mbar H in the LEBT in operation).

Further details on the construction and commissioning of the ion source and LEBT can be found in Ref. 7.

RFQ

The SARAF RFQ is a 176 MHz 4-rod CW RFQ [8]. The main challenge in this RFQ is removing 250 kW from its ~3.8 meter rods, an unprecedented heat density. A high flow water cooling system, including flow inside the rods, has been incorporated in the RFQ.

The RFQ commissioning is comprised of two processes which are being executed in parallel:

- RF conditioning up to 65 kV, the voltage that is required for acceleration of a CW 4 mA deuteron beam to 3.0 MeV.
- Beam commissioning, mainly with protons that require half of the deuteron field.

A few hundred hours of RF conditioning has been performed over the last 2 years in an effort to reach the specified field for CW deuterons. This field implies an input power of approximately 260 kW. Two conditioning schemes were used: setting the input power to a value of 280 kW at a duty cycle of approximately 1% and increasing the duty cycle and starting from a low value of CW power and gradually increasing the power.

So far we were able to reach a 15% duty cycle at 280 kW and CW operation at 195 kW. These values are not stable yet and the sources of these instabilities are currently being investigated. In an effort to improve the slow conditioning progress, several actions were taken at the beginning of 2008:

- The rods were dismantled and sharp edges at their bottom part were rounded off.
- While dismantled, the rods were cleaned with a special cleanser.
- A circuit for fast recovery after sparks was installed.

These measures improved performance for a while but still below the CW deuteron specification. To understand how the input power is converted to the electric field between the rods, the square of the voltage that was measured by one of the RFQ pickups was compared to the input power. The result is shown in Fig. 3.

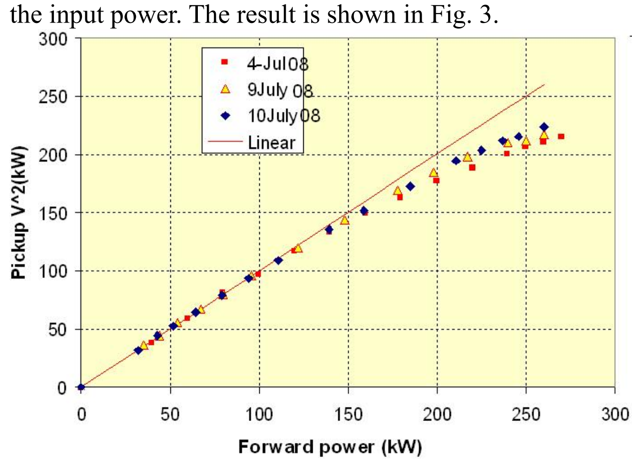

Figure 3: RFQ rod voltage squared versus the RFQ input power. Parting from the linear relation probably indicates onset of dark current due to poor conditioning.

It can be seen that the curve parts from the linear relation below 150 kW. This indicates that the input power generates current that flows between the rods instead of a sustained voltage between them.

The cause of this effect is not certain yet. Following action taken in other installations to circumvent excessive sparking and limited performance (e.g., [9]), an in-situ bake was recently performed by applying ~900 W of CW RF power with the cooling water switched off. The electrode temperature was monitored with PT100 probes that were inserted through the dried water cooling pipes into the rods and rose to 70 – 80 °C, accompanied by a vacuum pressure rise from 5×10^{-7} to 4×10^{-6} mbar. No significant vacuum pressure reduction (such as reported in Ref. 9) was observed after 3 days of baking. The vacuum returned to its base value after turning off the power. The effect of this process on the maximal attainable field in the RFQ will be investigated in the near future.

A description of RFQ beam commissioning, including preliminary results, is given in [10, 11]. Table 2 provides an updated summary of the proton beam performance of the RFQ. Emittance measurements were performed with a low duty cycle beam carrying total power of less than 200W, which is the maximum that the beam intercepting diagnostics can withhold [10]. Energy was measured by the Time-of-Flight (TOF) method using the summed output of beam position monitors in the MEBT and phase probes in the D-Plate. Current was measured by a MPCT and by a FC, both located at the D-Plate.

Table 2: RFQ measured performance. Values in parentheses are the specifications.

Parameter	Protons
Output energy [MeV/u]	1.5 (1.5)
Maximal CW current [mA]	4.0 (4.0)
Transverse emittance r.m.s., normalized, 100% [π·mm·mrad]	
(at 0.5 mA, closed LEBT aperture)	0.17 (0.30)
(at 4.0 mA, open LEBT aperture)	0.25 /0.29 (0.30)
Longitudinal emittance, r.m.s [π·keV·deg/u] (at 3.0 mA)	30 (120)
Transmission [%] (at 0.5 mA)	80 (90)
(at 2.0 mA)	70 (90)
(at 4.0 mA)	65 (90)
Required RF power (protons) [kW]	62 (55)
(deuterons) [kW]	248 (220)

The transverse and longitudinal bunch profile measurements were closely followed by beam dynamics simulations [5] using the code TRACK [12]. In Fig. 4 we show the comparison of the measured results with the simulations, which demonstrates good agreement.

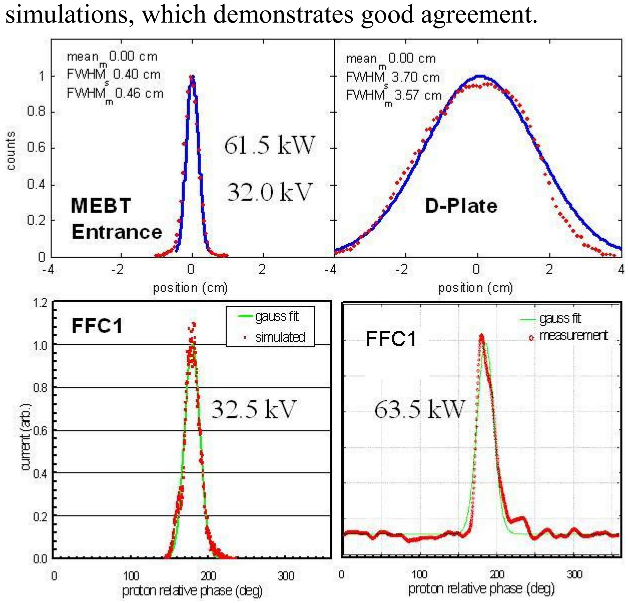

Figure 4: Comparison of post-RFQ measured results and beam dynamics simulations. Top left – Transverse profile at the MEBT entrance. Top right – Transverse profile at the D-Plate. Bottom left – simulated longitudinal profile at the upstream Fast Faraday Cup (FFC) at the D-Plate. Bottom right – measured longitudinal profile.

Short runs of very low duty cycle (10^{-4}) deuteron and H_2^+ beams were performed. The energy of a H_2^+ beam was established to be 3.0 MeV via TOF. The first RFQ transmission measurement for deuterons yielded 70%, without any optimization of LEBT parameters. Further deuteron and H_2^+ runs are foreseen following additional conditioning of the RFQ.

Prototype Superconducting Module

The prototype superconducting module (PSM) includes six 176 MHz, β=0.09 half wave resonators (HWR) made of bulk Nb and three 6 T superconducting solenoids inserted amongst them. Further details, along with single cavity vertical cold tests results are described in [13]. RF commissioning results for single cavities inside the PSM, using a voltage controlled oscillator operated at closed loop, are given in [11].

The most recent PSM RF measurements were performed by using the full LLRF system [14], which drives the cavities tuners in a generator driven resonator (GDR [15]) type closed loop. Cavity tuning is based on the forward and transmitted phase signals. An additional coupler was added before the drive amplifier in order to reduce the influence of the reflected signal on forward phase measurements. A further improvement was modification of the tuning loop software in order to include compensation of the piezo tuner hysteresis.

Due to the combination of microphonics, Lorentz force detuning and a possible effect by LHe-pressure variations, which reached peaks of 10 mbar, the cavities frequency variation turned out to be too large for tuning solely by piezo tuners. Therefore, the stepper motor control loop was modified to engage when the voltage input to the piezo approaches 80% of its maximal value.

These modifications enabled PSM operation with the tuners in closed loop. Preliminary results are given in Table 3.

Table 3: PSM RF performance of single cavities. Cavities operated with tuners in closed loop.

Cavity	V_{peak} [MV]	E_{peak} [MV/m]	Phase stability [°]	Amplitude stability [%]
1	0.8	23.5	±0.3	0.5
2	0.7	20.6	±0.3	0.5
3	1.0	29.5	±0.3	0.5
4	0.9	26.5	±0.3	0.5
5	1.14	33.5	±0.3	0.5
6	1.03	30.3	±0.3	0.5

The specified E_{peak} for the PSM cavities is 25 MV/m. Cavities 1 and 2 could not be raised to higher fields due to loss of lock. The phase and amplitude stability values are peak-to-peak and are determined by the ADC's least significant bit. It is expected that the actual stability is even better. These values are within specifications.

Operation times in this commissioning run were limited to a few minutes for each cavity, since each cavity was driven separately due to missing couplers.

An additional commissioning run was completed very soon before submission of this paper, where all six cavities were operated simultaneously with the tuners in closed loop. The data is still under analysis, but preliminary qualitative results indicate that it was possible to run the PSM continuously for several hours at an average E_{peak} of slightly less than 20 MV/m .

Summary and Outlook

The commissioning of Phase I of SARAF is on-going. The current challenges include conditioning the RFQ to enable acceleration of CW deuteron and H_2^+ beams and optimizing the PSM to enable beam acceleration through it. Beam commissioning of protons and deuterons through the entire Phase I is foreseen for the winter of 2008.

PHASE II

Phase II of SARAF will include an additional SC accelerating module (SM) similar to the PSM (six β=0.09 HWR cavities and three solenoids) and four additional SMs, including eight β=0.15 HWR cavities and 4 solenoids each.

In this section we shortly describe the extensive beam dynamics simulation effort that is undertaken, in order to ensure that the SARAF design will enable reaching the specified energy, current and emittance, with beam loss that will enable hands on maintenance.

Beam Loss Criterion

The beam loss criterion for the SARAF linac is defined as the beam loss value that generates residual activation of 2 mRem/hr after one year of operation, 30 cm away from the beam line, four hours after accelerator shut down.

In order to generate a conservative criterion, several meticulous assumptions were made:

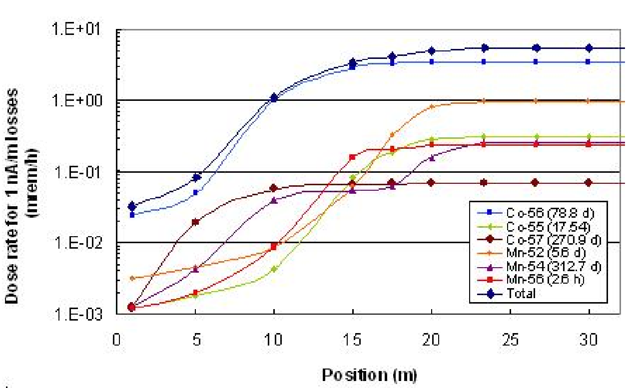

Figure 5: The dose rate along the 22 m long linac and an additional 10 m long beam line, after one year irradiation with beam loss of 1 nA/m, under the meticulous assumptions described in the text.

- The accelerator is operating 365 days per year.
- Only deuterons are accelerated all the time, and to the maximum energy of 40 MeV.
- The accelerator is made entirely of stainless steel.

These assumptions introduce a safety margin of a factor of 2-4. Based on these assumptions, the residual activation per lost deuteron was calculated [16] and this lead to the conclusion that the beam loss criterion is 0.4 nA/m at 40 MeV. As mentioned above, relaxation of the meticulous assumptions that we took may increase this limit by a factor of 2-4. Figure 5 shows the contribution of each isotope, all of which are produced by activation of ^{56}Fe, to the residual activity assuming beam loss of 1 nA/m. The residual activity is given along the 22 m long linac and an additional 10 m long beam line that leads the beam to the irradiation targets.

Beam Dynamics Simulations

We applied the tail emphasis method [17] in order to study particle losses along the linac. The method is based on the assumption that losses begin longitudinally, and problematic particles begin at the periphery of the longitudinal phase space at the RFQ exit (originate in the boundaries between the downstream bunches at the dc current entering the RFQ buncher section).

This method allows us to calculate losses along the SARAF accelerator at the 1 nA level with limited computational efforts: A Tail Emphasis deuteron beam with 2.1 million macro particles at the RFQ entrance is equivalent to the simulation of 3 bunches containing 42.6 million macro-particles (each 1:10, equivalent to 0.3 nA) for 4 mA CW at 176 MHz.

The reduced computation time allows us to run a large number of simulations in a relatively short span of time. This enables exploration of the effect of manufacturing and operational errors on the beam and estimate losses due to these factors. The values of the errors used on this study are given in [17] and [4].

Figure 6 shows an example of series of 200 simulation runs, each having slightly different manufacturing and operational parameters, which are generated from the distributions described in [17] and [4]. This result is from an application of the tail emphasis method using the simulation code GPT [18].

The result displayed in Fig. 6 is for a 32k/193k core/tail particle distribution of a deuteron beam, which exits the RFQ with a current of 3.4 mA and a normalized rms transverse emittance of 0.23 π·mm·mrad. The outer most macro particle is equivalent to a current of 1 nA. The bore radius is 19 mm within the solenoids and 15 mm everywhere else.

The conclusion from this simulation is that even when considering reasonable manufacturing and operational errors, no beam loss is expected within a simulation resolution of 1 nA. This is consistent with the beam loss criterion for hands on maintenance discussed above.

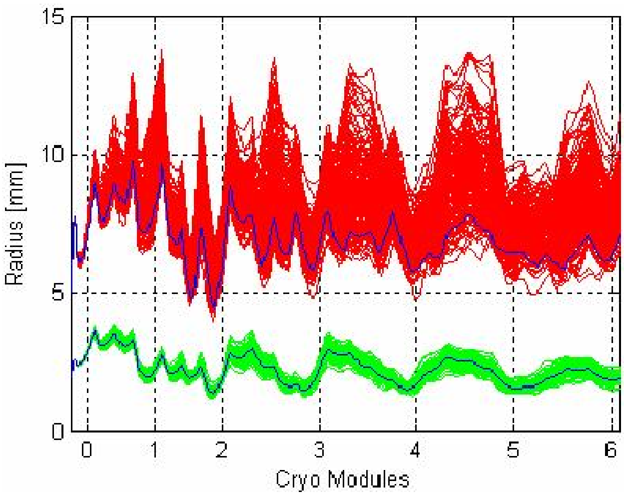

Figure 6: Deuterons transverse envelope (red) and rms radius (green) for a series of 200 error simulation runs through the six SC accelerating modules of the SARAF accelerator.

SUMMARY AND OUTLOOK

In this paper we presented the current status of the commissioning of Phase I of the SARAF accelerator, and briefly described selected results from the beam dynamics simulation effort which is a major part of the SARAF project.

The commissioning of Phase I is foreseen to be concluded towards the end of 2008 and it is expected that work on Phase II will commence at that time. Currently, Phase II is scheduled to be completed around the year 2013.

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