THE STATUS OF THE SARAF LINAC PROJECT

L. Weissman*, D. Berkovits, I. Eliyahu, I. Gertz, A. Grin, S. Halfon, G. Lempert, I. Mardor, A. Nagler, A. Perry, J. Rodnizki, Soreq NRC, Yavne 81800, Israel; K. Dunkel, M. Pekeler, C. Piel, P. vom Stein, RI Research Instruments GmbH, Bergisch Gladbach 51429, Germany; A. Bechtold, NTG, Gelnhausen 63571, Germany

Abstract

Phase I of the Soreq Applied Research Accelerator Facility, SARAF, has been installed and is currently being commissioned at Soreq NRC [1]. According to the Phase I design, SARAF should yield 2 mA proton and deuteron beams at energies up to 4 and 5 MeV, respectively. The status of the main Phase I components is reported. We further present beam commissioning results, which include acceleration of a 1 mA CW proton beam up to 3 MeV. Further improvements in the facility in order to achieve the desired performance are discussed.

INTRODUCTION

Phase I of SARAF [2] consists of a 20 keV/u ECR Ion Source (EIS), a Low Energy Beam Transport (LEBT) section, a 4-rod Radio Frequency Quadrupole (RFQ) injector, a Medium Energy (1.5 MeV/u) Beam Transport (MEBT) section, a Prototype Superconducting Module (PSM), a Diagnostic plate (D-plate) and beam dumps (BD). The main components of the Phase I are shown in Fig. 1. Previous installation and commissioning results have been reported in [2, 3].

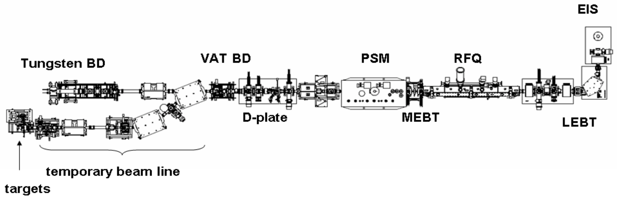

Figure 1: Layout of SARAF Phase I and the temporary beam line.

The results presented hereby include:

1. The demonstration of stable and robust acceleration of a 1 mA CW proton beam up to 3 MeV
2. Acceleration of a low duty cycle deuteron beam (0.4 mA) up to 4.3 MeV, in addition to the previously reported [3] acceleration of low duty cycle protons (2 mA) up to 3.7 MeV.
3. Further development work on the RFQ in order to achieve the required performance for CW deuteron operation. The emphasis was to study the stability and availability of the RFQ at high power.
4. Study of the PSM performance and planed improvements

STATUS OF MAIN COMPONENTS

EIS/LEBT

The SARAF ECR ion source has been in operation during the recent years effectively without any maintenance. The source provides up to 8 mA 20 keV/u proton or deuterons in a DC or pulsed mode. The LEBT optical elements consist of three solenoids, four steerers and a separating dipole magnet. The LEBT diagnostic devices include a beam blocker, an adjustable aperture, a Faraday cup and set of vertical and horizontal slits and wires for measurement of beam emittance and profiles. The performance of the EIS/LEBT system has been previously reported in detail, for example in Ref. [4].

Beam neutralization is widely used in LEBT sections to reduce the emittance and the space charge effects of intense slow beams. Tests performed to verify whether this technique could be exploited for 5 mA beams did not yield positive results. It is interesting to note, though, that neutral particles originating in the section after the dipole can be clearly differentiated in phase space from the charged particles even without adding argon. We used this effect for LEBT tuning and alignment [5].

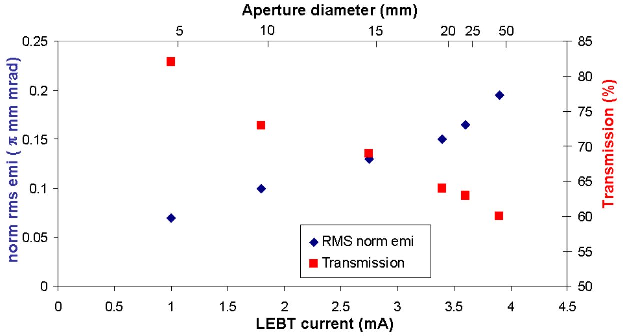

Figure 2: Dependence of LEBT emittance (blue diamonds) and overall RFQ transmission (red squires) on the LEBT current and aperture diameter.

Rather than using beam neutralisation technique we demonstrated that the beam transverse size and emittance can be modified by the LEBT aperture situated right after the dipole. Setting the aperture to its minimum opening (5 mm in diameter) enables transmission of a beam of the order of 1 mA and reduction of the beam emittance by a factor of 3. Correspondingly, the overall beam transmission through the RFQ improves significantly. A series of measurements of the LEBT emittance and overall transmission values as a function of the LEBT

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*Corresponding author: weissman@soreq.gov.il current, which is set by varying the aperture diameter, is shown in Fig. 2.

RFQ

The SARAF RFQ is a 176 MHz ~3.8 meter four-rod CW RFQ [6]. The rods are mounted on forty stems and the entire structure is secured to a base plate. Tuning block electrodes are mounted between some of the stems, and are used for adjusting the resonant frequency and achieving longitudinal field homogeneity. The small changes in the resonance frequency due to RF heating are compensated by two movable plunger electrodes. All the abovementioned elements as well as the RFQ chamber are cooled by de-ionized water.

The RFQ can be readily operated at the voltage and power required for a CW proton beams (~60 kW/32 kV). However, the main challenge in this RFQ is to condition it for the range 250-260 kW (65 kV voltage), which is required for CW deuteron operation. Several RF conditioning campaigns have been carried out during the last four years. The best results were achieved a year ago after two months of conditioning. It was then possible to reach 260 kW with a duty cycle of 80% for periods of up to 30 minutes [2].

During the conditioning campaigns several technical drawbacks hindering the high power operation were encountered. Some of these problems and the corresponding actions are listed in the Table 1.

Table 1: List of the Occurred Problems and the Corresponding Actions which were Performed

Problem/Failure	Actions
Field emission between the bottom part of the rods and the stems of the opposite voltage rods [2].	Rods were dismantled and re-machined to increase the gaps in the problematic region [2].
Melt of the tuning plates on two instances [2,3].	New tuning plates with improved electrical, thermal and mechanical contacts [2, 3] were installed.
Melt of the low-energy plunger electrode [3].	New plungers with smaller heat load and better cooling [7] were installed.
RF sliding contacts between the plunger shafts and the RFQ body were damaged or broken.	New, more robust, RF fingers; better centering of the plunger shaft; rhodium plating of the shaft surface.
Warming up of the RFQ end flanges [3,7].	New, water cooled, end flanges [3,7] were installed.
Warming up of the coupler region due to insufficient cooling [7].	A water cooled copper block was installed on the coupler port [7].

The failures describes above prompted an intensive, detailed, 3D simulation of RF fields, surface currents and the subsequent heat loads in the entire RFQ [7]. The above modifications were carried out in accordance with the simulation results of [7].

Several vacuum incidents took place during the RFQ conditioning campaigns. A few hundred Viton O-rings provide vacuum seals between the RFQ body and tubes delivering cooling water for the electrodes. Approximately ten of them were damaged or even destroyed during the conditioning campaigns. It, probably, occurred due to RF field penetration into these regions where one also expects poor vacuum. To verify this, we applied RF power in the range of several hundred Watts and measured the RF output directly on the cooling tubes. Anomalously high RF signals on some of the cooling tubes were found, mostly in correlation with the positions of the failed O-rings. At present, new type of flanges are being designed and produced. The new flanges will improve the RF connection between the tubes and RFQ in the vicinity of the Viton seals.

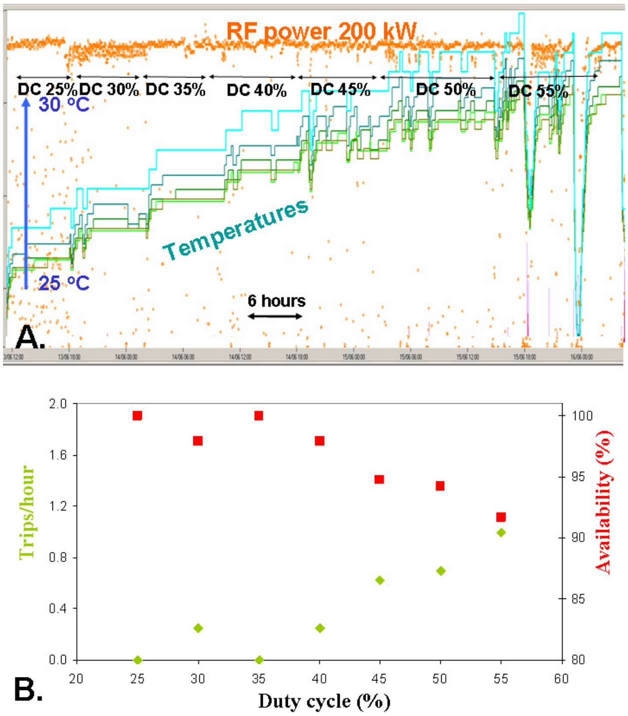

Figure 3: A) Log of the RFQ stability run. B) Trips per hour (green diamonds) and availability (red squares) of the RFQ at 200 kW, as a function of the RF duty cycle.

During the year 2010, significant efforts were delegated to study stability and availability of the RFQ at relatively high power, but not at the maximum in order to avoid further components failure. A long continuous run of more than three days was performed with the RFQ at 200 kW with gradual increase of its duty cycle from 25% to 55 %. The duty cycle was increased by 5% every 6-8 hours. The number of trips and the time to recover (usually a few minutes), were monitored. RFQ temperature mapping was also performed. Typically the temperatures stabilize within an hour after increase of the duty cycle. As shown in Fig. 3, the RFQ is stable up to

50% duty cycle. However, at higher duty cycles the availability deteriorates dramatically.

Prototype Superconductive Module

The Prototype Superconductive Module (PSM) includes six $\beta = 0.09$ Half Wave Resonators (HWR) made of bulk Nb, designed to provide acceleration of up to 4 mA protons and deuterons from 1.5 MeV/u to the maximum energy of 4 MeV and 5 MeV, respectively [8]. In addition, the PSM houses three superconducting solenoids for transversal focusing. The cavities are energized by 2 kW solid state amplifiers. The Low Level RF control of the cavities is composed of two sections: an analog Generator Driven Resonator algorithm for the control of the voltage and phase, and a digital control of the cavity tuner.

After installation on site the measurements of cryogenic losses indicated higher cryogenic losses and higher field emission than were measured during the single cavity testing [8]. Significant improvement was achieved after performing cavities' processing at pure helium pressure of a few 10^{-5} mbar [9]. Each of the cavities individually reached stable operation at its specified field (peak field of 25 MV/m, corresponding to a voltage of 840 kV), while operated using a Phase Locked Loop. At these fields, the total cryogenic loss of the PSM was 61.8 watts, within the specifications [2]. However, stable simultaneous operation of all cavities at nominal field gradient was not achieved for long periods due to instabilities.

The SARAF HWRs are fairly sensitive to fluctuations in the Liquid He (LiHe) pressure (60 Hz/mbar). The ±1.5 mbar pressure variation of the SARAF cryogenic system is reflected by frequency detuning easily exceeding the cavities loaded bandwidth of 130 Hz. This places challenging demands on the cavities tuners. The tuner includes a stepper motor and a piezo electric actuator. The former is used only for coarse tuning. Motor movement induces strong mechanical instabilities, so it is usually disabled when RF is applied. The piezo-electric tuners are used for fine adjustments. The required adjustment range is larger than several loaded band widths. In 2009 a dramatic reduction of the piezo range was observed, leading to the replacement of the piezo devices by modified ones [9].

In order to understand the source of the PSM instabilities, the PSM tuner was analyzed in detail. As part of this analysis, we operated one of the cavities using a self excited loop. The piezo tuner was driven by a sine input signal and cavity detuning was measured and recorded using a cavity resonance monitor. As can be seen in Fig. 4, there is a large dead band in the tuner response, which leads to hysteresis behavior. Such non-linear response characteristic of the tuner may reduce its effectiveness. The result is an increase in the RF power required to compensate for the detuning and maintaining field stability. Sometimes the maximal available power from the amplifiers (2 kW) is not sufficient.

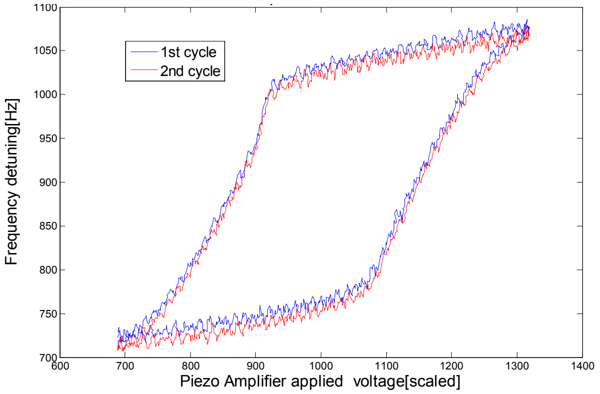

Figure 4: Response of one of the SARAF HWR tuners (cavity detuning shift) as a function of applied driving voltage.

In addition to the control problems, long term operation of some cavities at high voltages is limited by warming up in the regions of RF couplers. In particular, strong warming up of the coupler in cavity number four was observed at voltages higher than 600 kV. Therefore, this cavity is kept at voltage below 500 kV.

At present, robust simultaneous performance of all cavities can be achieved only at 70% of the nominal values, which allows for stable beam operation at modest energies. In the near future we plan to replace existing 2 kW by new 4 kW amplifiers in order to have additional power for microphonics compensation. In addition, we plan to implement a new digital control algorithm of the tuners on NI (National Instruments) Crio-FPGA. This should allow us to improve the response of the control system and account for the tuner non-linearity.

BEAM OPERATION

Pulsed Beam Operation

Since early 2009 we have performed a number of runs with pulsed proton and deuteron beams. The both the ECR ion source and the RFQ were pulsed. The timing overlap between these pulses defines the length of the ion pulse. Typically short pulses of 100 µsec duration at a frequency of a few Hz were used. Such a low duty cycle (10^{-4}) is necessary to enable the use of interceptive beam diagnostics. The RFQ duty cycle was close to 100 % in the case of protons and a few percent in the case of deuterons. Measuring the beam energy by monitoring particles undergoing Rutherford scattering on a thin gold foil was found to be the most convenient tool for cavities phasing [10]. As a result of the phasing procedure, the synchronous phase and voltage of the cavity can be calibrated [9, 10]. The Rutherford scattering method was cross-checked with the standard Time-of-Flight method and was found to be consistent [2]. The results are also consistent with beam dynamics simulations [2, 3].

Due to the distance of about 1 meter between the RFQ exit and the first PSM cavity, the latter must be used as a buncher. Bunching takes place as the beam drifts through the second cavity, so the beam is accelerated only by the four downstream cavities. The highest energy achieved for 2 mA proton low duty cycle beam was 3.7 MeV [3]. However, due to the cavities instabilities described above, most operations were performed at lower beam energies. The highest energy achieved for deuteron low DC beam was 4.3 MeV. This beam can be operated for many hours. Various measurements were performed with pulsed beams, including transversal emittance, beam transmission, dependence of deuteron beam profiles on RFQ duty cycle and more [2, 3]. Energy measurements using Rutherford scattering record also the beam energy spread. Thus, longitudinal emittance was obtained, as described in details in Ref. [11].

During operation with pulsed beam it became apparent that the beam is steered as a function of RFQ power. The effect was observed in the transmission curves and in the profile measurements as well (Fig. 5).

As mentioned in Table 1 of the previous section, the RFQ rods were modified in early 2009 [2]. This resulted in change of the capacitance, which, in turn, modified the resonance frequency. To cure the latter problem six of the nineteen tuning plate were removed from the RFQ high energy part. In the same time the distance between the rods in the high energy section was reduced by 0.4 mm in the horizontal plain in order to achieve somewhat better field flatness with the reduced number of the tuning plates. These actions allowed us to keep the resonance frequency in the working range; however, the field homogeneity has been compromised (Fig. 6). It is possible that the observed strong steering effects were associated with these modifications.

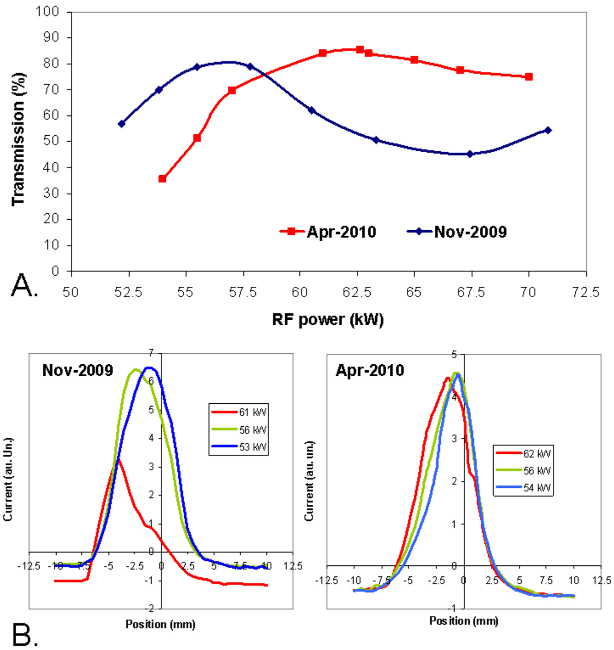

Figure 5: A) The dependence of the transmission on the RFQ power before and after shims replacement. B) Beam profile measurements after the RFQ before and after shims replacement.

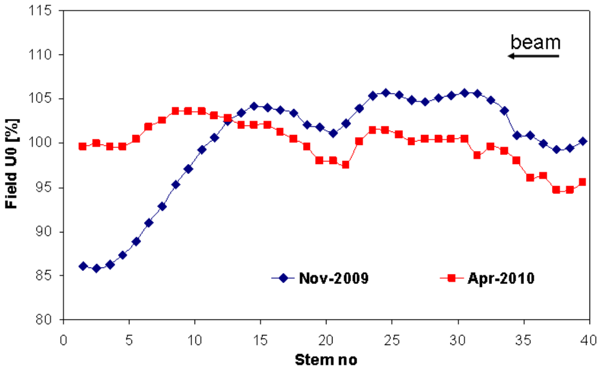

Figure 6: The RFQ field profile prior and after shims replacement [7].

In April 2010 the spacers between the rods and stems (shims) were replaced in the high energy section. The purpose of this operation was to reduce the distance between rods by 0.4 mm in the vertical plane. One tuning plate was added back to keep the resonance frequency in the working range. As a result the field homogeneity was recovered to a large extent (Fig. 6). The measurements of the beam transmission showed much smaller dependence on the RFQ power (Fig. 5A), although some small steering effects are still observed (Fig. 5B).

In the near future we plan to perform better rods alignment using an autocollimator telescope and specially designed optical equipment. By this we hope to completely eliminate beam steering effects in RFQ.

CW Proton Beam Operation

First attempts to conduct a high duty cycle beam through the PSM lead to significant uncontrolled rise in the PSM vacuum pressure as well as instabilities in the cryogenic system. We believe that these effects were due to interaction of the beam transverse tails with cryogenic part of the beam line, which was caused also by steering in the RFQ.

The abovementioned improvement in RFQ transport properties allowed us to start operation with CW proton beams. We reduced the LEBT variable aperture to its minimal opening (5 mm diameter), which enabled a 1 mA CW beam, with RFQ transmission of about 80% (Fig. 2). In order to decouple beam induced effects from possible effects of cryogenics due to the cavities operation [3], we started CW beam operation with the PSM cavities detuned (proton energy of 1.5 MeV). The beam optics (RFQ power and MEBT steers) was varied in order to minimize these beam induced effects until stable and robust operation of 1 mA, 1.5 MeV beam was achieved and reproduced several times for duration of 6-8 hours.

The next step was to accelerate 1.5 MeV the 1 mA CW beam by the PSM cavities fields. The moderate PSM accelerating voltages presented in Table 2 allowed for robust operation of the four accelerating cavities for extended periods. In the example presented in Fig. 6, a 1 mA, 3.07 MeV, proton beam was kept on the VAT beam dump (Fig. 1) for a period of more than 9 hours. The only break during this period was due to a single RFQ trip.

Table 2: The Resonators Parameters Used for CW Beam Operation. Nominal HWR Voltage is 840 kV

HWR #	Voltage kV	Eacc (MV/m)	Sync. Phase (deg)
1	150	1	-90
3	560	3.7	0
4	400	2.7.	-35
5	550	3.7	-35
6	520	3.5	0

Snapshots of the main components vacuum values, RFQ power and cryogenic system parameters are presented in Fig. 7. It can be observed that the beam still affects PSM vacuum and cryogenics parameters, so it is evident that 2-3 μA are still lost at the PSM. This, however, does not hinder stable beam operation.

We plan to introduce a beam scrapper in the MEBT, which may reduce the beam-induced effects in the cryomodule.

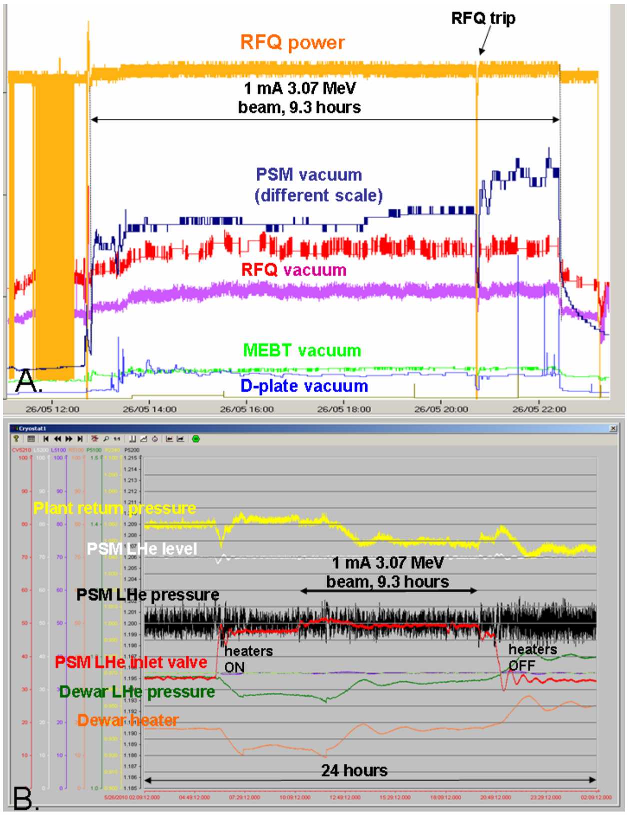

Figure 7: A) RFQ power and vacuum logs of the run with 3 MeV 1 mA run. B) The cryogenics log for same period.

CONCLUSION

During 2010 significant progress was achieved in operation and understanding of all main SARAF accelerator components. Many modifications and improvements were implemented. Significant experience was gained in beam operation, including CW proton beam. This experience will be used as a basis for further work towards reaching the designed specifications of Phase I, as well as, for design of the Phase II of the project. At present construction of the temporary beam line is being finalized in the accelerator tunnel (Fig. 1). The beam line will allow one to perform the experiments with Phase I beam until the SARAF Phase II is ready for installation. The first physics experiments (material science and astrophysics) with Phase I beams should take place by the end of this year. The concept of Phase II of the project is being developed.

We thank J. Delayen and K. Davis of Thomas Jefferson National Accelerator Facility for their assistance in the evaluation of the SARAF PSM tuning system.

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