STATUS OF THE SARAF CW 40 MEV PROTON/DEUTERON ACCELERATOR

I. Mardor#, D. Berkovits, I. Gertz, A. Perry, J. Rodnizki, L. Weissman, Soreq NRC, Yavne 81800, Israel, K. Dunkel, F. Kremer*, M. Pekeler, C. Piel, P. vom Stein, Research Instruments GmbH, Bergisch Gladbach 51429, Germany

Abstract

The Soreq Applied Research Accelerator Facility, SARAF, is currently under construction at Soreq NRC. 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). SARAF linac 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) 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, the RFQ is in routine operation with protons since 2008 and has been further operated with molecular hydrogen and deuterons at low duty cycle. RF conditioning of the RFQ to enable deuteron CW acceleration is on going. The superconducting module is being operated and characterized with protons. SARAF Phase I commissioning results 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. The facility schematic layout, its required parameters and a technical description of its components are given in [2].

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 [3]) and the design and risk reduction of foreseen applications. Phase II includes construction of rest of the accelerator and its applications.

This paper presents recent commissioning results of Phase I, including RF conditioning of the RFQ and first results of acceleration of proton beams through the PSM.

PHASE I COMMISSIONING

The SARAF accelerator is designed, manufactured, installed and commissioned by RI Research Instruments GmbH [4], in collaboration with Soreq NRC personnel.

Phase I is fully installed on site. The ECR source is routinely operated. Details on its construction and commissioning can be found in [5]. The RFQ and PSM are still under intense commissioning, which is described in the following sub-sections.

RFQ

The SARAF RFQ is a 176 MHz 4-rod CW RFQ [6]. 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 deuteron acceleration and beam commissioning, mainly with protons that require half of the deuteron field.

Up to September 2008 we accumulated a few hundred hours of RF conditioning over the preceding 2 years, in an effort to reach the specified field for CW deuterons, which implies an input power of approximately 260 kW. Up to that time, we were able to reach a 15% duty cycle at 280 kW and CW operation at 195 kW, in an unstable manner. Details of the conditioning effort during this period and results of proton beam commissioning through the RFQ are given in [7].

During February 2009 the RFQ rods were dismantled and signs of extensive field emission between the bottom part of the rods and the stems of the opposite voltage rods were observed. The rods were re-machined to circumvent this problem. The machined area is shown in Fig. 1.

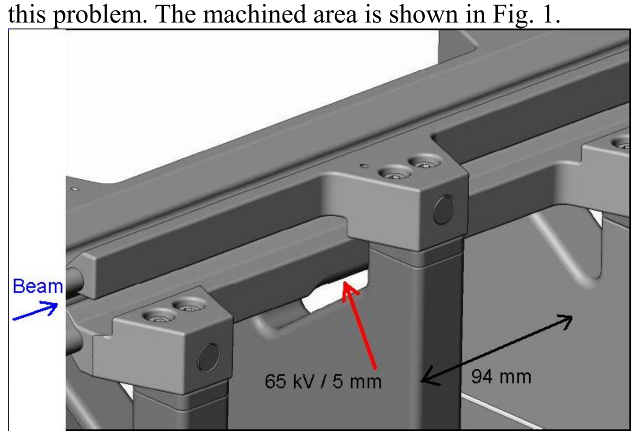

Figure 1: Back side of RFQ rods machined to avoid field emission to opposite voltage stem. Field in machined area is 65 kV per 5 mm. Red arrow marks the machined area.

The effect of this machining on RF conditioning was significant. We further added a cryogenic pump to the two

mardor@soreq.gov.il
* Currently with Varian Particle Therapy GmbH

existing turbo molecular pumps, reduced the cooling water input temperature from 21°C to 15°C, and added external fans to cool down certain RFQ tank areas.

Following two months of conditioning, we have reached 240 kW, CW, for periods of about 30 minutes. 210 kW, CW, was kept for 2 consecutive hours and 190 kW, CW was kept for 12 consecutive hours. In addition, the nominal deuterons power, 260 kW, was reached with a duty cycle of 80% for periods of 30 minutes. The base vacuum is currently 2×10^{-7} mbar, and it increases only up to 4×10^{-7} mbar at an average CW power of about 200 kW.

The conditioning progress and the improvement of vacuum are depicted in Fig. 2.

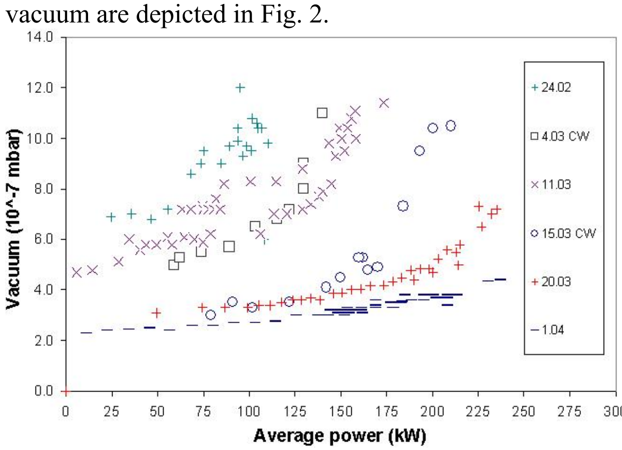

Figure 2: Vacuum inside RFQ as function of average power from amplifier, for selected dates between Feb. 24th 2009 and April 1st 2009.

Figure 2 shows the effects of conditioning, as the rise of pressure versus average power decreased with time. The most recent slope is low enough to be interpreted as an effect of the temperature rise with increasing power.

Currently, the RFQ is open again due to a malfunctioning tuning plate, which melted due to extremely high current density through it, for reasons that are not yet clear. This effect might have limited the RFQ performance. Replacement of this tuning plate is foreseen in the following weeks, and will hopefully enable reaching specified power for accelerating deuterons.

Prototype Superconducting Module (PSM)

The 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 [8].

Based on the PSM RF performance described in [7], proton beams were accelerated for the first time through the PSM. The beam was accelerated by the first three cavities, whose voltages were set to 100, 110 and 800 kV, respectively. The specified voltage per cavity (corresponding to E_{peak} = 25 MV/m) is 845 kV.

The proton beam was with a low duty cycle of 10^{-4} (100 μsec pulses at a frequency of 1 Hz). The beam current measured at the diagnostic plate (D-Plate) downstream of the PSM was 3 mA, corresponding to a 60% transmission from the LEBT, where 5 mA was measured. The beam was re-bunched and accelerated from 1.5 MeV (RFQ exit) to approximately 2.1 MeV.

The beam energy was determined by two methods: Time of Flight (TOF) using two phase probes in the D-Plate and Rutherford scattering (RS) off a gold foil inserted into the beam, also within the D-Plate. RS was implemented using the SARAF beam halo monitor, which is described in [9].

The beam energy, as a function of the voltage of the third cavity (HWR3), is shown in Fig. 3. As can be seen, the energy values determined by the two abovementioned methods are consistent amongst themselves and with beam dynamics simulations.

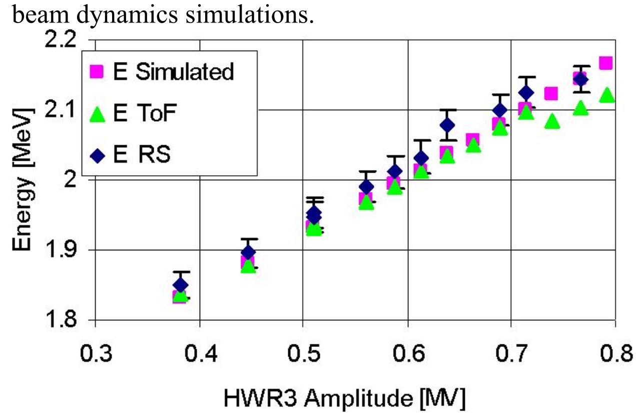

Figure 3: Proton beam energy as a function of HWR3 voltage, as determined by TOF and RS and compared to beam dynamics simulations.

A significant advantage of RS is its ability to measure the bunch energy width. The beam bunch shape for a beam that passes through the PSM with no acceleration is shown in Fig. 4.

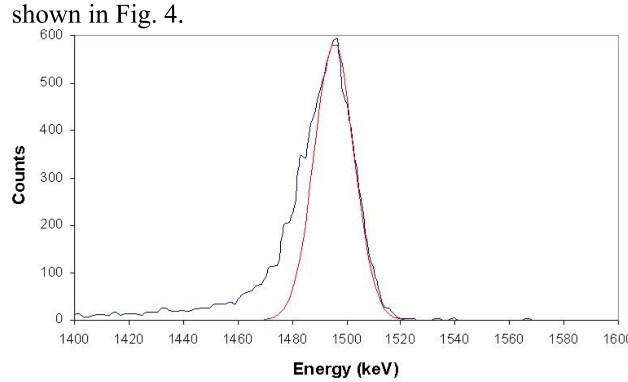

Figure 4: Shape of the beam bunch as measured by the SARAF halo monitor (blue) and a Gaussian fit (red)

A Gaussian fit is attempted for the bunch, and clearly there is a non-Gaussian low energy tail. Beam dynamics simulations indicate that the low energy tail is most probably enhanced due to rise time of RFQ voltage pulse, since the silicon detector was not gated in this measurement.

The FWHM of the Gaussian fit in Fig. 4 is 18 keV. This width includes the detector resolution (< 12 keV), scattering in the gold foil and the actual beam energy width. The effect of the PSM accelerating voltage and phase where clearly demonstrated and as an example, in Fig. 5 we present the bunch width as a function of the phase of HWR3.

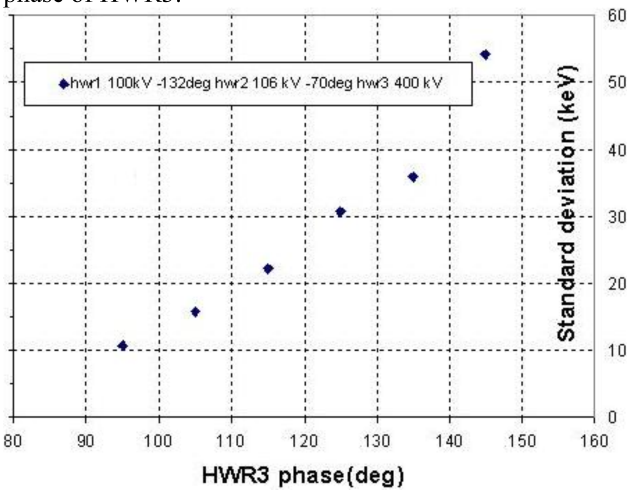

Figure 5: Proton beam energy width as a function of HWR3 phase, as determined by RS. Voltages and phases of the HWRs are given within the plot.

During attempts to increase the PSM cavities accelerating voltages, it became evident that it is necessary to further condition the cavities in order achieve the necessary accelerating fields.

At first, pulsed RF conditioning of up to about 40 MV/m (using a phase locked loop) was applied to all cavities, but this resulted in mediocre results both for the accelerating fields and cryogenic losses. The limiting effect was field emission that generated a significant amount of X-ray radiation. The next step was helium conditioning, which was much more effective. The helium was of 99.9999% purity and its amount in the PSM increased the vacuum level to the range of 10^{-5} mbar. The updated PSM RF performance is given in Table 1

Table 1: RF fields and cryogenic losses of PSM cavities, following RF and helium conditioning. Results are given at onset of field emission and at operation fields

Cavity	$E_{peak}^{FE\_onset}$ [MV/m]	P[W]	$E_{peak}^{Operation}$ [MV/m]	P[W]
1	20.7	2.4	25.4	5.7
2	21.0	5.3	25.9	9.3
3	20.6	7.4	26.0	16.0
4	20.2	4.0	25.7	11.2
5	21.2	3.7	24.9	8.7
6	20.0	5.4	25.2	10.9
Total		**28.2**		**61.8**

The total PSM cryogenic loss at 25 MV/m is within the design value of 72 W and constitutes a significant improvement to the previously presented 107.3 W [10]. We believe the improvement is due to the helium conditioning.

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 beams and optimizing the PSM to reach the proton and deuteron beam target values.

RF CW power of 240 kW has been reached in the RFQ, which is already close to the deuteron acceleration value of 260 kW. A low duty cycle 3 mA Proton beam has been re-bunched and accelerated by the PSM up to 2.1 MeV.

Finalization of protons and deuterons beam commissioning through the entire Phase I is foreseen for the summer of 2009.

REFERENCES

[1] http://www.soreq.gov.il/default_EN.asp

[2] A. Nagler et al., “Status of the SARAF Project”, LINAC'06, Knoxville, August 2006, MOP054, p. 168 (2006).

[3] J. Rodnizki et el., "Lattice Beam Dynamics Study at Low β For SARAF/EURISOL Driver 40/60 MeV 4 mA d&p Superconducting Linac", HB2008, Knoxville, August 2008, WGB15 (2008).

[4] http://www.research-instruments.de. A former Accel Instruments GmbH activity.

[5] K. Dunkel et al., "Performance of the SARAF Ion Source", PAC'07, Alboquerque, June 2007, TUPAN009, p. 1407 (2007).

[6] P. Fischer et al., "Tuning a CW 4-Rod RFQ", LINAC'06, Knoxville, August 2006, THP064, p. 728 (2006).

[7] A. Nagler et al., "The SARAF CW 40 MeV Proton/Deuteron Accelerator", LINAC'08, Victoria, September 2008, MO203 (2008).

[8] M. Pekeler et al., “Development of a Superconducting RF Module for Acceleration of Protons and Deuterons at Very Low Energy”, LINAC'06, Knoxville, August 2006, TUP034, p. 321 (2006).

[9] I. Mardor et al., "The Beam Halo Monitor of SARAF", LINAC'06, Knoxville, August 2006, TUP010, p. 265 (2006).

[10] C. Piel et al., "Phase 1 Commissioning Status of the 40 MeV Proton/Deuteron Accelerator SARAF", EPAC'08, Genoa, June 2008, THPP038, p. 3452 (2008).