PHASE-I PROTON / DEUTERON LINAC BEAM OPERATION STATUS

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Abstract

Phase I of the Soreq Applied Research Accelerator Facility, SARAF, is under operation at the Soreq Nuclear Research Center. The status of Phase I main components is reported, as well as beam operation experience accumulated over the recent two years. The latter includes operation of high power CW protons beams on beam dumps and special targets, and experiments with low-intensity deuterons beams. Recent and future improvements in the current facility performance are discussed.

INTRODUCTION

Phase-I of the SARAF linac is composed of a 20 keV/u ECR ion source and LEBT [1], a 176 MHz, 4 m long, 250 kW, 4-rod RFQ [2], a 65 cm long MEBT and a 4.5 K superconducting module housing 6 β_0=0.09 bulk Nb HWRs, 0.85 MV each and three 6T solenoids in a separated vacuum, 2.5 m long cryostat [3]. SARAFPhase-I routinely accelerates CW and pulsed protons and pulsed deuterons beams.

Significant new experience in beam operation has been accumulated during the recent two years. The main objective was learning how to deliver high power beams to the state of art beam dumps and targets, including the first proton irradiation of a liquid lithium target.

In this period we improved some of the accelerator subsystems, enabling more stable operation of the facility and several basic science experiments. The main limiting factors were lack of a target room, insufficient engineering resources and poor quality of the electrical network. These problems are being addressed and gradually solved: a new powerful 750 kW UPS system was procured and installed, a first target room is being designed and new personnel are being hired. These improvements will enable a significant increase in beam-on-target hours.

In this paper we report on the SARAF accelerator subsystems status, as well as experience in beam operations that has been accumulated since the recent reports [4-8].

STATUS OF MAIN COMPONENTS

EIS/LEBT

The SARAF ECR ion source has been in operation during recent years with minimal maintenance. Once a year the boron nitride parts are being replaced to avoid source instability. We have experienced several failures connected to magnetron operation. A test bench was built in the lab in order to test the magnetron electronics

First experience with the slow LEBT chopper and plans regarding the fast LEBT chopper were discussed in [9]. Introduction of the chopper would allow for a more flexible working range of the beam duty cycle. At present the beam intensity ramping is done by manipulation of LEBT parameters. Measuring of CW beam profiles with a non-destructive residual gas profiler monitor [10] showed that such a ramping method leads to variation in the beam optics during ramp. Introduction of the chopper will improve beam tuning and the beam ramping procedure.

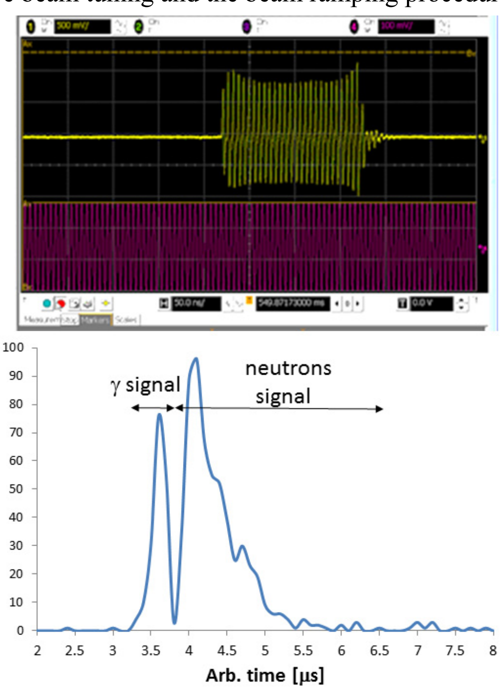

Figure 1: Layout of papers Top. A 160 ns beam pulse from the slow chopper. Pulse measured by BPM pick-ups. Bottom. A measured TOF neutrons spectrum generated with 4 MeV proton pulses on lithium target.

The shortest time of the chopping voltage obtained with the slow chopper is approximately 200 ns corresponding to approximately 160 ns beam pulse (Fig. 1). Simulations show that such a beam pulse length will allow measurement of neutron energy using the time-of-flight (TOF) technique. The first test for feasibility of TOF technique was successful. In this test a 0.5 mA, 4 MeV proton pulses were sent to the liquid lithium target (see

ISBN 978-3-95450-142-7

below). Duration of the pulses was 200 ns and frequency 500 Hz. The TOF spectrum was taken with a plastic scintillator placed at a 5 meter distance upstream from the target (Fig. 1 bottom).

Routine operation of the slow chopper was not possible without its introduction into the accelerator machine safety system (MSS). This required major upgrade of the latter. In 2014 the chopper was integrated into the MSS allowing for safe operation. We plan to start using the slow chopper for beam pulsing, instead of the current method of ion source pulsing.

RFQ/MEBT

The SARAF 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 of 250-260 kW (65 kV voltage), required for CW deuteron operation. Several RF conditioning campaigns have been carried out during 2007-2010. However, despite these extensive campaigns, we reached only 180 kW CW.

Several technical drawbacks in the RFQ design were encountered, which hinder high power operation. Some of these problems and the corresponding technical modifications were described in [5,6] and references therein.

Since 2010 we focused on proton beam operation and limited deuteron beam operation (a few percent duty cycle), and no RFQ conditioning campaign was performed. However, towards SARAF phase II, the need for a decision on the future RFQ prompted us to launch another conditioning campaign in 2014. The purposes of this campaign were: 1. to demonstrate whether the present RFQ needs to be replaced for Phase II; 2. to provide additional input regarding modification of the rod structure toward lower energy in the present RFQ; 3. enable operation of intense deuteron beam already at Phase I.

At the beginning of the conditioning campaign we had difficulties reaching deuteron operation level, even for very low duty cycle. This was probably due to the fact that the RFQ was not operated with deuterons since 2011. However, significant progress was achieved in a relatively short time after breaking through deuteron field threshold. In a few days of conditioning we achieved 50% duty cycle 250 kW (Fig. 2) and CW operation at 200 kW.

200 kW CW operation with a trip rate of less than one per 4 hours was reached after a few days of running at such power. For reference, in 2010 the RFQ trip rate was one per hour at 200 kW, 50% duty cycle [5].

We attribute the above progress to the RFQ modifications described in [5, 6], together with overall maintenance of the RF amplifier and general accumulated expertise in RFQ operation by our team.

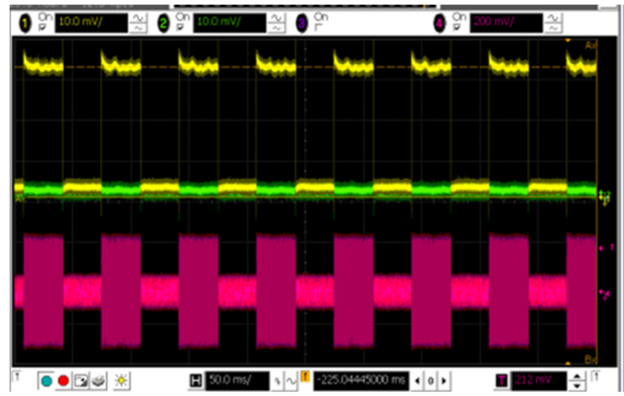

Figure 2: Screenshot of 250 kW operation at 50% duty cycle. The yellow, green and rose traces are forward power, reflected power and field pick up signals, respectively.

One of the proposed options for phase II is modification of the RFQ rod structure [11]. Such modification would lead to reduction of the RF power needed for deuteron operation to the 200 kW level. The corresponding beam energy at the RFQ exit will be 1.3 MeV/u. Demonstration of stable operation at 200 kW CW makes this proposal a valuable option.

Operation of the present RFQ at 250 kW CW does not seem to be unfeasible and should be the subject of the next conditioning campaigns. Several tasks should be performed prior to such a campaign, including polishing the front and backplane surface of the rods, improvement of vacuum in the coupler region and improvement of cooling of some of the RFQ parts.

Prototype Superconductive Module (PSM)

The main problem of the SARAF superconducting cavities is their susceptibility to mechanical deformation, which causes the following two phenomena:

1. The cavities are sensitive to fluctuations in the Liquid He (LHe) pressure (60 Hz/mbar compared to the designed value 15 Hz/mbar [3]). The ±1.5 mbar pressure variation of the SARAF cryogenic system is manifested by frequency detuning that exceeds the cavities loaded bandwidth of 130 Hz.
2. The cavities are sensitive to Lorentz detuning. High power resonance curves of the sixth HWR, measured according to [12], are shown in Fig. 3. One can observe the low frequency Lorentz detuning tilt already at 150 W RF power. Furthermore, intense ponderomotive oscillations appear at certain power on the high frequency side. These oscillations significantly hinder locking of the cavities at high RF power values.

ISBN 978-3-95450-142-7

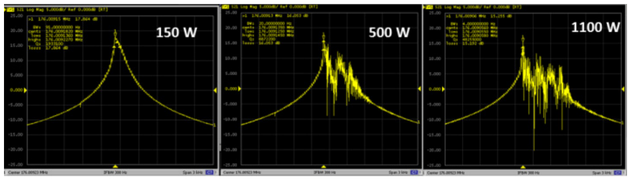

Figure 3: Resonance curves at several RF power values

The softness of the SARAF cavities brings forth challenging demands on the cavities' tuners. These tuners include a stepper motor for coarse tuning and a piezo electric actuator for fine tuning [3]. In 2009 a dramatic reduction of the piezo range was observed; leading to the replacement of the piezo devices by modified ones [13]. In 2011 the piezo tuners suffered once again from significant reduction of the tuning ranges. During the 2012 winter-spring maintenance period, the tuners were replaced by another type of piezo activators (Pst1000 [14]), which operate at higher voltage and have superior mechanical strength. The tuning ranges of the new piezos are measured regularly since May 2012. So far, no significant degradation of the tuning ranges has been observed, although a slight deterioration may be taking place (Fig. 4).

Replacement the piezo tuners, as well as, replacement of the original 2 kW RF solid state amplifiers by 4 kW ones [15] significantly improved the cavities operation. However, the microphonic oscillations shown in Fig. 3 still hinder stable operation of the accelerator at the highest beam energy (4 MeV and 5.5 MeV for protons and deuterons, respectively). This problem will be addressed in the future by improving of the cavity control loop. A proposal for a mechanical modification to improve the cavities rigidity is in preparation [16].

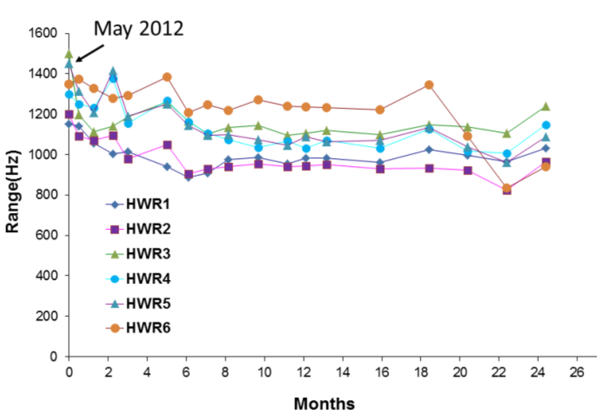

Figure 4: Tuning range of HV piezo tuners measured during the period over two years.

Warming of the RF capacitive couplers was another limiting factor in operating the linac at high fields. The couplers are cooled passively via cooling copper strip lines between the 70 K window and the 70 K thermal shield. This cooling proved to be non-adequate. Thus, we were compelled to reduce the field in the 2nd, 3rd and 6th cavities in order to keep the external coupler's temperature below 120 K during long operation [7].

It was suggested that multipacting in the coupler region is one of heating mechanisms. A common method of suppressing multipacting is to apply a DC bias voltage between the inner and outer conductors of the coupler. We developed DC bias breaker modules that conduct RF current and DC-insulate the coupler antennas from the amplifiers. A detailed report on the DC breaker unit is given in [17]. Several prototypes were built and tested before manufacturing the final configuration. The application of a DC bias successfully reduced the warming rate. An example of the effect of a 1 kV DC bias on the warming rates of three cavities is shown in Fig. 5. In parallel, further improvement of the coupler cooling is also considered [18].

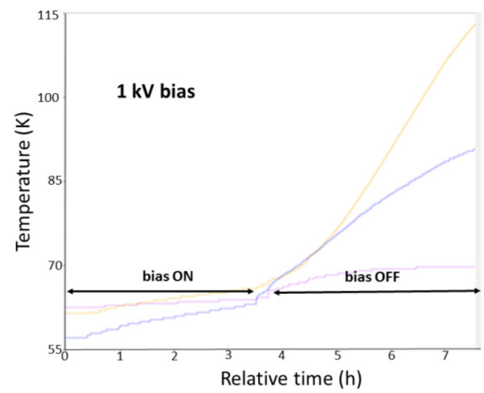

Figure 5: Effect of application of 1 kV bias on the coupler warming rates.

BEAM OPERATION

The summary of the main beam parameters achieved during recent beam operation is summarised in Table I. More detailed description of some of items in the table is in the text below.

Table 1: Summary of the beam operation achievements

Ion	E (MeV)	I (mA)	DC (%)	time (h)	Comments
p	3.6	1.6	100	1	pin beam dump test
p	2.0	2.1	100	4	max. current test
p	1.92	1.5	100	10	LiLiT experiment
p	3.7	0.3	100	50	foil target tests
d	5.6	0.01	1	20	cross section measurements

At the moment the main limiting factors for extending beam operation to the higher energy is the cavities instability. Operation of deuterons at the higher duty factor is limited at the moment by radiological concern. This will be addressed in the near future.

Beam Dumps

A desirable beam dump should enable long and reliable operation of the accelerator at the highest beam power, with minimal prompt and residual radiation. Over a few years of operation we have tested several beam dumps.

A commercial copper beam dump from VAT can take up to 6 kW of the beam intensity. However, use of CW mA at energy higher than 2 MeV leads to high activation of the device in a few hours of operation [19].

Two pure tungsten beam dumps were manufactured and tested. Each was made of a 250 micron thick tungsten sheet fused to a water cooled copper block. These beam dumps exhibit remarkably low prompt and residual radiation at phase I beam energies. However, they suffer from severe blistering effects [7].

We manufactured and used a third similar beam dump, made of copper free heavy metal instead of pure tungsten. High porosity of the heavy metal solved the blistering problem. Up to 4 kW of beam intensity was applied on this dump for many hours. The beam dump did not exhibit any signs of blistering. Long term operation of this beam dump still leads to severe activation due to low-Z metal content in heavy metal.

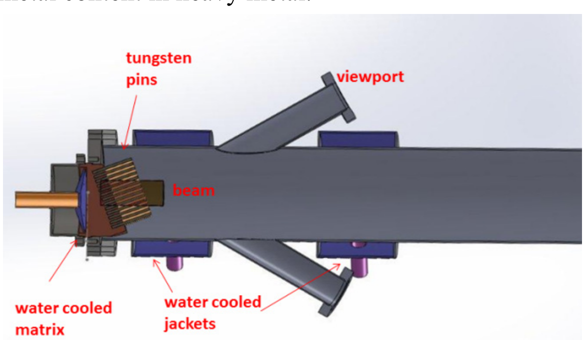

Figure 6: A schematic view of a pin beam dump

An alternative beam dump was made from tungsten pins inserted in a water cooled copper block (Fig. 6). The pins are arranged in such a way that beam does not impinge on the copper. The absorbed beam power is irradiated by the hot pins and reabsorbed by the water cooled environment. This type of beam dump should accommodate up to 20 kW of beam power. It should also not be susceptible to blistering due to efficient diffusion of hydrogen from the hot pins. 2 kW of beam energy was successfully applied to this beam dump prototype [20]. The first version of a 80 mm diameter pins dump was tested at SARAF with 5.7 kW, 3.6 MeV protons. It emitted lower gamma radiation relative to the previous beam dump and low neutrons radiation (~10 mrem/h at one meter distance from the dump) was measured. The heat from the pins, which is irradiated in visible light, enables this beam dump to serve for beam visualisation.

Thin Foil Target Experiment

The thin foil target experiments were the first steps in the program towards future production of radiopharmaceutical isotopes at SARAF. The targets were large area 25 micron thick steel foils cooled by a liquid metal coolant. A detailed description of the experiment can be found in [21]. 3.6 MeV σ_{xy}=4 mm proton beams at a current up to 300 μA were kept on targets for a period of many tens of hours. The beam current density was limited to a foil surface maximum temperature of 500±50 ºC. The cumulative irradiation time on one of the targets was more than 50 hours, which corresponded to the limit of radiation damage in the target foil - one displacement per each target atom (DPA). A few days after the end of irradiation the foil was tested under high gas pressure (at room temperature). The foil did not rupture and held pressure of 5 atmospheres, which demonstrated the target's ability to sustain beam dose corresponding to ~1 DPA.

Liquid Lithium Target (LiLiT) Experiment

The Liquid lithium target [22] was installed on-line and tested by the end of 2013. The target is a windowless wall assisted liquid lithium jet. Up to 1.6 mA CW protons at 1.92 MeV (~3 kW) were successfully delivered to the target [23]. Using a beam energy just above the $^{7}Li(p,n)^{7}Be$ reaction threshold, 1.88 MeV, lead to creation of a strong neutron source, a few 1010 n/s, with an energy distribution similar to stellar cores.

From the accelerator tuning point of view, generating the required neutron energy distributions from LiLiT was challenging, because of the demand for accurate knowledge of the beam energy (a few keV). Resonance $^{13}C(p,\gamma)^{14}N$ and threshold $^{7}Li(p,n)^{7}Be$ nuclear reactions were used for online beam energy calibration.

Another difficulty in beam tuning on LiLiT was the inability to read the beam current from the electrically grounded target. The beam current was monitored using non-destructive diagnostic elements and calibrated radiation dosimeters. Temperatures of the side plates of the liquid-lithium nozzle, measured by four thermocouples, were used for fine beam tuning. A LiLiT mockup was used for beam tune training prior to installation of the real liquid lithium target.

The LiLiT setup was used to study neutron induced reactions relevant to astrophysics. Nuclear astrophysics is the major scientific direction at SARAF for the near future. In addition, LiLiT will be used for demonstration of feasibility of accelerator based boron neutron capture therapy and for production of strong sources of high-energy neutrons via energetic proton and deuteron beams.

Measurements of Deuteron-Induced Reactions

In 2014 we also launched an experimental program for measurement of deuteron-induced reactions cross-sections using low-intensity deuteron beams. The motivation was limited experimental data, especially in the phase I energy range, 3-5.5 MeV. A special target

ISBN 978-3-95450-142-7

station enabling fast target sample replacement was built for this purpose.

In the first experiments we measured ^{23}Na(d,p)^{24}Na [23] and copper activation (^{63}Cu(d,p)^{64}Cu and ^{65}Cu(d,2n)^{65}Zn) [24] cross-sections in the 2.77-5.62 MeV energy range. The latter data are important for assessment of the activation of components of RFQ injectors and MEBT beam dumps in modern deuteron linacs.

CONCLUSION

Significant progress at SARAF phase I was achieved during 2012-2014, while overcoming numerous hurdles and bridging gaps of knowledge. Improvements and modifications were introduced to the accelerator components and operation of RFQ at deuteron duty cycle of 50% was demonstrated. The LiLiT target was installed and operated and first scientific experiments were performed. A program for measuring deuteron-induced cross-section was launched.

The accumulated experience showed that even at the present stage, SARAF already provides high intensity neutrons at a unique spectrum that can accommodate scientific experiments, and has the potential of becoming a user facility providing intense proton and deuteron beams at a viable schedule and high beam availability.

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