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INSTALLATION AND COMMISSIONING OF THE UPGRADED SARAF 4-RODS RFQ

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Abstract

Acceleration of a 1mA Continuous Wave (CW) deuteron (A/Q=2) beam at SARAF has been demonstrated for the first time. A 5.3mA pulsed deuteron beam with RFQ CW voltag has been accelerated as well. These achievements cap a series of major modifications to the Radio Frequency Quadrupole (RFQ) 4-rods structure which included the incorporation of a new end flange, introduction of an additional RF power coupler and, most recently, installation of a new set of rod electrodes. The new rod modulation has been designed to enable deuteron beam acceleration at a lower inter-electrode voltage, to a slightly reduced final energy of 1.27 MeV/u and with stringent constraints on the extant of beam tails in the longitudinal phase space. This report will focus primarily on the installation and testing of the new rods. The successful conditioning campaign to 200kW CW will be described. Beam commissioning with proton and deuteron beams will also be detailed. Results of beam measurements will be presented, including the characterization of the output beam in the transverse and longitudinal phase space. Finally, future possible improvements are discussed.

INTRODUCTION

The SARAF 176 MHz, 3.8 m long 4-rod RFQ is a critical component of the SARAF Phase I linac [1] which will also serve as an injector for the Phase II superconducting (SC) linac [2]. The original RFQ was designed by the University of Frankfurt [3], built by Neue Technologien (NTG) GmbH and RI-ACCEL GmbH, and has been able to generate up to 4 mA 1.5 MeV CW proton beams at RF power of about 60 kW. However, attempts to bring the RFQ to the level needed for CW deuteron operation (240-250 kW) were not successful [4,5].

Numerous improvements were introduced into the RFQ design since the earlier commissioning efforts [6-8]. Those measures have led to a considerable improvement of the RFQ performance, but the more recent RFQ commissioning campaigns still failed to bring the RFQ to CW operation at 250 kW [9-10].

At this stage it became evident that the RF coupler was the limiting factor. In 2016 the original RF coupler was replaced by two new couplers of superior design [11] in order to reduce the RF power density per coupler. The RF coaxial line was split and the RF coaxial sections were adjusted to match phases. Proper RF coupling was achieved successfully by a tedious, iterative procedure. In the following commissioning campaign, it was demonstrated that the new coupler configuration did not affect the RFQ beam transport. The upgrade of the RF system enabled us to improve the RFQ performance and its availability for beam operation. Record results of the high power operation were achieved (April 2016). For example, the RFQ was kept at 240 kW CW for a period of more than two hours without a trip. Nevertheless, reliable CW operation at the 250 kW level was still non-achievable.

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A proposal for a redesign of the SARAF RFQ rods with the purpose of reducing the integrated RFQ load required for deuteron operation at a comfortable operation level, 190 kW, was under consideration for several years [12]. The idea was to scale the rod modulation to allow for lowering of the required RFQ voltage from 65 kV to 56 kV. The new design involves a detailed redesign of the RFQ electrode modulation to maintain the desired beam characteristics for efficient matching to SARAF Phase II linac. Lowering of the applied RFQ voltage has the unavoidable consequence of a lowering of the inter-rod separation and a lowering of the outgoing beam energy from 1.5 MeV/u to 1.27 MeV/u. The most updated report on the RFQ redesign is given in [13]. The extensive beam dynamics simulations of the redesign RFQ were performed using the GPT beam dynamics code [14] with external routines for RFQ accelerating element [15]. The simulations showed that the optimized rod modulation should yield 5 mA proton and deuterons at 1.27 MeV/u with 93 % beam transmission with very few longitudinally lost particles and good beam optics and acceptance to the planned Phase II medium energy beam transport (MEBT) [2]. The transverse normalized rms emittance for a 5 mA deuteron beam should be of the order 0.2 π·mm·mrad and the corresponding longitudinal emittance of 0.85 π·keV/u·ns. Extensive CST calculations [16] of the upgraded RFQ were performed to guarantee proper RF resonance frequency and capacitance of the individual cells and the overall structure.

As result of this work the precise information for the new rod production was delivered to the manufacturer (NTG).

MANUFACTURE AND INSTALLATION OF THE NEW RODS

After production the electrodes have been measured by means of the WENZEL 3d portal measuring gauge with measuring precision of 2.7 μm/m. The measurement showed that the fabrication precision was well within the specs (better than ± 30 μm between adjacent cells) with the surface roughness within the range of 0.4-0.8 μm

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Short stainless steel cooling pipes were brazed to the electrodes before the precise machining. After the electrode production the length of the cooling pipes was increased by welding of stainless steel pipes.

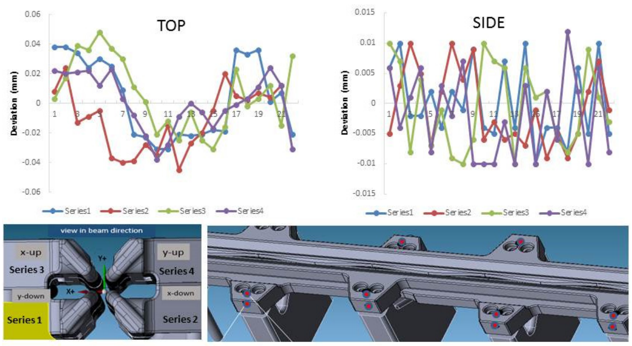

Figure 1: Deviations between the measured and calculated positions of the top and side surfaces of the installed new rods. The red spots indicate the measured positions.

Installation of electrodes has been accomplished by means of two sessions with a laser tracking system. The RFQ tank was opened and the old rods and tuning plates were disassembled and stored prior the first laser tracker campaign. The first campaign (May 2017) focused on measurements of the stems heights. As a first step we established the coordinate system by means of the two end flanges of the RFQ tank. The centres of the outer diameter of the flanges were measured and the connecting line between those points was defined as the beam axis. There were 5 measuring fiducials glued to the surface to find the coordinate system back again on the next working day or after moving the system. On the basis of the stem measurements and the metrology of the electrodes a set of precise shims spacers was manufactured to compensate for errors on stems and electrodes.

The new electrodes were installed in their positions with the adapted shims during the second installation campaign (June 2017). The top and side positions of all electrode supports were measured. The measuring positions are indicated as red spots in Fig. 1. As seen in Fig. 1 the deviations of the measured and calculated positions are within ±40 and ±10 microns for the top and side surfaces respectively.

The tuning plates had to be installed after the installation of the electrodes to adjust the resonance frequency and the field homogeneity. The exact height of the plates was determined by dummy plates made of aluminium. Fifteen dummy tuning plates were placed in between the stems into initial calculated positions. The RFQ couplers were adjusted manually to obtain good RF coupling. The resonance frequency and the field distribution were brought to the optimum via iterative procedure (Fig. 2). The field distribution was measured by means of the perturbation method.

After determination the optimum tuning plates positions the dummy tuning blocks were replaced by the newest generation high power tuning plates (made by copper covered by a silver plate). The high power plates have been installed after shortening the water tubes to match their individual mounting situation. The fine tuning of the plates positions was performed via additional field measurements. In the final state the resonance frequency was 175.943 MHz in air or 175.986 MHz in vacuum. This frequency corresponded to the positions of the RFQ plungers in the middle of their tuning range. The final field non homogeneity was around 1.8 % (standard deviation). For comparison the corresponding number for the old structure was 2.7 %, which only could be achieved by a deliberate misalignment of the rods toward the high energy end [5]. A typical RF coupler coupling value was better than -40 dB, although better values down to -60 dB were observed during the tuning.

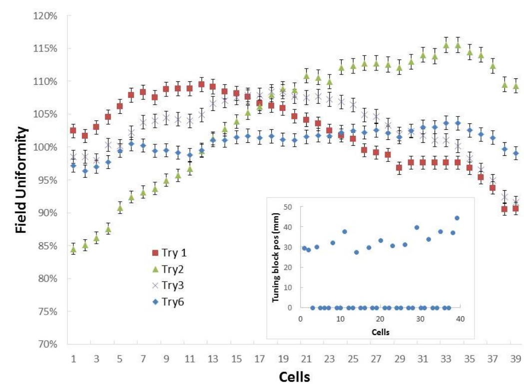

Figure 2: Iterative procedure for tuning the field homogeneity. The final position of the tuning plates is indicated in the inset.

HIGH POWER CONDITIONING

The first tests with proton beams (July 2017) demonstrated that the new RFQ structure is performing well within the designed parameters. According to the primary measurements with protons the power required for deuteron operation is in the range of 180-190 kW. However, conditioning at a higher power (>200 kW) is required to achieve stable operation at 180 kW.

It took five operational days (36 net hours) to reach 180 kW RF power (Fig. 3, left). In the first day only low duty cycle (<1 %) was used to bring the pulsed forward power to the 200 kW level. During the consecutive four days the pseudo CW duty cycle (> 99%) was used and the RF power was gradually increased. Relatively fast progress can be explained by all the recent modifications [6-8,11]. In addition a digital reflection protection box was used for the first time instead of a similar analogue device. The reflected power pulse measured by the directional coupler was analysed and introduced in a FPGA processor. In case of high reflected power the FPGA processor switched off for a predetermined period (usually ~60 msec) the input signal to the RF amplifier allowing for a discharge event to decay. Utilization of the protection box is the main reason for performing conditioning in the pulsed pseudo CW mode rather than real CW operation.

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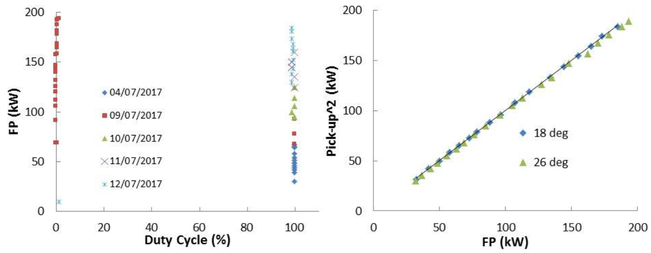

Figure 3: Left. The progress of the first stage of the high power conditioning. Right. Dependence of the normalized square of the pick-up amplitude versus the forward power taken for two temperatures of the cooling water.

As an example, the log of a 6 hour long operation at 180 kW is shown in Fig. 4. The forward power trace (orange) is almost constant during that time. The strip pattern of the orange trace is due to sampling of the pseudo CW signal. The power signal drops to 10% of its maximum value when it samples low RF power (1% of the time). However, one can also observe a few events when the forward power drops to zero (Fig. 4). These are high reflection power events which would cause a trip without the reflection box intervention. There were about 15 events of such type during the 6 hours operation presented in Fig. 4.

The following 30 net hours of conditioning were onset by two vacuum events when Viton o-rings in the vacuum barriers of the cooling tubes of the 39th and 19th stems were damaged. During further operation at the high power (>180 kW) it appeared that the tuning range of the RFQ plungers became marginal. It was decided then to open the RFQ chamber for minor modification of the resonance frequency. Only two tuning plates were slightly shifted down by less than 1 mm in order to shift the resonance frequency by approximately 60 kHz (plates # 2 and 39 in Fig. 2 inset) Consequent measurements showed that the field homogeneity practically did not change as result of this action.

The final stage of the high power conditioning (August 2017) comprised four days (33 net hours). At the end of this period we were able to keep RFQ: at 195 kW CW for many hours without a single trip and at 205-210 kW CW at the trip rate of one per hour. Note that the electric field at a power of level of 200kW in the new RFQ structure (1.58 Kilpatrick) corresponds to the electric field at a power level of 260kW in the old structure. The dependence of the electrical field (measured using a pick-up antenna) on the forward power is shown in Fig. 3, right. A deviation from linearity may be an indication of 'dark currents' in the RFQ. However, the measurements demonstrate that there is no measurable loss of RF power up to the highest used power values.

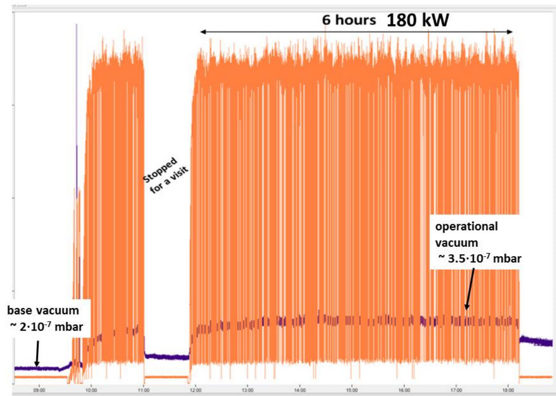

Figure 4: The log (forward power in orange, RFQ vacuum pressure in blue) at the end of the first part of the conditioning campaign; 6 hours of operation at 180 kW without a trip.

BEAM COMISSIONING

The next stage of the RFQ commissioning (September 2017) included detailed beam characterization using the SARAF diagnostic (D) plate. The D-plate is situated after the SARAF cryomoule which considerably hindered of measurement of some beam properties at the RFQ exit.

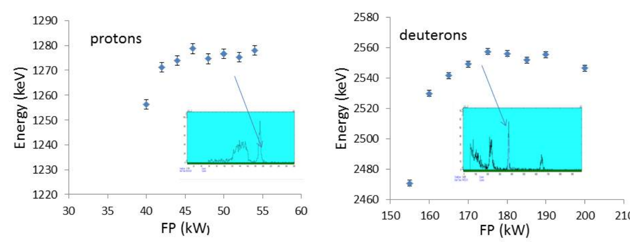

Figure 5: RBS measurement of beam energy as a function of the RF power for protons (a) and deuterons (b) are presented. The RBS spectra are shown in the inserts.

Accurate measurements of the beam energy were done using the Rutherford backscattering (RBS) of beam from a thin gold foil [17]. The Si detector used for particle detection was calibrated in situ by ^{148}Gd and ^{228}Th alpha sources. The results of energy measurements for proton and deuteron beams as a function of RF power are displayed in Fig. 5. The obtained beam energy is about 1.275 keV and 2.555 keV for protons and deuterons correspondingly which is very close to the designed values.

Transverse emittance measurements were performed using vertical and horizontal slit-wire sets at the D-plate. The measurements were done with beam pulses of 0.5 ms of protons and deuterons and for various intensities up to 5.5 mA. The measured values of the normalized rms emittances are within the specifications for both protons and deuterons (~0.2 π·mm·mrad).

The RFQ transmission was measured by comparing the current readings at the LEBT and the D-plate Faraday cups. The dependence of the transmission values on the input beam current is compared for the old and new rod structures in Fig. 6. The present and the previous (December

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2015) measurements were performed in the same manner - only the ion source magnetron RF power was changed to vary the LEBT current and all the LEBT optical parameters were kept the same, except fine tuning of the last LEBT solenoid. It is seen in Fig. 6 that the RFQ transmission has improved slightly for the proton beam, although the general trend of the transmission decrease with increase of the current persisted. There is also a modest increase of the transmission for deuterons for the new rod structure. Moderate improvement in RFQ transmission took place in spite of the fact that the physical aperture area between the new rods was reduced effectively by 30 % [13]. The improvement is due, in part, to a smother gentle bunching section and, in part, to a constant aperture in the accelerator region [13], as well as, due to better field homogeneity achieved with the new rod structure.

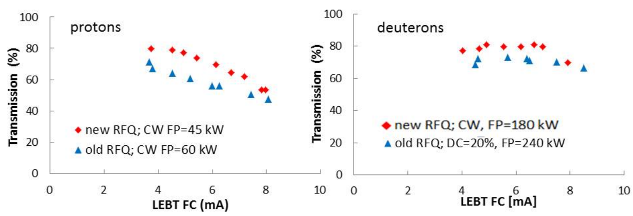

Figure 6: The RFQ transmission as a function of the input current for protons (left) and deuterons (right). Measurements for the new and old rod structures are compared.

Improvements are also seen in behaviour of the beam distribution as a function of the RF power. The horizontal beam profiles measured in the MEBT at various RF powers are compared for the new and the old structures in Fig. 7. The forward power was varied in 40-55 kW and 55-70 kW range for the new and old structure respectively. As it seen from the comparison that the new structure does not exhibit strong power dependent steering, that was observed with the previous rods [18].

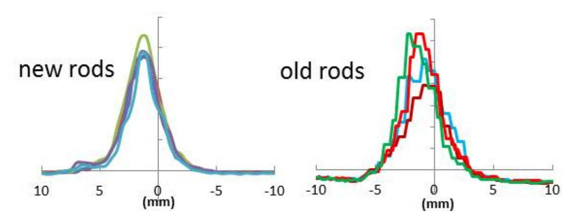

Figure 7: The effect of RF power on the MEBT beam profiles for new (left) and old (right) structure.

Significant efforts were devoted to the measurement of the longitudinal emittance. The emittance is measured for protons by monitoring the RBS energy distribution of the beam while varying longitudinal focusing by a superconducting cavity (gradient variation method [19]). The main difficulties of this measurement are associated with the fact that the longitudinal emittance value is affected by beam transport via the cryomodule. One has to rely on beam dynamics simulations in order to choose the appropriate tune with a moderate effect on the emittance in the whole tuning range. Three half wave resonator (HWR) cavities were used in the tune which was applied in the measurement: HWR1 in the bunching mode, HWR2 in accelerating mode and HWR4 also in the bunching mode. The HWR4 bunching voltage was varied in steps from 0 to 300 kV. The energy distribution was measured by the RBS monitor with typical energy resolution better than 15 keV. The results of energy width distribution measurements as a function of the focusing HWR4 voltage are presented in Fig. 8, left together with examples of the obtained RBS peak. As results of the measurements the longitudinal phase space rms ellipse at the RFQ exit was obtained (Fig. 8, right). This was done by propagating the results obtained at the D-plate back to the position of HWR4 resonator for each HWR4 bunching voltage and deducing the minimum size rms ellipse. The result for longitudinal emittance was measured for the position of the HWR4 resonator. The simulations show in the transport from the RFQ exit to that point an emittance grows of approximately 20 %. The result at the RFQ exit corresponds to ~1.1 π·keV/u·nsec.

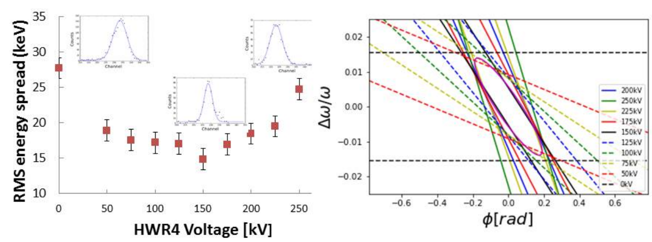

Figure 8: Left. The results for measurement of energy distributions are presented. Some examples of spectra are shown in the insets. Right. The phase space ellipse obtained from the RBS measurements.

Demonstration of CW deuteron operation is the important milestone of SARAF Phase I which was overdue for a decade. The test, performed in October 2017, started with acceleration of a low duty cycle beam while RFQ was working in CW mode at 190 kW. The cryogenic cavities were detuned. The beam duty cycle was set by the slow chopper, beam was stopped at the beam dump after the D-plate. The pulse intensity was kept at 1.15 mA. The duty cycle was gradually increased to 99.5 % while monitoring vacuum in the cavities and cryogenics. After reaching the pseudo CW level RFQ was operational for half an hour smoothly until a RFQ trip. Operation of deuteron beam in CW mode is feasible now with the upgraded RFQ structure.

SUMMARY

A new 4-rod structure has been designed and implemented at SARAF, with the goal of reducing the RF power required for CW deuteron operation while compromising the RFQ exit energy to 1.27 MeV/u. The new 4-rod structure was manufactured by NTG, and successfully installed in place of the old rod electrodes. Superior field homogeneity was achieved during the installation. The upgraded RFQ was successfully conditioned to the RF power of

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200 kW required for CW deuteron operation, with a sufficient power margin. The first operation of ~1 mA CW deuteron beam was demonstrated and up to 5.6 mA deuteron pulses were extracted while the RFQ was operated in pseudo CW mode. The extensive commissioning tests with proton and deuteron beams were performed. The main designed and measured RFQ parameters are compared in Table I. As seen from the table the main RFQ parameters such as the working RF power, exit energy, and emittances (transverse and longitudinal) are close to the design specifications. The relatively low value of the RFQ transmission is a long standing issue, which is, at least partially, the result of beam neutralization loss in the LEBT/RFQ interface region [20]. Nevertheless, the new rod structure exhibits a slight improvement in transmission in spite of its lower effective aperture. We also do not observe the strong power dependent steering effects which took place in the previous structure. A more detailed report on this work is available [21].

Table 1: The Comparison of the Designed and Measured RFQ Specifications. The beam current at the RFQ exit. “zero” current values correspond to the measurements involving the RBS monitor.

Parameter			Beam (mA)	Designed value	Measured value
Energy (keV/u)			5/0	1.270	1.275(5)
Working power (kW)		p	5/0	46.5	45-50
		d	5/0	186	180-190
Transmission (%)		p	5	88	60
		d	5	93	70
norm. rms emittance	Transversal (π·mm·mrad)	p	5	0.2	≤0.2
		d	5	0.2	≤0.2
	Longitudinal (π·keV/u·nsec)	p	0	1.35	1.1
		d		1.35	N/A

A number of issues still need to be resolved in the near future include: further improvement reliability of the vacuum sealing, improvement of stability of the RF amplifier at the high power and solving some issues with the control system. The low RFQ transmission, especially in the case of high proton current, calls for further studies of all complex phenomena taken place at the RFQ entrance. With further RFQ operation some fresh copper evaporation was observed on the insulated ceramic of one coupler. This issue will be further studied. More work and improvements will be done in the next future to make the SARAF RFQ a reliable injector of the SARAF Phase II superconducting linac.

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