THE BEAM HALO MONITOR OF SARAF

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Abstract

A major requirement for the SARAF accelerator [1] is 'hands-on' maintenance, which implies a maximum beam loss of 1 nA per meter. In Phase I of SARAF (4-5 MeV ions at 2 mA), we need to map the beam halo (BH) down to below 1 nA in order to predict, using beam dynamics calculations, the beam loss in the full accelerator. Mapping the halo of a 4 MeV, 2 mA ion beam down to below 1 nA is unprecedented. We have therefore developed a BH monitor, which incorporates a direct charge measurement as well as several nuclear techniques, including Rutherford scattering on gold, $^{7}Li(p,n)^{7}Be$ leading to both neutrons and the radio-isotope ^{7}Be (measured offline post irradiation) and $^{19}F(p,\alpha)^{16}O$ leading to high energy gamma rays, with the BH current being derived by using published cross sections. In this paper, we present the SARAF Phase I BH monitor and describe the various measurement techniques. In addition, results of feasibility studies at the Koeffler Pelletron accelerator of the Weizmann Institute are given.

THE MEASURMENT TECHNIQUES

The techniques that we use in the BH monitor include one direct charge measurement and several nuclear reactions techniques. These nuclear techniques are effective up to a proton beam energy of about 10 MeV, so they are relevant for SARAF Phase I and slightly beyond it. Upon proving that all these methods yield consistent results, we will use the direct charge technique, which is almost independent on energy, throughout Phase II of SARAF. Fig. 1 shows the BH monitor target holders.

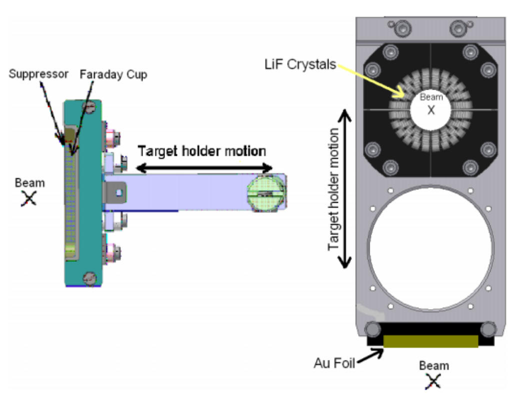

Figure 1: Left – The special Faraday Cup for the direct charge measurements. Right – Target holder for the nuclear techniques. Possible beam positions (entering the page) and targets motions are shown.

Direct Charge Measurement

The beam halo charge will be measured using a Faraday Cup (FC), which is inserted gradually into the beam halo and maps it (Fig 1, left). The FC includes a suppressor, which will be optimized to circumvent uncertainties induced by secondary electrons resulting from interactions of the primary 2 mA beam. The FC can be upgraded by adding an electrically biased thin foil in front of the FC, from which secondary electrons will be scattered and detected by a MCP, Channeltron or silicon. The FC can measure current down to 10 pA, whereas the additional secondary electron measurement can measure down to below 1 pA.

Rutherford Scattering

The beam halo current is measured by detecting beam protons which undergo Rutherford scattering off a thin gold foil (Fig. 1, right), using ion-implanted 100 mm^2 Si detectors with a depletion depth of 0.5 mm and 12 keV FWHM for 5.5 MeV α particles, placed inside the vacuum. The gold foil, whose edges are glued to a graphite holder (graphite chosen for background reduction), is gradually inserted into the beam halo and maps it. Measurements are made at 100º and 45º in order to increase the dynamic range.

At 4 MeV, $^{197}Au(p,p)^{197}Au$ is purely Coulomb and the differential cross sections at laboratory angles of 45º and 100º are 23.6 barn/sr and 1.47 barn/sr, respectively. For an Au target of 1 mg/cm^2 covering ~12% of the 1 nA halo, Si detectors placed ~35 cm away (~1/1200 sr) will yield ~48 cnts/sec at 45º and ~2.7 cnts/sec at 100º.

The prime background source is backscattered protons off the tungsten beam dump, located ~6 meters downstream to the BH monitor, which might scatter off the Au foil into the detectors. This background amounts to 2% and 0.1% at the 100º and 45º Si detectors, respectively. Thus the 45º detector will enable detection of beam halo down to 100 pA.

Activation of LiF Crystals

The beam halo is determined offline post irradiation by measuring the activation of thick LiF crystals, due to $^{7}Li(p,n)^{7}Be$. 478 keV gammas of ^{7}Be ($T_{1/2}$ = 53.23 days) are measured by a high purity Ge detector (HPGe) [2]. Rings of crystals of several radii are placed around the beam on a graphite backing (chosen for background reduction, see Fig. 1, right). Measuring the activity of each ring enables beam halo profile reconstruction. This measurement is immune to EMI and RF interference, which might hinder the online measurements described in this paper.

The average cross section in the above energy range is ~300 mbarns. Given that the 0.9 mm thick LiF crystals are thick targets for 4 MeV protons, the abundance of the 478 keV gammas in the decay of ^{7}Be is 0.103 and the abundance of ^{7}Li in LiF is 25%, the ^{7}Be activity after a 1 nA irradiation for 30 minutes should reach nearly 250 Bq. Since the detection limit of our high purity Ge detector is 0.5 Bq [3], halo down to 100 pA can be easily measured with this method.

Online Monitoring of LiF Reactions

During LiF irradiation, gammas of 6.13, 6.92 and 7.13 MeV are emitted by de-excitation from the 3^-, 2^+ and 1^- states of $^{16}O^*$, obtained from $^{19}F(p,\alpha\gamma)^{16}O^*$. The total cross section at 4 MeV is ~200 mbarns [4].

The isotropically emitted gammas will be detected with a well shielded NaI(Tl) detector of diameter 15 cm and thickness 15 cm, which has a full energy peak efficiency of ~50% at this energy (including 1st and 2nd escape). Assuming a solid angle of 0.15 sr, about 2500 photo-peak cnts/sec will be recorded for a proton beam halo of 1 nA.

The main background sources are (p,γ) and $(p,\alpha\gamma)$ off copper at the RFQ [1] and tungsten at the beam dump. These gammas are either below the energy window (6 - 7 MeV) or will be mostly blocked by the NaI(Tl) shielding.

In addition, prompt neutrons from $^7Li(p,n)(^7Be+^7Be^*)$ can be detected via a neutron monitor. At 70 cm away from a 1 nA proton halo, the cross section of these reactions [5] at 4 MeV yields 21 neutrons/sec/cm^2, which amounts to 3.1 mrem/hour (ICRU-57).

Background neutrons might be produced by W(p,n) in the beam dump. Neutrons from Cu(p,n) in the RFQ are not expected since its maximum proton energy is 1.5 MeV and the reaction's negative Q value is larger.

Online Detection of Short Lived Activation

This is a real-time technique where the beam is pulsed, a short lived isotope is generated by the ion beam pulse and its decay radiation is measured between pulses. The candidate reaction is $^{93}Nb(p,\alpha)^{90m}Zr$. The isomer ^{90m}Zr ($T_{1/2}$ = 0.83 sec, $E\gamma$ = 2.32 MeV (83.2%)) implies a preferred beam structure of 2 sec pulses with 4 sec gaps. This ensures nearly saturated creation of ^{90m}Zr and ample time to detect most of its decay radiation (the first 2 sec of the gap) and measure the background (the latter 2 sec).

We assume that the cross section for this reaction is ~ 30 mb. Thus, irradiating a ^{93}Nb target of 25 mg/cm^2 with a 1 nA proton beam during a 2 seconds pulse will result in 3×10^4 ^{90m}Zr disintegrations per second. A detector with a solid angle of 0.15 sr and a full energy peak efficiency of 0.5 will record 180 counts between each of the pulses.

Background sources to this method (Th emitting 2.61 MeV gammas, cosmic rays and activated accelerator components) are expected to be suppressed by the pulse structure and side shielding.

THE VACUUM CHAMBER

The irradiation targets, the silicon detectors and the Faraday Cup are placed in a vacuum chamber (Fig. 2), which in turn will be integrated into the SARAF diagnostics system. The vacuum chamber is based upon a six-way cross, with an additional special opening at 45º. Two openings are for the beam, two (including the one at 45º) are for the Si detectors, one is for inserting the LiF crystals and gold foil target holder, one is for inserting the Special FC and one is for external viewing. Nuclear and charge measurements can be performed simultaneously.

The LiF crystals and the gold foil can be replaced without breaking the entire vacuum by using a 'load-lock' and a rectangular gate valve. The Si detectors are also replaceable with vacuum loss in a small volume.

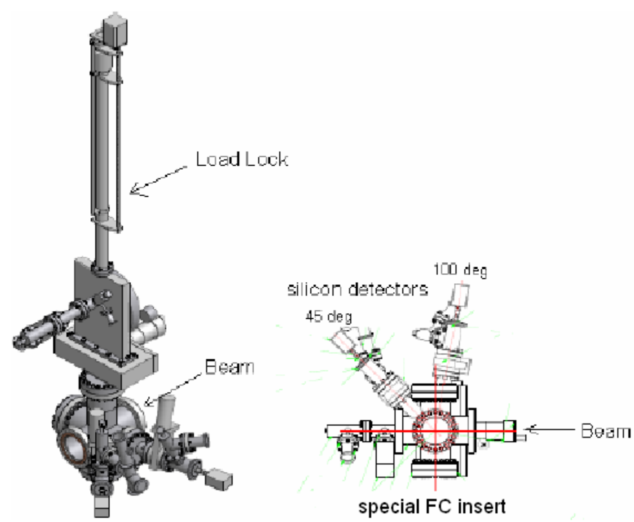

Figure 2: Left – 3D view of the BH monitor vacuum chamber. Right – Bottom view of the BH monitor.

FEASIBILITY STUDIES

The BH monitor was tested in the Pelletron accelerator at the Weizmann Institute of Science. We used 10 MeV protons (the lowest achievable energy at the Pelletron) with a total current of 1 nA, which simulated the SARAF halo. We compared the BH current readings to a calibrated standard FC (SFC) at the end of the beam line.

Direct Charge Measurement

We used the BH FC to scan the Pelletron beam with the beam collimated to a 3×3 mm^2 spot of 0.5 nA on the SFC and then, the slit normal to the BH FC scan direction was decreased to 1.2 mm, resulting at 0.2 nA on the SFC. The suppressor voltage was -300 V.

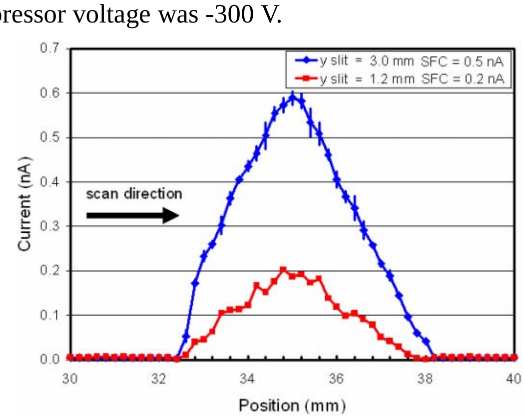

Figure 3: Results of BH FC scans of the Pelletron 10 MeV proton beam.

The scan shapes (Fig. 3) are a convolution of the beam spot and the BH FC horizontal size (3 mm). One can see that the peak currents are consistent with the SFC results.

Rutherford Scattering

We measured the rate of the Rutherford scattered protons off the gold foil in both the 45º and 100º Si detectors and compared it with the expected rate, based on the full beam current measured simultaneously by the SFC. In order to measure the method's energy resolution, we replaced the 45º detector, originally 0.5 mm thick, with a 4 mm thick detector, which is sufficient to stop the 10 MeV protons.

The calculated and experimental scattered protons rates are consistent to within 10% (Table 1). The measured energy resolution is 49 keV (FWHM), which is a combination of the 4 mm detector resolution (33 keV) and straggling due to variations in the foil path length, the foil thickness and multiple scattering inside the foil.

Activation of LiF Crystals

We irradiated 4 LiF crystals placed adjacent to each other (generating a square target of 6.4×6.4 mm^2) by a 1 nA beam that was collimated to a square cross section of 3×3 mm^2. To obtain the calibration current, we retracted the target every few minutes and recorded the SFC reading. The total irradiation charge on the crystals was 2170 nA·sec. We then measured the activity of the LiF crystals with an HPGe detector at Soreq and compared to the calculated value based on the SFC. The results were consistent to within 2% and well within the errors (see Table 1).

Online Monitoring of LiF Reactions

Monitoring both the gammas of ^{19}F(p,αγ)^{16}O* and the neutrons of ^{7}Li(p,n)(^{7}Be+^{7}Be*) was performed while irradiating the LiF crystals, using the large NaI(Tl) detector described above (110 cm away) and a ^{3}He flat response Victoreen 190N neutron dose equivalent detector (70 cm away), respectively.

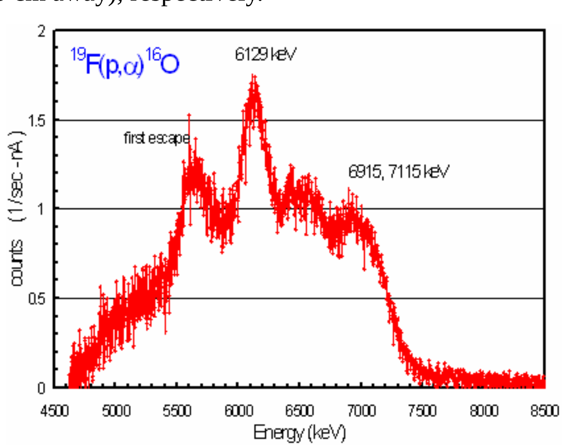

Figure 4: Background subtracted NaI(Tl) spectrum of gammas from LiF irradiation by 10 MeV protons.

For the gamma measurement, the energy scale was calibrated with a ^{207}Bi source, using its gamma lines at 570, 1064 and 1770 keV. A high energy calibration was derived from a background run on a C target (4438 keV). Additional background runs were done with Al and with no target. The gamma spectrum obtained from the LiF runs, after background subtraction is given in Fig. 4. The 6.13 and 6.92 MeV peaks are visible and the number of counts in then is consistent with the calculated amount (see Table 1). The NaI detector was not shielded.

For the neutron experiment no background was subtracted, and the monitor was not shielded, which may be the cause for the significant excess of measured neutrons (see Table 1).

SUMMARY AND OUTLOOK

In Table 1 we present the experimental results of the BH monitoring methods and compare them either directly to the SFC (BH FC case), or to the expected results, which are based on deriving the relevant detector reading from the SFC result and the known nuclear reaction cross sections.

Table 1: Summary of the Pelletron feasibility studies

Reaction	**Detector**	**Derivation from SFC**	**Experiment**
Charge collection	BH FC	0.50 nA 0.17 nA	0.6 nA 0.2 nA
^{197}Au(p,p')	Si 100	3.5 cnts/sec	3.2 cnts/sec
	Si 45	61.9 cnts/sec	55.2 cnts/sec
^{7}Li(p,n)^{7}Be	HPGe	1230 ± 40 Bq	1200 ± 120 Bq
	Neutron monitor	15.0 mRem/hr/nA	25.4 mRem/hr/nA
^{19}F(p,α)^{16}O*	NaI(Tl)	900 ± 42 cnts/sec/nA	910 ± 90 cnts/sec/nA

The results are consistent with the standard Pelletron FC within 20%. Thus, these methods are sufficient for mapping the SARAF Phase I beam halo to an accuracy that will enable us to predict, using beam dynamics calculations, the beam loss in the full accelerator.

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