Cyclotron Institute upgrade project

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On January 3, 2005 the Cyclotron Institute Upgrade Project (CIUP) began with the approval of the CIUP management plan by the Department of Energy Nuclear Physics Office. The project will extend at least to the second quarter of calendar year 2016. When completed, the upgraded facility will provide high-quality re-accelerated secondary beams in a unique energy range in the world. Funding for the upgrade comes from several sources: the Department of Energy, matching support from TAMU, the Robert A. Welch Foundation and beam time sales for testing electronics components at the Cyclotron Institute.

The CIUP is divided into three major tasks: (1) Re-commission of the existing K150 (88") cyclotron and refurbish beam lines; (2) Construct light-ion and heavy-ion guides and produce 1+ radioactive ions; (3) Transport and charge boost radioactive ions and accelerate in the K500 cyclotron.

Effort made during this year included beam development of the K150 cyclotron, testing and development of the Light Ion Guide (LIG) gas cell and assembly of the Heavy Ion Guide (HIG) transport system equipment. Below we report on a few of the accomplishments listed above.

I. K150 Cyclotron Development

In the past year, we provided eleven beams, proton to silicon, using the H^- and the ECR ion sources, for in-house groups and one alpha beam for the STAR/LIBERACE collaboration. The late start for the beams and a water leak in the 88 LCW heat exchanger limited the time available for the experiments. The efficiency for the proton beams from the H^- source continues to be very high, up to 50% throughput (the ratio of beam currents on FC02 divided by ILC02). For the ECRIS beams, about 10% for the 1st harmonic beams and about 3% for the 3rd harmonic beams were obtained for the throughput. We continue to strive to improve the beam tune.

The installation of a new "target probe", which measured the beam current very close to the inflector, and the complete replacement of the deflector spark shields took a long time to complete. The old deflector spark shield plates were found to be heavily damaged and had to be replaced; most of the plates were made of stainless steel except for a few plates near the deflector entrance which were made of tungsten. Due to the expense of making a complete new set of tungsten plates, the newly installed plates consist of new tungsten plates near the deflector entrance and a mix of new and used stainless steel plates for the middle and exit sections of the deflector. Even after the spark shield replacement, the difficulties with the deflector conditioning and necessary beam studies with the new target probe further delayed the start of beams for experiments to late July. Also, we moved the deflector power supply from the basement to above the deflector cage (at near the height of the top of the cyclotron yoke), (Fig. 1), bringing it close to the deflector and minimizing the HV cable length (from 75 ft to 8 ft), this in turn reduced the stored energy in the cable substantially. This reduction in the stored energy should help with controlling damage to the deflector spark plates. The power supply relocation also in resulted in much calmer operations for the former neighbors of the deflector supply, such as Sol 3, which used to regularly fault off due to sparking from the deflector.

FIG. 1. The deflector power supply was relocated closer to the deflector above of the deflector cage. The supply is shielded from neutrons inside a box with 3 layers of 1" borated polyethylene panels.

II. Target Probe Measurements

The motivation for the target probe measurements was to study how and where the beam losses occur, especially for the 3rd harmonic beams. (The 3rd harmonic beams are beams with the final energies less than 6 AMeV, where the RF runs at 3 times the orbital frequency of the beam.) The target probe was temporary installed using the same port in the dee tank that is normally used for the stripper foil mechanism for the H- extraction. The probe ran radially and it reached just 0.4” outside the inflector on the dummy dee side, intercepting the beam as it exited from the inflector. The probe was fitted with two heads, flat 5/8” wide copper paddles, oriented radially and perpendicular to the beam. One head was made 1/8” longer than other one in order to resolve the radii of the first few orbits at the cyclotron center, see Fig. 2.

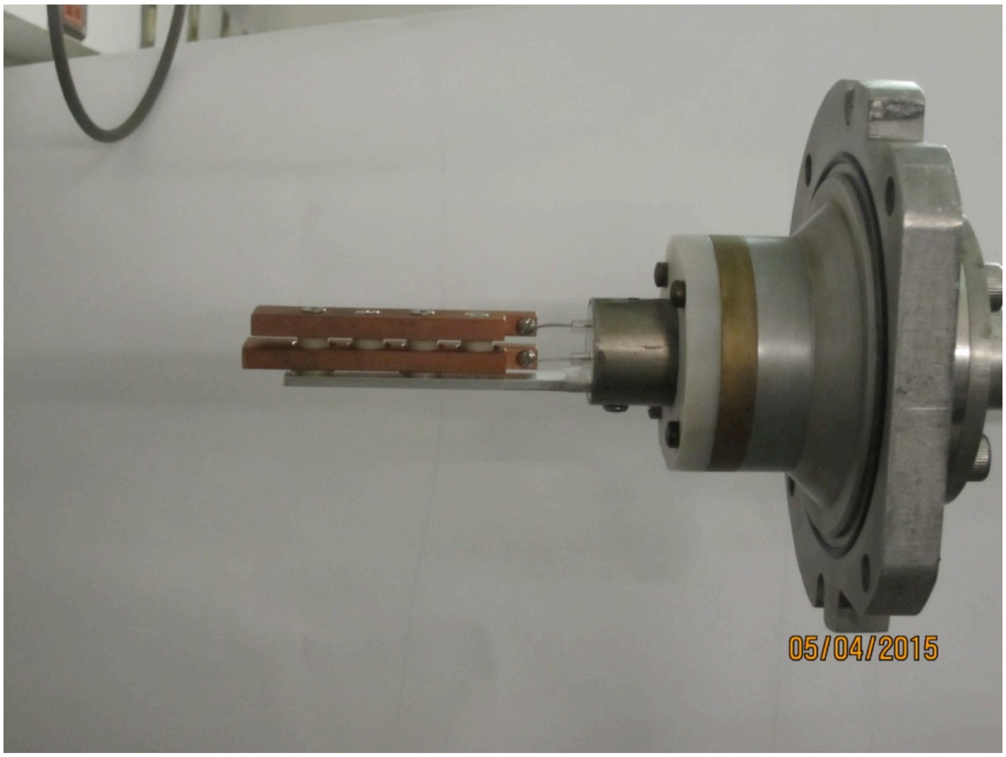

FIG. 2. Target probe runs radially from the dummy dee side.

We used several ^{16}O and one ^{40}Ar beams from 5 to 10 AMeV to look at beam transmissions from ILC02 to FC02, with interests in beam losses and the RF acceptance at the center of the cyclotron; these measurements were then compared with the center region particle tracking calculations. The most radially inward position of the target probe was 0.9” from the center of the cyclotron, and 0.4” away from the inflector. At this radius, the transmission efficiency with respect to the current on ILC02 was about 35%, it was the same for the 1st and the 3rd harmonic beams. This number depends mainly on the injection line optics to focus the beam onto the mirror inflector; higher extraction voltages on the ECR ion source gave slightly better numbers. Since this was before any acceleration, the beam bunchers did not affect the measurement at 0.9”. The transport efficiency from ILC02 to the inflector was about 65%, and it seemed that about half of the beam made it through the mirror inflector. Next, the beam transmission from 0.9” to 5”, which is after 7 to 8 turns for the 1st harmonic beams and 6 to 7 turns for the 3rd harmonics beams, was about 60% for the 1st harmonic beams and about 35 to 50% for the 3rd harmonic beams. The probe readings were obtained with the bunched beams using both the 1st and 2nd harmonics bunchers. The lower numbers for the 3rd harmonic beams seemed to be due to a smaller RF acceptance compared with the 1st harmonic beams. Also, the 2nd harmonic buncher was not always effective for the 3rd harmonic beams. Interestingly the 2nd harmonic buncher for the K150 cyclotron is much more effective than that for the K500. For example, for one 1st harmonic beam from the K150, the 1st harmonic buncher increased the beam intensity (on FC02) by a factor of 3.6 and then the 1st and 2nd harmonic bunchers together increased the beam by another factor of 1.7, for the total 6. On the K500, the 1st harmonic buncher boosts the beam by a factor of 2 to 4 and then the addition of the 2nd harmonic buncher helps only about 10% more. From R = 5" to 15", all beams had better than 85% transmission, except the 5 AMeV $^{40}Ar^{12+}$ only 65%.

Comparing with the center region calculations, a typical orbit of a 1st harmonic beam is shown in Fig. 3. Looking at the turn-to-turn radius of the orbits at 110 deg, which is the location of the target probe, for turns 1 to 6 the radii of the orbits are at 2.3", 3.1", 3.8", 4.4", 4.9", and 5.3". These numbers compare very well with the measured radii of 2.5", 3.2", 3.9", 4.4", 4.9", and 5.3". The agreement gives confidence to the dee voltage that was used. This dee voltage translates into about 340 turns inside the cyclotron for the 1st harmonic beams. Also, from the orbit calculations, about 40 degree width (out of 360) for the RF acceptance was found for proper accelerations, and this gives 6 x 40/360 = 0.67 (including 6 for the bunching factor) and this compares well with 60% efficiency measured for the 0.9" to 5" transmission. Thus, the overall 10% throughput may be understood by 0.1=0.35 (injection) x 0.6 (RF acceptance) x 0.85 (internal transmission) x 0.6 (extraction).

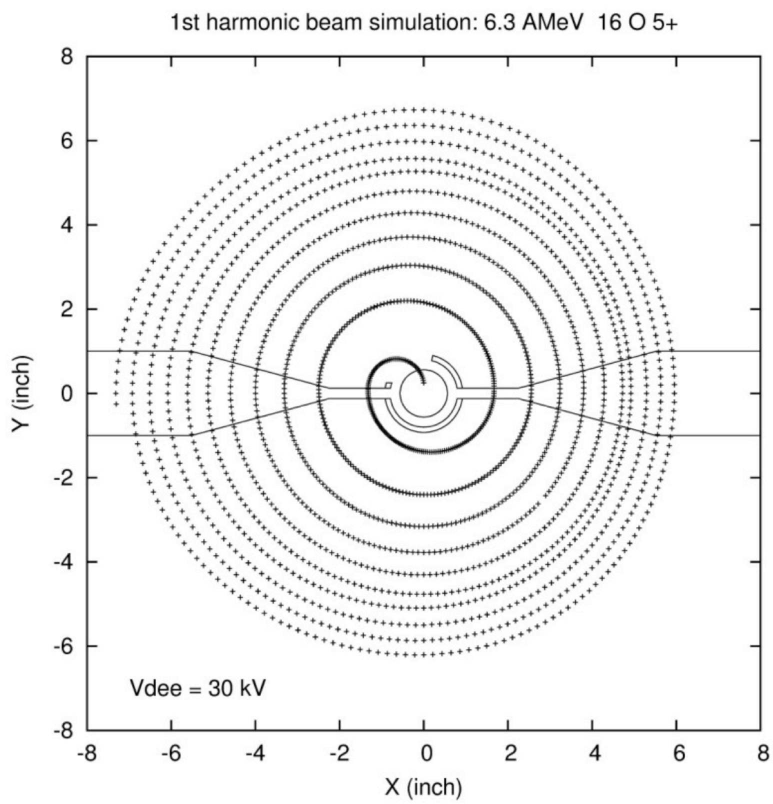

FIG. 3. First ten orbits of a 1st harmonic beam, specifically 6.3 AMeV $^{16}O^{5+}$, are shown. The beam exits from a mirror inflector at the center and into the dummy dee side before the acceleration begins.

Next, the 3rd harmonic beam data are compared with the center region calculations. A typical 3rd harmonic orbit is shown in Fig. 4. The radii of the first few orbits are at: 2.4", 3.5", 4.3", 5.0" and 5.6", which shows a little larger steps than the probe measurements of: 2.4", 3.1", 3.7", 4.3", 4.6", 5.1", and 5.4". Thus, it seems that the dee voltage used for the experimental measurements was less than the voltage for the calculation. Using a lower dee voltage in the calculation would have brought the orbit radii closer to the experimental numbers, however, it would have resulted in a smaller RF width for the acceptance. A computer simulation showed a 25 degree (out of 3×360, but 3 bunches per orbit) RF acceptance (using a 224 turn scheme) for the 3rd harmonics beams. The RF acceptance is then 6 x 25/360 = 0.4 (using the same bunching factor of 6), and this number is compatible with the measured 35 to 50% efficiency for the 0.9" to 5" transmission. There is undoubtedly some vacuum attenuation, especially for the slower 3rd harmonic beams, but it is not possible to separate out this effect from the RF acceptance at this time.

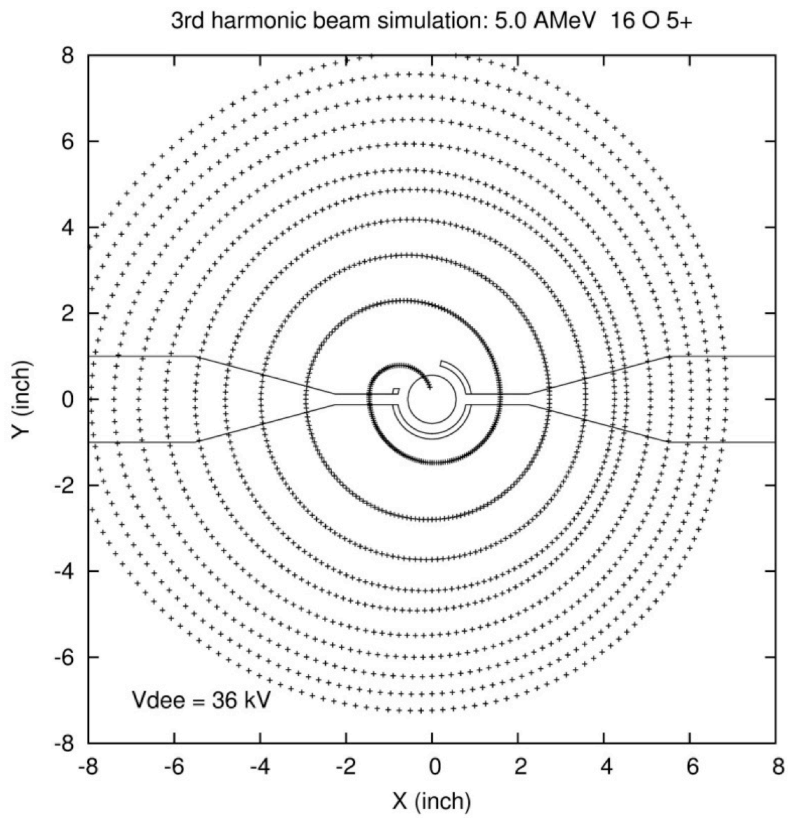

FIG. 4. 3rd harmonic beam simulation, specifically 5 AMeV $^{16}O^{5+}$ beam.

III. New Beam Tuning Scheme using VC04

For some beams a rapid intensity loss close to the extraction radius was observed. A new way of using VC04 (valley coil 4) was tried to reduce the beam loss near the extraction. In the past VC04 did not help to increase the beam current on FC02, and so it was usually not used. However, this time we tried to peak the beam current at the extraction radius with VC04 turned on and VC05 off. After that, we turned on VC05 to extract the beam onto FC02. The required VC05 bump was less and the bump angle was also different than if the beam was tuned without VC04. With the use of VC04, the beam loss at the extraction was reduced and the extraction efficiency improved. Using VC04 this way, we were able to tune out a few more (1st harmonic) beams in the fall of 2014 to get close to the desired 10% mark for the throughput.

IV. Light Ion Guide

The Light Ion Guide project continued to advance in the last year with the coupling of the Roots pumps chambers to the Charge Breeding-ECR Ion Source (CB-ECRIS). As explained previously [1], a campaign of experiments were performed in order to better characterize the device. Proton beams of 15 MeV and a natural zinc target were used to produce ^{64}Ga and ^{66}Ga as radioactive ion beams. The production cross-section for ^{64}Ga ($T_{1/2}$=2.6 min) is about 170 mbarn for 14.1 MeV, the final energy after passing through Havar windows in the target chamber. At this cross-section, sufficient products are stopped and extracted from the gas cell, as seen in the previous report. The 1 meter long RF-only sextupole was replaced by a shorter and larger one with the following characteristics: 2 sections of approximately 8 cm each long, with 4 mm diameter rods and the inner diameter of 8 mm (Fig. 5). This design is similar to the one presented in reference [2], although adapted to our chamber. The second section was replaced later with a longer one, double in length, in order to provide a better transport through the region of poor vacuum.

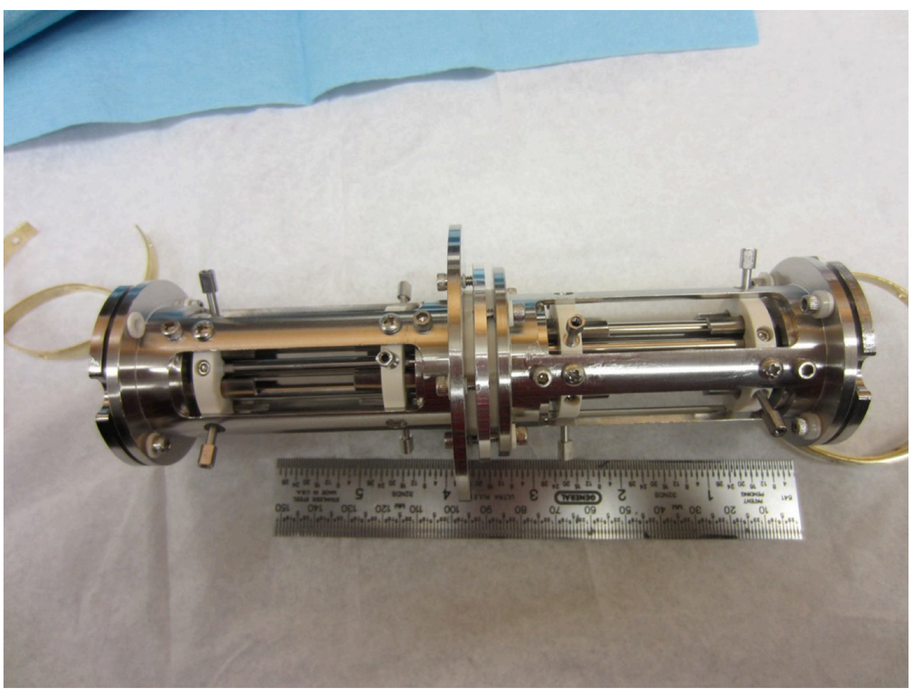

FIG. 5. The new RF-only sextupole before installation in the Light-Ion-Guide

The radioactive products are transported through the RF-only sextupole in the second Roots chamber where a grounded extraction tube was installed to provide the final acceleration (see Fig. 6). The region between the exit of the sextupole and the entrance to this tube should have good vacuum, so

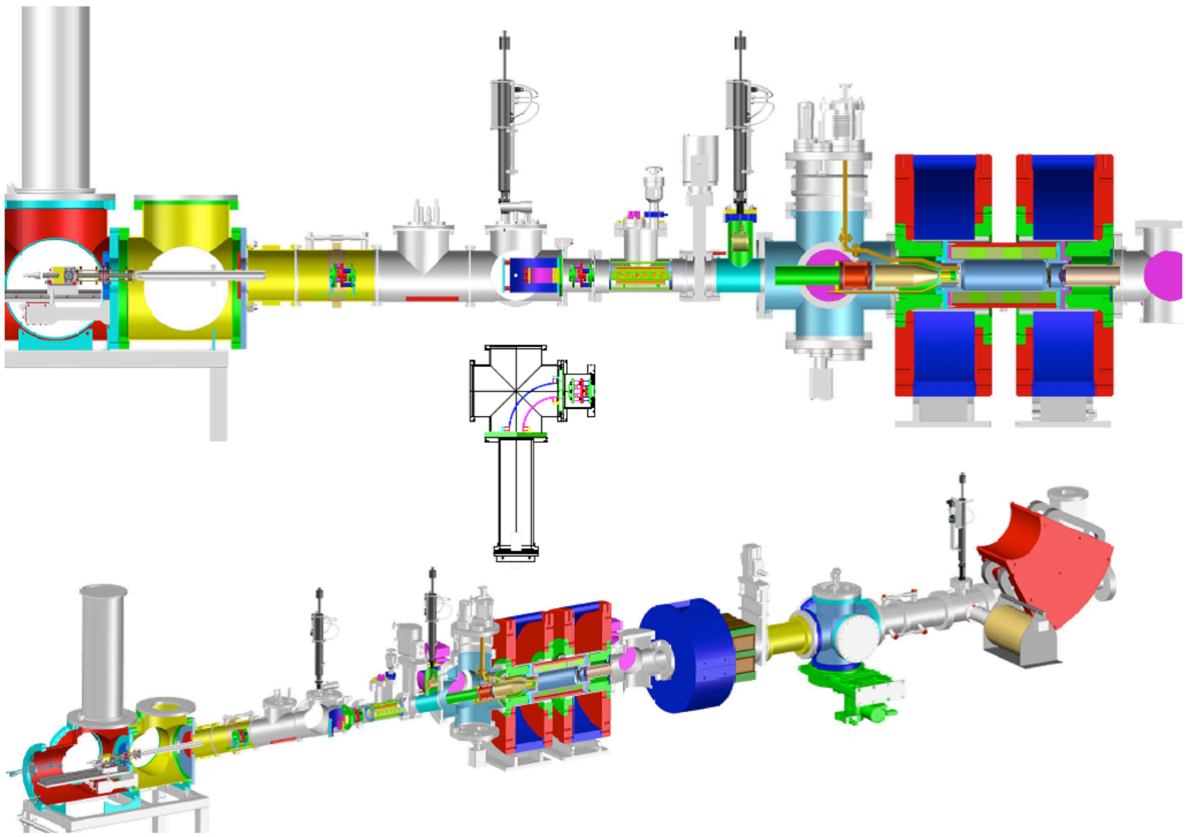

FIG. 6. Drawing of the Light Ion Guide coupled with the CB-ECRIS.

different strategies were tested and checked. Finally a turbo-molecular pump with 700 l/s pumping speed and a backing Roots blower of 1000 m^3/h pumping speed were chosen. A compromise in the vacuum design of the whole system, the Light Ion Guide plus CB-ECRIS, must be made: good vacuum in the sextupole-to-ground acceleration region and excellent vacuum (10^{-7} torr range) in the CB-ECRIS injection region in order not to overload the ion source. The acceleration tube has an inner diameter of 19 mm and various apertures can be mounted at its entrance. An aperture of 6 mm diameter was the best choice to provide good vacuum at the extraction end and 10^{-7} torr range at the CB-ECRIS injection region. Another important parameter to be selected is the distance from the exit of the sextupole and the extraction tube. Various tests were performed, using the ^{228}Th open source, and a distance of 25 mm was chosen as optimal. A shorter distance leads to the majority of the ions colliding inside the acceleration tube, and a larger distance leads to the ions being neutralized or scattered in the poor vacuum region. Simulations made with SIMION ion optics software show that for larger distances, better transmission is achieved, but the software does not take into account the transport through a poor vacuum region, so the direct comparison of SIMION with the experiment is not adequate.

The new set-up was tested first with the radioactive ^{228}Th open source and online with the proton beam on the zinc target. The tests performed using the ^{228}Th open source used a helium pressure of 28 mbar in the target chamber, consequently good vacuum was achieved along the beam line. However the on-line p+Zn tests use a helium pressure of 130 mbar and the transport of the radioactive ^{64}Ga was very sensitive to the vacuum conditions. With the choices mentioned previously we were able to find stable conditions and collect ^{64}Ga at the entrance of the CB-ECRIS. No transport efficiency was measured due to the difficulty of the measurements.

The next step was to transport ^{64}Ga through the CB-ECRIS and turn on the microwave power. The energy of the injected ^{64}Ga should be slightly above the CB-ECRIS plasma potential in order to achieve charge breeding. Multiple tunings were made to achieve the good transport settings, but due to the small amount of radioactivity involved and the difficulty of the measurements we only found settings with the energy of ^{64}Ga 3.5 keV higher than the CB-ECRIS potential. This energy difference is too big to achieve charge breeding, however interesting results were found: the radioactivity collected with the microwave turned on is higher than the case of the microwave turned off. Possible explanations for this behavior are either better focusing is achieved inside the plasma chamber, or more ions are produced by stripping or breaking complex molecules with radioactive products attached to it. In the Fig. 7 is represented the ratio of the number of counts from 991 keV line (^{64}Ga) to the Background for eight runs where the CB-ECRIS microwave power was turned on with different power settings and subsequently off.

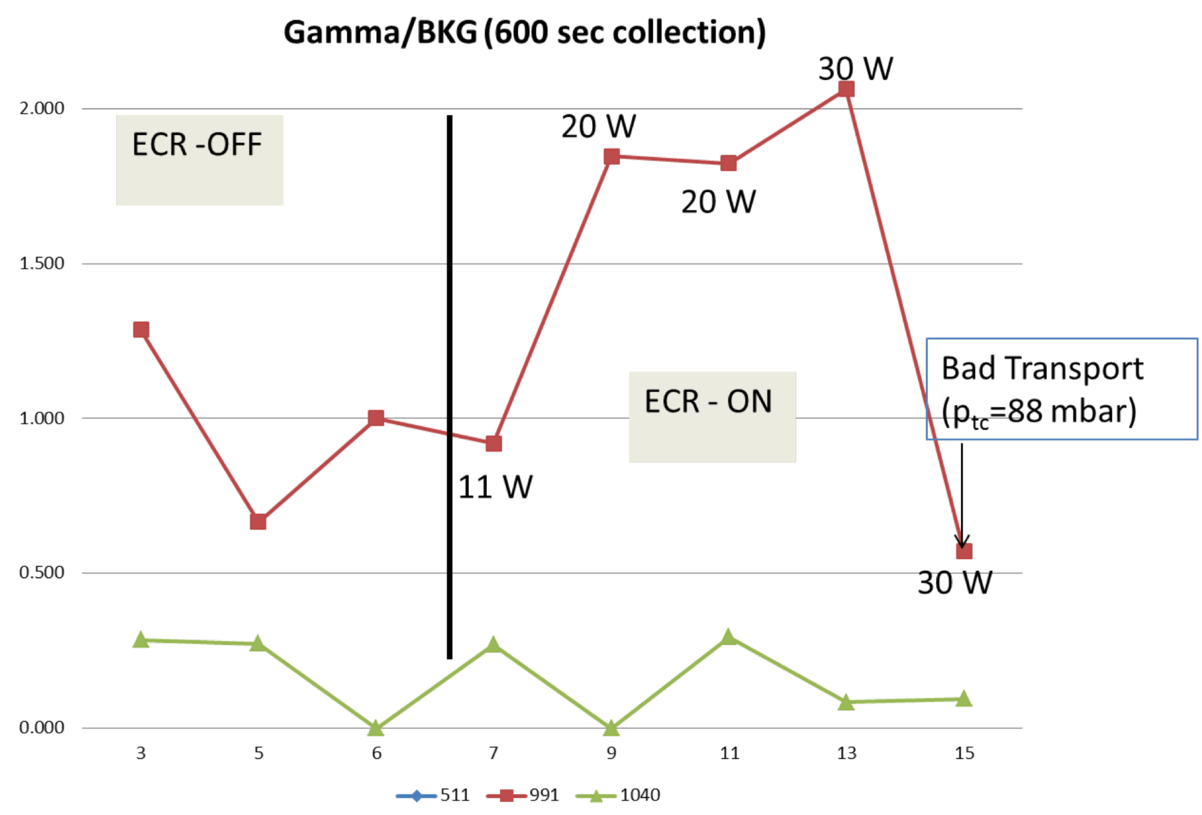

FIG. 7. Ratio of number of counts from 991 keV line (^{64}Ga) to the background for different runs with **microwave**

The lack of an efficient diagnostic system make the fine-tuning of the device very difficult. In the future our efforts will be directed towards improving the vacuum conditions in the second Roots chamber, finding better transport conditions for the radioactive products and developing an efficient diagnostic system for low intensity and low energy radioactive beams.

V. Heavy Ion Guide

The main components of the heavy-ion guide including the gas catcher and multi-RFQ have been assembled (see Fig. 8). Testing with a Cf source will begin in the fall.

FIG. 8. Heavy ion guide gas catcher (left) and multi-RFQ (right).

[1] G. Tabacaru *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2013-2014), p. IV-9. http://cyclotron.tamu.edu/2014%20Progress%20Report/cyclotron_progress_2014.pdf

[2] P. Karvonen *et al.*, Nucl. Instrum. Methods Phys. Res. **B266**, 4794 (2008).