Title
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Radiation Effects Testing at the 88-Inch Cyclotron[1]

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Abstract

The 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory provides radiation effects test facilities for both heavy ions and protons. The wide range of ions available, and the use of "cocktail" beams, allowing users to switch back and forth between several heavy ion beams without a retune of the accelerator, makes this facility a very versatile and economical choice for radiation effects testing.

Le 88-Inch Cyclotron, situé à Lawrence Berkeley National Laboratory délivrant des faisceaux d'ions légers et des ions lourds (de protons à ^{238}U). Cette diversité allait permettre d'utiliser les faisceaux d'ions composés – "cocktail", donc le expérimentateur peut choisir entre les différents ions sans changer la réglage du cyclotron. Cette possibilité fait le 88-Inch Cyclotron un centre de recherche des effets de la radiation tres pratique et économique.

I. INTRODUCTION

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory is run by the U.S. Department of Energy for basic research in low energy nuclear physics and chemistry. Up to 1000 hours/year is available for applied work on a recharge basis. Much of that time is used for radiation effects testing (RET) and a lesser amount for calibration of detectors for upcoming space flights. Other applications include radiation hardness measurements of bulk material and some ion implantation studies.

II. THE CYCLOTRON AND ITS BEAMS

The central component of the 88-Inch facility, shown in Figure 1, is a sector-focussed, variable-energy cyclotron fed by two Electron Cyclotron Resonance (ECR) high charge-state ion sources, the LBL-ECR and the recently upgraded Advanced ECR, the AECR-U. Light ions — p, d, ^{3}He and ^{4}He – are produced up to total energies of 55, 65, 135 and 130 MeV, respectively. Light heavy ions can be produced at energies up to 32 MeV/nucleon. As the mass increases, the maximum energy per nucleon decreases. 45 different elements and 95 isotopes have been accelerated through the 88-Inch Cyclotron, including the radioactive beam ^{11}C. Other beams can be developed as needed.

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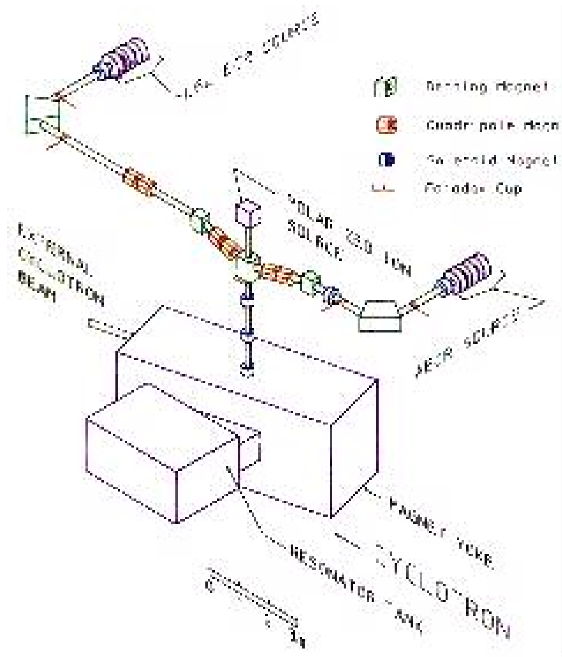

Figure 1. The 88-Inch Cyclotron and its Sources

A. High LET Beams

During the last several years a series of upgrades to both the ion sources and the cyclotron have led to progressively higher intensities of the heavier ions. Figure 2 gives the maximum energy at 1 pnA of beam as a function of mass for the past, present and future ion sources.

In 1996 the AECR-U source was upgraded to give higher ionization efficiencies for high charge states of heavy ions. Vacuum improvements in the extraction region of the cyclotron in 1998 improved the transmission for these high charge state ions by a factor of three. Table 1 gives measured energies and intensities for accelerated ultra-high charge state beams of Bi and U. At the present time, the 904 MeV Bi beam – with a Linear Energy Transfer (LET) in silicon of 98 MeV/mg/cm^2 – is routinely available for RET work. At low intensities, higher energy heavy beams can be obtained on request.

Included in Figure 2 are estimates for VENUS, a third generation, superconducting ECR source which is slated to begin operation in 2002. VENUS will expand the capability of the Cyclotron to allow acceleration of ions at energies above the Coulomb barrier for the full range of stable elements. Using VENUS, it will be possible to run a beam of 2.1 GeV Bi, with an LET of 92 MeV/mg/cm^2 and with a range of >100μ, twice that of the 900 MeV Bi beam.

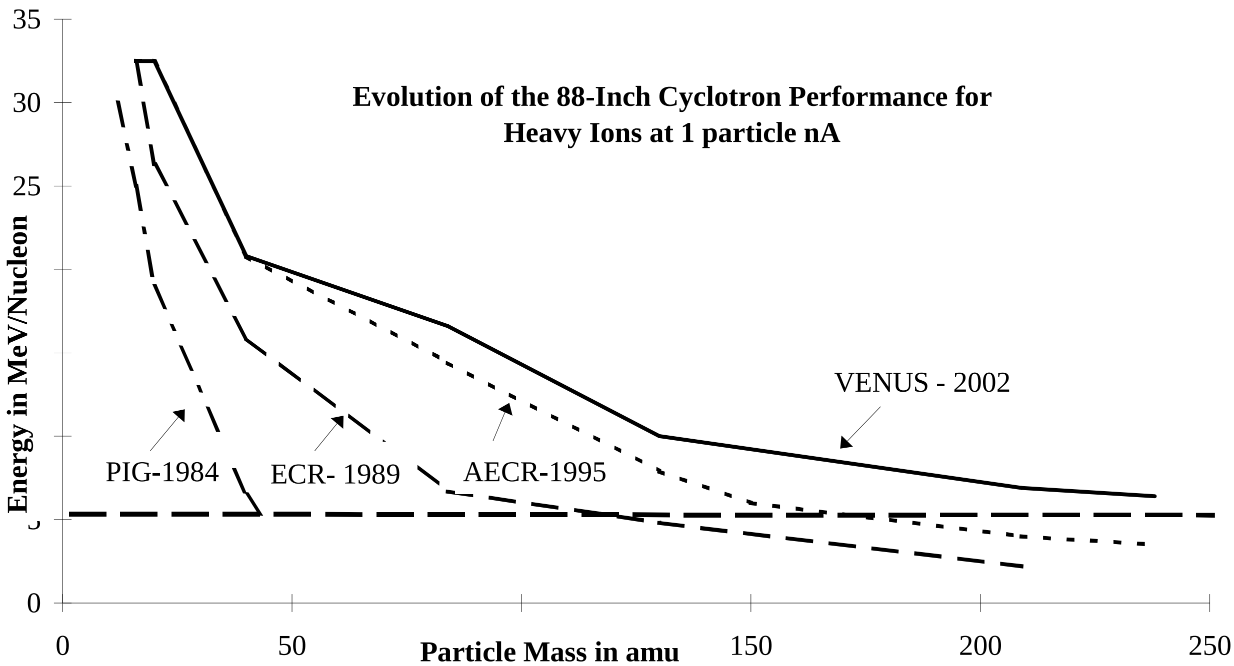

Figure 2. Performance of the 88-Inch Cyclotron with present and future ion sources.

Table 1. Ultra-high Charge States accelerated through the 88-Inch Cyclotron

Ion	E/A (MeV/u)	E (MeV)	I_{ex} (pnA)
$^{209}Bi^{41+}$	4.31	904	92
$^{238}U^{47+}$	4.68	1115	14
$^{238}U^{49+}$	5.09	1211	4
			(pps)#
$^{238}U^{60+}$	7.62	1814	507
$^{238}U^{61+}$	7.88	1875	427
$^{238}U^{62+}$	8.13	1936	110
$^{238}U^{63+}$	8.40	1999	24
$^{238}U^{64+}$	8.67	2063	10

Identified using a silicon particle detector

B. Cocktail Beams

The combination of cyclotron and ECR source provides the unique ability to run "cocktails" of ions. [1] A cocktail is a mixture of ions of near-identical charge-to-mass (q/m) ratio. The ions are tuned out of the source together and the cyclotron acts as a mass analyzer to separate them, allowing one to switch from one ion to another with small adjustments of the accelerator RF frequency. This means that the ion and therefore the linear energy transfer (LET) delivered to the component can be changed in approximately one minute. Intensity variations between the components of the cocktail are compensated for with a series of attenuator grids at the ion source which allow adjustments over nine orders of magnitude.

The four cocktail combinations most commonly in use at the 88-Inch Cyclotron are summarized in Table 2, with the LET versus range for each element plotted in Figure 3. Certain elements of each cocktail (solid squares in Figure 3) are standard, others (open squares) can be added as needed. For example, the 4.5 MeV/nucleon heavy ion cocktail is the combination most commonly used for RET work and, in standard form, gives a LET range of 2.9 to 61.8 MeV/mg/cm^2. If lower LET is needed, B can be added at 1.5 MeV/mg/cm^2. For higher LET, Bi (LET = 98.3 MeV/mg/cm^2) is run. Bi requires an oven and use of the AECR-U, so several weeks notice must be given.

The cocktail method is limited by the resolution of the RF frequency of the cyclotron. This has proven to be a problem at some cyclotrons used for RET work. In the case of the 88-Inch, the frequency resolution is approximately 2 khZ. Table 3 gives the cyclotron resonance table for the 4.5 MeV/u cocktail, with the elements of the full cocktail in boldface. One can see that in most cases, the frequency difference – proportional to the mass difference between species – is sufficient to cleanly separate them. The exception to this is Ar and Cu, which have a frequency difference of 2.4 kHz. Contamination of the Ar would also arise from ^{80}Kr and ^{130}Xe; in order to avoid this,

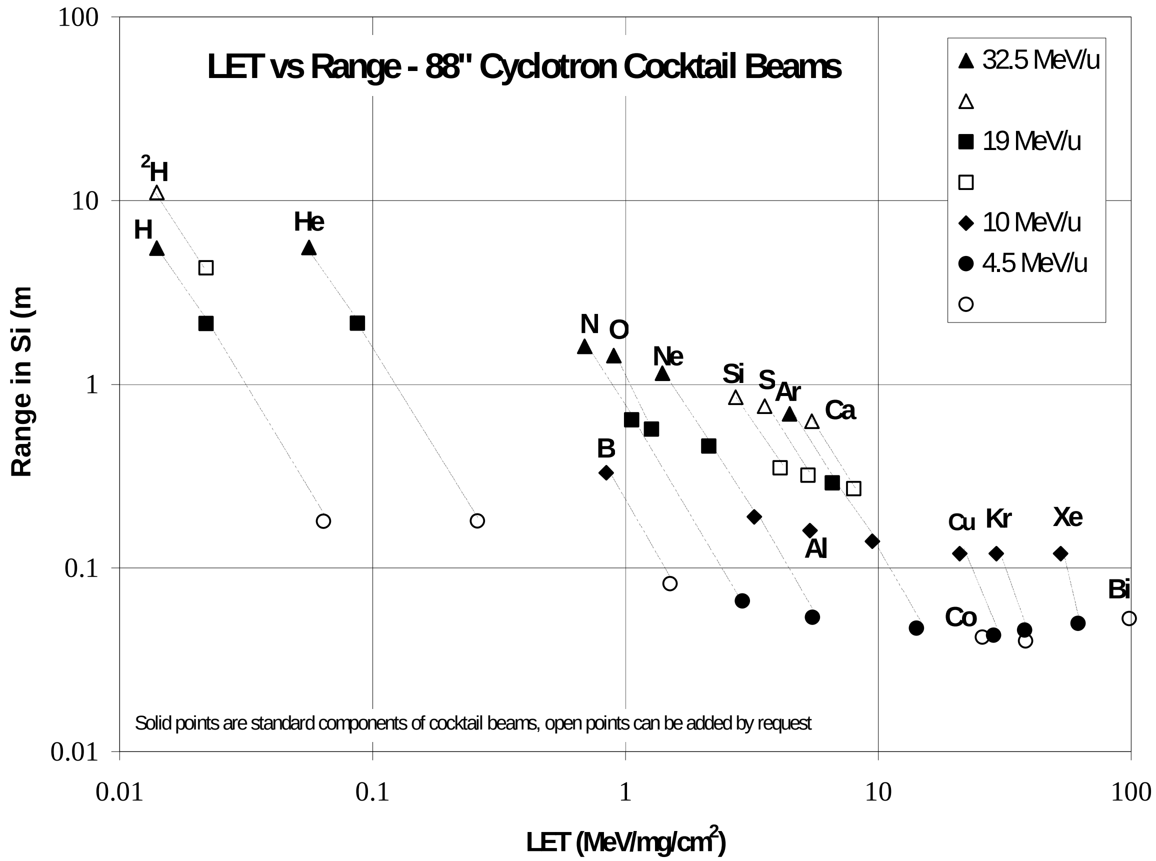

Figure 3. LET versus Range for the four standard cocktail beams listed in Table 2. Standard components are shown with solid squares and additional components with open squares.

Table 2. Summary of commonly used cocktail beams

Cocktail	Standard Ions	Other Ions[a]	LET (MeV/mg/cm$^{2)}$	Range in Si
4.5 MeV/nucleon (q/A = 0.2)	^{15}N, ^{20}Ne, ^{40}Ar, ^{65}Cu, ^{86}Kr, ^{136}Xe	HeH[b], ^{10}B, ^{59}Co, ^{78}Kr, ^{209}Bi	2.9-61.8 (standard) 0.26-98.3 (all)	43-69 μ (standard) 40-180 μ (all)
10 MeV/nucleon (q/A = 0.3)	^{10}B, ^{20}Ne, ^{27}Al, ^{40}Ar, ^{63}Cu, ^{86}Kr, ^{136}Xe	None	0.84-52.7	115-330 μ
19 MeV/nucleon (q/A = 0.5)	H_2[b], ^{4}He, ^{14}N, ^{16}O, ^{20}Ne, ^{36}Ar	^{2}H, ^{28}Si, ^{32}S, ^{40}Ca	0.022-6.58 (standard) 0.022-8.01 (all)	0.29-2.15 mm (standard) 0.27-4.29 (all)
32.5 MeV/nucleon (q/A = 0.5)	H_2[b], ^{4}He, ^{14}N, ^{16}O, ^{20}Ne, ^{36}Ar	^{2}H, ^{28}Si, ^{32}S, ^{40}Ca	0.014-4.46 (standard) 0.014-5.46 (all)	0.69-5.56 (standard) 0.63-11.1 (all)

[a]These ions require special arrangements and advance notice.

[b] LETs and Ranges for molecular ions are calculated for separate components after breakup in target or scattering foil.

the cocktail beam is run with separated isotopes of ^{86}Kr and ^{136}Xe. The cross-contamination of Ar and Cu can be alleviated in one of two ways: a) some groups have chosen to use Co as a mid-range LET ion instead of Cu, or b) careful tuning of the frequency away from the center of the intensity peak can get rid of the interfering beam. This is done while monitoring a particle detector.

Sometimes ions which have run recently in the ion source for other experiments remain in the source for a period of up to weeks, and can overlap in frequency with members of the cocktail. For example, if Cl or Ti have been recently in the source, they can interfere with the Ar or Cu beams. These are dealt with on a case-by-case basis with careful tuning. In FY2000, it is planned to commence a development project to improve the frequency resolution of the 88-Inch Cyclotron. This will benefit the radioactive beams program as well as improve the cocktail beams for RET work.

The versatility of the ECR/cyclotron combination allows other tricks, such as quickly changing the beam energy by changing the charge state of the ions. [2] This results in expanded versions of the heavy ion cocktails which are not included in Table 1. For example, the standard 10 MeV/nucleon cocktail contains seven elements. With expanded tuning, N, O, Si and S are available, as well as a wider range of energies for the standard components. For example, by varying the charge state of the ^{136}Xe from +34 to +42, the energy changes from 1014 to 1544 MeV and the LET from 52.0-57.4 MeV/mg/cm^2 over ≈0.7 MeV/mg/cm^2 steps.

Table 3. Resonance table for 4.5 MeV/u cocktail and common contaminants

Ion	Energy (MeV)	Frequency (MHz)	Δf rel. to ^{40}Ar (kHz)
$^{10}B^{+2}$	**44.9**	**14.20604**	**-31.6**
$^{15}N^{+3}$	**67.4**	**14.2786**	**-13.4**
$^{20}Ne^{+4}$	**89.9**	**14.2840**	**-8.0**
$^{30}Si^{+6}$	135.0	14.2911	-0.9
$^{35}Cl^{+7}$	157.5	14.2913	-0.7
$^{40}Ar^{+8}$	**180.**	**14.292**	**0.0**
$^{50}Ti^{+10}$	225.0	14.2943	2.3
$^{59}Co^{+12}$	**274.6**	**14.5346**	**242.6**
$^{65}Cu^{+13}$	**292.5**	**14.2944**	**2.4**
$^{80}Kr^{+16}$	360.0	14.2935	1.5
$^{86}Kr^{+17}$	**378.1**	**14.1287**	**-163.3**
$^{130}Xe^{+26}$	584.9	14.2892	-2.8
$^{136}Xe^{+27}$	**602.9**	**14.1843**	**-107.7**
$^{209}Bi^{+41}$	**904.2**	**14.0092**	**-282.8**

B. Protons

Protons are available over the energy range of 1-55 MeV, and at currents ranging from a few hundred ions/sec up to 20μA. Depending on the size of the area to be irradiated and the dosimetry method employed, total doses of 10^{15} ions/cm^2 can easily be obtained and higher doses are feasible.

III. THE RADIATION EFFECTS TEST FACILITIES

A map of the 88-Inch facility is shown in Figure 4. Two main "caves", shaded on the map, are dedicated to applied work. Cave 4b is used for heavy ion tests and Cave 3 for protons and other light ions.

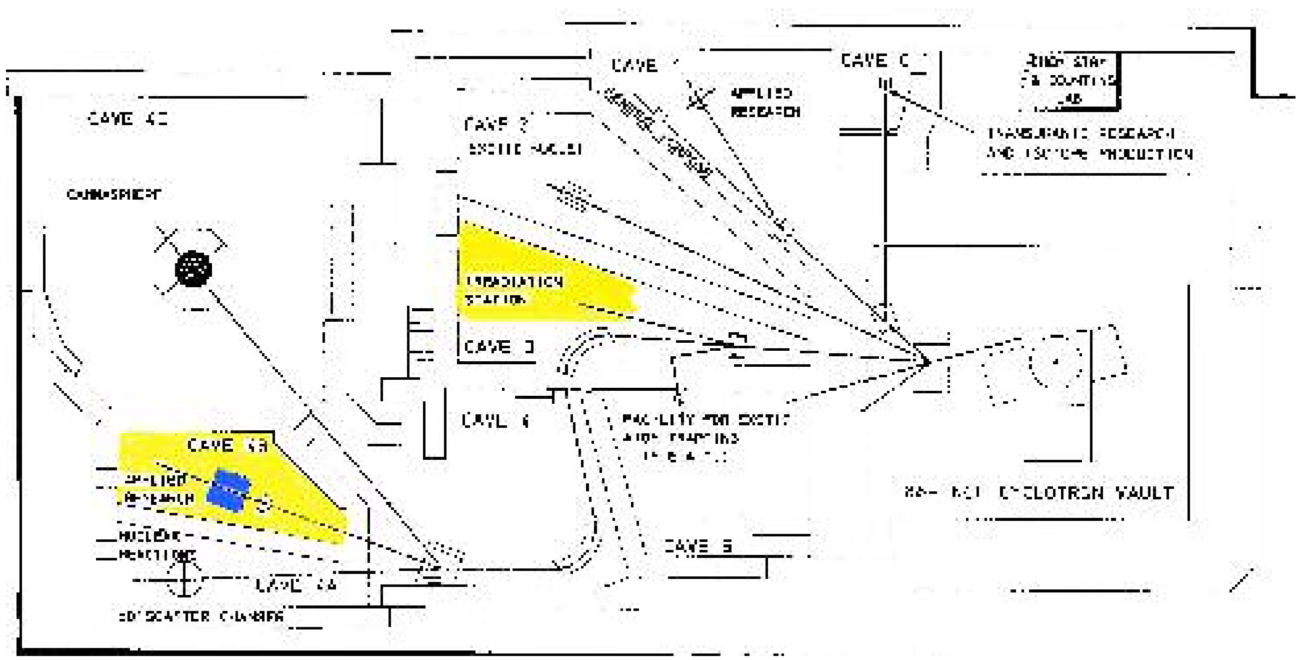

Figure 4. Map of 88-Inch Cyclotron Facility

A. *The Cave 4b RET Chamber*

The primary test chamber for heavy ion RET studies is located in Cave 4b, in which Aerospace Corporation and 88-Inch Cyclotron Operations have collaborated to install an end station for RET and detector calibrations. The vacuum chamber, shown in Figure 5, is large in order to accommodate large circuit boards or whole systems. It has been designed to pump down in only a few minutes. A special table allows remote movement of the circuit board in any direction or angle, and a laser and CCD camera system enables alignment of parts remotely while under vacuum. The vacuum controls are presently being upgraded to allow remote operation as well.

Figure 5. Aerospace test chamber in Cave 4b

A diagnostic box, shown in Figure 6, is located upstream of the main vacuum chamber. It contains a scintillator system for dosimetry, a silicon detector for energy measurements and various collimators and shutters. These can be operated manually from within the cave, or remotely from the counting trailer.

Flanges are available with various kinds of connectors to interface to the outside of the vacuum system. BNC, SHV and ribbon cables run approximately 10 meters to a trailer located directly above the cave. The trailer contains electronics and computers for dosimetry plus room to set up user electronics and diagnostic equipment.

The counting trailer, shown in Figure 7, is located directly above the cave on the roof to minimize the length of cables. Computer software has been developed by Aerospace Corporation which can 1) control the high voltage and thresholds for the scintillator photomultiplier tubes, 2) control the laser and CCD camera and give a view of the chamber on line, 3) control the position of all elements in the diagnostic box, 4) control the position of the table in the x,y and z planes, 5) allow the rotation of a DUT to an arbitrary angle, 6) record the dosimetry and upset date in a spreadsheet and 7) plot an upset curve versus LET. A simplified version of this software is supported by 88-Inch Operations staff and is available for general users.

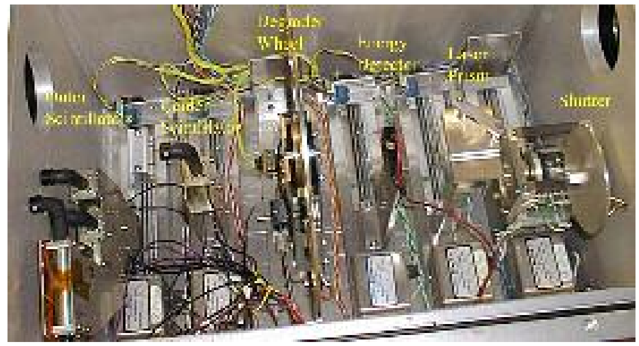

Figure 6. Cave 4b RET diagnostic box showing various components.

B. *The Light Ion Irradiation Station*

The Irradiation Station, located in Cave 3, was developed for biology studies, and is used extensively for biology, high energy and applied irradiations with protons and other light ions. Experiments are set up in air on an optical bench. A uniform beam (to approximately 5%) can be delivered with a diameter up to 10 cm. Large diameter beams are achieved through a combination of Ta scattering foils and beam optics. Uniformity and dose are measured using a segmented ionization chamber. A Faraday cup is available to verify the calibration of the ionization chamber. It can also be used to measure the dose for very low energy runs when the energy straggling in the ion chamber is unacceptable. In this case users must leave a hole in the center of their sample to allow some beam to get through to the Faraday cup.

A Macintosh/Labview[‡] system displays dose and flux and controls the beam for runs at the Cave 3 Irradiation Station. Other available equipment include an X-ray film developer for confirming beam uniformity and silicon detectors for measuring beam energy.

For some applications a larger beam is required. In these cases the ionization chamber can be set up in Cave 4a, which has a 20 cm diameter beam line. A large vacuum chamber in this cave can be used for large-area heavy ion irradiations . An automatic sample changer is available for implantation of silicon wafers of either 7.6 cm or 15 cm in diameter. A set of scintillators similar to those used in the Cave 4b RET setup is used to measure the dose.

Figure 7. The RET counting trailer with Rocky Koga of Aerospace Corporation

IV.FUTURE DEVELOPMENTS

Radiation effects testing is a small but vital part of the program at the 88-Inch Cyclotron. Many development projects are underway for the nuclear science programs at the Cyclotron which will have a direct benefit to the RET community.

In the near future, vacuum improvements have already increased by a factor of three the transmission of very high charge state beams through the Cyclotron. Further vacuum improvements are ongoing. In 2002, the next generation ECR source, VENUS, will begin operation. VENUS will allow the acceleration of bismuth to more than double the present energy – and thus double the range, important for many modern parts.

Improvements in the frequency resolution of the cyclotron will also benefit users of the cocktail beam,decreasing the contamination between the Ar and Cu beams within the cocktail and between cocktail ions and other species which may be present in the ion source in small amounts. For the standard 4.5 MeV/u cocktail this is an annoyance rather than a problem – there is plenty of Ar and Cu to throw away by detuning the frequency for both species. However, improvements in the frequency resolution will clean things up and make the tuning more efficient.

In addition to improvements in the Cyclotron and its beams, the Cave 4b RET facility will become more user friendly in the near future through efforts on two fronts:

a) The hardware and software for the table in the main vacuum chamber and for the components in the diagnostic box is being made more reliable and easier to use through an effort by Aerospace Corporation.

b) 88-Inch Operations engineers are in the process of installing a Program Logic Control system to control the vacuum of the main chamber. This will allow users to vent and pump down the chamber using a simple computer interface.

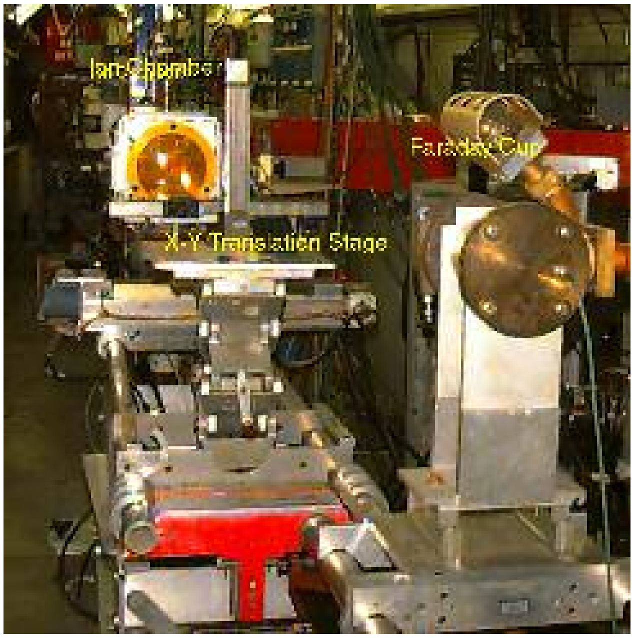

Figure 8. Light Ion Irradiation Station showing the ion chamber and Faraday Cup for dosimetry. All components are placed on a translation table on an optical bench for easy alignment.

‡ ™National Instruments, 6504 Bridge Point Parkway, Austin, TX 78730

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