



## **UC Davis 76 Inch Isochronous Cyclotron: Radiation Effects Infrastructure**

**For questions regarding this document please contact:**

Spencer C. Hartman, Ph.D.  
Head Space and Radiation Effects Facility & Cyclotron  
Cell: 530-388-0083  
ScHartman@UCDavis.edu

Mailing Address:  
Crocker Nuclear Laboratory  
University of California, Davis  
One Shields Avenue  
Davis, CA 95616

Physical Address:  
210 Jungerman Hall

# UC Davis Cyclotron Facility Capabilities

## Beam Properties:

### Summary:

The UC Davis 76 inch cyclotron was designed and built for nuclear physics research and as such has the capability to tune the beam energies continuously across their ranges as shown in table 1. This results in very clean beams with low energy spreads that are ideal for Space and Radiation testing.

The Space and Radiation Effects Facility is limited to 100 nA at the radiation effects experimenter location for radiation safety. Users typically use 50 pA to 100 nA under normal conditions. Fluences can be easily varied from  $5.0 \times 10^4$  to  $1.6 \times 10^{10}$ . Higher current can be run, but these may result in higher activation levels.

### 1. Particle species available.

Protons, Deuterons, Alphas, Neutrons, Helions are available. The Proton beam is most commonly used for space and radiation effects testing. Since the Davis cyclotron does not have a heavy ion source there are no common groups or cocktails produced. Table 1 gives a summary of the particles typical parameters. The Neutron Beams are generated from bombarding targets with the proton beam so all fluxes are determined by the users target configuration.

**Table 1. Beam Parameters**

Particle	Max Energy MeV	Max Current in uA	Max Flux protons/(cm2-sec)
Protons ( <sup>1</sup> H)	67.5	0.100	$1.6 \times 10^{10}$
Deuterons ( <sup>2</sup> H)	45	0.100	$1.6 \times 10^{10}$
Alphas ( <sup>4</sup> He)	90	0.100	$8 \times 10^9$
Helion ( <sup>3</sup> He)	130	0.100	$8 \times 10^9$

### 2. Typical particle energies that are operational.

The Proton beam is the radiation effects main particle and is tuned typically to 67.5 MeV. The beam is also tuned to the following energies: (6.3, 7.5, 8.1, 10.7, 12.5, 14.6, 17.5, 20, 25, 30, 35, 40, 45, 50, 55, 60, and 67.5) MeV. The currents are typically in the range of 50 pA to 100 nA.

The Deuteron beam is currently used to produce small quantities of designer radioactive materials for nuclear nonproliferation detection standards. Deuteron beams are typically run at 40 MeV and 100 nA. The Deuteron beam has also been run at the following energies: (20, 25, and 30) MeV.

The Alpha beam is typically run at the following energies: (18, 30, 40, 45, 50, 55, 60, 70, 75, and 80) MeV. The Alpha beam maximum current is 100nA.

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The Helion, ( $^3\text{He}$ ) beam is typically run at the following energies: (6.2, 9, 18, 22, 24, 55) MeV. With the Helion beam maximum current is 100 nA. Table 1 gives a summary of typical beam parameters.

The Neutron Beams are generated from bombarding targets with the proton beam so all fluxes are determined by the users target configuration.

### 3. Operational fluxes.

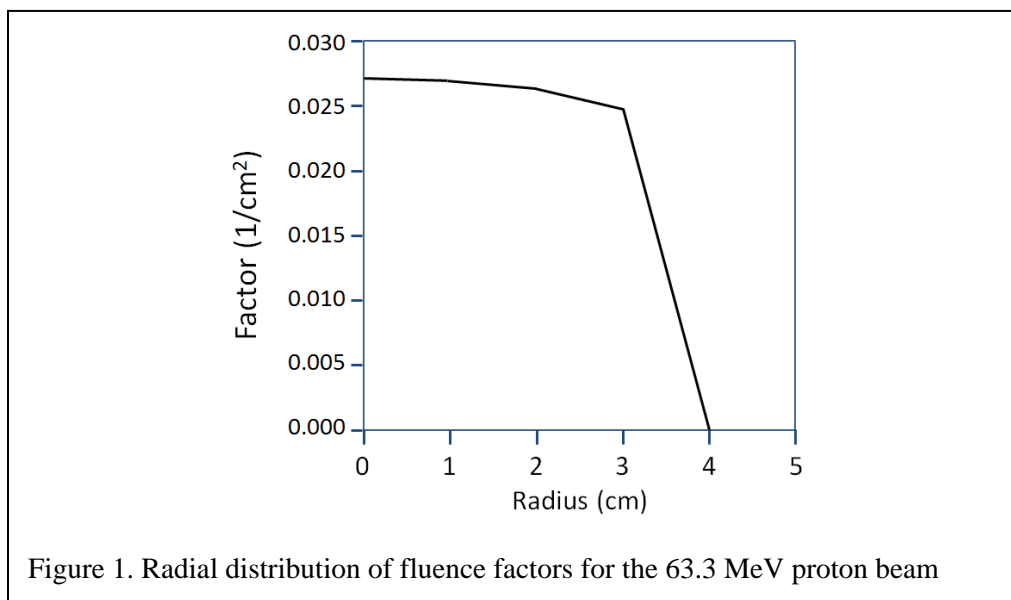
The typical flux is  $1.6 \times 10^8$  with the maximum flux of  $1.6 \times 10^{10}$ . Protons and Deutrons can run up to a maximum flux of  $1.6 \times 10^{10}$ . Alphas and Helions can run up to maximum flux of  $1.6 \times 10^9$ . Table 1 gives a summary of beam parameters.

### 4. Typical beam diameter.

The typical beam diameter is three inches (7.6 cm). It can be restricted to any smaller size with apertures. The beam size can be enlarged by additional defocusing beam optics, a wobbler, or a diffuser foil.

### 5. Beam uniformity.

The typical beam diameter is three inches (7.62) cm. The beam intensity profile is measured with a Gafchromic film. Within a radius of 2.0 cm, the beam intensity varies by no more than 5%. The uncertainties in the fluence at 0 cm, 1 cm and 3 cm from the beam center are estimated to be less than 4%. Figure 1 shows the measured beam profile. As discussed at our meeting, the addition of a heavy ion source will expand the cyclotron's capabilities accordingly. Figure 2 demonstrates some of the possibilities.



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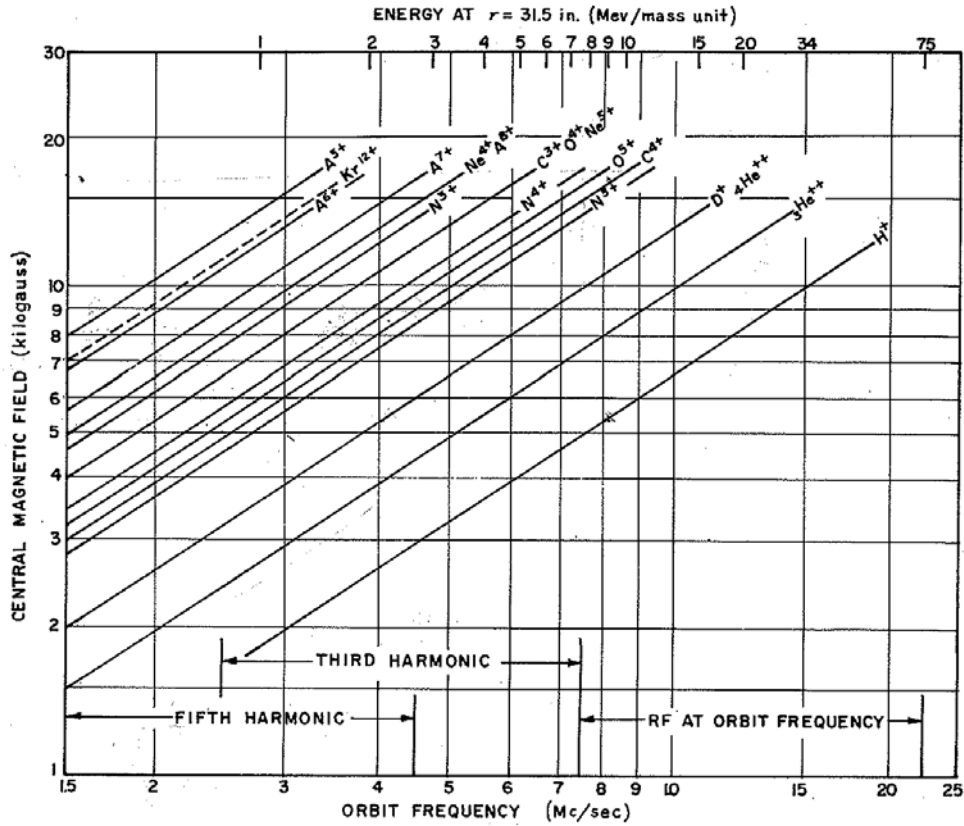


Figure 2. 76 Inch Cyclotron Tune Diagram

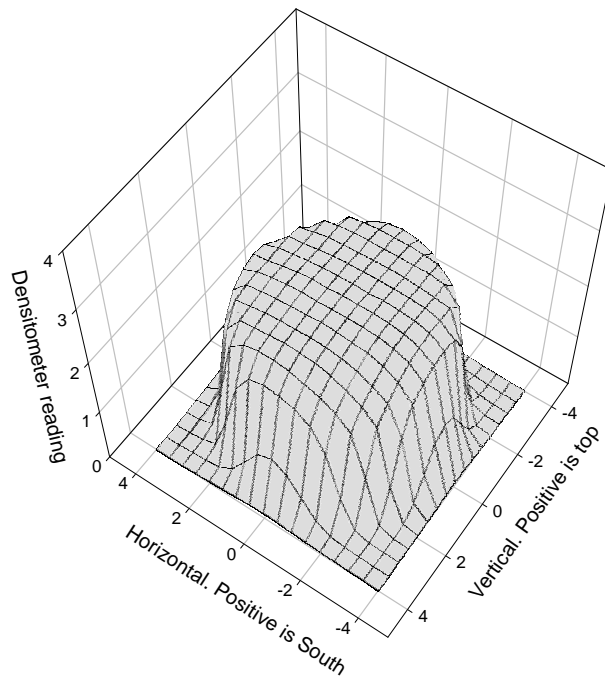


Figure 3. Spatial distribution. BL2 67.5 MeV on 0.015" Ta Final Energy 63.3 MeV

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6. The dosimetry used to measure the beam flux, fluence, and/or dose. What is the expected accuracy / precision of the measurements.

The beam fluence can be measured to an accuracy of 2%. The dose measurement and beam distribution is achieved by the use of a combination of a Secondary Electron Emission Measurements, SEEM, and a retractable Faraday Cup, FC, and GAFchromic film for relative spatial beam distribution. The software used in the dose measurements at CNL requires the relative distribution of the beam in concentric circular sectors. The factors used to obtain the fluence at a given radius are extracted from the exposed film. The film is scanned on a 8 cm by 8 cm grid with 5 mm pixels. From this 17 by 17 matrix, factors are obtained for extracting the fluence as a function of the distance from the center of the beam. Figures 2 and 3 show the spatial distribution of these factors.

Table 2 shows the values of the multiplying factors at the center, and at 1cm, 2cm, and 3cm radius. Column 2 is for 63.3 MeV obtained using the Gafchromic HD-810 film with a beam flux of  $3.5 \times 10^9$  p/cm<sup>2</sup>-sec (0.47 KradsSi/sec) for a dose of 28 KradsSi. Column 3 and 4 are the values for beam flux of 200 p/cm<sup>2</sup>-sec, 27 and 62  $\mu$ radsSi/sec, respectively, for energies of 63.3 and 21.6 MeV. The low flux values were measured with two Bicron CsI(Tl) detectors coupled to Si photodiodes. Measurements at 1, 2, and 3 cm were taken at 8 different angles and normalized to the center detector. The average of these 8 values was used to obtain the factors at the different radius. The beam distribution is independent of beam intensity and the Tantalum diffuser thickness was chosen to produce a beam distribution that is nearly independent of beam energy. The fluence for a given radius at the Device Under Test, DUT, location is given by multiplying the total number of particles collected in a run by these factors.

**Table 2. BEAMMON Multiplying Factors for Calculating Fluence**

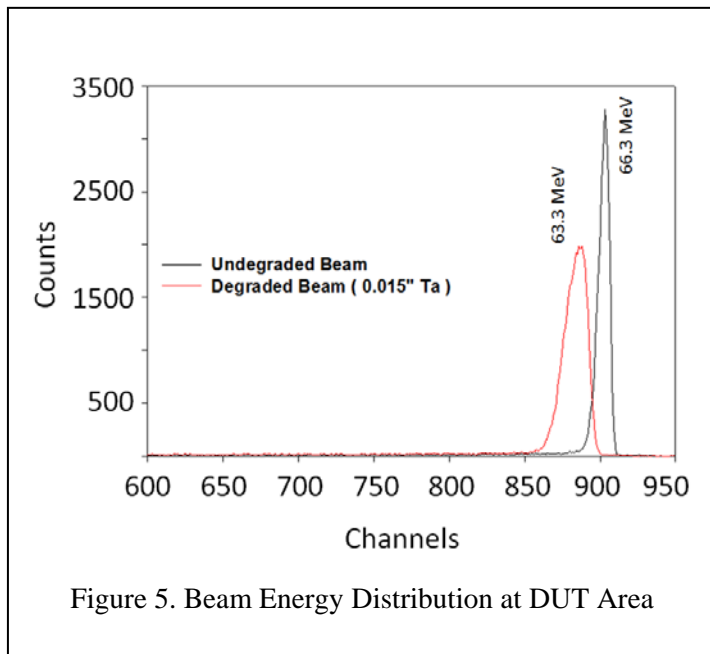
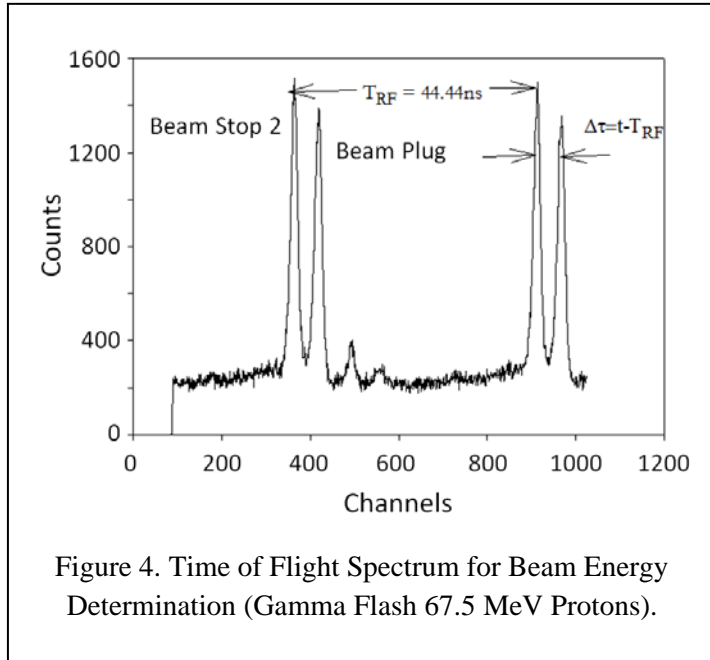
Radius in cm	Factor in 1/cm <sup>2</sup> Gafchromic film @63.3MeV	Factor in 1/cm <sup>2</sup> CsI(Tl) detector @63.3MeV	Factor in 1/cm <sup>2</sup> CsI(Tl) detector @21.6MeV
0	0.0273	0.0276	0.0276
1	0.0272	0.0276	0.0270
2	0.0267	0.0276	0.0262
3	0.0251	0.0243	0.0175

To check the values given by the combination of SEEM, FC and beam distribution, an external Faraday Cup (EFC) is placed at the DUT position, and the beam collimated by a 1 X 1 cm<sup>2</sup> aperture. With this arrangement the central fluence is sampled and directly compared to the central value using our BEAMMON software package. The current from the EFC was integrated by an ORTEC 439 Digital Current Integrator, coupled to an ORTEC 771 Time Counter. Table 3 compares the values by BEAMMON and from the External Faraday Cup. The agreement is good with a systematic difference of 2%.

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**Table 3. BEAMMON and External FC Center Fluence for 63.3 MeV**

Beammon Fluence Protons cm <sup>-2</sup>	Efc Fluence Protons cm <sup>-2</sup>	Ratio Efc/Beammon
2.19 E11	2.23 E11	1.02
2.18 E11	2.22 E11	1.02
2.20 E11	2.22 E11	1.01



Regarding the cyclotron beam energy measurement and particle identification, a time of flight (TOF) system, based in the work of Jungerman et al. has been implemented to measure the cyclotron beam energy. The TOF system consists of a plastic scintillator to measure the gamma flash from two beam stops intercepting the beam. The method measures the time a particle travel between the two stops. The time spectrum from the gamma flash from the stops with respect to the radio frequency (RF) is recorded. From the time spectrum we obtain the proton transit time between both stops. In this measurement, only one every other RF pulse is used to stop the Time to Analog Converter (TAC), furnishing two peaks from each one of the stops as shown in Figure 4. The time calibration uses the RF period ( $T_{RF}$ ) and the channel difference from peaks produced in the same stop. Linearity of the TAC is checked by the separation of both sets of peaks ( $\Delta\tau$ ). With this method the energy can be determined with a precision of 0.1 MeV.

The beam energy distribution at DUT position, for a 67.5MeV proton beam, is shown in Figure 5. The beam was collimated to 0.64 cm spot on a 1 cm<sup>3</sup> Bismuth Germanate Oxide (BGO) detector. The crystal was coupled to a Hamamtsu R6095 photomultiplier. The same figure displays the spectrum for the beam diffused by a 0.0381 cm thick

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Tantalum foil. For both cases there is a long tail after the beam peak. This tail is produced by the interaction of the beam protons and the nuclei in the detector. For energies of 67.5 and 63.3 MeV, the tail to peak ratio is generally between 5 and 10%. The size of the tail is very much the same for both cases. The major difference in the spectra is the width of the peaks. For the diffused beam, the FWHM is 1.7 times the FWHM for the undegraded beam.

### 7. Initial tuning time for a new beam or particle group.

#### a. Heavy ions: switching time from one ion species to another (within a group).

CNL does not have a heavy ion source. The Cyclotron is however designed for heavy ion acceleration and has all of the necessary penetrations in the shielding, magnet yoke, and mid plane central field region. A heavy ion beam of Nitrogen 14(N<sup>+++</sup>) was successfully accelerated in the cyclotron and was used for basic physics research. Figure 2 shows some possible heavy ion tune energies.

#### b. Protons: time to retune for a fixed, new energy (not degraded).

Proton beam can be retuned in typically 60 minutes.

**Table 4. Degraded Wheel foil thickness and Beam Energies**

	1	2	3	4	5	6
Beam Energy		0.003 Ta	0.004 Ta	0.04 Ta	0.015 Ta	0.0092 Ta
67.5 MeV	Open	66.567	66.363	58.551	64.05	65.273
55 MeV	Open	53.905	53.675	44.325	50.926	52.405
45 MeV	Open	43.736	43.457	32.204	40.258	41.965
40 MeV	Open	38.617	38.306	25.572	34.791	36.679
35 MeV	Open	33.461	33.131	18.15	29.175	31.307
30 MeV	Open	28.267	27.883	8.606	23.337	25.81
25 MeV	Open	23.002	22.552	0	17.069	20.098
20.4 MeV	Open	18.038	17.494	0	10.46	14.492
14.6 MeV	Open	11.444	10.701	0	0	5.877
12.5 MeV	Open	8.844	7.935	0	0	0
	7	8	9	10	11	12
Beam Energy	0.005 Ta	0.011 Ta	0.02 Ta	0.00025 Ta	0.002 Ta	0.001 Ta
67.5 MeV	66.157	64.897	62.974	67.136	66.775	66.928
55 MeV	53.432	51.961	49.674	54.575	54.153	54.396
45 MeV	43.171	41.453	38.764	44.498	44.01	44.293
40 MeV	38.005	36.112	33.117	39.453	38.923	39.224
35 MeV	32.782	30.659	27.242	34.39	33.808	34.14
30 MeV	27.483	25.056	21.028	29.308	28.647	29.027
25 MeV	22.09	19.183	14.103	24.197	23.447	23.874
20.4 MeV	16.95	13.332	5.694	19.455	19.069	19.071
14.6 MeV	9.892	3.336	0	13.347	12.156	12.846
12.5 MeV	6.936	0	0	11.064	9.694	11.491



## UC Davis Cyclotron Facility Capabilities

The Radiation Effects Facility at CNL is based in the 76" Isochronous Cyclotron. The extracted beam is steered and focused by magnetic elements and transported to the REF beam line. A quadrupole doublet focuses the beam on a 0.794 cm circular collimator in front of a multiple diffuser wheel. This wheel is remotely controlled from the control room, and the thickness of the diffuser can be changed appropriately to obtain the desired beam energy.

8. What is the beam spill structure, if any? Note duty cycle and average vs. instantaneous flux if applicable?

The UC Davis 76 inch cyclotron runs continuously so the beam current is the average current and the bunch repetition rate is the CW RF frequency of the beam tune. For example, at 22.5 MHz a bunch is 2 ns long with a 22.5 MHz repetition rate.

9. For protons, what capability is there for low energies (0.3-2 MeV), i.e., for proton direct ionization?

A 0.322 MeV proton beam with a one sigma energy spread of 0.05 MeV can be obtained by directly tuning to a 1 MeV proton beam and then using an 11.58 micron Aluminum foil.

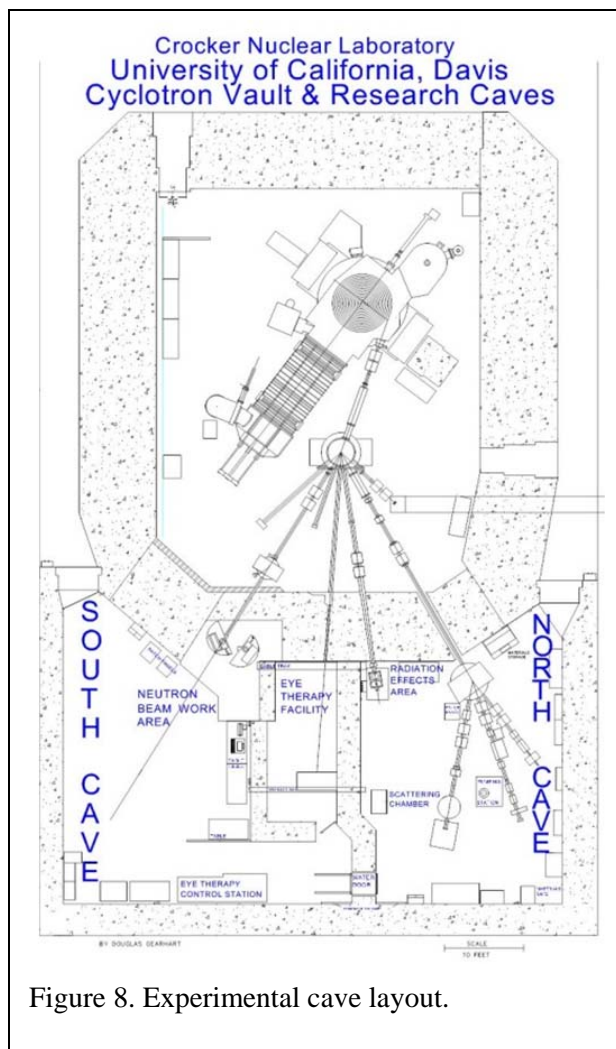


Figure 8. Experimental cave layout.

10. Is there capability for ion micro beams to study specific portions of a device?

The beam size can be only controlled now with collimators. The capability could be added by installing a suitable micro beam final focusing objective.

11. How is beam shared with other activities at the facility? Are there activities that can interrupt delivery of beam for effects testing either during a run or restricting available days? Please describe.

This facility is unique in that the users do not share the beam and cannot be interrupted. Currently the beam is booked on a first come,

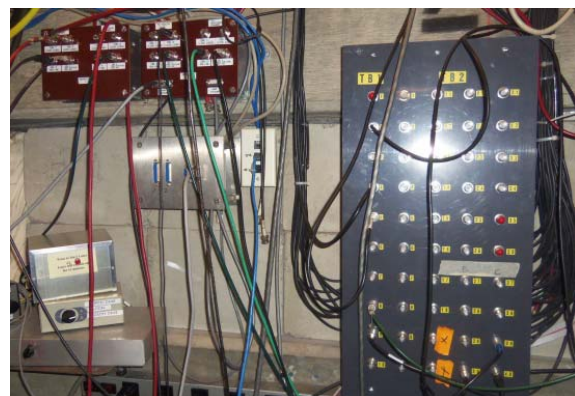


Figure 9. Patch panels in experimental area.



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first served basis. Once a user books the time, the user cannot be bumped. The beam is booked on a single shift per work day excluding holidays, weekends, and scheduled maintenance.

What types of ion sources are available? Which are commonly used for radiation effects and what are their capabilities?

The UC Davis 76 inch Cyclotron employs a PIG source which produces Protons, Deuteron, Alphas, or Helions. Each ion is produced one species at a time.

### Test Setup

1. What is the typical cable length from the experimenter's work area to a device set up in the beam line? Please describe any facility installed user cables and patch panel connections.

The cable run is 50 feet from the user control room to the radiation effects experimenter's work area. The current cabling includes 30 BNC cables, four DB-25 serial interface cables, two USB cables, two CAT-5 cables, and four Ethernet cables. More cables can be installed as required. Figures 8 and 9 show the experimental cave layout and patch panel access.

2. How are devices mounted in the beam? Describe stands, holders, etc.

Device are mounted on a remotely user-controlled X, Y, Z optical bench. The surface has standard optical bench threaded holes for mounting clamps. The facility has a large amount of clamp downs, flexible stands, vices, and other mounting hardware. The cyclotron machine shop can also provide real time fabrication of mounting fixtures, if required. Figure 10 shows the radiation effects experimental area.



Figure 10. Radiation effects experimental area.

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3. Please describe any remotely controllable motion fixtures available.

The radiation effects facility has a remotely controlled x and y precision (24" x 36") table. The table can move 19.5" vertically and 7.37" transversely.

4. Is testing done in air, vacuum, or are both available?

The testing can be done in vacuum or in air. To reduce user personnel radiation exposure, an external beam stop is automatically moved to a shielded enclosure when personnel are accessing the area.

5. Please describe any vacuum chamber available, including size, available feedthroughs, time to pump down/vent, and typical vacuum pressure.

For testing in vacuum the facility has a 16" x 16" x 24" box. The box is isolated from the beamline and has its own turbo pump. The typical pressures achieved are  $2 \times 10^{-5}$  Torr. There are eight BNC feed throughs, a 30 pin D connector for digital/serial interfaces, and two vacuum gauge connections.

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## Facility Infrastructure

1. Please describe any support facilities (machine shop, electronics shops, etc.) and diagnostic instrumentation available to users. Can users use the shops directly, or if not, during what hours is support available?

The cyclotron has a complete machine and mechanical shop (Figure 11).

The cyclotron machine shop has the following capabilities:

- 3 axis CNC milling & turning
- Full CAD/CAM interface
- Complex surface and contour machining
- Sheet metal fabrication
- Welding, brazing & soldering
- Mechanical repairs
- System fabrication & assembly
- Vacuum systems
- Parts duplication for analytical systems & research instruments

The equipment available in the machine and mechanical shop is as follows

### Machining and Fabrication

- 2 ACER CNC Knee Mills, 10" x 50" Table, 25"X x 14"Y x 4.5"Z travel, 3-Axis Anilam 3000M Controllers
- 1 ACRA CNC Lathe, 16" x 40", 2-Axis Anilam 4200T Controller
- 2 LeBlonde 16" x 40" Manual Lathes with Digital Readouts
- 1 Gorton Mastermill Vertical Knee Mill, 10" x 42" Table
- 1 Cincinnati No 2MH Horizontal Knee Mill 10½" x 53" Table



Figure 11. Dedicated cyclotron machine shop.

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- 1 Do-All Vertical Band Saw, 16" throat depth
- 1 Rockwell Vertical Band Saw, 19" throat depth
- 1 Wells Horizontal Band Saw, 9" round capacity
- 1 Wysong Sheet Metal Shear, 12 ga. x 6' capacity
- 1 Lincoln Idealarc 300/300 AC/DC Arc Welder, Bernard water circulator, HW-20 and HW-18 TIG torches
- 1 Miller Millermatic 251 Wire Welder
- 1 Oxy – Acetylene Welding/Cutting/Brazing

### Test and Inspection

- 1 Alcatel Model ASM – 142 Helium Leak Detector
- 1 Fowler 12" Optical Comparator with 10x, 20x and 40x objectives
- 2 Granite surface plates, 24" x 24" 2 ledge, 24" x 18" 4 ledge

### Heat Treating

- 1 Jelrus Oven, 2000 °F, 9" x 5" x 3½" capacity

### CAD/CAM

- 1 AutoCAD LT 2000i
- 1 edgeCAM Ver. 11.5 2D/3D Mill, Lathe

An electrical shop is also available to perform the following services

- Electrical & electronic design, repair & fabrication
- Circuit prototyping
- Pc board design (wirewrap for small projects, electronically generated gerber files for larger scale circuits)
- PLC system design (hardware setup and ladder logic development)
- Repair of analytical instruments & systems
- Repair of radiation monitoring & survey equipment
- Repair Gas chromatographs
- Repair Optical spectrometers
- Repair Vacuum systems & electron microscopes
- Custom design of process controls

The electrical shop has data acquisition hardware and can perform software development on the following systems:

- Visual basic.net (visual studio environment, using National Instruments hardware)
- C#.net (visual studio environment, using National Instruments hardware)
- Labview (using National Instruments hardware)
- C/c++ for CAMAC hardware (Linux based systems)
- Micro controller development (embedded software)

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2. Please describe available work areas. Is bench space available for multiple experiments / groups? Are electrical circuit loads adequate for several simultaneous test setups? Enough outlets, power strips for large groups of workers?

There are several work benches in the user control room area and two in the experimenter's cave area. Each has plenty of electrical power and both wired and wireless internet access. One of our large customers comes with a semi-truck full of equipment and places it in the room and powers up all of their computers, racks, and test equipment. We supply power to their trailer for the additional cooling systems that they require.

3. How is equipment brought into the lab? Is there a separate shipping/receiving dock or is equipment delivered directly? Are user computers subject to registration?

Crocker Nuclear Laboratory was custom built for the Cyclotron and has its own high bay access for receiving large semi-truck size loads. It also has its own shipping and receiving room for smaller shipments. Heavy equipment can be off loaded and rolled into the lab. A forklift is also available for heavy items.

User computers are not subject to registration.

4. Is there guest access to internet (wired and/or wireless)? Can users set up a local hotspot or LAN for their test setup?

The laboratory has high speed internet connection available via a wireless network or RJ-45 plug in jacks. Users can setup their own hotspots and LANs for their testing requirements.

5. What is the typical cell phone coverage availability inside and outside the building? (may vary by carrier, of course, general impression is ok).

Cell phone coverage is good to excellent in the laboratory high bay and office areas. Inside the experimenter caves there is poor cell phone coverage.

Is food allowed in work areas? Is some location to store food and eat meals available?

Food is allowed in the high bay, kitchen galley, CNL outer waiting room, and office areas. The laboratory has a kitchen galley located next to the control room with two refrigerators, a hot water machine, a coffee machine, a microwave, and sink.

A Starbucks coffee house, sit-down restaurant and fast food outlets are located approximately a block walking distance from the laboratory.

**Food is not allowed in the experimental caves due to radiation safety guidelines.**

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## Availability

1. How is beam time awarded? Is there a competitive proposal process? How far into the future can time be scheduled?

Beam time is currently awarded on a first come, first served basis. Once a user agreement and a purchase order have been executed, beam time can be scheduled online using the web form. Currently, there is no limit on how far in advance beam time can be scheduled.

2. Is the schedule fully booked? How much time typically elapses between booking and the first available opening? Is it longer if the user needs several days compared to a few hours?

Currently UC Davis Beam time is scheduled on a single shift which is usually about 60% booked. If beam time is available booking can occur in less than a day. If several days concurrently are required it may take a few weeks find an open slot.

3. Is time available on short notice (1 day – 2 weeks)?

Yes, the 76 inch cyclotron usually has a few days available every other week.

4. Once on the schedule, can low priority users be bumped in favor of high priority needs?

No, all users have the same priority.

5. If beam cannot be delivered to a user, how are they placed back on the schedule for a later run?

The user is given the choice to re-schedule for the next free beam time.

6. What restricts the scheduling of beam time?

- a. Is there a maximum length of test?
- b. Do other users run experiments that may restrict the radiation effects schedule for days or weeks at a time? Do other users restrict times of day available for effects testing?

The current maximum is 8 hours.

Proton beam cancer therapy typically runs four consecutive 8 hour days per month. They have their own cave and do not otherwise restrict radiation effects usage. Also they do not bump radiation testing users since they are on tight patient and doctor schedules.

There are no maximum consecutive day runs at this time. Some users run for a week at a time, with the beam on for 8 hours per day. Other users do not restrict the times of day for radiation effects testing.



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## 7. What does the typical shift schedule look like? (Available times of day, days/week)

On a typical shift the operators turn on the Cyclotron at 8:00 am and have it warmed up and tuned up for use by 9:00 am. The run ends at 4:00 pm.. The core hours are 8:00 am to 5:00 pm during the standard work, (MTETF), week.

## Administrative

### 1. What procedures are required for personnel access to the facility? (badging, forms, etc)

All users must fill out and sign a Machine Use Authorization which takes 5 minutes.

### 2. What are the training requirements to work at the facility or to be an observer?

There are no training requirements. The Head Cyclotron Physicist and Operators ensure that the users comply with all safety procedures.

### 3. What is the procedure to contract with the facility to purchase beam services? How much lead time does that take?

All non-UC entities must have a fully executed UC service agreement in place before Cyclotron services can be provided. There are two options for securing a UC service agreement:

1. **Delegated Agreement.** This is the easiest and fastest way to access beam time. If your organization accepts UC's terms and conditions as they are stated in the "Delegated Agreement form", our business office staff will work with you to complete the form. (Please also complete and submit the "Client Billing Information form". As soon as your organization's representative signs the "Delegated Agreement Form" and returns it to Crocker Nuclear Laboratory's business office, you may schedule beam time.

2. **Negotiated Agreement.** If your organization requires a modification of UC's terms and conditions as they are stated in the "Delegated Agreement Form" form, please complete the "Client Billing Information form" to initiate a UC service agreement. UC service agreements are facilitated by Crocker Nuclear Laboratory's business office, but negotiated and executed by the UC Davis Business Contracts Office. Typical processing times are 2-3 weeks but can take longer of UC Davis and customer's legal departments need to negotiate extensive changes to standard terms and conditions.

### 4. Does the facility retain any rights to the data obtained? If so, what?

No.

### 5. What data is stored by the facility? If applicable, how is it stored, archived, and protected?

All dose and fluences are recorded to hard drive and archived. User data can only be accessed by the user who performed the test. The data is used to monitor the state of the cyclotron health.

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1. Is there a minimum buy for radiation effects hours?

The minimum buy is eight, (8), hours of beam time or full shift with one hour allotted for beam tune.

2. Is time charged only for beam delivery, or also for setup/teardown time?

Time is charged for one hour of beam tune, beam delivery, and potentially for breakdown and setup time that interferes with other users of the beam.

3. Is unused scheduled time bankable for later visits to the facility?

No. You will be billed if not cancelled ten, (10), working days prior to cancellation.