Title

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The Berkeley Accelerator Space Effects Facility (BASE) - A New Mission for the 88-Inch Cyclotron at LBNL*

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ABSTRACT: In FY04, the 88-Inch Cyclotron began a new operating mode that supports a local research program in nuclear science, R&D in accelerator technology and a test facility for the National Security Space (NSS) community (the U.S. Air Force and NRO). The NSS community (and others on a cost recovery basis) can take advantage of both the light- and heavy-ion capabilities of the Cyclotron to simulate the space radiation environment. A significant portion of this work involves the testing of microcircuits for single event effects. The experimental areas within the building that are used for the radiation effects testing are now called the Berkeley Accelerator and Space Effects (BASE) facility. Improvements to the facility to provide increased reliability, quality assurance and new capabilities are underway and will be discussed. These include a 16 AMeV "cocktail" of beams for heavy ion testing, a neutron beam, more robust dosimetry, and other upgrades.

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INTRODUCTION

The 88-Inch Cyclotron at Lawrence Berkeley Laboratory, operated by the University of California for the US Department of Energy (DOE), is a K=140 sector-focused cyclotron with both light- and heavy-ion capabilities. Protons and other light-ions are available at high intensities (10-20 pμA) up to maximum energies of 55 MeV (protons), 65 MeV (deuterons), 135 MeV (^{3}He) and 140 MeV (^{4}He). Most heavy ions through uranium can be accelerated to maximum energies which vary with the mass and charge state.

The 88-Inch has a long history of providing beams for radiation effects testing. Early in its forty-year history, it was realized that the variable frequency of the cyclotron translated to a mass resolution of 1/3000, meaning that the cyclotron could separate most – but not all – ions of near-identical mass-to-charge (m/q) ratio emanating from the ion source. [1] This was both a blessing and a curse - a curse because there were a few beams that could never be delivered uncontaminated, and a blessing for performing tasks such as detector calibrations or device testing, for which several different beams could be delivered to an experiment with a minimum of retuning. By the late 1970s, single event effect testing was occurring on a small scale. Some effects discovered at LBNL by Aerospace Corporation include the first single event latchup (SEL) (1979), the variation of SEL sensitivity with device temperature (1986) and single event transients (SET) in digital devices (1987). [2]

Radiation effects testing with heavy ions using the 88-Inch came into its own when the first electron cyclotron resonance (ECR) ion source was coupled to the Cyclotron in the early 1980s, the first such combination in the world. [3] With the ECR source, it was very easy to ionize a mixture of noble gases to an integer m/q (2, 3, 4, 5) to make a “cocktail” of beams of near-identical m/q. [4] This proved very beneficial in the SEE studies since users could switch from ion to ion with a minimum of tuning time. Cyclotron staff developed a “light-ion cocktail” of fully-stripped m/q=2 ions (through ^{36}Ar) and a “heavy-ion cocktail” of m/q = 5 at 4.5 AMeV. This latter cocktail was available through xenon from the LBNL ECR.

In the early 1990s, the ion source group built a second state of the art ECR source, the Advanced ECR (AECR) source. [5] With this source it was possible to obtain Bi^{+41}, which at m/q = 5.1, could be accelerated together with the 4.5 AMeV cocktail. At a linear energy transfer (LET) value of 98 MeV/mg/cm^2, this was very useful for testing radiation-resistant electronics. Throughout the decade of the 1990s, improvements were made in the ion sources and cyclotron vacuum which benefited both the nuclear science and radiation effects users alike. A new cocktail was developed at 10 AMeV, which allowed ions as heavy as xenon to penetrate silicon to depths of greater than 100 μm; this was important because chips were becoming increasingly more complex and difficult to delid. The amount of radiation effects testing performed at the Cyclotron with either heavy ions or protons increased steadily to 15-20% of the scheduled time, or about 1000-1200 hours/year.

In 2003, the DOE announced plans to close the 88-Inch Cyclotron as a DOE National User Facility in FY04. This was a major blow to heavy ion testing in the United States, as neither of the other facilities at Brookhaven National Lab or Texas A&M University could replace what was being done at Berkeley. The US Air Force Space Missile Command (USAF-SMC) and National Reconnaissance Office (NRO) came to the rescue, signing a Memo of Understanding with DOE to provide 40% of the operating funds of the Cyclotron in FY04 and FY05; DOE agreed to continue funding the Cyclotron at the 60% level. Thus the 88-Inch Cyclotron was reborn with a dual mission: 1) an in-house basic research program in nuclear science to serve

LBNL and UC Berkeley scientists and students, and 2) a state-of-the-art, multifaceted radiation effects facility – the Berkeley Accelerator Space Effects (BASE) Facility - to serve the National Space Security community funded by USAF-SMC and NRO. When time is available, the BASE facility is also used by commercial and other government agencies on a cost recovery basis and for LBNL experiments in radiation biology. In addition, a neutron beam line has been funded by a DOE-NNSA Academic Alliance grant to measure neutron cross sections on unstable targets for stockpile stewardship and nuclear astrophysics.

THE BASE FACILITY

The layout of the 88-Inch Cyclotron facility and the beamlines which are part of BASE is shown in Figure 1. Heavy ion testing takes place in the vacuum chamber located in Cave 4B. Three heavy ion cocktails have been developed at energies of 4.5, 10 and 16 AMeV and are summarized in the first three rows of Table 1. The 16 AMeV cocktail is a recent addition and is available through krypton, at an LET of 26 MeV/mg/cm2 and a range of almost 700 µm. [6] It is possible to run this cocktail in air if needed although the energy at the DUT will be degraded to ≈9 AMeV. For each listed cocktail, a group of standard ions are listed which are regularly available.

LET versus Range in Si is plotted in Figure 2 for four cocktail energies plus a few of the more commonly used light ion tunes. Several orders of magnitude are available in both range and LET, making the BASE test facility very versatile.

Several improvements to the BASE facility are in progress or planned. For the heavy ion test facility, the control system and user interface has been converted to a PC-based LABVIEW™ system from the original Macintosh system written at Aerospace Corporation. This will allow the 88-Inch staff to maintain and upgrade both the hardware and software. The new system was implemented in September and is undergoing beta-testing.

In addition, we have been investigating ways to implement a more reliable and robust dosimetry system. The present dosimetry system, consisting of plastic scintillator, is not very radiation hard. With a combination of increased use, more use of high-energy cocktails, and more use of higher doses of high-LET ions such as xenon and bismuth, the scintillators have been degrading over time, sometimes within a few hours. We have been testing an inorganic scintillator, YAP(Ce), which has been shown for electrons to be 10-100x more radiation resistant than organic scintillators such as plastic. Little data is available for heavy ions.We are testing it for our application and, based on initial performance, anticipate replacing all the plastic in the next few months. Another limitation to the dosimetry is saturation of the system at levels of < 10^5 ions/second for the heaviest ions. The cause of this is under investigation.

A third improvement to the heavy ion test facility is planned for next year. We expect to incorporate a memory chip which has a well characterized SEU cross section curve. This chip will be on a lever arm inside the chamber so it can be dropped in front of the DUT and give a check on whether the upset cross section is within certain preset limits; this will insure that all aspects of the beam delivery and dosimetry are working correctly.

The Light Ion Irradiation Facility (LIIF) is presently located in Cave 3 but is being moved to Cave 4A. This will allow better access and convenience, being adjacent to the Heavy Ion Facility. The LIIF is set up to run samples in air. The beam is 10 cm in diameter and a transmission ion chamber is used to tune a uniform beam and to perform dosimetry. The facility can be used for protons from 13.5-55 MeV, other light ions, and the light ion cocktail. The energy loss in the ion chamber limits lower energy running in this facility. For instance, the 13.5

MeV proton beam degrades to 9 MeV at the DUT position. It's possible to go to lower energies in this beam line if other means of dosimetry are employed.

A neutron capability is being developed at the Cyclotron which will be available for radiation effects testing. In Phase 1, to be finished in 2005, a white spectrum of neutrons will be available for RET. Neutron dosimetry is being developed for this application. In Phase 2, quasi-monoenergetic beams will be available in the range of 10-32 MeV, as well as a beam around 200 keV. These energies of beams are useful for ground based soft error studies and for studies related to lunar and Martian surface enclosures, e.g. shielding studies, radiation biology and radiation effects on materials and electronics.

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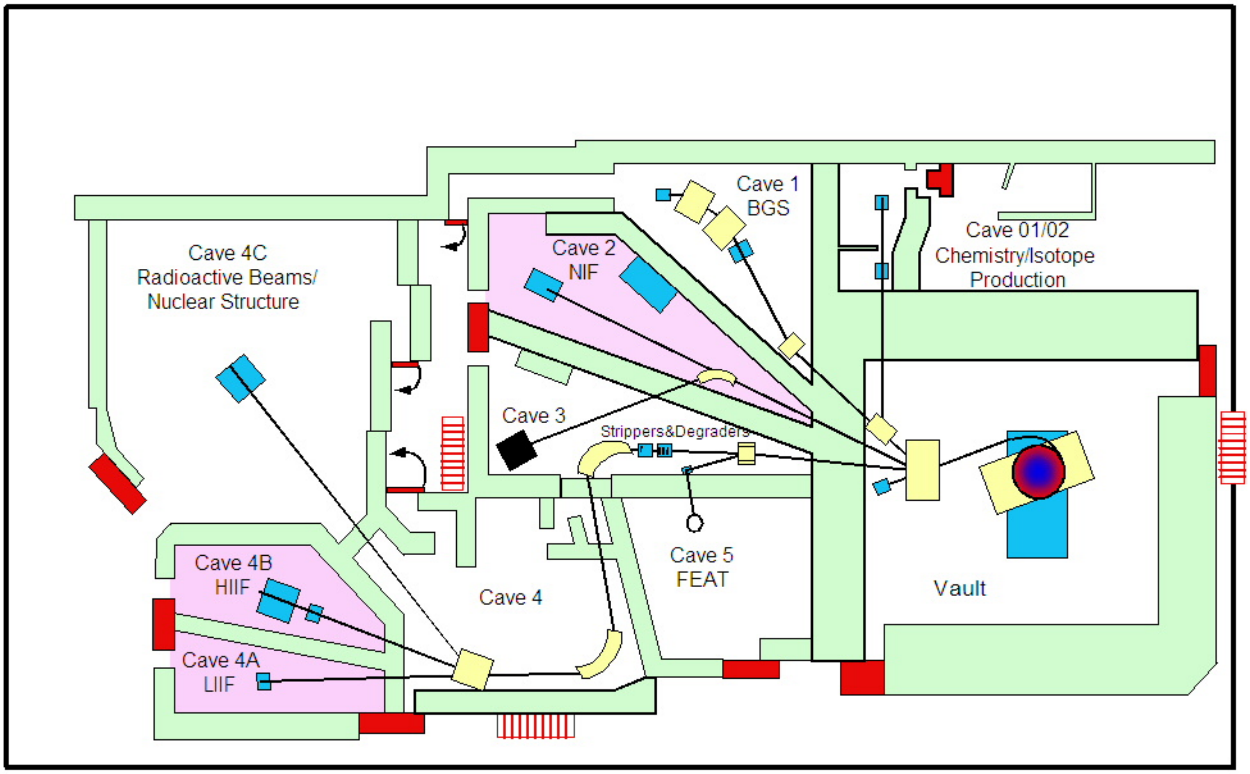
Table 1. Summary of standard BASE cocktails and other beams. Other ions and energies are available by special arrangement.

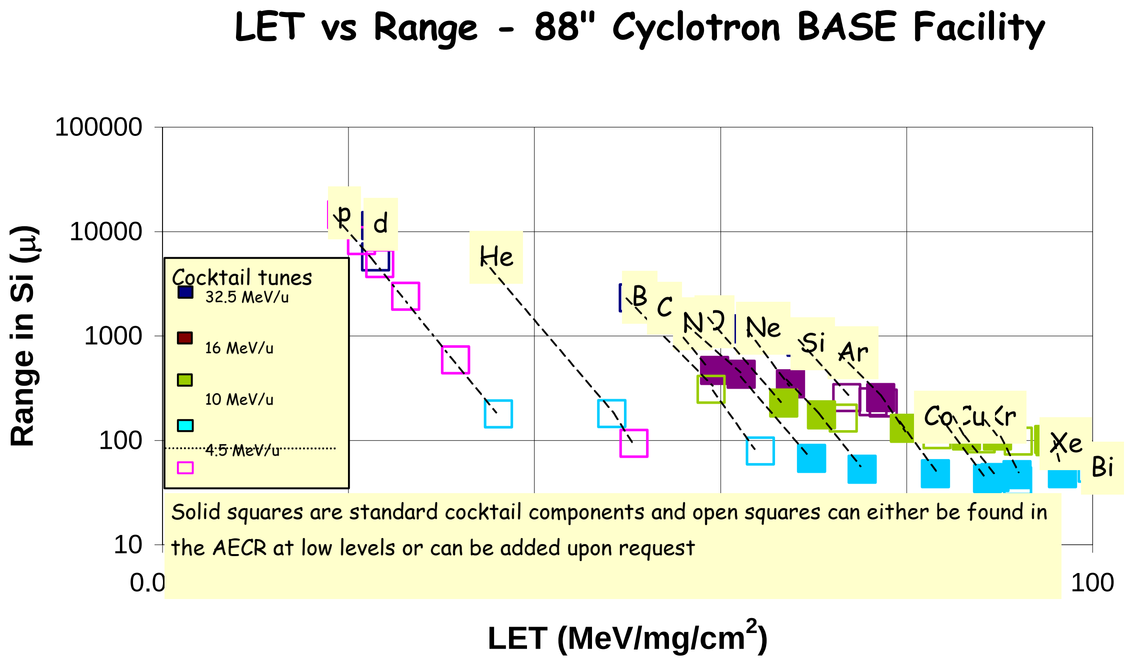
Cocktail (AMeV)	Standard Ions (st)	Other Ions[a]	LET (MeV/mg/cm$^{2)}$	Range in Si (μm)
4.5	^{15}N, ^{20}Ne, ^{40}Ar, ^{59}Co, ^{63}Cu, ^{86}Kr, ^{136}Xe	HeH[b], ^{10}B, ^{78}Kr, ^{209}Bi	3.1-68.8 (st) 0.064-99.6 (all)	43-67 (st) 41-180 (all)
10	^{18}O, ^{22}Ne, ^{40}Ar, ^{65}Cu, ^{86}Kr, ^{136}Xe	^{10}B, ^{27}Al, ^{51}V, ^{73}Ge, ^{98}Mo	2.2-59.1 (st) 0.89-59.1 (all)	97-227 (st) 98-307 (all)
16	^{12}C, ^{14}N, ^{17}O, ^{20}Ne, ^{40}Ar, ^{63}Cu, ^{78}Kr	^{28}Si, ^{35}Cl, ^{55}Mn,	0.93-25.7 (all)	171-467 (all)
32.5	^{4}He, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{36}Ar^{18+}	^{2}H, H_2[b], ^{28}Si, ^{32}S, ^{40}Ca	0.022-8.01	0.29-4.29 mm
Light Ion Tunes	^{1}H, ^{4}He		0.009-0.342	93.4-14,430

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

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

Figure 1. Map of 88-Inch Cyclotron Facility. The shaded areas are the beamlines which are used now or will be used in the future for BASE.





Solid squares are standard cocktail components and open squares can either be found in the AECR at low levels or can be added upon request

Figure 2. Range versus LET for all LBNL cocktail tunes and other standard beams for radiation effects testing.