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A 16 MeV/nucleon Cocktail for Heavy Ion Testing

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Abstract—**The Operations Group at the 88-Inch Cyclotron at LBNL has developed a new cocktail of heavy ions ranging from Z=7-36 at 16 MeV/nucleon, which provides LETs from 1-26 MeV/mg/cm^2 at ranges from > 500 μm for the lightest components down to 163 μm for krypton. This adds a more penetrating high-LET cocktail to the standard 4.5 MeV/nucleon and 10 MeV/nucleon cocktails presently available. When the new VENUS ion source is coupled to the Cyclotron in 2005, xenon will be available as well, at an LET of 48 MeV/mg/cm^2 and a range of 164 μm.**

Keywords- heavy ion facility; cocktail;

I. INTRODUCTION

As the latest generations of microelectronics trend towards increasingly smaller feature sizes, there can be more layers for a heavy ion to traverse before reaching the sensitive region of a chip. Because of this the use of higher energy heavy ions - with effective Bragg peak ranges of > 100 μm - becomes an advantage.

The 88-Inch Cyclotron is a sector-focused cyclotron fed by two high-charge-state Electron Cyclotron Resonance (ECR) ion sources. A third ECR ion source, VENUS, is being commissioned and will be coupled to the Cyclotron in 2005. Figure 1 shows a schematic layout of the 88-Inch Cyclotron and its ion sources.

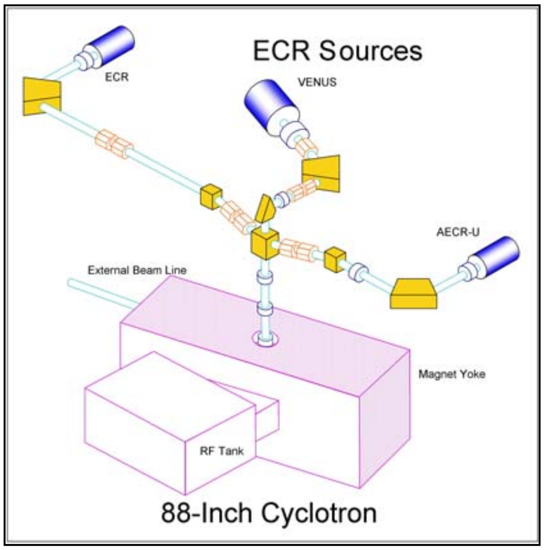


Figure 1. Schematic layout of the 88-Inch Cyclotron accelerator facility.

Advances in electron cyclotron resonance (ECR) ion sources over the past twenty years have allowed the 88-Inch Cyclotron at Lawrence Berkeley National Lab (LBNL) to keep up with some of these trends by accelerating higher charge state ions, giving higher final energies. In the mid-1980s - the LBNL-ECR source - the first ECR source built in the U.S - extended the range of ions available from the Cyclotron through krypton at the Coulomb barrier, xenon at lower energies. It also enabled development of the first “cocktail” beams [1], which were used for detector development for the nuclear physics program. Almost immediately, the utility of these cocktail beams for the radiation effects testing (RET) program was realized, and the first two cocktail beams for RET were developed, a “light-ion” cocktail (H-Ar) at 32.5 MeV/nucleon, and a heavy-ion cocktail (B-Xe) at 4.5 MeV/nucleon. The synergy between developments on the nuclear physics side and the RET program continues at the Cyclotron to this day.

In the early 1990s, a second-generation ion source was built at the Cyclotron, again the first of its kind in the U.S. With the Advanced ECR source, the AECR, bismuth was available at 4.5 MeV/nucleon, extending the LET range of the heavy-ion cocktail to 98 MeV/mg/cm^2. The source was upgraded to give higher intensities in the mid-1990s, which made bismuth delivery routine and also allowed the development of a heavy-ion cocktail at 10 MeV/nucleon, with which ions through xenon could be used at ranges of 100 μm or greater. Further improvements in the upgraded AECR source, the AECR-U, and in the cyclotron vacuum have led to development of our latest cocktail beam, at 16 MeV/nucleon.

II. TECHNIQUE

The cocktail beam technique works because the electron plasma of an ECR source ionizes indiscriminately and with high efficiency any ion entering the plasma zone. The ECR source sits on a high voltage platform and the positive ions exit the source and are tuned into the injection line using a 90° bending magnet we call PACMAN. When the ion source is tuned up for the cocktail beams, three different gases are mixed together in the ion source plasma: a special oxygen cocktail gas (containing 1% argon, 1% neon and 1% nitrogen), a krypton gas enriched in one isotope, and a xenon gas also enriched in one isotope, all supplied by separate precision gas valves. Metals – boron, copper, bismuth, etc. - are radially fed into the plasma using various evaporation techniques. A typical distribution of ions extracted from the source and tuned through PACMAN onto a Faraday cup is shown in Figure 2. Not only the gas and solids being introduced into the ion source are extracted, but also impurities from recent runs and components of the source itself, such as aluminum and molybdenum. Some of these are at levels that can’t be seen on the Faraday cup in the injection line.

These mixtures of ions of near-identical charge-to-mass (q/A) ratio are tuned out of the ion source and injected into the cyclotron together. The cyclotron is then utilized as a mass analyzer by shifting the accelerating frequency. The mass resolution is high because the path of the ions inside the magnetic field of the cyclotron is long (200 to 300 turns). Since the mass of the ions is directly proportional to the ion cycling frequency in the cyclotron magnetic field, the mass resolution can be directly computed out of the frequency resolution of the cyclotron

$$R = \frac{m}{\Delta m} = \frac{f}{\Delta f} = \frac{2 \cdot \pi \cdot H \cdot N}{1.5} \qquad (1)$$

where R is the resolution, Δf is the RF frequency shift, N is the number of turns and H is the harmonic of acceleration. The frequency shift for nearby q/A beams are on the order of 1 to 200 kHz. Therefore, the extracted beam can be rapidly switched from one ion to another with small adjustments of the accelerator RF frequency. This means that the ion species and therefore the linear energy transfer (LET) delivered to the experiment can be changed in approximately one minute once the tune up procedure is completed.

A careful frequency scan is performed in order to verify the different ion species, and to look for impurities at levels which would not have been seen in the injection line scan. Ions at intensities of ≥ 10 electrical-picoamps can be identified in this way. Intensity variations between the ions of the cocktail are compensated for with a series of attenuator grids at the ion source, which allow adjustments over nine orders of magnitude

III. RESULTS

The 16 MeV/nucleon cocktail is based on ^{40}Ar^{+14} at an energy of 642 MeV, or 16.06 MeV/nucleon. q/A = 0.351 for this beam and the accelerating RF frequency is 8.9175 MHz. The other “standard” components of this energy cocktail, shown in Table 1, vary in frequency by ±5-200 kHz. Since the frequency resolution of the Cyclotron is 2 kHz, these provide clean, uncontaminated beams. It should be noted that rare isotopes such as ^{17}O (0.04% of natural oxygen) are used in this cocktail in order to avoid potential contamination. With the efficiency of the AECR-U, enough ^{17}O is available from natural oxygen gas to be usable. Also in this cocktail we are using enriched ^{78}Kr instead of ^{86}Kr as used in the lower energy cocktails. The lighter isotope means a lower charge state, thus more beam intensity. We were not able to obtain a high enough intensity of ^{136}Xe to be usable in this cocktail, but enriched ^{129}Xe has been obtained and will be tested in the near future. We believe that we will be able to provide at least 10^3 ions/cm^2/sec of this isotope in the near future.

LET versus depth in silicon curves for the standard components of the 16 MeV/nucleon cocktail are plotted in Figure 3. These curves can be used to estimate the LET at the sensitive layer of a chip. The LET at the surface and at the Bragg peak are given in Table 1 as well as the depth of the Bragg peak and the depth where the particle finally ranges out.

IV. FUTURE IMPROVEMENTS

VENUS – the prototype ion source for the Rare Isotope Accelerator (RIA) - is the first third generation ECR ion source being built in the world [3]. With confining magnetic fields of 4 Tesla (as compared to the AECR-U’s 1.7 Tesla) and a microwave source of 28 GHz (compared to 14 GHz for the AECR-U), VENUS will deliver substantially higher beam intensities of the high-charge state heavy beams needed for the cocktails. Already in initial tests at low powers, VENUS has demonstrated world record intensities of Bi^{+41}, used in the 4.5 MeV/nucleon cocktail, and xenon at several charge states, used in all the cocktail beams.

VENUS is being commissioned now and tests are underway for RIA development and the low energy transport of the beam. Space charge effects in the injection line presents a major challenge at these high intensities of low-energy, high-charge-state heavy beams, and careful beam dynamic studies are underway before the beamline is designed to couple VENUS to the Cyclotron. It is expected that this will take place late in 2005.

Another challenge which will have to be met is access to the ECR plasma chamber, now located inside a cryostat for the superconducting magnets. It will be much more difficult to get a variety of gases and solids into a cocktail beam using VENUS, but oven designs are underway to solve this problem.

In addition, plans are underway to upgrade the vacuum of the Cyclotron to be able to take full advantage of the improved intensity of heavy ions expected with VENUS. This will improve the transmission of the present beams, in particular for xenon and bismuth.

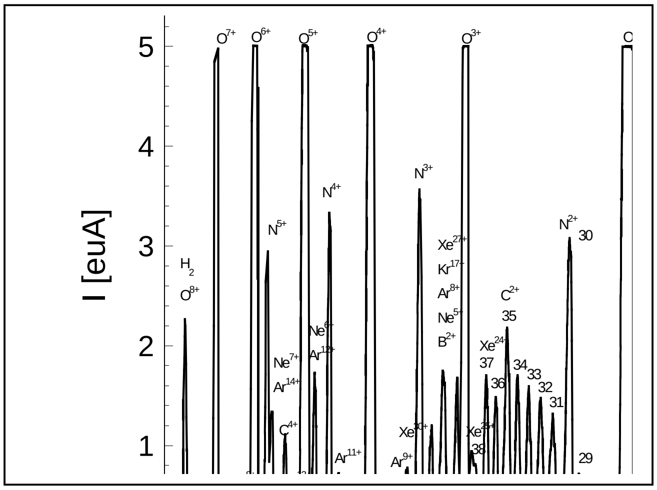


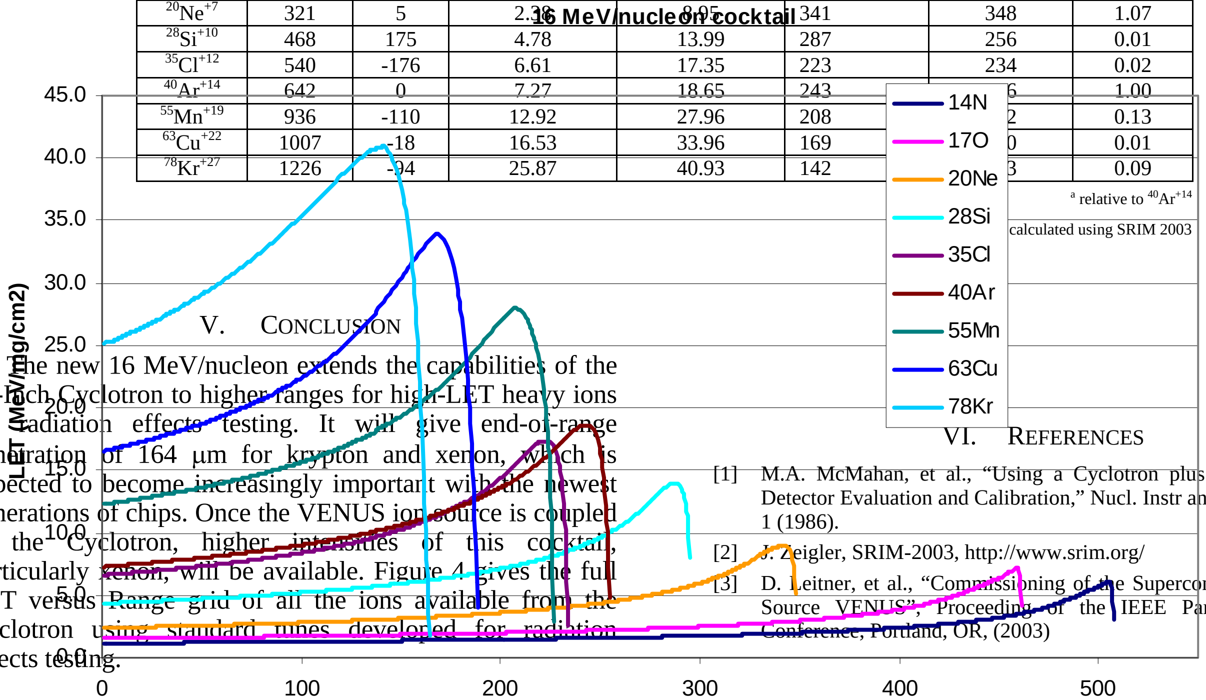
Figure 2. Typical ion spectrum, for the AECR-U source with bismuth added to the standard 4.5 MeV/nucleon cocktail.

TABLE I. 16 MEV/NUCLEON COCKTAIL: “STANDARD” COMPONENTS

Ion	Energy (MeV)	Δf[a] (kHz)	LET$_{\text{initial}}$[b] (MeV/mg/cm2)	LET$_{\text{Bragg}}$[b] (MeV/mg/cm2)	Range$_{\text{Bragg}}$[b] (μm)	Range$_{\text{final}}$[b] (μm)	Relative Intensity[a]
$^{14}\text{N}^{+5}$	234	166	1.13	6.03	505	508	0.01
$^{17}\text{O}^{+6}$	277	64	1.54	7.15	459	462	0.07
$^{20}\text{Ne}^{+7}$	321	5	2.38	8.95	341	348	1.07
$^{28}\text{Si}^{+10}$	468	175	4.78	13.99	287	256	0.01
$^{35}\text{Cl}^{+12}$	540	-176	6.61	17.35	223	234	0.02
$^{40}\text{Ar}^{+14}$	642	0	7.27	18.65	243	[illegible]	1.00
$^{55}\text{Mn}^{+19}$	936	-110	12.92	27.96	208	[illegible]	0.13
$^{63}\text{Cu}^{+22}$	1007	-18	16.53	33.96	169	[illegible]	0.01
$^{78}\text{Kr}^{+27}$	1226	-94	25.87	40.93	142	[illegible]	0.09

[a] relative to $^{40}\text{Ar}^{+14}$

calculated using SRIM 2003



V. CONCLUSION

The new 16 MeV/nucleon extends the capabilities of the 88-Inch Cyclotron to higher ranges for high-LET heavy ions for radiation effects testing. It will give end-of-range penetration of 164 μm for krypton and xenon, which is expected to become increasingly important with the newest generations of chips. Once the VENUS ion source is coupled to the Cyclotron, higher intensities of this cocktail, particularly xenon, will be available. Figure 4 gives the full LET versus Range grid of all the ions available from the Cyclotron using standard tunes developed for radiation effects testing.

VI. REFERENCES

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[3] D. Leitner, et al., “Commissioning of the Superconducting ECR Ion Source VENUS”, Proceeding of the IEEE Particle Accelerator Conference, Portland, OR, (2003)

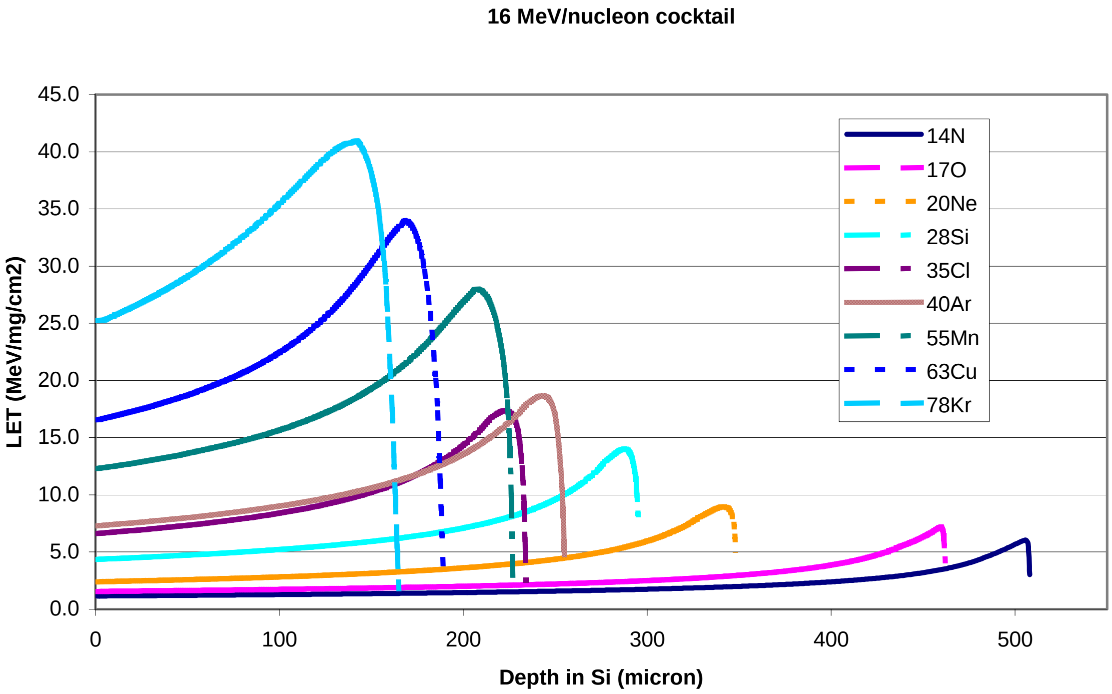

Figure 3. Depth in silicon (μm) versus LET (MeV/mg/cm^2 for the standard components of the 16 MeV/nucleon cocktail.

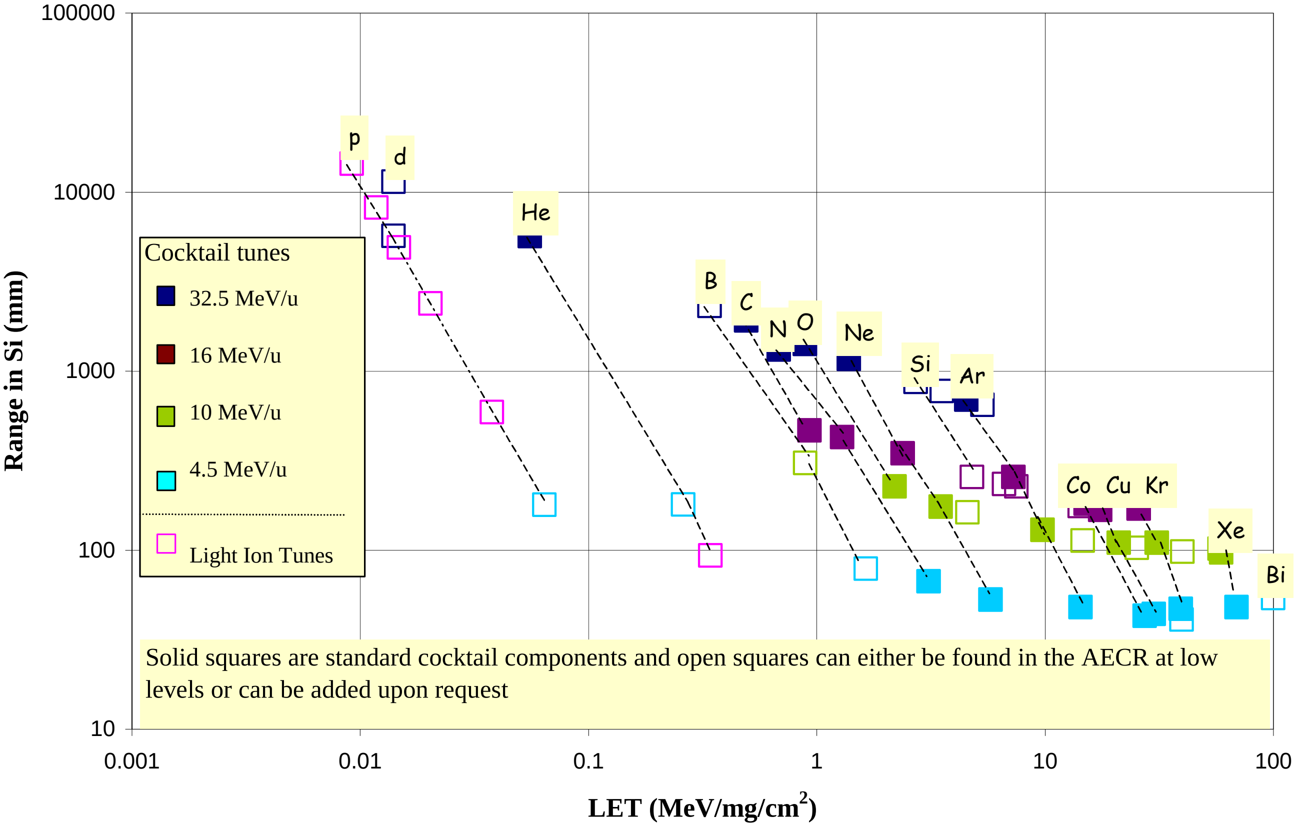

Figure 4. Initial LET versus Range for all the 88-Inch Cyclotron cocktail and light ion tunes