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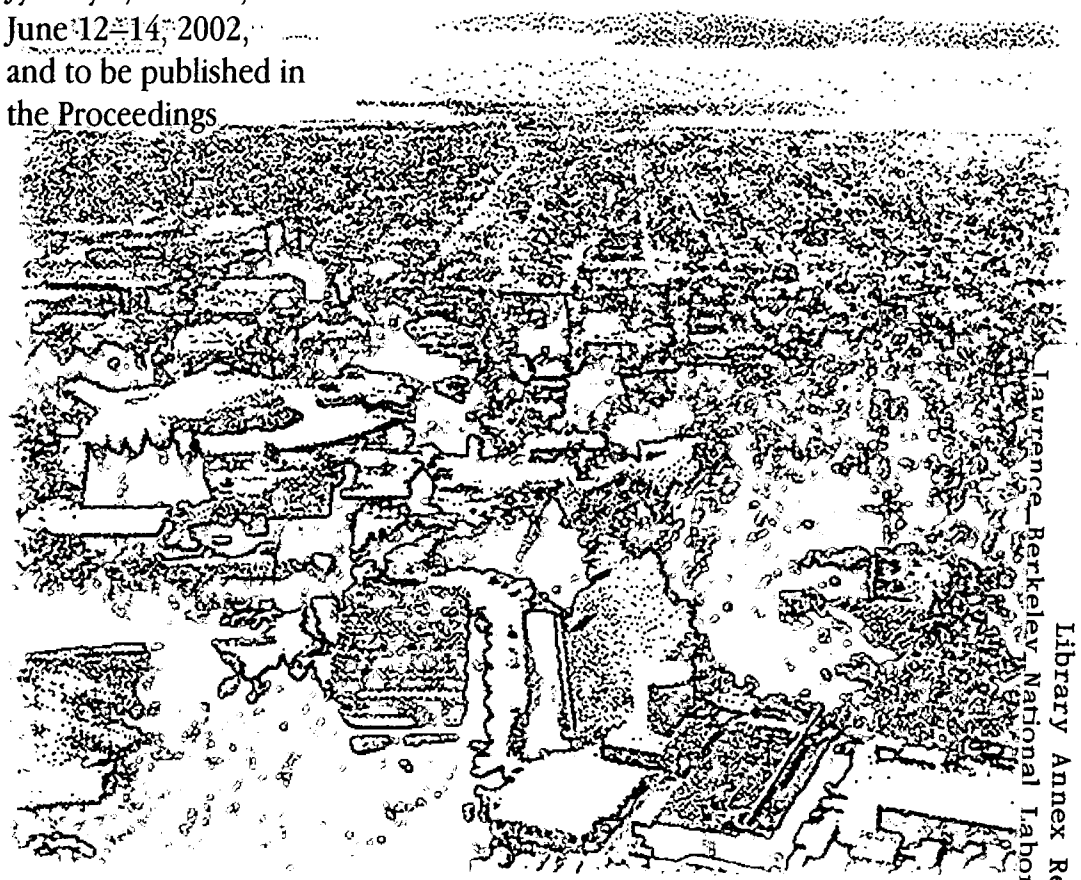

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HEAVY ION COCKTAIL BEAMS AT THE 88 INCH CYCLOTRON

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Abstract

Cyclotrons in combination with ECR ion sources provide the ability to accelerate "cocktails" of ions. A cocktail is a mixture of ions of near-identical mass-to-charge (m/q) ratio. The different ions cannot be separated by the injector mass-analyzing magnet and are tuned out of the ion source together. The cyclotron is then utilized as a mass analyzer by shifting the accelerating frequency. This concept was developed soon after the first ECR ion source became operational at the 88-Inch Cyclotron and has since become a powerful tool in the field of heavy ion radiation effects testing.

Several different "cocktails" at various energies are available at the 88-Inch cyclotron for radiation effect testing, covering a broad range of linear energy transfer and penetration depth. Two standard heavy ion cocktails at 4.5 MeV/nucleon and 10 MeV/nucleon have been developed over the years containing ions from boron to bismuth. Recently, following requests for higher penetration depths, a 15MeV/nucleon heavy ion cocktail has been developed.

Up to nine different metal and gaseous ion beams at low to very high charge states are tuned out of the ion source simultaneously and injected together into the cyclotron. It is therefore crucial to balance the ion source very carefully to provide sufficient intensities throughout the cocktail. The paper describes the set-up and tuning of the ion source for the various heavy ion cocktails.

1 INTRODUCTION

The effect of ionizing particles on sensitive microelectronics is an important design component for systems such as satellites, space probes, and detectors for high energy physics experiments. Understanding the effects of radiation on human cells is an equally important endeavor to develop treatments for cancer and to determine the risk associated with radiation-induced cell damage during travel in outer space [1].

Radiation in the space environment consists of a variety of charged particles that greatly differ in the energy that can be transferred to the matter they are passing through or in which they stop. A particle passing through matter transfers its energy to the medium mainly by ionizing atoms along its path. The amount of energy lost by the particle per unit path length is called linear energy transfer (LET) and varies directly by the square of the atomic number of the particle and inversely as its energy.

Besides the LET the other important ion beam parameter is the range of the ions at a particular energy in matter. The deeper the ions have to penetrate the device, the higher the energy needed for the testing.

The ideal radiation effect testing facility should offer great flexibility and variety in energy and ion species, because a wide range of ions is needed to fully test a device. It is also critical to minimize the time between beam changes (in the order of 1 to 5 min).

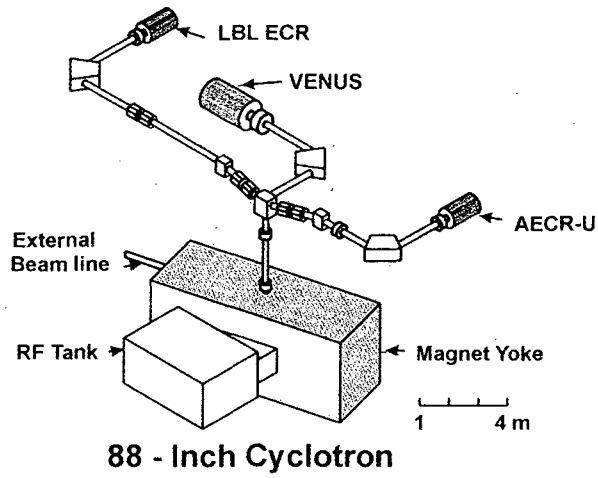

Fig. 1 Schematic layout of the 88-Inch Cyclotron accelerator facility

2 ACCELERATOR

2.1 The 88-Inch Cyclotron

The 88-Inch Cyclotron is a sector-focused cyclotron fed by two high-charge-state Electron Cyclotron Resonance (ECR) ion sources, the double-frequency (14 GHz and 10 GHz) driven AECR-U [2] and the 6.4 GHz driven LBL ECR [3] ion sources. A third ECR injector ion source, the superconducting source VENUS [4] is in the process of being installed and is expected to inject into the cyclotron spring 2003. Fig. 1 shows a schematic layout of the 88-Inch Cyclotron accelerator facility with the three ECR ion source injectors.

The 88-Inch Cyclotron is nominally a K140 cyclotron. The RF frequency can be varied from 5.5 MHz to 16.2 MHz and both first and third harmonic beams are routinely accelerated. Minimum and maximum energies for the first harmonic and for the third harmonic acceleration are 6.1 MeV and 55MeV/nucleon and 0.7 to 6 MeV/nucleon, respectively.

The factor K can be described as the energy constant of a cyclotron and is connected with the final energy/ nucleon over the equation

$$\frac{E}{A} = \left(\frac{Q}{A}\right)^2 \cdot K, \qquad (1)$$

where E/A is the energy/nucleon, Q is the ion charge and K is the bending limit of the cyclotron magnet.

With a K of 140, mass to charge ratios of about 5 for 4.5 MeV nucleon, 3.6 for 10 MeV/nucleon and 2 for 32.5 MeV/ nucleon are needed to produce the different cocktails, respectively. Typical components of our standard cocktails are shown in Table 1, together with the LET and the range in silicon. Clearly, very high charge states are needed for the heavy ions to reach the required energy with the 88-Inch Cyclotron accelerator.

Cocktail	Standard Ions	LET (MeV/mg/cm$^{2)}$	Range in Si
4.5 MeV/nucleon (q/A = 0.2)	$^{10}B^{2+}$, $^{15}N^{3+}$, $^{20}Ne^{4+}$, $^{40}Ar^{8+}$, $^{59}Co^{12+}$, $^{65}Cu^{13+}$, $^{86}Kr^{17+}$, $^{136}Xe^{27+}$, $^{209}Bi^{41+}$	1.5-98.3	43-180 μm
10 MeV/nucleon (q/A = 0.3)	$^{11}B^{3+}$, $^{18}O^{5+}$, $^{22}Ne^{6+}$, $^{27}Al^{7+}$, ($^{29}Si^{8+}$), $^{40}Ar^{11+}$, $^{51}V^{12+}$, $^{65}Cu^{18+}$, $^{59}Co^{16+}$, $^{86}Kr^{24+}$, ($^{98}Mo^{27+}$), $^{136}Xe^{37+}$, $^{136}Xe^{38+}$	0.84-52.7	115-330 μm
15 MeV/nucleon (q/A = 0.3)*	$^{12}C^{4+}$, $^{15}N^{5+}$, $^{18}O^{6+}$, $^{20}Ne^{7+}$, $^{30}Si^{10+}$, $^{35}Cl^{12+}$, $^{38}Ar^{13+}$, $^{40}Ar^{13+}$, $^{51}V^{14+}$, $^{59}Co^{27+}$, $^{63}Cu^{21+}$, $^{86}Kr^{29+}$, $^{86}Kr^{30+}$	0.96-25.45	166-468 μm
19 MeV/nucleon (q/A = 0.5)	[b] H_2^+, $^4He^{2+}$, $^{14}N^{7+}$, $^{16}O^{8+}$, $^{20}Ne^{10+}$, ($^{28}Si^{14+}$),($^{32}S^{16+}$), $^{36}Ar^{18+}$, ($^{40}Ca^{20+}$)	0.022-8.01	0.29-4.29 mm
32.5 MeV/nucleon (q/A = 0.5)		0.014-5.46	0.69-11.1 mm

[b] LETs and Ranges for molecular ions are calculated for separate components after break-up in target or scattering foil.
*Ions identified in a beam development run

Table 1. Summary of available heavy ion cocktail beams and of the new 15MeV/u cocktail, ions in brackets are added by request.

2.2 Mass Resolution

Since an "ion cocktail" is a mixture of ions of near-identical mass-to-charge (m/q) ratio, the ions 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

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

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 m/q beams are in the order of 1 to 100kHz. 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. 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. The attenuator grids can be controlled from either the ion source console, the control room, or the counting area of the experimenters.

3. ION SOURCE SET-UP

When the ion source is tuned up for the standard cocktails, three different gases are mixed together in the ion source plasma: A special oxygen cocktail gas (containing 1% argon, 1% neon and 1% nitrogen), 80% enriched ^{136}Xe, and 99% enriched ^{86}Kr, all of which are supplied by separate precision gas valves. Oxygen is used as a mixing gas and the added impurities supply sufficient currents of argon, neon and nitrogen from the ion source. Metals are radially fed into the plasma using various evaporation techniques. Six radial slots between the sextupole magnet bars provide access to the plasma chamber. They are used for ovens, feedthroughs and pumping. Fig. 2 shows the standard set-up for the AECR-U for cocktail ion beams.

The radial low temperature oven is utilized to evaporate bismuth. In addition, copper and cobalt metal strips are mounted together on a radial probe. This probe is used for the production of copper and cobalt ions by direct

inserting the metal into the plasma edge. Finally, each source has a MIVOC (Metal Ions from Volatile Compounds) chamber connected, which is loaded with m-carborane ($C_2B_{10}H_{12}$) for the production of boron ion beams. Additional oven ports and gas valves are available in case a special ion beam is requested. In the near future we will also install a multi-sample sputtering probe into the source to further increase the metal ion beam flexibility.

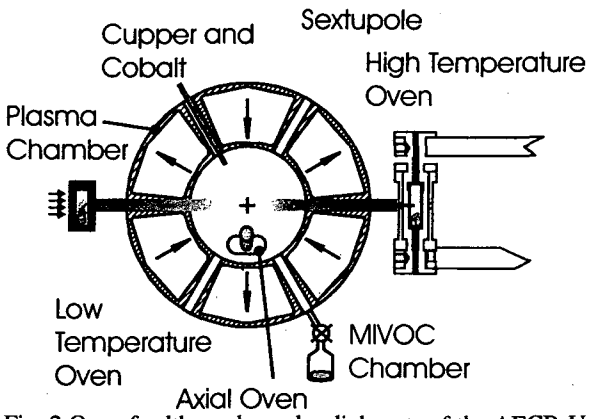

Fig. 2 Oven feedthroughs and radial ports of the AECR-U ECR ion source

It is very important to maintain a careful balance of the different gases and metals introduced into the source plasma to ensure stable operation. Too much Xe for example would suppress lighter ions (inverse gas mixing effect). If the Cu and Co probe is inserted too deep, the electron temperature decreases reducing the output of Xe^{38+} or Bi^{41+}. Therefore, the goal of the tuning process is to extract a low intensity (between 1 to 50 enA) of each ion species out of the cyclotron. This is still 2 to 3 orders of magnitude higher than what is actually used for the testing. A typical spectrum taken after all the different gases and metals have been introduced is shown in Fig. 3 for the 4.5 MeV/u cocktail.

During a typical tune-up procedure the "cocktail" oxygen would first be introduced into the source to extract about 1euA of Ar^{8+} out of the source, which is then tuned through the cyclotron. Once the argon beam has been extracted from the cyclotron, a frequency scan is performed to verify the neon and nitrogen in the spectrum. As a next step the Kr and later the Xe is introduced into the source.

Finally, if Bi is requested for the 4.5 MeV/u cocktail, it is added to the plasma and the source is optimized for the production of Bi^{41+}. Currently we are not able to provide sufficient intensities of Bi^{56+} for the 10 MeV/u cocktail, but it may be available in the future after VENUS has started regular operation with the cyclotron [4].

A careful frequency scan needs to be done in order to verify the different ion species. Furthermore, ions, which have been recently produced in the ion source for other experiments, may remain in the source for several weeks and must be identified. They can then be used in addition to the standard cocktail. For instance, high intensity vanadium ion beams are extensively used for the heavy element program at our facility. Therefore, several enA of V^{12+} are usually available without actively adding V to the plasma. It's mass lies conveniently between Ar and Cu and is routinely used for the 10 MeV/u cocktail.

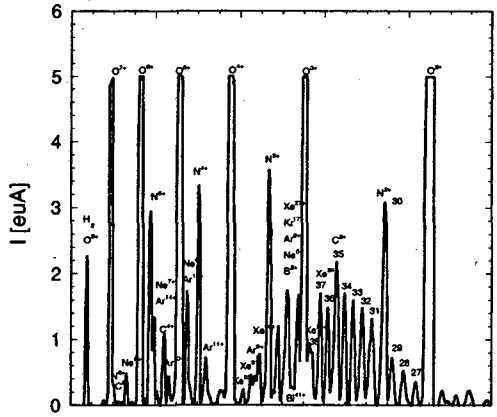

Fig. 3 Typical ion spectrum, for the AECR-U ECR ion source with Bi added to the standard 4.5 MeV cocktail.

As an illustration, Fig. 4 shows relative intensities of different ions found in the high energy cocktail after different high intensity metal ion beams have been tuned out of the AECR-U ion source. The ions were identified with a particle detector. Fig.4 also demonstrates that the cocktail can be easily expanded to more species, if requested before the run.

Ultimately, the cocktail method is limited by the mass resolution of the cyclotron. In the case of the 88-Inch Cyclotron, the frequency resolution is approximately 3000 or 3 kHz for the 10 MeV/u cocktail. Therefore, it is important to know the ion beam production history of the injector ion sources for metals prior to the cocktail tune-up. As an illustration, table 2 shows the cyclotron resonance values for the 10 MeV/u cocktail. In most cases, the frequency difference – which is proportional to the mass difference– is sufficient to cleanly separate two ion species. Since for the radiation effect testing experiments, LET and deposition depths are the main parameters, the contamination from elements with the same mass and similar Z (e.g. ^{40}Ca and ^{40}Ar) do not present a problem. A critical contamination in the case of Ar would arise from $^{80}Kr^{22+}$ or $^{80}Se^{22+}$, which has a frequency difference of only .7 kHz. Therefore the cocktail beam is run with separated isotopes of ^{86}Kr. Contamination could also arise between $^{86}Kr^{24+}$ and $^{136}Xe^{38+}$, which are about 6 kHz apart, if the relative ion beam intensity differences of the two beams are too large, in which case the tail of the adjacent beam contaminates the other. Therefore, it is important to ensure the right intensity levels throughout the cocktails. In addition, the beam purity is confirmed by the experimenters using a silicon energy detector prior to utilization for testing.

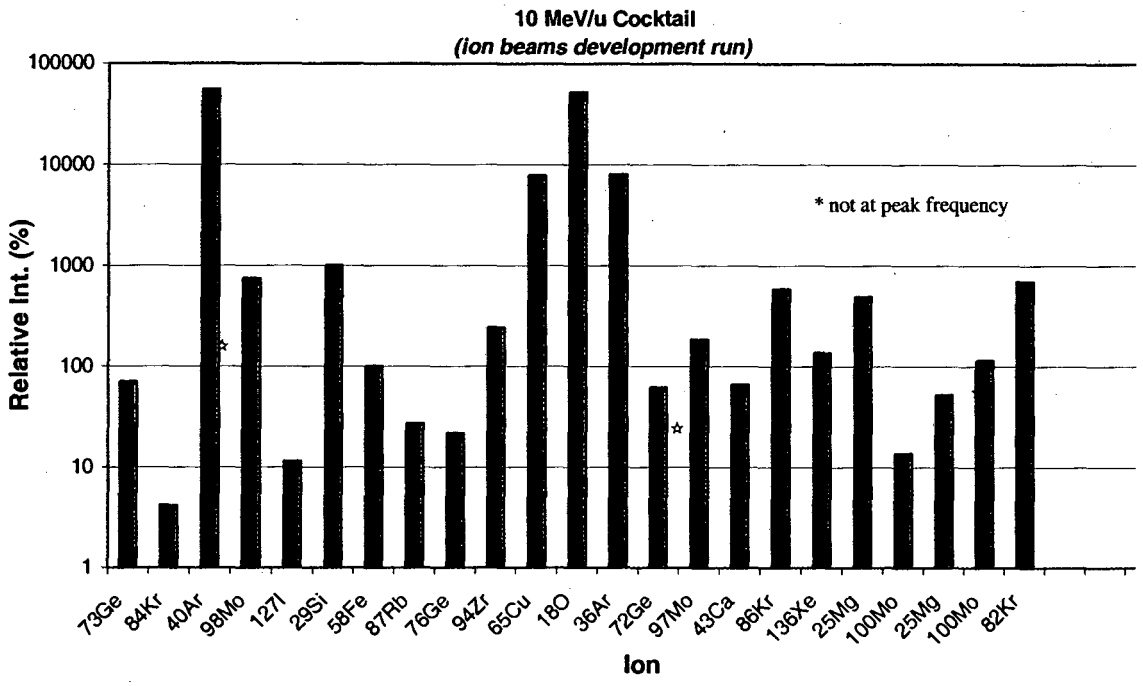

Fig. 4 Relative Intensities of different ions found in the 10 MeV/u cocktail from the AECR-U ECR ion source.

Table 2. Resonance table, energy and typical ion beam intensities for the 10 MeV/u cocktail and some contaminants. Vanadium is also shown as a typical example of a residual beam from a previous run that can be used in the cocktail.

Ion	M	Q	M/Q	Energy	MeV/u	f[MHz]	Δf [kHz]	I [enA]
Xe	136	38	3.58	1403.4	10.32	7.1799	109.20	.1-.3
Kr	86	24	3.58	885.60	10.3	7.1739	103.10	1-5
O	18	5	3.60	183.50	10.19	7.1344	63.7	25
Cu	65	18	3.61	659.20	10.14	7.1203	49.6	.5-2
Kr	80	22	3.63	800.10	10.0	7.0715	0.7	1-2
Se	80	22	3.63	800.10	10.0	7.0715	0.7	
Ar	40	11	3.63	400.00	10.0	7.0708	0.00	30-100
Ca	40	11	3.63	400.00	10.0	7.0707	0.00	
V	51	14	3.64	508.30	9.97	7.0595	-11.2	.3-10
Ne	22	6	3.67	216.30	9.83	7.0098	-61.0	.1-1
B	11	3	3.67	108.00	9.82	7.0013	-69.5	.5
Xe	136	37	3.67	1330.9	9.79	6.9949	-75.8	.1-.3
Co	59	16	3.68	573.9	9.73	6.97604	-94.7	.5-2

CONCLUSION

Radiation effects testing research is a small but vital part of the program at the 88-Inch Cyclotron. It is a challenging program in respect to the ion source performance, pushing the developing work of the ion source to the highest possible charge states. It is crucial to balance the different gases and metals introduced into the source plasma very carefully in order to maintain stable plasma conditions and sufficient intensity levels throughout the cocktail.

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