INTRODUCTION TO ECR SOURCES IN ELECTROSTATIC MACHINES

CONF-891043--2

DE90 006849

D. K. Olsen
Oak Ridge National Laboratory*
P. O. Box 2008
Oak Ridge, Tennessee 37831

I. INTRODUCTION

Electron Cyclotron Resonance, ECR, ion source technology has developed rapidly since the original pioneering work of R. Geller and his group at Grenoble in the early 1970s. These ion sources are capable of producing intense beams of highly charged positive ions and are used extensively for cyclotron injection, linac injection, and atomic physics research. In this paper, the possible use of ECR heavy-ion sources in the terminals of electrostatic machines is discussed. The basic concepts of ECR sources are reviewed in the next section using the ORNL source[1] as a model. The possible advantages of ECR sources over conventional negative ion injection and foil stripping are discussed in Section III. The last section describes the possible installation of an ECR source in a large machine such as the HHIRF 25-MV Pelletron.

* Research sponsored by the U.S. Department of Energy under contract DE-AC05- 84OR21400 with Martin Marietta Energy Systems, Inc.

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II. ELECTRON CYCLOTRON RESONANCE ION SOURCES

The ionization processes in an ECR source are in some sense inverse to the stripping processes in a foil. In conventional foil stripping, high-velocity ions are passed through a thin foil whose crystalline structure confines a cloud of low-velocity electrons. In an ECR source, low-velocity ions drift through a cloud of high-velocity electrons confined in a magnetic well. In both cases, the ions are stripped to higher charge states which increase with increasing ion-electron relative velocity, electron density, and interaction time between the ions and electron cloud.

An ECR zone in space is created whenever a magnetic field B and microwave electric field E are superimposed and the frequency of the applied microwave radiation equals the electron gyro frequency. This requires the microwave frequency f in GHz and the magnetic field B in Tesla to be related by $f = 28B$. Whenever an electron crosses this zone, it has the possibility of being accelerated to high energies by the component of E perpendicular to B much like a circulating ion in a cyclotron. A highly charged ion beam is produced by allowing the ions of the plasma to drift through the corresponding electron cloud of the plasma. The electrons are confined in space by a magnetic mirror or minimum magnetic field configuration similar to that used for fusion research. The electrons are heated to high velocity by absorbtion of microwave power in those regions where the microwave frequency equals the electron gyro frequency, which is determined by the local magnetic field strength.

Many ECR sources have been built worldwide. The ORNL source has reliably produced ion beams over a wide range of atomic species and charge states for a large variety of atomic physics experiments.[1] The salient features of the ORNL source are shown in Fig. 1. The source consists of two stages. In the main or second stage, electrons are confined in a minimum-B configuration and heated by resonant absorption of 10.6 GHz microwaves. The minimum-B structure is produced by a superposition of an axial mirror field and a radial hexapole field. Three conventional water-cooled solenoids are used to produce the axial mirror field which is pinched on both ends. The hexapole field is produced by a compact assembly of SmCo permanent magnets positioned around the

cylindrical vacuum wall of the main stage. Cooling of the permanent magnet assembly is achieved by water circulation through the voids created between the cylindrical vacuum wall and the duodecagon defined by the placement of the SmCo bars. This second stage operates at a pressure of about 10^{-6} Torr. The injector or first stage also operates in an electron cyclotron resonance mode at 10.6 GHz, and serves as a source of ions and electrons to "fuel" the main stripper stage. This first stage produces a stable plasma of singly charged ions at a pressure of about 10^{-3} Torr. A single 2.2-kW microwave power source is used for both stages. A total of 60 kW of electrical power is used for the solenoidal magnetic field.

Ion extraction from the ECR source is straightforward and accomplished by a three-element electrode operating up to 20 kV; the first two elements can be biased independently for ion focusing and prevention of electron back-streaming. An electrostatic einzel lens images the extracted beam onto the entrance slit of a magnetic charge analyzer. The ORNL ECR source has the capability to produce both metal as well as gas ions. Metal ions are produced using a solid sample feed technique in which a metallic vapor is created from a thin foil sample heated by mechanical insertion into the edge of the main stage plasma.[1] Metal ions could also be produced using an oven technique.[2] A support gas, usually nitrogen, is needed for metallic ions.

Table 1 summarizes representative ion currents attainable from the existing ORNL 10.6-GHz source. Some charge state distributions from the ORNL source for Au ions are shown in Fig. 2. The right panel shows results for the source optimized for Au^{27+}. About 15 pnA of Au^{27+} was obtained. The left panel shows results for the source optimized for Au^{30+} production. Worldwide, over a dozen ECR sources have been built and operated. These sources have proved to be very robust, in part because the plasma is produced with an electrodeless discharge.

III. ECR SOURCES IN ELECTROSTATIC MACHINES

An ECR source could possibly be advantageous for an electrostatic accelerator if larger currents of higher charge states could be obtained

than with conventional sources. For single-ended accelerators, this comparison is straightforward. For tandem accelerators, the comparison is more complicated, since negative ions are injected and then stripped to a positive charge state in the terminal. Furthermore, for the most interesting cases, the ions are foil stripped, and the maximum beam current in the terminal is in fact limited by foil lifetime considerations.

Figure 3 attempts to make this comparison for a ^{208}Pb beam where the expected current available in the high-voltage terminal of an electrostatic machine for acceleration through the high-energy tube is plotted as a function of charge state. Results for six cases are shown. The three lower curves are for tandem accelerators with foil strippers and operated at terminal voltages of 6, 12, and 24 MV. The upper curves are for terminal ECR sources, for which the available beam current is independent of terminal voltage. Results for three ECR sources are shown: (1) Measured Bi currents from the all permanent magnet, lower power, compact, 8-GHz NEOMAFIOS source;[3] (2) Measured Au currents from the ORNL 10.6-GHz source previously described;[1] and (3) Measured Bi currents from the large, high power, 6.4-GHz LBL source with a 700°C oven vapor feed.[2]

As the terminal voltage increases from 6 to 24 MV, the peak charge state for an equilibrium distribution from foil strippers increases from 9 to 17 and the corresponding beam energy increases from 0.29 to 2.16 MeV/nucleon. Equally important, the higher beam energy for stripping increases the foil lifetime and hence current from 10 pnA to 35 pnA. For the results of Fig. 3, a foil lifetime of 30 minutes was required, assuming beam-current-lifetime products of 1.4, 2.8, and 5.6 pμA-min for 6-, 12-, and 24-MeV lead beams, respectively. These beam-current-lifetime products were estimated for 5 $\mu g/cm^2$ thick glow-discharge slackened foils from the work of Auble et al.[4] Clearly the beam currents available from foil stripping are foil-lifetime limited.

A lead beam above the Coulomb barrier, with an energy between 4.5 and 6.0 MeV/nucleon, and an intensity between 0.1 and 1.0 pnA, is of great interest for nuclear structure physics. Unfortunately, such a beam cannot be produced with existing electrostatic accelerators with either conventional or ECR ion sources. With single-foil stripping, a terminal

potential of 38 MV would be required to produce a useful beam of 4.7 MeV/nucleon Pb^{208}. Such an electrostatic accelerator is presently not available; consequently, an energy booster must be used.

Acceleration of a lead beam above the Coulomb barrier at the HHIRF can be accomplished using the ORIC energy booster. The product of the transmission, foil fraction, and bunching factor through ORIC is about 5%. Consequently, to deliver one pnA of beam on target would require about 40 pnA of lead in the tandem terminal to inject into ORIC, assuming a 50% beam loss in the tandem high-energy tube. As shown in Fig. 3, 40 pnA of lead cannot be obtained in the tandem terminal at 24 MV with the present foil lifetime limits. However, the three ECR sources whose currents are shown in Fig. 3 all produce at least 40 pnA of beam. In particular, the NEOMAFIOS, ORNL, and LBL ECR sources produce over 40 pnA of lead for charge states less than 23+, 25+, and 29+, respectively. The charge states of interest for ORIC injection are between 17+ and 24+ for nuclear physics studies.

The determination of the ORIC output energy is somewhat complicated. Injection into ORIC is achieved by stripping from the tandem charge state to a higher charge state Q through an injection foil. The maximum energy/nucleon from ORIC is then given by $E/M = 105\ (Q/M)^2$. Consequently, the maximum energy from ORIC is determined by the charge state Q from the injection foil, which is energy dependent and determined by the tandem energy which, in turn, is determined by the tandem terminal charge state.

These relationships are illustrated for ^{208}Pb in Fig. 4, which shows the maximum current one can obtain from ORIC in coupled operation as a function of energy per nucleon. Five curves are shown: conventional tandem operation with a terminal gas stripper, conventional tandem operation with a terminal foil stripper, and tandem operation with a terminal ECR source using the NEOMAFIOS, ORNL, and LBL current results. The numbers on the curves give the terminal charge state, whereas the bottom scale gives the ORIC charge state Q. The energy range of interest for nuclear structure physics is also shown. Clearly, the installation of a terminal ECR source would allow the HHIRF coupled accelerators to

produce lead beams for nuclear structure physics with intensities above one pnA.

IV. ECR SOURCE INSTALLATIONS

There are many factors to consider in the possible installation of an ECR source in a tandem terminal, among which are space, weight, power, cooling, vacuum, control, and beam optics requirements. The solution to these problems for a small machine has been worked out by a group at TUNL, who are installing an extremely compact ECR source in the TUNL KN Van de Graaff. This 2.45-GHz permanent-magnet source is designed to produce proton, deuteron, and alpha particle beams with very low energy spread. This work is described in detail in these proceedings.[5]

In this paper, the possible installation of an ECR source in a very large machine, the HHIRF tandem, is discussed. The source for such an installation would probably be very similar to and developed from the NEOMAFIOS source built at Grenoble.[6] This source was designed to operate on a high-voltage platform. The magnetic structure is made entirely of 250 Kg of FeNdB permanent magnets and is designed for resonance at 8 GHz, B = 0.29 T, a frequency for which powerful air-cooled rf generators exist. About 0.8 kW of rf power is required and the total power consumption for the source is less than 3 kW. The ECR chamber is 8 cm in diameter and about 15 cm long. The source is a single-stage device, is vacuum pumped only through the extraction electrode, and requires a space about 50 cm long and 50 cm in diameter. It operates at 12 kV and the position of the extraction electrode is adjustable. A more optimum source for the HHIRF tandem would operate at 10 GHz with perhaps some electromagnetic solenoid field capability to adjust the mirror field. Also, a controllable oven vapor feed for metallic beams would be very desirable.

The beam transport system between such a source and the high-energy tube would be similar to that of the ORNL ECR facility and would select a single charge state for acceleration. In particular, an einzel lens would focus the beam from the extraction aperture to the object slits of a

40-cm radius, 90°, double focusing dipole magnet. The source potential would be at 50 kV positive with respect to the terminal voltage. The image slits would select a single charge state to be focused by a second einzel lens through an electrostatic mirror. This mirror would bend the ions by 90° to merge the beam into the existing tandem terminal optics system. A terminal bunching system would also be needed to prepare the beam for the ORIC phase acceptance. It is important to appreciate that with the electrostatic mirror off and the ECR transport system valved off, the tandem would operate without interruption in the normal manner using the negative ion source at ground potential. This transport scheme seems plausible. The Pelletron terminal has a diameter of 3.9 m and 38 kW of power are available. The installation of an ECR source in the HHIRF tandem is under serious consideration.

IV. ACKNOWLEDGEMENTS

The author gratefully acknowledges the many helpful discussions on ECR ion technology with F. Meyer and G. Alton of ORNL and R. Geller and G. Melin of Grenoble.

REFERENCES

1. "Operation of the ORNL ECR Source," F. W. Meyer and J. W. Hale, Proc of 1987 IEEE PAC, 1987, Washington DC, p. 319.
2. "The Production of Beams from Solid Materials at the LBL ECR Source," D. J. Clark and C. M. Lyneis, Proc. of Fourth International Conf. on ECR Sources and Related Topics, Grenoble, France (1988).
3. Measured results for the NEOMAFIOS source, private communication, R. Geller, December 1989.
4. "Procedure for the Rapid Evaluation of Carbon Stripper Foils," R. L. Auble and D. M. Galbraith, Proc. of Ninth World Conf. of the International Target Development Society, Gatlinburg, TN, 1980.

5. "Development of a Compact ECR Source for a Single-Ended Van de Graaff," W. M. Hooke, C. R. Jackson, and C. R. Westerfeldt, contribution to this conference, 1989.
6. "The Grenoble ECRIS Status," G. Melin et. al., Proc. of Inter. Conf. on Multiply-Charged Ion Sources, Grenoble (1988) 673.

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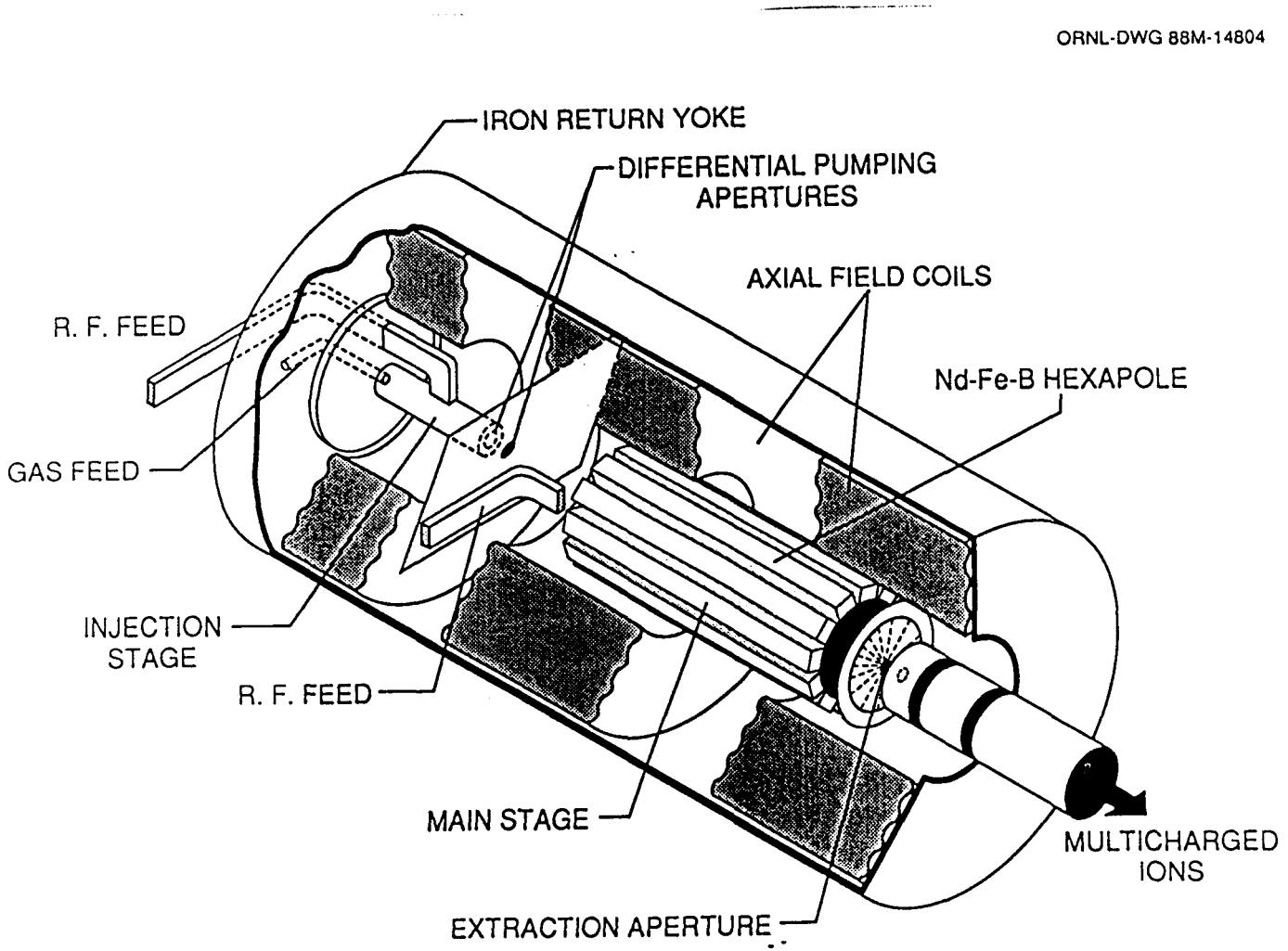
Figure Captions:

1. Schematic view of the ORNL 10.6-GHz ECR ion source. Singly charged ions are produced in the injection or first stage at a pressure of about 10^{-3} Torr and highly charged ions are produced in the main or second stage at a pressure of about 10^{-6} Torr.
2. Measured charge state distributions in electrical μA for Au ions from the ORNL 10.6-GHz ECR source. The left panel shows results for the source optimized for Au^{30+}, whereas the right panel shows results with the source optimized for Au^{27+}.
3. Comparison of expected ^{208}Pb beam currents in the terminal of a tandem accelerator between conventional negative ion injection with foil stripping and a terminal ECR source. Results for 6-, 12-, and 24-MV terminal voltages are shown. The maximum beam current in this case is limited by the foil lifetime. Measured results for three ECR sources are shown. Over a factor of 20 more current could be expected from the ORNL ECR source than with foil stripping at 24 MV.
4. Expected ^{208}Pb beam currents from the HHIRF tandem and ORIC accelerators operated in the coupled mode. Results for the tandem operated at 24 MV with either gas or foil single stripping are shown , as well as results for the NEOMAFIOS, ORNL, and LBL ECR sources mounted in the tandem terminal. The charge states in the tandem terminal are listed along the curves, whereas the ORIC charge states are given on the bottom of the figure. For these calculations, ORIC transmissions of 0.42, 0.42, and 0.35 were assumed with tandem transmission of 0.49, 0.26, and 0.50 for the gas, foil, and ECR cases, respectively. The current injected into the tandem for the gas stripping was limited to 2000 nA, whereas the injected current for foil stripping was limited to 183 nA because of the need to have at least a 30-minute lifetime for a foil with an expected 5.6-μA-min beam-current-lifetime product.

Table 1. Representative 10.6 GHz ORNL ECR source beam currents in eμA

	^{16}O	^{40}Ar	^{56}Fe	^{58}Ni	^{84}Kr	^{127}I	^{129}Xe[a]	^{181}Ta	^{197}Au
+1	400	110	10						
+2	300	120	*						
+3	170	90	20						
+4	100	75	*						
+5	83	*	23	3	20				
+6	50	65	25	5	25				
+7	2.5	73	*	7	26				
+8	0.1	105	*	12	27				
+9		45	20	20	33		5.0		
+10		*	10	17	31	8	4.5	12	25
+11		3.0	5	*	33	10	3.5	*	27
+12		0.7	*	5	40	14	3.5	12	21
+13			2	3	23	18	3.2	12	18
+14			*	1	21	20	2.5	12	*
+15			1.5	0.5	15	18	1.5	12	18
+16				0.15	5	*	1.2	12	15
+17				0.03	1	10	1.0	11	12
+18					*	*	0.6	8	10
+19					0.25	3	0.6	5	7
+20						2	0.5	3.5	5
+21						*	0.25	2	5
+22						0.5	0.12	1.8	4
+23								*	3
+24								1.5	2.5
+25							0.08	1.0	*
+26							0.05	*	0.9
+27								0.4	0.4
+28								0.1	*
+29								0.05	0.1
+30									0.015[b]
+31									0.005[b]

*Indicates m/q degeneracy with contaminant beam.
[a]5 x 5 mm slits.
[b]2 x 2 mm slits.



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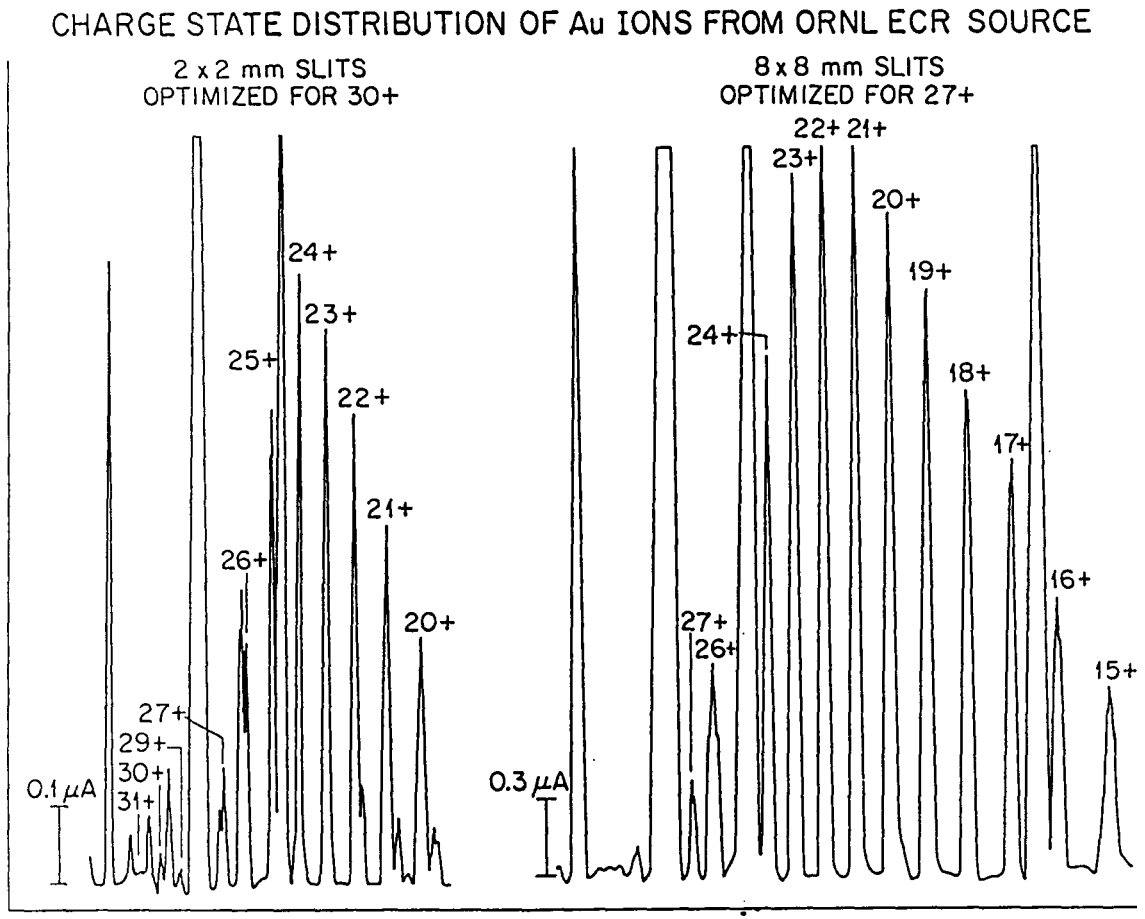

Fig. 2. Measured charge state distributions in electrical μA for Au ions from the ORNL 10.6-GHz ECR source. The left panel shows results for the source optimized for Au^{30+}, whereas the right panel shows results with the source optimized for Au^{27+}.

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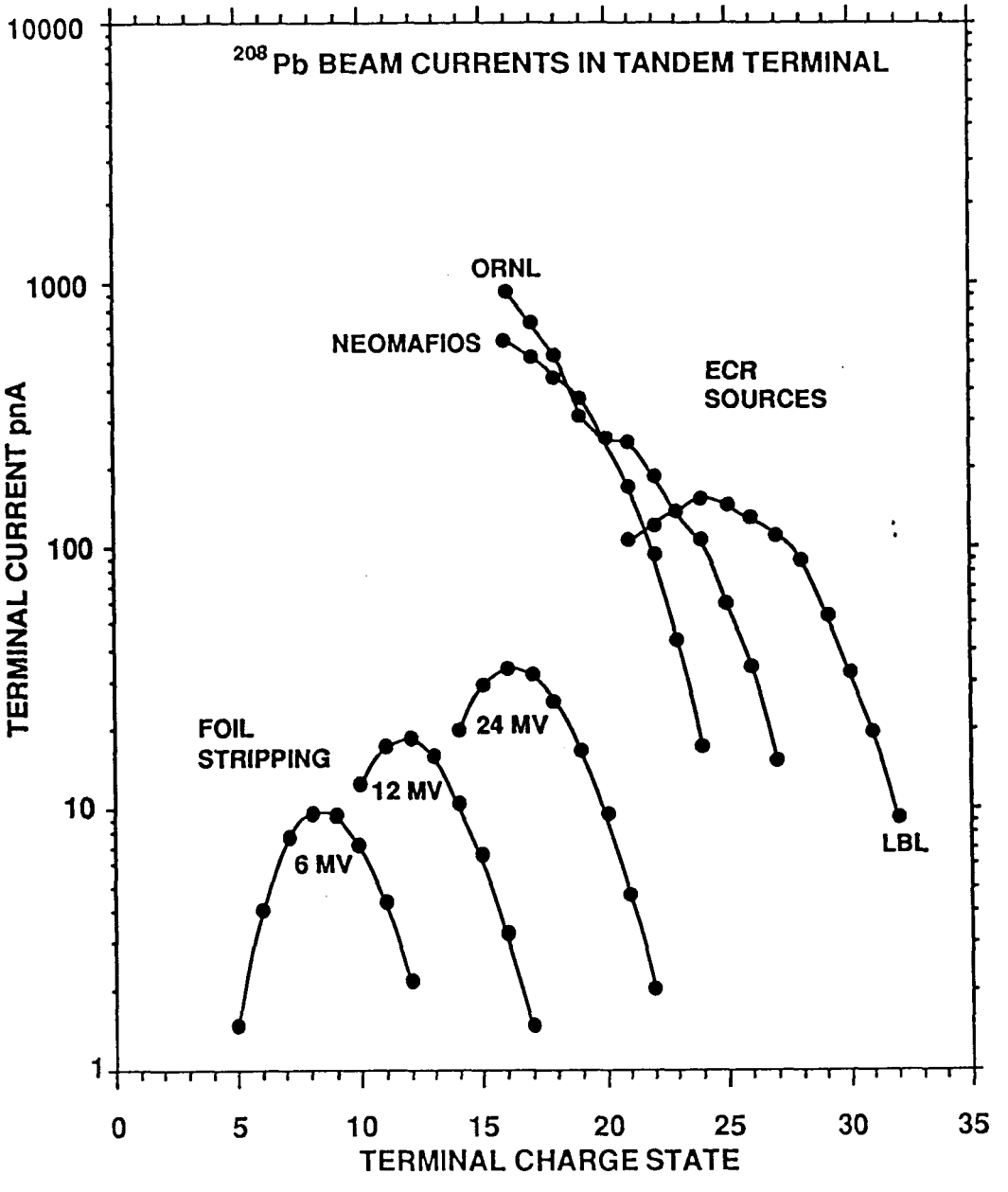

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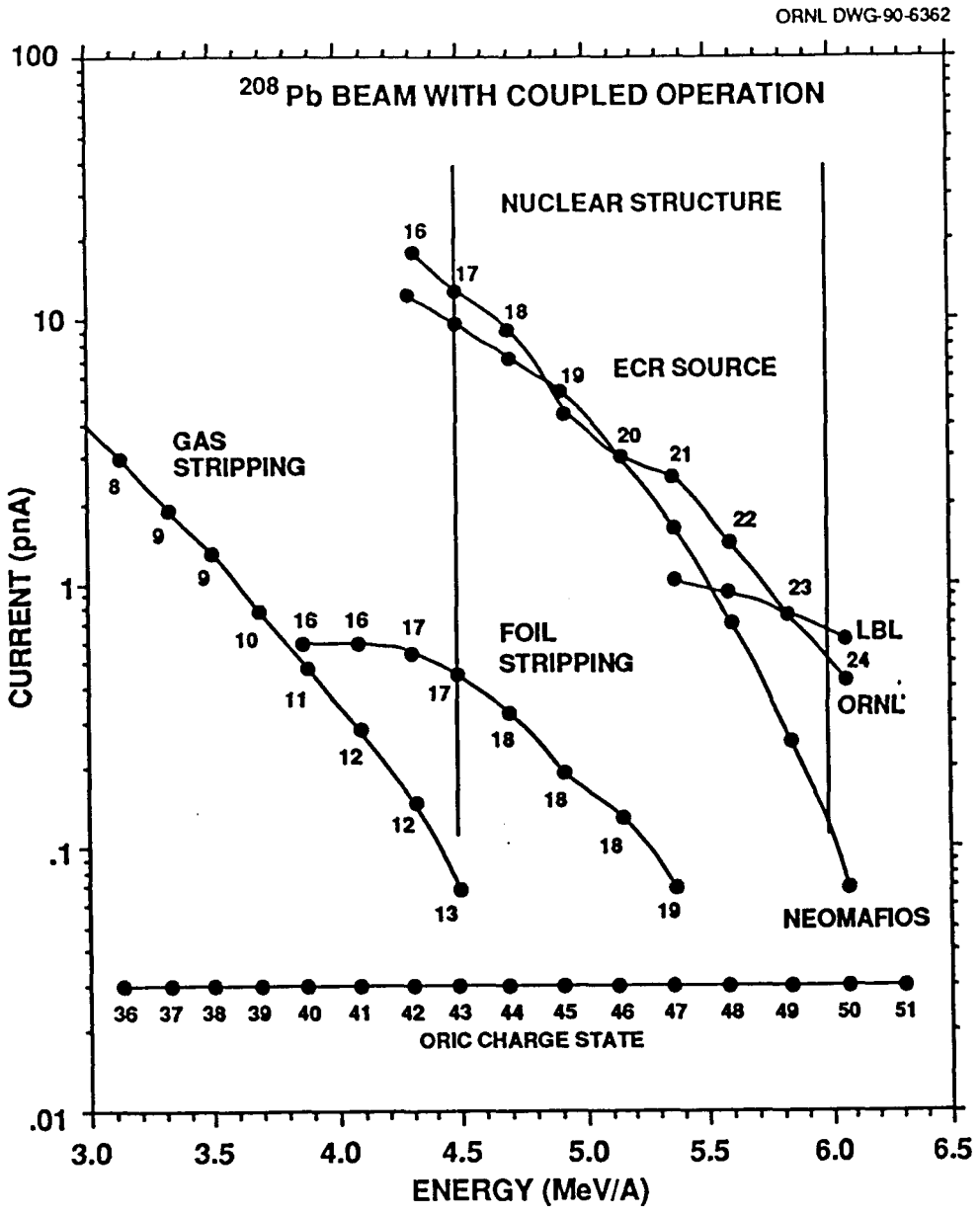

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