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A COMPARISON OF METHODS OF PRODUCING VERY HIGHLY STRIPPED URANIUM BEAMS

I.G. Brown

October 1983

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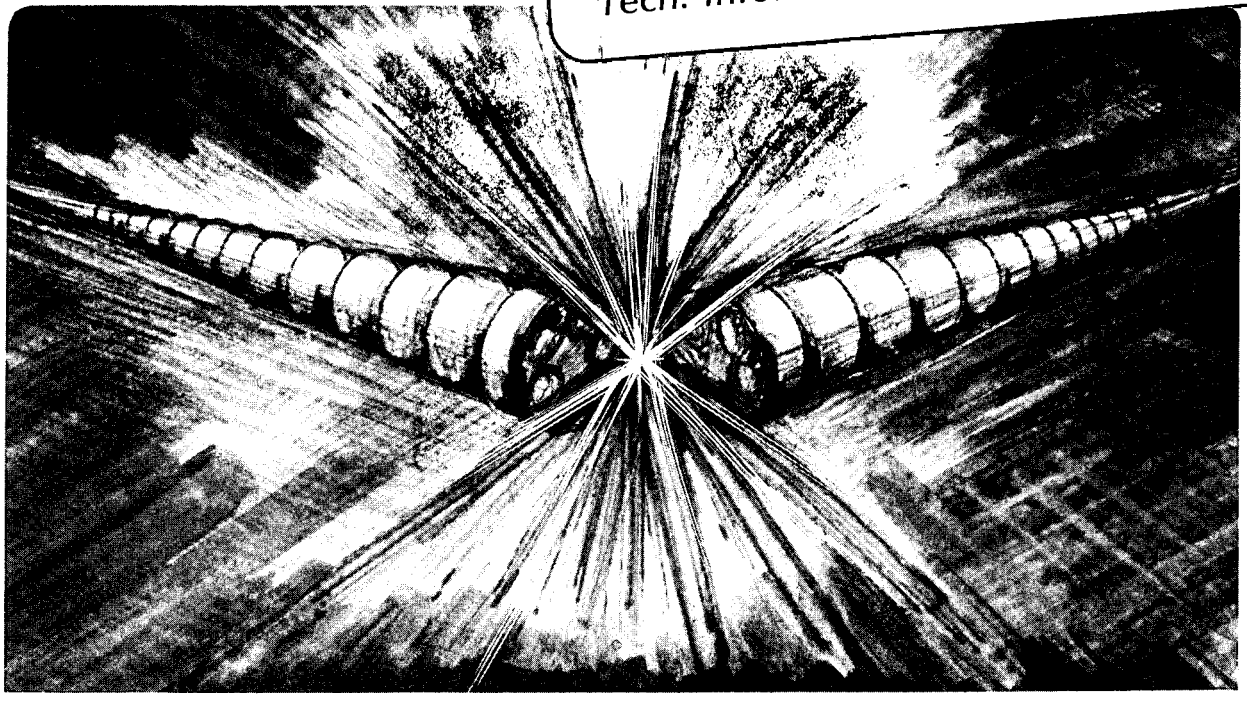

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A Comparison of Methods of Producing Very Highly Stripped Uranium Beams

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Abstract

A comparison is made between the production of high intensity beams of helium-like uranium ions, U^{90+}, by conventional and exotic ion sources, and by the foil stripping of highly accelerated ions output from the Bevalac.

The parameter requirements are specified and compared to the parameters achievable by present day ion source technology. The EBIS (Electron Beam Ion Source) comes closest to satisfying the necessary parameters, and this possibility is considered in some detail.

We conclude that existing and near-future ion source technology does not provide a means of production of high intensity U^{90+} beams. Foil stripping of lower charge state species that have been accelerated through the Bevalac provides a convenient approach.

I. Introduction

Interest in heavy ion atomic and nuclear physics has created a need for a means of production of reasonably intense beams of highly stripped heavy ions. Helium-like uranium, U^{90+}, is of particular interest for a variety of reasons, and here we consider this ion.

Concomitant with this interest in highly stripped species has been a renaissance in high charge state ion source development. Several devices have attracted considerable interest as possible sources of very highly stripped ions, especially the EBIS and ECR ion sources. It is natural to consider whether or not it might be possible to push these sources sufficiently far beyond their present operating regimes to produce U^{90+} ions.

We consider here the parameters that determine the charge states evolved by an ion source, and then briefly survey existing and possible ion source performance in terms of high charge state production. The source that shows the greatest potential for production of very highly stripped species is the EBIS, and the Appendix contains an informal proposal, written late 1982, for a possible U^{82+} EBIS R and D Project.

II. Ion Sources

A. Source Parameters

In an ion source, a plasma is created from the desired elemental species and the plasma ions are extracted by an electrode arrangement to produce the ion beam. There are thus two fundamental components – plasma discharge and extraction optics. The plasma parameters determine, largely if not completely, extracted beam ion composition, current, energy spread, and charge state; these beam parameters reflect the parent plasma parameters – plasma composition, ion density, ion temperature, and charge state distribution (C.S.D.). Thus consideration of the ion beam charge state distribution must focus upon the plasma physics of the discharge.

Ions are created by ionization from the neutral state by electron impact. The plasma ions may be stripped by a number of different processes, but the most important process is stepwise ionization by successive electron impact. As one intuitively expects, the maximum charge state that can be obtained is determined by:

(i) The electron temperature T_e,

(ii) The product $n_e t_i$ of electron density n_e and ion confinement time t_i.

Thus the plasma electrons must be sufficiently energetic to remove the bound electrons by collisions, and the plasma electron density and ion residence time must be sufficiently great to allow the stripping to evolve.

Calculations of the parameters necessary to achieve different charge states for a variety of elements have been carried out by a number of authors,[1, 2] and involve evaluating expressions of the type:

$$n_e \, t_i(Q) = \sum_{k=0}^{Q-1} \frac{1}{\langle \sigma_{k,\,k+1} \, v_e \rangle} \qquad (1)$$

where n_e is the electron density, $t_i(Q)$ is the time which must elapse to produce ions of charge state Q, $\sigma_{k,\ k+1}$ is the cross section for ionization from charge state k to charge state k + 1 by electron impact, v_e is the electron velocity, and the average $\langle\sigma v\rangle$ is taken over the distribution of electron velocities. The cross sections can be taken as given by the semi-empirical formula of Lotz[3]. It is in some instances more appropriate to consider the parameter jt rather than nt, where j is the electron current density. Since j = nv, the two are simply related by

$$nt = jt/v, \tag{2}$$

where it is understood that j is measured in electrons/cm^2sec. We ignore the difference between the electron energy E_e for the case of a directed beam of electrons and the electron temperature T_e for the case of a Maxwellian plasma, and note that the results are quite insensitive to the electron distribution[4].

Results of calculations of $jt(E_e)$ for a number of ion species are shown in Figs 1 - 5; these calculations were carried out by the Orsay/Saclay EBIS group. For a given charge state, the required jt becomes finite at an energy equal to the ionization potential for that particular charge state, and has a broad minimum at an energy several times the ionization potential, corresponding to the maximum in the ionization cross-section curve that occurs at several times the ionization potential.

From data such as those shown in Figures 1 - 5 it is thus possible to predict the plasma requirements necessary to produce a particular ion in a particular charge state.

B. Comparison of Ion Sources

We consider the following sources:

PIG (cold and hot cathode)

Duoplasmatron

ECR ion source

EBIS

Laser ion source

Vacuum spark

Exploding wire

Tokamak

The progression is from conventional to unconventional. Thus, the PIG and duoplasmatron are quite commonly used as accelerator sources; the ECR and EBIS are currently being developed at a number of laboratories; laser plasmas, vacuum sparks and exploding wires have been investigated for their possible use on a very preliminary basis; and the Tokamak fusion reactor device is added as an interesting comparison.

1. PIGs

The PIG source is the most commonly used ion source for accelerator application. The PIG plasma has been well described (e.g. 5, 6, 7), as also have PIG ion sources (e.g. 8 – 16). In the PIG the bulk plasma electron temperature is ~ 10–100 eV, and there is also a component of primary, non-thermalized, reflexing electrons with energy of the same order as the cathode-anode voltage drop and it is these electrons whose energy is pertinent to the ionization process. Primary electron densities up to $\sim 10^{14}$ cm^{-3} and ion confinement times up to several microseconds

have been estimated[11], for an nt ~ 10^9 cm^{-3} sec or jt ~ 2 X 10^{18} electrons/cm^2 at E = 1 keV. These numbers are reasonably consistent with the observed maximum charge states such as Ar^{9+} and U^{11+}, (recall that for any real distribution in ion lifetime and electron energy, there will not be a sharp cut-off in charge state distribution, but a gradual reduction in intensity). Table I (from ref. 9) shows examples of the kinds of charge state species that have been observed. Fig. 6 (from ref. 11) shows a comparison of measured and calculated charge state distributions. Fig. 7 shows the spectrum obtained from a uranium PIG source, tuned to maximize the U^{5+} and U^{6+} yield (ref. 16).

2. Duoplasmatron

This source has been well investigated also (ref. 17 - 19). Its advantages are long lifetime, quiet operation, and high beam current. The charge state species available, however, are modest.

3. ECR Source

In an ECR ion source (20 - 25) the ionizing electrons are the hot electrons of a plasma that is produced by the injection of high power microwaves into a static magnetic field. When the microwave frequency is equal to the electron cyclotron frequency eB/m of a particular magnetic surface, energy is efficiently transfered from the microwave field into electron temperature, and an energetic electron component can be produced. Most ECR ion sources are two-stage devices; eg Fig. 8 which is a schematic of the ECR ion source under construction for the 88" cyclotron.[25] Plasma created in the first stage at a pressure ~ 10^{-3} torr is allowed to drift along the magnetic field into a second region where the pressure is much reduced, ~10^{-6} torr. In the second stage the

magnetic field configuration is that of a minimum-B stabilized magnetic mirror[26] so as to maximize the ion confinement time within this stripping region. Typically several kilowatts of microwave power at a frequency ~5-15 GHz are used to create a plasma of hot electron density up to a maximum of $\sim 10^{12}$ cm $^{-3}$ and temperature up to ~10 KeV, with an ion confinement time of up to several milliseconds; thus n values up to $\sim 10^{9}$ cm^{-3} sec are obtained. The chief advantages of the source are its simplicity and cw operation.

Performance of ECR ion sources in terms of the output ion charge state distribution has been well investigated, and Fig. 9 shows a comparison of a measured CSD to that calculated[24]. The source output is fairly well predicted.

4. EBIS

The electron beam ion source has attracted considerable interest in recent years because of its ability to produce very highly stripped heavy ions. To date the record charge state produced is Xe^{52+}, by the Dubna group[27]. Fig. 10 shows some CSD data obtained by this group. EBIS operating principals are described in some length in the Appendix. Briefly, a batch of ions is confined electrostatically within a high current density electron beam; after maximum stripping is achieved the ion potential well is switched and ions are extracted. The electron beam is magnetically compressed to a current density over 100 Amps/cm^2, and the device is cryogenically pumped to a vacuum $\sim 10^{-12}$ Torr allowing an ion confinement time of several seconds. Thus jt is over 10^{21} electrons/cm^2, which is far superior to that achievable with any other ion source. The electron beam energy can be any desired value from a few

keV up to a few tens of keV or higher. The disadvantages of the source are its low duty cycle, ~50μsec pulses every few seconds, and low particle output (~10^8 particles per pulse). Nonetheless, because the EBIS provides a possible means of producing very highly stripped species, this source is considered in some detail in the Appendix. Fig. 11 is a schematic of a conceptual superconducting and cryogenic EBIS.

5. Laser Ion Source

By virtue of the ability to concentrate energy into very small areas in very short duration pulses, pulsed lasers can attain field intensities that are many orders of magnitude greater than achievable by any other means. This pulse of optical radiation can be focused onto a surface in a vacuum to create a dense, hot plasma from which ions may be extracted. Because of the application of this phenomenon to fusion (both controlled and uncontrolled), the field has received a great deal of attention, (see e.g. refs. 28 - 34). The plasma conditions created are unique in that the density is extremely high (approaching solid density) and the lifetime extremely short (inertial disassembly time); typically, $n \leq 10^{21}$ cm^{-3} and $t \leq 1$ nsec, for $nt \leq 10^{12}$ cm^{-3} sec. High charge states such as Co^{23+}, Fe^{16+}, Gd^{26+} have been observed. (see Fig. 12). Fig. 13 shows a schematic of a laser-produced plasma device proposal as a more-or-less complete ion source including the extractor (ref. 29).

6. Exploding Wires

Exploding wires constitute a phenomenon of interest to fusion research, but it seems that this kind of plasma device has not been investigated by the ion source community. The short pulse and low duty cycle inherent to the method are severe disadvantages. In high power

exploded wire discharges, the density, ion confinement time and electron temperature are similar to that obtained in laser discharges. The record charge state achieved seems to be Au^{51+} [35].

7. Vacuum Sparks

The vacuum spark has been used for a long time as a spectral source for multiply ionized species. As for laser and exploding wire discharges, the electron density is high ($\leq 5 \times 10^{20}$ cm^{-3}) and ion residence time short (of order nanoseconds), but here the electron temperature may be as high as 10 keV or more. Species like Ti^{20+}, Fe^{24+}, Cu^{27+} have been observed.[36].

8. Tokamak

The tokamak is a controlled fusion research device which has been very well developed[37]. At the present time this magnetic confinement geometry is the leading contender for the first power-producing fusion reactor, and energy breakeven (fusion power out equal to plasma heating power in) is expected to be demonstrated within only a few years on a presently existing device. It is of some interest to consider the tokamak as a comparison. Parameters that have been achieved are approximately -- density 5×10^{13} cm^{-3}, ion confinement time $\leq$ 50 msec, electron temperature up to several keV. Species such as W^{35+}, Mo^{32+} have been observed.[38,39,40] Fig. 14 and Table II indicate the kinds of ion lines that have been observed in the Princeton ST tokamak device.

In Figure 15 the operating regions in E - nt space for the above sources are shown. The boundaries of the various regions are not meant to be precise, but indicative. The soft boundaries yield as source performance is continually improved.

III. Foil Stripping

The stripping of ions to high charge state by causing the beam to pass through a thin foil of solid material or through a gas cell is common. In a sense this is the inverse process of that employed in multiply charged ions sources, such as those just described in section II. In an ion source, cold ions are stripped by encounters with energetic electrons, whereas in foil stripping energetic ions are stripped by encounters with cold electrons. Note that another significant difference is that the excited state relaxation time of the multiply-charged ionization states produced may not be short (in foil stripping) compared to the time between successive encounters. Thus the cross-sections for ionization to successively higher charge-states may be significantly larger than cross-sections estimated for the case of de-excited multiply-charged species, and the stripping may proceed at a faster rate than otherwise expected.

This effect can be seen in the following way. Consider the ion residence time t to be equal to the transit time of the ion through the foil (or gas cell), and the electron density n_e to be the electron density of the stripper material. For comparison with our calculations (Figs. 1-5), consider the 'equivalent electron energy' E_e to be given by equating the ion velocity to the equivalent electron velocity. Then

$$E_e \text{ (equiv)} = \frac{m_e}{m_i} E_i \quad , \tag{3}$$

and for comparison with the Figures,

$$jt = n_e v_e t$$

$$= \frac{\sigma \; Z \; v_i}{m_p \; A \; v_i}$$

$$= \frac{\sigma \; Z}{m_p \; A}$$

$$= \text{line electron density} \qquad (4)$$

where σ is the foil or gas line density (gm/cm^2), Z the atomic charge of stripper material, A the atomic weight of stripper material, m_p the proton mass. Consider now the following examples using equations (3) and (4).

1. ^{84}Kr at 444 MeV through a carbon foil of $100 \mu gm/cm^2$ produces [42, 43] a charge state distribution peaked at Q = 30+, whereas one would predict Q = 18+.
2. ^{238}U at 962 MeV/amu through a copper foil[44] of 150 mg/cm^2 yields Q = 92+, whereas Q = 83+ is predicted.

Thus the naive treatment presented yields an underestimate of the charge state reached, which effect we ascribe to the enhanced ionization cross-sections of excited states and the short time between collisions compared to the de-excitation time. As supporting evidence for this hypothesis, the agreement is better between measured and predicted charge states for the case of gas stripping cells, where the time between successive collisions is greater.

For the present purposes, the point is that foil stripping of highly energetic accelerated ions can produce charge states of heavy ions that cannot by any means be produced in normal (or exotic) ion sources. Thus, at the Bevalac, uranium beams have been produced of 2×10^6 particles per pulse extracted (before stripping) at up to 1 GeV/amu. After

stripping with foils of mylar or copper or tantalum, the dominant charge state obtained is fully stripped uranium, U^{92+} (44). This is a very significant achievement.

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FIGURE CAPTIONS

Figs. 1-5 Calculated jt(E) for Ar, Kr, Xe, Ta and U ions. The jt (electrons/cm^2 sec) calculated necessary to obtain the ion charge states indicated, as a function of electron energy (KeV). (From ref. 2)

Table I. Performance characteristics of some PIG sources (From ref. 9)

Figs. 6. Measured CSD for a PIG ion source, compared with predicted CSD. (From ref 11).

Figs. 7. CSD obtained from a uranium PIG source. (From ref. 16).

Figs. 8. Schematic of the 88" cyclotron ECR source.

Figs. 9. Calculated and measured CSD output from an ECR ion source (From ref. 24)

Figs. 10. Measured CSD spectra obtained from EBIS. (From Reprint of the Joint Institute for Nuclear Research, Dubna, USSR, Report P7-80-515, 1980).

Figs. 11. Conceptual cryogenic EBIS. (From LBL-5043, 1980)

Figs. 12. CSD produced in a laser-produced plasma. (From ref. 29).

Figs. 13. Conceptual laser-plasma ion source (From ref. 29).

Figs. 14.
Table II } Line emission of high charge state ions observed in Princeton ST Tokamak (From ref. 40).

Figs. 15. E - nt space showing obtained operating regimes for various ion sources.

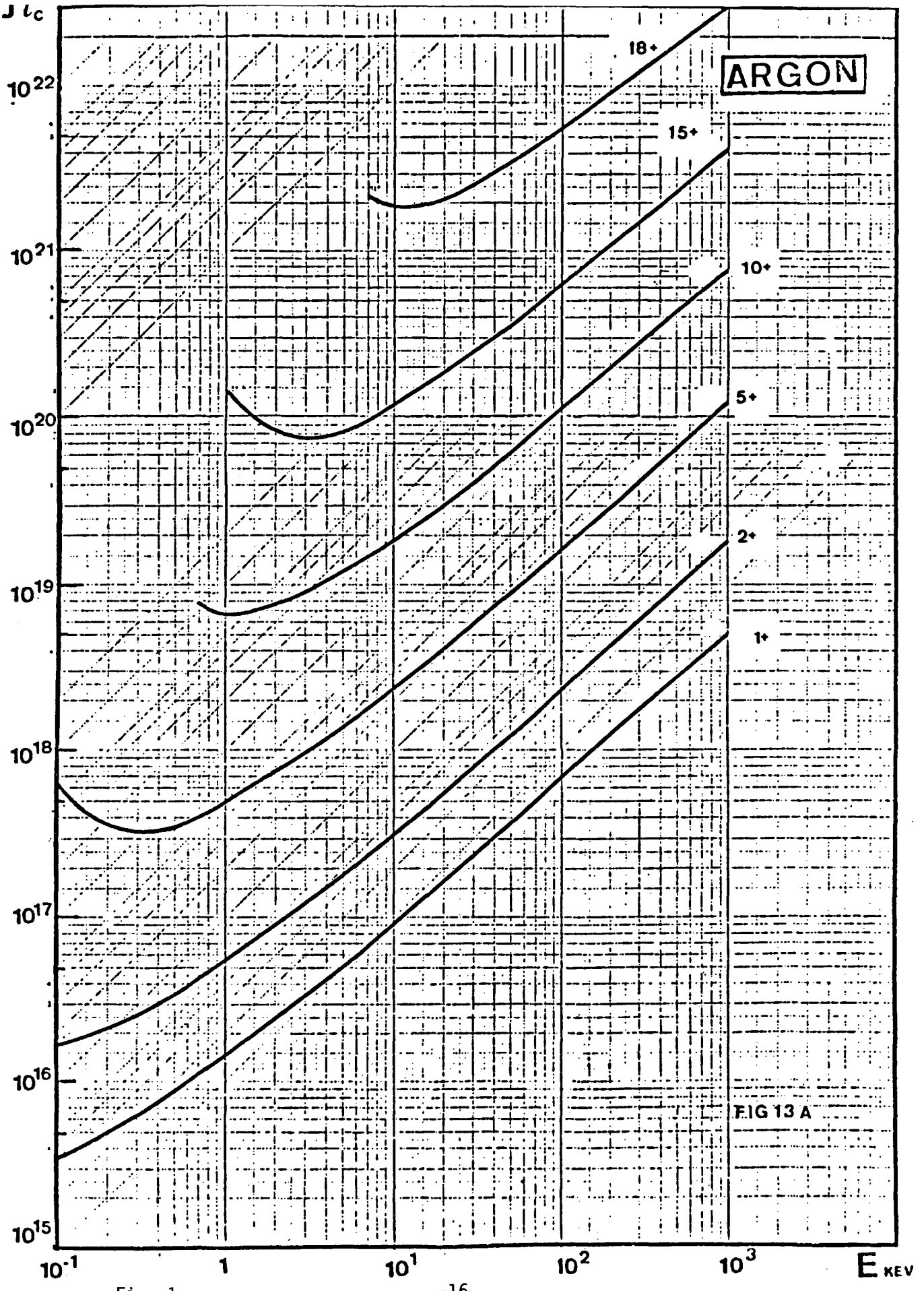
J t_c
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
ARGON
18+
15+
10+
5+
2+
1+
FIG 13 A
10^{-1}
1
10^{1}
10^{2}
10^{3}
E KEV

Fig. 1

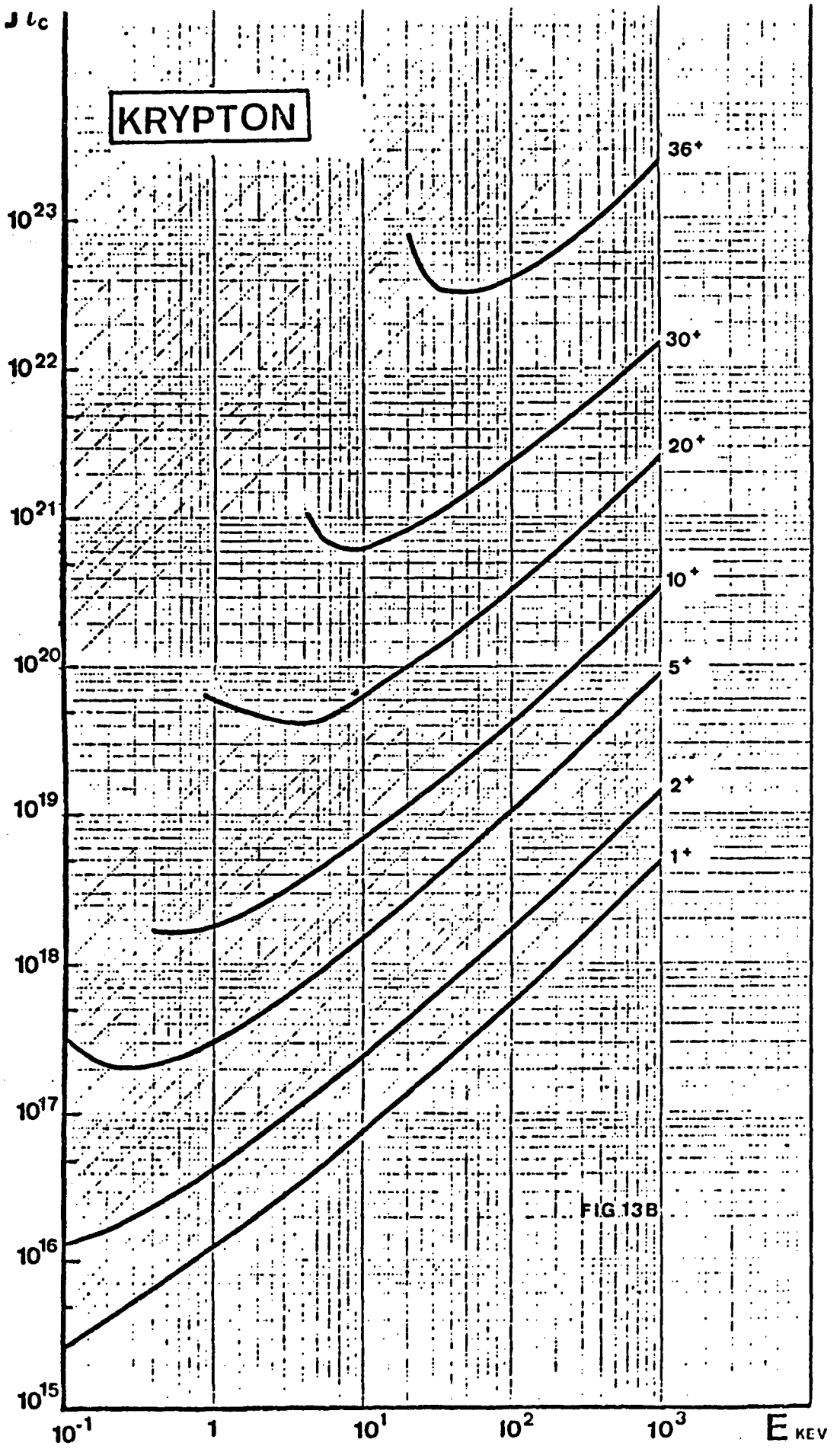
J l_c
KRYPTON
36+
30+
20+
10+
5+
2+
1+
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{-1}
1
10^{1}
10^{2}
10^{3}
E KEV
FIG 13B

Fig. 2

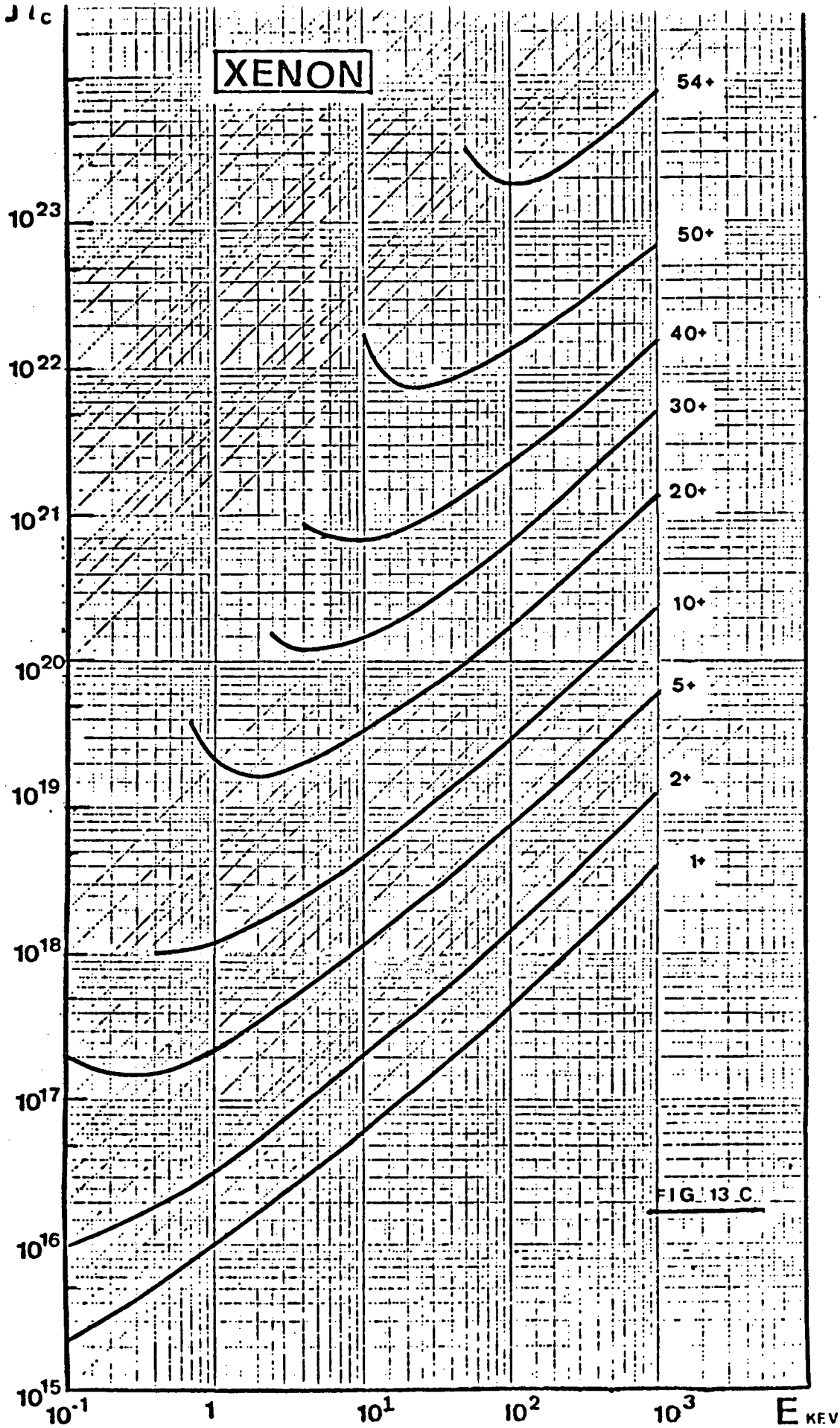
XENON
J lc
54+
50+
40+
30+
20+
10+
5+
2+
1+
FIG. 13 C
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{-1}
1
10^{1}
10^{2}
10^{3}
E KEV

FIG. 3

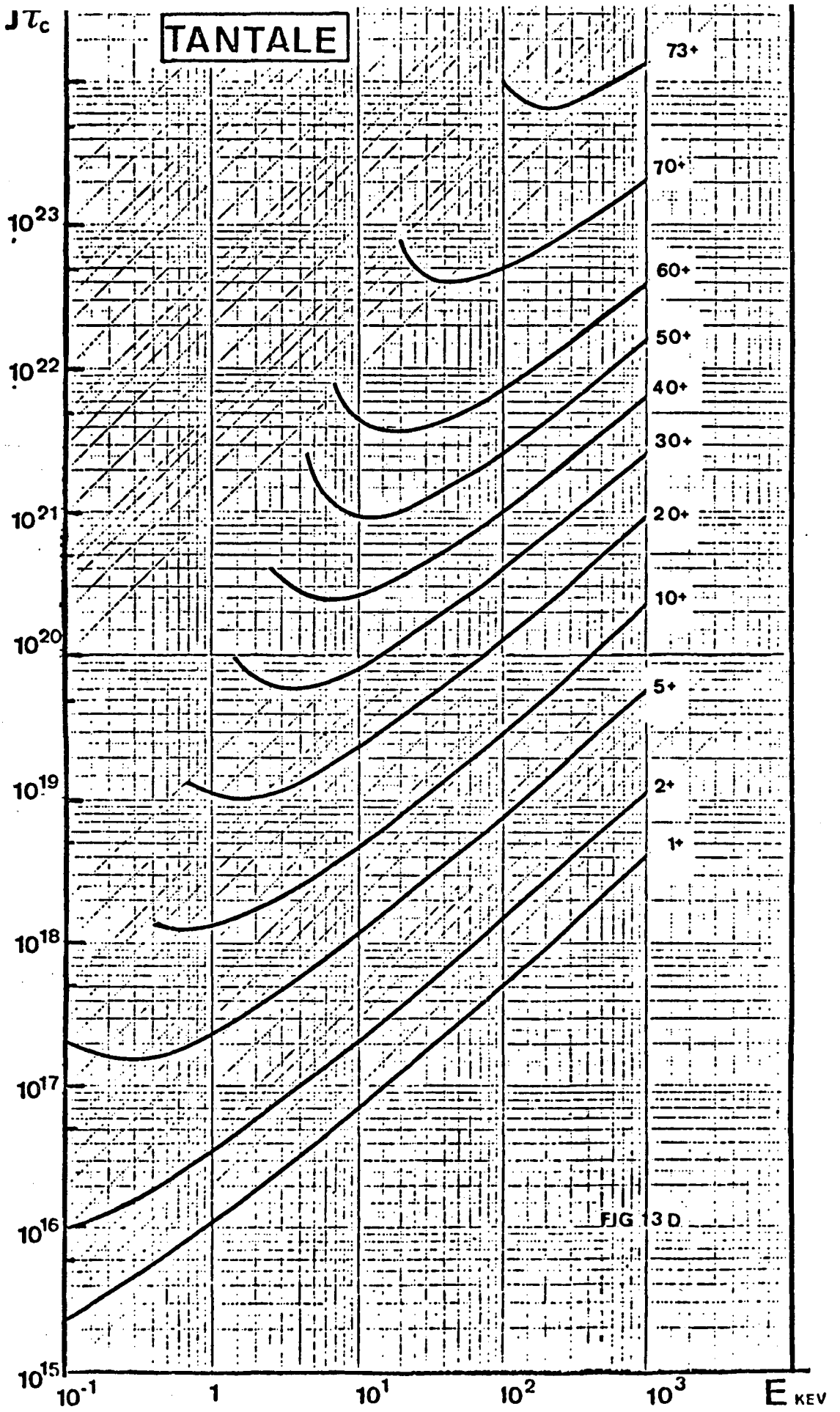
TANTALE
$J\tau_c$
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{-1}
1
10^{1}
10^{2}
10^{3}
E KEV
73+
70+
60+
50+
40+
30+
20+
10+
5+
2+
1+
FIG 13 D

Fig. 4

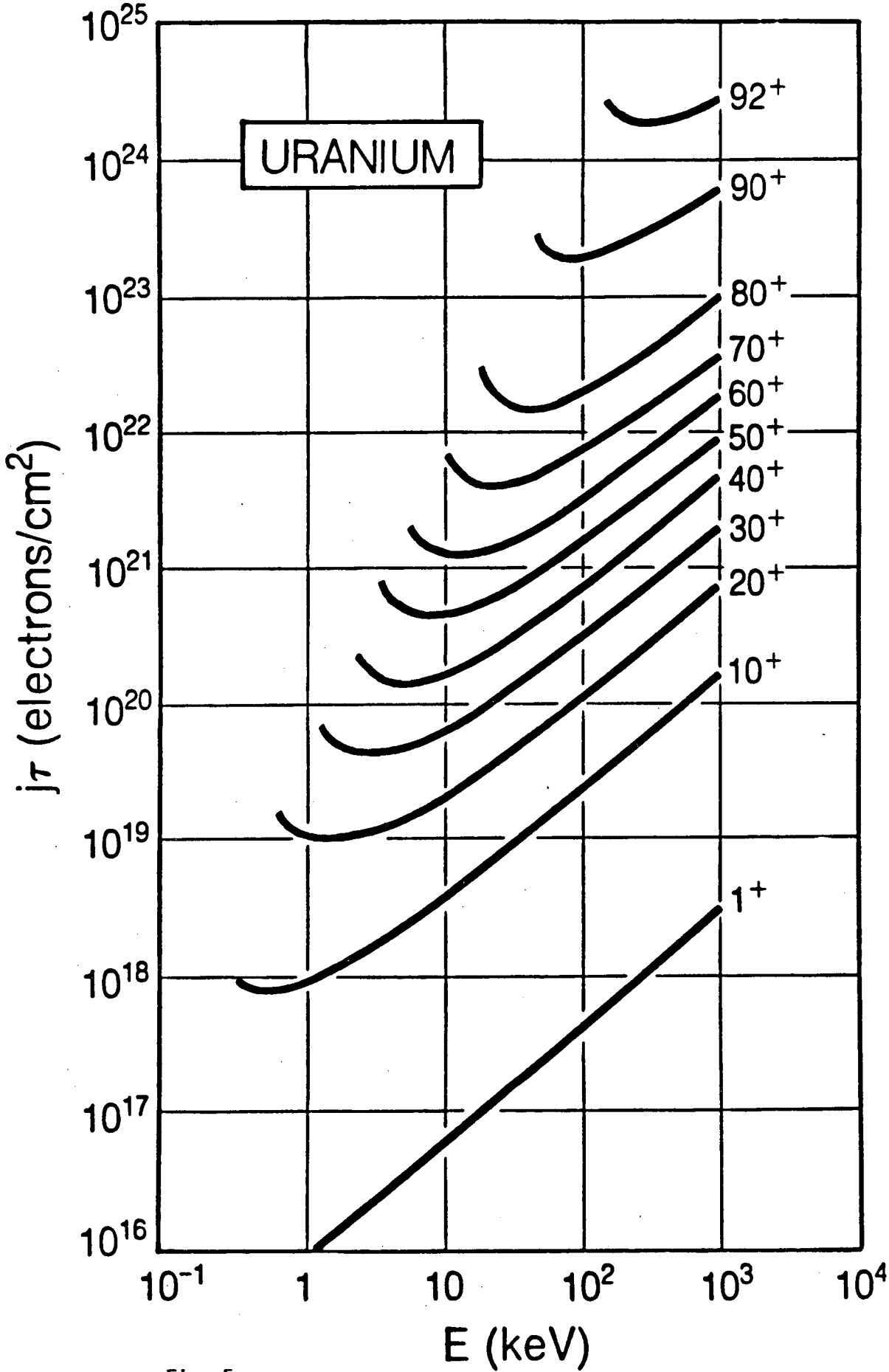
URANIUM
92+
90+
80+
70+
60+
50+
40+
30+
20+
10+
1+
10^{25}
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
j_T (electrons/cm^2)
10^{-1}
1
10
10^2
10^3
10^4
E (keV)

Fig. 5

TABLE 1. PERFORMANCE OF MULTIPLY CHARGED HEAVY ION SOURCES WITH NITROGEN, NEON, ARGON, KRYPTON, XENON AND TUNGSTEN

GAS	SOURCE	AUTHOR	ARC CONDITIONS: Potential	Current	Power	Pulse Length ms	Repetition Rate c/s	PERCENTAGE OF ION CURRENT IN CHARGE STATE: 1	2	3	4	5	6	7	8	9	10	11	12	Mean Charge State
NITROGEN	side extraction, indirectly heated cathode	Kakov[23]	580	4.6	2.67		Continuous	25.2	39.9	29.0	5.5	.4								1.8
		Papineau et al[30]	300	10	3.0		Continuous	40.0	46.6	12.3	1.0	.05								1.5
		Papineau et al[30]	-	10 (mean)	-		Pulsed	10.8	37.6	42.8	8.1	.64								2.2
		Basile & Lagrange[31]	520	5	2.6		Continuous	33.0	33.5	30.0	3.5	.15								1.7
		Navrogenes et al[32]	300	10	3.0		Continuous	22.0	42.0	31.2	4.2	.15								1.8
		Pigarov & Morosov[49]	800	24	19.2	.02	—	9.2	21.7	35.0	20.0	14.1								2.5
	side extraction, self heated cathode	Bennett[35]	730	8	5.84		Continuous	15.8	37.0	37.0	9.6	.6	.006							2.0
		Jones & Zucker[7]	600	5.1	3.06		Continuous	28.2	31.4	30.4	9.8									1.8
		Bennett & Davin[37]	450	6.2	2.8		Continuous	9.1	33.1	44.3	12.6	.8								2.3
		Clark et al[10]	1000	3.1	3.1		Continuous	32.0	40.0	23.0	4.1	.36	(Magnetic field varied)							1.6
	side extraction, floating cathode	Jones & Zucker[7]	500	2.5	1.25		Continuous	42.6	41.3	12.9	3.4									1.5
		Ehlers[18]	350	1.5	.53		Continuous	36.0	45.0	17.0	2.0									1.6
	side extraction cold cathode	Anderson & Ehlers[8]	2000	1.3	2.6	2	10	47.8	42.4	8.5	1.2									1.4
		Bolotin et al[12]	1600	-	-	.4	5	-	(1.1	1	1.2	currents in mA after acceleration to 400 kV)								-
	end extraction cold cathode	Mineev & Kovpik[15]	800	8	6.4	.2	-	37	48	15										1.5
		Isaila & Preloc[14]	6500	1.5	9.75	.1	20	92	7	.7										1.0
		Isaila & Preloc[14]	5000	2.5	12.5	.1	20	59	34	4	2	0.5 (?) (at end of pulse, for 30 μs)								1.3
		Bennett[16]	2000	2	4	2	10	62	31	5	3									1.3
	end extraction self heated cathode	Bajard et al[39]	320	4	1.28		Continuous	15.5	42.4	31.9	10.2									2.0
NEON	side extraction indirectly heated cathode	Navrogenes et al[32]	300	10	3		Continuous	30	41	23	2									1.7
		Pigarov & Morosov[49]	240	22	5.3	.02	-	10.2	31.3	39.6	12.1	6.4	(with the order of 30% impurities)							2.3
	side extraction self heated cathode	Bennett[35]	350	9	3.15		Continuous	11.4	43	36.1	8.0	1.6	.02							2.1
	side extraction cold cathode	Anderson & Ehlers[8]	2500	1	2.5	2	10	52	37	10	1									1.4
	end extraction cold cathode	Isaila & Preloc[14]	6000	.5	3	.1	20	94.5	5	.5										1.0
		Isaila & Preloc[14]	3000	3	9	.1	20	15	74	11	(at end of pulse)									1.8
	end extraction self heated cathode	Bajard et al[39]	350	1.6	.56		Continuous	20.7	41.8	28.6	8.9									1.9

Table I

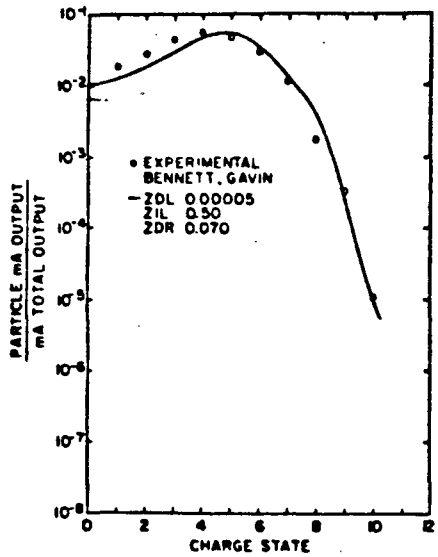

FIG. 5. Calculated fit for argon for limited Auger effect for an electron cloud of 9% primaries at 500 eV and 91% secondaries at 100 eV. For $n_e \sim 3\times10^{14}$ cm^3 and $\sigma_{01} \sim 1.2\times10^{-16}$ cm^2 at 100 eV, $\tau \sim 2.9\times10^{-7}$ sec and $\alpha \sim 1.4\times10^{-8}$.

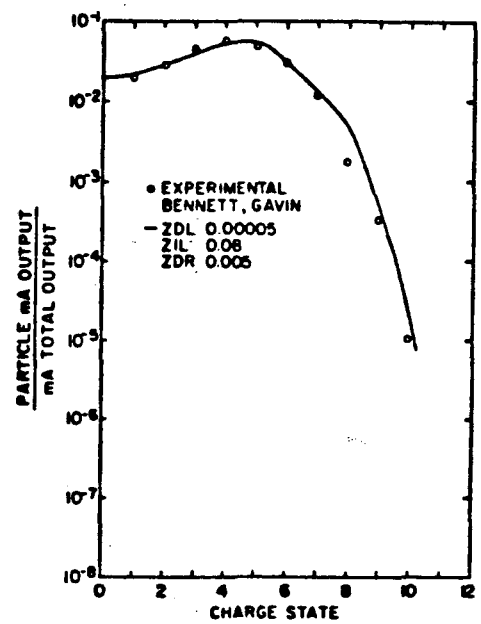

FIG. 7. Calculations with limited Auger contribution and an electron distribution as shown by the bars on Fig. 6. For $n_e \sim 3\times10^{14}$/cm^3 and $\sigma_{01} \sim 1.2\times10^{-16}$ cm^2, $\tau \sim 4.2\times10^{-6}$ sec and $\alpha \sim 4.5\times10^{-10}$.

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Fig. 6

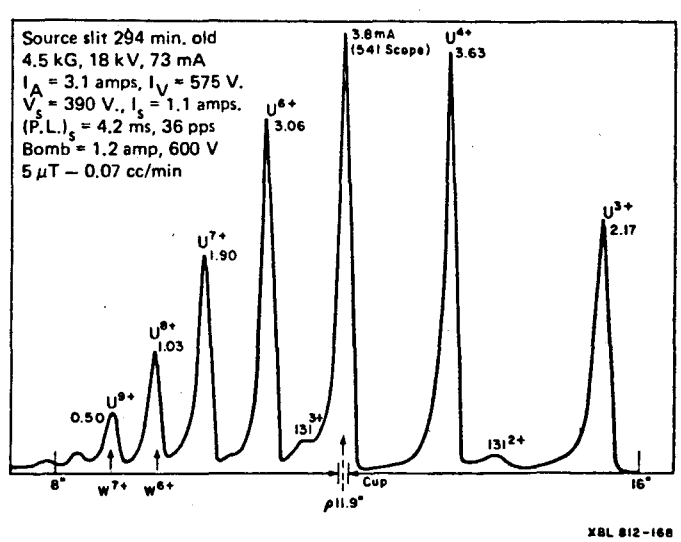


Figure 1. Ion current vs. ρ(radius). Modified GANIL slit, 1.1 x 45 mm; U/Xe; source age: 13 hrs.; cup width: .63 cm.

Fig. 7

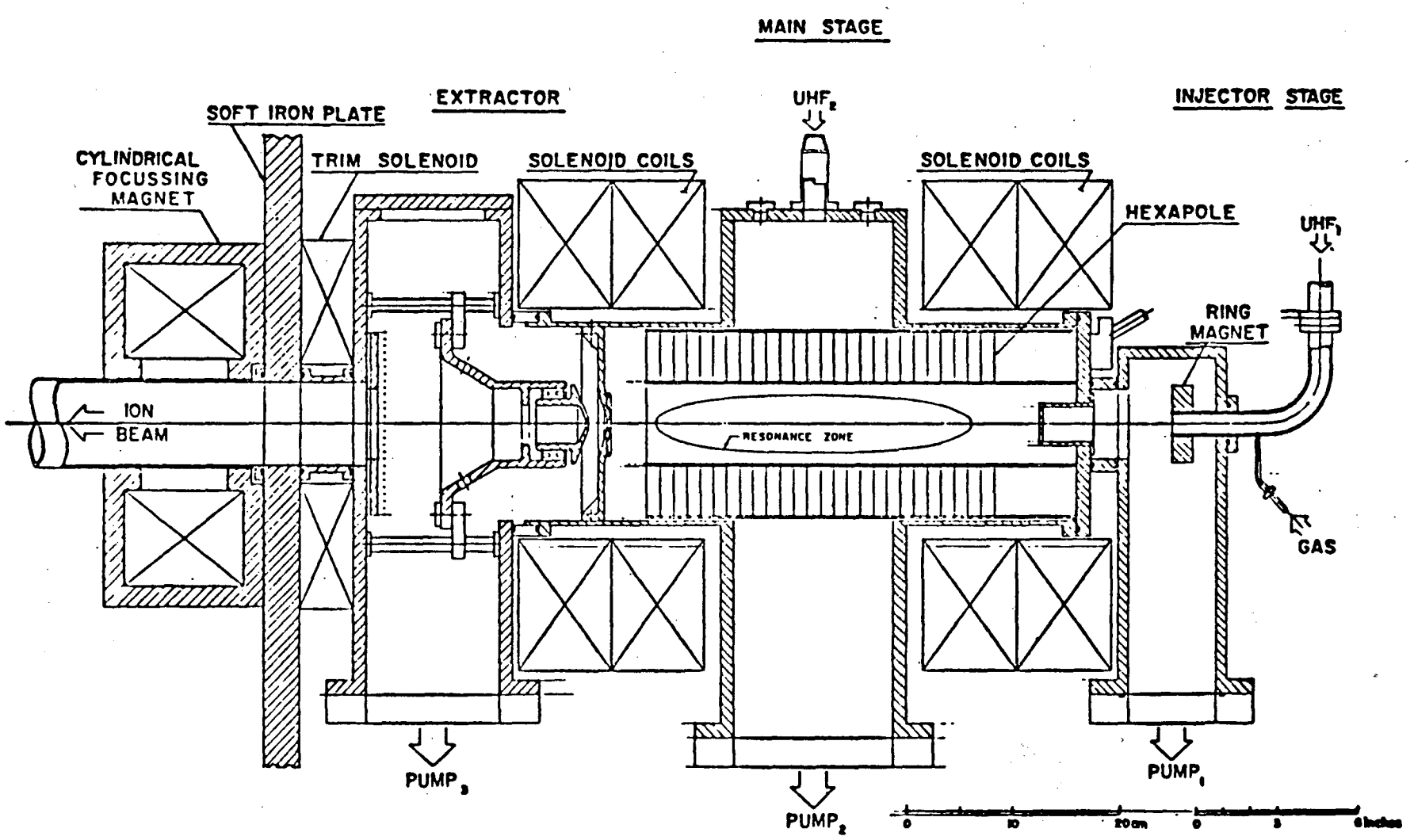


Fig. 8

ECR source proposed for 88-Inch Cyclotron. Plasma is formed in the injector stage at the right. High charge states are produced in the main stage and extracted toward the left.

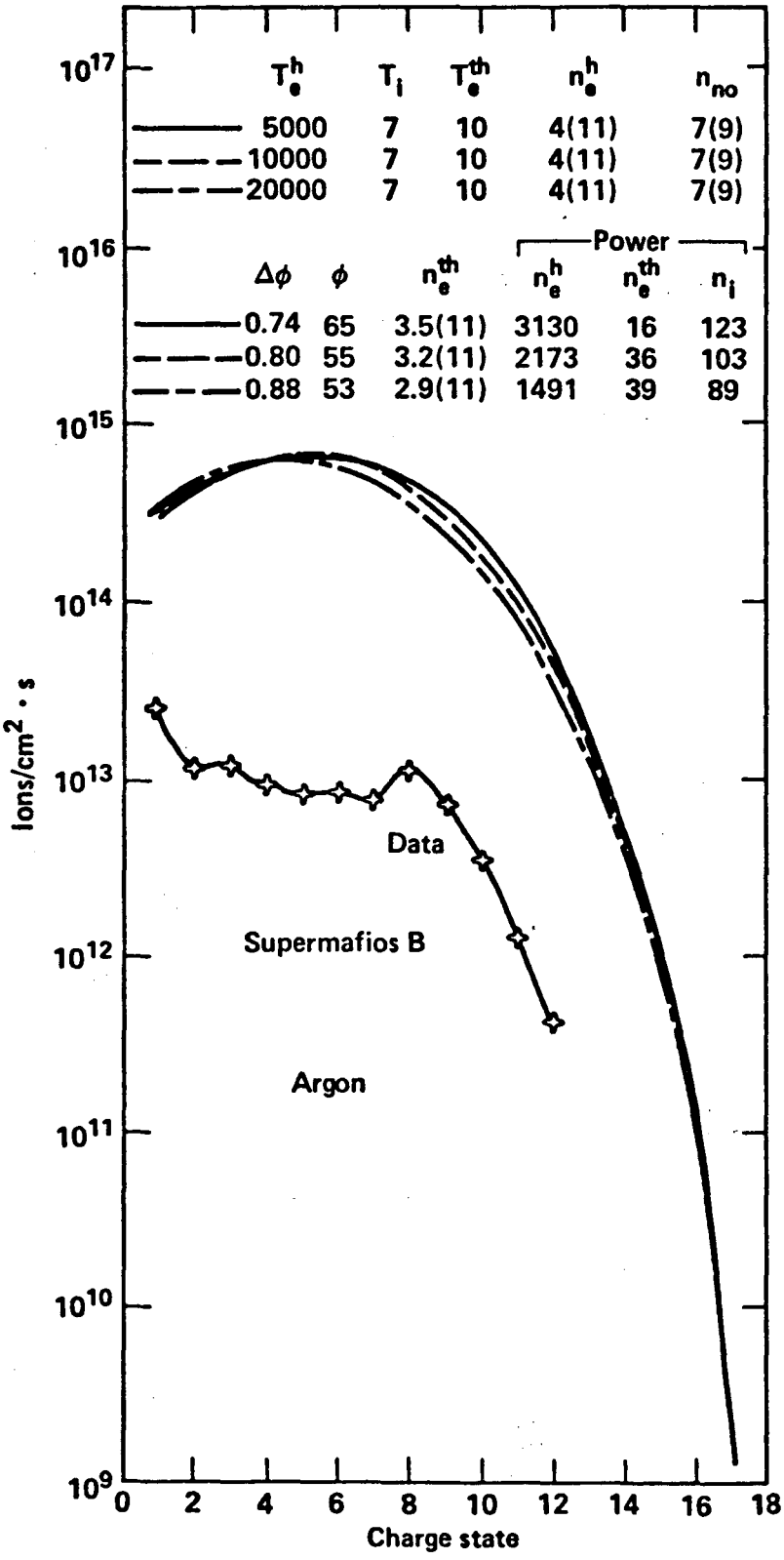


Figure 7. Supermafios B data, experimental and modeled. The middle calculated curve (o) is picked as the best representation of experiment on the basis of power requirement. The experimental curve is low by about 1/50, which is considered reasonable when one allows for extraction and charge-state analysis.

Fig. 9

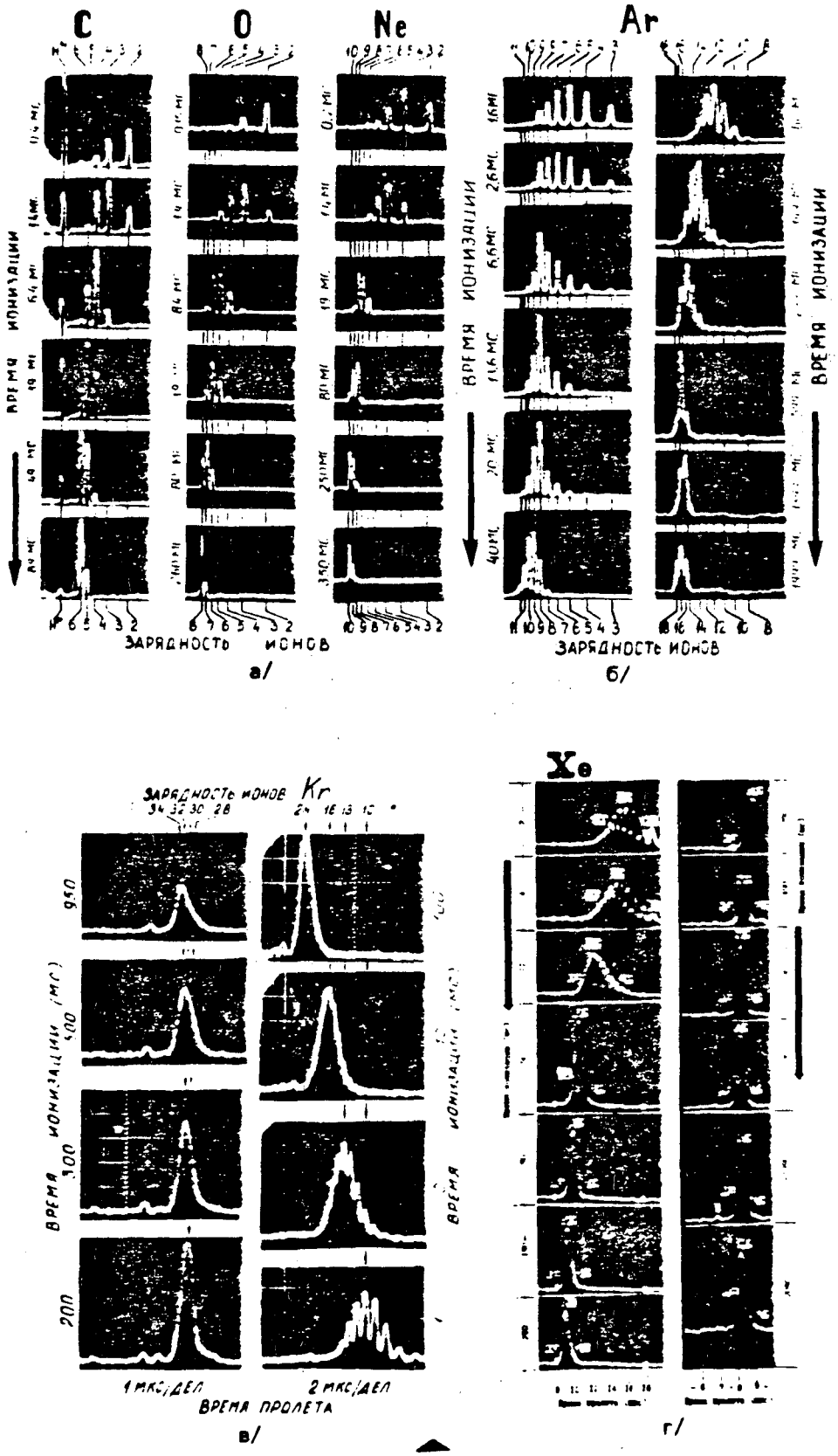


Рис.13. Иллюстрации зависимости вида спектров зарядностей ионов от времени ионизации r_1 а/ - C, O, Ne б/ - Ar, в/ - Kr, г/ - Xe.

Fig. 10

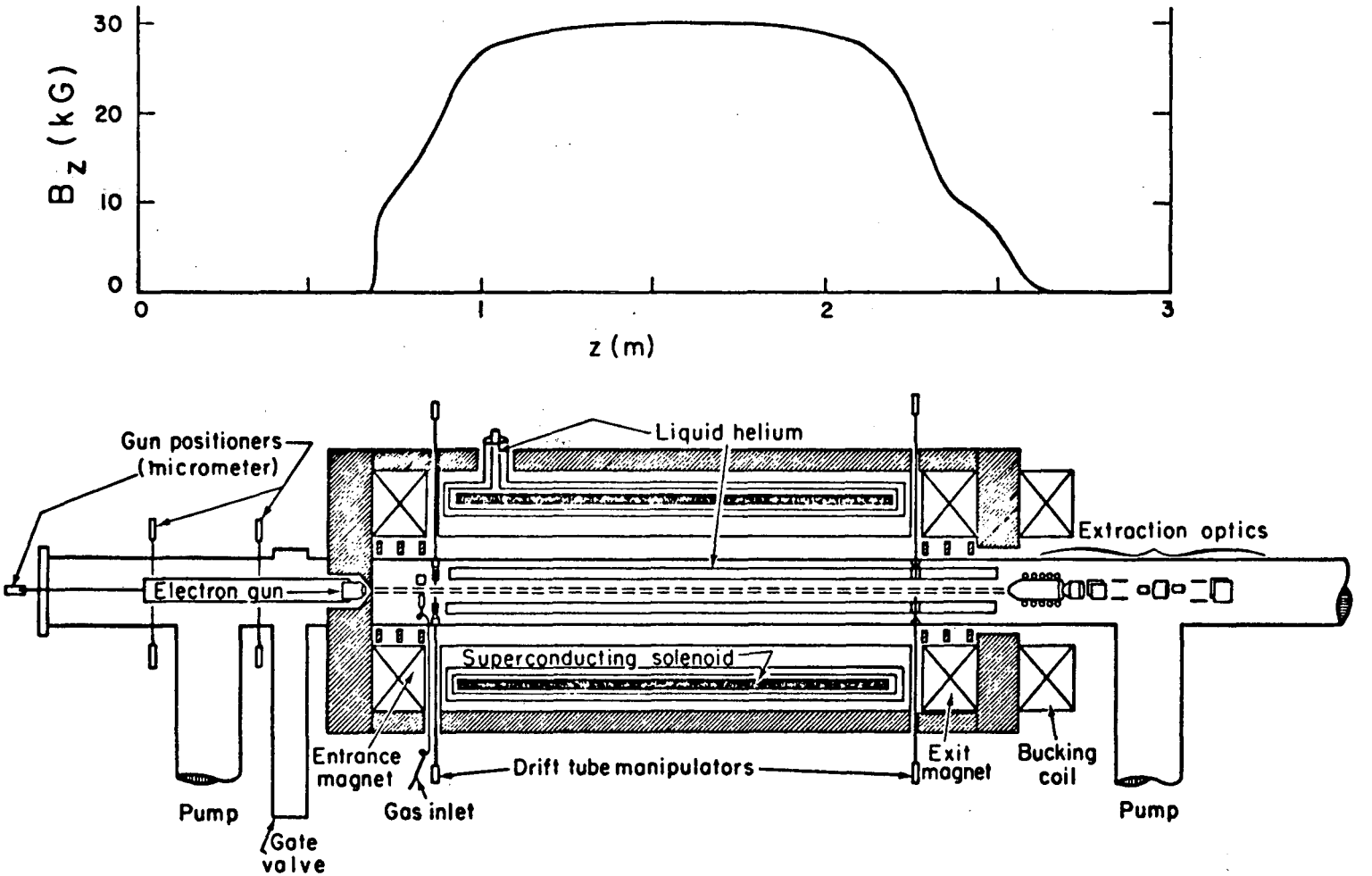
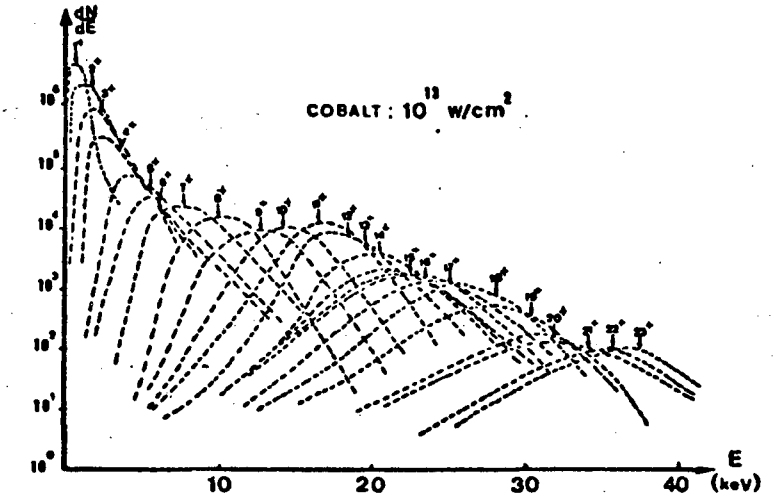


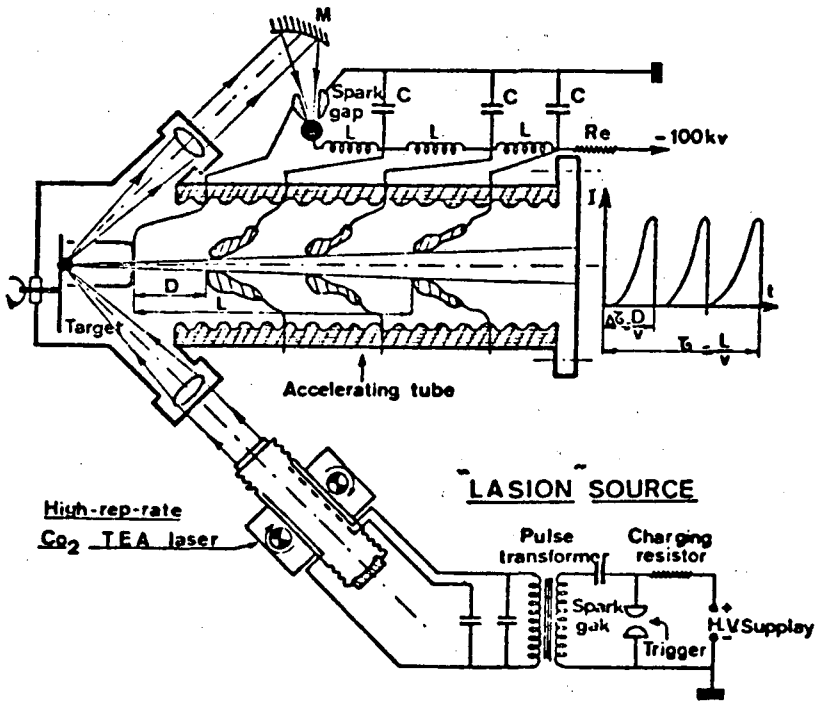
Fig. 11

XBL808-1784



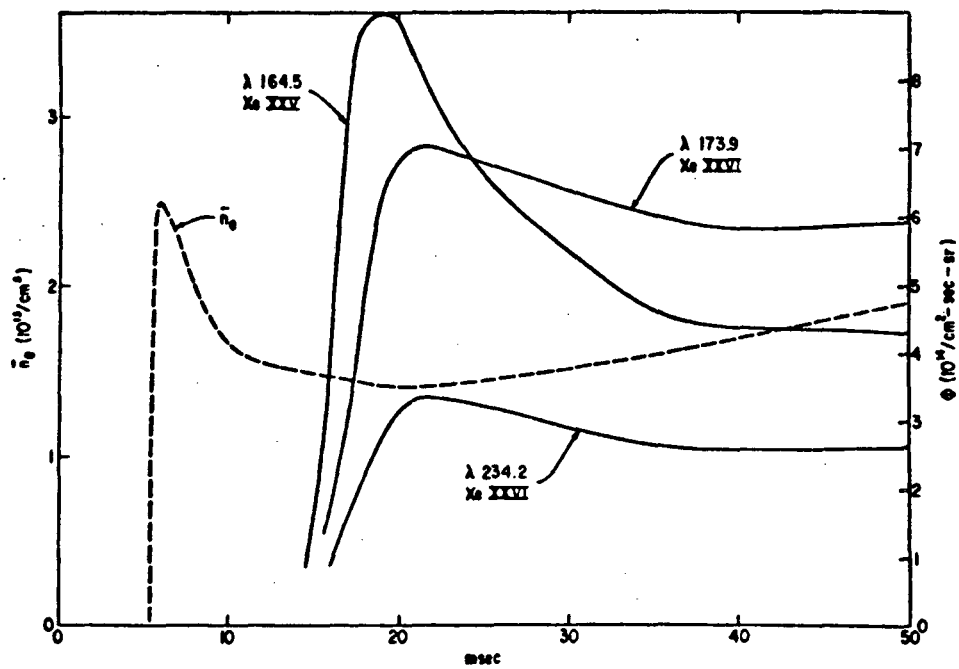
Energy distribution of Co ions produced with a laser flux $\lambda^2\Phi = 10^{13}$ W/cm^2 according Y.A. Bykovski [7]

Fig. 12



Schematic outlay of the "Lasion" source

Fig. 13



Time behavior of the Zn- and Cu-sequence resonance lines of xenon and the average electron density.

Fig. 14

Wavelengths and transitions of the lines observed in the ST tokamak.

Ion	Transition	Wavelength (Å)	Sequence
Xe XXV	$4s^2\,{}^1S - 4s4p\,{}^1P$	164.5	Zn
Mo XIII	$4s^2\,{}^1S - 4s4p\,{}^1P$	341.0	Zn
Xe XXVI	$4s\,{}^2S - 4p\,{}^2P_{3/2,1/2}$	173.9, 234.2	Cu
Mo XIV	$4s\,{}^2S - 4p\,{}^2P_{3/2,1/2}$	373.8, 423.5	Cu
Mo XXXI	$3s^2\,{}^1S - 3s3p\,{}^1P$	117.0	Mg
Kr XXV	$3s^2\,{}^1S - 3s3p\,{}^1P$	159.0	Mg
Mo XXXII	$3s\,{}^2S - 3p\,{}^2P_{3/2,1/2}$	129, 177	Na
Kr XXVI	$3s\,{}^2S - 3p\,{}^2P_{3/2,1/2}$	179.6, 220.6	Na
Fe XXIII	$2s^2\,{}^1S - 2s2p\,{}^1P$	133.2	Be
Ar XV	$2s^2\,{}^1S - 2s2p\,{}^1P$	221.2	Be
Fe XXIV	$2s\,{}^2S - 2p\,{}^2P_{3/2,1/2}$	192, 256	Li
Ar XVI	$2s\,{}^2S - 2p\,{}^2P_{3/2,1/2}$	354.1, 389.3	Li

Table II

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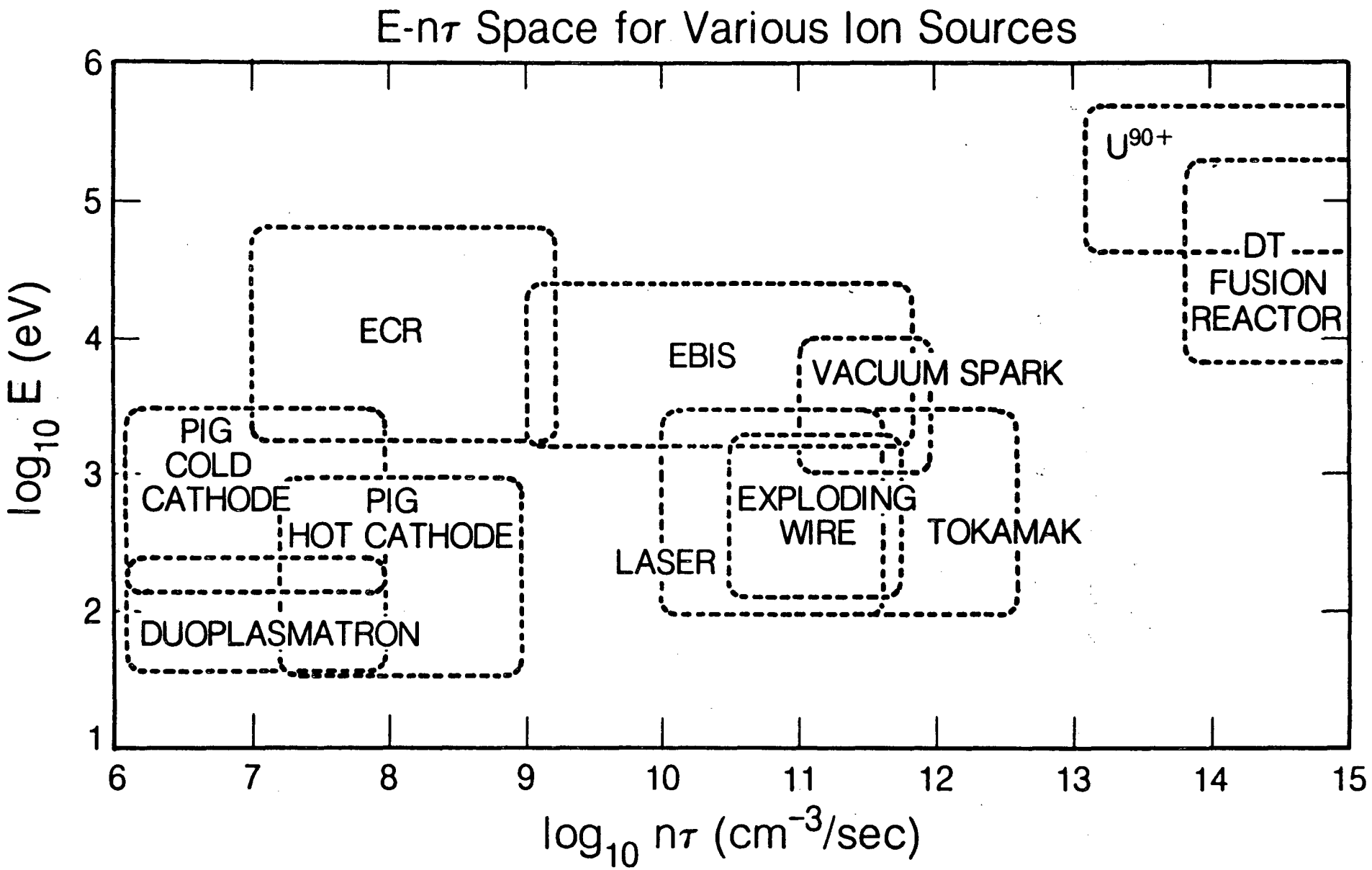

XBL 837-431

Fig. 15

APPENDIX

Draft proposal for a U^{82+} EBIS, written November, 1982. Recall that the nt needed for U^{90+} is about an order of magnitude greater than for U^{82+}, and so also (loosely speaking) is the degree of difficulty.

A Proposal for a

U^{82+} (Neon-Like Uranium) EBIS

I. Introduction

II. Some EBIS Background

III. Design Requirements

- A. Beam
- B. Vacuum
- C. EBIS Parameters
- D. Related Work

IV. Some High-Risk Aspects

V. A Possible R and D program

VI. Cost and Schedule

VII. Conclusion

I. Introduction

This is an informal, preliminary summary of a possible program for the develoment of an EBIS capable of producing neon-like uranium ions, U^{82+}. We set out some aspects of the design requirements and of the program as perceived at first blush.

The layout is as follows: After a brief discussion of past EBIS work and a statement of EBIS operating principles, we present a derivation of the design requirements. This leads naturally to a consideration of several aspects of the design that are high risk in that the requirements are severe. Then a possible approach to the program is suggested, and finally an estimate of the cost and schedule.

II. Some EBIS Background

The multiple ionization of positive ions by successive electron impact is a well known phenomenon. For maximum ionization the ions should be confined within the stripping region for times that are sufficiently long for the trapped ions to be repeatedly struck by ionizing electrons. With this philosophy, Redhead(A1) made use of both a magnetic field to confine the electron beam and externally applied potentials to confine the positive ions. Donetz and the Dubna group(A2) added the features of extremely high vacuum, of operation in a pulsed mode so as to trap the ions until they are maximally stripped, and of injecting the electrons into the magnetic field from a high quality electron gun so as to produce a high density electron beam, and thereby created what has become known as the EBIS. In the ensuing 15 years EBIS development has been carried out by workers at a number of laboratories(A3) most notably by Donetz et. al. at Dubna(A4) and by Arianer et. al. at Orsay/Saclay(A5, A6).

In the EBIS, a high density electron beam is used to ionize a batch of ions in a straight magnetic field. The ions are confined radially by the space-charge field of the electron beam itself and axially by the electrostatic potential well established by voltages applied to a set of cylindrical metal tubes (the drift tubes) surrounding the beam (see Figure A1). Feed material - the atomic species to be ionized - is injected into the beam and is stripped by successive electron impact to a maximum charge state determined by the electron beam current density and energy, the ion residence time within the beam, and the background gas pressure. When this maximum degree of ionization is obtained, the axial potential distribution is switched from ion confinement to ion expulsion, and the ions are extracted and steered into the experimental chamber. The cycle is then repeated.

At LBL we have constructed a small EBIS Test Stand (called BEBIS - Berkeley EBIS) on which we have carried out EBIS R and D, (see Figures A2 and A3). With this device we have obtained the following results (among other things):

We created a magnetic field which is straight on-axis to better than $\pm$ 50 μ over a 55 cm. axial distance[A7], and also measured the electron beam trajectory and found it to be straight to the same tolerance.

We designed and installed systems allowing the micro-manipulation of the electron gun, the drift tubes structure, and the magnetic axis; this had not previously been done on other EBIS devices.

Using a high sensitivity time-of-flight charge state analyzer we measured output ion species as highly stripped as Ar^{11+}. As an important guide for EBIS design, we verified that the number of ions created per pulse varies approximately linearly with the electron beam energy, linearly with the

confinement region (well) length, and is independent of magnetic field strength.

The device operated highly reliably and reproducibly, both on a shot-to-shot basis and on a long term (weeks to months) basis, when properly aligned and tuned up. A full final report on the BEBIS experiment has been written.[A8]

EBIS behavior is not fully understood, and there are a number of design requirements - such as magnetic field quality, alignment, gun and electron beam quality, super high vacuum - that make the EBIS a "tricky" device. However, the EBIS device offers a means of producing very high charge state ion species that cannot be produced by any other means excepting for foil stripping of energetic ions produced by the big accelerators.

III. Design Requirements

In an EBIS highly stripped ions are produced by multiple collisions between the ions that are resident within the electron beam and the beam electrons. For a given charge state species to be produced the ions must suffer collisons with sufficiently energetic electrons a sufficient number of times. This translates into a requirement on (i) the electron beam energy, V_e, and (ii) the product jt of the electron beam current density j and the ion confinement time t. Figure A4 shows the results of a calculation of jt necessary to produce a given charge state of uranium versus the beam energy V_e[A9]. jt minimizes at a beam energy around 3 times the ionization potential for ionization to the final charge state, reflecting the shape of the ionization cross-section curve. It is interesting to note that these calculations are based upon the Lotz model[A10] for the ionization cross-section, and provide a conservative estimate of the required jt. Thus the EBIS design is set in very large part by the two parameters jt and V_e.

A. Beam Requirements

The results shown graphically in Figure A4 indicate that U^{82+} can be produced by a minimum jt of approx 2.5×10^{22} electrons/cm^2 at a beam energy V_e of about 35 keV. The minimum in jt (V_e) is broad and one could operate down to around 20 keV. As a reference point let us take as required conditions:

$$V_e = 30 \text{ keV}, \tag{A1}$$

and

$$jt = 2.5 \times 10^{22} \text{ electrons/cm}^2 \tag{A2}$$

A trade-off between j and t is possible. Again as a reference let us take a long confinement time, say

$$t = 5 \text{ seconds} \tag{A3}$$

We will return below to discuss the implications of this long time.

Then

$$j = 5 \times 10^{21} \text{ electrons/cm}^2 \text{ second}$$

$$= 800 \text{ Amps/cm}^2 \tag{A4}$$

This is a quite moderate current density. For comparison, the bare-beam (electron beam without any ion loading) current density actually measured on BEBIS is up to 200 Amps/cm^2 at a gun voltage of just 2 kV.

An electron gun designed for 30kV operation and with perveance of around 1.5 μperv is readily available from Hughes Electron Dynamics Division[A11]; 30 kV and 1.5 μp implies a beam current I of 8 Amps. For a 2 cm diameter gun cathode, a beam area compression of just 300 (total electrostatic focussing and magnetic compression) will yield an 800 Amp/cm^2 beam, and the beam diameter will be 1 mm. This is a large diameter beam; compare to the BEBIS bare beam diameter of 0.3 mm. I.e., these requirements don't seem too severe.

Having now determined the gun and beam parameters necessary, consider the following. The gun of an EBIS may be operated as an 'external' gun or in a 'semi-immersed' mode or in an 'immersed' mode, according to whether the magnetic field at the cathode, B_k, is zero or intermediate or the full magnetic field strength, respectively. i.e., the gun may be well shielded from the magnetic field into which the beam is being injected, or it may be located in the (spatially) rising magnetic field region, or in the full strength field. BEBIS was operated in the external gun mode, as was the case for the Orsay device CRYEBIS. In this mode Brillouin flow[A12] can occur and, as the beam loads with ions and space charge neutralization occurs, the beam diameter can collapse and the current density can increase to very high values. It is this phenomenon of beam compression that is hypothesized as the explanation for the very high charge states that were seen with the CRYEBIS. The Dubna device, KRION 2, on the other hand, operates with the gun semi-immersed. In this mode of operation the high jt is achieved by using moderate j and long t(several seconds), as opposed to the very high j and short t ($\sim 10^{-2}$ seconds) of CRYEBIS. There is thus this trade-off between j and t corresponding to the two alternative operating modes, and to some extent this choice is quite optional and depends on the application. However and here is the key point - experience has shown that the semi-immersed mode of operation is more reliable. This may well reflect the necessity for good Brillouin flow in the external gun case, a difficult condition to meet in the real EBIS world. It is much more attractive to be able to operate the gun semi-immersed than external.

Thus the gun would probably be operated semi-immersed in the design we are considering. Beam neutralization and compression to high current density

by running an external gun is an option that one would wish to allow for and to try, but one would not count on it. A purely electrostatic area compression (i.e., the electrostatic focussing inherent to the gun design) of around 50 is normal for a gun such as would be used here, and a further magnetic compression of less than a factor of ten would thus be required. The gun would be located in the fringing field of strength a few kilogauss or less, and would be axially moveable so as to empirically determine the best operating position. Similarly the field at the cathode should be variable, and empirically optimized.

B. Vacuum Requirements

Let us return now to the consideration mentioned above - the vacuum requirement that is imposed by the condition (A3), t = 5 seconds.

We require:

(i) Beam confined uranium ions should not suffer significant collisions with background gas neutrals within the time t.

(ii) Beam electrons should not ionize the background gas and load the beam with background gas ions significantly within the time t.

Consider now these requirements one at a time.

(i) We can take as an approximation the relationship[A13]

$$n_o = 5.3 \times 10^9 j \left(\frac{A}{pV_e}\right)^{\frac{1}{2}} \frac{n_z - 1}{n_z} \quad Z^{-4.2} \qquad \text{(A5)}$$

which for a given gun and charge species relates the neutral gas density n_o to the equilibrium ratio $\frac{n_{z-1}}{n_z}$, the ratio of ions in charge state

Z - 1 to those in charge state Z. In this expression, the neutral gas density n_o is in particles/cm^3, j is the beam current density in Amps/cm^2, A the ion mass in amu, P the gun perveance in micropervs, V_e the beam energy in kV, and Z is the final charge state. Here we take:

$$j = 800$$

$$A = 238$$

$$p = 1.5$$

$$V_e = 30$$

and

$$Z = 82$$

Whence we obtain $$n_o = 9 \times 10^4 \frac{n_{z-1}}{n_z},$$

or, say, $$n_o < 5 \times 10^4 \text{ cm}^{-3}$$

This corresponds to a pressure

$$P < 10^{-12} \text{ Torr}, \tag{A6}$$

— A severe requirement!

The relationship (A5) was derived from a model for electron capture by fully stripped ions from the background neutrals. Here we are considering uranium ions stripped down to the L shell, rather than fully stripped ions. Thus one should take the above requirement as being a first approximation. Since condition (A6) is a severe requirement, this should be investigated more closely.

(ii) Ionization of background neutrals by the electron beam proceeds at a rate given by

$$\frac{dn_i}{dt} = n_e \, n_o \, v_e \, A_b \, L \, \sigma_i \quad , \tag{A7}$$

where n_e is the beam electron density, n_o the neutral density, v_e the beam electron velocity, A_b the beam cross-sectional area, L the beam length, and σ_i the cross-section for ionization of background neutrals by the 30kV beam electrons. If we require that ions produced in this manner comprise no more than 10% of the total uranium ion number at the end of the confinement time t, then (A7) can be written

$$n_o < \frac{0.1e\ N_i}{IL\sigma_i t}$$

or using (A11)

$$n_o < \frac{0.1}{v_e Z_i \sigma_i t} \qquad \text{(A8)}$$

For 30 kV electrons, a final charge state Z of 82, taking $\sigma_i = 2 \times 10^{-18}$ cm^2 and letting t = 5 seconds, then we obtain from (A8).

$$P_o < 3 \times 10^{-13} \text{ Torr} \qquad \text{(A9)}$$

a more severe requirement than that obtained above. This vacuum requirement can be relaxed significantly only by reducing the required confinement time, say from 5 seconds down to around one second. This in turn would require an increase in j by the same factor.

We conclude that a base pressure within the drift tubes of less than 10^{-12} Torr is required: this condition can be relaxed by shortening the confinement time.

C. EBIS Parameters

Most parameters have already been set in the previous two sections. It remains to fix the magnetic field strength and device length.

The magnetic field should be a minimum of around 15 kG, in order to obtain the necessary beam compression and to have flexibility in the choice of

compression (and hence, beam current density). This can be achieved from a simple normal conducting solenoid. However, extrapolating from the BEBIS field, the power consumption would be about 1 MWatt at 15 kG, and this is a considerable power to deal with steady state, quite apart from the power cost. For this reason as well as for the added flexibility, we conclude that a superconducting magnet should be used. Recalling that a high field allows a higher current density and relaxed vacuum requirements, we tentatively decide on a field of 20 kG, with the capacity to run up to 30 kG.

The 'device length' can refer to the length of the confinement region (well) L_w, or to the overall magnet length L_m. Let's assume for now that $L_m = L_w + \sim 50$ cm. The number of ions produced per pulse varies linearly with L_w[A8]. The cost will increase with length, as will also the degree of difficulty involved in precisely aligning the field, drift tubes and electron beam. There is thus a trade-off between these considerations. Contingent upon the importance attached to the number of ions produced per pulse, we choose here a well length of 1 m.

The number of ions confined is up to a maximum such that the ion charge confined within the beam equals the beam electron charge,

$$Q_1 = Q_e \tag{A10}$$

Which can be written

$$N_i = \frac{I\, L_w}{e\, v_e\, Z_i} \tag{A11}$$

where N_i is the number of ions confined and Z_i is the average ion charge state. For the parameters we have chosen,

$$N_i = 6 \times 10^9 \text{ ions/pulse} \tag{A12}$$

The trapping and extraction will not be 100 efficient however, and based on our BEBIS experience, let's say that about 30% of this number is extracted. Further, not all of the confined ions will be U^{82+}; there will be other uranium ion charge states as well as impurity ions. Note though U^{82+} is indeed neon-like, and the ionization potential for U^{83+} is 24 kV; further, the cross-section at 24 kV, (and at 30 kV), is small. Thus there will be a strong tendency for the uranium charge state distribution to 'pile up' at U^{82+}. Let's conservatively say that 20% of the extracted ions are U^{82+}. Then

Finally, we can now list our EBIS design parameters:

1.	Electron beam energy	V_e	=	30	kV
2.	Electron beam current	I	=	8	Amps
3.	Gun perveance	P	=	1.5	μp
4.	Well length	L_w	=	1.0	m
5.	Magnet length	L_m	=	1.5	m
6.	Magnetic field strength	B	=	20	kG
7.	Beam current density	j	=	800	Amps/cm^2
8.	Ion confinement time	t	=	5	seconds
9.	Ion output	N	=	4×10^8	U^{82+} ions/pulse
10.	Background pressure	P	=	10^{-12}	Torr

NOTE:

1. V_e: Anything within the range 20 - 50 kV.
2. I: Take 8 Amps as an upper limit. This could be reduced to near, say 0.5 - 1 Amp by requiring a higher beam current density.

3. p: a gun perveance of 1.5 μp is standard and achievable.

4. L_w: Can be varied up (for more particles) or down (for cost and simplicity) as application permits.

5. L_m: We somewhat arbitrarily take $L_m = L_w + 50$ cm.

6. B: We take 20 kG as a good 'middle-of-the-road' number, but we want to be able to run as high as 30kG. To be empirically determined.

7. j: 800 Amps/cm^2 is achievable. To the extent that a higher current density can be obtained so the vacuum requirements are lessened.

8. t: Following an increase in j, t may be decreased by the same factor.

9. N: Can be varied a little as needs dictate as per eqn.(A11)
A decrease in beam current will decrease N. The number given is near the top of the likely possible achievable range.

10. P: Can be relaxed by decreasing t as above.

D. Related Work

Some of the parameters needed seemed quite fierce at first blush, and it is interesting to review briefly what other workers have accomplished, as a comparison.

(i) Hughes.

Hughes Electron Dynamics Division(A11) has a great deal of experience in designing and manufacturing guns of the type we will use here, in the propagation of compressed beams through small diameter tubes in a magnetic field, and in the design and construction of biased electron beam dumps (depressed collectors) for the recovery of the beam energy. These aspects of the UREBIS are not new, but have been investigated for many years because of the application to high power electron beam microwave devices (amplifier and

oscillator tubes). The gun that we would require is essentially off-the-shelf; cost would be in the range K$10 - 20, and delivery time approximately 6 months. The Hughes laboratory group has propagated a beam of this type (several tens of kV, several amps) through a 0.15" diameter tube in a magnetic field. We might estimate the beam diameter as around 2 mm or less. This circumstance thus provides evidence for the stability of an electron beam under conditions not too far removed from those we require. Finally, we have spoken with Hughes about their electron collector design. That the beam is a quarter-magawatt d.c. seems to be not an insurmountable obstacle in terms of electron collector design, and a guess based on experience indicates that approximately 90 of this power can be recovered electrically; this still leaves 25kw to be dumped, however.

(ii) Dubna

Donets's group at Dubna has constructed and operated the cryogenic device KRION 2[A4]. This device utilizes a 20kV, 0.2 Amp (approximate) electron beam, and a 5 second ion confinement time has been achieved by means of the liquid helium cooled drift tubes. The 'record' charge state obtained most recently is Xe^{52+}. Figure A5 shows calculated jt versus V_e curves for various charge states of xenon. For Xe^{50+} a jt of 7×10^{21} electrons/cm^2 sec is required at a beam energy of about 20 kV. This is only about a factor of three less than that needed here. Furthermore, a 5 second confinement time has been achieved, assuring us that the vacuum quality needed is indeed realistic.

IV. Some High Risk Aspects

Here we list a number of components of the program that are particularly uncertain, and that will require special attention.

A. Uranium injection

Uranium atoms or ions must be injected into the electron beam. Ideally, the injection would occur as a pulse of duration about 10 msec, and would focus the material into the beam. A focussed gas puff is feasible, but it appears that the only gaseous uranium compound that one might use is UF_6, which has a boiling point of 65° C. Thus there are at least two major drawbacks: (i) the temperature required is not only non-cryogenic, but in fact is elevated above room temperature, (ii) The ion output would be mostly flourine, with only a minor uranium concentration.

Another method of injection is the laser evaporation of material from a solid surface. This was tried on the BEBIS device without any notable success. We used a manganese target and we produced some manganese ions, but this was in the presence of a high impurity ion concentration. Our set-up used a ruby laser simply because of convenience, and this may not be optimum; further, the impurity concentration would be much reduced when cryogenic drift tubes are used. We can say that this way of going is a possibility, and it will certainly require R and D.

Finally, one can inject metal ions into the electron beam by creating the ions in a more conventional source, such as a PIG, and guiding these ions into the electron beam through a small hole in the gun cathode. Saclay is currently planning on this method of injection. Again, significant R and D will be required.

B. Electron Collector

As previously pointed out, the electron beam will contain a power of up to about 250 kWatt, and a 'depressed' (electron retarding) collector will be necessary to recover as much of this power as is possible and reduce the thermal loading to a reasonable level. Hughes has had considerable experience in the design of this kind of collector, and we should interact strongly with them. Orsay, also, has looked into this feature. We have some reason for optimism because of the work of these two groups; but nonetheless, this is an area in which there is a risk.

C. Electron Beam

We will have a high voltage, high current, high current density electron beam propagating along a strong magnetic field, and there occurs the question of beam stability. One can discuss the various kinds of plasma instabilities to which the beam might be prone, and the various possible stabilizing mechanisms[A13], but the uncertainties are great, and the only reliable evidence for stability is an experimental demonstration. Beams of parameters approaching those required by us have been obtained, and we thus anticipate stability. But this won't be known for sure until actually done in the lab.

D. Vacuum

A pressure within the drift tubes, in the electron beam environment, of 10^{-12} Torr or better is required. Dubna has obtained such a vacuum, and we are comforted by this fact. But the actual pressure obtained in a given case is determined by the balance between cooling and thermal loading on the drift tubes surfaces. Thus it is important ot provide a good thermal connection between the drift tubes and the refrigerant. Also note that we will be using

a 250 kWatt beam, and the fraction of this power that can be deposited on the drift tubes must be very small, $\lesssim 10^{-5}$, in order to avoid evaporating cooled material. To the extent that the number of ions per pulse can be reduced, so can the beam current, and so also the magnitude of this concern.

V. A Possible R and D Program

A possible modus operandi might consist of the following steps:

1. Visit Other Laboratories

The Dubna device KRION 2 has many features similar to the device proposed here, and it would be advantageous to visit the group there to learn from them first-hand. Similarly one would like to visit the groups at Orsay/Saclay, and the Hughes electron beam people.

2. Engineering and Design Studies

Those features with which there is a risk associated should be selected out for special attention first, early in the program:

Uranium injection,

Electron collector,

Electron beam,

Vacuum.

The assumption could be reasonably be made, based partially on the BEBIS experience, that the following features are fairly straightforward and will present no problem:

Magnet,

Electrical/electronics systems,

Ion extraction and optics,

Charge state analysis,

Drift tubes structure design.

3. Preliminary R and D

One might choose to proceed a little cautiously and to experimentally demonstrate that a few key parts of the device can indeed be solved in practice. These would be those things that have been selected out for special

attention above, V.2. These are aspects of the hardware that need to be taken care of anyway; the suggestion here is that they be demonstrated as solved before advancing further.

4. EBIS Construction

This constitutes the bulk of the time, money and effort, and includes all electronics, superconducting magnet, and all peripheral parts of the system. It is proposed here that commitment to this major construction phase not be made until all the steps above have been satisfactorily demonstrated.

5. Cost and Schedule

The UREBIS project would be similar in magnitude to the cryogenic EBIS that was under consideration for the 88-inch cyclotron, with a few extra twists such as the uranium injection and high power electron beam. Thus we can base our estimate, for now, on the estimate made for the cyclotron project. On this basis, a very preliminary indication would be a total project duration of about 4 years for a cost of about $5 million. One would not commit until phases V 1 - 3 have been handled, and this might entail a 1 - 2 year period for a cost of about $2 million, say. These estimates are rough, and could be refined by a preliminary design study.

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FIGURE CAPTIONS (APPENDIX)

Fig. A1. (a) EBIS schematic showing electron gun and collector, drift tubes, and solenoid.
(b) Drift tubes axial potential distributions for ion injection, trapping and expulsion.

Fig. A2. Schematic of the BEBIS test stand.

Fig. A3. Photograph of the BEBIS test stand.

Fig. A4. jt necessary to produce various charge states of uranium, as a function of electron beam energy.

Fig. A5 Same as Fig. A4, for Xenon.

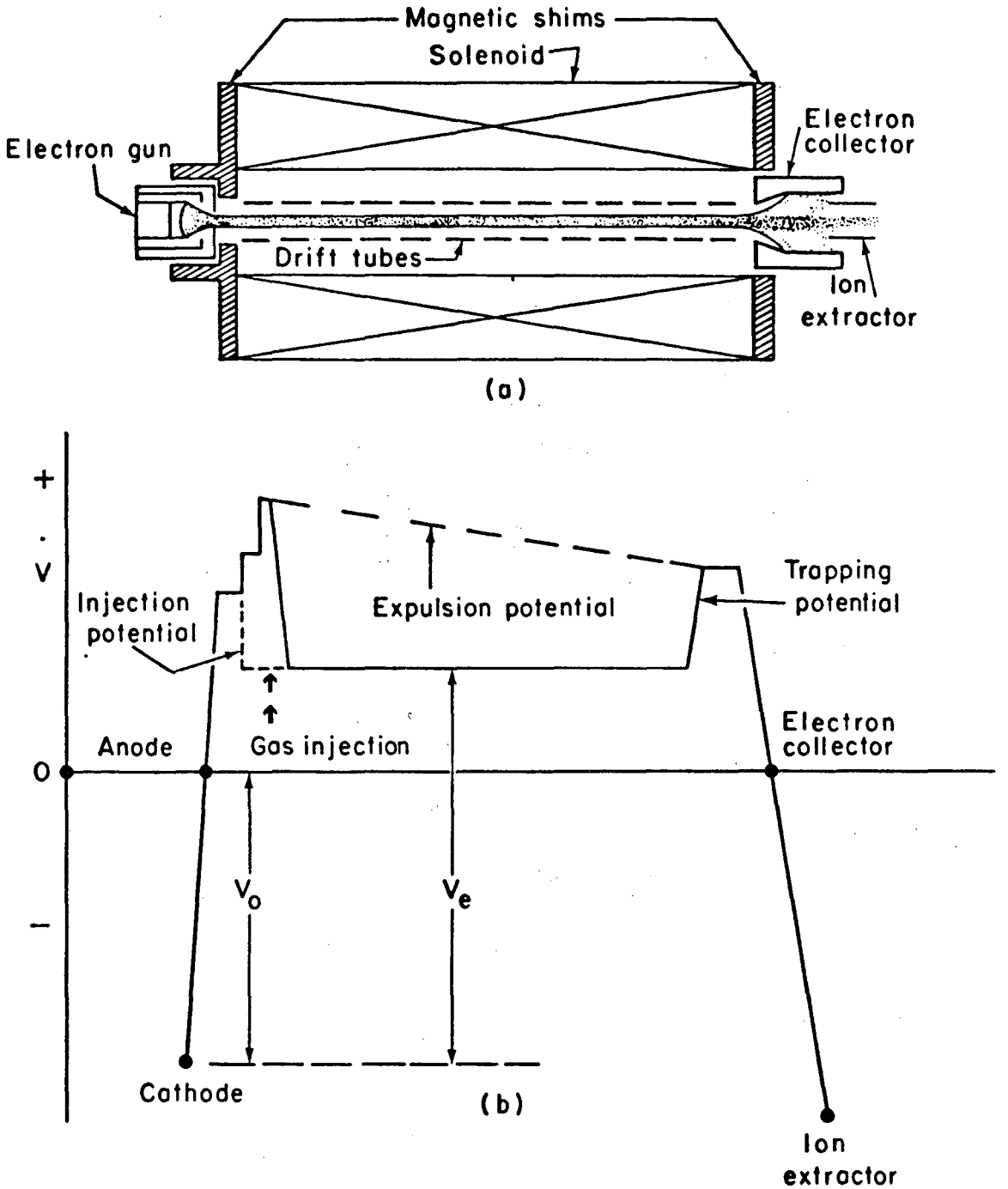


Fig. A1

XBL808-1785

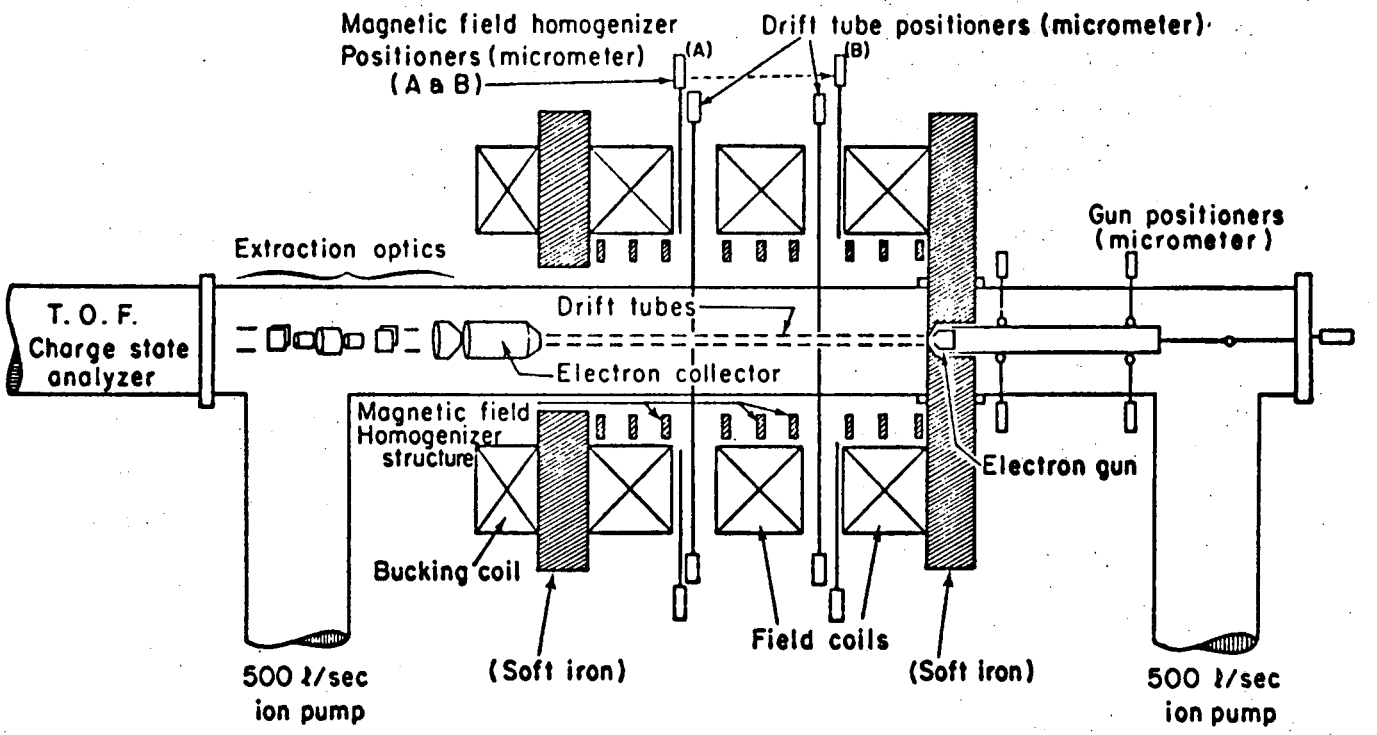
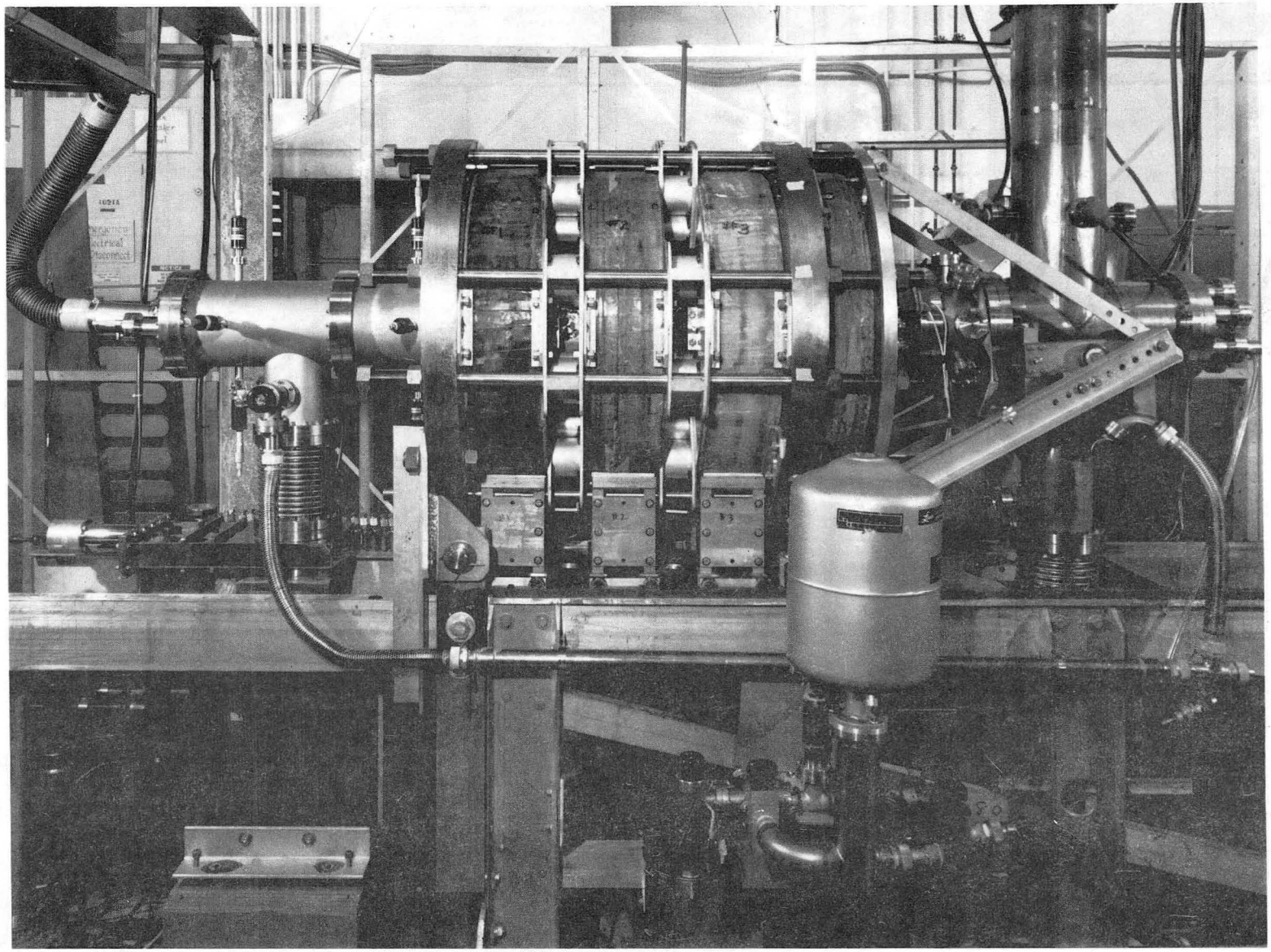


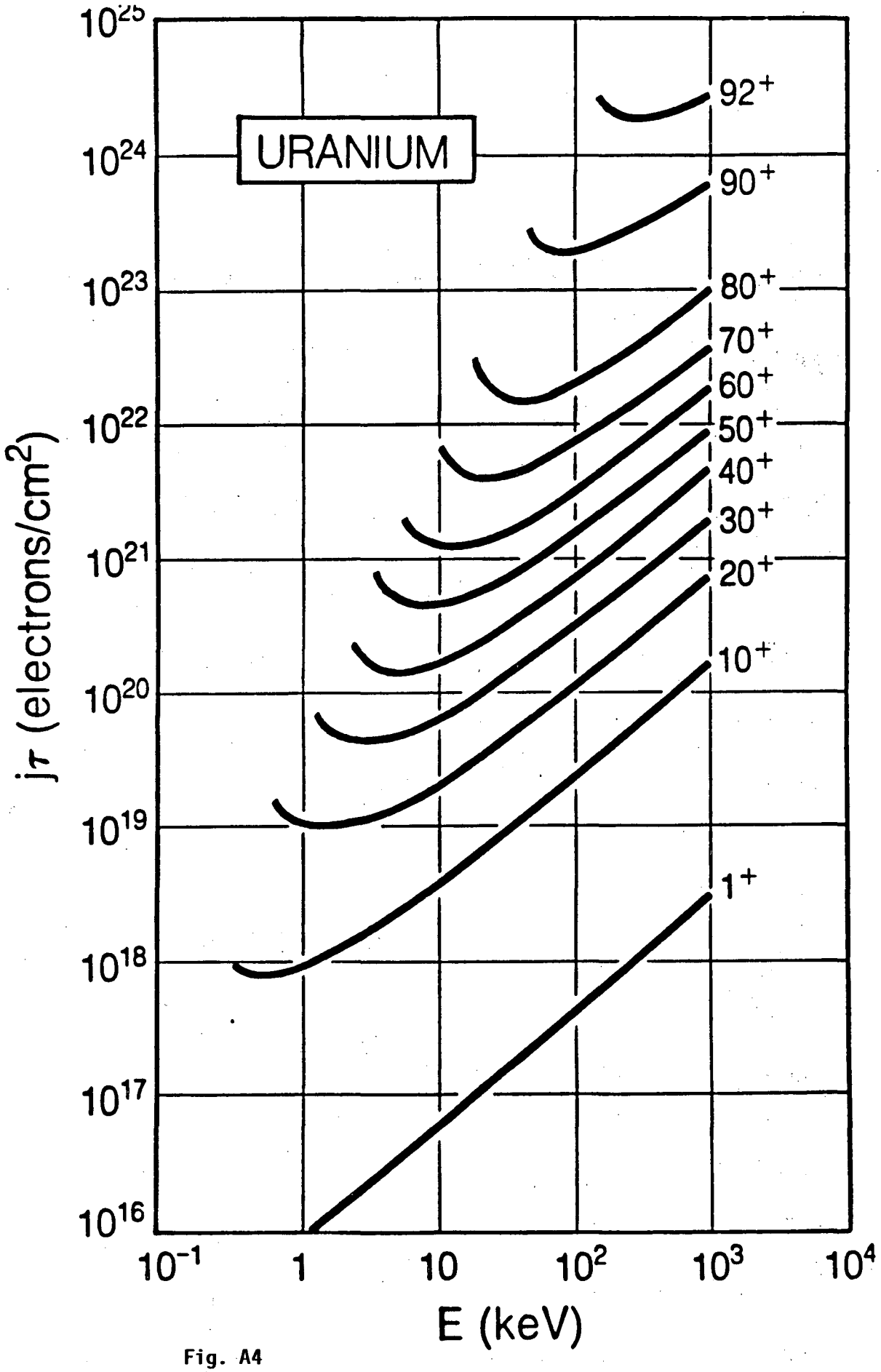
Fig. A2

XBL808-1786



CBB 800-12339

Fig. A3


URANIUM
92+
90+
80+
70+
60+
50+
40+
30+
20+
10+
1+
10^{25}
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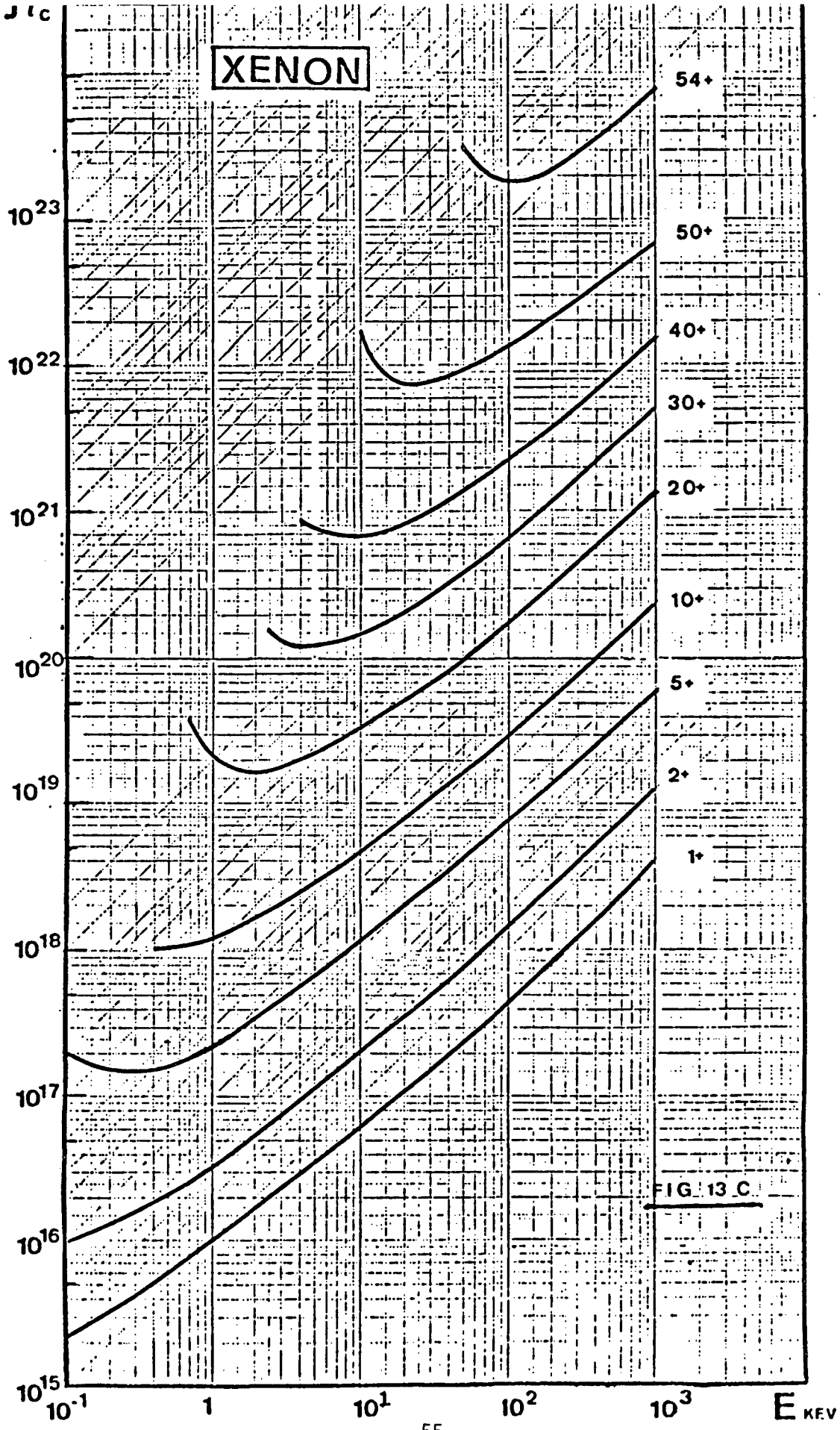
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
$j\tau$ (electrons/cm^2)
10^{-1}
1
10
10^2
10^3
10^4
E (keV)

Fig. A4


XENON
54+
50+
40+
30+
20+
10+
5+
2+
1+
FIG 13 C
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E KEV

Fig. A5

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