VACUUM ARC ION SOURCES

(or "MEVVA" ION SOURCES)

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CAS
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OUTLINE

- Background
- The Basics
- Embodiments
- Characteristics / Parameters
- Applications
- Summary

HISTORY

- **1940s – U.S. Manhattan Project**
  - **For isotope separation. Some basic studies, but work was abandoned**
- **1950s & ’60s – USSR (Plutto et al; and others).**
  - **Demonstration of ion extraction from the vacuum arc plasma**
- **1970s – Sandia, LANL, U.K., USSR**
  - **For various applications, but work was not pursued.**
- **1980s – Berkeley (LBNL) and Tomsk (HCEI)**
  - **More-or-less parallel & simultaneous development at both places.**
  - **Large sources developed and demonstrated for accelerator injection and ion implantation.**
  - **Ongoing programs established, including many collaborative projects.**

SUITABILITY OF THE VACUUM ARC PLASMA

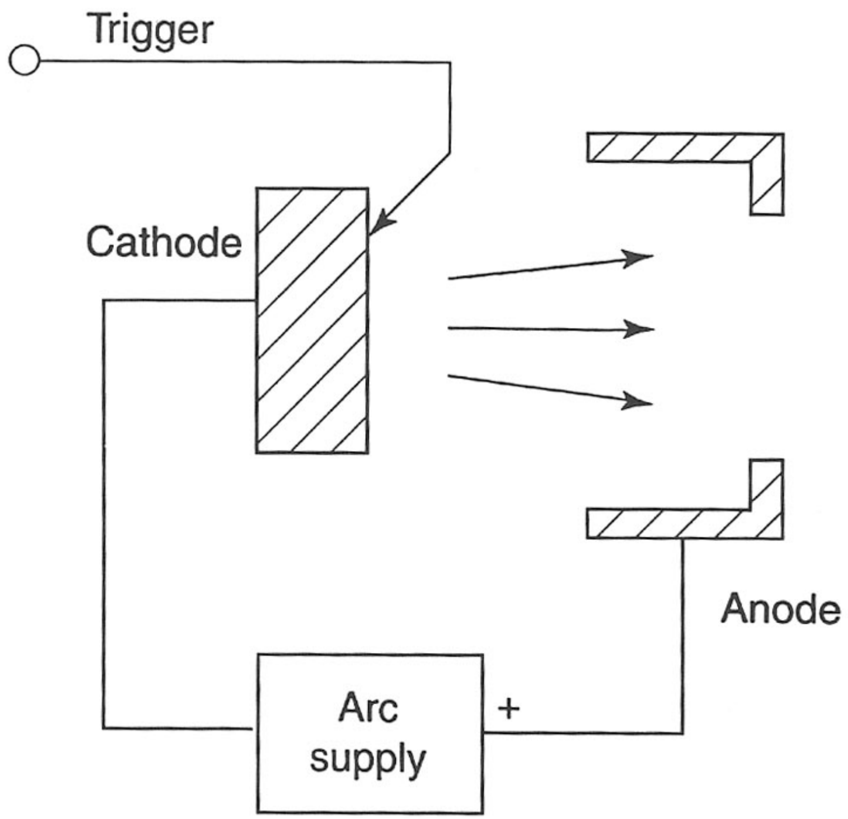
FOR A

HIGH CURRENT METAL ION SOURCE

The plasma formed by a vacuum arc discharge is

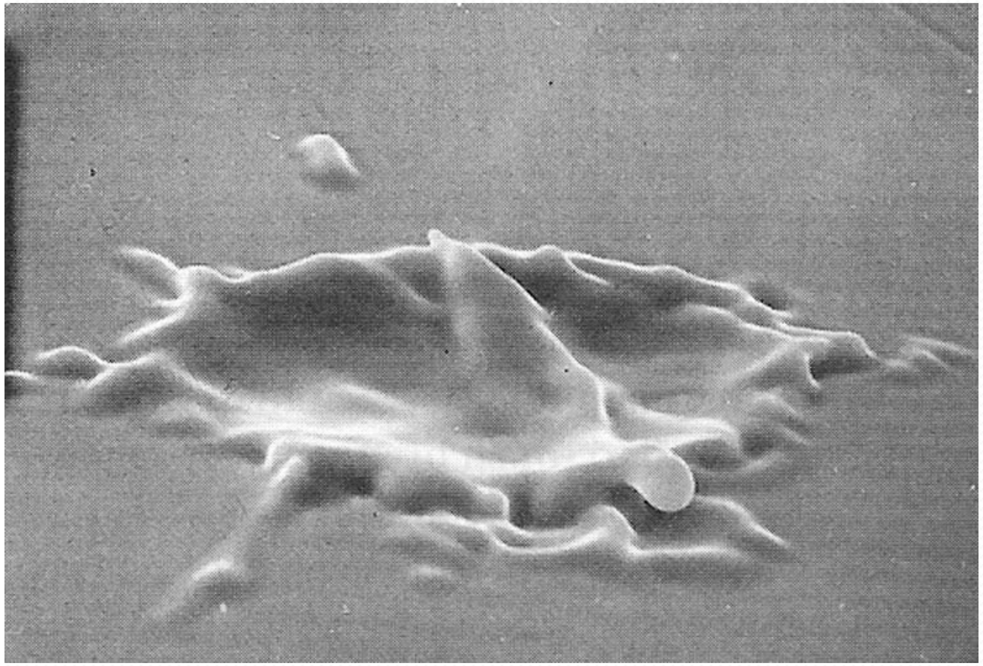
- **Pure (no, or low, gas content)**
- **Dense**
- **OK for a wide range of metal species**
- **Simple – no tricky parts**
- **Simple electrical system**
- **Efficient – I_{ion} / I_{arc} is high**

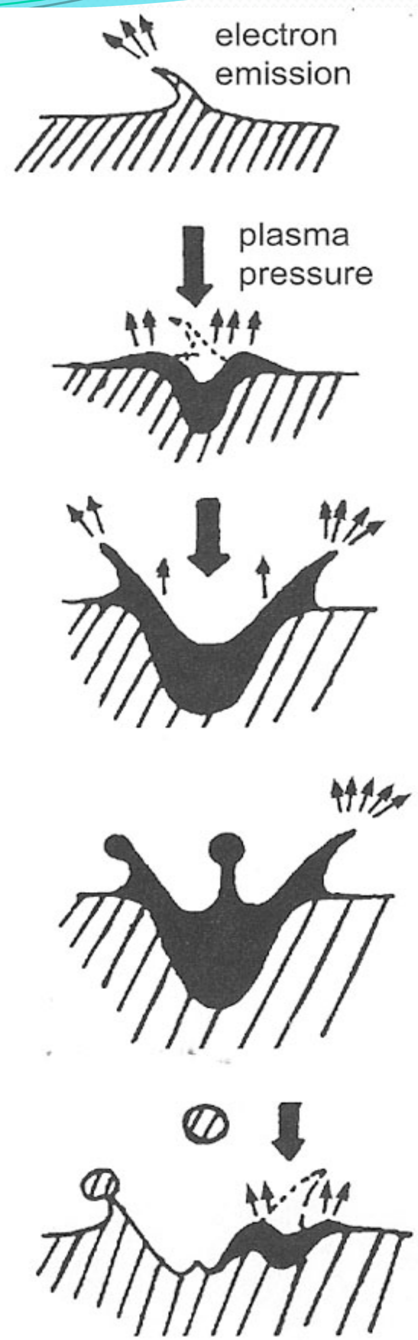
THE BASIC VACUUM ARC



- **Extreme simplicity**
- **Also called "cathodic arc"**
- **Plasma is born at the cathode and streams toward the anode**
- **On the cathode, the plasma emission sites are tiny "cathode spots"**
- **Metal plasma jets away from the spots in a manner very similar to a laser-produced plasma**

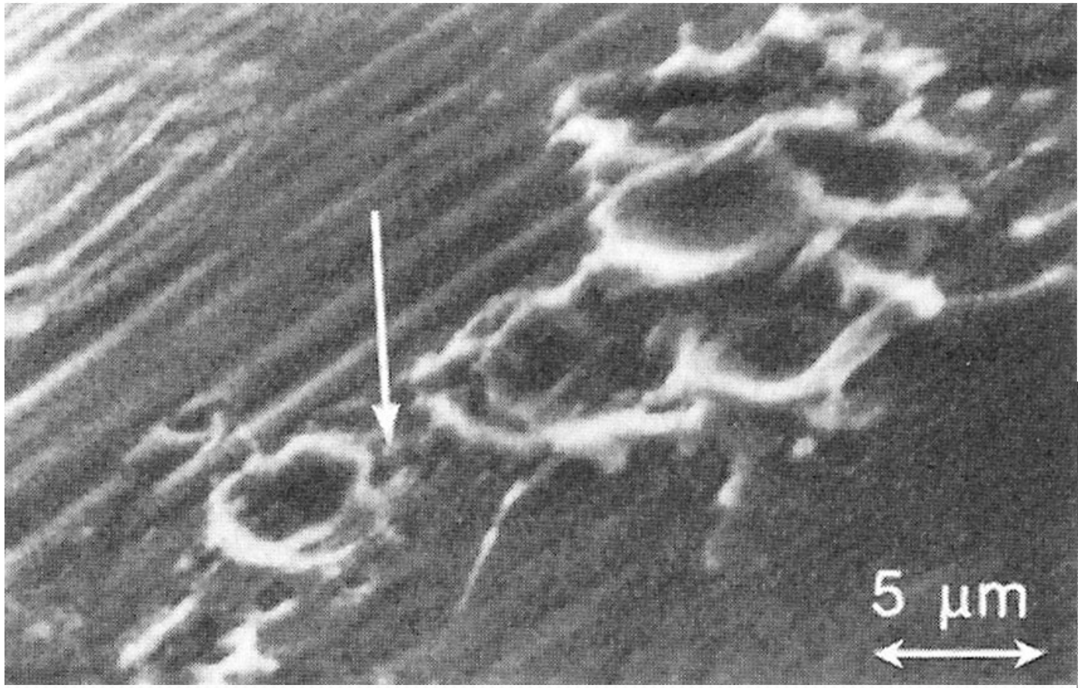
Cathode Spots

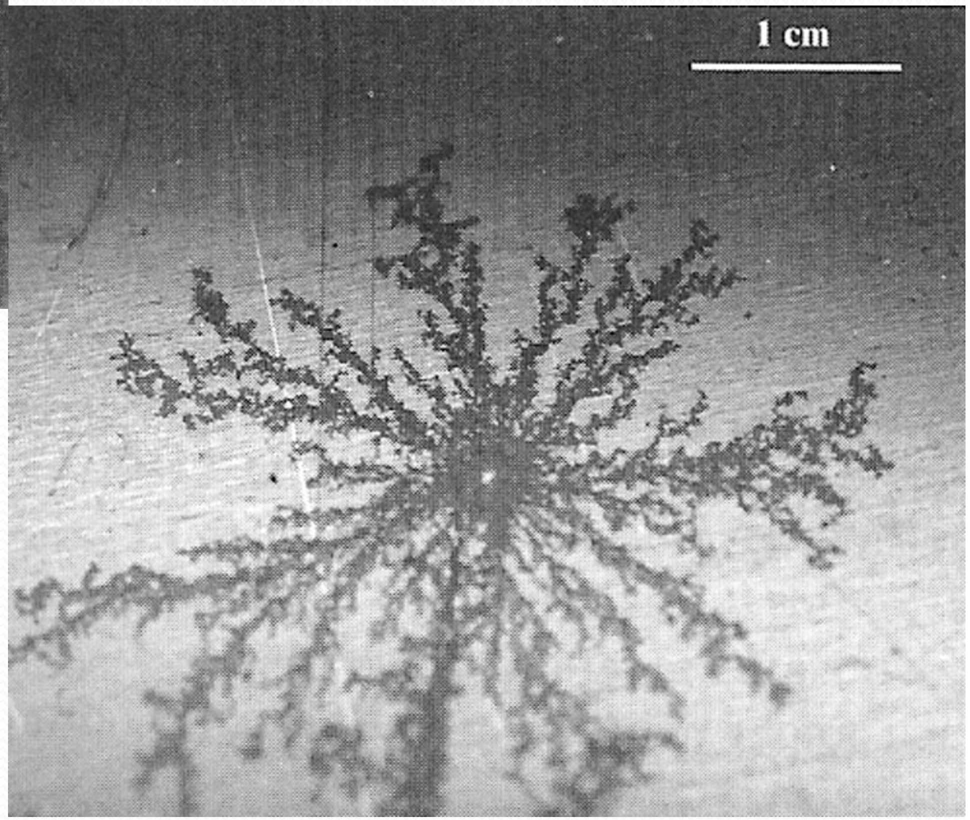




- Cathode spots are the plasma emission sites
- Each spot ejects a plasma plume quite similar to a laser-produced plasma
- Size ~ *μ*ms, lifetime ~ *secs* (or less)
- Current density ~10^{11} A/m^2; Power density ~10^{12} W/m^2
- Along with metal plasma, "macroparticles" are also formed

CATHODE SPOT MOTION





- **New spots form, leaving "chicken tracks", as seen in many plasma devices**

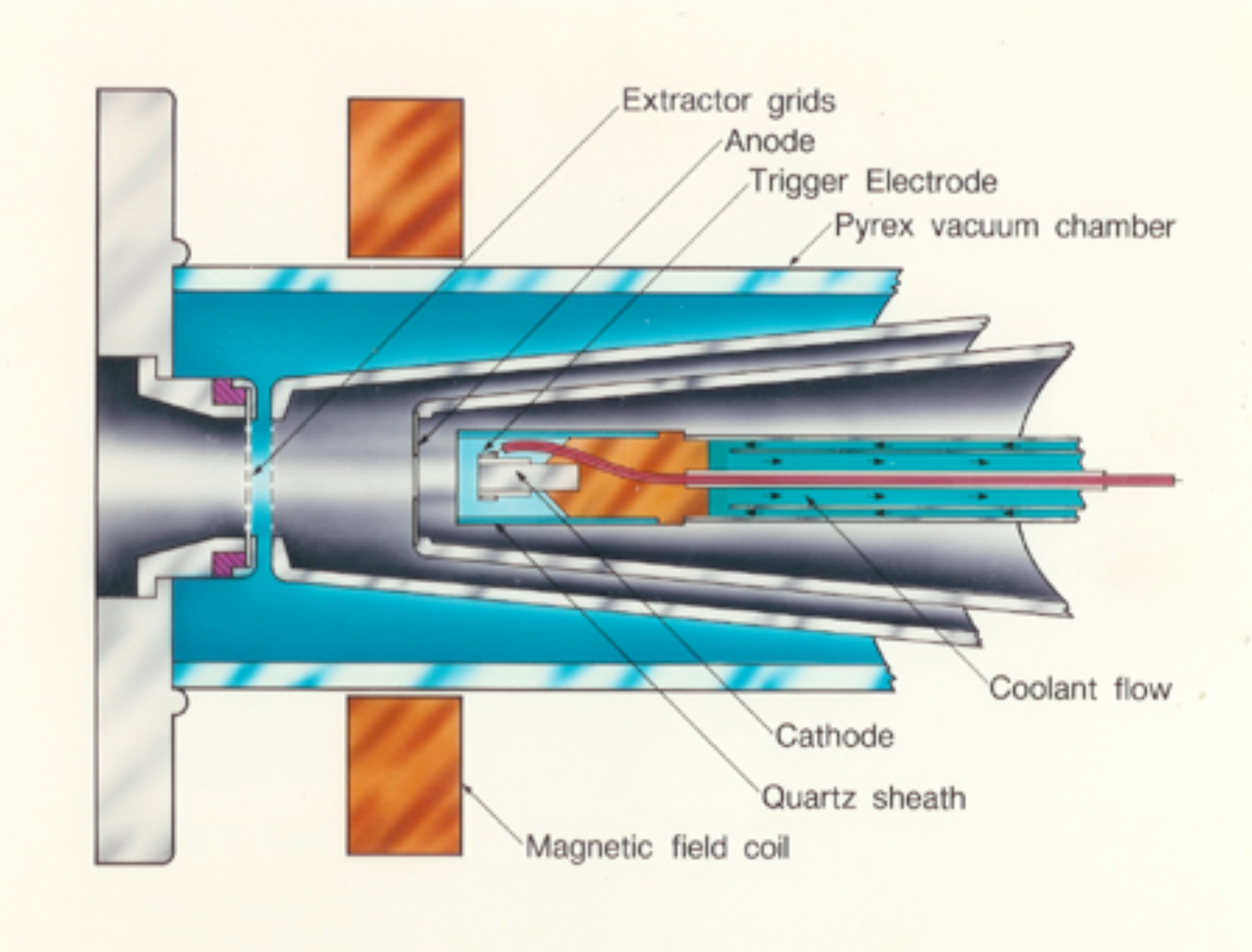
The Vacuum Arc Ion Source in Essence

- Metal plasma ıs formed by a vacuum arc plasma discharge
  - Very efficient: I_{ion} ~ (0.05 – 0.1) I_{arc}
- Energetic ion beam ıs “extracted” by beam formation electrodes
- The ion beam is typically
  - Metal ions (almost all in the Periodic Table)
  - Extraction energy typically 20 – 150 keV (10 – 50 or more kV)
  - Ps)Beam current typically 10 mA – 1 A (up to 10s of Amps)

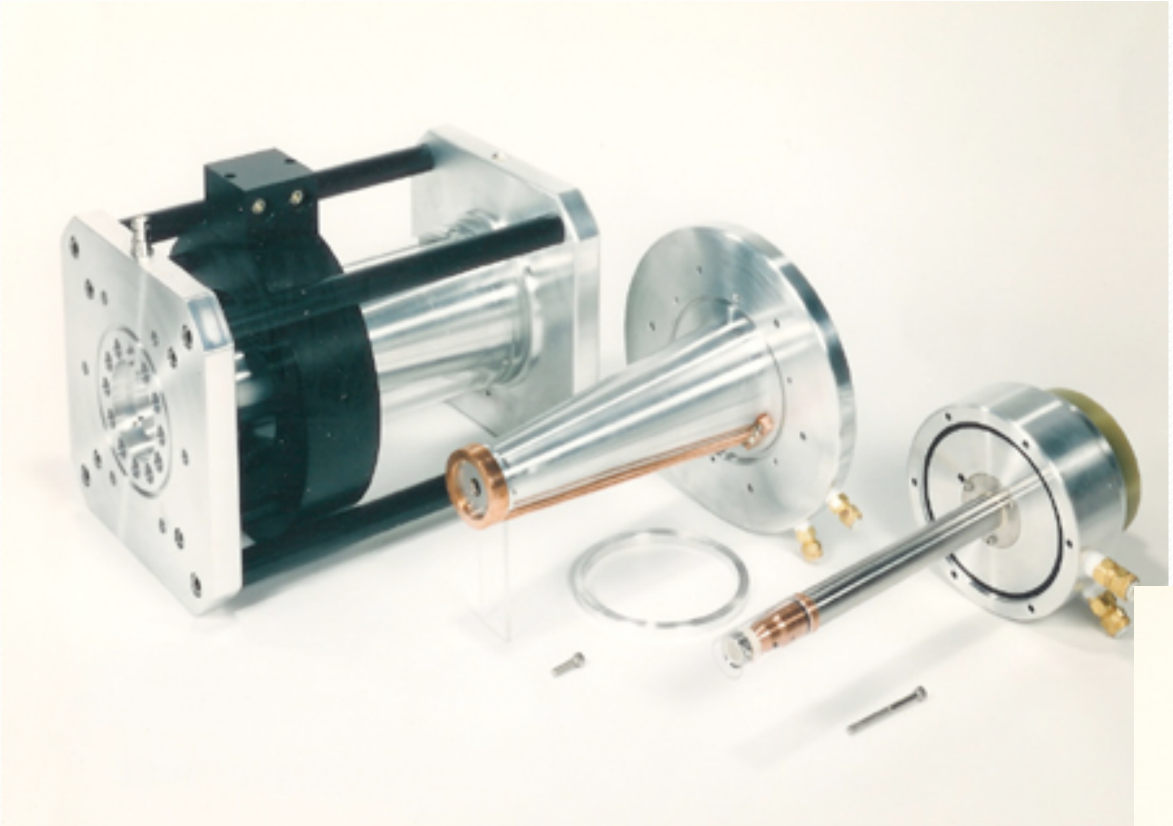
☞ An ion beam generator for ***high current*** beams of ***metal*** ions ☜

THE MEVVA II VACUUM ARC ION SOURCE

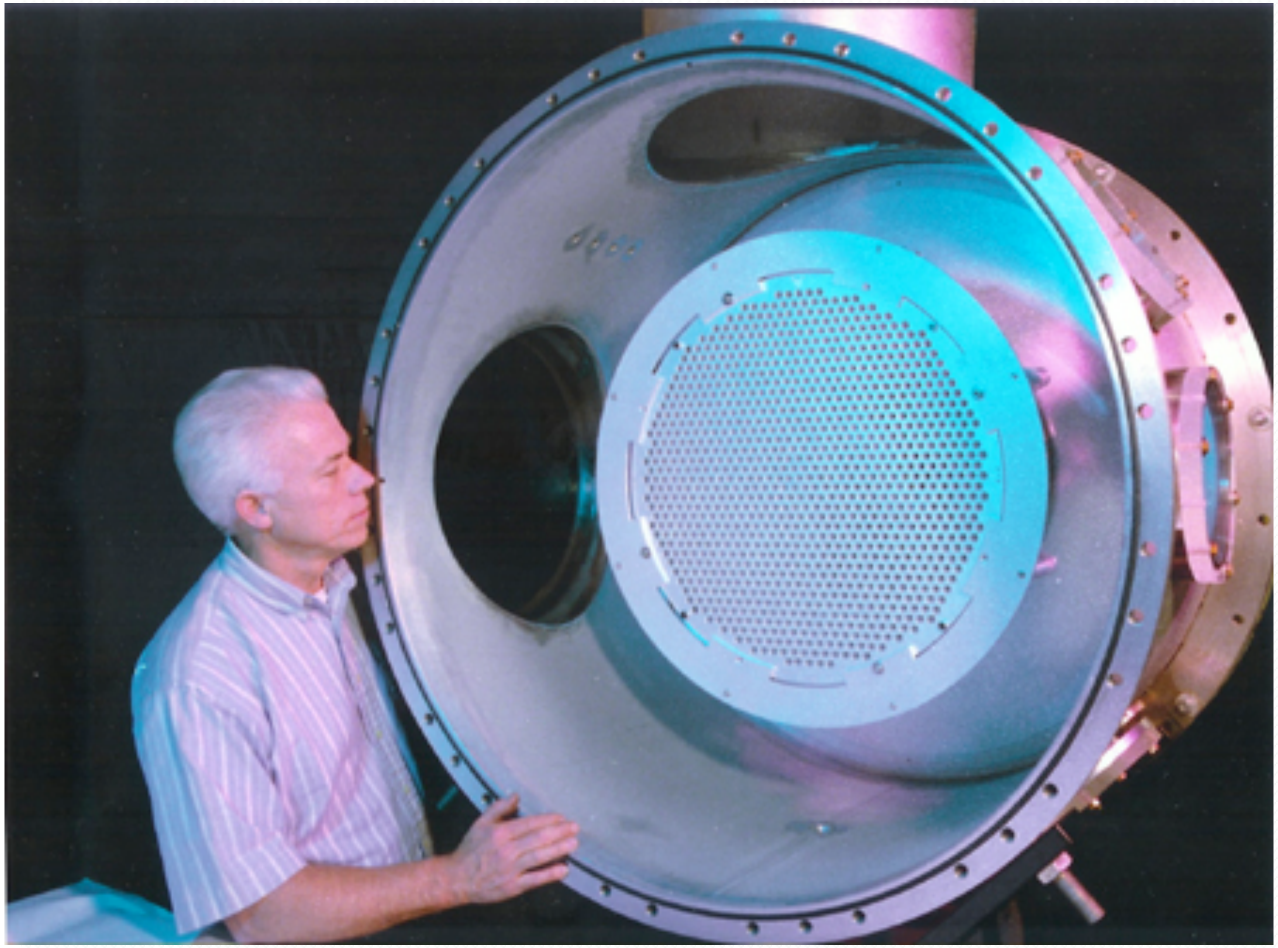
☞ Make a vacuum arc plasma and extract ions from it ☜



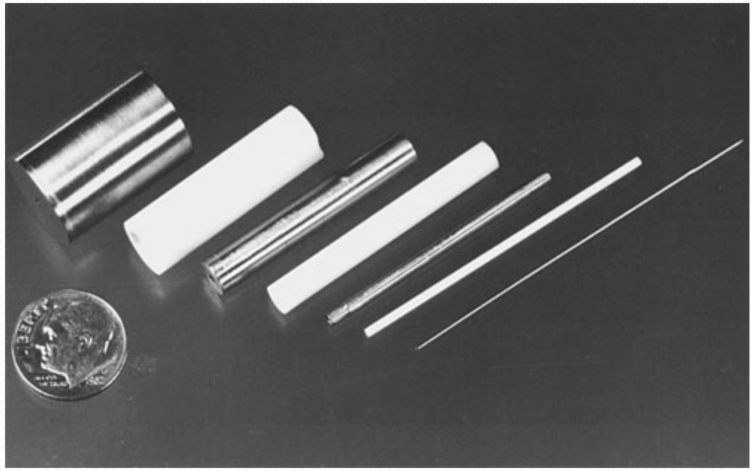
MEVVA II ION SOURCE



BIG & SMALL MEVVA EMBODIMENTS

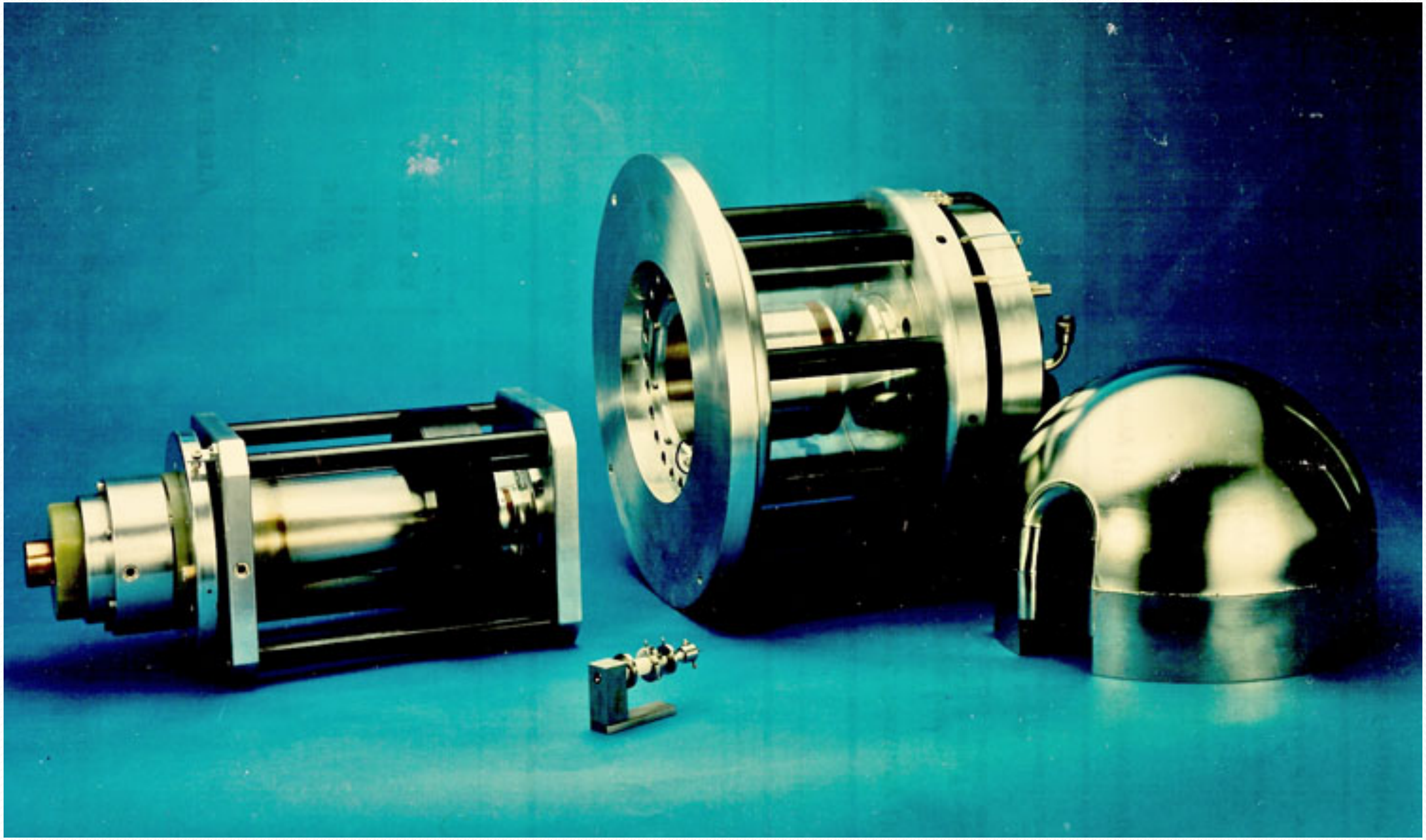


50 cm diameter extractor: 100 keV Ti ion beam with current up to ~20 A

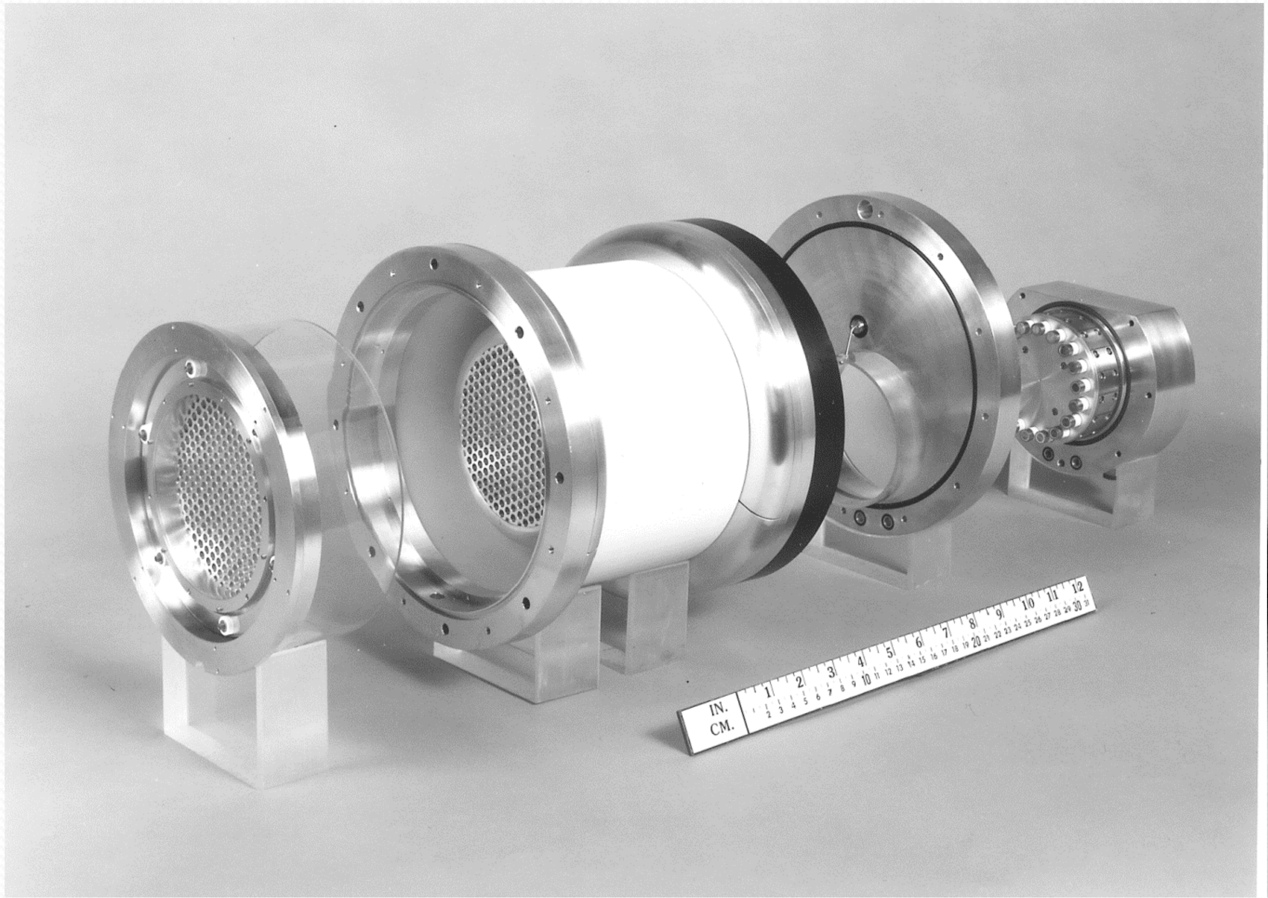


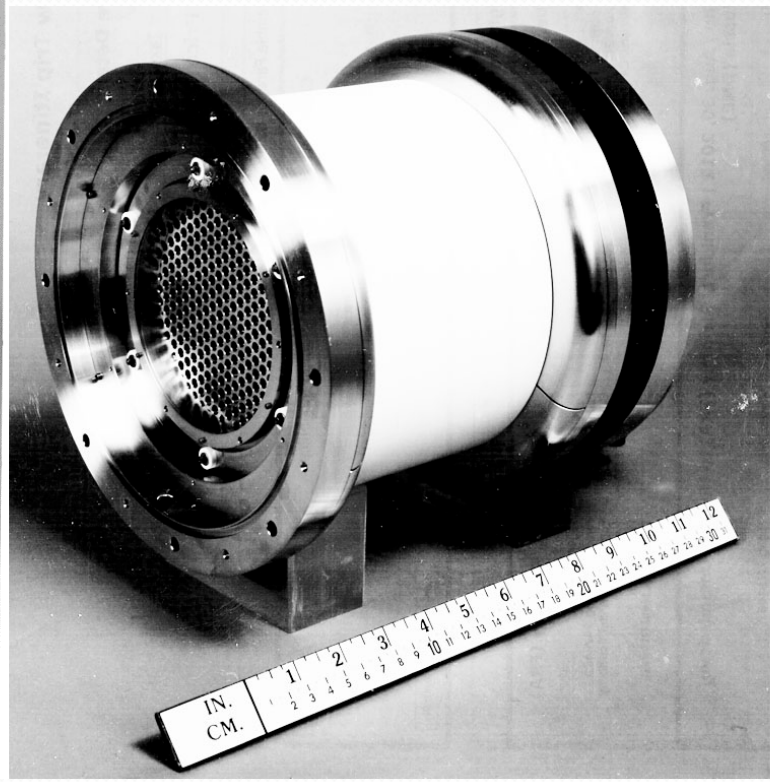
About "thumb sized": Short pulse, low rep rate

MEVVA II, MEVVA IV, MICROMEVVA



MEVVA V -- "WORKHORSE SOURCE"

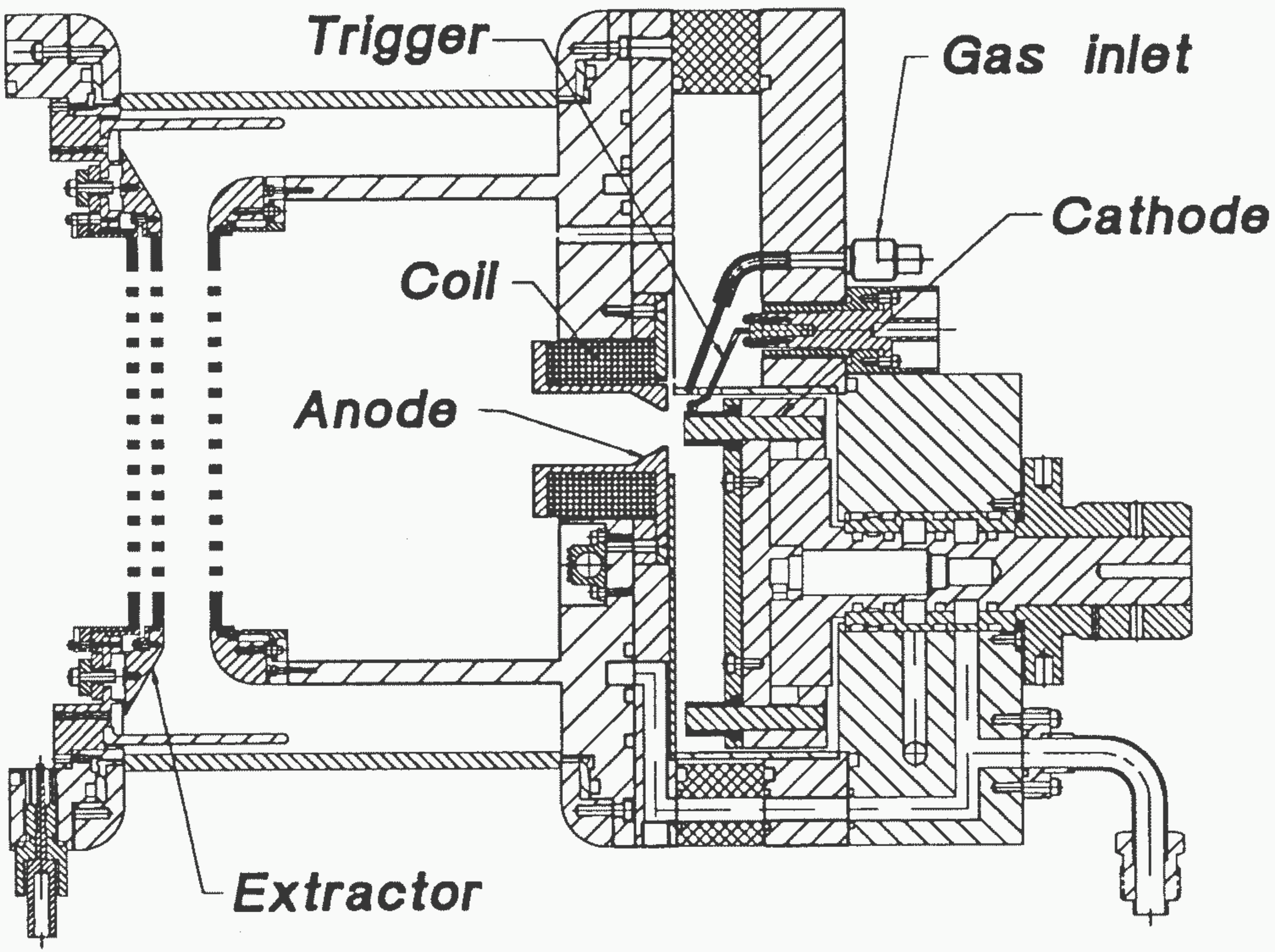




Used for ion implantation research for many years.

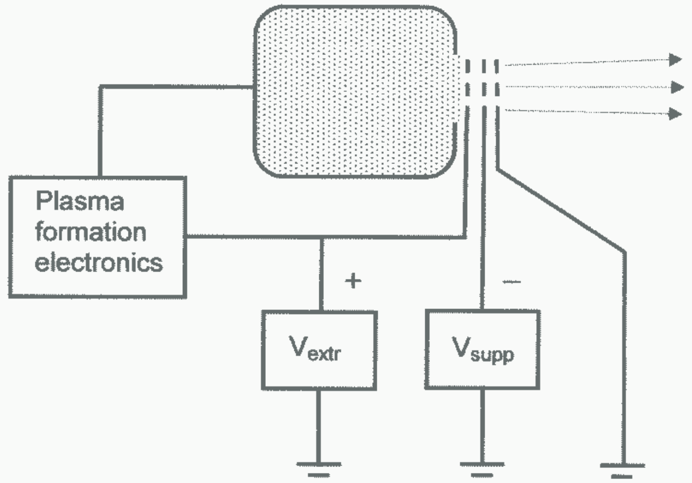
18 cathodes, 10 cm extractor, up to ~150 keV, ~1 A

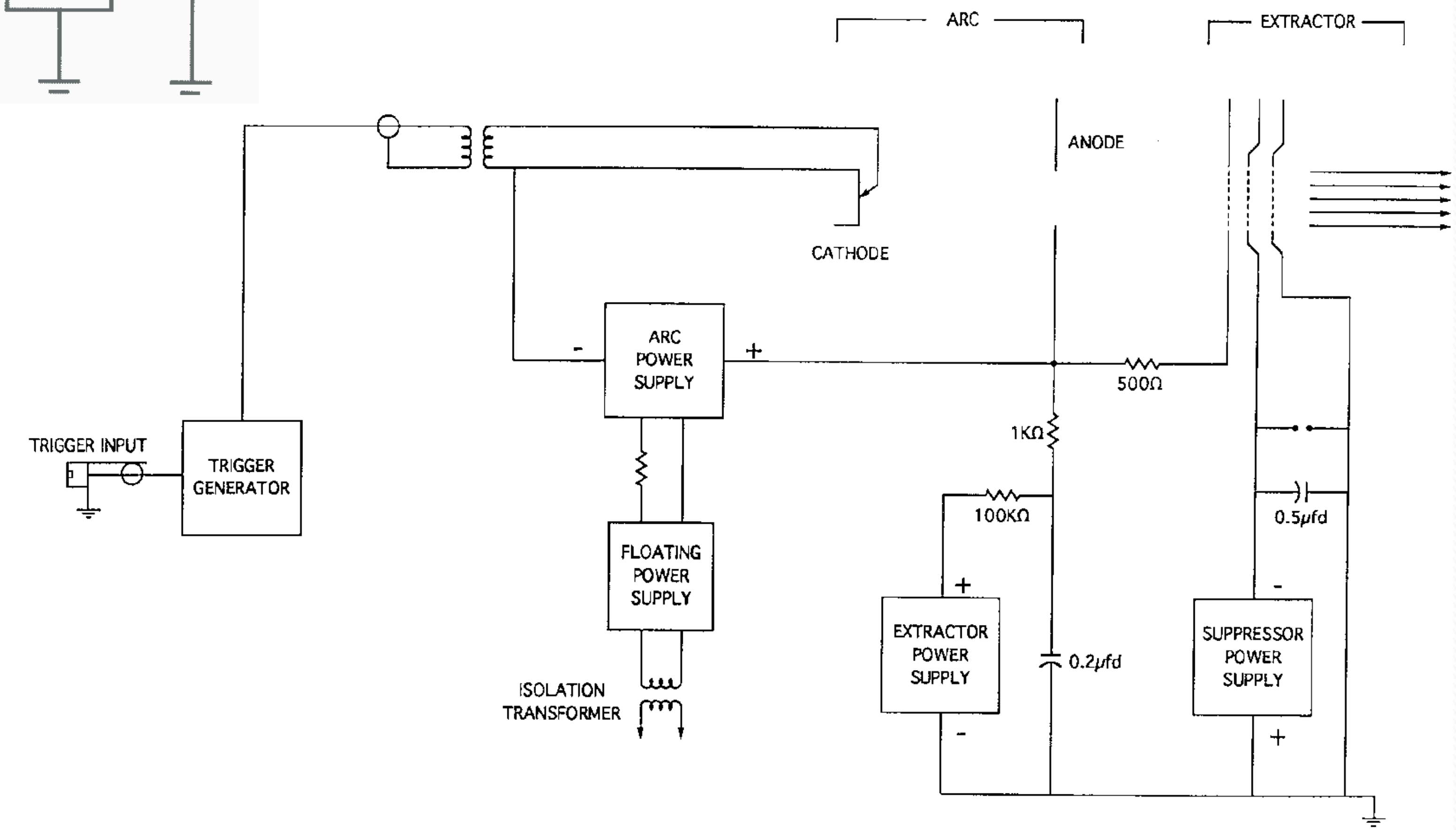
MEVVA V SCHEMATIC



Outline of the Mevva V ion source

BASIC ELECTRICAL SCHEMATIC





ION CHARGE STATES

Ions formed in the vacuum arc plasma are in general multiply-stripped, with a mean charge state <Q> between 1 and 3.

Iridium CSD

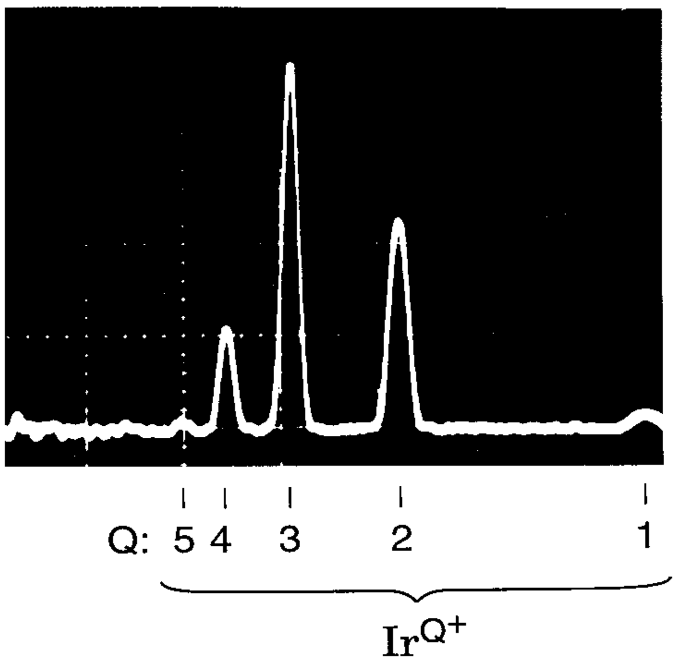


TABLE I. Vacuum arc ion charge state distributions. [Ion charge state fractions and mean charge states, expressed in terms of particle current. * trace (under 1%).]

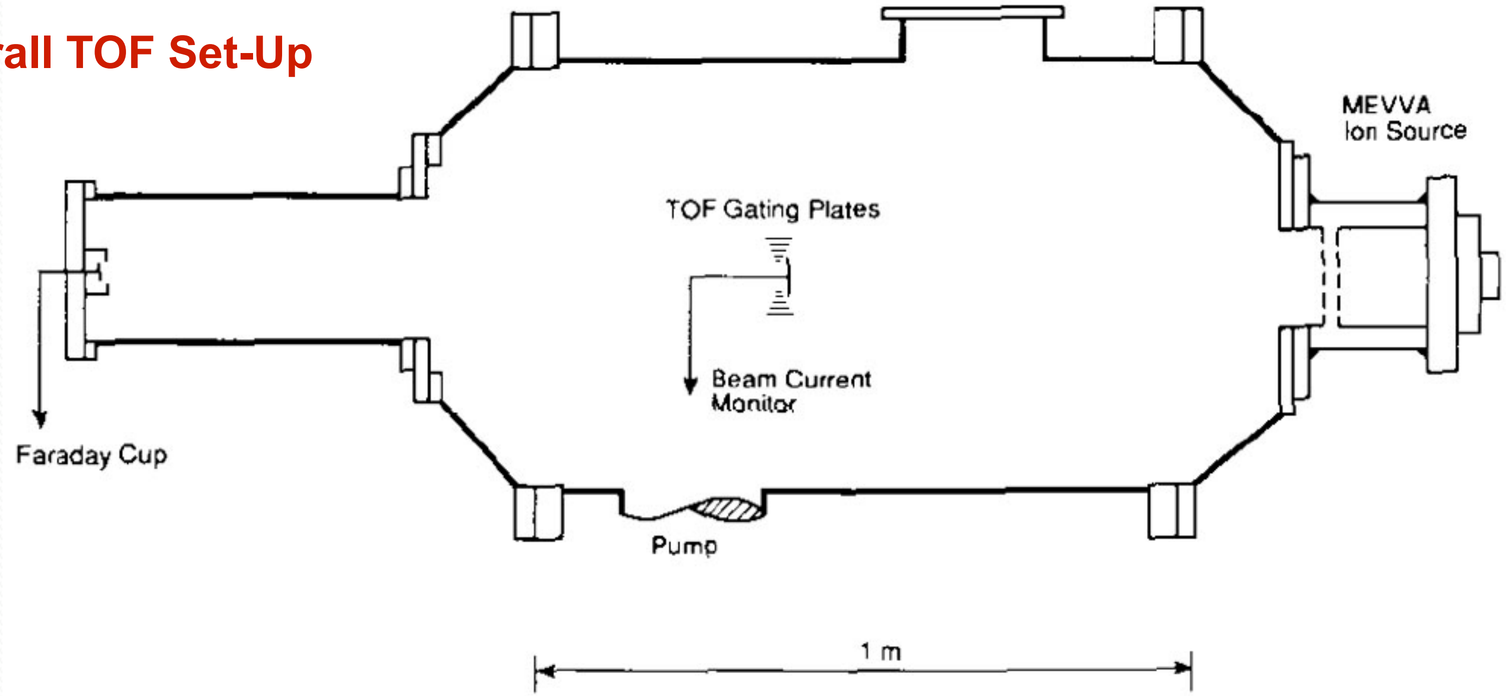
Element	Z	Q=1+	2+	3+	4+	5+	6+	$\bar{Q}_p$
Li	3	100						1.0
C	6	100						1.0
Mg	12	46	54					1.5
Al	13	38	51	11				1.7
Si	14	63	35	2				1.4
Ca	20	8	91	1				1.9
Sc	21	27	67	6				1.8
Ti	22	11	75	14				2.1
V	23	8	71	20	1			2.1
Cr	24	10	68	21	1			2.1
Mn	25	49	50	1				1.5
Fe	26	25	68	7				1.8
Co	27	34	59	7				1.7
Ni	28	30	64	6				1.8
Cu	29	16	63	20	1			2.0
Zn	30	80	20					1.2
Ge	32	60	40	*				1.4
Sr	38	2	98					2.0
Y	39	5	62	33				2.3
Zr	40	1	47	45	7			2.6
Nb	41	1	24	51	22	2		3.0
Mo	42	2	21	49	25	3		3.1
Pd	46	23	67	9	1			1.9
Ag	47	13	61	25	1			2.1
Cd	48	68	32					1.3
In	49	66	34	*				1.4
Sn	50	47	53					1.5
Sb	51	100	*					1.0
Ba	56		100					2.0
La	57	1	76	23				2.2
Ce	58	3	83	14				2.1
Pr	59	3	69	28				2.2
Nd	60		83	17				2.2
Sm	62	2	83	15				2.1
Gd	64	2	76	22				2.2
Dy	66	2	66	32				2.3
Ho	67	2	66	32	*			2.3
Er	68	1	63	35	1			2.4
Tm	69	13	78	9				2.0
Yb	70	3	88	8				2.1
Hf	72	3	24	51	21	1		2.9
Ta	73	2	33	38	24	3		2.9
W	74	2	23	43	26	5	1	3.1
Ir	77	5	37	46	11	1		2.7
Pt	78	12	69	18	1			2.1
Au	79	14	75	11				2.0
Pb	82	36	64					1.6
Bi	83	83	17					1.2
Th	90		24	64	12			2.9
U	92		12	58	30			3.2

TIME-OF-FLIGHT Q/A ANALYSIS SYSTEM

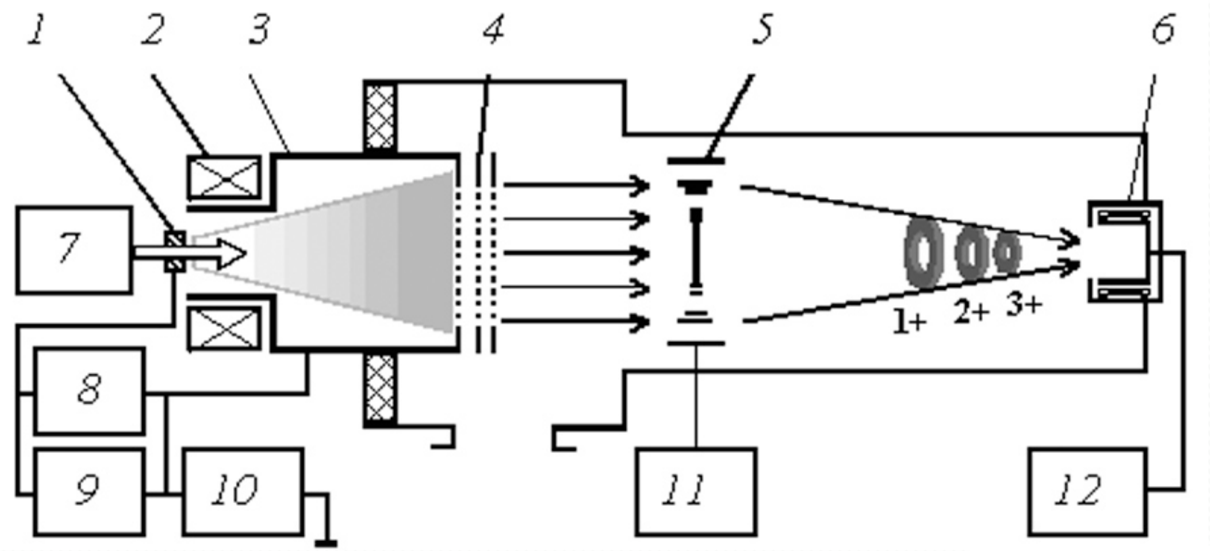
A relatively simple way of obtaining a Q/A spectrum of an ion beam:

- Gate a (sub-)microsecond piece of the beam,
- Monitor the beam components, separated according to their flight times,
- Analyze according to $\frac{1}{2} m_u A v^2 = eQV_{ext}$
- Or $t = L[2eV_{ext}(Q/Am_u)]^{-1/2}$

Overall TOF Set-Up

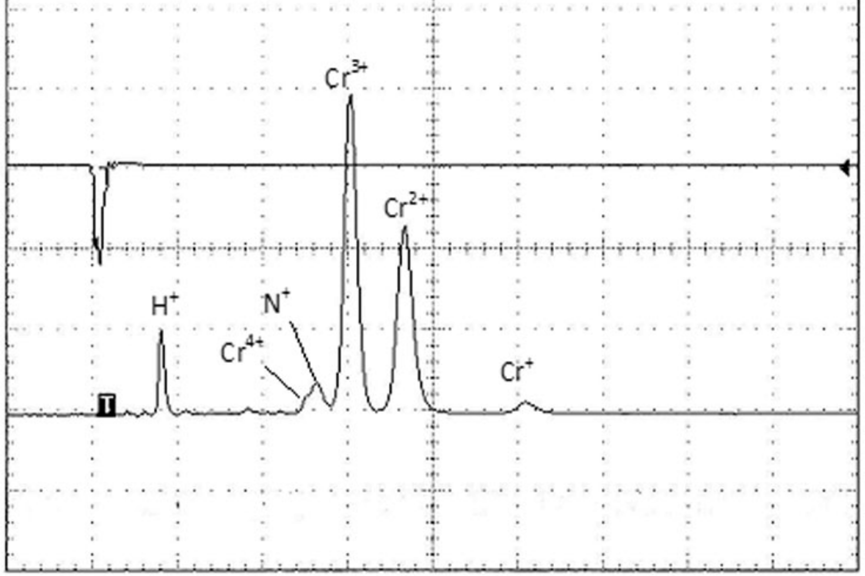


TOF SYSTEM



Gating plates

Typical TOF spectrum



TOF CSDs

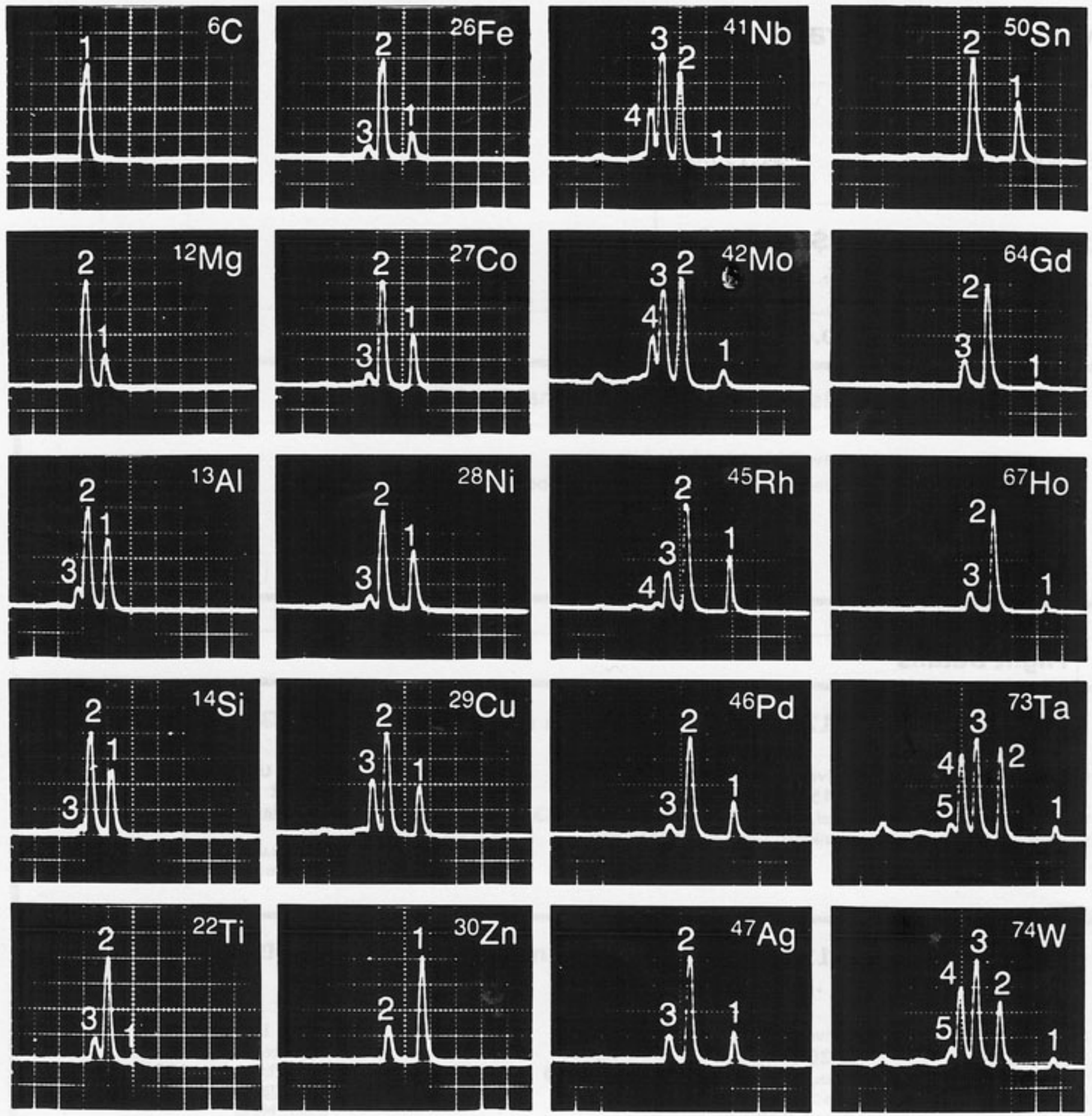
Low multiply-stripped, typically Q = 1, 2, 3, 4

<Q> = 1 to 3

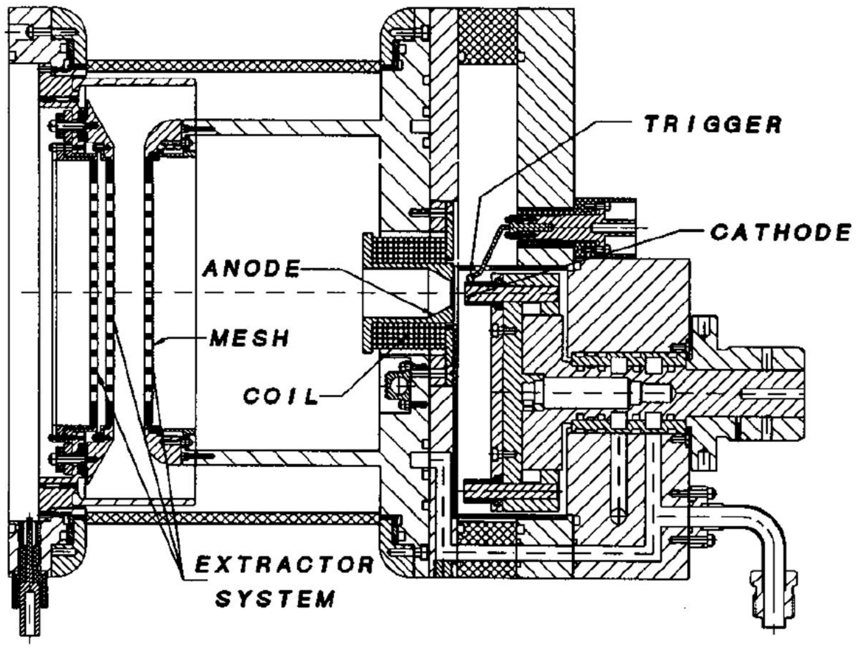
The more refractory metals have higher Q:

$\langle Q_p \rangle = 0.38(T_{BP}/1000) + 1$

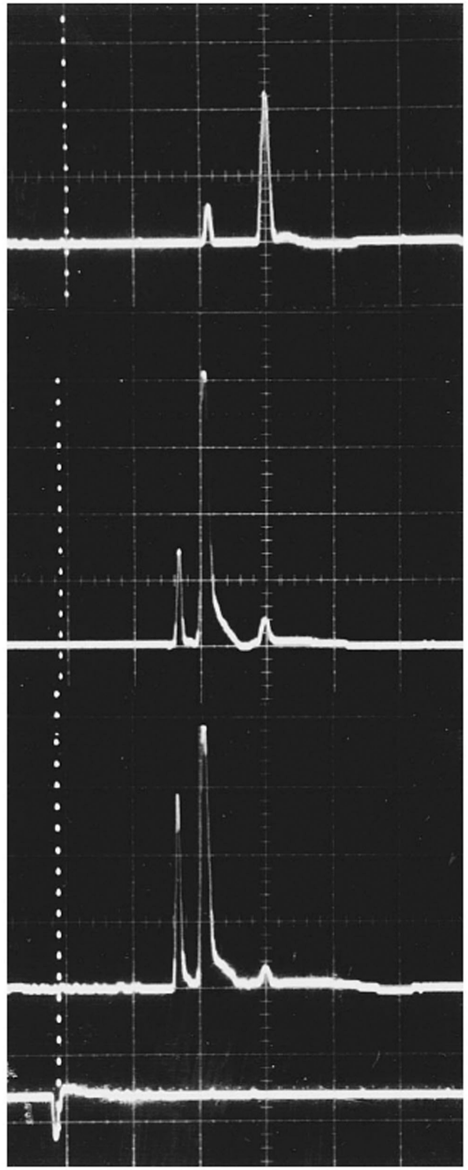
Low contamination



Q-CONTROL VIA B



Vacuum arc ion source with magnetic field coil.



TOF charge state spectra for Bi ions (i) without magnetic field (upper) and (ii) with magnetic field (middle, $B=2$ kG; lower, $B=3.75$ kG). The spectral peaks are for charge states $Q=1+$, $2+$, and $3+$, right-to-left. The oscilloscope signals are electrical current into a Faraday cup.

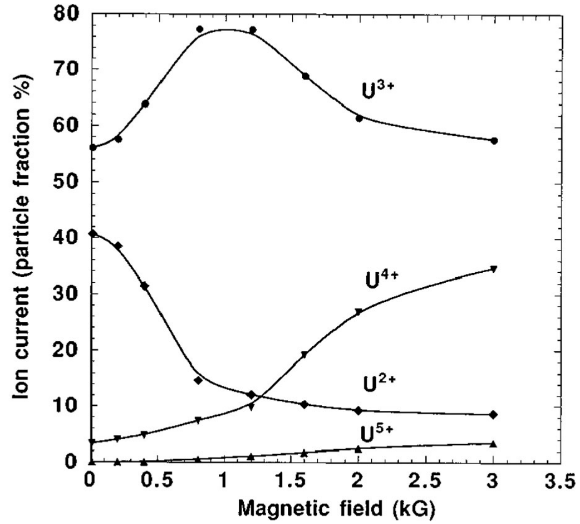
The ion charge state can be increased by immersing the arc in a magnetic field of up to several kG.

B-ENHANCED CHARGE STATES

Charge state distributions and mean charge states (all in particle current fractions) for a range of metal ion species with and without magnetic field applied. I_{arc}=220 A, B_{max}=3.75 kG.

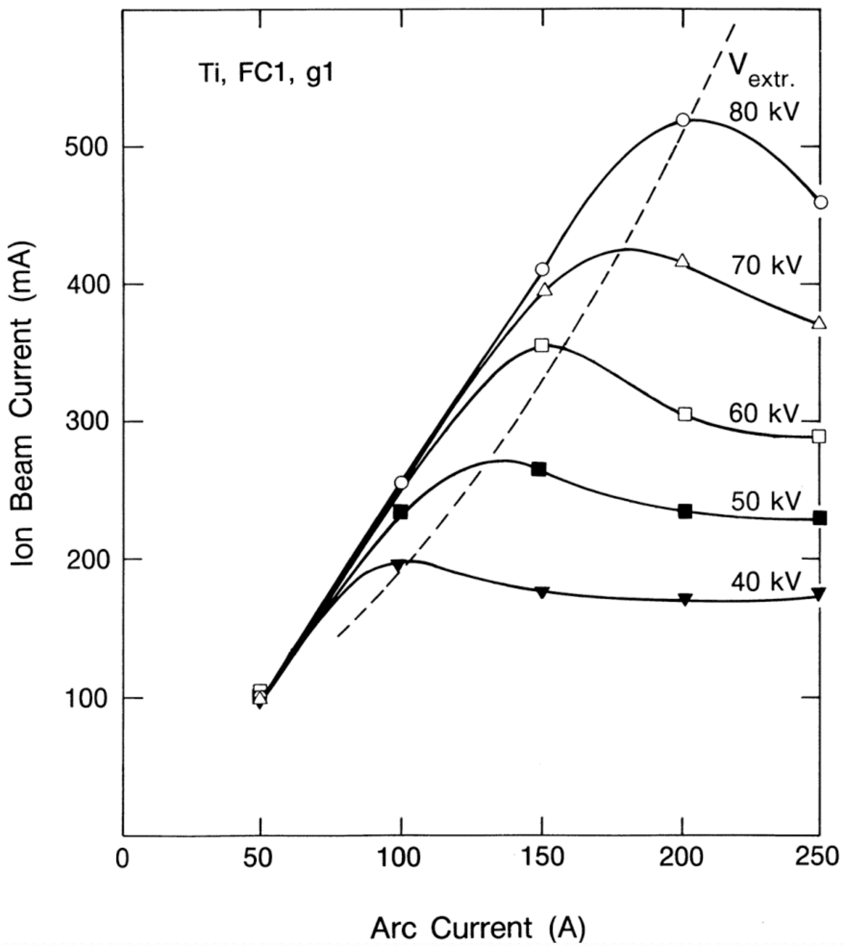
	Without magnetic field						With magnetic field							
Metal	1+	2+	3+	4+	5+	$\bar{Q}_1$	1+	2+	3+	4+	5+	6+	$\bar{Q}_2$	$\bar{Q}_2/\bar{Q}_1$
C	96	4				1.0	60	40					1.4	1.40
Mg	51	49				1.5	5	95					1.9	1.27
Al	38	51	11			1.7	10	40	50				2.4	1.40
Sc	23	66	11			1.9	16	23	59	2			2.5	1.31
Ti	11	76	12	1		2.0	5	35	54	6			2.6	1.30
V	11	72	15	2		2.1	13	31	48	8			2.5	1.20
Cr	14	70	15	1		2.0	11	26	55	8			2.6	1.30
Mn	48	52				1.5	26	47	25	2			2.0	1.33
Fe	28	68	6			1.8	7	58	35				2.3	1.28
Ni	43	50	7			1.6	19	62	18	1			2.0	1.25
Co	34	59	7			1.8	9	56	31	4			2.3	1.27
Cu	28	53	18	1		1.9	8	41	47	3	1		2.5	1.32
Y	7	63	29	1		2.2	6	9	77	8			2.9	1.32
Nb	3	40	39	16	2	2.7	1	9	23	52	13	2	3.7	1.37
Mo	7	30	40	20	3	2.8	5	11	26	48	10		3.5	1.25
Ba	3	97				2.0	2	41	53	3	1		2.6	1.30
La	4	65	31			2.3	3	16	61	20			3.0	1.30
Gd	8	81	11			2.0	1	43	41	15			2.7	1.35
Er	8	62	30			2.2	2	12	70	16			3.0	1.36
Hf	7	26	48	18	1	2.8	5	16	31	32	15	1	3.4	1.21
Ta	1	17	39	39	4	3.3	1	5	13	40	41	2	4.2	1.27
W	1	17	35	35	12	3.4	1	5	16	39	32	7	4.2	1.20
Pt	12	70	18			2.1	3	25	64	8			2.8	1.30
Pb	40	60				1.6	1	75	24				2.2	1.37
Bi	89	11				1.1	9	60	31				2.2	2.00

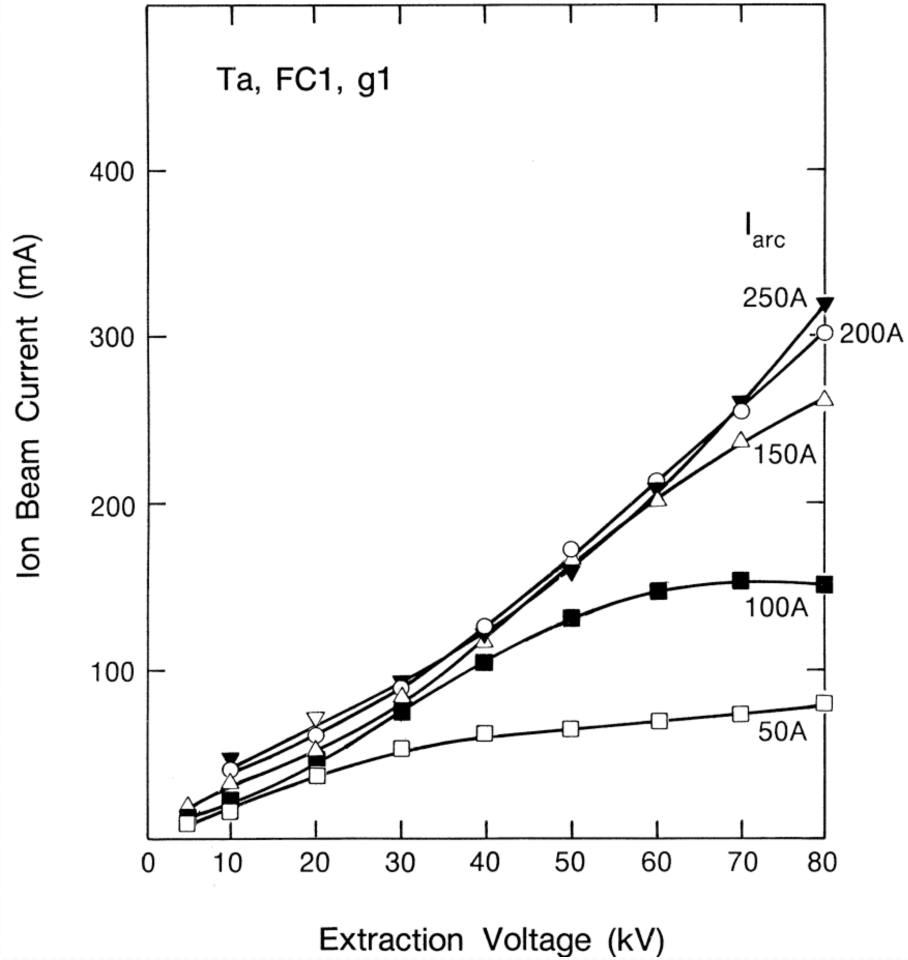
Uranium



Ion beam current fractions as a function of magnetic field strength for the different ionization states of a uranium ion beam; I_{arc}=280 A.

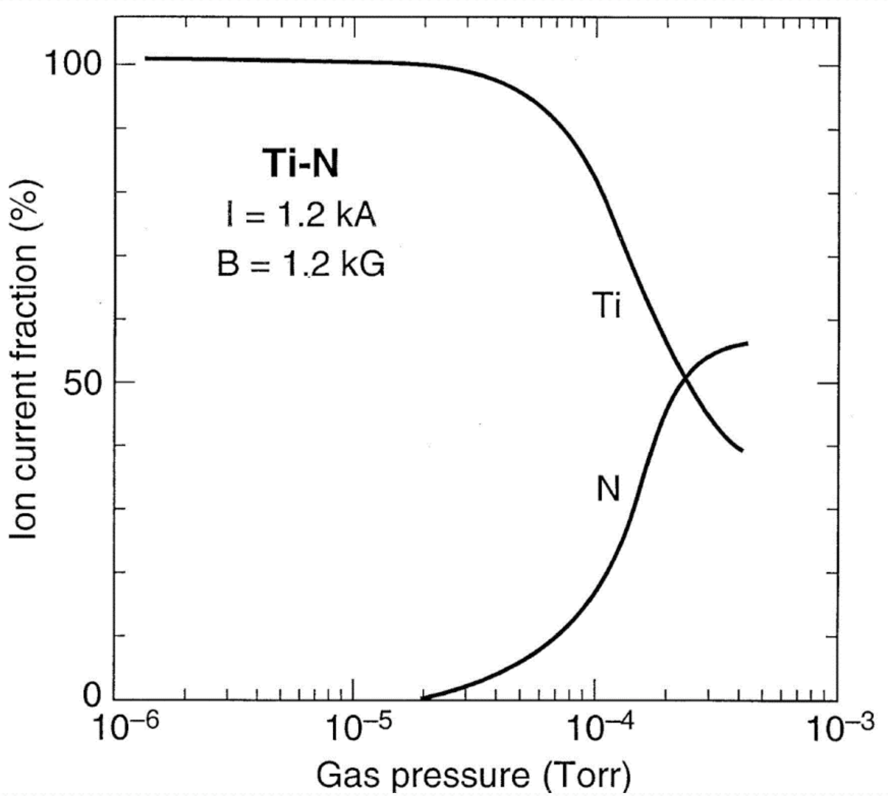
BEAM CURRENT

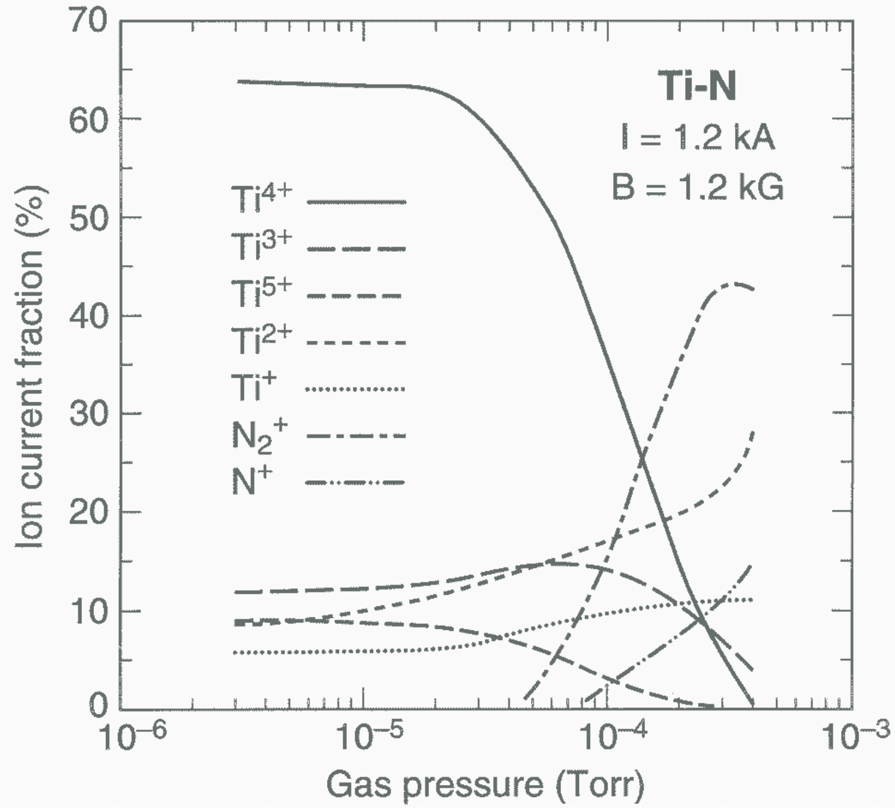




Extracted ion beam current can be a few mA up to several Amps, depending on arc current and extractor size. (Mevva IV data).

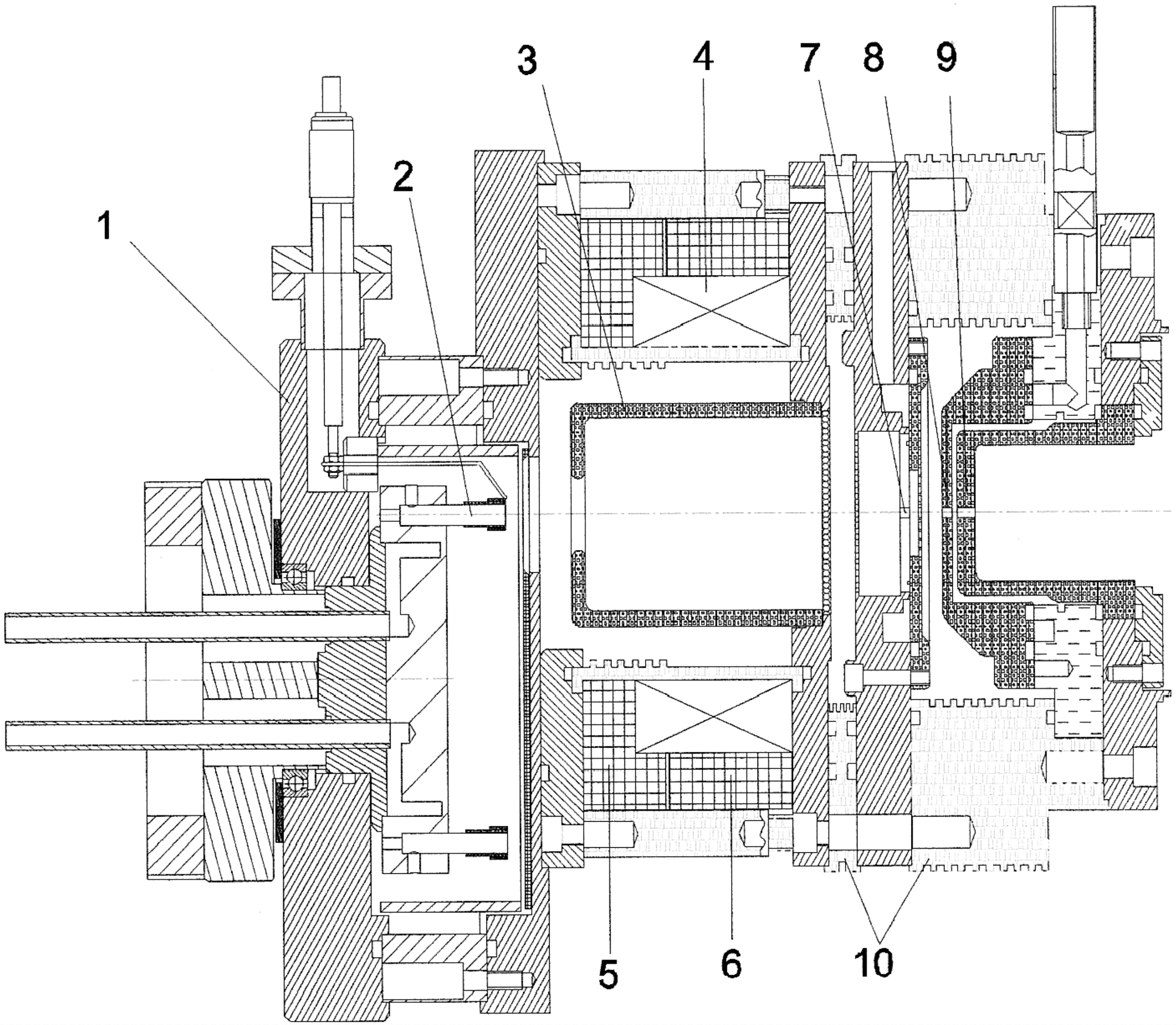
HYBRID METAL/GAS OPERATION





Gaseous fraction increases and charge states decrease with increasing gas pressure.

GSI SOURCE (FOR UNILAC INJECTION)



1 – Cathode flange

2 – Cathode

3 – Anode (stainless steel)

4 – 10 SmCo cusp magnets

5 – Coil I

6 – Coil II

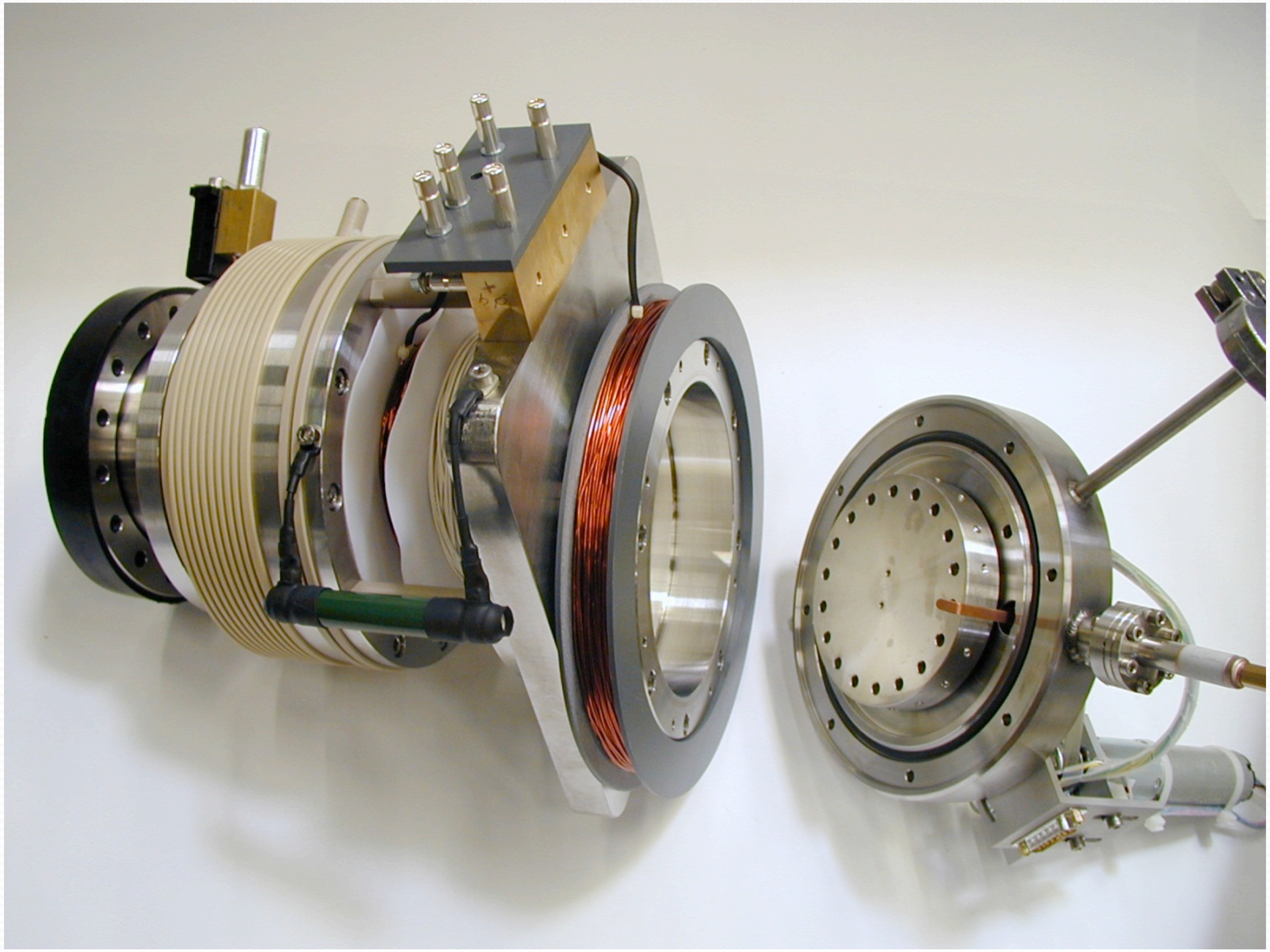
7 – Plasma electrode and grid

8 – Screening electrode

9 – Ground electrode

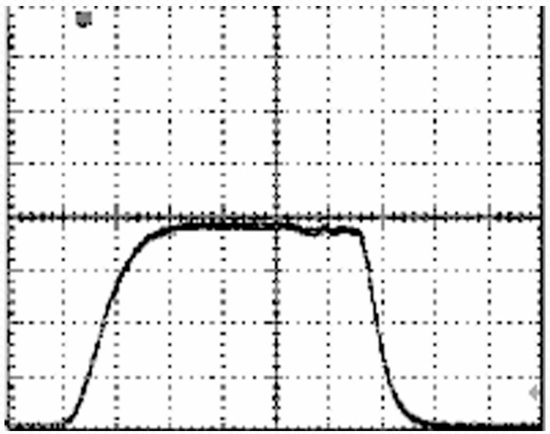
10 – Insulators

GSI VACUUM ARC SOURCE

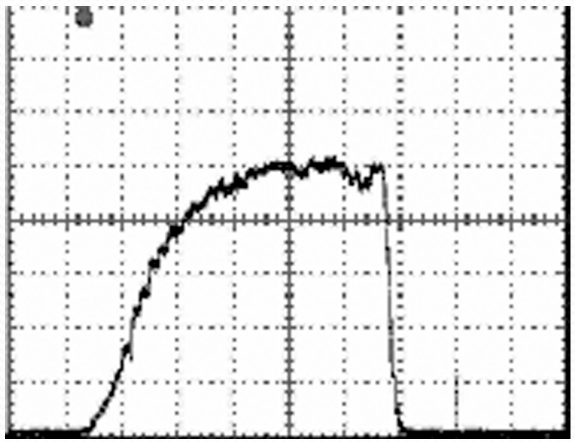


U^{4+} INJECTION AT GSI

- U^{4+} at 2.2 keV/amu matches the required RFQ injection velocity
- Beam is extracted at ~30 kV, followed by ~100 kV post-acceleration
- Beam parameters:
  - 25 mA U^{4+} at ~525 keV, measured at RFQ entrance
  - 56% of the extracted Mevva U beam is in U^{4+} charge state
  - U^{4+} beam noise is up to but not greater than ~10%
  - Pulse-to-pulse repeatability is good



I_{ion}, total beam (all charge states)
40 mA/cm, 100 μs/cm
30 cm from ion source

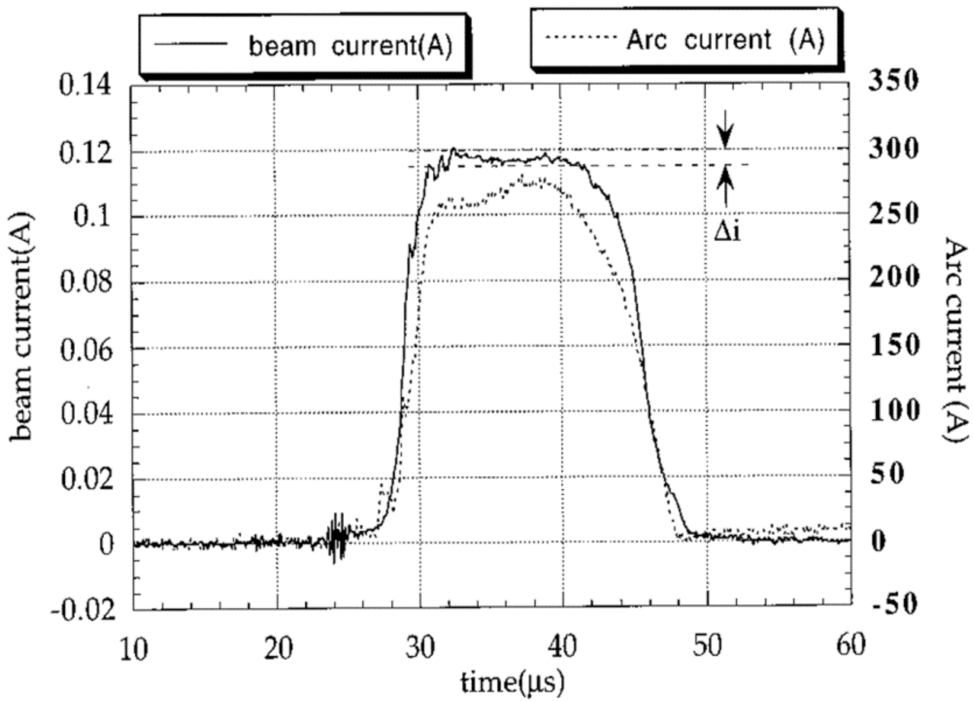


I_{ion}, U^{4+} only (post-analysis)
5mA/cm, 100 μs/cm
12 m from ion source

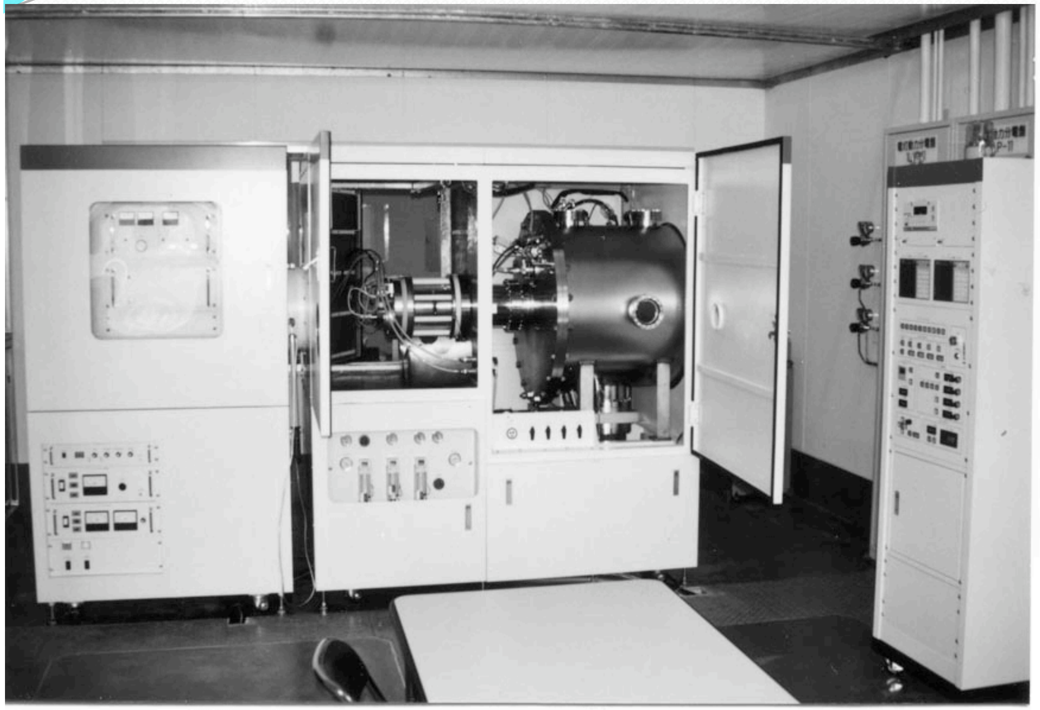
As an HIF Ion Source

As an example / demonstration of potential HIF application:

Gd beam (85% in the Gd^{2+} charge state),
at an ion energy of 120 keV (60 kV extraction voltage),
with a collected beam current of 120 emA,
for a 20 μs pulse width,
a pulse rise time of < 1 μs,
and a beam emittance about 0.3π mm. mrad (normalized).



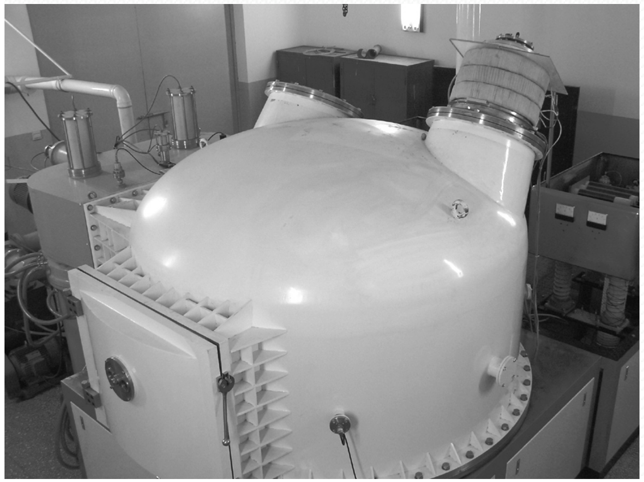
As a Metal Ion Implanter



Nagasaki implanter:

- up to 80 kV
- 0.5 A pulsed beam current,
- 1 ms @ up to 20 pps,
- for 10 mA average beam current
- beam size >15 cm diameter

(Industrial Technology Center of Nagasaki)

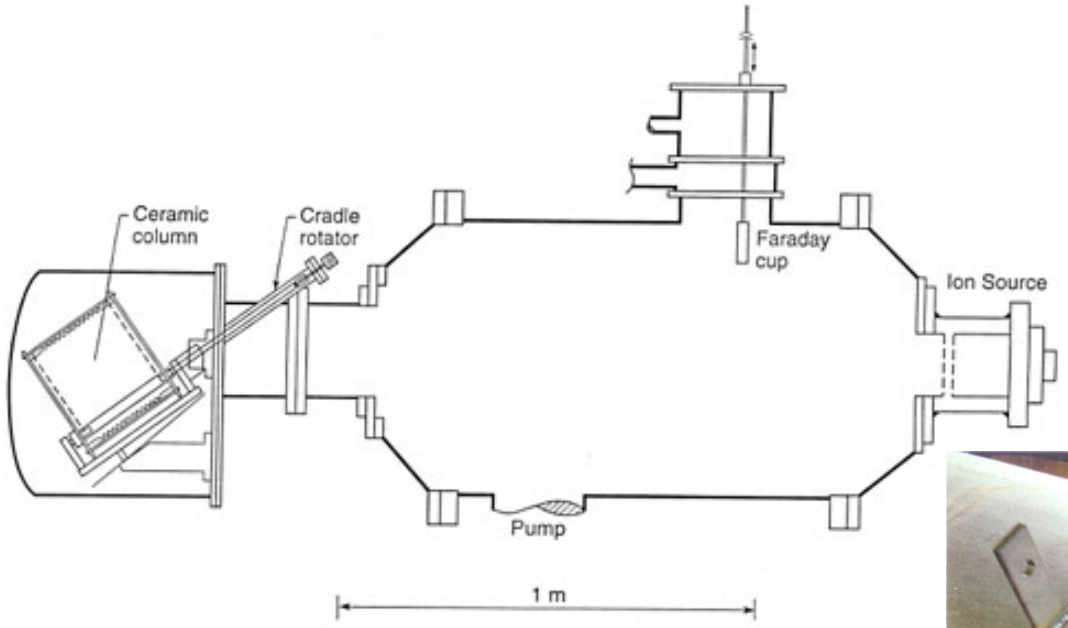


Beijing implanter:

- up to 50 kV
- 3.3 ms @ up to 33 pps,
- for 10 mA average
- beam size >80cm diameter
- 2 m diameter vessel

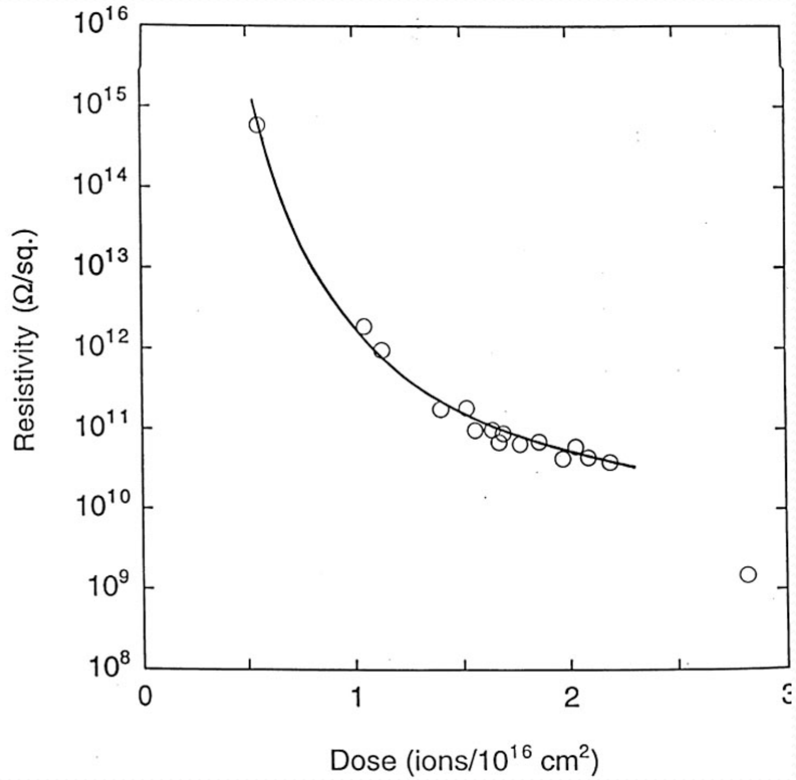
(Beijing Normal University)

CEBAF Accelerator Column Implant



Pt Implantation into column to grade (and thus increase) voltage hold-off

CERAMIC COLUMN RESISTIVITY TAILORING



CONCLUSION

- The vacuum arc ion source (Mevva) is unique in its
  - *High current*
  - of *metal ions*

- It is essentially a repetitively-pulsed source

- Beam noise and pulse shape irreproducibility have been greatly improved, and the source is suitable for accelerator injection

- Main demonstration of accelerator injection application is provided by GSI Darmstadt

- Other applications include metal ion implantation

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- And all the references there-in