

Progress on the MEVVA source VARIS at GSI

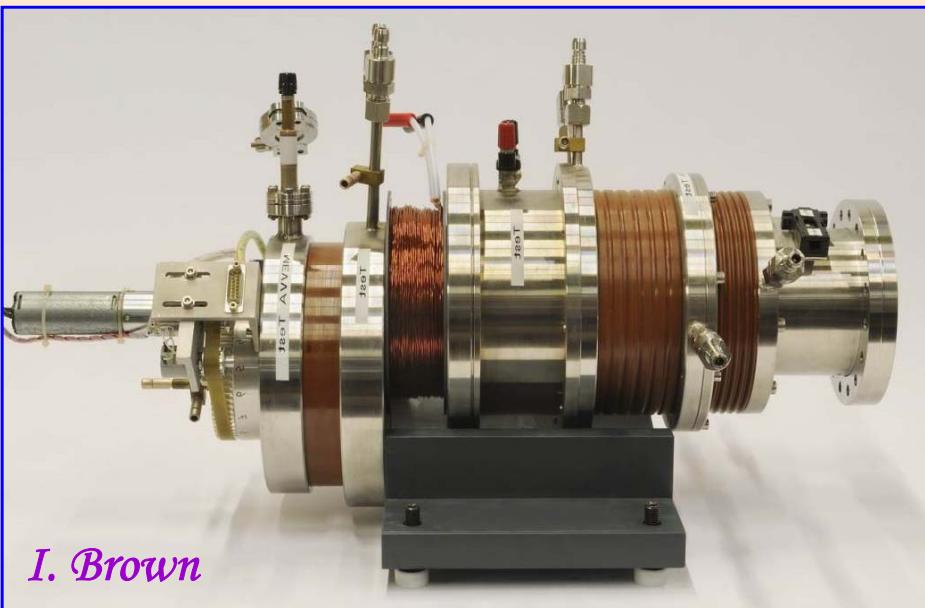
Aleksey Adonin

Ion Sources, GSI

- **Short introduction of VARIS source:**
 - history, purpose, construction specificity, features
- **Development of VARIS for the last years**
 - 3 main directions, progress, main results
- **Present and further development**
 - goals, plans, challenges
- **Conclusions**

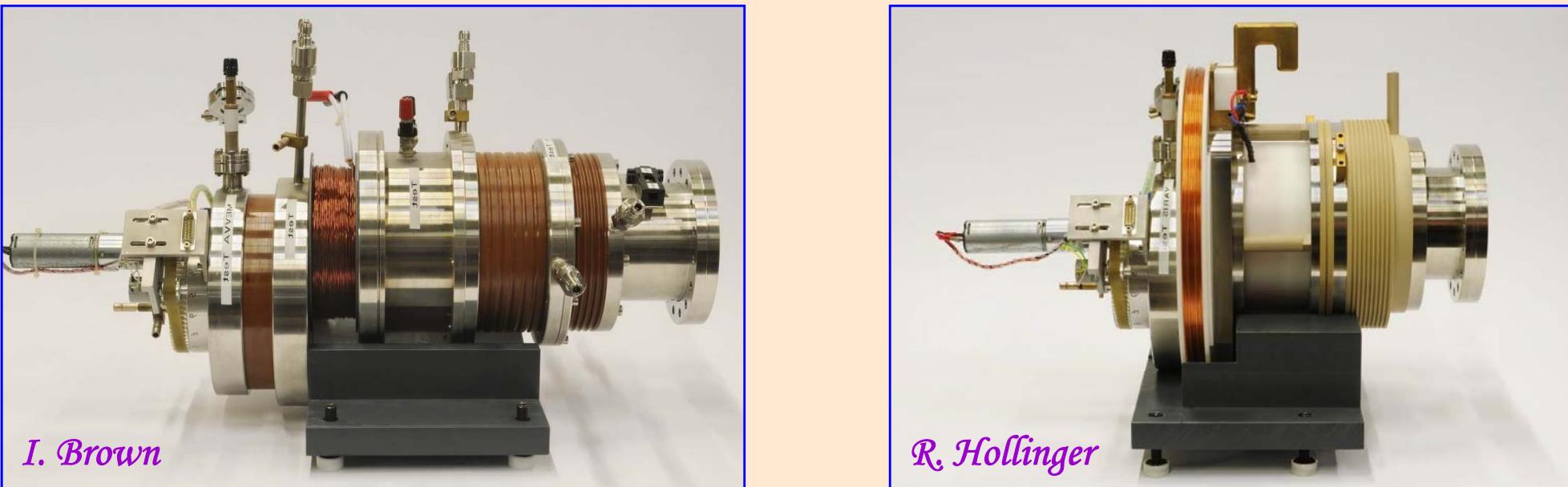
MEVVA-IV

Metal Vapor Vacuum Arc Ion Source



VARIS

Vacuum Arc Ion Source



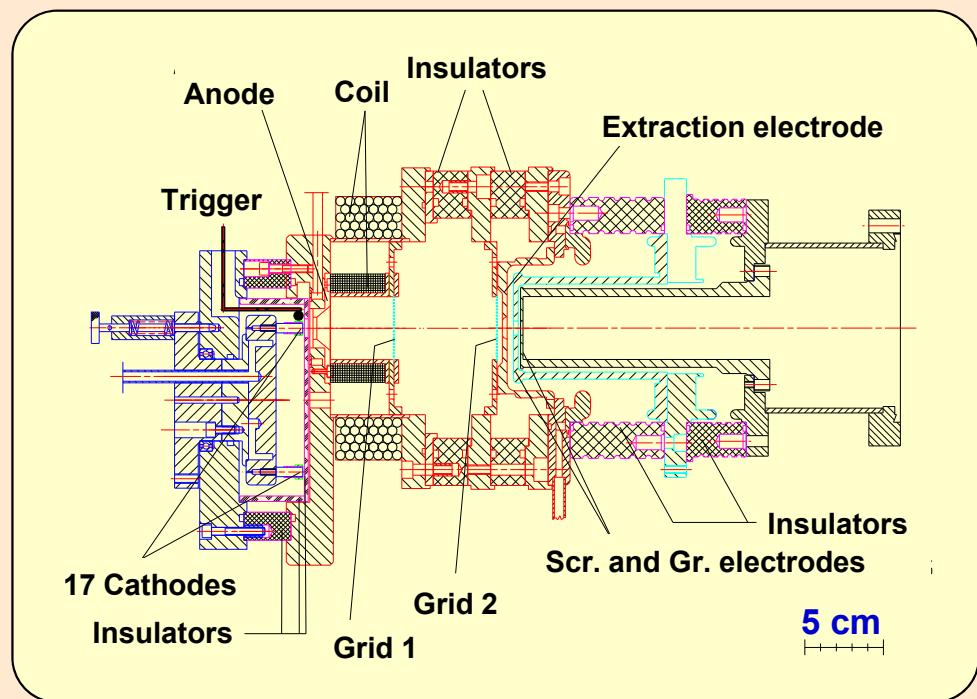
Main purpose of VARIS:

Production of high current U^{4+} ion beam
for synchrotron operation.

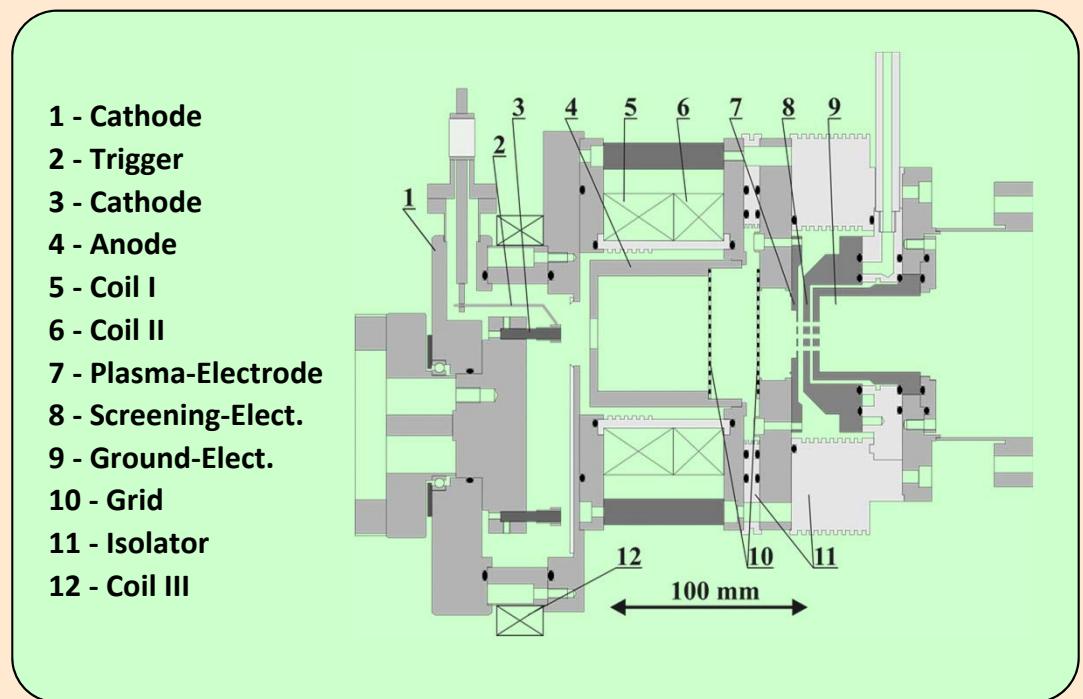
Construction difference to MEVVA:

- enhanced geometry of plasma chamber
- improved positioning of coils and grids
- more compact extraction system

MEVVA-IV



VARIS



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Production of high current U^{4+} ion beam
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Construction difference to MEVVA:

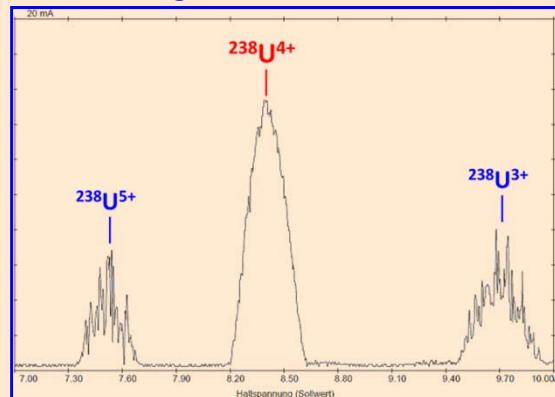
- enhanced geometry of plasma chamber
- improved positioning of coils and grids
- more compact extraction system

Features:

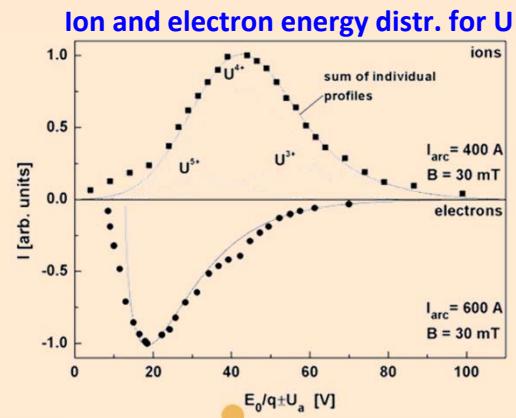
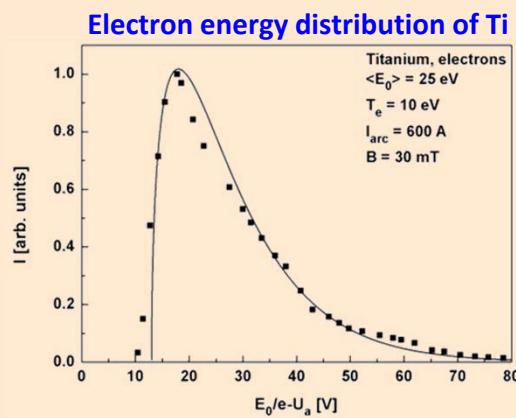
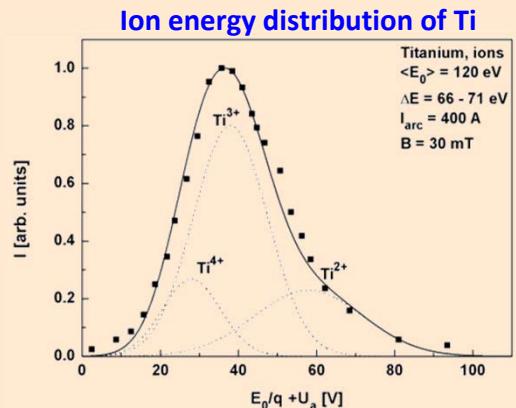
- optimized for production of Uranium beam: **67% of U⁴⁺**
- better vacuum conditions: **up to $8 \cdot 10^{-8}$ mbar**
- no water cooling necessary
- higher emission current density: **170 mA/cm²**
- better pulse-to-pulse stability
- reduced intensity fluctuations during the pulse
- U⁴⁺ beam current in front of the RFQ: **15 mA**



Ion charge state distribution for U



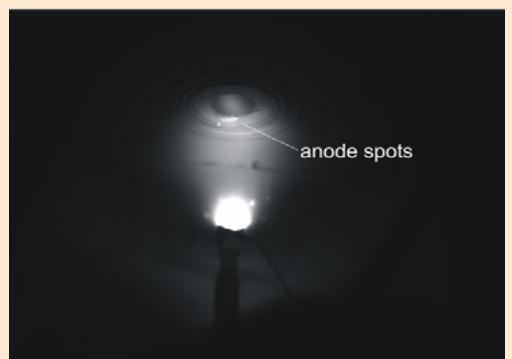
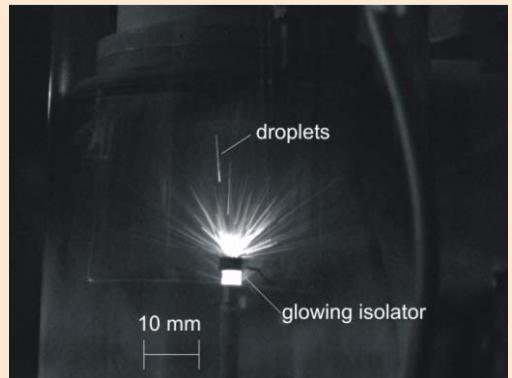
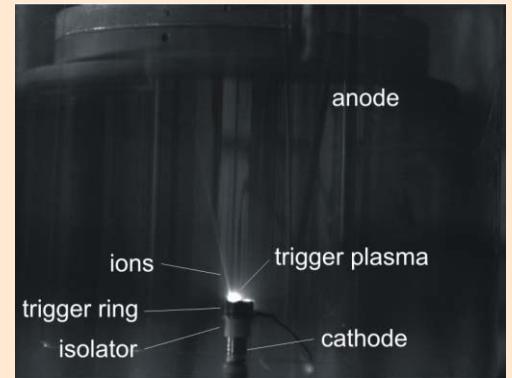
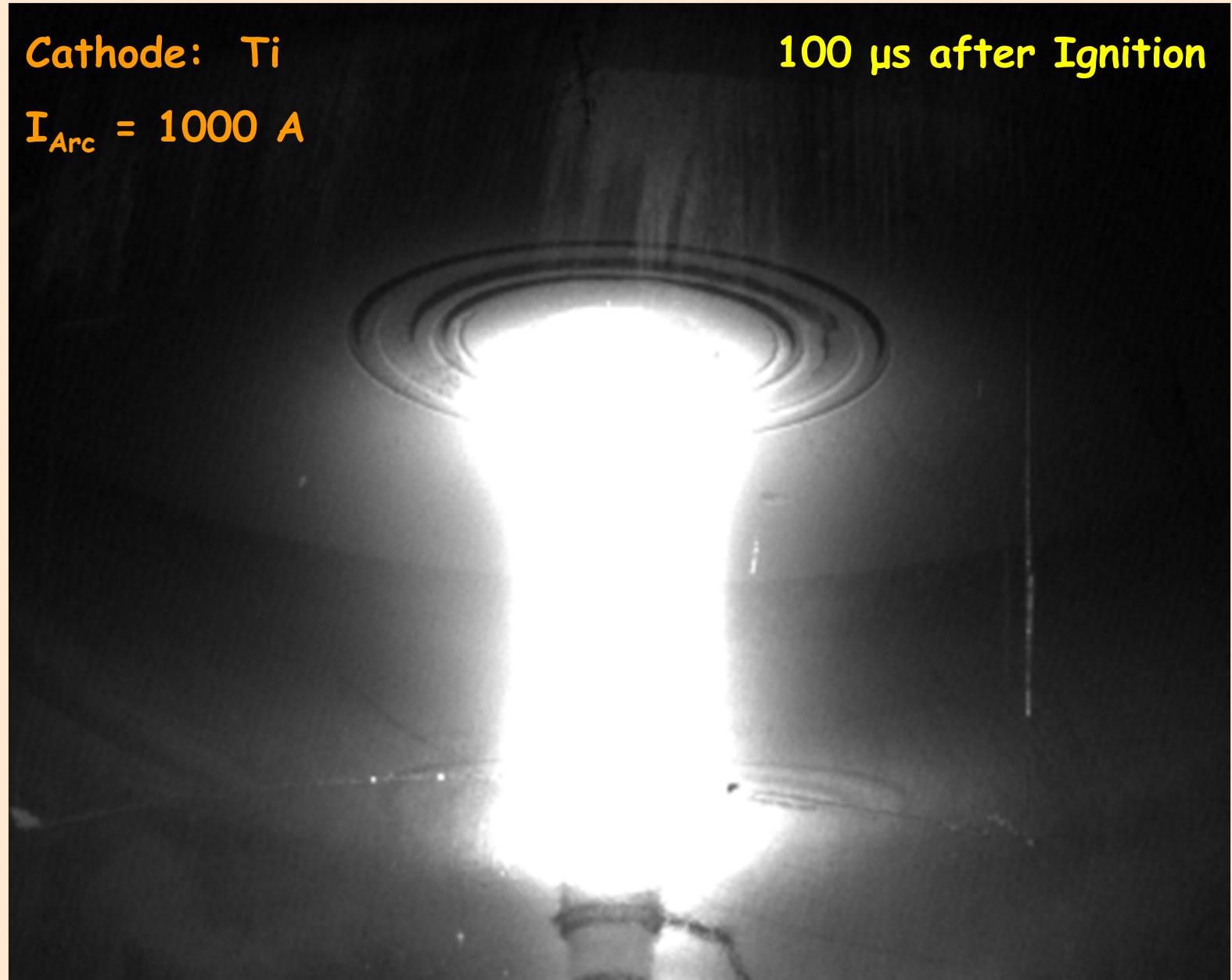
R. Hollinger, M. Galonska, Nucl. Instr. and Meth. in Phys. Res. B 239 (2005)



Cathode: Ti

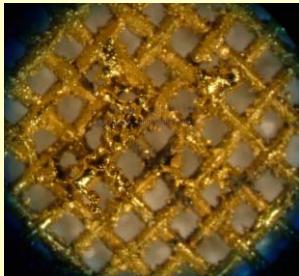
$I_{Arc} = 1000 \text{ A}$

100 μs after Ignition

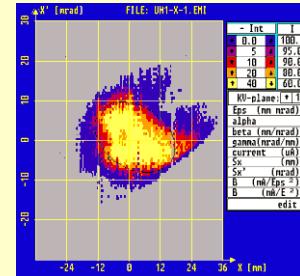


Development of VARIS for the last years

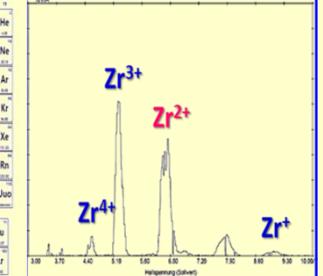
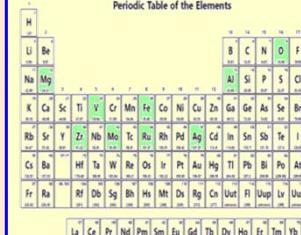
Production of high current beams of heavy elements:
Au, Pb and Bi



Increasing of the beam brilliance for intense **U^{4+} ion beam**



Development of the new projectiles in middle-heavy region



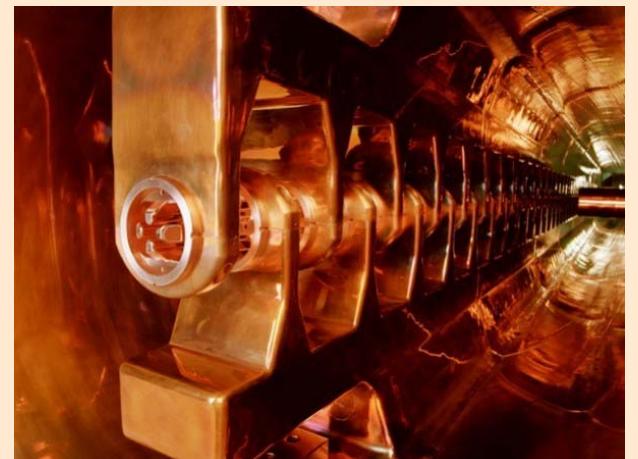
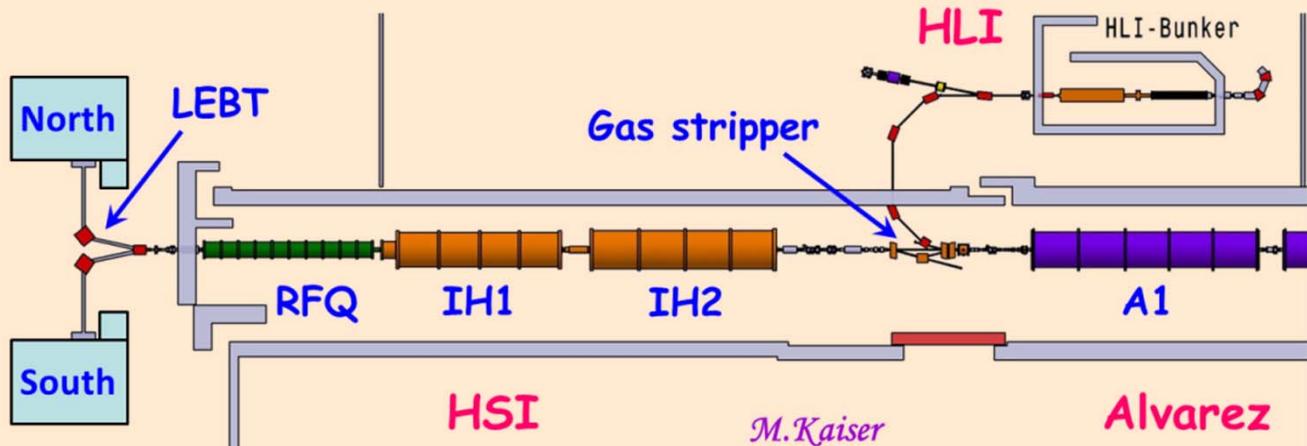
Production of high current ion beams of heavy elements: ^{197}Au , ^{208}Pb and ^{209}Bi

Injection requirements into RFQ (UNILAC):

- Specific ion energy: **2.2 keV/u**
- MAX mass to charge (A/Q): **65**
- Space-charge limit RFQ: **$0.25 \times A/Q$ [mA]**
- Acceptance RFQ: **$\epsilon_{x,y} = 138\pi$ mm·mrad**
- Beam pulse length: **$\geq 120 \mu\text{s}$ (for SIS operation)**

Required charge state for ^{197}Au , ^{208}Pb and ^{209}Bi : **4+**

UNILAC (Universal Linear Accelerator)



Physical properties of the Elements:

Soft and Fusible metals with Low Melting Point

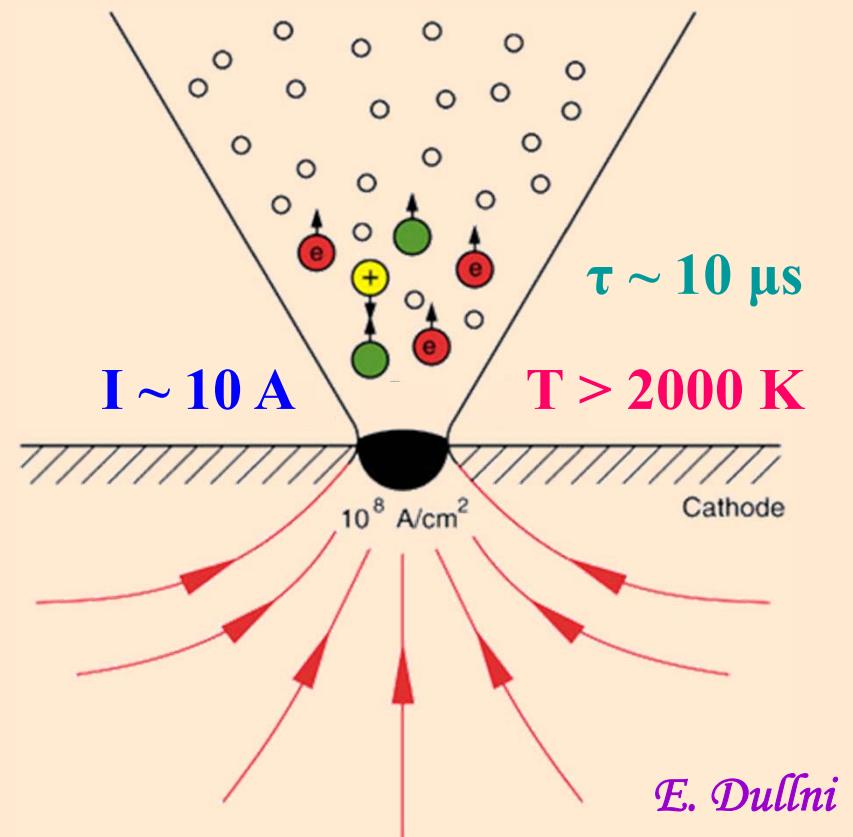
- operation with **Low discharge current**
- danger of **Melting** of the cathode material
- high flux of **Neutrals** from the surface

**Hard to produce
4+ charge state**

Material	Melting point (K)	Electrical resistivity (nΩ·m)	Thermal conductivity (W/m·K)	Temperature (K) for certain Vapor Pressure					
				1 Pa	10 Pa	100 Pa	1 kPa	10 kPa	100 kPa
Ta	3290	131	57.5	3297	3597	3957	4395	4939	5634
U	1405	280	27.5	2325	2564	2859	3234	3727	4402
Pb	601	208	35.3	978	1088	1229	1412	1660	2027
Au	1337	22.14	318	1646	1814	2021	2281	2620	3078
Bi	545	1290	7.97	941	1041	1165	1325	1538	1835



Cathode spot



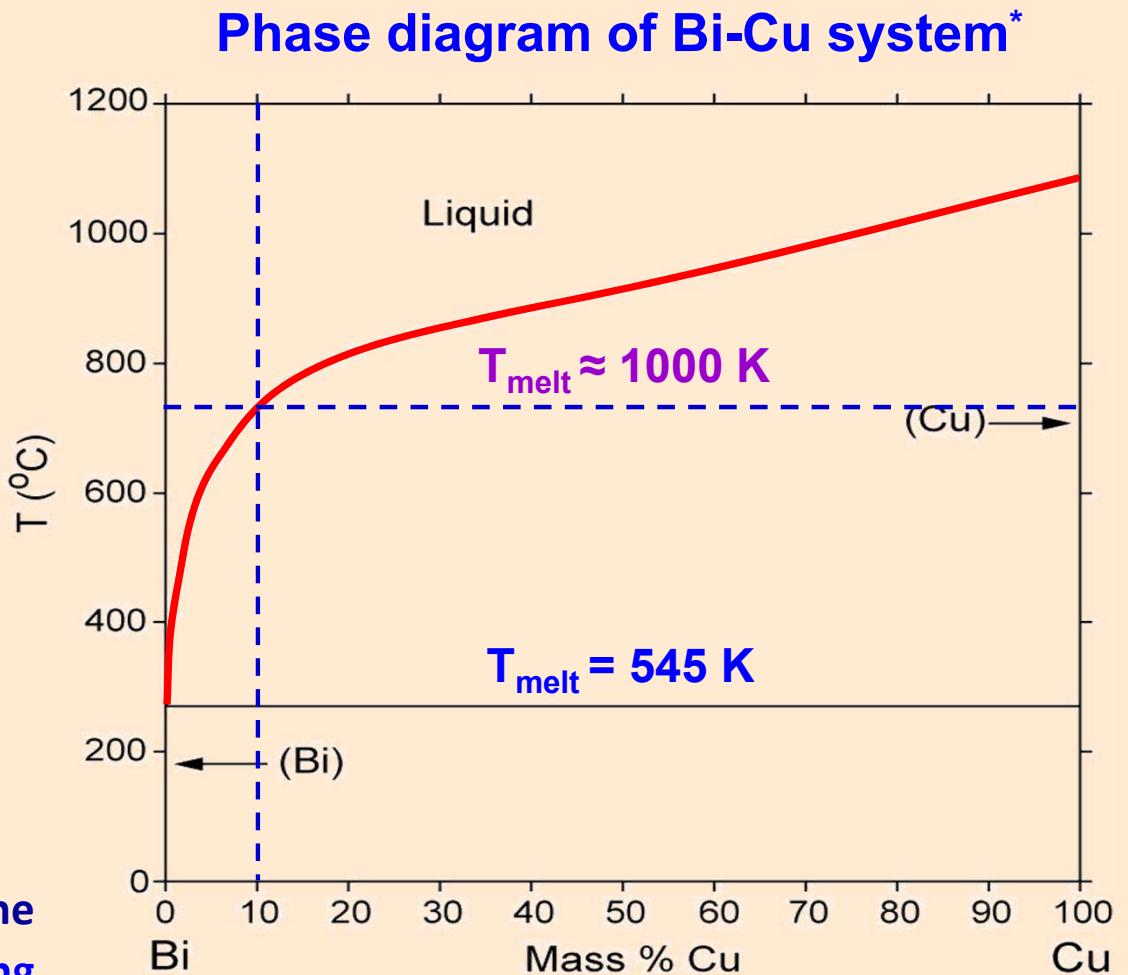
Pb	601	208	35.3	978	1088	1229	1412	1660	2027
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To FIND...

- proper admixed Material
- optimal Ratio between desired and admixed
- admixed should NOT intersect by M/Q with desired

Solution:

The production of neutrals during the discharge pulse can be reduced by changing the physical properties of the cathode material. This can be achieved by using an alloy or a mixture of the desired material with a more refractory metal.



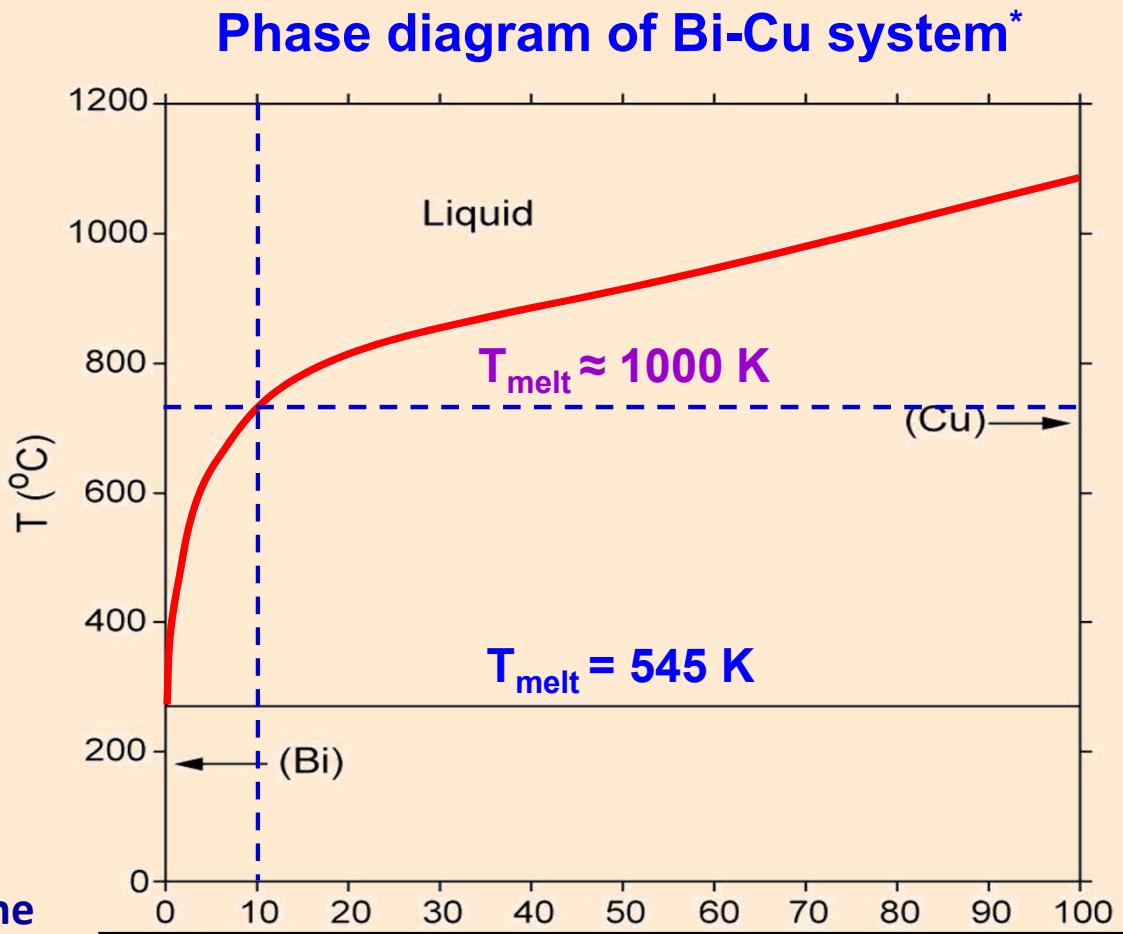
*Calculated Phase Diagram from NIST, Metallurgy Division,
Material Measurement Laboratory

To FIND...

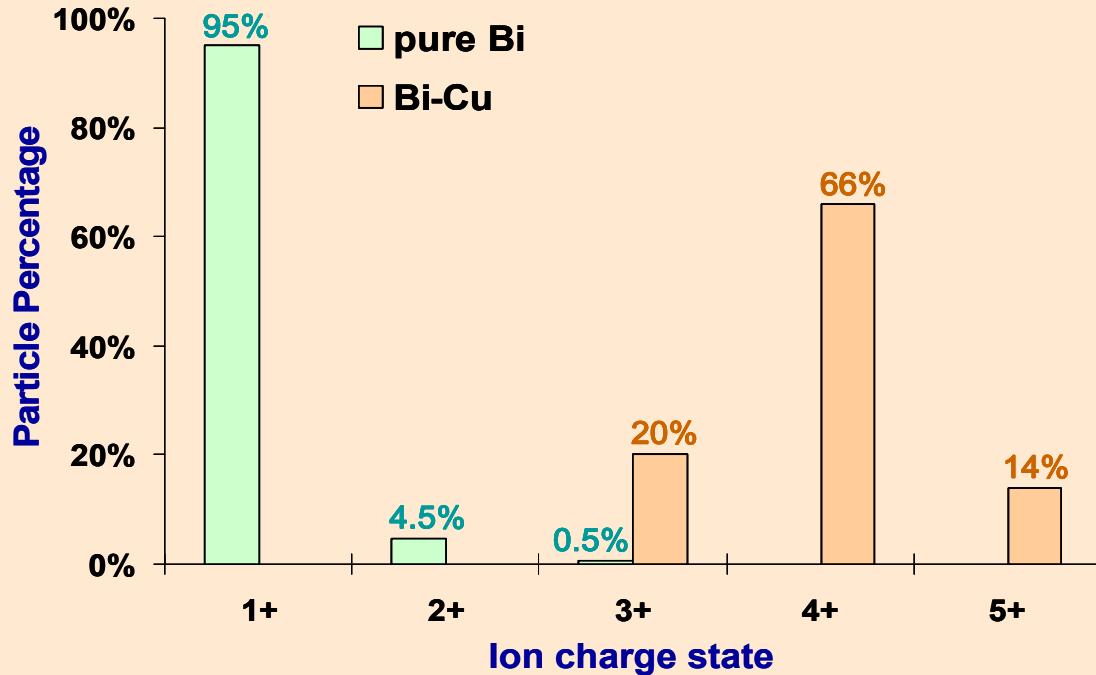
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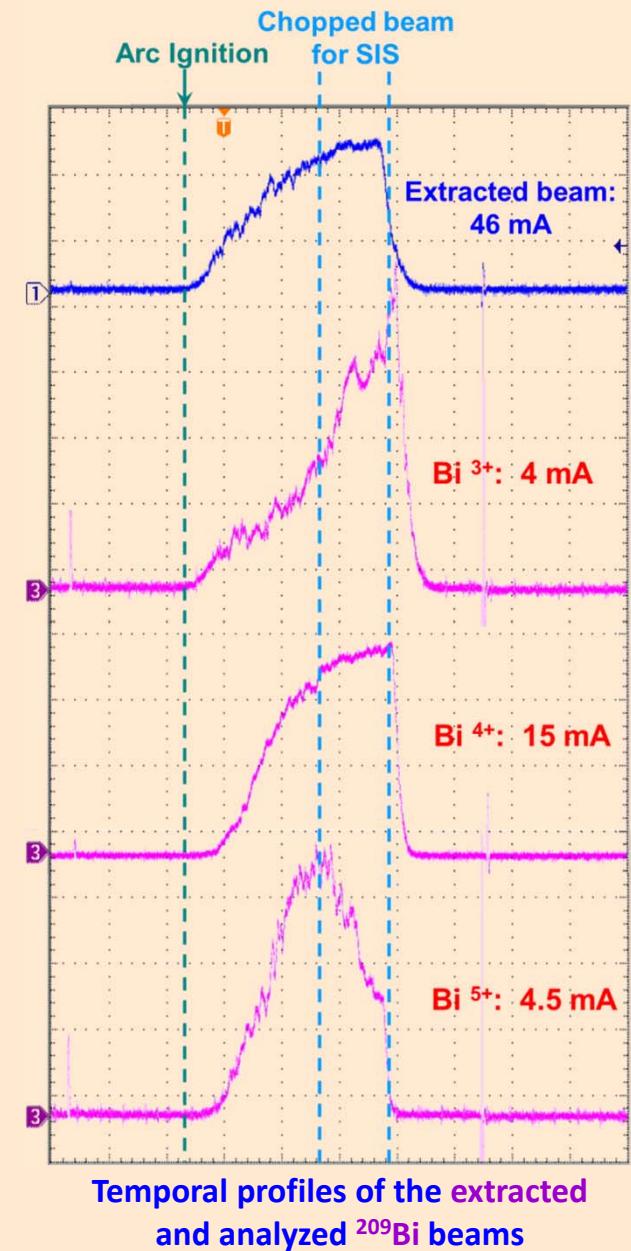
	Temperature (K) for certain Vapor Pressure					
	1 Pa	10 Pa	100 Pa	1 kPa	10 kPa	100 kPa
Bi	941	1041	1165	1325	1538	1835
Cu	1509	1661	1850	2089	2404	2834

**pure Bi**

- discharge currents below 500 A
- melting of the material at higher currents
- **NO 4+ charge state was observed**

Bi-Cu

- admixture of Cu b/w 8% and 15%
- discharge currents up to 900 A
- peak current of $^{209}\text{Bi}^{4+}$ in front of the RFQ: **15 mA**
- stable operation with good pulse-to-pulse repetition



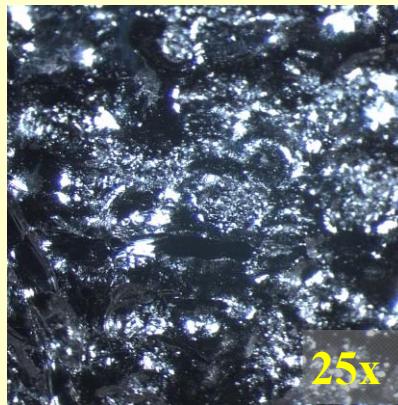
Composition: Bi – Cu (15% Wt.)

Deposited energy: 90 kJ

Time in operation: 5 minutes

Performance: BAD

- inappropriate pulse structure (NO 100 μ s flat top)
- noisy operation
- bad pulse-to-pulse repetition



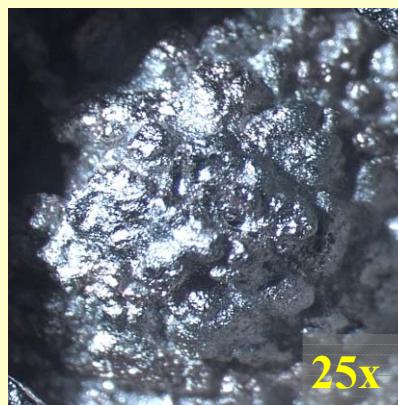
Composition: Bi – Cu (15% Wt.)

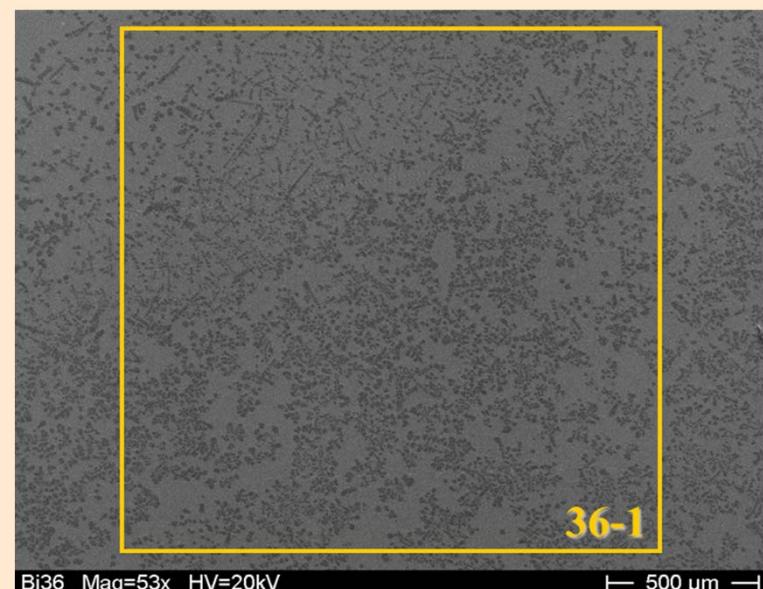
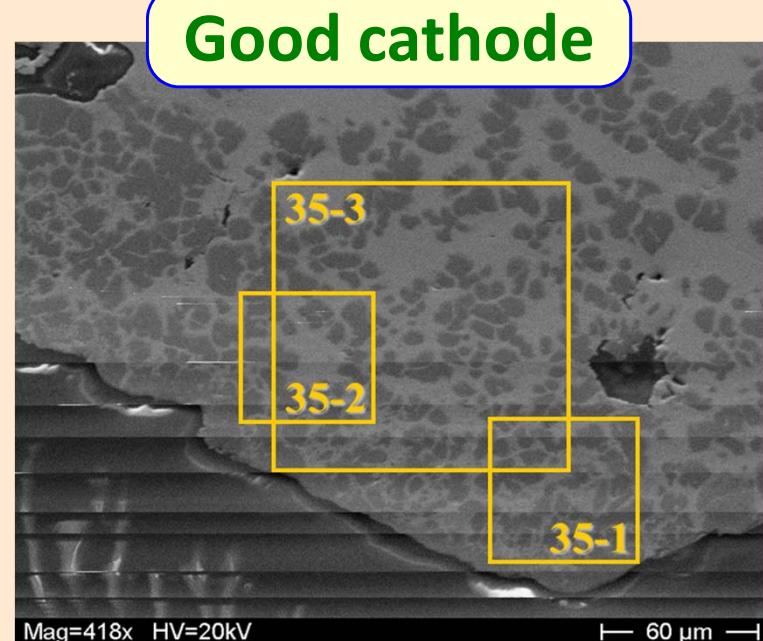
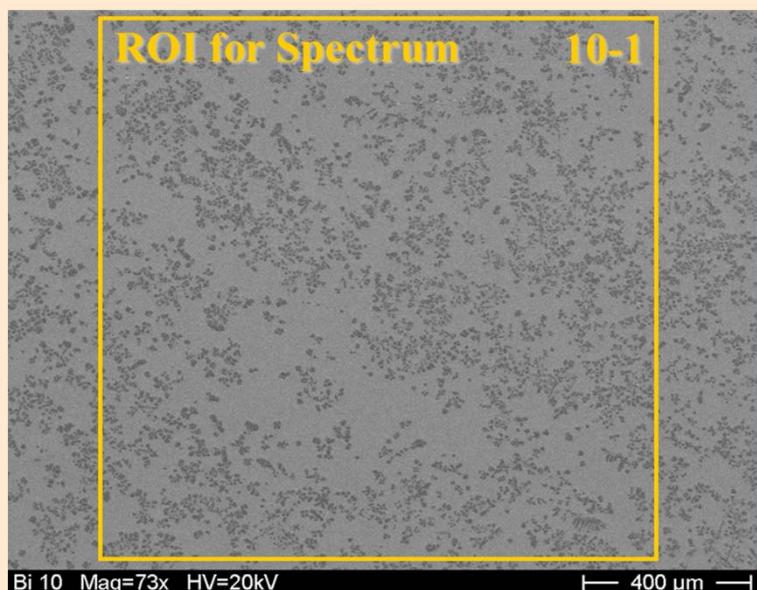
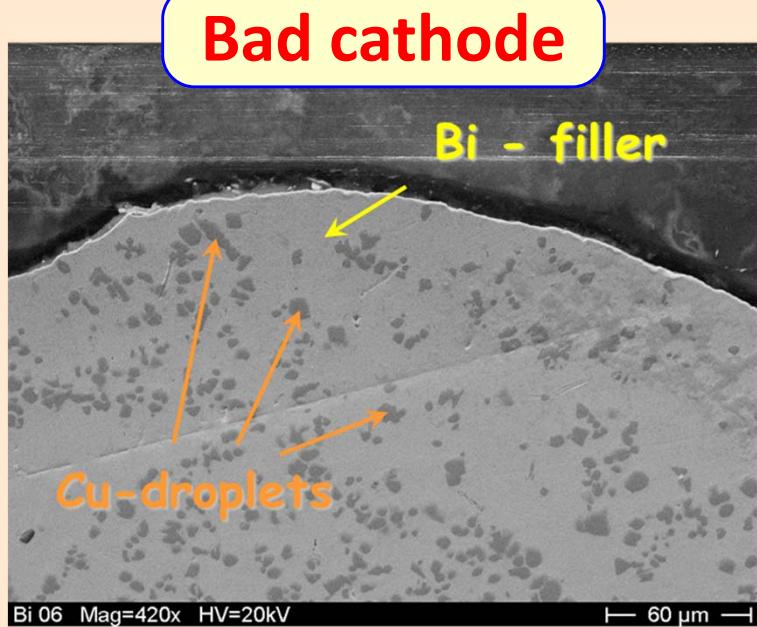
Deposited Energy: 2.27 MJ

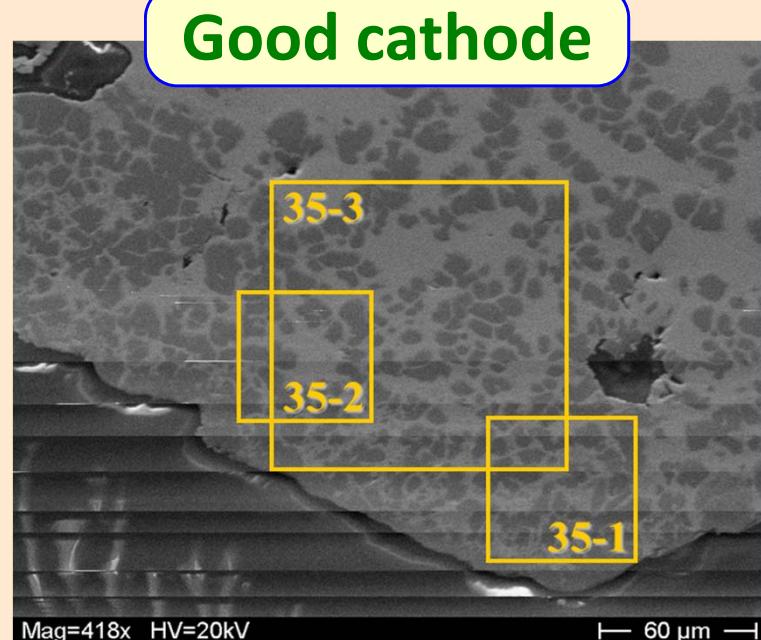
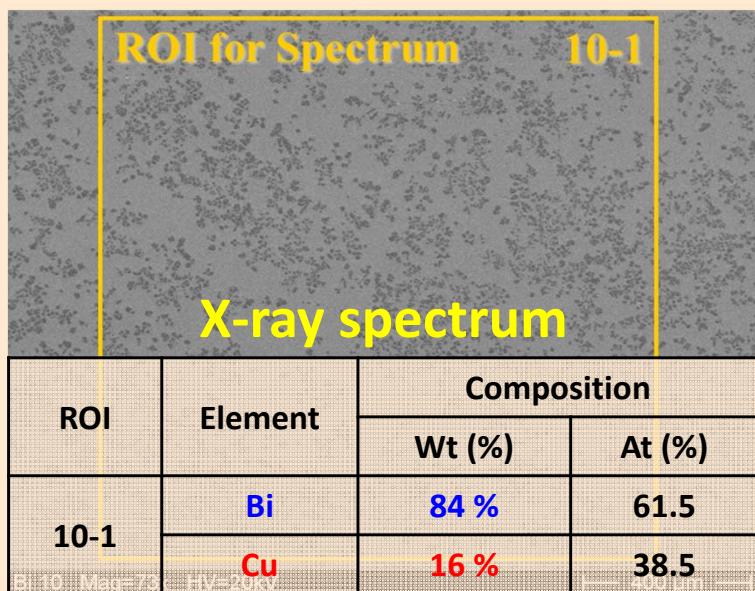
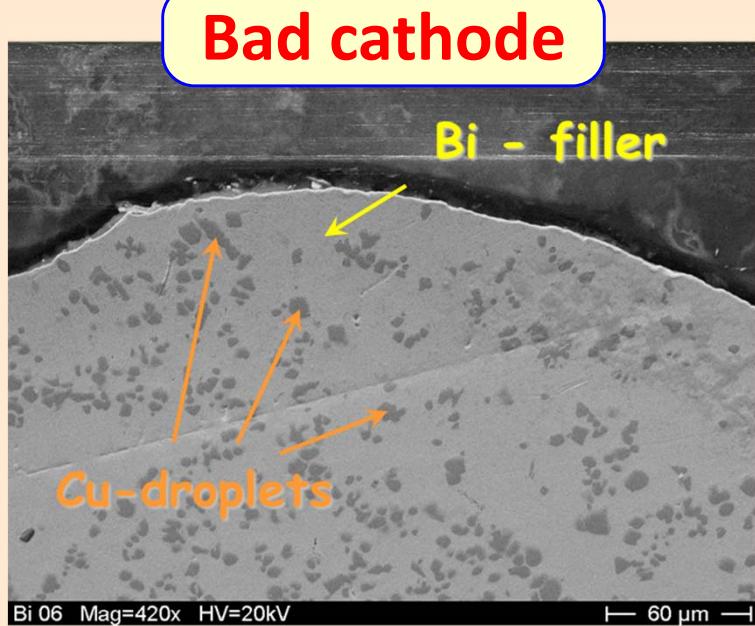
Time in operation: 41 hours

Performance: GOOD

- optimal pulse structure (with flat top at the end)
- stable operation
- good pulse-to-pulse repetition







X-ray spectrum

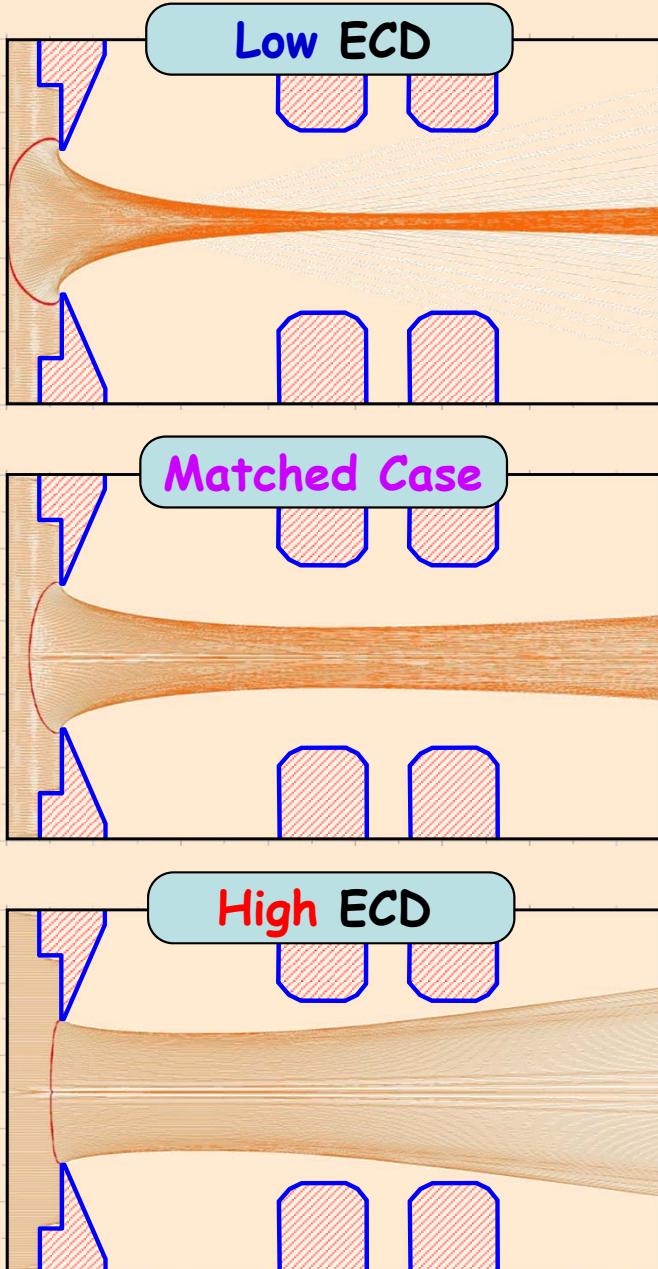
ROI	Element	Composition	
		Wt (%)	At (%)
35-1	Bi	50.3	23.5
	Cu	49.7	76.5
35-2	Bi	56.9	28.6
	Cu	43.1	71.4
35-3	Bi	63.8	34.9
	Cu	36.2	65.1
36-1	Bi	83	59.7
	Cu	17	40.3

Bi 06 Mag=550x HV=20kV

	Tested compositions	Duty cycle	Pulse length	Total beam current	Analysed beam current (4+)
Au	Au – Cr (10; 20; 50; 75%)	0.5 Hz	0.25 ms	55 mA	6 mA
	Au – Pd (10% Wt.)	1 Hz	0.3 ms	50 mA	4 mA
	Au – Ta (50% Wt.)	2 Hz	0.3 ms	50 mA	< 1 mA
	Au – Ti (5; 10% Wt.)				
	Au – Zr (20% Wt.)				
	Au – Cr (50% Wt.)				
Pb	Pb – Cu (40; 60% Wt.)	0.25 Hz	0.35 ms	45 mA	6 mA
	Pb – Cu (40% Wt.)	0.5 Hz	0.25 ms	45 mA	6 mA
		2 Hz	-	-	-
Bi	Bi – Cu (5; 10; 15; 30; 40% Wt.)	0.5 Hz	0.4 ms	40 mA	12 mA
	Bi – Cu (40% Wt.)	1 Hz	0.25 ms	40 mA	8 mA
		2 Hz	-	-	-

	Tested compositions	Duty cycle	Pulse length	Total beam current	Analysed beam current (4+)
Au	Au – Cr (10; 20; 50; 75%)	0.5 Hz	0.25 ms	55 mA	6 mA
	Au – Pd (10% Wt.)	1 Hz	0.3 ms	50 mA	4 mA
	Au – Ta (50% Wt.)				
	Au – Ti (5; 10% Wt.)				
	Au – Zr (20% Wt.)				
	Au – Cr (50% Wt.)	2 Hz	0.3 ms	50 mA	< 1 mA
Pb	<p>Conclusions:</p> <ul style="list-style-type: none"> ➤ Concept of composite materials in cathodes works quite well ➤ Conditioning effect is partially understood ➤ The micro-structure plays a very important role ➤ Several successful beamtimes have been performed 				
Bi					

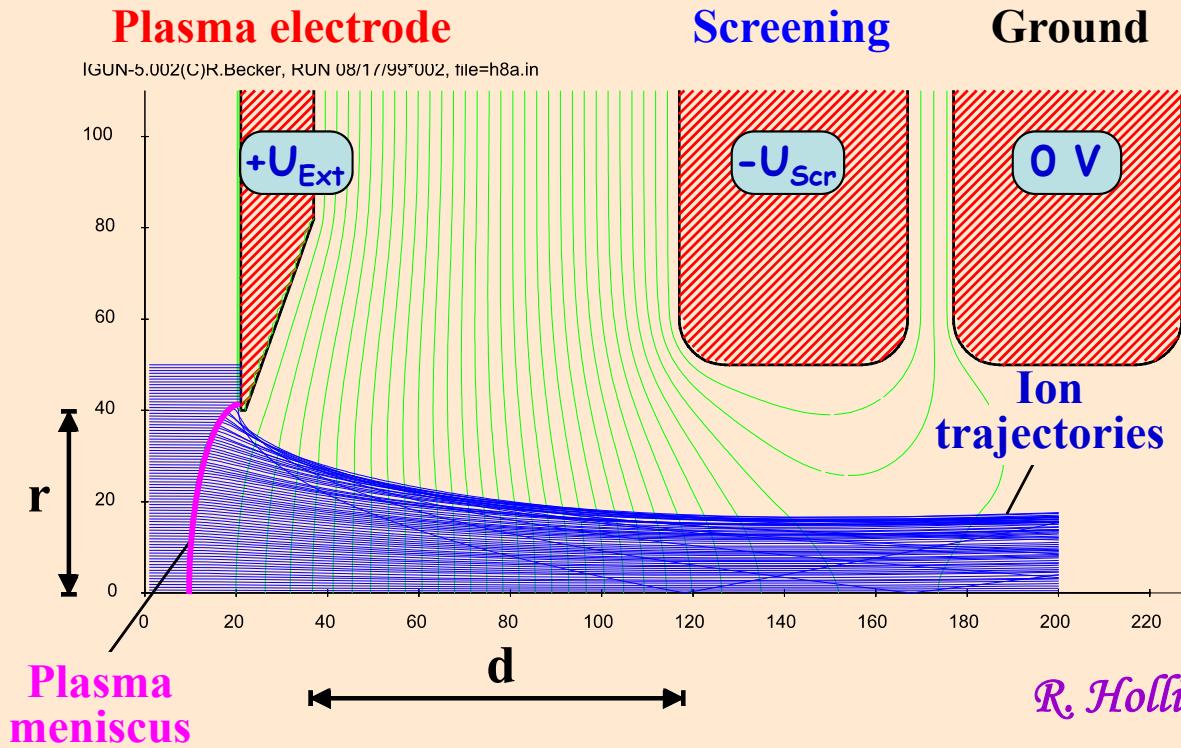
Increasing the beam brilliance for intense $^{238}\text{U}^{4+}$ ion beam



Child-Langmuir Law:

$$j_{CL} = \frac{4}{9} \epsilon_0 \cdot \sqrt{\frac{2e\zeta}{m}} \cdot \frac{1}{\sqrt{d}} \cdot E^{3/2} \quad S = \frac{r}{d} \quad E = \frac{U_{Ext}}{d}$$

$$I_{CL} = \frac{4}{9} \pi \cdot \epsilon_0 \cdot \sqrt{\frac{2e\zeta}{m}} \cdot S^2 \cdot U_{Ext}^{3/2}$$

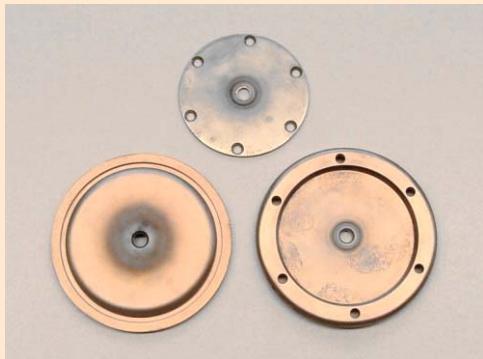


R. Hollinger

Triode extraction systems:

1 hole

$\varnothing 4 \div 8$ mm



7 holes

$\varnothing 4 \div 6$ mm



13 holes

$\varnothing 3$ mm



19 holes

$\varnothing 2 \div 3$ mm



Plasma - Screening
distance:

$r = 3$ mm

Aspect Ratio:

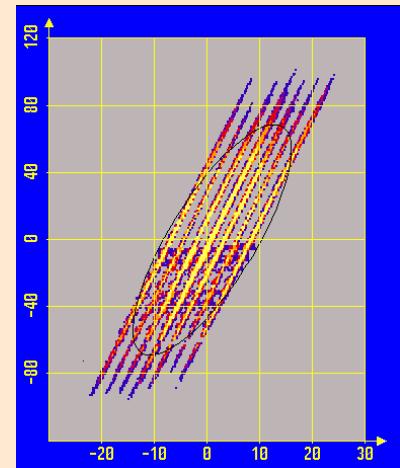
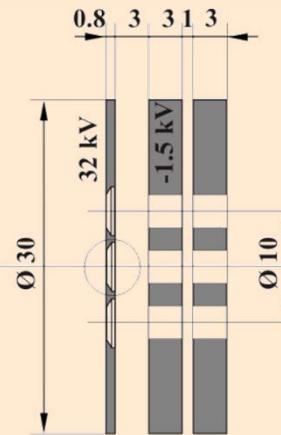
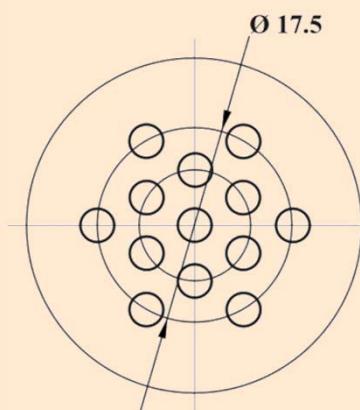
$S = 0.5$

MAX Ext. Voltage:

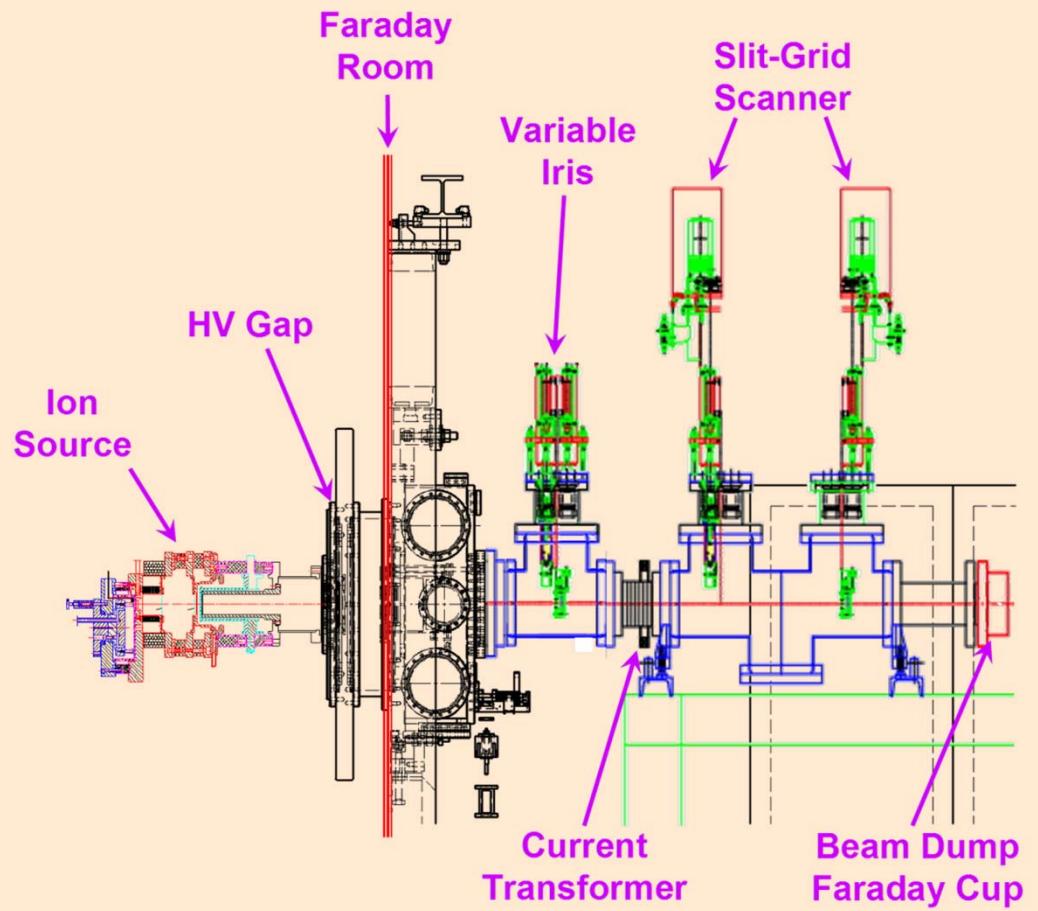
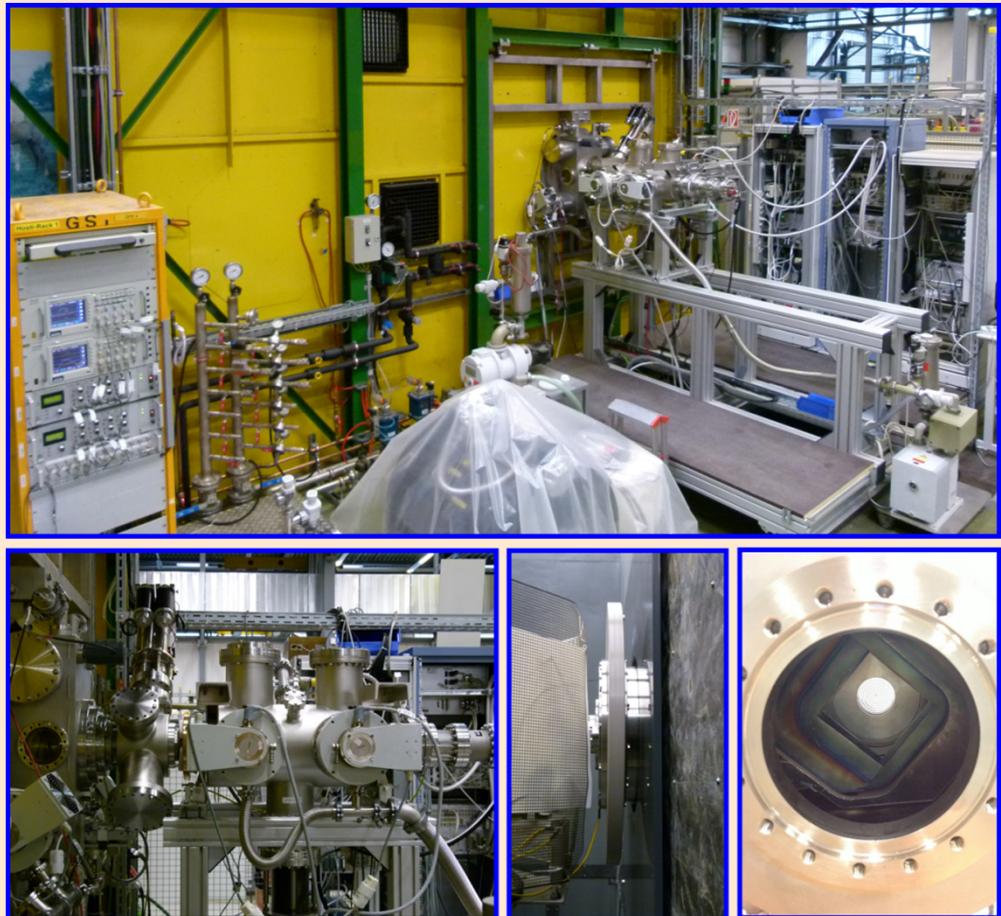
35 kV

Emission Area:

92 mm²



High current test injector – HOSTI

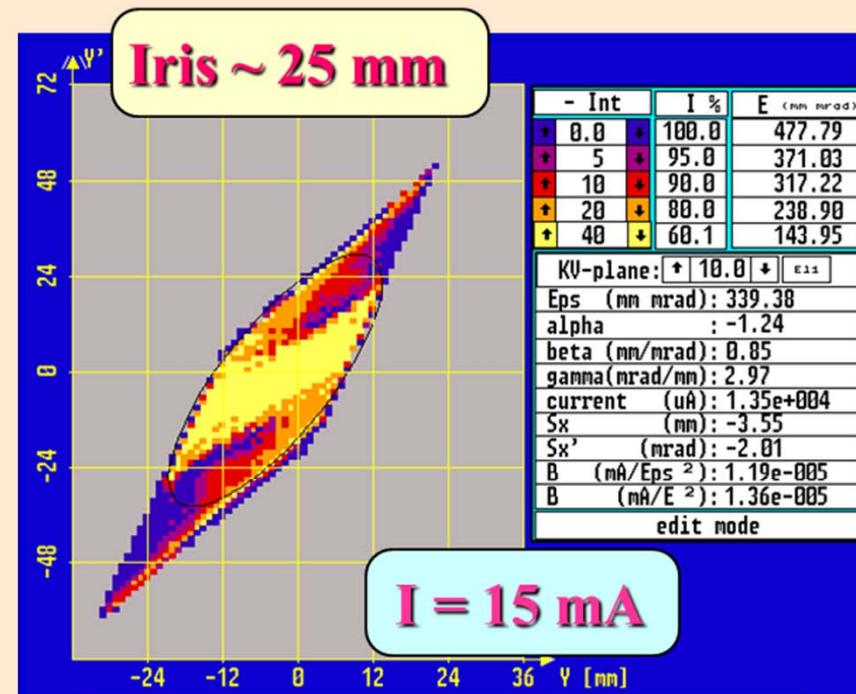


Optimization of the beam core by optimization of IS parameters

$$I_{Arc} = 480 \text{ A}$$

$$U_{Ext.} = 19 \text{ kV} \quad U_{PA} = 114 \text{ kV}$$

$$I_{Ext.} = 120 \text{ mA} \quad I_{PA} = 100 \text{ mA}$$

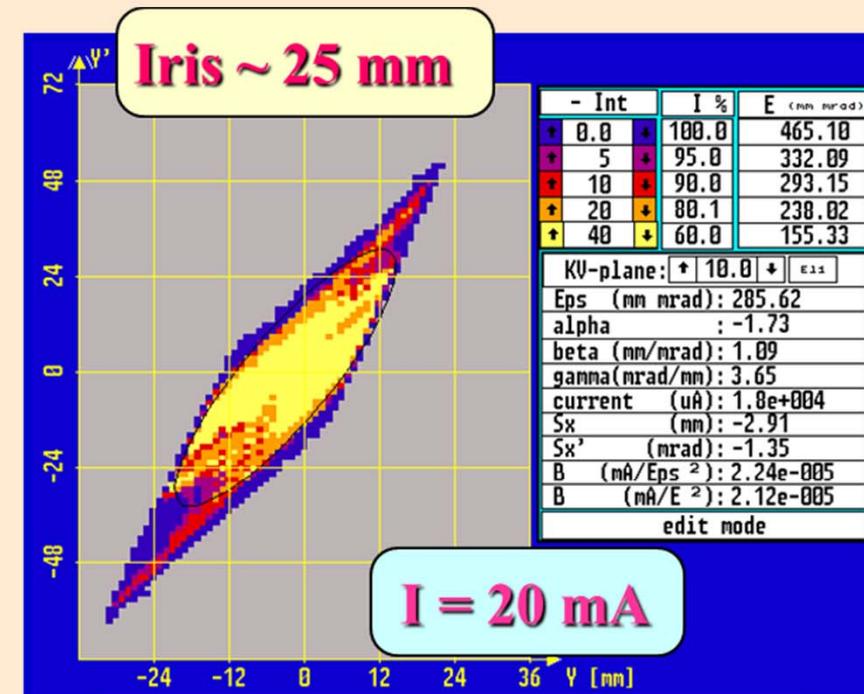


$$\epsilon_{RMS} (90\%) = 339 \text{ mm} \cdot \text{mrad}$$

$$I_{Arc} = 480 \text{ A}$$

$$U_{Ext.} = 17 \text{ kV} \quad U_{PA} = 116 \text{ kV}$$

$$I_{Ext.} = 110 \text{ mA} \quad I_{PA} = 75 \text{ mA}$$



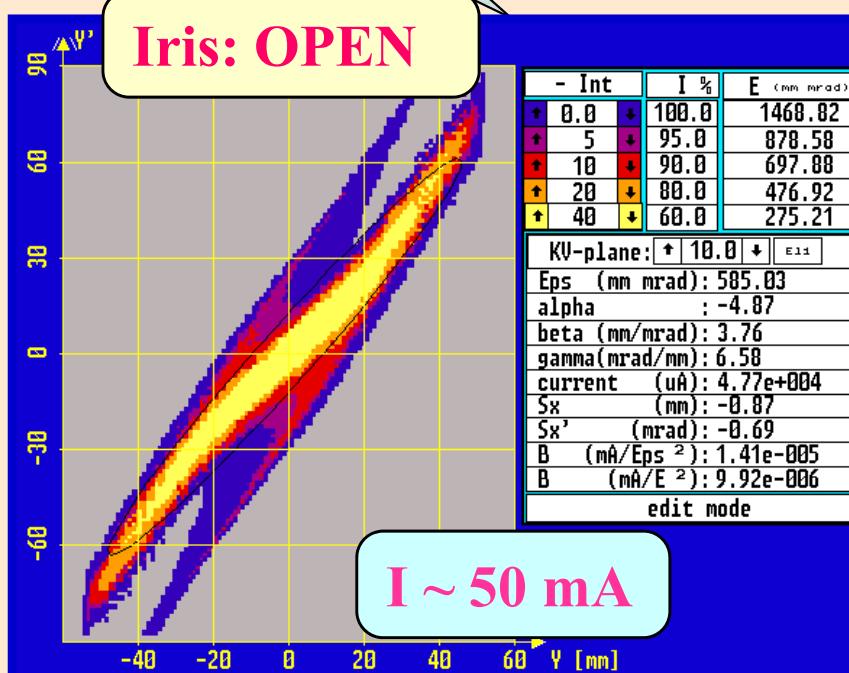
$$\epsilon_{RMS} (90\%) = 286 \text{ mm} \cdot \text{mrad}$$

Influence of electrostatic beam compression in the PA-gap

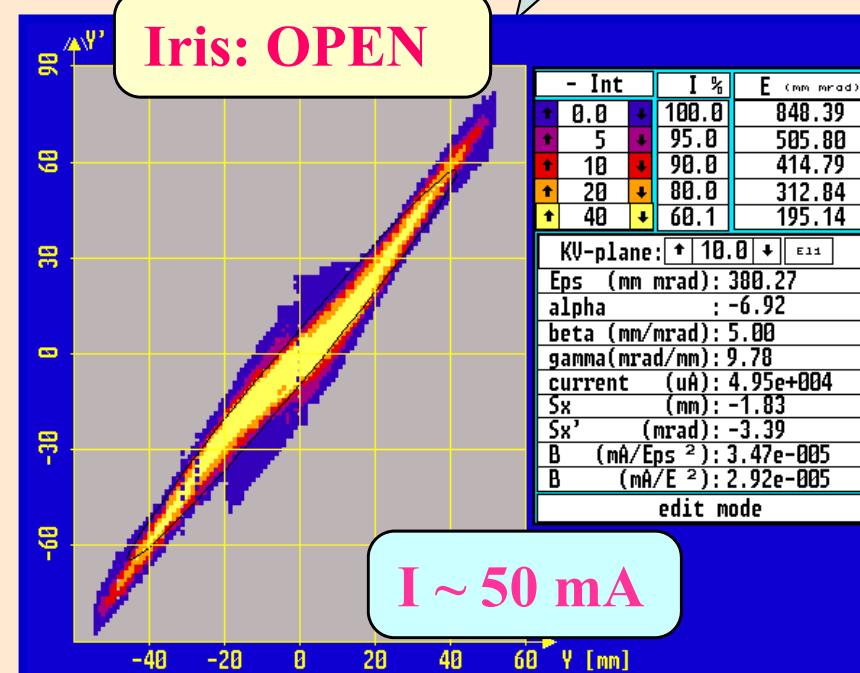
ø60 mm

HV-electrode:

ø40 mm



$$\epsilon_{\text{RMS}} (90\%) = 585 \text{ mm} \cdot \text{mrad}$$



$$\epsilon_{\text{RMS}} (90\%) = 380 \text{ mm} \cdot \text{mrad}$$

New extraction system for uranium:

Plasma - Screening distance:	$r = 4 \text{ mm}$
Aspect Ratio:	$S = 0.5$
MAX Ext. Voltage:	42 kV
Emission Area:	88 mm^2

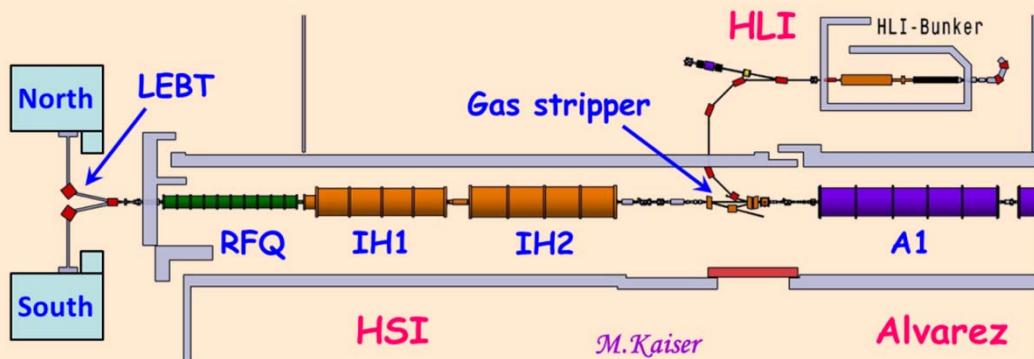
7 holes, $\phi 4 \text{ mm}$



New intensity record for Uranium beam

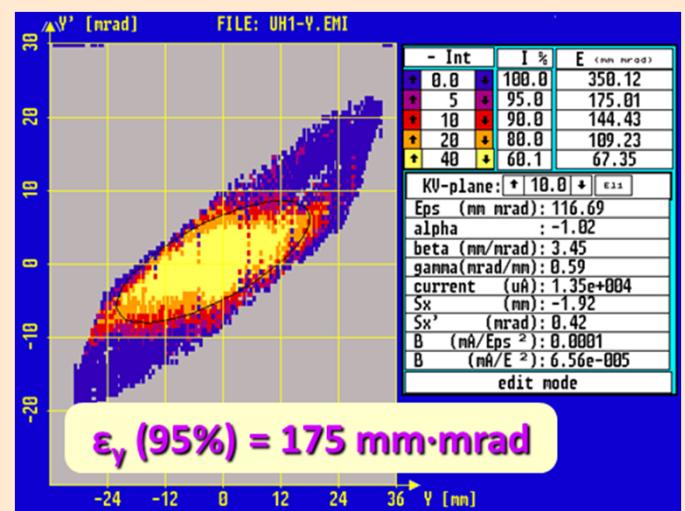
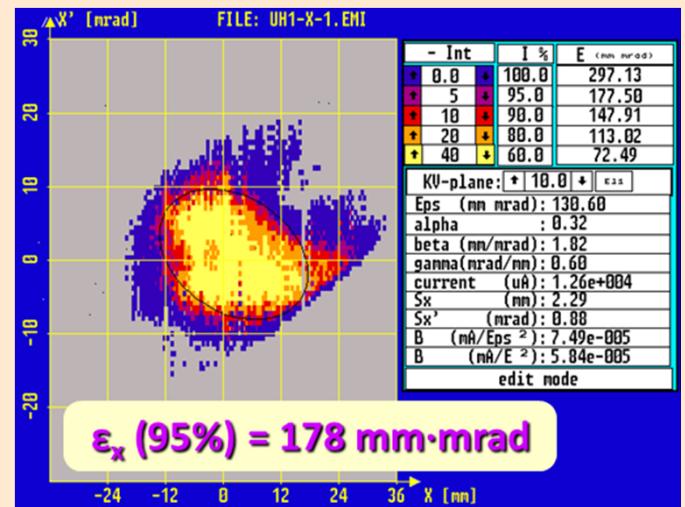
Ion beam	Position	Current transformer	Beam current	
Unanalyzed	Ion source	Extraction	130 mA	
	LEBT	GUL4DT4	43 mA	
		GUL5DT5	36 mA	
	HSI	GUL5DT8	16 mA	
U^{4+}		GUH1DT1	15 mA	
		GUH4DT4	7 mA	
U^{29+}	Post strip.	GUS4DT6	11 mA	

W.Barth et al., Phys. Rev. AB, 20 (5), art. no. 050101 (2017)



$2.3 \cdot 10^{12}$ part.
in 100 μ s
 $2.4 \cdot 10^{11}$ part.

Emittance in front of the RFQ



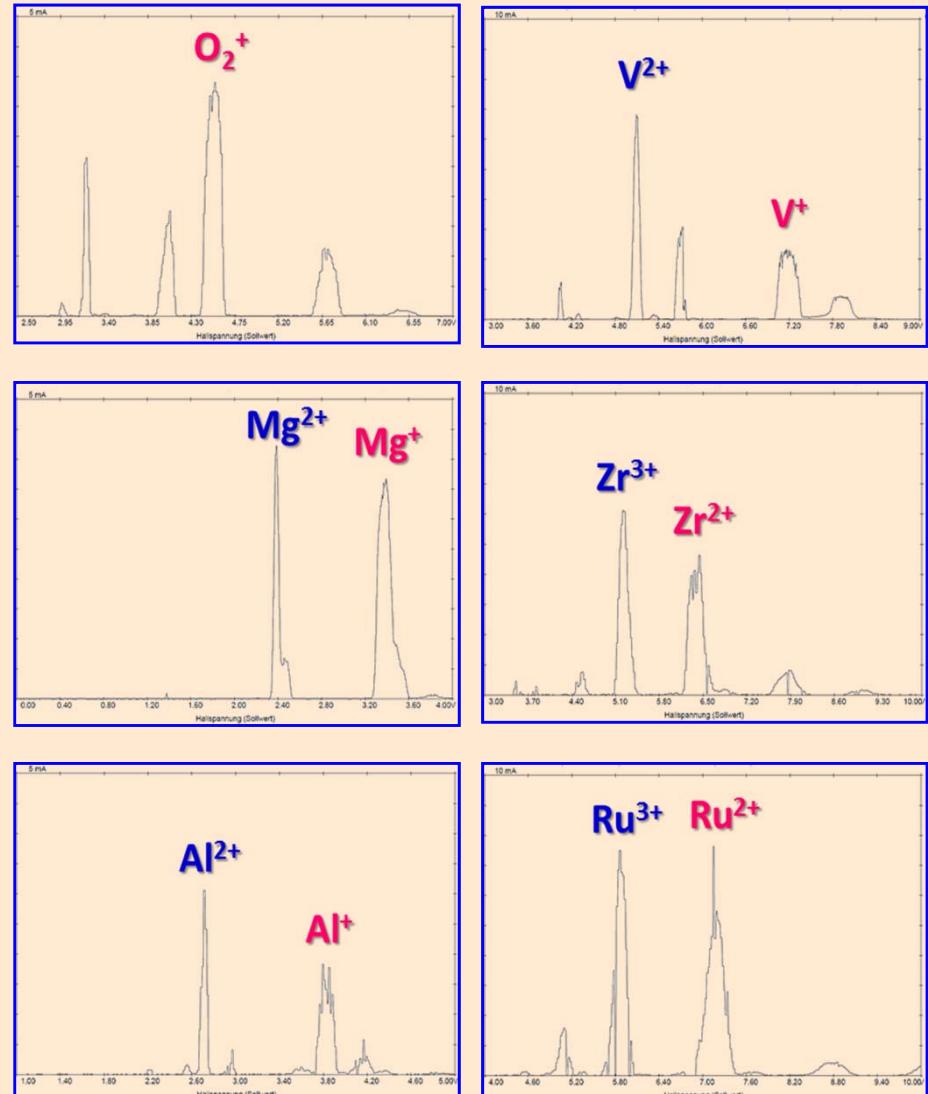
Development of new projectiles in middle-heavy region

Element	Nat. isotopes	Desired isotopes	MIN charge state	Aux. gas/ material	Toxicity	T _{Melt.} (K)	Vapor pressure at ~1800 K	Achieved with MEVVA
O ₂	16-O: 99.76% 18-O: 0.2%	¹⁸ O	1+	Mg or Al	-	-	-	I _{DT8} = 3.5 mA (³⁶ O ₂ ⁺)
Mg	24-Mg: 78.99% 25-Mg: 10.00% 26-Mg: 11.01%	²⁵ Mg ²⁶ Mg	1+	O ₂	-	923	> 100 kPa	I _{DT8} = 2.5 mA (²⁴ Mg ²⁺)
Al	27-Al: 100%	²⁷ Al	1+	O ₂	-	933	100 Pa	-
Si	28-Si: 92.23% 30-Si: 3.1%	³⁰ Si	1+		-	1687	< 1 Pa	-
V	51-V: 99.75%	⁵¹ V	1+		-	2183	< 1 Pa	-
Zn	64-Zn: 48.6% 66-Zn: 27.9% 68-Zn: 18.8% 70-Zn: 0.6%	⁷⁰ Zn	2+	-	-	693	> 100 kPa	from ECR only
Mo	92-Mo: 14.84% 95-Mo: 15.92% 96-Mo: 16.68% 97-Mo: 9.55% 98-Mo: 24.13% 100-Mo: 9.63%	⁹² Mo ⁹⁵ Mo ⁹⁷ Mo ¹⁰⁰ Mo	2+	-	-	2896	< 1 Pa	-
Ru	96-Ru: 5.52% 99-Ru: 12.7% 100-Ru: 12.6% 101-Ru: 17.0% 102-Ru: 31.6% 104-Ru: 18.7%	⁹⁶ Ru	2+	-	-	2607	< 1 Pa	-
Zr	90-Zr: 51.45% 91-Zr: 11.22% 92-Zr: 17.15% 94-Zr: 17.38% 96-Zr: 2.8%	⁹⁶ Zr	2+	-	-	2128	< 1 Pa	-
Sn	112-Sn: 0.97% 114-Sn: 0.66% 116-Sn: 14.54% 118-Sn: 24.22% 120-Sn: 32.58% 122-Sn: 4.63% 124-Sn: 5.79%	¹¹² Sn ¹¹⁴ Sn ¹¹⁶ Sn ¹²² Sn ¹²⁴ Sn	2+	-	-	505	100 Pa	from ECR only
Nd	142-Nd: 27.2% 143-Nd: 12.2% 144-Nd: 23.8% 146-Nd: 17.2%	¹⁴² Nd	3+	-	-	1297	10-20 Pa	I _{DT8} = 3.5 mA (gesamt) 1.5 mA (¹⁴² Nd ³⁺)

Recent results:

Element	Provided ions	Duty cycle	Beam current	Auxiliary material
O ₂	³² O ₂ ⁺	2 Hz	3.5 mA	V-cathode
Mg	²⁴ Mg ⁺	2 Hz	3.5 mA	He-gas
Al	²⁷ Al ⁺	2 Hz	2 mA	O ₂ -gas
V	⁵¹ V ⁺	2.7 Hz	2.3 mA	O ₂ -gas
	⁵¹ V ²⁺	2.7 Hz	4.5 mA	—
Fe	⁵⁶ Fe ²⁺	1 Hz	8 mA	—
Zr	⁹⁰ Zr ²⁺	1 Hz	8 mA	N ₂ -gas
	⁹⁰ Zr ³⁺	2 Hz	6 mA	He-gas
Mo	⁹⁸ Mo ³⁺	2 Hz	5 mA	He-gas
Ru	¹⁰² Ru ²⁺	2 Hz	9 mA	He-gas
	¹⁰² Ru ³⁺	2 Hz	5 mA	—
Ag	¹⁰⁷ Ag ²⁺	1 Hz	10 mA	—

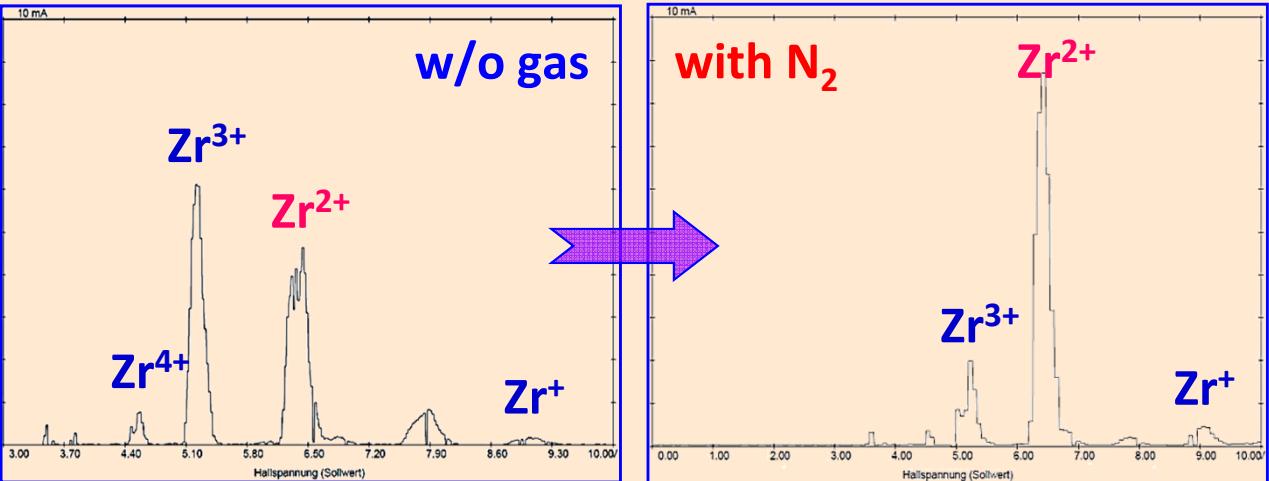
Mass-spectra of extracted ion beams



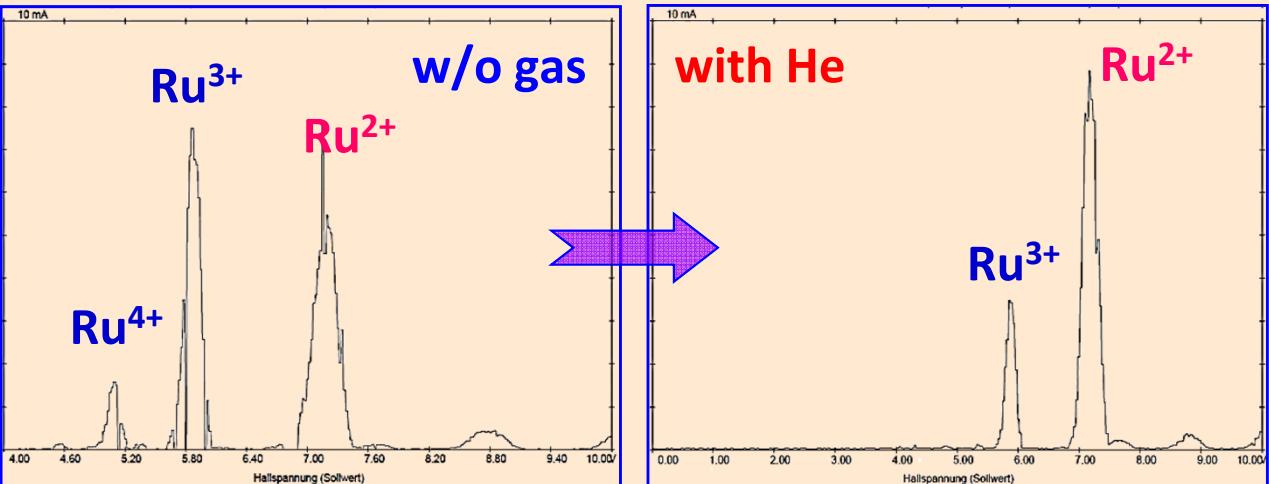
Using proper auxiliary gas

- optimal charge-state distribution
- higher particle current
- lower beam pulse noisiness
- better pulse-to-pulse stability
- better performance by higher duty cycle
- lower rate of ignition failures

Influence of the auxiliary gas on the charge state distribution in plasma



Periodic Table of the Elements																	
1 H 1.01	2 Be 9.01	3 Li 6.94	4 B 10.81	5 C 12.01	6 N 14.01	7 O 16.00	8 F 19.00	9 Ne 20.18	10 Ne 20.18	11 Na 22.99	12 Mg 24.31	13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 51.99	24 Cr 54.94	25 Mn 55.95	26 Fe 56.99	27 Co 58.93	28 Ni 63.55	29 Cu 65.38	30 Zn 69.72	31 Ga 72.63	32 Ge 74.92	33 As 78.97	34 Se 79.90	35 Br 80.80	36 Kr 83.80
37 Rb 84.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.81	42 Mo 95.95	43 Tc 98.91	44 Ru 101.07	45 Rh 102.91	46 Pd 104.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.6	53 I 126.90	54 Xe 131.25
55 Cs 132.91	56 Ba 137.33	57 Hf 178.49	58 Ta 180.85	59 W 183.84	60 Re 186.21	61 Os 190.23	62 Ir 192.22	63 Pt 195.99	64 Au 200.59	65 Hg 204.38	66 Tl 207.2	67 Pb 208.98	68 Bi (208.00)	69 Po 209.99	70 At 222.02	71 Rn 222.02	
87 Fr 223.02	88 Ra 226.03	89 Rf (261)	90 Db (262)	91 Sg (264)	92 Bh (264)	93 Hs (269)	94 Mt (268)	95 Ds (269)	96 Rg (272)	97 Cn (277)	98 Uut unknown	99 Fl unknown	100 Uup unknown	101 Lv unknown	102 Uus unknown	103 Uuo unknown	
57 La 138.91	58 Ce 140.12	59 Pr 144.24	60 Nd 144.91	61 Pm 150.36	62 Sm 151.96	63 Eu 157.25	64 Gd 158.93	65 Tb 162.50	66 Dy 164.93	67 Ho 167.26	68 Er 169.93	69 Tm 173.06	70 Yb 174.97	71 Lu 174.97			
89 Ac 227.03	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu 244.06	95 Am 243.06	96 Cm 247.07	97 Bk 247.07	98 Cf 251.08	99 Es (254)	100 Fm 257.10	101 Md 258.1	102 No 259.10	103 Lr (262)			



Outlook for further development of VARIS

Next important step:

Increasing the operation duty cycle from 1 to 2.7 Hz for all elements

Goal:

To provide the maximum availability of high current ion beams for future FAIR experiments.

- Light and middle-heavy elements ($Q \leq 3+$): NO difficulties
 - Heavy elements ($Q = 4+$): Problematic

Inhibiting factors:

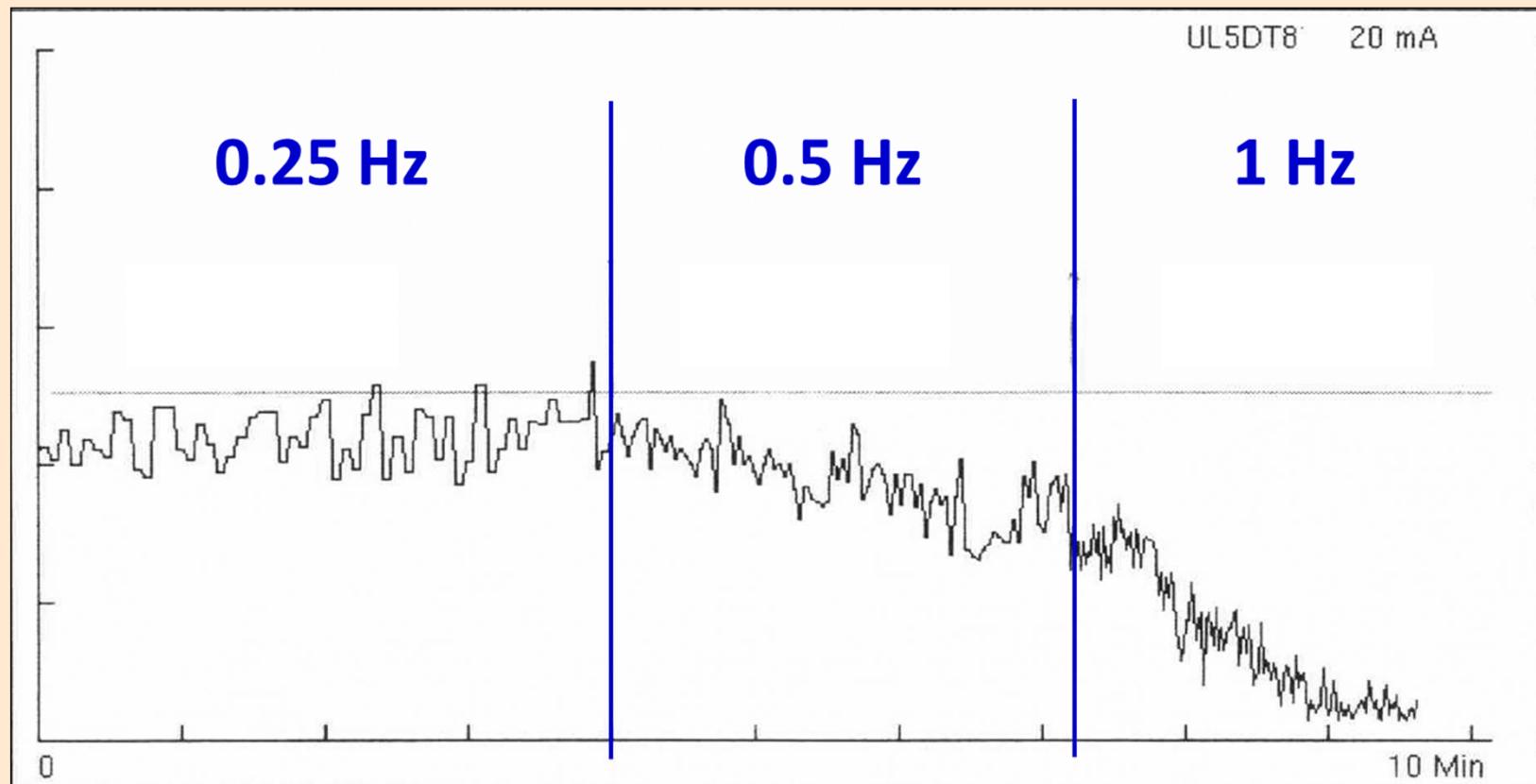
- High flux of neutrals from the surface
- Shifting of the spectrum to the lower charge states
- Problems with arc ignition
- Sparking in the extraction system

Possible solutions:

- Reduce the thermal load of the cathode
 - short pulse operation
- Enhance the physical properties of the cathode material
 - composite materials: U-W(10%)
- Improve cathode cooling

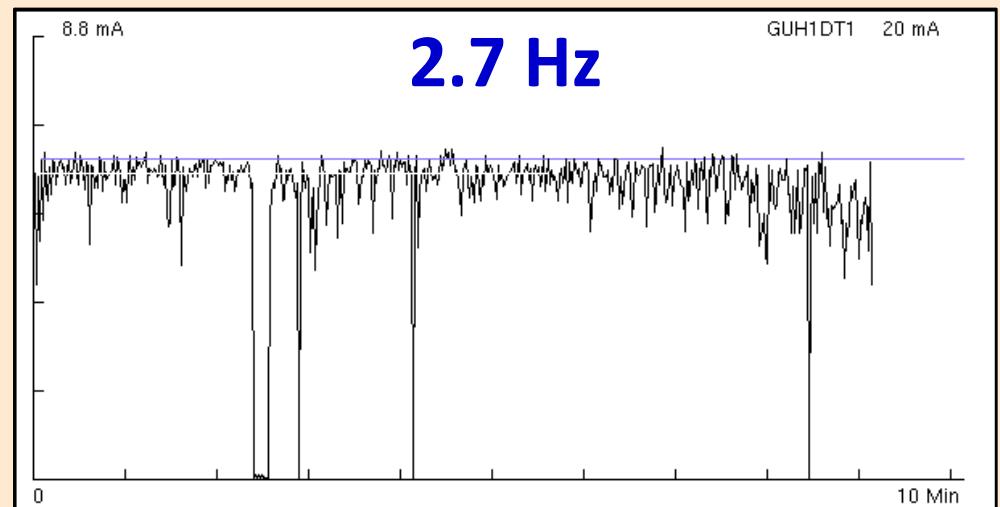
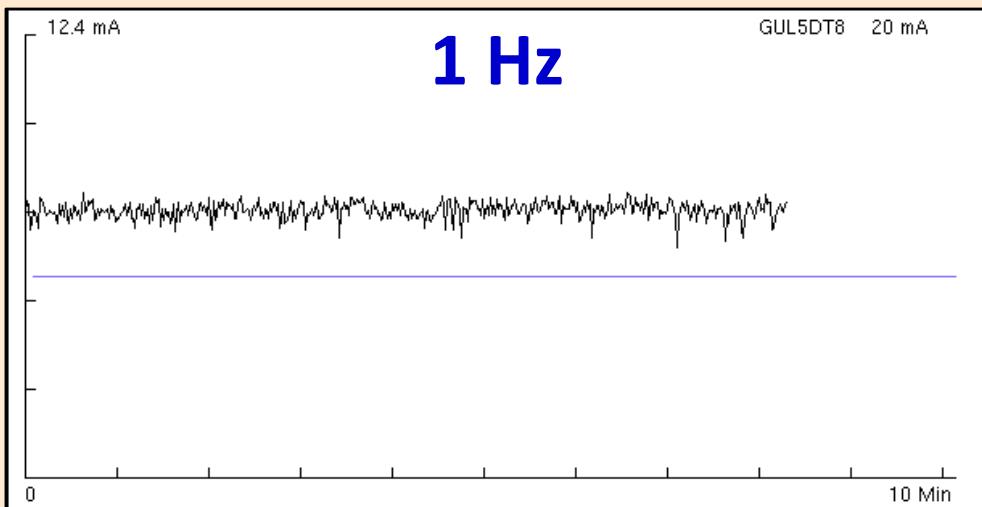
Inhibiting factors:

VARIS performance with Bi by increasing
the duty cycle (pulse length = 0.5 ms)



Inhibiting factors:

**VARIS performance with U by increasing
the duty cycle (pulse length = 0.5 ms)**



Progress over the last 7 years

Periodic table of the elements

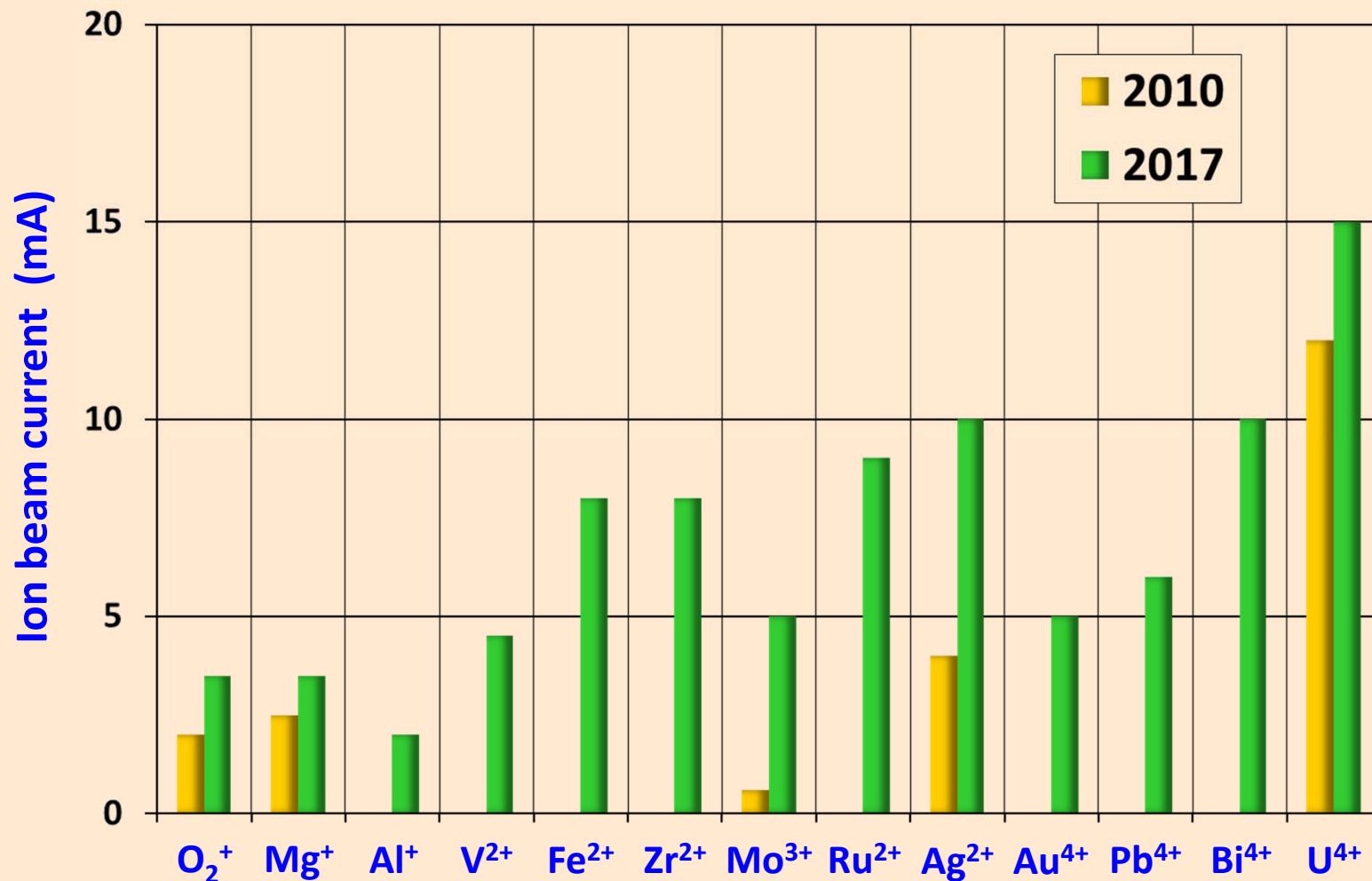
Ion species provided at GSI

Total: 33

HC ion sources: 25

57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm 144.91	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.06	71 Lu 174.97
89 Ac 227.03	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu 244.06	95 Am 243.06	96 Cm 247.07	97 Bk 247.07	98 Cf 251.08	99 Es [254]	100 Fm 257.10	101 Md 258.1	102 No 259.10	103 Lr [262]

Progress over the last 7 years



*Thank you
for your Attention*