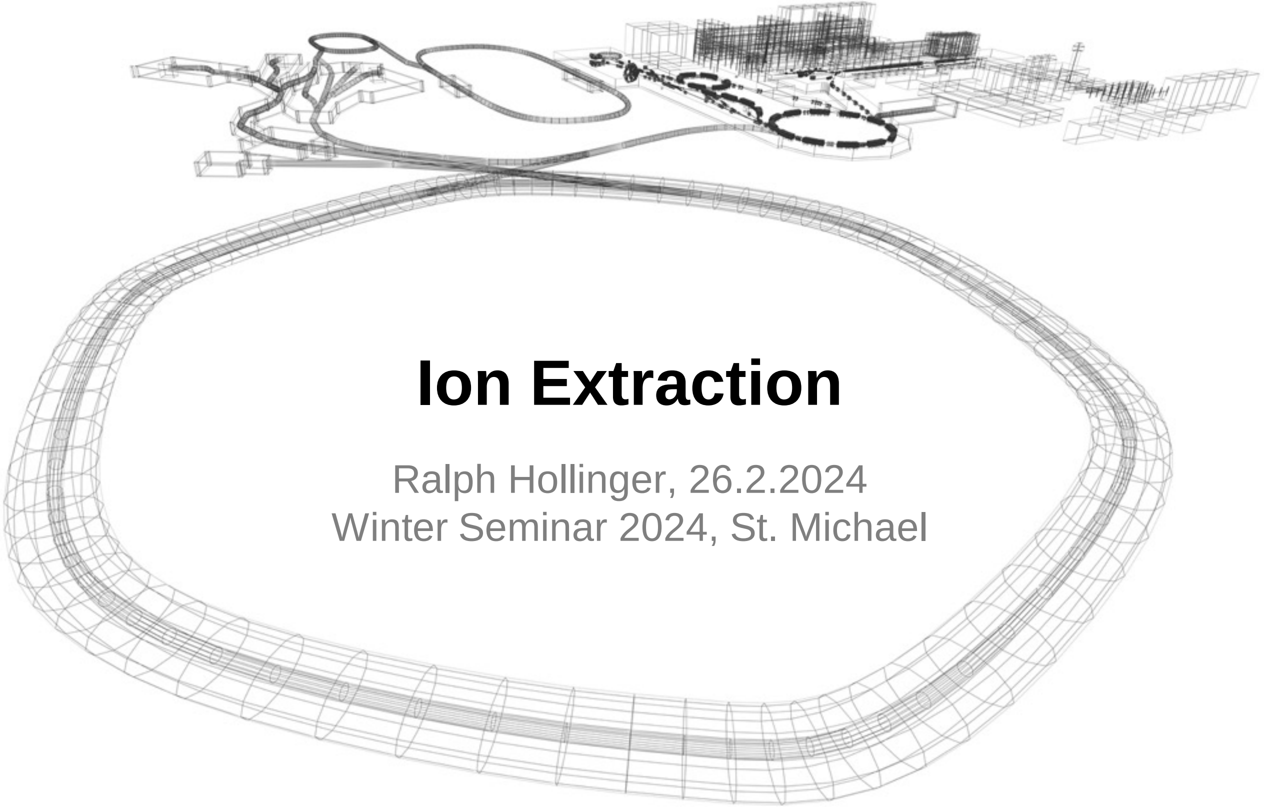
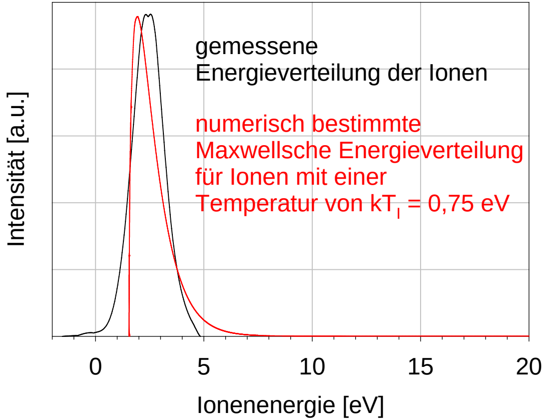


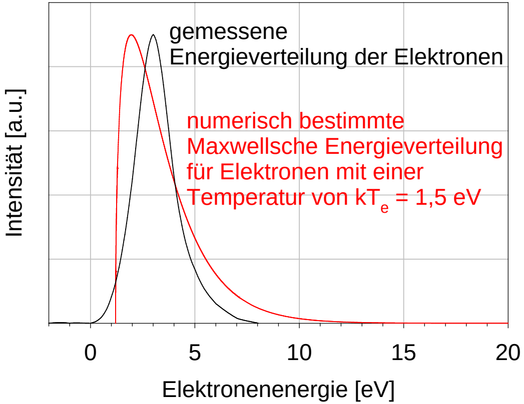
Ion Extraction

Ralph Hollinger, 26.2.2024
Winter Seminar 2024, St. Michael

Plasma Parameter – Ion Extraction

- Particle density: n_i, n_e, N
- Particle: temperature: T_i, T_e
- Particle energy: E_i, E_e
- Plasma wall Potential: U_{PW}
- Charge state distribution
- Ion mass
- Magnetic fields
- Electric Fields
- Geometry
- Residual gas particles
- …

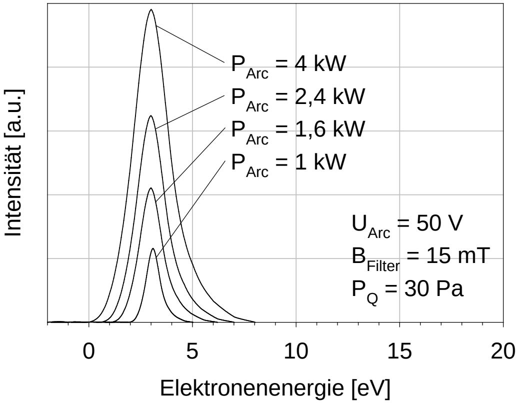


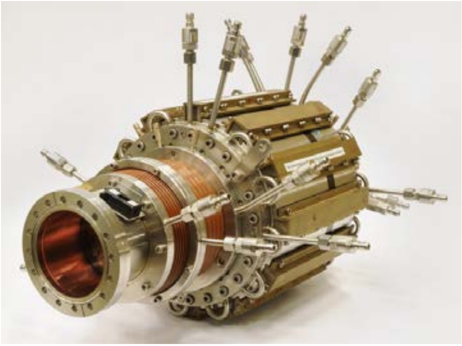


Ion Sources at GSI

Filament driven Ion Sources, MUCIS and CHORDIS

- Low charge state (1 to 3+, max. 1+)
- High emission current density (>100mA/cm²)
- Low electron temperature (few eV)
- Low ion temperature (<1eV)
- U_{PW}=10-50V
- Very low ion energy (few eV)

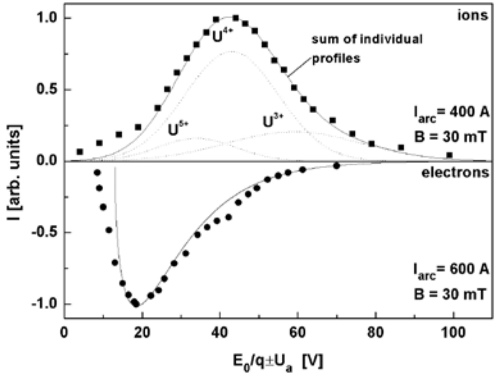




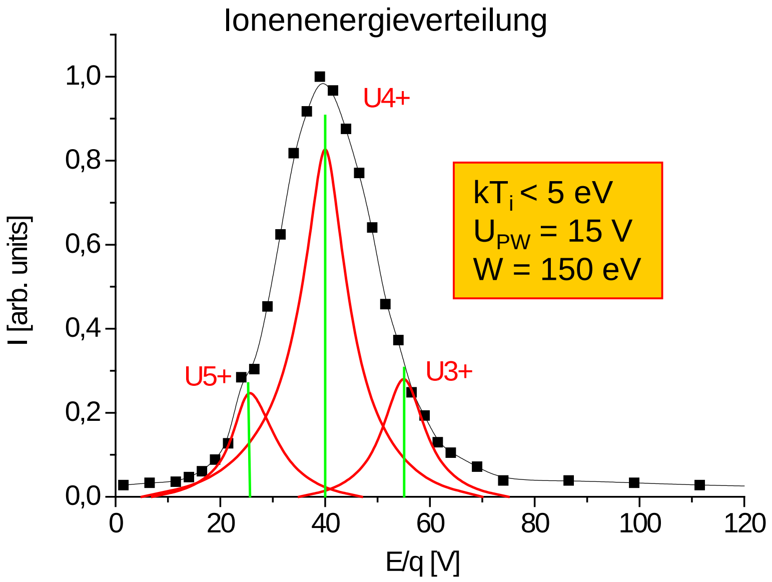
Ion Sources at GSI

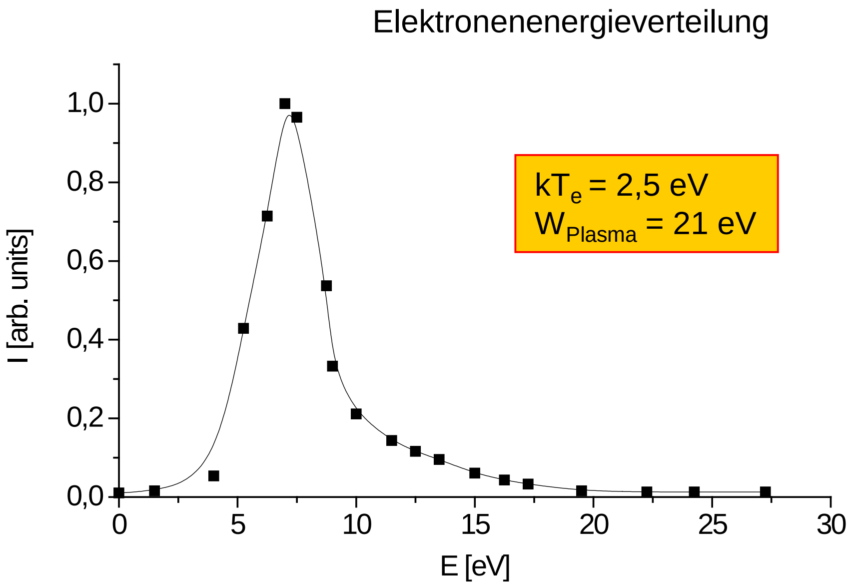
Vacuum Arc driven Ion Sources, VARIS

- Low charge state (1 to 5+, max. 2-4+)
- High emission current density (>300mA/cm^2)
- Low electron temperature (few eV)
- Low ion temperature (<1eV)
- U_{PW}=0-20V
- High ion energy (100eV)



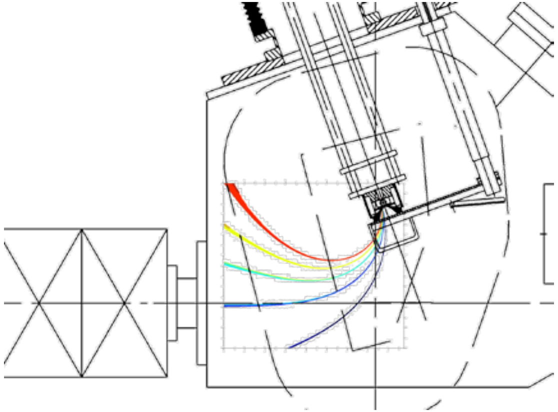
Vacuum Arc driven Ion Sources, VARIS

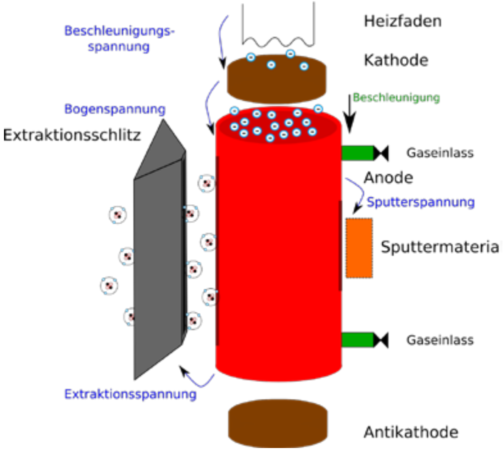




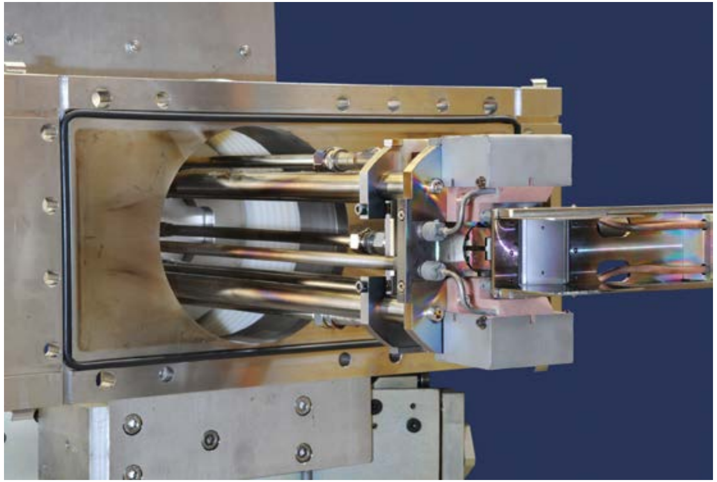
Ion Sources at GSI

High Duty Factor Ion Source - PIG



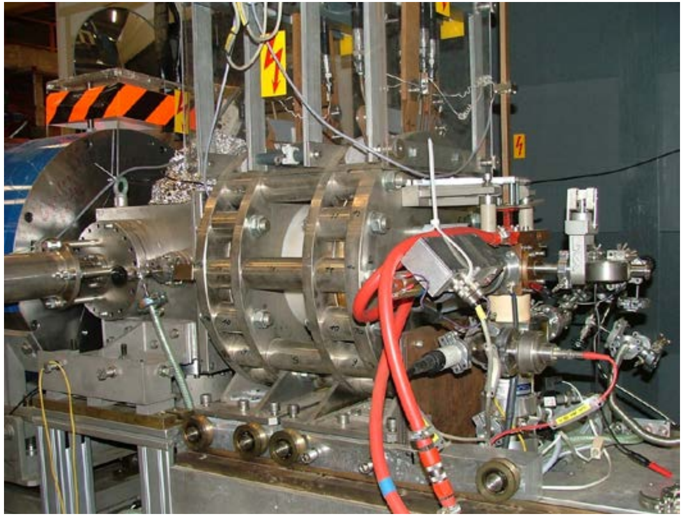


- Middle charge state (2-8+)
- Middle emission current density
- Middle electron temperature (few eV)
- Middle ion temperature (few eV)
- U_{PW}=20-50V
- Low ion energy

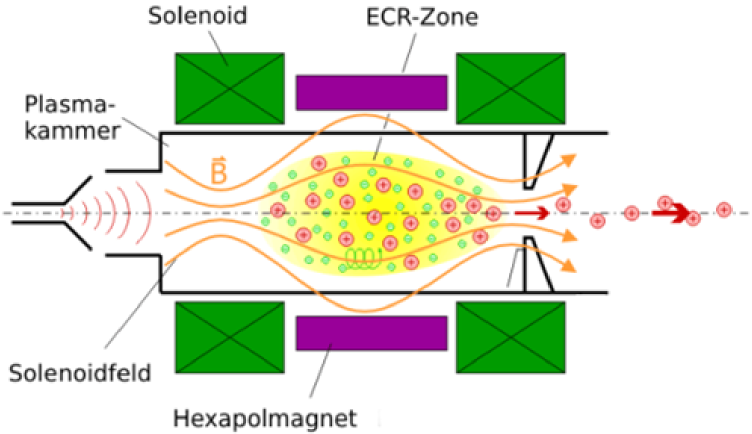


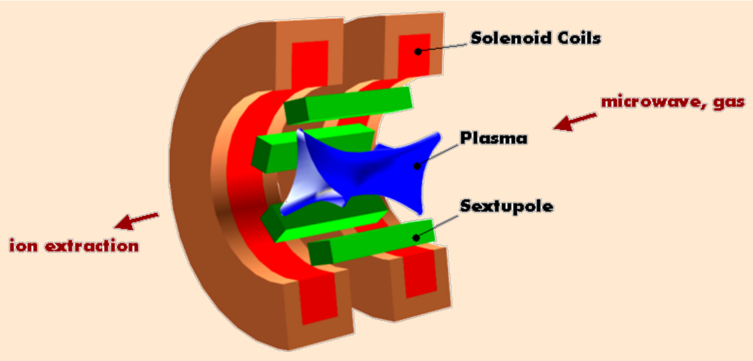
Ion Sources at GSI

High Charge State Ion Source

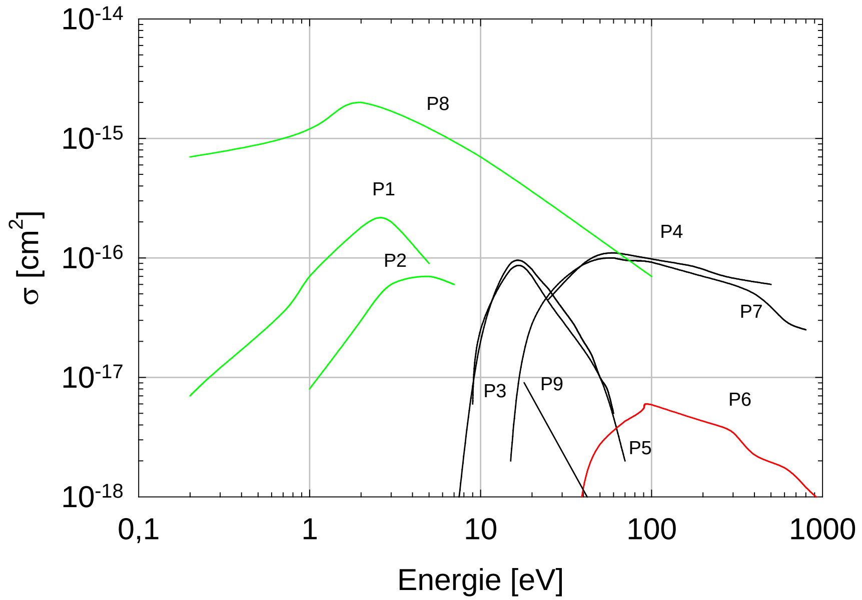


ECR



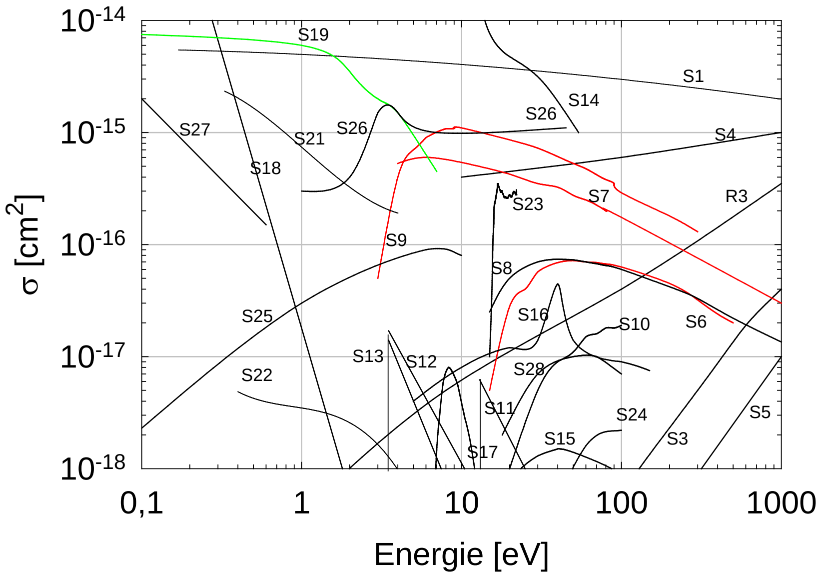


Primary Cross Sections for H2



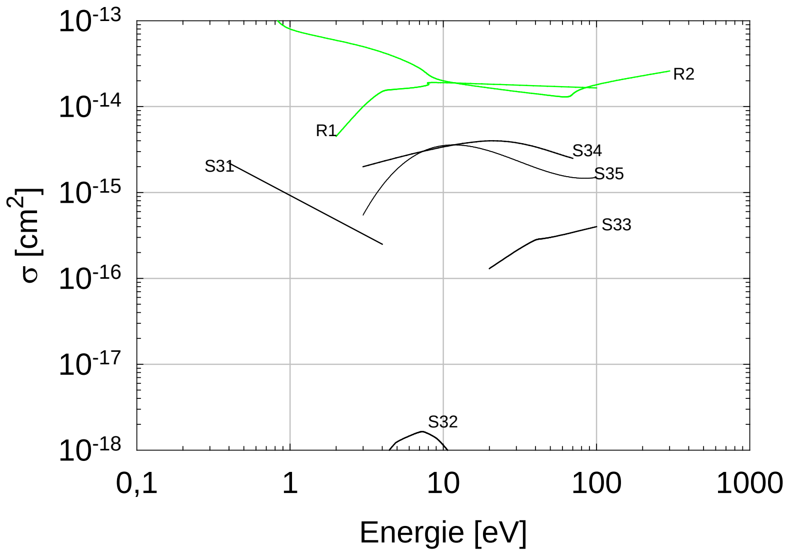
Primärstoß	Reaktion
P1	$e + H_2 \rightarrow H_2^*$ (rot) + e
P2	$e + H_2 \rightarrow H_2^*$ (vib) + e
P3	$e + H_2 \rightarrow H_2^*$ (elec) + e
P4	$e + H_2 \rightarrow H_2^+ + 2e$
P5	$e + H_2 \rightarrow 2H + e$
P6	$e + H_2 \rightarrow H^+ + H + 2e$
P7	$e + H_2$ (total)
P8	$e + H_2$ (elastic scattering)
P9	$h\nu + H_2 \rightarrow 2H$
P10	$e + H_2 \rightarrow H^- + H$ ($< 10^{-21}$)
P11	$e + H_2 \rightarrow H^- + H^* + e$ ($< 10^{-20}$)

Secondary Cross Sections for H2



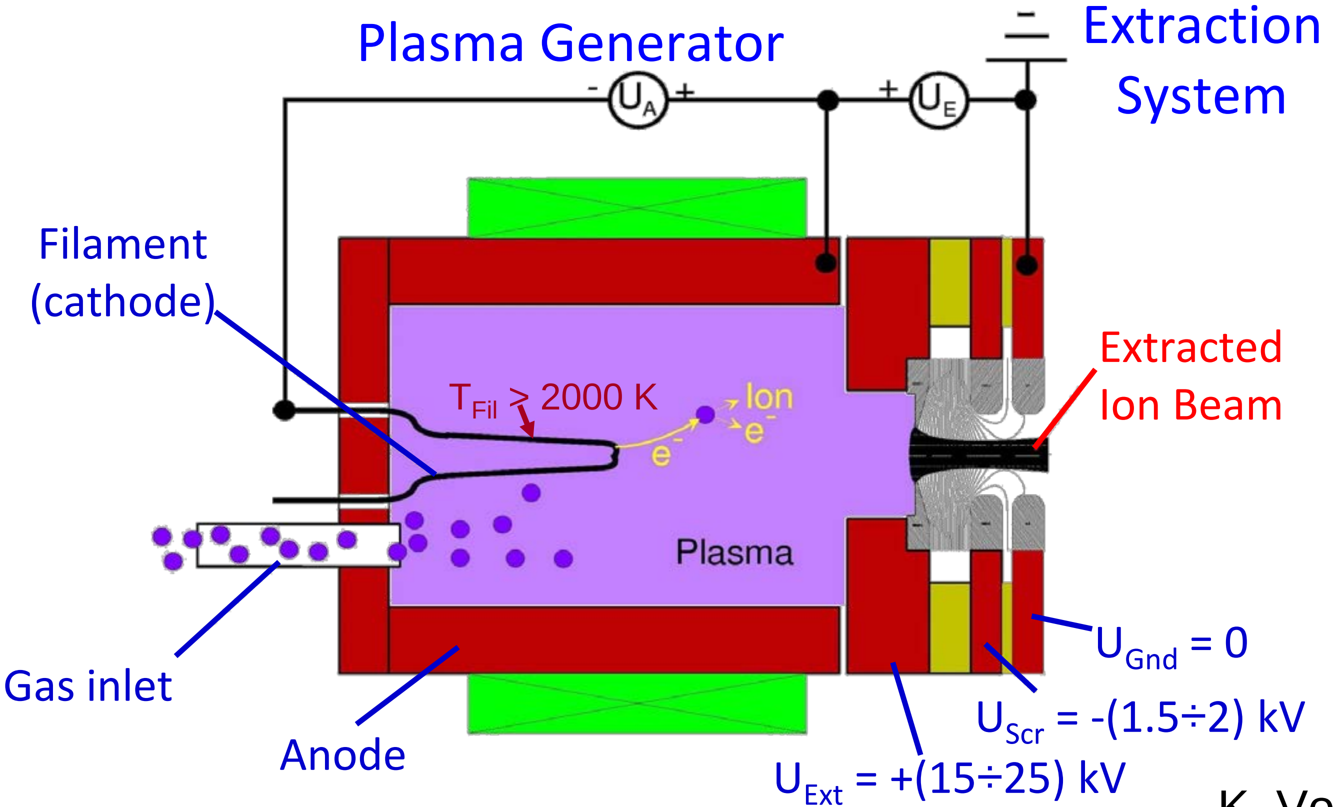
Sekundärstoß	Reaktion	[eV]	Referenz
S1	$H^+ + H \rightarrow H + H^+$	< 0,2	[Taw, Sa]
S2	$e + H_3^+ \rightarrow H_2 + H^+ + e$		[Chan 2]
S3	$H_2 + H \rightarrow H^+$	< 100	[Nak]
S4	$H^- + H_2 \rightarrow H + ...$	< 10	[Nak]
S5	$H^- + H_2 \rightarrow H^+ + ...$	< 300	[Nak]
S6	$e + H \rightarrow H^+ + 2e$	13,6	[Kie, Ch, Taw 2, Chan]
S7	$e + H_2^+ \rightarrow H^+ + H + e$	< 1	[Step, Chan]
S8	$e + H\ (1s) \rightarrow H\ (2p) + e$	< 13,6	[Cou, Cal]
S9	$e + H\ (2s) \rightarrow H^+ + 2e$	< 2	[Taw 2]
S10	$e + H_2^+ \rightarrow 2H^+ + 2e$		[Kie, Step]
S11	$h\nu + H\ (1s) \rightarrow H^+ + e$	13,6	[Cro]
S12	$h\nu + H\ (2p) \rightarrow H^+ + e$	3,5	[Cro]
S13	$h\nu + H\ (2s) \rightarrow H^+ + e$	3,5	[Cro]
S14	$e + H\ (1s) \rightarrow H\ (1s) + e$		[Cal, Kie 2]
S15	$e + H\ (1s) \rightarrow H\ (3s) + e$	< 15	[Cal, Kie 2]
S16	$e + H\ (1s) \rightarrow H\ (3p) + e$	< 3	[Cal, Kie 2]
S17	$h\nu + H_2^+ \rightarrow H^+ + H$	< 6	[Cro]
S18	$e + H_2^+ \rightarrow H + H^*$	< 0,2	[Step]
S19	$H_2^+ + H_2 \rightarrow H_3^+ + H$	< 0,1	[Ale, Chan]
S20	$e + H_2^*\ (vib) \rightarrow H^- + H$		[Wad]
S21	$e + H_2^+ \rightarrow 2H$	< 0,2	[Step, Chan]
S22	$e + H_2^+ \rightarrow H^+ + H^-$	0,3	[Pear 1]
S23	$e + H_3^+ \rightarrow 2H + H^+ + e$	15	[Pear 2]
S24	$H + H_2 \rightarrow H^- + ...$	< 50	[Nak]
S25	$H + H_2 \rightarrow H^+ + H_2 + e$	< 0,1	[Nak]
S26	$H_2^+ + H_2 \rightarrow H_2 + H_2^+$	< 1	[Mor]
S27	$e + H_3^+ \rightarrow H$	< 0,1	[Brian]
S28	$e + H^- \rightarrow H^+ + 3e$		[Det]
S29	$e + H \rightarrow H^*\ (elec)$		[Iti, Bas]
S30	$e + H \rightarrow H^-$	< 8	[Kie]
S31	$e + H_3^+ \rightarrow H_2 + H$	0,3	[Ale]
S32	$e + H_3^+ \rightarrow H_3^*(vib) \rightarrow H^- + H_2^+$	< 2	[Pear 3]
S33	$H^- + H_2 \rightarrow H + H_2 + e$	4,48	[Taw 3]
S34	$e + H^- \rightarrow H + 2e$	< 0,1	[Pear 4]
S35	$H^- + H^- \rightarrow H^- + H + e$	1,1	[unbekannt]
S36	$h\nu + H^- \rightarrow H + e\ (<10^{-18})$		[Gel]
S37	$H^- + H \rightarrow H + H^-(<10^{-18})$		[unbekannt]

Recombination Cross Sections for H2



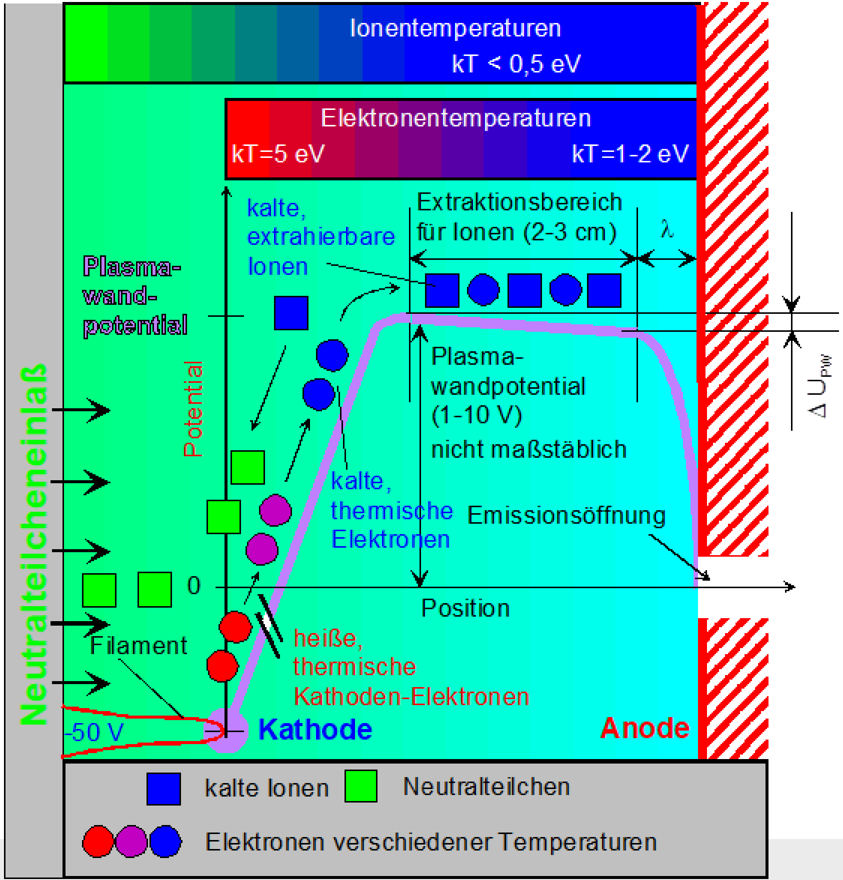
Rekombination	Reaktion	[eV]	Referenz
R1	$H^+ + H^- \rightarrow H^+ + H + e$	0,5	[unbekannt]
R2	$H^+ + H^- \rightarrow 2H$	< 0,1	[Mosley]
R3	$H^+ + H_2 \rightarrow H + H_2^+$	< 1	[Nak]

Ion Source Principle

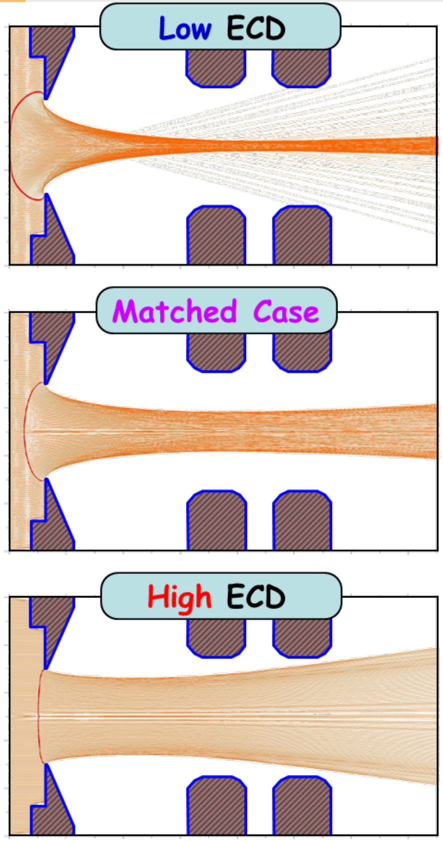


K. Volk

Filament Driven Plasma



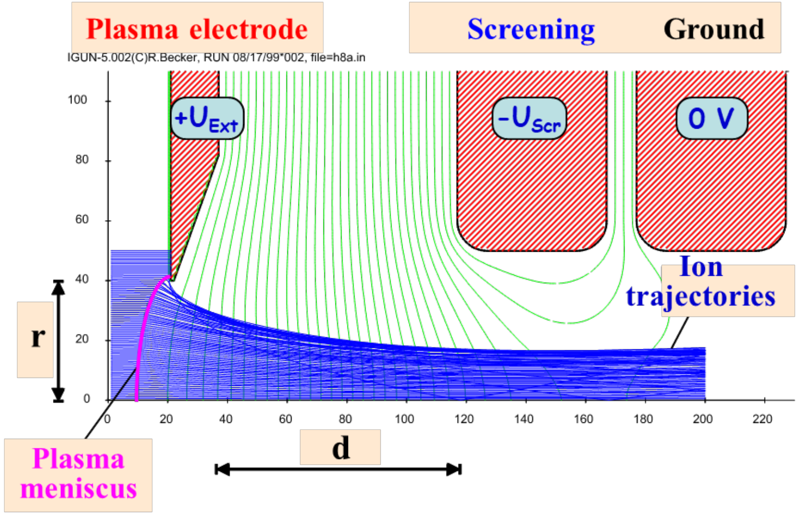
Ion Extraction



Child-Langmuir Law:

$$j_{CL} = \frac{4}{9}\varepsilon_0 \cdot \sqrt{\frac{2e\zeta}{m}} \cdot \frac{1}{\sqrt{d}} \cdot E^{3/2} \qquad S = \frac{r}{d} \qquad E = \frac{U_{Ext}}{d}$$

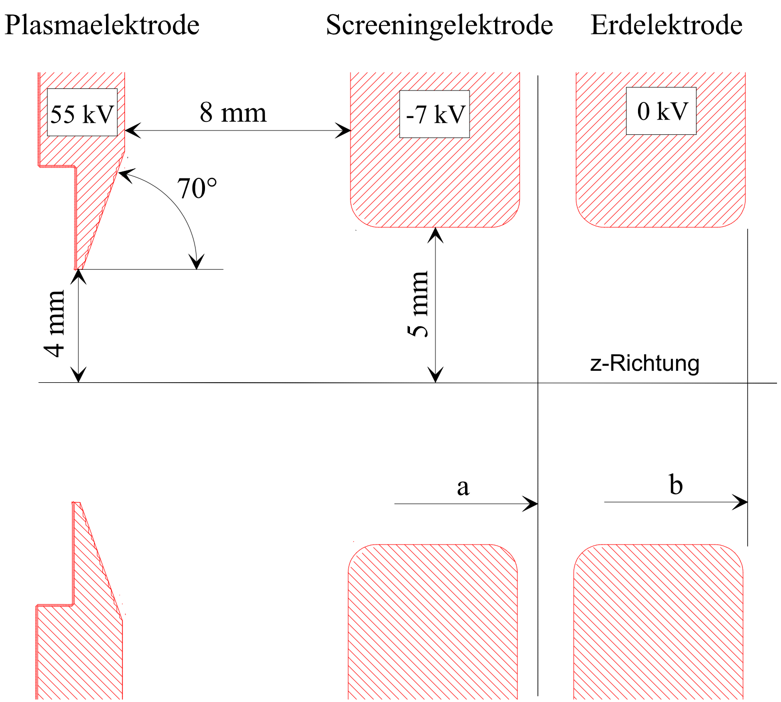
$$I_{CL} = \frac{4}{9}\pi \cdot \varepsilon_0 \cdot \sqrt{\frac{2e\zeta}{m}} \cdot S^2 \cdot U_{Ext}^{\;3/2}$$



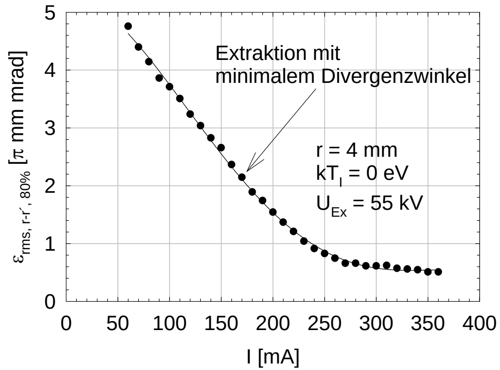
Extraction Types:

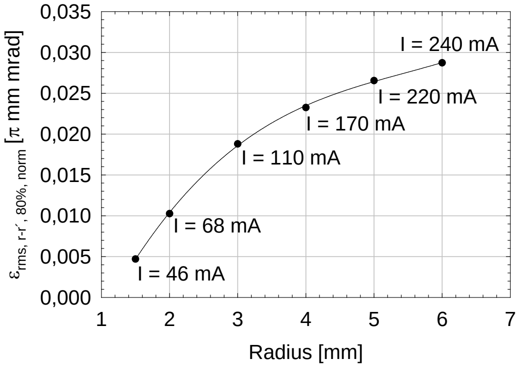
- space charge limited (high current ion sources)
- emission limited (EZR ion sources)

Extraction System

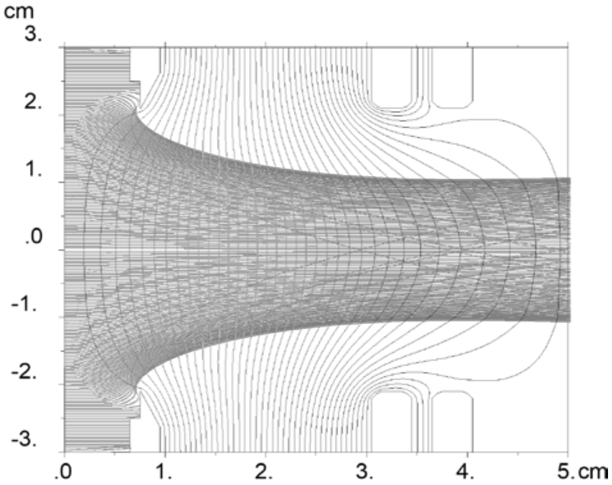


$$\varepsilon_{rms,\,89\%,\,norm} = 16{,}325 r \sqrt{\frac{kT}{A}}$$

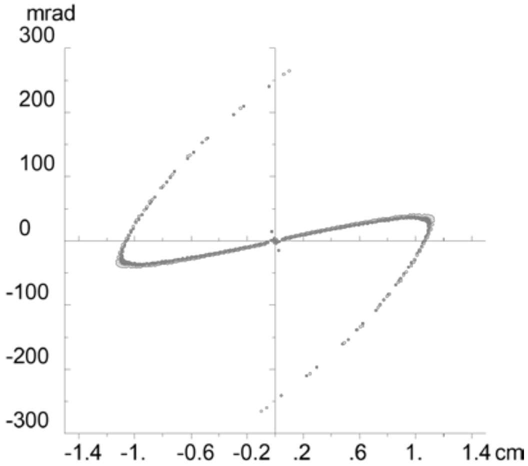




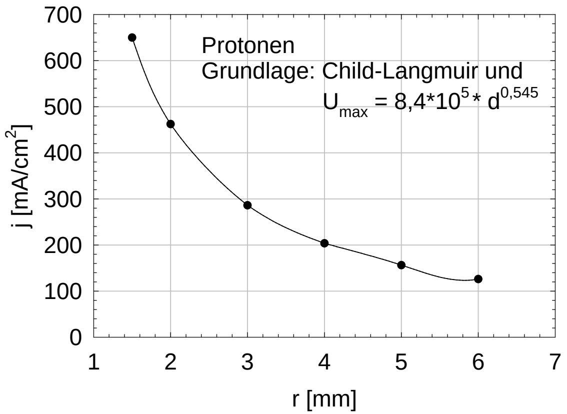
Single to Multi Aperture Extraction System - why



AXCEL-INP simulation for extraction of 35 mA Bi^{+} and 8.75 mA Bi^{2+} with a single aperture extraction system



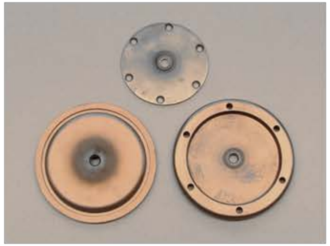
Emittance pattern of the trajectory plot of Figure 5.19 ($\varepsilon_{100\,\%}$ = 3000 π mm mrad, ε_{rms} = 367 π mm mrad)



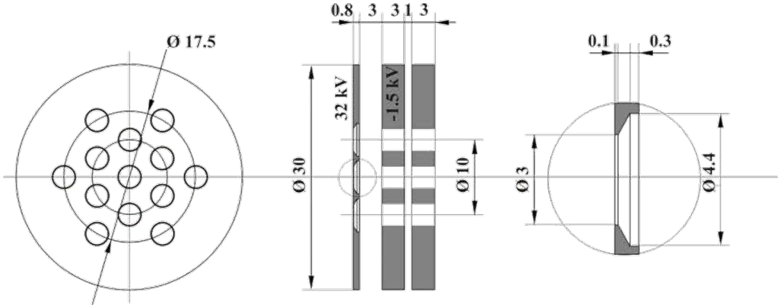
Extraction Sytems

Triode Extraction Systems:

1 hole	7 holes	13 holes	19 holes
ø 4÷8 mm	ø 4÷6 mm	ø 3 mm	ø 2÷3 mm

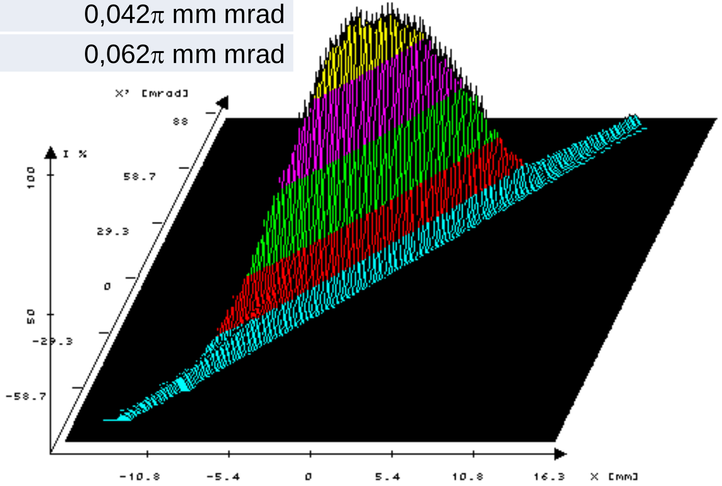


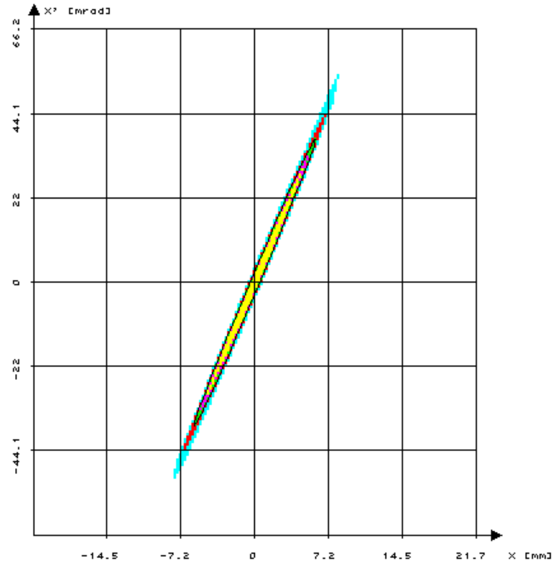

Plasma - Screening distance:	r = 3 mm
Aspect Ratio:	S = 0.5
MAX Ext. Voltage:	35 kV
Emission Area:	92 mm^2



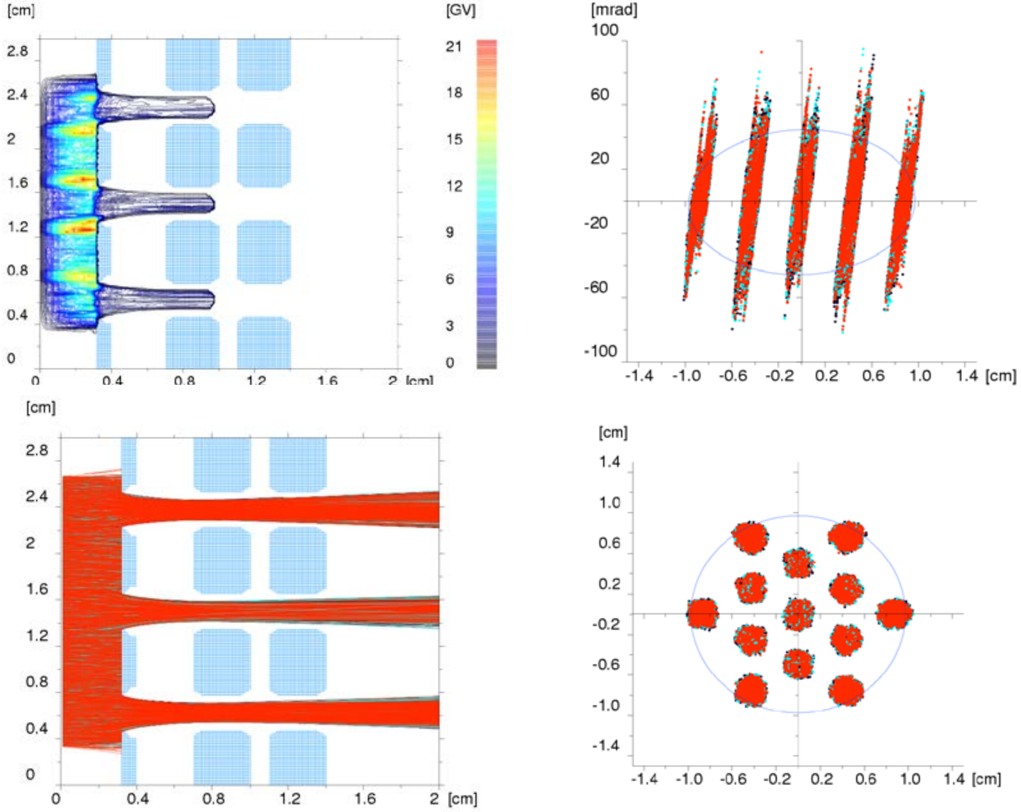
Emittance

Meßergebnisse (85 % H^+, 56 mA, 26 keV)	
Divergenzwinkel (80 %)	38 mrad
Strahlradius (80 %)	5,9 mm
ε (x-x´, 80 %)	6,3π mm mrad
ε (rms, x-x´, 80 %)	4,55π mm mrad
ε (rms, x-x´, 89 %)	5,66π mm mrad
ε (rms, x-x´, 80 %, norm.)	0,034π mm mrad
ε (rms, x-x´, 89 %, norm.)	0,042π mm mrad
ε (rms, x-x´, 100 %, norm.)	0,062π mm mrad





Computer Simulation – KOBRA3D

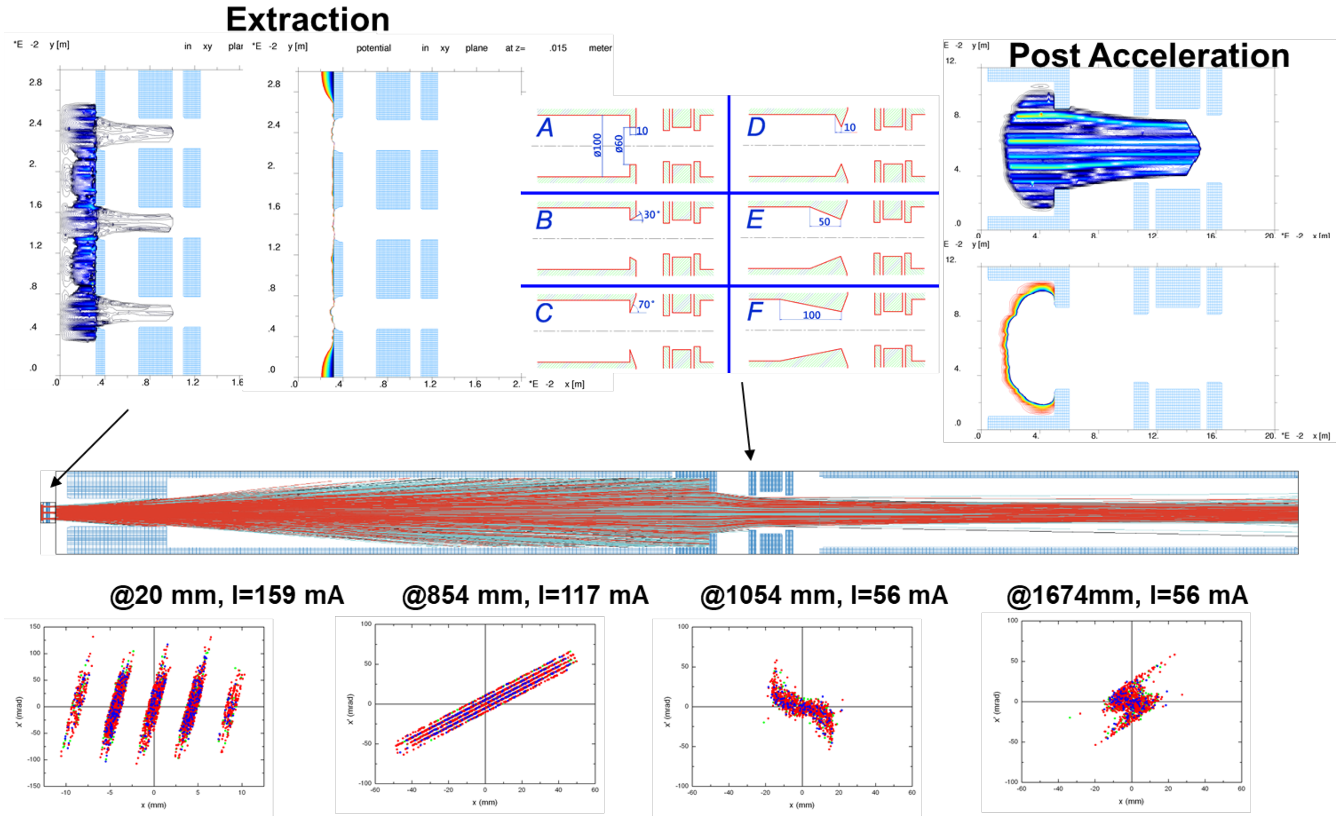


Ion fraction	U^{3+} = 16 %, U^{4+} = 67 % U^{5+} = 14 %, U^{6+} = 3 %
Potential plasma electrode	32 kV
Potential screening electrode	-1.5 kV
Emission current density for standard operation	150 mA/cm^2
Longitudinal ion energy	160 eV
Transversal ion energy*	100 eV
Ion temperature	5 eV
Plasma potential hump	10 V
Electron temperature	10 eV
Potential hump for electrons**	-10 eV
Number of meshes x, y, z	151, 151, 201
Number of trajectories	250000

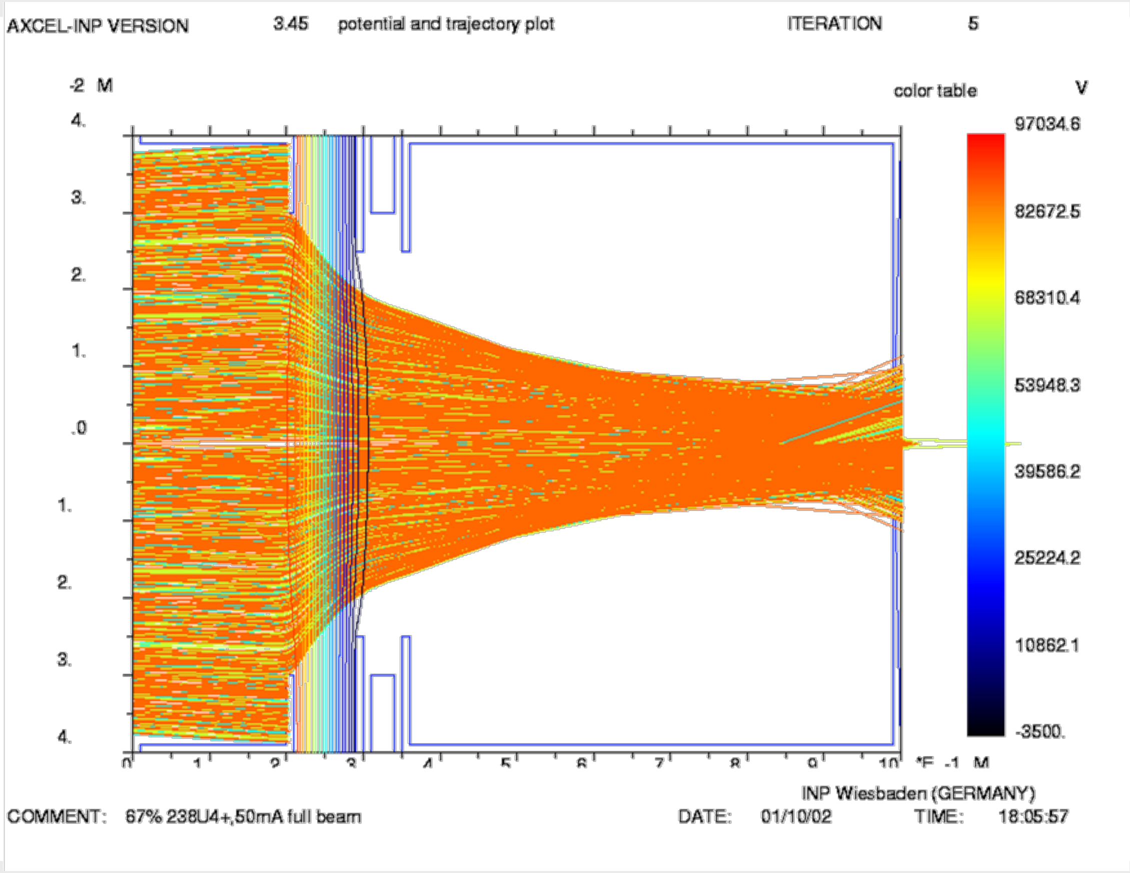
Computer Simulation – KOBRA3D

Extracted ion beam current	140 mA
Divergence angles, rms	80 mrad, 40 mrad
Beam Area (rms)	$3 \cdot 10^{-4}$ m^2
Beam diameter (real)	19.4 mm
Effective emittance, 100 %	400 π mm mrad
Horizontal 4rms values, 88 % of the ion beam current	
Emittance	440 π mm mrad
α	-0.0354
β	0.2148 m/rad
γ	4.661 rad/m
Vertical 4rms values, 89 % of the ion beam current	
Emittance	470 π mm mrad
α	-0.0224
β	0.2016 m/rad
γ	4.963 rad/m

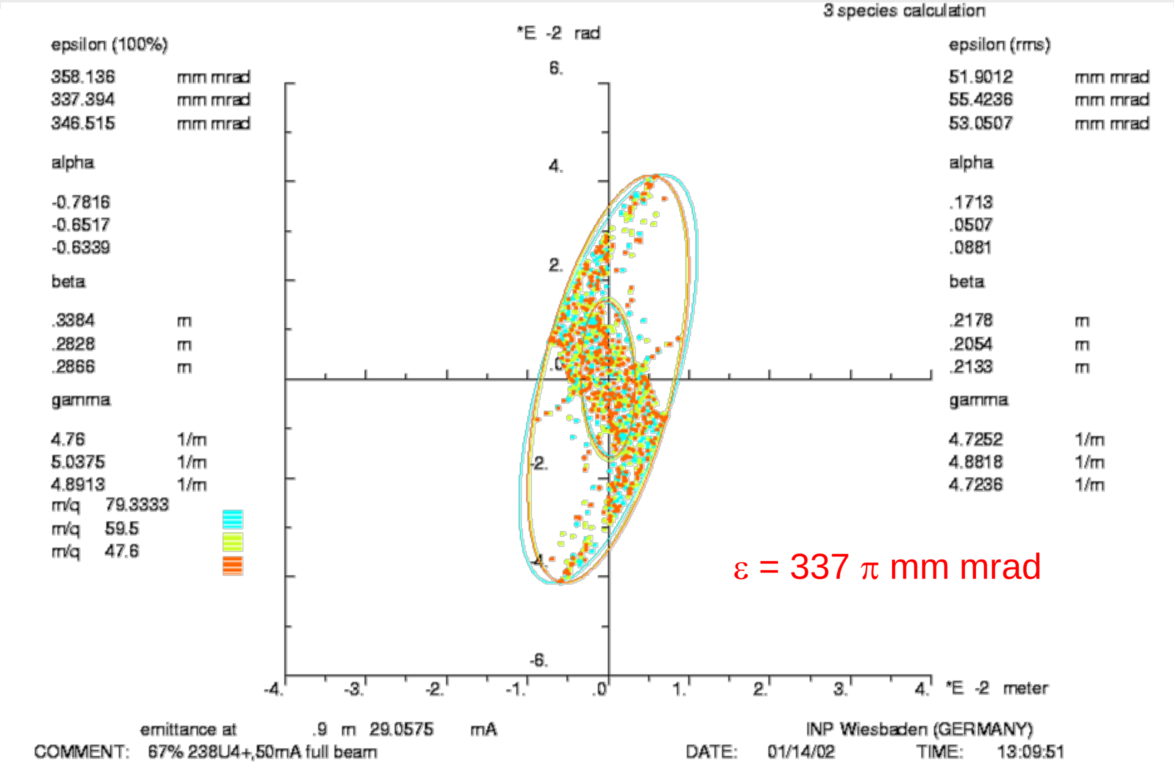
Computer Simulation – KOBRA3D



Axcel-Simulation (67 % $^{238}U^{4+}$) 50 mA (FC 1), 28 mA acc.

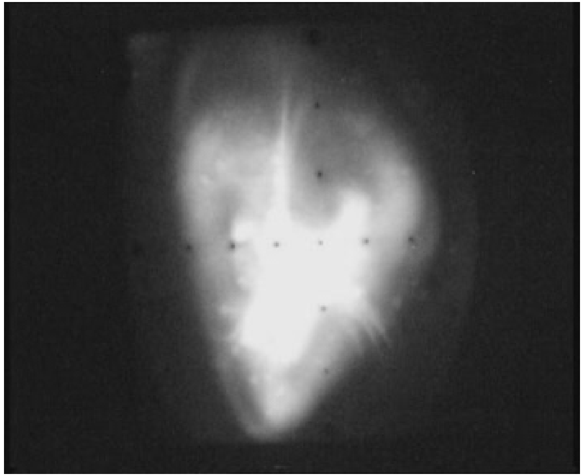


Axcel-Simulation 50 mA (FC 1), 28 mA acc.



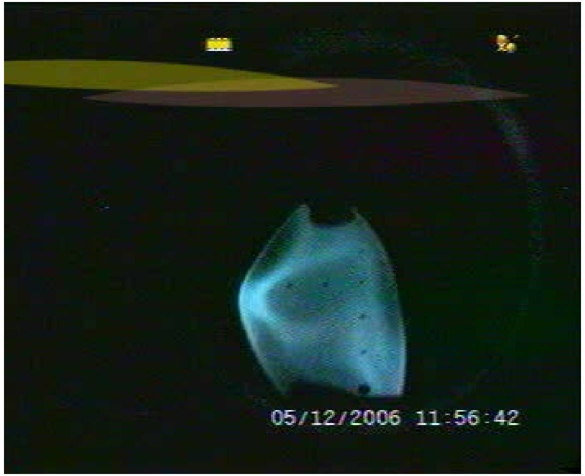
ECR ion beam - full beam and analysed

full beam behind extraction

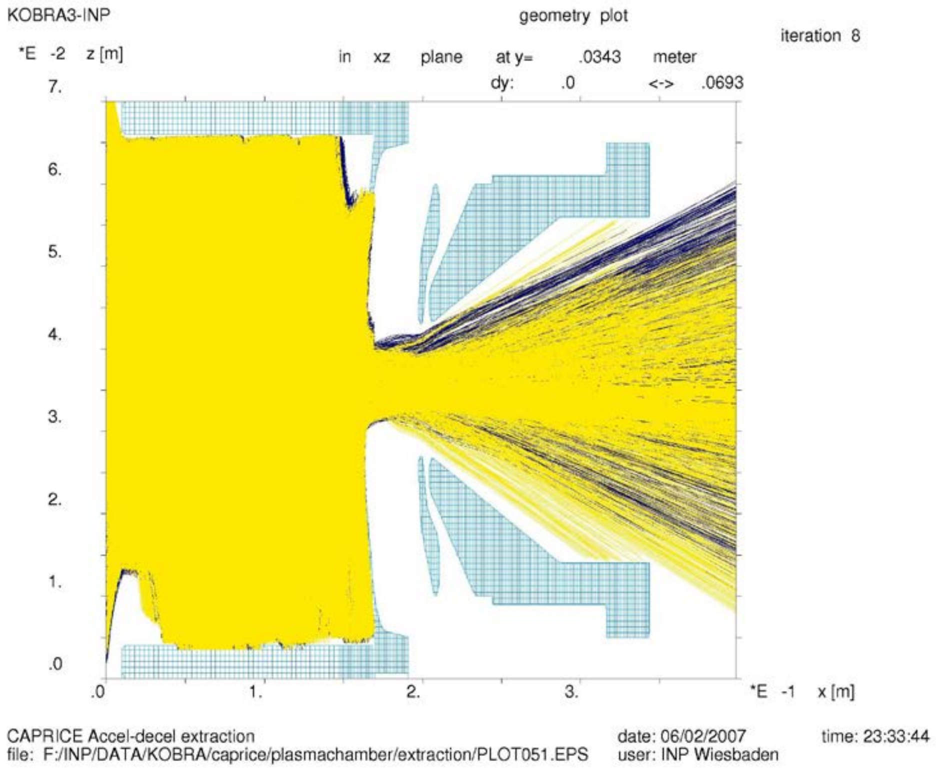


full beam behind solenoid

analysed beam



Computer Simulation – Kobra3D for ECR

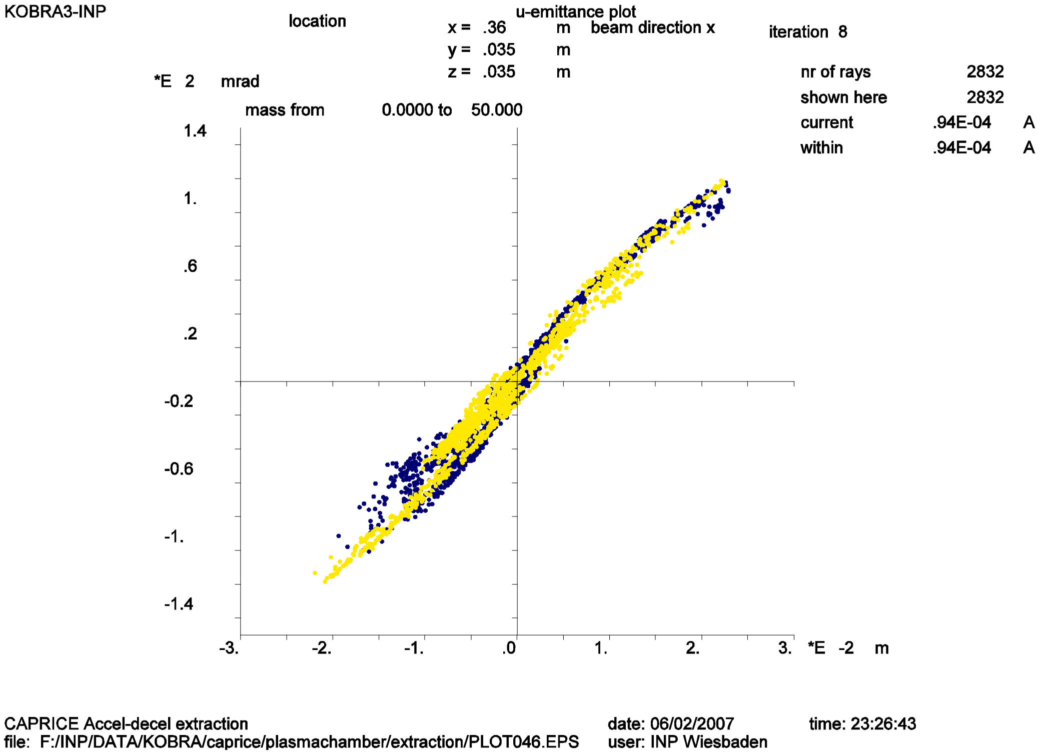


geometry of plasma chamber and accel-decel extraction system, 15kV,-2kV.

Only Ar^{3+} (yellow) and He^{+} (blue) are displayed.

P.Spädtke

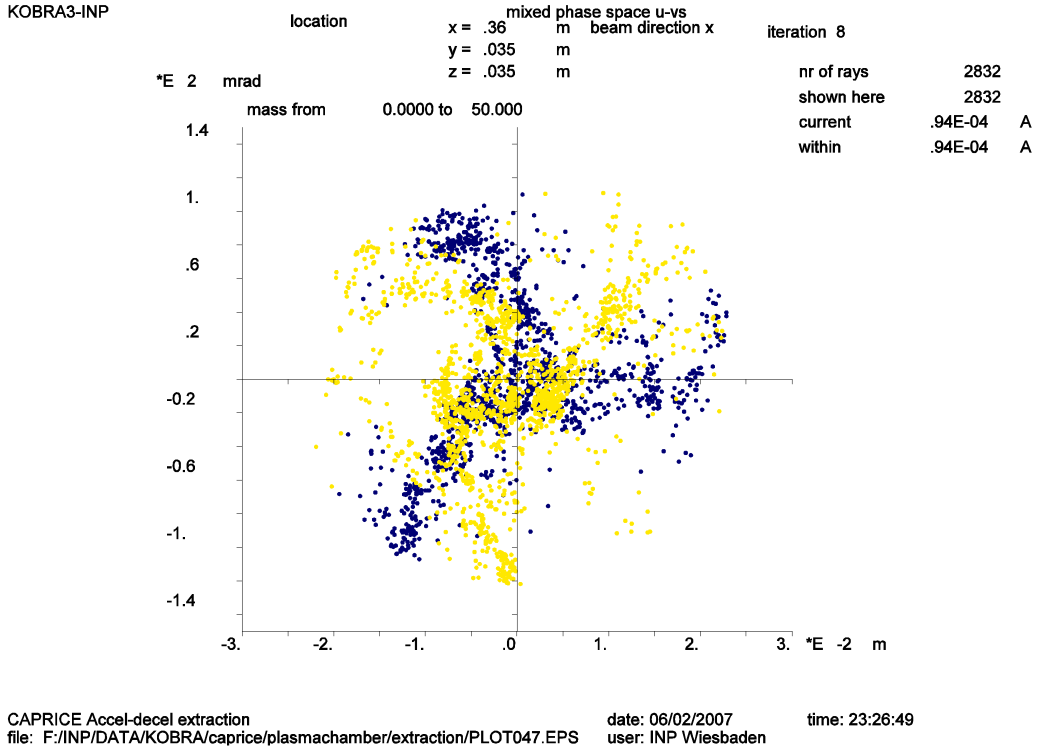
Computer Simulation – Kobra3D for ECR



x – x' emittance

P.Spädtke

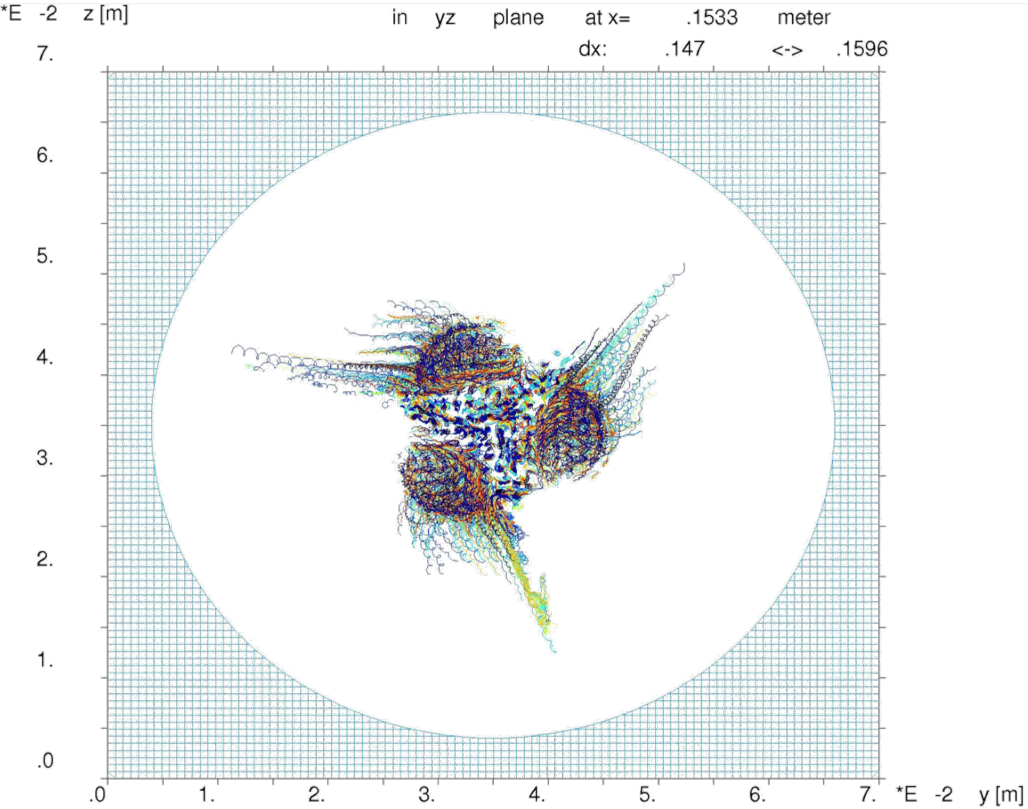
Computer Simulation – Kobra3D for ECR



x – y' phase space

P.Spädtke

Computer Simulation – Kobra3D for ECR



all extracted ions

not homogeneous at all !

P.Spädtke

Danke für die Aufmerksamkeit