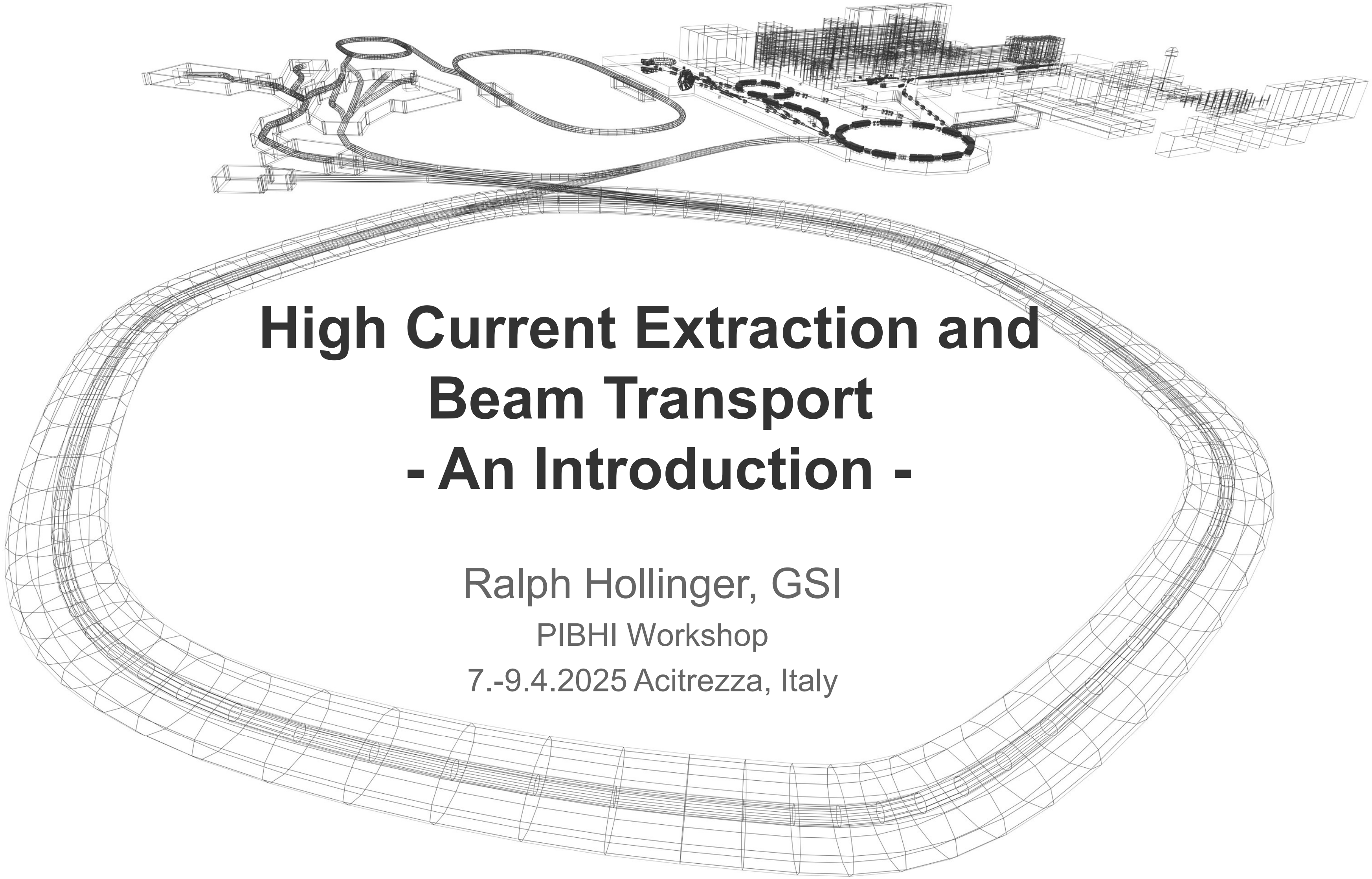


High Current Extraction and Beam Transport - An Introduction -

Ralph Hollinger, GSI

PIBHI Workshop

7.-9.4.2025 Acitrezza, Italy

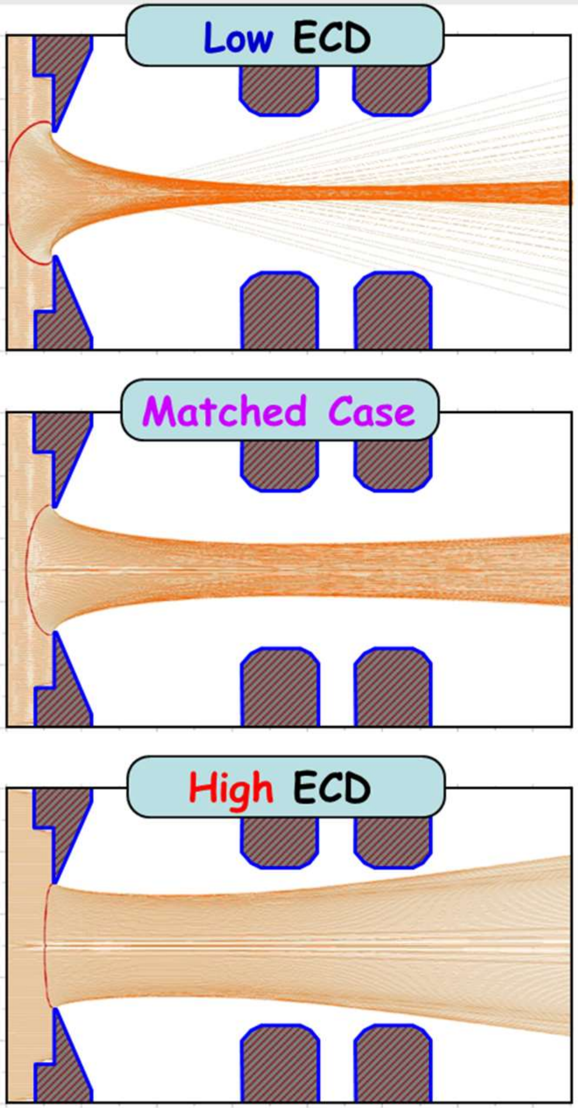
High Current Extraction – what I know or believe to know…

- High Current: 0.1-1 mA, when space charge plays an important role
- Two ways of extraction: space charge limited and emission limited
- Child-Langmuir is valid, I is only a function of r. S=r/d=0.5 is optimal, E_{max} is limited and a function of d. @GSI: E_{max}=12kV/mm for 3-4mm
- Kilpatrick and Coupland for E_{max}
- Use triode extraction system with screening electrode; Usc=10% of Uex
- Emittance is a function of Ti, r and aberrations in the extraction system (no magnetic fields); $\varepsilon_{rms,\ 89\%\ norm.} = 16r(kT/A)^{0.5}$
- Use pierce geomety (~70°) and a thin (0.1mm) edge thickness
- Electrode material: W, Ta, W-Cu (85/15) to increase E_{max}
- For high extr. voltage (>40…50kV) use pentode or post acc. systems
- Switch to multi aperure ext. systems for currents which can not delivered with extrac. hole diameter of max. 8-10mm; emittance growth is the price to pay
- Minimum divergence angle of 20mrad possible; in practice: 40mrad
- H minus is different and Laser ion sources, too
- Simulation: 2d and 3d (with magnetic fields)

High Current Ion Transport – what I know or believe to know…

- High space charge compensation absolut nescessary (>95%)
- No chance to transport a not compensated beam
- You can not avoid scc, electrons a everywere
- Time for scc: 10-30mus
- scc is more easy for pulsed beams (not chopped), increase of plasma density produces wall electrons by sputtering
- Electrons were generated with residuals gas and losses of the beam (sputtering)
- Electrons are trapped inside the beam and can move inside the beam potential: U=30*I/beta (not compensated)
- Beam is compensated also in magnets: QT and bending magnets
- Do not use electrostatic focussing (50s and 60s, nA beam current), use magnets, but only 60% of aperture
- Laser ion beams are different (ns pulse length, no scc, very high dp/p) and H minus
- Solenoids are critical for slow beams (some keV/u) and large beam diameters (>50-60% of aperture) and multi charged beam but good for protons with 100keV/u or below
- Liouville
- Chopper System

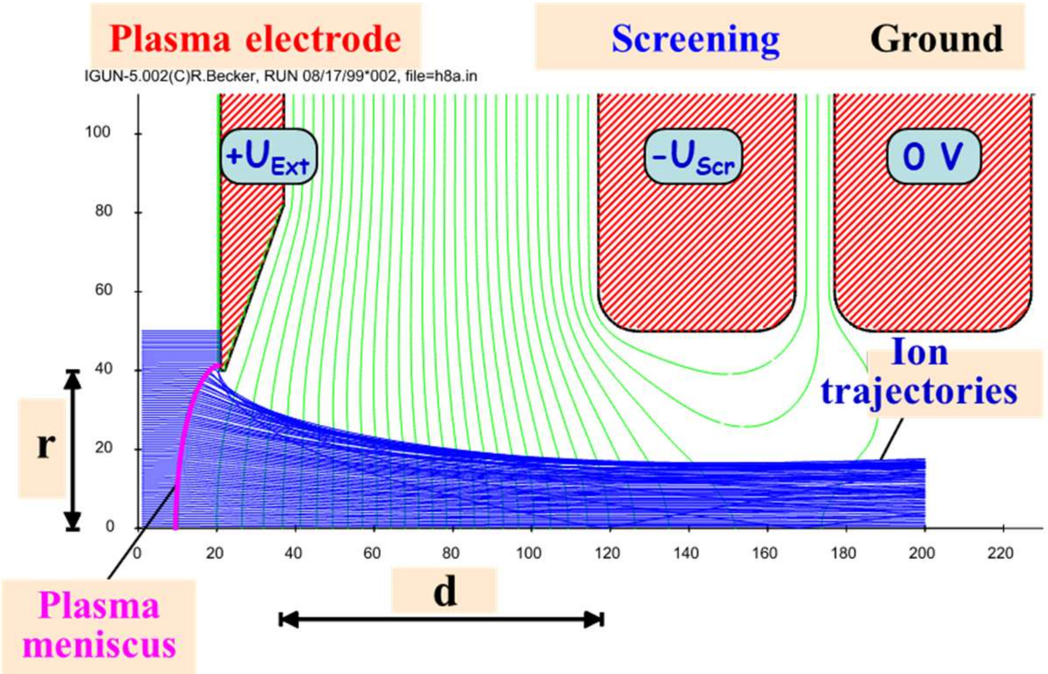
Extraction



Child-Langmuir Law:

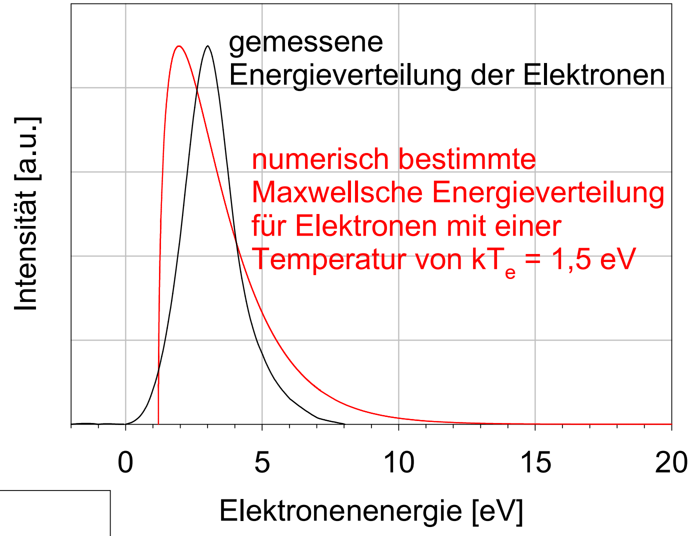
$$j_{CL} = \frac{4}{9}\varepsilon_0 \cdot \sqrt{\frac{2e\zeta}{m}} \cdot \frac{1}{\sqrt{d}} \cdot E^{3/2} \qquad S = \frac{r}{d} \qquad E = \frac{U_{Ext}}{d}$$

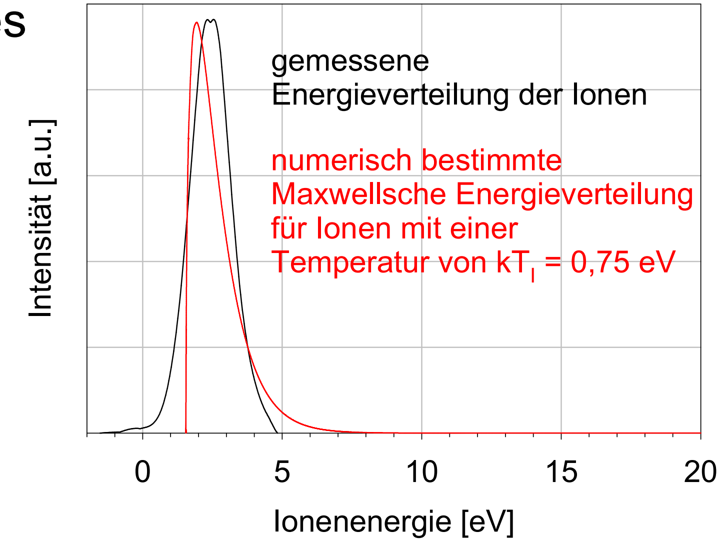
$$I_{CL} = \frac{4}{9}\pi \cdot \varepsilon_0 \cdot \sqrt{\frac{2e\zeta}{m}} \cdot S^2 \cdot U_{Ext}{}^{3/2}$$



Plasma Parameter

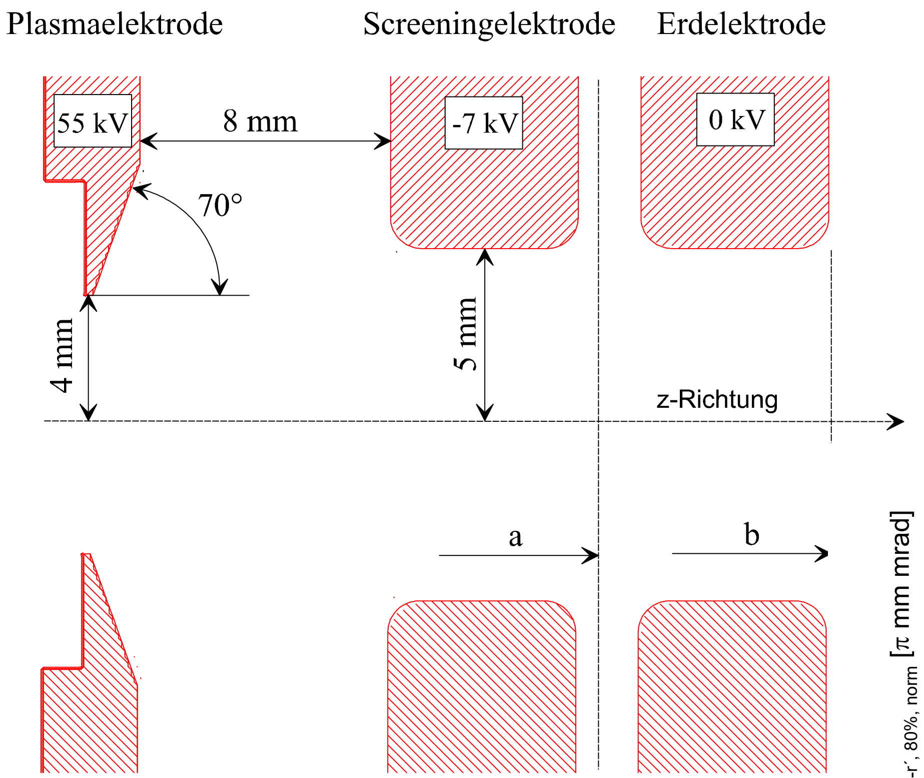
- Particle density: n_i, n_e, N
- Particle: temperature: T_i, T_e
- Particle energy: E_i, E_e
- Plasma wall Potential: U_{PW}
- Charge state distribution
- Ion mass
- Magnetic fields
- Electric Fields
- Geometry
- Residual gas particles
- …

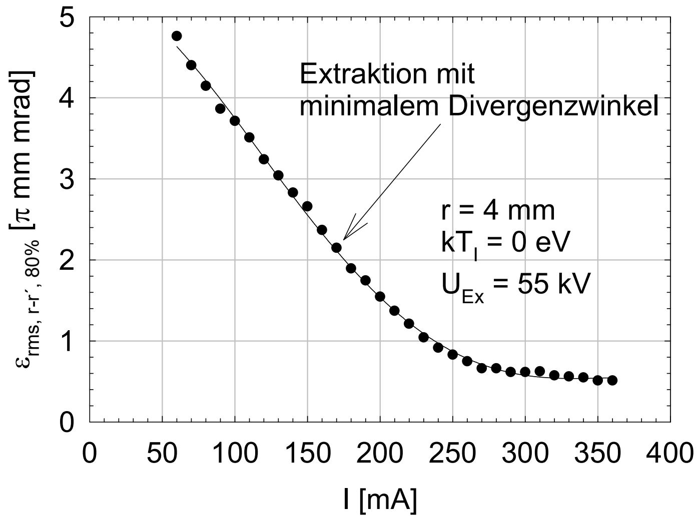


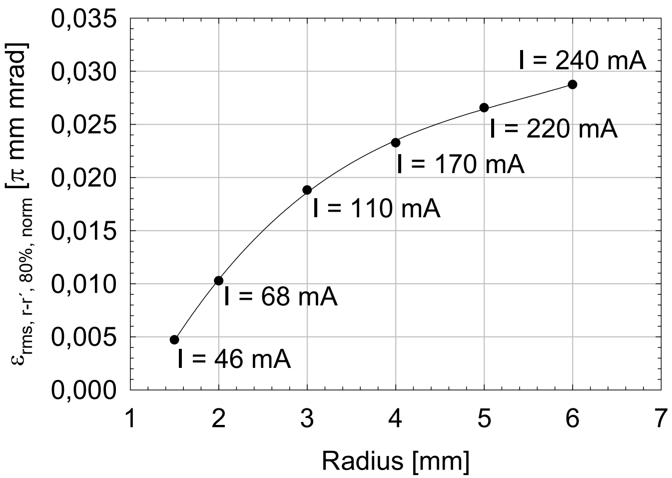


Extraction System

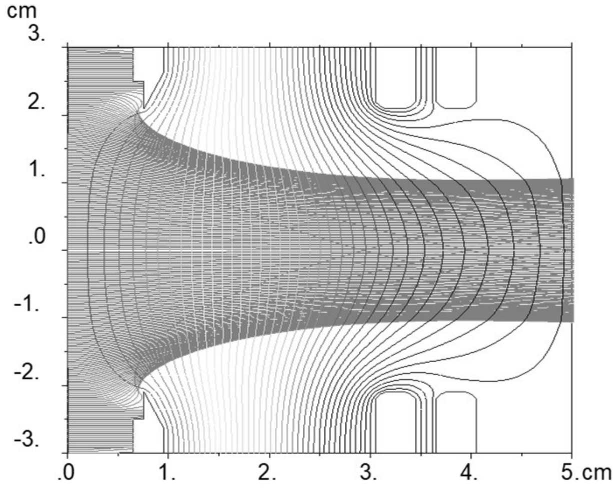
$$\varepsilon_{rms,\,89\%,\,norm} = 16{,}325\, r \sqrt{\frac{kT}{A}}$$



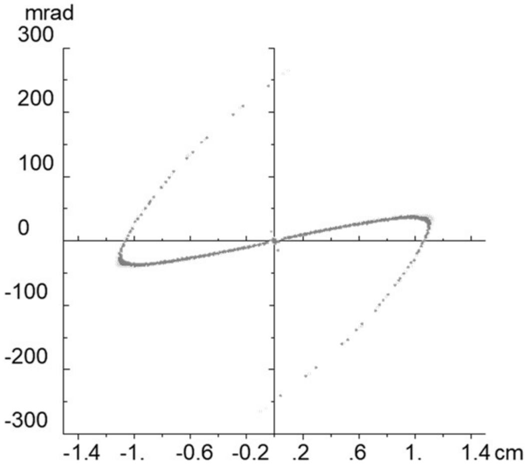




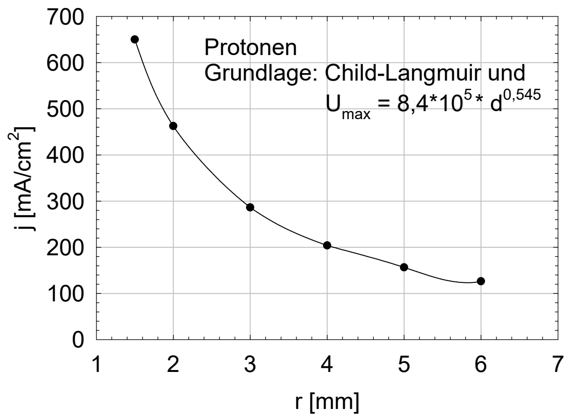
Multi Aperture Extraction System – why?



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



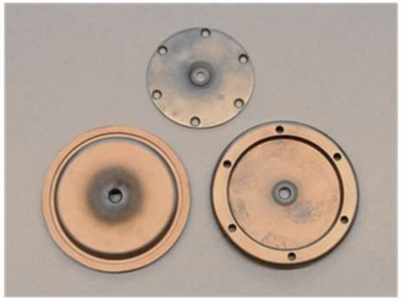
Emittance pattern of the trajectory plot of Figure 5.19 ($\varepsilon_{100\,\%}$ = 3000 π mm mrad, ε_{rms} = 367 π mm mrad)



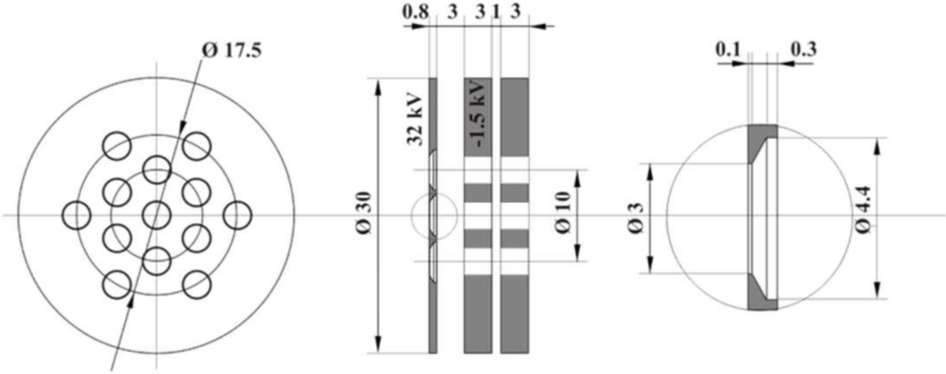
Multi Aperture Extraction System

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

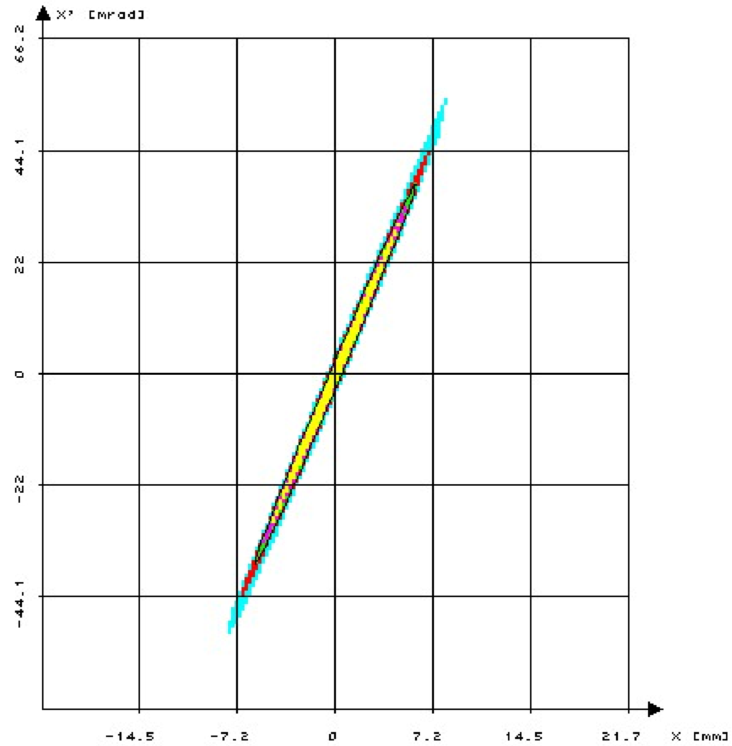


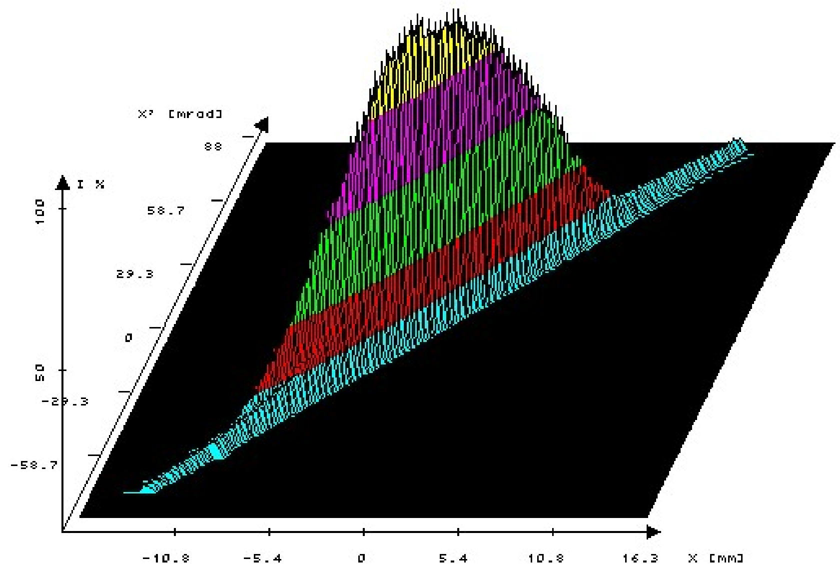

Plasma - Screening distance:	r = 3 mm
Aspect Ratio:	S = 0.5
MAX Ext. Voltage:	35 kV
Emission Area:	92 mm^2



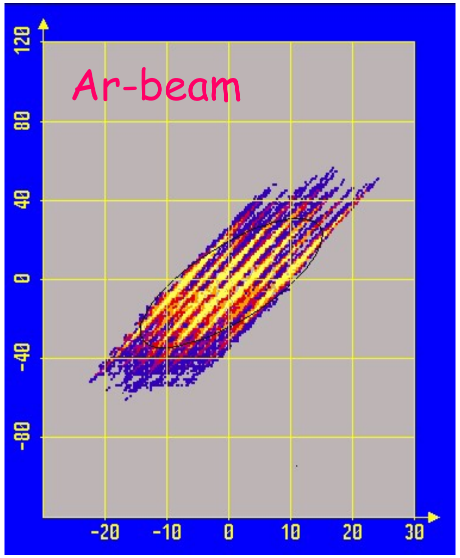
56mA Protons @ 26kV

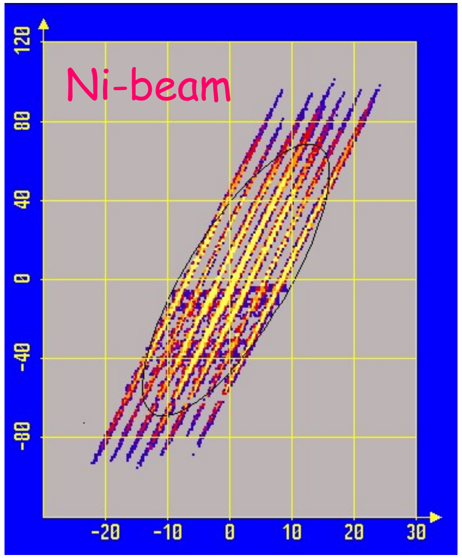
(85 % H^+, 56 mA, 26 keV)	
Divergence angle (80 %)	38 mrad
Beam radius (80 %)	5,9 mm
ε (x-x´, 80 %)	6,3π mm mrad
ε (rms, x-x´, 80 %)	4,55π mm mrad
ε (rms, x-x´, 89 %)	5,66π mm mrad
ε (rms, x-x´, 80 %, norm.)	0,034π mm mrad
ε (rms, x-x´, 89 %, norm.)	0,042π mm mrad
ε (rms, x-x´, 100 %, norm.)	0,062π mm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





Filament vs. Vacuum Arc Ion Source

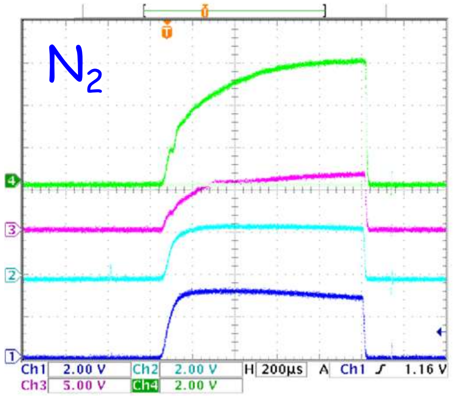




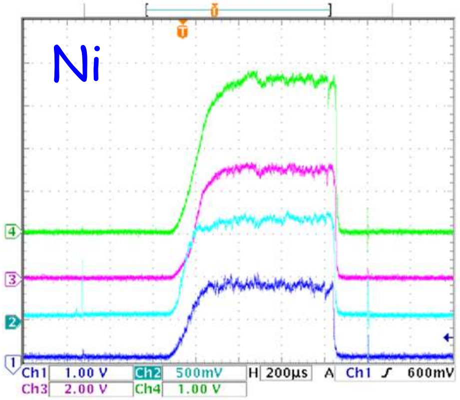
Beam Characteristics

	Ar-beam (CHORDIS)	Ni-beam (VARIS)
U_{Exr}:	18 kV	18 kV
I_{Ext}:	60 mA	60 mA
Div. Angle:	50 mrad	95 mrad

CHORDIS



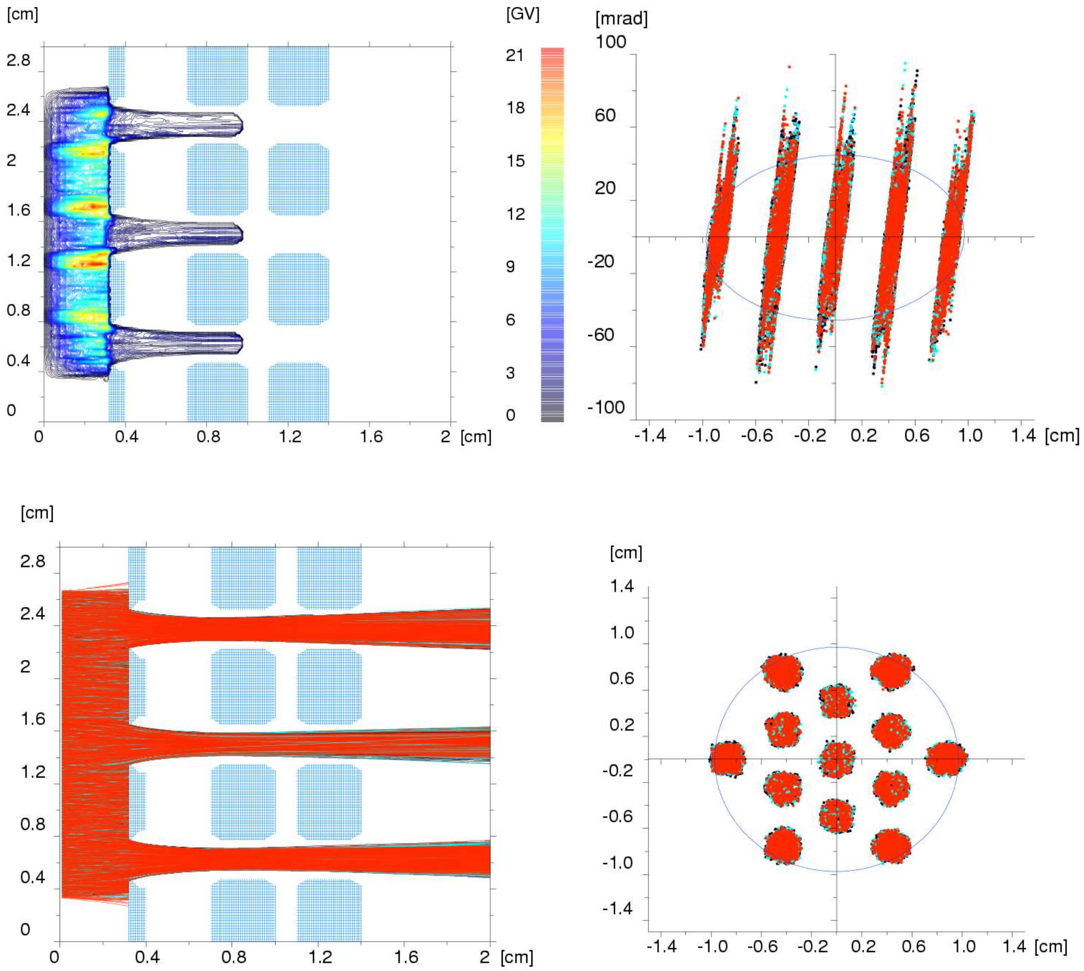
VARIS



Ion beam pulses along the LEBT

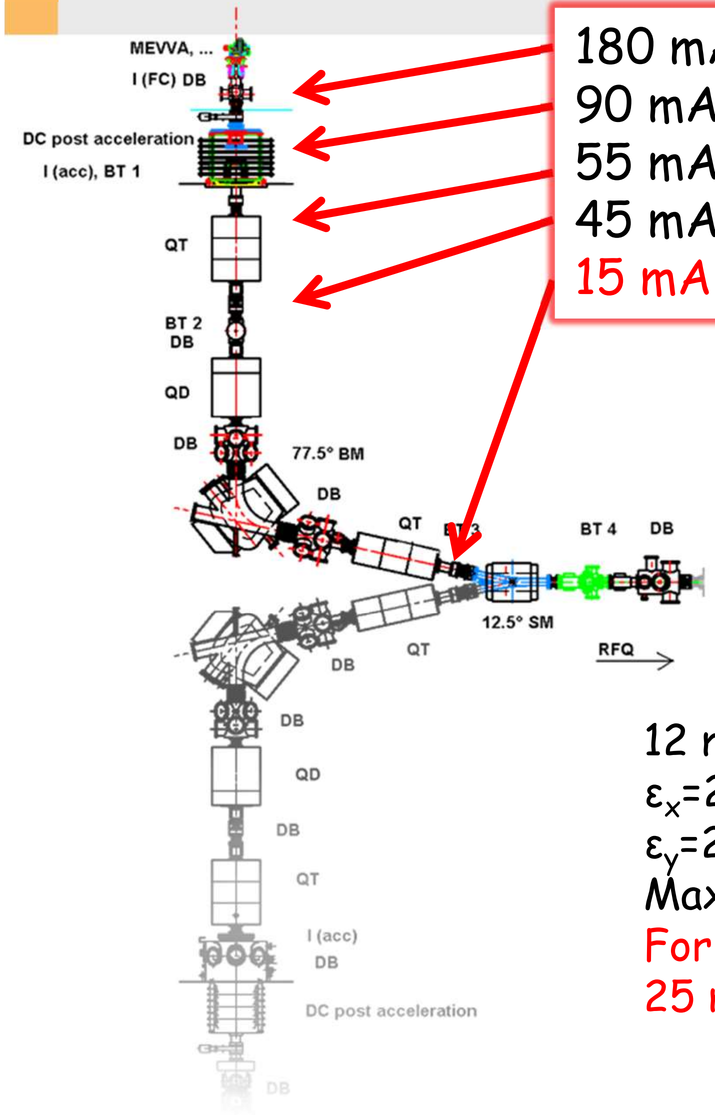
	N_2-beam (CHORDIS)	Ni-beam (VARIS)
CT 1:	20 mA/div	10 mA/div
CT 2:	20 mA/div	5 mA/div
CT 3:	5 mA/div	2 mA/div
CT 4:	2 mA/div	1 mA/div

KOBRA3D-Simulation



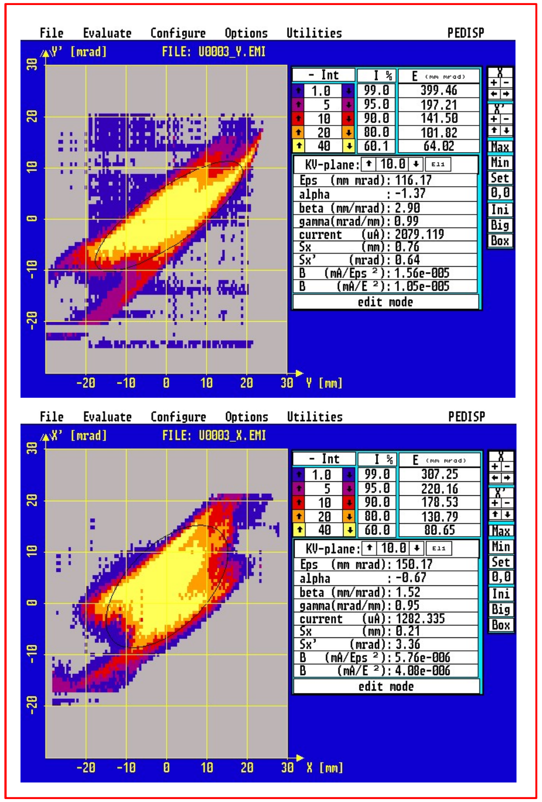
Ion fraction	U^{3+} = 16 %, U^{4+} = 67 % U^{5+} = 14 %, U^{6+} = 3 %
Potential plasma electrode	32 kV
Potential screening electrode	-1.5 kV
Emission current density for standard operation	150 mA/cm²
Longitudinal ion energy	160 eV
Transversal ion energy*	100 eV
Ion temperature	5 eV
Plasma potential hump	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

High Current LEBT

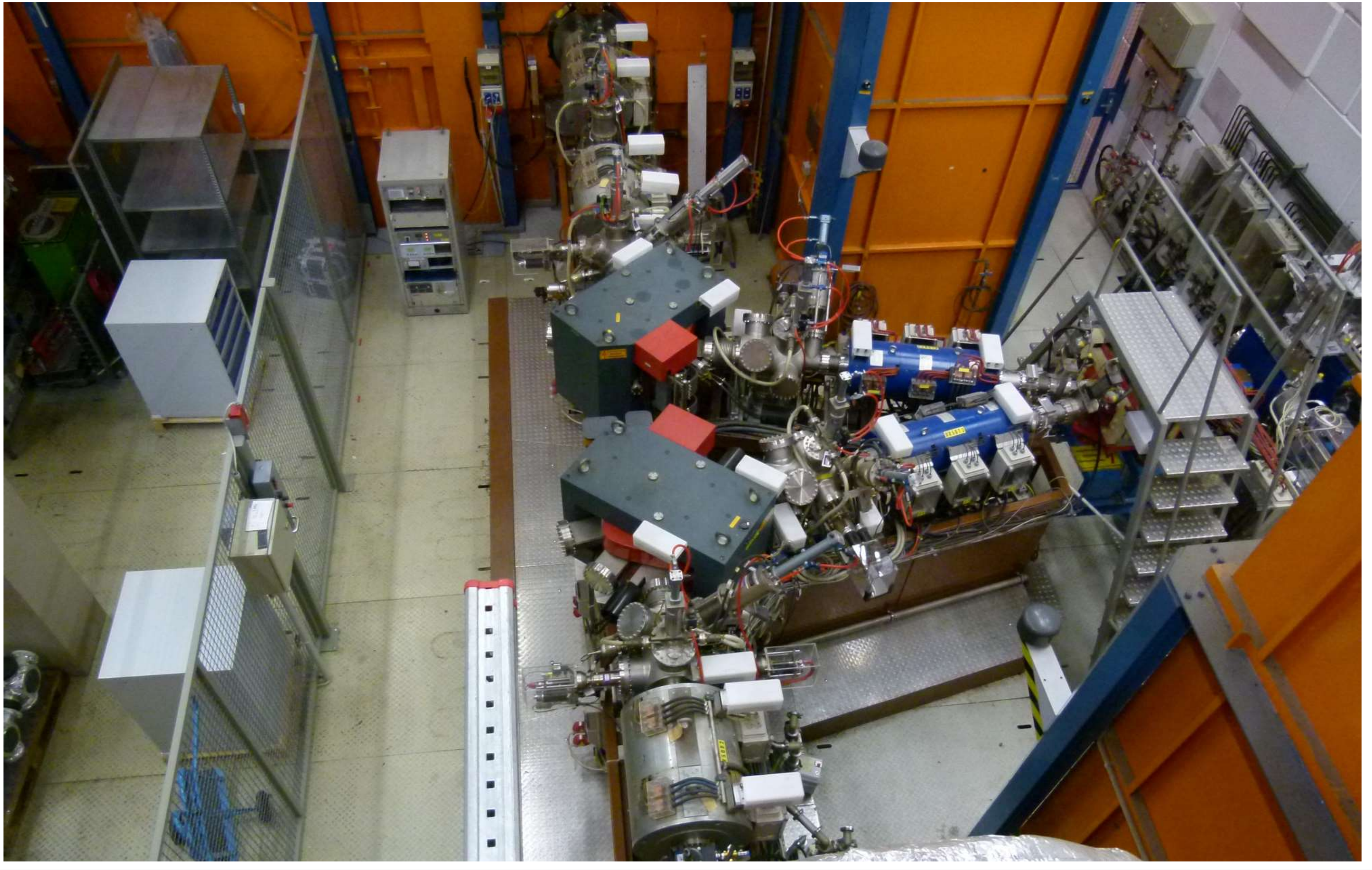


180 mA, 120 mA U^{4+}
90 mA, 60 mA U^{4+}
55 mA, 37 mA U^{4+}
45 mA, 30 mA U^{4+}
15 mA U^{4+}, Max.: 25 mA

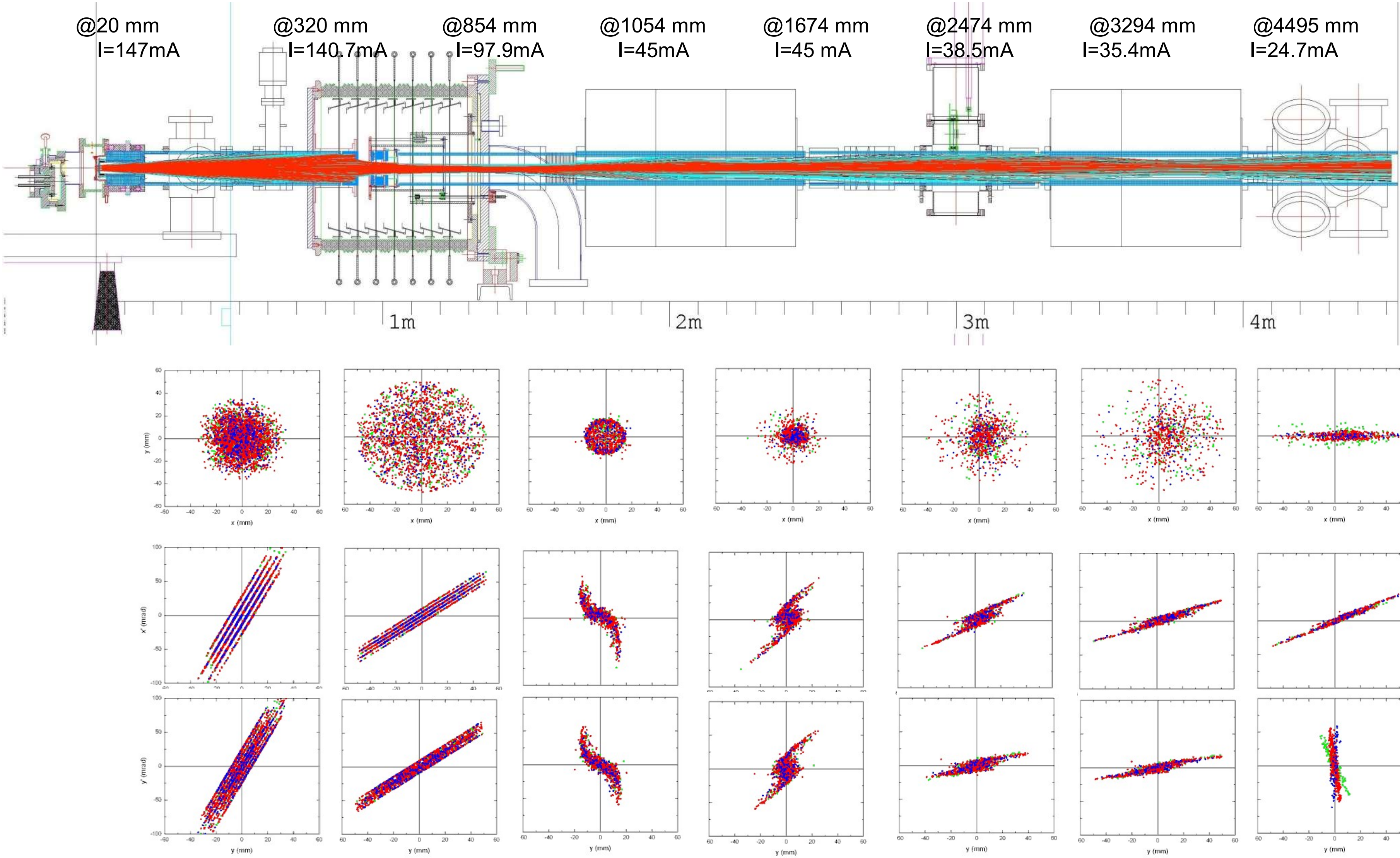
12 mA U^{4+} (in front of RFQ)
ε_x=220π mm mrad
ε_y=200π mm mrad
Max.: 16 mA
For FAIR:
25 mA, ε_x=250π mm mrad



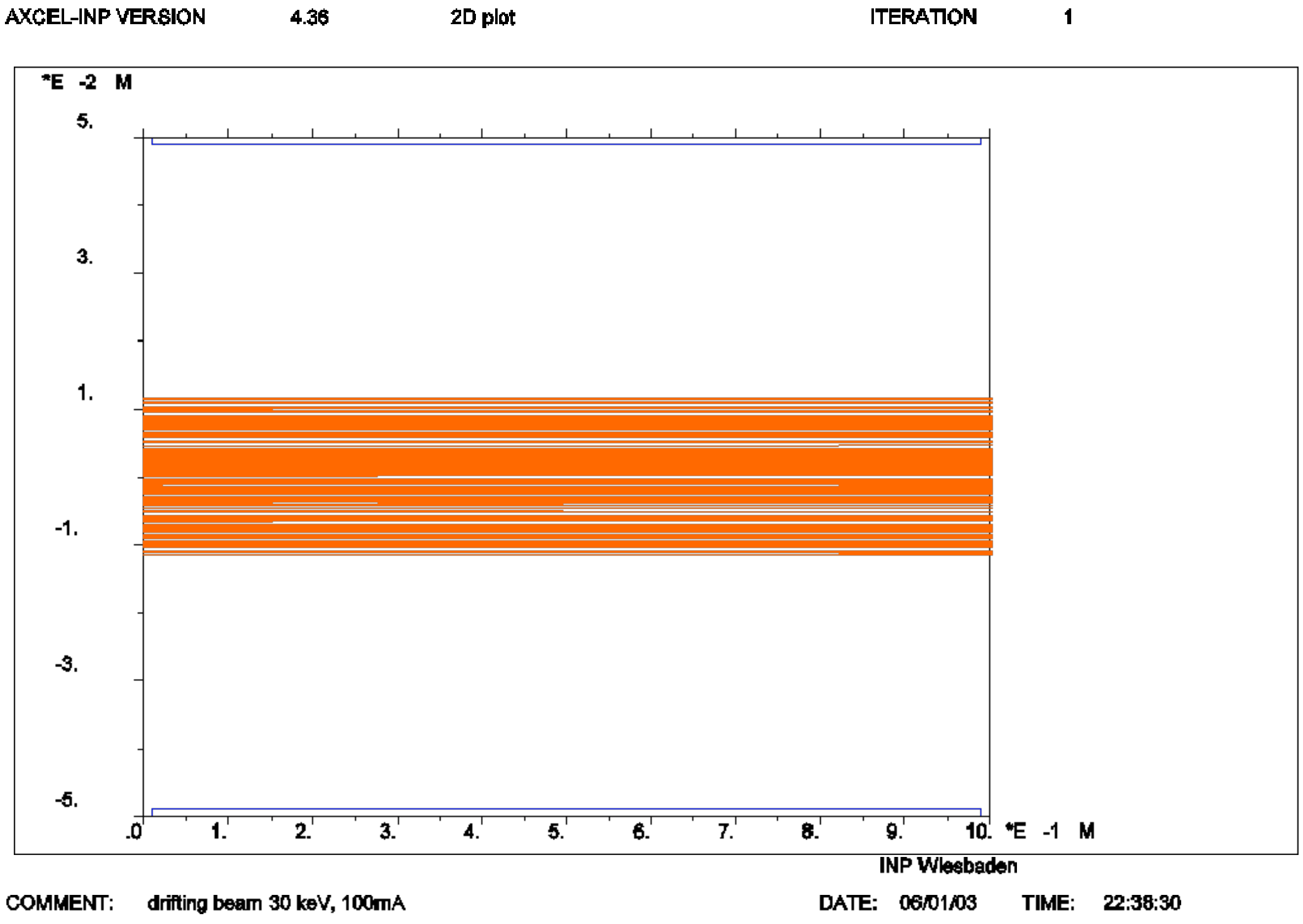
High Current LEBT



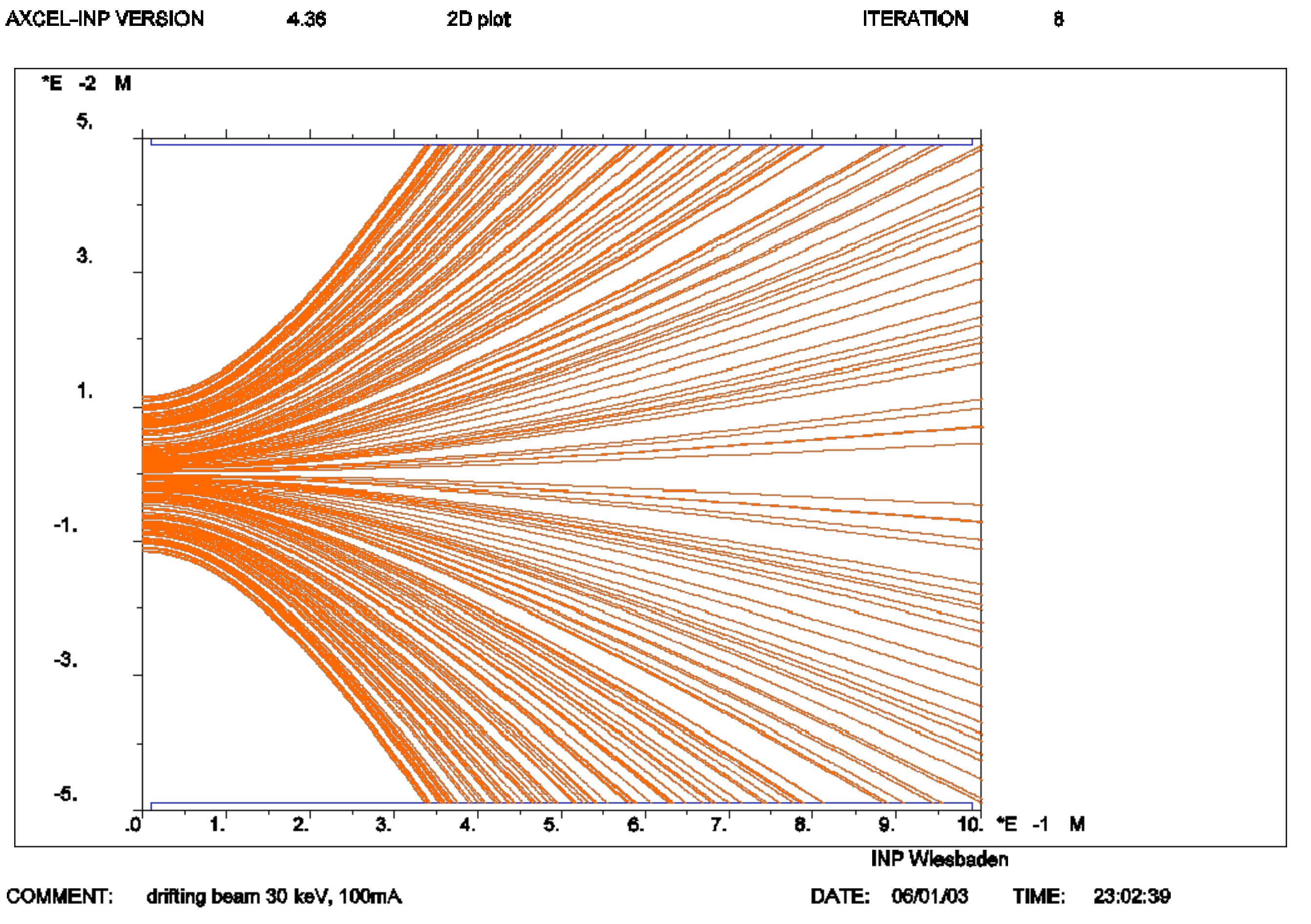
KOBRA3D-Simulation



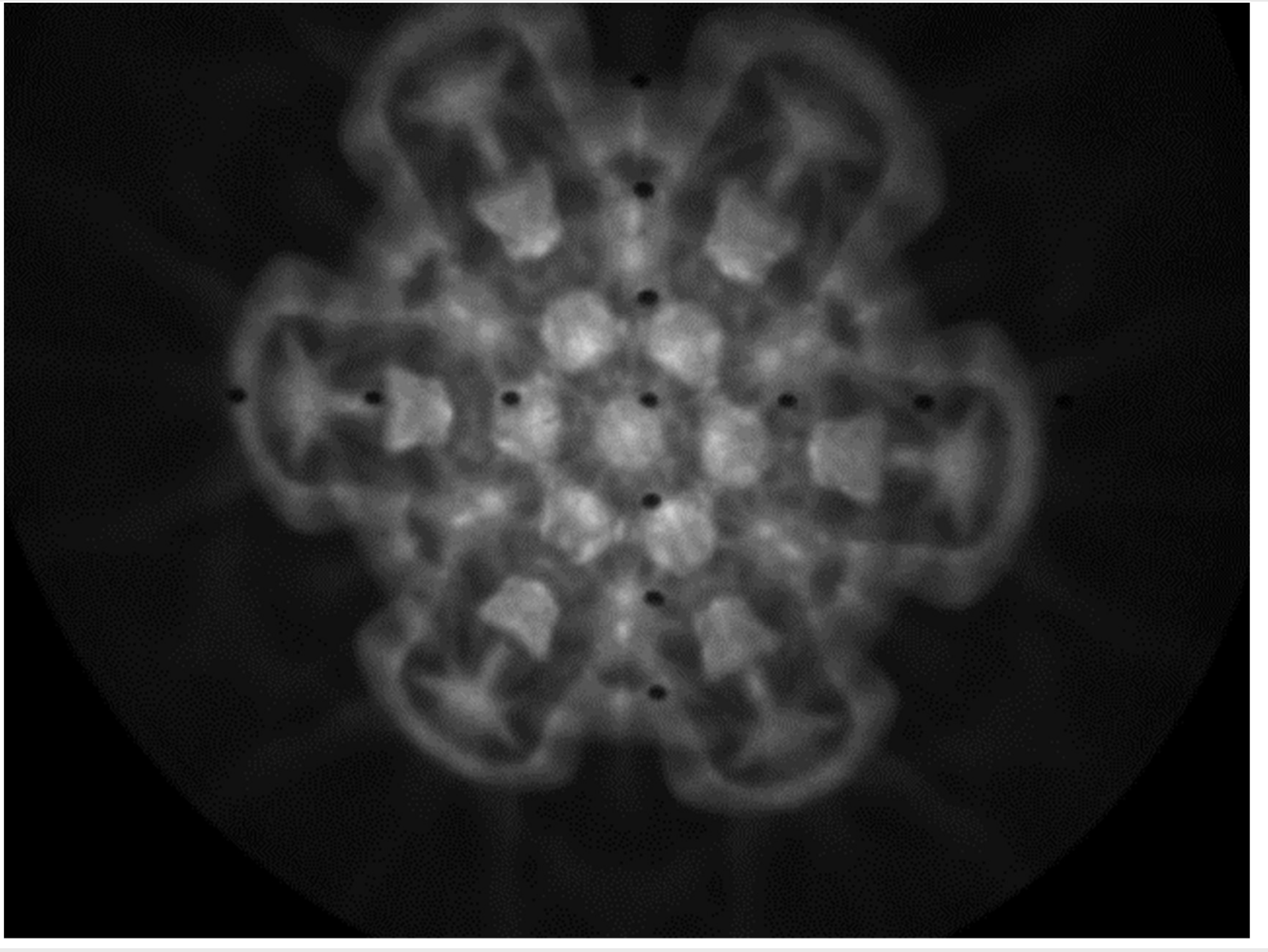
SCC is Important !



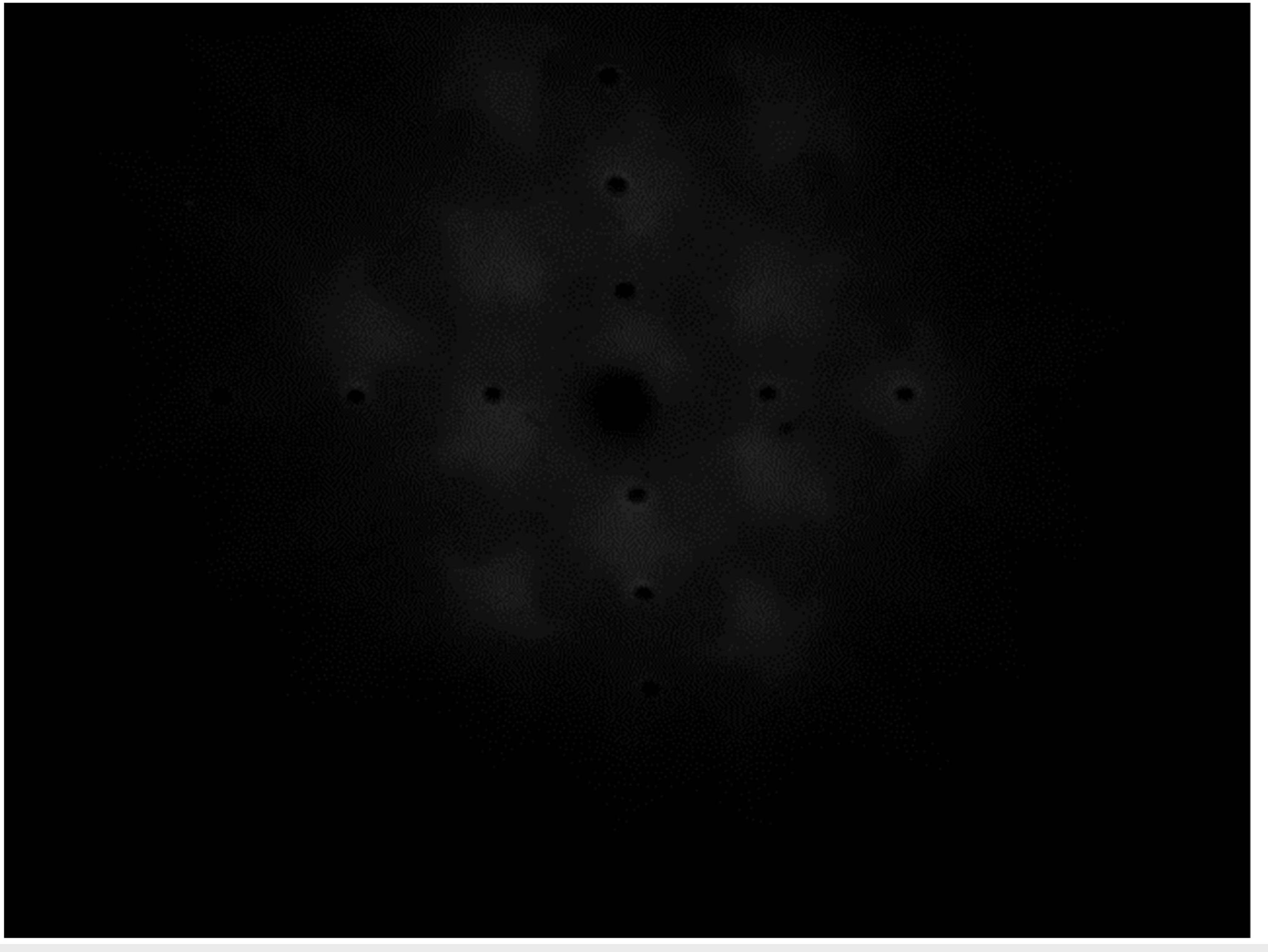
SCC is Important !



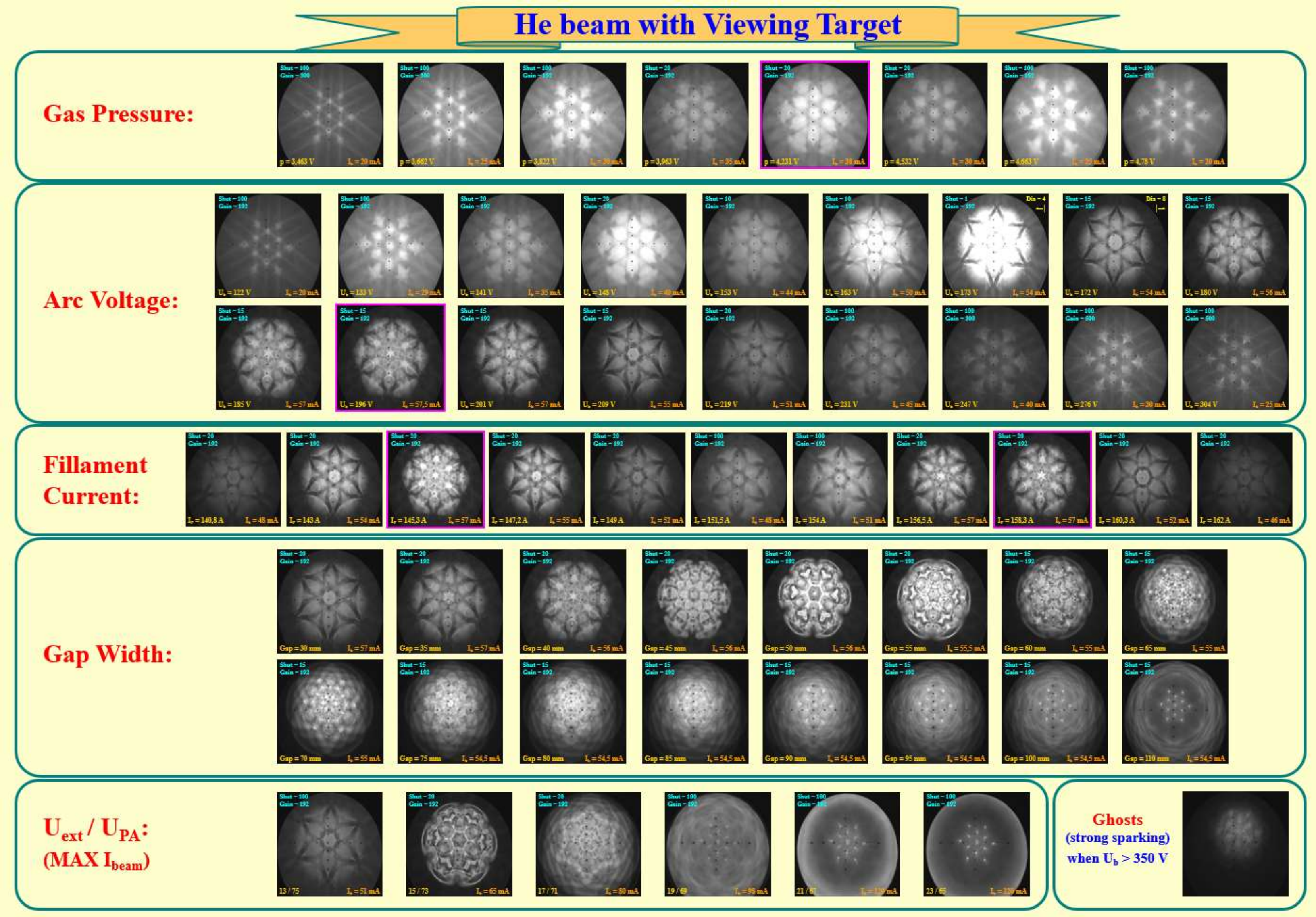
Video Solenoid



Video Solenoid



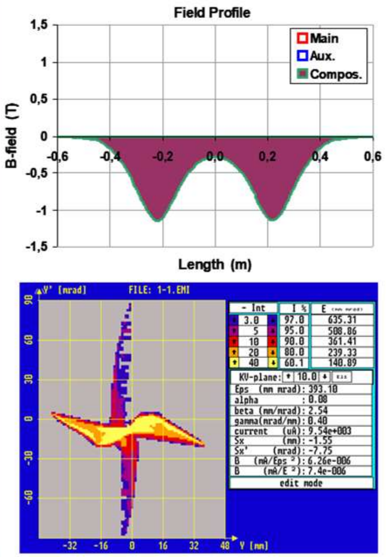
Solenoids


He beam with Viewing Target
Gas Pressure:
Arc Voltage:
Fillament Current:
Gap Width:
U_{ext} / U_{PA}:
(MAX I_{beam})
Ghosts
(strong sparking)
when U_b > 350 V

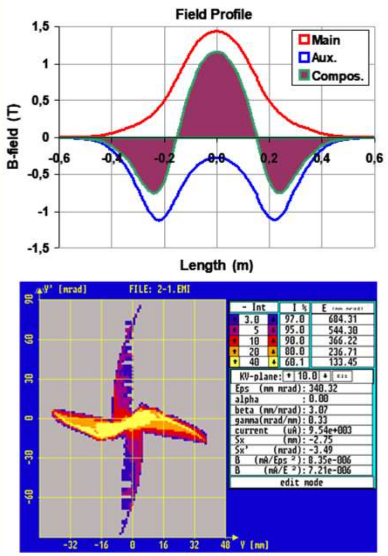
Solenoids

Influence of the Field Profile on the Beam Emittance

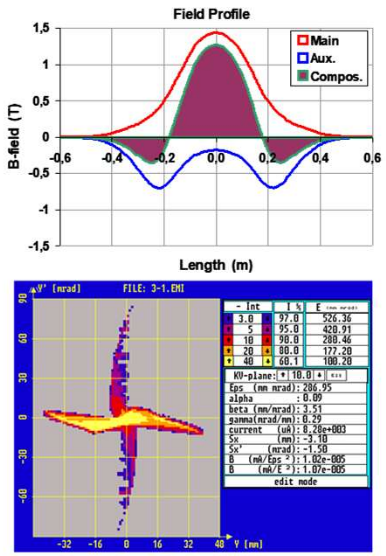
B_{main} = 0 T; $B_{comp.}$ = 1.13 T
$(B^2 \cdot L)_m$ = 0; $(B^2 \cdot L)_c$ = 80.2
$(B^2 \cdot L)_{total}$ = 80.2
I_{beam} = 10.6 mA



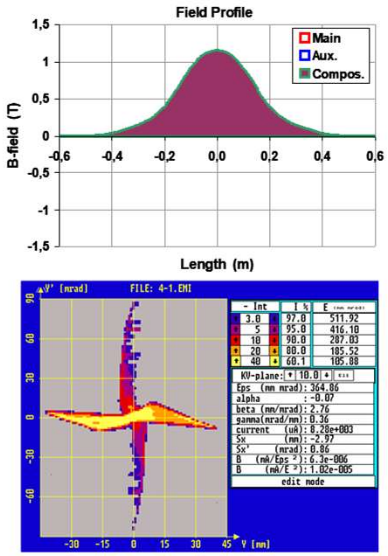
B_{main} = 1.4 T; $B_{comp.}$ = 1.12 T
$(B^2 \cdot L)_m$ = 44.3; $(B^2 \cdot L)_c$ = 25
$(B^2 \cdot L)_{total}$ = 69.3
I_{beam} = 10.6 mA



B_{main} = 1.4 T; $B_{comp.}$ = 0.7 T
$(B^2 \cdot L)_m$ = 59.6; $(B^2 \cdot L)_c$ = 4.8
$(B^2 \cdot L)_{total}$ = 64.4
I_{beam} = 9.2 mA



B_{main} = 1.12 T; $B_{comp.}$ = 0 T
$(B^2 \cdot L)_m$ = 67.4; $(B^2 \cdot L)_c$ = 0
$(B^2 \cdot L)_{total}$ = 67.4
I_{beam} = 9.2 mA

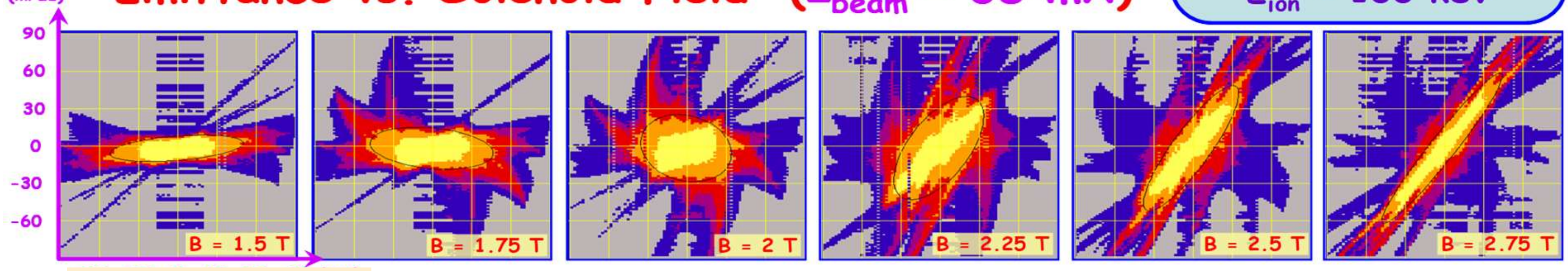


Solenoids

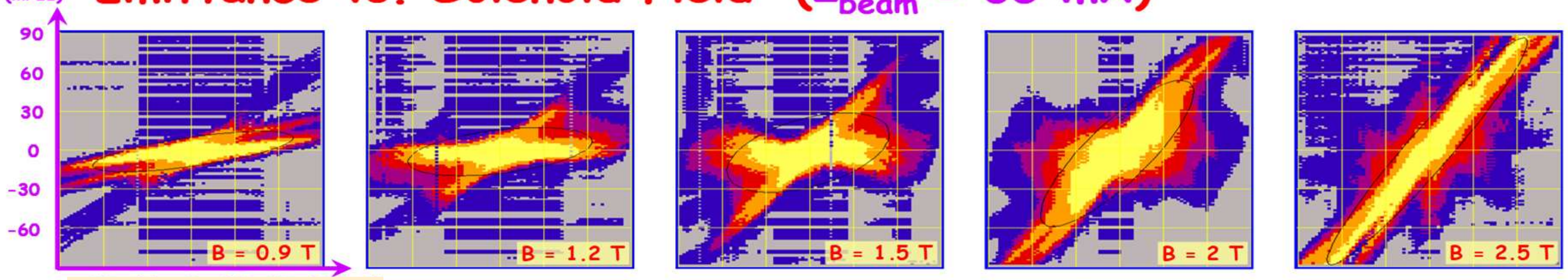
$^{181}Ta^{3+}$ (MEVVA)

E_{ion} = 133 keV

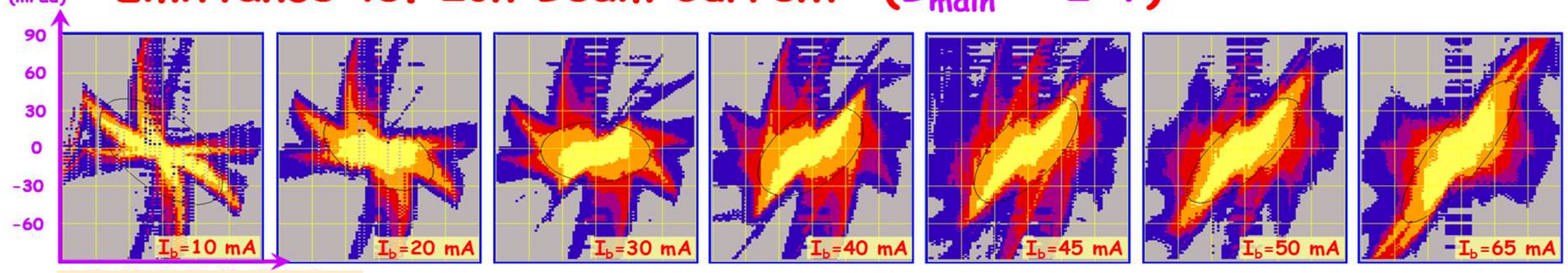
Emittance vs. Solenoid Field (I_{beam} = 38 mA)



Emittance vs. Solenoid Field (I_{beam} = 65 mA)



Emittance vs. Ion Beam Current (B_{main} = 2 T)



Experimental Setup

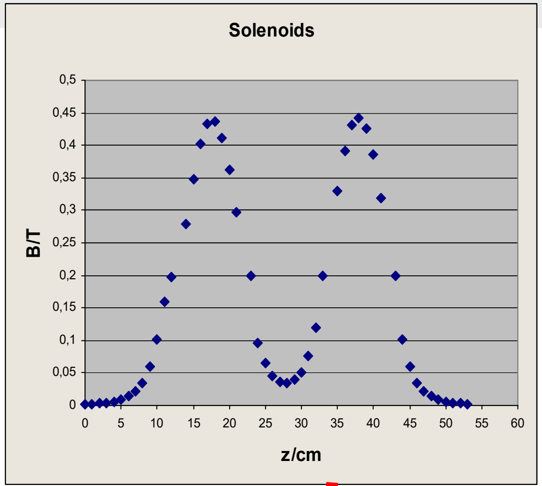
Ion Source:
CHORDIS

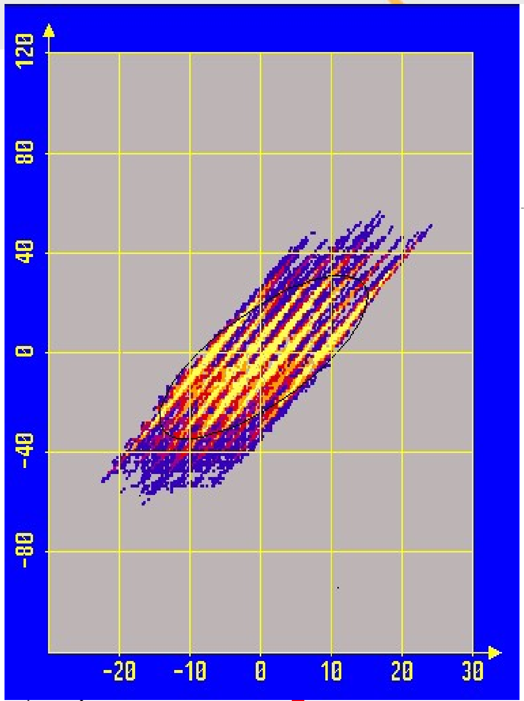
Ions:
98% He^{+}
2% He^{2+}

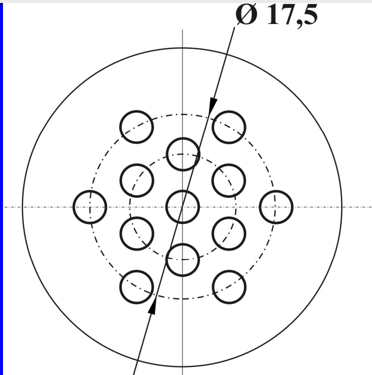
Ion Current:
60mA@22kV

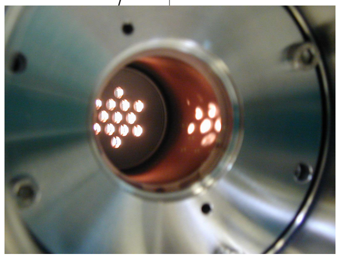
Extraction System:
13 x 3mm

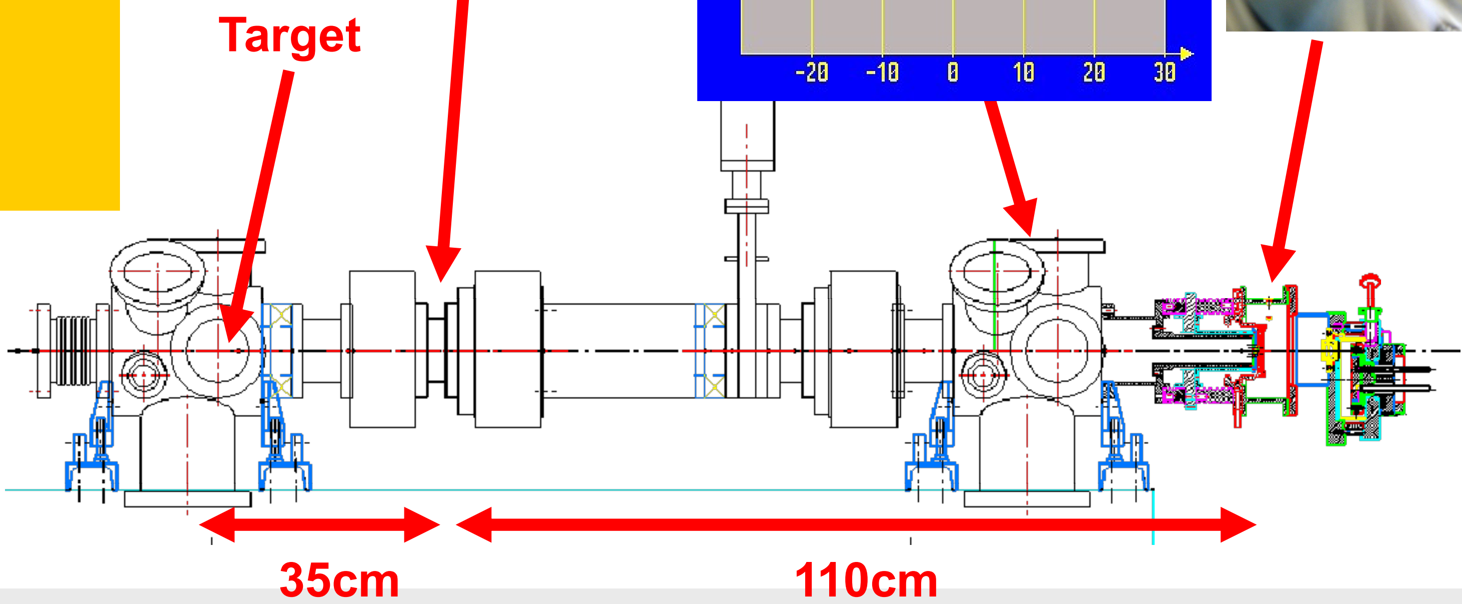
Viewing Targets:
YO_2S
KBr
BaF



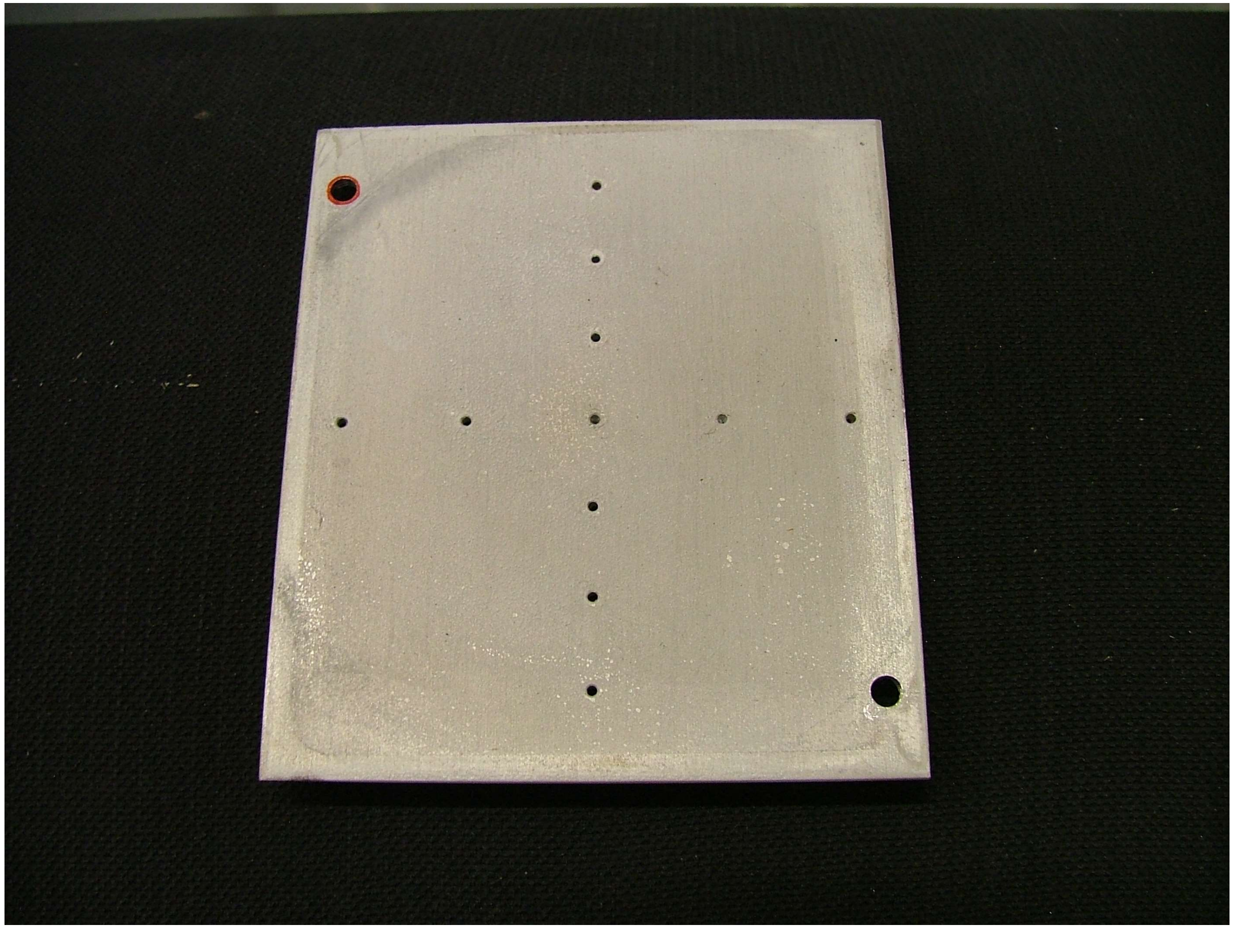




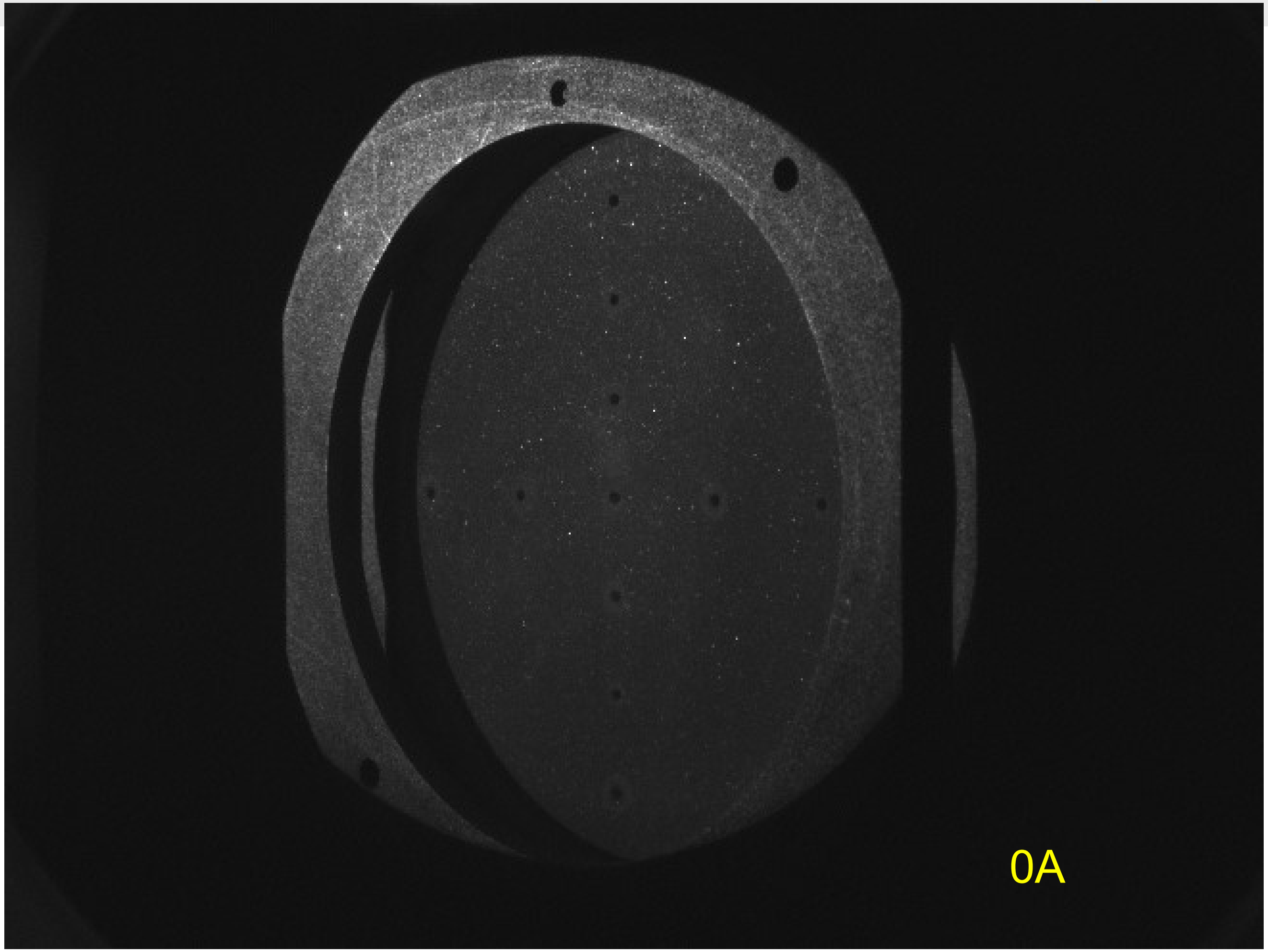




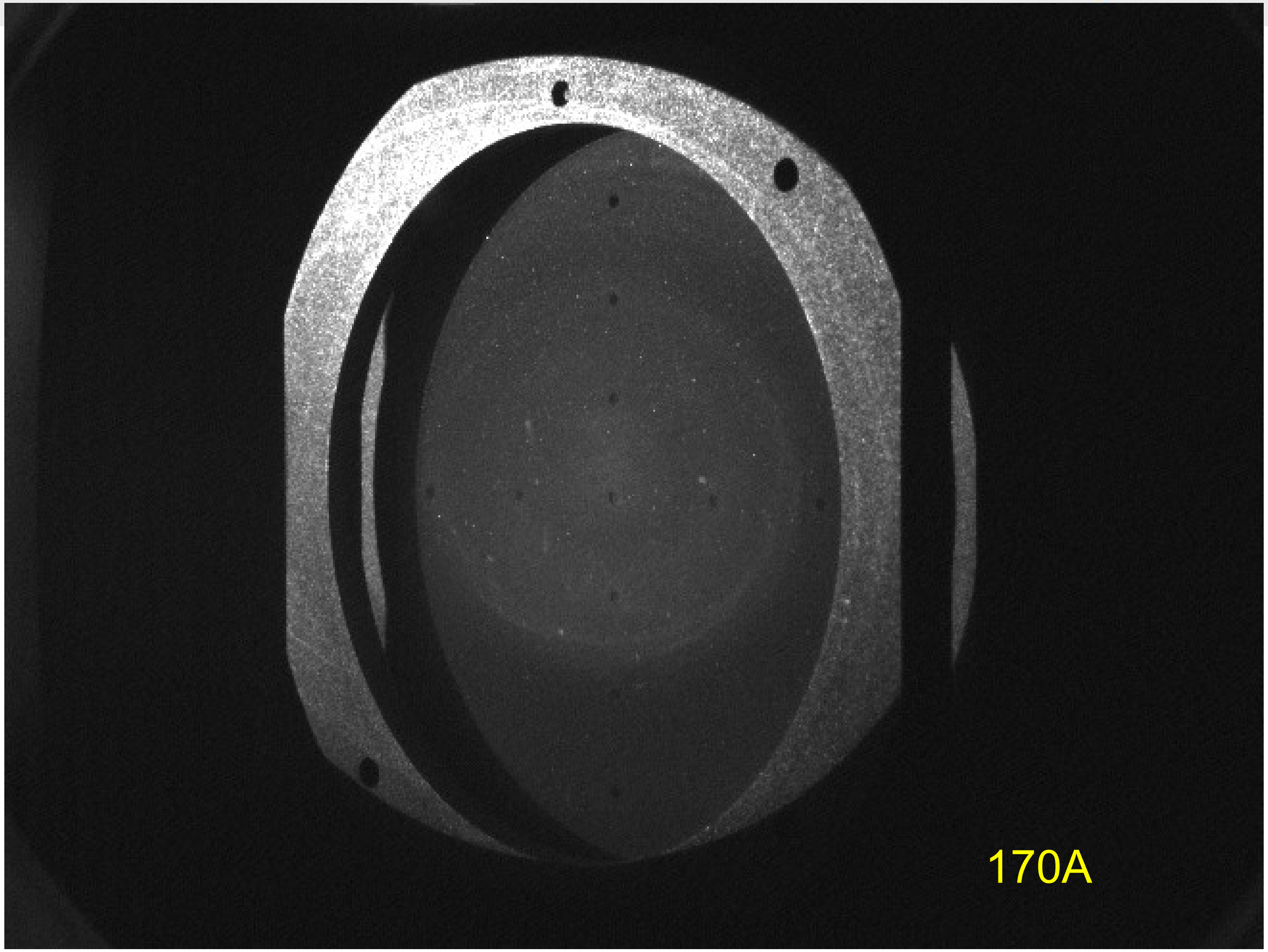
Viewing Target



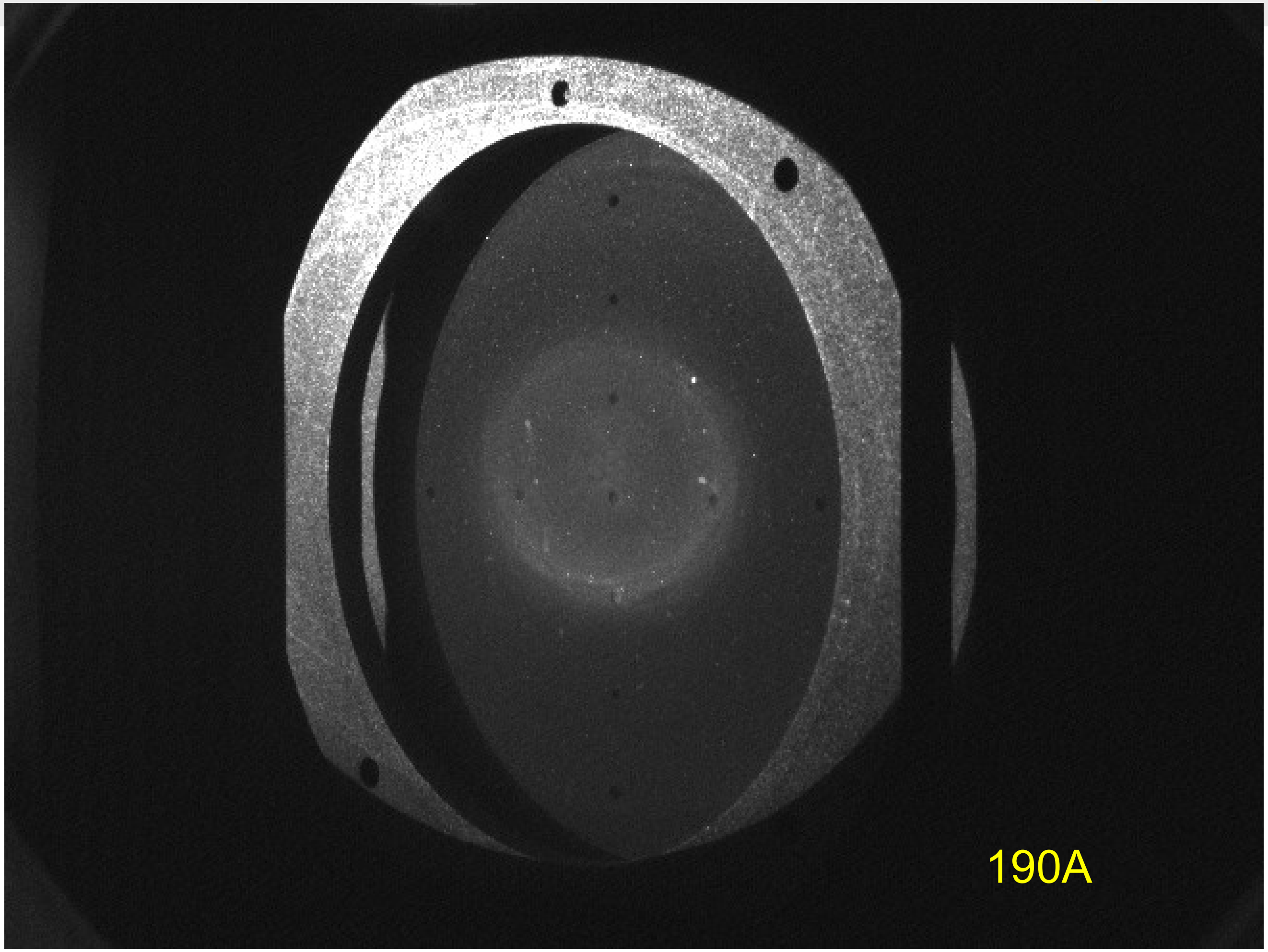
Viewing Target (YO_2S), no Impurities, High Curr.



Viewing Target



Viewing Target



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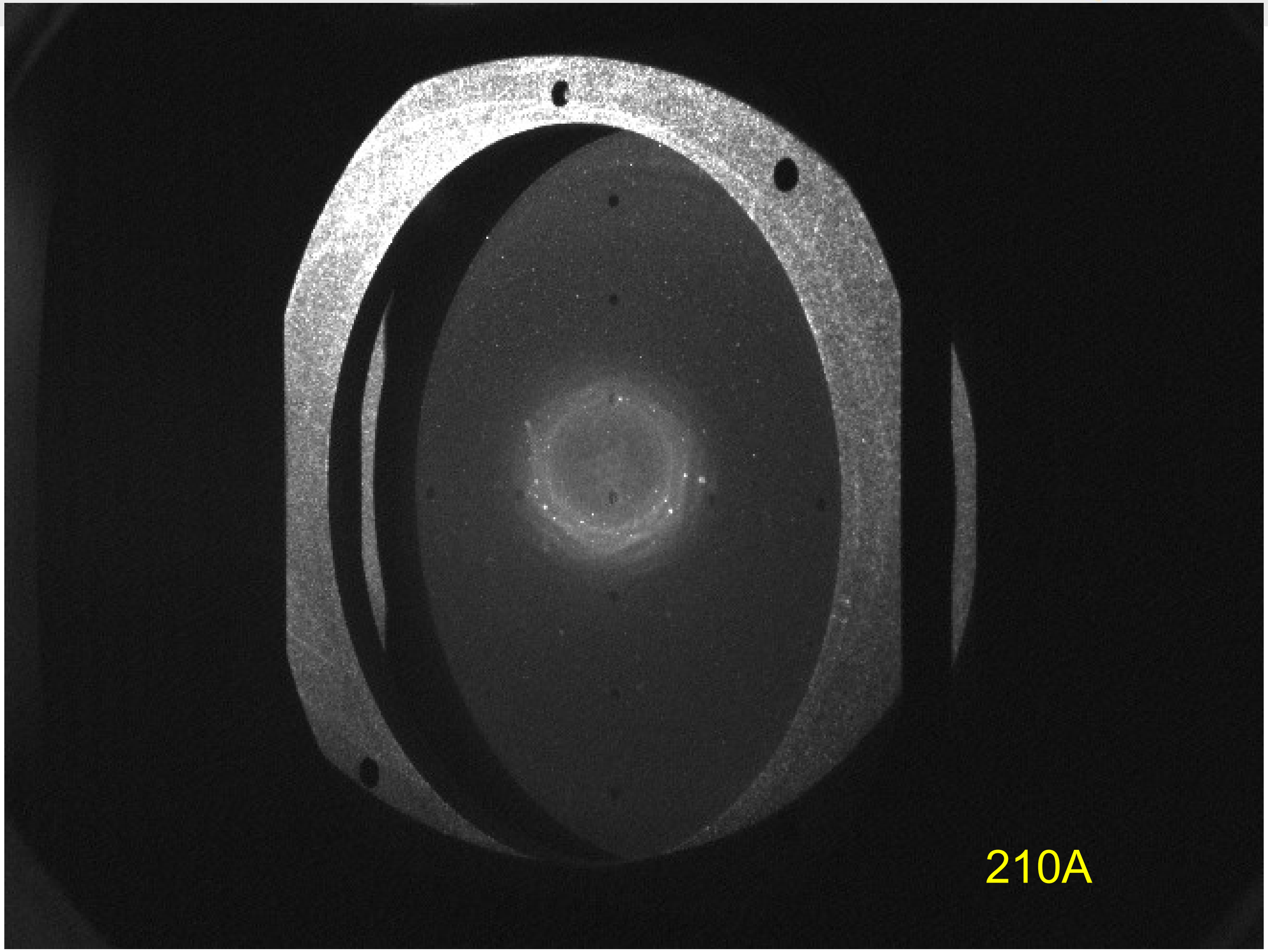
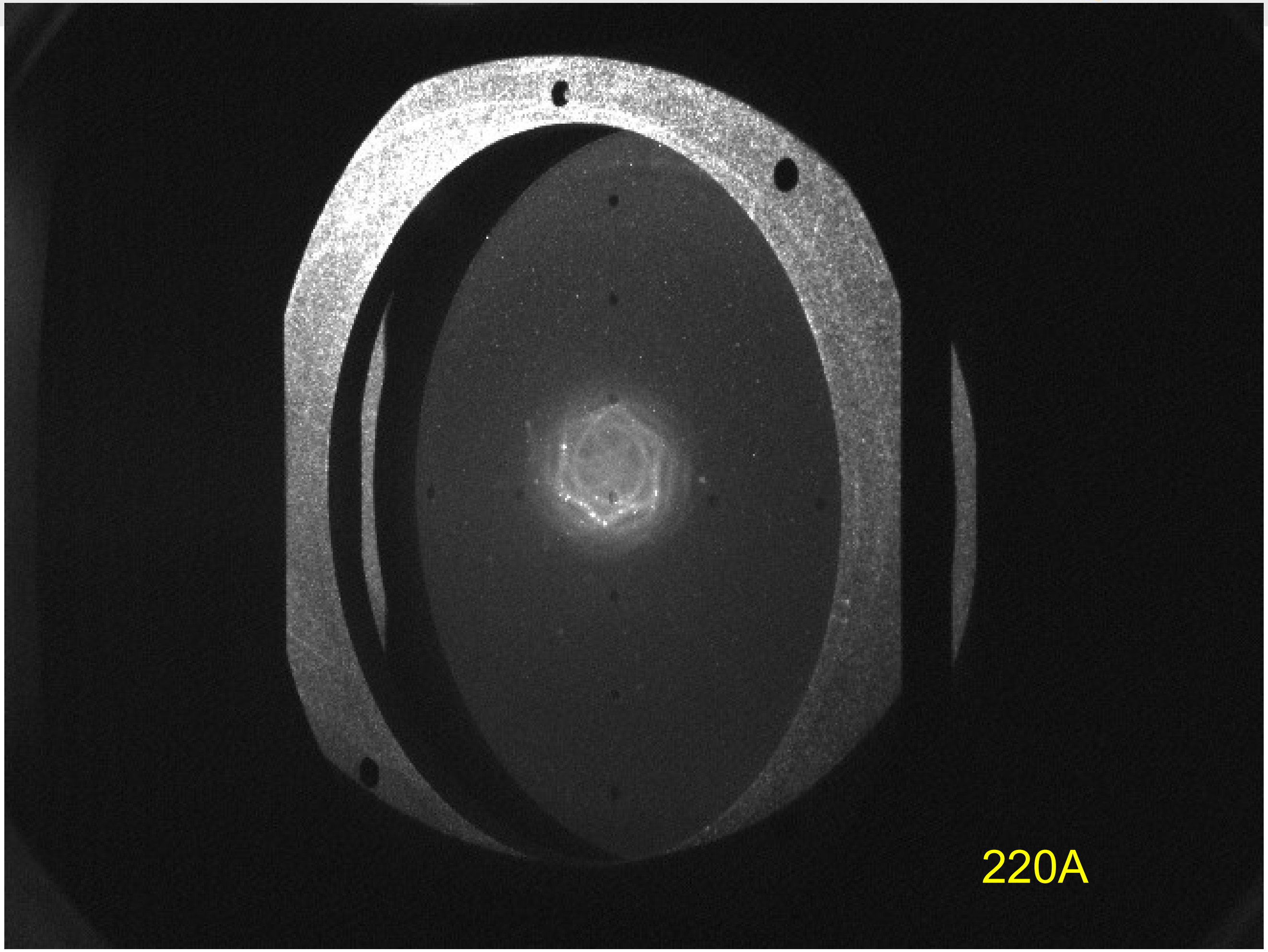


Viewing Target



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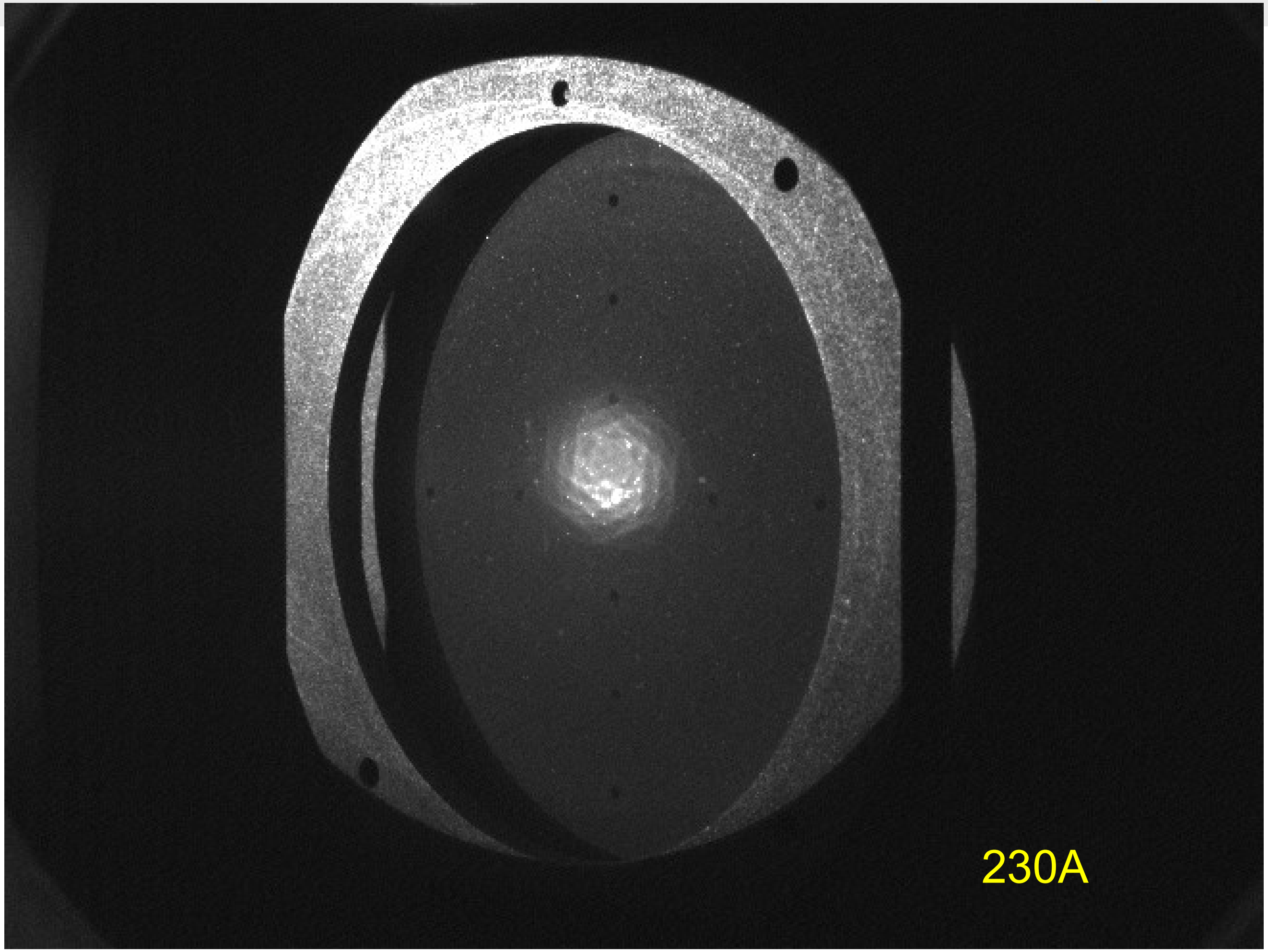

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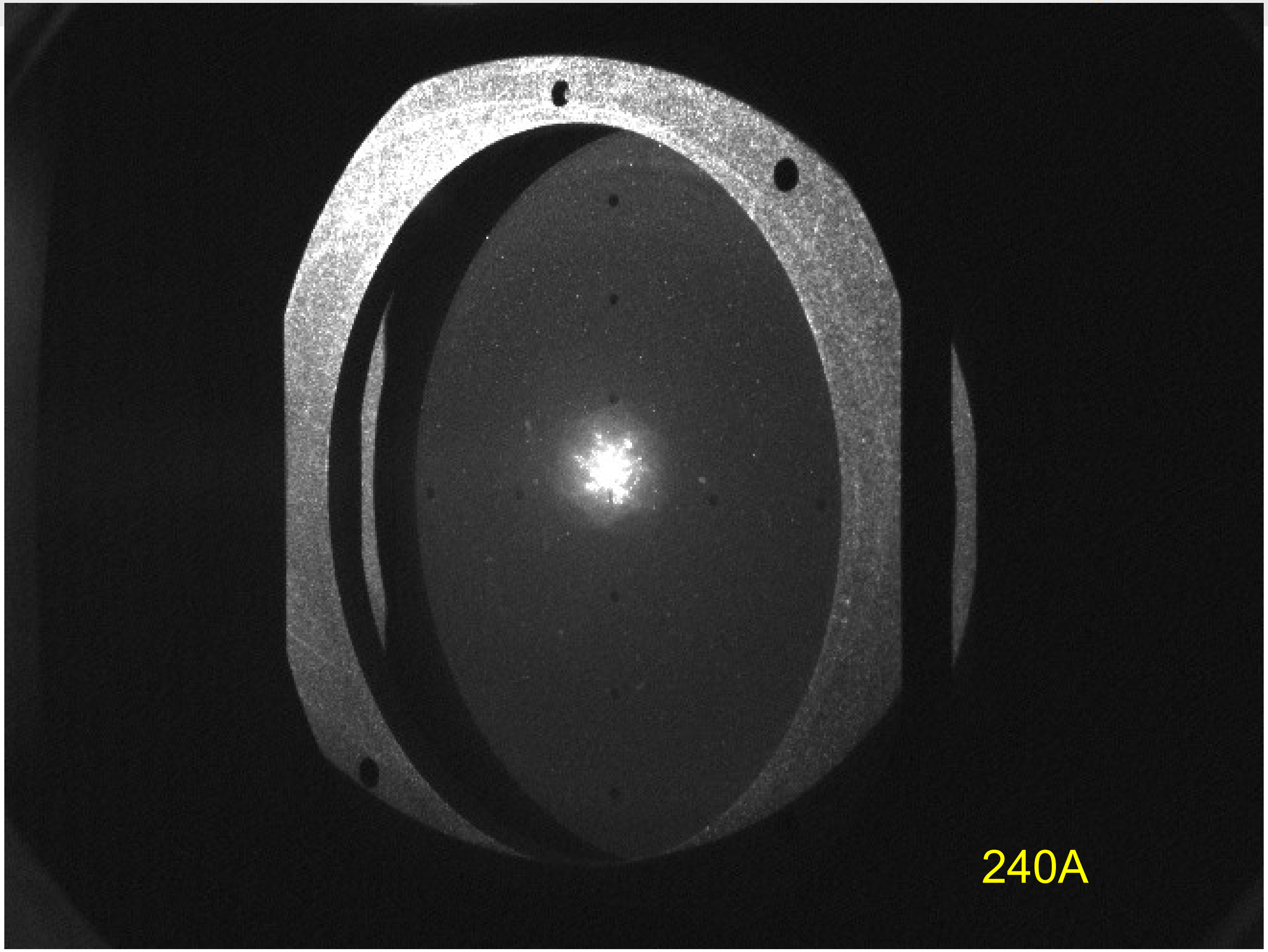
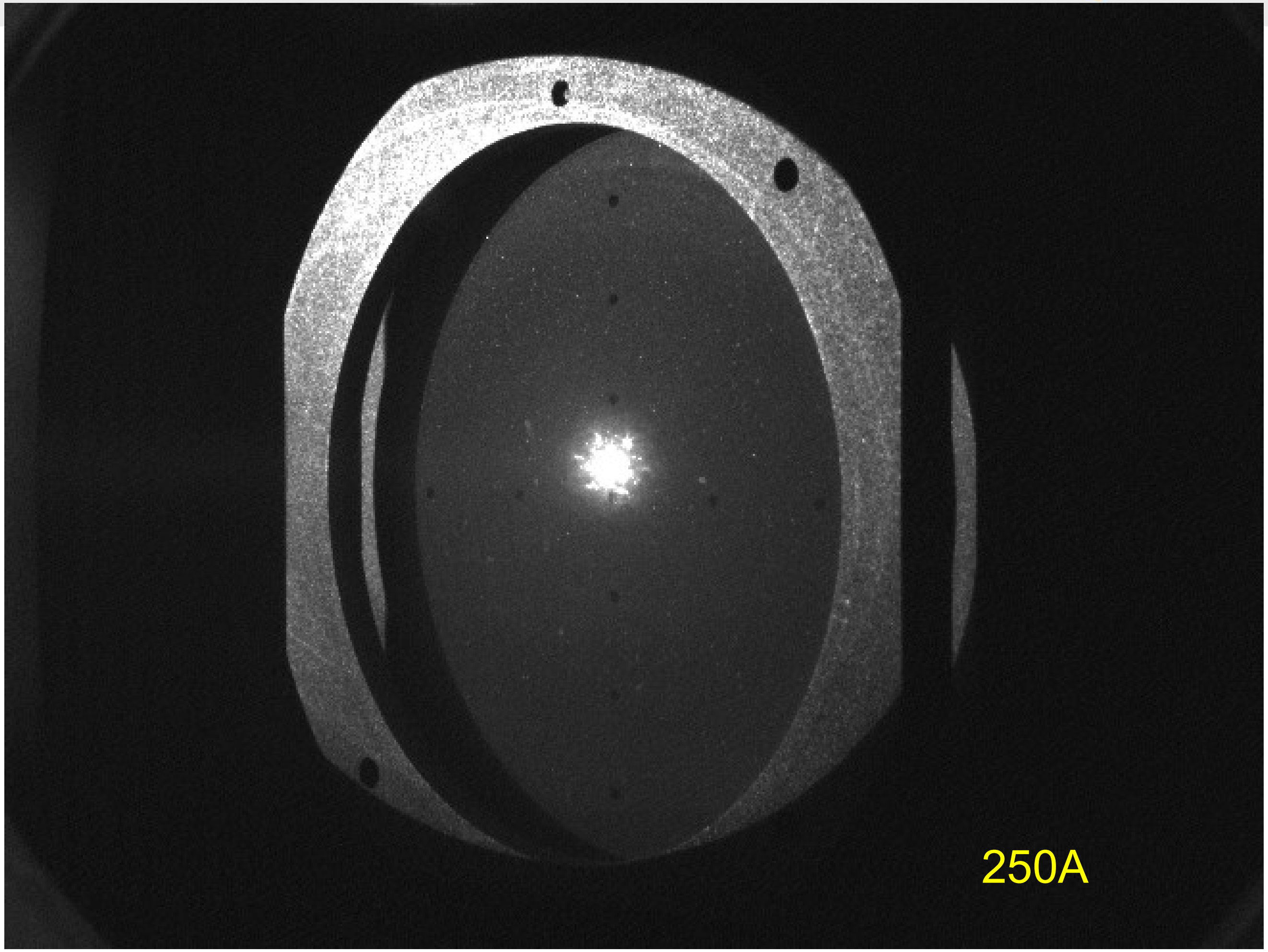
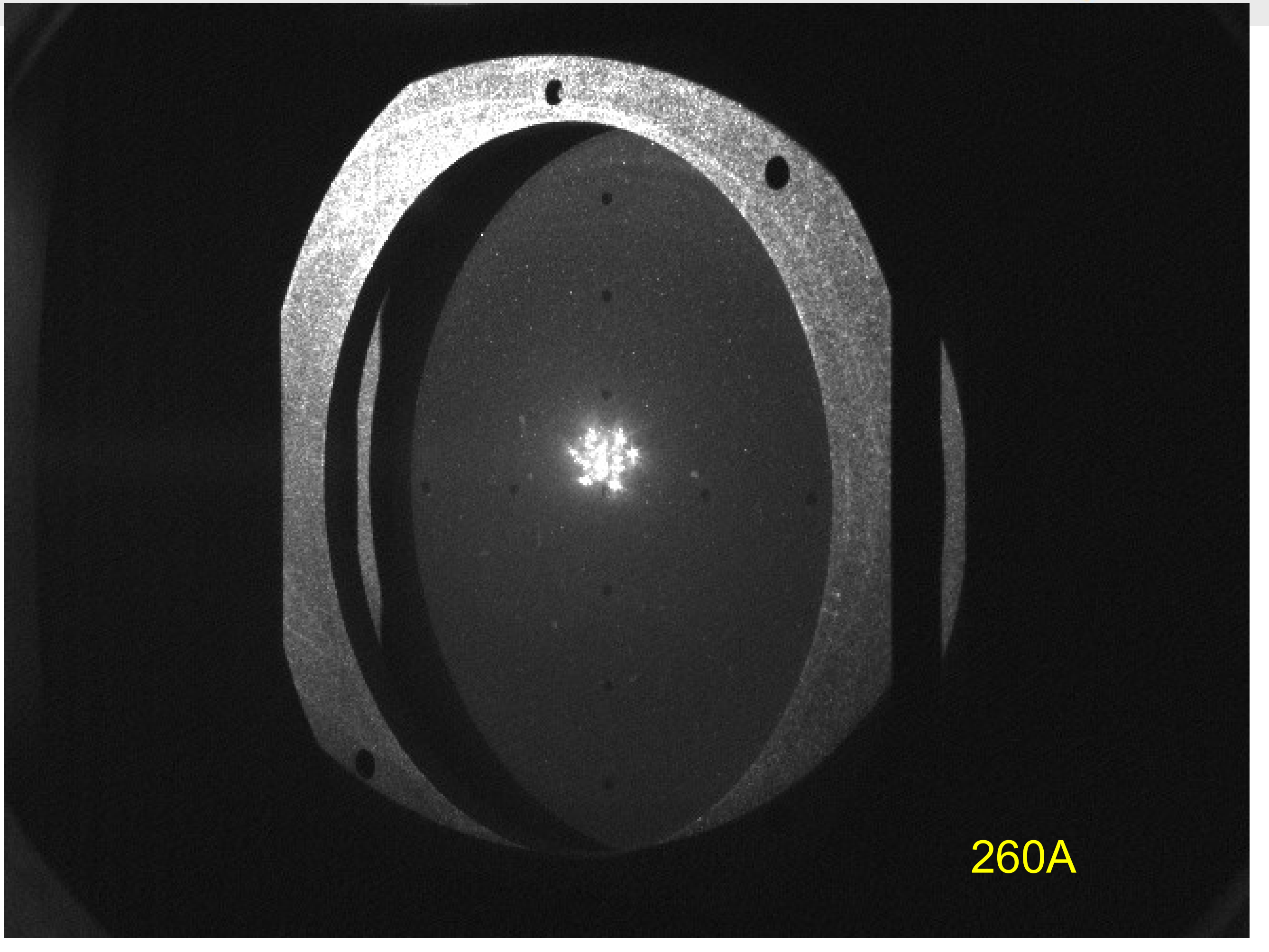


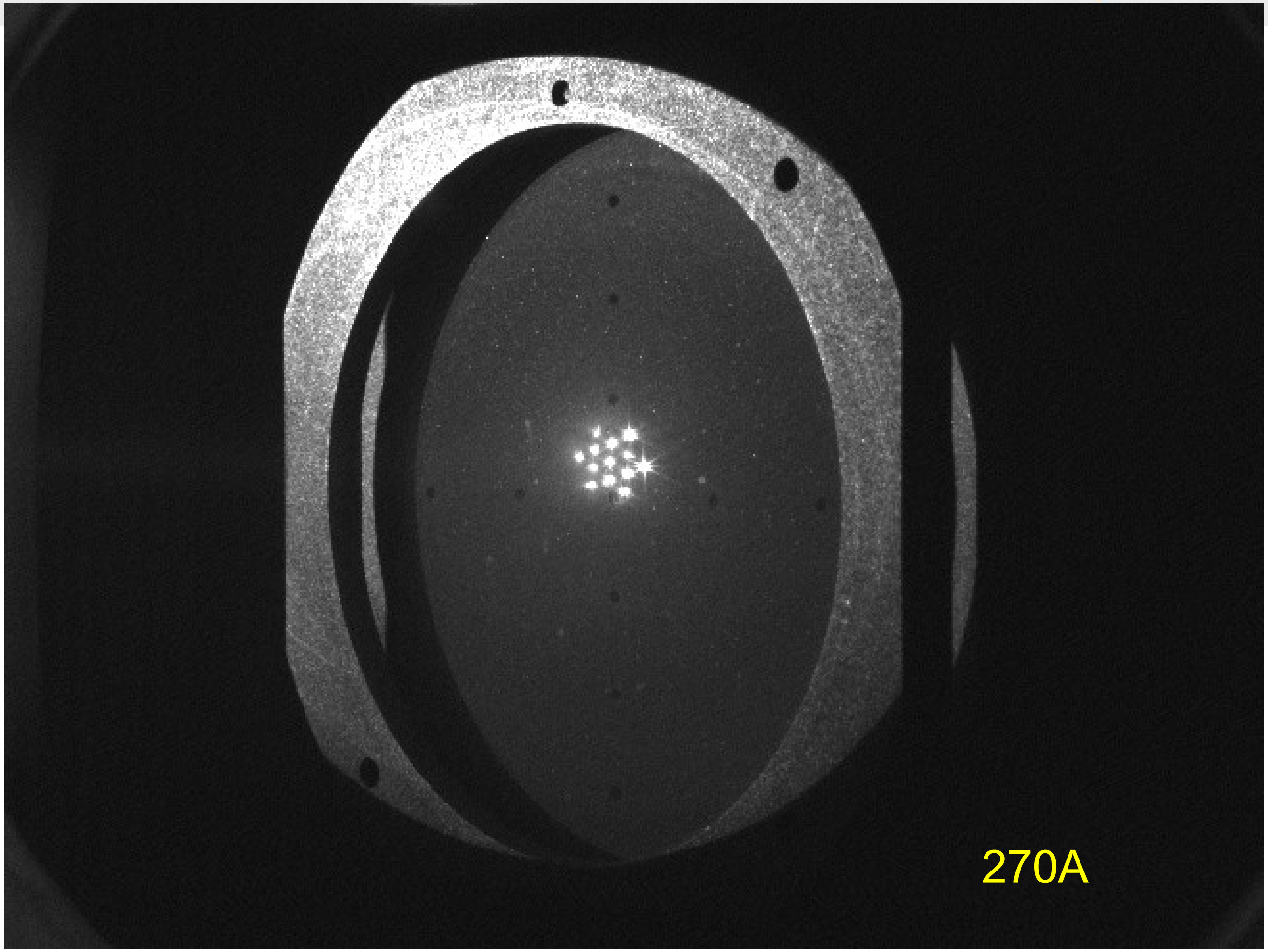
Viewing Target



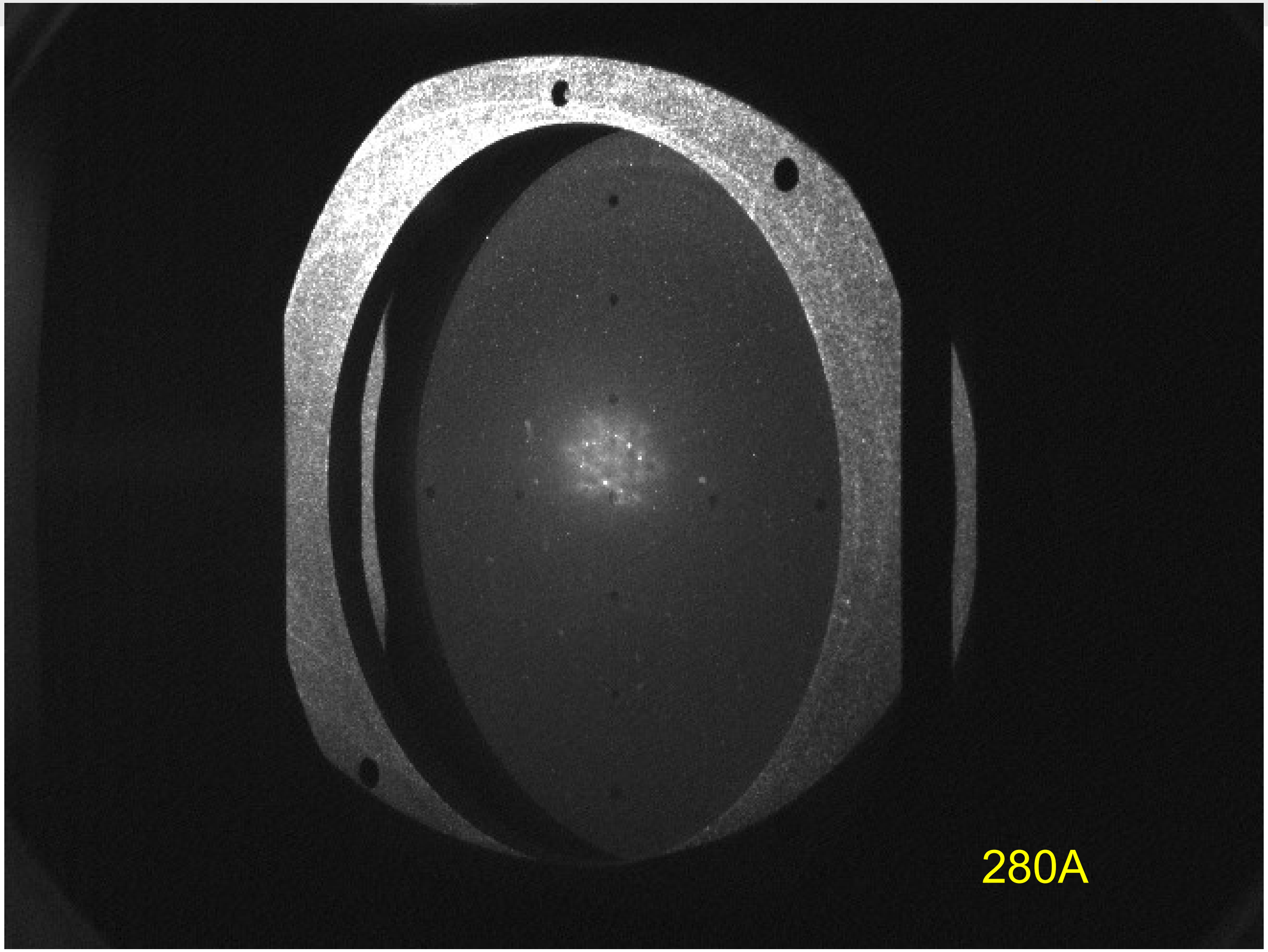
Viewing Target



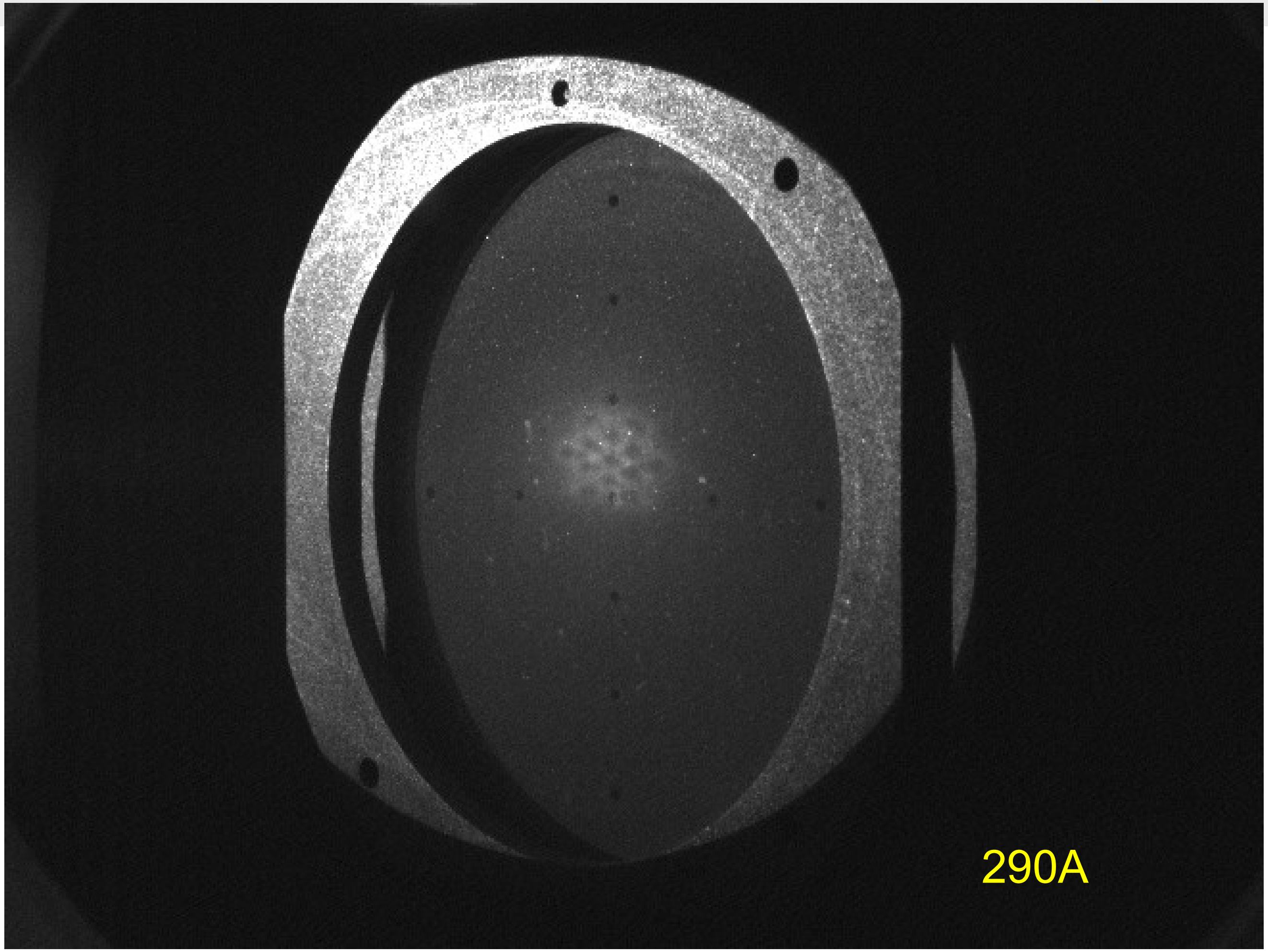
Viewing Target



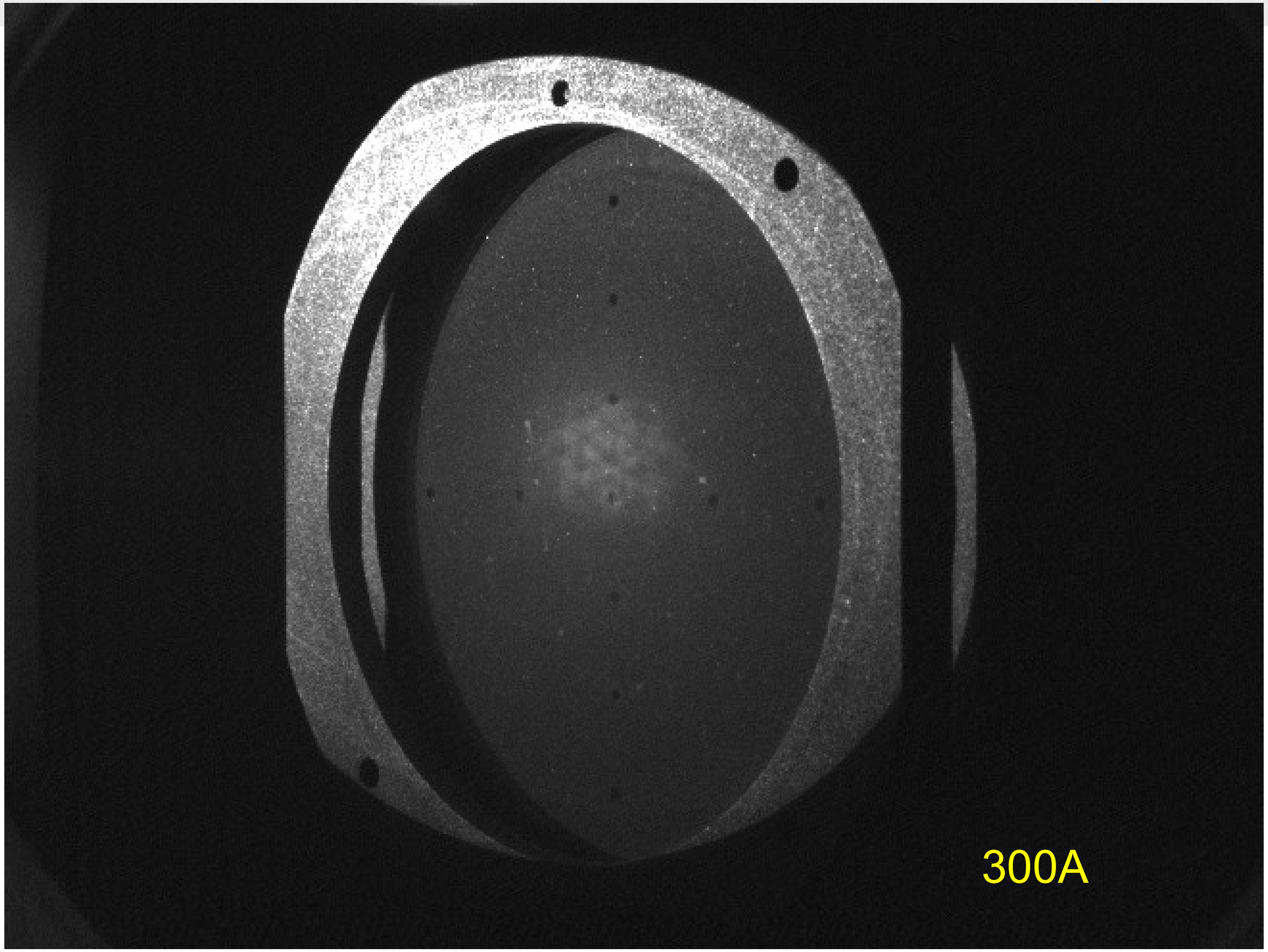
Viewing Target



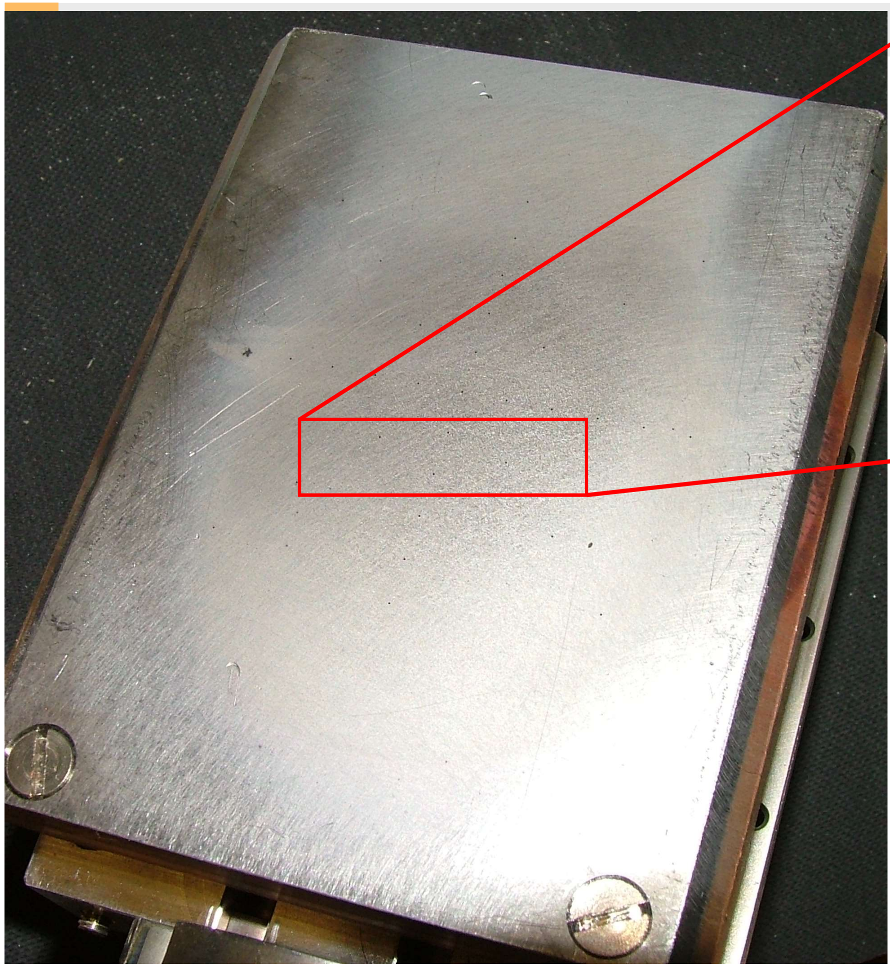
Viewing Target

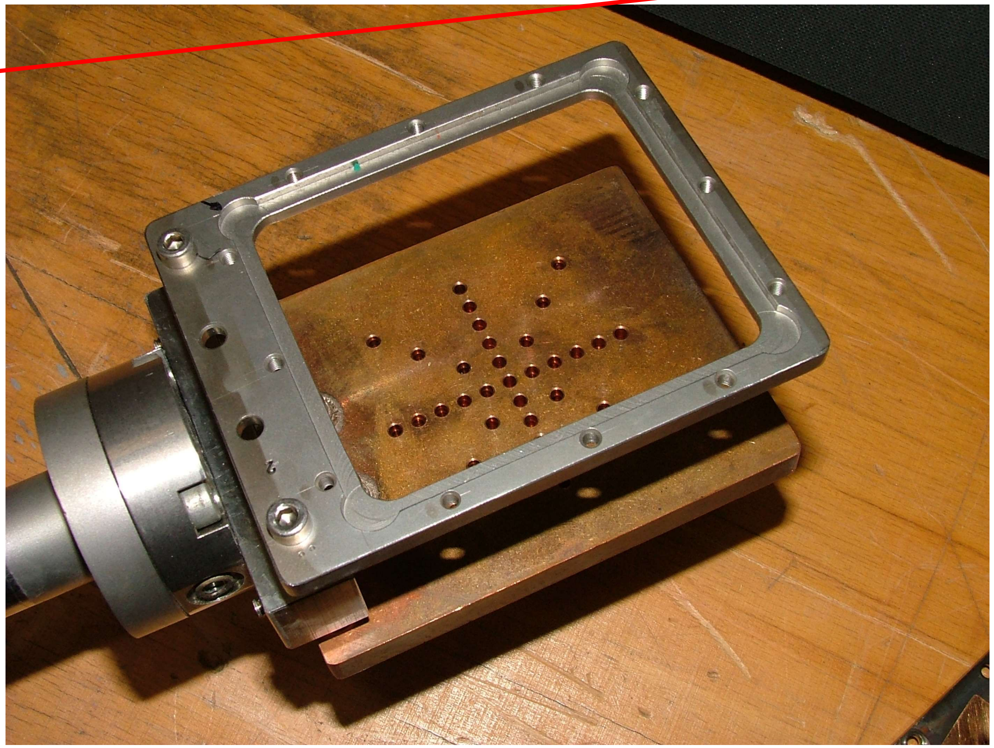


Viewing Target



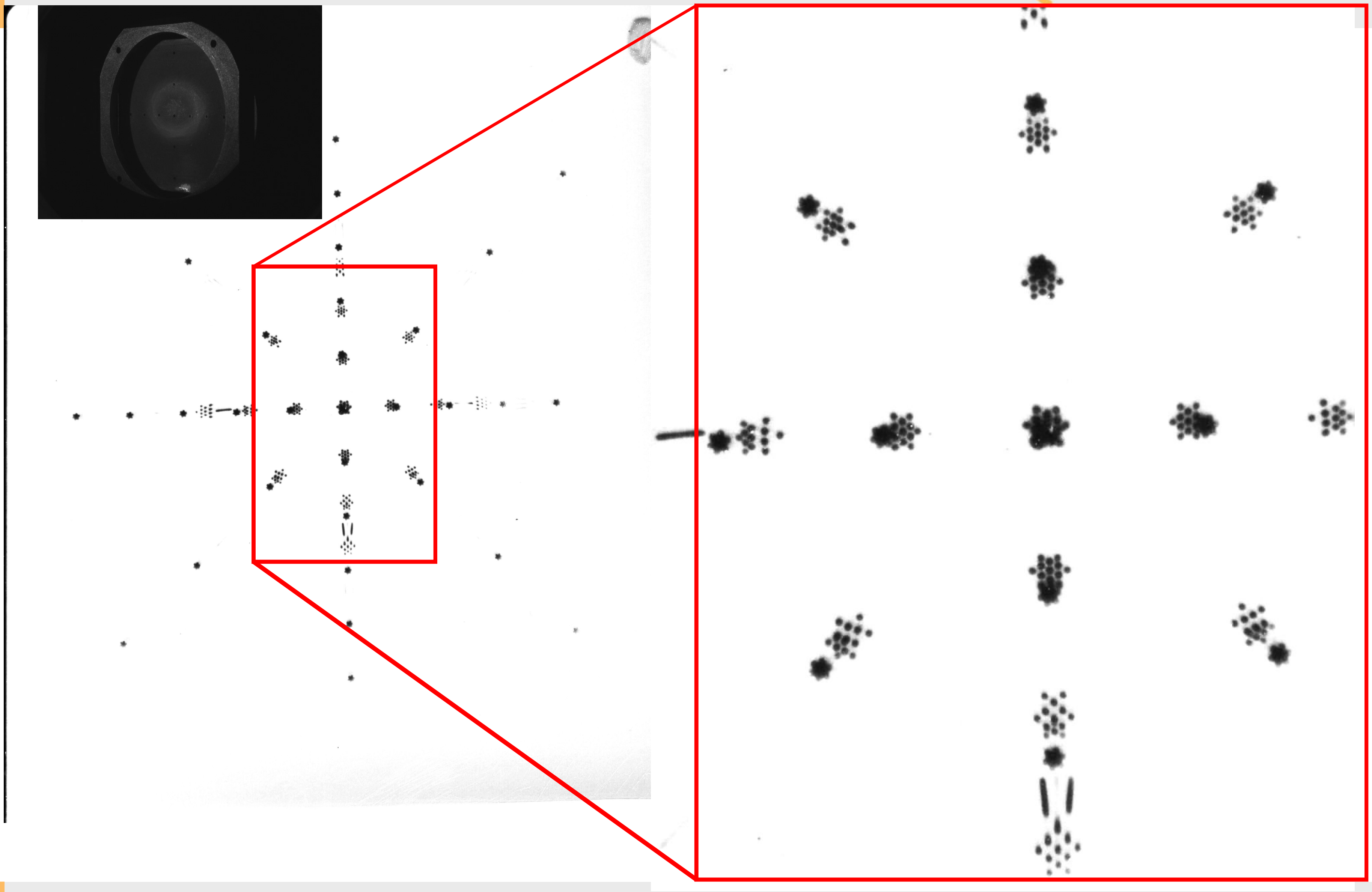
Pepper Pot





0.2 mm hole
5 mm distance

Pepper Pot for I_{sol}=160A



Pepper Pot, Ions bended by a Dipole