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The CUBE-ECRIS prototype — towards a 100 GHz ECRIS

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Hannu Koivisto[a] and Olli Tarvainen[b]

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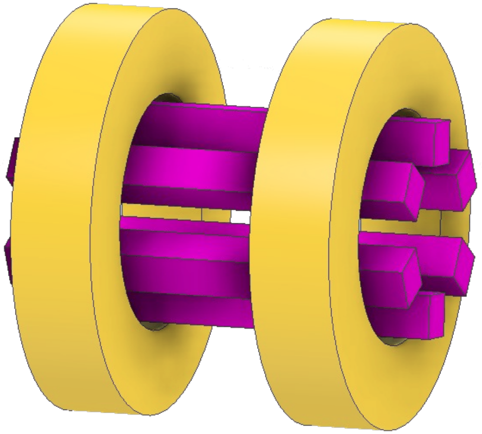
20.9.2023, 20th International Conference on Ion Sources, Victoria, BC, Canada

Outline

- Introduction to ARC-ECRIS quadrupole Bmin
- Permanent magnet CUBE-ECRIS
- High charge state generation
- Extraction from quadrupole Bmin field
- Scaling from 10 GHz to 100 GHz?



Conventional ECRIS

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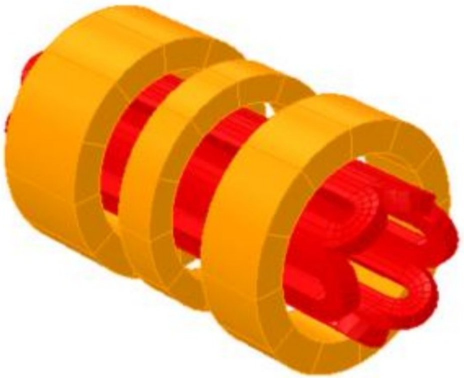
Towards the next generation ECRIS

State-of-the-art NbTi limited at 28 GHz



Sextupole within solenoid:
LBNL Venus

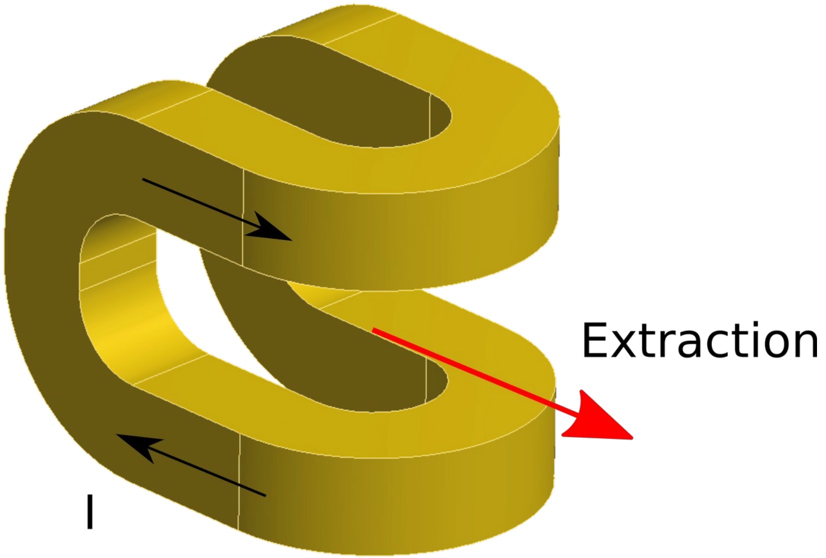
Solenoid within sextupole:
IMP SECRAL

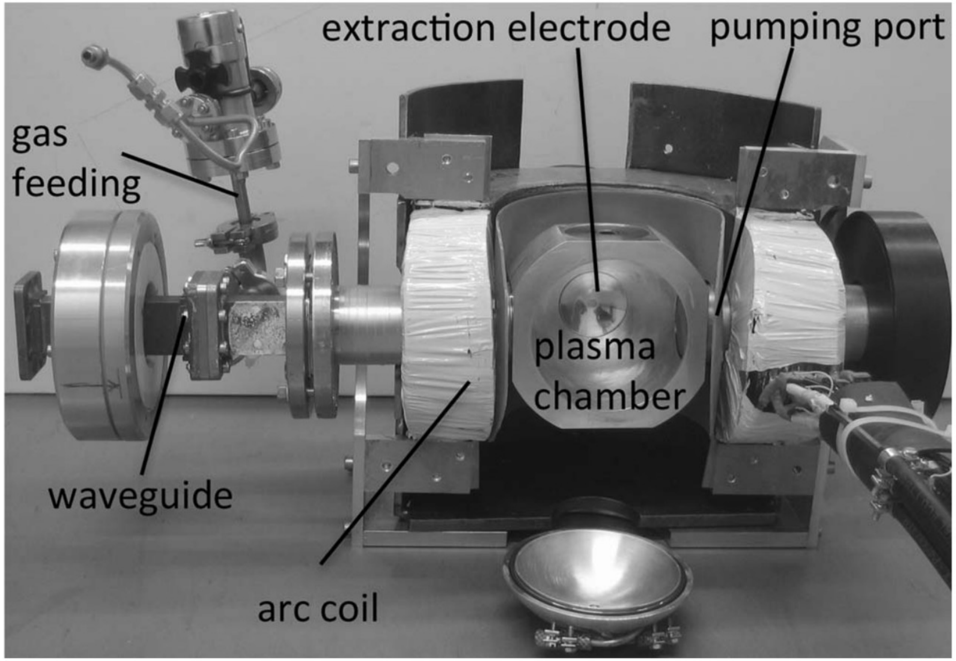
M. Juchno, et al., “Shell-Based Support Structure for the 45 GHz ECR Ion Source MARS-D”, IEEE Transactions on Applied Superconductivity 32, 4101005 (2022).

Mirror Fusion Test Facility

Basball-seam /
Yin-yang magnetic
trap from 1980s

The first 6.4 GHz ARC-ECRIS at JYFL





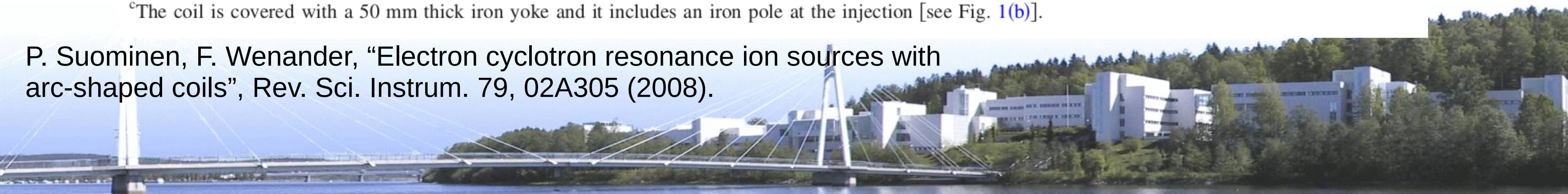
P. Suominen, T. Ropponen, and H. Koivisto, Nucl. Instrum. Methods A 578(2), 370 (2007).

Feasible for 100 GHz operation

TABLE I. Examples of the magnetic fields achievable with a three layer arc-shaped coil (coil parameters shown in Fig. 2).

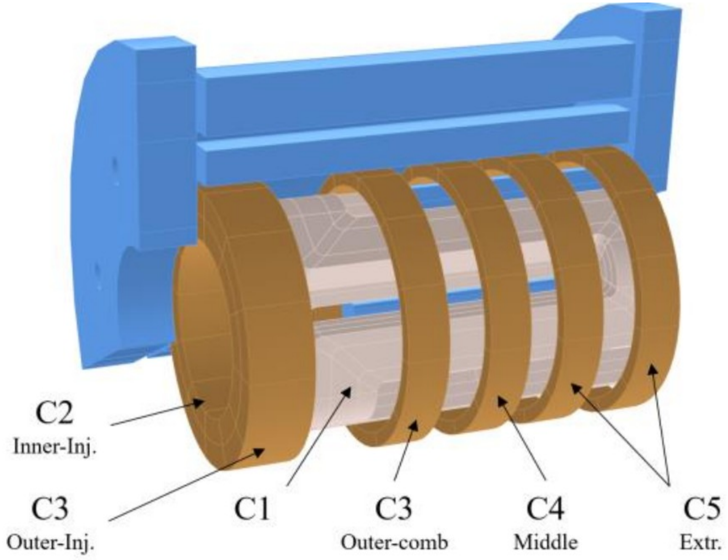
No.	Coil material	Layer current density (A/mm^2) a	b	c	Magnetic field strength (T) B_{inj}	B_{min}	B_{ext}	B_{radX}	B_{radZ}	$B_{critical}$	Frequency (GHz)	Mirror ratios B_{inj}/B_{ecr}	B_{min}/B_{ecr}	B_{ext}/B_{ecr}	B_{radX}/B_{ecr}	B_{radZ}/B_{ecr}
1	NbTi[a]	122	122	122	6.5	1.0	2.0	2.6	6.3	9.6	36	5.0	0.8	1.6	2.0	4.8
2		118	100	180	6.6	1.3	2.7	3.4	6.4	9.7	45	4.1	0.8	1.7	2.1	4.0
3											42	4.4	0.9	1.8	2.3	4.3
4		67	120	250	6.2	1.7	3.7	4.5	6.9	9.9	60	2.9	0.8	1.7	2.1	3.2
5	Nb_3Sn[a]	145	230	410	11.7	2.9	6.2	7.7	12.6	18.4	100	3.3	0.8	1.7	2.1	3.5
6											80	4.1	1.0	2.2	2.7	4.4
7	Copper[a]	30	30	30	1.6	0.3	0.5	0.6	1.5	[b]	9	5.0	0.8	1.6	2.0	4.8
8	Copper[c]	30	30	30	2.9	0.3	0.7	0.8	3.0	[b]	10	8.1	0.8	1.8	2.3	8.4

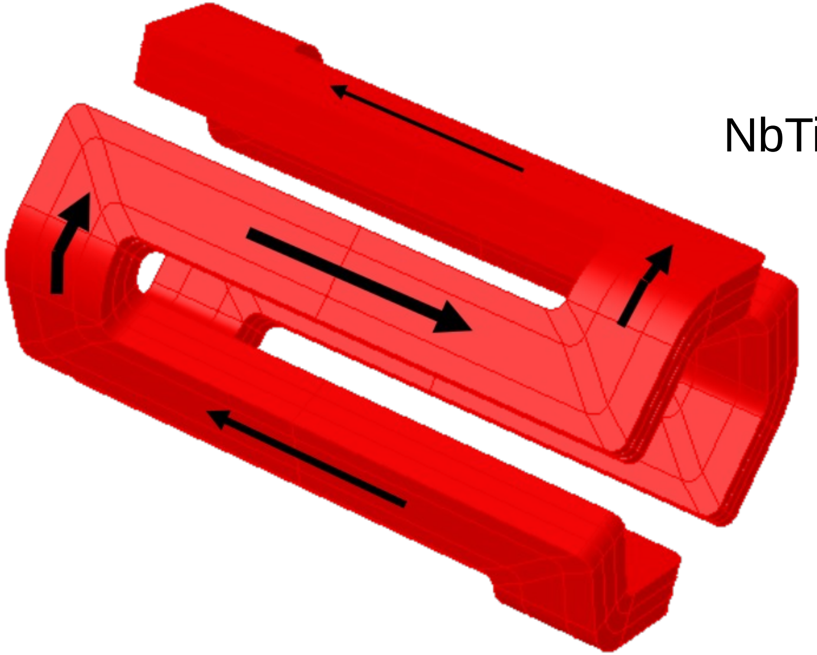
[a]There is no soft iron in the simulation.
[b]There is no critical magnetic field in the case of copper coil and the current density is only limited by the coil cooling system.
[c]The coil is covered with a 50 mm thick iron yoke and it includes an iron pole at the injection [see Fig. 1(b)].



P. Suominen, F. Wenander, "Electron cyclotron resonance ion sources with arc-shaped coils", Rev. Sci. Instrum. 79, 02A305 (2008).

MARS-D 45 GHz, Mixed Axial and Radial field System Demonstrator



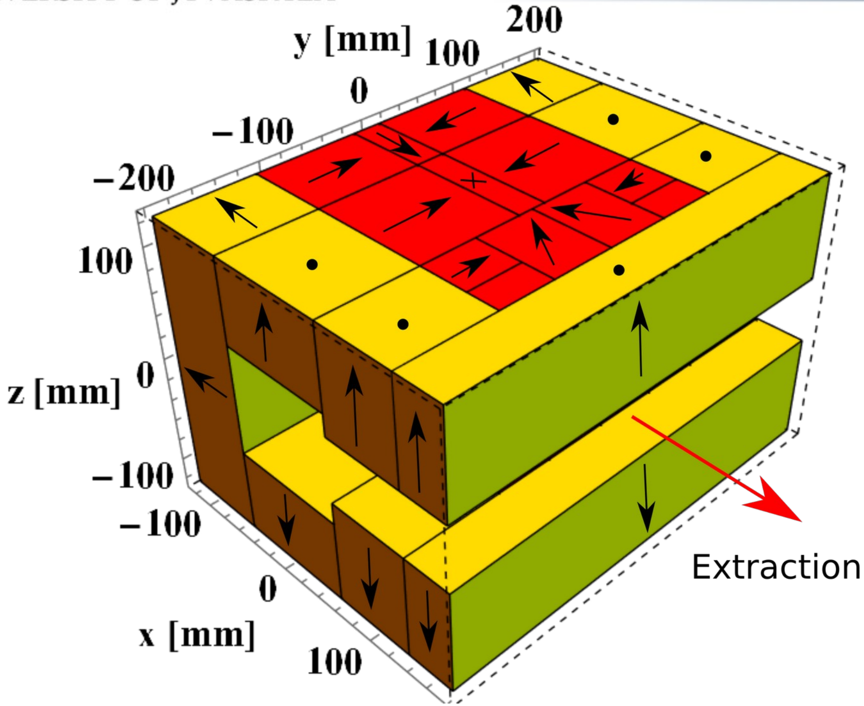


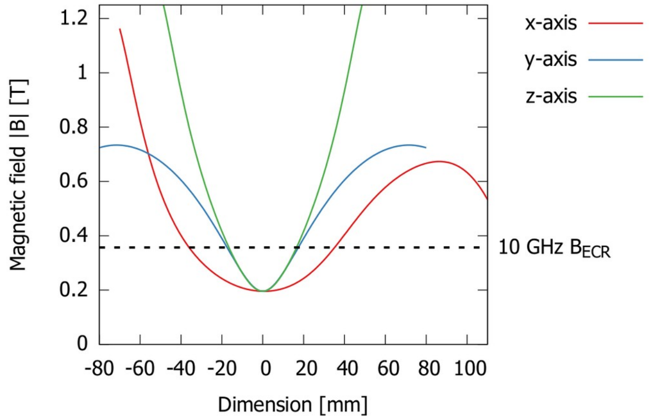
NbTi

M. Juchno, et al., “Shell-Based Support Structure for the 45 GHz ECR Ion Source MARS-D”, IEEE Transactions on Applied Superconductivity 32, 4101005 (2022).

D. Todd, “Recap of the MARS-D review”, unpublished.

Permanent magnet 10 GHz CUBE-ECRIS





Direction	$-x$	$+x$	$\pm y$	$\pm z$
B_{max}	1.07 – 1.00 T	0.67 T	0.73 T	1.14 – 1.07 T
B_{max}/B_{ECR}	2.97 – 2.78	1.86	2.03	3.17 – 2.97

T. Kalvas, O. Tarvainen, V. Toivanen, H. Koivisto, “Design of a 10 Ghz minimum-B quadrupole permanent magnet electron cyclotron resonance ion source, J. Instrum. 15 (2020) P06016.

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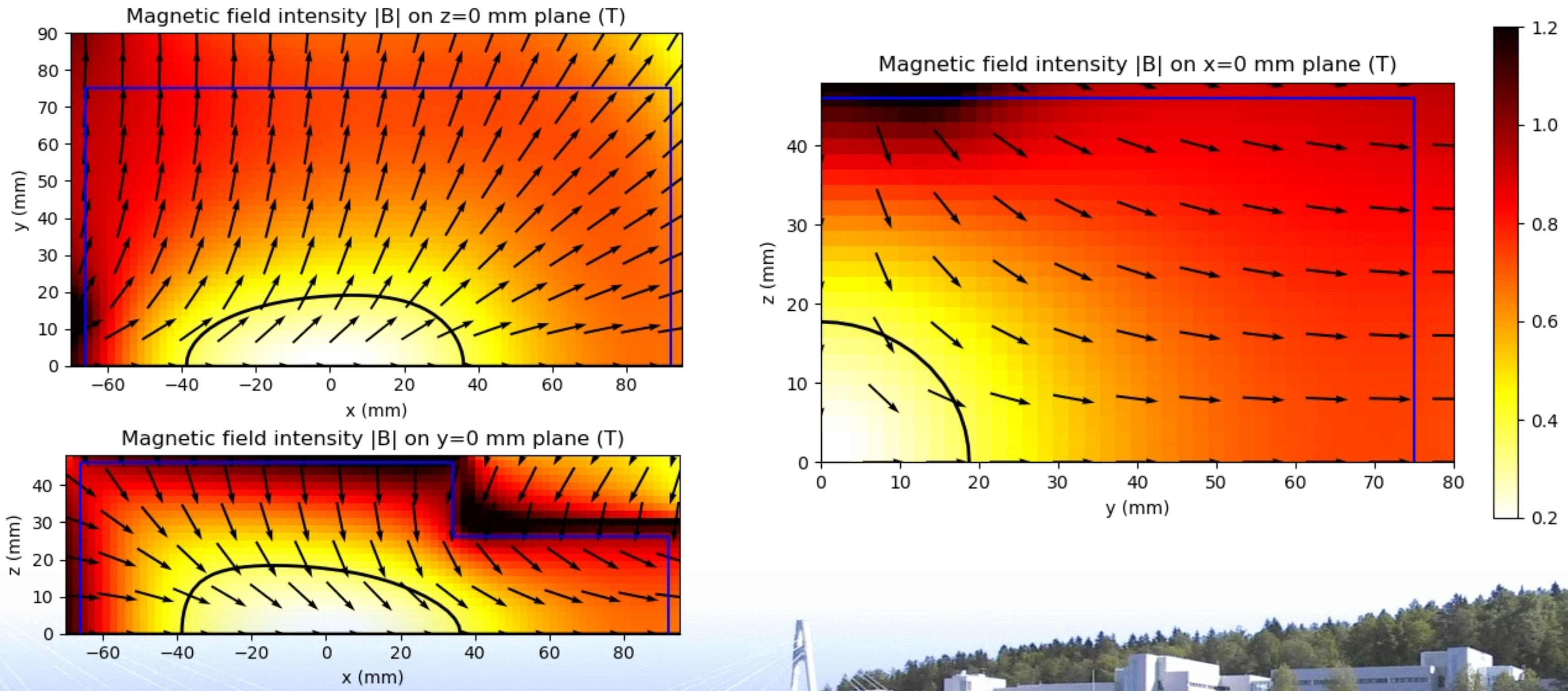
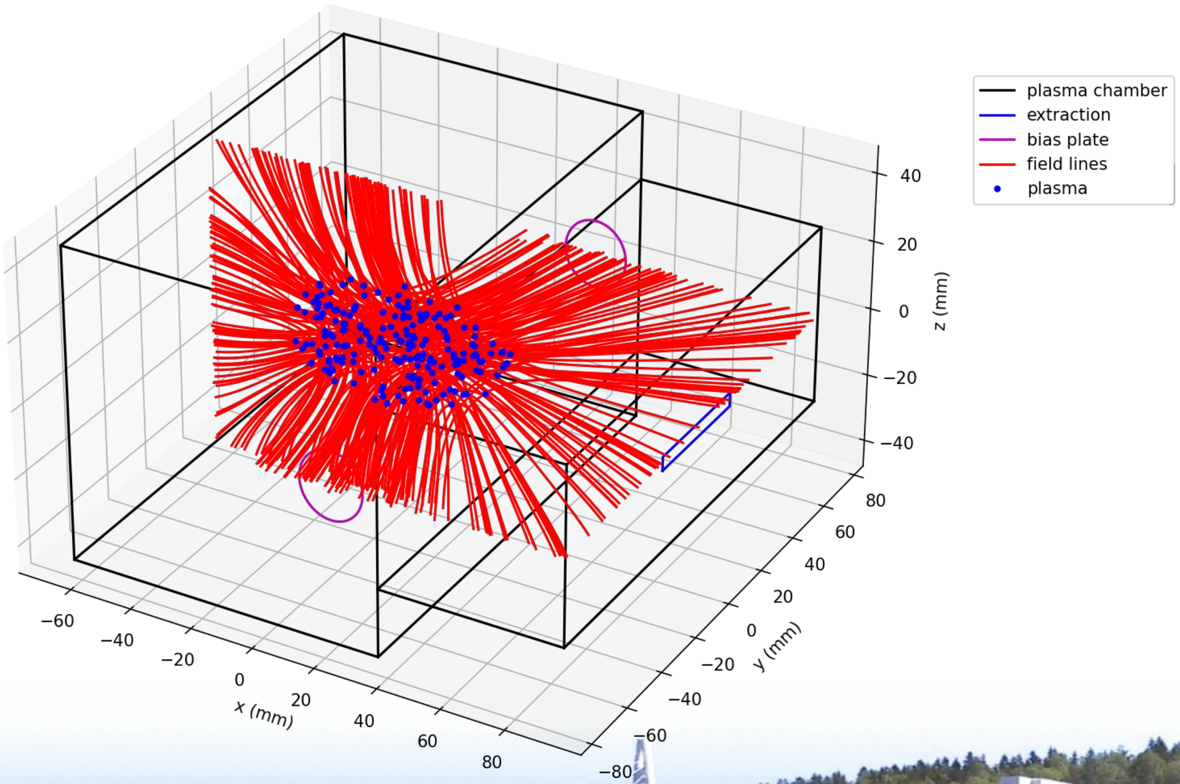
Permanent magnet 10 GHz CUBE-ECRIS

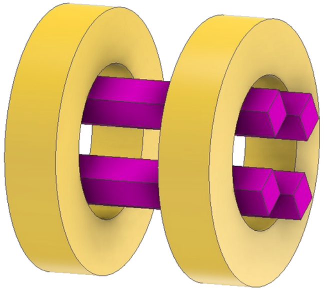


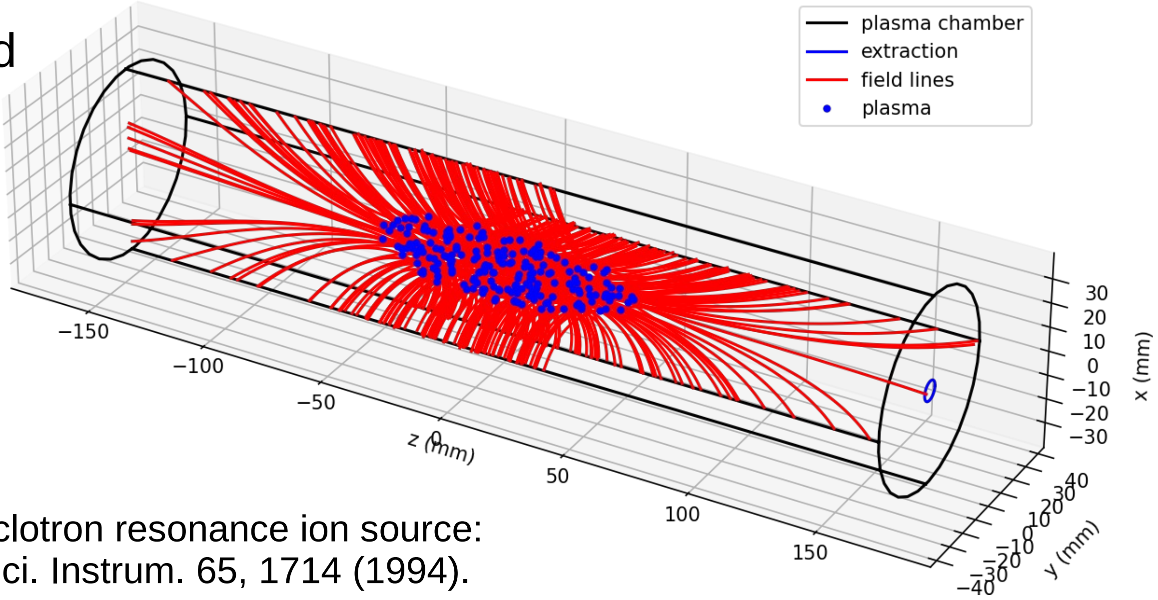
Loss lines from CUBE-ECRIS plasma



Loss lines comparison

JYFL 14 GHz solenoid
+ quadrupole 1.07 T



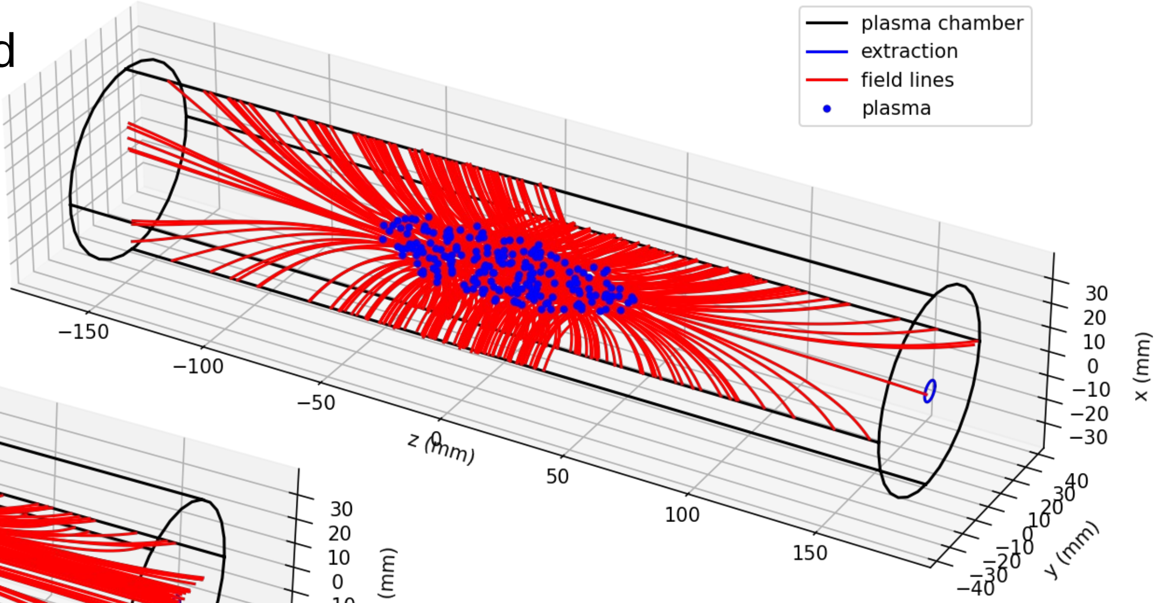


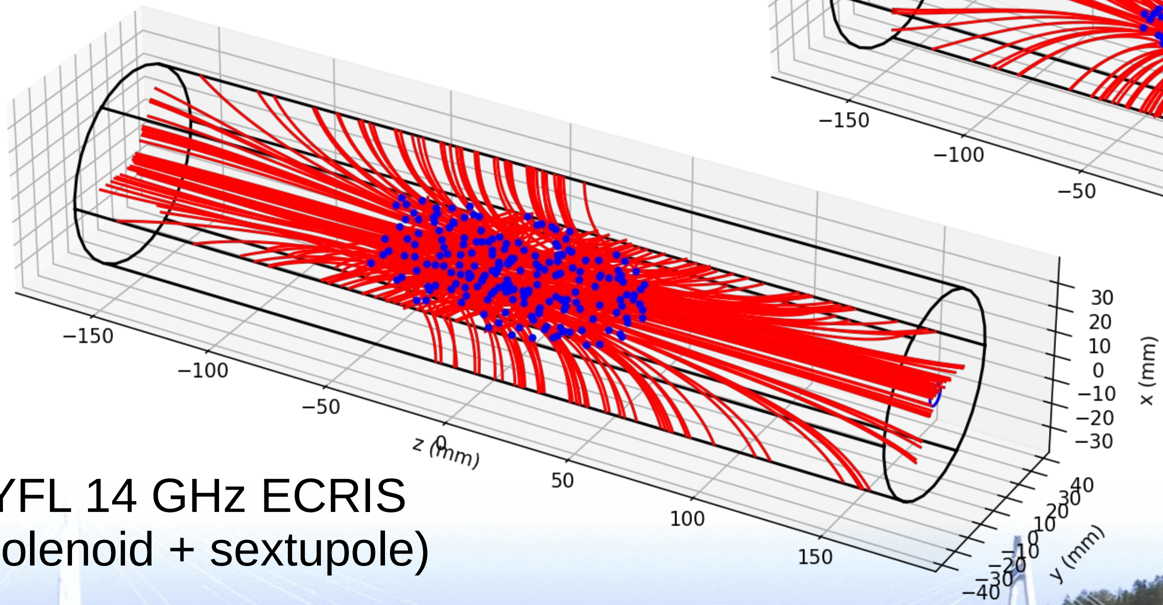
A. Girard, et al., “The Quadrumafios electron cyclotron resonance ion source: Presentation and analysis of the results”, Rev. Sci. Instrum. 65, 1714 (1994).

H. Tamagawa, I. Alexeff, C. M. Jones, P. D. Miller, “Use of the hot-electron mirror machine INTEREM as a high-Z ion source”,
IEEE Trans. Nucl. Sci. NS-23, 994 (1976).

Loss lines comparison

JYFL 14 GHz solenoid
+ quadrupole 1.07 T

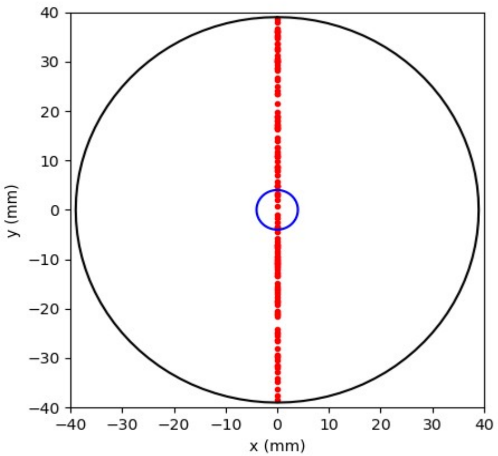




JYFL 14 GHz ECRIS
(solenoid + sextupole)

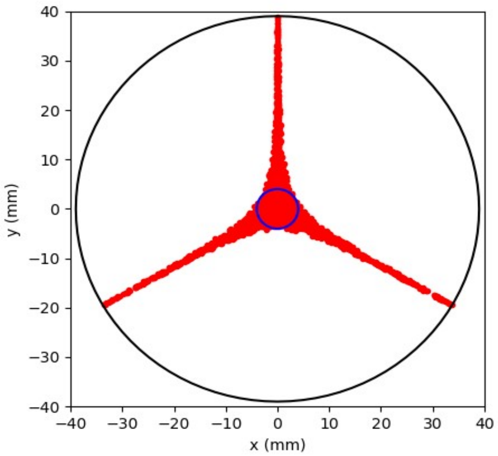
Loss lines comparison

JYFL 14 GHz solenoid + quadrupole field 1.07 T



0.1 % to extraction
⌀8 mm

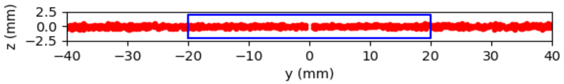
JYFL 14 GHz solenoid + hexapole field 1.07 T



4.2 % to extraction
⌀8 mm

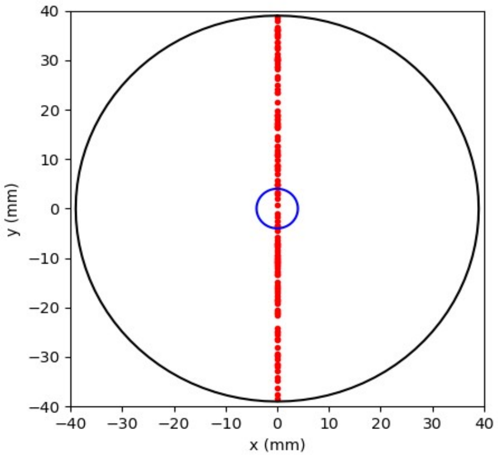
Loss lines comparison

CUBE 10 GHz



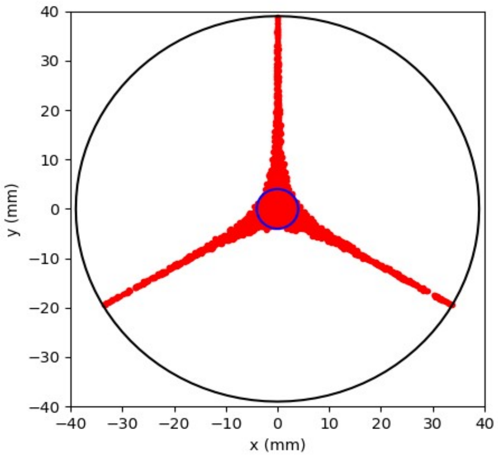
2.8 % to extraction
40x4 mm^2

JYFL 14 GHz solenoid + quadrupole field 1.07 T



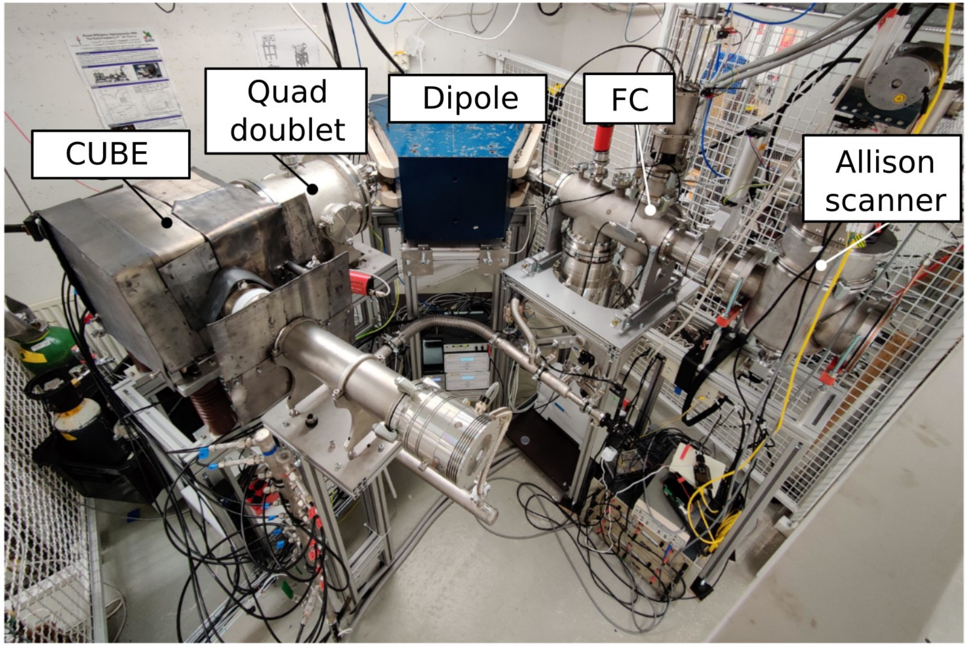
0.1 % to extraction
⌀8 mm

JYFL 14 GHz solenoid + hexapole field 1.07 T

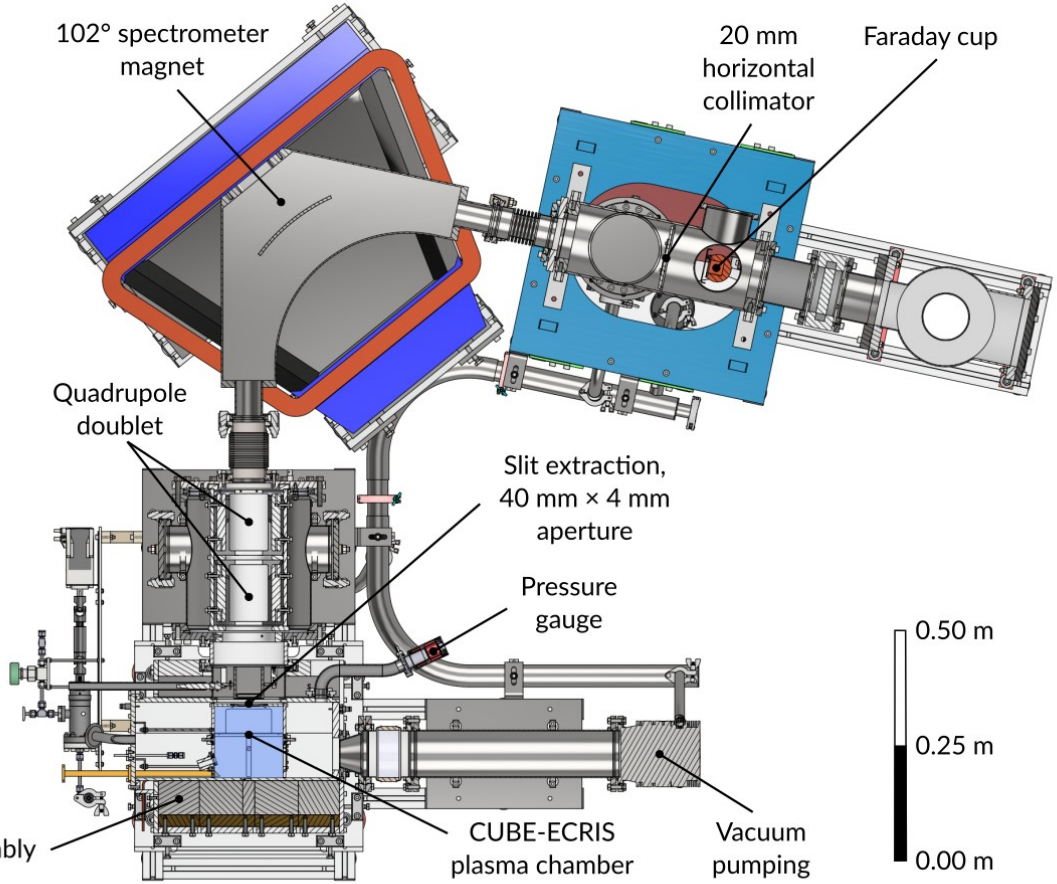


4.2 % to extraction
⌀8 mm

Test stand

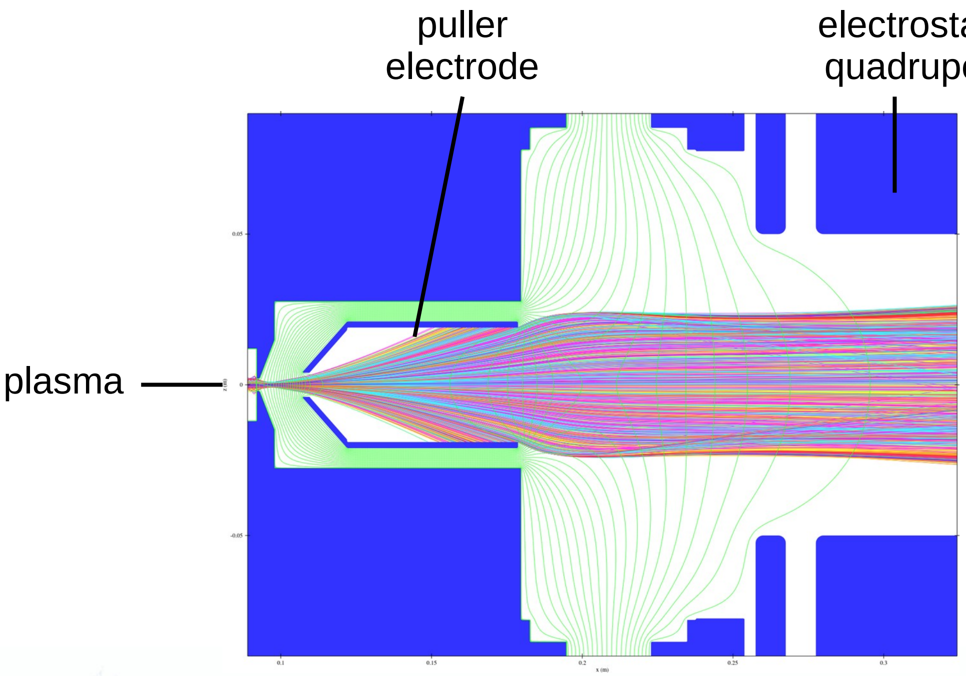


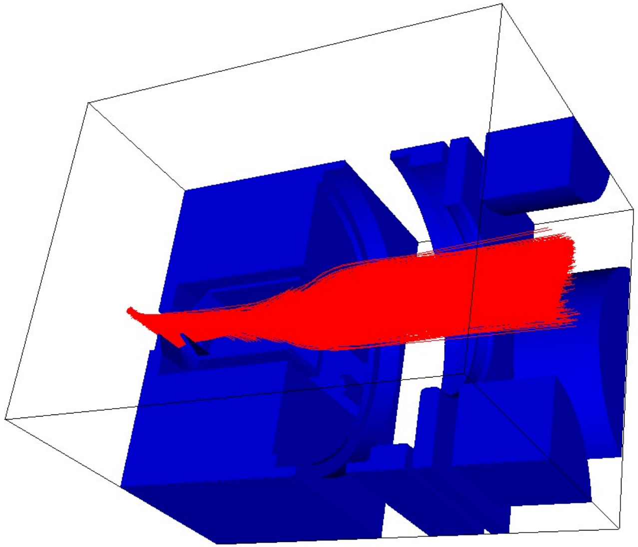
CUBE
Quad doublet
Dipole
FC
Allison scanner



102° spectrometer magnet
20 mm horizontal collimator
Faraday cup
Quadrupole doublet
Slit extraction, 40 mm × 4 mm aperture
Pressure gauge
Permanent magnet assembly
CUBE-ECRIS plasma chamber
Vacuum pumping
0.50 m
0.25 m
0.00 m

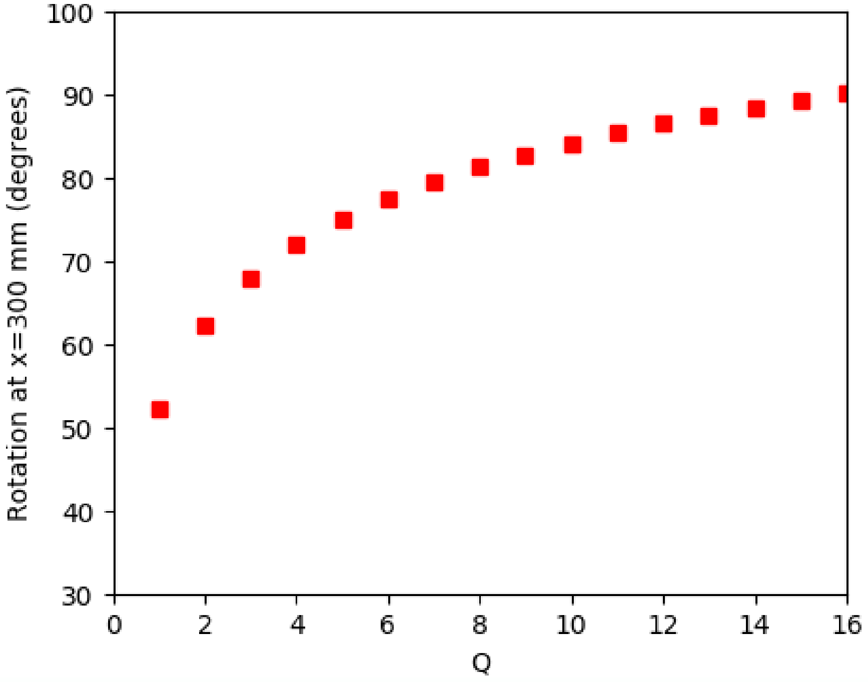
Extraction from CUBE



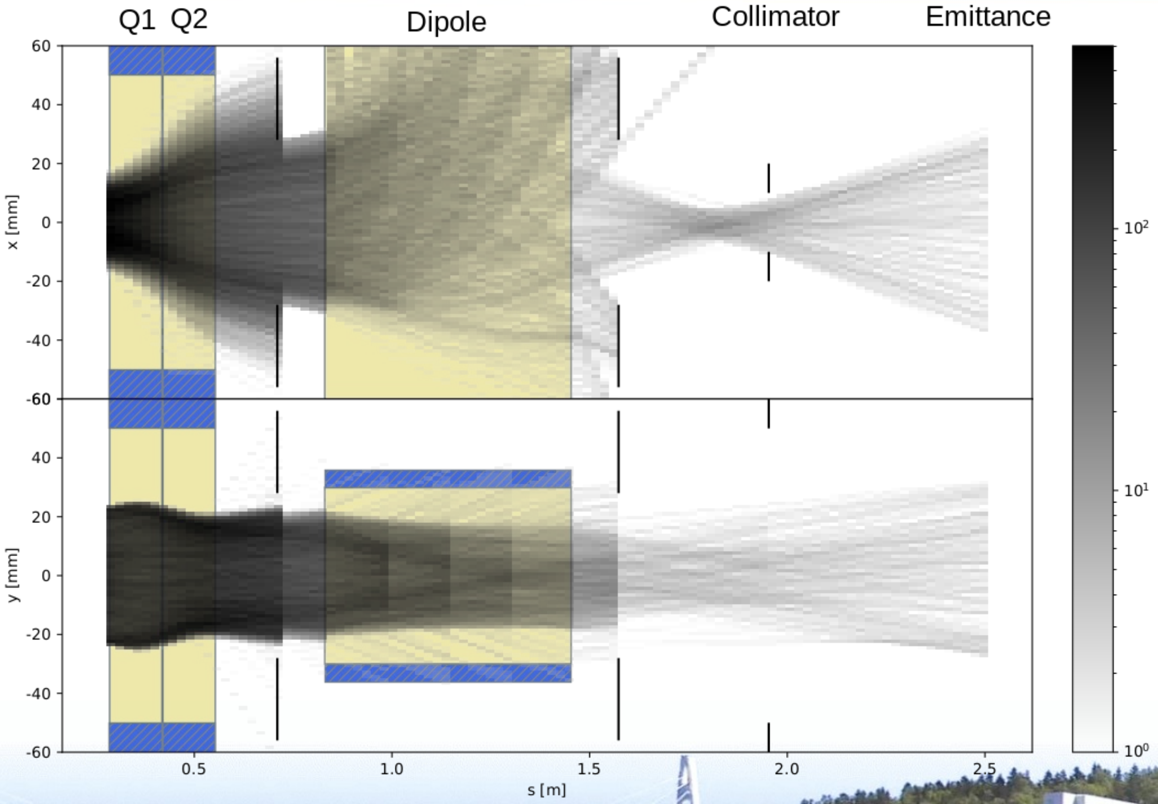


Made with IBSimu

Beam rotation due to diverging B-field



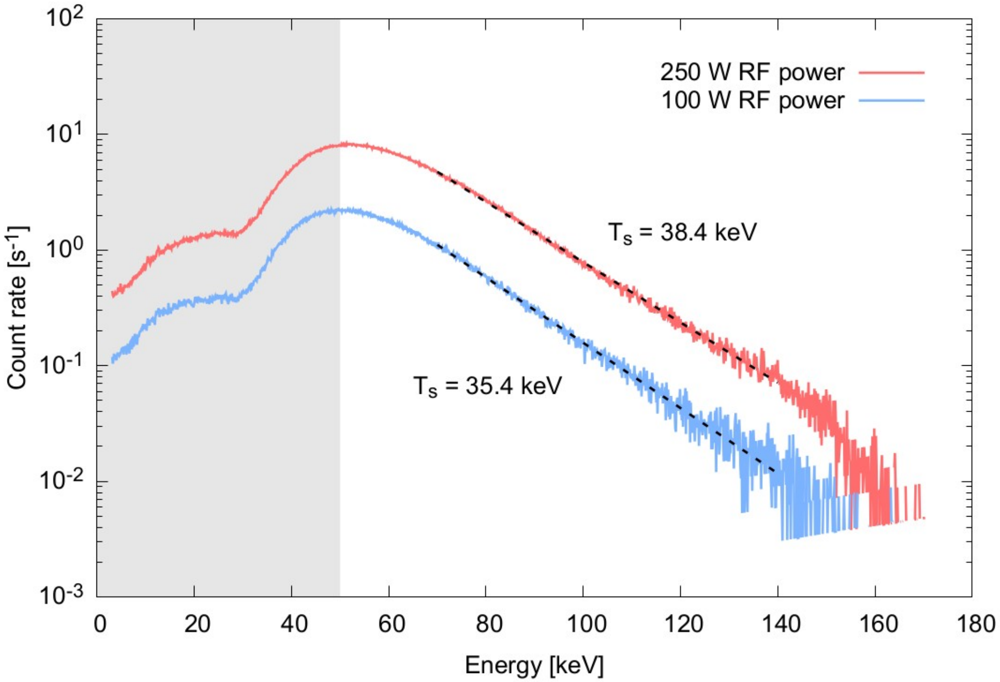
LEBT simulations: Ar^{8+}, 100 % SCC



Optimized quad voltages
V_{Q1} = -867 V
V_{Q2} = 482 V

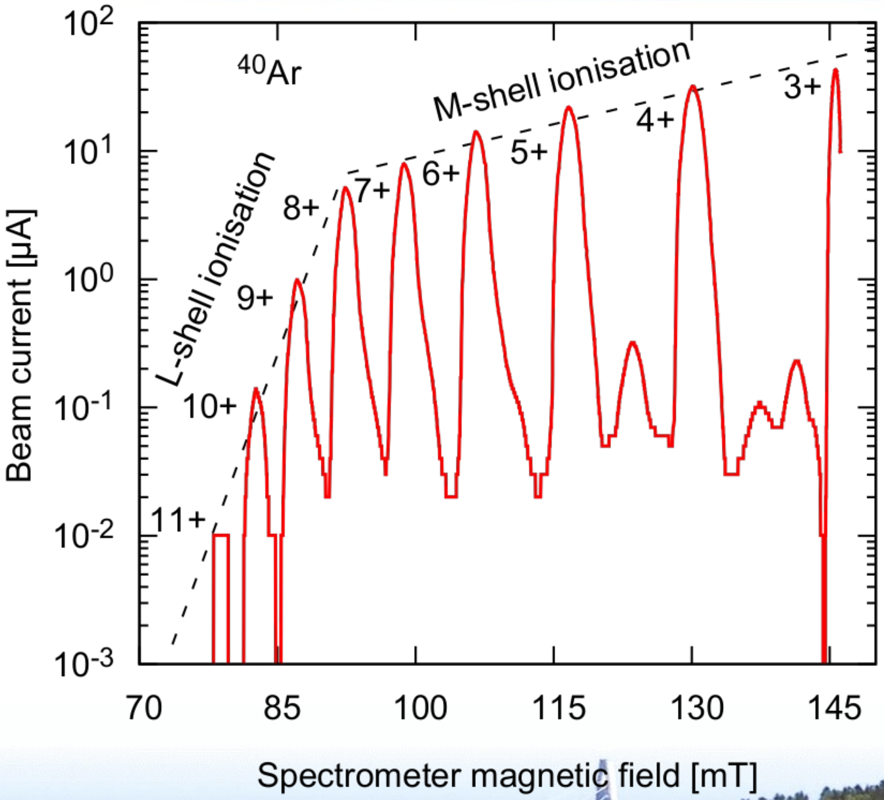
Made with Python-driven Ion Optics library (PIOL)

First results: bremsstrahlung



T. Kalvas, et al., “First results of a new quadrupole minimum-B permanent magnet electron cyclotron resonance ion source”, Plasma Sources Sci. Technol. 31, 12LT02 (2022)

First results: high charge state extraction



Round ⌀8 mm aperture

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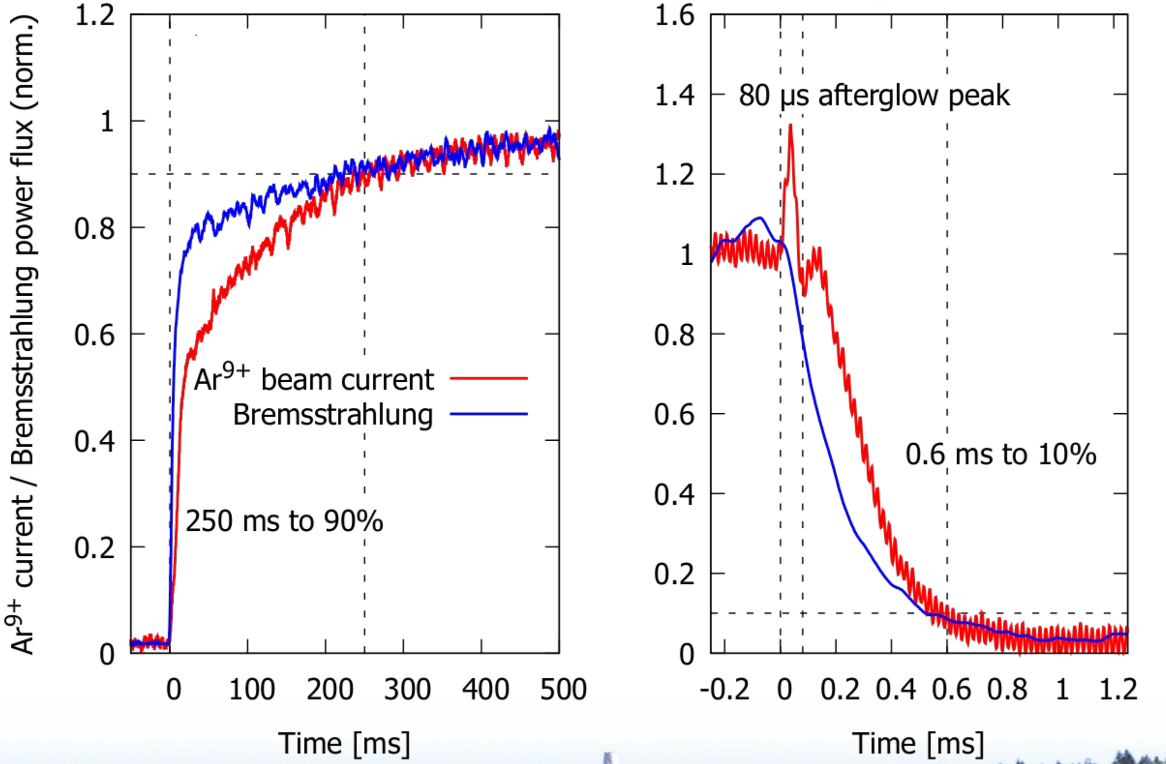
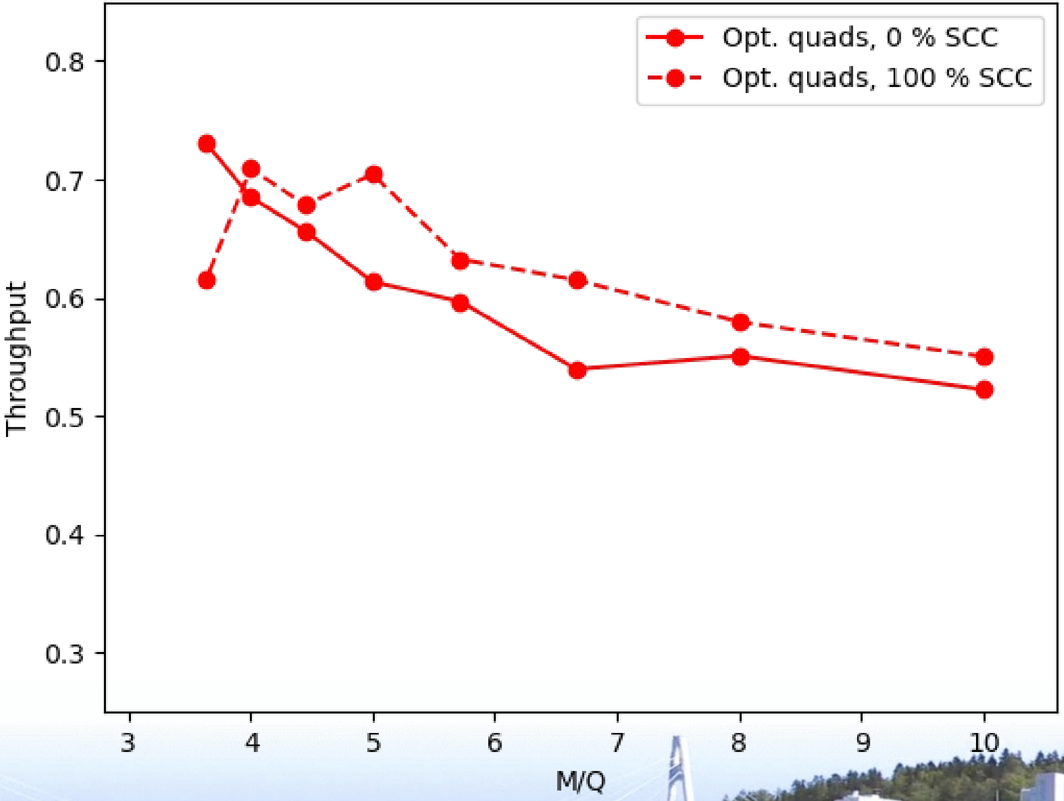
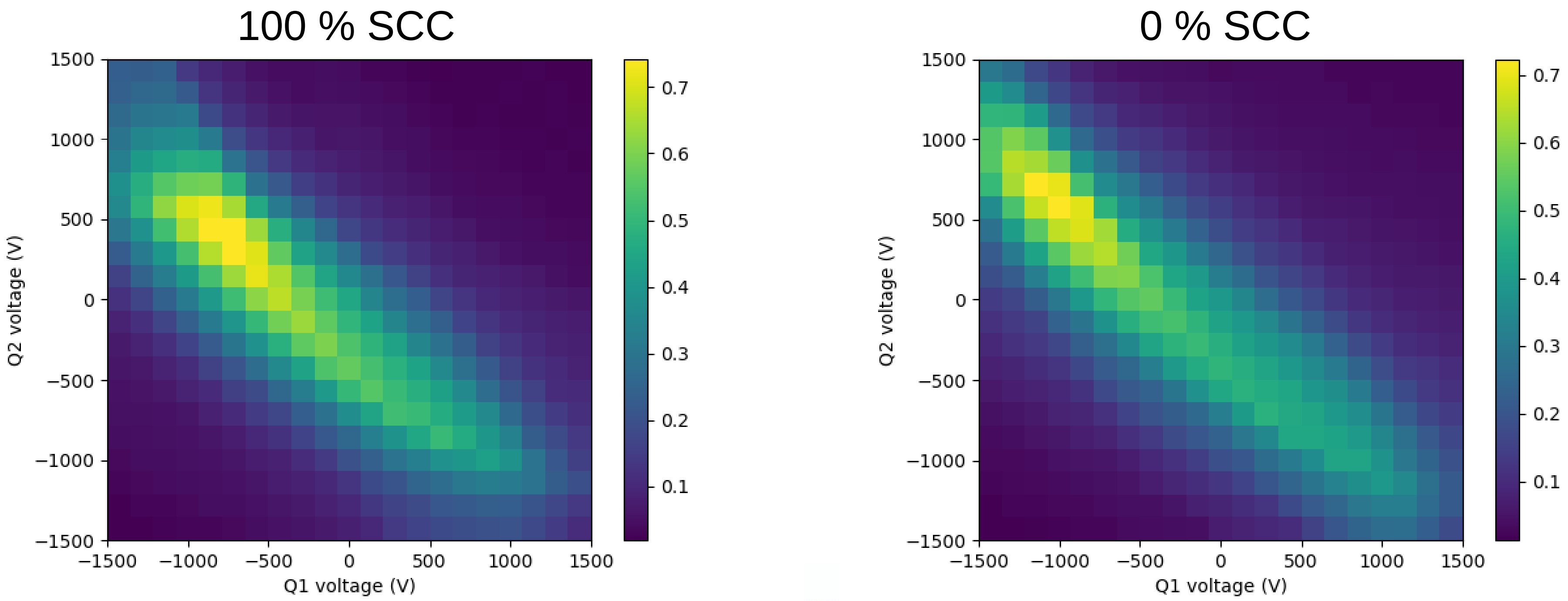
First results: afterglow peak



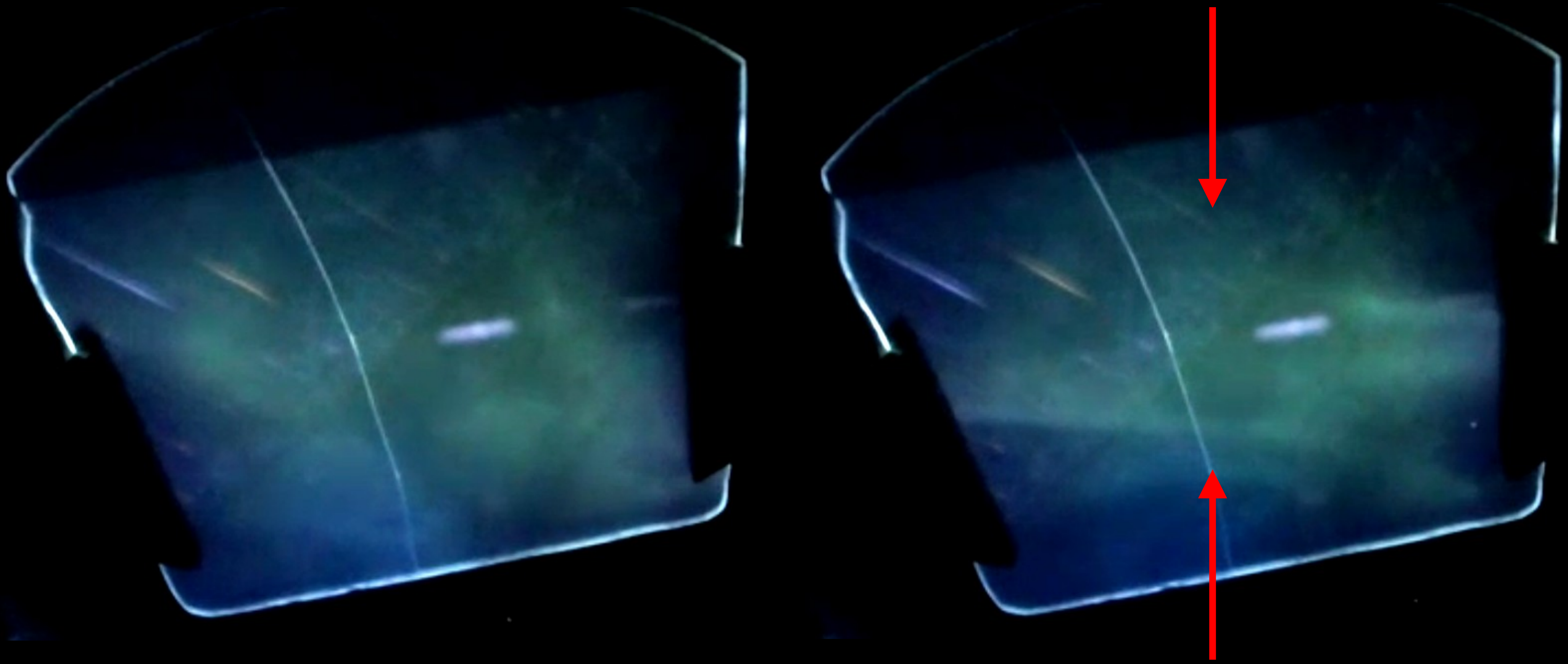
Argon throughput to FC



Transport efficiency for Ar^{8+}, quadrupole focusing



Quadrupole focusing effects on viewer



0 V on quad 1
0 V on quad 2

800 V on quad 1
0 V on quad 2

Mode jumping in extraction?

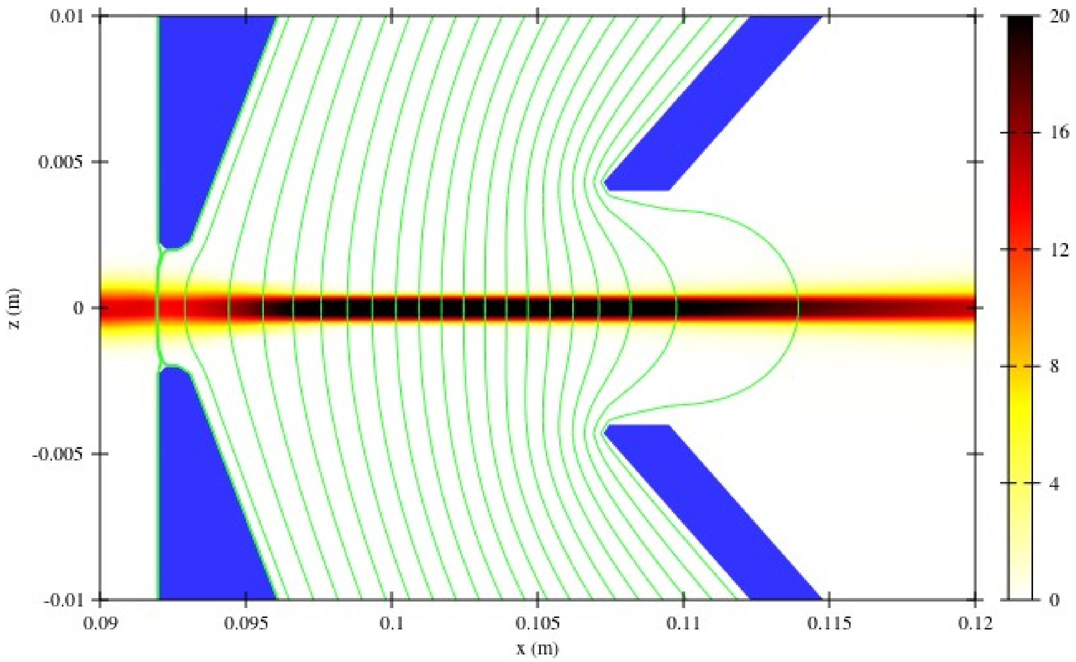
- Use of quadrupole focusing seems to cause changes in extraction at higher quad voltages.
- Abrupt change in FC reading and beam shape in viewer.
- No effect in plasma: bias plate and HV currents are constant.

Electrostatic quads are expected to drain SCC electrons.

Magnetic quads?

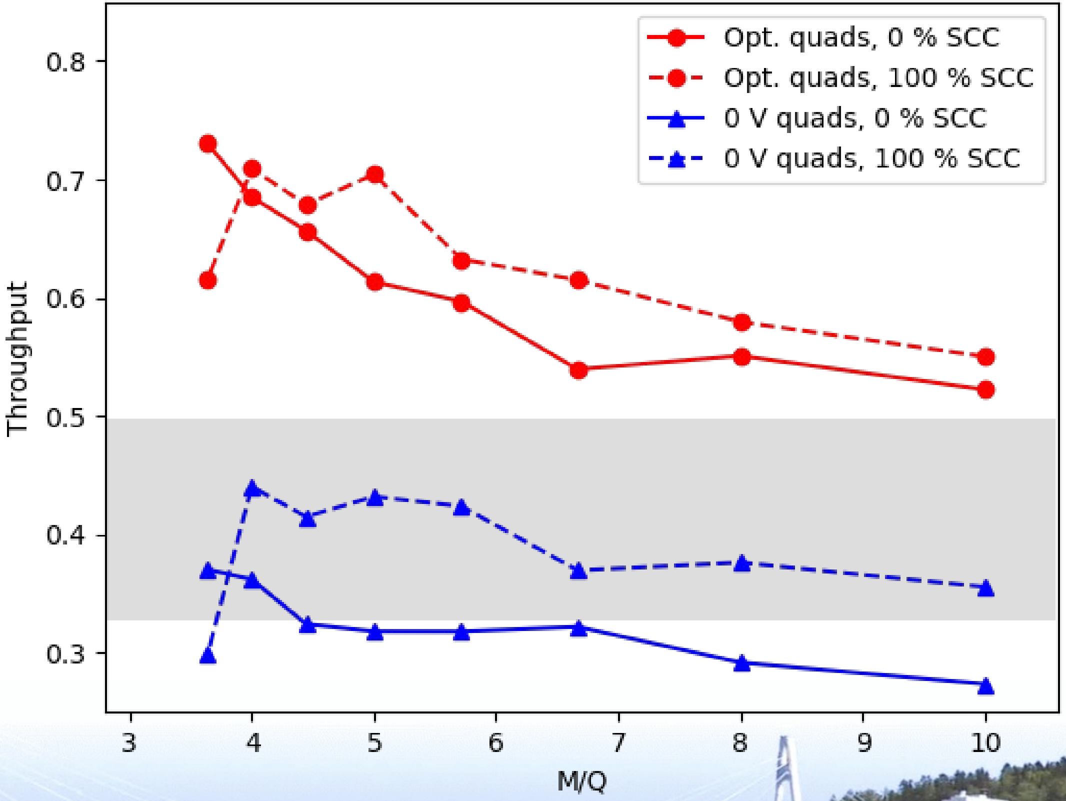
Meniscus effect?

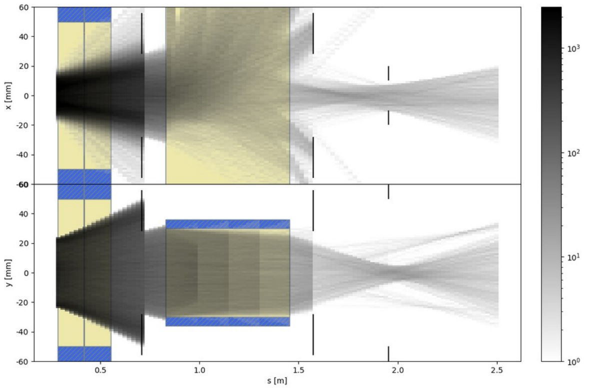
- Non-uniform ion and electron distributions near plasma sheath
- Meniscus can not be flat
- Meniscus attachment point can be sensitive (mode)
- Gun-type codes are unable to model the physics.



To be experimentally studied by varying extraction slit width: 2 and 4 mm.

Argon throughput to FC

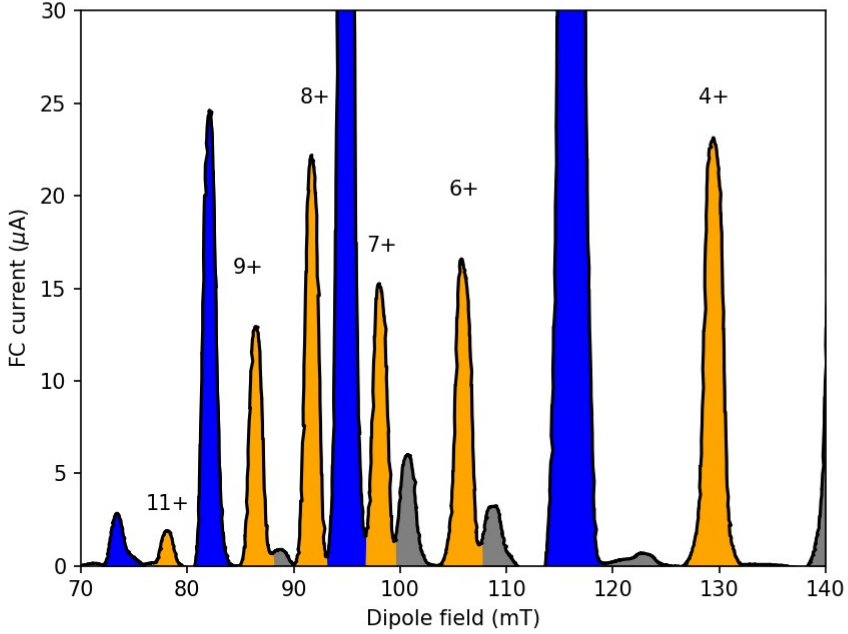




Experimental observations with helium

Beam currents, Argon

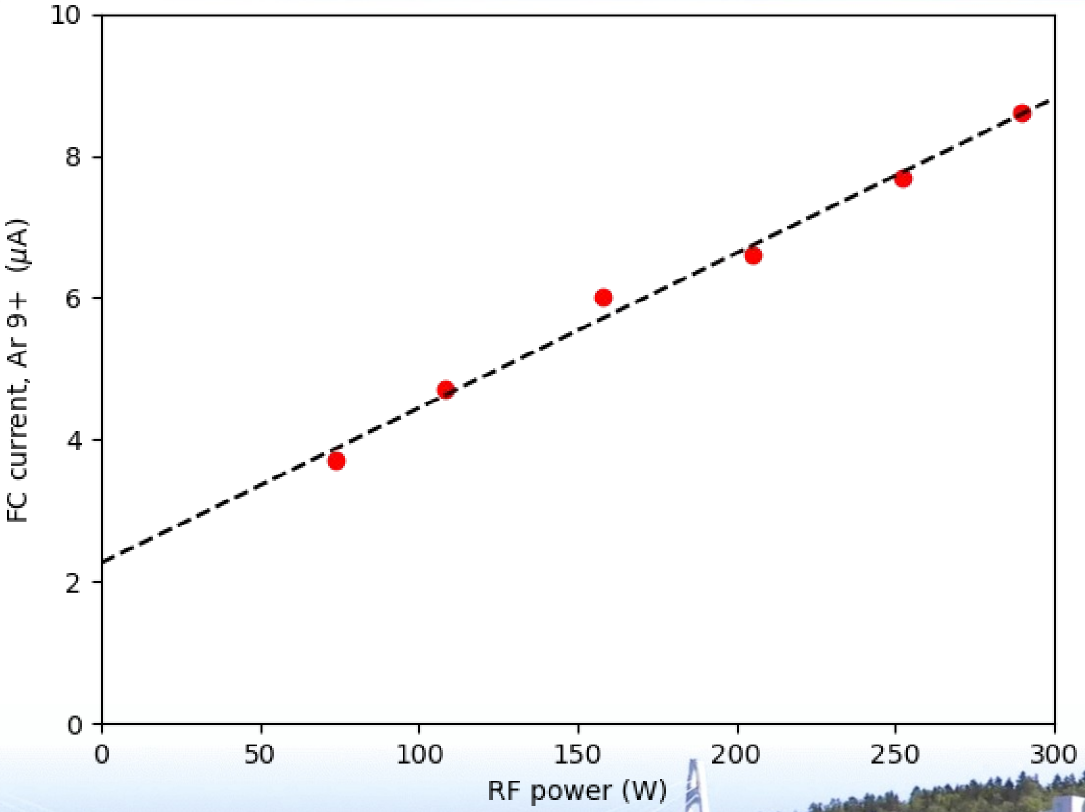
Optimized for argon 11+



These results are made with gas mixing and
two frequency heating, see poster by V. Toivanen, Poster #75

Record beams	
Ion	I (uA)
Ar 6+	27
Ar 7+	24
Ar 8+	31
Ar 9+	16
Ar 10+	5.8
Ar 11+	1.9
Ar 12+	0.4

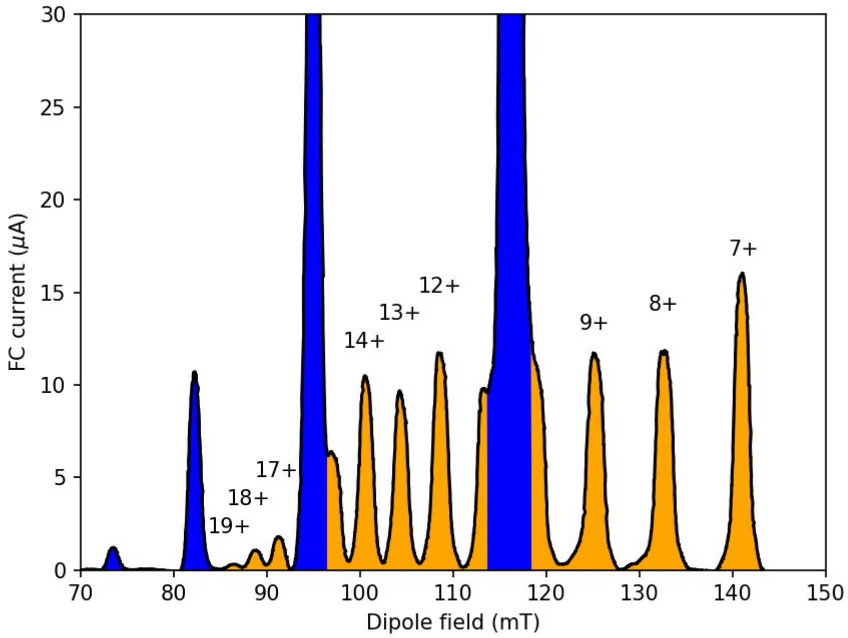
Beam currents, Argon



No saturation observed

Beam currents, Krypton

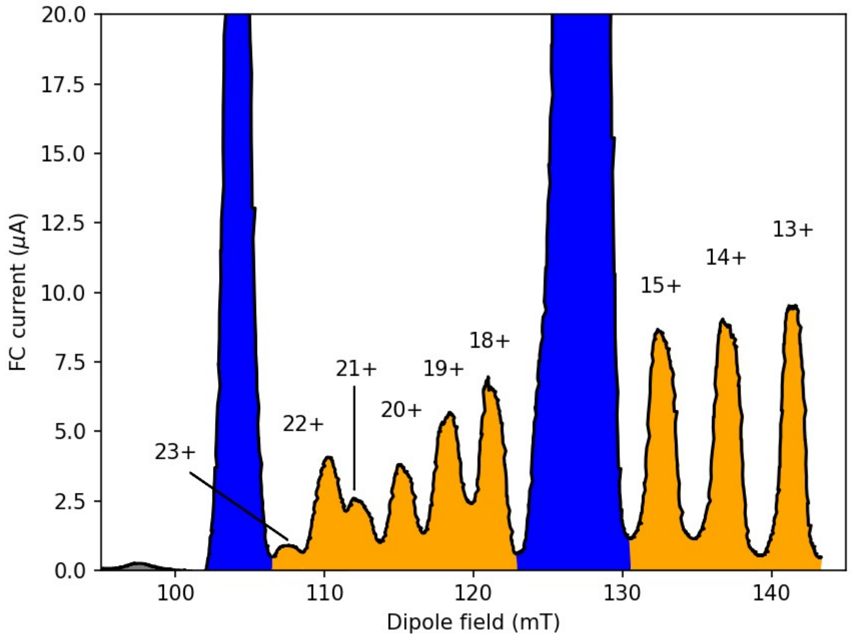
Optimized for krypton 19+



Record beams	
Ion	I (uA)
Kr 13+	9.5
Kr 15+	6
Kr 17+	1.8
Kr 18+	1.1
Kr 19+	0.31

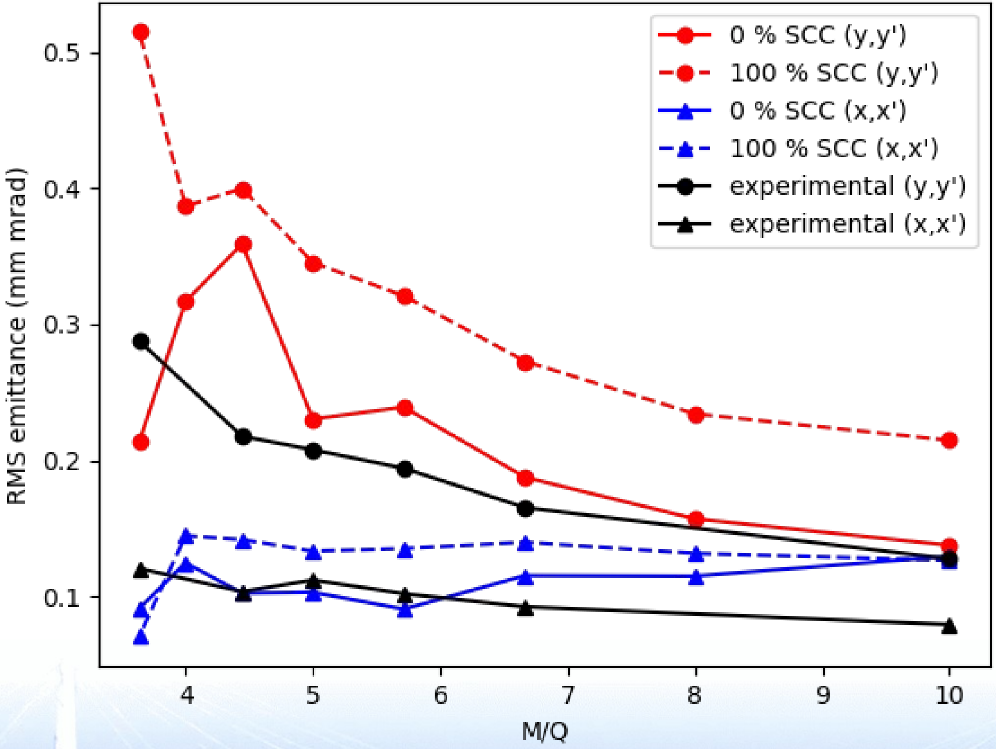
Beam currents, Xenon

Optimized for xenon 23+



Record beams	
Ion	I (uA)
Xe 18+	6.1
Xe 19+	5.2
Xe 20+	3.7
Xe 21+	2.5
Xe 23+	0.9
Xe 24+	0.2
Xe 27+	0.02

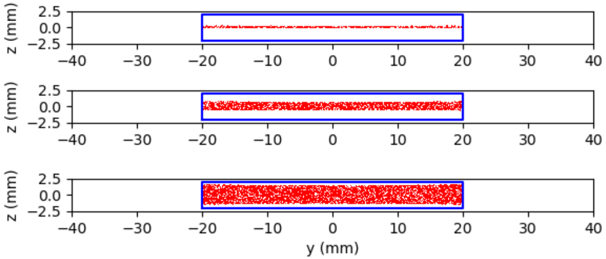
Beam emittance for argon



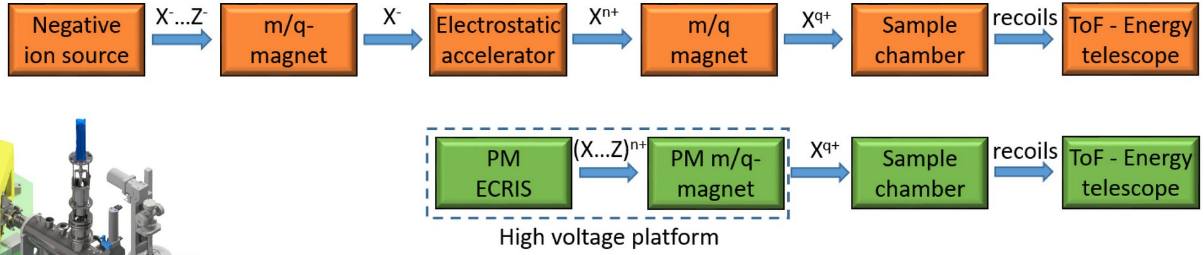
Emittance increases with increasing Q due to rotation

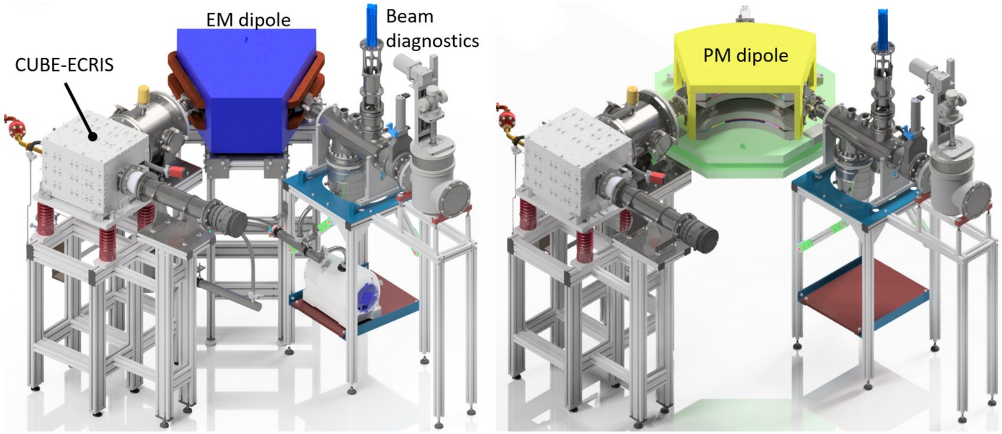
$$\varepsilon_{\mathrm{rms,n}} = \frac{qB_0}{8mc} r_0^2$$

In conventional ECRIS an opposite trend is often observed: "effective aperture radius".



CUBE for material analysis: ToF-ERDA



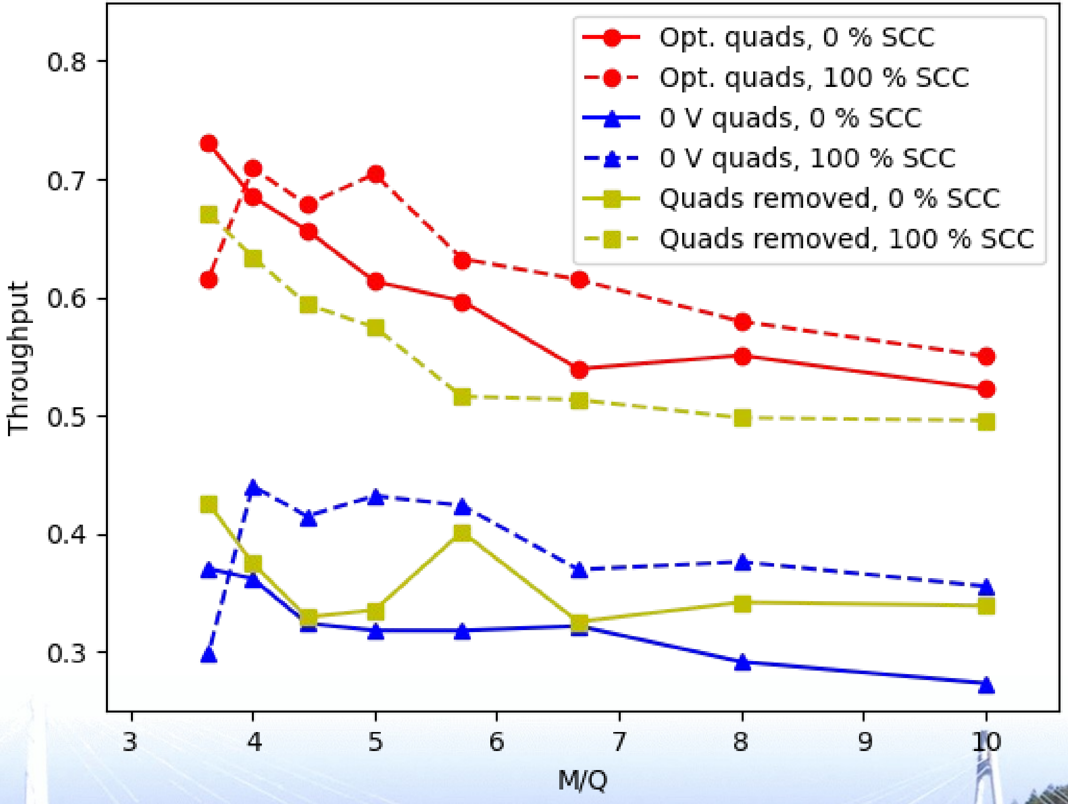


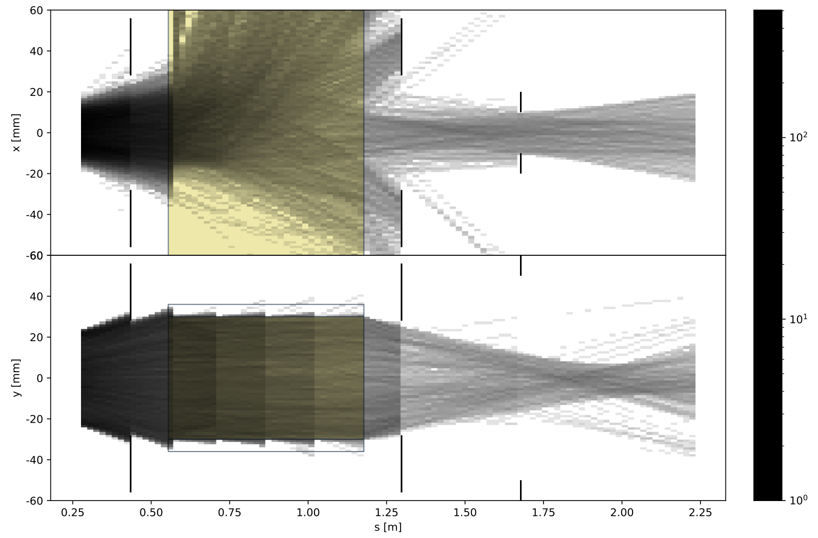
Poster #59: O. Tarvainen et al.,
“Permanent Magnet ECR Ion Source and LEBT Dipole for Single-Ended Heavy Ion ToF-ERDA Facility”

O. Tarvainen, et al., “Ion source and low energy beam transport prototyping for a single-ended heavy ion ToF-ERDA facility”, Nucl. Instrum. Meth. B 538, 110 (2023).

O. Tarvainen, et al., “Permanent magnet ECR ion source and LEBT dipole for single-ended heavy ion ToF-ERDA facility”, Poster XXX

Argon throughput to FC





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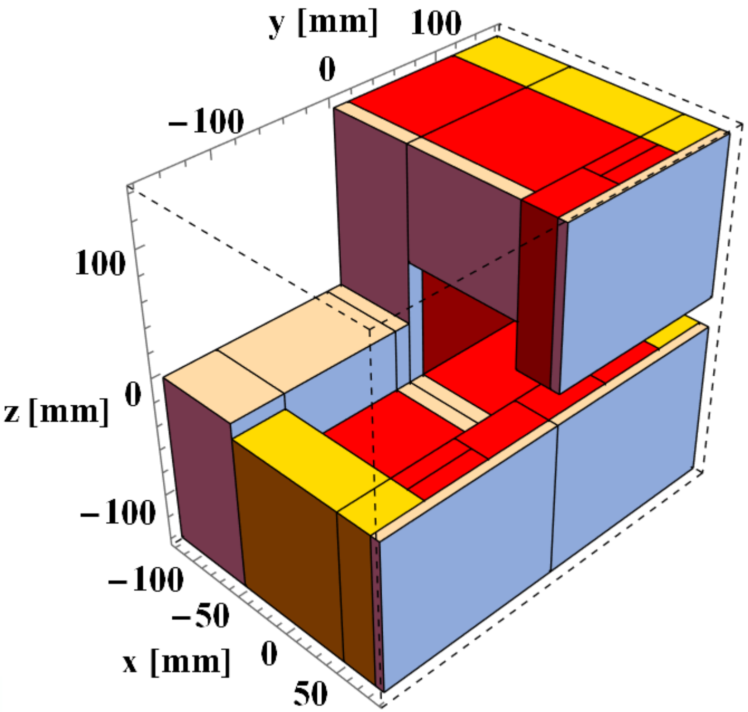
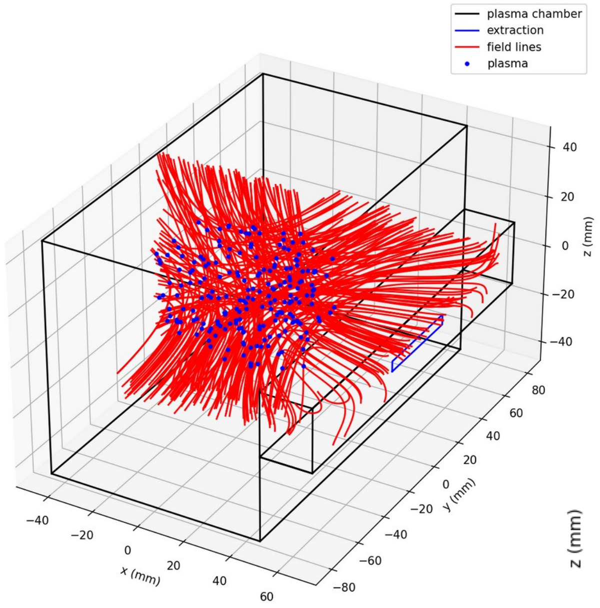
14 GHz PM CUBE-ECRIS

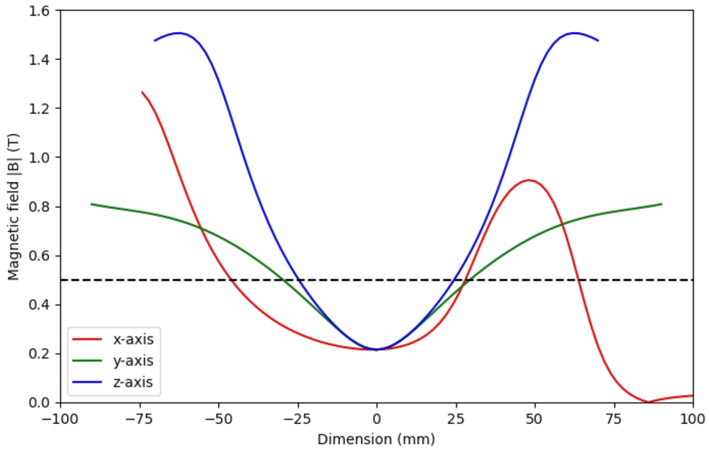


Next step?

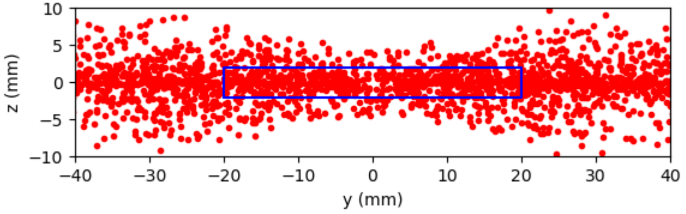
- Magnet grade from N45H to N48H
- Smaller openings in z in ±y and +x directions
- Shortened extraction opening
- Chamber needs to be integrated within the magnets
- Mass of magnets from 190 to 115 kg.

14 GHz PM CUBE-ECRIS





3.2 % to extraction
40x4 mm^2



Conclusions

- PM CUBE-ECRIS has demonstrated its capabilities as a source of high-Q ions
- Has potential applications
- It is still to be seen if slit beams can be efficiently used
- Scaling of ARC-ECRIS concept to higher frequencies is to be demonstrated

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Thank you

European Cyclotron Progress Meeting
in Jyväskylä May 27-30, 2024

https://www.jyu.fi/en/congress/ecpm2024