Lithium ECRIS for CLIP

C-AD MAC-18

Dec. 9, 2021

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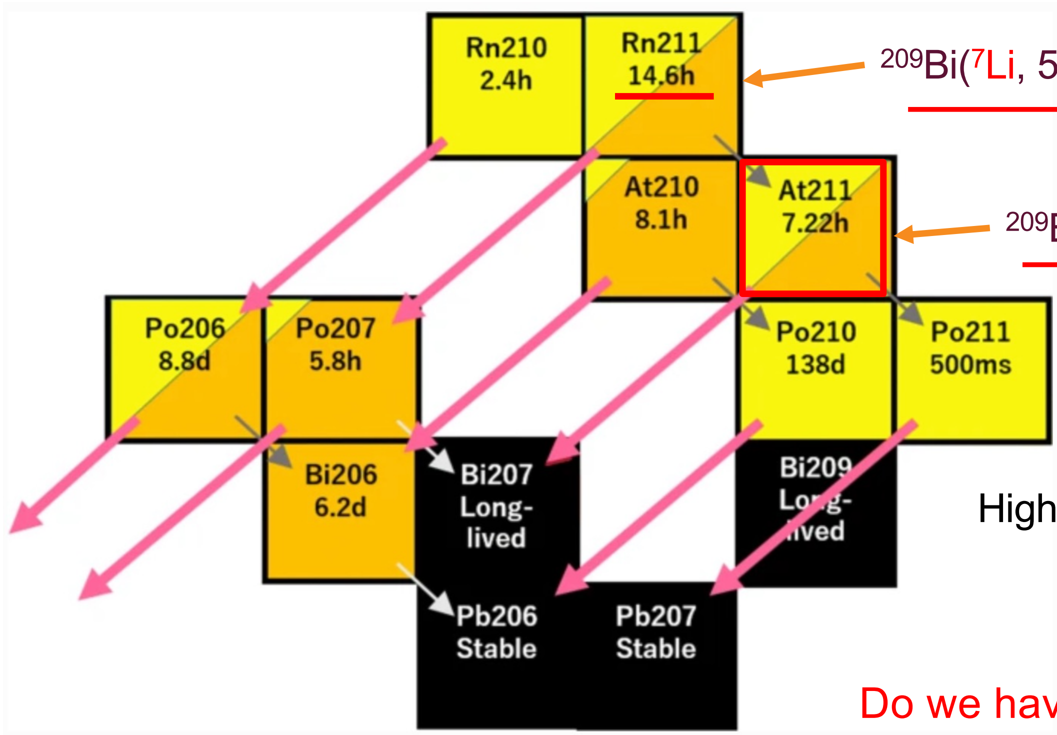
Outline

- Background
- Proton and Deuteron ion source
- LI and He ion source
- Handling difficulties of Li
- Li feeding study
- Hexapole design limitation
- Beam extraction
- Summary

High performance ECRIS for He^{2+} and Li^{3+} beam.



Nuclear chart and decay processes relating to ^{211}Rn production

Journal of Radioanalytical and Nuclear Chemistry (2020) 323:921–926

$^{209}Bi(^{7}Li, 5n)^{211}Rn$ — Li^{3+} beam

$^{209}Bi(^{4}He, 2n)^{211}At$ — He^{2+} beam

High current Li3+ and He2+ beams are required.

Do we have enough technologies for the ion source?

Why ECRIS??

At CAD, we have world class ion sources. However,,

	Li^{3+} capability	He^{2+} capability	High current	CW like operation
EBIS	✓	✓		
LIS	✓		✓	
OPPIS				
H^- magnetron			✓	✓
ECRIS	✓	✓	✓	✓

Why is the R&D required??

- No great Li ECRIS in the world.
- Lithium is a chemically active material.

Prototype test is indispensable.

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Target species:

	Mass	Charge	Total Energy (keV)	Column Voltage (kV)	Peak Current (mA)
H^{+}	1	1	20	20	2
D^{+}	2	1	40	40	2
He^{2+}	4	2	80	40	2
Li^{3+}	7	3	140	46. 7	2

RFQ input energy : 20 keV/u
Duty factor : 10 %
Emittance : 0.2 pi mm mrad nor. rms

Frequency Choice

Species / charge state	Ionization energy
H^+, D^+	13.6 eV
Li^{3+}	122.4 eV
He^{2+}	54.4 eV
C^{4+}	64 eV
C^{5+}	392 eV
O^{5+}	113 eV
Ar^{7+}	124 eV

Geller's scaling laws

$$q_{opt} \propto \log B^{3/2}$$

$$q_{opt} \propto \log \omega^{7/2}$$

$$q_{opt} \propto P^{1/3}$$

$$P_{rf} \propto \omega^{1/2} q^3 V$$

$$I^{q+} \propto \omega^2 M_i^{-\alpha}$$

ECR condition

$$\omega_{ce} = \frac{eB}{m_e}$$

Better emittance ↑ / Plasma temperature ↓

Microwave Frequency	Magnetic field	
2.45 GHz	875 Gauss	← For Proton
10 GHz	3.6 KGauss	
14 GHz	5.0 KGauss	For He & Li
18 GHz	6.4 KGauss	For He & Li
28 GHz	1.0 T	

Beam emittance is proportional to the magnetic field strength at the extraction.

High field -> Large emittance

He^{2+} can be provided from a higher frequency ECRIS

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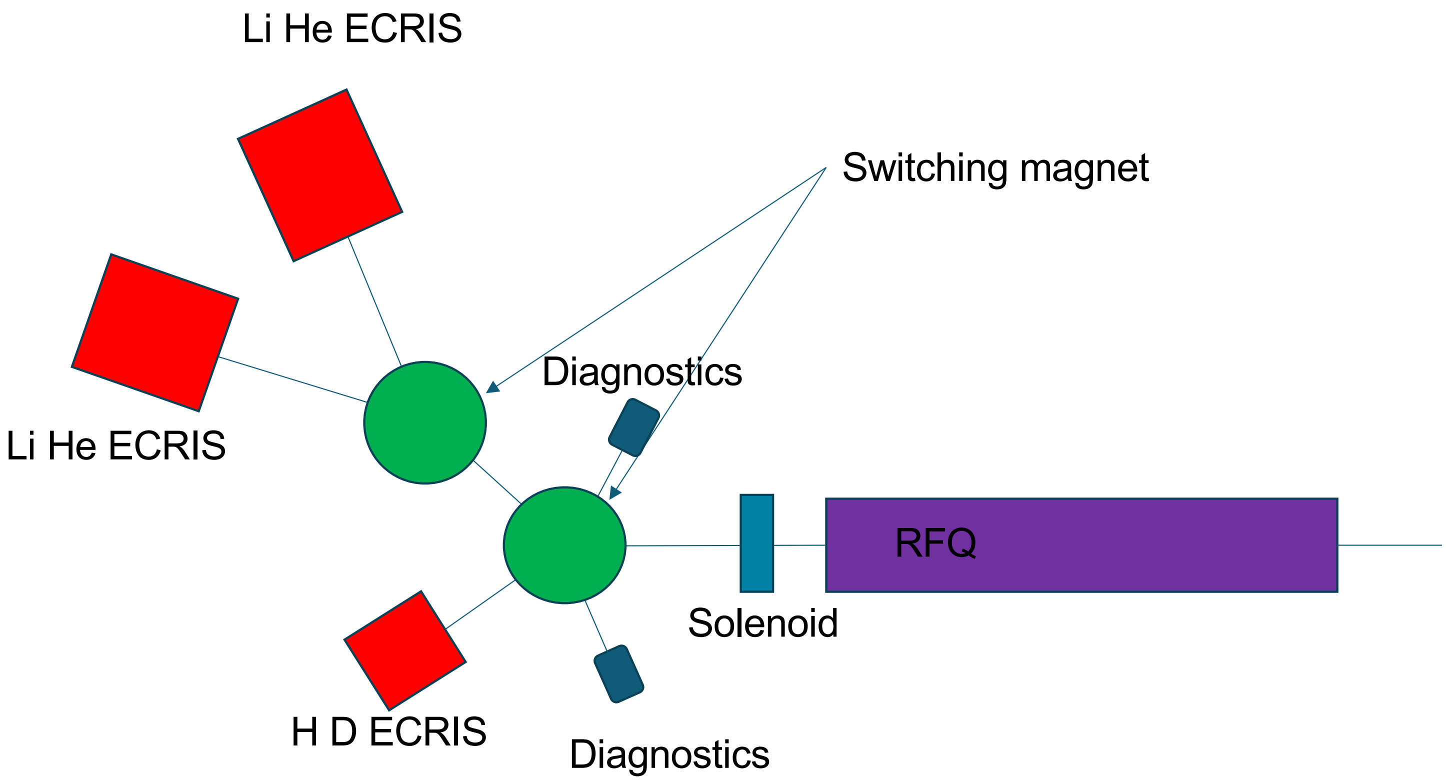
Layout of Front End



For H^+ and D^+, Taylor type ECR works good.

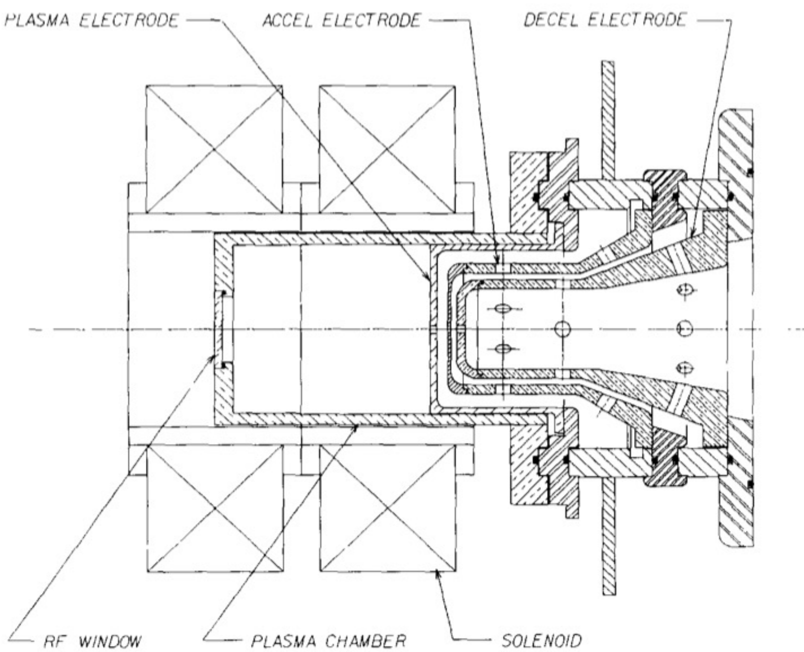


Fig. 1. Schematic of high-current low-emittance dc ECR proton source.

NIMA 309 (1991) 37-42

- 2.45 GHz (same frequency to a kitchen microwave)
- Two axial solenoid magnets
- No transverse confinement magnet
- 2 kW provides more than 10 mA
- Proton fraction more than 90%

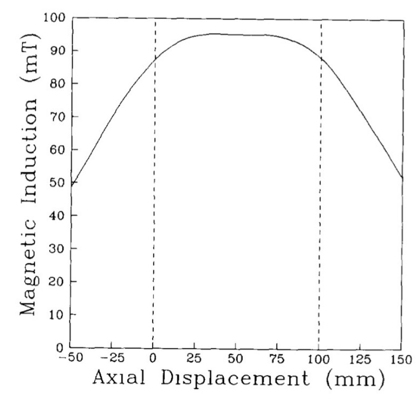


Fig. 3. Magnetic induction on the axis of the solenoids as a function of axial displacement from the microwave window. The dashed vertical lines define the axial extent of the plasma chamber.

Permanent magnet 2.45 GHz ECR is getting popular now

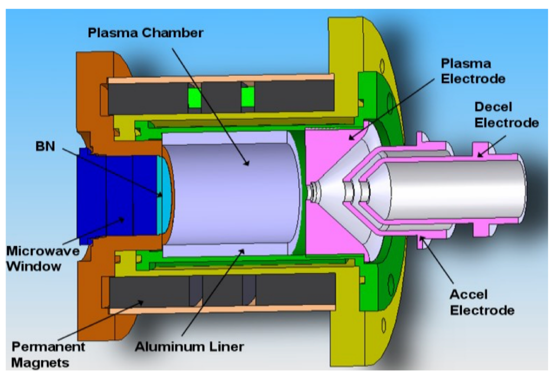


Figure 1: Schematic diagram of 2.45 GHz ECR ion source in PKU.

TUCOCK02 Proceedings of ECRIS2010, Grenoble, France

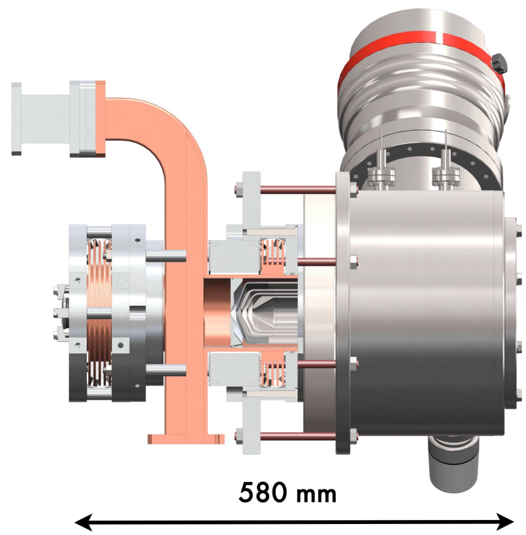


Figure 2: Internal view of the multi-electrode system optimized for high intensity beam production.

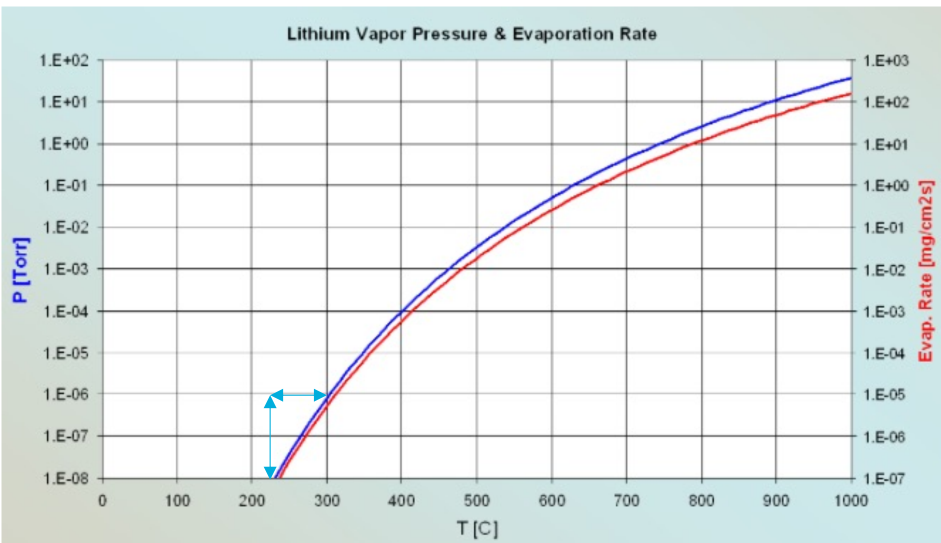
Commercial solution is available
Pantechnik Monogan M-1000

Proton ECRIS can be fabricated in house or purchased.

There have been no mA class Electron Cyclotron Resonance Ion Source for Li^{3+} beam.

Lithium is classified as an alkali metal on the Periodic Table.

At 300°C, lithium has a significantly high enough vapor pressure to cause ppm level contamination in a vacuum system.



- How to control lithium vapor pressure?
- How to manage lithium contamination?

ECR requirement range from E^{-8} to E^{-6}.
Temperature range from 230 °C to 310 °C.

Temp. (°C) for Given Vap. Press. (Torr)	
	10^{-8}: 227
	10^{-6}: 307
	10^{-4}: 407

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Comparison with other alkali metals

Natural abundance of ^7Li is 93 %. 7 % is ^6Li which is not our interest.

Name	Lithium	Sodium	Potassium	Rubidium	Caesium
Atomic number	3	11	19	37	55
Standard atomic weight (u)	6.94	22.98	39.09	85.46	132.9
Electron configuration	[He] $2s^1$	[Ne] $3s^1$	[Ar] $4s^1$	[Kr] $5s^1$	[Xe] $6s^1$
Melting point (°C)	180.54	97.72	63.38	39.31	28.44
Boiling point (°C)	1342	883	759	688	671
Density ($g \cdot cm^{-3}$)	0.534	0.968	0.89	1.532	1.93

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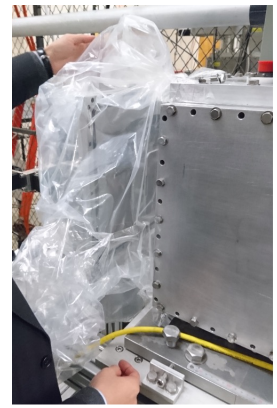
Notable chemical properties of Li

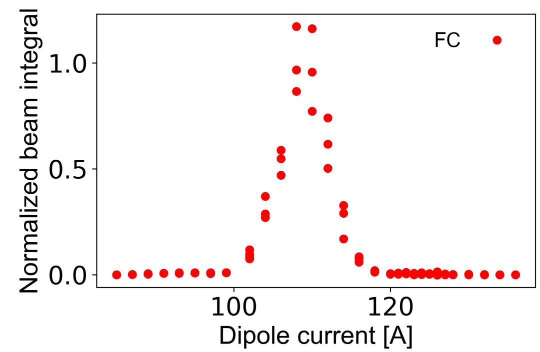
- Li does not readily react with water-free 0_2 below 373 K, but reacts above 373 K to form an oxide (Li_2O).
- The reaction between metal Li and N_2 is slow in the case of N_2 without moisture, but when even a small amount of moisture is present, the exothermic reaction proceeds rapidly even at room temperature to produce nitride (Li_3N).
- This is highly corrosive to iron and steel (the melting point of Li_3N itself is almost 1118 K).
- Li and C react at high temperatures to form carbides (Li_2C_2). The reaction with H_2 produces a stable solid compound (LiH: melting point 960 K, decomposition temperature ~1245 K), which is the most stable among alkali metal hydrides.
- Li at room temperature easily loses its luster and turns black when it comes in contact with air containing moisture, and becomes a white powder if left for a long time, but this is thought to be due to the formation of compounds such as Li_3N, LiOH, and LiOH-H_2O first, and finally Li_2CO_3 powder.
- From the standpoint of corrosion resistance, it is desirable to make the device out of Mo, Nb, Ta, Zr, Ti and W. Fe is also relatively safe, and SUS316 is used in fusion reactors as a non-magnetic material.

Li feed line is kept between 200 C and 300 C.

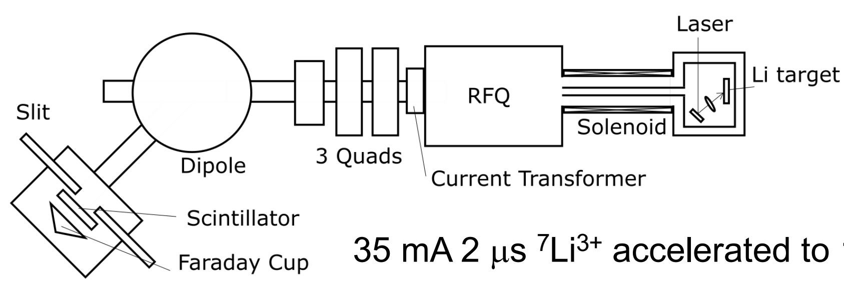
Interior of the ion source should be made of Mo, Nb, Ta, or SUS316.

Experience in handling Li for Laser Ion Source operation

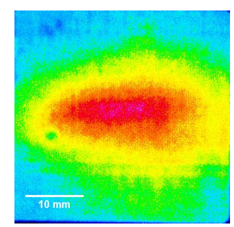




- Glove bag filled with Ar was used.
- Li was cut and contained in pouch without exposure to air.

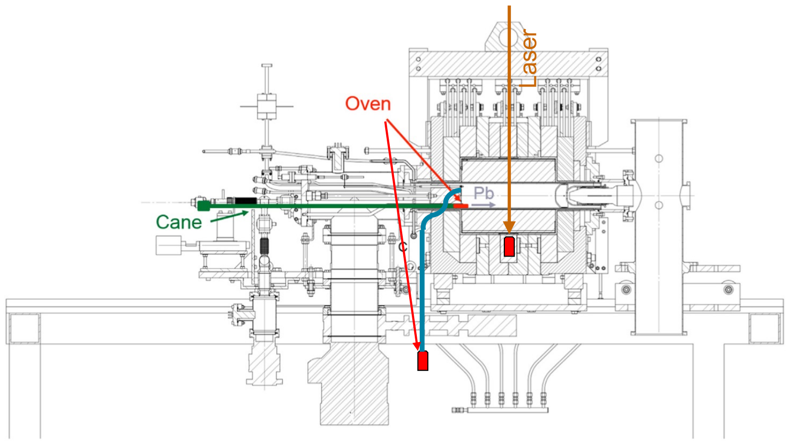


35 mA 2 µs $^{7}Li^{3+}$ accelerated to 1.4 MeV

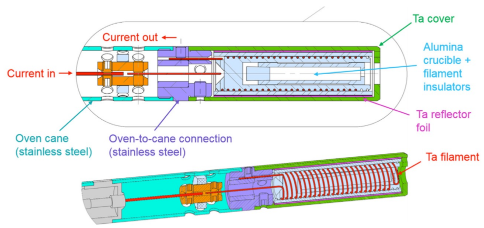


Captured image of scintillator

Develop Li feeding system



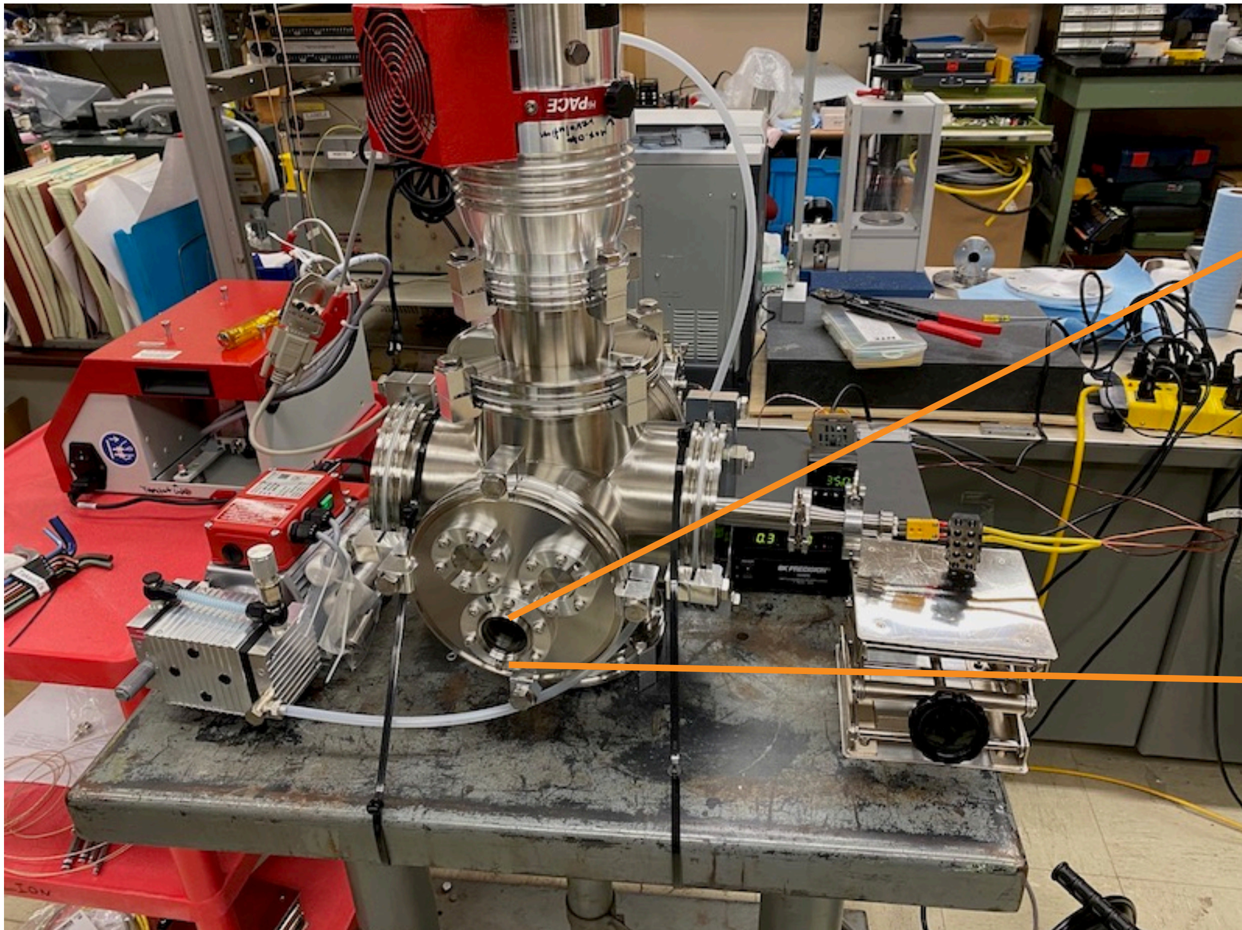
Oven type: Internal or external

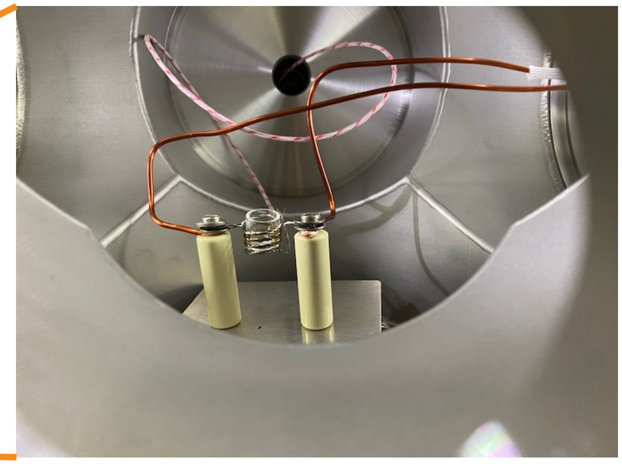


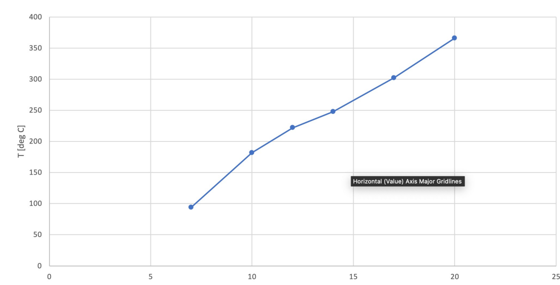
Laser ablation type

Lithium laser target at LIS

Li evaporation test is in preparation







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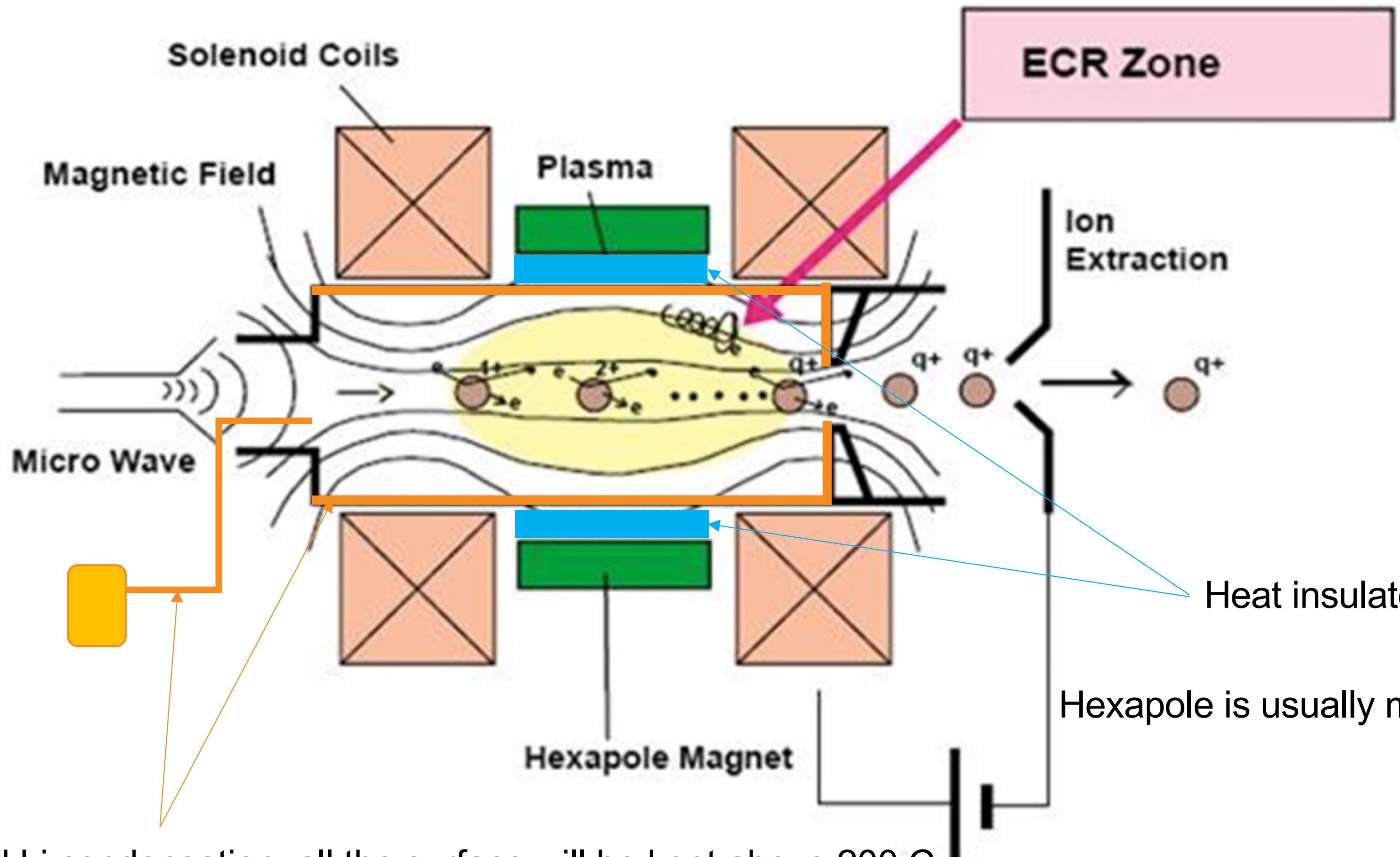
Based on the evaporation experiment, we will design temperature distribution in the ECRIS.



Heat insulator to protect PM

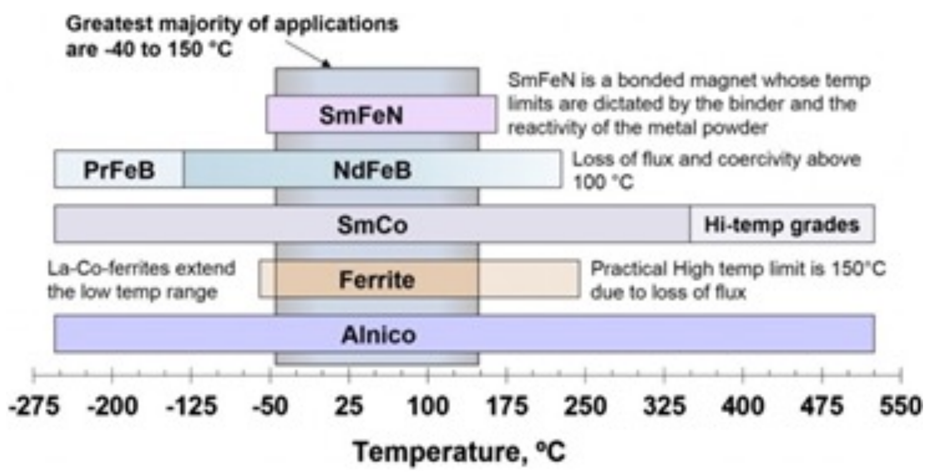
Hexapole is usually made of Nd magr

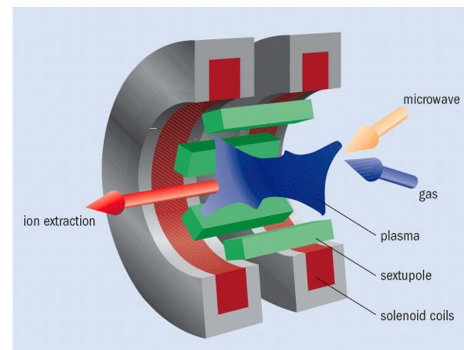
To avoid Li condensation, all the surface will be kept above 200 C.

Materials for Hexapole magnet

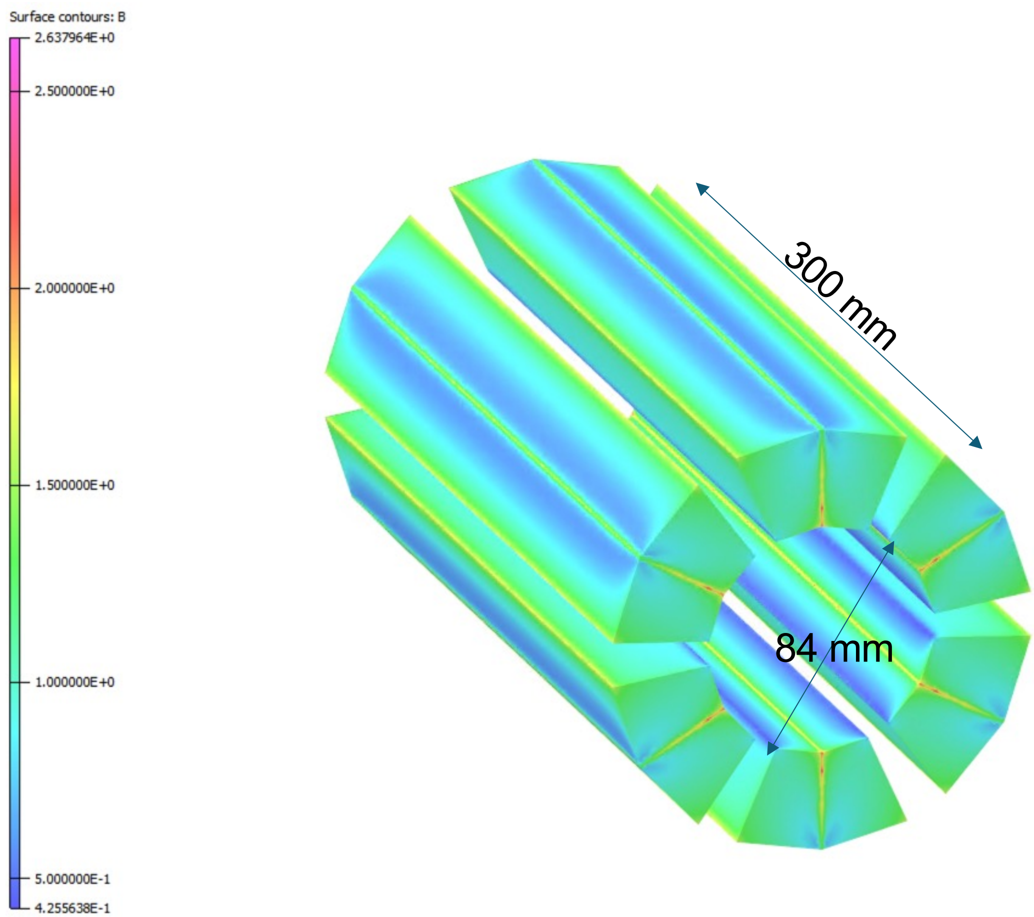
18 GHz microwave needs 6.4 kG.
$Nd_2Fe_{14}B$ is commonly used to form hexapole field for transverse confinement.
However, it is strongly recommended below 100 °C to avoid irreversible demagnetization.

- Choice of a different PM material.
- Electrical magnet without core. (Core cannot be used because it will reduce the axial field of the solenoids.)
- Good design to prevent thermal penetration to the hexapole magnet.



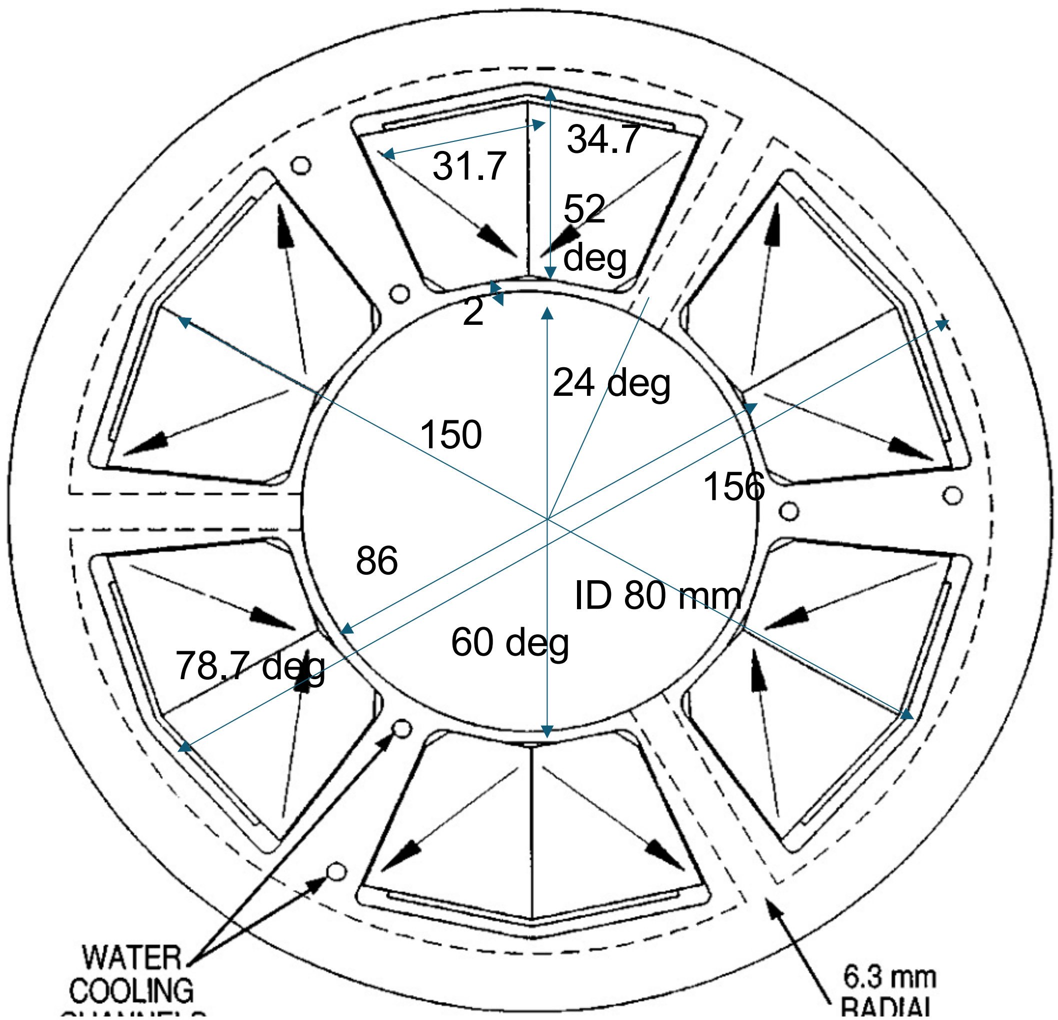


Solenoid mirror and cusp field



Permanent magnet hexapole

The simulation was conducted based on ANL's ECR design.



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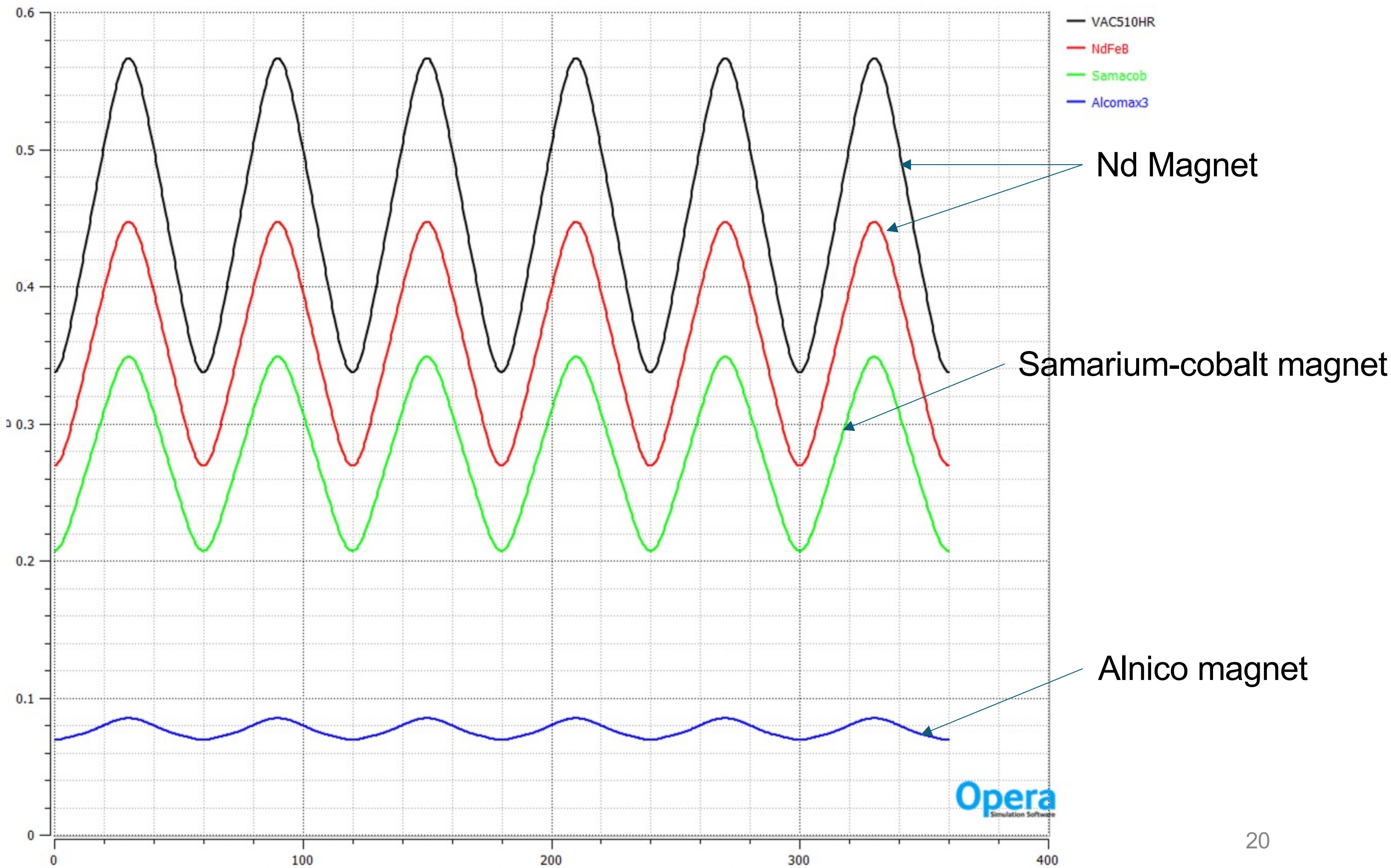
Magnetic fields at r = 35 mm



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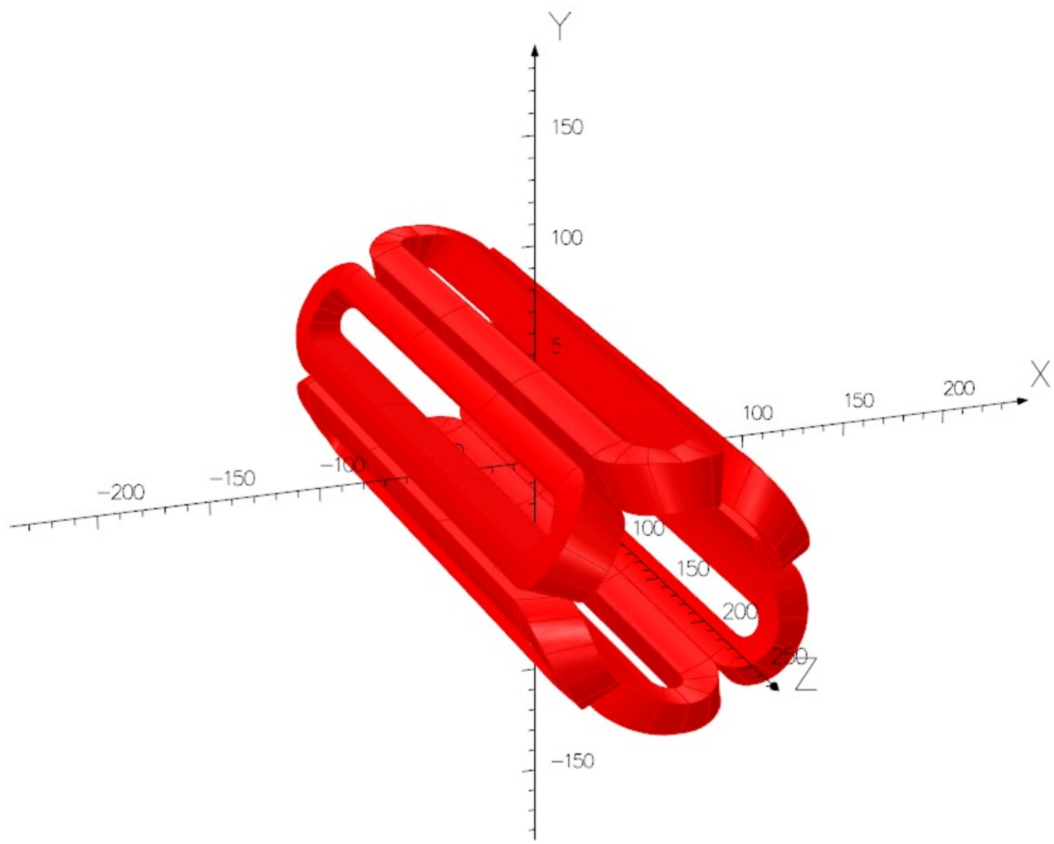
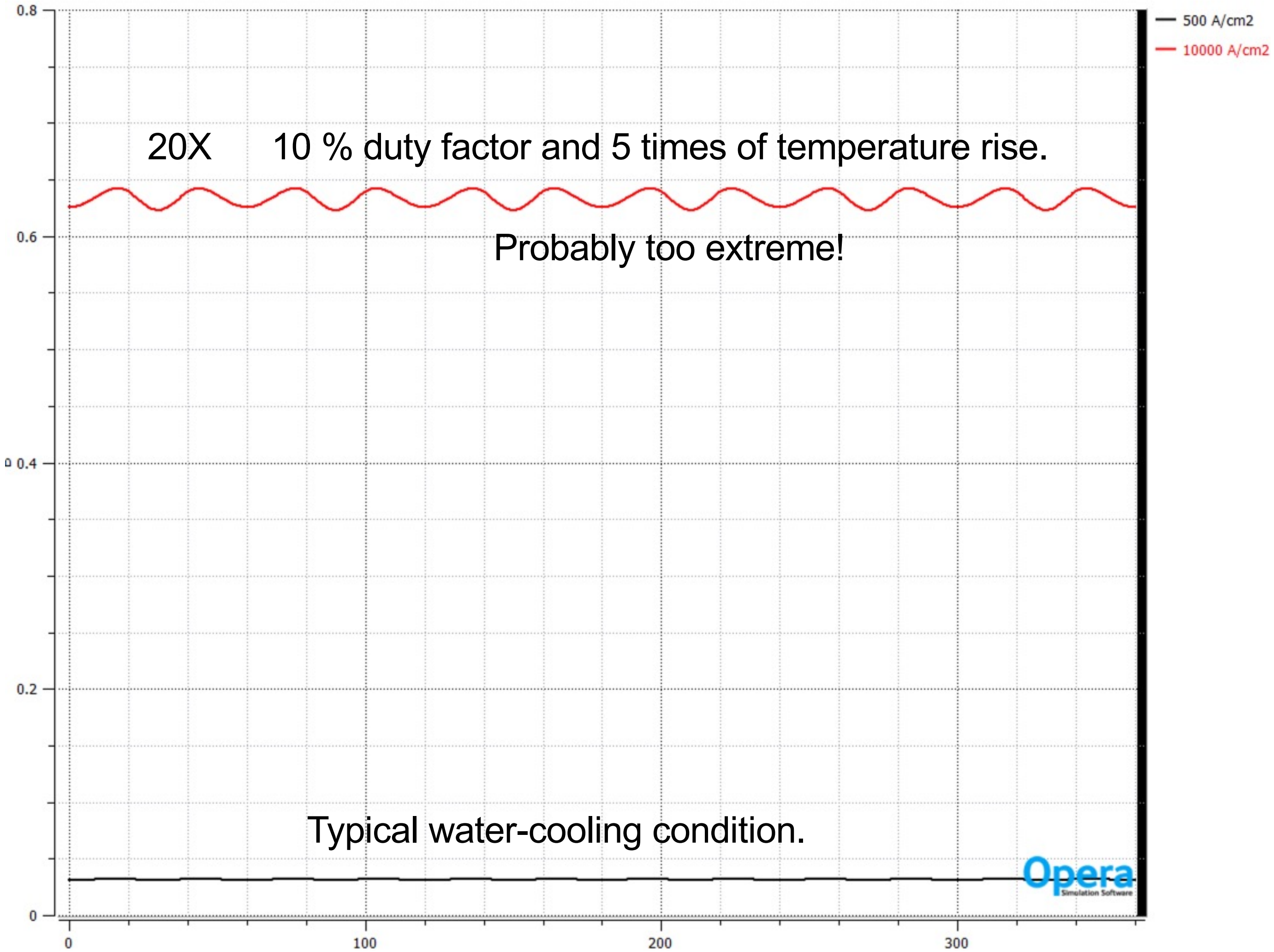
Electromagnet can be used??



Same dimension as the PM model

Magnetic filed by electromagnet



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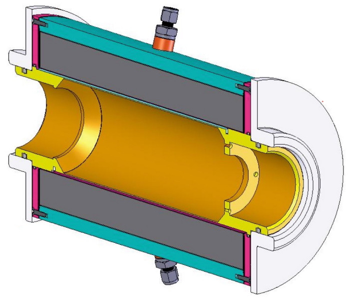
TEST ECRIS is proposed

for investigating the feasibility and beam current.

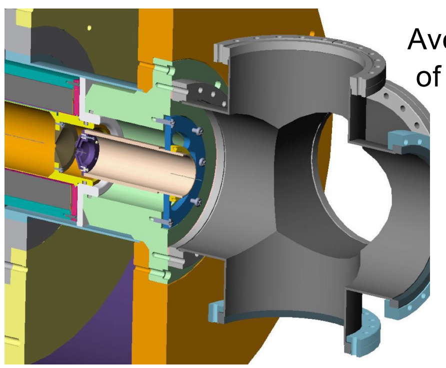
Design of plasma chamber



Heat insulation
to permanent magnets

Volume less than 0.5L

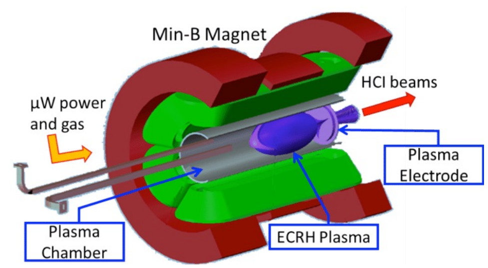
Design of beam extractor



Avoid condensation
of lithium

Design of microwave feed line

Parameters	XTD-750DBSL	XTD-750DBS
FREQUENCY RANGE (extended frequency coverage available)	17.3 to 18.1 GHz (optional 17.3 to 18.4 GHz)	
OUTPUT POWER		
Traveling Wave Tube	750 W (58.8 dBm) Peak 500W (57.0 dBm) CW max.	750 W (58.8 dBm) CW
Rated Power @ Amplifier Flange	340 W (55.3 dBm)	650 W (58.2 dBm)



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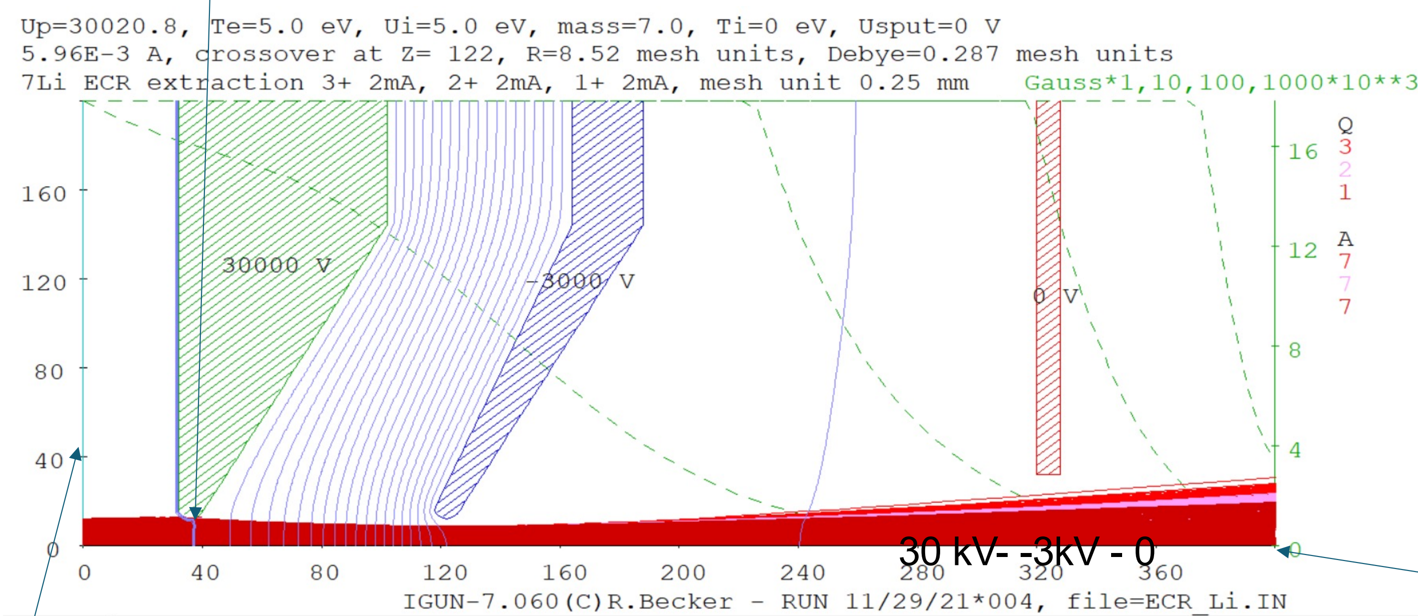
Effect of a support gas will be also tested.

IGUN simulation: 1.68 T at extraction aperture



30 kV- -3kV - 0

Li3+: 2mA
Li2+: 2mA
Li1+: 2mA

Extraction aperture R=3mm

Z=400 means 100 mm
(Mesh uniti is 0.25 mm)

R=40 means 10 mm
(Mesh uniti is 0.25 mm)

r-r'

	Erms	Erms_norm	E_tot_norm
	p mm mrad	p mm mrad	p mm mrad
Li3+	6.795	0.021	0.103
Li2+	7.174	0.022	0.109
Li1+	3.805	0.012	0.058

x-x' and y-y'

	Erms	Erms_norm	E_tot_norm
	p mm mrad	p mm mrad	p mm mrad
Li3+	3.398	0.010	0.052
Li2+	3.587	0.011	0.054
Li1+	1.903	0.006	0.029

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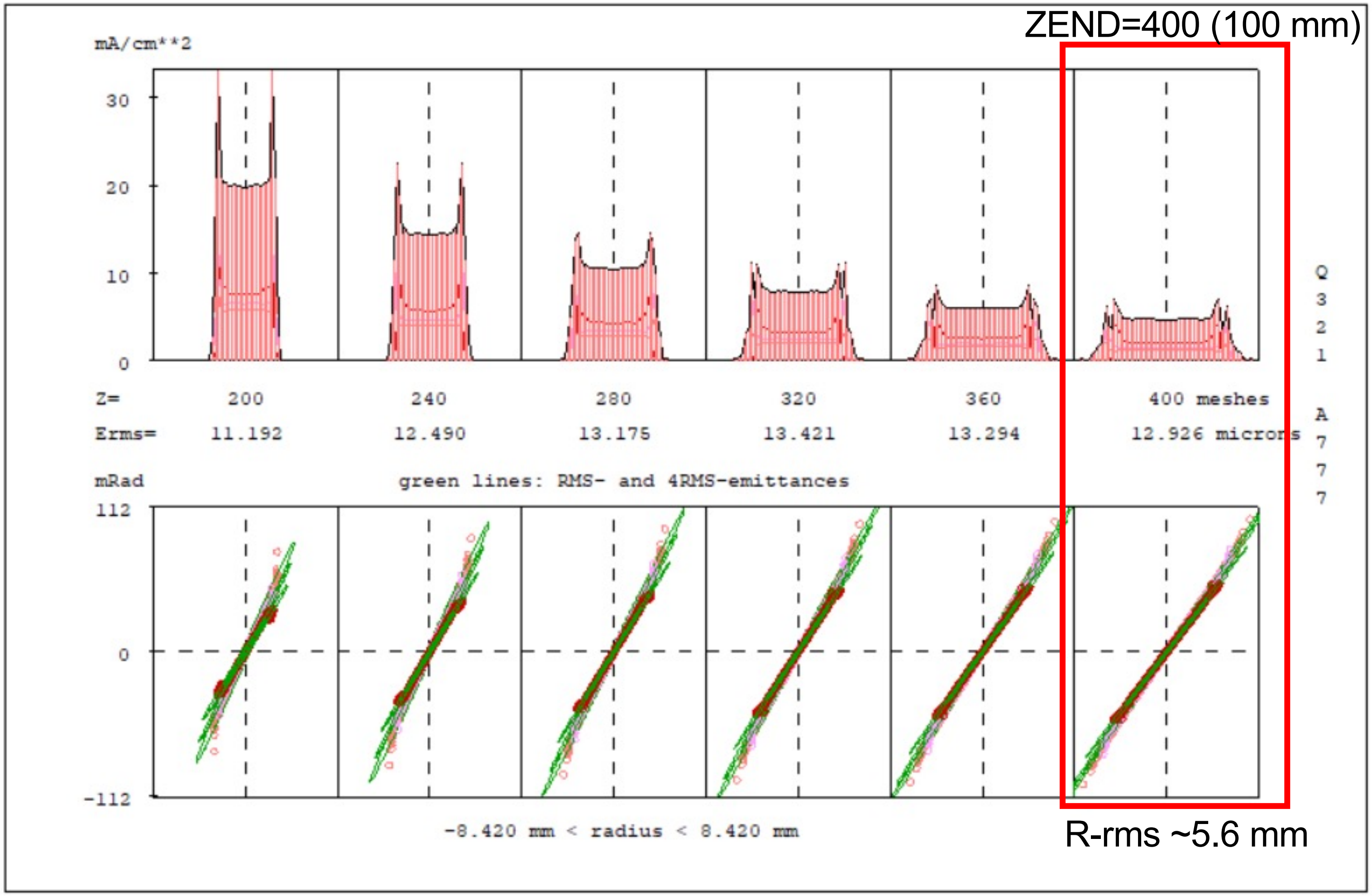
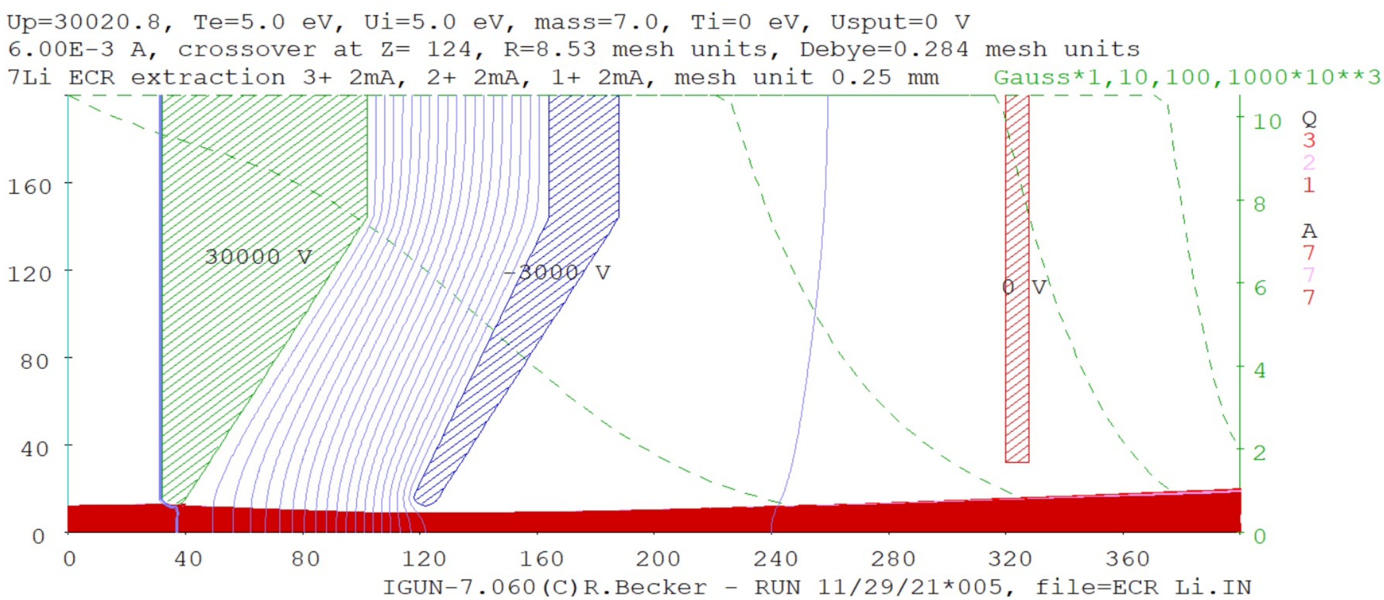
1.68 T at extraction aperture



IGUN simulation: 1.0 T at extraction aperture



r-r'

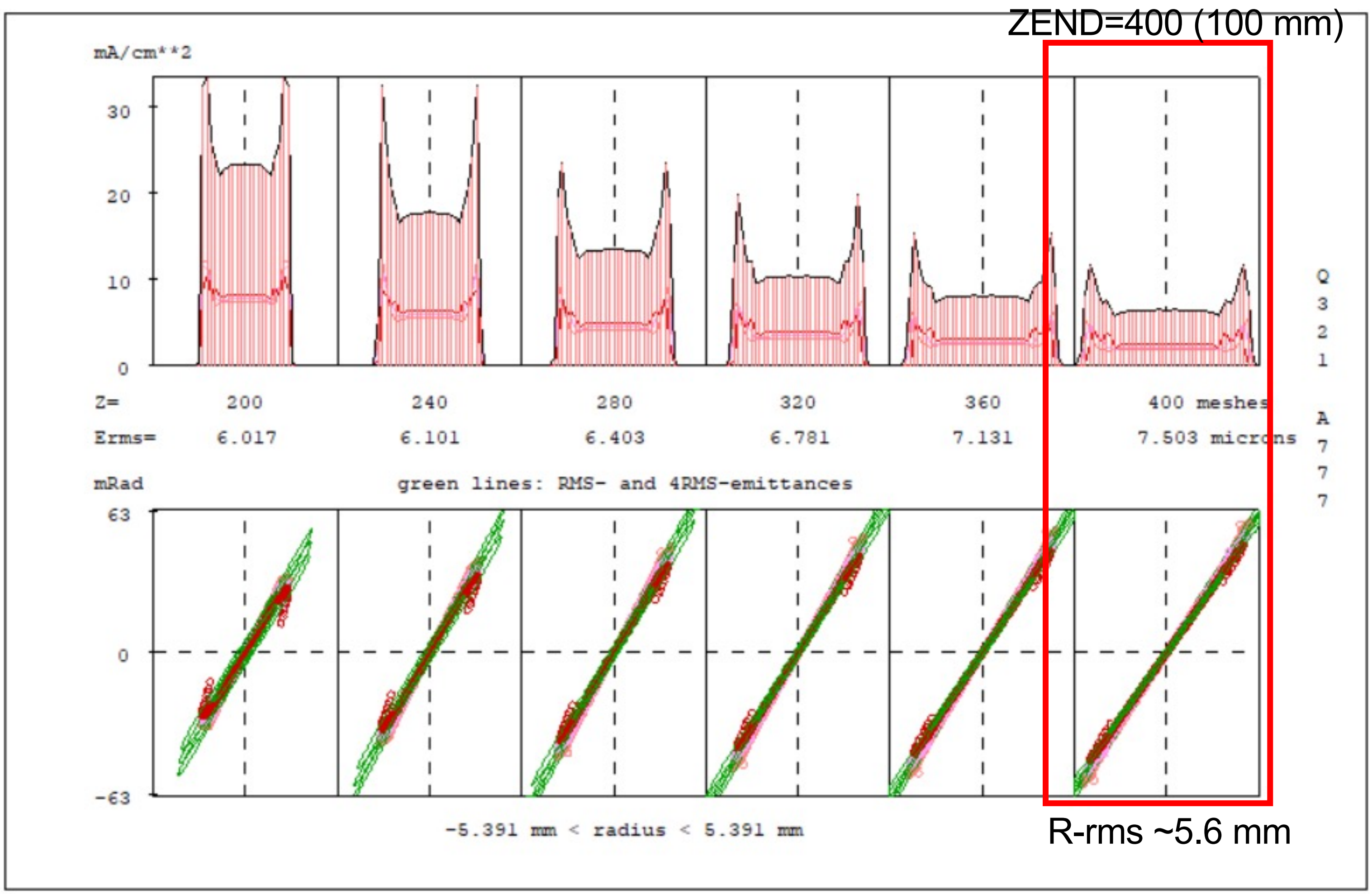
	Erms	Erms_norm	E_tot_norm
	p mm mrad	p mm mrad	p mm mrad
Li3+	3.649	0.011	0.055
Li3+	2.048	0.006	0.031
Li3+	3.262	0.010	0.049

x-x' and y-y'

x-x'

	Erms	Erms_norm	E_tot_norm
	p mm mrad	p mm mrad	p mm mrad
Li3+	1.825	0.006	0.028
Li2+	1.024	0.003	0.016
Li1+	1.631	0.005	0.025

1 T at extraction aperture



Summary

- Proton and deuteron ECRIS can be built or purchased.
- mA class LI^{3+} ECRIS is a challenging task.
- Li is chemically highly reactive. Needs to establish maintenance procedure.
- Li vapor supply systems will be studied. External oven, internal oven or laser.
- Hexapole magnet design must be experimentally confirmed.
- Based on test ECRIS study, we will scall every design parameters.
- He^{2+} can be delivered from the Li ECRIS.

Establish high current ECRIS for He^{2+} and Li^{3+} beams.