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U.S. DEPARTMENT OF ENERGY

Development of high current highly charged laser ion source

FY23, FY24, FY25(NCE)

Maashiro Okamura (BNL), Guy Garty (Columbia University)

Dec. 2, 2024

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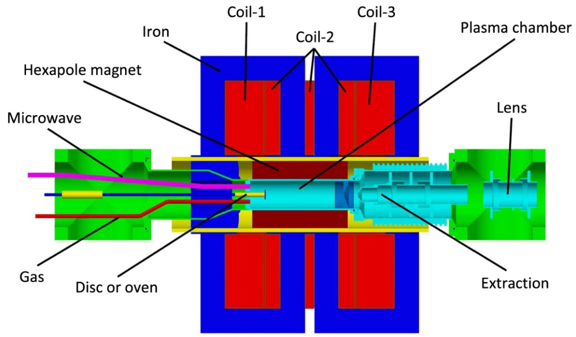
Project goals

- Develop Laser ion source (LIS) and Radio Frequency Quadrupole (RFQ).
- Very high current and highly charged state ion beam will be delivered.
- Use Direct Plasma Injection Scheme which was invented by the PI.
- Target species are from light to medium mass ions.

State of the art ion sources for heavy ion beams



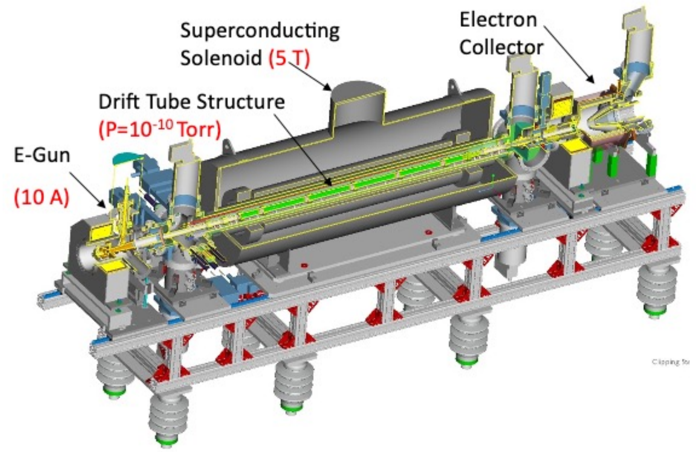
Biri, S., Vajda, I.K., Hajdu, P. *et al.* The Atomki Accelerator Centre. *Eur. Phys. J. Plus* **136**, 247 (2021). https://doi.org/10.1140/epjp/s13360-021-01219-z

Electron Cyclotron Resonance Ion Source (ECIRS)

Good for CW beam (cyclotron or LINAC)
High average current

Electron Beam Ion Source (EBIS)

Pulsed beam for synchrotron
High flexibility



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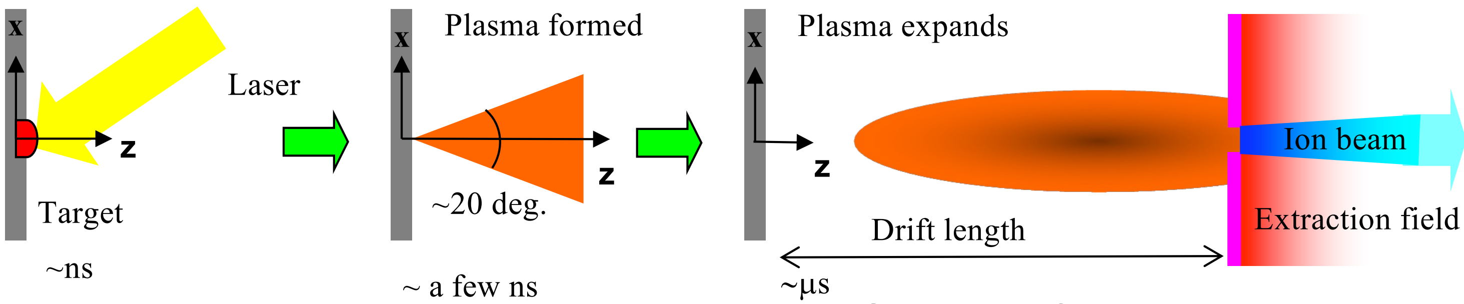
laser ion source (LIS)



Scheme of laser ion source

- High density plasma created from a solid.
- Fast switching target materials.
- Low temperature after adiabatic expansion.
- Uniform density of beams.

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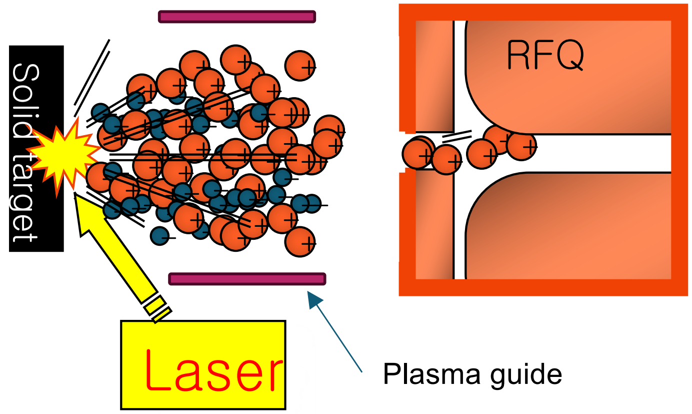
Direct Plasma Injection Scheme (DPIS)



- Dense expanding plasma from solid targets.
- Retaining high brightness, heavy ions can be delivered to RFQ.
- Since ions in plasma state, space charge effect can be neglected.
- No focusing lenses.
- No high voltage cage, no isolating transformer.

Performance of DPIS was verified by some limited species.
We explore possibility to accelerate heavy ions with DPIS.
This work will give a benchmark for future accelerator project.

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Project Status (control milestones)

FY2023-Q1

1 Subcontract with Columbia University
Dec. 31, 2022 Dec. 22

2 Open call for a postdoc position
Dec. 31, 2022 Oct. 4 Madhawa joined Sep. 1 2023

FY2023-Q2

1 The first beam through the RFQ
Feb. 28, 2023 Feb. 10 ($^{11}B^{5}$)

FY2023-Q3

1 The second species acceleration
Jun. 30, 2023 Jun. 30 ($^{12}C^{6}$)

2 Design of new laser irradiation box
Jun. 30, 2023 May 20

FY2023-Q4

1 Design of RFQ electrodes
Sep. 30, 2023 Sep. 30

3 Presentation at international conference
Sep. 30, 2023 Sep. 30, 5 presentations at ICIS2023

FY2024-Q1

1 Procurement of new electrodes type 1
Dec. 31, 2023 Mar. 2024 Procurement placed

2 The third species acceleration
Dec. 31, 2023 Sep. 20 ($^{26}Mg^{10}$)

FY2024-Q2

1 Installation of type 1 electrodes
Mar. 30, 2024 Nov. 10

2 The forth species acceleration
Mar. 30, 2024 Mar. 25 10 ($^{27}Al^{11}$)

FY2024-Q3

1 Procurement of new electrodes type 2
Jun. 30, 2024 To be placed

FY2024-Q4

1 Installation of electrodes type 2
Aug. 30, 2024 TBD

2 The fifth species acceleration
Sep. 30, 2024 Oct. 3 ($^{28}Si^{12}$)

3 Submit a journal paper
Sep. 30, 2024 Ready to submit

Summary of expenditures by fiscal year (FY):

	FY23 ($K)	FY24 ($K)	Totals ($K)
a) Funds allocated	400	400	800
b) Actual costs to date	256	269	525

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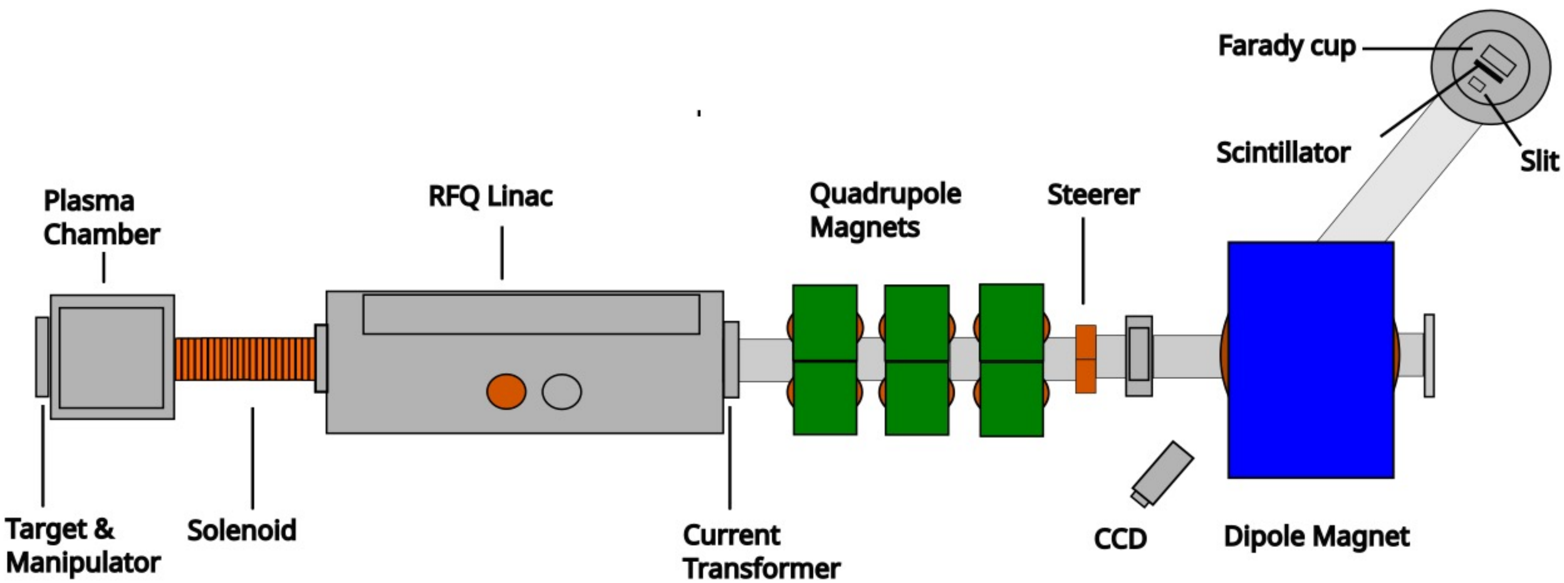
Laser Ion Source and RFQ



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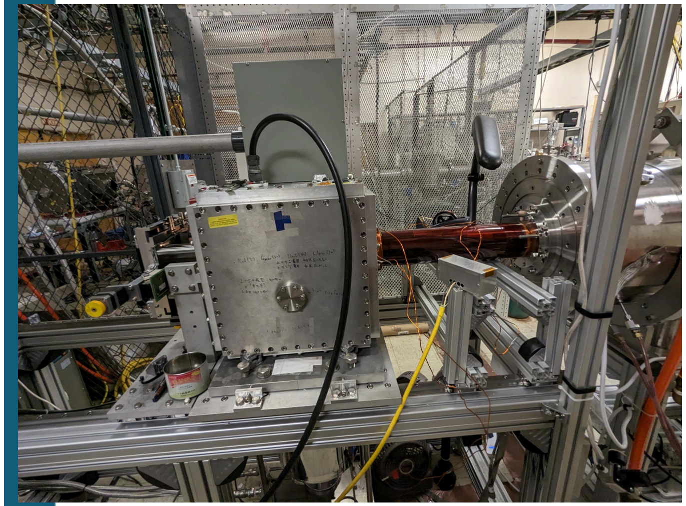
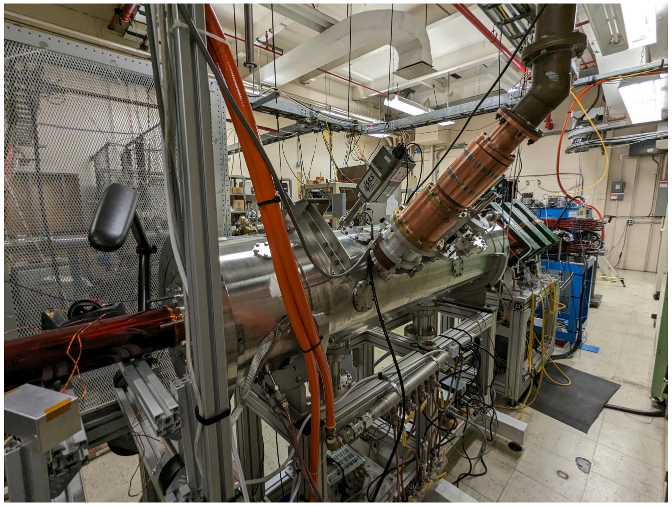
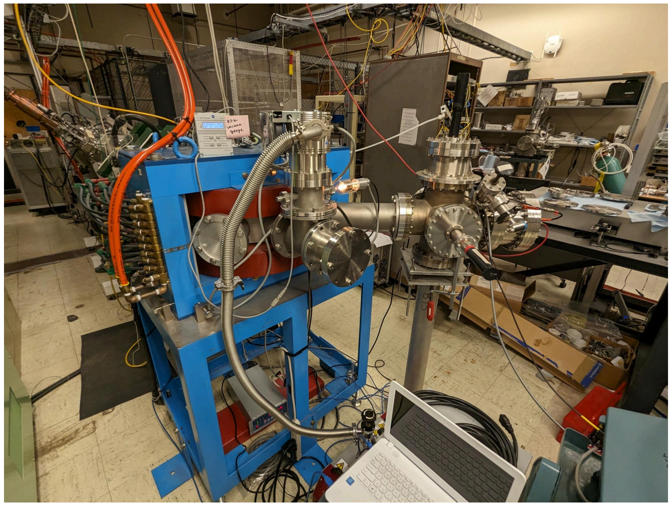
Beamline



Plasma Chamber



RFQ accelerator and
beam line



Dipole magnet and
end of beamline

FY24, Accelerated Species

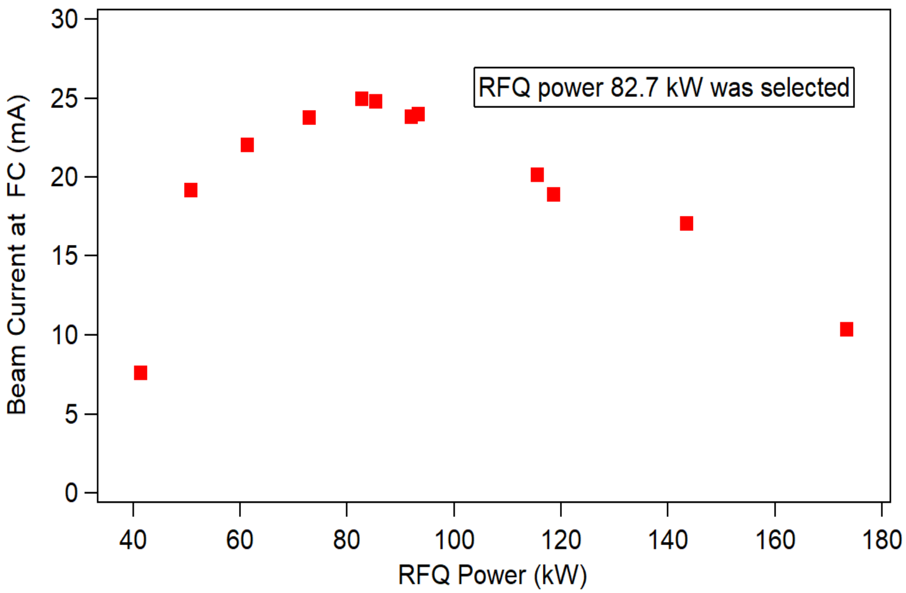
$_{12}Mg$ ^{24}Mg 79%, ^{25}Mg 10%, ^{26}Mg 11%,

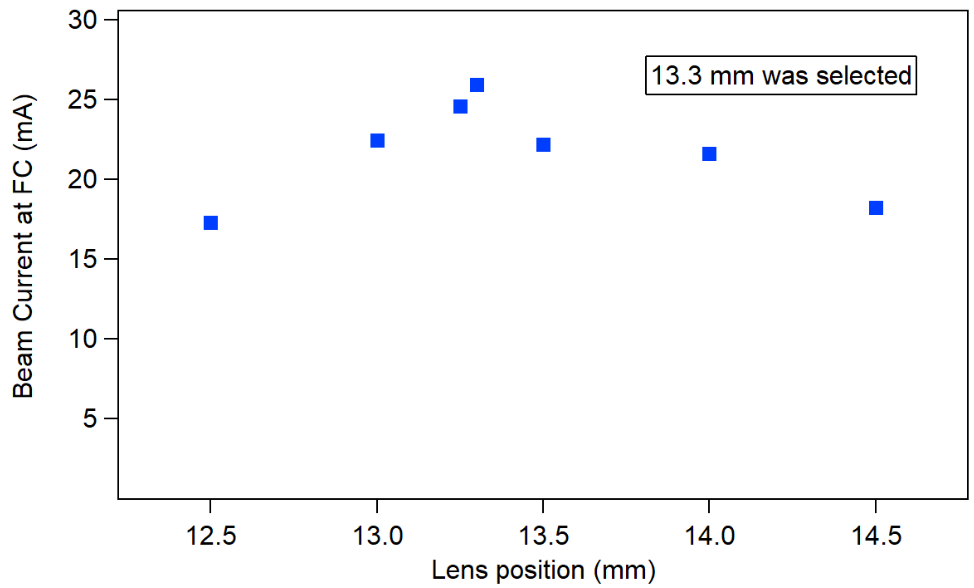
$_{13}Al$ ^{27}Al 100%

$_{14}Si$ ^{28}Si 92%, ^{29}Si 4.7%, ^{30}Si 3.1%

$_{12}Mg^{9+}$

RFQ and Lens Position Optimization

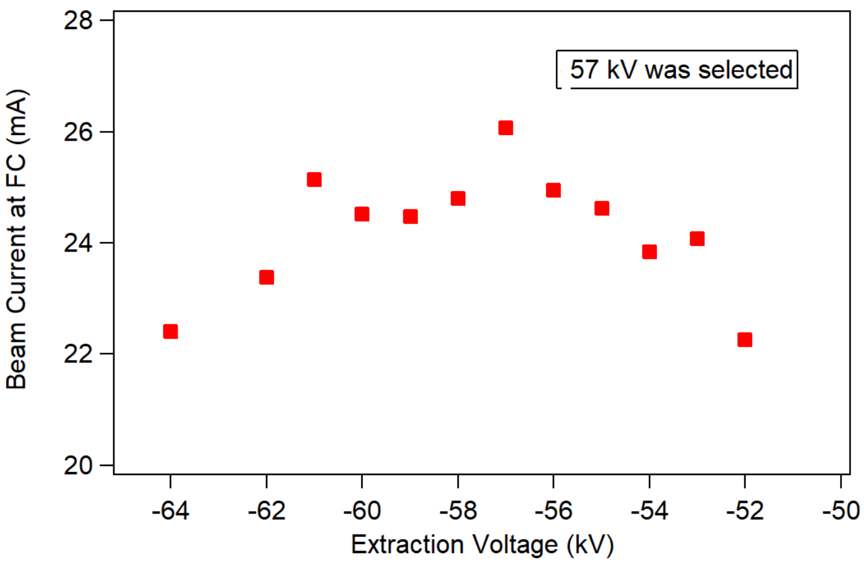


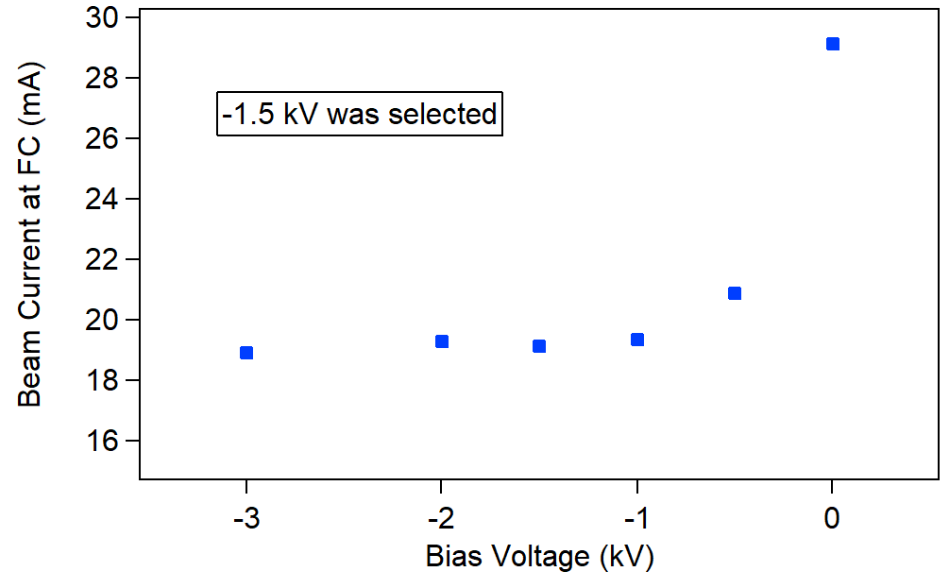


- Best RFQ power was 82.7 kW.
- Best Lens position was 13.3 mm.

$_{12}Mg^{9+}$

Extraction Voltage and Bias Voltage Optimization

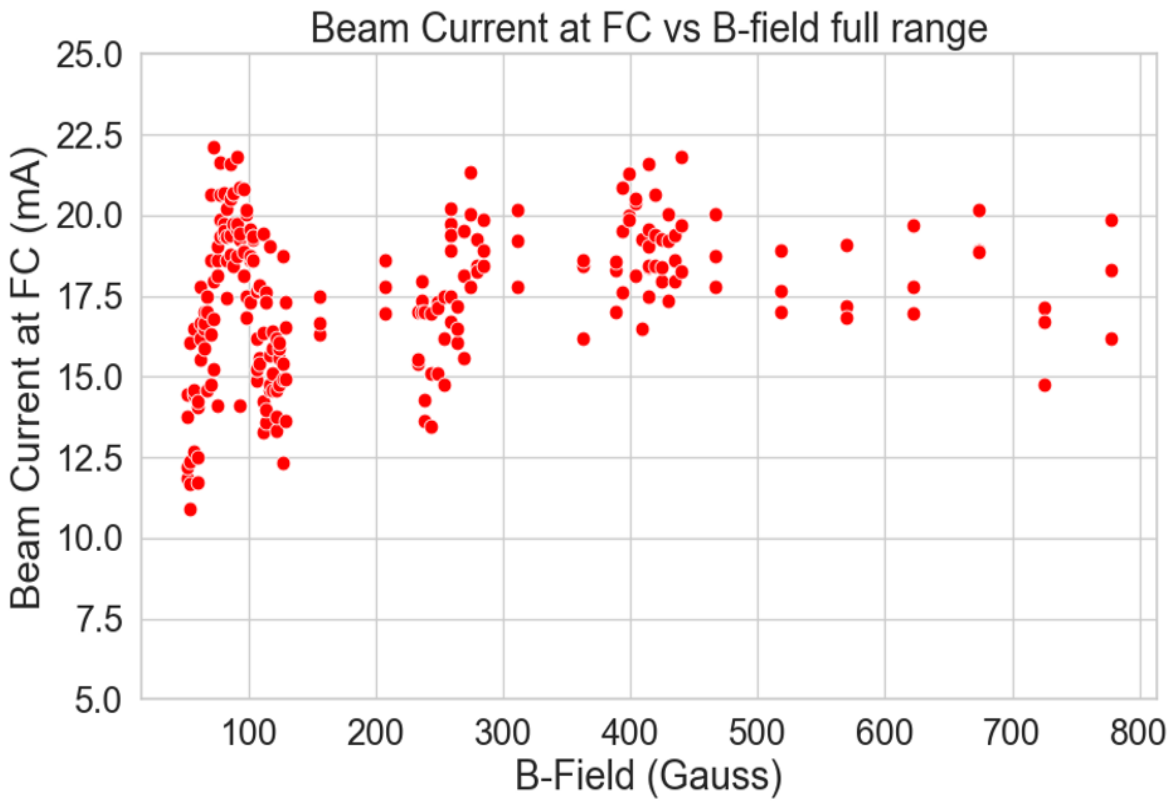




- Suitable extraction voltage was 57 kV.
- Used bias voltage was-1.5 kV.

$_{12}Mg^{9+}$

Solenoid B-field Optimization



- Lower B-fields were identified for optimization of beam currents.
- Higher beam currents were observed in a periodic pattern in relation to B-fields.

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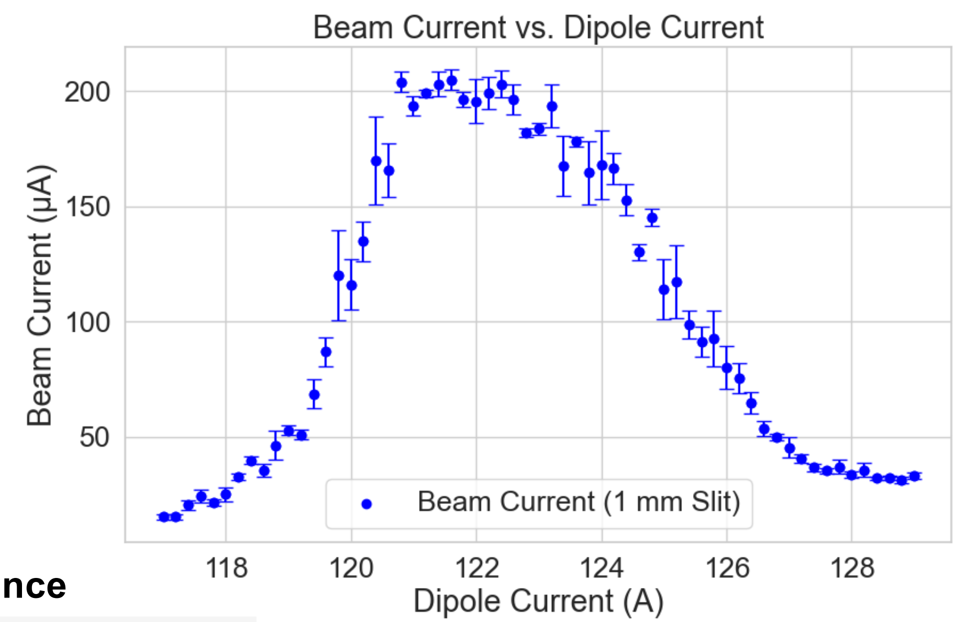
$_{12}Mg^{9+}$

Dipole Current Scan for Mg^{9+}

- 1 mm slit width was used.
- Isotopes separation was difficult
- Dipole current -122 A was identified as center of the peak and used for Mg^{9+} .



Isotope	Abundance
^{24}Mg	79%
^{25}Mg	10%
^{26}Mg	11%

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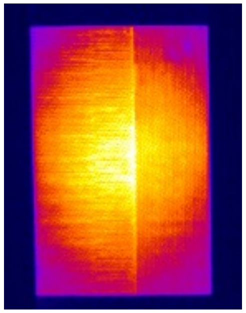
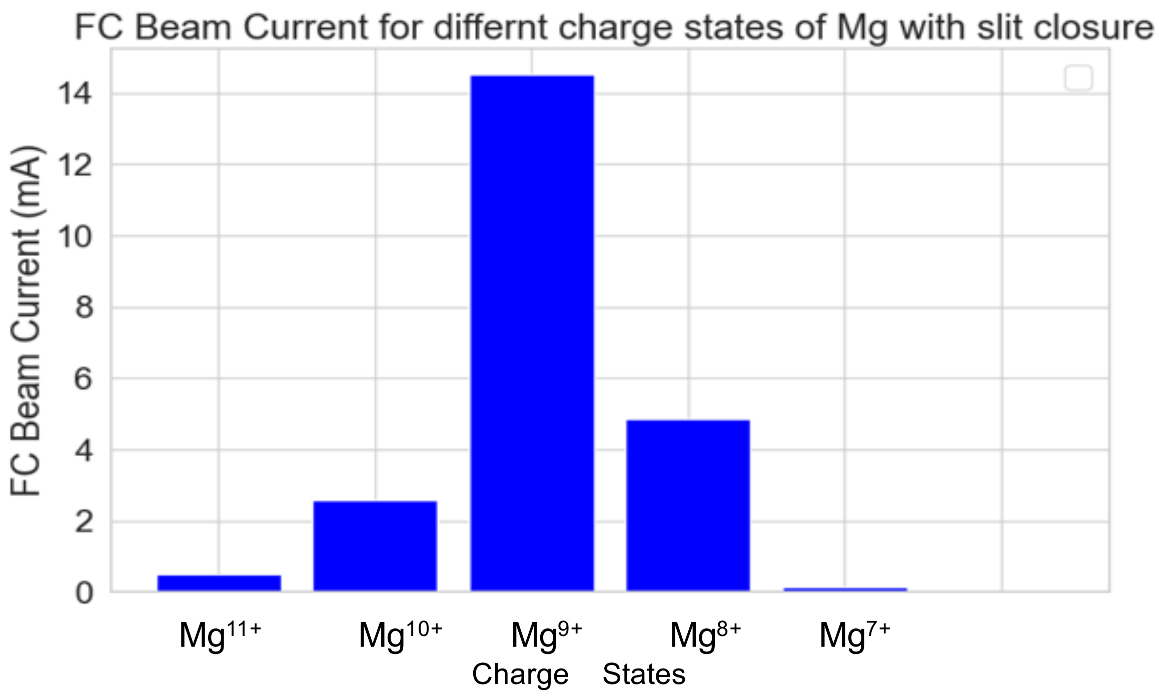
$_{12}Mg^{9+}$

Different Charge states for Mg with 25 mm slit closure

- Different charge states were observed with Mg^{9+} beam parameters.
- Highest observed state - 11+
- Lowest observed state - 7+



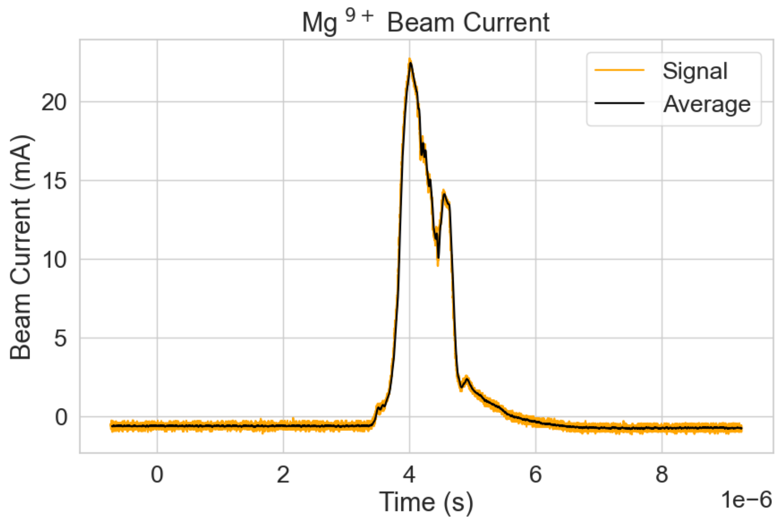
Beam Spot with 25 mm slit closure

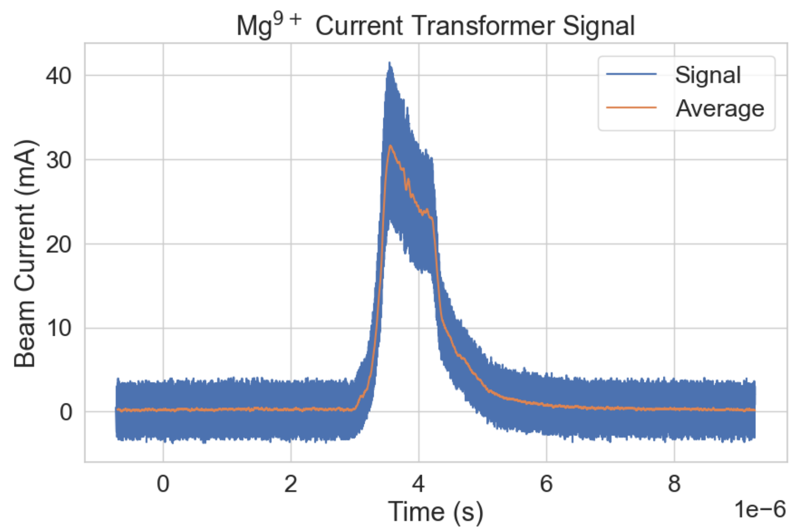


May contains isotope contamination

$_{12}Mg^{9+}$

Mg^{9+}





- An ion beam current of 23.07 mA was achieved for Mg^{9+} ions.
- The number of particles ~ 9.82×10^9.
- The installation of a mesh before the CT resulted in a 72% reduction in the beam intensity. (The measurement without the mesh would be 32.04 mA .)

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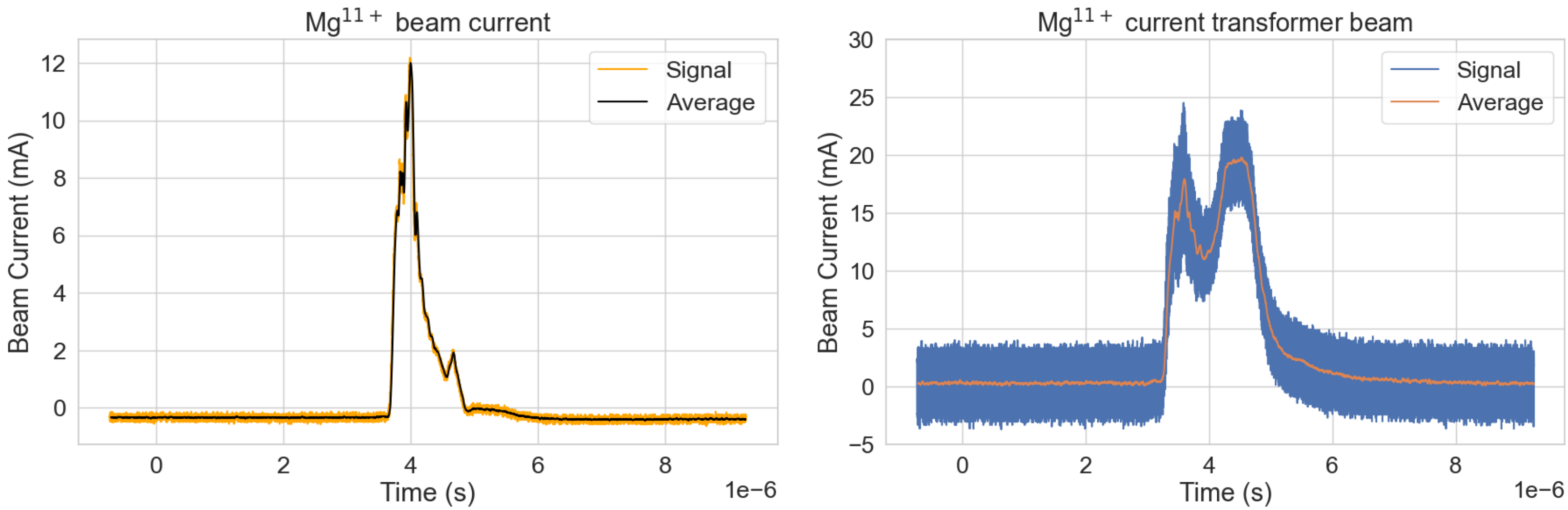
$_{12}Mg^{11+}$

Mg^{11+}



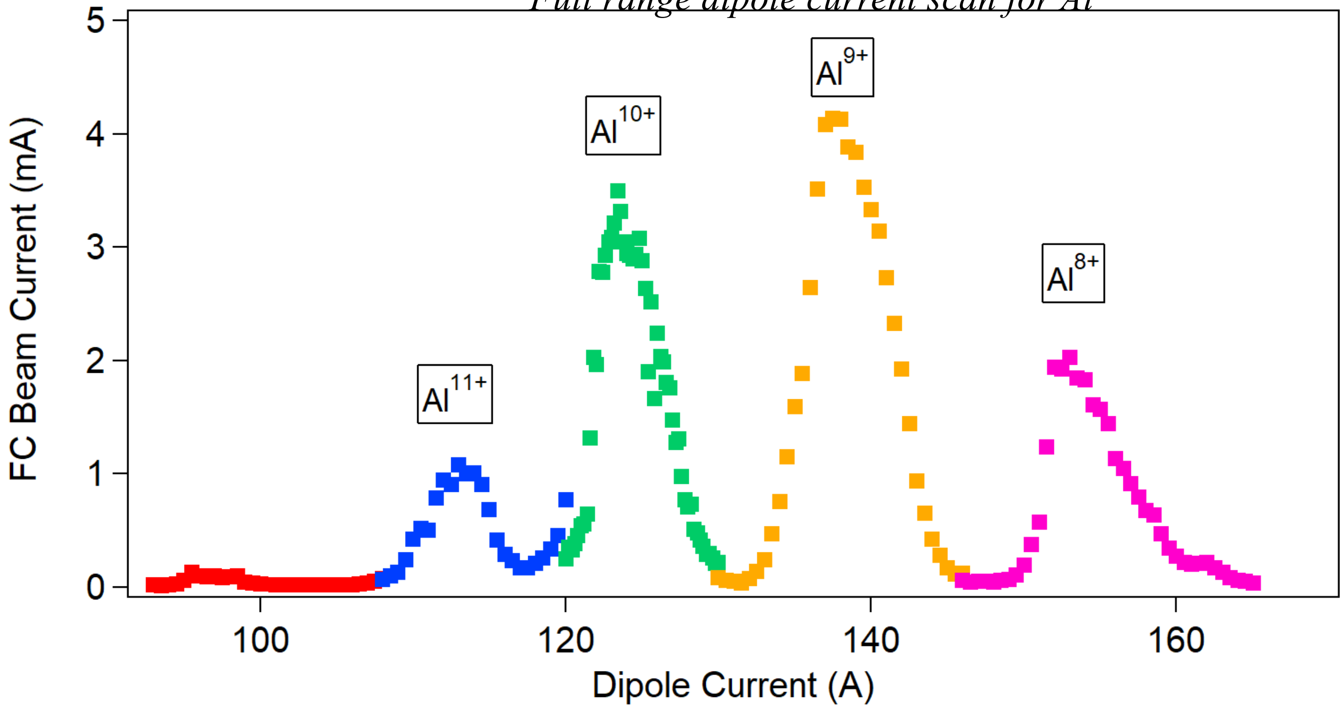
- An ion beam current of 12.34 mA was achieved for Mg^{11+} ions.
- The number of particles ~ 2.49 x 10^9.
- The measurement without the mesh would be 17.13 mA.

$_{13}Al$

Al Ion Production

- Al highly charged ion production was observed.
- Only ^{27}Al (stable isotope) readily produced.
- Al^{11+},Al^{10+}, Al^{9+} and Al^{8+} charge states were noticed.

Full range dipole current scan for Al



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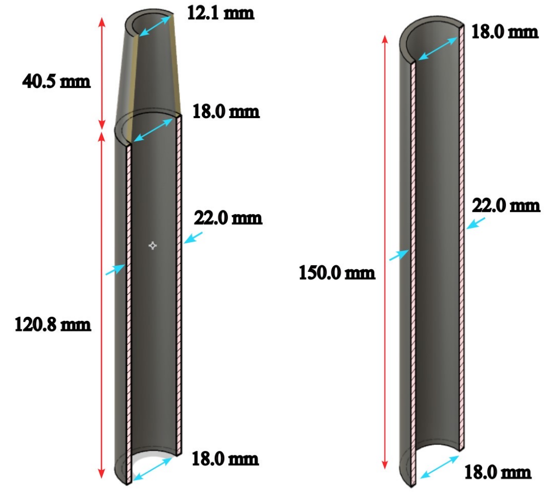
Different Nozzle Geometries

8 mm nozzle (old)

12 mm nozzle (new)

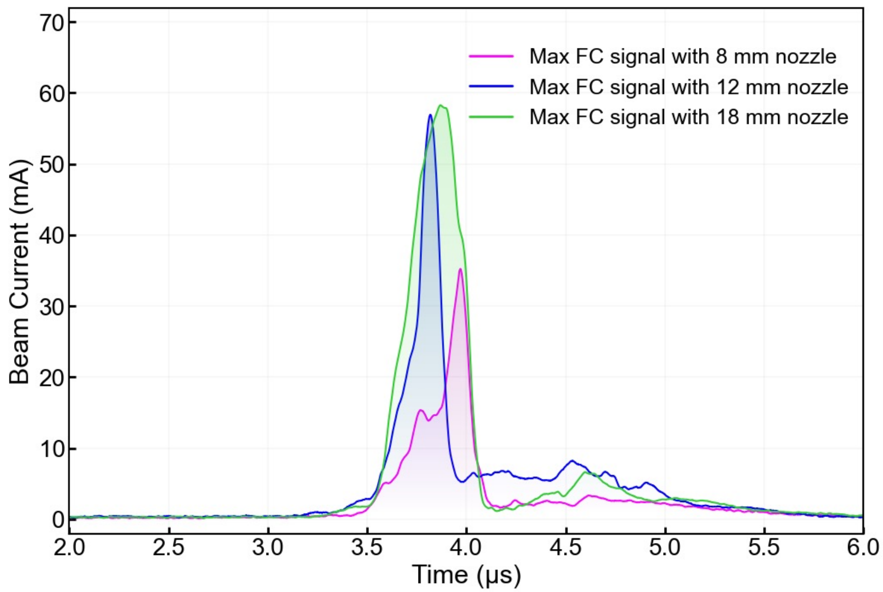
18 mm nozzle (new)



$_{13}Al^{11+}$

Al^{11+}

- The best Al ion production was achieved.
- Pink – 8 mm aperture nozzle
- Blue – 12 mm aperture nozzle
- Green - 18 mm aperture nozzle



Nozzle Size	FC measurement	No of Particles	Calculated beam current with mesh compensation
8 mm	25.27 mA	2.74×10^9	35.10 mA
12 mm	40.83 mA	4.94×10^9	56.70 mA
18 mm	41.84 mA	7.42×10^9	58.10 mA

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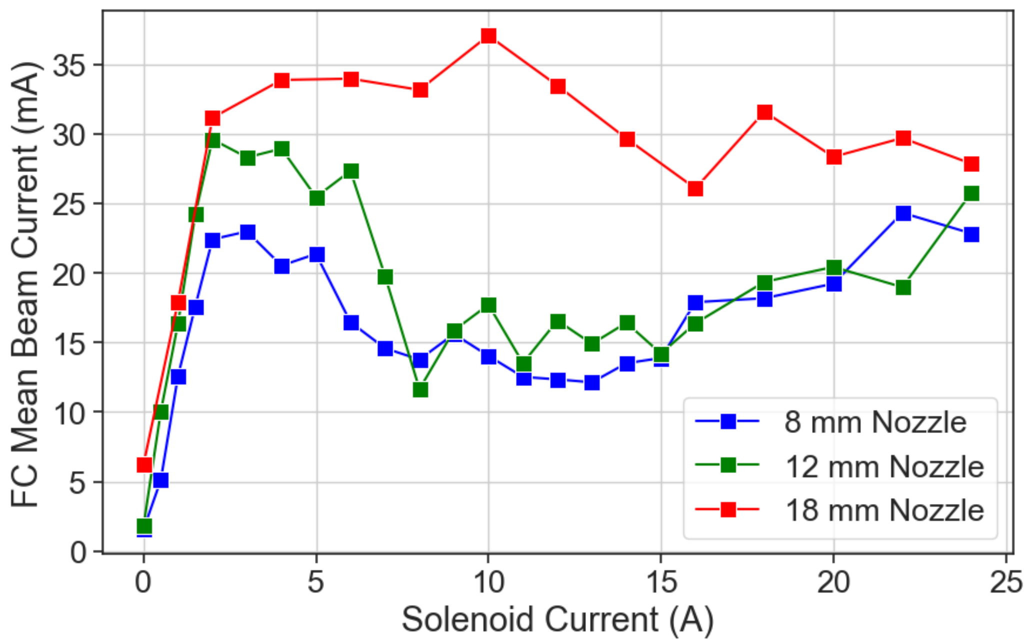
$_{13}Al^{11+}$

Al^{11+} Solenoid Current Scan for three different nozzle sizes

- At 10 A solenoid current, the highest ion beam current was achieved using 18 mm nozzle.
- High beam currents were achieved for 12 mm nozzle at 2 A, 4 A, and 24 A.
- Both nozzles produced over 50 mA ion beam currents. (Record beam current for Al^{11+} ions)



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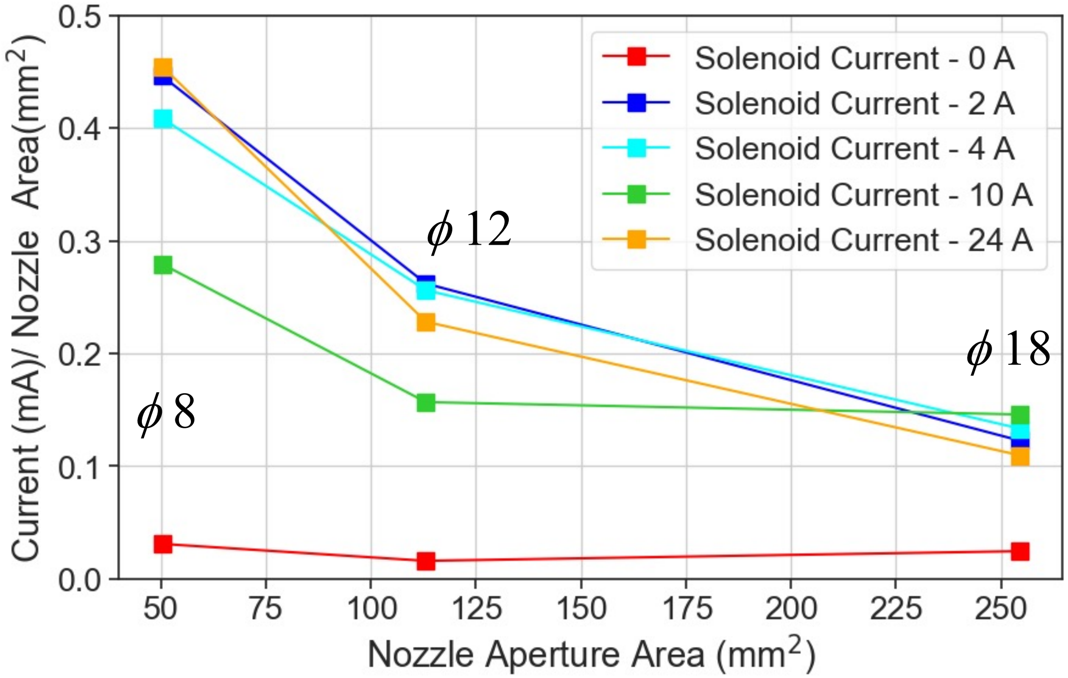
$_{13}Al^{11+}$

Relationship between beam current normalized by nozzle aperture area Vs nozzle aperture area



- The highest beam current density was observed for 8 mm aperture, while the lowest was observed for 18 mm aperture.
- For 10 A and 0 A solenoid currents, ion beam currents with 12 mm aperture nozzle were close to those with 18 mm aperture nozzle

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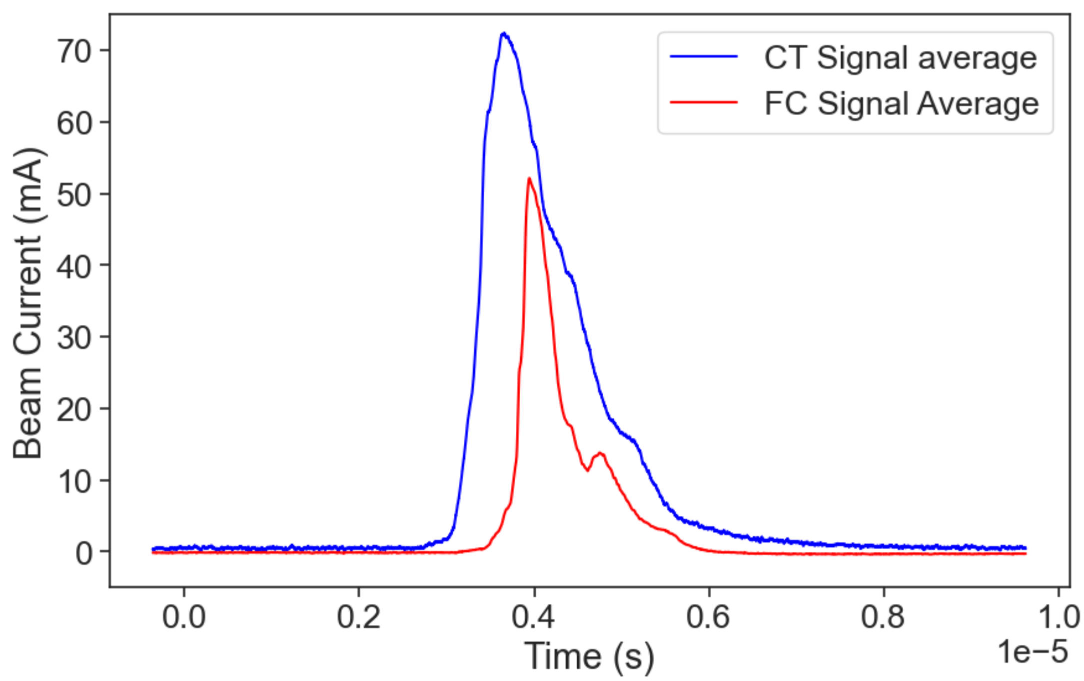
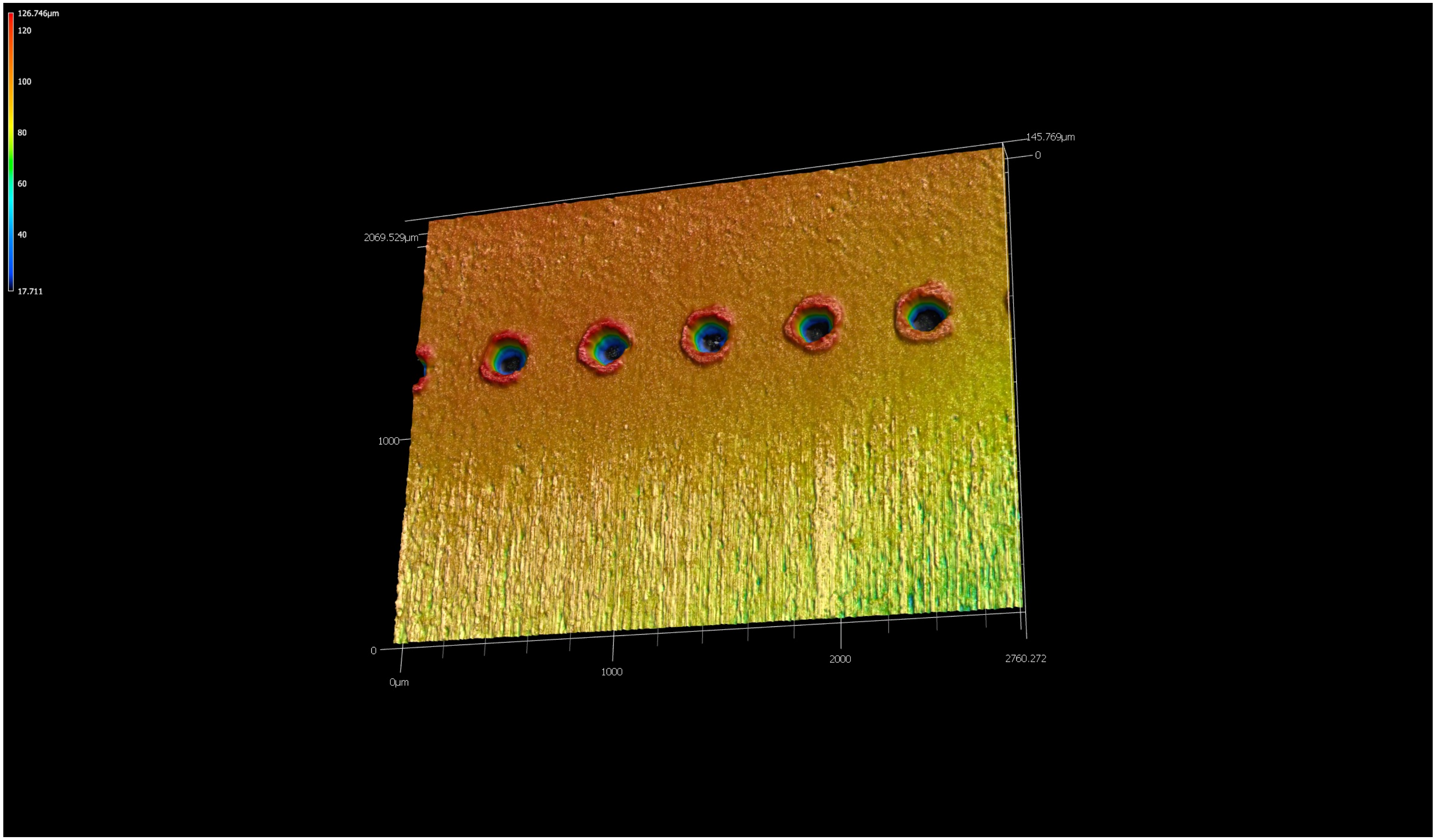
$_{13}Al^{10+}$

- For Al^{10+}, accelerated ion beam current exceeded 50 mA again.
- Red- FC signal with mesh compensation
- Blue – Current transformer signal with mesh compensation

Al^{10+}

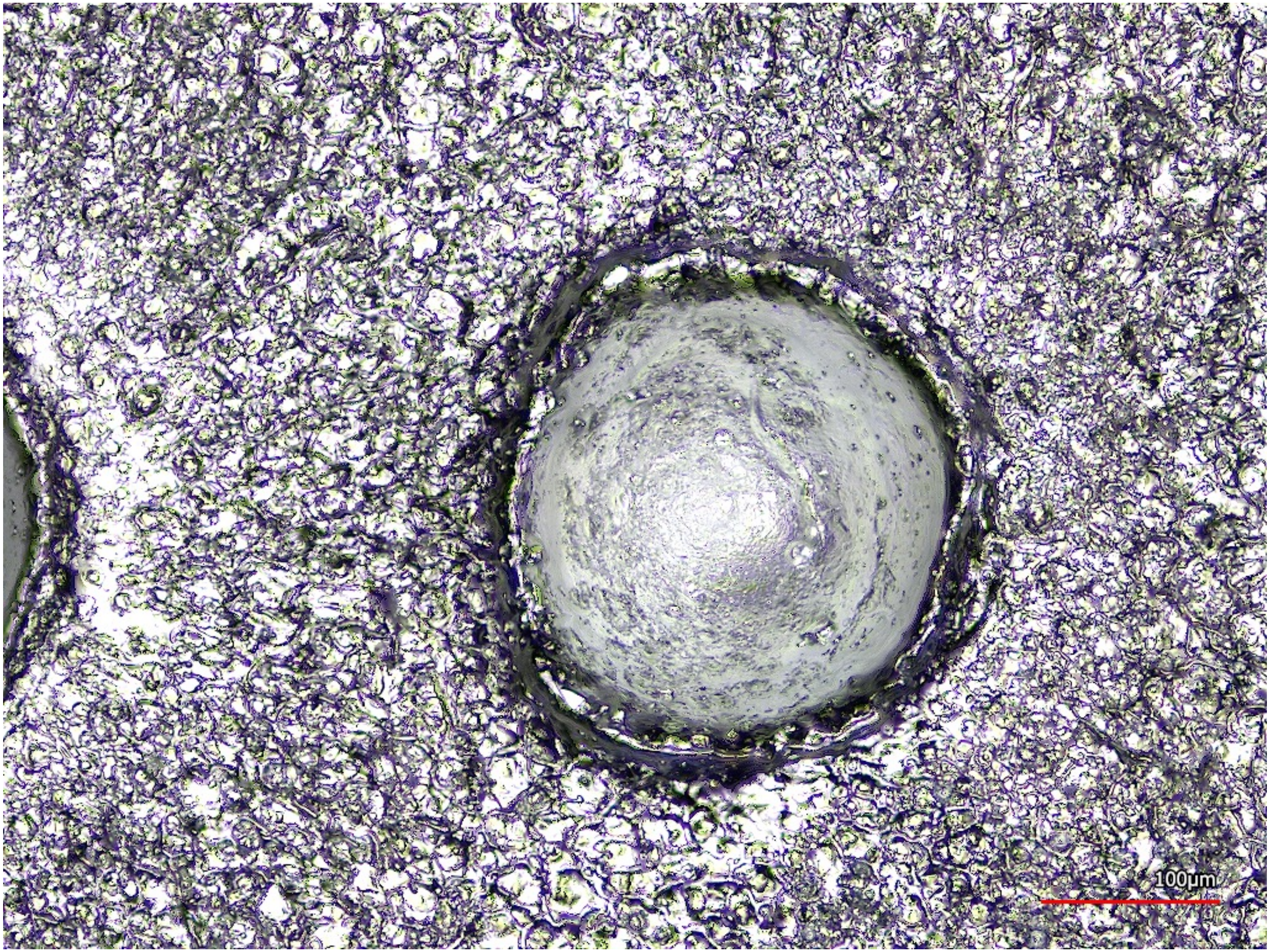


$_{13}Al$



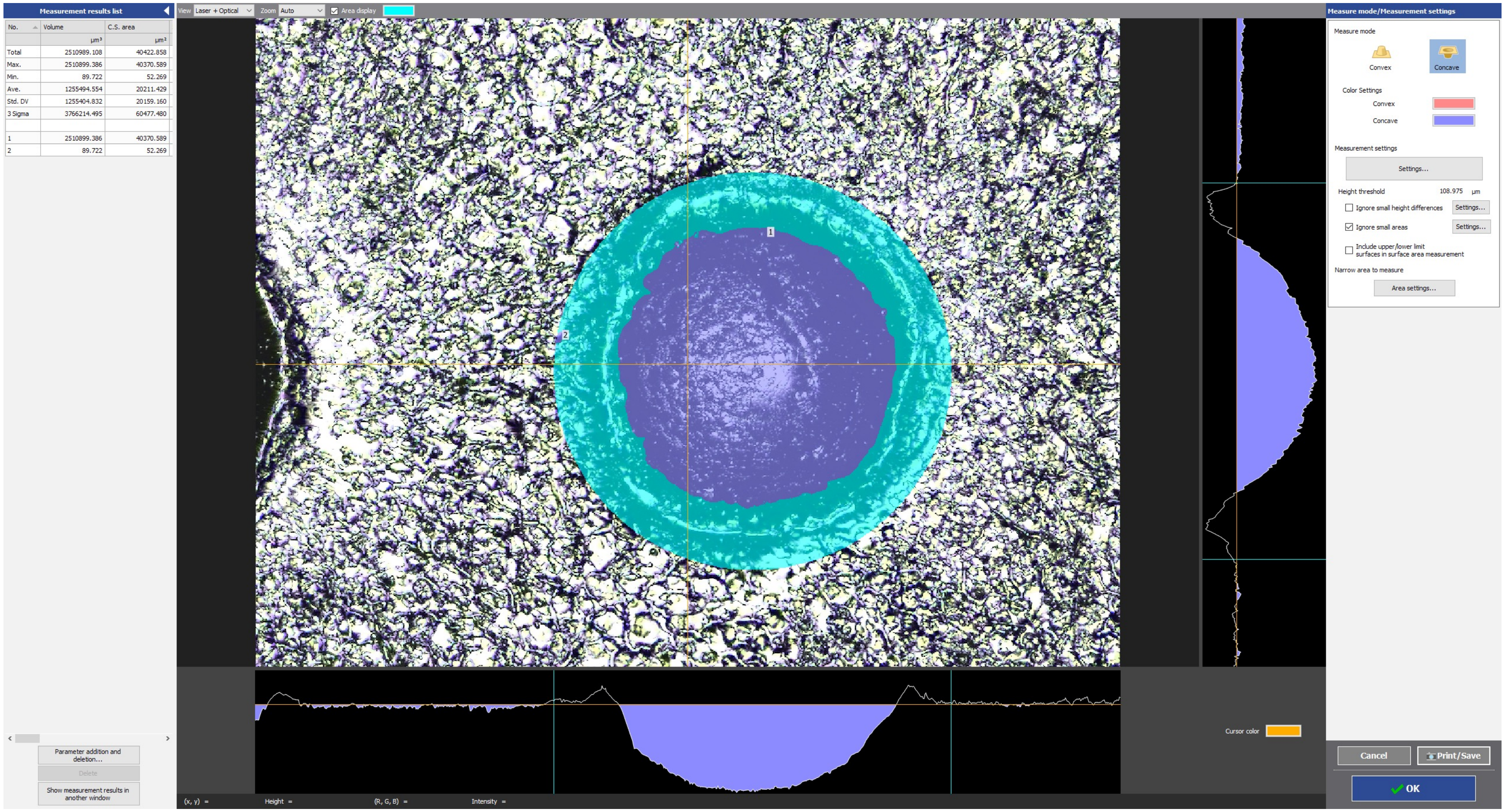
Aluminum laser target

$_{13}Al$



Crater size is about 200 μm

$_{13}Al$



Lost volume is about 2.51E-3 mm^3

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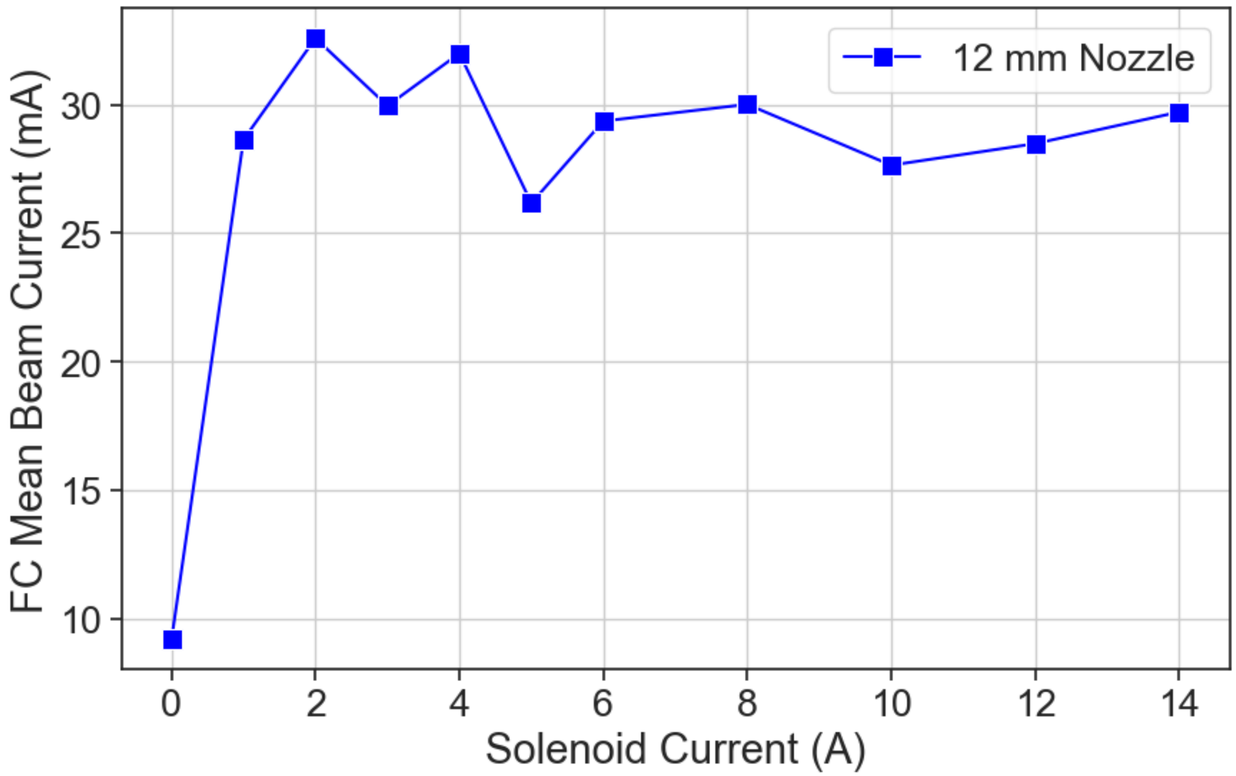
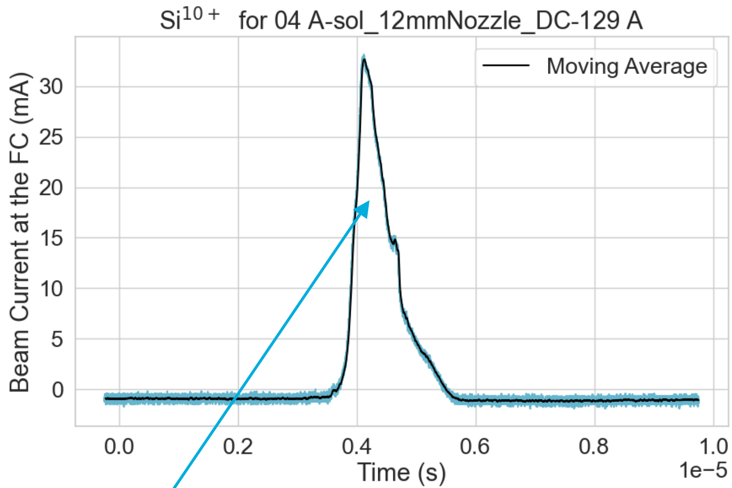
$_{14}Si^{10+}$

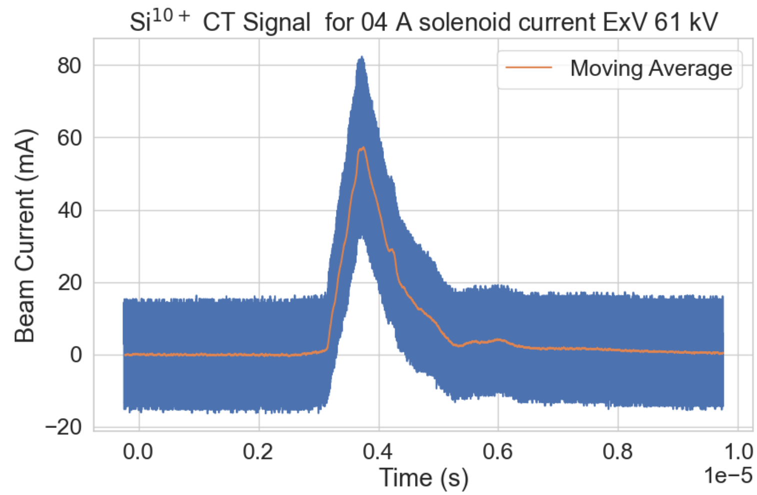
- The highest Si^{10+} beam current was produced at 2A solenoid current.
- 32.58 mA mean beam current at 2 A solenoid current.

Si^{10+} Solenoid Current Scan

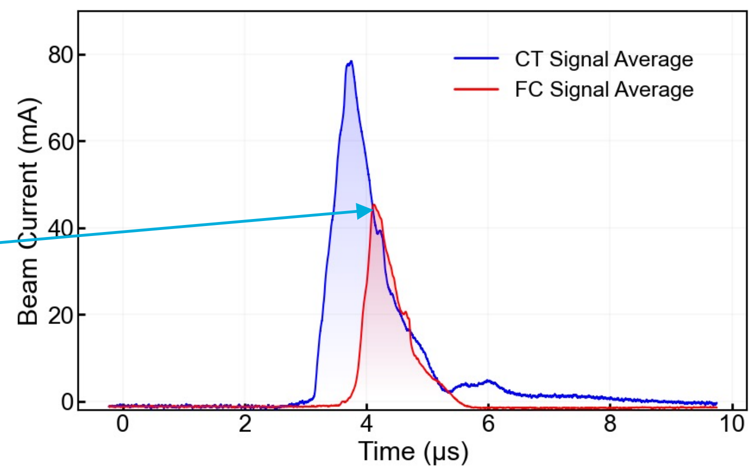


$_{14}Si^{10+}$





- Beam Current- 33.67 mA
- No of Particles-1.3x10^{10}
- Beam Current with mesh compensation- 46.76 mA



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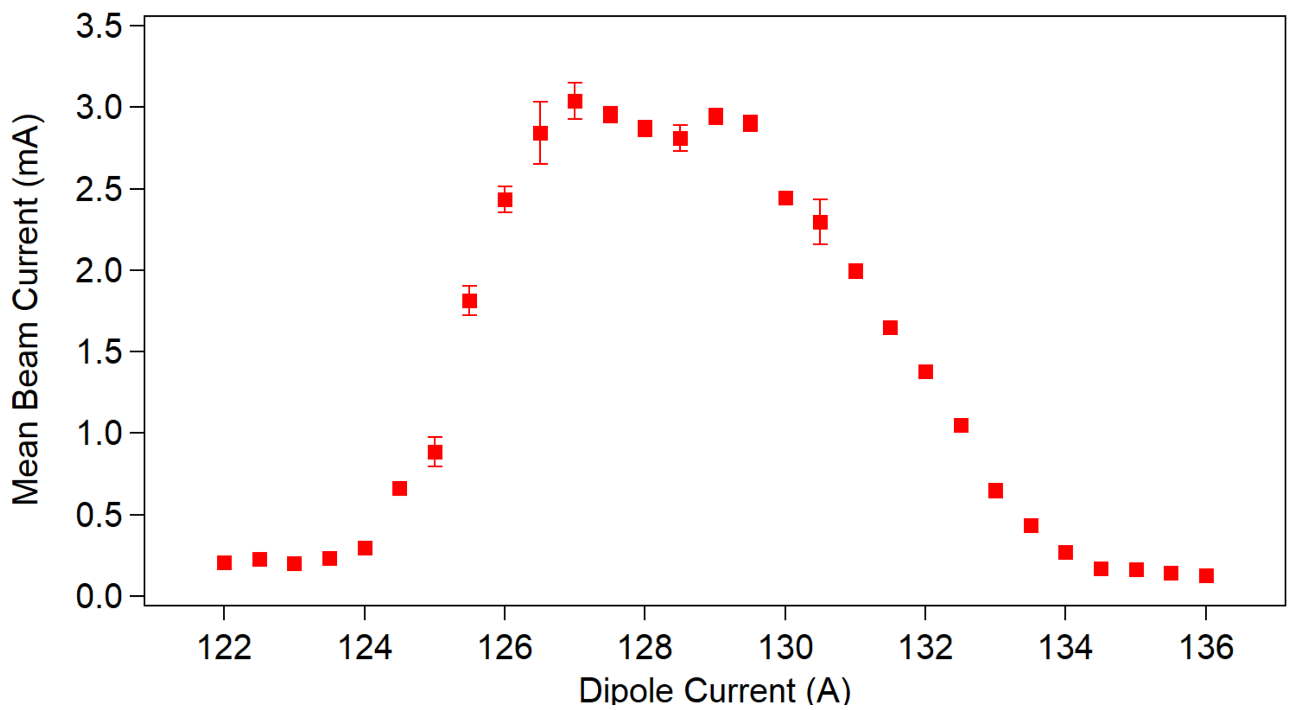
$_{14}Si^{10+}$

Dipole Scan for Si^{10+}



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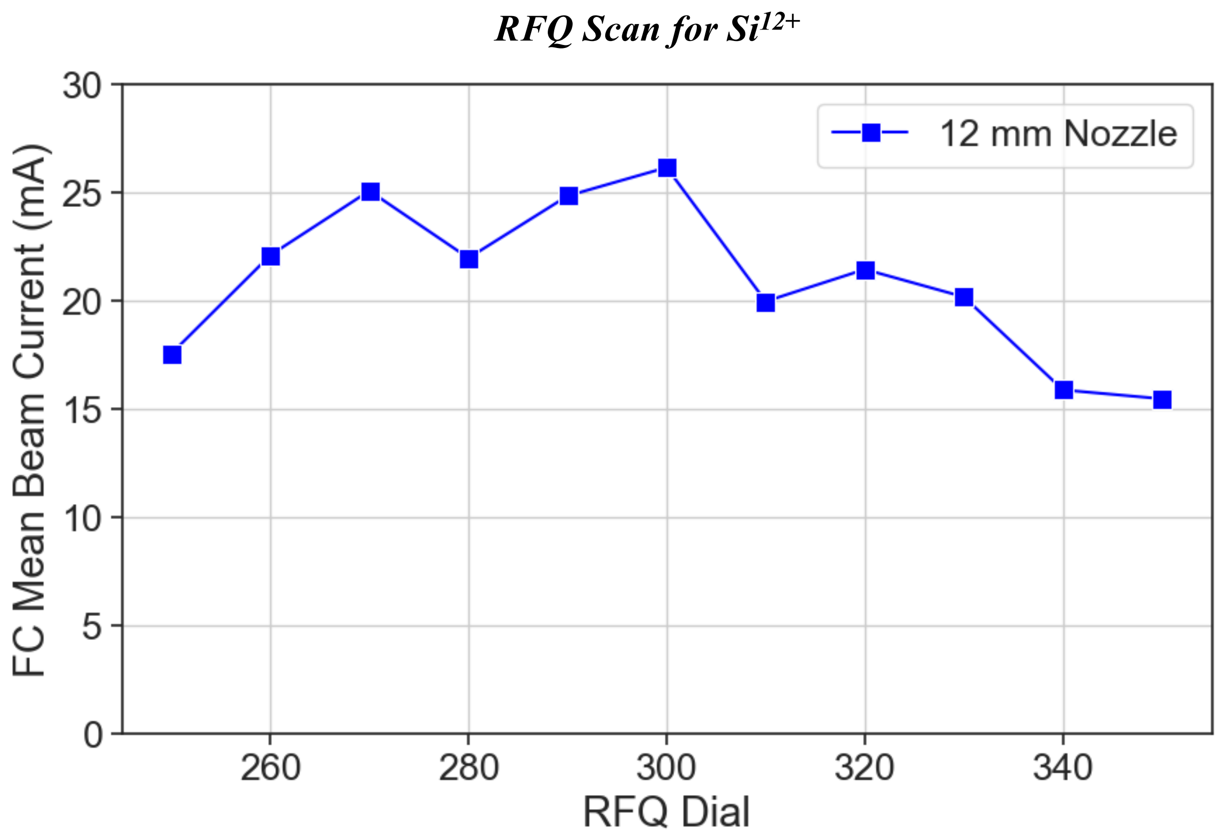
$_{14}Si^{12+}$

Si^{12+}

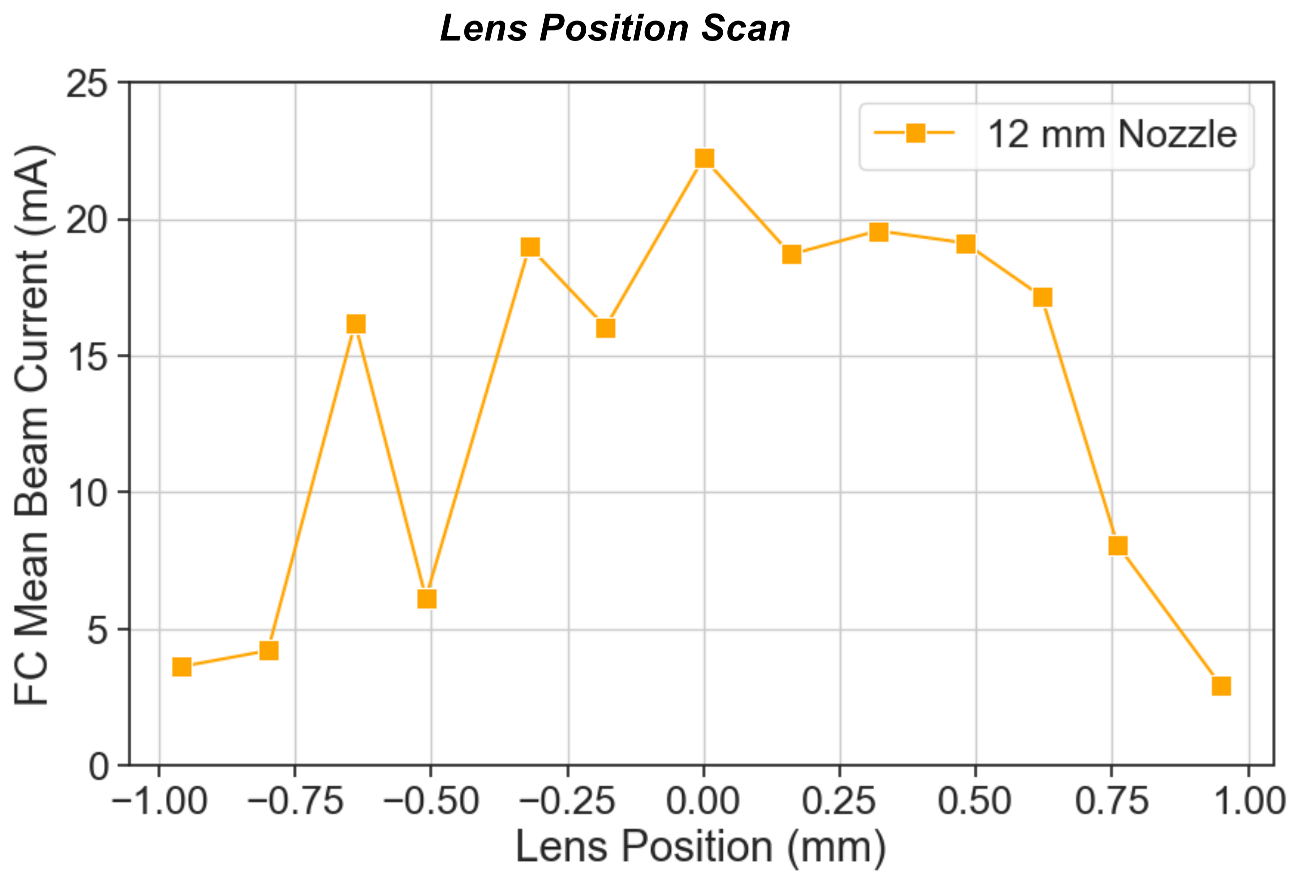


- Best RFQ dial was 300.
- Best RFQ power was 59.47 kW.

$_{14}Si^{12+}$

Si^{12+}

- The optimal lens position for Si12+ was the same as for Si10+, which was 12.9 mm.



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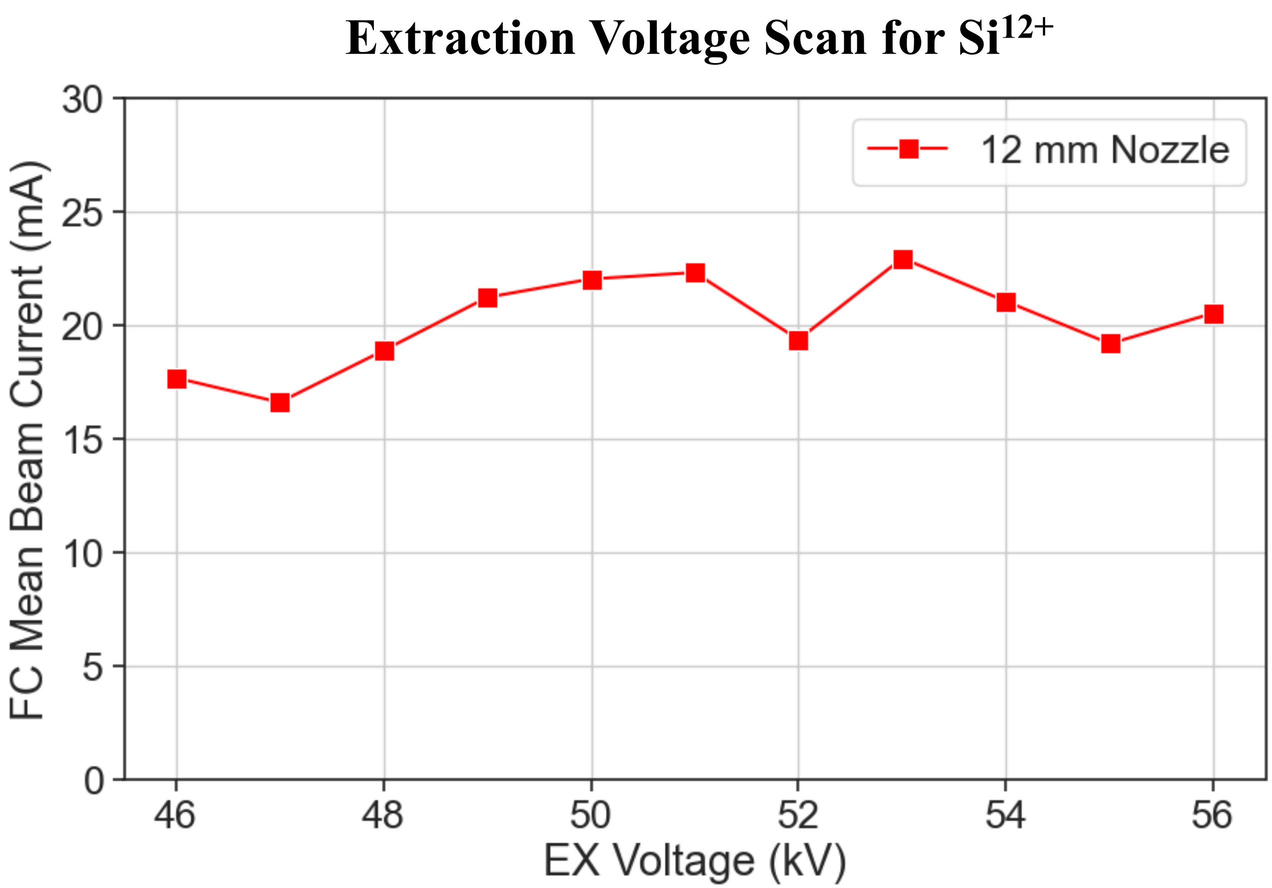
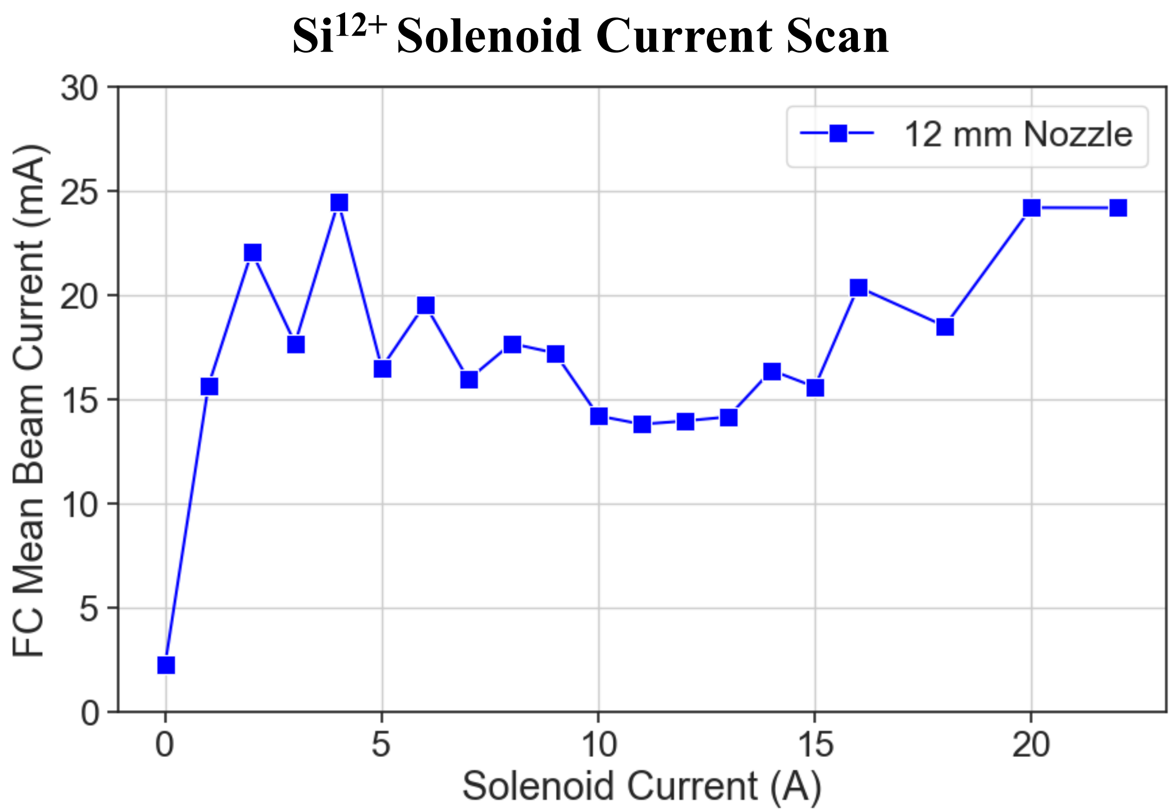
$_{14}Si^{12+}$



- 51 kV was selected

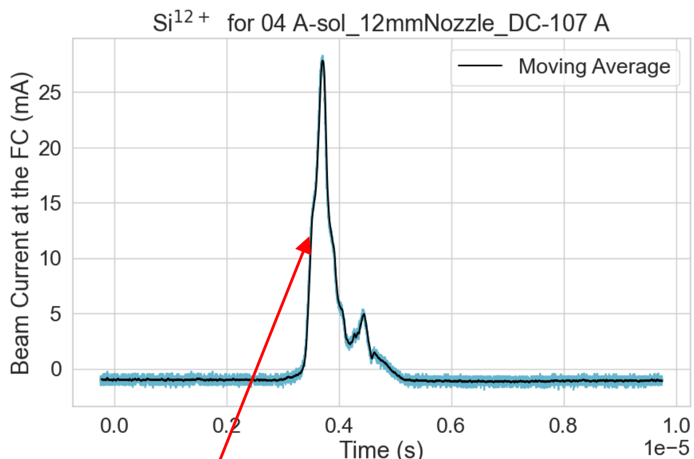
$_{14}Si^{12+}$

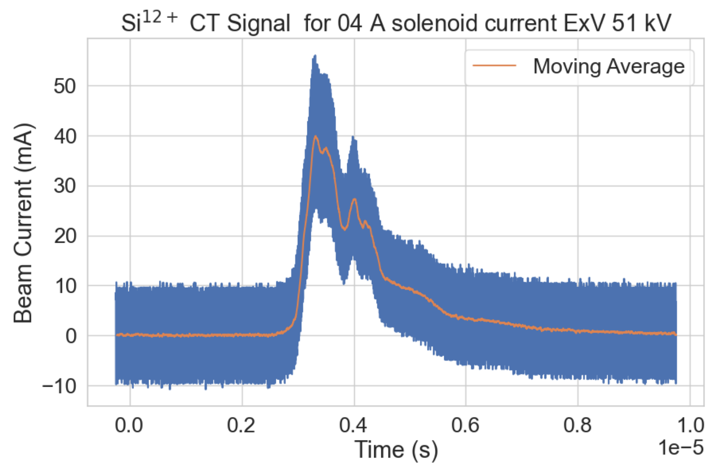


- The highest Si^{12+} beam current was produced at 4A solenoid current.

$_{14}Si^{12+}$

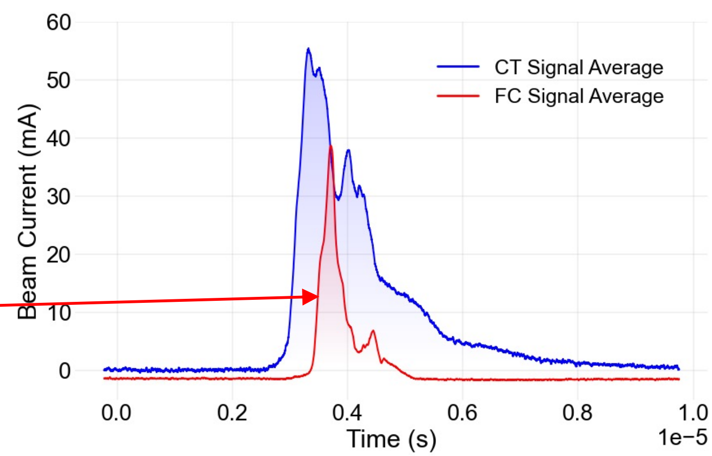
Si^{12+}





FC Beam Current – 28.91 mA

No of Particles – 5.57×10^9



FC Beam Current with mesh compensation– 40.15 mA

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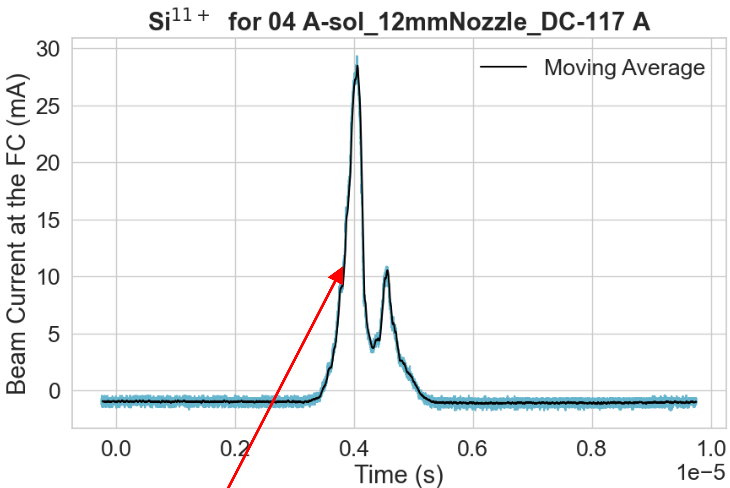
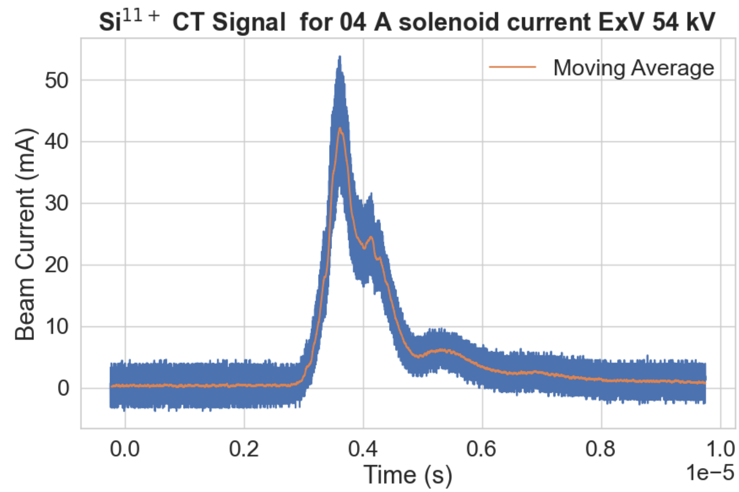
$_{14}Si^{11+}$

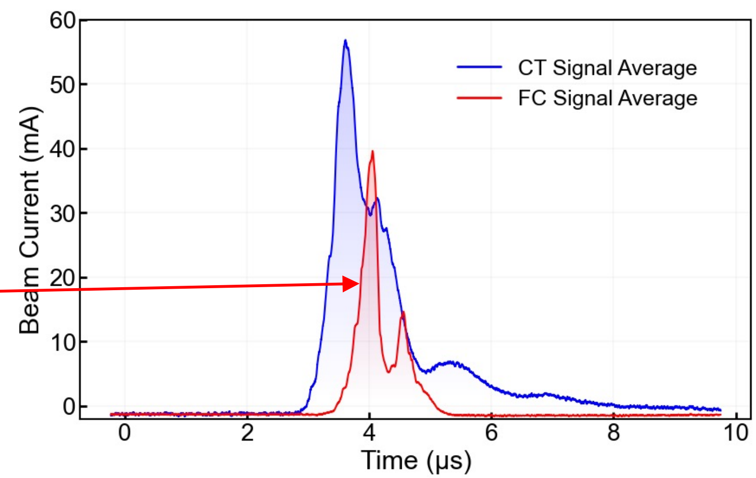
Si^{11+}





FC Beam Current – 29.51 mA
No of Particles – 6.88×10^9

FC Beam Current with mesh compensation– 40.98 mA



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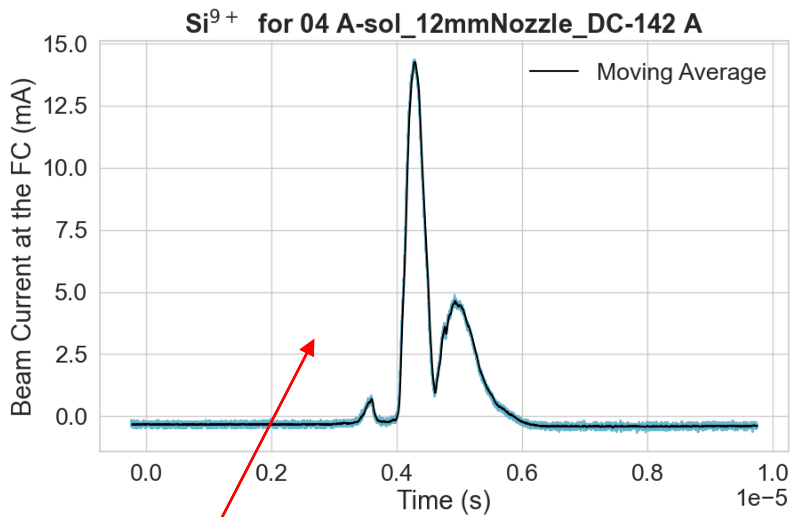
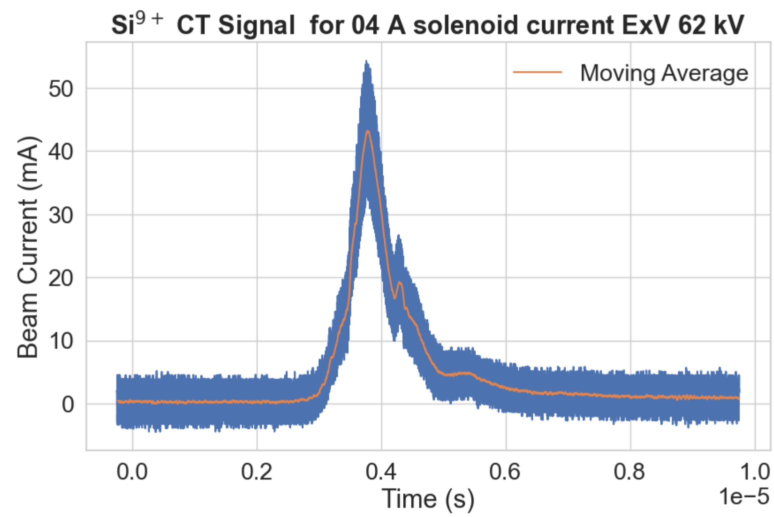
$_{14}Si^{9+}$

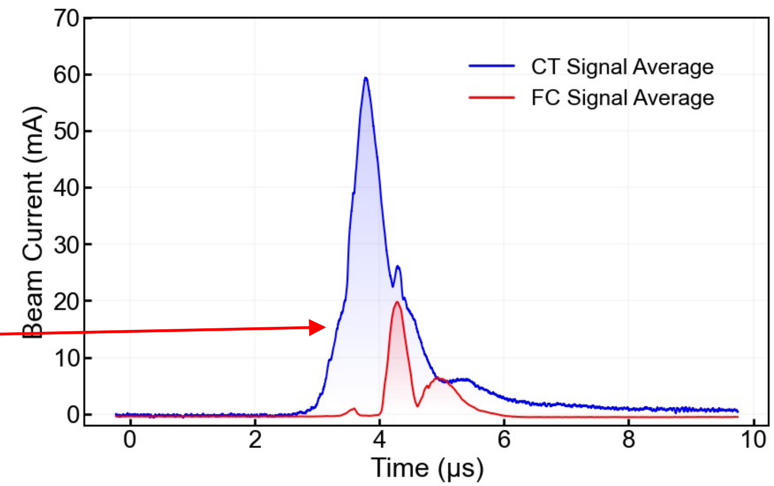
Si^{9+}





FC Beam Current – 14.62 mA
No of Particles – 5.09×10^9

FC Beam Current with mesh compensation– 20.30 mA



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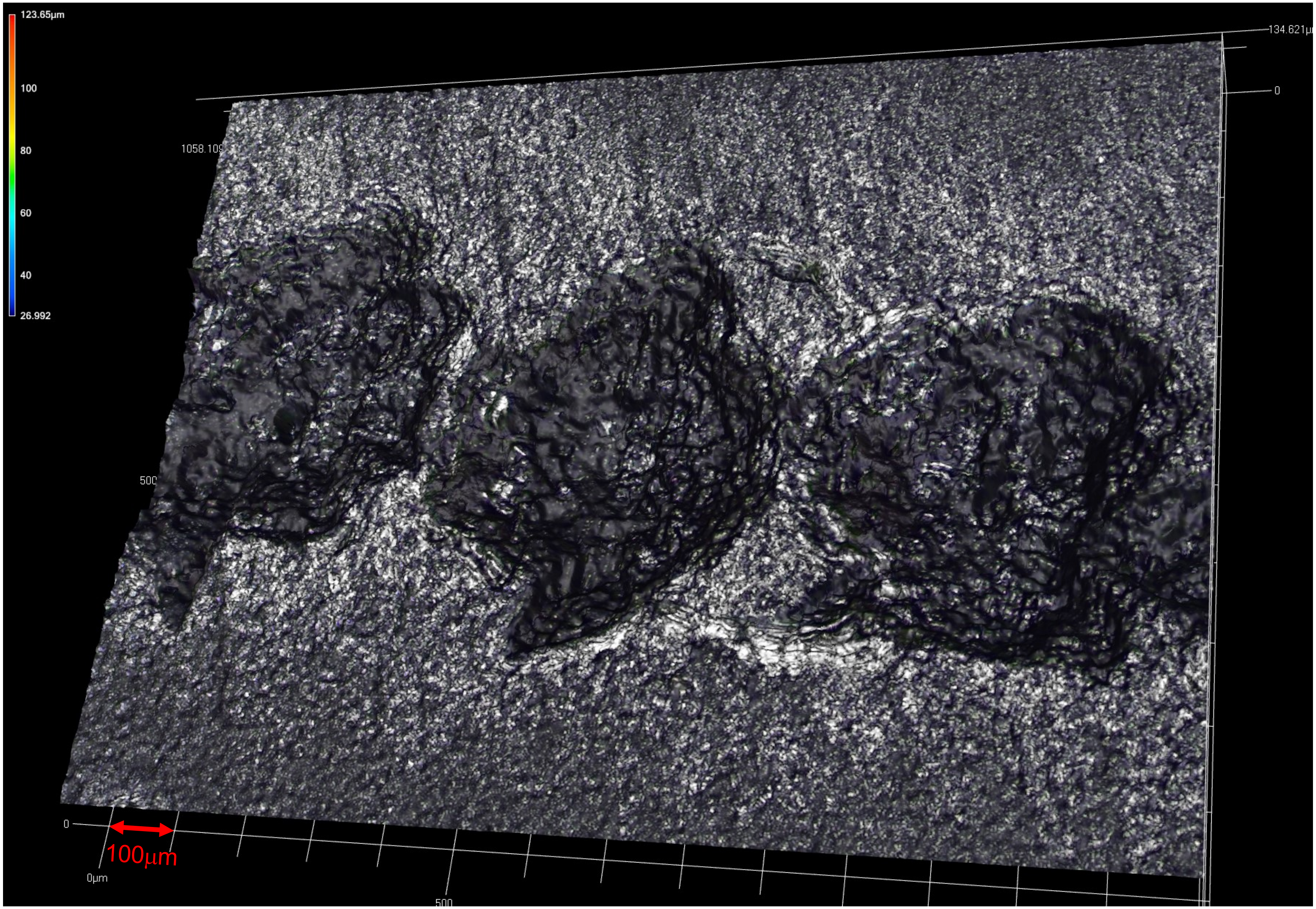
$_{14}Si$



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New design of RFQ electrode (type 1)

Design criteria

- Max m/q = 7/3 (assuming $^{7}Li^{3+}$)
- Target output peak current > 100 emA
- Extraction voltage ~50 kV
- 100 MHz
- Transmission ~ 75% inter-vane voltage of 105 kV
- Kilpatrick factor less than 2
- 2 m long
- Output energy above 300 keV/n

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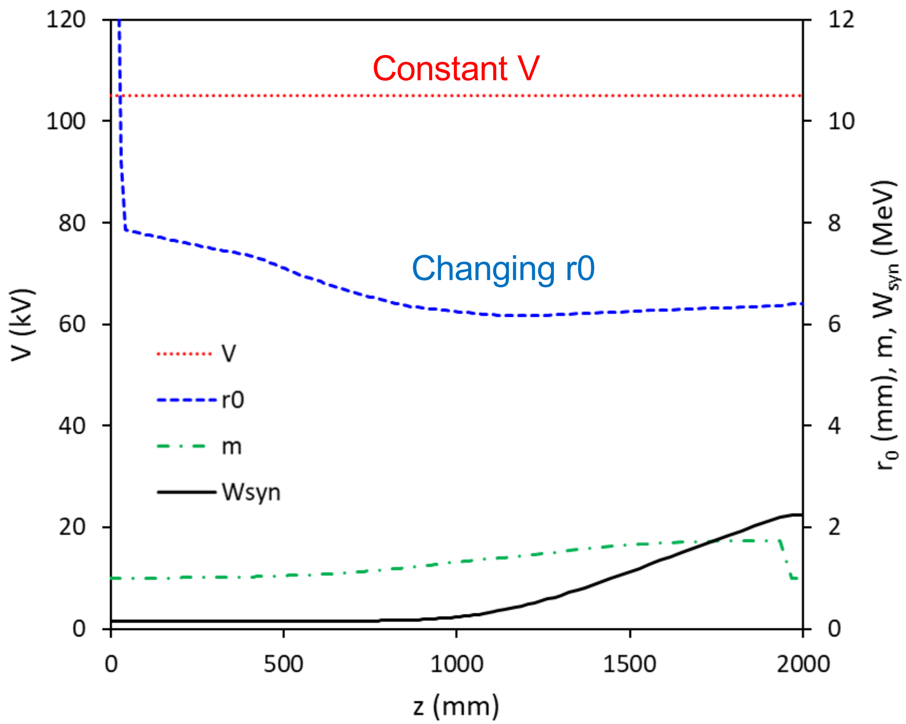
Variable focusing force strategy

Resonant frequency	100 MHz
Accelerated particle	$^{7}Li^{3+}$
Peak beam current	≧100 emA
Input energy	21.8 keV/u
Output energy	320 keV/u
Imput normalized rms emittance	0.33 mmmrad
Number of cells	138
Rod length	1997.5 mm
V	105 kV
r_0(without RMS)	6.2-7.8 mm
Transverse vane-tip curvature	Variable (≦1.0r_0)
E_{max} (Kilpatrick factor)	≦22.3 MV/m (1.96)



Vane voltage is always constant, but the beam aperture varies from place to place.

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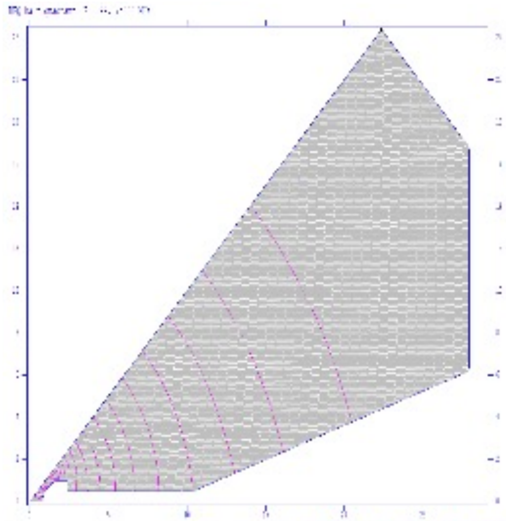
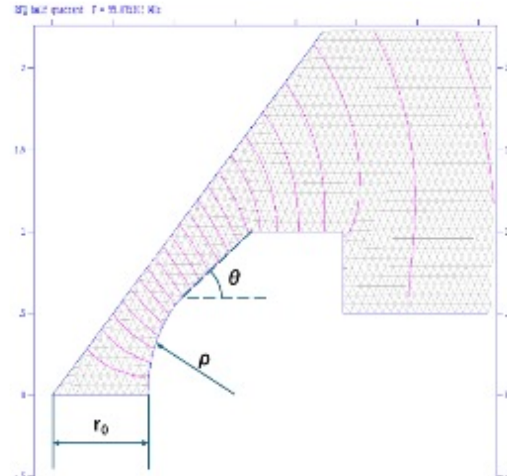
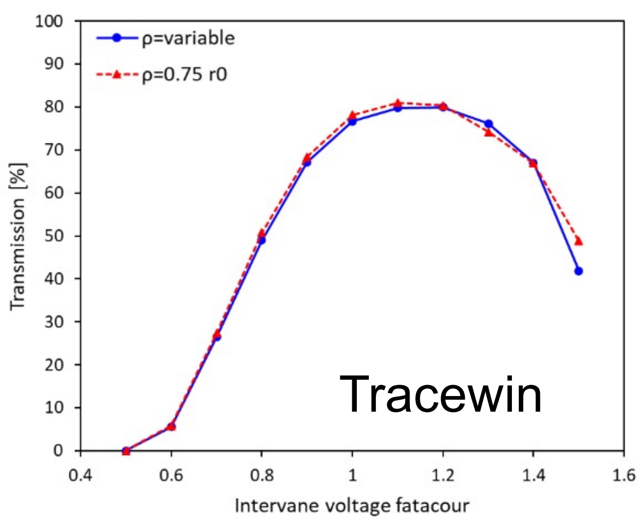
Total 138 cells

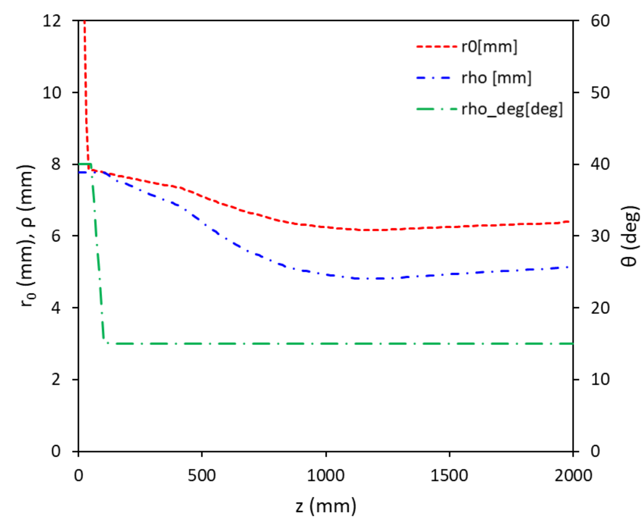
Vane tip geometry of each cell was optimized 2D simulation code assuming 4 vane structure.





Simulate to have a same capacitance in every cross-section.





The cross-sectional shape of Vane varies with location.

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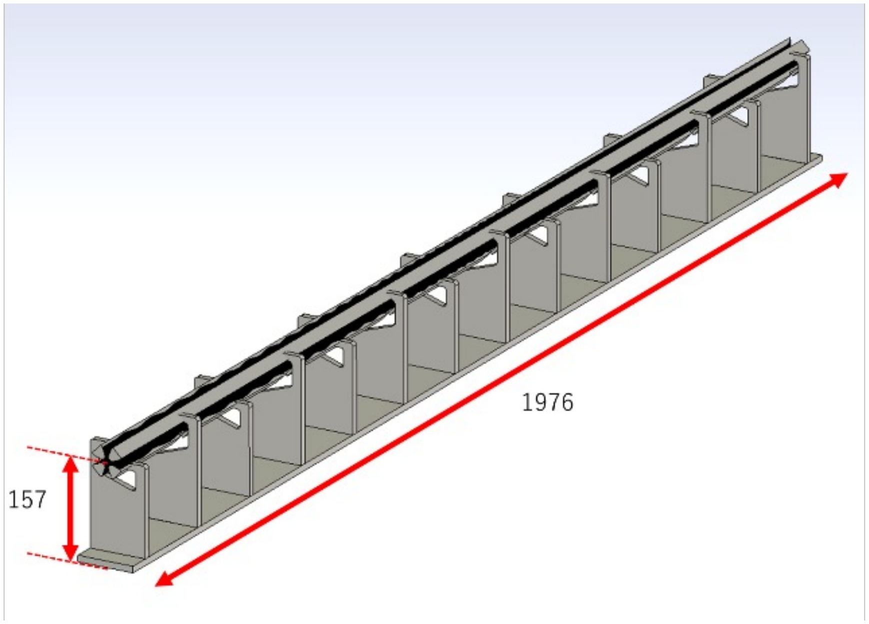
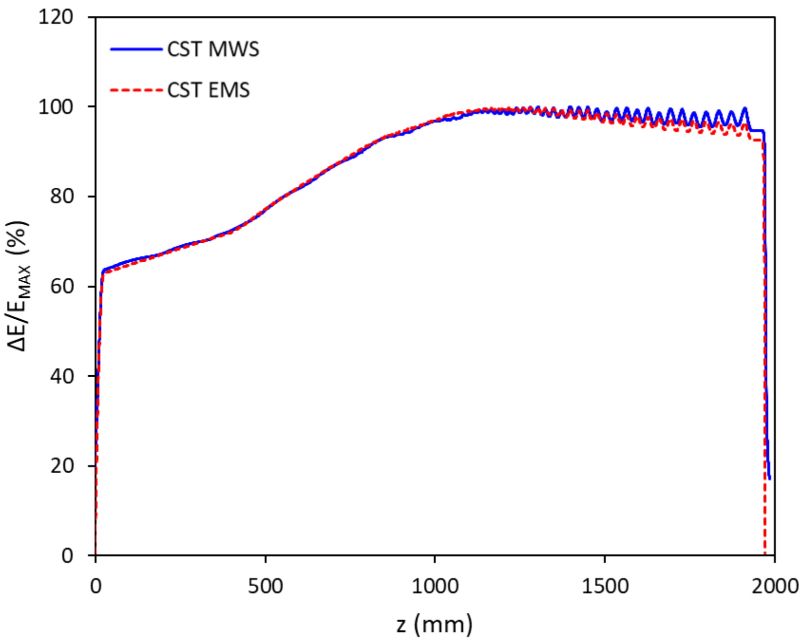
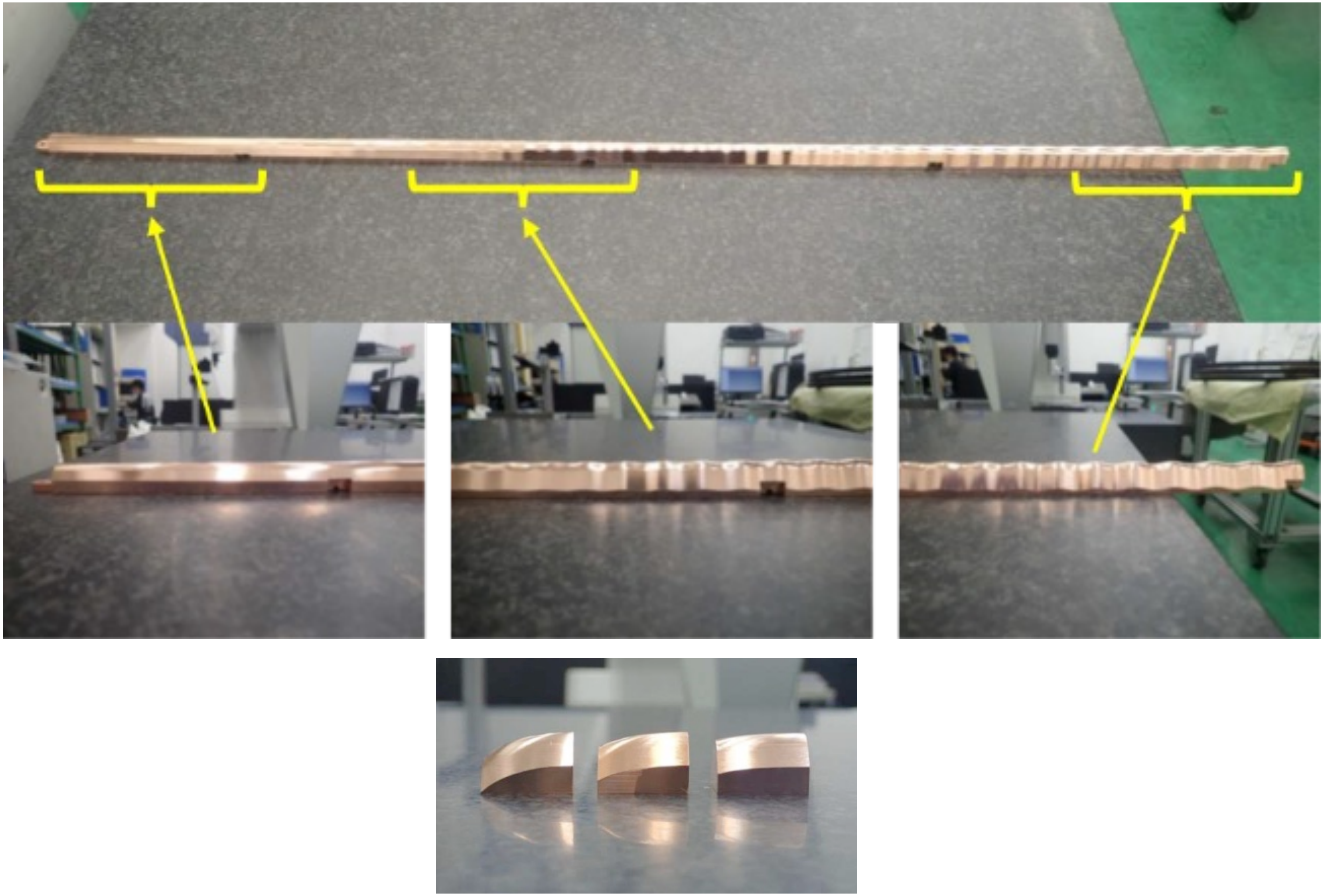




Full 3D calculation vs. forced constant voltage

Resonant frequency	**94.86 MHz (94.99 MHz)**
Unloaded Q value	3324.3
E_{max} (Kilpatrick factor)	≦24.8 MV/m (2.18 kilp)



Conclusion (Major deliverables up to now)

1. World records of peak currents were achieved on B, C, Mg, Al, Si.
2. New beam extraction system enhance beam current dramatically.
3. Aluminum(Al^{11+}) peak current exceeds 55 mA
4. Effect of the guide solenoid was studied.
5. Particle number is limited by the laser performance.
6. New RFQ vanes are being installed.
   (expected to accelerate more than 100 mA)
7. NCE was submitted and the research will continue in FY 2025.

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Thank you for your attention

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