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U.S. DEPARTMENT OF ENERGY

Development of high current highly charged laser ion source

FY23, FY24, FY25(NCE)

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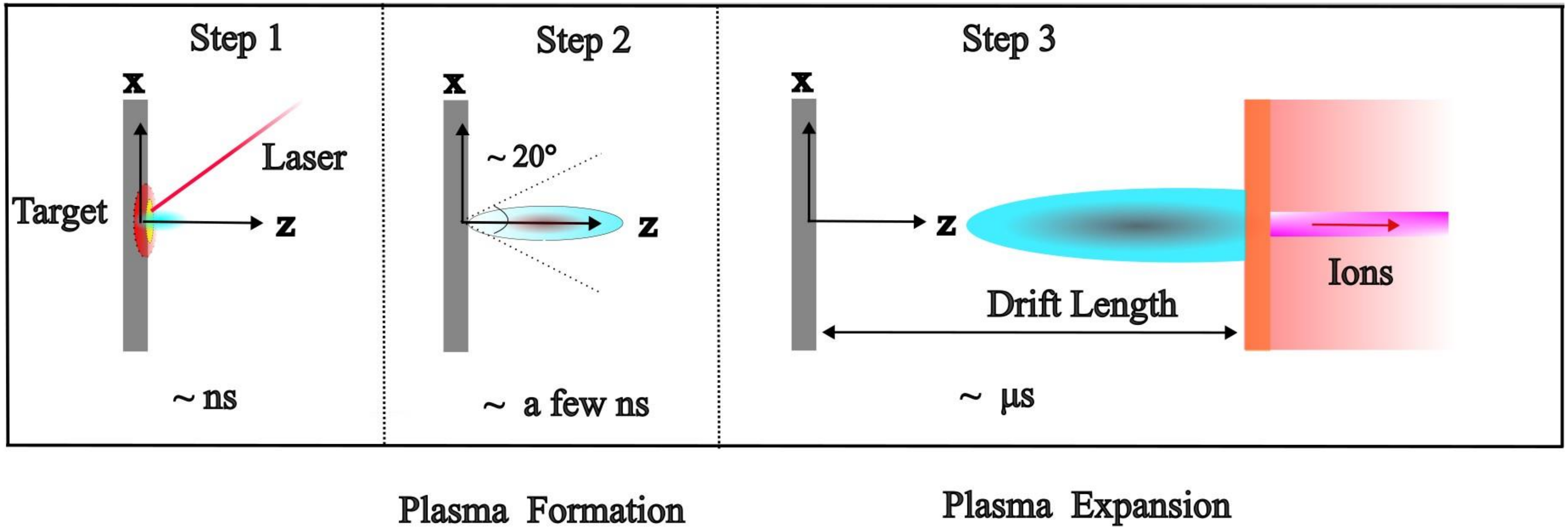
Project goals

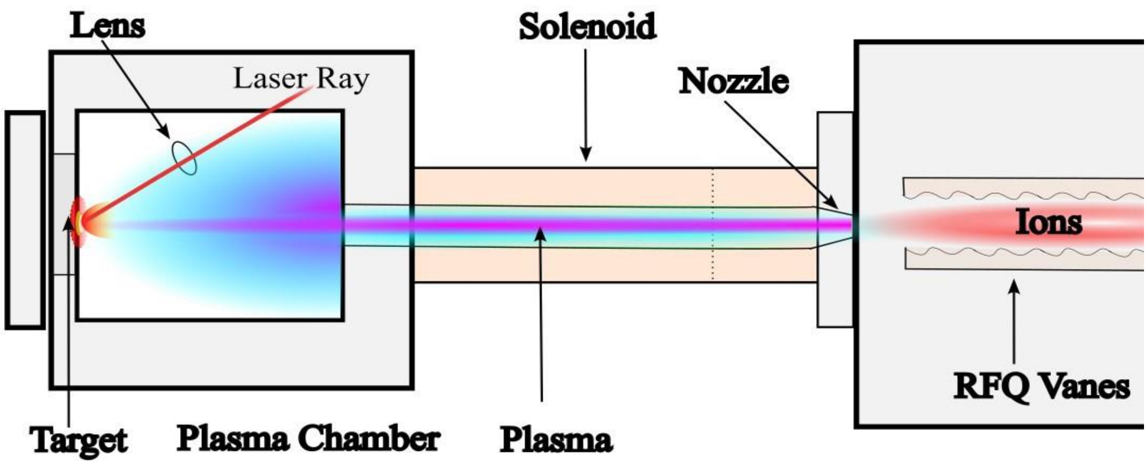
- Develop Laser ion source (LIS) and Radio Frequency Quadrupole (RFQ).
- Very high current and highly charged state ion beam will be delivered.
- Use Direct Plasma Injection Scheme which was invented by the PI.
- Target species are from light to medium mass ions.

laser ion source (LIS)



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

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.

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 Nov. 21

FY2024-Q4
- 1 Installation of electrodes type 2
  Aug. 30, 2024 TBD
- 2 The fifth species acceleration
  Sep. 30, 2024 Oct. 3 ($^{28}Si^{12}$)

FY2025-Q2
- 1 Procurement of type 2
  Mar. 30, 2025 Feb. 28 Procurement placed
- 2 Design of type 2 electrodes
  Jan. 31, 2025 Dec. 31, 2024

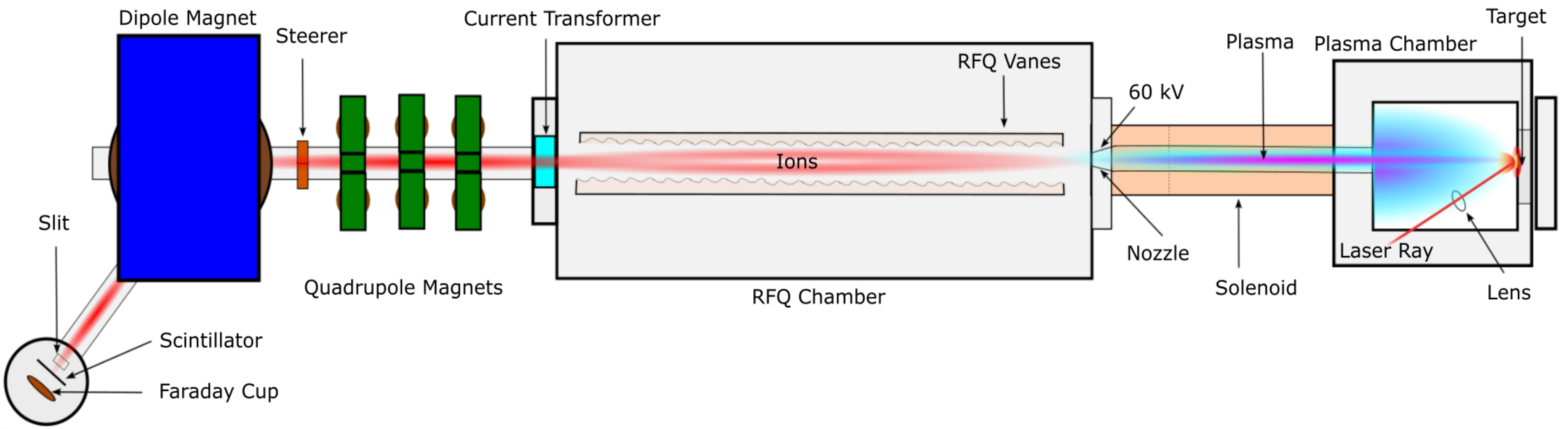
FY2025-Q3
- 1 Paper submission
  Apr. 30, 2025 submitted
- 2 Design of chamber
  May. 31, 2025 Jan. 15
- 3 Fifth species acceleration
  May. 15, 2025 TBD

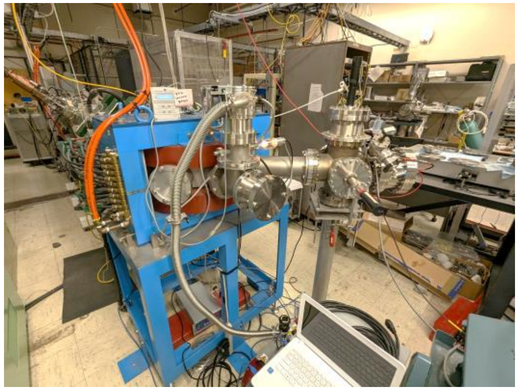
FY2025-Q4
- 1 International conference report
  Aug. 31, 2025 HIAT25 invited talk
- 2 Fabrication of target station
  Aug. 31, 2025 Being fabricated
- 3 Installation of target station
  Sep. 15, 2025 TBD
- 4 Installation of type 2 electrodes
  Sep. 15, 2025 TBD
- 5 First species acceleration
  Sep. 30, 2025 TBD

Summary of expenditures by fiscal year (FY):

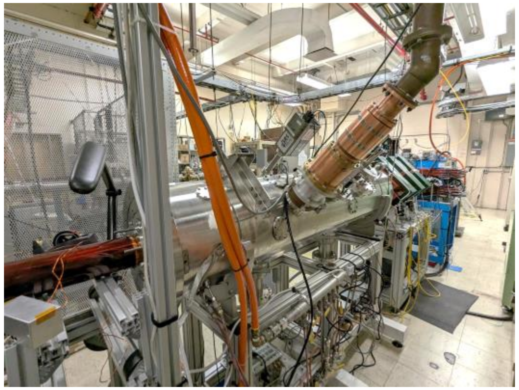
	FY23 ($K)	FY24 ($K)	FY25 ($K)	Total ($K)
a) Funds allocated	400	400	N/A	800
b) Actual costs to date	256	269	73	598

Laser Ion Source and RFQ

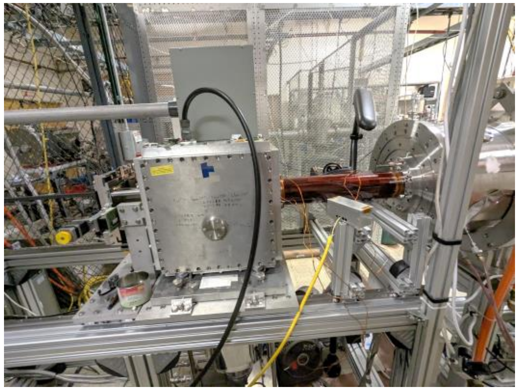




Dipole magnet



RFQ accelerator



Plasma Chamber

FY25, Accelerated Species

Original and Type I RFQ

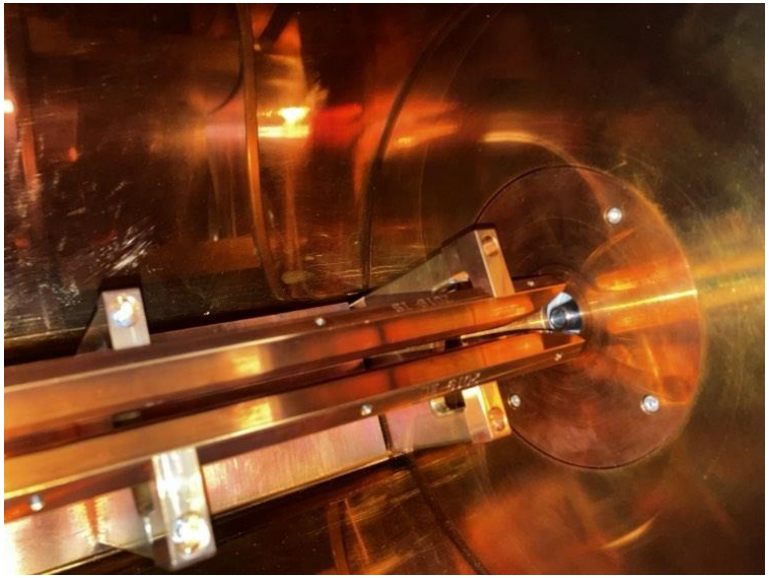
Al^{11+} 58 mA

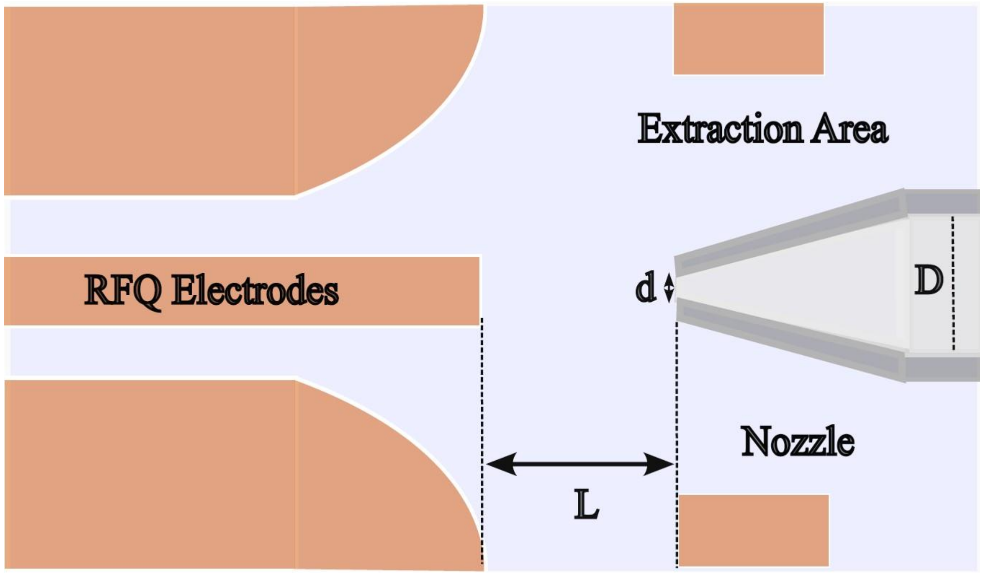
Type-1 electrodes

C^{6+} 97 mA

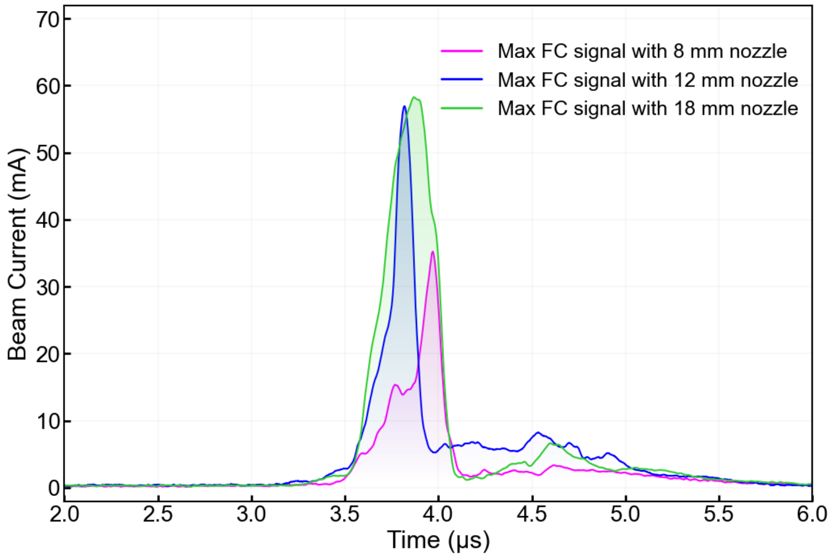
Al

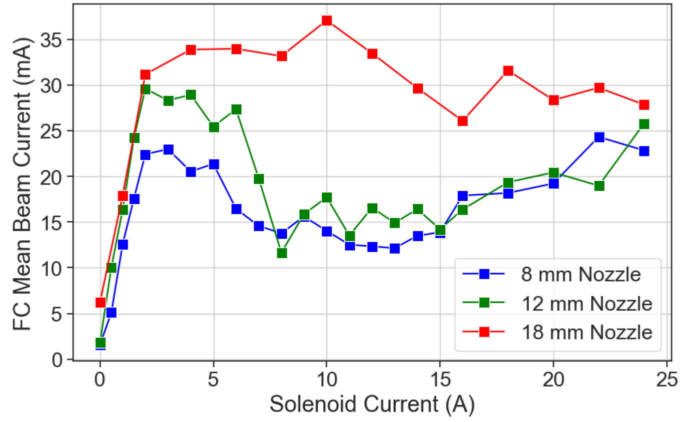
Beam Extraction Region

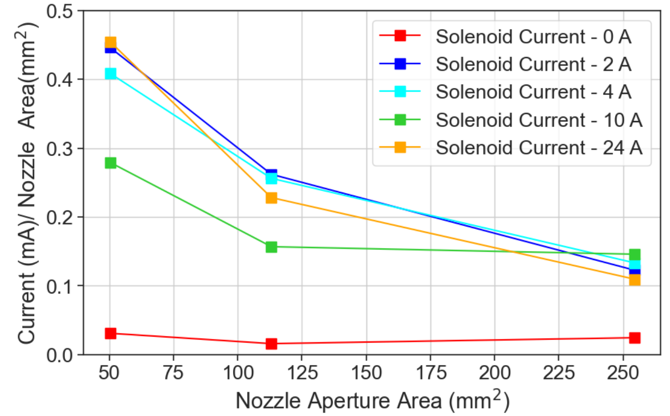




Detailed aluminum beam acceleration







58 mA of Al^{11+} beam was achieved after optimization

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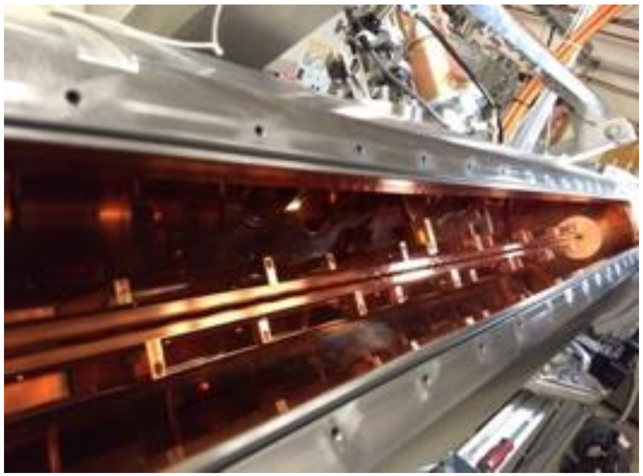
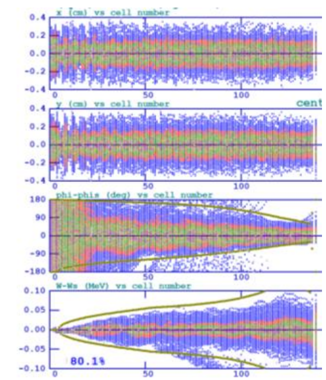
Original RFQ design



Parameter	Value
Structure	4 Rod
Frequency	100 MHz
Input energy	22 keV/n
Output energy	204 keV/n
Input beam current	50 mA
Number of cells	138
Input emittance (norm., 100%)	1 pi mm mrad
Transmission	80 % (40 mA)
RFQ length	1977 mm
V (for $^{7}Li^{3+}$)	59 kV
R0	4.5 mm
Transverse vane-tip curvature	0.75 R0
Kilpatrick factor	1.5



RFQ linac was designed with parmteq (constant voltage and R_0) for 40 mA output

Accelerated beam current was limited by the RFQ design

So, New RFQ was developed for higher beam current

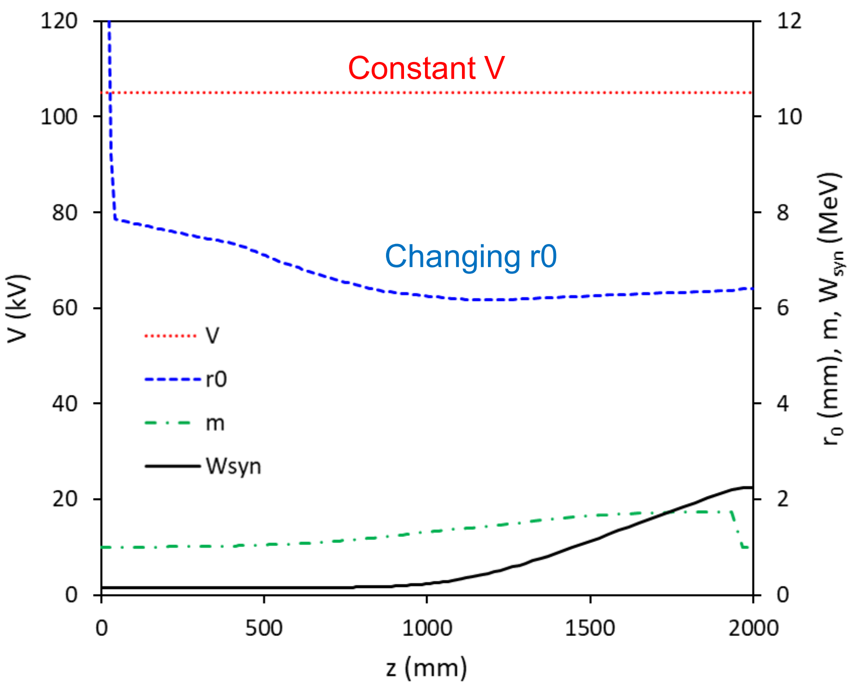
Type-1 RFQ design

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

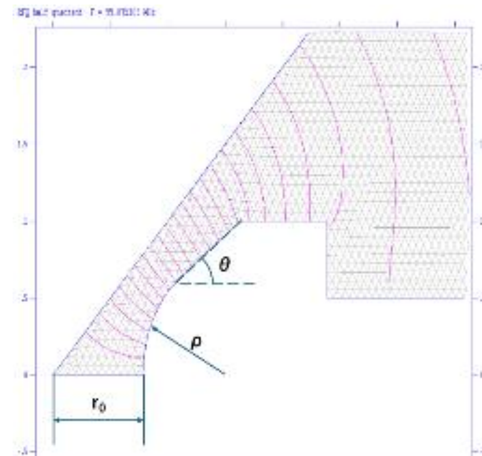
Variable focusing force strategy

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)

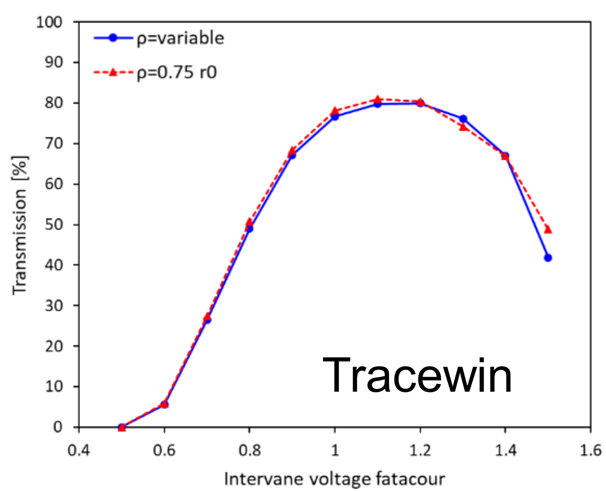


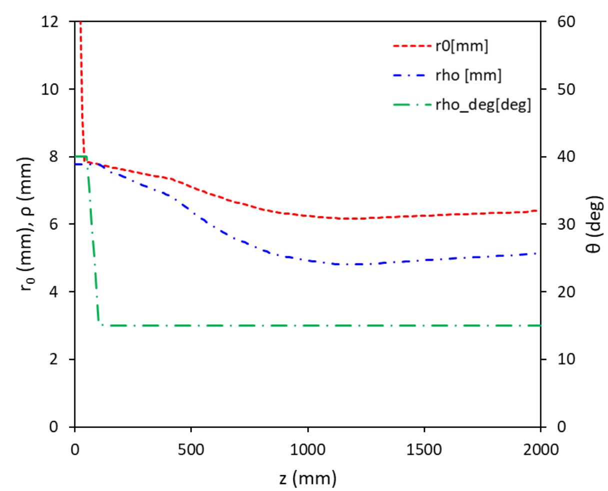
Vane voltage is always constant, but the beam aperture varies from place to place.

2D simulation along beam axis for 3D simulation



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





The cross-sectional shape of Vane varies with location.

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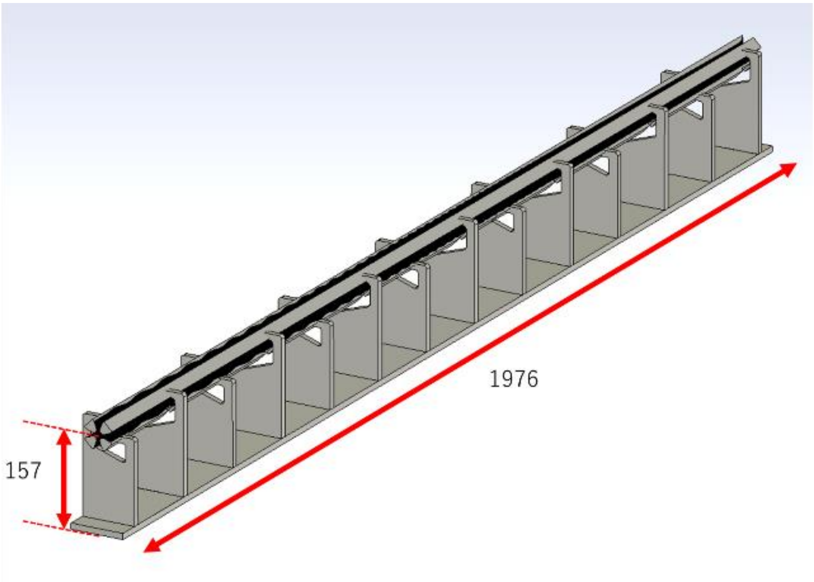
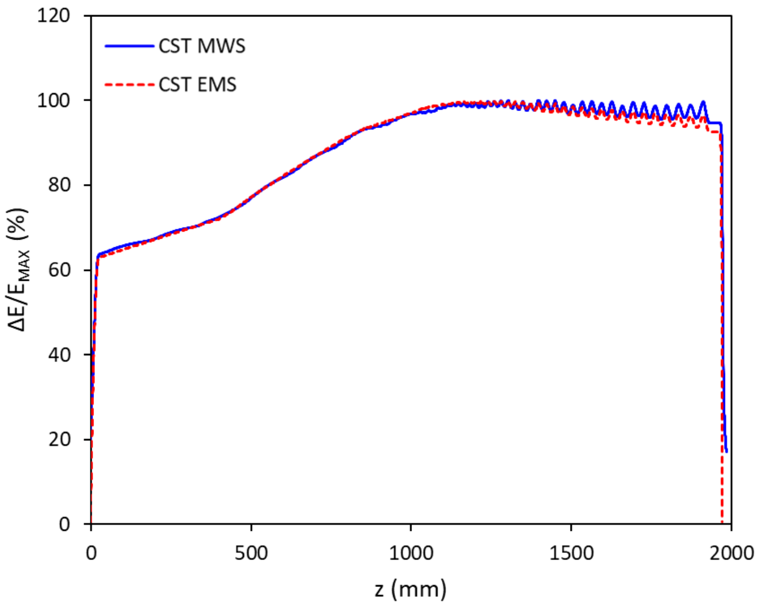
Full 3D simulation



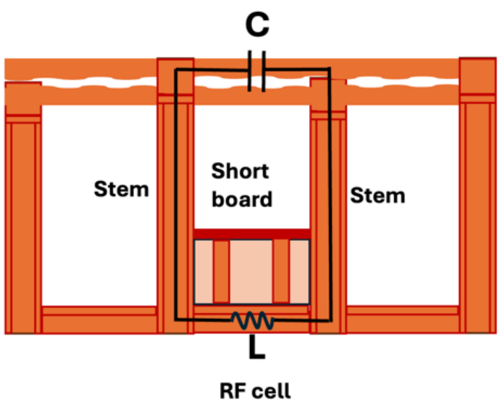


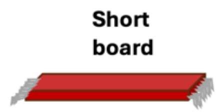
Full 3D calculation vs. forced constant voltage

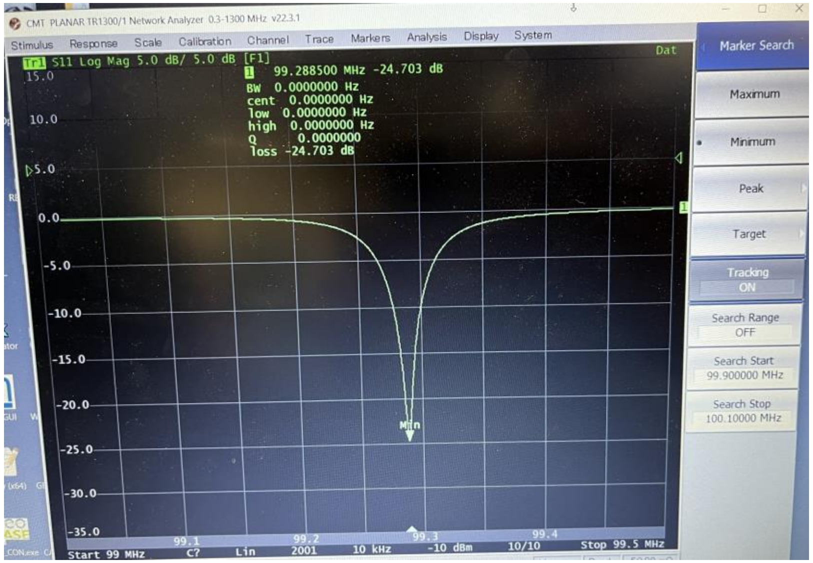
Resonant frequency	**94.86 MHz (94.99 MHz)**
Unloaded Q value	3324.3
E_{max} (Kilpatrick factor)	≦24.8 MV/m (2.18 kilp)

Type-1 electrodes installation

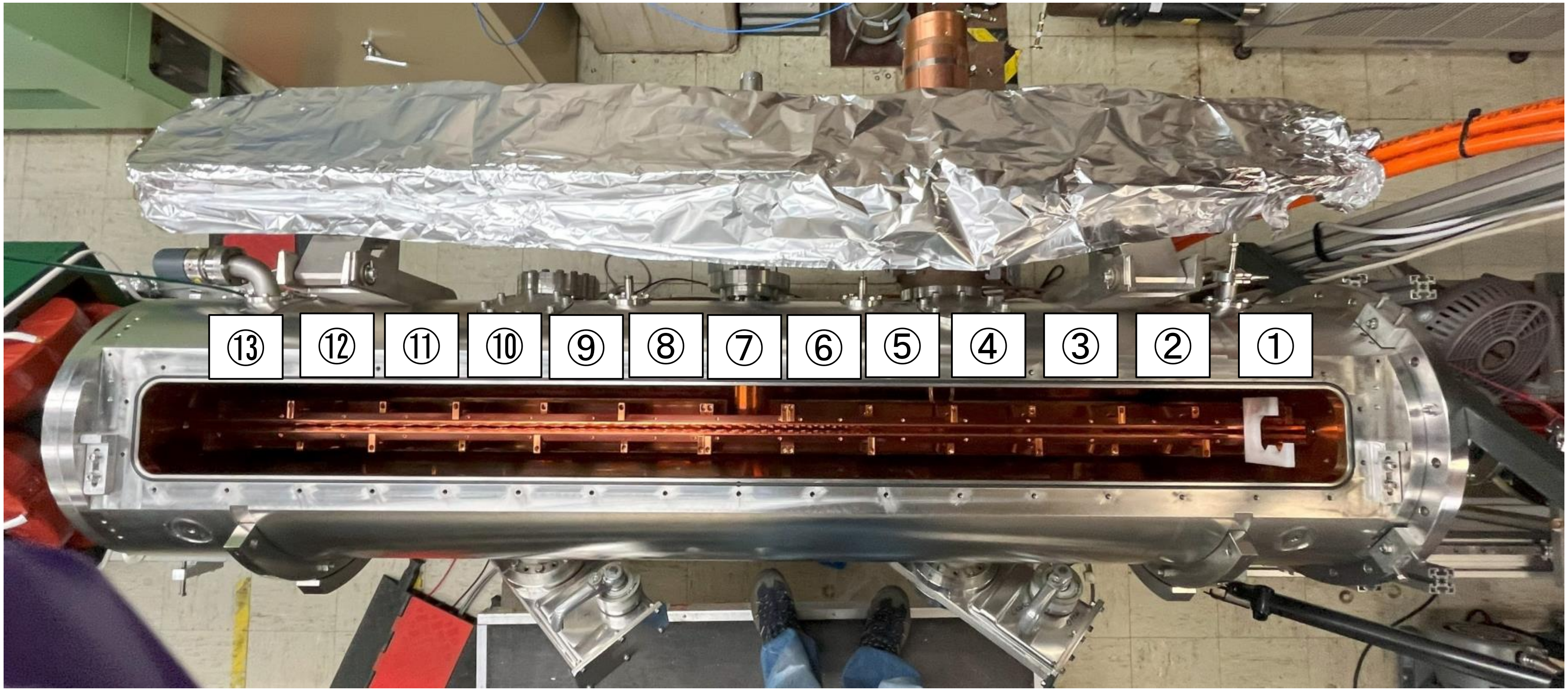
Type-1 electrodes Low power RF tuning







Perturbation Positions



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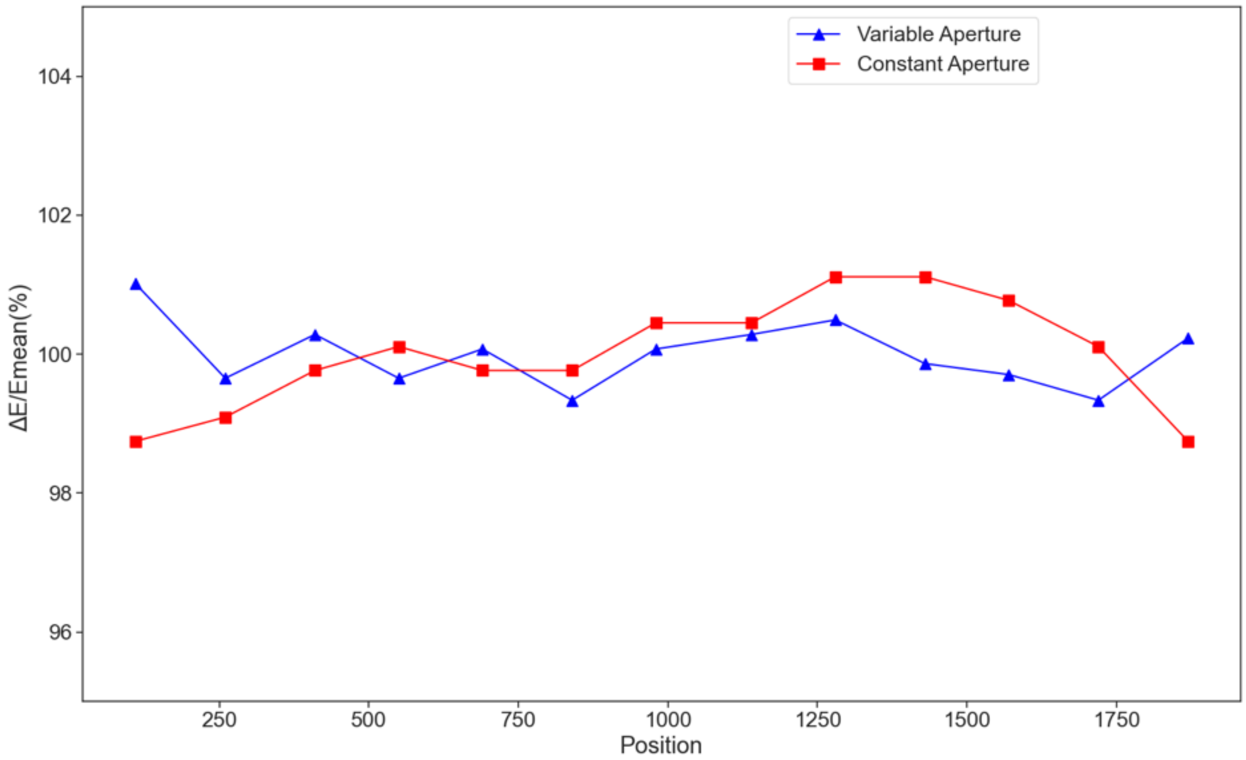
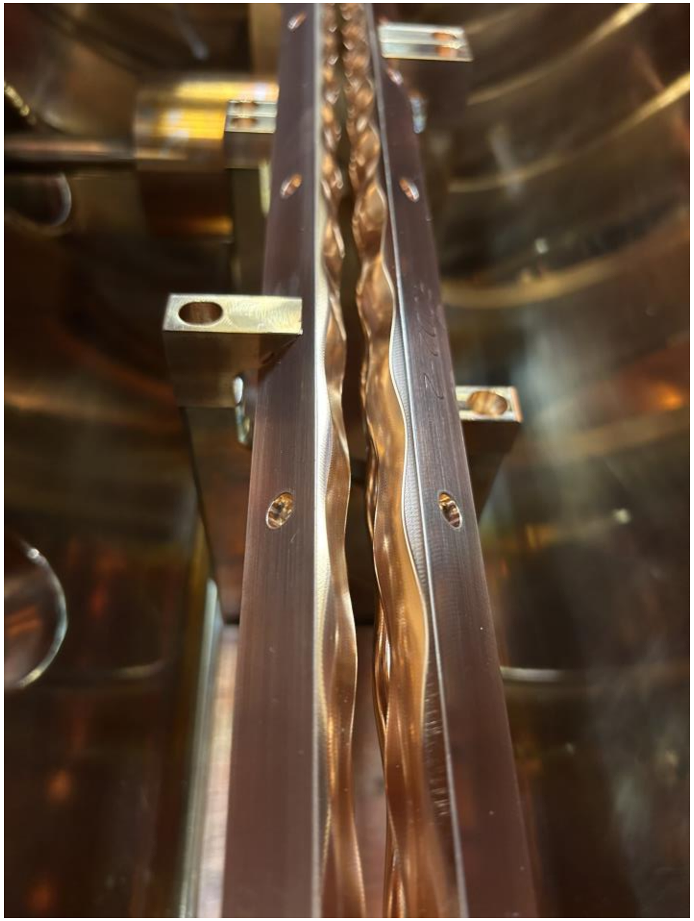
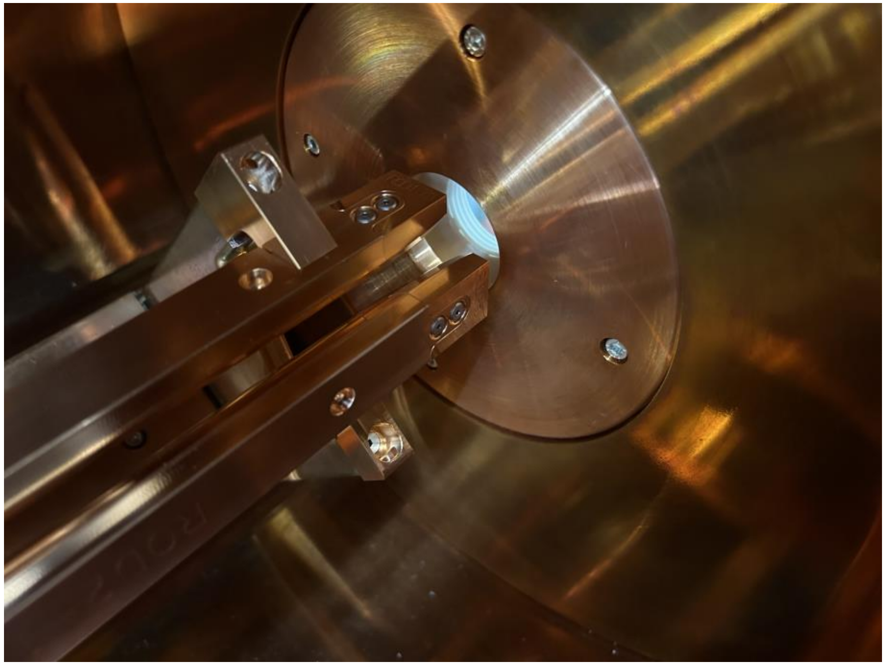
Completion of Type-1 electrodes Low power RF tuning



Desired voltage distribution was achieved with desired resonant frequency

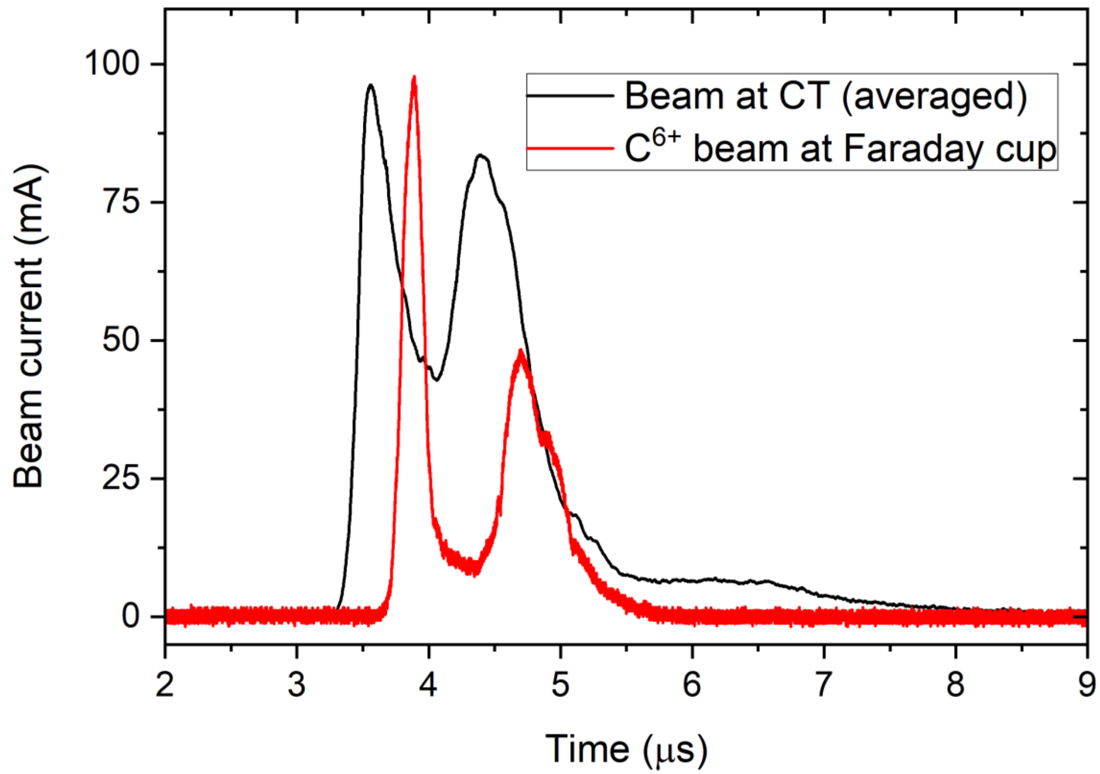
Type-1 RFQ electrodes ready for high power test





With high power test, 300 kW was achieved.

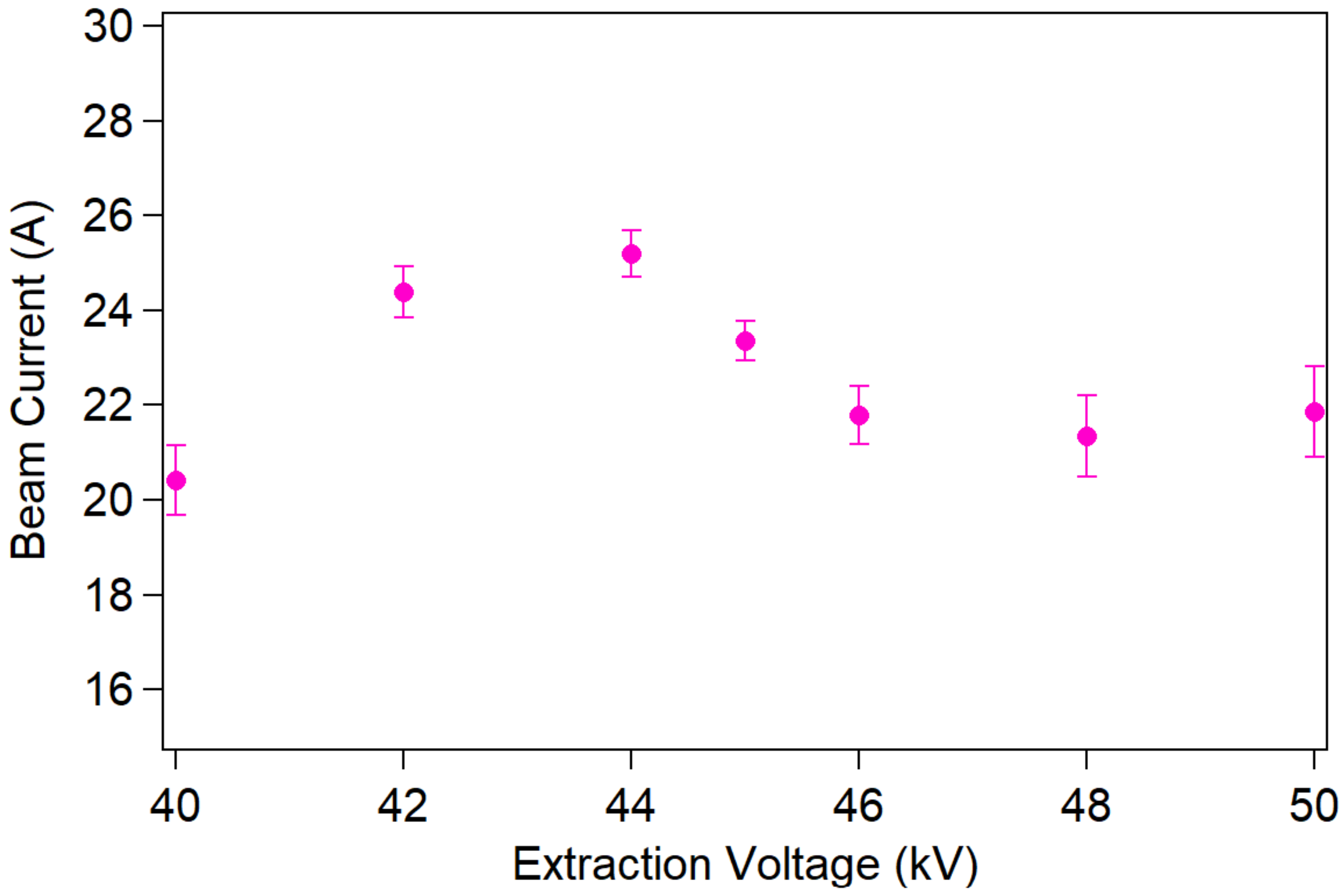
Record-breaking 97 mA Carbon 6+ beam with Type-1 electrodes



96 mA Carbon 6+ beam was achieved after optimization

$4x10^{10}$ particles

Extraction Voltage and Bias Voltage Optimization



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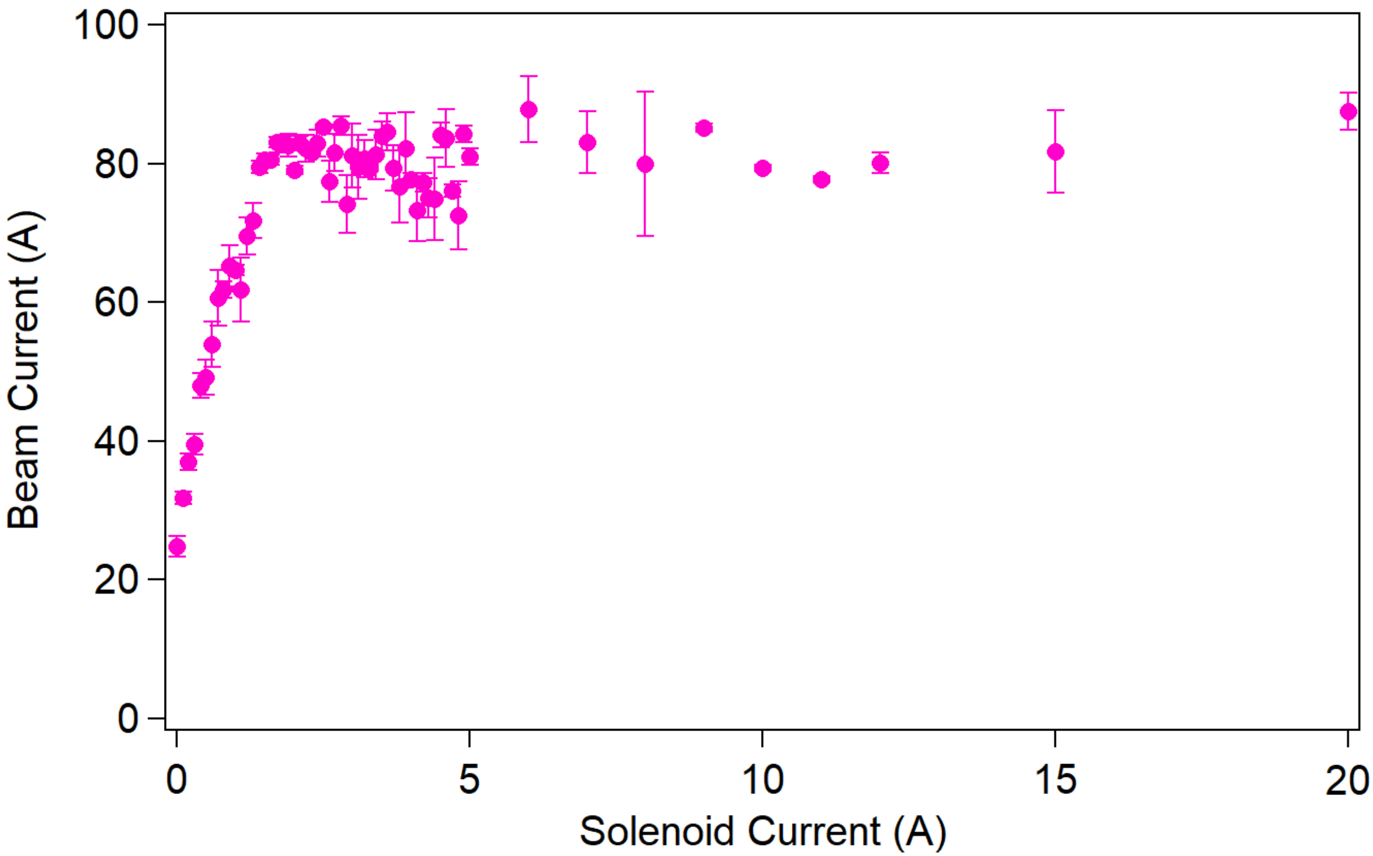
Solenoid B-field Optimization



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Conclusion (Major deliverables up to now)

1. Aluminum(Al^{11+}) peak current exceeds 55 mA
2. Type-1 RFQ electrodes were delivered
3. Low power and high power test were completed
4. Type-1 RFQ electrodes were commissioned with C beam
5. Record-breaking 96 mA of C^{6+} beam was achieved
7. Continuing beam acceleration with Type-1 RFQ electrodes
8. New target station is being fabricated

Thank you for your attention

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