Development of high current highly charged laser ion source

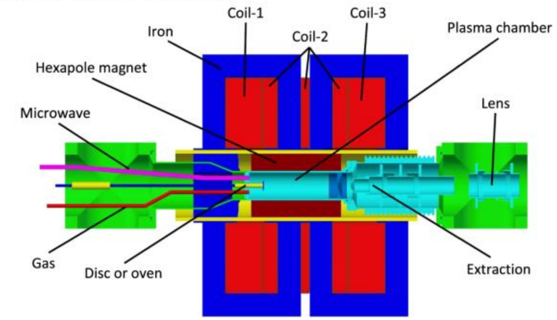
Maashiro Okamura (BNL), Guy Garty (Columbia University)

Dec. 7, 2023

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



From: The Atomki Accelerator Centre

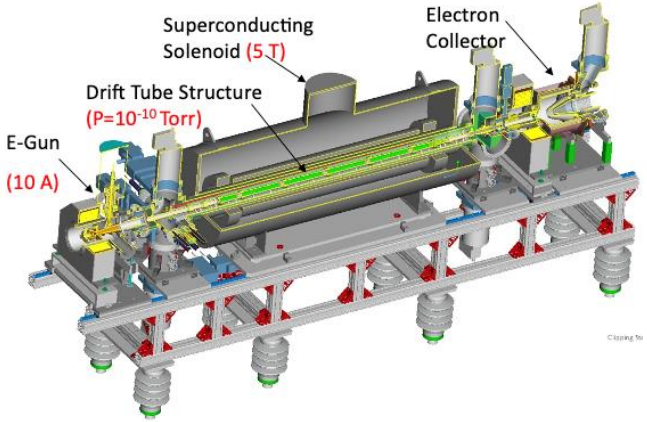
Biri, S., Vajda, I.K., Hajdu, P. *et al.* The Atomki Accelerator Centre. *Eur. Phys. J. Plus* **136**, 247 (2021). https://doi.org/10.1140/epjp/s13360-021-01219-z

Electron Cyclotron Resonance Ion Source (ECIRS)

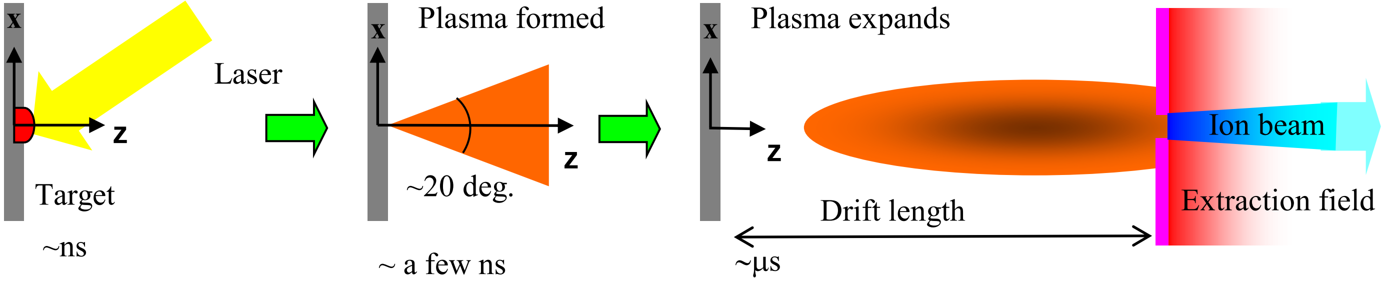
Good for CW beam (cyclotron or LINAC)
High average current

Electron Beam Ion Source (EBIS)

Pulsed beam for synchrotron
High flexibility



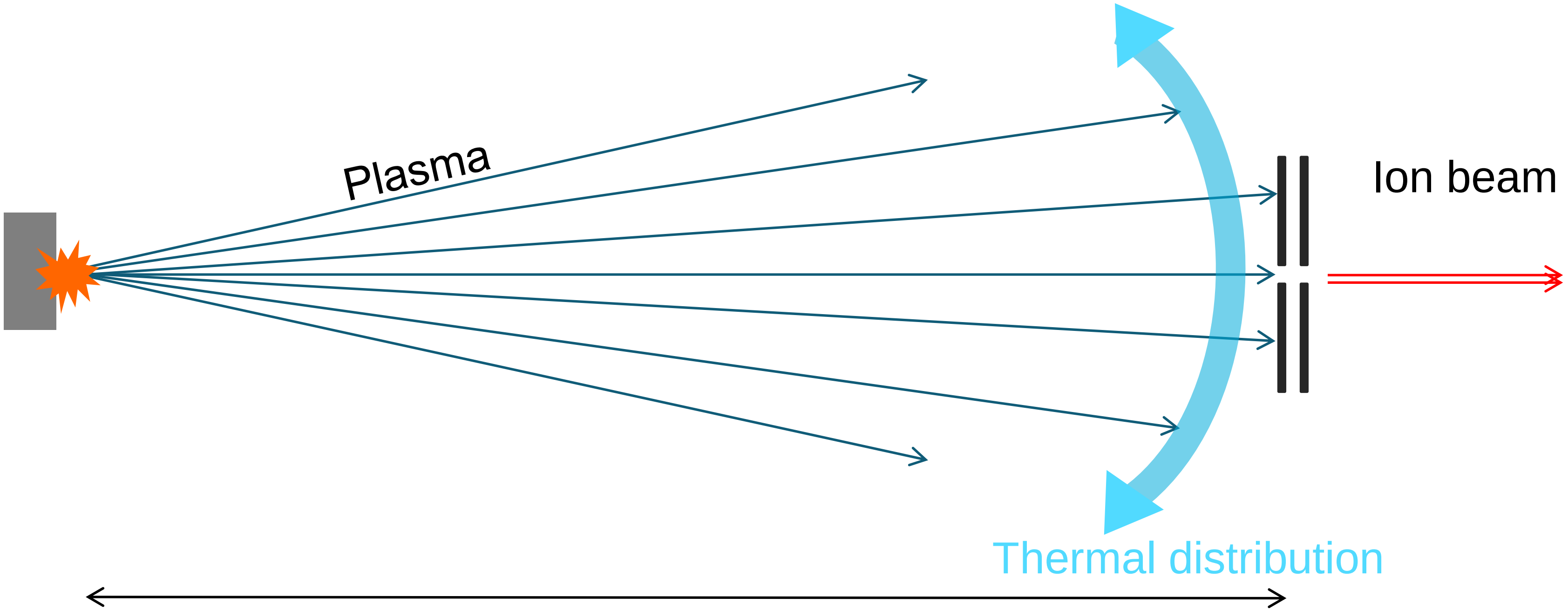
laser ion source (LIS)

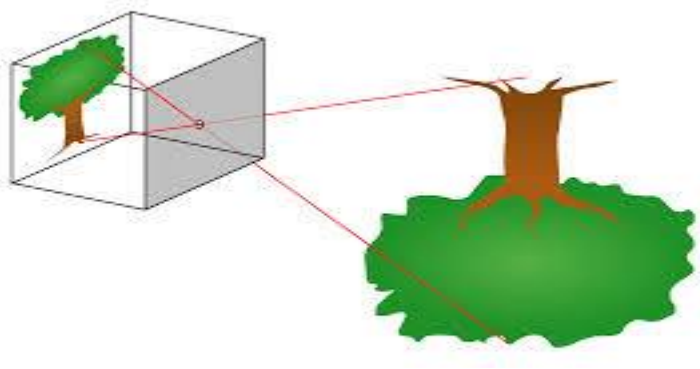


Scheme of laser ion source

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

Hot plasma becomes very cold at the extraction

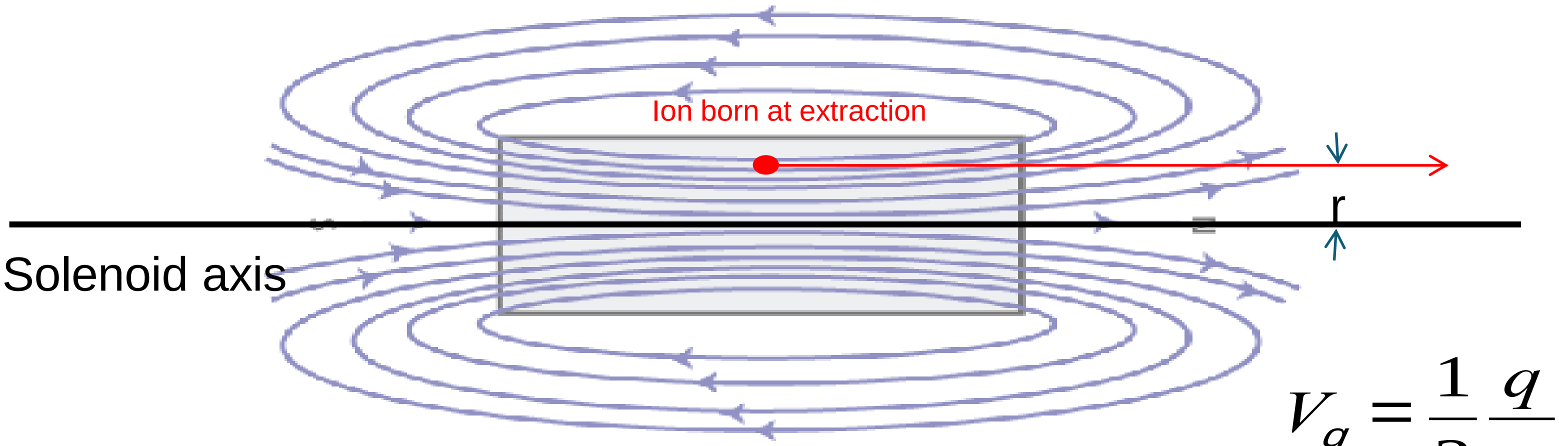




Pin point ionization
-uniform plasma density-

Less emittance growth

Magnetic field at extraction point increases emittance.



$$V_q = \frac{1}{2}\frac{q}{m}B_z r$$

No strong magnetic field in laser ion source

Why Laser Ion Source is good for next generation accelerators??

LIS provide very high current beam
No hysteresis effect
High charge state ions using high laser power density

LIS has been spoken badly:

poor stability
uncontrollable emittance
not great for long time operation

Why Laser Ion Source is good for next generation accelerators??

LIS provide very high current beam
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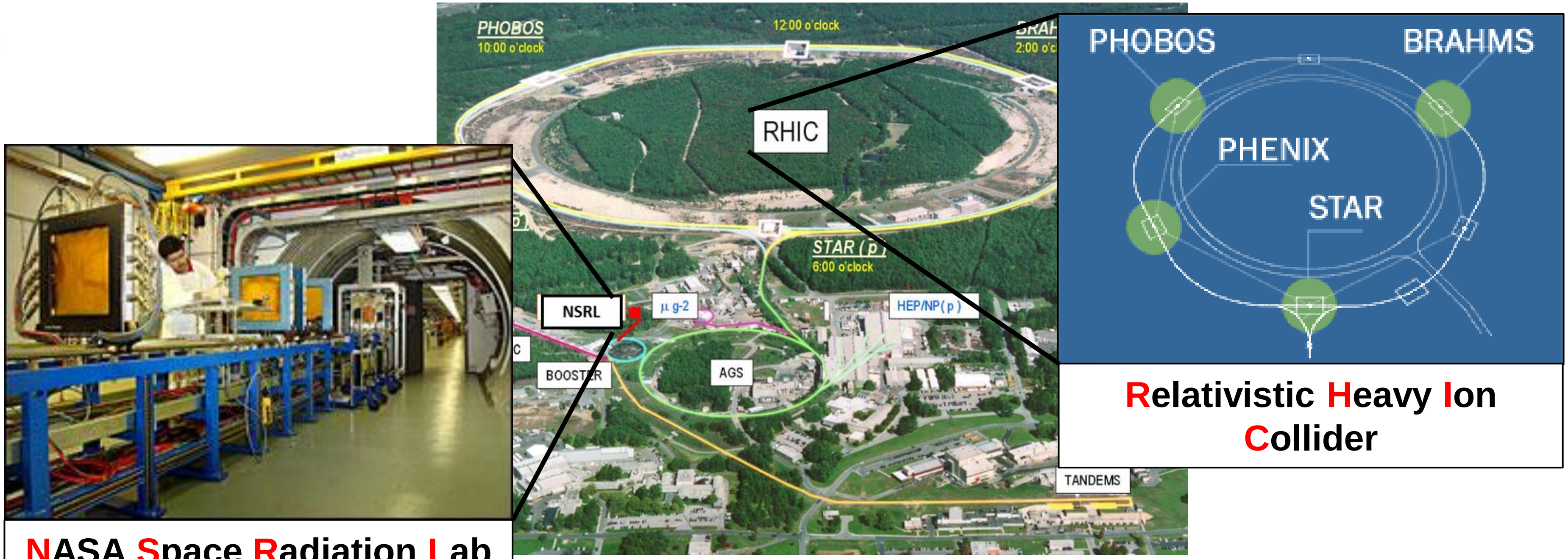
LIS has been spoken badly: poor stability
uncontrollable emittance
not great for long time operation

These are false statements

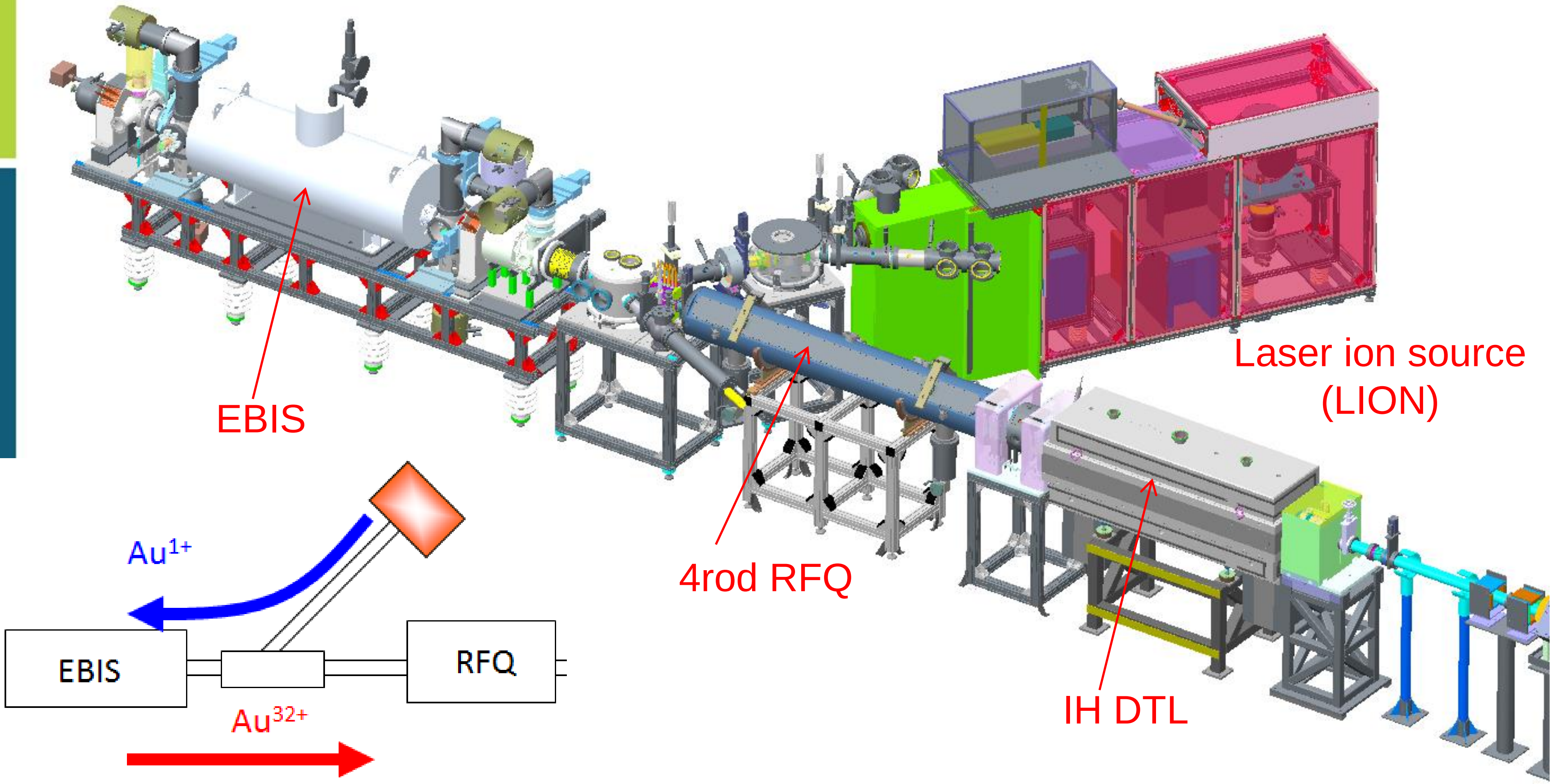
Low current LIS is providing beams to



Relativistic Heavy Ion Collider

NASA Space Radiation Lab

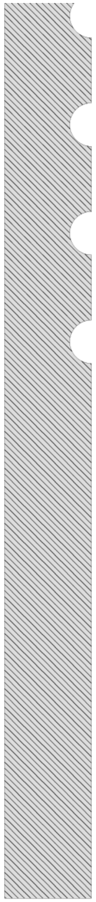
	NSRL	RHIC
For what?	Simulate galactic cosmic rays	Create quark gluon plasma
species	All kinds of cosmic rays	Au
energy	Fe ~1GeV/n	100GeV/n



Since 2014, we have provided various ion beams without major maintenances.

Never opened the beam extractor assembly.
No need to change optical window or lens for laser beam.
Very good beam current reproducibility.

What is Direct Plasma Injection Scheme (DPIS)?



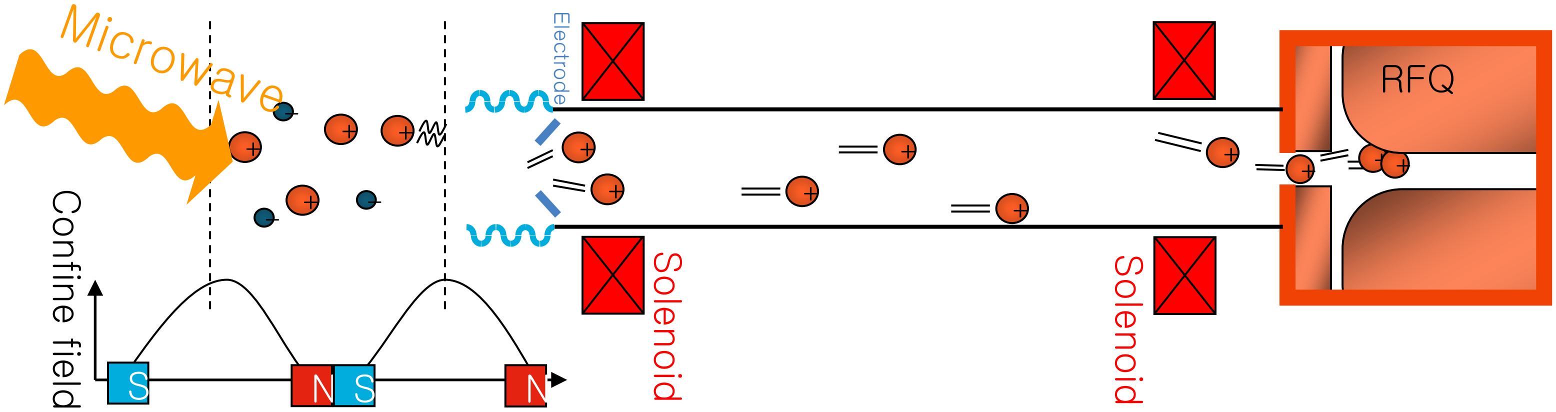
Since the plasma start from solid state (not gas), the current density can be very high.

🟧 Expanding plasma

🟨 Laser light

We can provide ultra high current, but,,

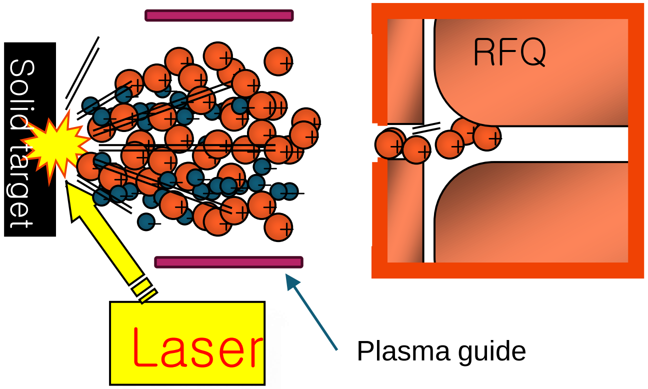
It's not so easy to put it into an RFQ!!



DPIS source

Traditional injection scheme is not good for very high current beam

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.

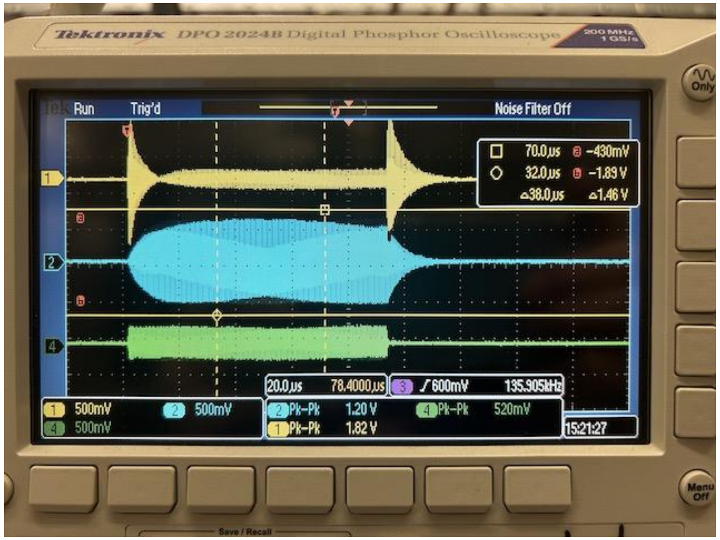
Project Status (control milestones)

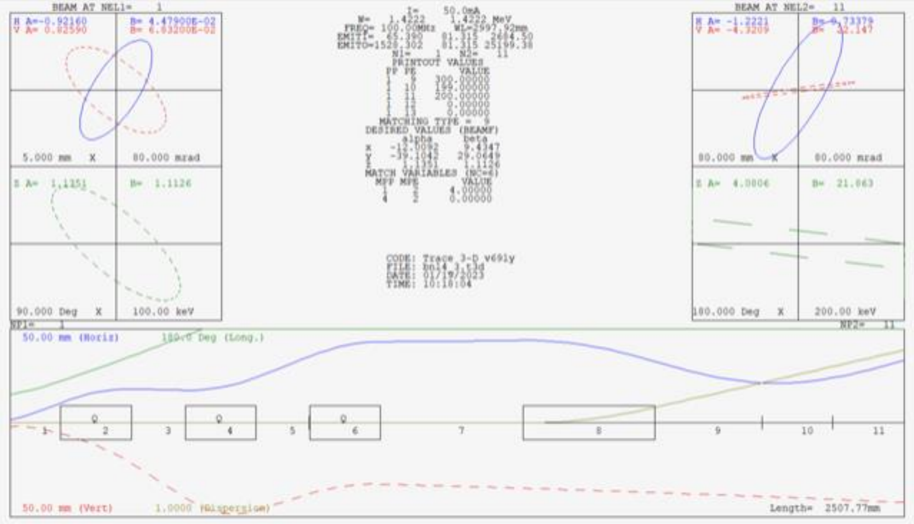
FY2023-Q1
    1 Subcontract with Columbia University
    Dec. 31, 2022 Dec. 22
    2 Open call for a postdoc position
    Dec. 31, 2022 Oct. 4 Madhawa joined Sep. 1 2023
FY2023-Q2
    1 The first beam through the RFQ
    Feb. 28, 2023 Feb. 10 ($^{11}B^{5}$)
FY2023-Q3
    1 The second species acceleration
    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 In progress
    2 The third species acceleration
    Dec. 31, 2023 Sep. 20 ($^{26}Mg^{10}$)

Summary of expenditures by fiscal year (FY):

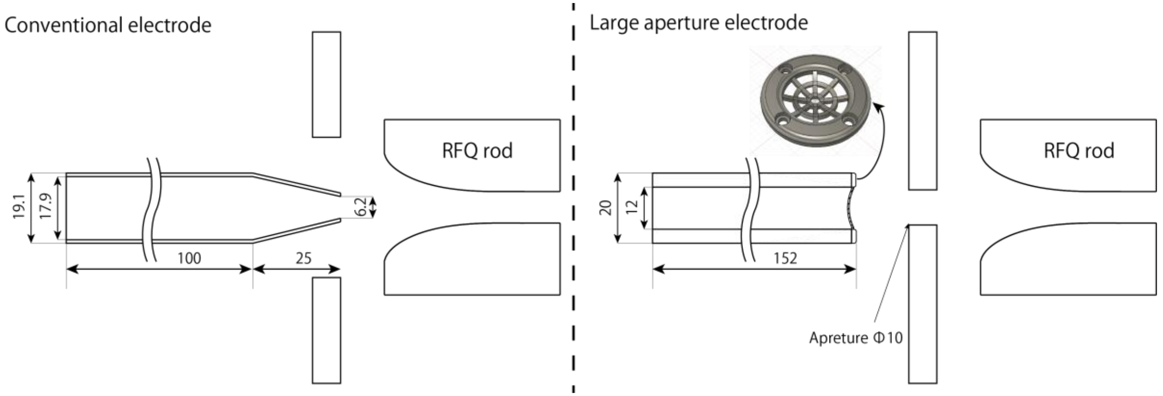
	FY22 ($K)	**FY23 ($K)**	**Totals ($K)**
a) Funds allocated	400	400	800
b) Actual costs to date	256	198	454

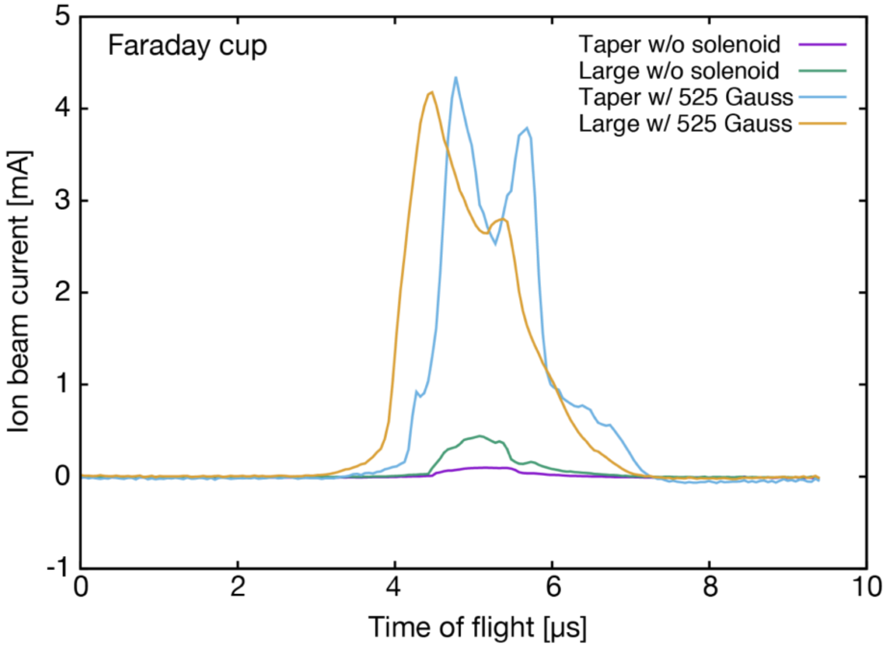
Improvement of the accelerator system and R&Ds



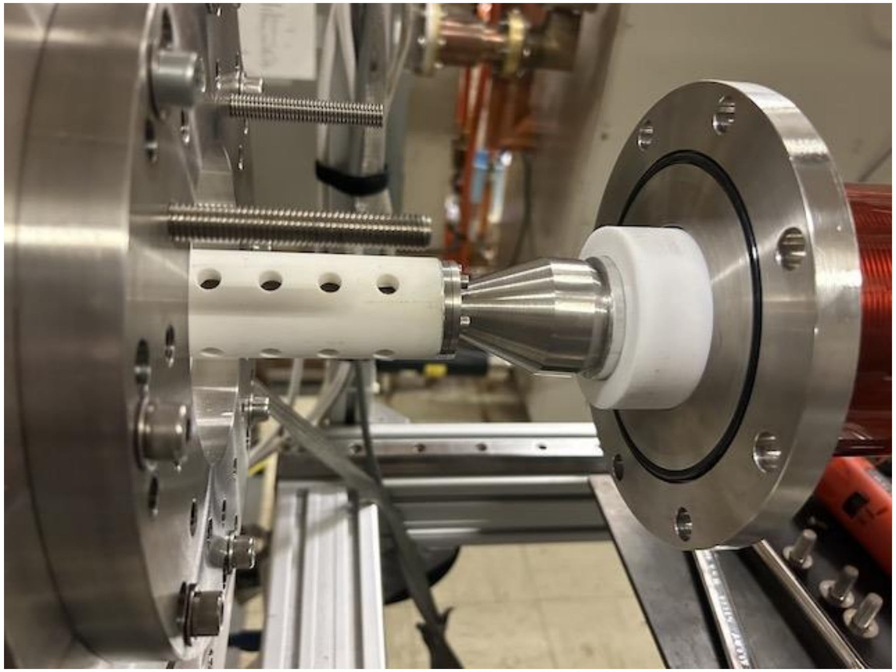


Test of new beam extraction structure

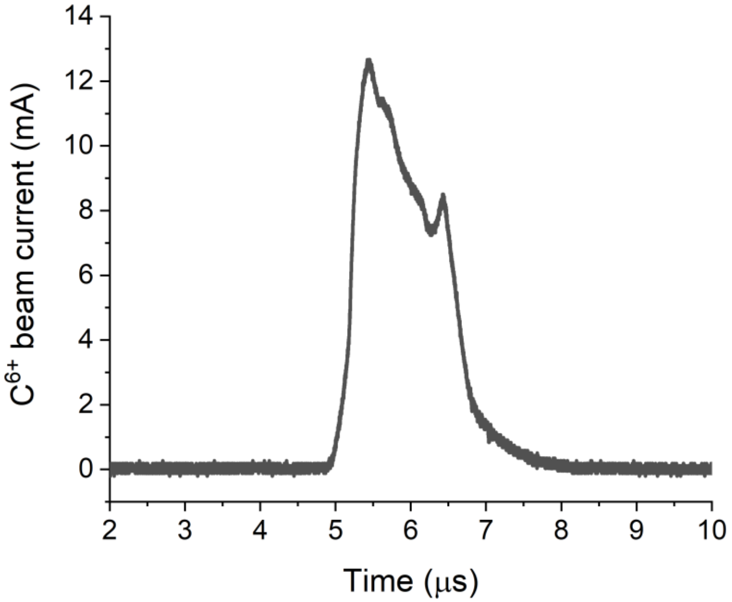




$^{11}B^{5}$ beam was accelerated. Accelerated particle number reached 7.43E9 ions.



To prevent magnetron discharge in the solenoid, the space was filled by Teflon.



$^{12}C^6$ beam with the new ion source structure.

- 1.58E10 ions (BNL EBIS: 2.5E9)
- 12.7 mA peak current

So far, we tested Li, B, C and Mg.

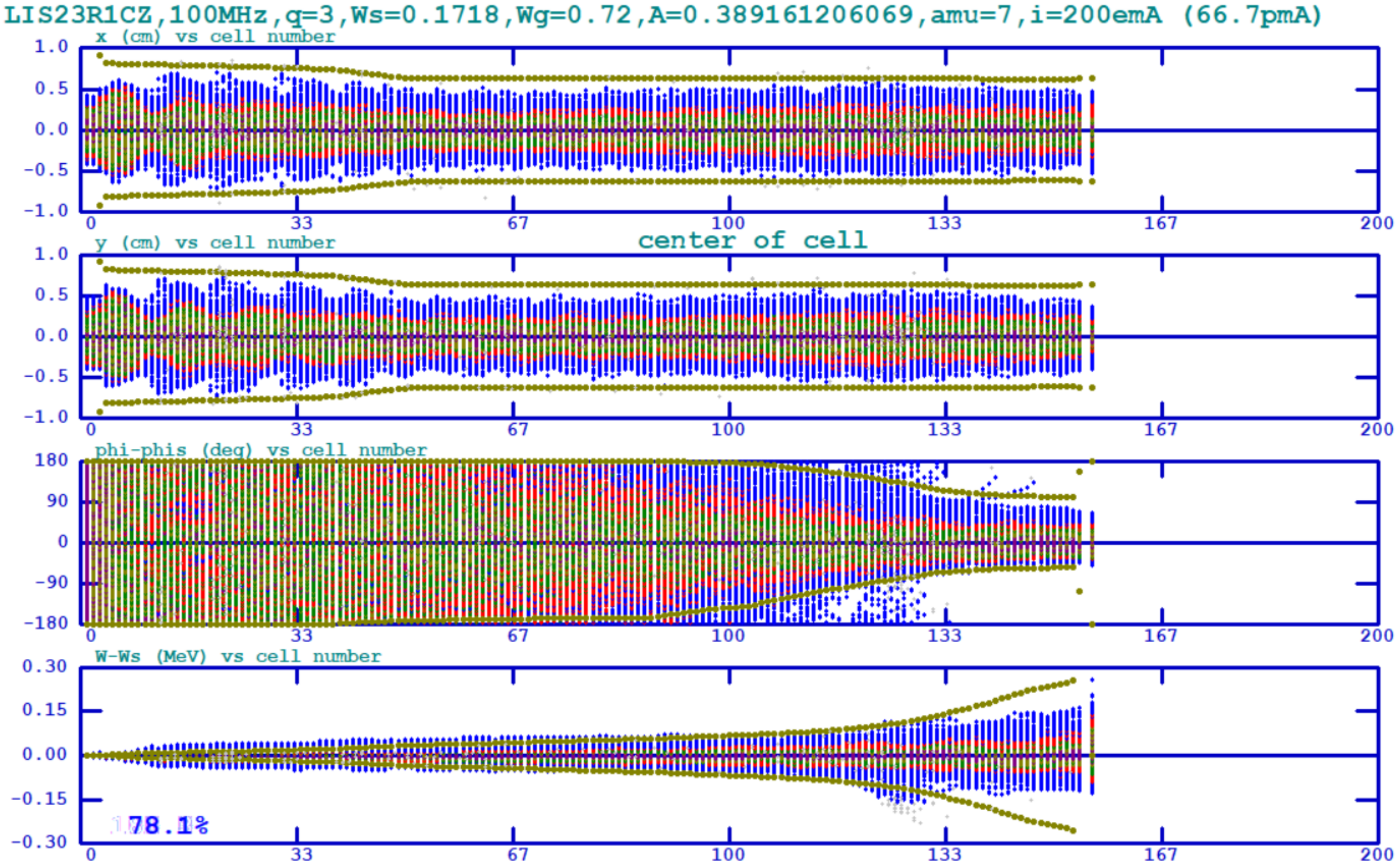
New design of RFQ electrode (type 1)

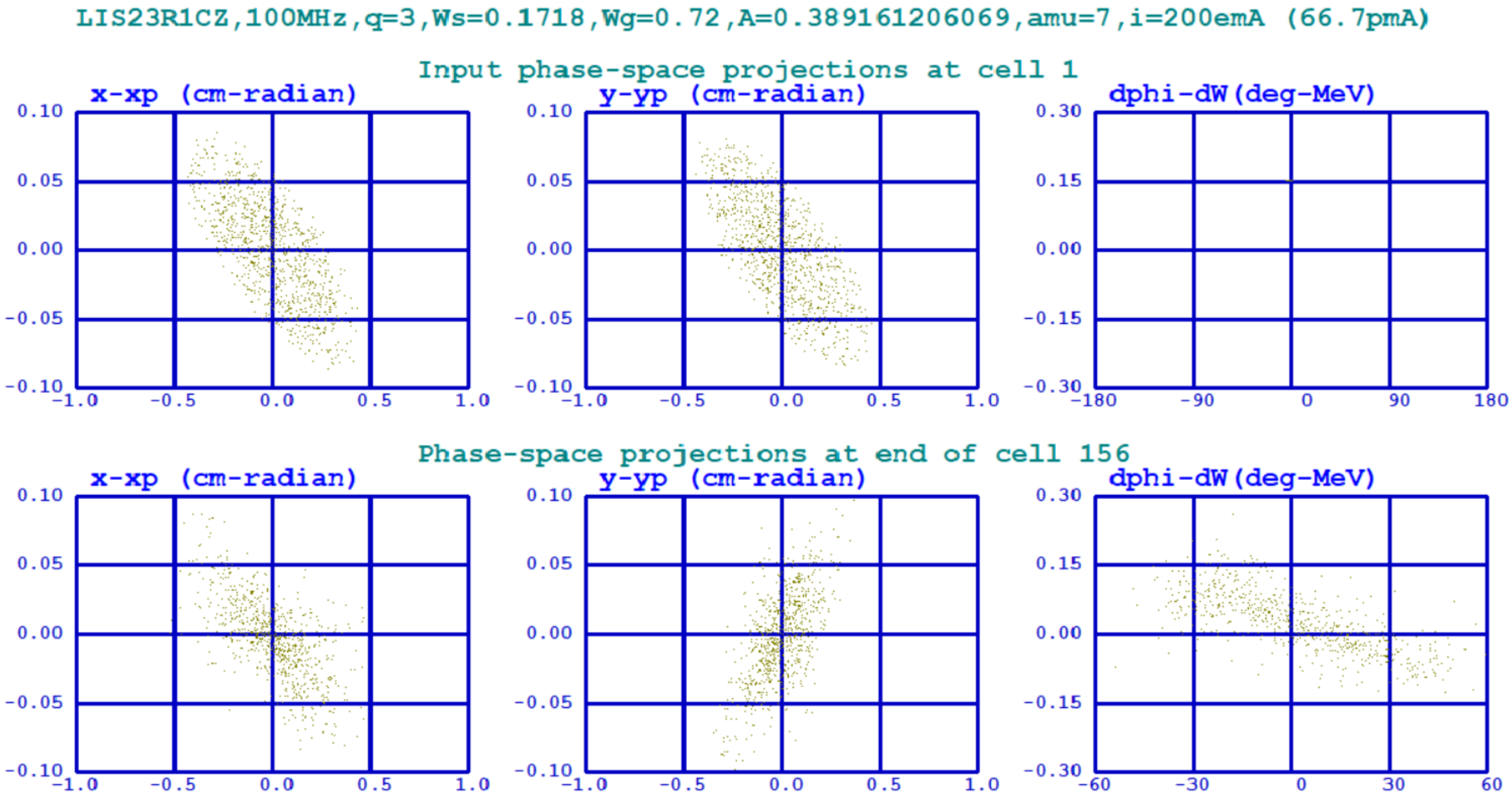
Design criteria

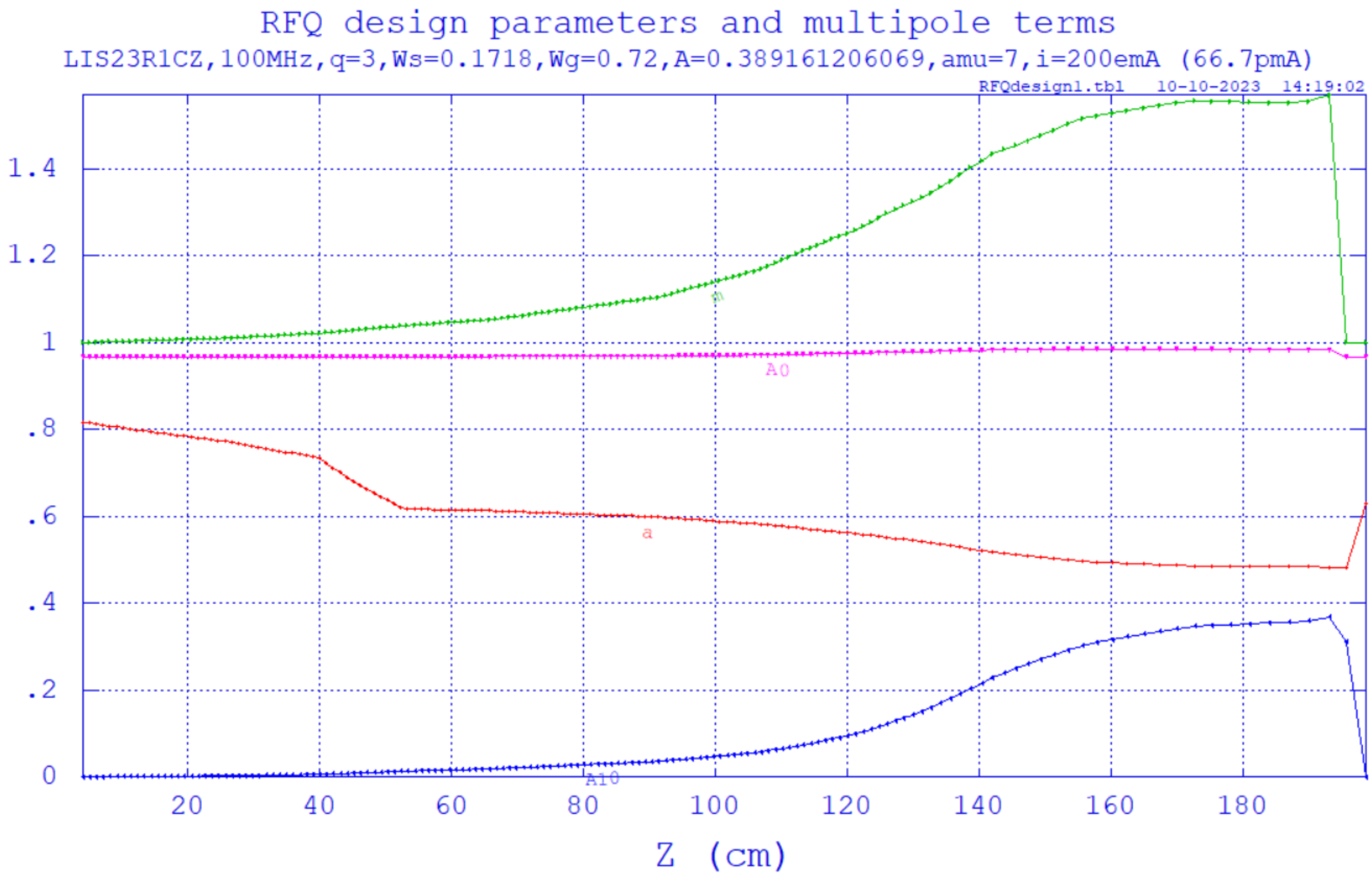
- Max m/q = 7/3 (assuming $^{7}Li^{3+}$)
- Target output peak current > 100 emA
- Extraction voltage ~50 kV
- 100 MHz
- Transmission ~ 75% inter-vane voltage of 105 kV
- Kilpatrick factor <2
- 2 m long
- Output energy 280 keV/n

BNL test RFQ for DPIS

Brookhaven
National Laboratory


LIS23R1CZ,100MHz,q=3,Ws=0.1718,Wg=0.72,A=0.389161206069,amu=7,i=200emA (66.7pmA)

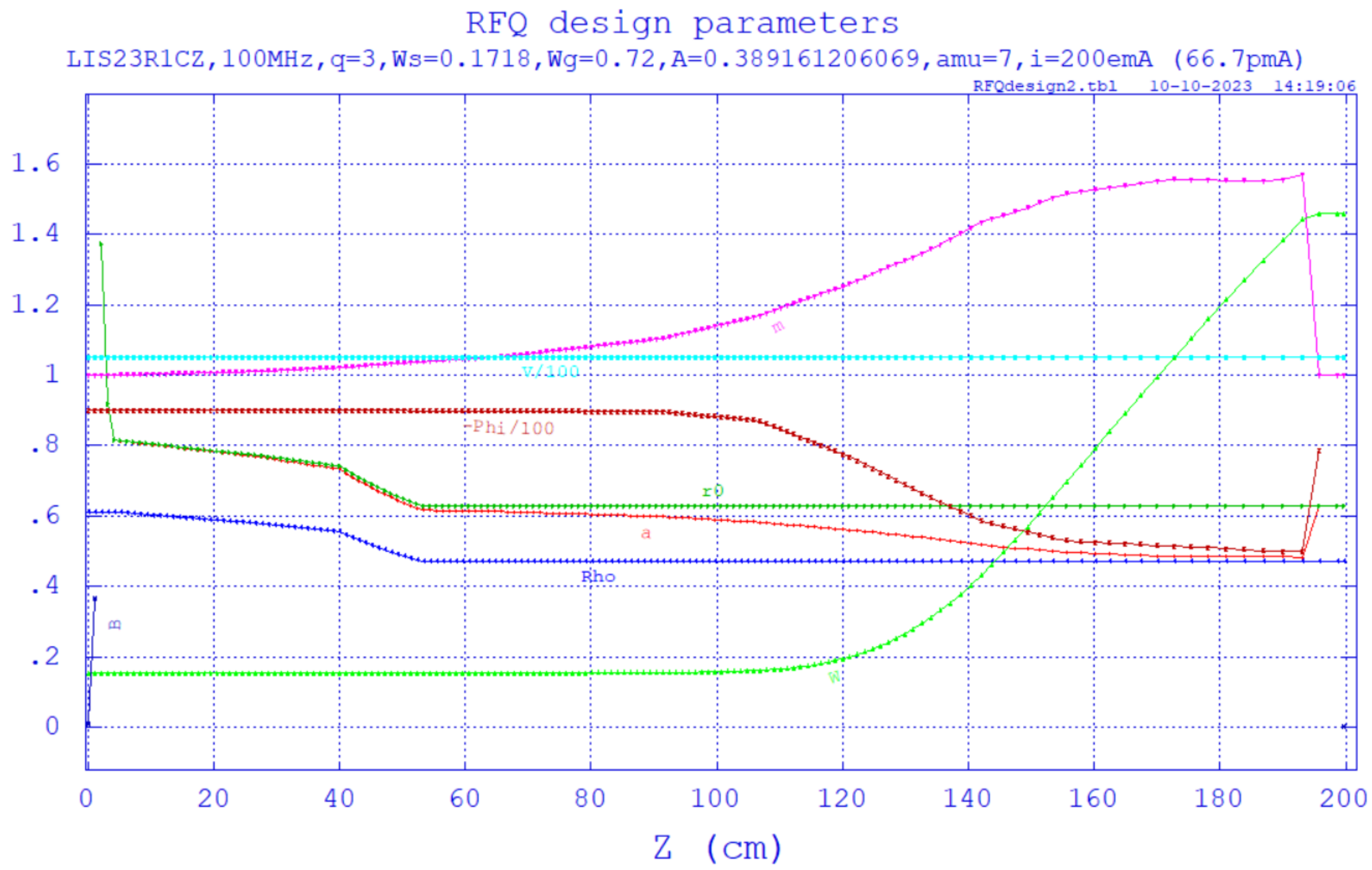

LIS23R1CZ,100MHz,q=3,Ws=0.1718,Wg=0.72,A=0.389161206069,amu=7,i=200emA (66.7pmA)
Input phase-space projections at cell 1
x-xp (cm-radian)
y-yp (cm-radian)
dphi-dW(deg-MeV)
0.10
0.05
0.00
-0.05
-0.10
0.30
0.15
0.00
-0.15
-0.30
-1.0
-0.5
0.0
0.5
1.0
-180
-90
0
90
180
Phase-space projections at end of cell 156
x-xp (cm-radian)
y-yp (cm-radian)
dphi-dW(deg-MeV)
-60
-30
0
30
60



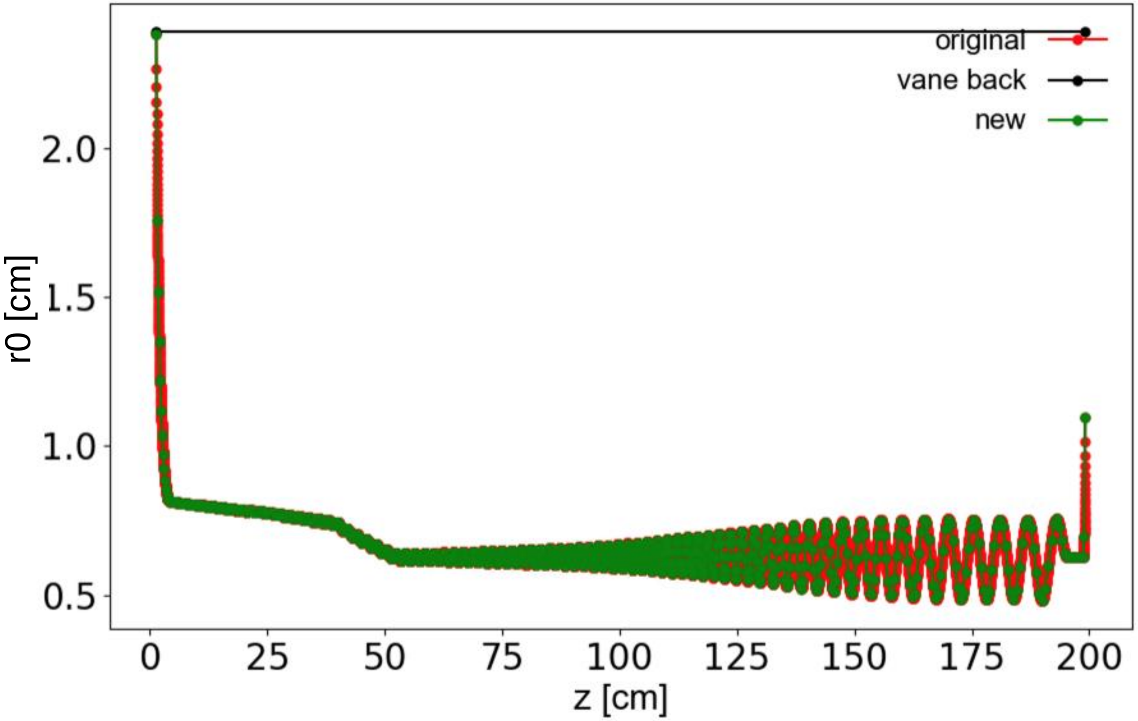
RFQ design parameters and multipole terms

LIS23R1CZ,100MHz,q=3,Ws=0.1718,Wg=0.72,A=0.389161206069,amu=7,i=200emA (66.7pmA)

RFQdesign1.tbl 10-10-2023 14:19:02

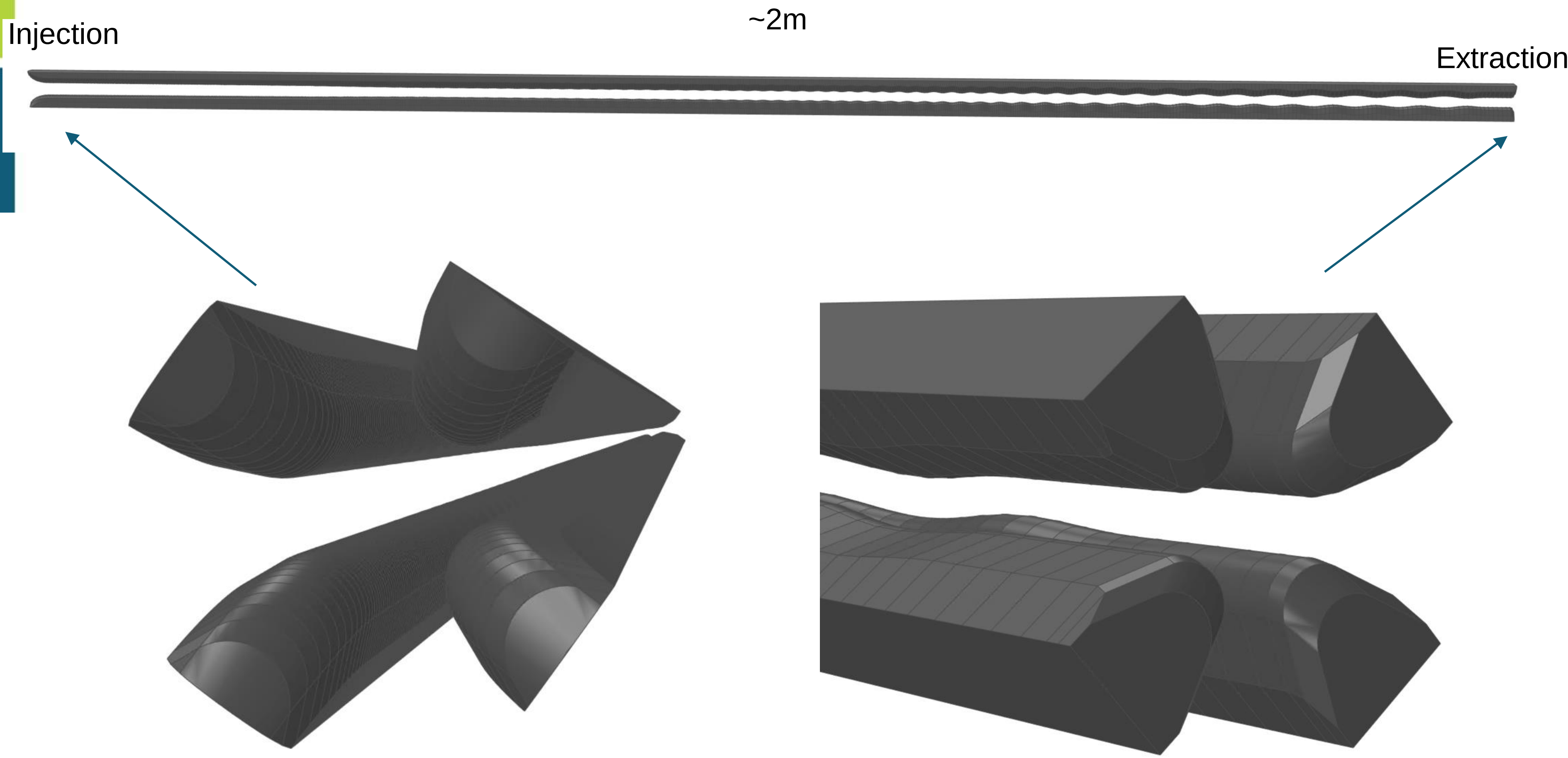

RFQ design parameters
LIS23R1CZ,100MHz,q=3,Ws=0.1718,Wg=0.72,A=0.389161206069,amu=7,i=200emA (66.7pmA)
RFQdesign2.tbl 10-10-2023 14:19:06
1.6
1.4
1.2
1
.8
.6
.4
.2
0
0
20
40
60
80
100
120
140
160
180
200
Z (cm)
m
V/100
-Phi/100
r0
a
Rho
B
W

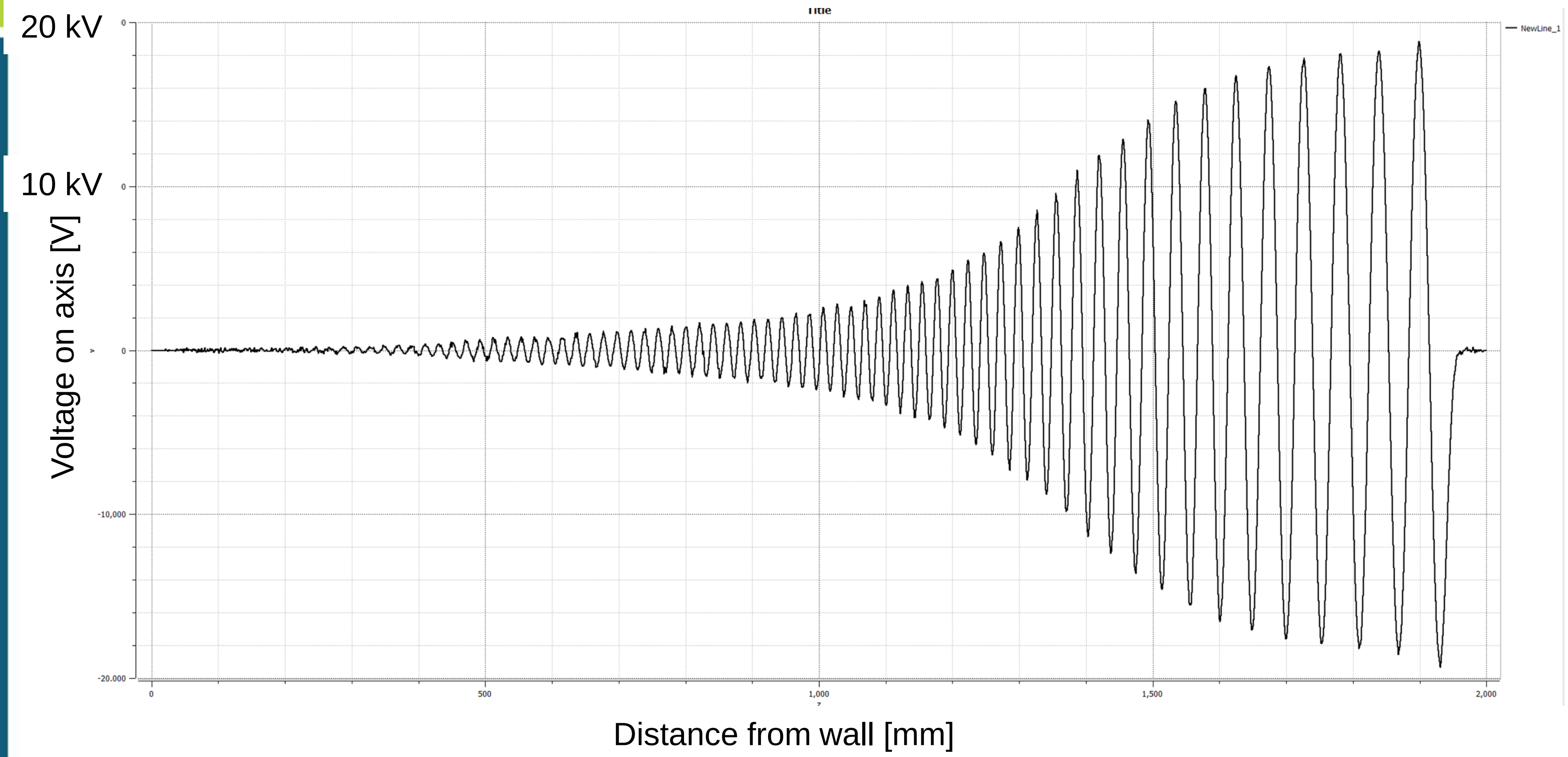
Variable aperture design



- Larger aperture around injection to keep beam radius large until finishing bunch formation.
- Property as a RF resonator need to be verified.

Shape of RFQ vanes

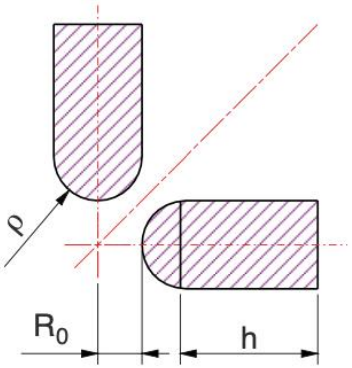




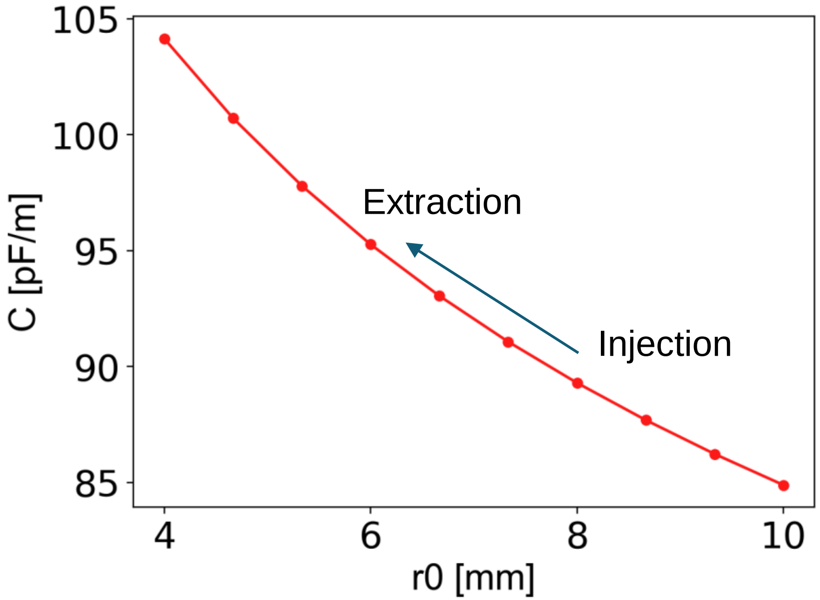
3D modeling is almost done. Ready for RF simulation

- Simulation: Pk-pk = 36.4 kV
- Design: A0=0.36, V=105kV -> 37.8 kV

Consideration of capacitance variation

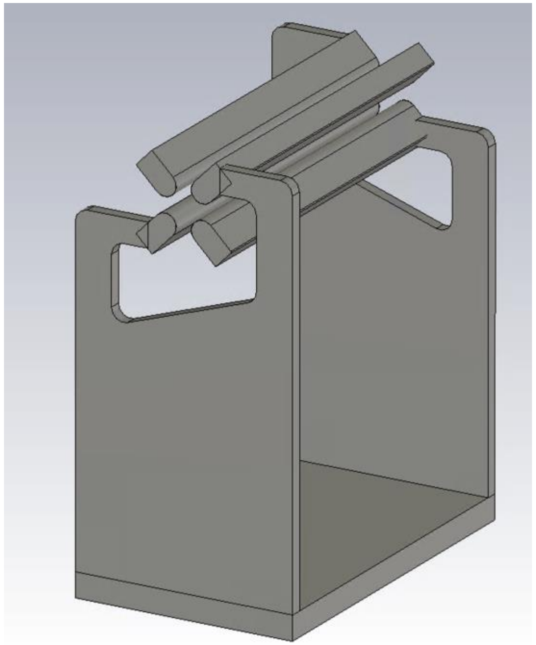


$$C'_Q / pF / m = \frac{39.37}{\cosh^{-1}((1+R_o/\rho)/\sqrt{2})} + \frac{31.05}{R_o/\rho - 0.414} + 25.28 \ln\left(1+\frac{h}{a+\rho}\right).$$



- As r0 is reduced from entrance to exit, capacitance of electrodes also decreases
- This may result in variation of resonant frequency and electrode voltage

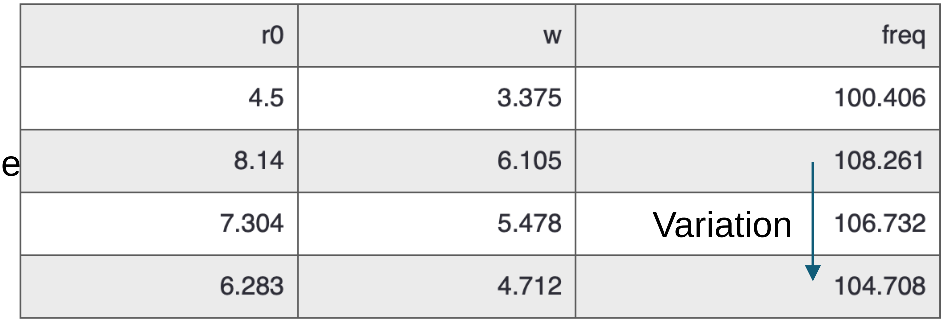
Investigation of resonant frequency variation with simple model



Short model with periodic boundary condition

Entrance

Exit



r0	w	freq
4.5	3.375	100.406
8.14	6.105	108.261
7.304	5.478	106.732
6.283	4.712	104.708

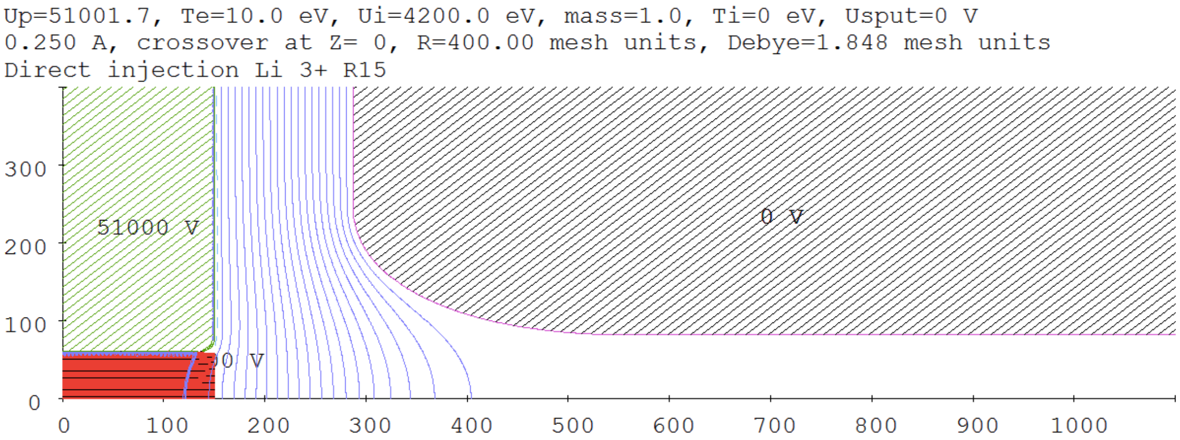
Variation

- Vane shape needs to be designed to have small variation of capacitance and voltage

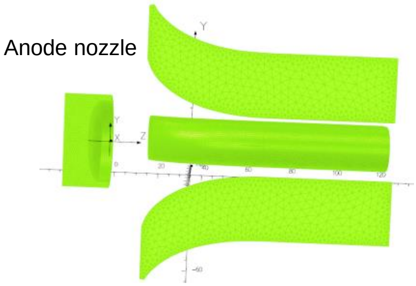
The final RF property is being simulated by CST.

Simulation strategy at the injection region

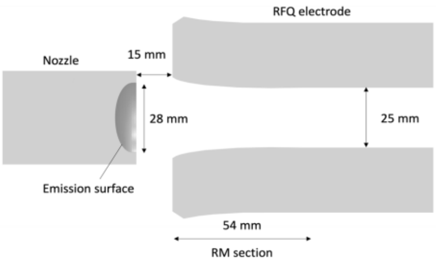
Plasma sheath: IGUN
3D field: OPERA
Tracking: GPT



```
Up=51001.7, Te=10.0 eV, Ui=4200.0 eV, mass=1.0, Ti=0 eV, Usput=0 V
0.250 A, crossover at Z= 0, R=400.00 mesh units, Debye=1.848 mesh units
Direct injection Li 3+ R15
```



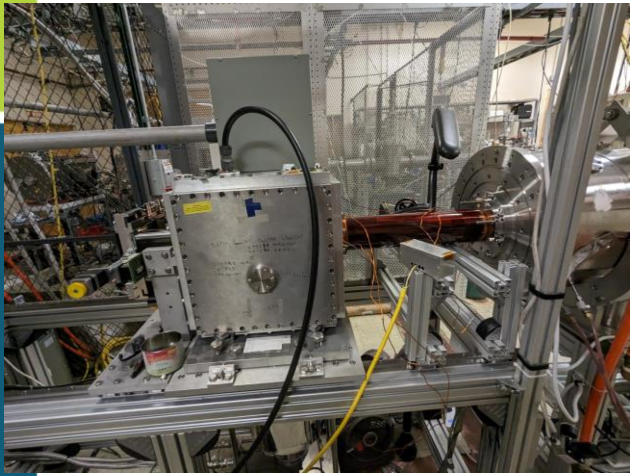
Parmteq design



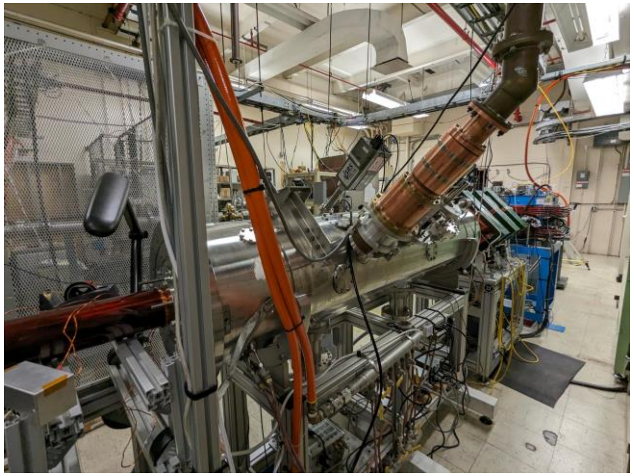
Optimized design

The first beam simulation paper is almost ready to submit.
The first set of the vanes are being procured.

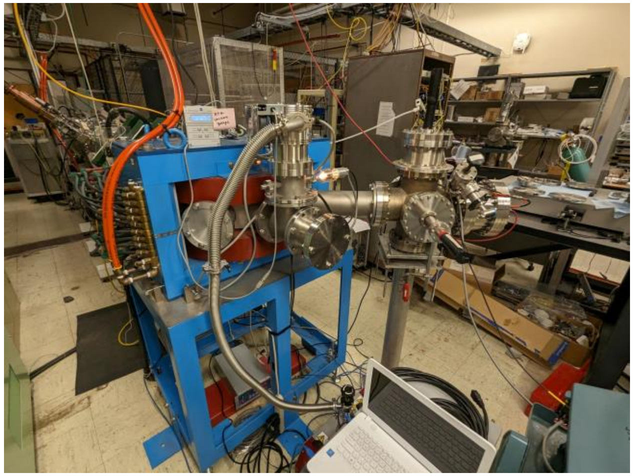
Mg acceleration test



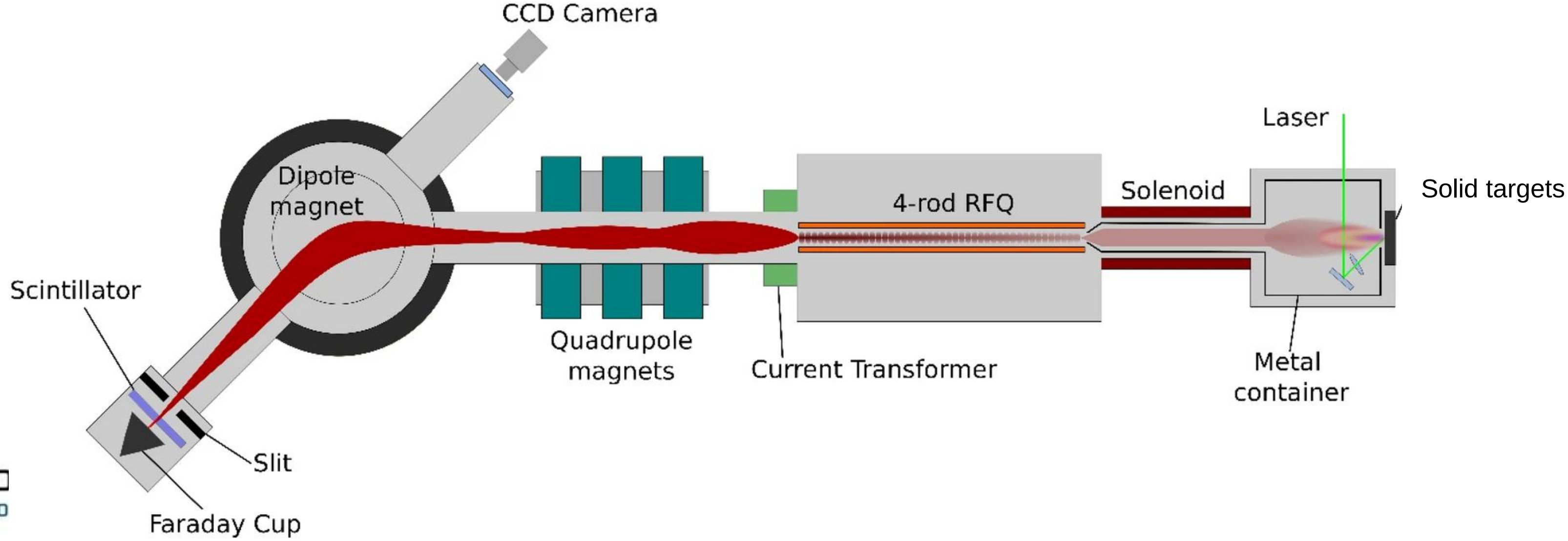
Plasma Chamber



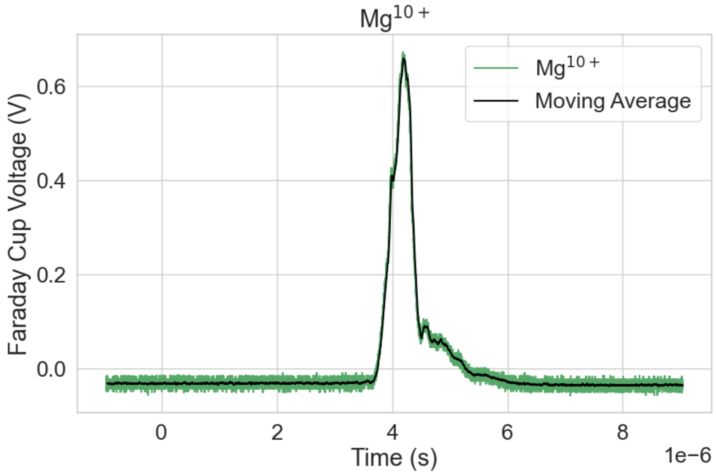
RFQ accelerator and beam line



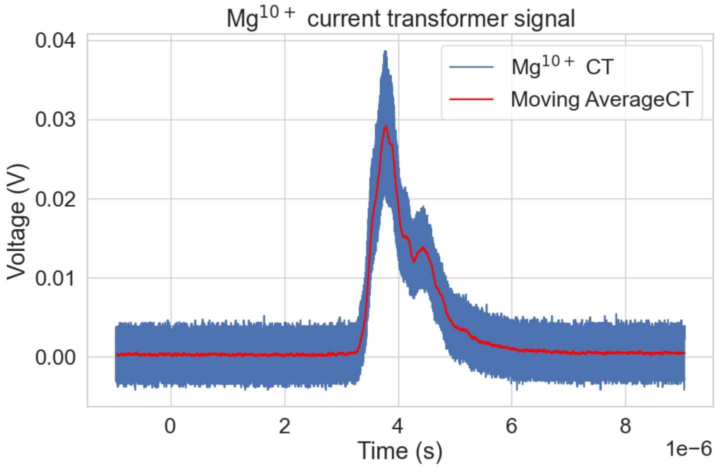
Dipole magnet and end of beamline



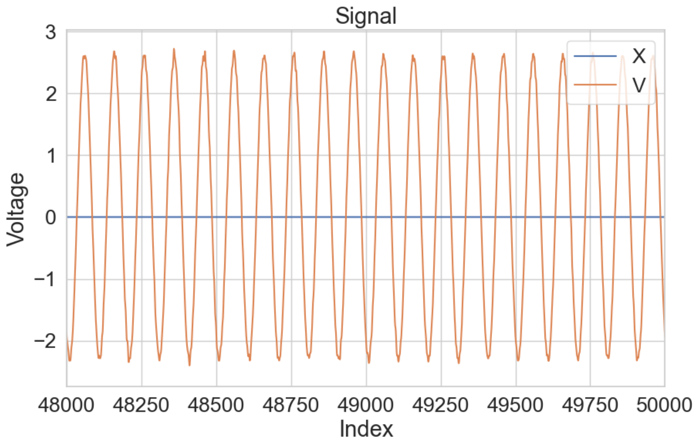
Faraday Cup Signal

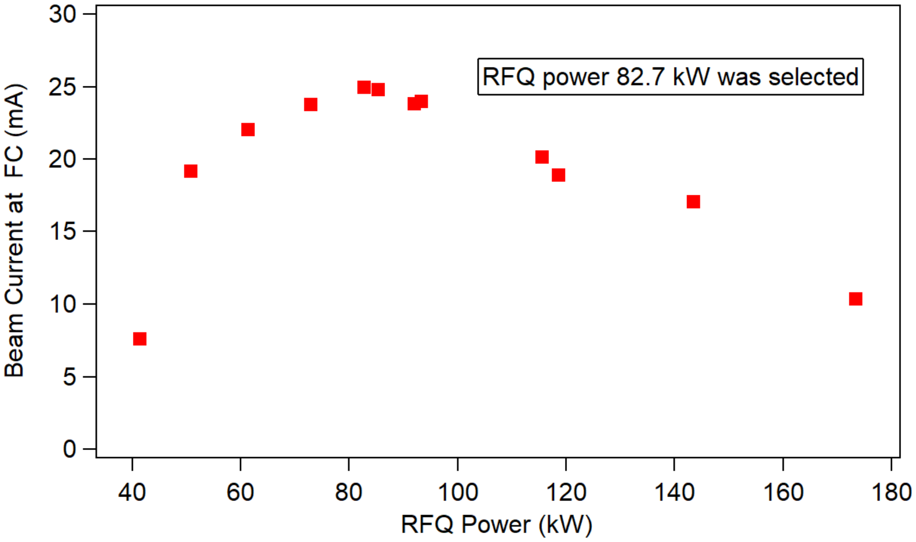


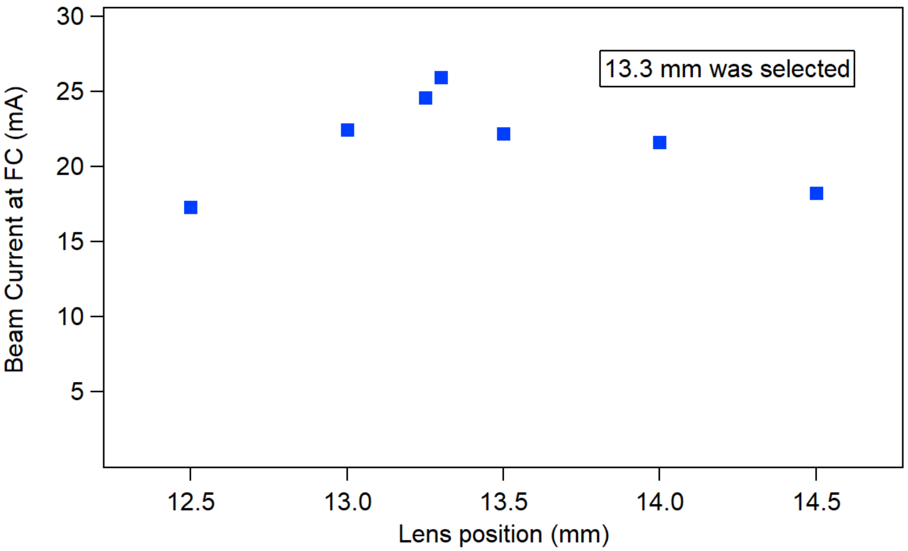
Current Transformer Signal



RFQ cavity signal

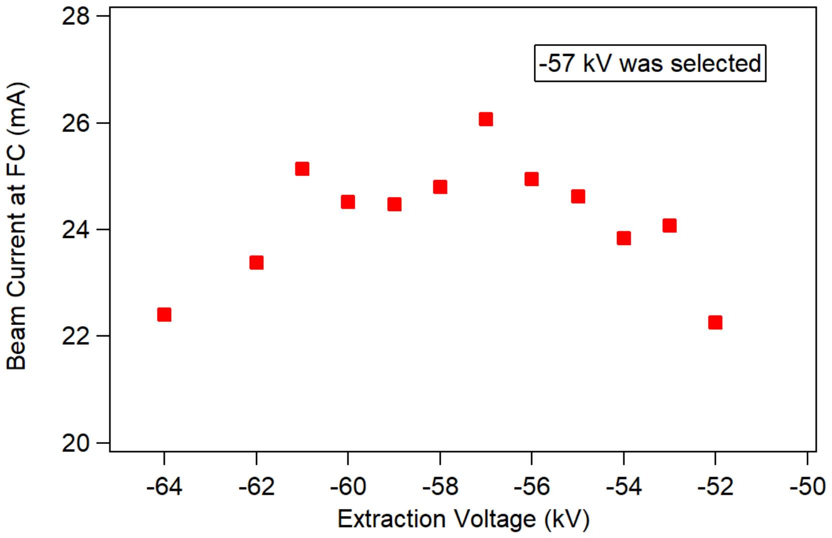



FC Max Voltage vs RFQ Power

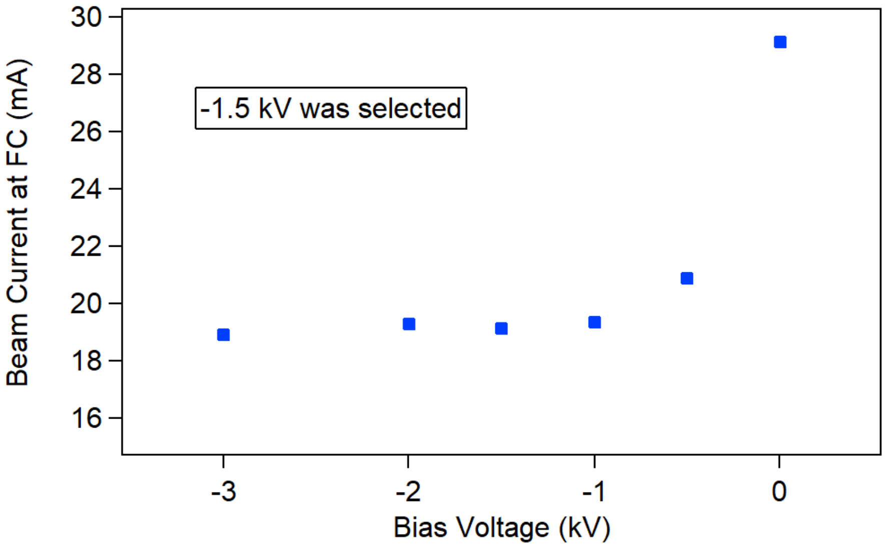

FC Max Voltage vs Lens Position

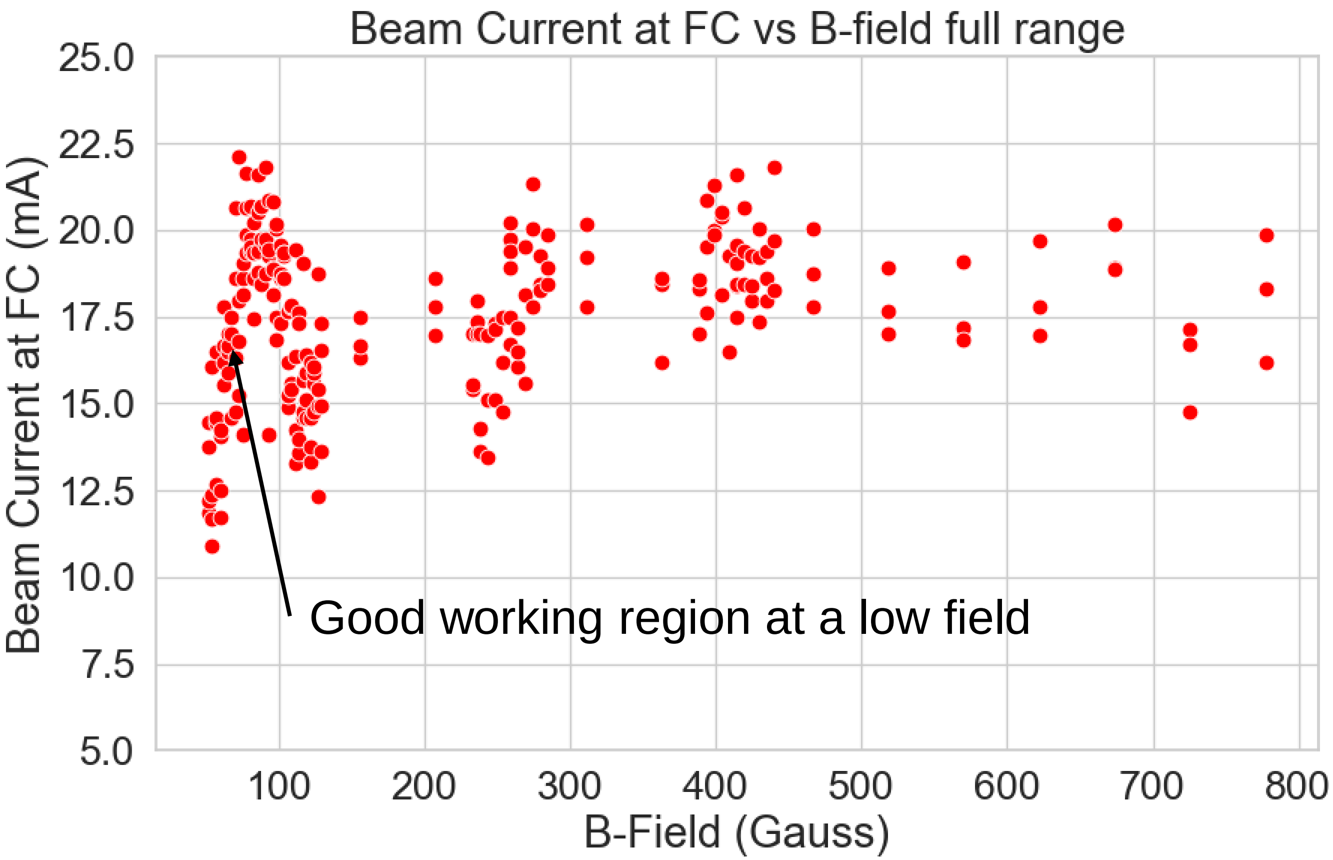
These data were taken without biasing Faraday cup.

FC Max Voltage vs Extraction Voltage


-57 kV was selected

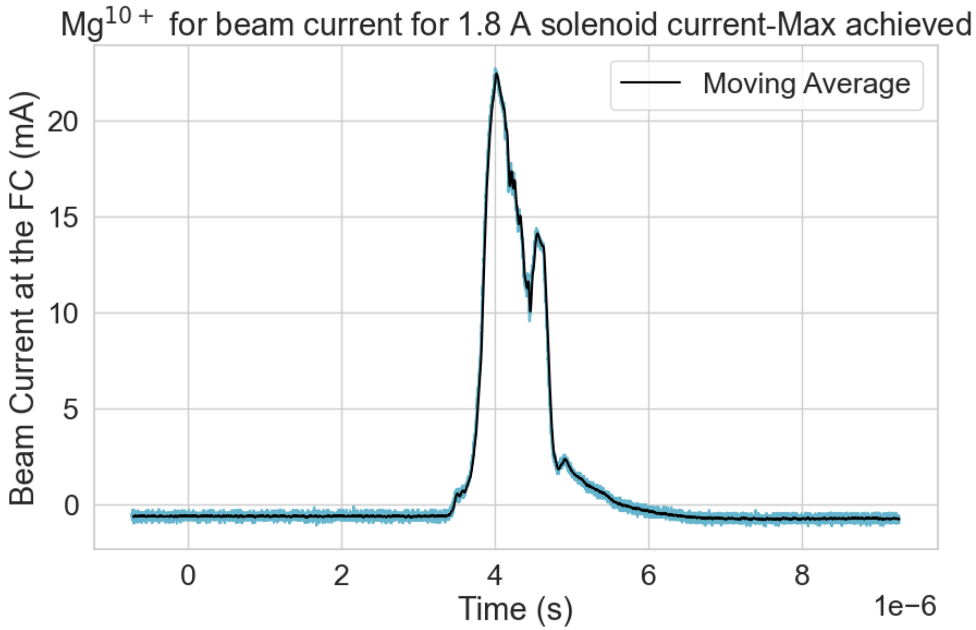
FC Max Voltage vs Bias Voltage


-1.5 kV was selected

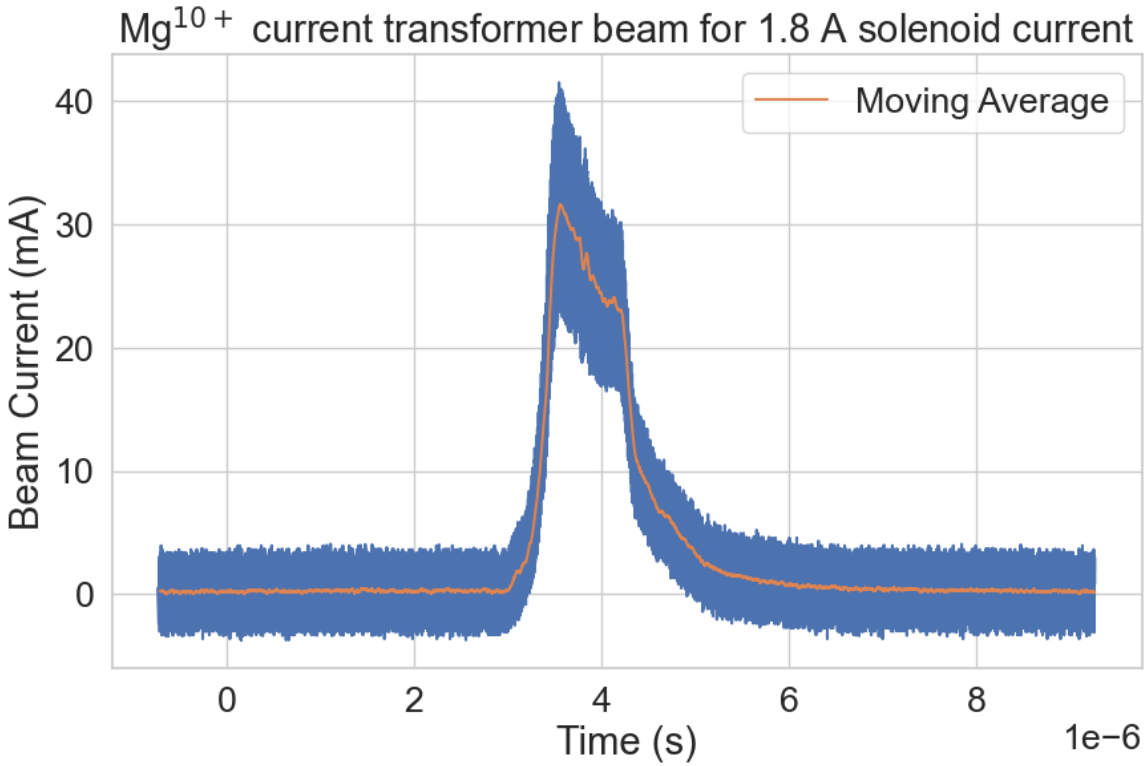


Good working region at a low field

Mg^{10+} max beam current (Tentative results)

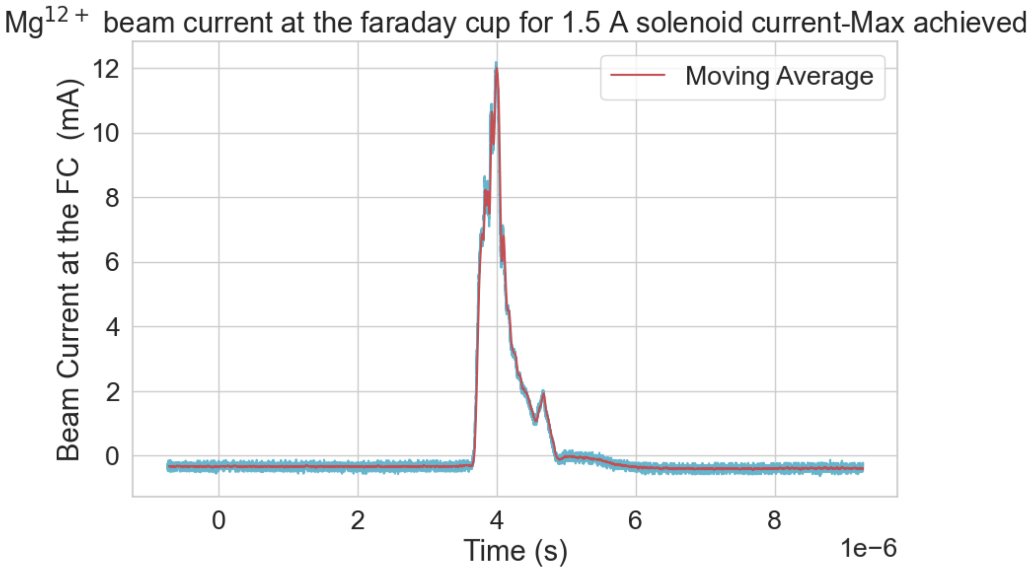


Parameters FC	Analysis	Measured from Oscilloscope
Area under the curve	785 nVs	689.9 nVs
Ch2 Max Voltage	1.153 V	1.137 V
Total charge	1.57e-08 C	
No of particles	9.82e+09	
Beam current at faraday cup	23.07 mA	

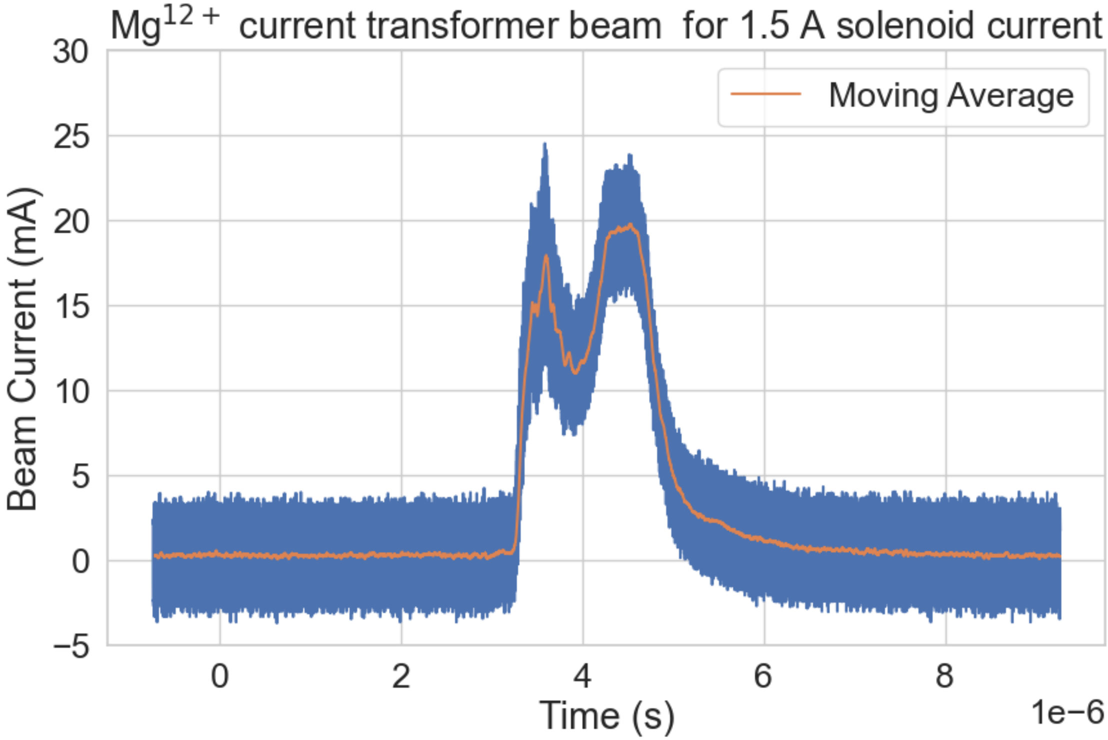


Parameters CT	Value
Vmax	0.039 V
Beam current	31.39 mA
Area under curve	40 nVs

Mg^{12+} max beam current

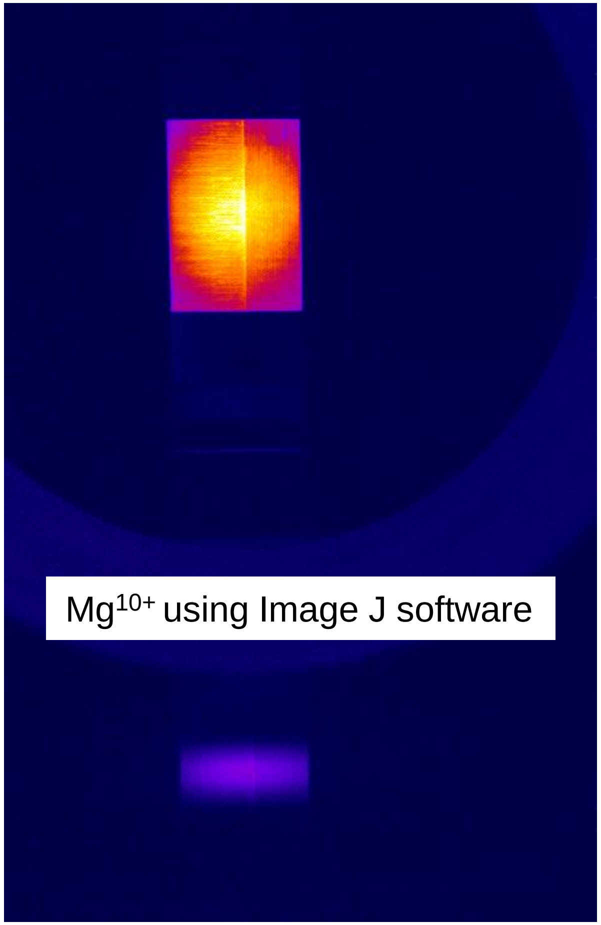


Parameters FC	Analysis	Measured from Oscilloscope
Area under the curve	238 .7 nVs	133.6 nVs
Faraday Cup Max Voltage	0.61 V	0.609 V
Total charge	4.77e-09 C	
No of particles	2.49e+09	
Beam current ar faraday cup	12.34 mA	



Parameters CT	Value
Vmax	0.022 V
Beam current	17.65 mA

Scintillator image of Mg^{10+} beam



Mg^{10+} using Image J software

Slit width ~25 mm

Data analysis of Mg beam is in progress

Isotopes separation

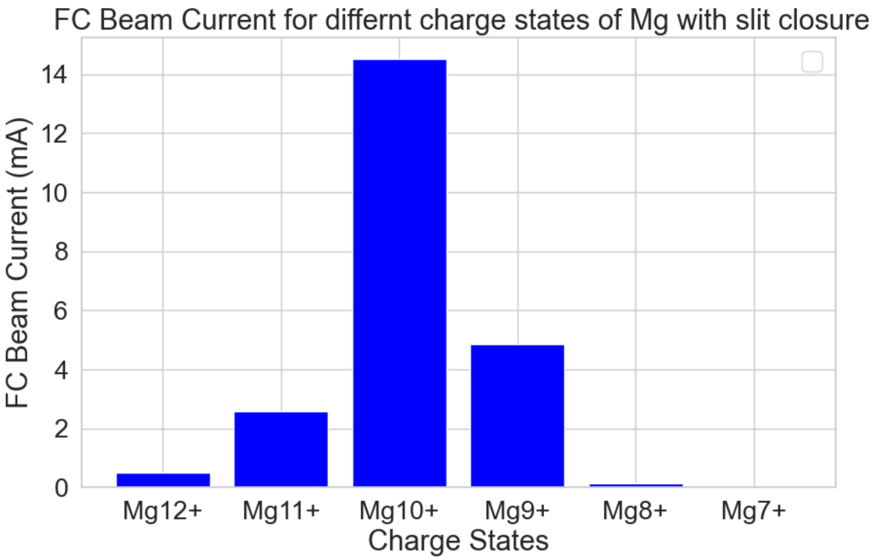
Isotope	Abundance
^{24}Mg	79%
^{25}Mg	10%
^{26}Mg	11%

Scan from 117A -129 A dipole current range to find isotopes and contaminants that could be influence to Mg^{10+} beam current

m for Mg Isotopes	q	m/q	Dipole current based on Mg^{10+}
24	12	2	102.5
25	12	2.083333	106.7708
26	12	2.166667	111.0417
24	11	2.181818	
25	11	2.272727	116.4773
26	11	2.363636	121.1364
24	10	2.4	123
25	10	2.5	128.125
26	10	2.6	133.25
24	9	2.666667	136.6667
25	9	2.777778	142.3611
26	9	2.888889	148.0556
24	8	3	153.75
25	8	3.125	160.1563
26	8	3.25	166.5625
24	7	3.428571	175.7143
25	7	3.571429	183.0357
26	7	3.714286	190.3571

m	q	m/q	Dipole Current	Ion
16	7	2.285714		16O7+
14	6	2.333333		14N6+
26	11	2.363636	121.1364	26Mg11+
24	10	2.4	123	24Mg10+
12	5	2.4		12C5+

Charge State	FC Beam Current (mA)	CT Beam Current (mA)
Mg^{12+}	0.51	31.38
Mg^{11+}	2.58	31.85
Mg^{10+}	14.51	31.27
Mg^{9+}	4.85	30.31
Mg^{8+}	0.14	32.37
Mg^{7+}	0.01	30.96



Charge state distribution optimized for Mg^{10+}

Major deliverables up to now

1. Test RFQ and beam analyzing line were improved and commissioned.
2. New beam extraction system was introduced.
3. Plasma guide solenoid and ion source chamber were modified.
4. A low solenoid field region for good working condition was discovered.
5. High current heavy ion RFQ was designed.
6. Four species were accelerated. (Mg^{10+} more than 20 mA)

   Peak currents of $^{5}\mathrm{B}^{11+}$, $^{26}\mathrm{Mg}^{10+}$ and particle number of $^{12}\mathrm{C}^{6+}$ are world records.

1. Fully striped Mg was detected. (Mg^{12+} more than 10 mA)

Schedule

FY2024-Q2
  1 Installation of electrodes type 1
  Mar. 30, 2024
  2 The fourth species acceleration (plan to accelerate Oxygen)
  Mar. 30, 2024
FY2024-Q3
  1 Procurement of new electrodes type 2 (This is for heavier species)
  Jun. 30, 2024
FY2024-Q4
  1 Installation of electrodes type 2
  Aug. 30, 2024
  2 The fifth species acceleration (Ti, Fe,,,)
  Sep. 30, 2024
  3 Submit a journal paper
  Sep. 30, 2024

Thank you for your attention