Next-Generation High-Current Ion Sources for Nuclear Physics Facilities: Demonstration with Niobium and Roadmap to Heavy Ions

Institution	FY 2027	FY 2028	Total
BNL	600	500	1,100

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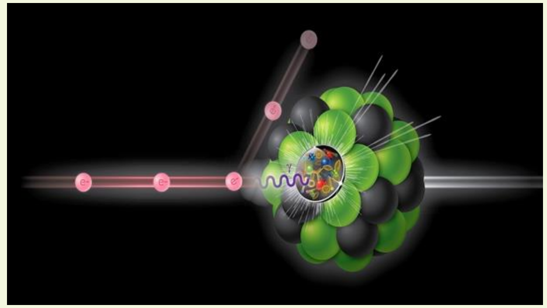
Co-PI: T. Kanesue, S. Ikeda

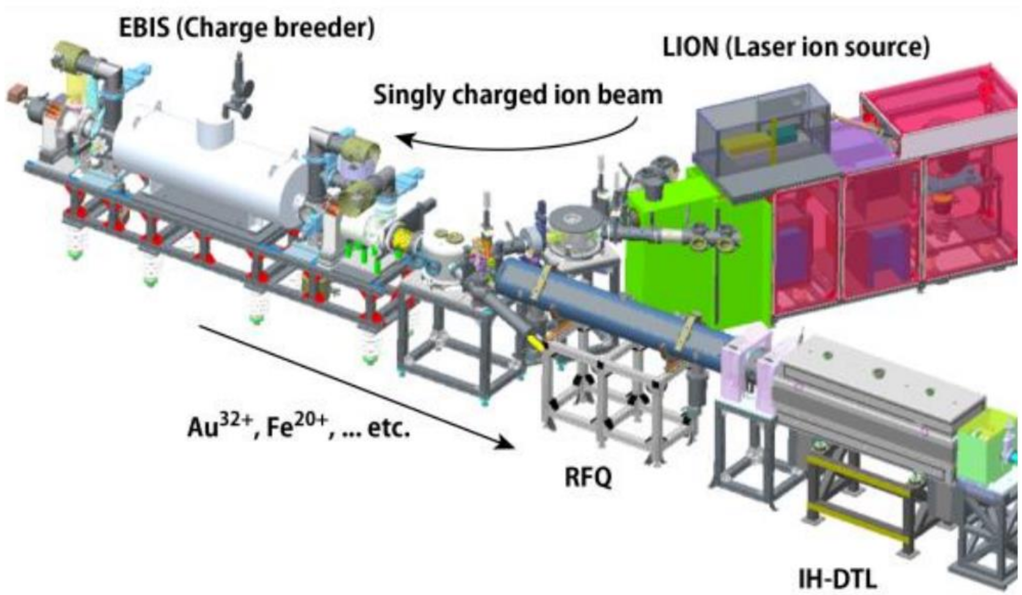
Investigators: A. Cannavo, S. Kondrashev

Main Goal: Highly Charged Nb beam

Niobium
- Z/A = 0.440860
- monoisotopic
- easily available
- high purity
- high melting point



Achieve most intense ion beam current



EEBIS generated (@CT1):

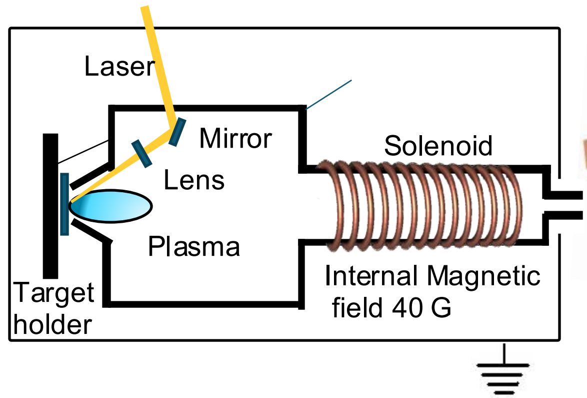
H^{1+}	1.2×10^{11}
$^{4}He^{2+}$, $^{4}He^{2+}$	3.5×10^{10}
C^{5+}, O^{7+}	1.3×10^{10}
Ne^{8+}	1.1×10^{10}
Si^{11+}	7.3×10^{9}
Ti^{17+}, Ti^{18+}	6.6×10^{9}
Fe^{20+}	6.9×10^{9}
Ag^{29+}	5.2×10^{9}
Tb^{35+}	4.2×10^{9}
Ta^{38+}	4.2×10^{9}
Au^{32+}	6.0×10^{9}

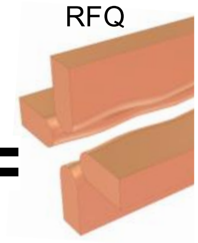
and more ...

1. Theoretical limit (charge trap capacity)
2. Practical Performance limit (compensation factor, charge state distribution)

Scientific & Technological Concept

Advances in Laser Technology ✚ Direct Plasma Injection Scheme (DPIS)





Okamura, M., Takeuchi, T., Jameson, R. A., Kondrashev, S., Kashiwagi, H., Sakakibara, K., ... & Hattori, T. (2008). Direct plasma injection scheme in accelerators. *Review of Scientific Instruments*, 79(2).

Laser Energy ↔ e^- Temperature ↔ Charge state

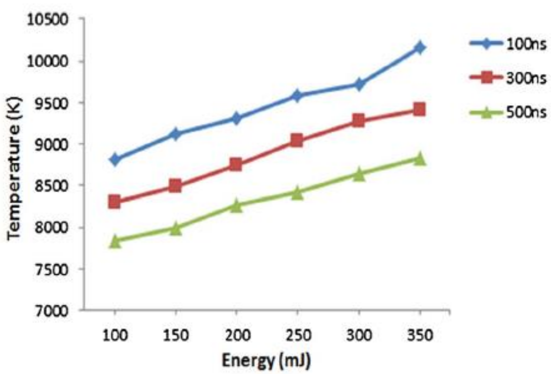


Fig. 8 Plot of the electron temperature against laser energy, at three different delay times, 100, 300 and 500 ns

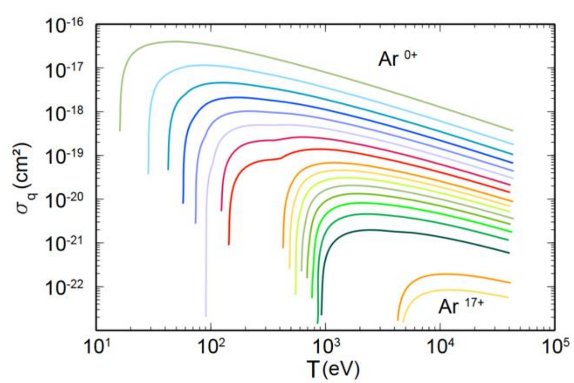


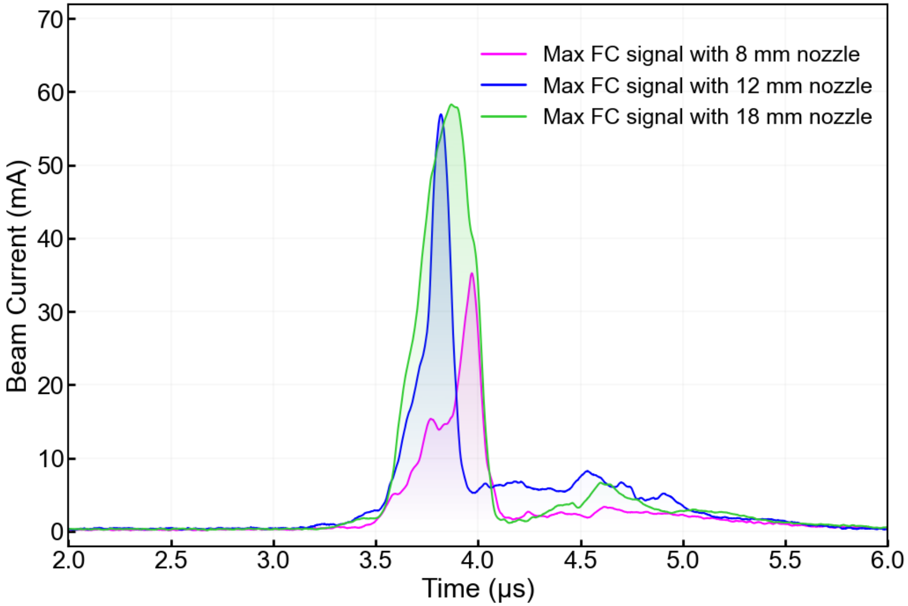
Figure 1.2.1. Electron-impact ionization cross-section of the argon atom and ions in dependence of electron energy T, (taken from [ZSCH2013]).

Asamoah, E., & Hongbing, Y. (2017). Influence of laser energy on the electron temperature of a laser-induced Mg plasma. *Applied Physics B*, *123*, 1-6.

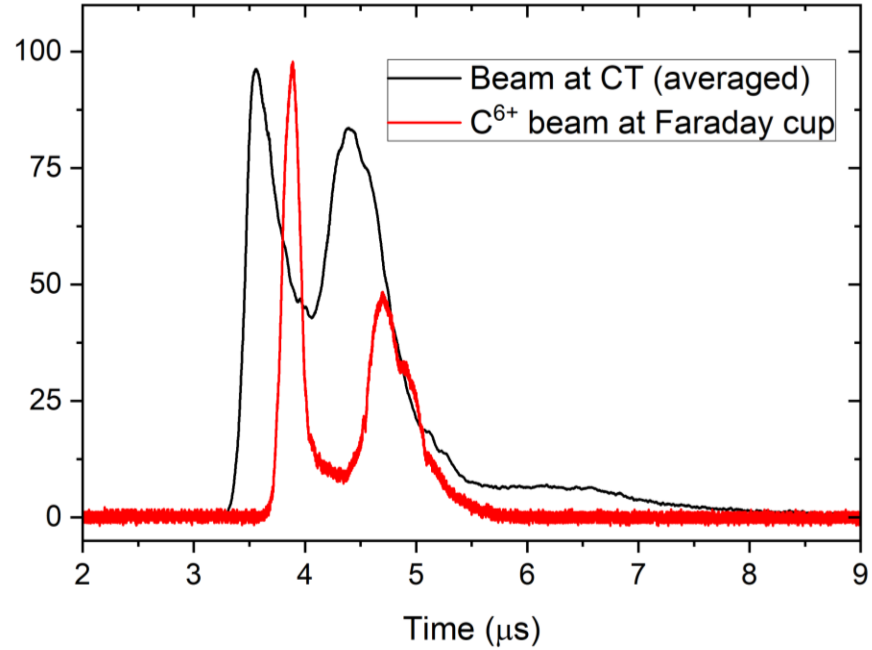
Lapierre, A., Benitez, J., Okamura, M., Todd, D., Xie, D., & Sun, Y. (2022). Ion Sources for Production of Highly Charged Ion Beams. *arXiv preprint arXiv:2205.12873*.

The promised outcome

Achieved a new record using an aluminum ion beam.



An ion current equivalent to that of the strongest class of proton ion beam



Accelerated and analyzed beam current profile: left 58 mA Al^{11+}beam corresponding to a total 1.0×10^{10} ions/pulse; right 96 mA C^{6+} beam corresponding to 4.0×10^{10} ions/pulse.

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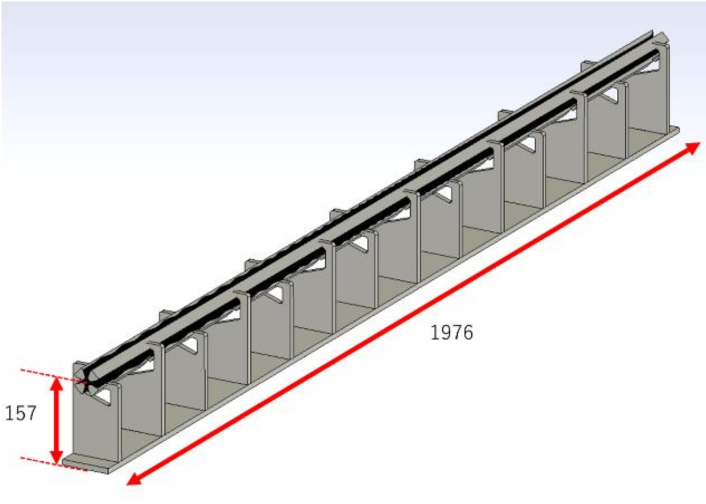
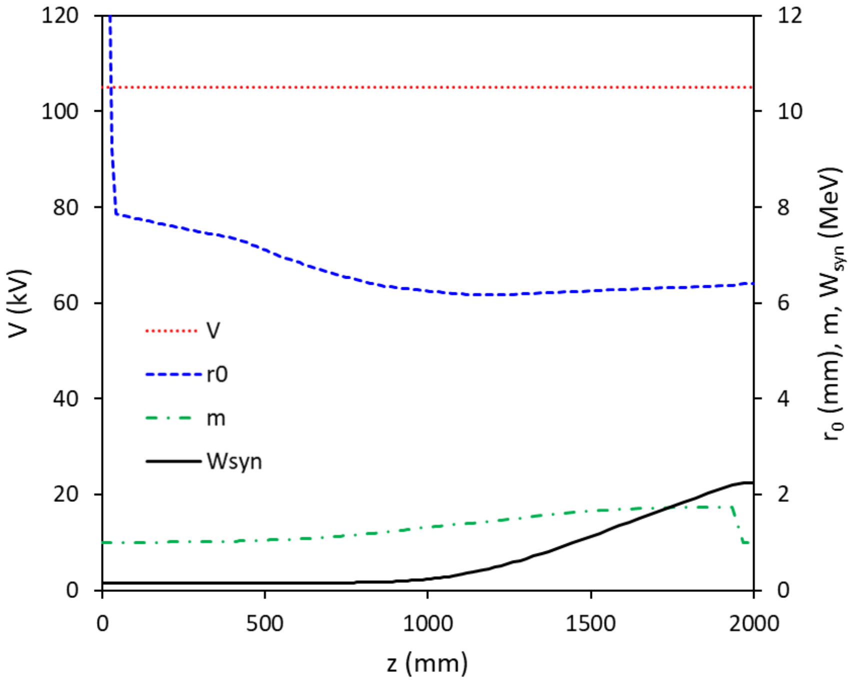
World's first variable B-structure 4 rod RFQ



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)



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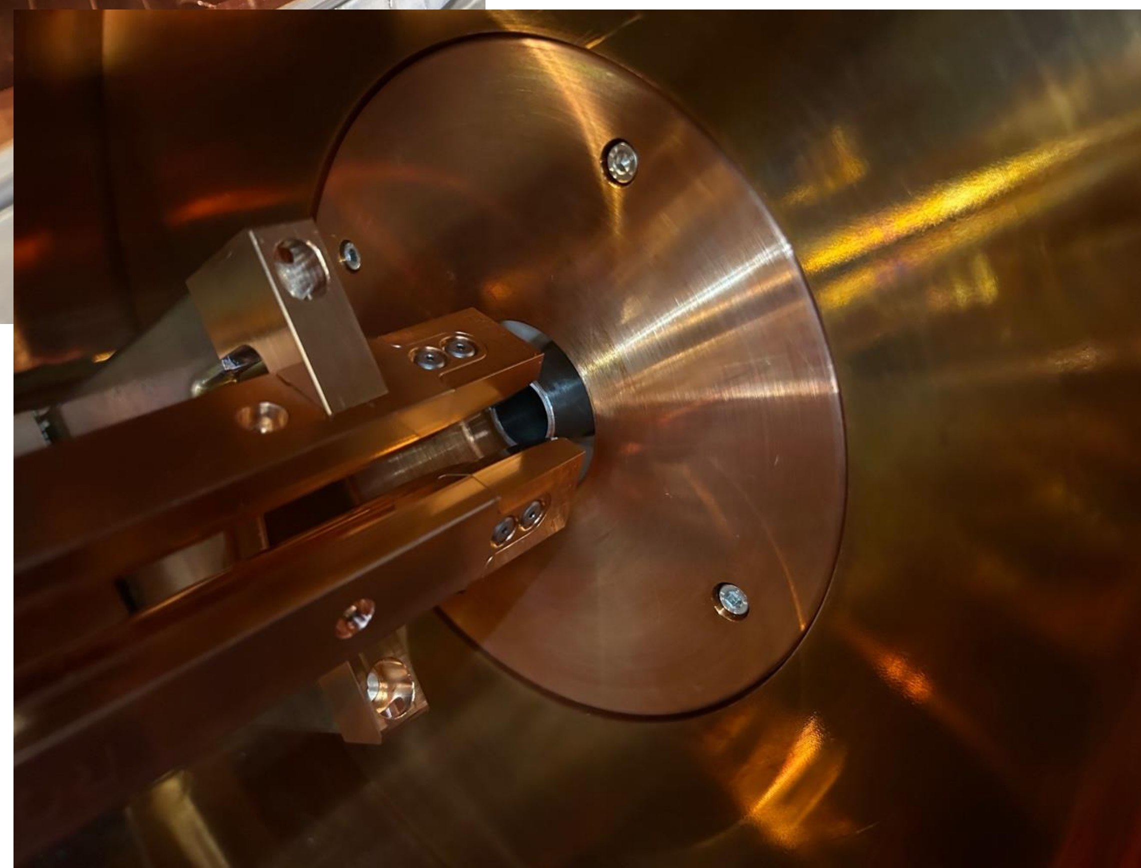
New Li vanes were commissioned and achieved full power within half a day.

250 kW



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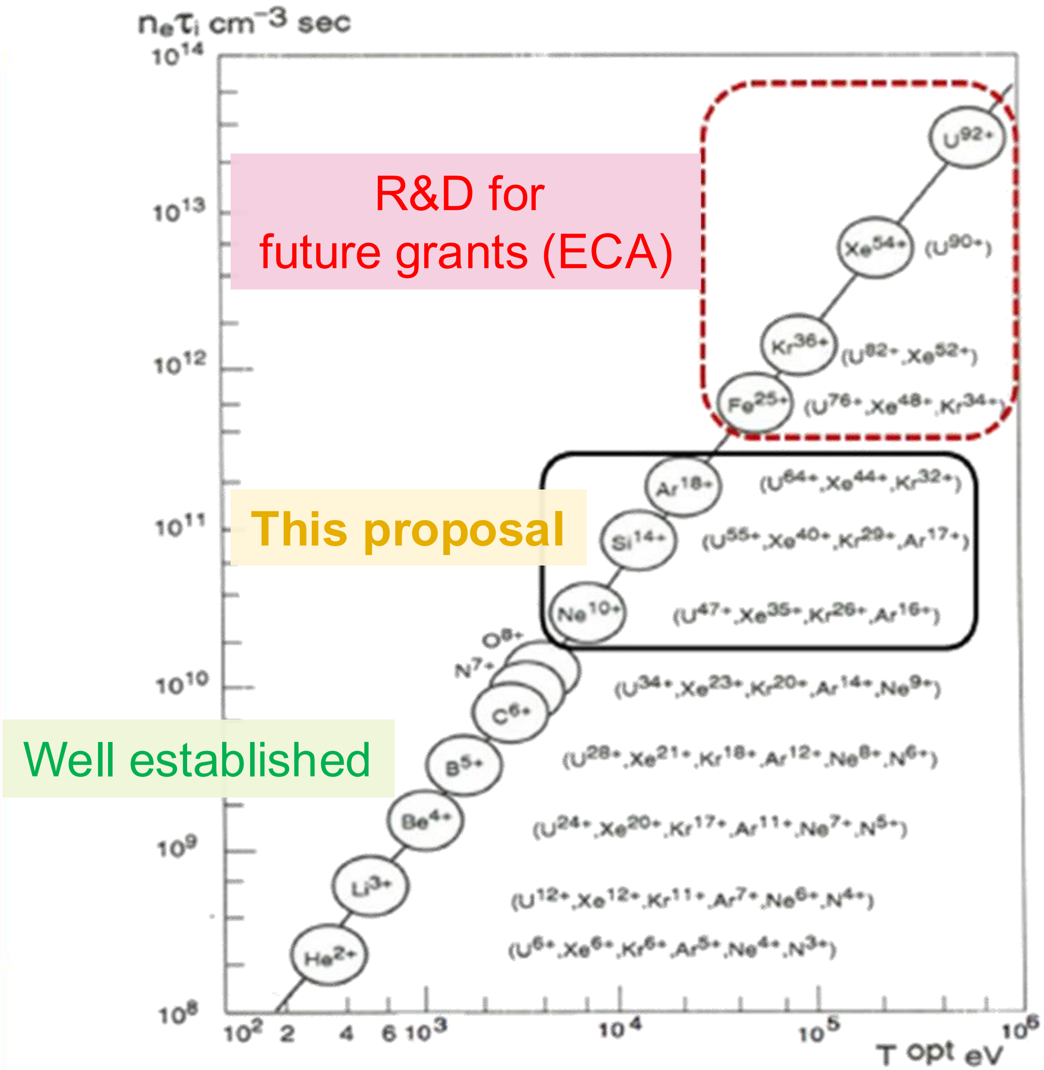
Road map to very heavy ion

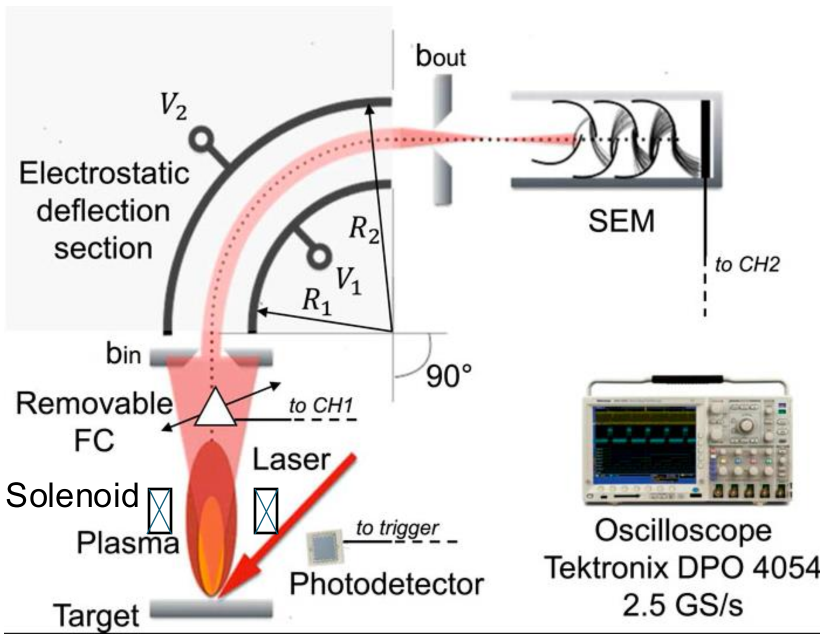


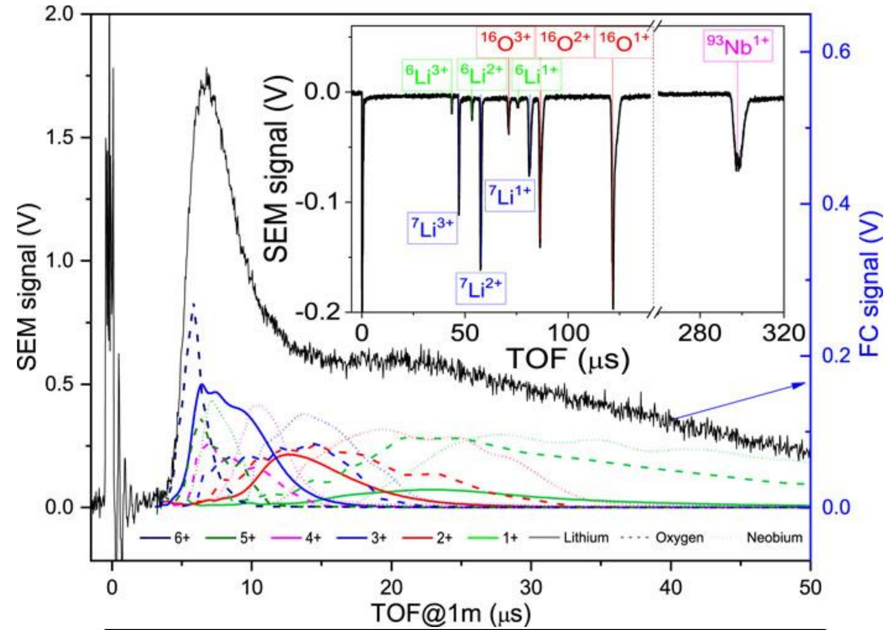
- Beneficial for the successful commissioning of the EIC
- Fundamental knowledge for the next generation of accelerator

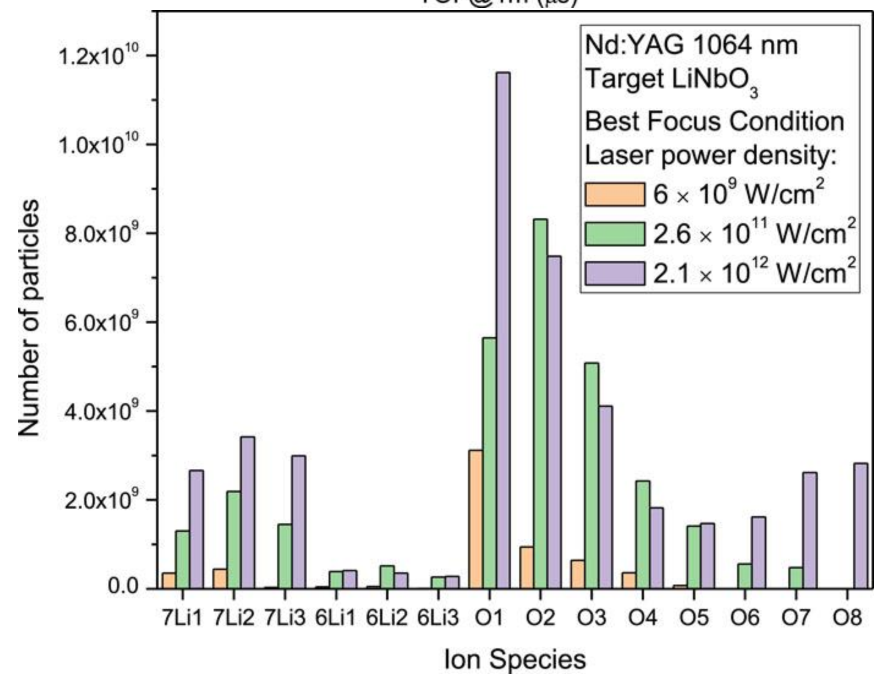
- BNL would take a significant step forward compared to the state-of-the-art, boosting its competitiveness and leadership

Lapierre, A., Benitez, J., Okamura, M., Todd, D., Xie, D., & Sun, Y. (2022). Ion Sources for Production of Highly Charged Ion Beams. *arXiv preprint arXiv:2205.12873*.

Method







Nd:YAG Laser Quantel
- Wavelength: 1064 nm
- Pulse energy: 850 mJ → 8 J
- Repetition rate: 5 Hz
- Pulse width: 6 ns (FWHM)
- Temporal pulse: Gaussian like

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Cannavò, A., et al. (2020), Optimization of laser-target parameters for the production of stable lithium beam. *Review of Scientific Instruments* 91.3

R&D menu

A. Plasma Study
A.1 Laser System Optimization
A.1.1 **Laser energy**
A.1.2 **Laser width**
A.1.3 **Laser incidence angle and double pulse mode**
A.2.1 Target surface quality control
A.2.2 **Advanced target development**

B. Design Testing and Commissioning of the RFQ for high current Nb16+ beams
B.1 Design of the new set of RFQ vanes
B.1.1 **Plasma-RFQ Interface Optimization**
B.1.2 **Variable-Aperture Vane Parameter Generation**
B.1.3 RF Resonator Design
B.2. Installation and testing
B.2.1 Reconfiguration of the RFQ beamline
B.2.2 Optimization of the Solenoidal magnetic field and extraction electrode
B.2.3 Optimization of the RF power
B.2.4 Optimization of the medium-energy-beam-transport line between the RFQ and the analyzing dipole magnet
B.2.5 Commissioning of the Ultra-Intense Nb16+ beam production test
B.2.6 **Long-term stability test**

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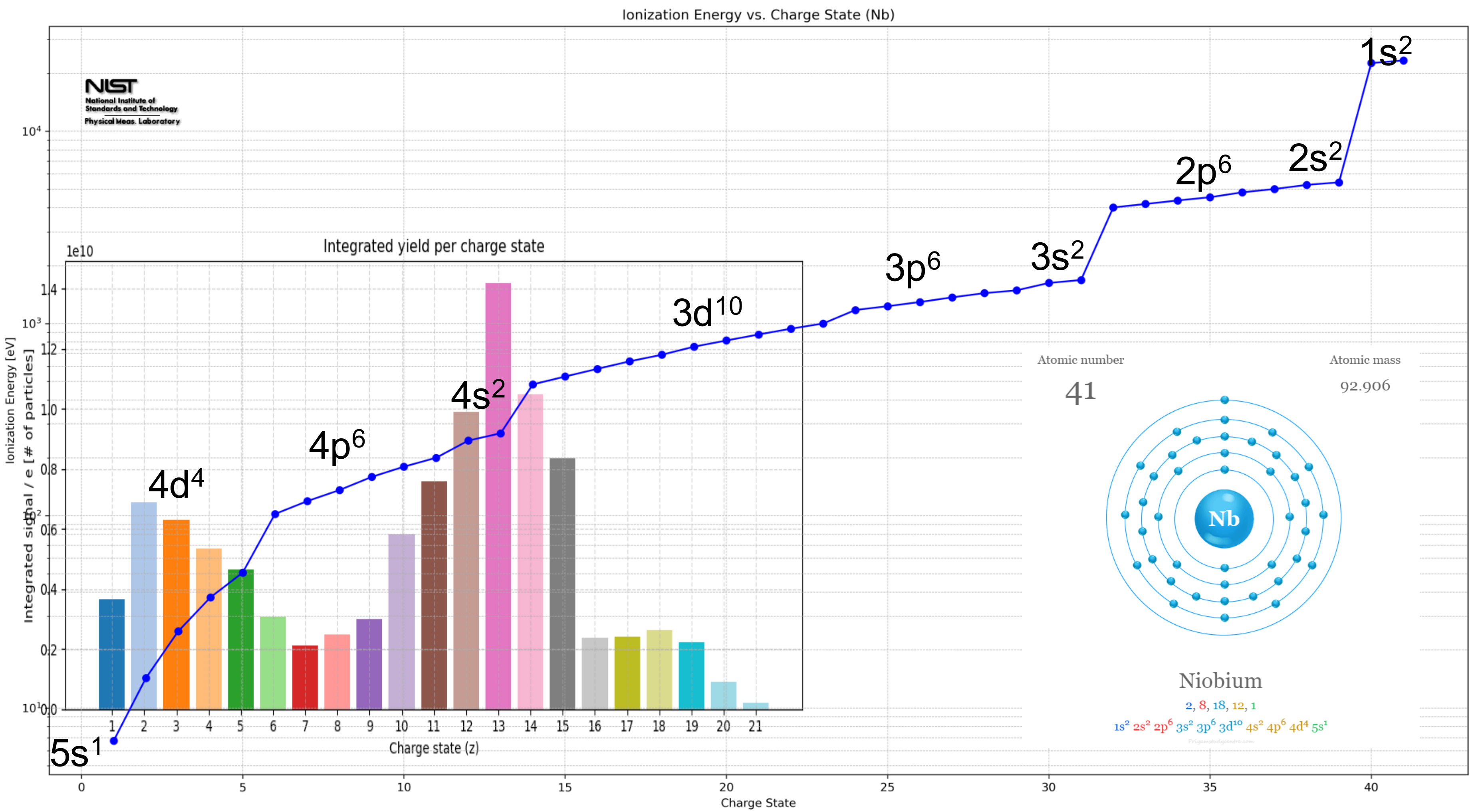

Laser Energy: 780 mJ

	Task/Activity	M1-3	M4-6	M7-9	M10-12	M13-15	M16-18	M19-21	M22-24
PHASE 1: PLASMA OPTIMIZATION									
A.1	Procure Laser Amplifiers	■							
A.1	Laser energy optimization	■							
A.1	Laser width optimization	■							
A.1	Laser incidence angle and double pulse mode		■						
A.2	Target surface quality control	■	■						
A.2	Advanced target development		■						
PHASE 2: RFQ DESIGN AND BEAM ACCELERATION DEVELOPMENT									
B.1	Plasma-RFQ interface optimization			■					
B.1	Variable-Aperture vane parameter generation			■					
B.1	Resonator Design			■					
B.1	Procure new RFQ vane				■				
B.2	Reconfiguration of the RFQ beamline					■			
B.2	Optimization of the Solenoid magnet & Extraction					■			
B.2	Optimization of the RF power					■			
B.2	Optimization of the MEBT						■		
B.2	Commissioning of the ultra-intense Nb beam							■	
B.2	Long-term stability test							■	■
Dissemination and reporting									
C	Conference Presentations		■					■	
C	Journal Publications			■		■			■

5.0×10^{10} Nb^{15+} ions/pulse

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Summary

Project's goal
- Achieving the highest intensity of highly charged Nb beam
- Overcome the EEBIS actual performance by a factor of 10
- Powerful tool, especially for EIC commissioning
- It will allow to get fundamental knowledge of laser-matter interaction and for the next generation of accelerator

Nb beam is just a pivot species:
- Technology and achievements can be exported to uncountable number of applications and therefore attract interest from different funds source (medical isotope production….)

Thank you for your attention.

We strongly hope that this proposal will be adopted.

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