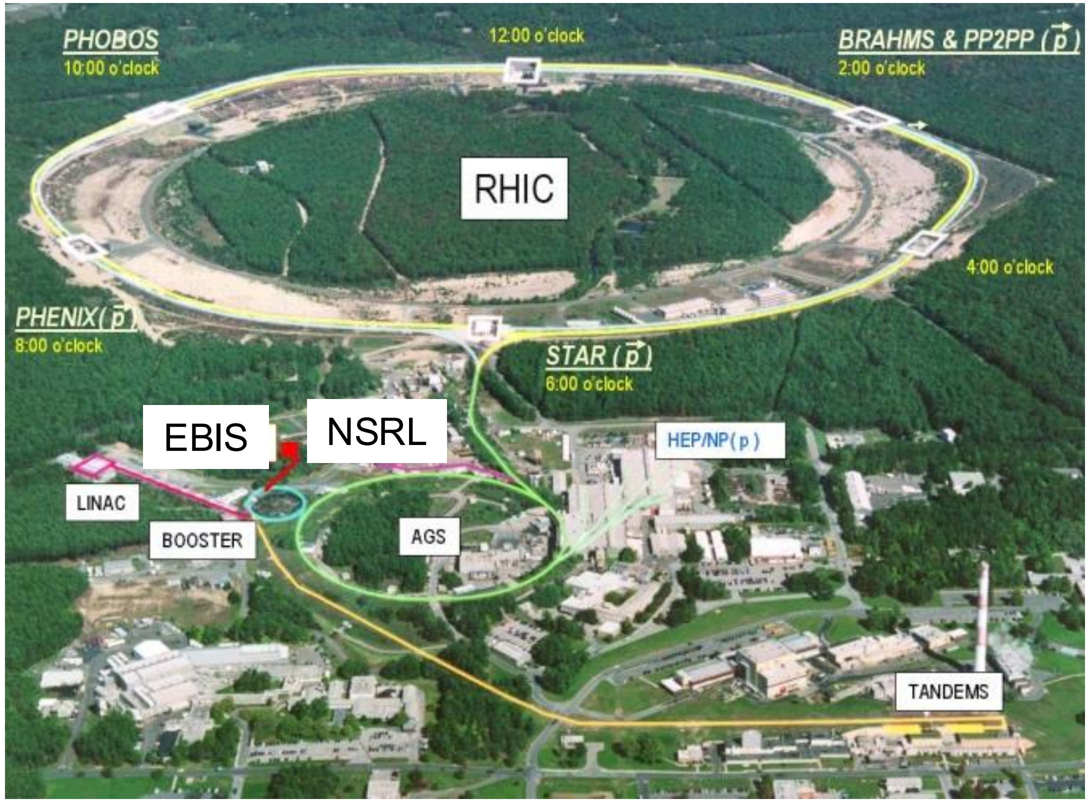
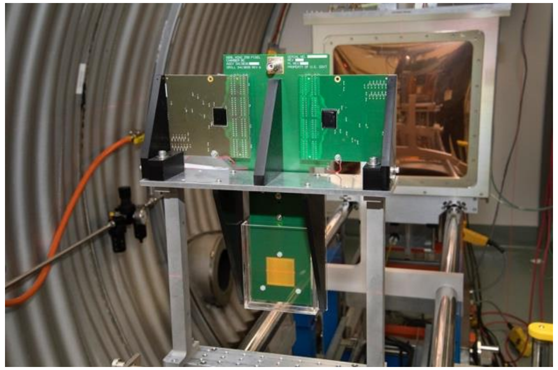
Production and acceleration of molecular ion beams (H_2^+, H_3^+) at EBIS (LDRD 25-043)

Shunsuke Ikeda

Multiple types of ions delivered to NASA Space Radiation Laboratory





Galactic cosmic rays

penetrating protons and heavy nuclei

large biological uncertainties limits ability to evaluate risks and effectiveness of mitigations

GCR simulator: 33 types of ions and energies irradiation using fast switch (p:70% -> He:15% -> heavier ions: remainder)

Solar Particle event

largely medium energy protons

shield's weight optimization

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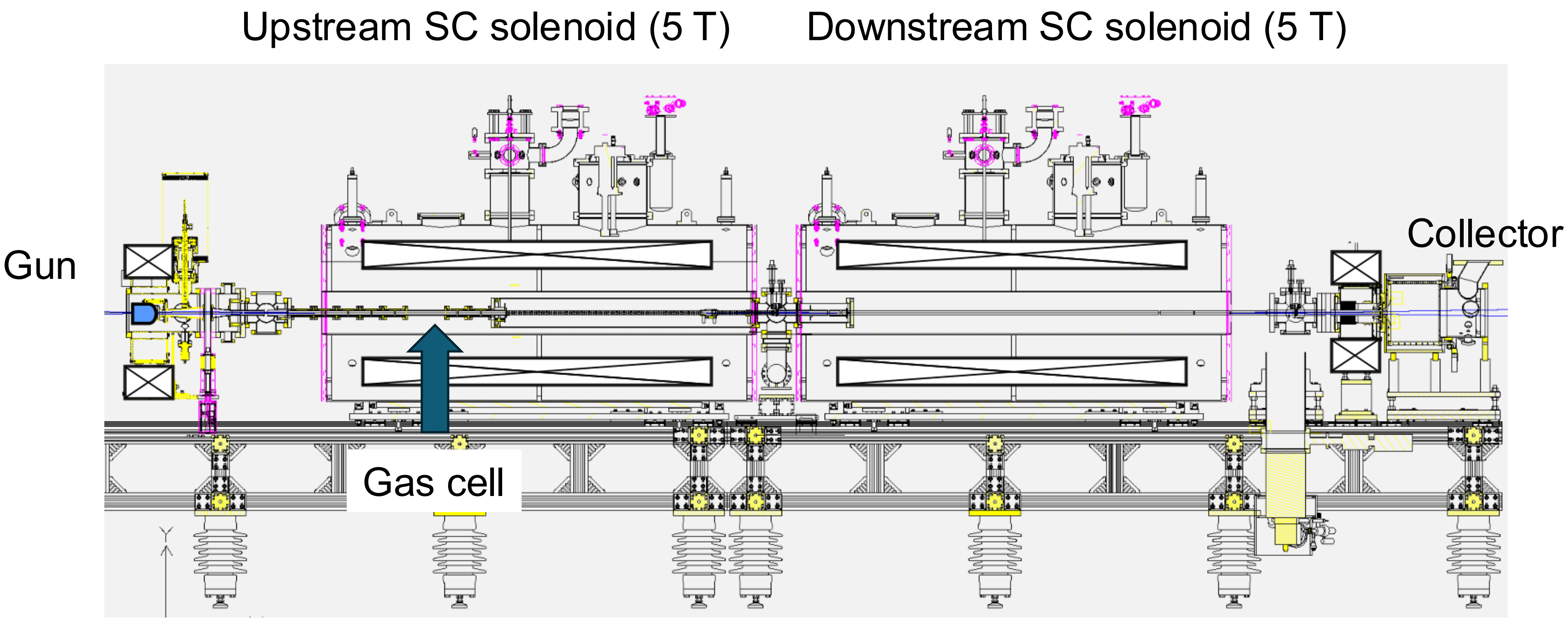
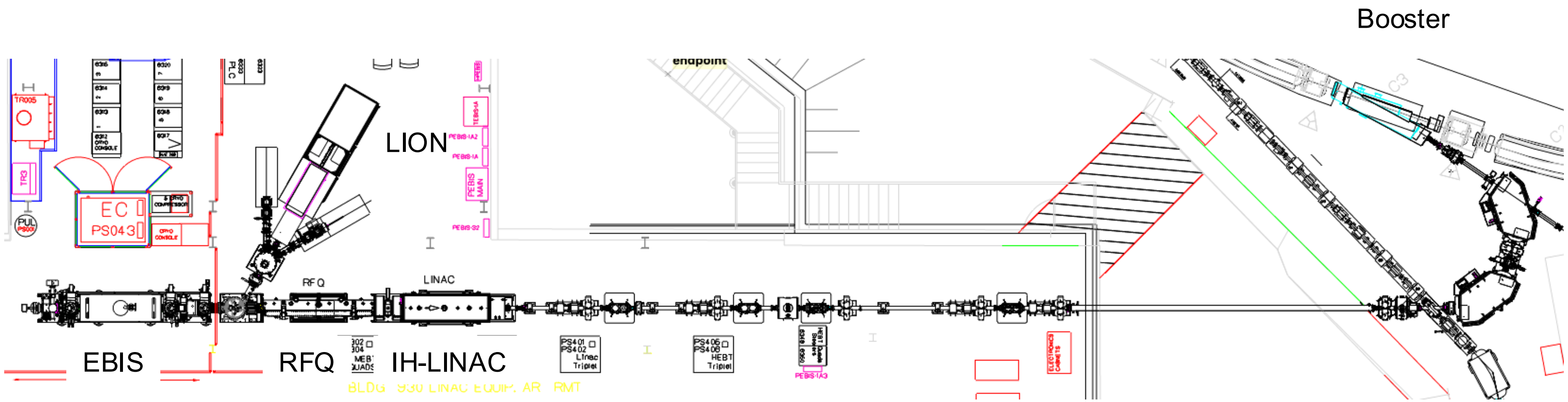
- Most ions but proton were provided by EBIS.
- Protons were delivered from 200 MeV LINAC or TANDEM.

Upgrade of EBIS for gas injection capability



- Extended EBIS has a gas cell with pulsed valve for efficient production of gas ions including protons.
- It will simplify the operation and time management with LINAC and Tandem.

Protons from EBIS could not be accelerated in the booster ring



- RFQ+IH LINAC accelerates ions to 2 MeV/n.
- $^{3}He^{2+}$ was used in operation successfully.
- However, protons from EBIS 2 MeV could not be accelerated.

0.02 T for $^{3}He^{2+}$ 2MeV/u (2014)

0.09 T for Au^{32+} 2MeV/u

I (Amp)	B (Tesla)	B / I
0	0.000775	–
50	0.012757	2.55136E−04
100	0.024791	2.47913E−04
200	0.048930	2.44652E−04
400	0.097380	2.43451E−04
600	0.145961	2.43268E−04
800	0.194595	2.43244E−04

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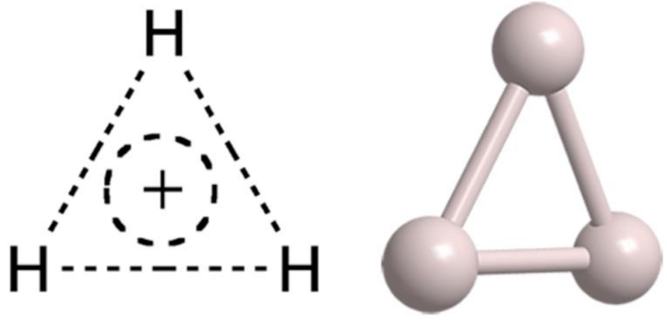
Hydrogen molecule ions were proposed

- H_2^+, H_3^+ are generated in laboratory plasma or space.
- Acceleration of ions with Q/A=1/2 and ~1/3 is always carried out.

$$e + H_2 \rightarrow H_2^+ + 2e$$

$$H^+ + H_2 \rightarrow H_2^+ + H$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$



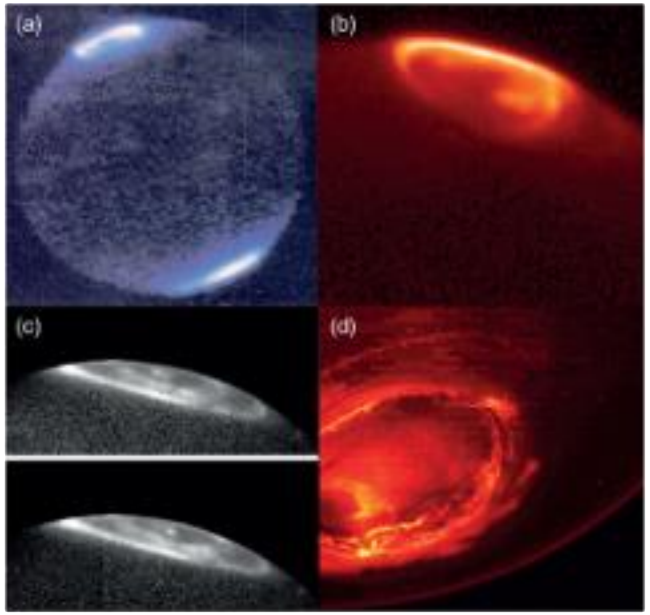
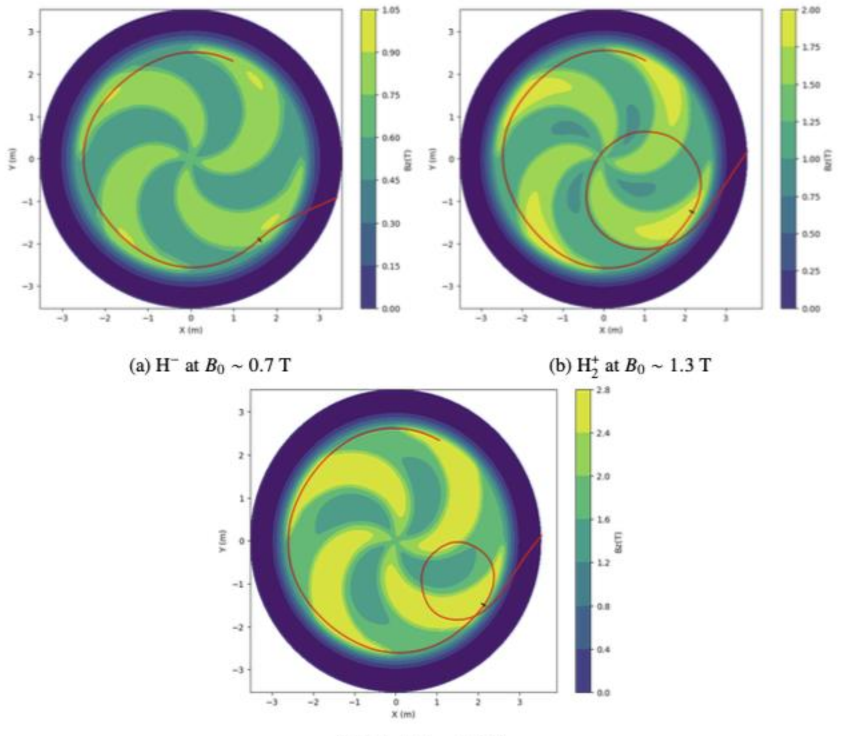


FIG. 4. Four images of Jupiter's H_3^+ aurora, showing the changes in resolution over the past 30 years. (a) One of the first

S. Miller et al, "Thirty years of H3+ astronomy" Rev. Mod. Phys. **92**, 035003

Concern about dissociation by strong Lorentz force in 1 GeV



(a) H^- at $B_0 \sim 0.7$ T (b) H_2^+ at $B_0 \sim 1.3$ T (c) H_3^+ at $B_0 \sim 1.9$ T

Figure 1. Sample trajectories to strip the three different types of H ions (red) in order to obtain 150 MeV/u H^+ beams. The stripper foil is indicated by the small black line. Note that B_0 is the average central magnetic field at the median plane of the cyclotron.

Journal of Instrumentation

PAPER

Lorentz dissociation of hydrogen ions in a cyclotron

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	H^-	H_2^+	H_3^+
Energy (MeV/u)		100	
Momentum, $\beta\gamma$		0.47	
Extraction radius, ρ (m)		1.5	
Ave. B field, B_0 (T)	1	2	3
Peak B field (T)	1.5	3	4.5
Max. Lorentz dissociation (%)	0.4	0.4	< 0.01
Energy (MeV/u)		500	
Momentum, $\beta\gamma$		1.2	
Extraction radius, ρ (m)		3.64	
Ave. B field, B_0 (T)	1	2	3
Peak B field (T)	1.5	3	4.5
Max. Lorentz dissociation (%)	100	1	0.01
Energy (MeV/u)		1000	
Momentum, $\beta\gamma$		1.8	
Extraction radius, ρ (m)		5.65	
Ave. B field, B_0 (T)	1	2	3
Peak B field (T)	1.5	3	4.5
Max. Lorentz dissociation (%)	100	1.5	0.1

- Strong electric field in rest frame lowers dissociation barriers.
- Theory predicts almost no dissociation for H_2^+ and H_3^+.
- Experimental verification is needed.
- EBIS and Booster are an ideal test bench.

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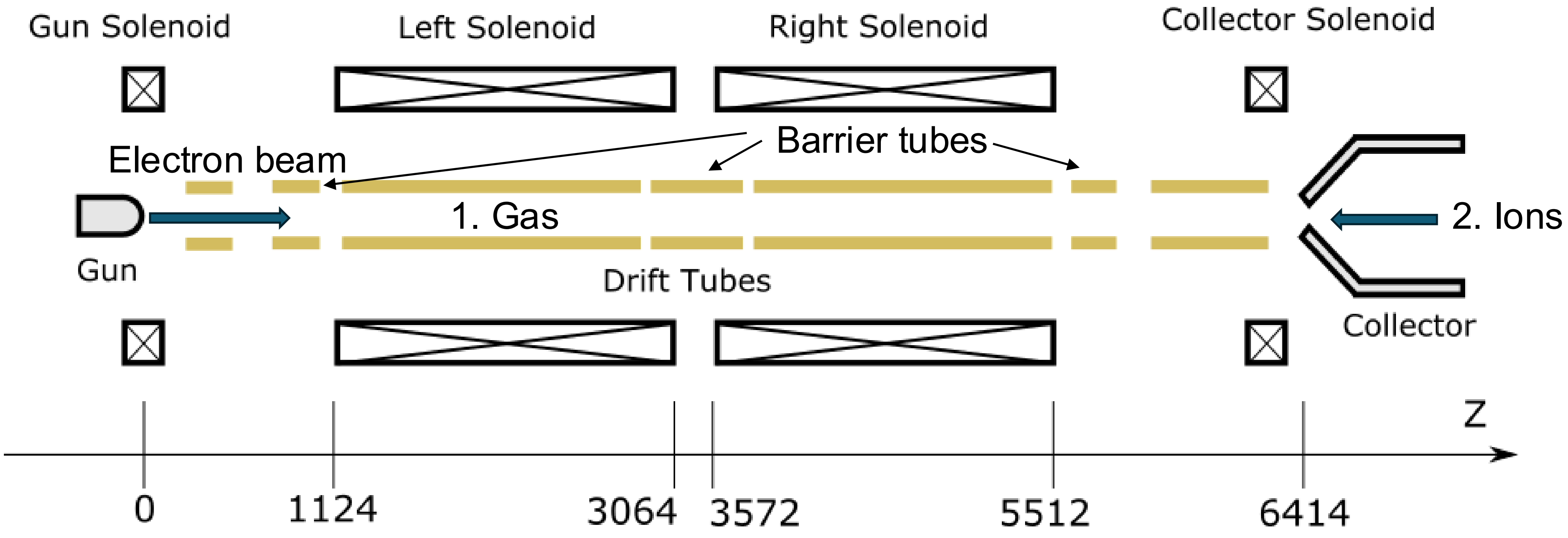
EBIS and ECR ion sources

- Production and acceleration of the molecule ions from EBIS were tried.
- An ECR ion source is under development for larger number of molecule ions especially for H_3^+.

Electron Beam Ion Source (EBIS)



- 5 A electron beam is compressed by magnetic field to 1.6 mm (up to 500 A/cm2)
- (1) Internal gases are ionized by the electron beam or (2) ions are injected from the outside.
- Ions are confined to a desired period:
  - Longitudinal: barrier drift potentials
  - Radial: electron beam
- Highly charged ions can be produced (Au32+, Au43+, Fe20+,,,)

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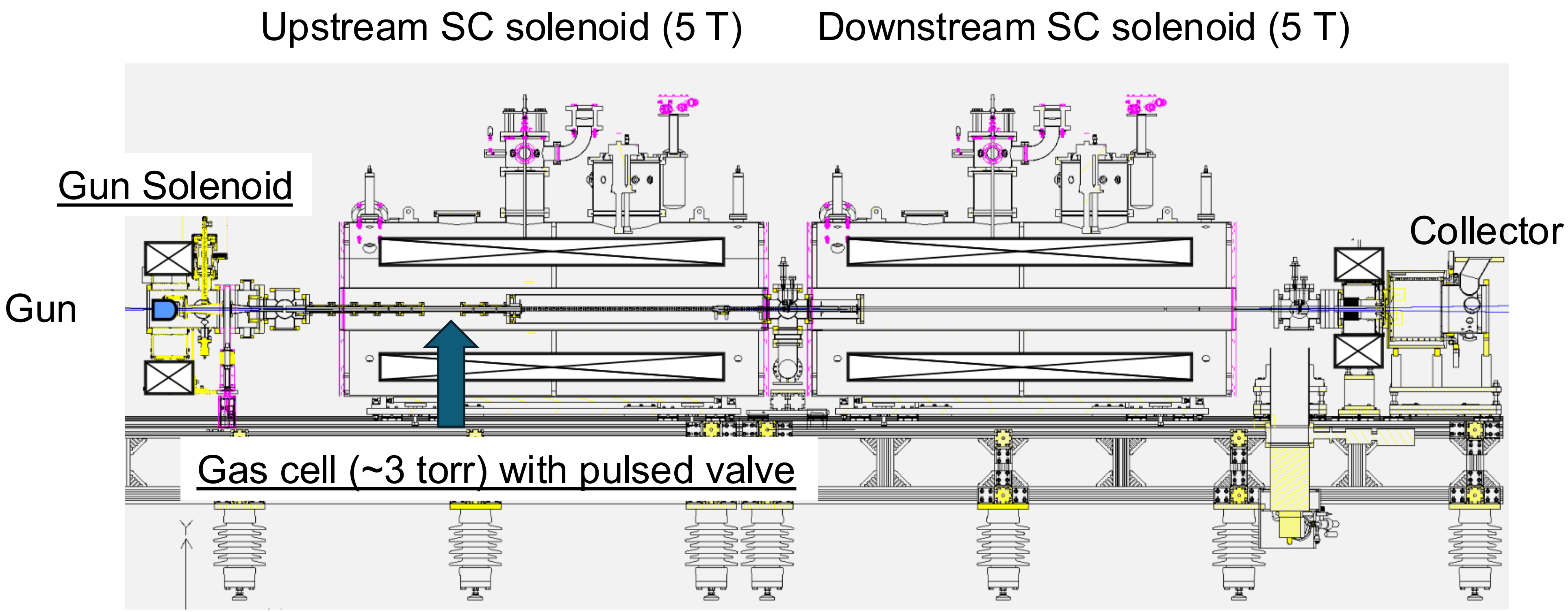
EBIS optimization process



- EBIS is designed to generate highly charged ions with 10 keV class electrons.
- However, it was also said molecule ions were observed under certain situation.
- At first with the condition for proton production, only small number of H_2^+ were observed.
- By increasing amount of gas injection and tuning Gun solenoid, the number was increased by a factor of 10 or more.

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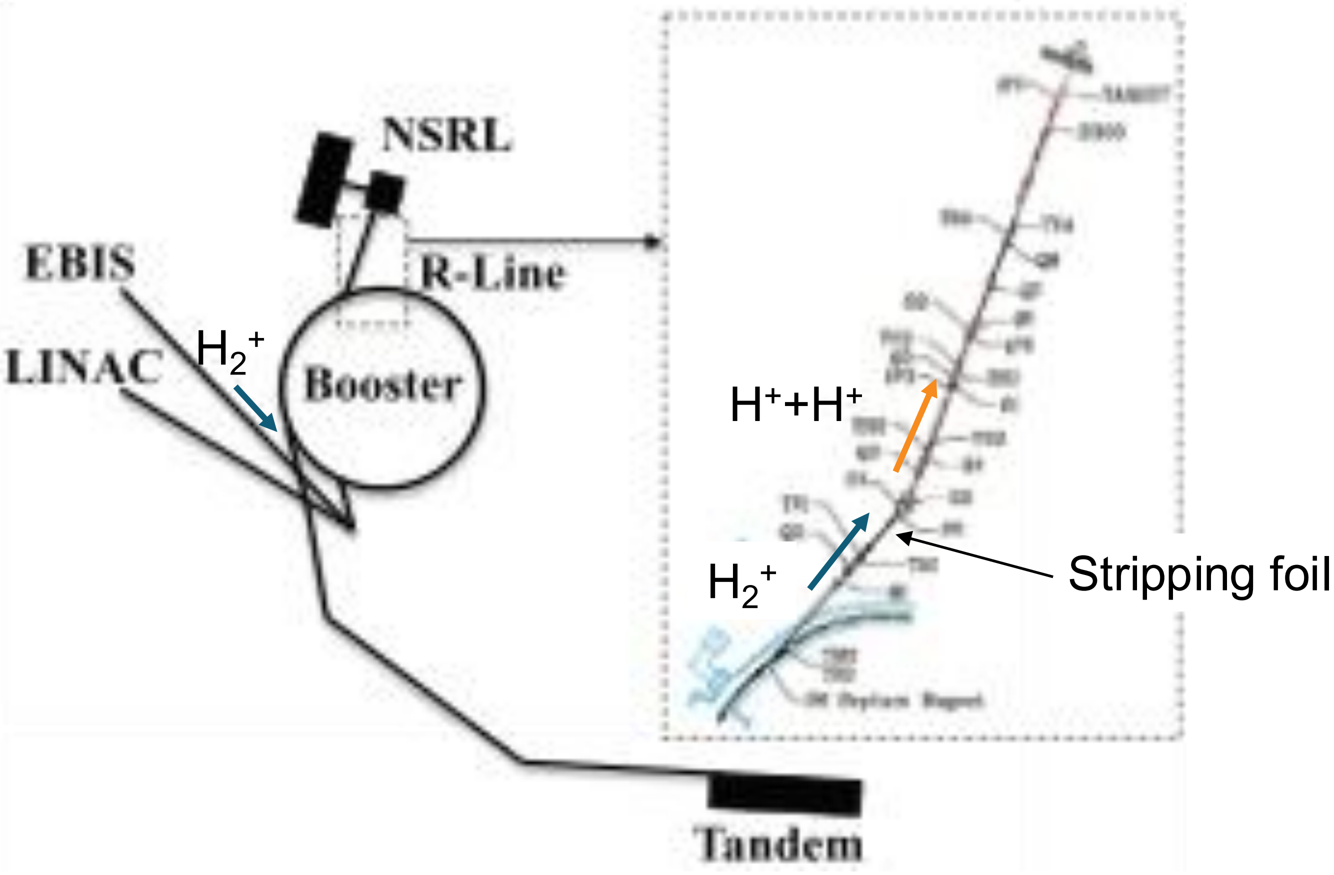
Acceleration test



Booster input (H_2^+)	NSRL (proton)
1.1×10^{10}	1.2×10^{10}

cf) LINAC~10^{11}, Tandem~10^{10}

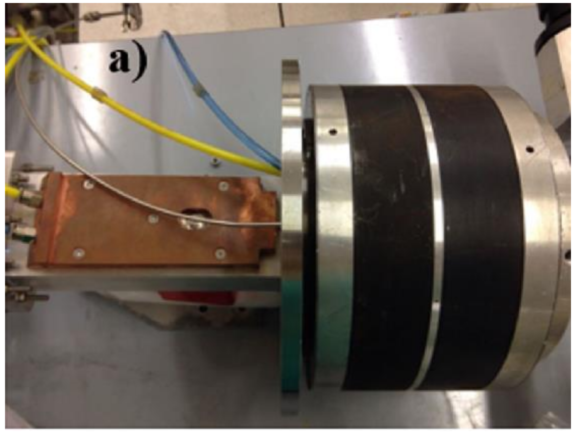
- Acceleration of H_2^+ to 1 GeV/n was succeeded.

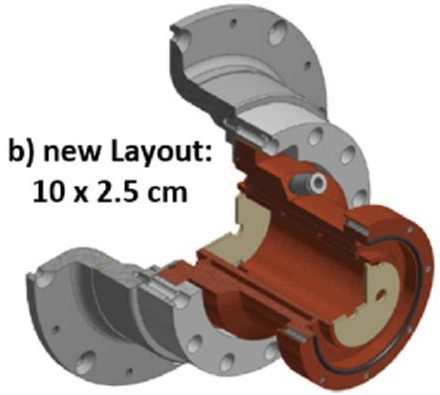
EBIS development result and future

- Now it is used for daily operation heavily.
- This is the first demonstration of acceleration and operational use in high energy accelerator.
- Further improvement may be possible.
  - optimistically 3x enhancement is expected while drawbacks needs to evaluated.
- H_3^+ production needs to be investigated more.
- Other types of molecule ions also may be possible. This may open new applications.

ECR ion source for molecule ions

VIS at INFN, Italy

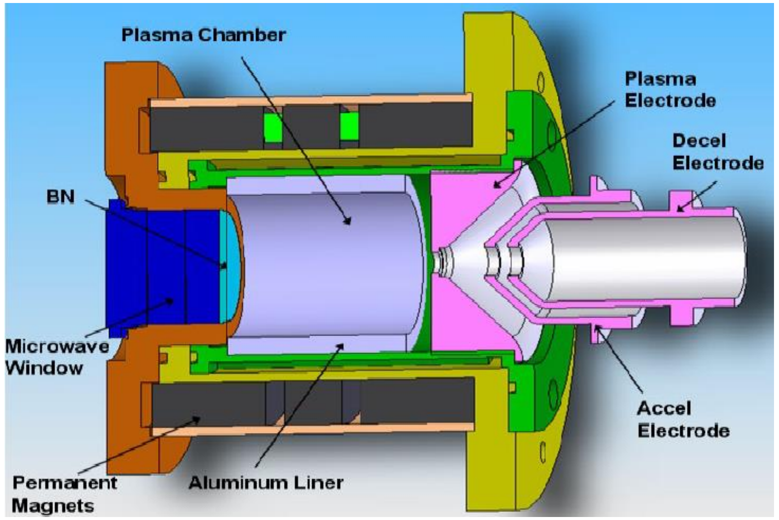




10 mA, 8 mm aperture, 2.45 GHz, 500W, 1x10^{-5} torr

"G. Castro et al, "AnewH+2 source:Conceptual study and experimental test of an upgraded version of the VIS - Versatile Ion Source," PRSTAB, 2015."

PMECR II at PKU, China



10 cm x 10 cm vacuum pipe

40 mA, 5 mm aperture, 2.45 GHz, 1.1 kW, 3x10^{-6} torr (20 mA H_3^+)

- 10 mA x 40 us = 2.5x10^{12} ions (40 us is typical for Au beam from EBIS)
- Small emittance
- Independent on EIC operation.

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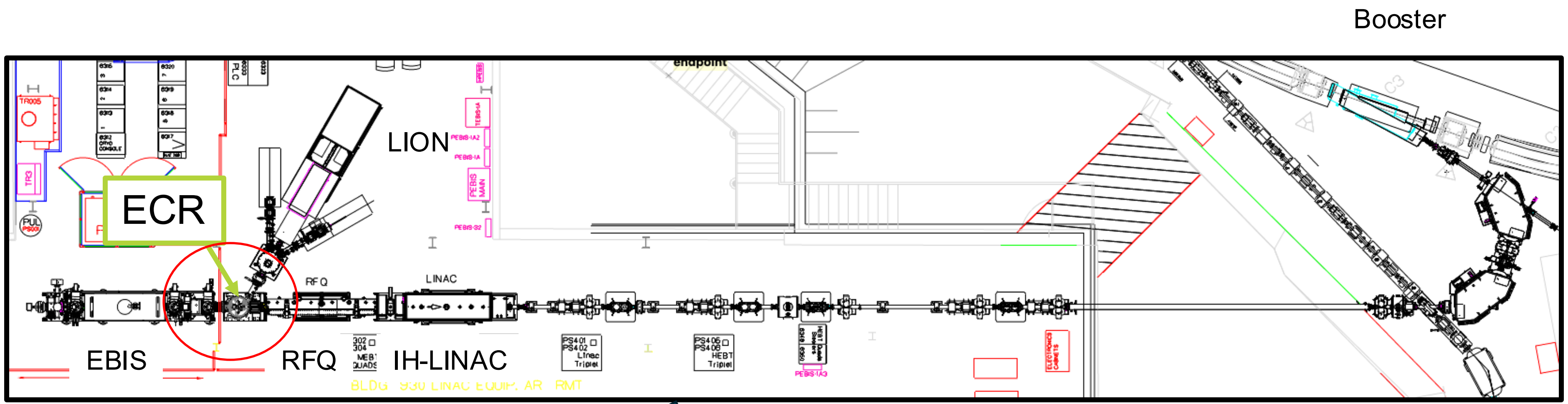
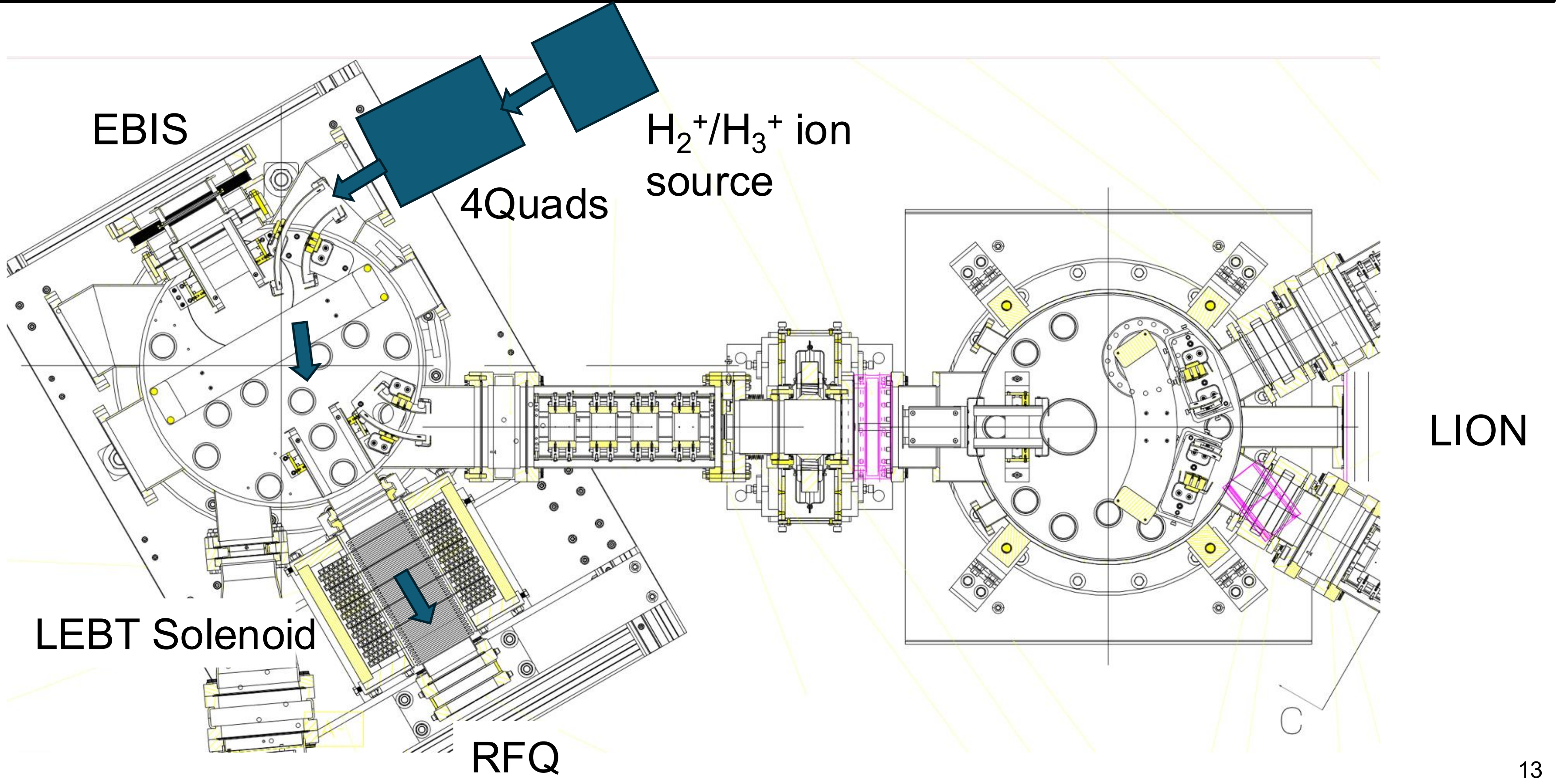
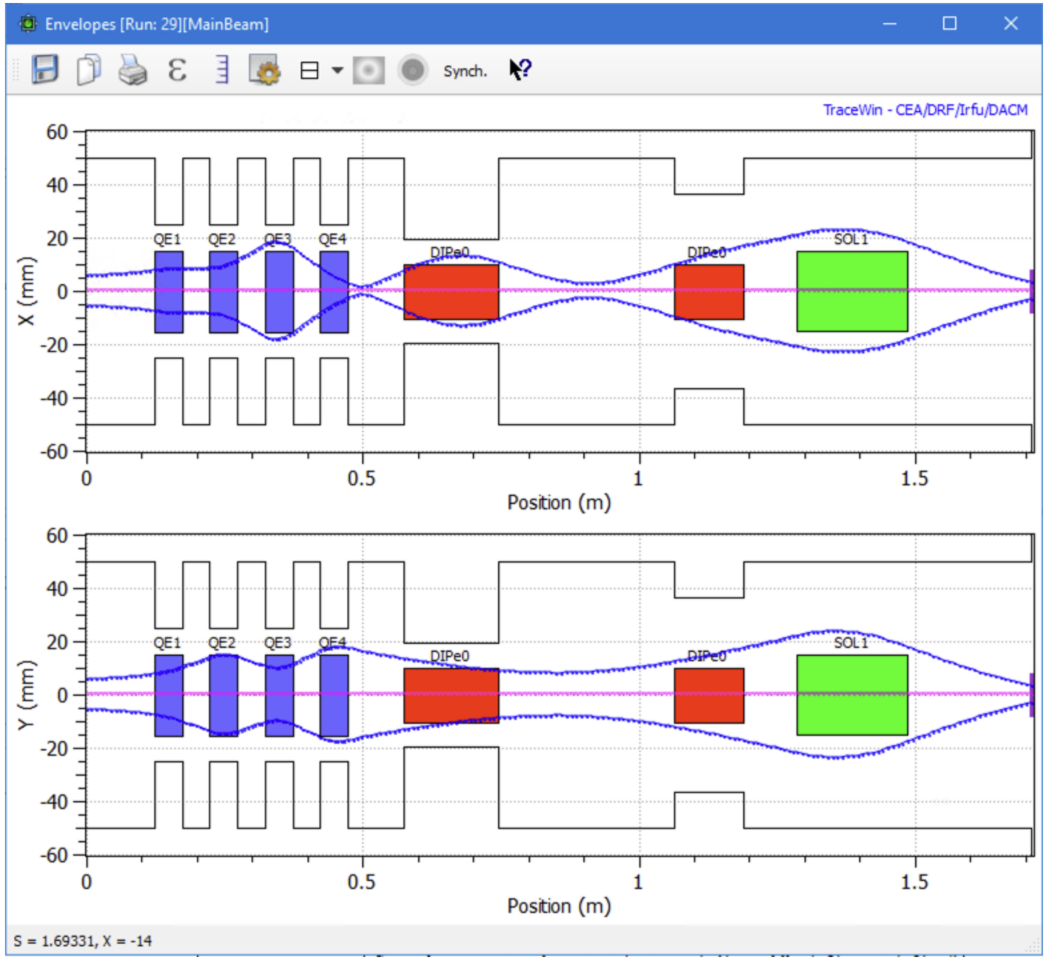
Possible location



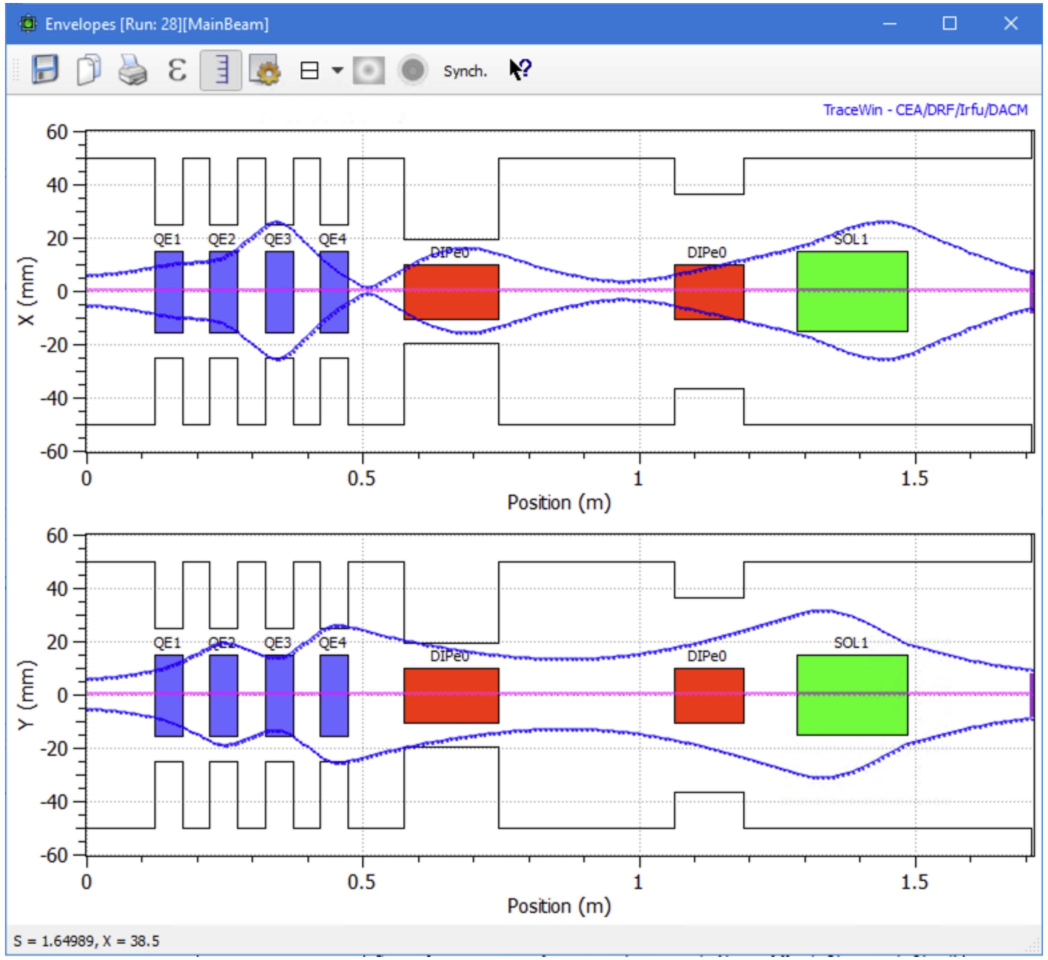


Envelope calculation shows H_3^+ up to 20 mA can be transported to RFQ

H3+, 10 mA



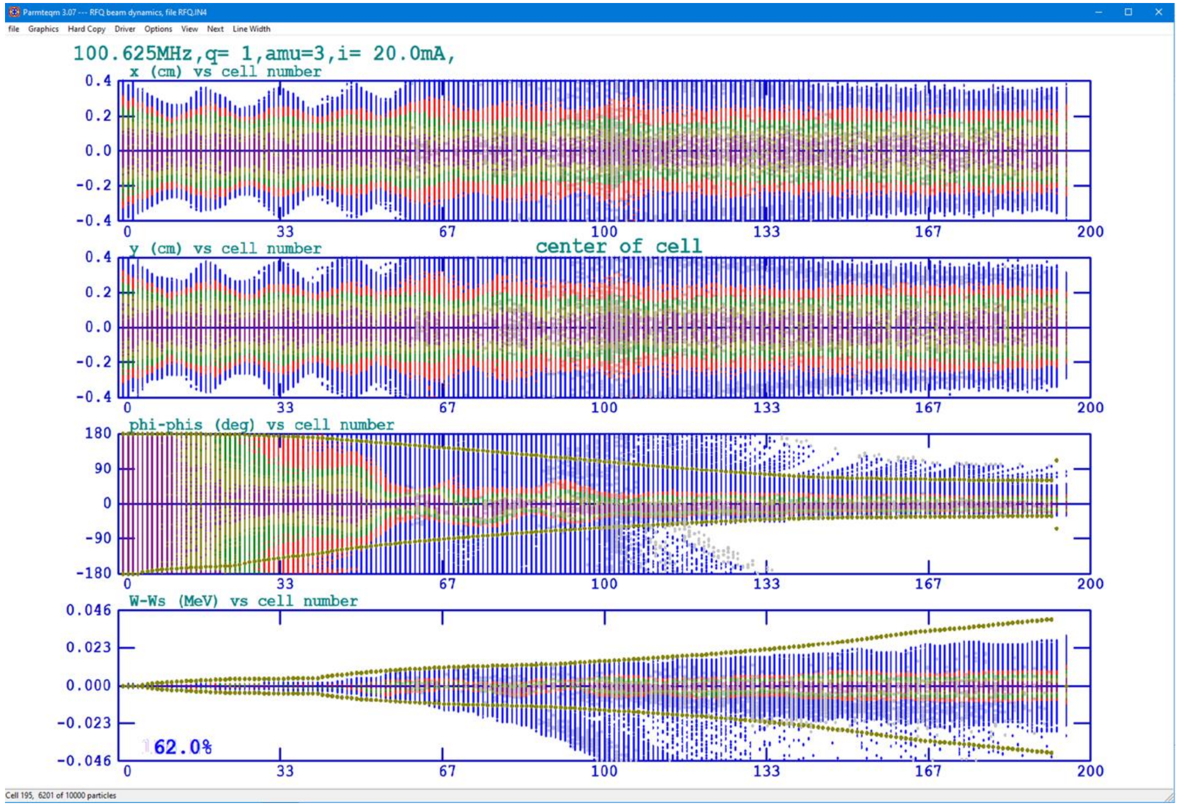
H3+, 20 mA

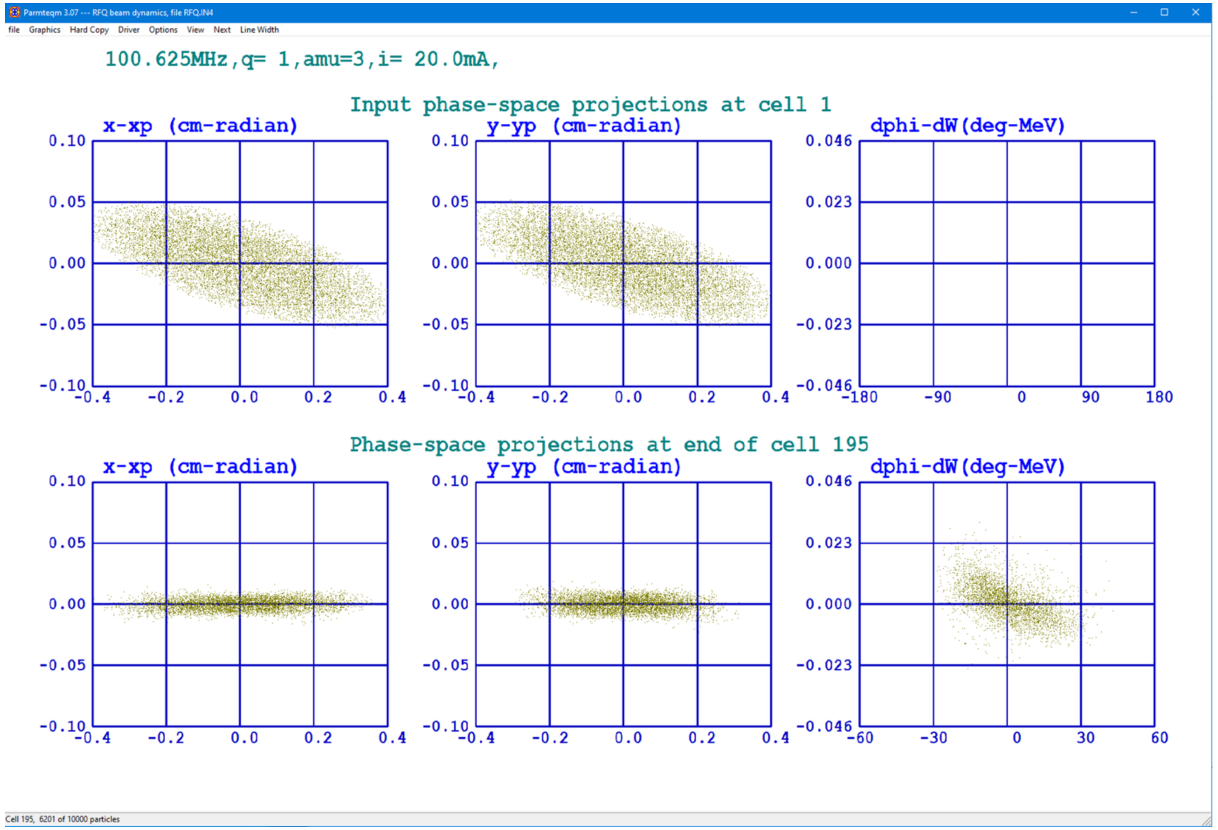


Source 4Quads Bend1 Bend2 Solenoid

Up to 20 kV 0.63 T

H_3^+ up to 12 mA can be accelerated by RFQ





20 mA input, 12 mA output

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RFQ end to Booster

- 2.5×10^{11} (1mA – 40 us) should be delivered based on EBIS to Booster line design,
- Q/A: $H_3^+ \sim Fe^{20+}$
    - It is expected to be not too difficult to find operation condition for H_3^+.

ELECTRON BEAM ION SOURCE PRE-INJECTOR PROJECT (EBIS)

CONCEPTUAL DESIGN REPORT

J. Alessi, Editor

D. Barton, E. Beebe, D. Gassner, R. Grandinetti, H. Hseuh, A. Javidfar, A. Kponou, R. Lambiase, E. Lessard, R. Lockey, V. LoDestro, M. Mapes, K. Mirabella, T. Nehring, B. Oerter, A. Pendzick, A. Pikin, D. Raparia, J. Ritter, T. Roser, T. Russo, L. Snydstrup, M. Wilinski, A. Zaltsman, S. Zhang

September 2005

The expected parameters of the EBIS beam at Booster injection are presented in Table 5-12.

Table 5-12 Expected beam parameters at Booster injection

Au^{32+}		Au^{32+}	D^+	Unit
Particles per pulse	N	3	250	10^9
Kinetic energy	E_k	2	2	MeV/u
	β	0.0652	0.0652	
	γ	1.002	1.002	
Pulse width	d	10 – 40	10 - 40	μs
Energy spread	ΔE	±2	±3	keV/u
Momentum spread	$\Delta p/p$	±0.05	±0.075	%
Norm. 90% emittance	$\varepsilon_{N,90}$	0.7	0.7	πmm mrad

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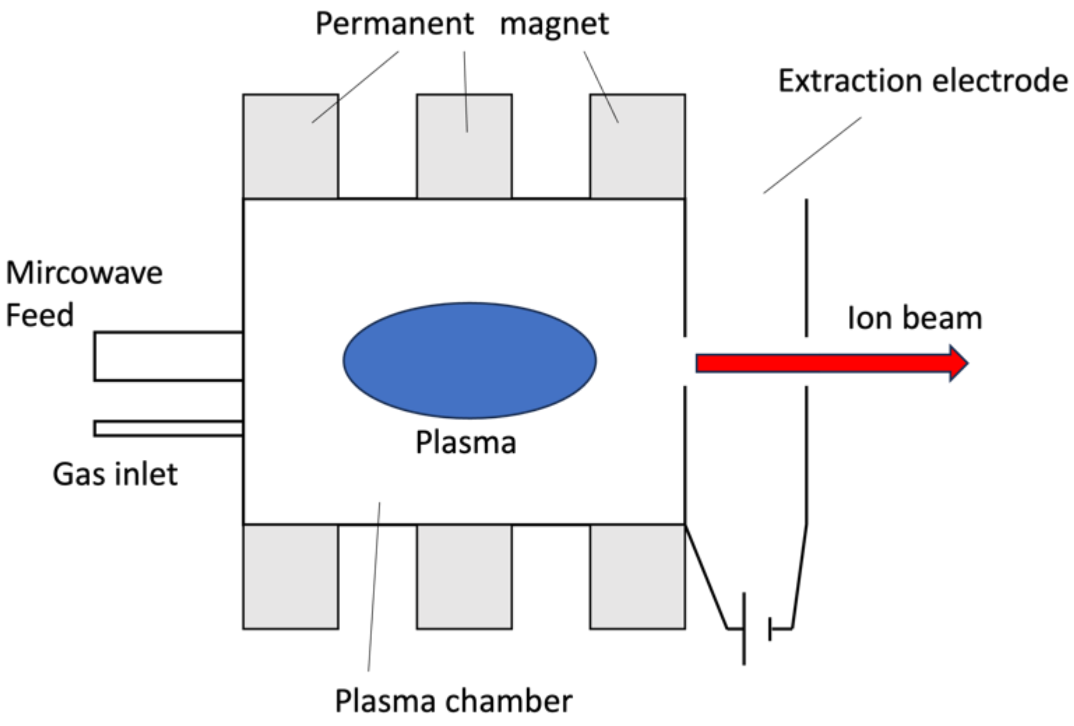
R&D for ion source

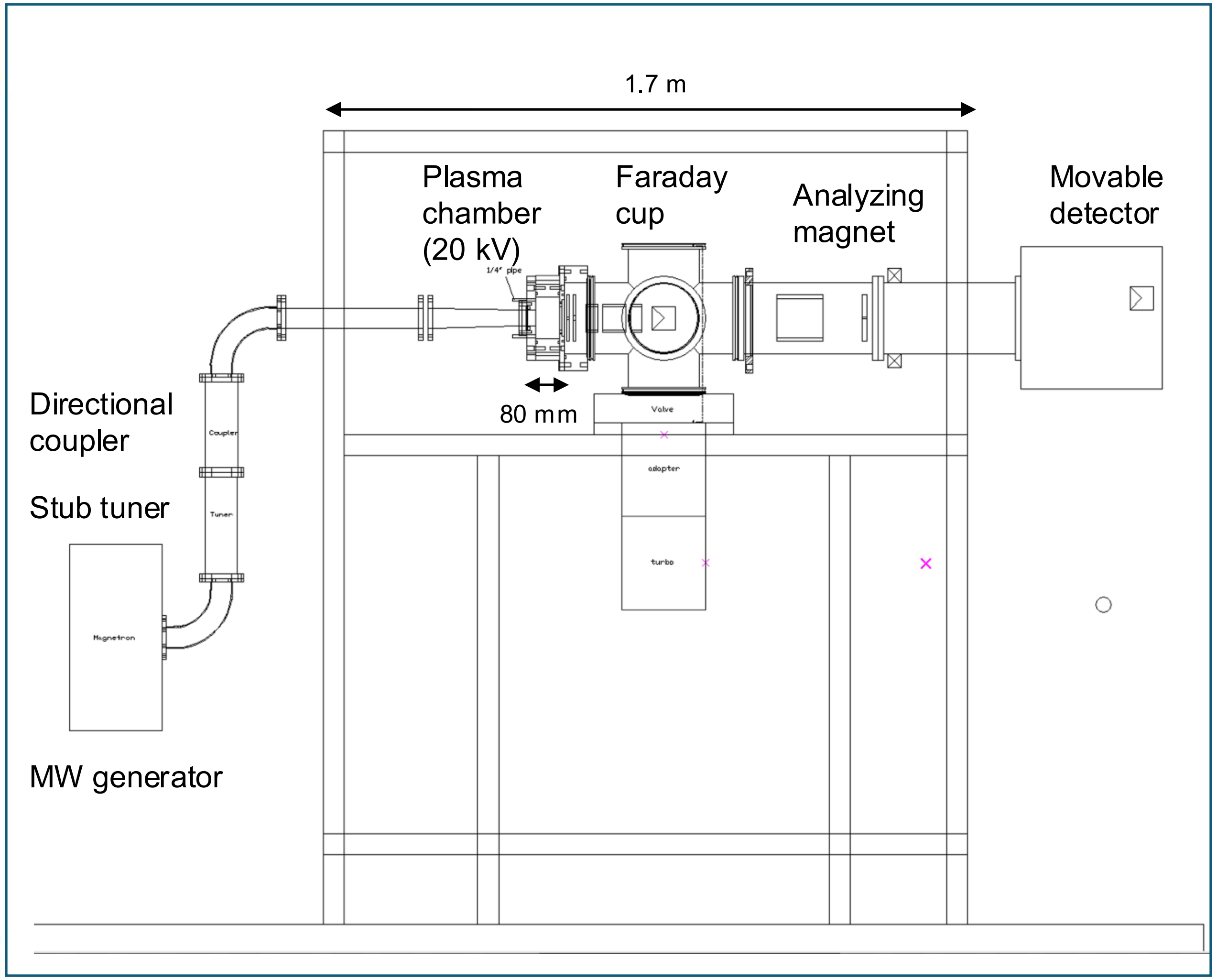
Working condition is different from typical proton sources

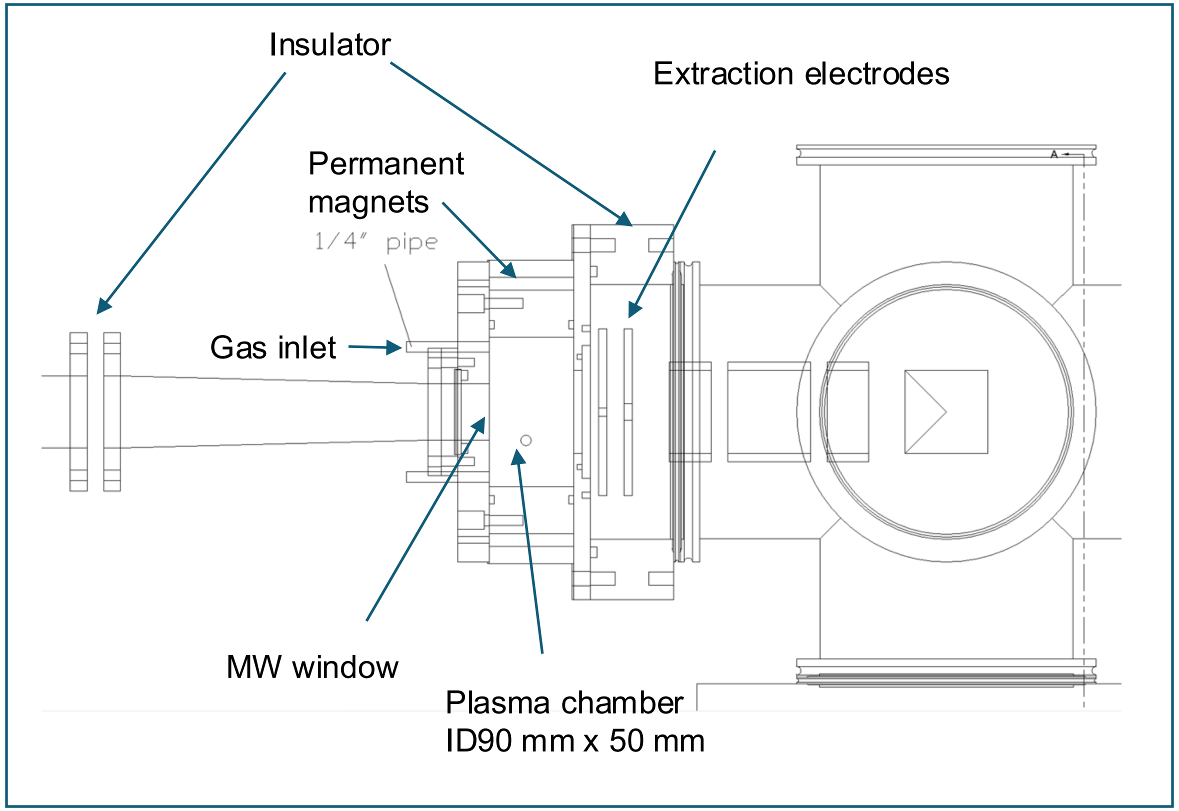
- Establish low temperature plasma:
    - Lower RF power
    - Larger amount of gas
    - Magnetic configuration
- Make it compact:
    - Limited space
    - Chamber volume vs ionization rate (RF power and gas density)
- Pulse Operation (~40 us beam, low gas load to EBIS and accelerator):
    - Pulsed valve
    - Short MW pulse
    - Chopper



ECR condition: 2.45 GHz – 875 Gauss

Test stand for development





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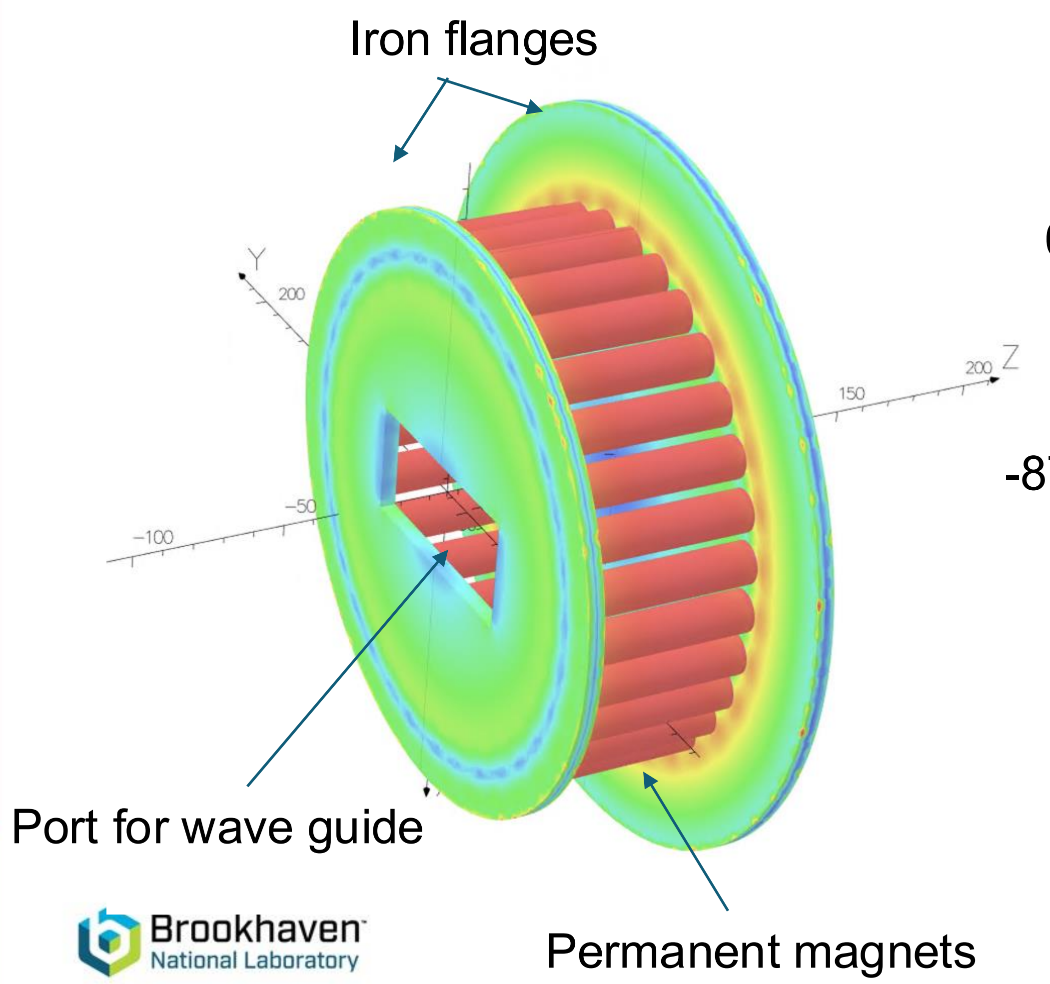
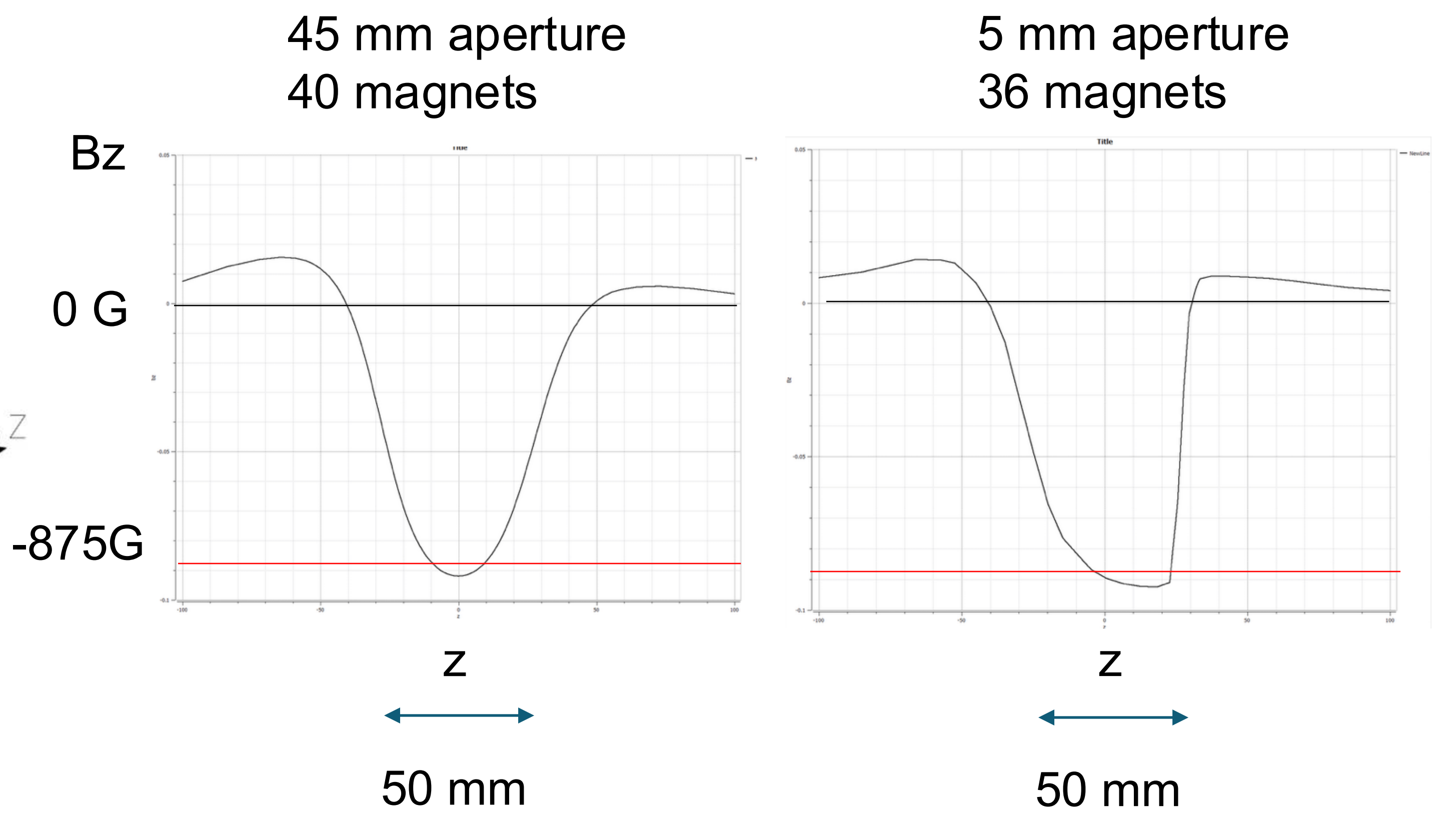
Magnet design





- Permanent magnet (N42) is used for compactness.
- Field configuration can be adjusted by the number of the magnets and the aperture size.

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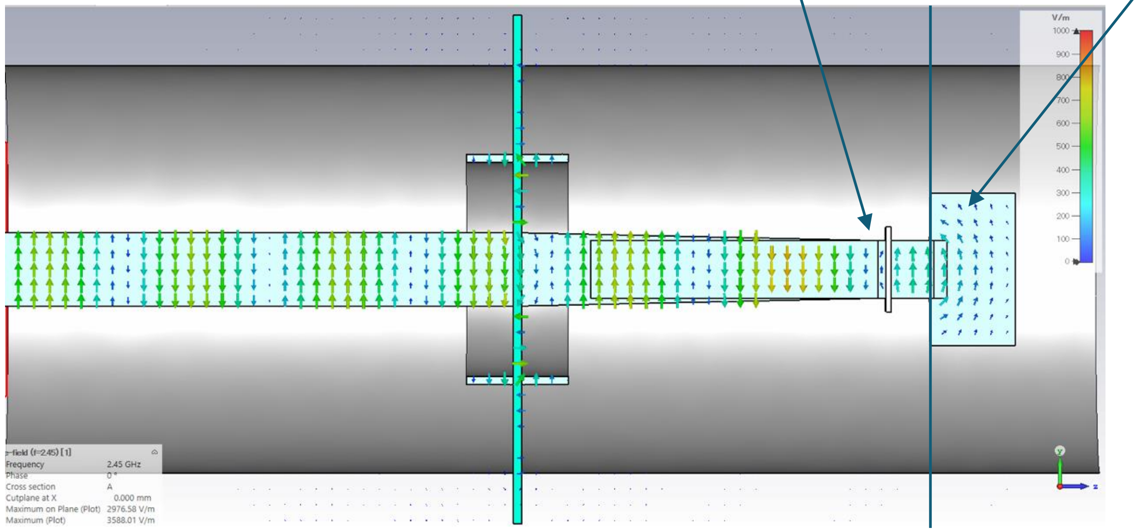
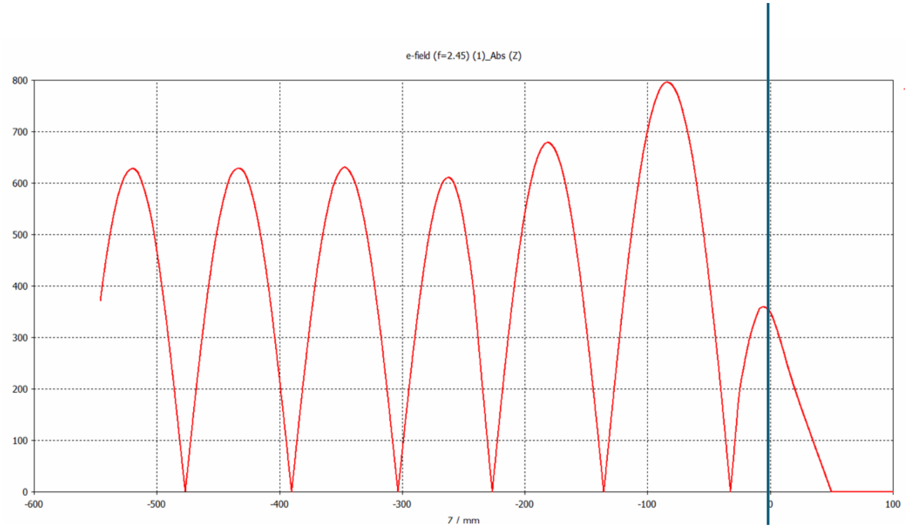
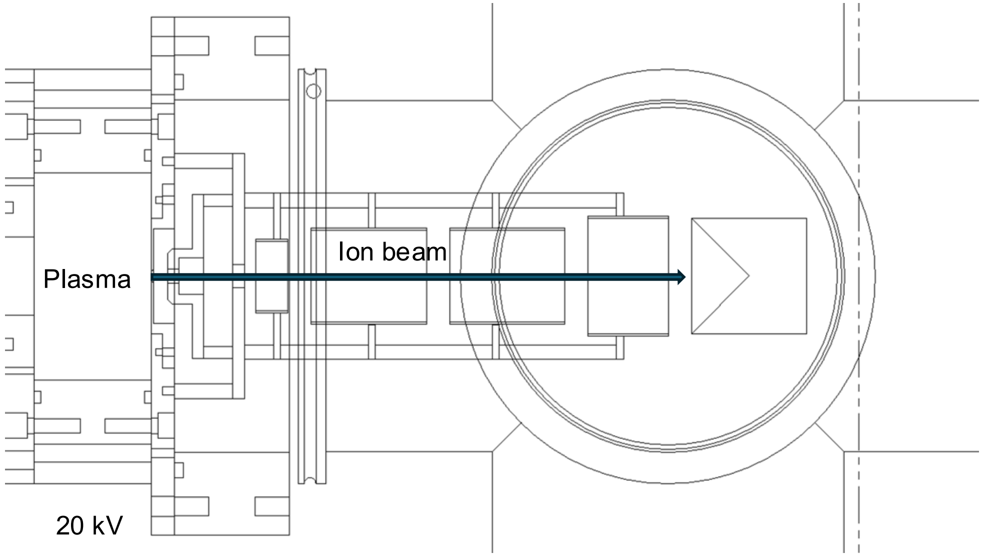
Microwave line design

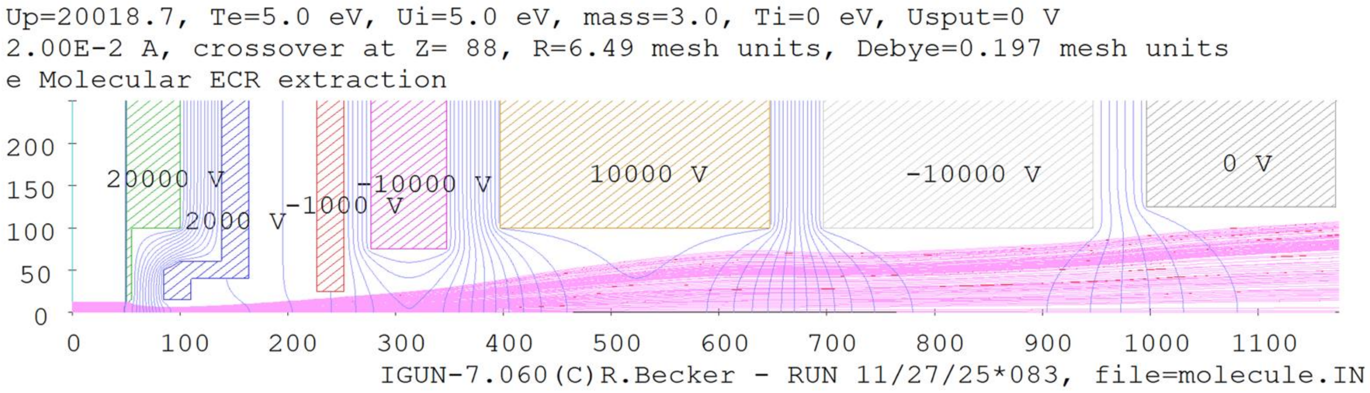




- MW simulation shows that MW power can be transmitted to the plasma chamber through the insulator plate and the 3-mm-thick alumina window.
- No plasma is assumed.
- With plasma present, the reflection will be minimized by adjusting stub tuner and optimizing MW window thickness for good matching.

Ion extraction simulation





- A 20-mA (H_2^+:H_3^+=1:1) extraction was confirmed using the IGUN simulation.
- The extraction aperture diameter is 5 mm, which is a typical value.
- The aperture size, gap distances, and voltages will be adjusted experimentally.
- During operation, beam transport will be much easier because of the higher plasma chamber voltage.
  - 34 kV for H_2^+, 51 kV for H_3^+.

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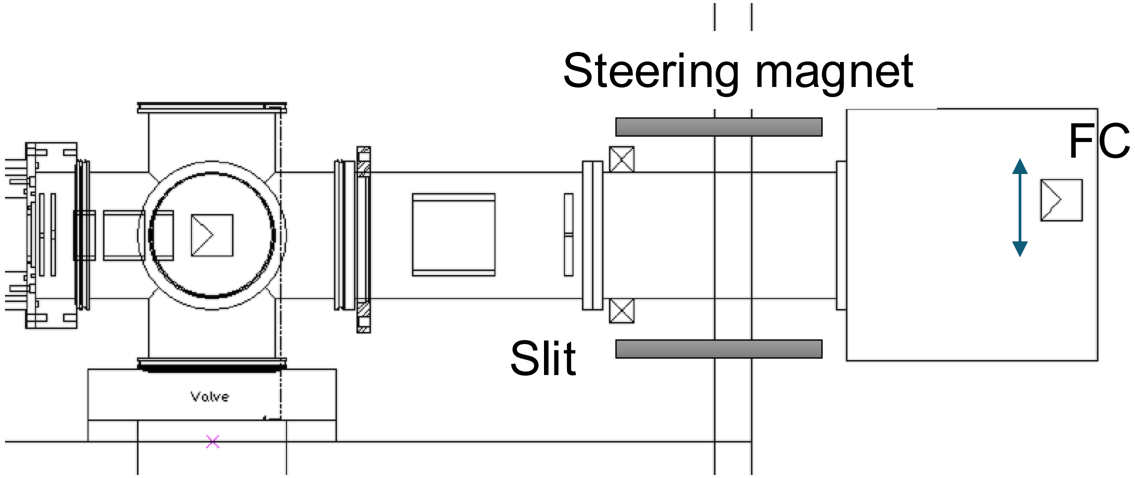
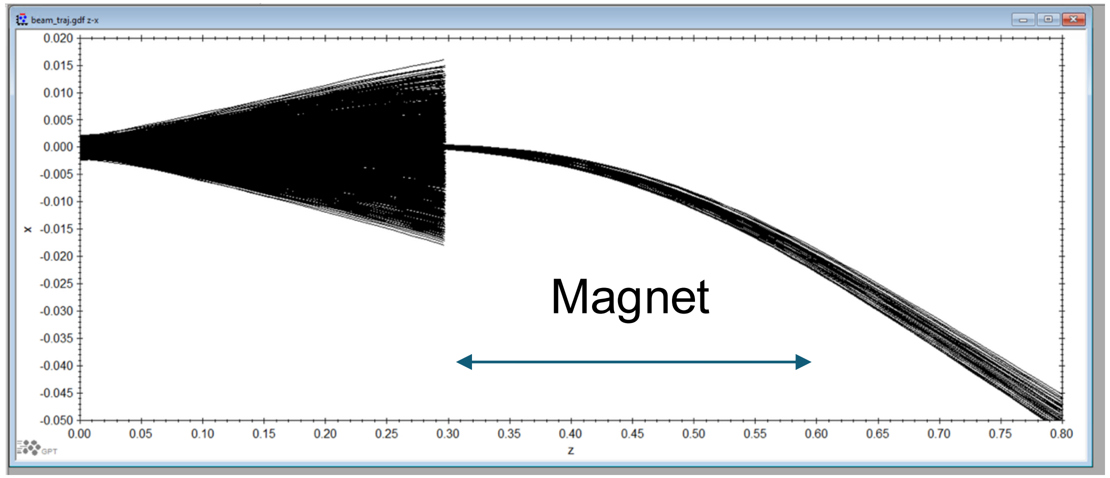
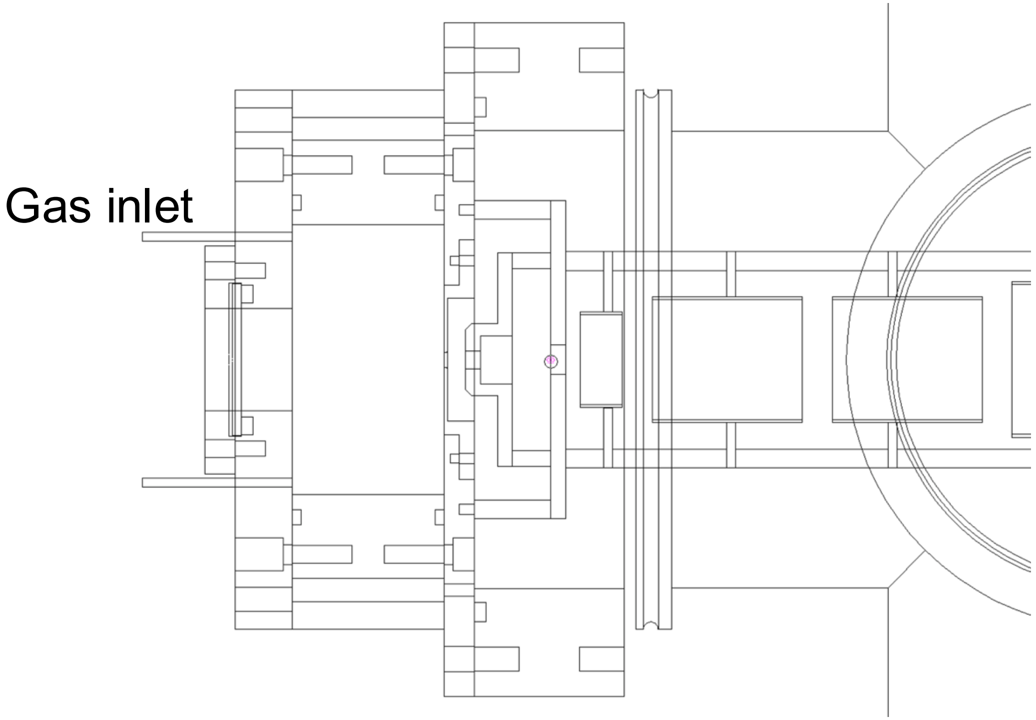
Analyzing magnet for separation of molecules

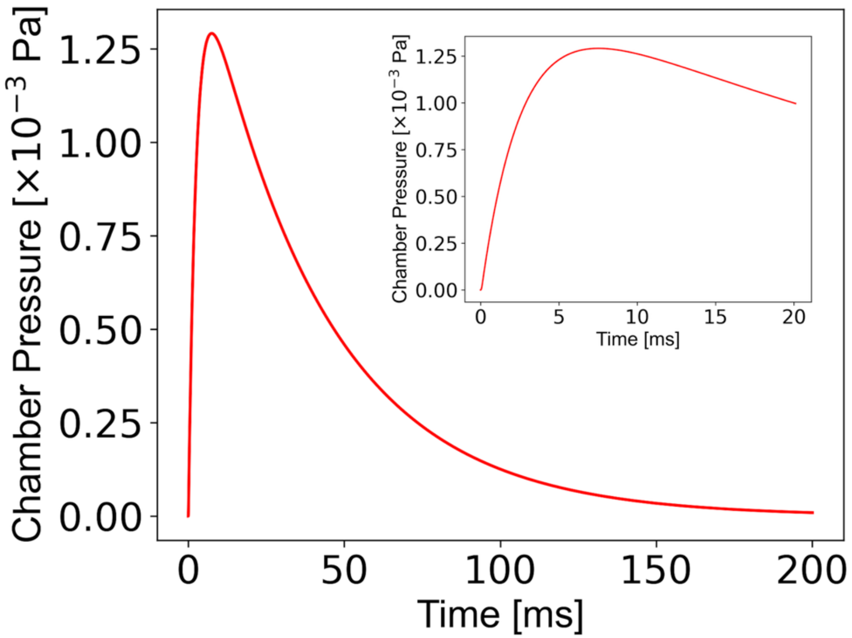




- A 1 mm slit is needed for resolution.
- A typical steering magnet (100 G, 30 cm) is enough to bend molecules trajectories.
- Movable FC is scanned to get spectrum.
- It is useful at optimizing the gas pressure and the MW power.

Pulsed gas valve and pressure response





- Pulsed valve will be used to reduce the gas load to the downstream.
- Commercial valves (~1 ms) will be tested.
- 0D rough estimation shows a quasi-steady state around the peak for the beam pulse.
- Experimentally investigate:
  - Minimum opening time for steady operation
  - Gas load to downstream

Next plan

- Gas valve test.
- Magnetic field measurement.
- MW window optimization after MW generator arrives.
- Plasma generation and ion extraction.
- Parameter optimization.

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Summary

- H2+ ions were successfully produced by EBIS and accelerated by the booster.
- The acceleration to 1 GeV/n was achieved for the first time as far as we know.
- It is operationally used.
- ECR IS is being developed for higher intensities of H_2^+ and H_3^+.
- The design work was done. The experiment will start soon.