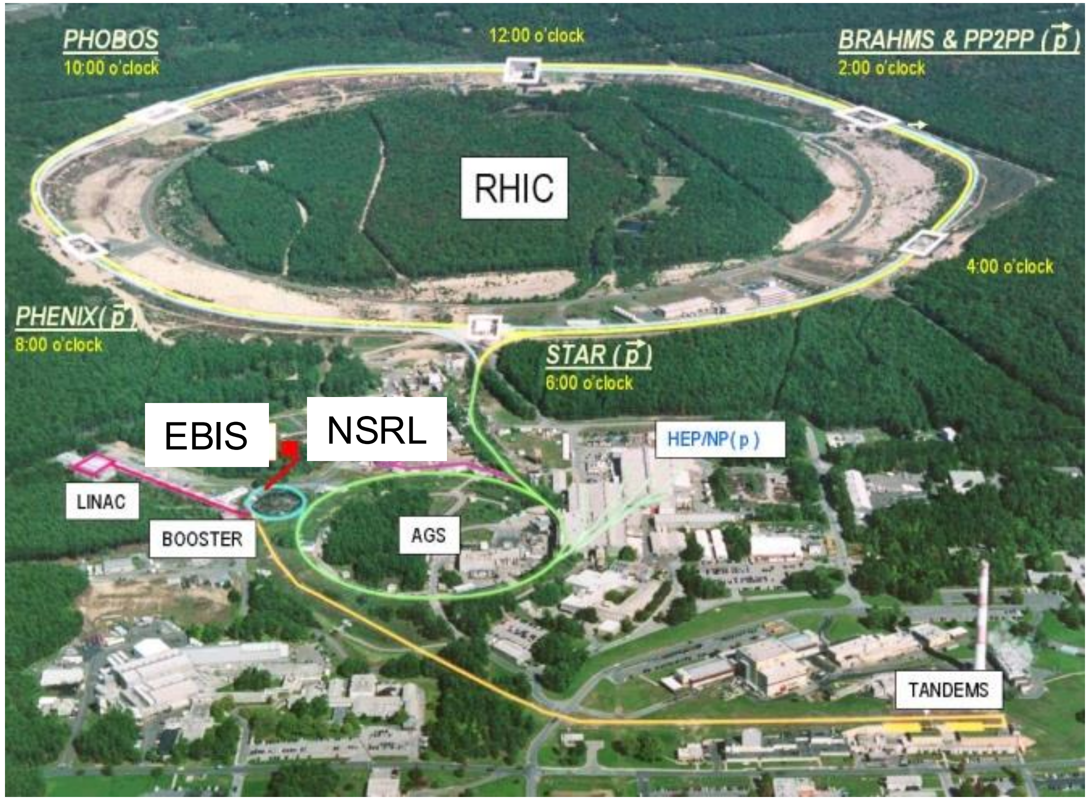
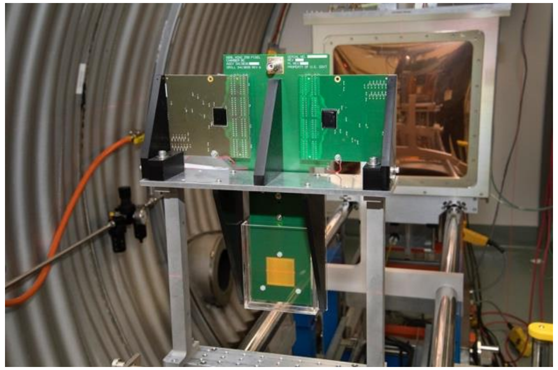
Production and acceleration of molecular ion beams (H_2^+, H_3^+) at EBIS (LDRD 25-043)

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

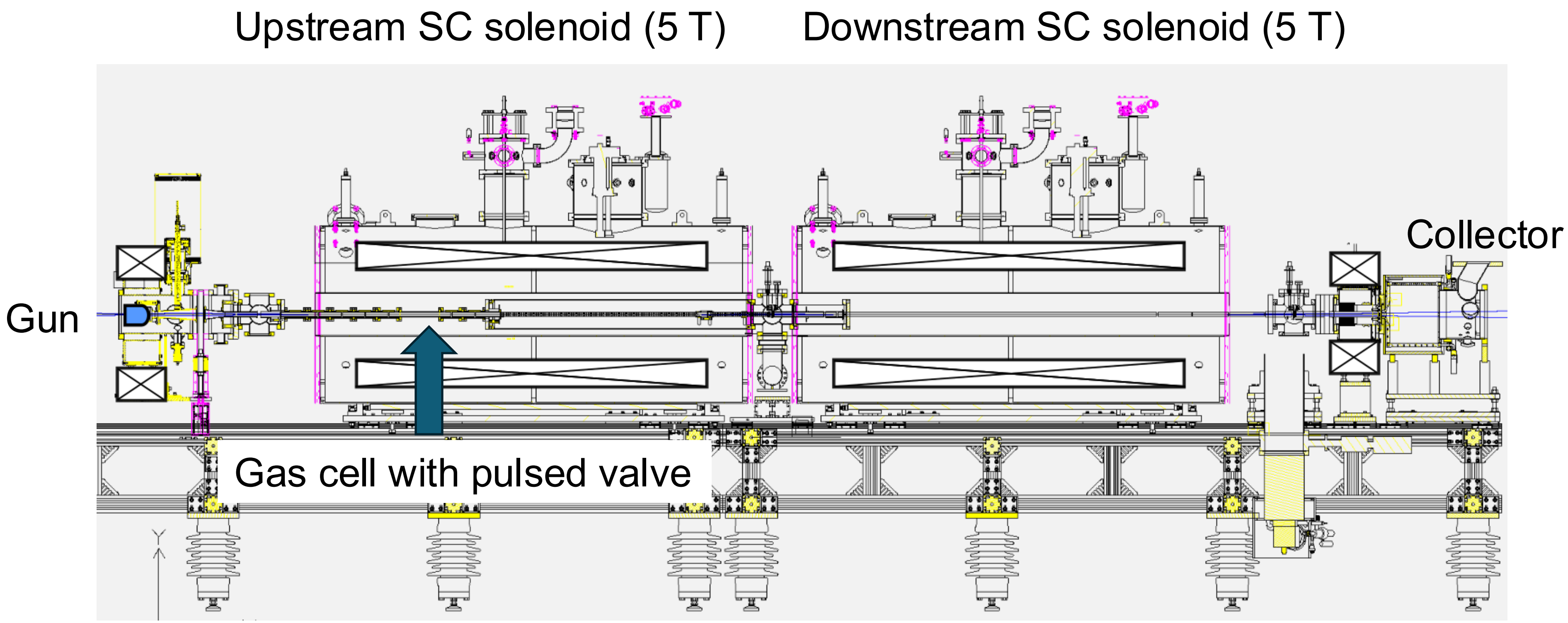
largely medium energy protons

shield's weight optimization

In the previous runs

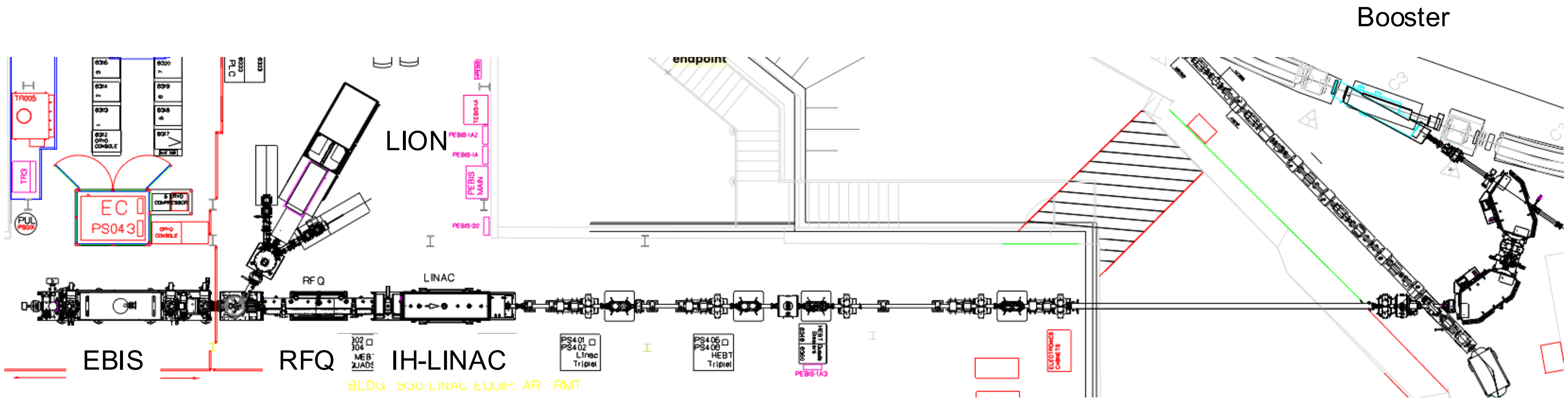
- Most ions but proton were provided by EBIS.
- Protons were delivered from 200 MeV LINAC or TANDEM.
- Motivation: Proton beams from EBIS line for simpler and cheaper operation.

EBIS upgraded for gas injection capability



- Previous EBIS (RHIC EBIS) was used as a charge bleeder for externally injected ions. Not for protons.
- With the gas injection system, Extended EBIS can produce ions from the injected gas, including protons.
- Protons from EBIS was expected.

Not many protons from EBIS accelerated in the booster ring



- RFQ+IH LINAC accelerates ions to 2 MeV/n.
- $^{3}He^{2+}$ was used in operation successfully.
- However, only a small fraction of the protons from the EBIS could be accelerated in the Booster.

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

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

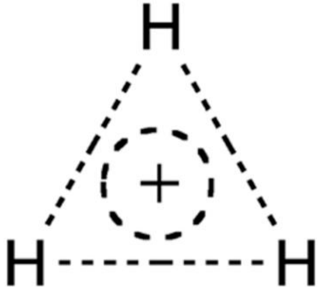
Hydrogen molecule ions were proposed

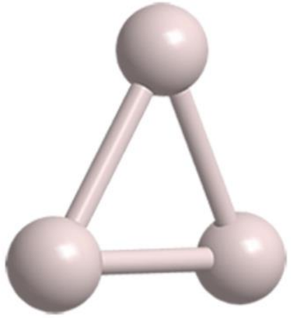
- H_2^+, H_3^+ are generated in laboratory plasma or space.
- Acceleration of ions with Q/A=1/2 and ~1/3 is always carried out.

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

$$H^+ + H_2 \text{ -> } H_2^+ + H$$

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





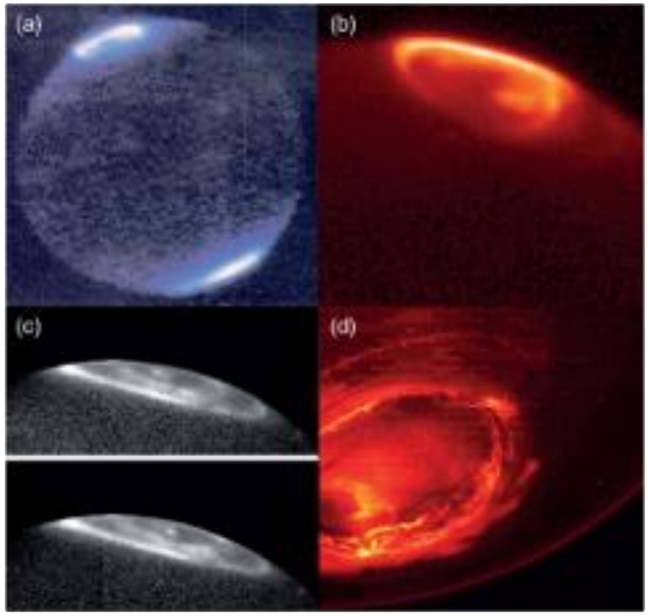
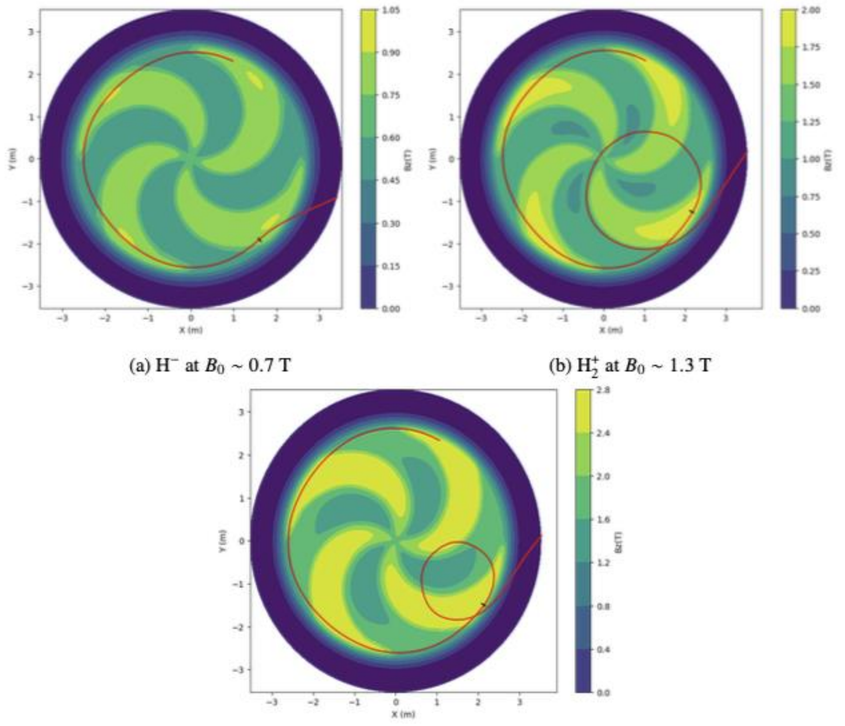


FIG. 4. Four images of Jupiter's H_3^+ aurora, showing the changes in resolution over the past 30 years. (a) One of the first

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.

H_2^+ and H_3^+ production using EBIS and ECR ion source

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

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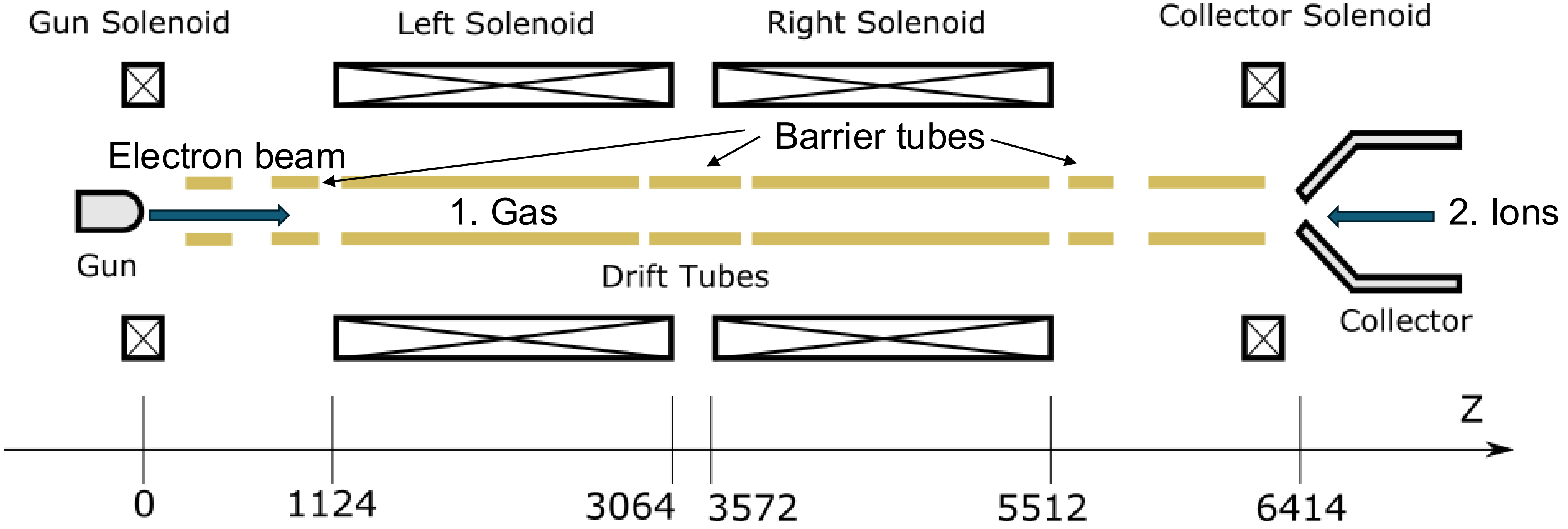
Electron Beam Ion Source (EBIS)



- 5-A, 20-keV electron beam is compressed by magnetic field to 1.6 mm (up to 500 A/cm^2)
- (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 (Au^{32+}, Au^{43+}, Fe^{20+},,,)

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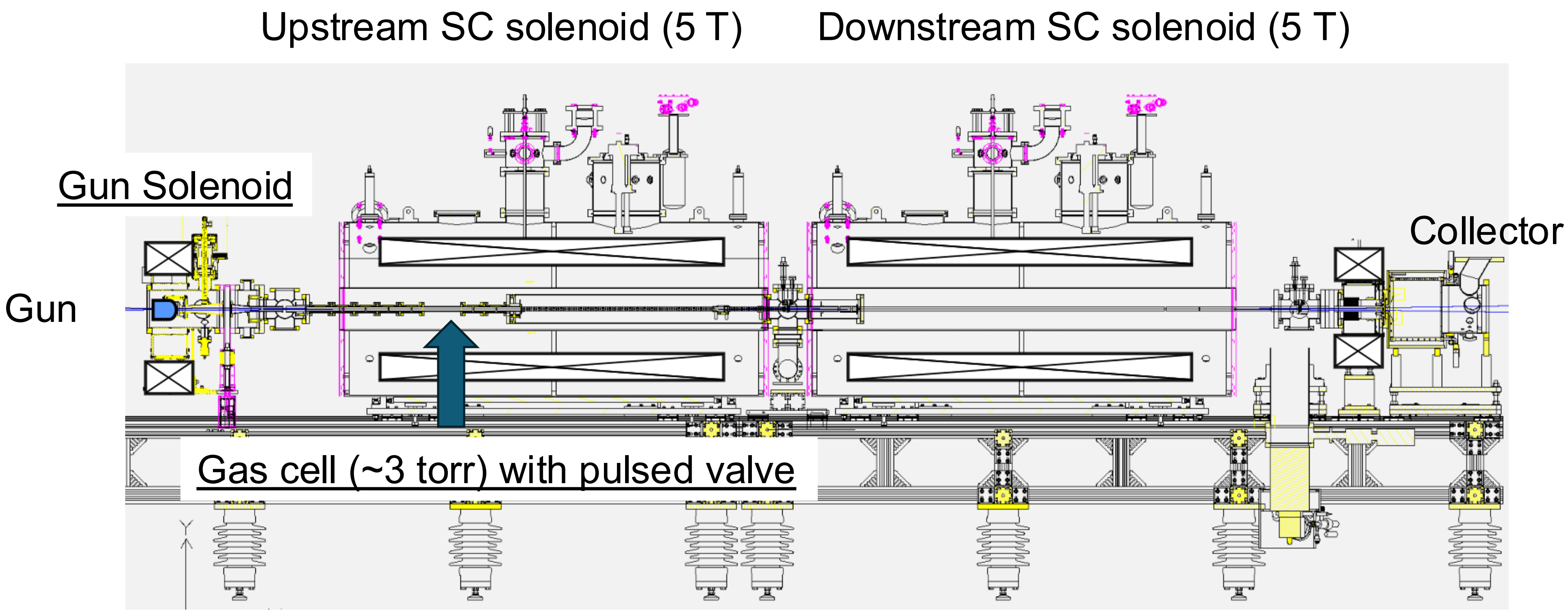
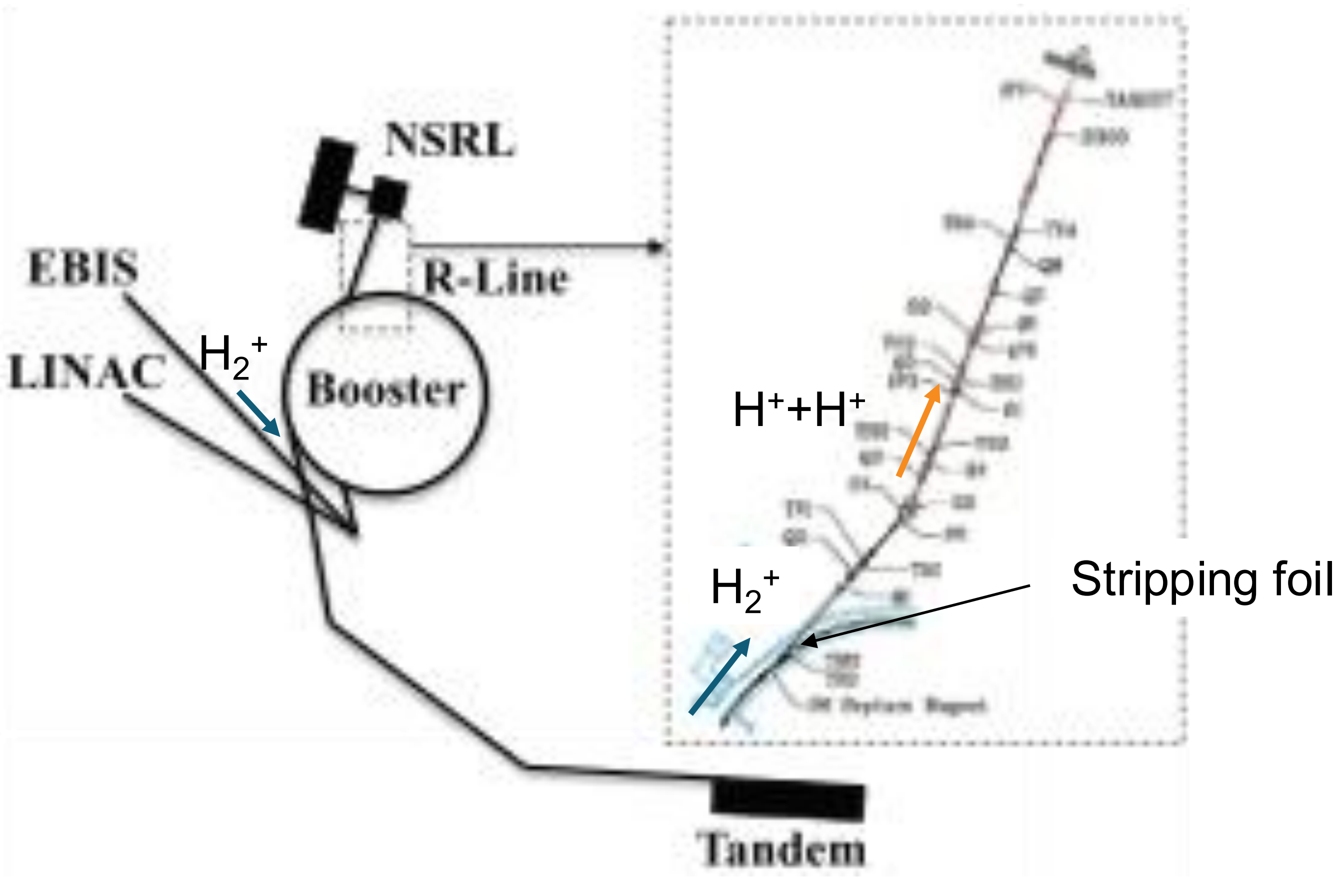
EBIS optimization for molecular ions



- EBIS is designed to generate highly charged ions.
- However, it was also said molecular 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.

Acceleration test



Booster input (H_2^+)	NSRL (proton)
1.1×10^{10}	1.4×10^{10}

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

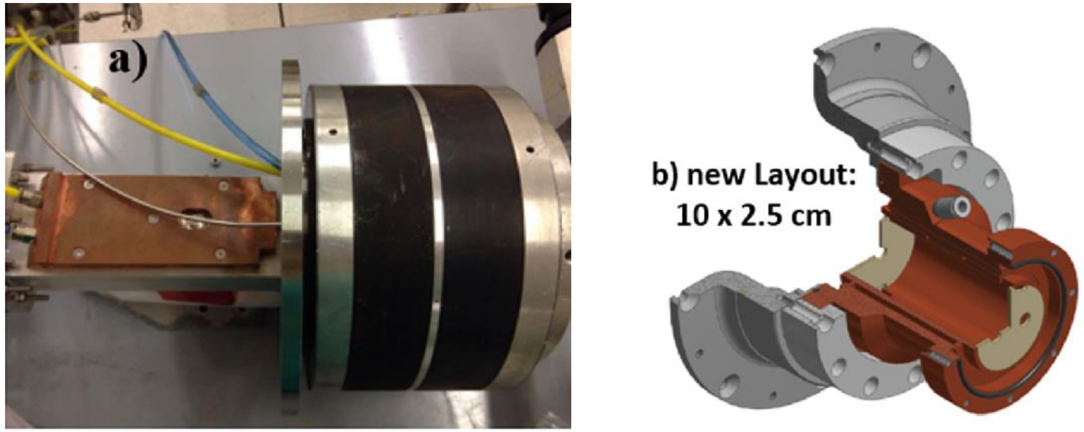
- Acceleration of H_2^+ to 1 GeV/n was succeeded.

EBIS development result and future

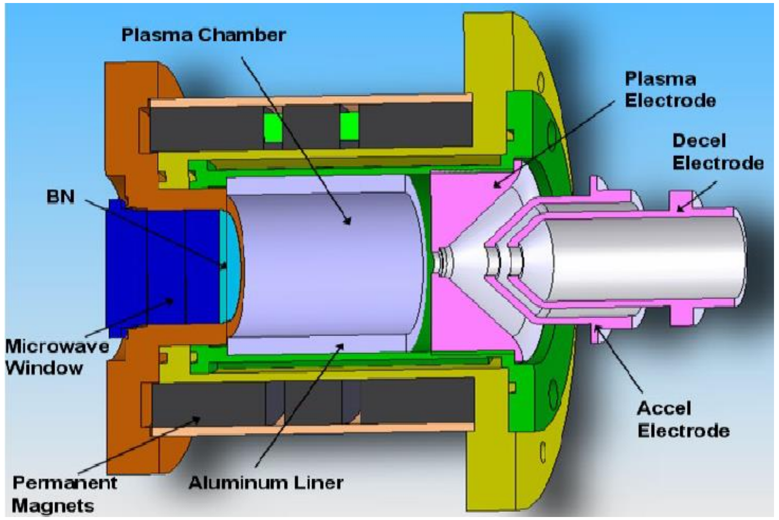
- Now it is used for daily operation heavily with fast switching capability.
- This is the first demonstration of acceleration to 1 GeV/n and operational use in high energy accelerator.
- Further improvement may be possible.
  - optimistically 3x intensity is expected while drawbacks need to be evaluated.
- H_3^+ production needs to be investigated more.
- Other types of molecule ions also may be possible.

Electron Cyclotron Resonance (ECR) ion source for molecule ions

VIS at INFN, Italy



PMECR II at PKU, China



10 cm x 10 cm vacuum pipe

10 mA H_2^+, 8 mm aperture, 2.45 GHz, 500W, $1x10^{-5}$ torr

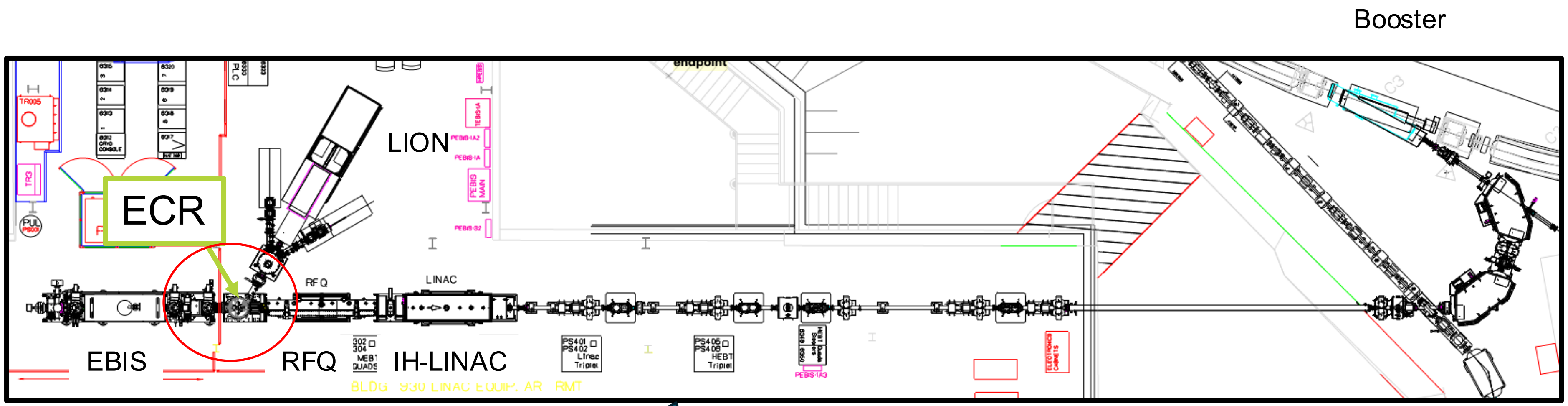
40 mA H_2^+, 20 mA H_3^+
5 mm aperture, 2.45 GHz, 1.1 kW, $3x10^{-6}$ torr

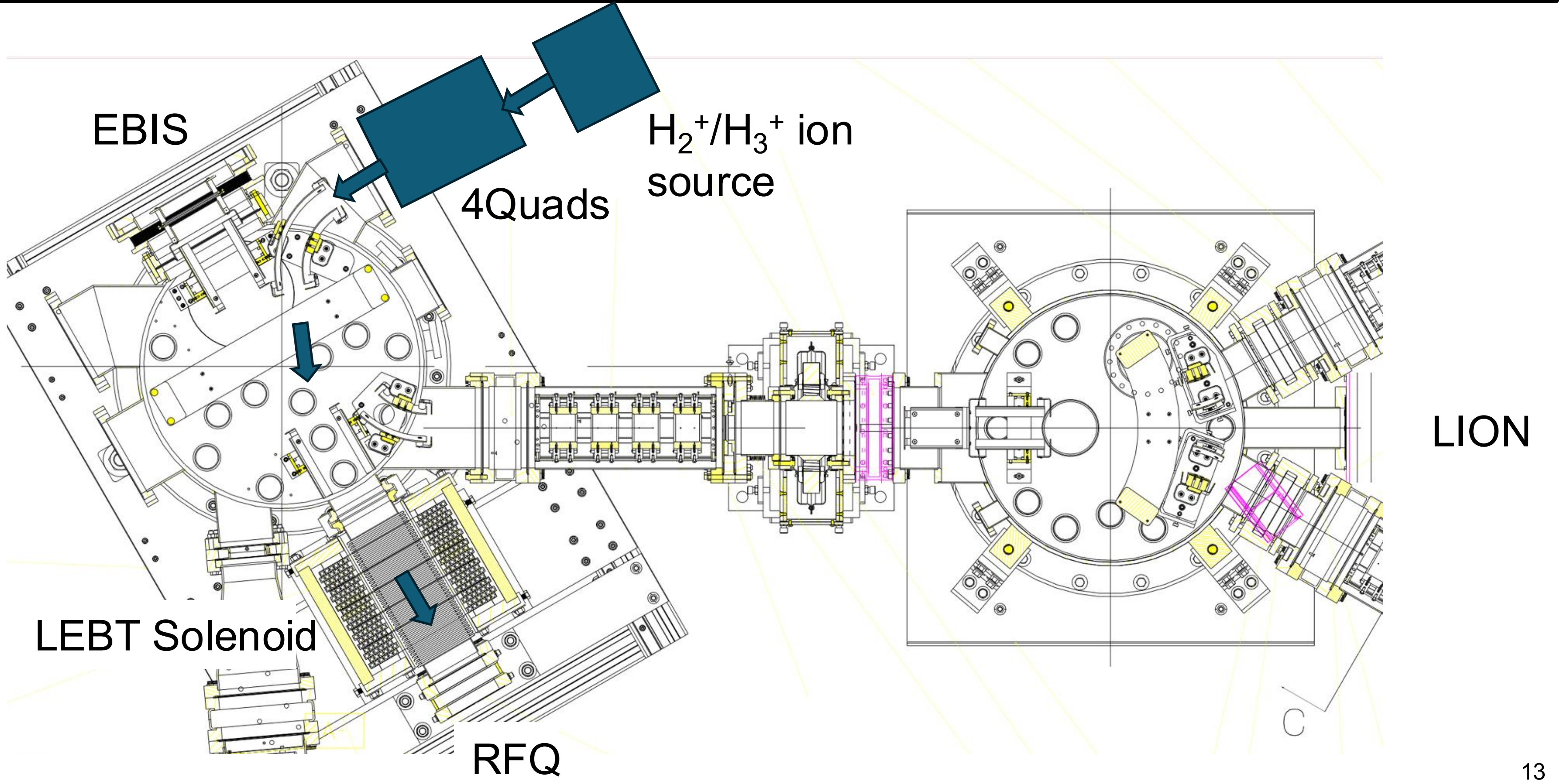
"G. Castro et al, "AnewH+2 source:Conceptual study and experimental test of an upgraded version of the VIS - Versatile Ion Source," PRSTAB, 2015."

S. X. Peng, et al, "STATUS OF THE HIGH CURRENT PERMANENT MAGNET 2.45GHZ ECR ION SOURCE AT PEKING UNIVERSITY", Proceedings of ECRIS2010, France, TUCOCK02

- 10 mA x 40 us = $2.5x10^{12}$ ions (40 us is typical for Au beam from EBIS)

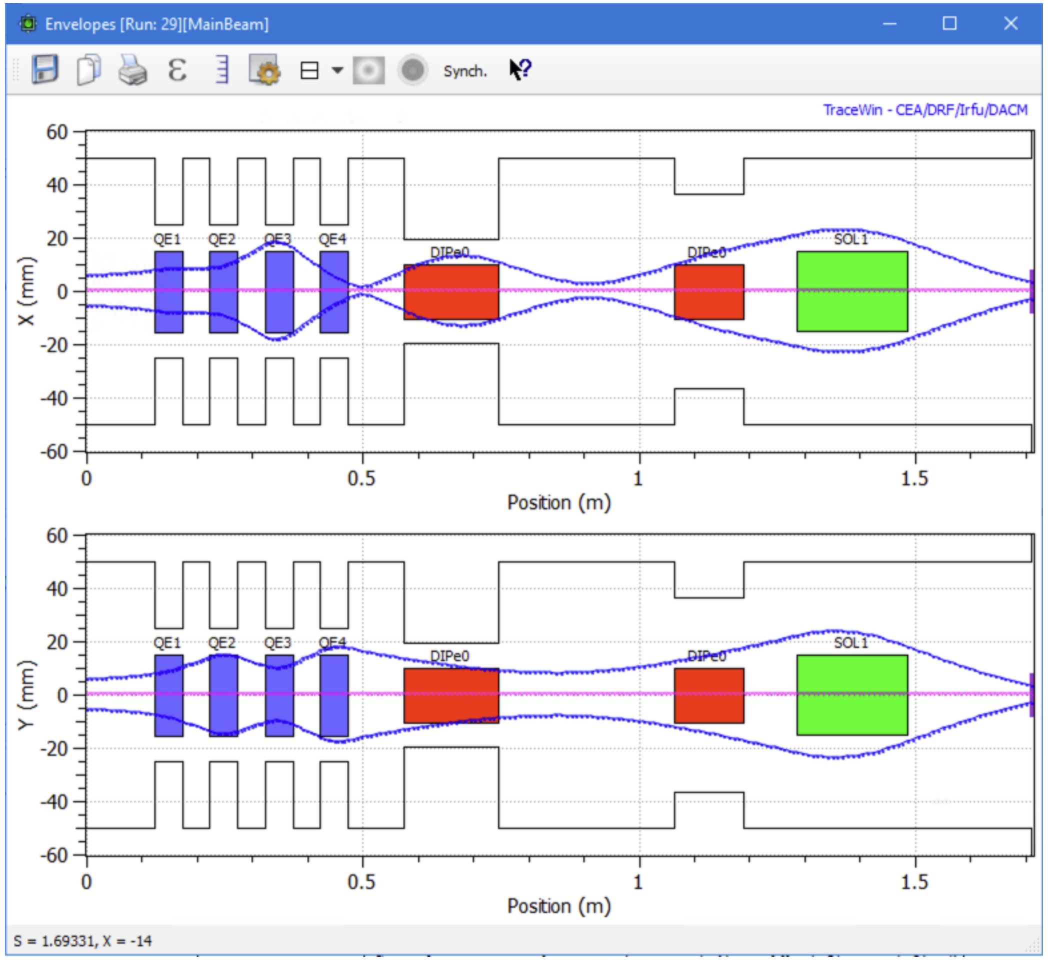
We have space and port for ECR



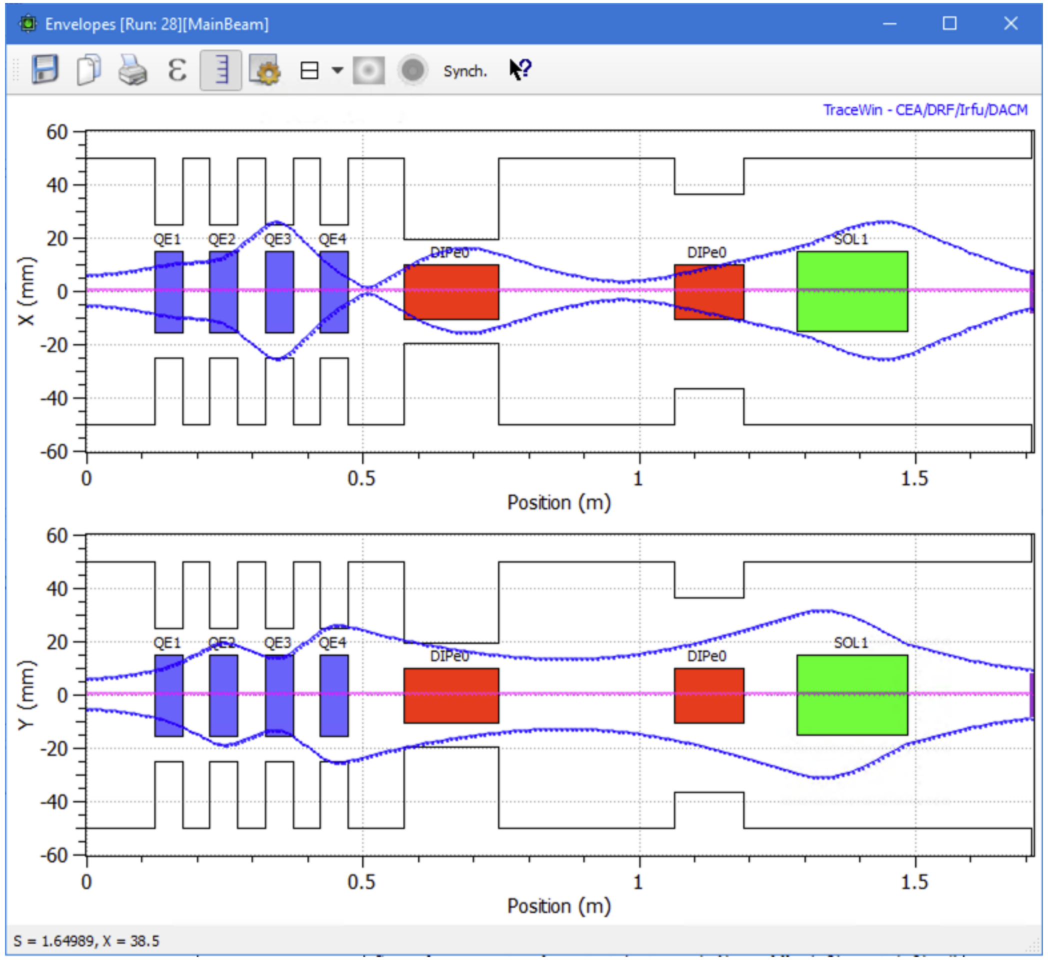


Envelope calculation shows H_3^+ up to 20 mA can be transported to RFQ

H_3^+, 10 mA



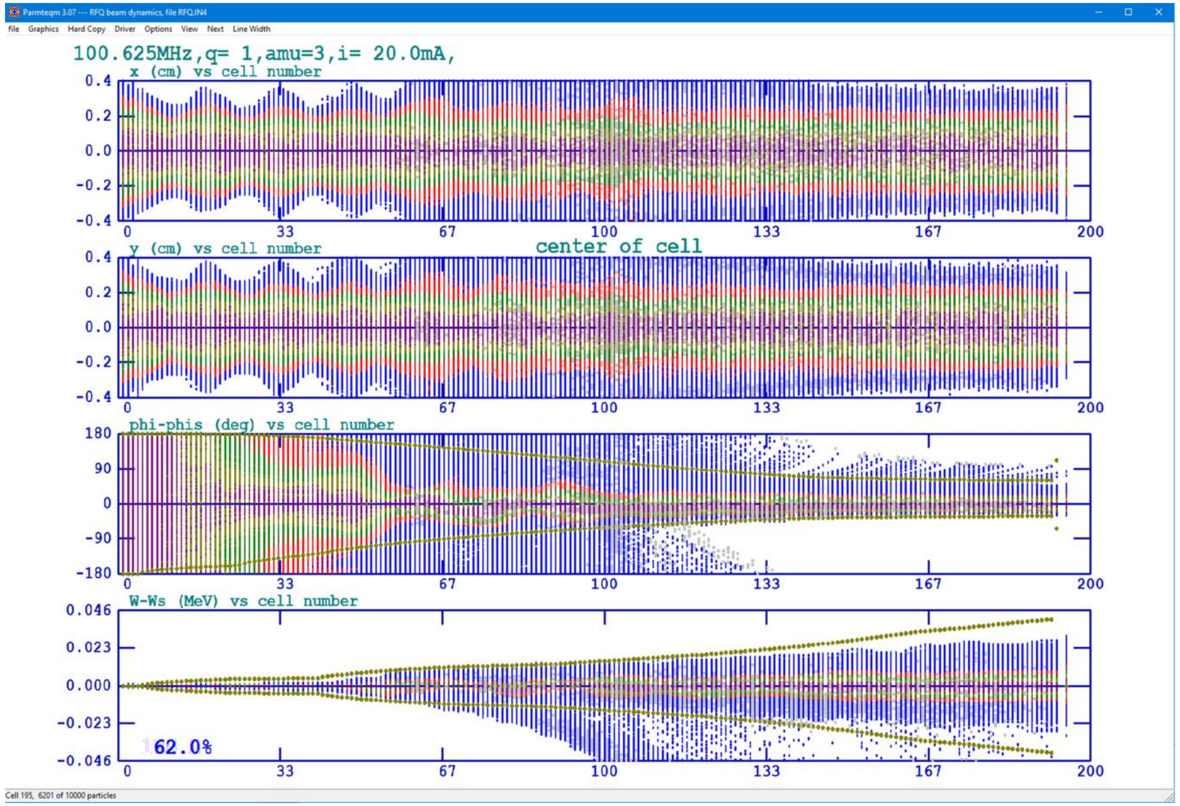
H_3^+, 20 mA

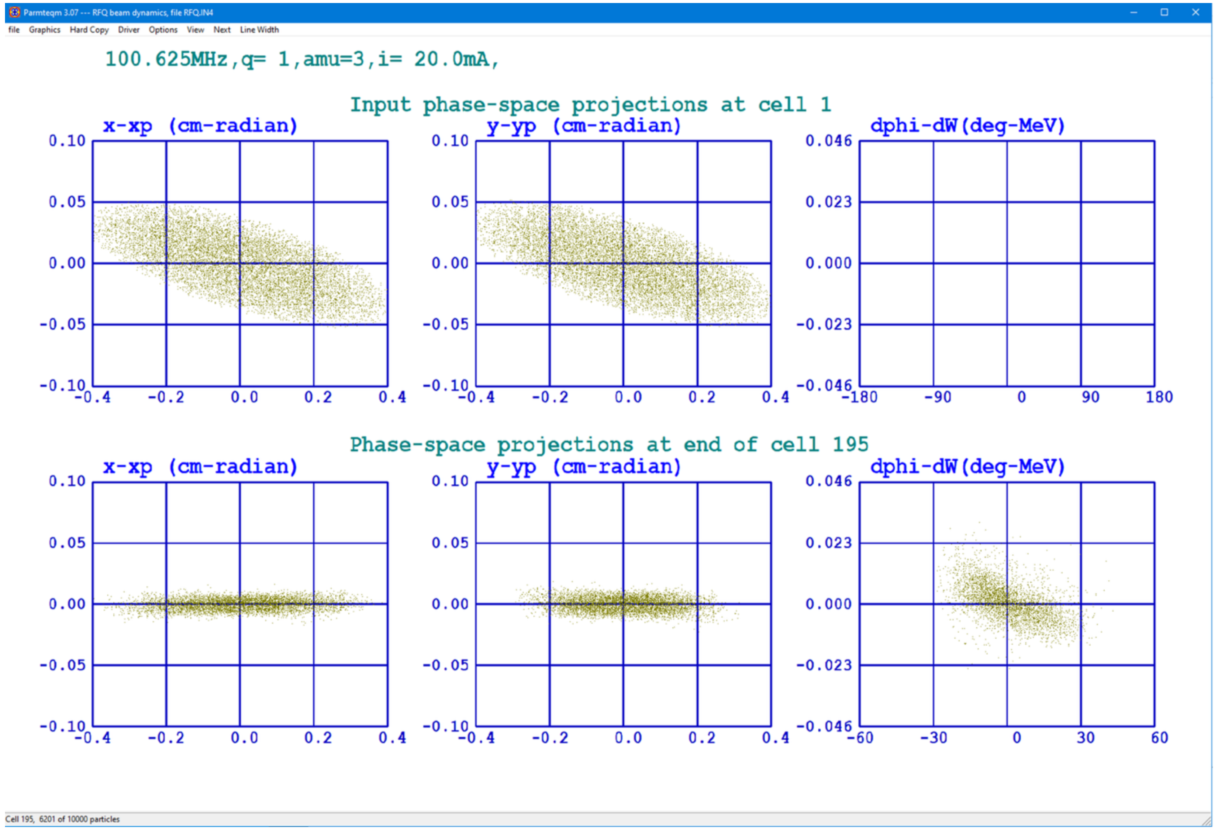


Source 4Quads Bend1 Bend2 Solenoid

Up to 20 kV 0.63 T

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





20 mA input, 12 mA output

RFQ end to Booster

- IH linac was designed for a 10-mA beam.
- 2.5×10^{11} (1mA – 40 us) should be delivered based on EBIS to Booster line design,
- Q/A: H_3^+ ~ Fe^{20+} accelerated daily
  - It is expected to be not too difficult to find operation condition for H_3^+.

- With ECR, 10 times more protons should be available.
- We started the ECR development.

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

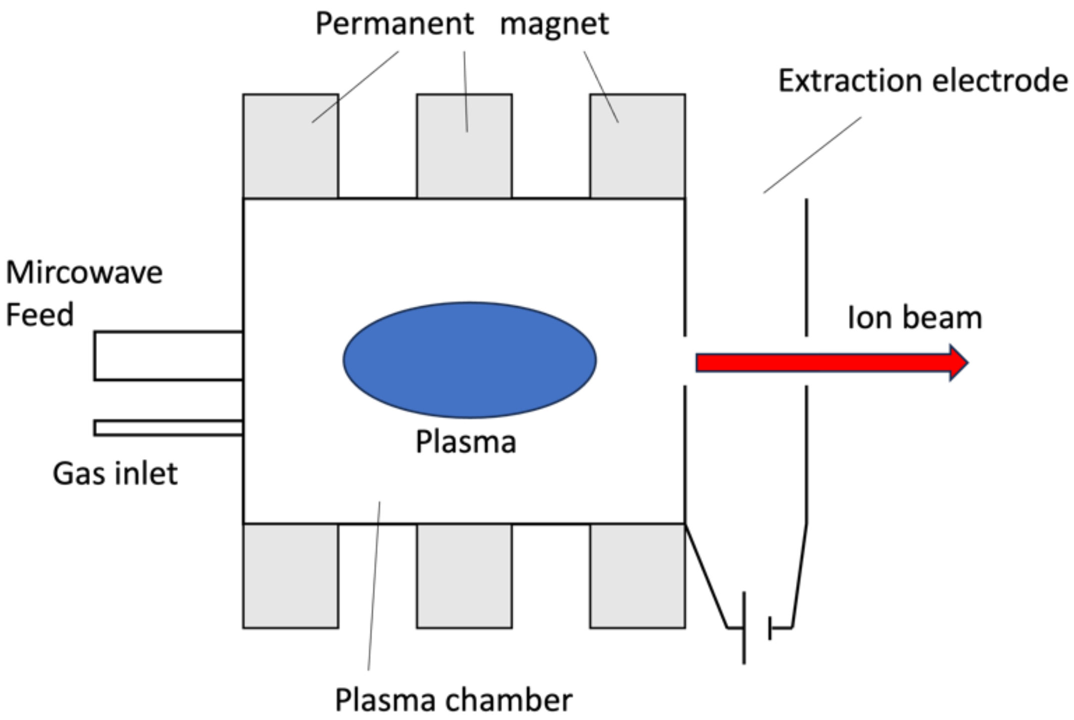
September 2005

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	Δp/p	±0.05	±0.075	%
Norm. 90% emittance	$\varepsilon_{N,90}$	0.7	0.7	πmm mrad

R&D for ion source

- Establish low temperature plasma:
  - Lower RF power
  - Larger amount of gas
  - Magnetic configuration
- Make it compact:
  - Limited space
  - Permanent magnet
- 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

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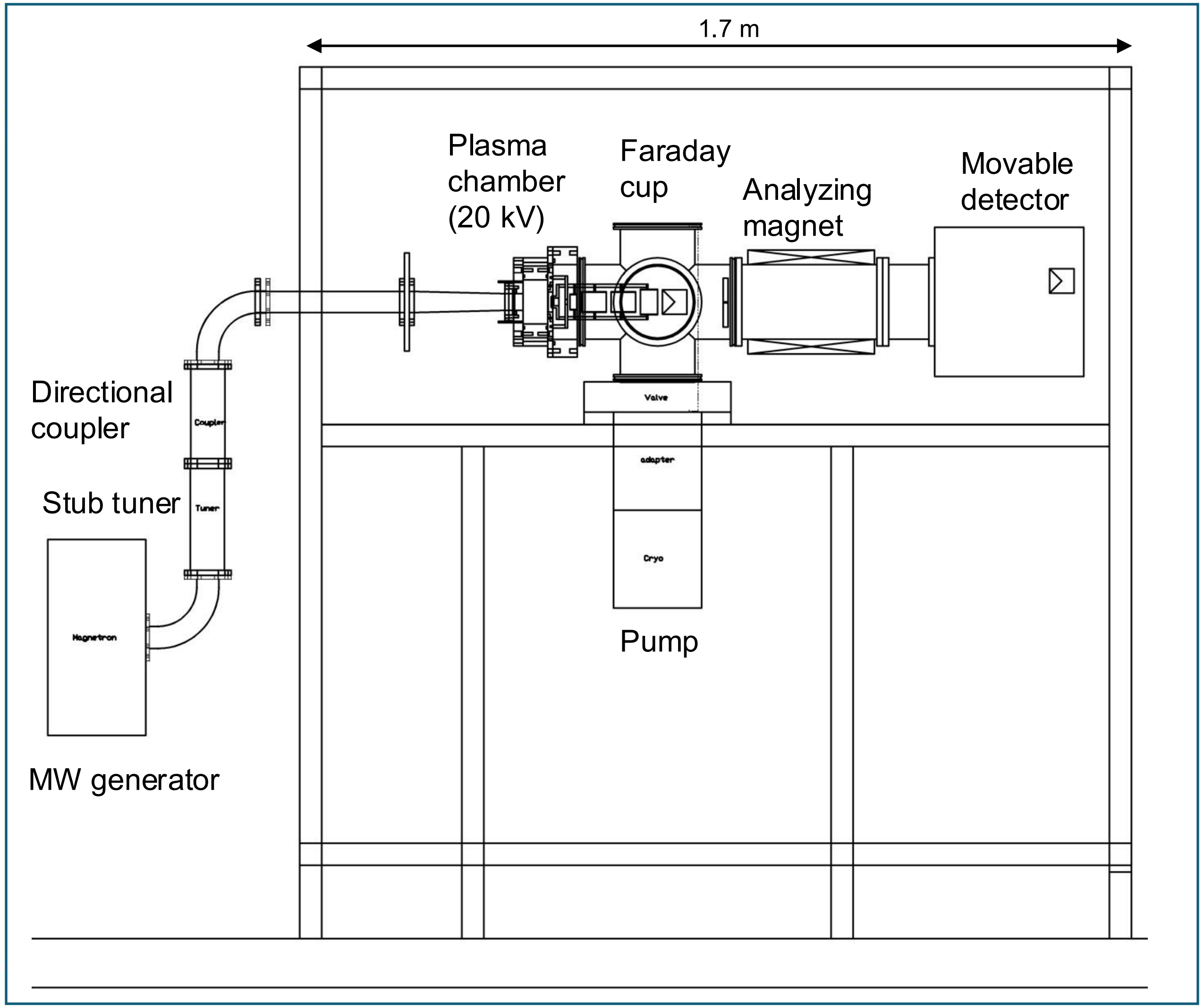
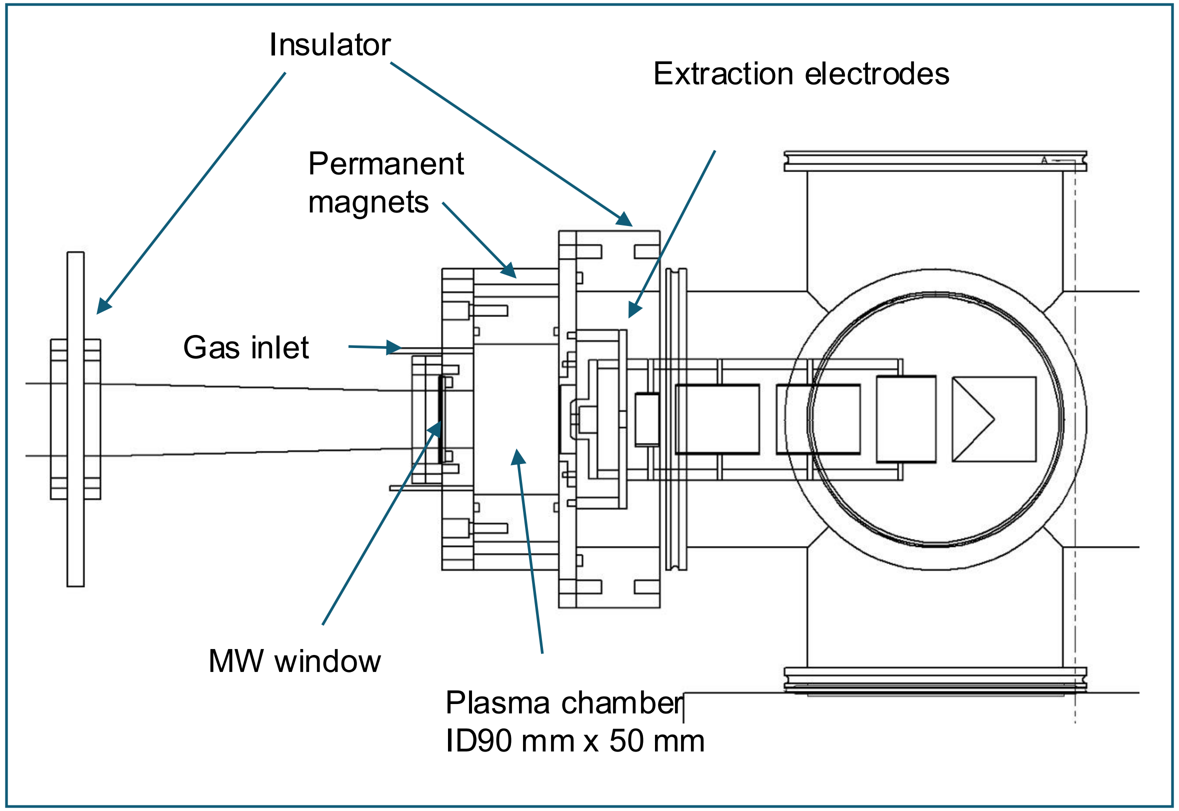
Test stand for development





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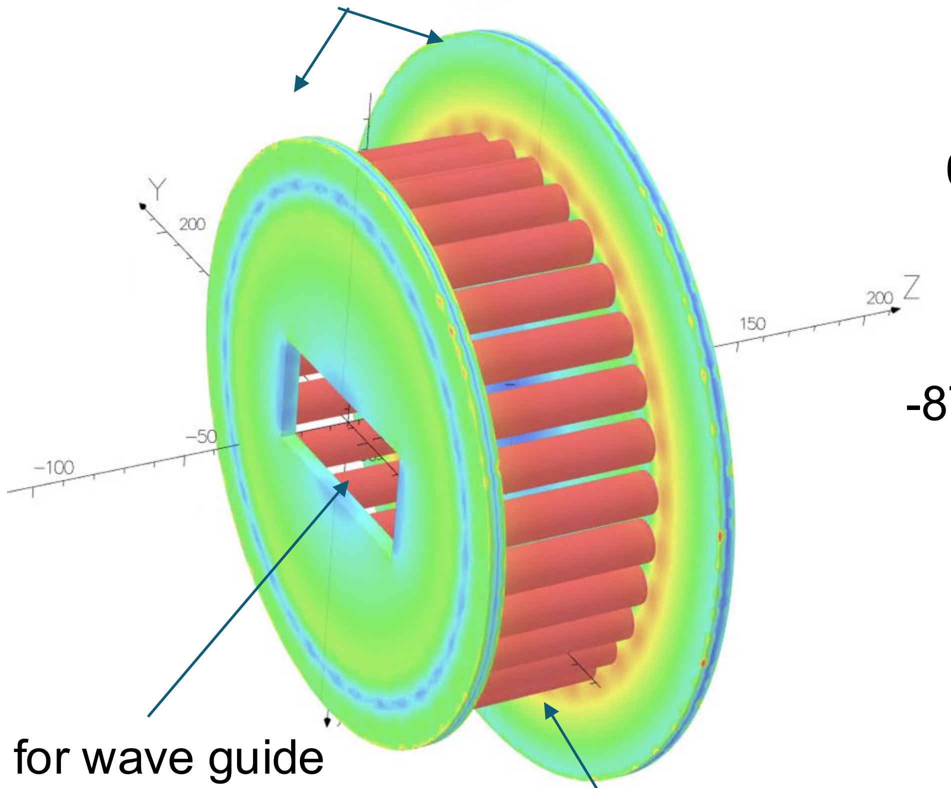
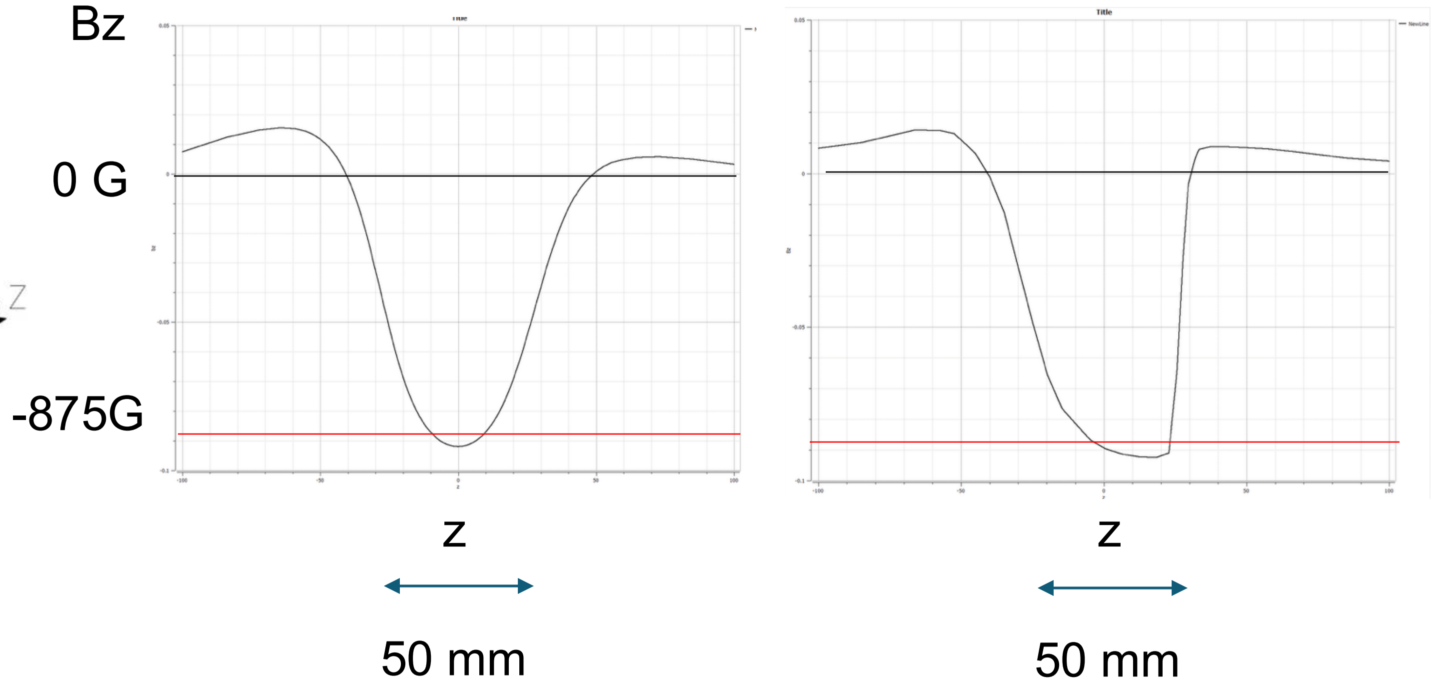
Magnet design



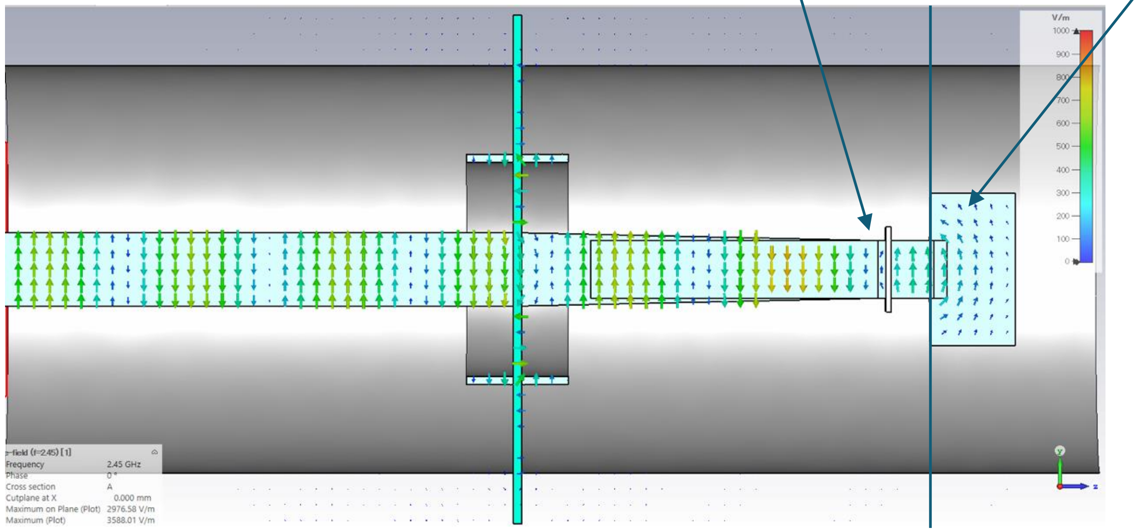
45 mm aperture
40 magnets

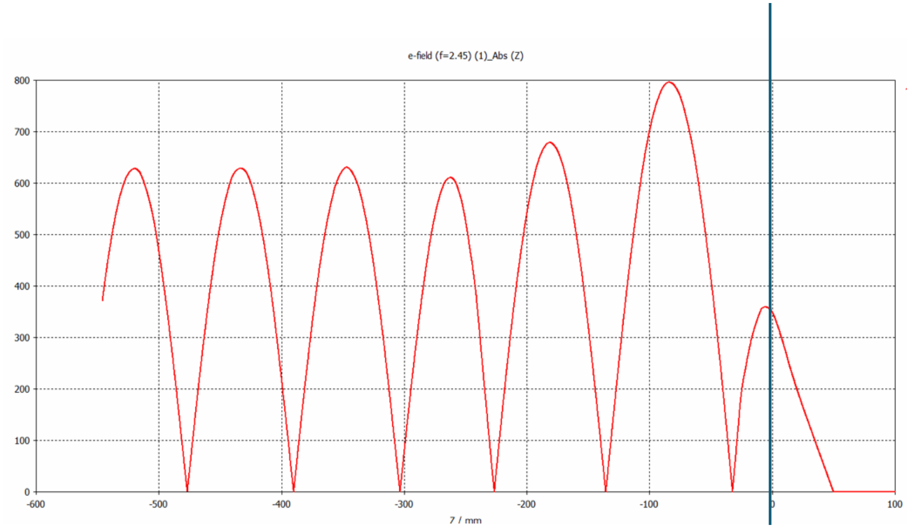
5 mm aperture
36 magnets



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

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.

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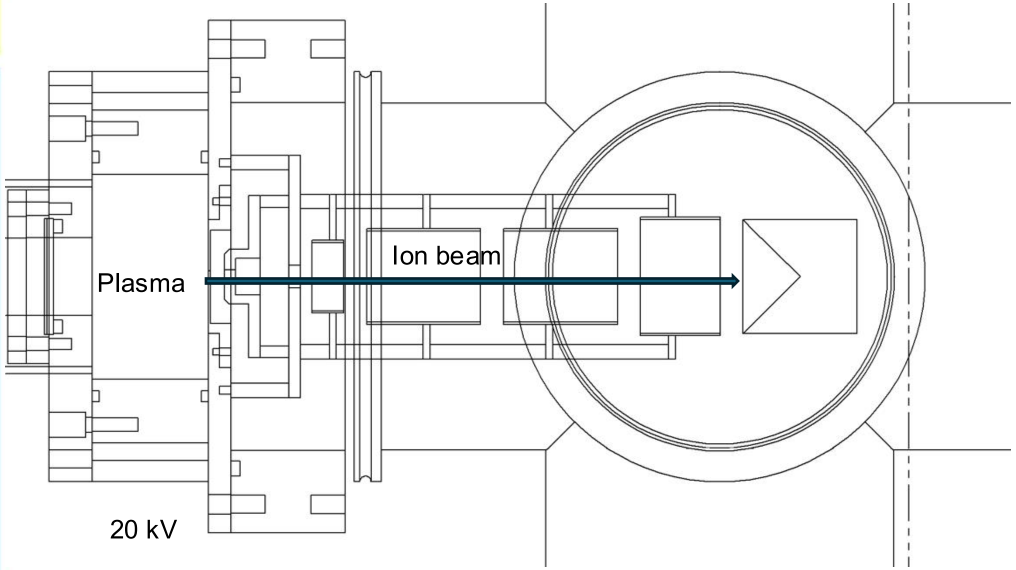
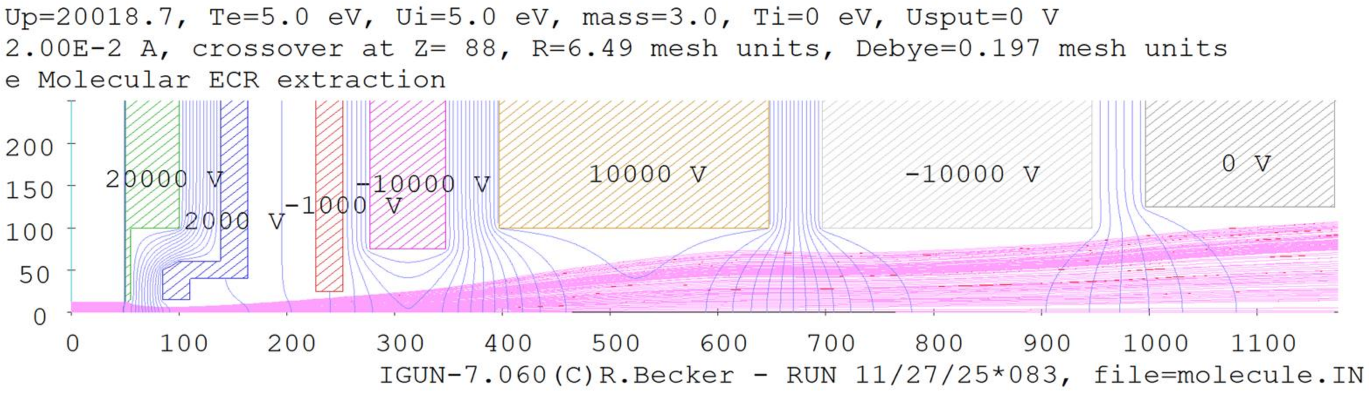
Ion extraction simulation





- 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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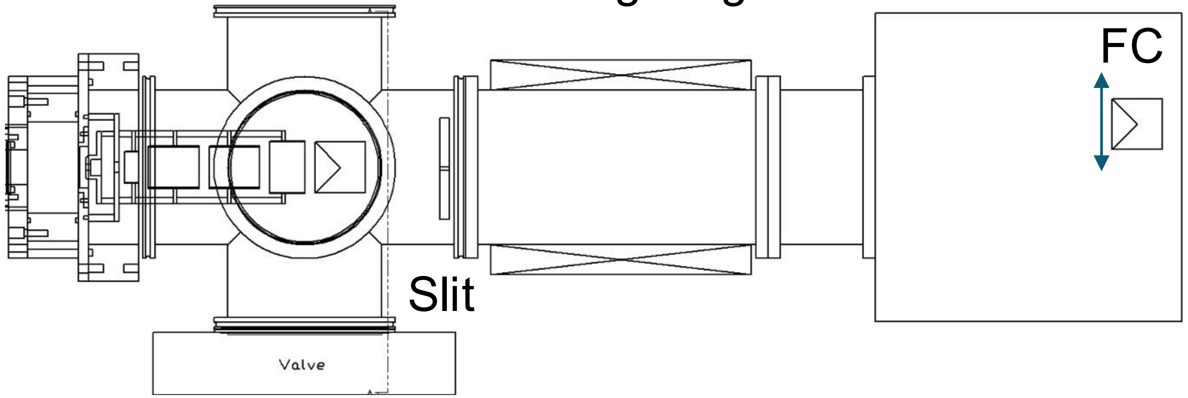
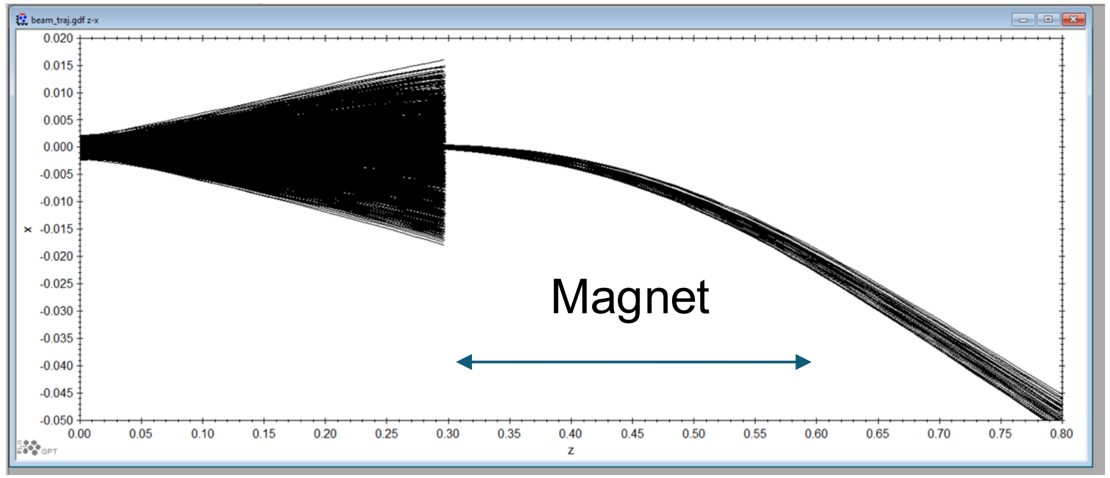
Analyzing magnet for separation of molecules

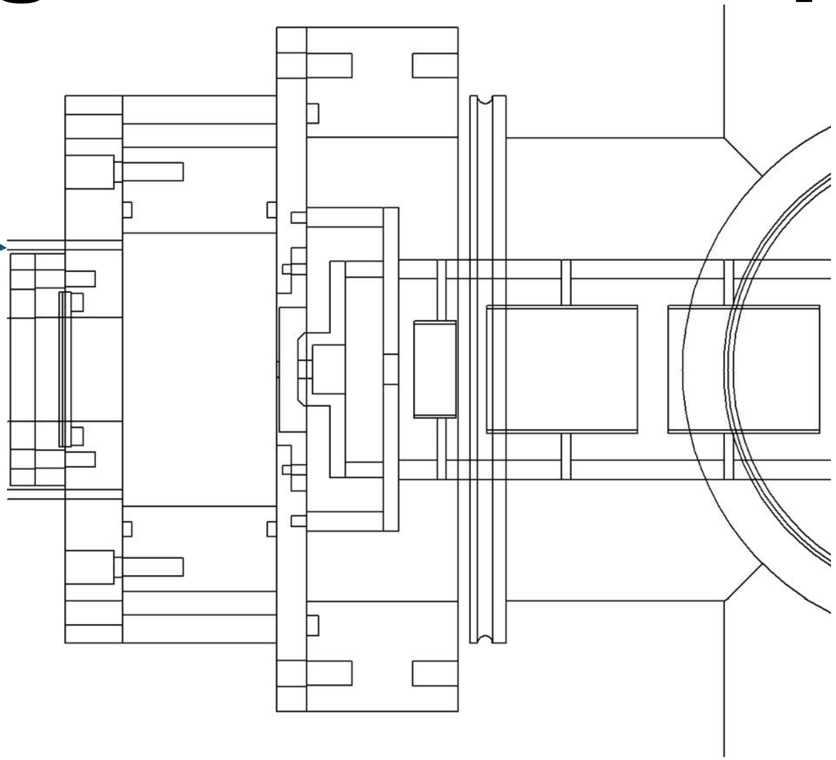


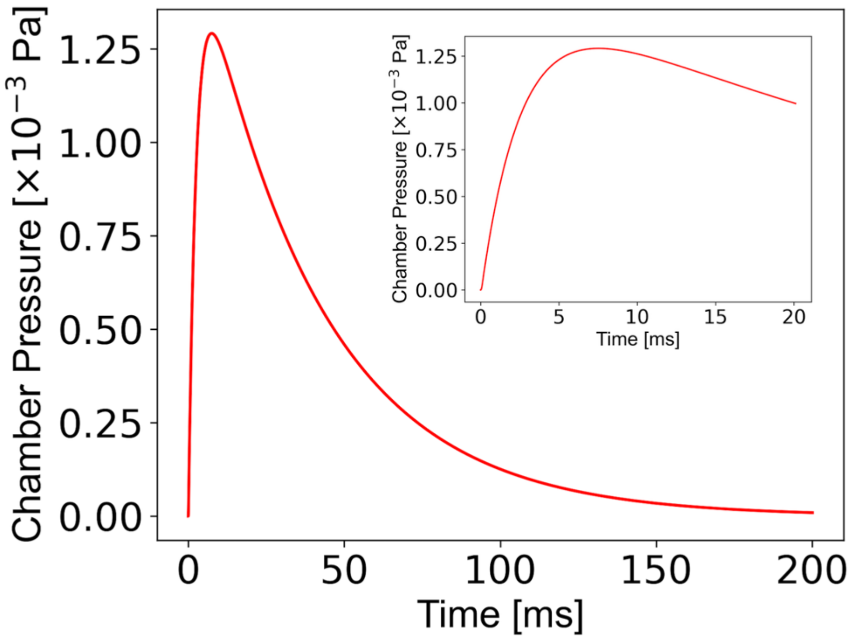


- A 1 mm slit is needed for resolution.
- A typical steering magnet (100 G, 30 cm) is enough to bend molecules trajectories.
- Movable FC is scanned to get spectrum.
- It is useful at optimizing the gas pressure and the MW power.

Pulsed gas valve and pressure response

Gas inlet





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

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Next plan

Design work was done.

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

Summary

- H_2^+ ions were successfully produced by EBIS and accelerated by the booster. (10^{10} ions)
- 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^+. (10^{11} ions)
- The design work was done. The experiment will start soon.

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Thank you