Status of J-PARC RF H^- source

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High Energy Accelerator Research Organization (KEK)
Takanori Shibata

Outline

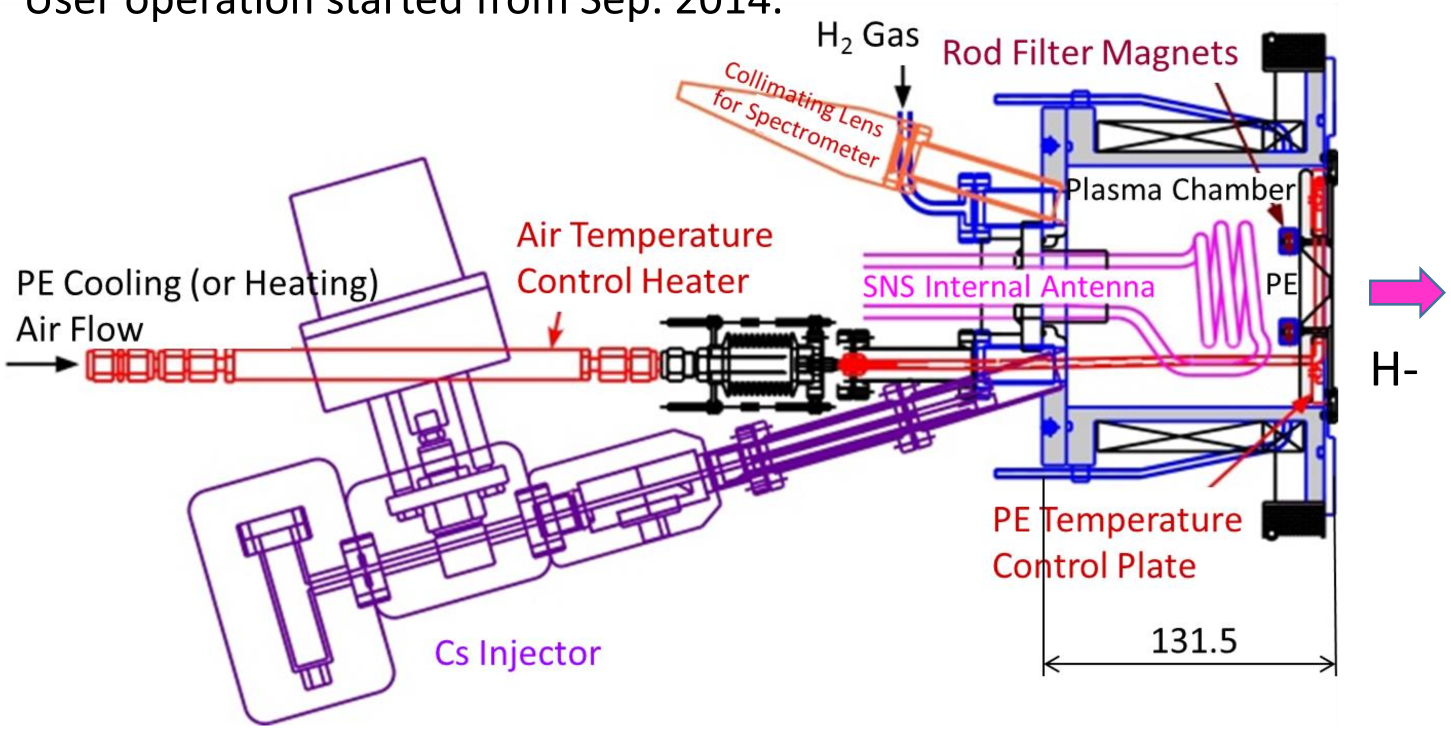
- Present status of J-PARC H- source
  - H- beam production mechanism in ion source
  - Operation status of J-PARC RF source
  - Feed back and beam monitoring system
- For further improvement for high power linac
  - Results from offline R&D in Test-Stand
  - Numerical modeling of RF plasma
- Summary

J-PARC H⁻ ion source

Main Specifications

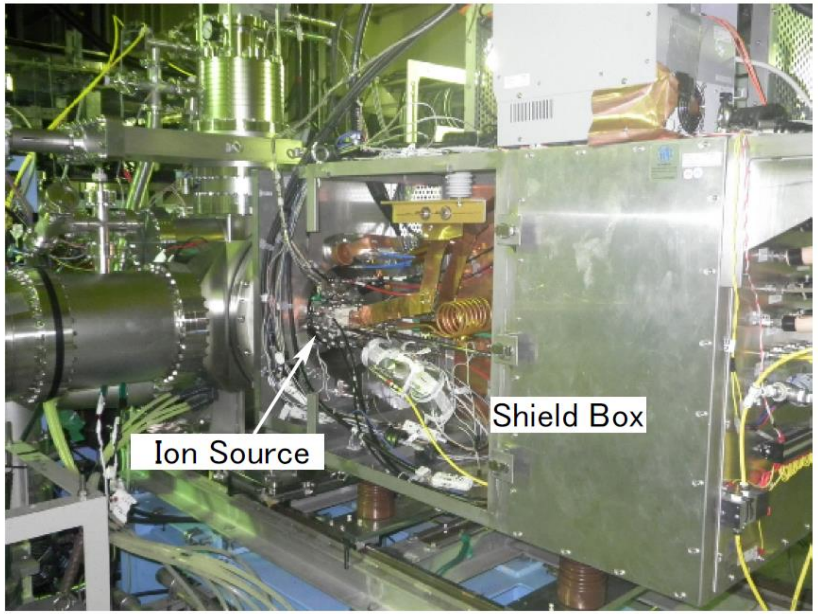
- Cesium (Cs) seeded
- Multi-cusp magnetic field configuration
- Radio Frequency (RF) – driven with internal antenna coil

* User operation started from Sep. 2014.



Present Status of H- Beam Performance

	Main Parameters
Beam current in user operation	45 mA I_{H-} Fraction < ± 0.1 mA
Duty factor	1.25 % (25 Hz repetition, 500 us pulse width)
Beam Emittance	< 1.5 π mm mrad
Lifetime of ion source	1.5 – 2 months (1,350 hours achieved)



[1] H. Oguri, et al., Rev. Sci. Instrum. **87**, 02B138 (2016).

H- beam production from RF-driven ion source

① production of inductively coupled electromagnetic field

Inductively coupled E and B field

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}_{\mathbf{coil}} + \varepsilon_0 \mu_0 \frac{\partial \boldsymbol{E}}{\partial t}$$

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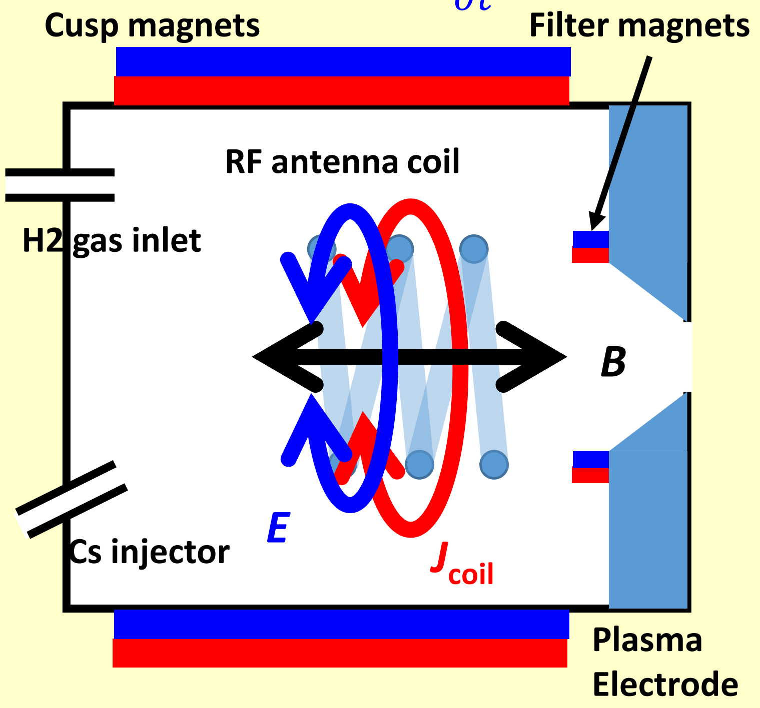
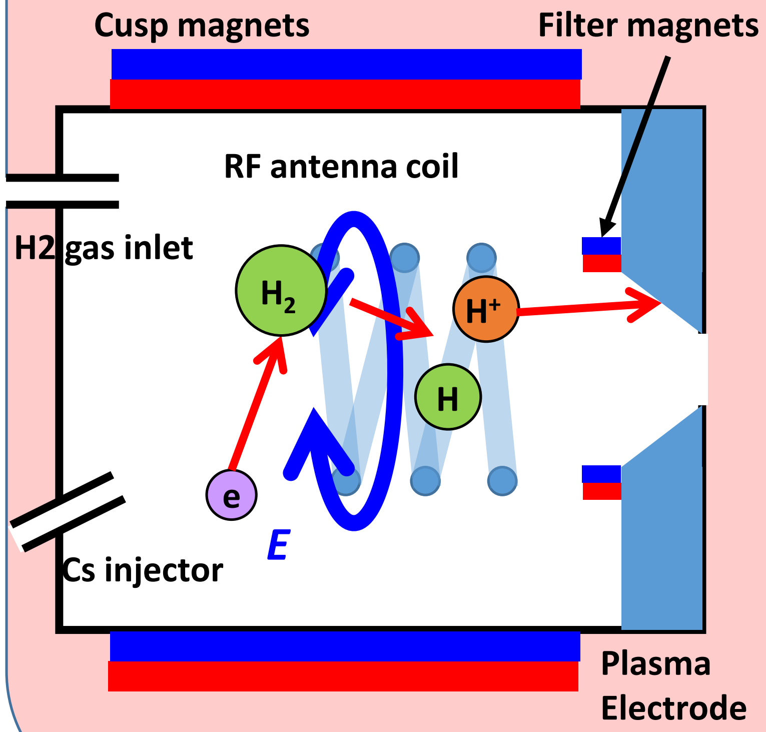


② Production of plasma and proton/atomic flux to PE

Main ionization/dissociation reac.

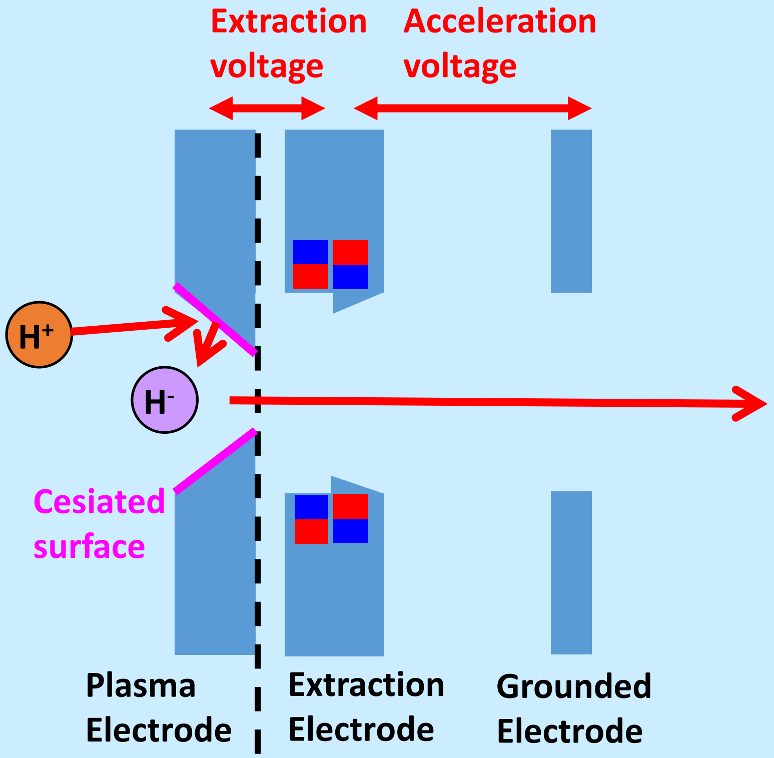
$e + H_2 \rightarrow e + H_2^+$ or $e + 2H$

$\rightarrow e + H^+ + H + e$



③ production and extraction of H-

Two stage acceleration of H- by three electrodes with aperture.



J-PARC H$^-$ ion source

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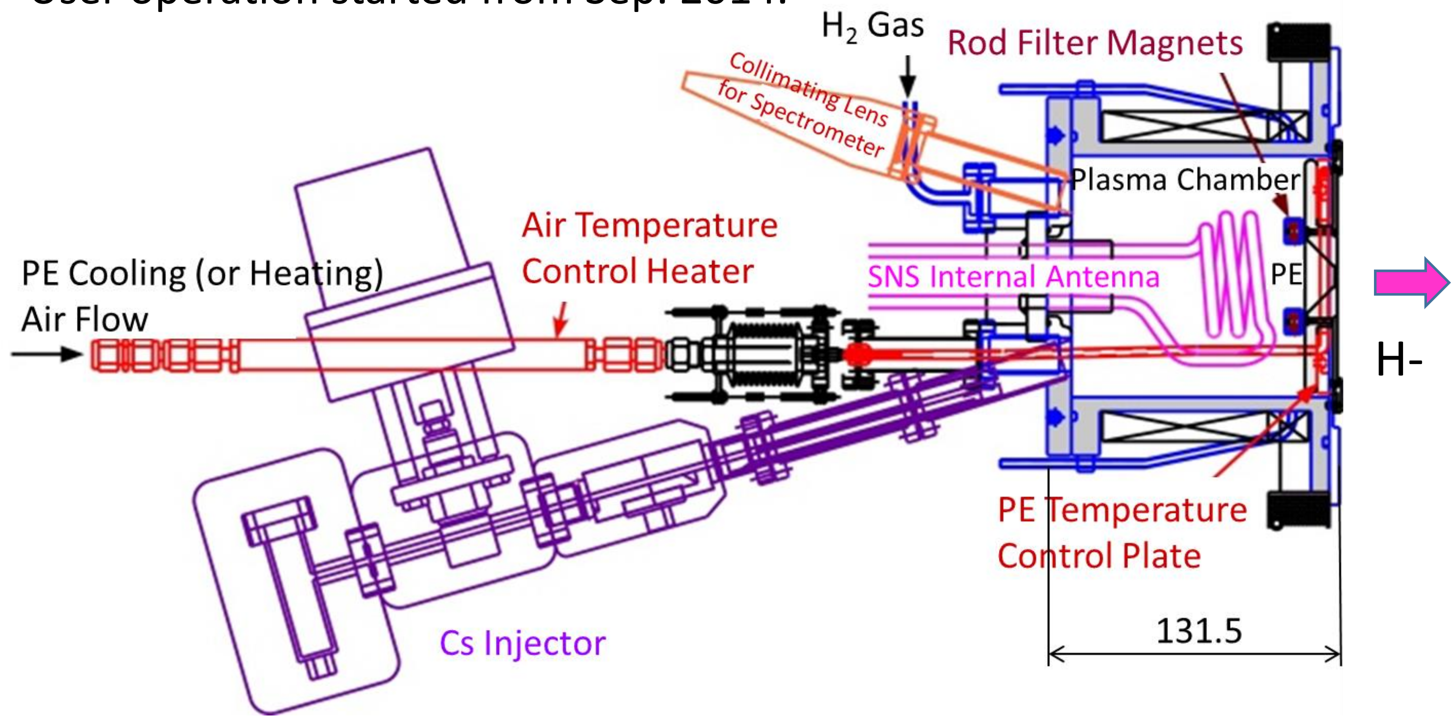

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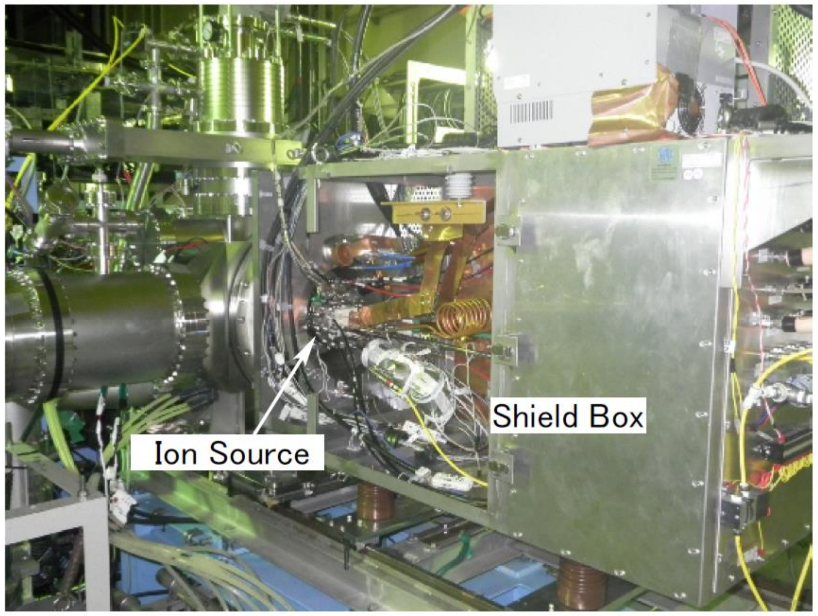
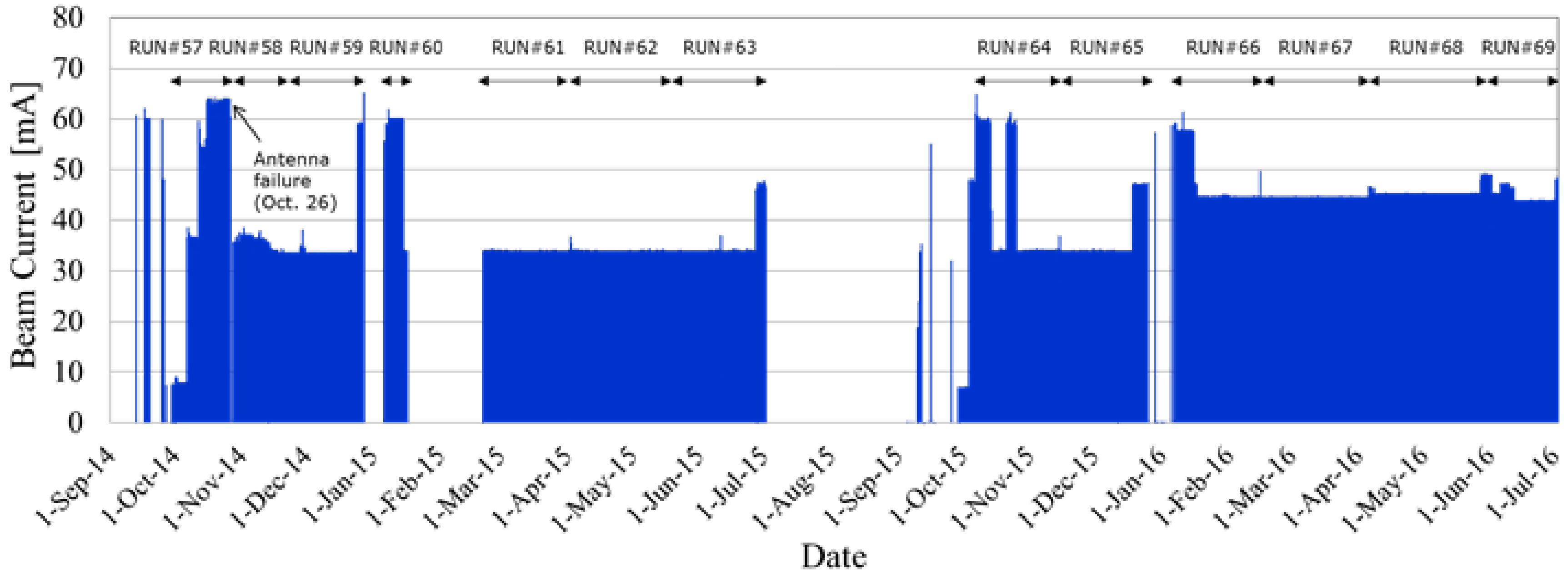


Operation Status of J-PARC H^- ion source: Improvement of beam performance

- Operation of the RF ion source started from Sep. 2014.
- In this **2 years** (RUN#57 – 69), several beam improvement has been achieved **without serious trouble**.
  - RUN#57 : RF H- ion source was commenced operation
  - RUN#58 : User operation with the RF H- IS was started.
  - RUN#60 : 3GeV-synchrotron demonstrated **1-MW-equivalent beam**.
  - RUN#66 : H- current for the user operation increased **33 → 45 mA**.
  - RUN#68 : **1,350 h** continuous operation was achieved with 45 mA.

Beam current in these 2 years operation.

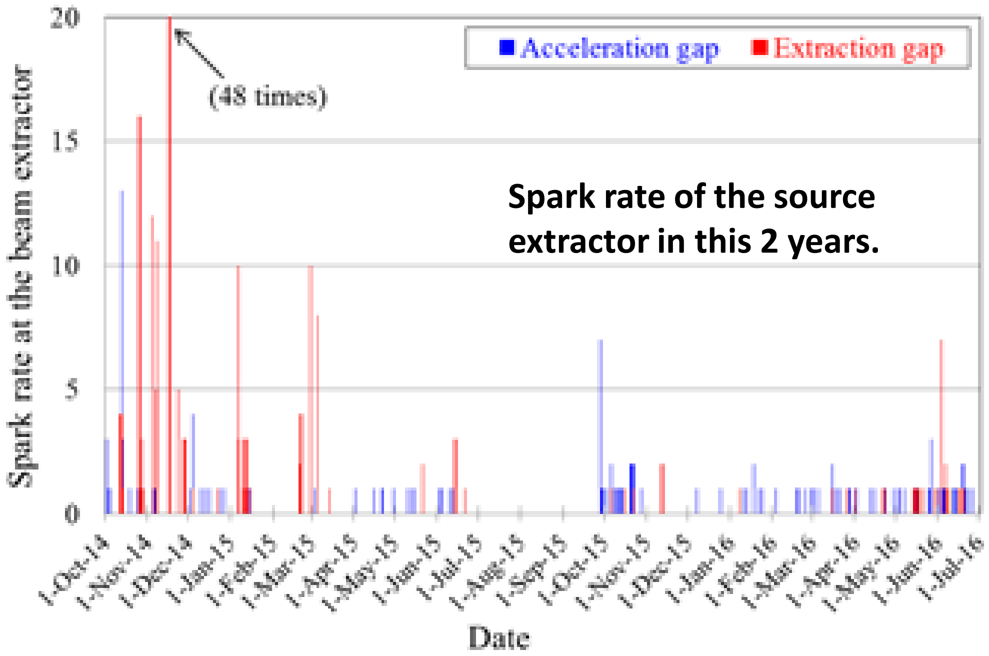


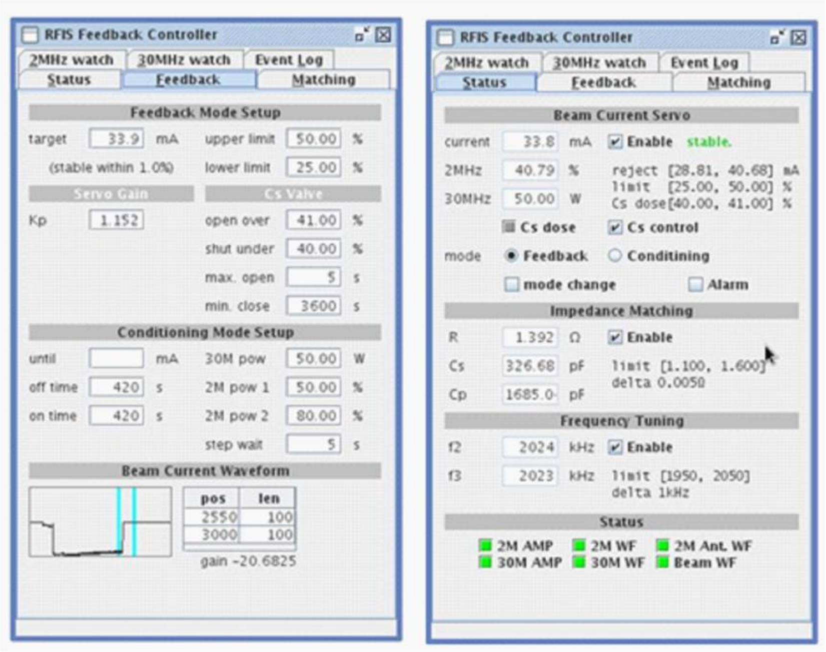
[1] H. Oguri, et al., "Operation Status of the J-PARC RF-driven H- Ion Source", *5th International Symposium on Negative Ions, Beams and Sources*, 12 – 16 Sep. 2016, Oxford, UK.

Operation Status of J-PARC H$^-$ ion source: Decrease of spark rate and Feed Back

- **Spark rate** in the ion source extractor has been decreased to **less than once per a day**, which is acceptable for user operation.
- The maximum spark event up to 48 occurred in the extraction gap in Nov. in 2014, when the excessive amount of cesium (Cs) injection was made.
- The spark rate decreased afterward.

- Currently, amount of Cs injected to the ion source in the user operation is **controlled by Feed Back system**.





[1] H. Oguri, et al., "Operation Status of the J-PARC RF-driven H- Ion Source", 5th *International Symposium on Negative Ions, Beams and Sources*, 12 – 16 Sep. 2016, Oxford, UK.

Feed back system

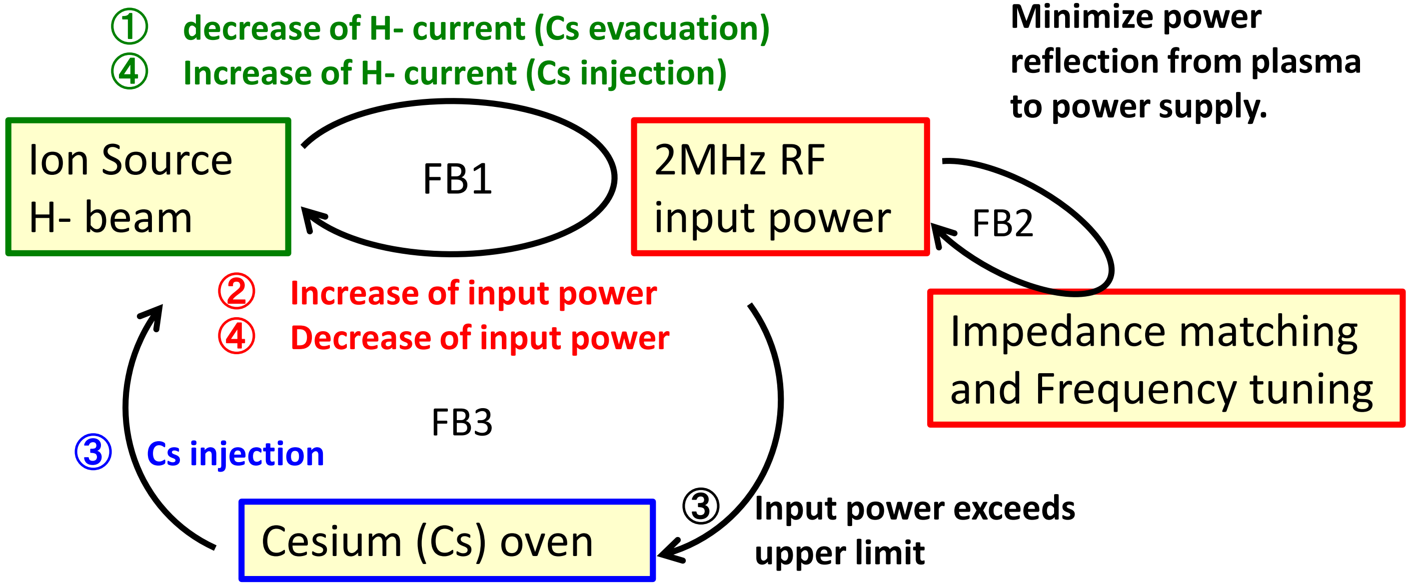
- The Feedback system also keeps **fraction of H- current within ±0.1 mA**.
- In order to keep the current constant, 3 stage Feed Back (FB) systems are applied.

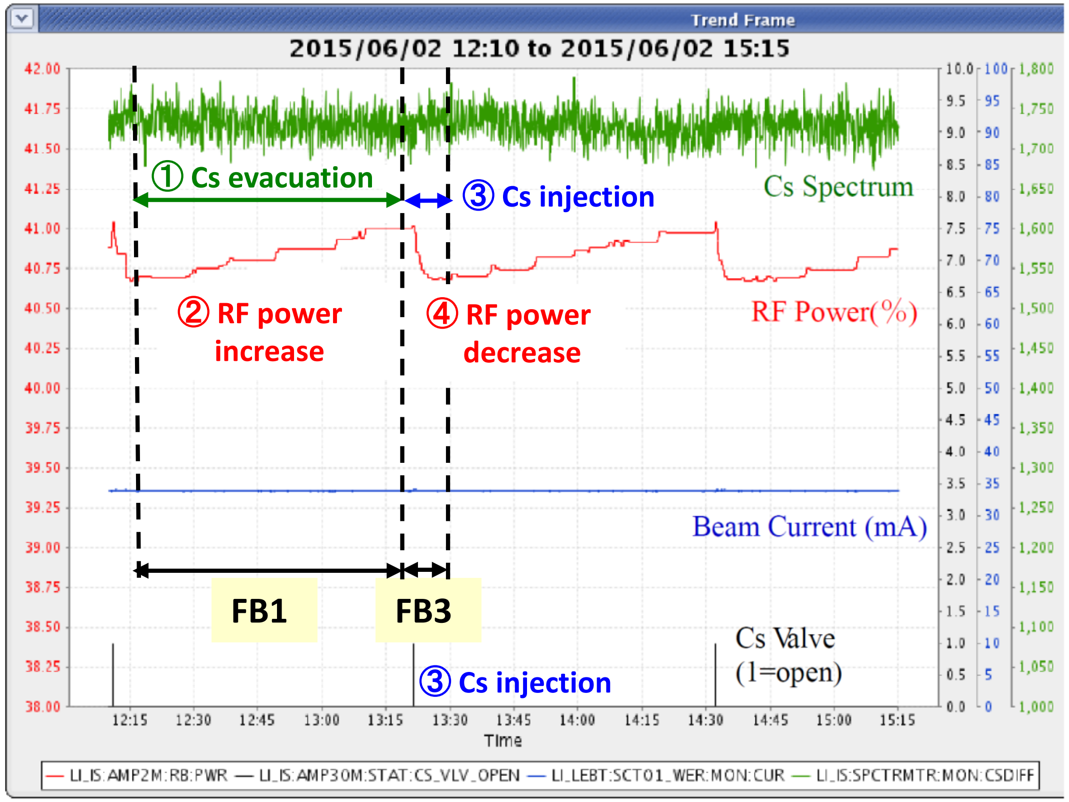
FB1 : In general, **H- current decreases due to Cs evacuation (①)**. In the FB, 2MHz **RF input power increases (②)** which leads to higher H- production rate in the ion source.

FB2 : To minimize **power reflection** due to impedance mismatching between plasma and 50 Ω output of power supply, **impedance matching and frequency tuning** are made each time RF power is varied.

FB3 : When the input **RF power exceeds the upper limit**, Cs injector valve is opened for **Cs injection (③).**

FB1 : Instead of increase in the H- current, **the RF input power decreases by FB1 (④).**





[1] H. Oguri, et al., Rev. Sci. Instrum. **87**, 02B138 (2016).

For further improvement for high power linac

Ion Source status	Present status	Next stage
Beam current	45 mA (in user operation)	**>60 mA**
Duty factor	1.25 % (25 Hz repetition, 500 us pulse width)	**2.5 % (50 Hz repetition, 500 us pulse width)**
Beam Emittance	< 1.5 π mm mrad	
Lifetime of ion source	1.5 -2 months	> 2 months

For improvement of ion source performance …

- Understandings of **plasma behavior** (distribution, particle flow, dominant reactions, …) in RF sources
- Understandings of **relation between ion source equipment, discharging conditions** and plasma behavior

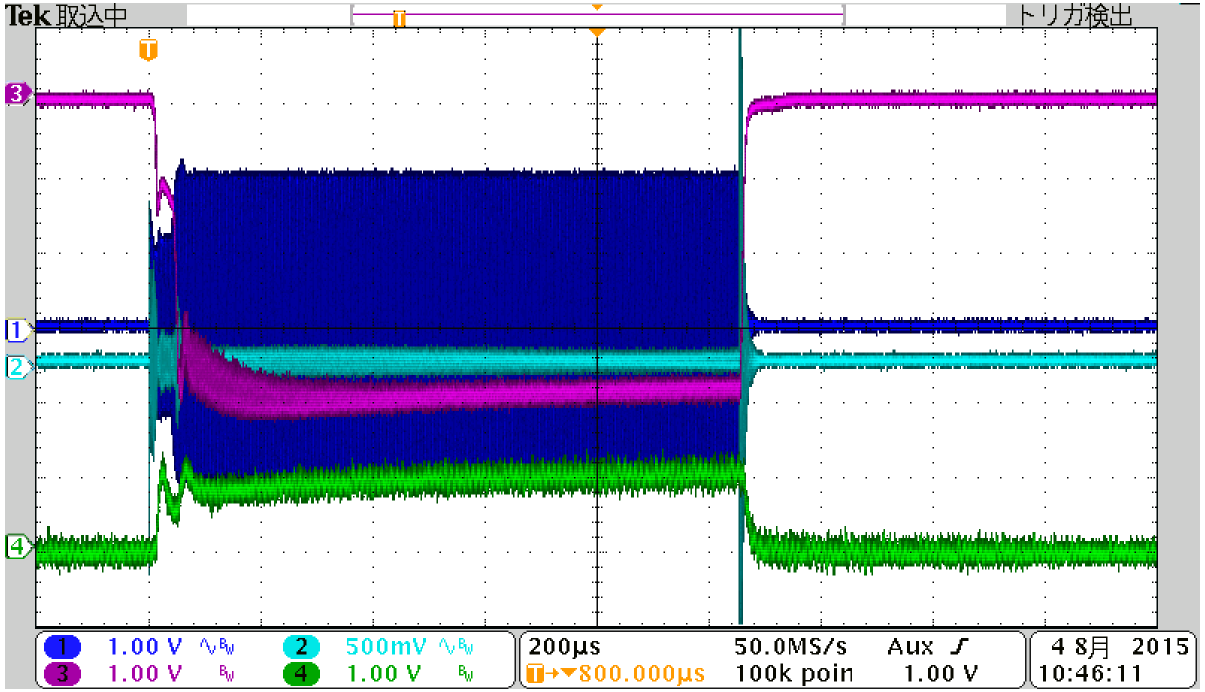
are necessary.

In J-PARC, following **experimental and numerical studies** are on-going.

- Off-line study for high current operation in **Test-stands**
- Development of **Numerical model** for RF plasma.

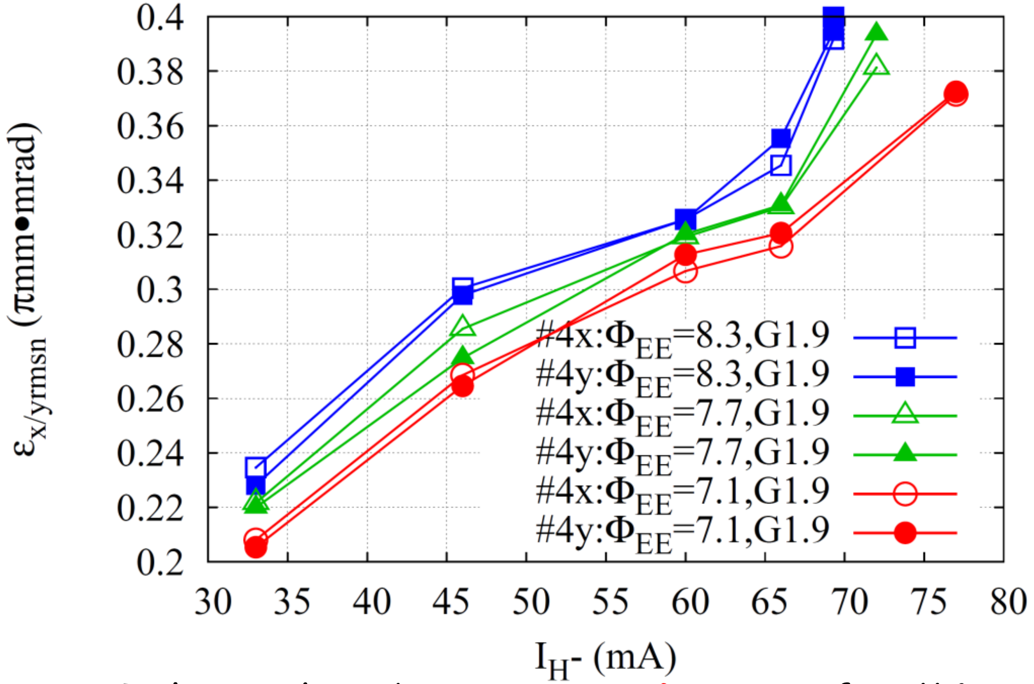
Offline R&D of ion source

Measured Waveforms for I_{H^-}=80mA



Measured waveforms of 2MH-RF forward & reflected voltages V_{RFF}(trace1, arb. : P_{RF}=50kW) & V_{RFR}(trace2, arb), H⁻ ion intensity I_{H}-(trace3, 20mA/Div. : initial 500µs average of flat top is 80mA) and extraction current I_{ext}(trace4, 100mA/Div.) for #2 PCH with Φ_{EE}=7.1mm & G1.9mm.

ε_{xrmsn} & ε_{yrmsn}=0.394 & 0.394πmm·mrad.



Relationships between I_{H^-} & $\varepsilon_{x/yrmsn}$ for #4 PCH with Φ_{EE} of 8.3,7.7 and 7.1mm.

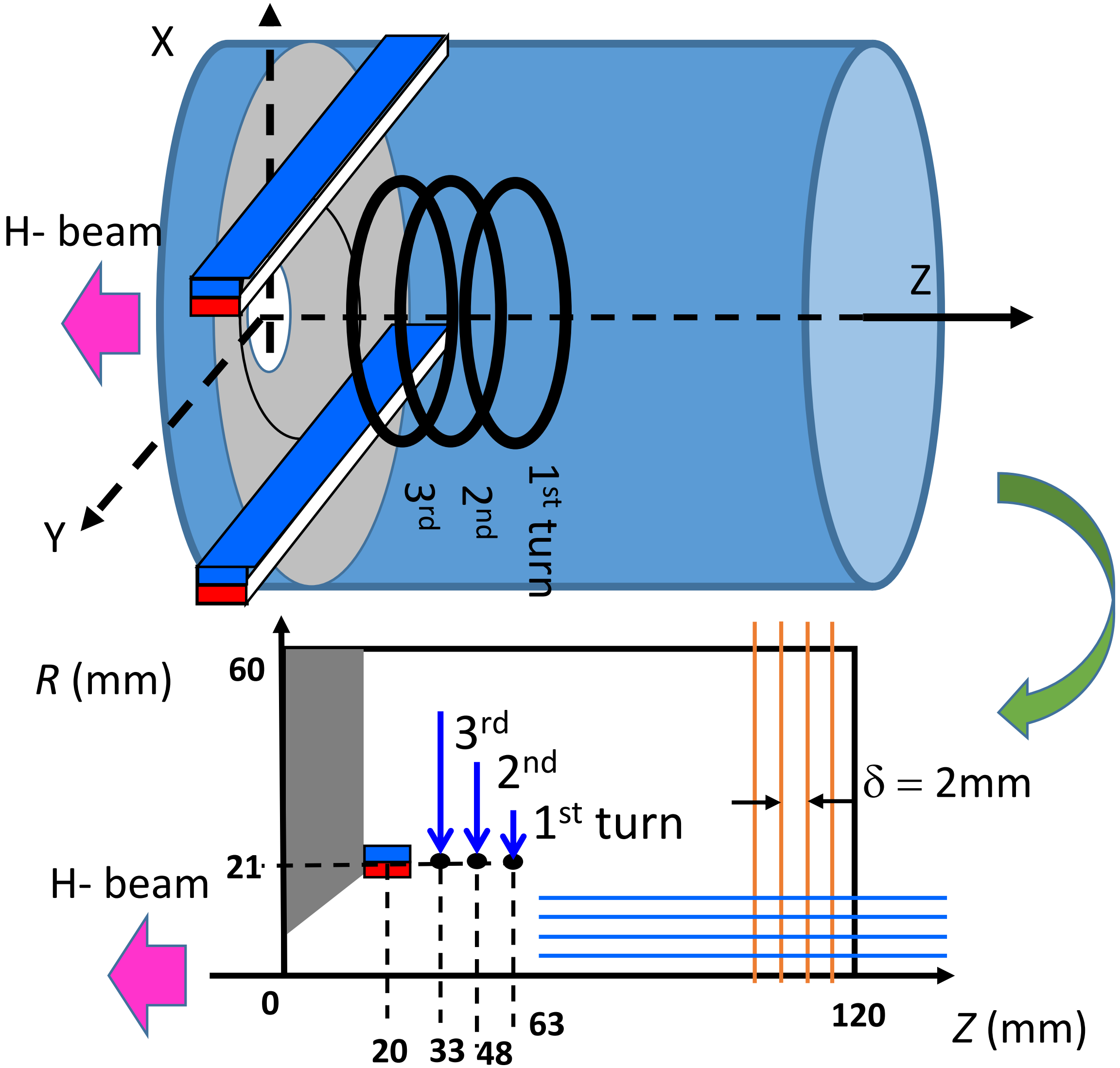
In the offline study, H- beam intensity up to **80 mA** was achieved with normalized RMS emittance **0.394πmm•mrad**.

The next challenge is **high current and continuous operation with lower RMS emittance** in the high beam current operation.

By Ueno ICIS2015 2015/8/25 @New York

Development of numerical model

2D -3V (two dimensional in real space, three dimensional in velocity)
PIC-MC (Particle-In-Cell, Monte-Carlo) model is developed and applied.



2D -3V
modeling

Particle transport (e^-, H^+, H_2^+, Cs^+)
Leap—Frog method

$$m\frac{d\boldsymbol{v}}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) + \boldsymbol{F}_{\mathbf{CC}} + \boldsymbol{F}_{\mathbf{inelas}}$$

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v}$$

Coulomb collision
(Binary Collision Model)

Elastic/Inelastic collision
(Null Collision Method)

EM field
B, E

Δt

Plasma current
J_{pl}

Inductively coupled

$$\nabla \times \boldsymbol{B} = \mu(\boldsymbol{J}_{\mathbf{RF}} + \boldsymbol{J}_{\mathbf{pl}}) + \varepsilon\mu\frac{\partial \boldsymbol{E}}{\partial t}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

Capacitive

$$\mathrm{div}\,\boldsymbol{E} = \sigma_{\mathrm{coil}}/\varepsilon$$

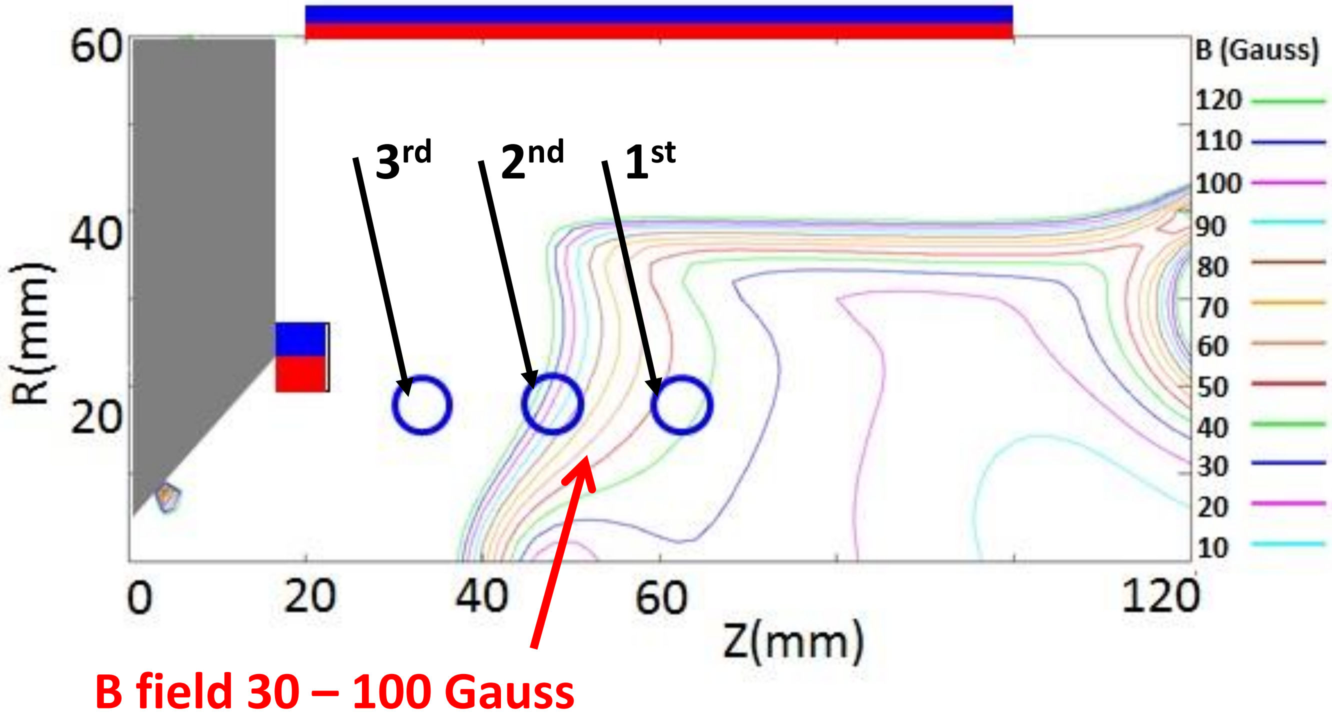
Electromagnetic field
FDTD・SOR model

[1] T. Shibata, et al., "High density plasma calculation of J-PARC RF negative ion source", *5th International Symposium on Negative Ions, Beams and Sources*, 12 – 16 Sep. 2016, Oxford, UK.

APPENDIX : Calculation parameters

parameters	
RF antenna current (J_0)	280 A
RF antenna voltage (V_0)	1800 V
RF frequency (ω_{RF})	2 MHz
H_2 gas pressure (p_{H2})	1.0 Pa
H_2 temperature (T_{H2})	500 K

Magnetic flux density distribution by filter, cusp and electron suppression magnets.



Dealing of antenna voltage and current:

- Time variation of antenna current:
  $J(t) = J_0 \sin(2\pi\omega_{RF}t)$
- Amplitude of antenna voltage is given as follows;
  1st turn : $V_0 = 1800V$
  2nd turn : $V_0 = 1800\ V \times 0.75$
  3rd turn : $V_0 = 1800\ V \times 0.5$

  Time variation of antenna voltage :
  $V(t) = V_0 \cos(2\pi\omega_{RF}t)$

APPENDIX : Calculation parameters

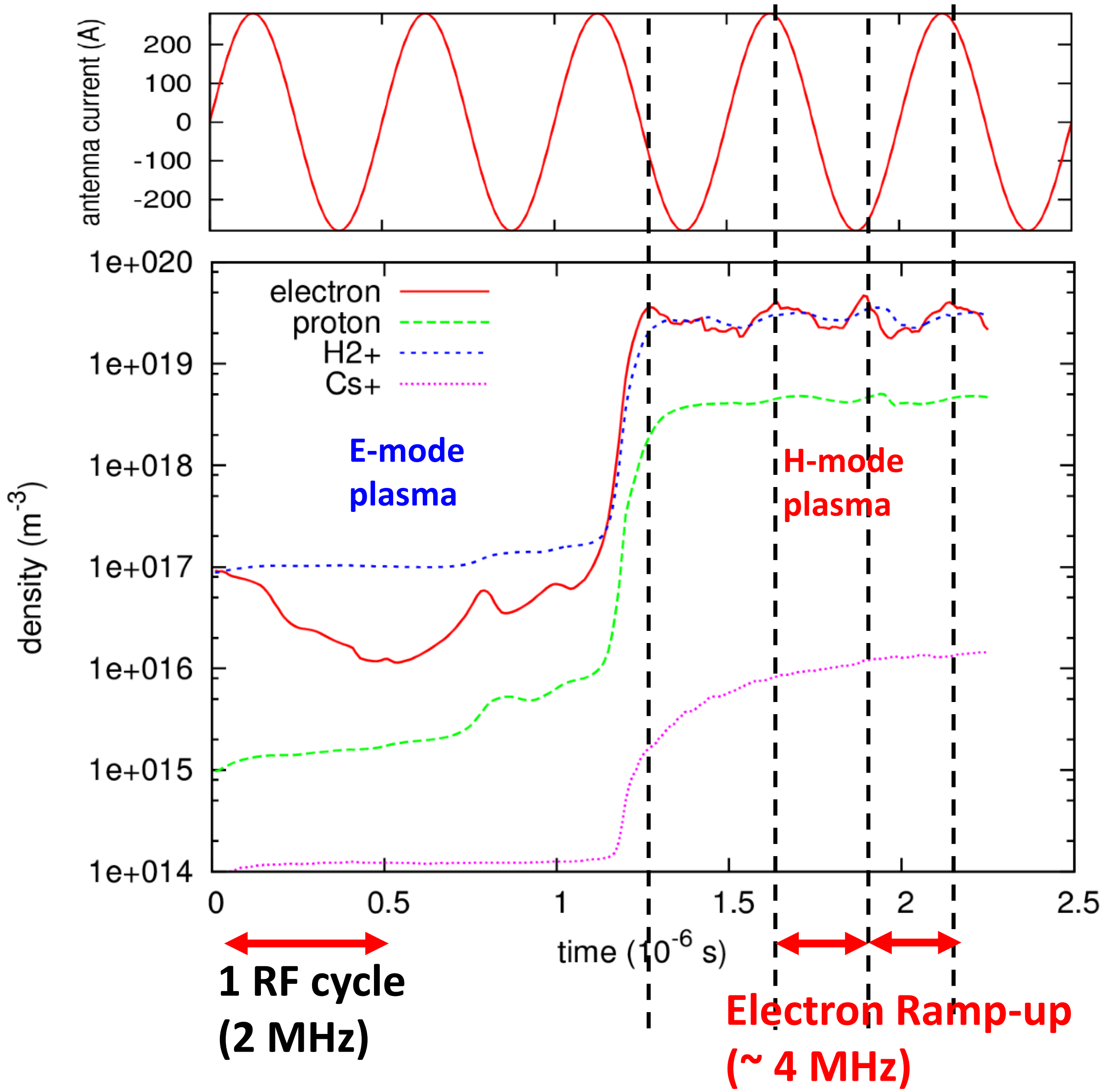
- Two different conditions of RF plasma are calculated;

CASE 1 : low density plasma calculation (just after plasma ignition)
CASE 2 : high density plasma calculation (reaching to steady state)

parameters	CASE1	CASE2
Time step width for orbit (Δt)	1×10^{-13} s	1×10^{-12} s
Time step width for collision (Δt_{col})	1×10^{-11} s	1×10^{-10} s
Cell width for FDTD (Δx)	2×10^{-3} m	2×10^{-3} m
Particle number	**$10^5 – 10^6$**	**$10^6 – 10^7$**
Particle weight	**$10^7 – 10^8$**	**$10^8 – 10^9$**
Initial electron density	**6.0×10^{16} m^{-3}**	**1.0×10^{17} m^{-3}**
Initial proton density	**6.0×10^{15} m^{-3}**	**1.0×10^{15} m^{-3}**
Initial H2+ density	**5.4×10^{16} m^{-3}**	**9.9×10^{16} m^{-3}**

Time variation of spatially averaged plasma density

- Plasma density : $n_p \sim 10^{19} - 10^{20}\ m^{-3}$



- Numerical simulation for (i) ignition and (ii) steady-state phase RF plasma has been made.
- In (i) **E-mode** phase, low density (**$n_p \sim 10^{17}\ m^{-3}$**) RF plasma takes place.
- After 1 us, RF plasma transition from E-mode to H-mode is seen.
- In **H-mode** (steady state) plasma (ii), **electron density oscillation frequency is ~ 4 MHz**, doubled value of RF frequency. The plasma density is in the order of **$n_p \sim 10^{19}\ m^{-3}$** for this case (50 kW power injection from internal antenna).

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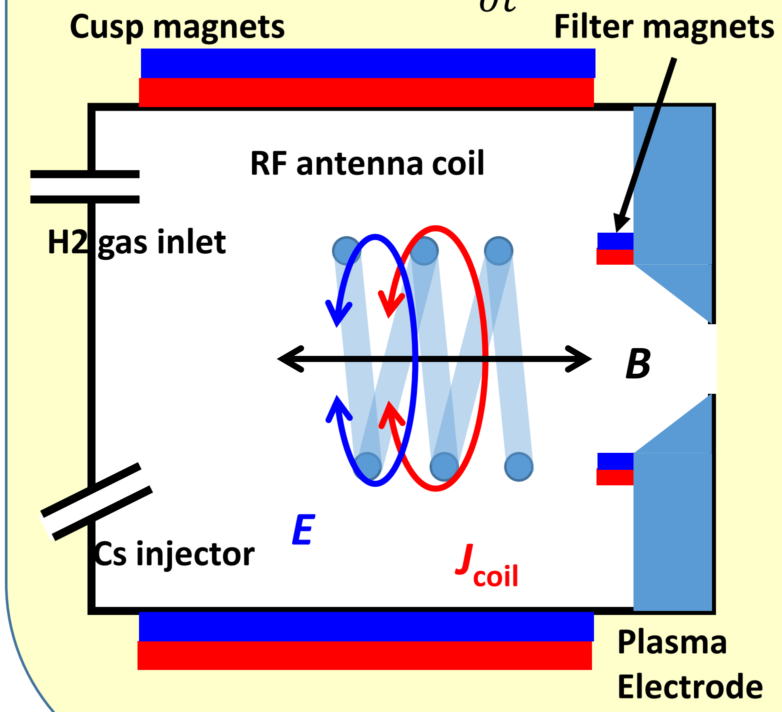
H- beam production from RF-driven ion source

① production of inductively coupled electromagnetic field

E-mode plasma

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}_{\mathbf{coil}} + \varepsilon_0 \mu_0 \frac{\partial \boldsymbol{E}}{\partial t}$$

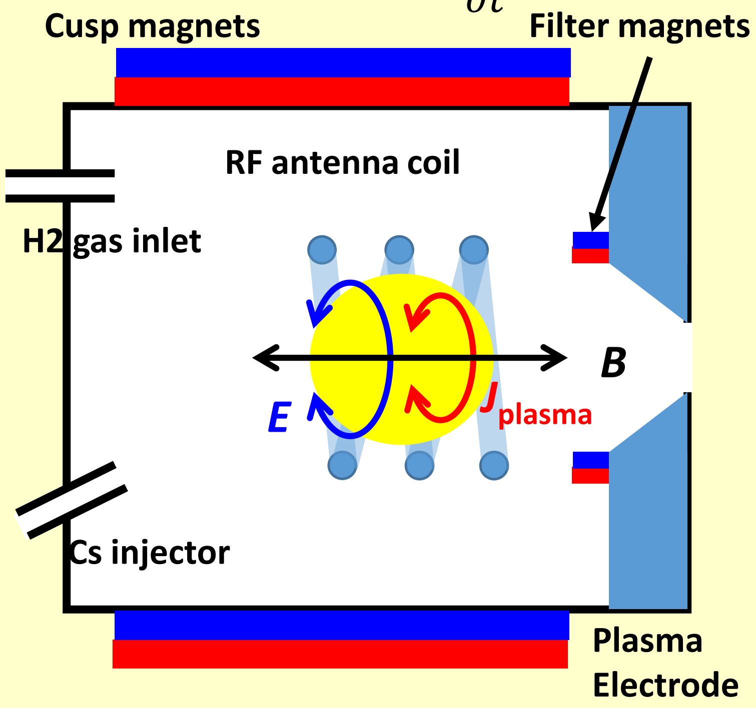
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$



H-mode plasma

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}_{\mathbf{plasma}} + \varepsilon_0 \mu_0 \frac{\partial \boldsymbol{E}}{\partial t}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$



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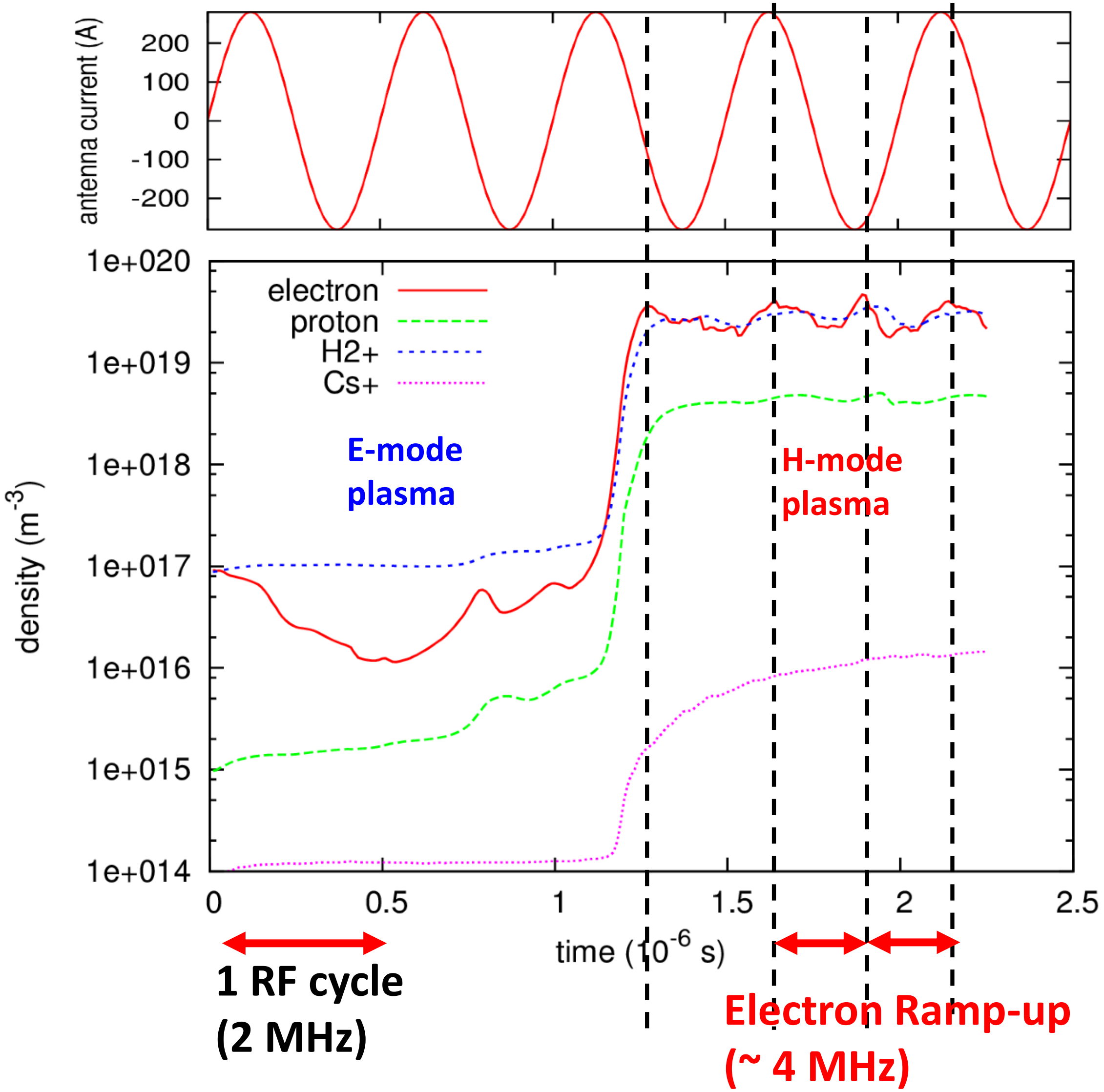

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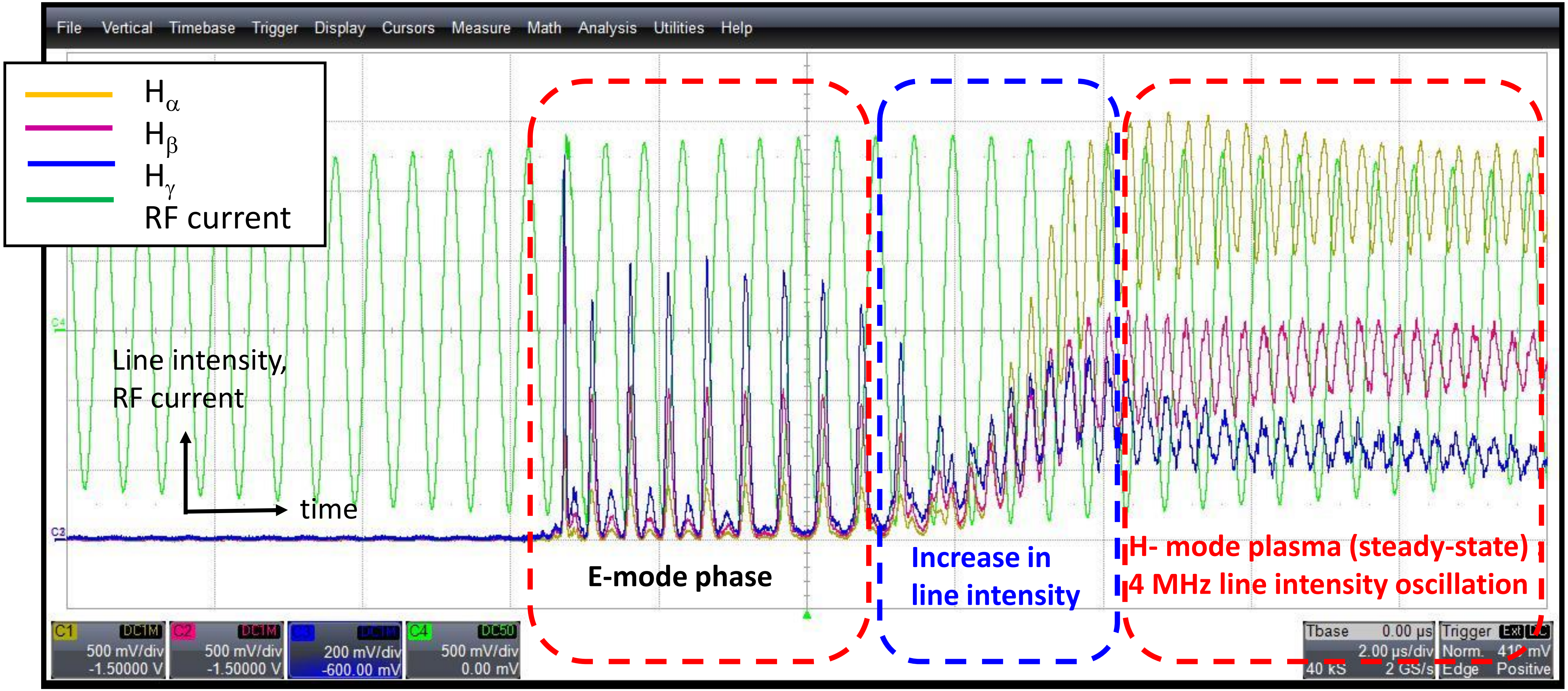
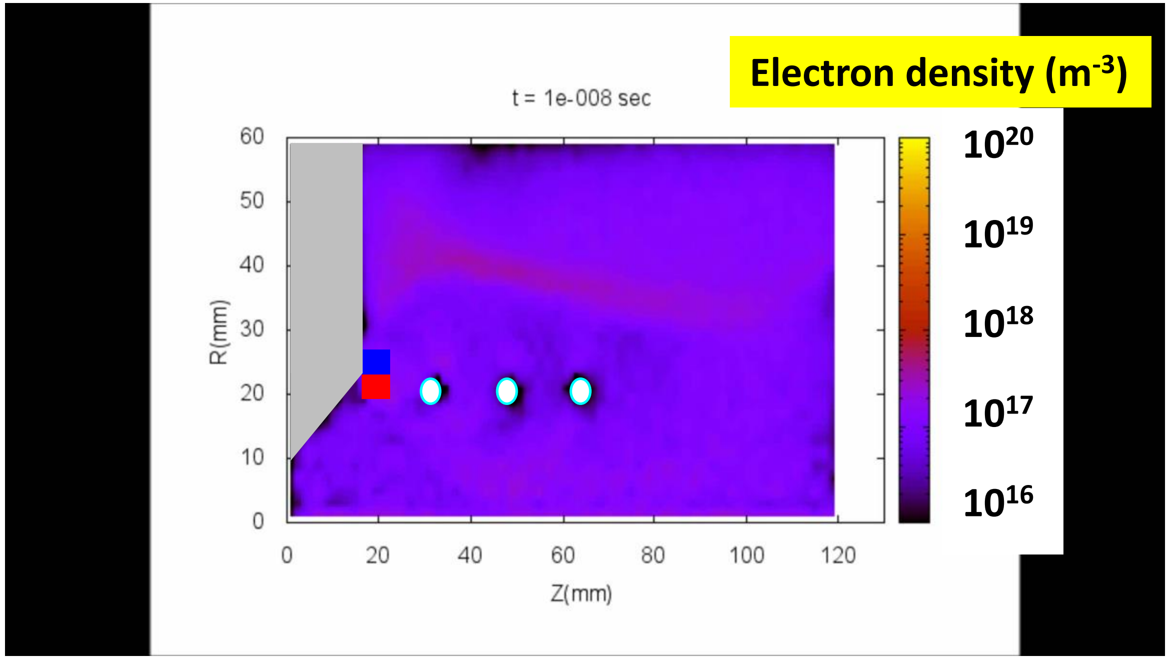
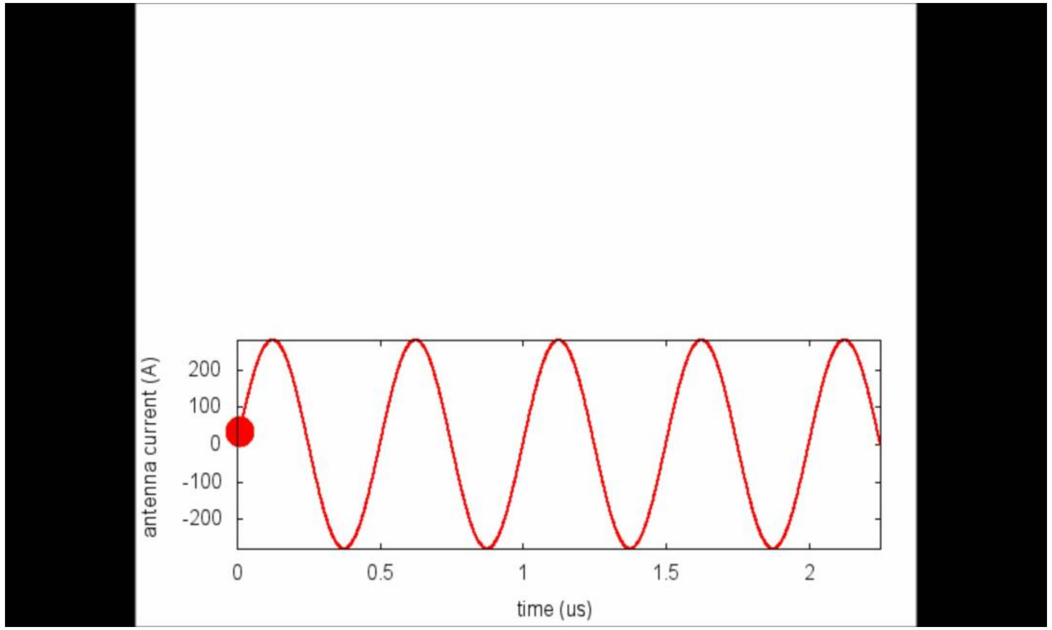
APPENDIX: Time Structure of Balmer line emission observed in Linac4 RF H- source

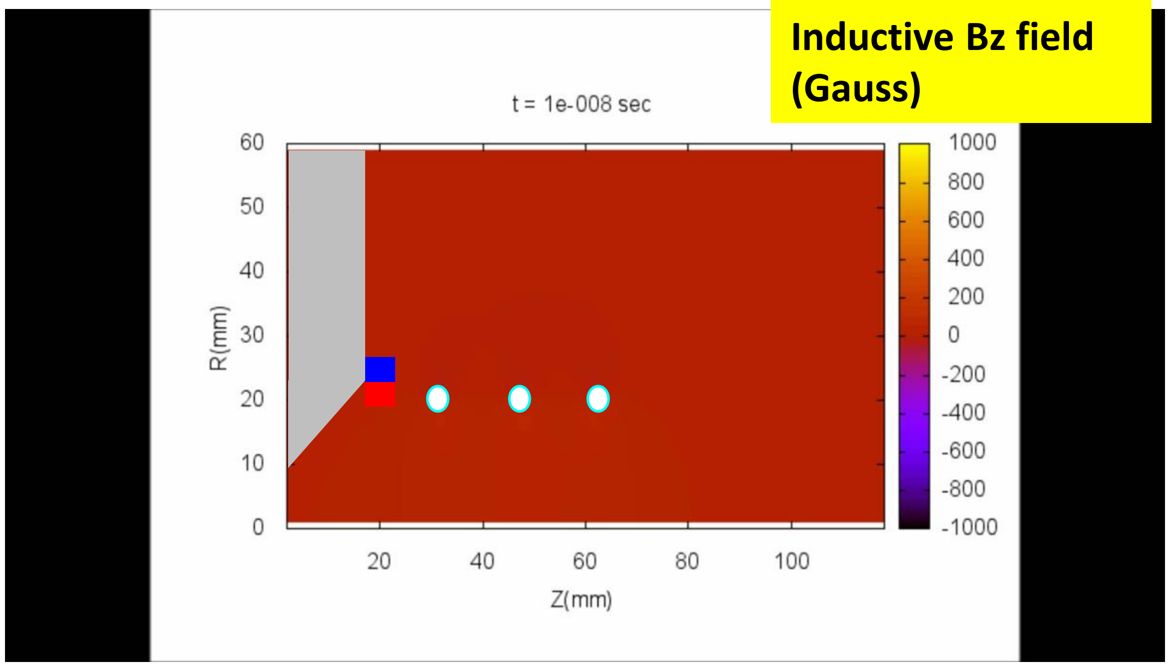


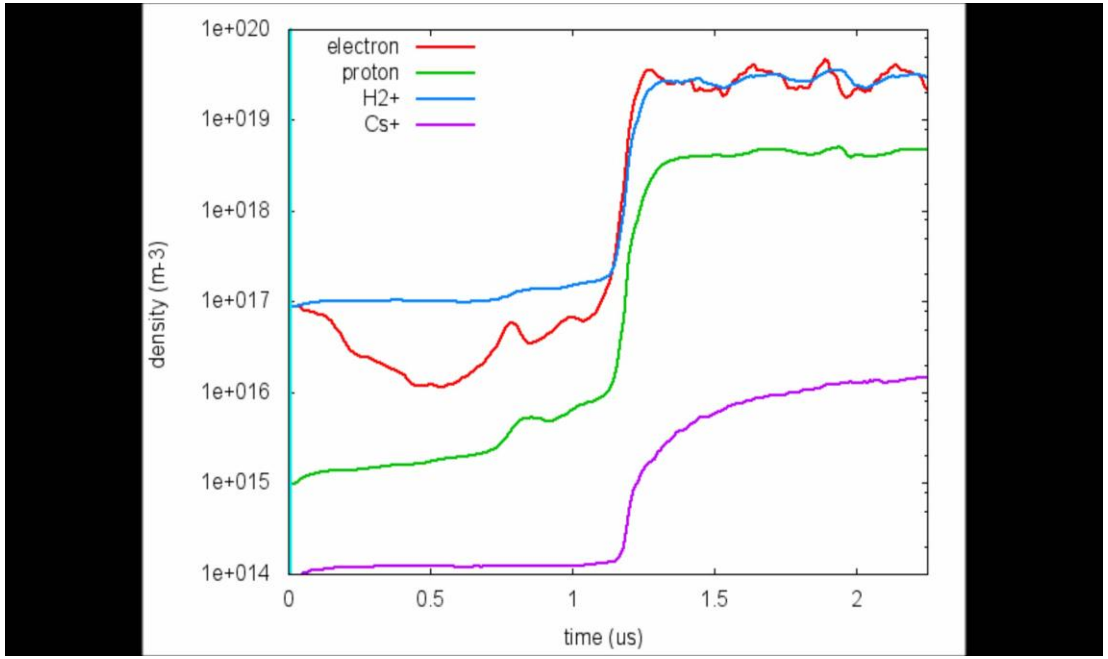
[1] J. Lettry, et al., Rev. Sci. Instrum. **85**, 02B122 (2014).

[2] T. Shibata, et al., AIP Conf. Proc. **1655**, 020008 (2015).


Electron density (m-3)
t = 1e-008 sec
R(mm)
Z(mm)
0 10 20 30 40 50 60
0 20 40 60 80 100 120
10^20
10^19
10^18
10^17
10^16

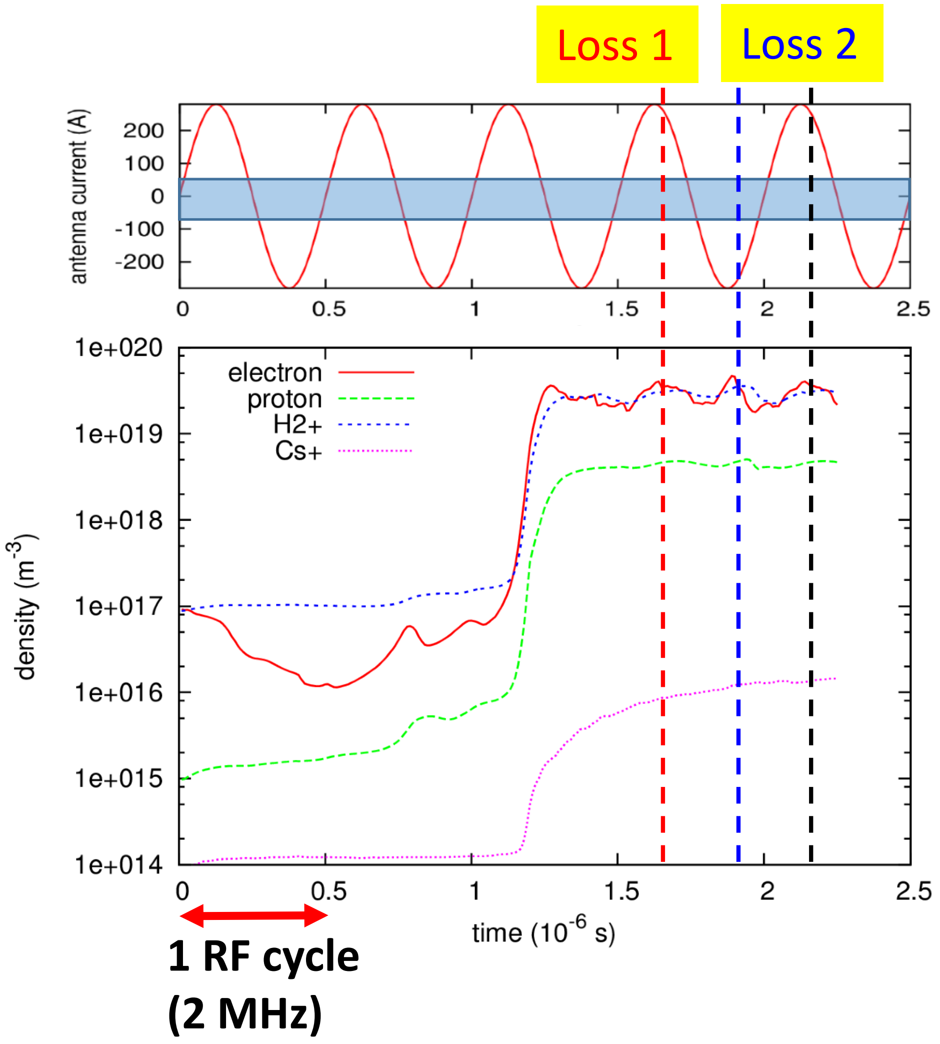

antenna current (A)
time (us)
200 100 0 -100 -200
0 0.5 1 1.5 2

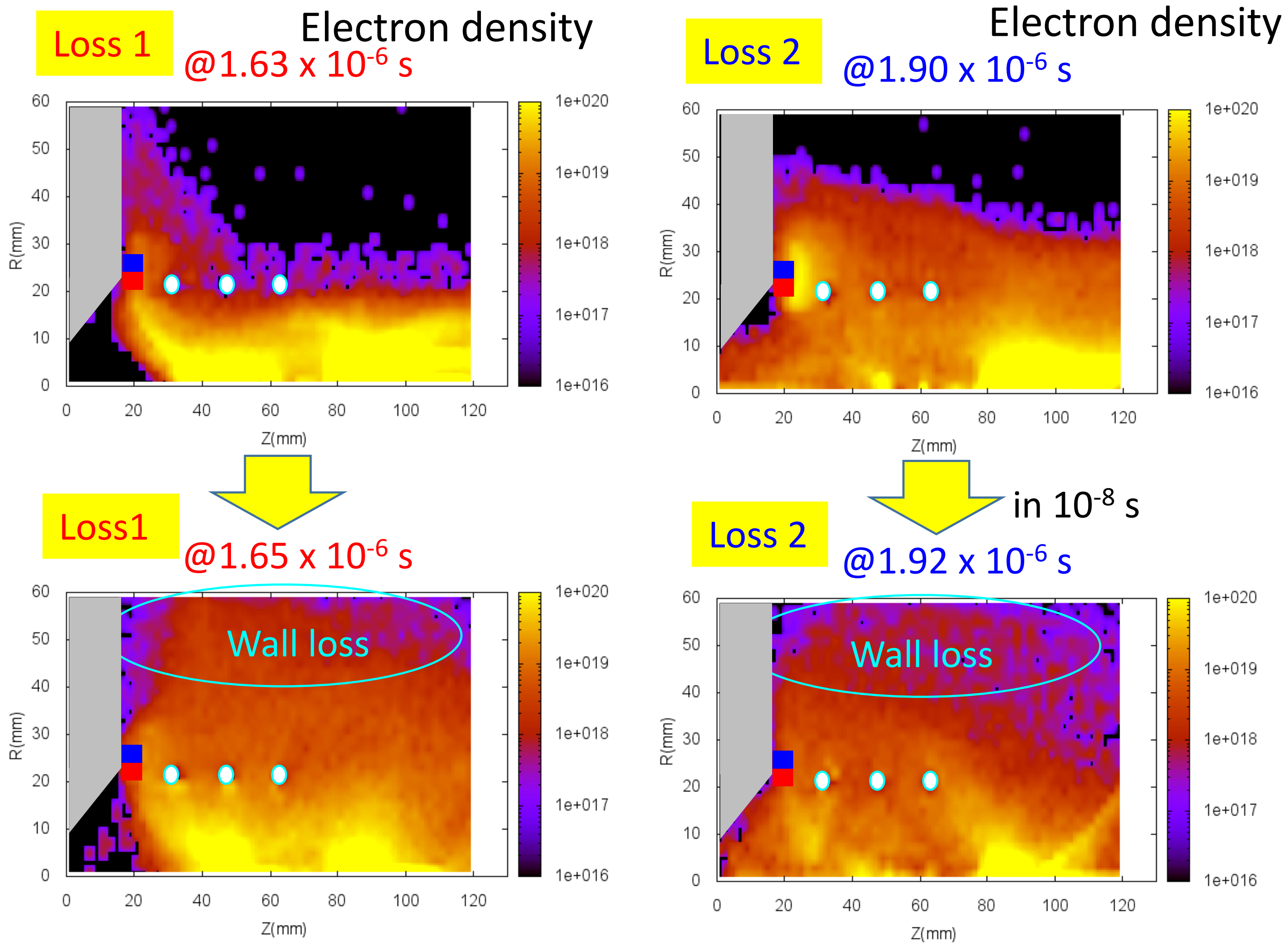

Inductive Bz field (Gauss)
t = 1e-008 sec
R(mm)
Z(mm)
0 10 20 30 40 50 60
20 40 60 80 100
1000 800 600 400 200 0 -200 -400 -600 -800 -1000


electron
proton
H2+
Cs+
density (m-3)
time (us)
1e+020 1e+019 1e+018 1e+017 1e+016 1e+015 1e+014
0 0.5 1 1.5 2

Electron loss takes place at peaks of antenna current

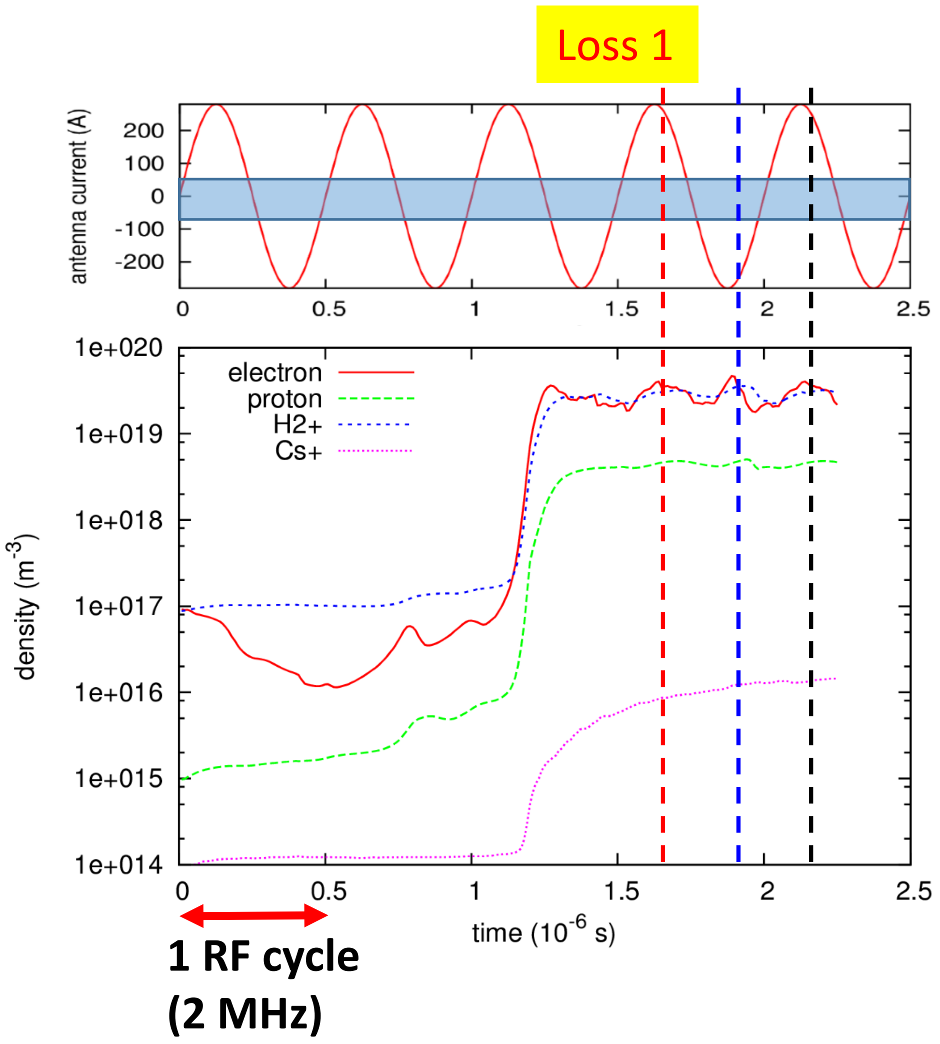
- Plasma density : $n_p \sim 10^{19} - 10^{20}\ \mathrm{m}^{-3}$

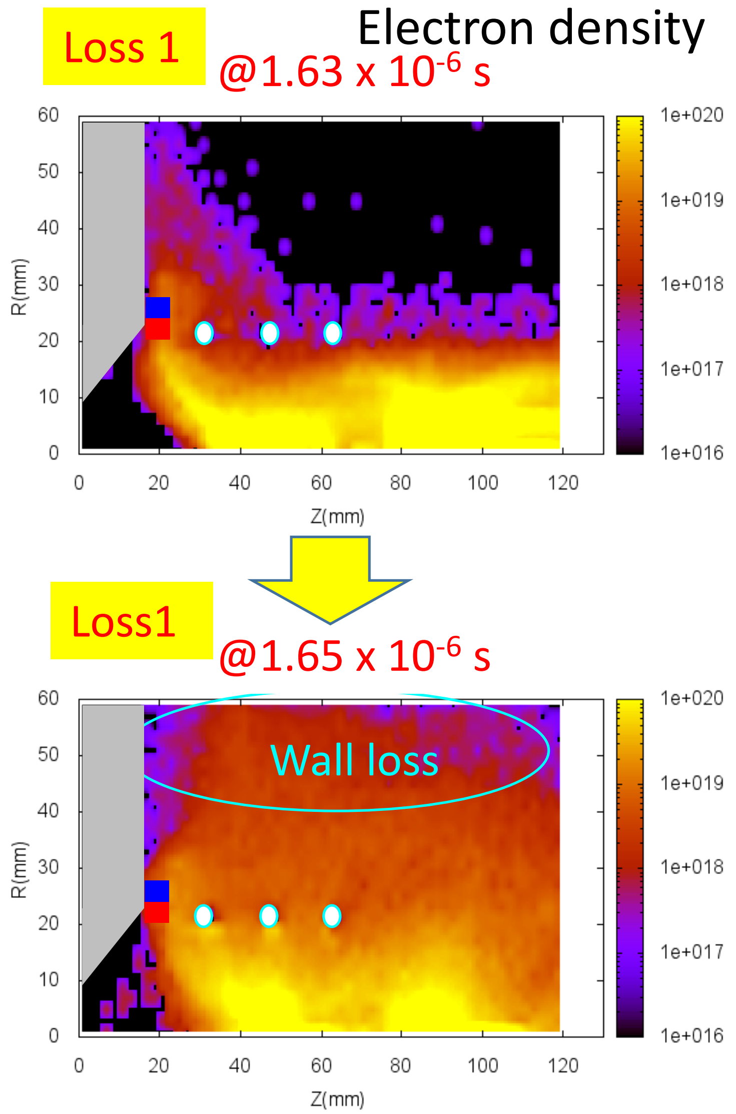


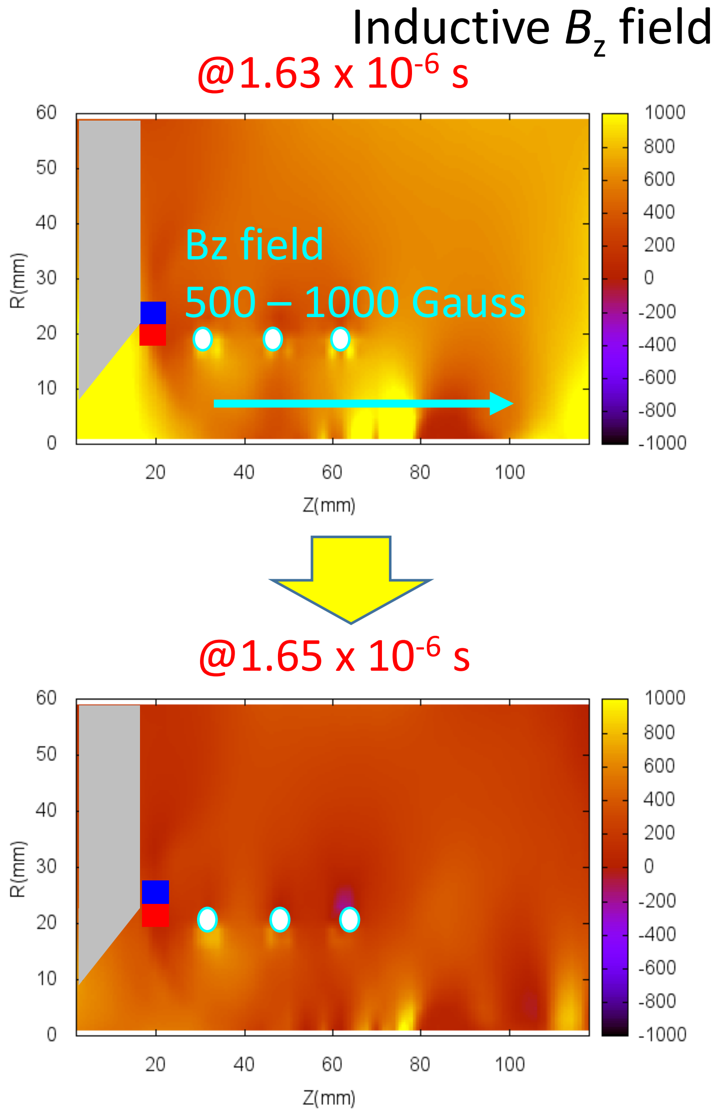


Electron loss takes place at peaks of antenna current

- Plasma density : $n_p \sim 10^{19} - 10^{20}\ \mathrm{m}^{-3}$







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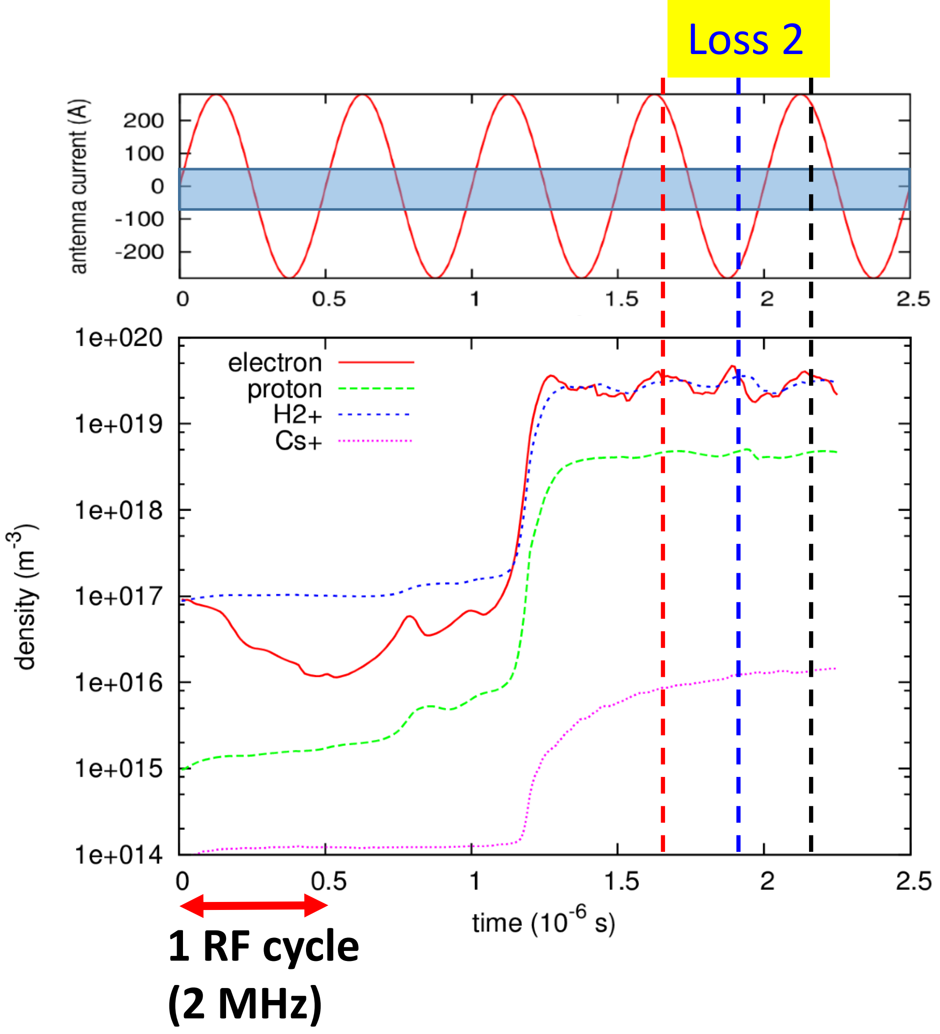
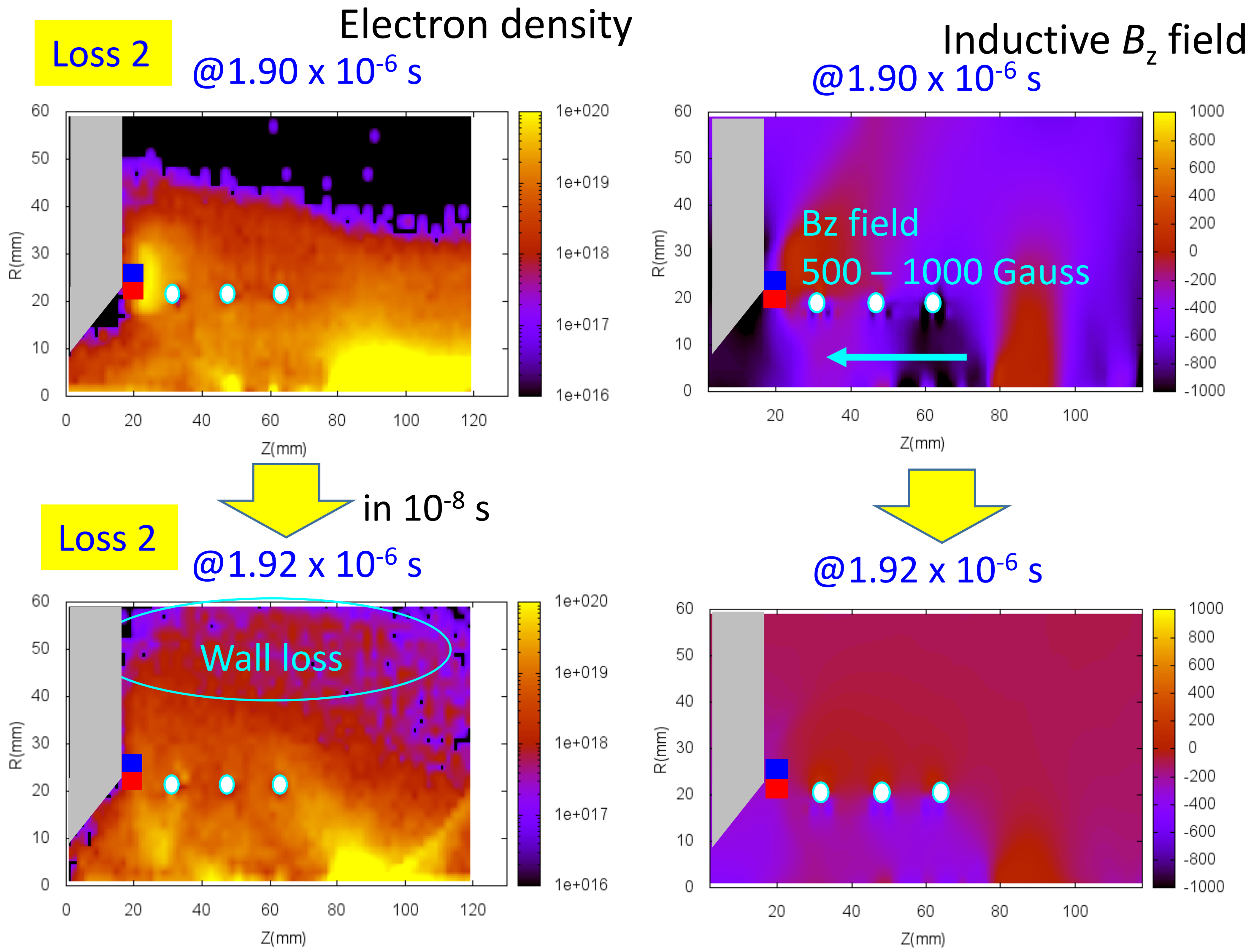
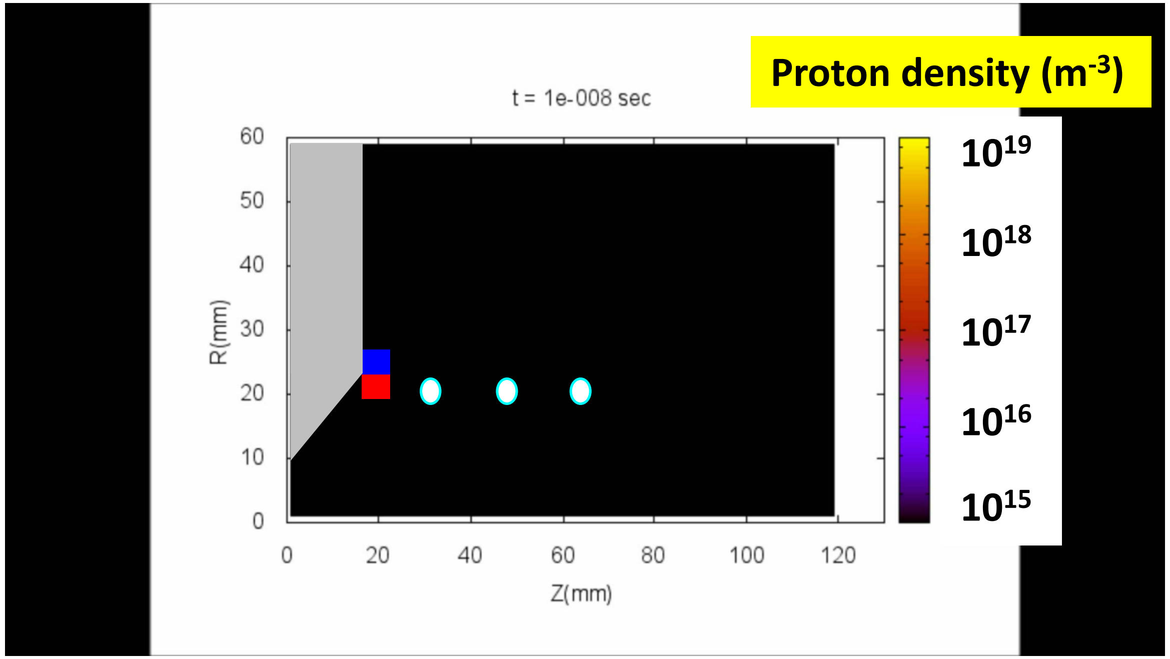
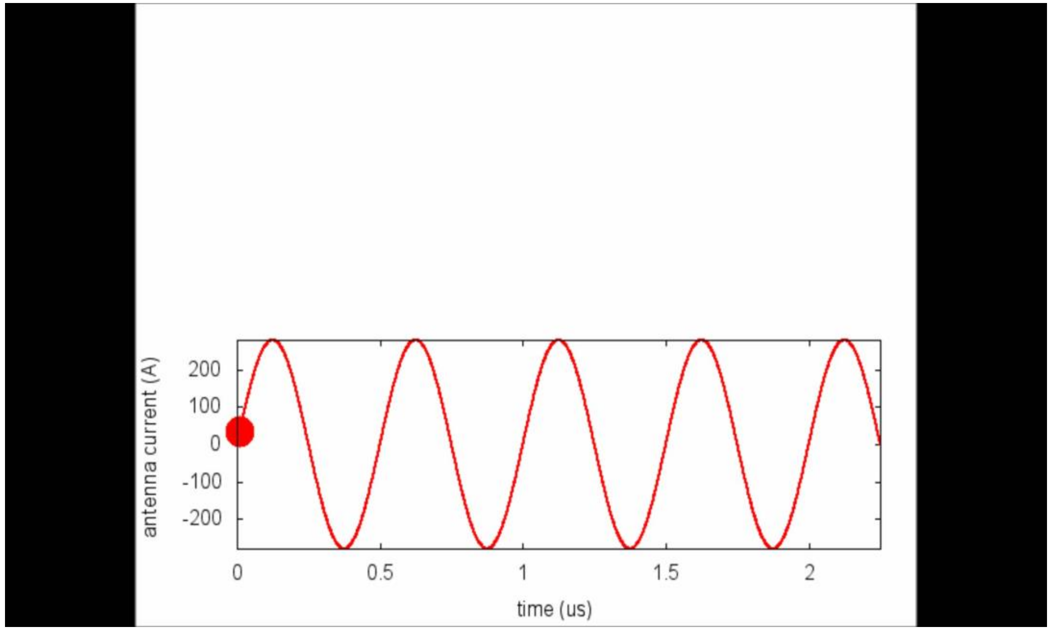
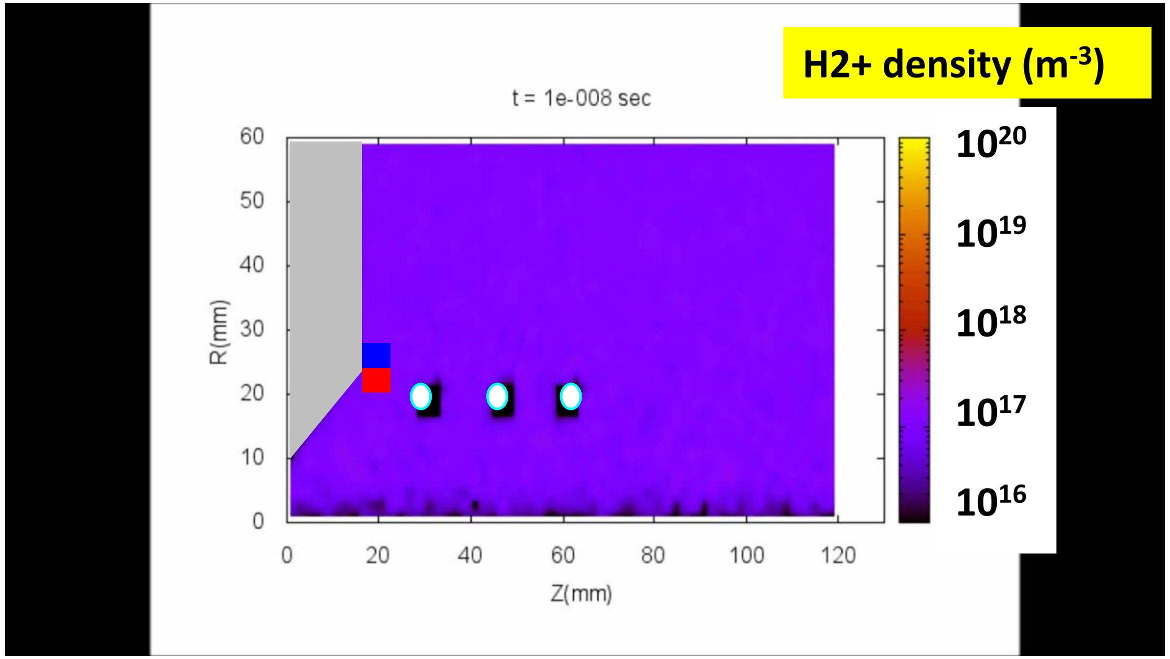
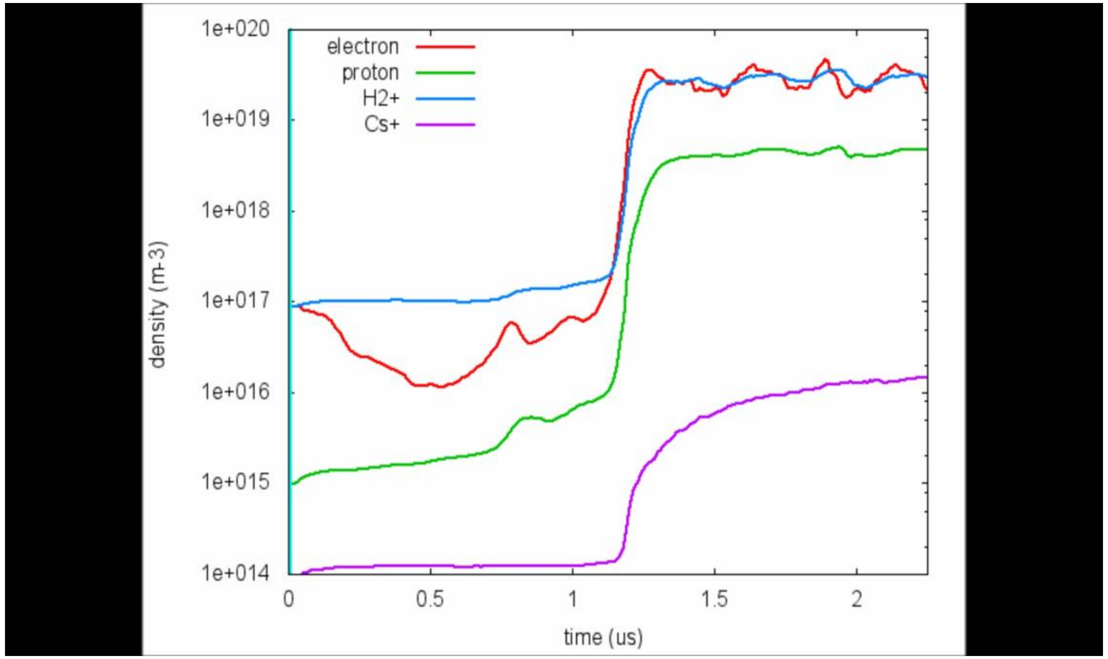





Proton density (m-3)
t = 1e-008 sec
R(mm)
Z(mm)
0 10 20 30 40 50 60
0 20 40 60 80 100 120
10^15 10^16 10^17 10^18 10^19


antenna current (A)
time (us)
200 100 0 -100 -200
0 0.5 1 1.5 2

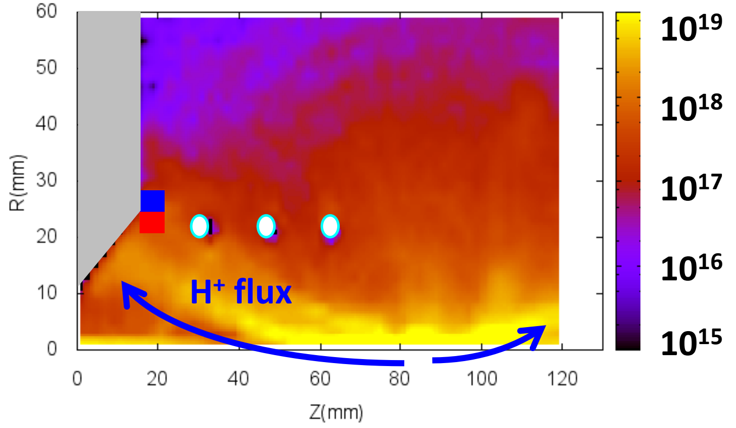

H2+ density (m-3)
t = 1e-008 sec
R(mm)
Z(mm)
0 10 20 30 40 50 60
0 20 40 60 80 100 120
10^16 10^17 10^18 10^19 10^20


electron
proton
H2+
Cs+
density (m-3)
time (us)
1e+014 1e+015 1e+016 1e+017 1e+018 1e+019 1e+020
0 0.5 1 1.5 2

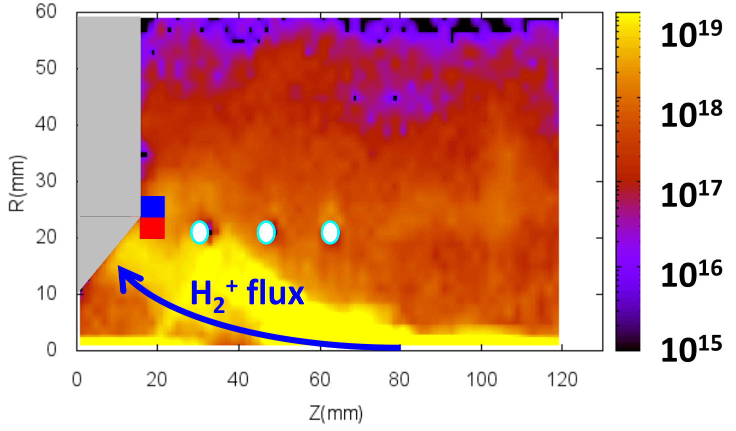
Proton (H^+) and H_2^+ flows toward Plasma Electrode (cesiated surface)

Four processes for H^+ and H_2^+ flux production (seen in the calculation)

Proton density (m^{-3})

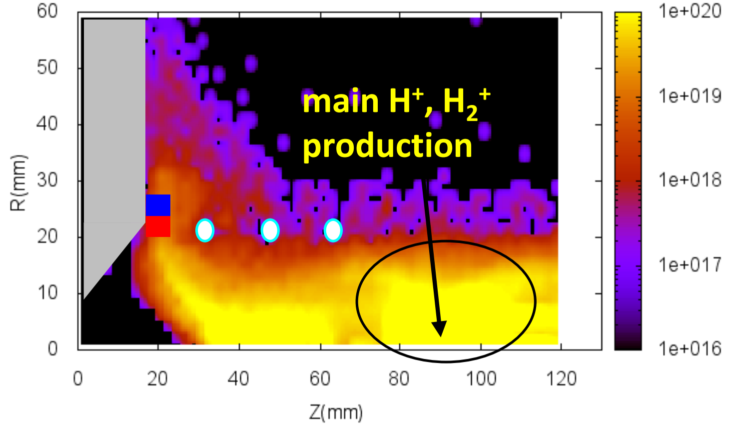


H_2^+ density (m^{-3})



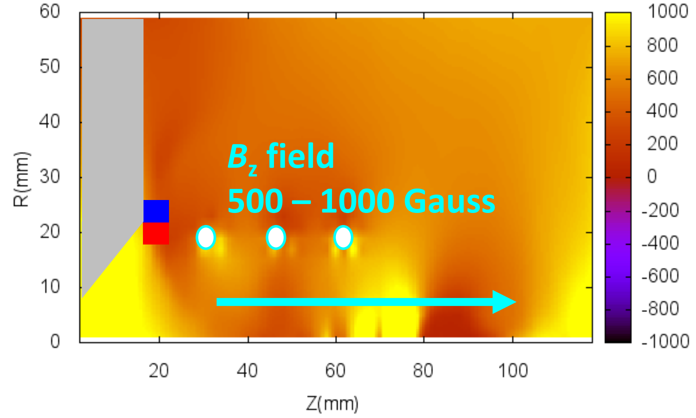
(1) Production of H^+ and H_2^+ above RF antenna coil

Electron density (m^{-3})

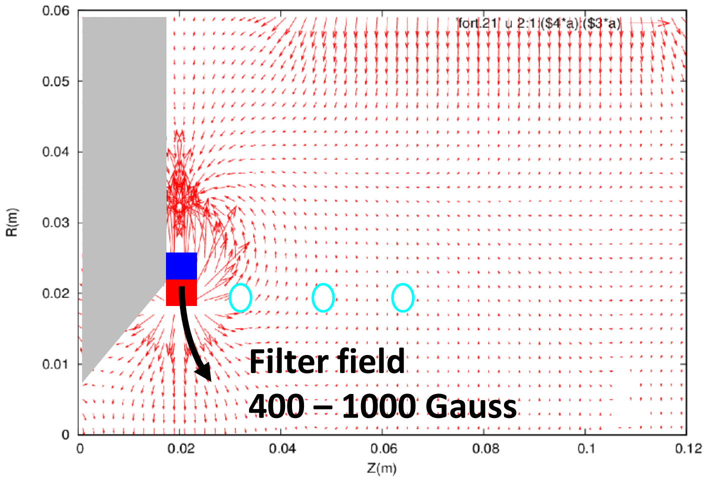


(2) Transport of H^+ and H_2^+ along inductive B_z field

Inductive B_z field (Gauss)

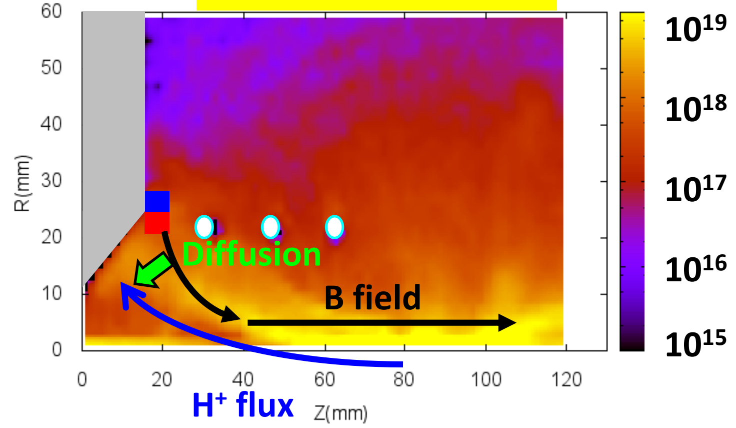


(3) Transport of H^+ and H_2^+ along filter field



(4) Diffusion perpendicular to field line

Proton density (m^{-3})



Characteristic values for H^+ diffusion perpendicular to B field

Cyclotron frequency:

$$\omega_L = qB/m_{\mathrm{H+}} \sim 4.8 \times 10^6\ \mathrm{s}^{-1}.$$

Collision frequency for elastic/CX collision:

$$\nu_{\mathrm{coll}} = n_{\mathrm{H2}}\sigma_{\mathrm{total}}v_{\mathrm{thermal}} \sim (3 \times 10^{19}\ \mathrm{m}^{-3}) \times (10^{-20}\ \mathrm{m}^2) \times (4 \times 10^5\ \mathrm{m/s}) \sim 10^5\ \mathrm{s}^{-1}$$

Diffusion Coefficient perpendicular to B field:

$$D_\perp = \frac{D}{(1+\omega_L^2/\nu_{\mathrm{coll}}^2)} \sim 4.2 \times 10^2\ \mathrm{m}^2\mathrm{s}^{-1},$$

where $D = \frac{k_B T_{\mathrm{H+}}}{m_{\mathrm{H+}}\nu_{\mathrm{coll}}}$ and $T_{\mathrm{H+}} \sim 10^2$ - 10^3 eV

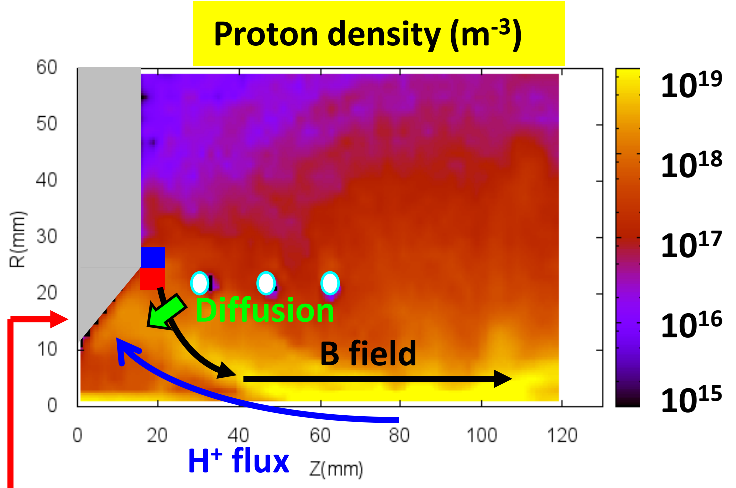
When protons are transported along field line by convection for x = 100 mm (distance between H^+ production point to vicinity of filter magnet), characteristic time is given as

$$\tau = \frac{x}{v_{\mathrm{thermal}}} \sim 10^{-6}\ \mathrm{s}$$

Characteristic length of H^+ diffusion from original field line is estimated to be

$$\sqrt{D_\perp \tau} = 9.8 \times 10^{-3} \sim \boxed{1\ \mathrm{cm.}}$$

(4) Diffusion perpendicular to field line



Summary

- Operation status of J-PARC RF H- ion source in this 2 years is shown.
- Due to several dedicated efforts, improvement of beam performance has been achieved;
  - 1-MW equivalent proton beam intensity was demonstrated at 3-GeV Synchrotron.
  - Maximum beam current in the user operation is increased from 33 mA to 45 mA.
  - Continuous operation of 1,350 hours is achieved for 45 mA beam current operation.
- The spark rate in the ion source extractor was decreased successfully by controlling Cs injection amount via three-stage Feed Back system.
- The Feed Back system has been also effective for maintaining the fraction of H- current with in ±0.1 mA in the 45 mA beam operation.
- For the improvement of J-PARC ion source performance, several projects are started;
  - Off-line R&D for high intensity study
  - Development of numerical model for understandings of plasma behavior and for obtaining hints on source design.

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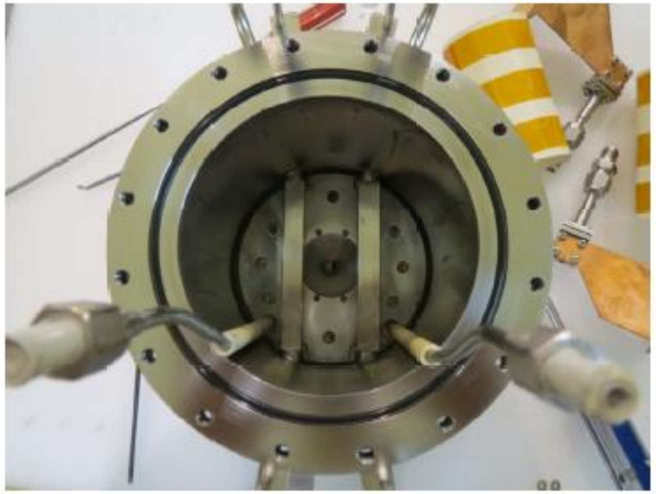
  - Off-line R&D for high intensity study
  - Development of numerical model for understandings of plasma behavior and for obtaining hints on source design.

Thank you for your attention!

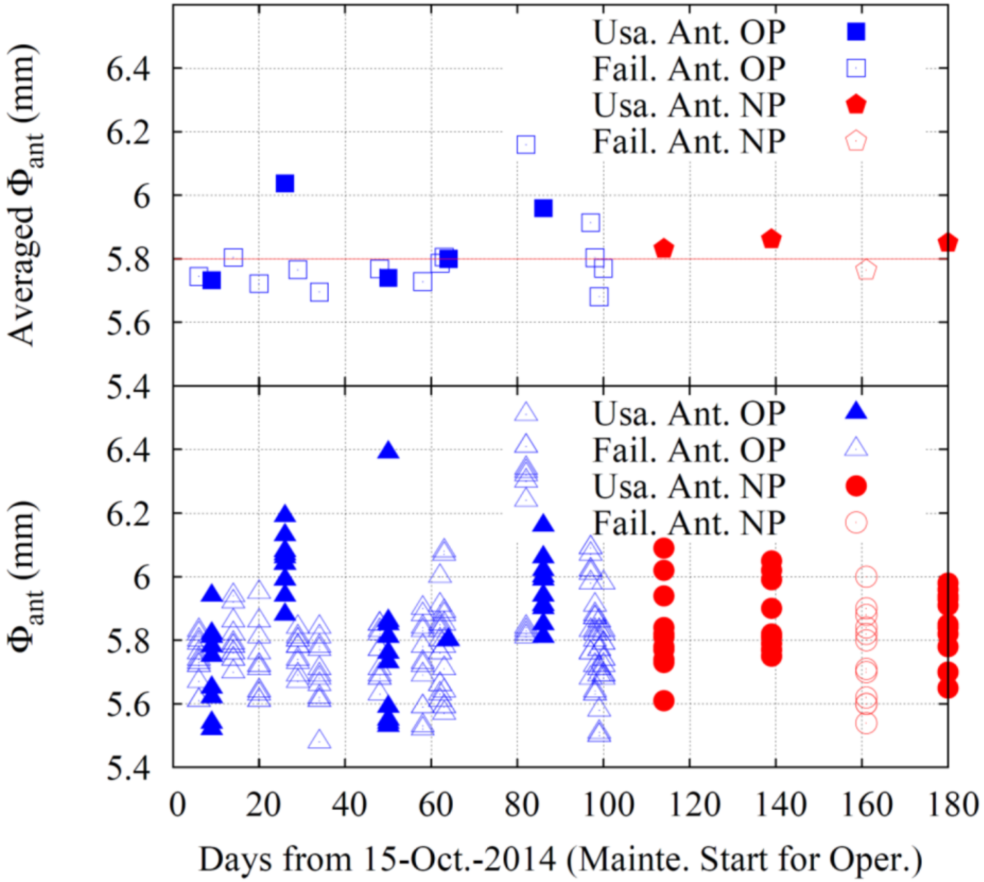
APPENDIX :
Pre-Conditioning of plasma chamber

- In order to **reduce the duration of beam commissioning** (to obtain desired H- beam performance) after exchange of ion source on J-PARC Linac, **"pre-conditioning"** of plasma chamber is made **off-line.**



<u>Pre-conditioning procedure</u>

1. **Cleaning plasma chamber** (Stainless Steel) by ethanol and alumina powder.
2. After assembling the chamber, **vacuum drawing** has been done until gas pressure becomes lower than 1.5 x 10^{-5} Pa.
3. At the same time, short duration of **low RF power discharge** (input power 25 kW) is repeated to **evacuate impurity gas**.
4. After reaching low gas pressure, **cesium is injected** to obtain target H- beam current.
5. The "pre-cesiated" chamber is filled with Ar gas for storage.

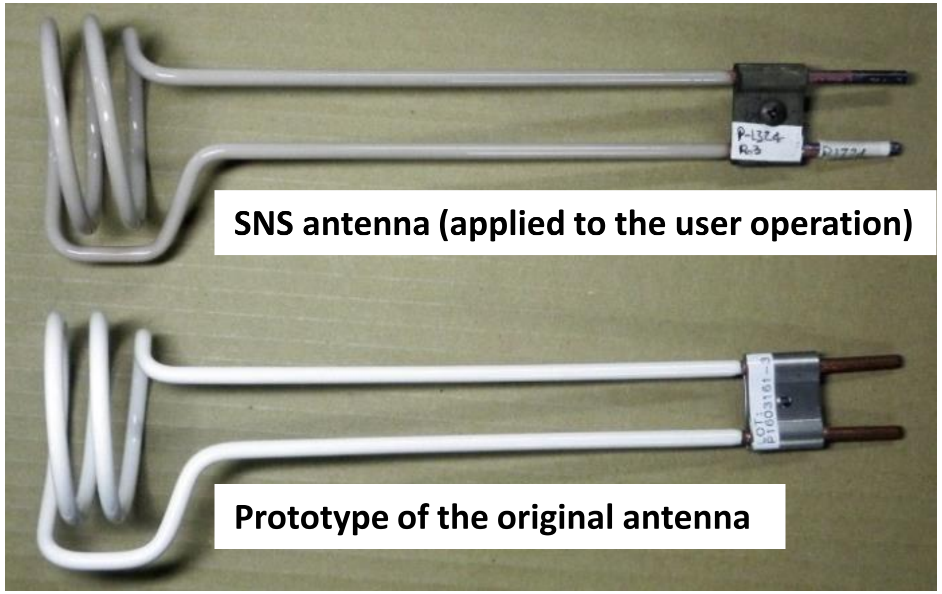


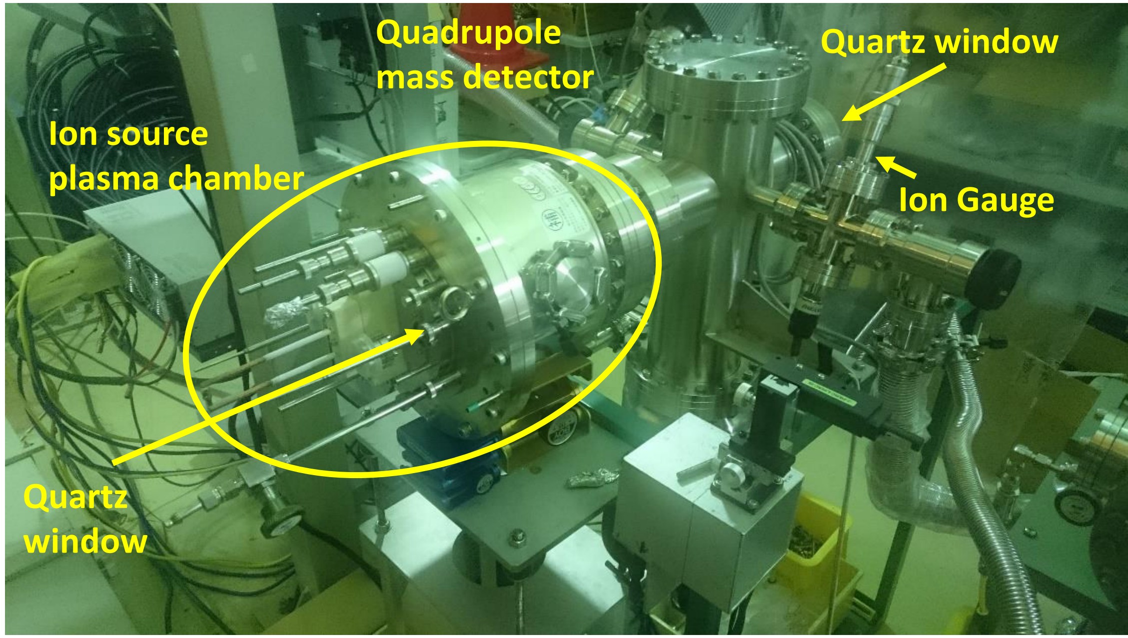
[1] A. Ueno, et al., Rev. Sci. Instrum. **87**, 02B129 (2016).

APPENDIX:
Manufacture of Original Antenna Coil

- In J-PARC, manufacture of **original antenna coil** was started in 2015.
- In the first campaign, **20 prototypes** of the coil are produced. Enamel coating of the coils contain high ingredient amount of **antimony emulation glass** in order to **prevent cracks and pinholes** which may take place during manufacture.
- For testing the original antenna, development of **test-bench** is started. The performance of antenna;
  - **Impurity-gas** evacuation during discharge
  - **Lifetime** of antenna coil

  will be investigated.

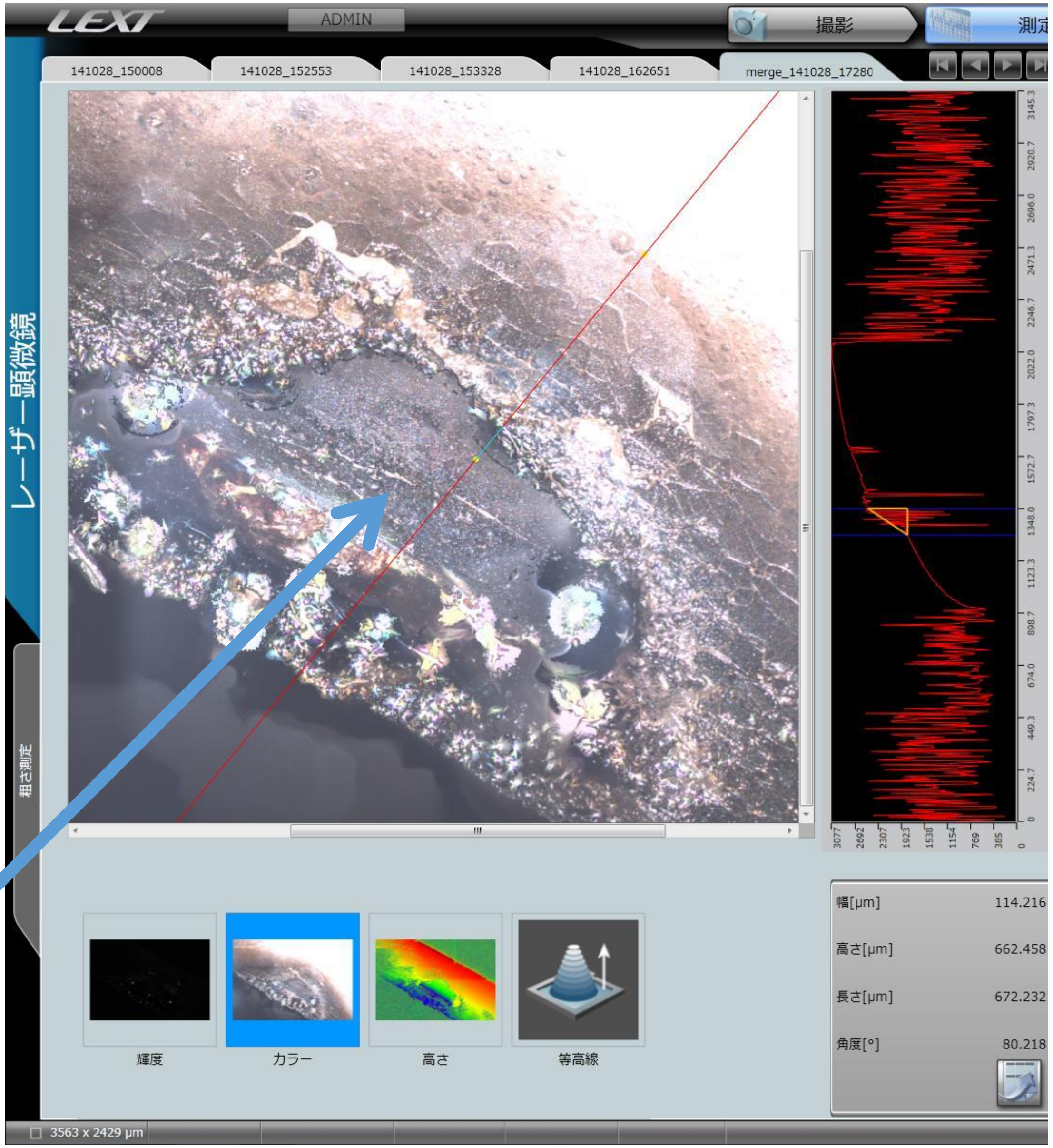




[1] K. Ohkoshi, et al., proceedings of 12th Annual Meeting of Particle Accelerator Society of Japan, 2016.
[2] A. Takagi, H. Asano, private communication.

APPENDIX : Antenna Coil Screening

Observed from microscope



Exposure of the conducting wire (Cu)

Diameter : 1.2mm

Depth : 0.6mm

[1] A. Takagi, private communication.

APPENDIX : Feed back system

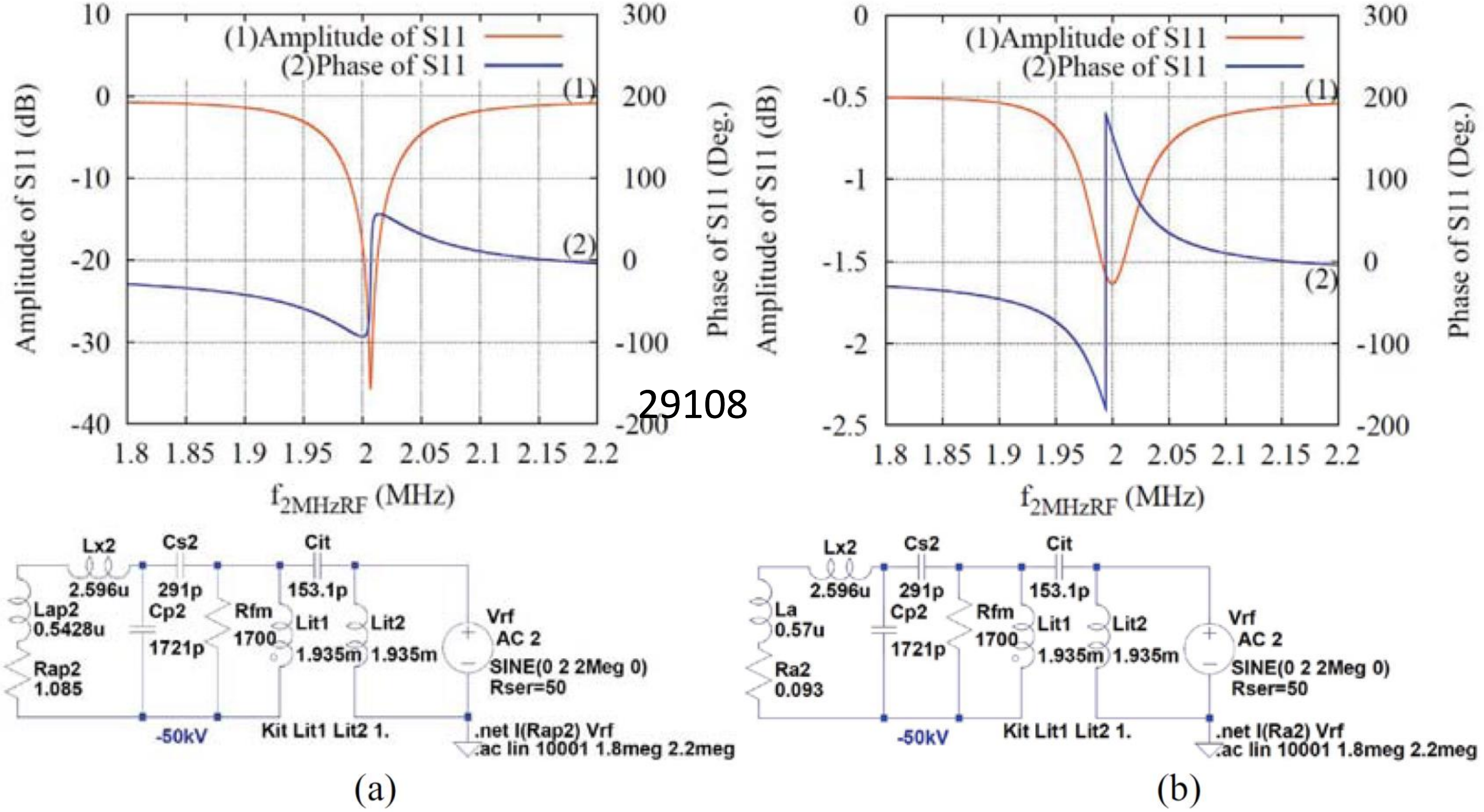


FIGURE 3. The equivalent circuits (bottom figures) for pulsed 2MHz-RF matching networks including the isolation transformer with (a) and without (b) hydrogen plasma and each simulated result (top graph) , in which the amplitude and phase of the S11 parameter are shown as plots(1) and (2), respectively, by using LTspice IV.

[1] A. Ueno, et al., AIP Conf. Proc. **1515**, 409 (2013).

APPENDIX : Calculation Resource

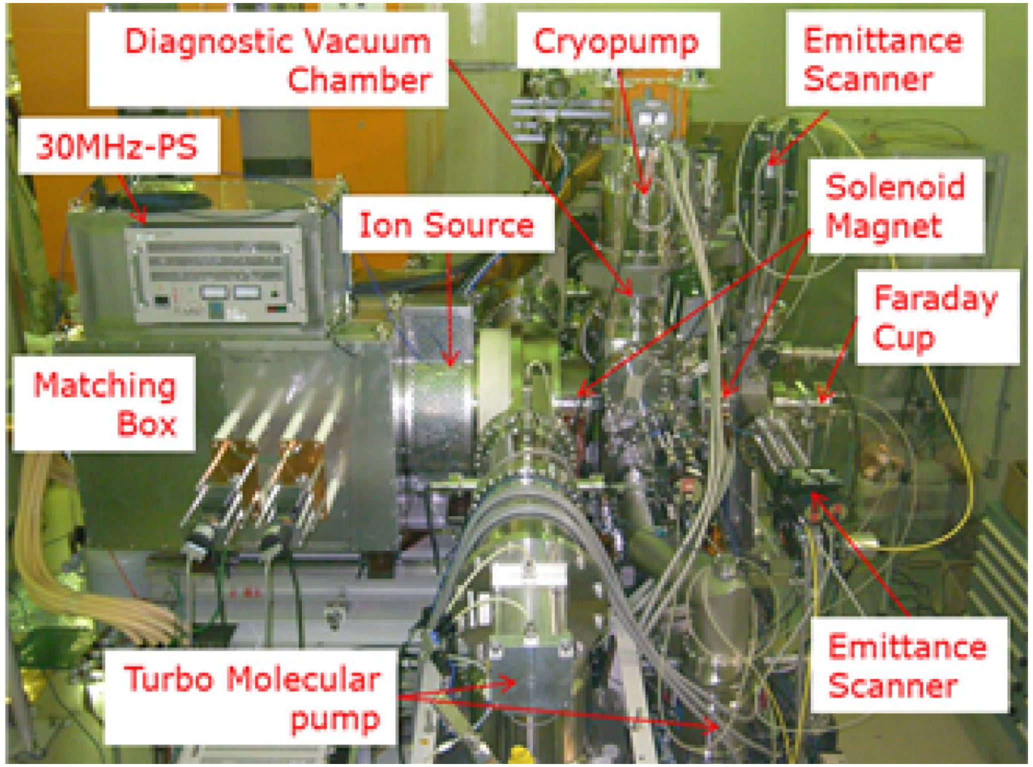
KEK system-A : Hitachi Super Technical Server SR16000 model M1

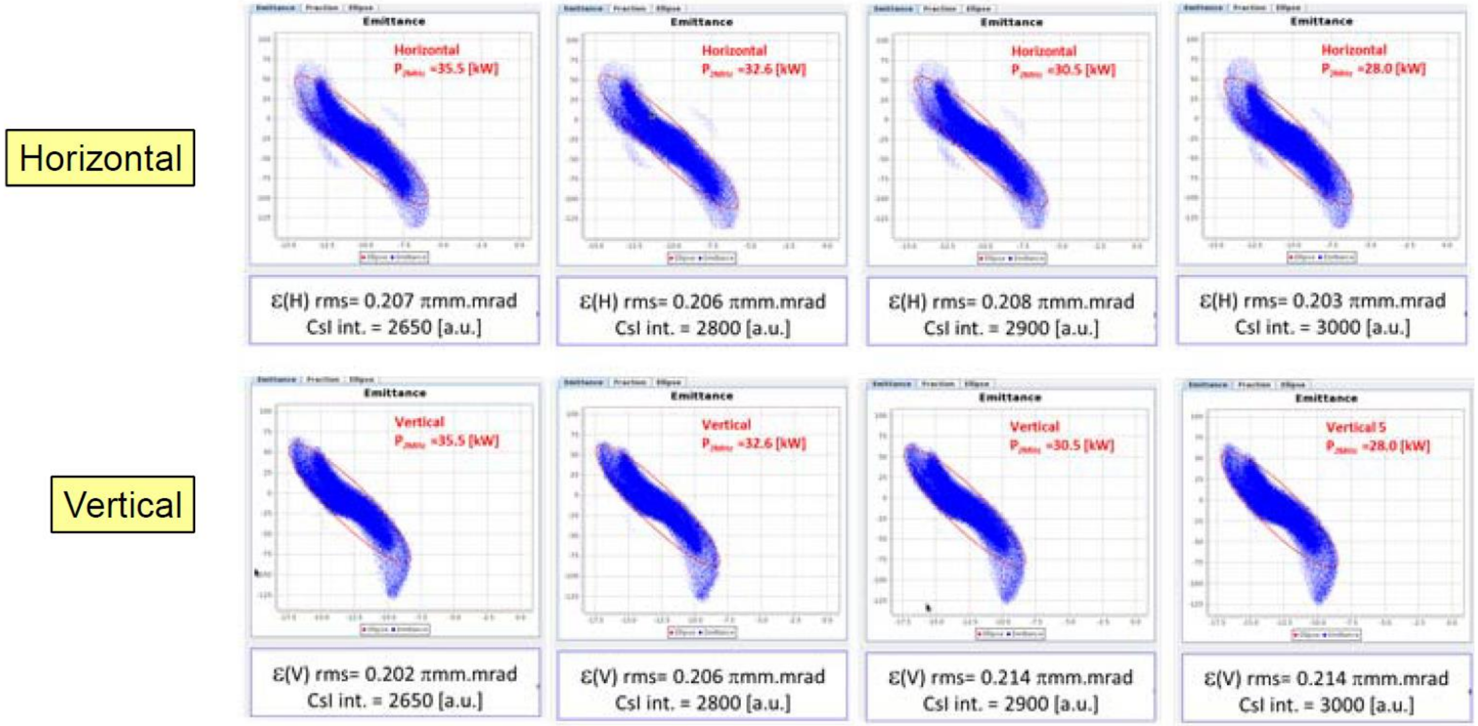
Parallel calculation with 64 core CPU, 256 GB memory server in 1 node (56 nodes total)
Processor : POWER7 (3.83 GHz)
Estimated operation speed per node : 980.48 GFlops

Parallelization : SMP parallelization among 64cores, MPI parallelization among 64 nodes

Assembling of Test-stand

- In spring of 2016, **Test-stand** which has almost the **same construction** of Ion source – LEBT system as in J-PARC LINAC, has been assembled.
- The test-stand is equipped with **two Faraday Cups** in the center of LEBT and at the end of LEBT, which corresponds to RFQ vane in actual LINAC configuration. Also at **RFQ vane** position, **Emittance Monitor** in **horizontal and vertical** directions is installed.
- At the test-stand, **relation between beam transport** and IS discharging condition is investigated. In the figure, emittance diagrams for 40 mA beam are measured with **different Cs injection amount** and 2MHz RF power.





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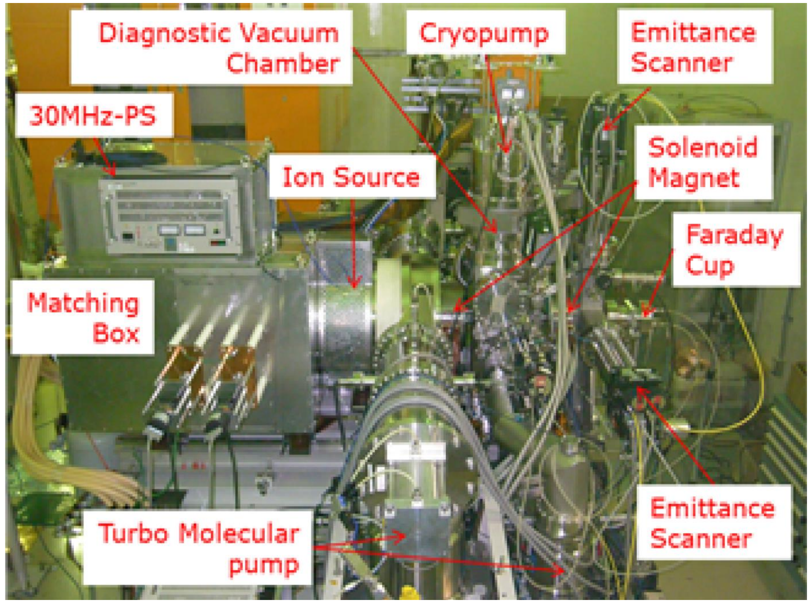
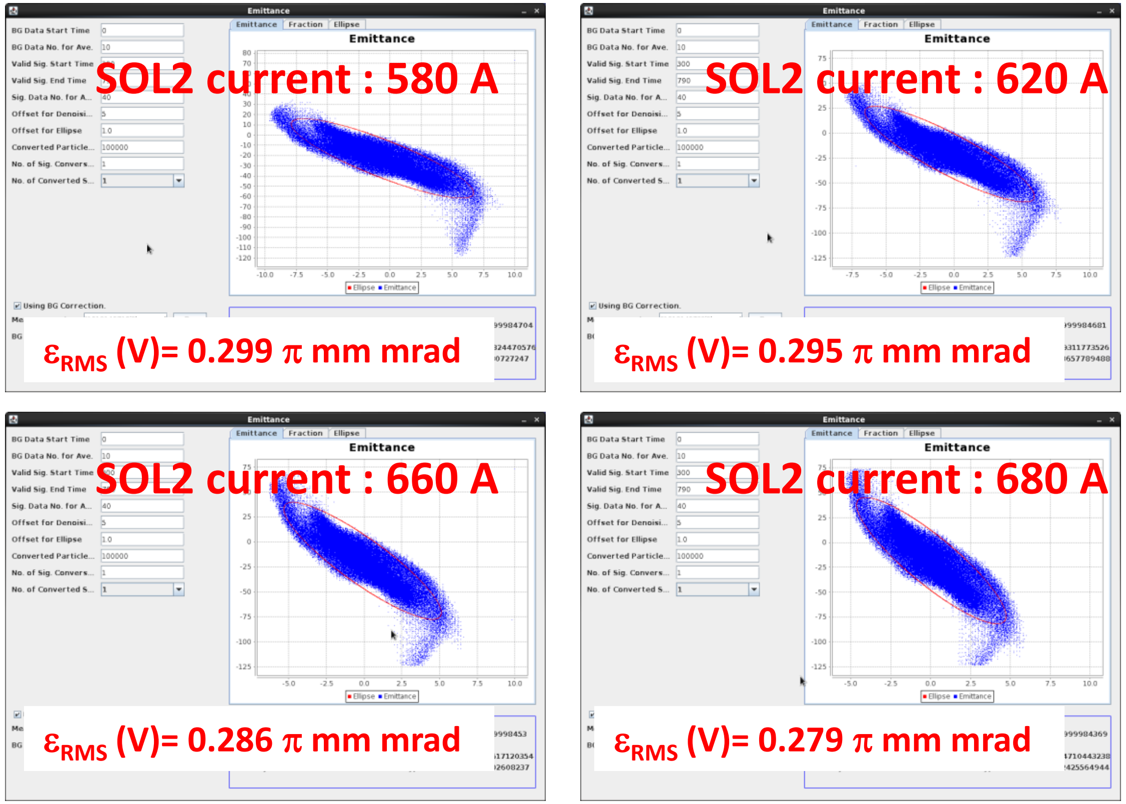
- Study of operation with **H- current up to 70 mA** can be performed from ion source in the test-stand.
- At the test-stand, (i) establishment of **beam commissioning technique for high beam current** is one of the targets. Also, (ii) **understanding of beam transport** and emittance diagram at RFQ vane is investigated **in high H- current** condition.



<u>LEBT Solenoid coil 2 current scan</u>
I_{H-} = 68 - 72.5 mA, V_{ext} = 11.2 kV, V_{acc} = 41.3 kV, SOL1 current = 575 A, RF input power = 48.3 kW, H2 gas injection : 17 SCCM



APPENDIX : Characteristic values for H^+ diffusion perpendicular to B field

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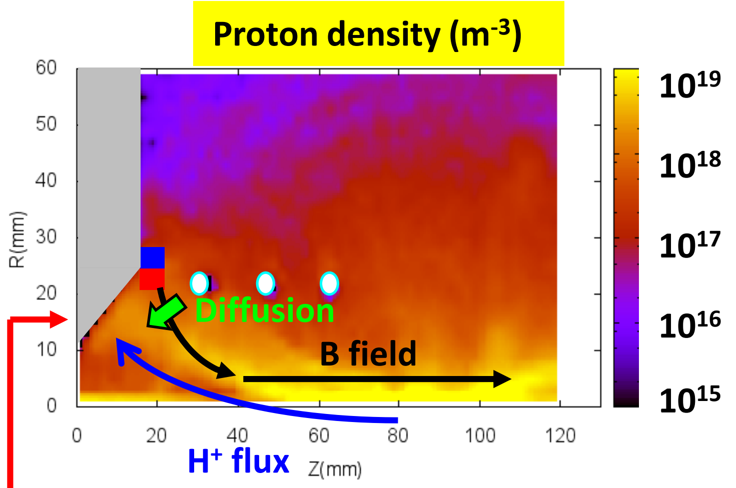

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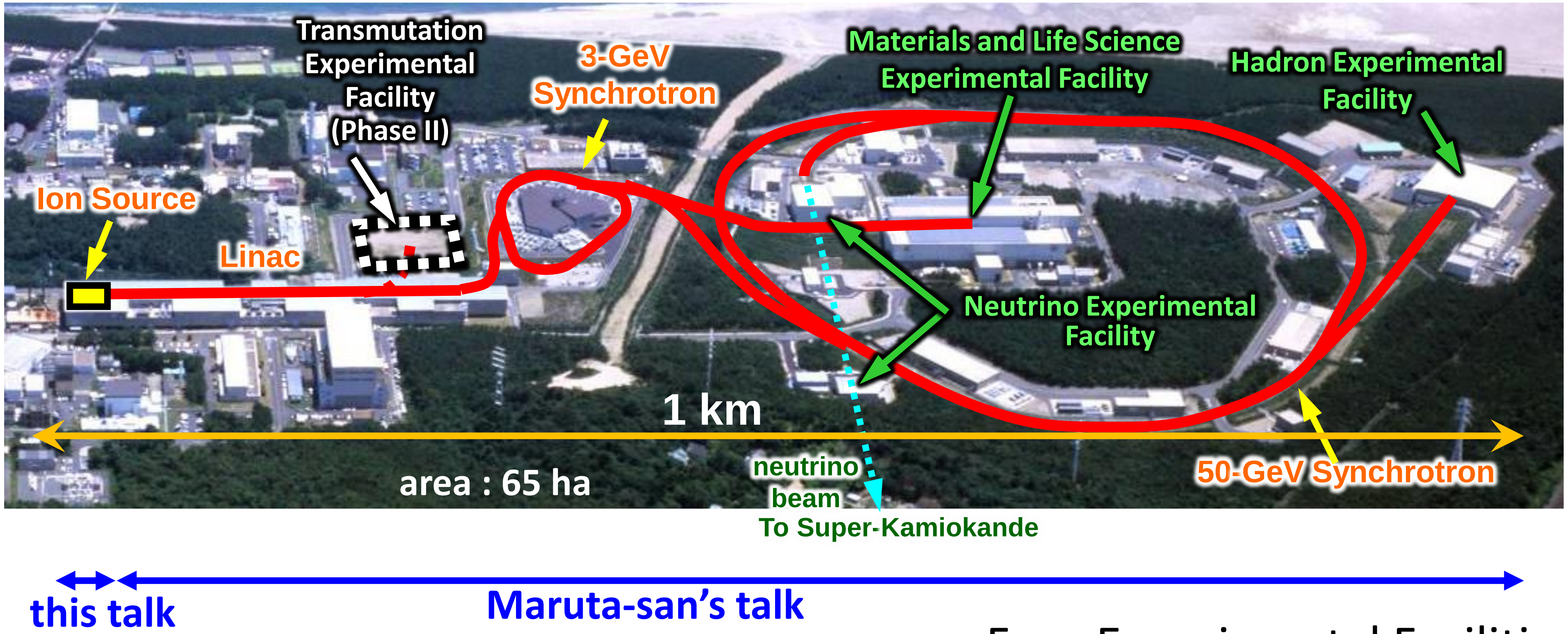
J-PARC Accelerator Complex and Application of proton beam



- Three Accelerators
  - Linear Accelerator (LINAC)
  - 3-GeV Synchrotron
  - 50-GeV Synchrotron
- Four Experimental Facilities
  - Transmutation
  - Material and Life Science
  - Hadron
  - Neutrino