The development of 6MeV Heavy Ion Beam Probe System in LHD

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Introduction

History of Heavy Ion Beam Probe (HIBP)

1960 — HIBP measurements in cathod arc Plasma **R. L. Hickok**

1970 — toroidal current in ST-tokamak **(30 keV)**; TMX

1980 — TEXT **(500 keV)**; ISX-B **(160 keV)**

1990 — TEXT-U **(2 MeV)**; T10 **(300 keV)**; TJ-II **(200 keV)**

2000

NIFS Activity: NBT **(40 keV)**; JIPP-TIIU **(500 keV)**; JFT-2M **(500 keV)**; CHS **(200 keV)**; **LHD-HIBP(6 MeV)**

LHD-HIBP should be the most challenging project in plasma diagnostics.

- Highest Probing Beam Energy
- Non axis symmetric magnetic field configuration

Outline

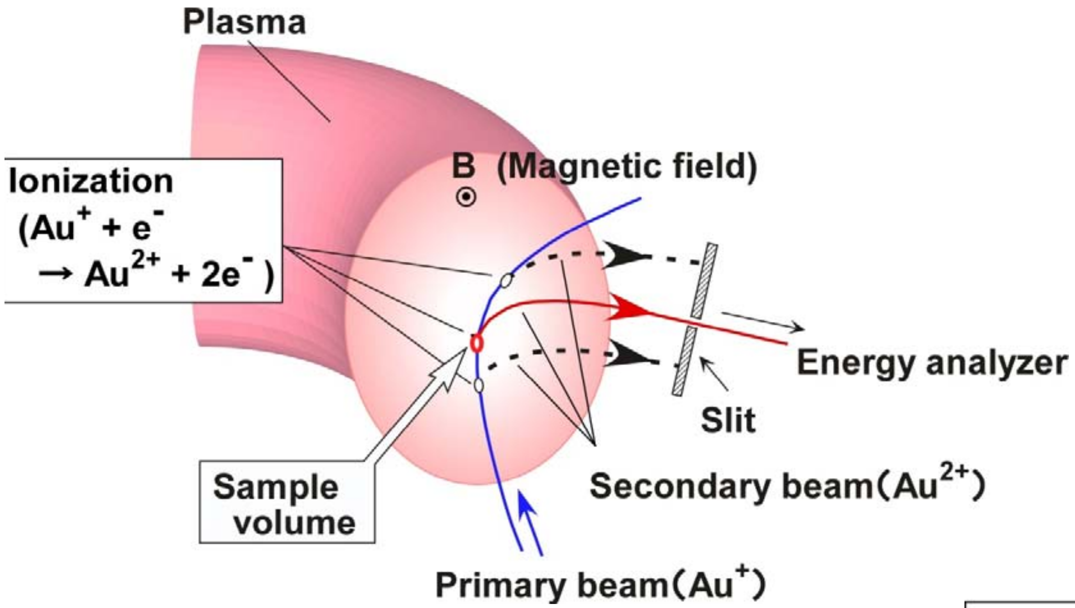
- **Principle of HIBP**

- **LHD-HIBP**
  - *Requirements
  - *Tandem Energy Analyzer

- **Results**
  - *Potential profile
  - *Temporal change of potential
  - *Fluctuation measurement of potential

- **Summary**

Principle of HIBP



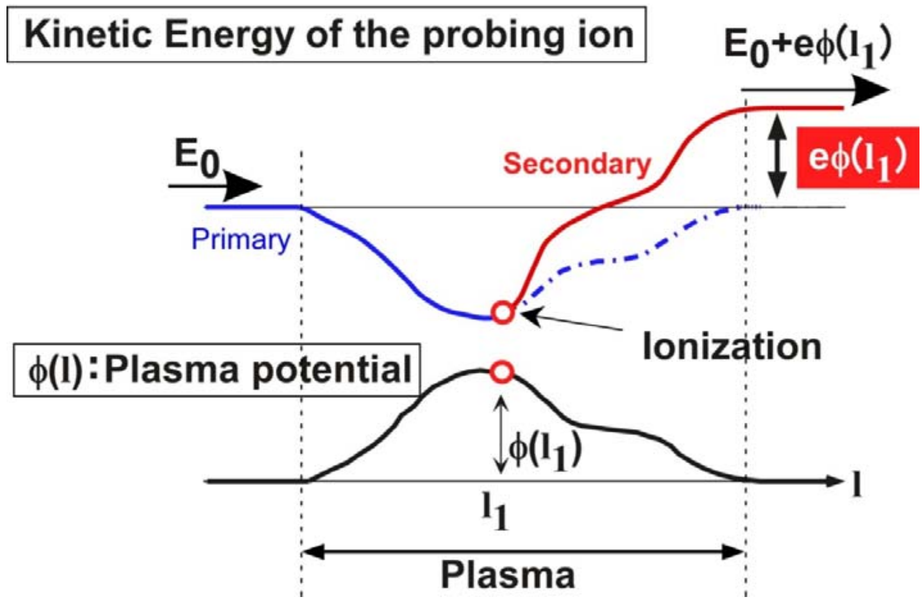
Injected Beam Energy: E_0
(Primary Beam, Au^+)

Detected Beam Energy: E_s
(Secondary Beam, Au^{2+})

Energy deference corresponds to plasma potential

$$E_s - E_0 = e\phi$$

Secondary Beam Current Intensity
~ Plasma density
(path integral effect is included)



Requirements for LHD-HIBP

1, The acceleration energy of HIBP,

$$E_{beam} \sim B^2 r^2 / M$$

B: Magnetic field strength
r: minor radius
M: mass of beam

In large sized device, very large acceleration energy and heavy ion is needed

In LHD, B_t ~ 3 T, r ~ 0.6 m $E_{beam} \sim 6$ MeV for $Au^+(197)$

2, If we would like to measure 1V fluctuation, **<u>extremely high resolution</u>** (10^{-6}) is required. Parallel 30 degree energy analyzer has been traditionally used, for its second order focusing of injection angle.

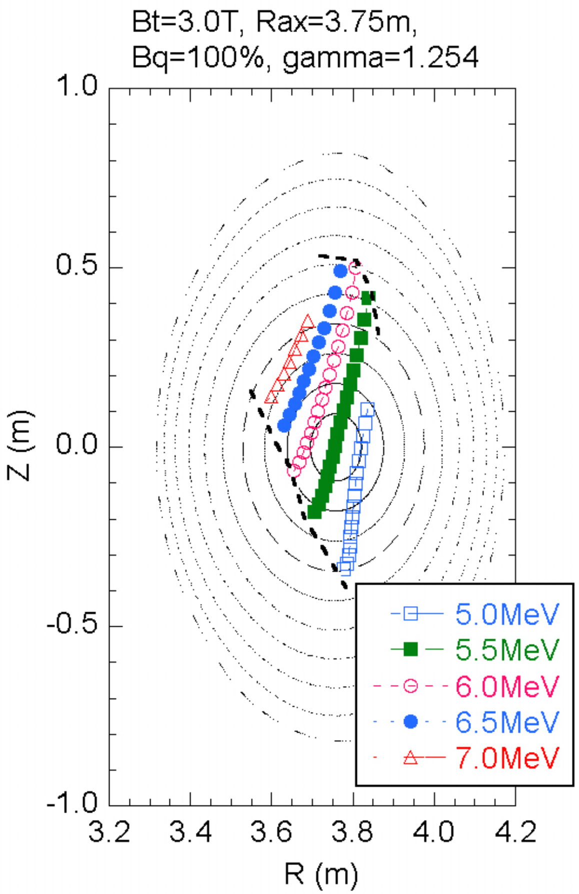
3, For the long orbit length inside of plasma, **<u>strong beam attenuation</u>** is predicted.

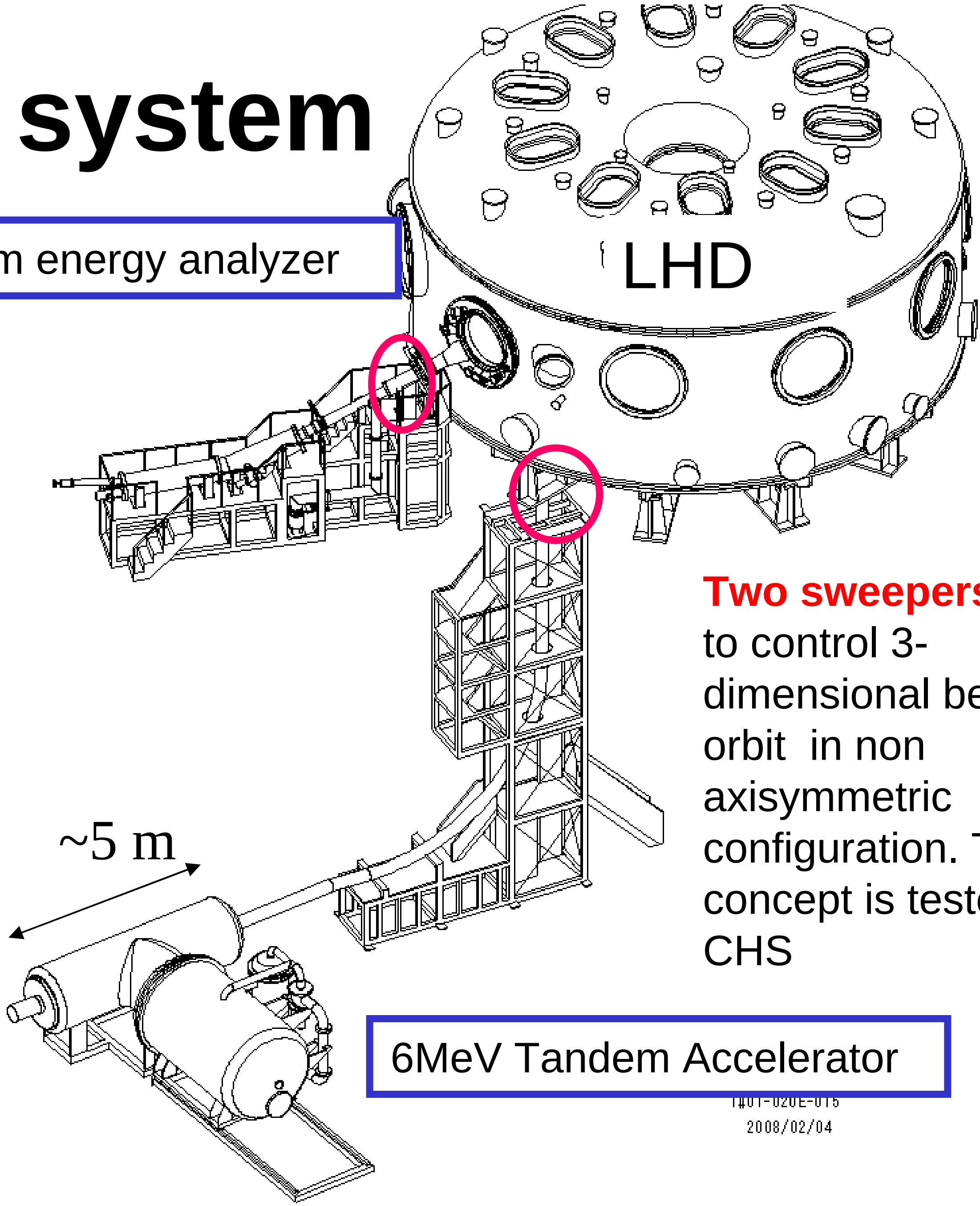
$I_s / I_0 \sim 10^{-5}$, when $n_e \sim 1 \times 10^{19}$ m^{-3}

As a sensitive detector, MCP is used.

LHD-HIBP system

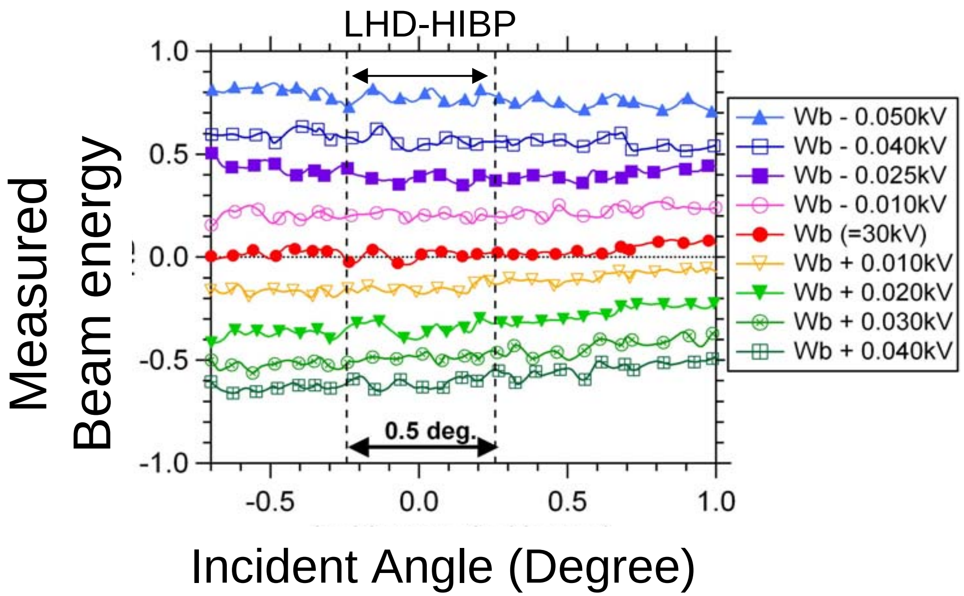
Observable region





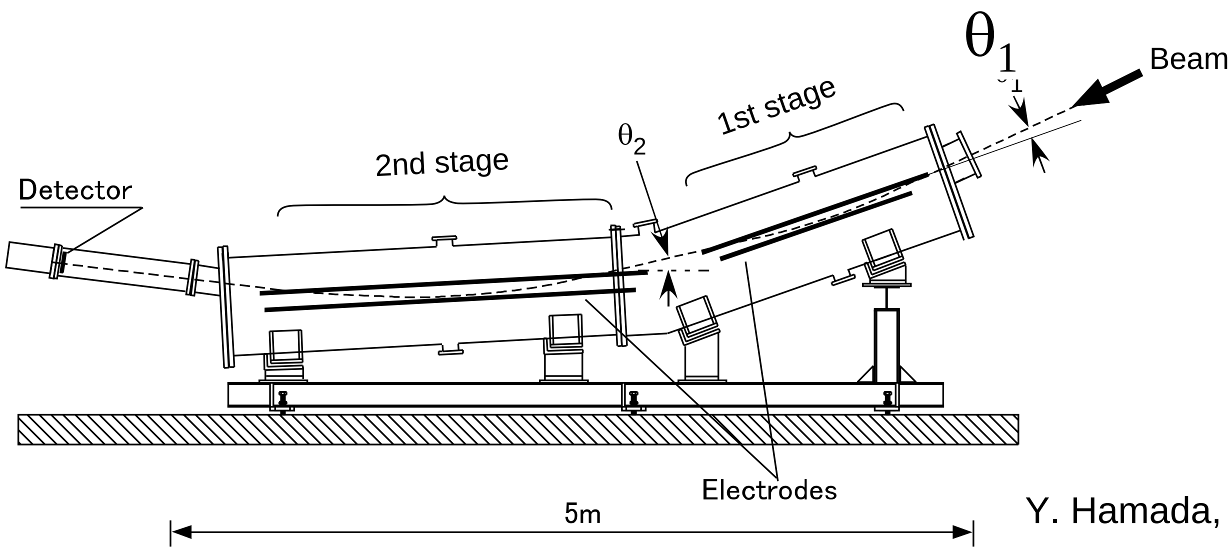
Two sweepers to control 3-dimensional beam orbit in non axisymmetric configuration. This concept is tested in CHS

Tandem Energy Analyzer



Ordinal type of 30 degree parallel plate analyzer requires high voltage of **~1 MV. Not realistic.**

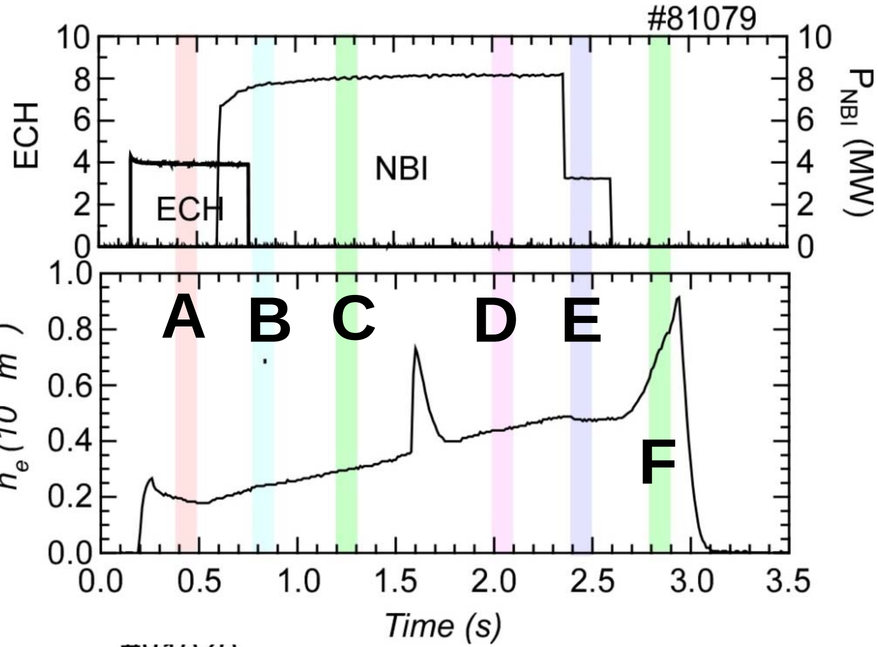
We use tandem energy analyzer to reduce required voltage to 120kV.

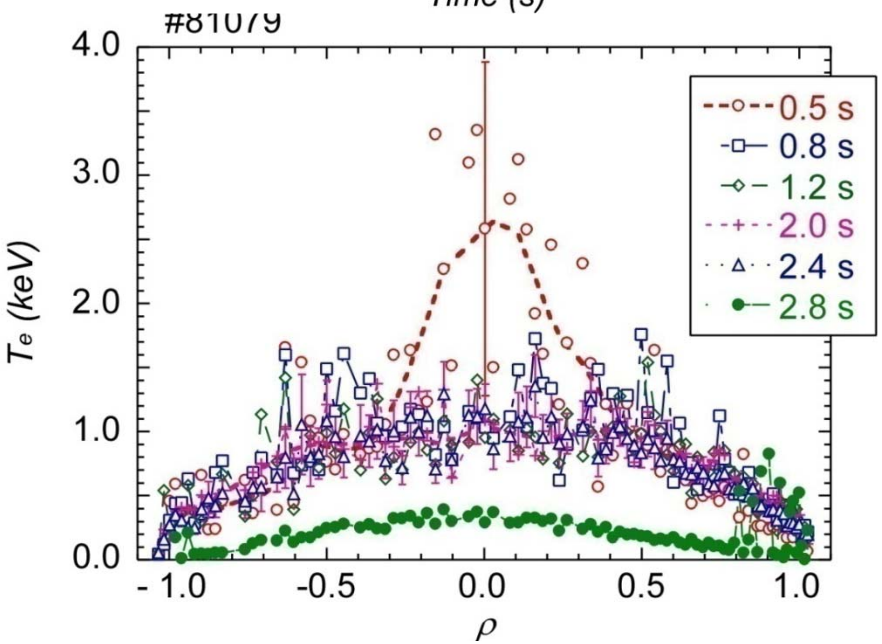


Second order focusing is realized

Y. Hamada, et al., Rev. Sci. Instrm., 68 (1997) 2020

Observed potential profiles





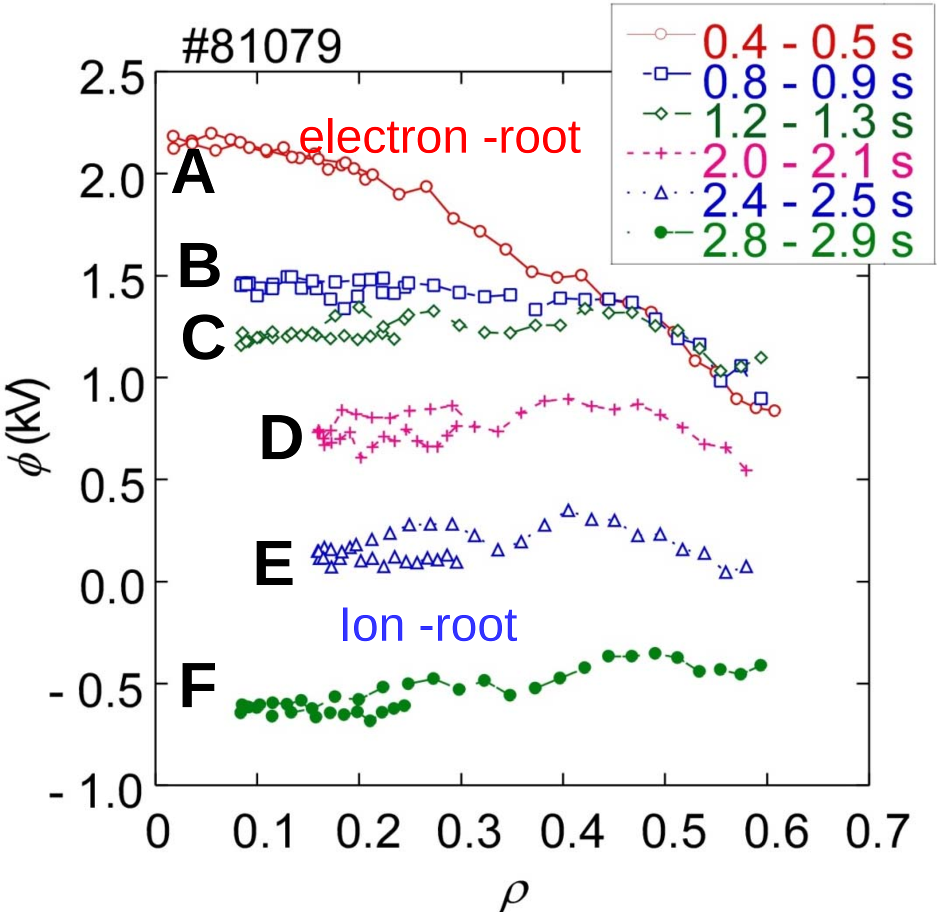
During ECH,

E_r = - grad ϕ > 0 : electron-root.

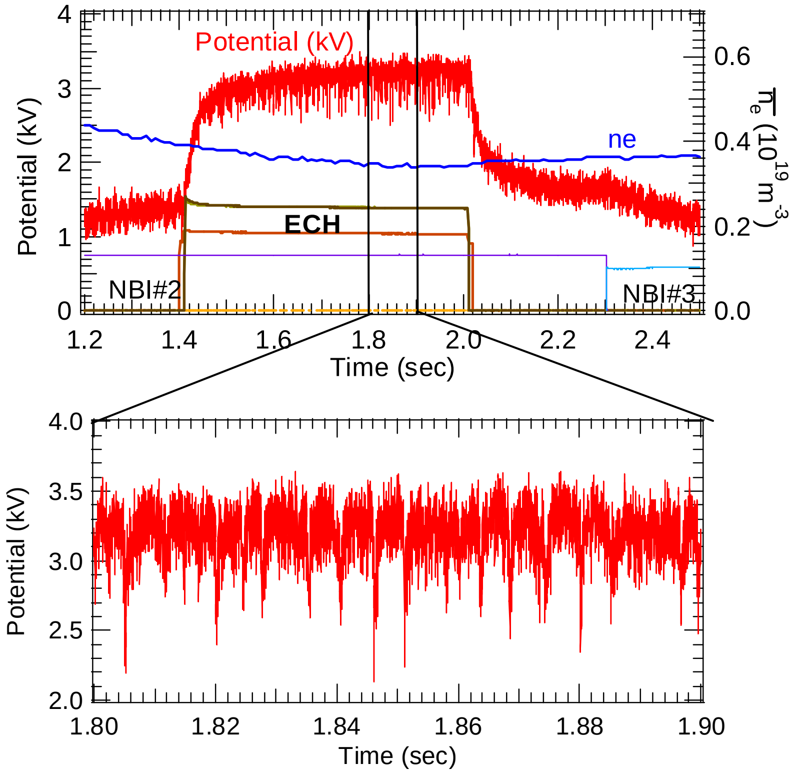
As the density increases,

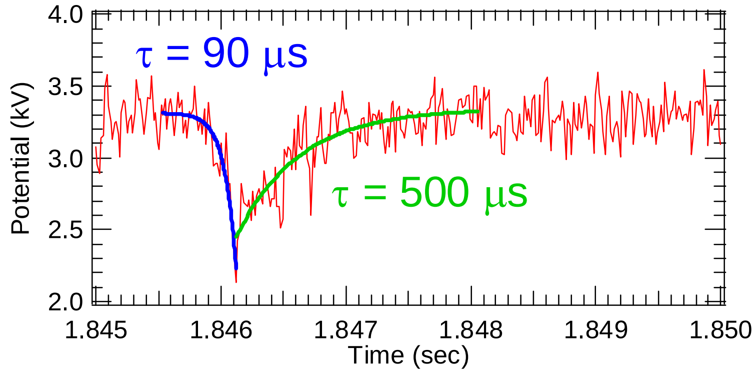
E_r changes

to negative in ρ < 0.4 : ion-root



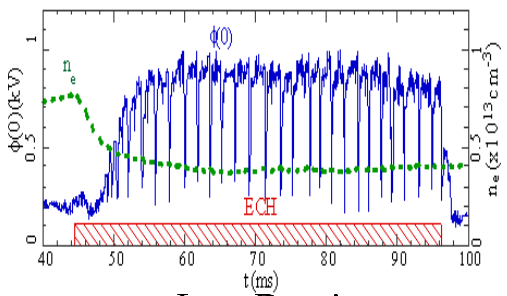
Negative Palsies observed in LHD



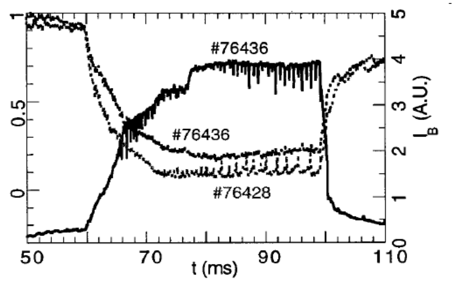


- Potential Fluctuation like pulse is observed in LHD. It is similar to CHS pulsation.
- Typical time constant of potential change is faster than energy confinement time.
- Pulse depth is less than in CHS

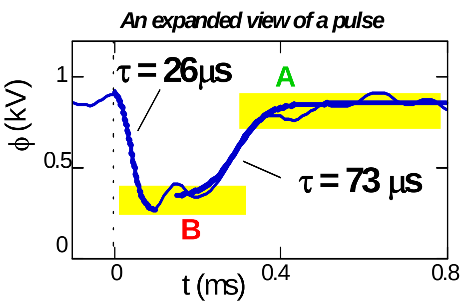
Pulsation in CHS

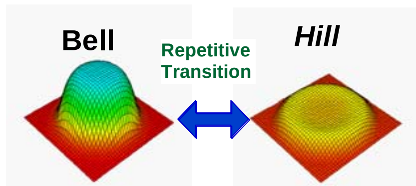


Low Density

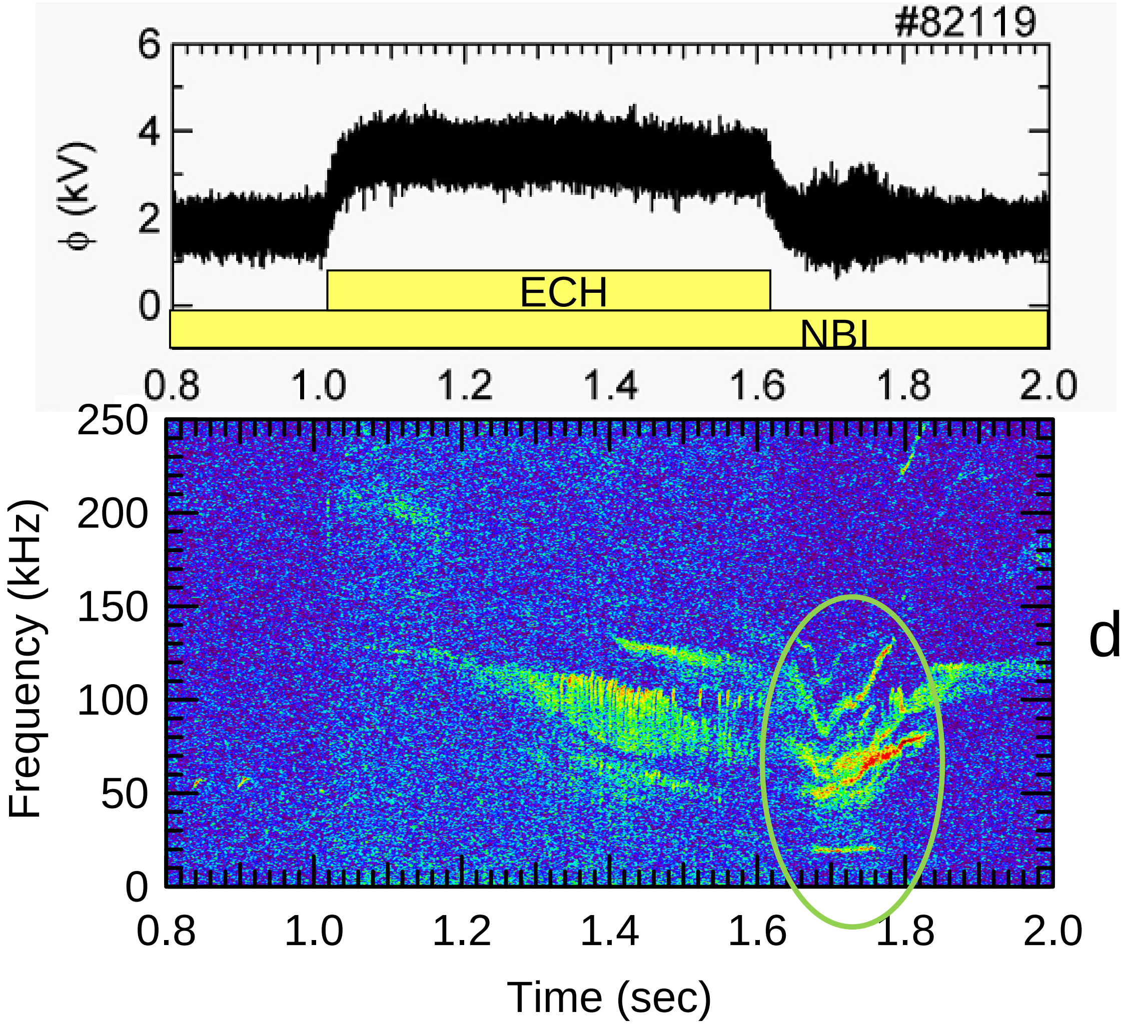


High Density





Observation of coherent modes

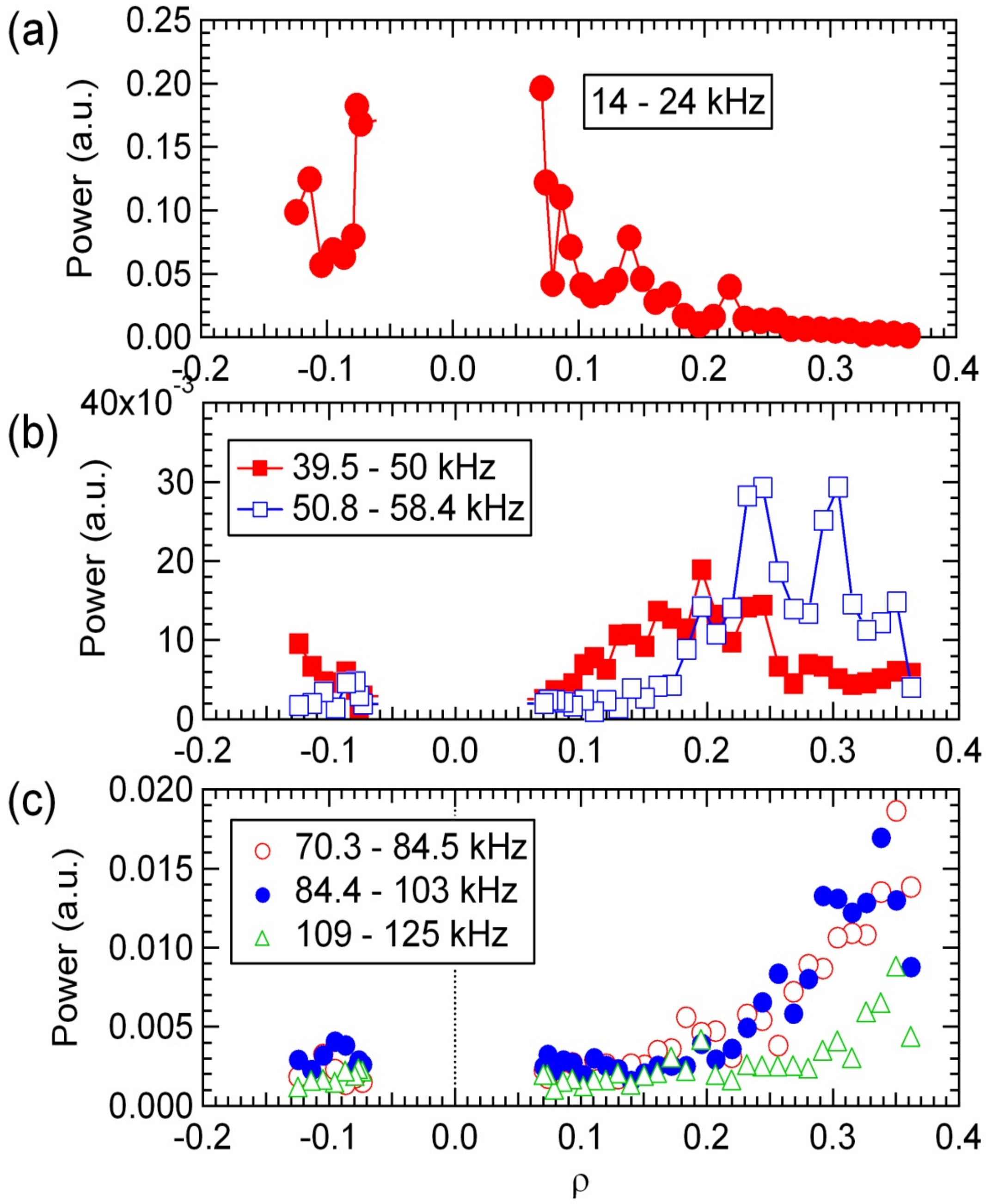


density ~ 0.1×10^{19} m^{-3}

$|\phi(f_{GAM})|$ ~ Several hundreds V

It is considered to be Geodesic Acoustic Mode (GAM) caused by high energy particle driven mode, such as RSAE.

Radial profile of the coherent modes



The mode corresponds to GAM frequency

Large coherence with magnetic probe signal

These are considered to be RSAE modes

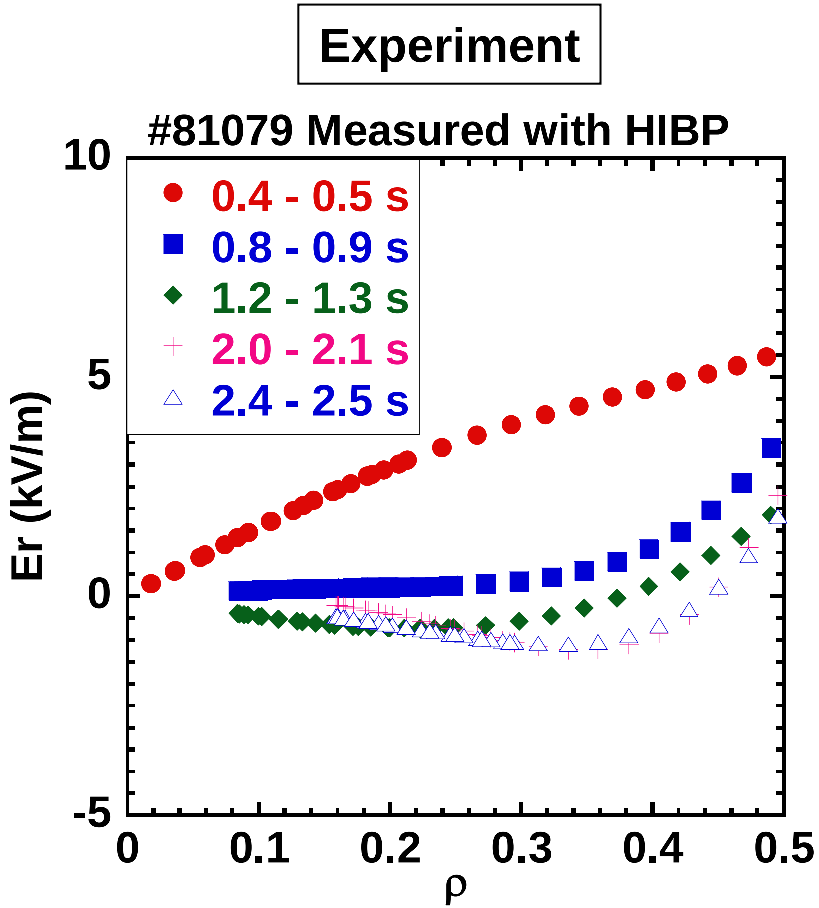
Summary

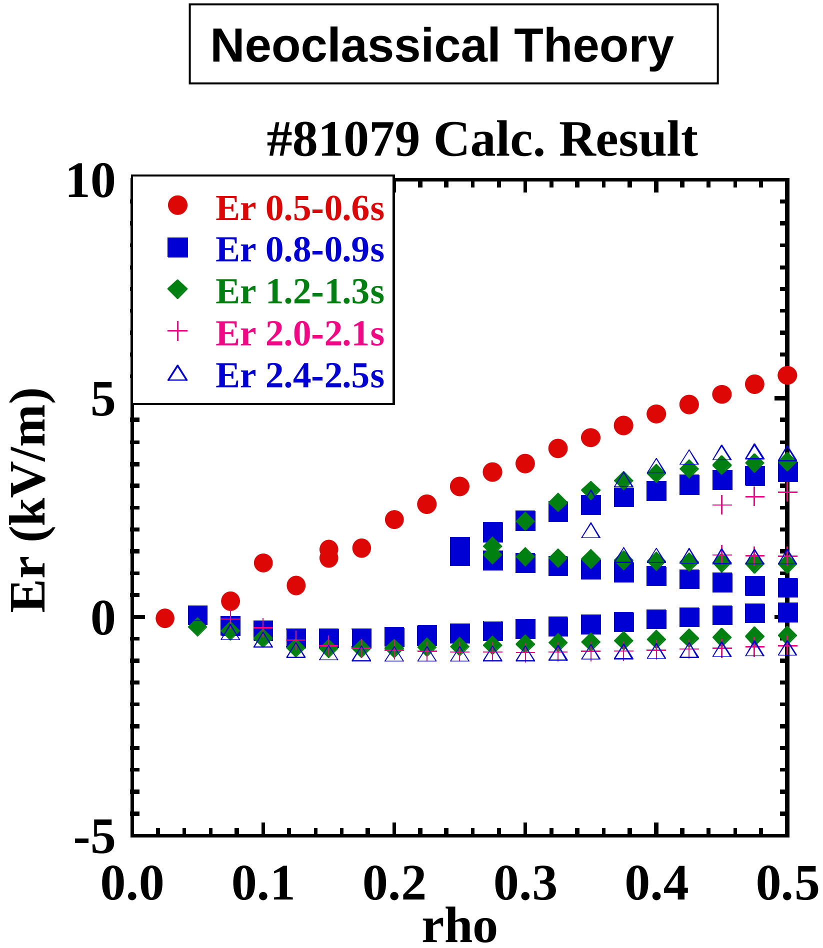
- LHD HIBP can be the most ambitious and challenging trial as diagnostics for large-scale plasma devices.

- The LHD HIBP starts to operate after researches and development of many components and methods,
  particularly,
  - the tandem parallel plate analyzer to analyze the probing beam with a high energy resolution ($\sim 10^{-4}$)
  - the control method to manage 3-dimensional beam orbit in non-axisymmetric magnetic field configuration

- Thanks to these efforts, several interesting observations have been already made, such as, the potential profile, potential change in microsecond range, coherent mode fluctuations, and their radial profiles in density range of 10^{18} m^{-3}.

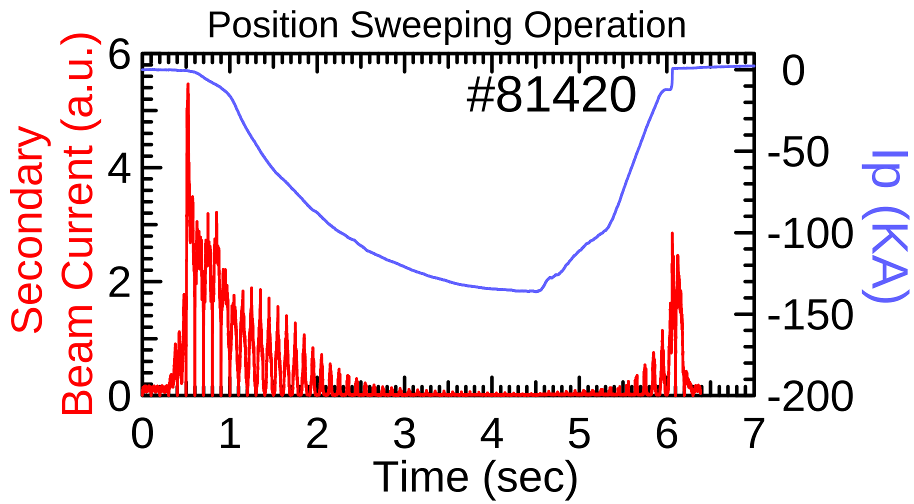
Comparison between Experiment and Simulation

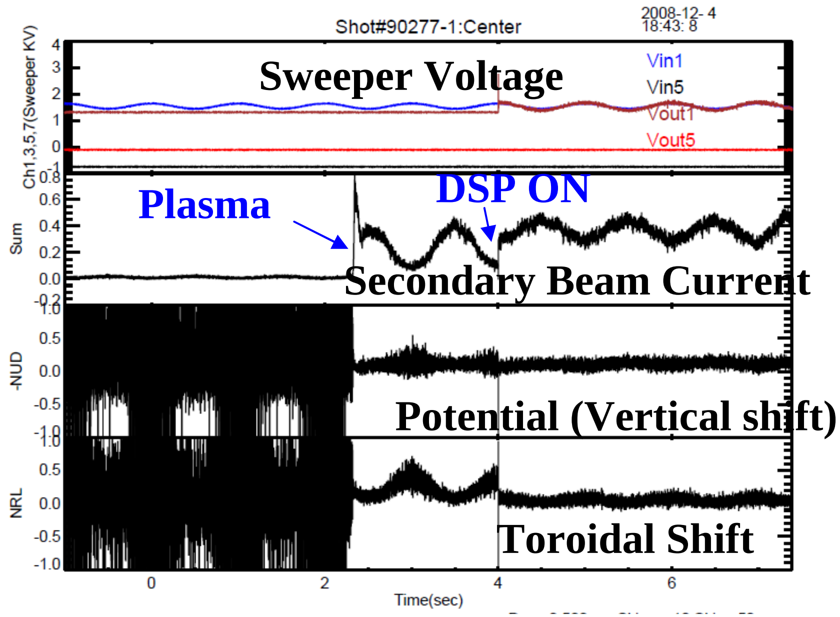




Neoclassical simulation roughly agrees with the experimental results in core region.

Real Time Feedback Control

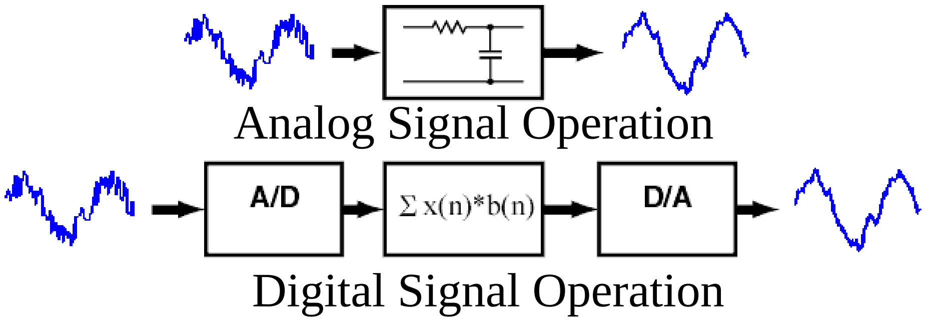




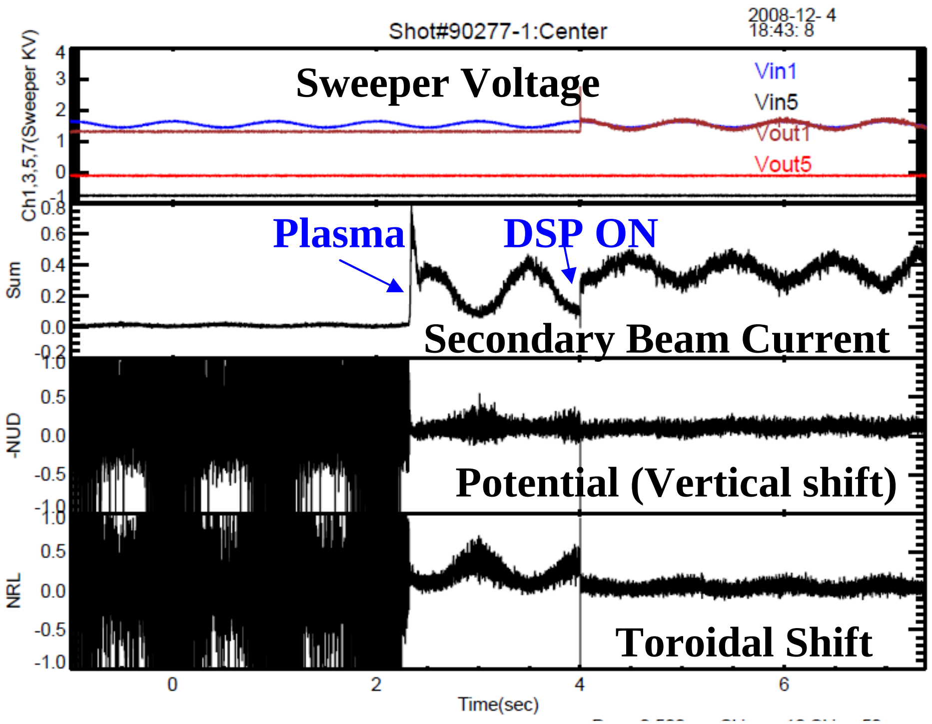
When the large toroidal current conducts, the beam strongly shifts to toroidal direction, so we cannot detect the secondary current because of exceeding.

Real time feed back control of beam by using sweep system may be required.

Real Time Feedback Control with DSP



- non linear control
- real time control
- flexible system
- C Language programming



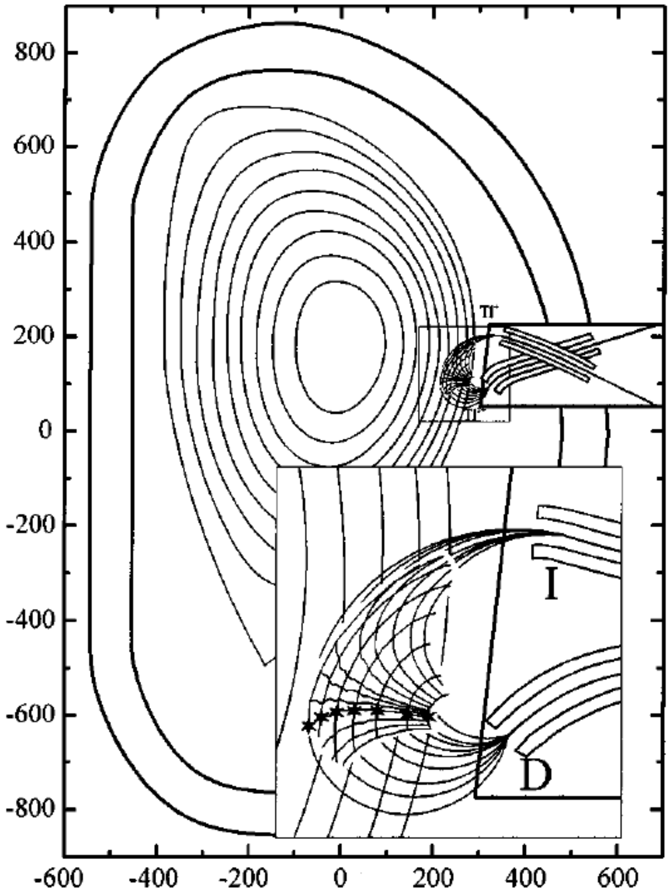
DSP real time feed back system is now being developed.

In test stand, up to 100 Hz perturbations can be canceled out.

P control is used. By using PI control, feed back control will be improved.

Can HIBP be installed to ITER?

A. V. Melnikov, L. G. Eliseev, Review of Scientific Instruments 70, 951, 1999

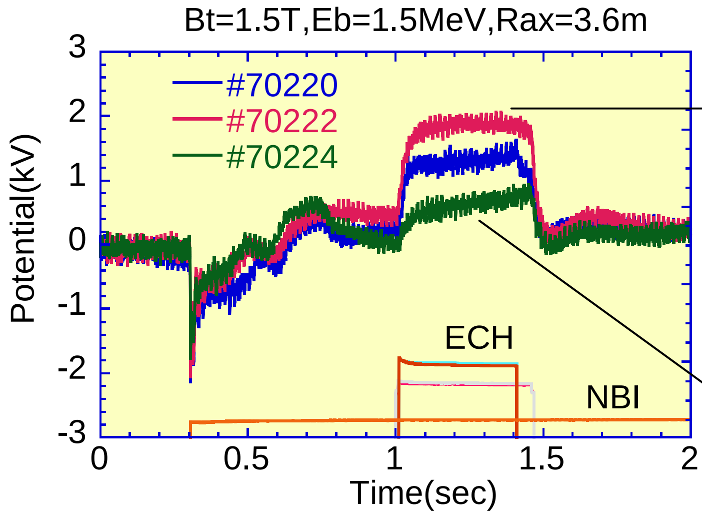


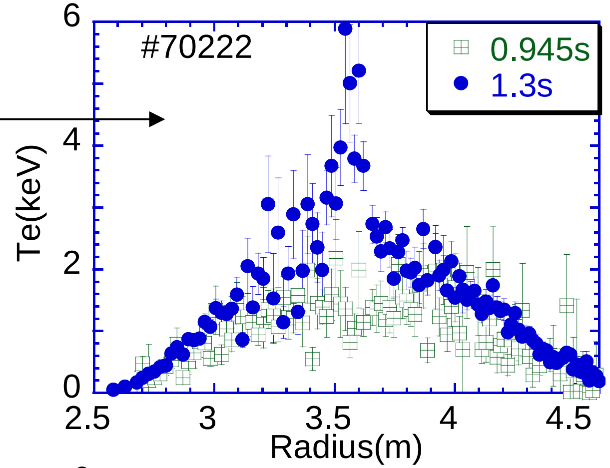
ρ	E, MeV, at Tl^{+a}	Attenuation in terms of $\mathbf{I}_S/\mathbf{I}_0$[a]	$E_{\text{optimized}}$, MeV, at Tl^{+}	Attenuation in terms of $\mathbf{I}_S/\mathbf{I}_0$
0.76	⋯	⋯	3.3	3.1×10^{-11}
0.8	5.6	7.4×10^{-12}	2.8	4.6×10^{-9}
0.86	4.4	2.5×10^{-9}	2.1	3.3×10^{-6}
0.91	3.7	1.2×10^{-7}	1.6	3.2×10^{-4}
0.98	2.9	5.7×10^{-6}	1.2	1.3×10^{-4}

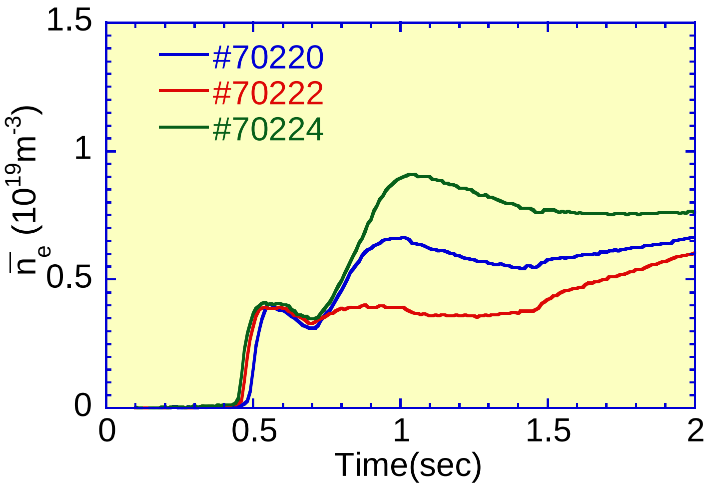
[a]Reference 3.

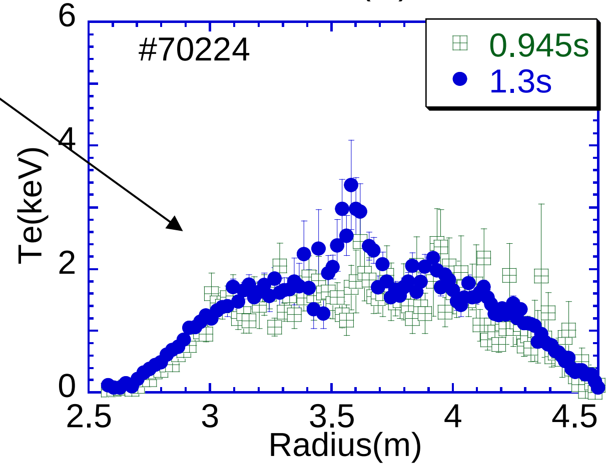
Temporal change of the potential by ECH

R_{ax}=3.6m, B_t=1.5T,ECH : on-axis heating (1.0 – 1.5 s)
The plasma is produced and sustained by NBI.
HIBP : W_{beam}=1.5MeV , The sample volume is near the magnetic axis.





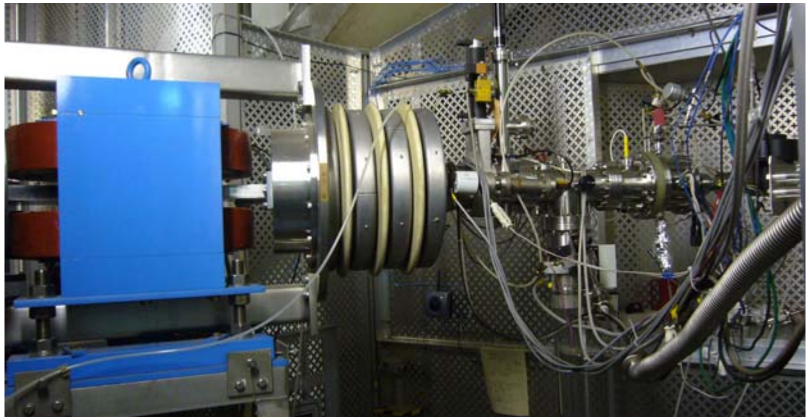




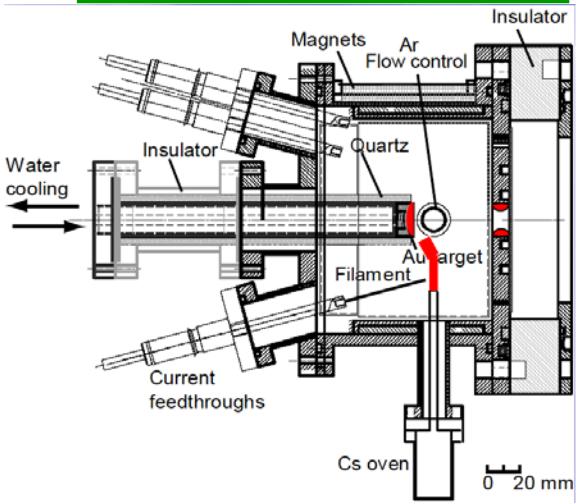
The increase in the potential tends to related to the increase in T_e.

Negative Ion source

Negative ion source,pre accelerator, sector magnet



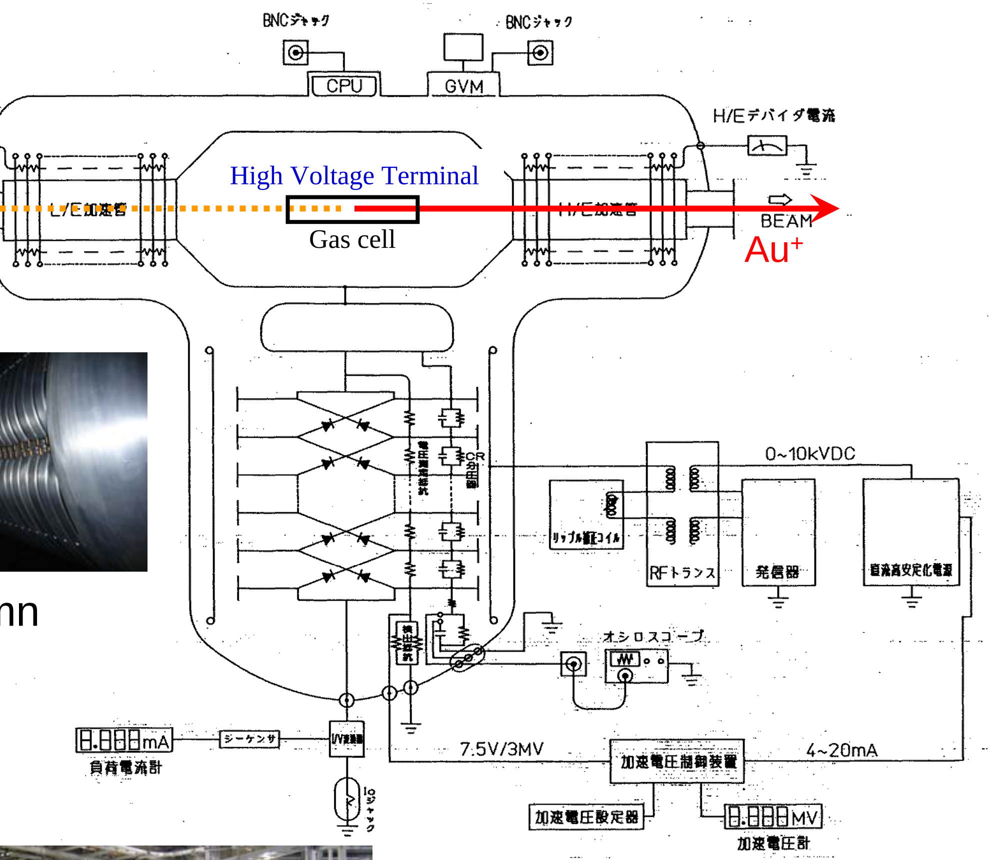
Negative ion source



Control Box

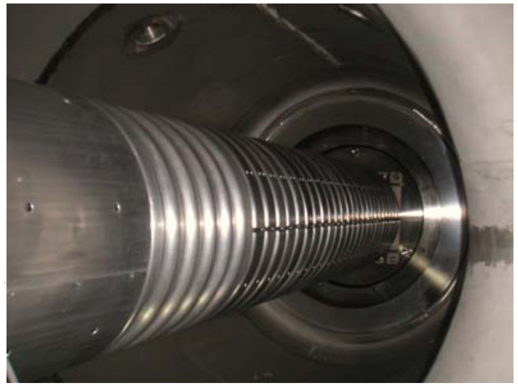
- Target sputtering Au^- ion source
- Au^- ion is pre-accelerated to 50kV, and injected to the tandem accelerator
- Produced current is ~ 20μA

Tandem Accelerator



Column

Chamber of accelerator

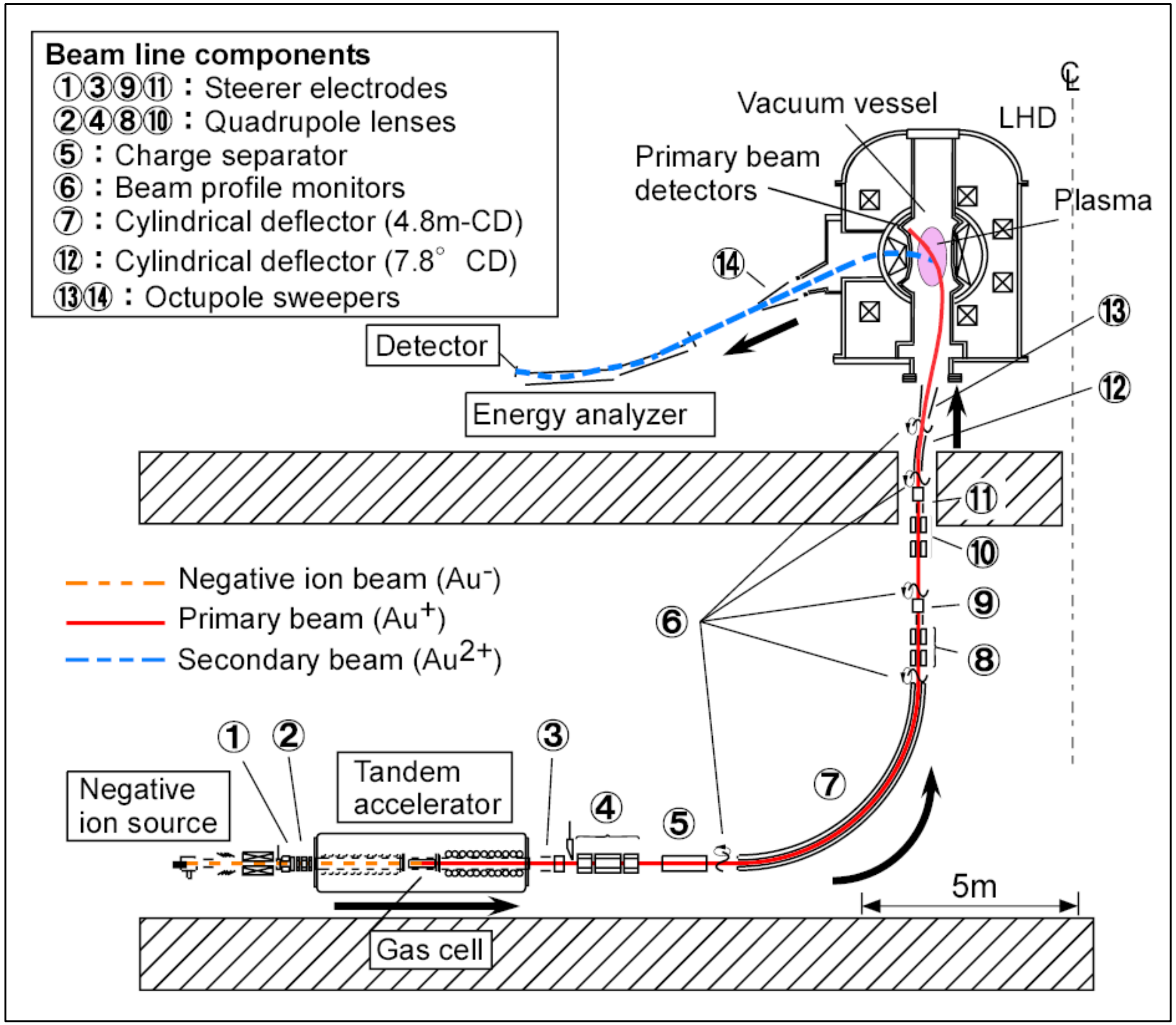


Accelerator tube

High frequency wave generator

- By using tandem accelerator, we can generate 6MeV beam with the voltage of 3 MV
- Very stable voltage is needed to measure the plasma potential. (10^{-5} ~ 10^{-4})

Beam Control System



①③⑨⑪**Steerer**

Beam Position

②④⑧⑩**Quadrupole Lens**

Beam Focus

⑤**Charge Separator**

Select Au^+ from Au^{n+}

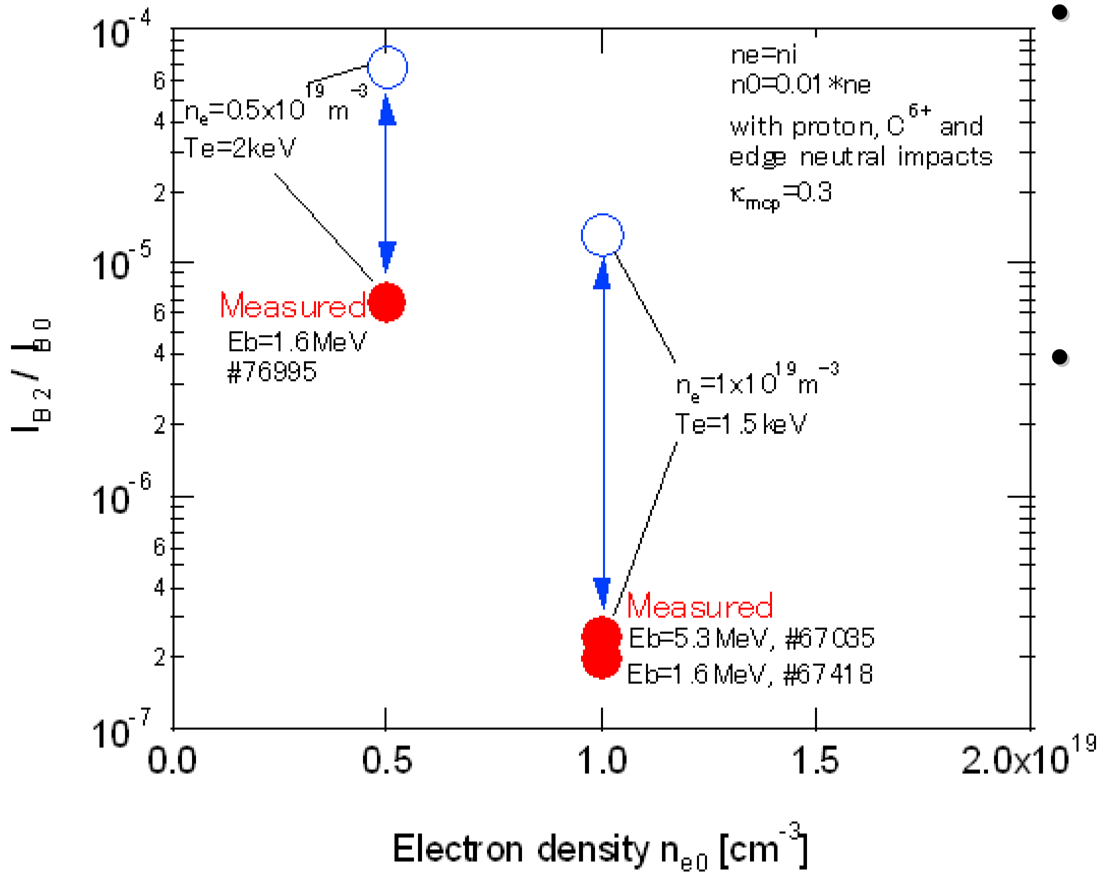
⑥**Beam Profile Monitor**

⑦**4.8m Cylindrical Deflector**

⑬⑭**8 pole electrical deflector**

Control of injection and ejection angle of beam

Beam Attenuation in LHD



- Secondary beam intensity attenuates 5 ~ 9 times by neutrals (H_2) in the edge region and impurity ions (C^{6+}) in the core plasma.
- But the calculated secondary beam intensity is still one order of magnitude higher than the experimental one.

We found MCP detection efficiency 0.1~0.5 **(Good agreement!!)**