P7-05

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Advanced Imaging and Plasma Diagnostics
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Fast-ion-diagnostics for CHS experiment

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Outline

- Compact Helical System (CHS) project
- CHS fast ion experiments
- Review of fast-ion-diagnostics in CHS
    - Neutral particle analyzer
    - Lost-fast-ion probes
    - Neutron diagnostics
- Summary of experimentally obtained knowledge on fast ions

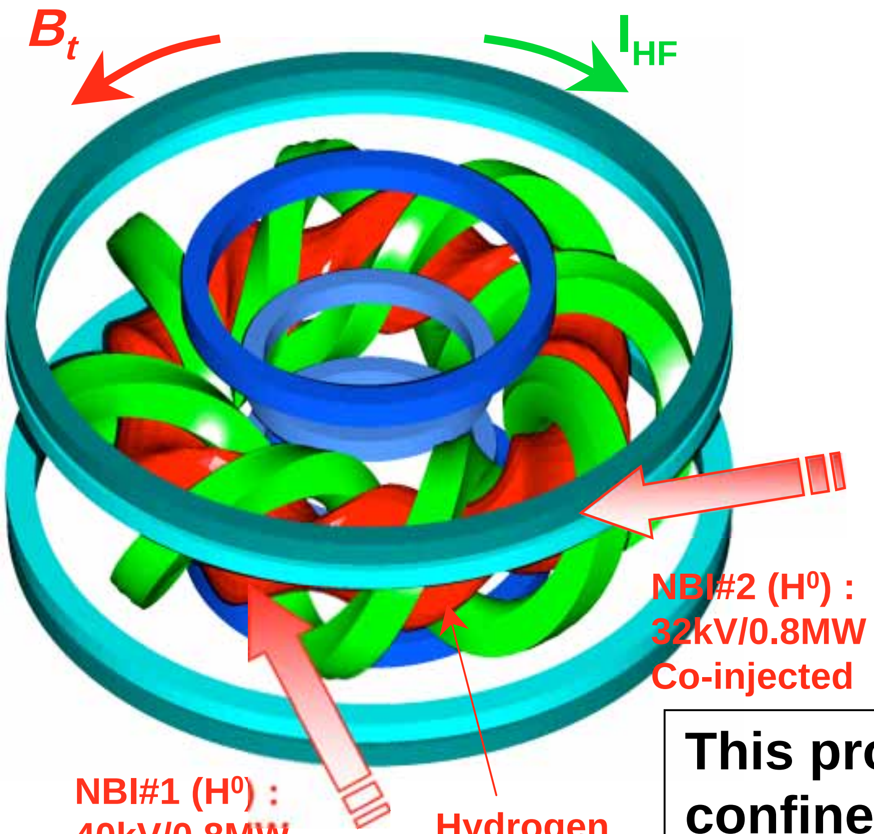
1. Issues related to fast-ion-orbits and/or loss cone
    - Confinement study of helically trapped fast ions
    - Confinement study of co-passing fast ions
    - Effect of radial electric field on trapped ion behavior

2. Excitation of fast-ion-driven MHD instabilities and their effects on fast ion transport

CHS project

CHS was a medium-sized helical device having a major radius *R* of 1 m and averaged plasma minor radius a_p of ~0.2 m.

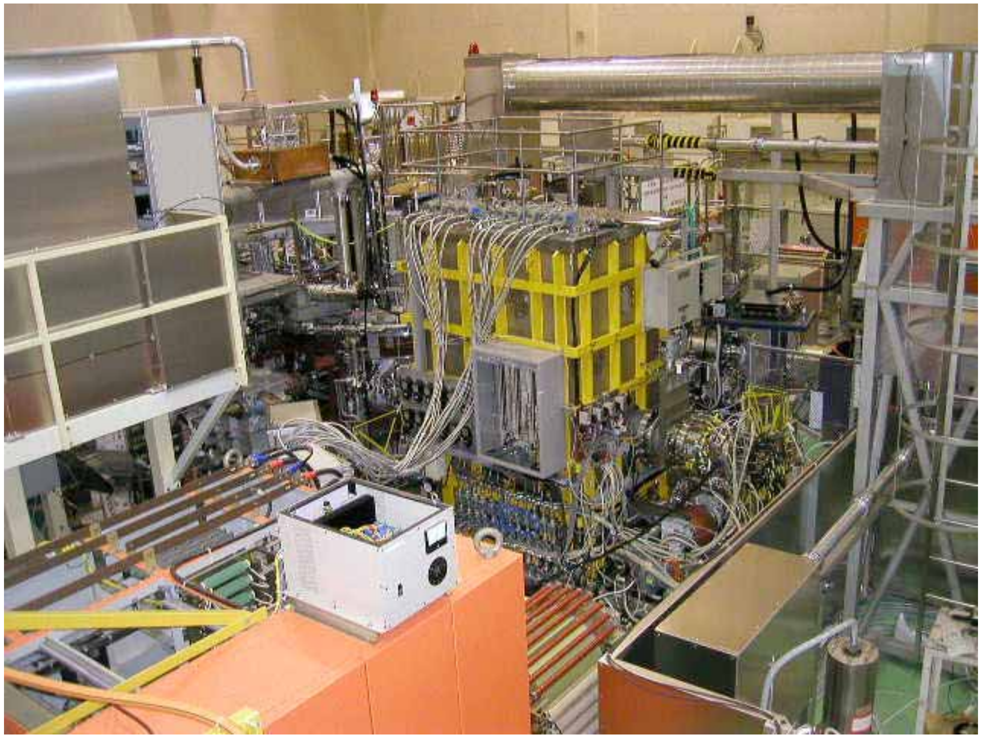
The CHS project since June 1988 came to a close at the end of August 2006.



NBI#2 (H^0) :
32kV/0.8MW
Co-injected

NBI#1 (H^0) :
40kV/0.8MW
Co-injected

Hydrogen
plasma



This project has primarily aimed at clarifying confinement properties of a low-aspect-ratio helical plasma

On fast ions in CHS

NBs for heating

The CHS was equipped with two NB injectors. One (NB#1) can provide P_{nb} of 800 kW with E_b of 40 keV. The NB#1 was capable of varying the injection angle from tangential to perpendicular direction in order to explore efficient heating condition. The other (NB#2) provides P_{nb}/E_b of 800 kW/32 keV.

In the **Higashiyama site**, two NBs were **injected in the balanced manner** to study confinement property of low-aspect-ratio helical plasma in the net current free condition.

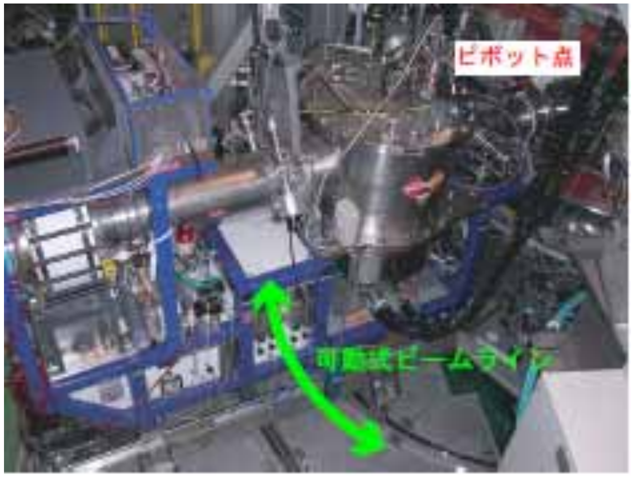
When CHS was moved to the **Toki-site**, NB injectors were rearranged so as to **inject beams in the same direction**. NBs have been typically co-injected to obtain efficient plasma heating.

Beam ions also have played an important role for the studies of fast-ion-driven MHD instabilities such as TAE and EPM since they can be free energy source to destabilize those instabilities.

Diagnostic NB

A diagnostic neutral beam (DNB) injector (E_b<40 keV, P_{nb}~50 kW) was convenient for the detailed study of loss cone structure.

The DNB as a **test particle source** is characterized by the narrower beam and much lower P_{nb} than NBs for heating.

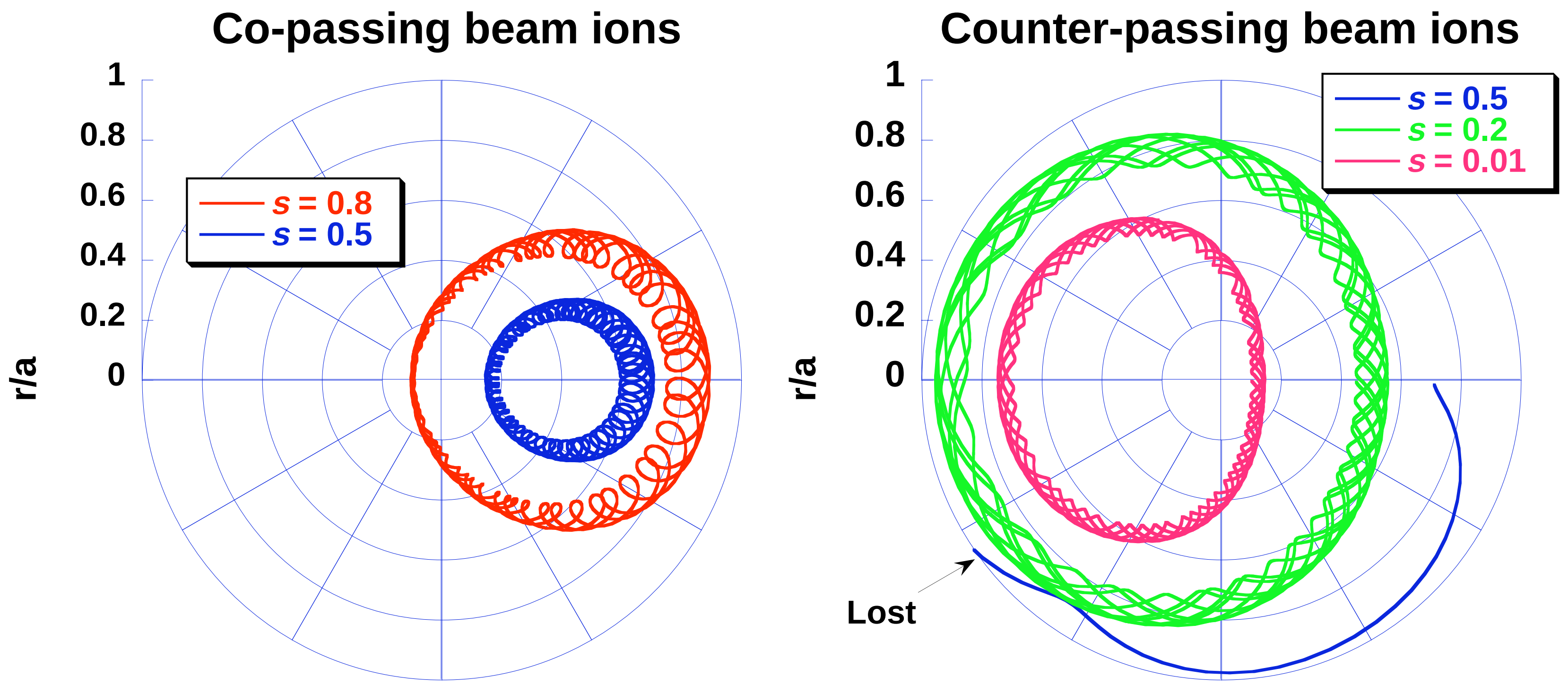


Beam current I_b	< 2 A
Beam diam.	10 cm
Pulse duration	100 ms
Focal length	3.04 m

H. Matsushita *et al*., Rev. Sci. Instrum. **75**, 3607 (2004)
H. Matsushita, ph D thesis, Grad. Univ. for Advanced Studies 2006

Characteristics of CHS beam ion orbits

Orbits of passing beam ions substantially deviate from the flux surfaces in the low field (< 1 T) operation of CHS



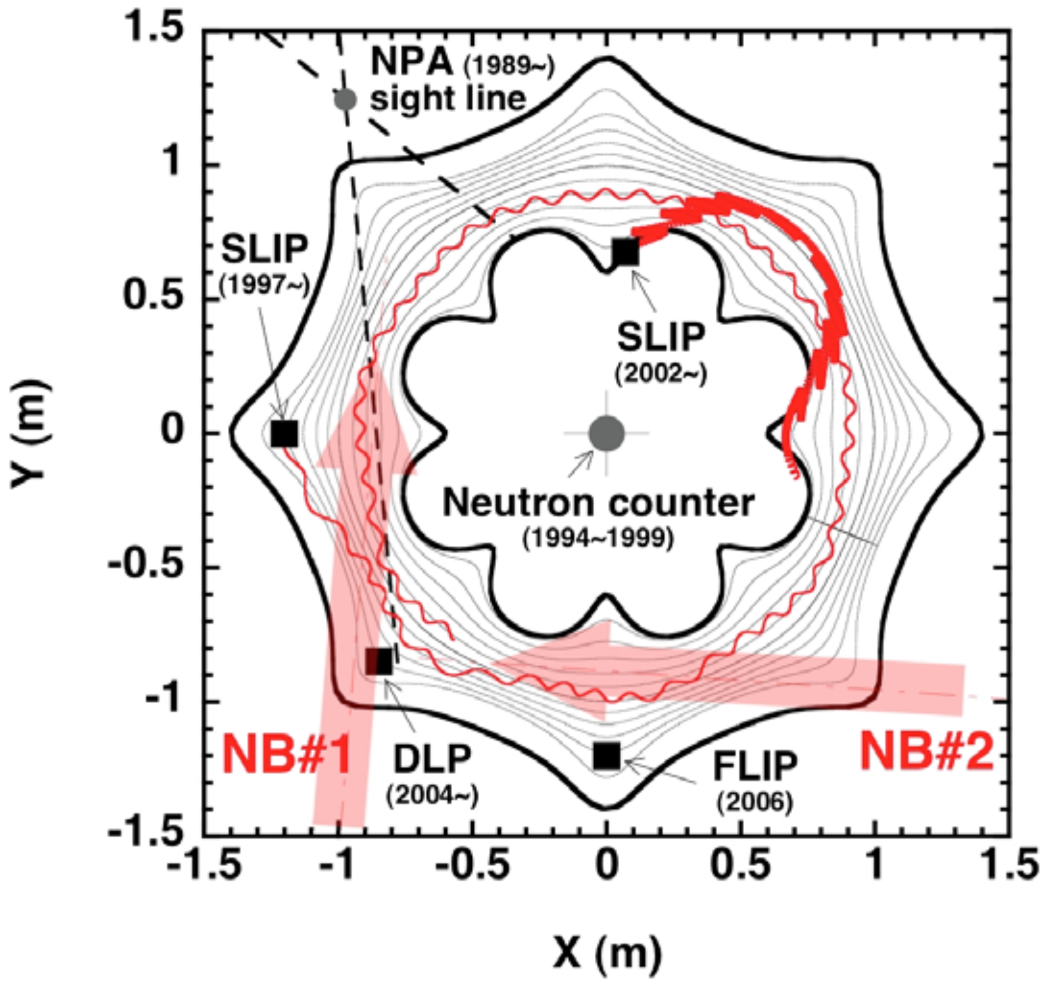
Co-passing beam ions

Counter-passing beam ions

- Coliisionless guiding center orbits in the vacuum configuration of **R_{ax}=0.962 m** and volume-averaged field strength of **0.94 T**.
- **E=38 keV**, initial **$v_{//}/v$ = 0.8**.
- Beam ions are launched on the outboard side of the torus (**$R>R_{ax}$**).

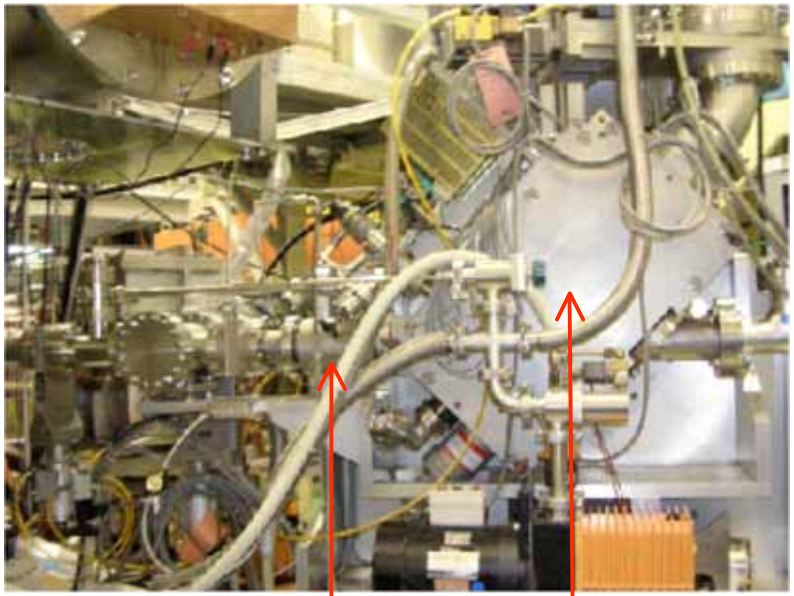
Arrangement of fast-ion-diagnostics

A variety of fast-ion-diagnostics have been developed and applied to CHS



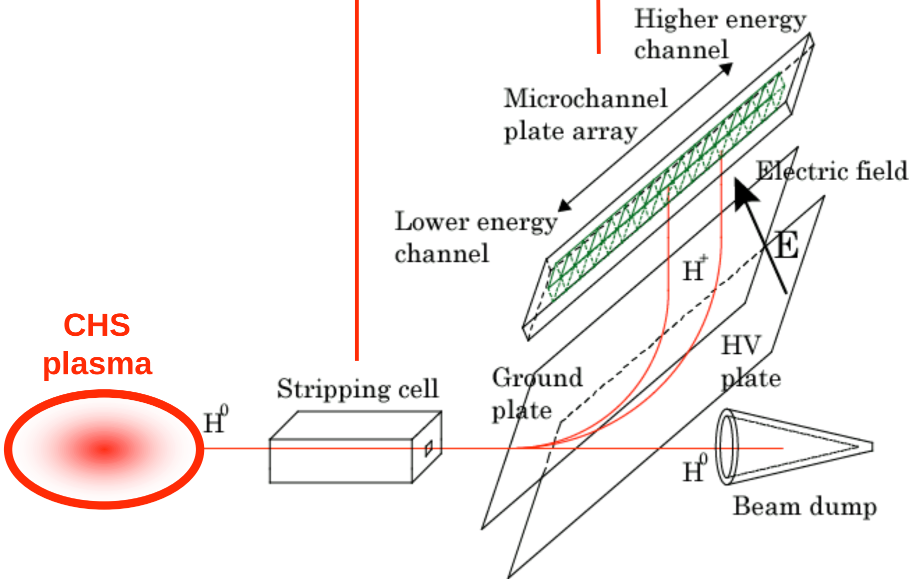
1. Neutral particle analyzer (NPA)
2. Lost-fast-ion probes
    - Scintillator (SLIP)
    - Faraday-cup (FLIP)
3. Directional Langmuir probe (DLP)
4. Neutron counter

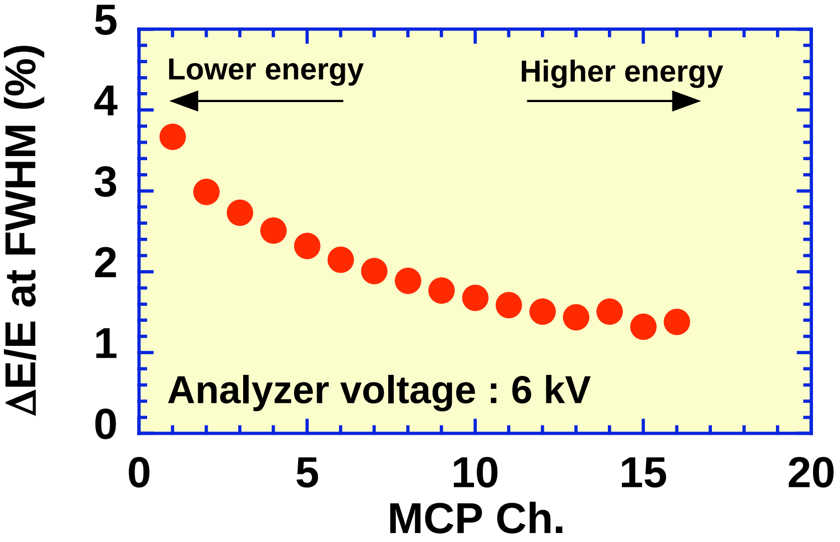
Neutral particle analyzer (NPA)



- **Energy range : 0.1 keV ~ 50 keV**
- **MCP channels : 16**
- **Max. counting rate : ~3x10^5 cps**
- **Viewing angle variable**
- **CHS NPA was fabricated in 1989 by Toshiba**

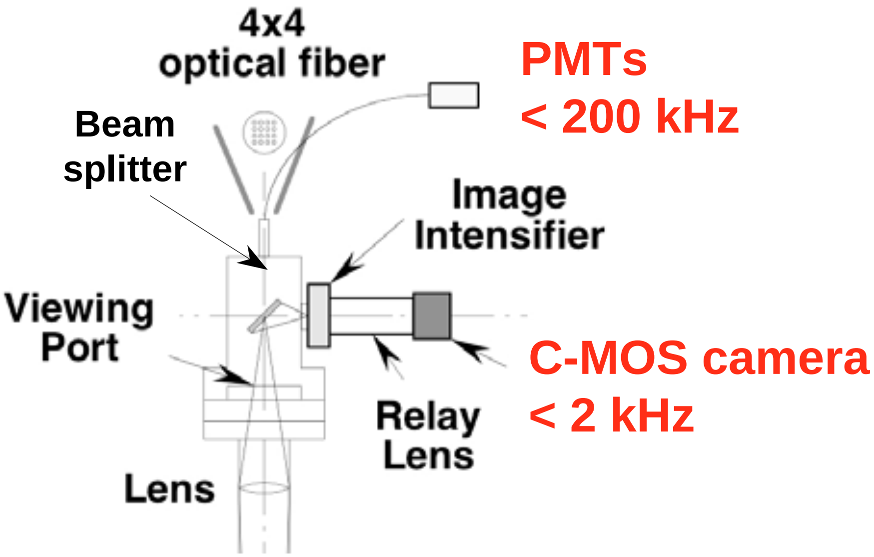
ΔE/E was examined by use of a test proton beam source of which energy is up to 10 keV.

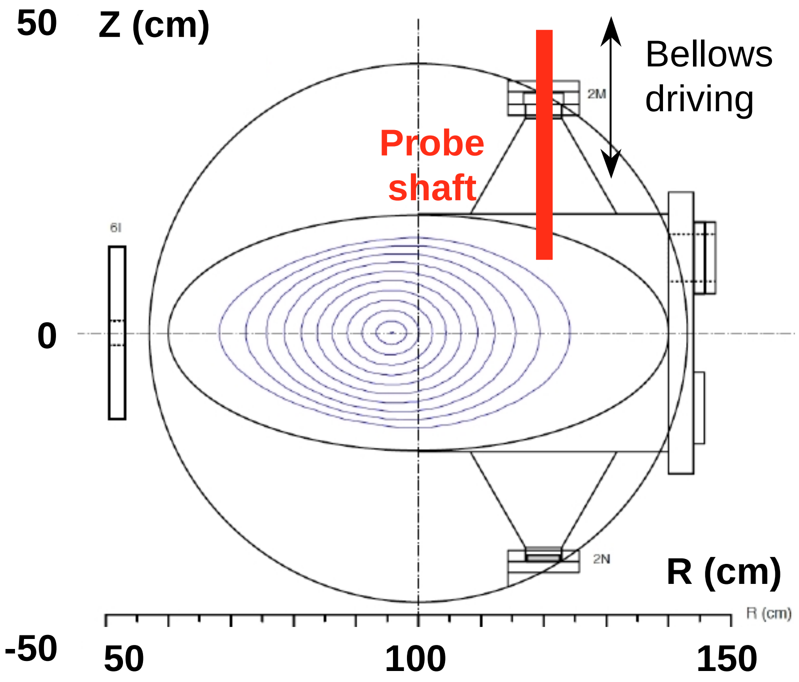




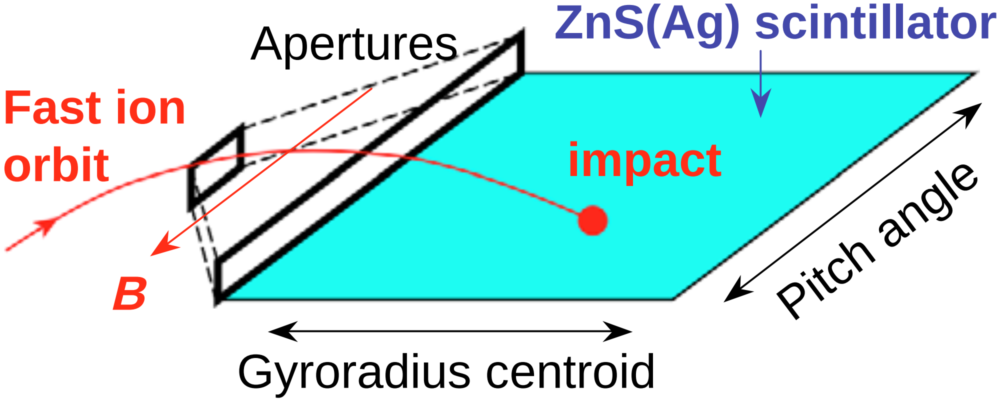
References
- H. Matsushita *et al.*, Rev. Sci. Instrum. **75**, 3607 (2004)
- H. Matsushita, ph D thesis, Grad. Univ. Advanced Studies, 2006

Lost-fast-ion probe : Scintillator (SLIP)





Perspective view of probe tip



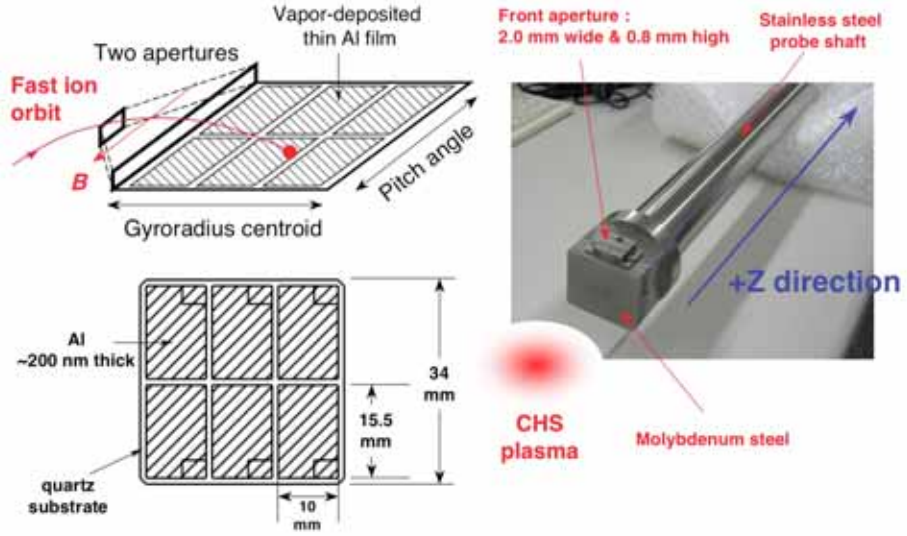
- **Only fast ions can enter the detector box and hit the scintillator surface.**

- **Location of scintillation light due to impact of fast ions involves both information of pitch angle and energy of lost fast ions.**

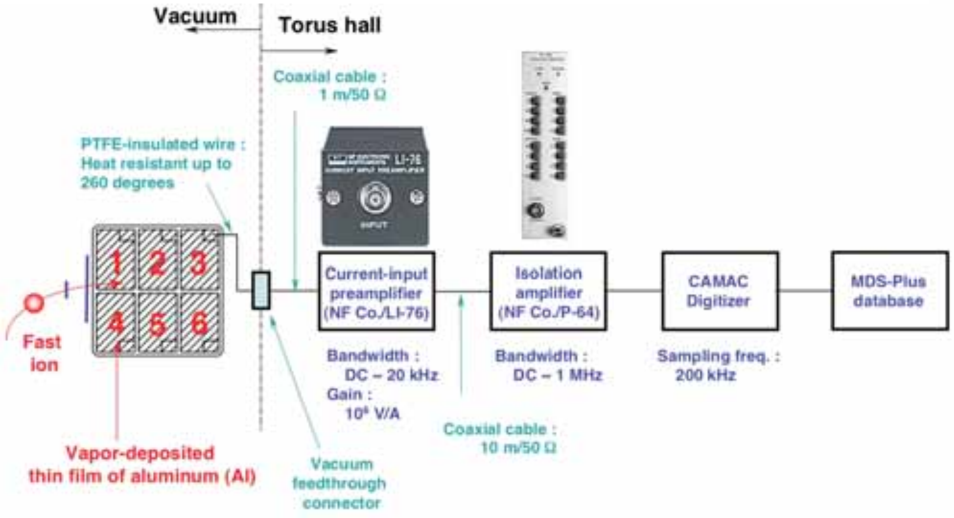
D. S. Darrow *et al.*, J. Plasma Fusion Res. SERIES **1**, 362 (1998).
M. Isobe *et al.*, Rev. Sci. Instrum. **70**, 827 (1999).
D. S. Darrow *et al.*, Rev. Sci. Instrum. **70**, 838 (1999).

Lost-fast-ion probe : Faraday film (FLIP)

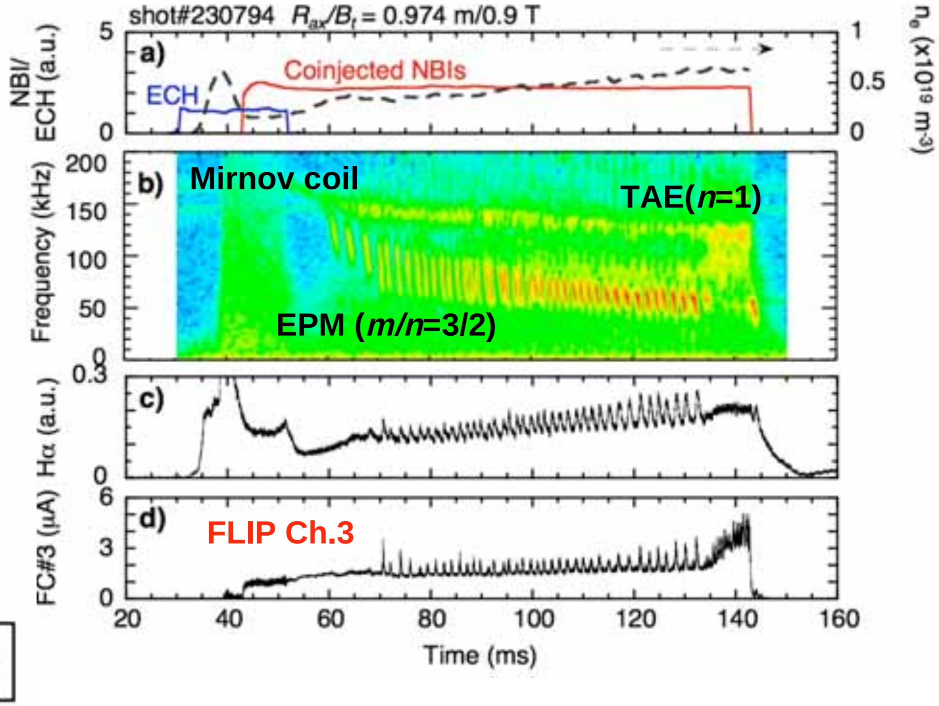
Detail and function of FLIP



Electric circuit



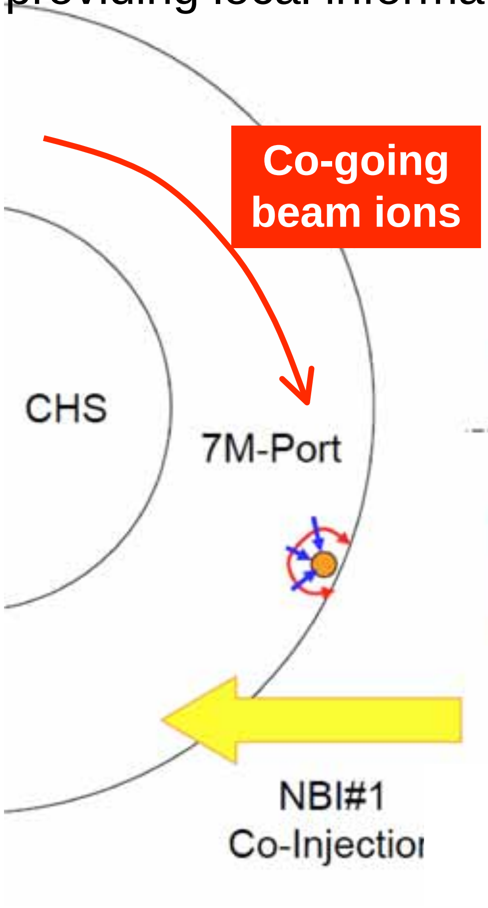
Observation of anomalous fast ion transport due to fast-ion-driven MHD instabilities by FLIP

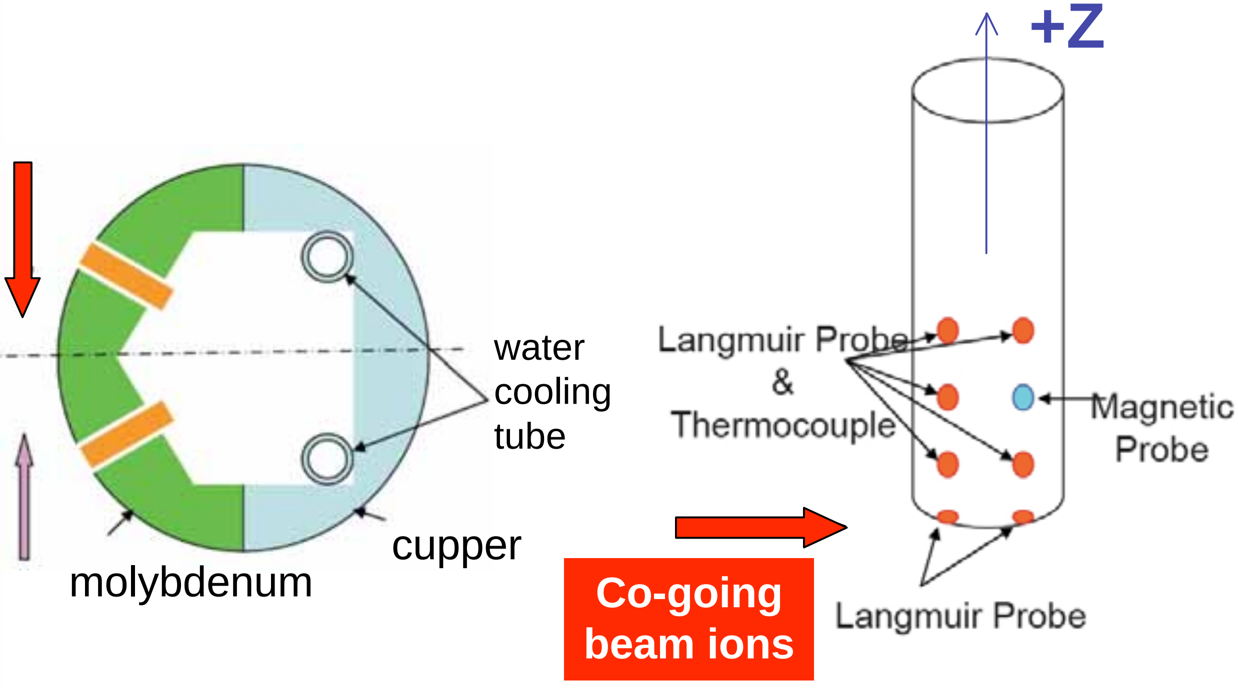


M. Isobe *et al.*, Rev. Sci. Instrum. **77**, 10F508 (2006)

Directional Langmuir probe (DLP)

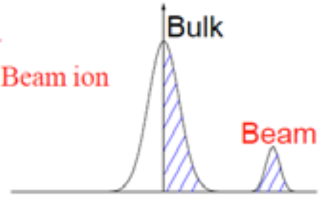
DLP was designed to be tough for heat load so as to insert into an NB-heated plasma, providing local information of fast ion behavior in an interior region of CHS plasma.





$$I_{\mathrm{Co}} = I_{\text{Bulk ion}} + I_{\text{Beam ion}}$$

$$I_{\mathrm{Ctr}} = I_{\text{Bulk ion}}$$



The beam current can be evaluated by

$$\therefore I_{\text{Beam ion}} = I_{\mathrm{Co}} - I_{\mathrm{Ctr}}$$

K. Nagaoka *et al.*, this conference, P8-07

Neutron measurement

Neutron measurement provides information of global confinement of NB-injected fast ions.
In our experiments, D-D neutrons were generated by injecting 1 % deuterium-doped hydrogen NB of which pulse duration was less than 5 ms into deuterium ECRH plasmas at the Higashiyama site.

When D^0 beam is injected into the deuterium plasma, the total neutron emission rate S_n is dominated by neutrons generated from beam-target reactions and can be scaled as

$$S_n \propto n_d n_{fd} <\sigma v>_{D-D}$$

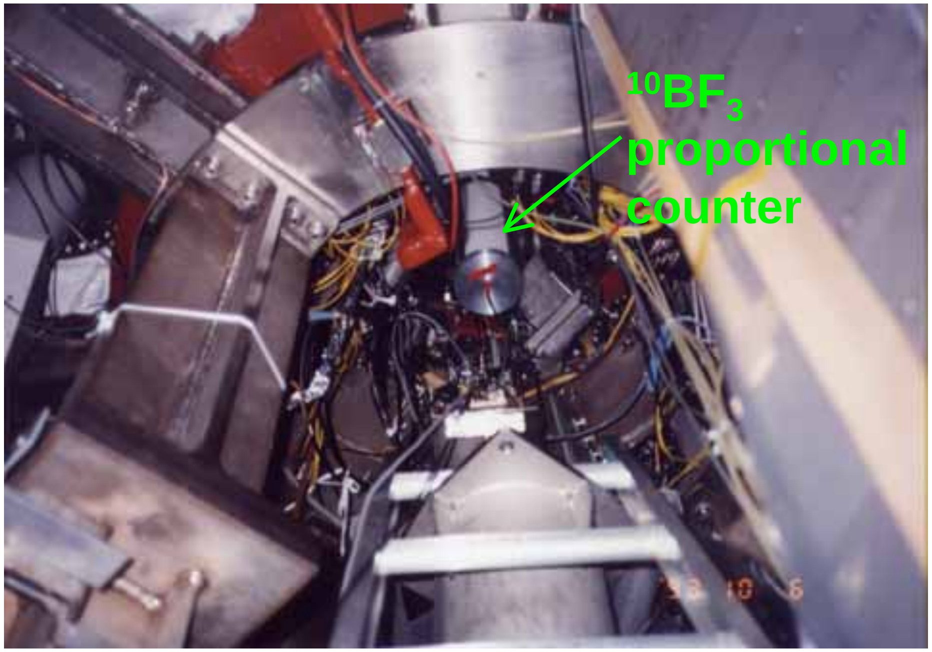
Here, n_d and n_{fd} represent deuteron (D^+) density in the target plasma and fast D^+ beam density, respectively.

Neutron decay time predicted by classical slowing down model after NB turn-off :

$$\tau_{n-class} = -\int_{E_n}^{E_{inj}} \frac{dE}{\{dE/dt\}_{classical}} = \frac{\tau_{se}}{3}\ln\left(\frac{E_{inj}^{3/2}+E_{crit}^{3/2}}{E_n^{3/2}+E_{crit}^{3/2}}\right)$$

If we take account of beam ion loss, the experimental decay τ_{n-exp} is expresses as

$$1/\tau_{n-exp} \approx 1/\tau_c + 1/\tau_{n-class}$$



In CHS at Higasiyama-site (~1999),

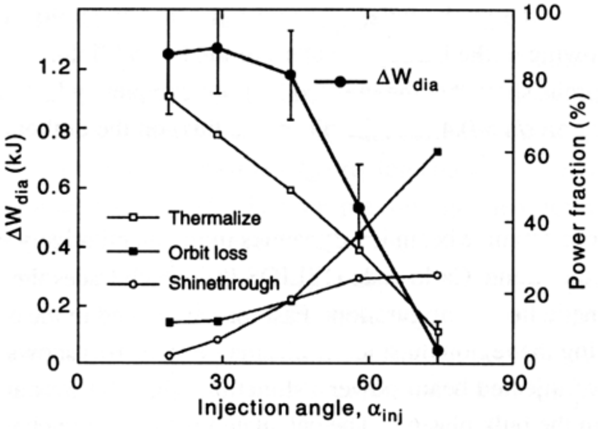
- **$^{10}BF_3$ and ^3He proportional counters**
- **Fast plastic scintillator**

were employed.

References on diagnostic system ;
M. Isobe *et al.*, Rev. Sci. Instrum. **66**, 923 (1995)
M. Isobe *et al.*, Rev. Sci. Instrum. **68**, 532 (1997)

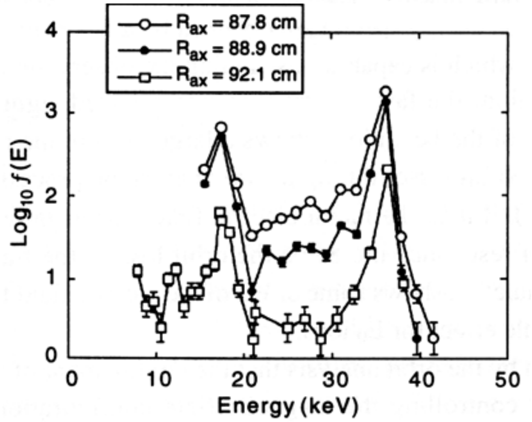
Confinement of perpendicularly injected beam ions

1



Perpendicularly injected NB could no increase plasma stored energy in R_{ax}/B_t of 0.921 m/1.5 T, suggesting poor confinement of helically trapped beam ions.

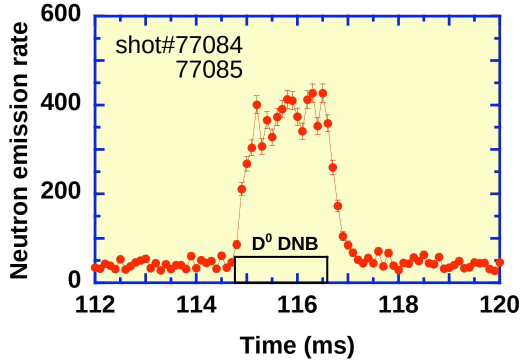
2

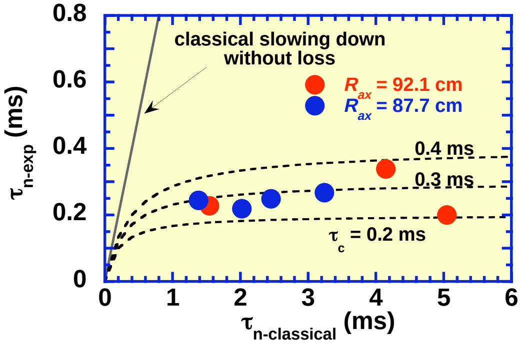


Although particle orbit is expected to be improved as the plasma column is shifted inward, NPA viewing perpendicularly showed significant depletion on the energy spectrum of beam ions even for R_{ax} of 0.878 m.

S. Okamura *et al*., Plasma Physics and Controlled Nuclear Fusion Research 1992 (Proc. 14th Int. Conf. Würzburg, 1992), IAEA, Vienna Vol. **2**, 597 (1993).

3

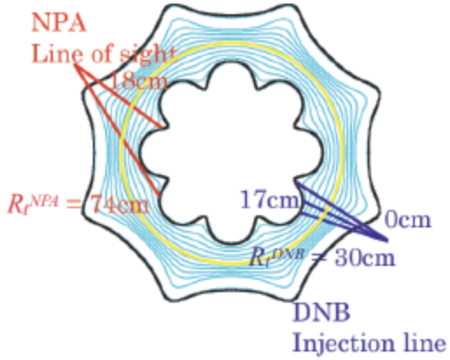




The result of "blip" injection experiment of perpendicular D^0 DNB was similar to the above result.

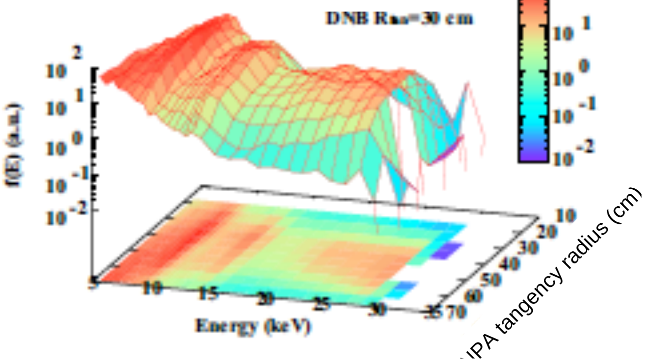
M. Isobe *et al*., Nuclear Fusion **41**, 1273 (2001)

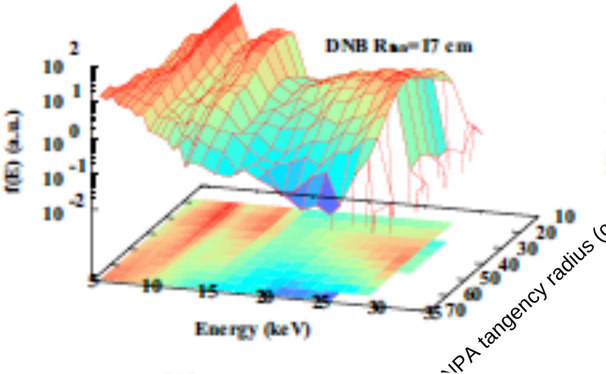
Studies on perpendicularly injected beam ions by means of DNB and NPA

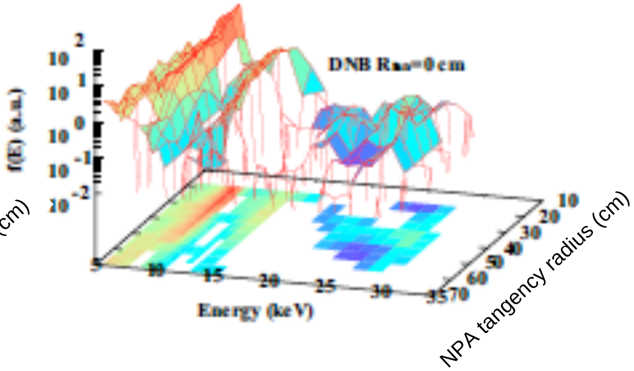


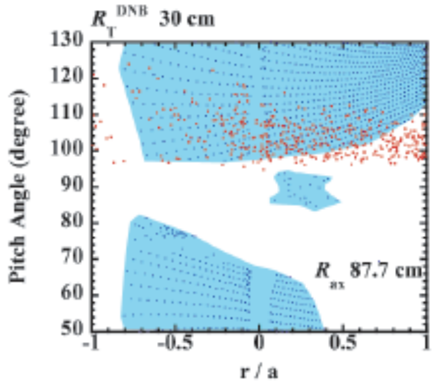
Energy spectrum of beam ions are investigated in the wide range of pitch angles ($v_{//}/v$) by scanning injection angel of DNB and viewing angle of NPA.

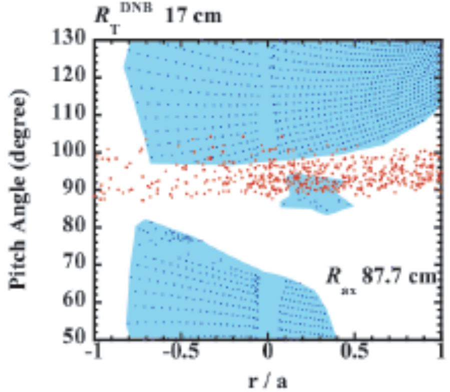
H. Matsushita *et al.*, Rev. Sci. Instrum. **75**, 3607 (2004)
H. Matsushita, ph D thesis, Grad. Univ. Advanced Studies, 2006

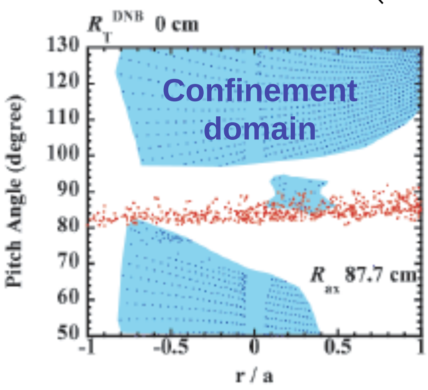








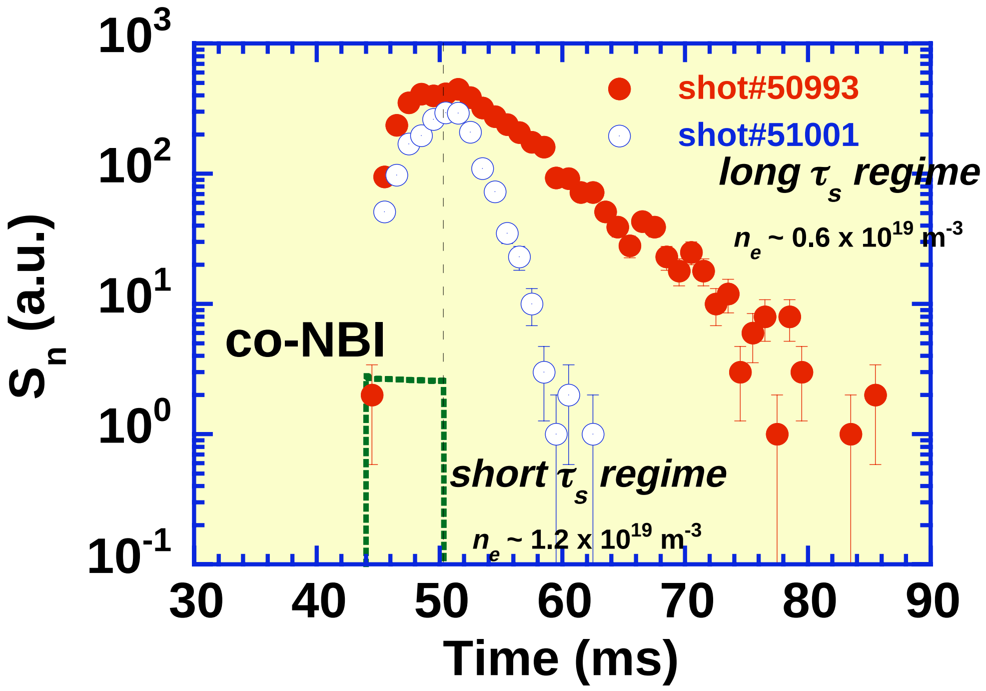


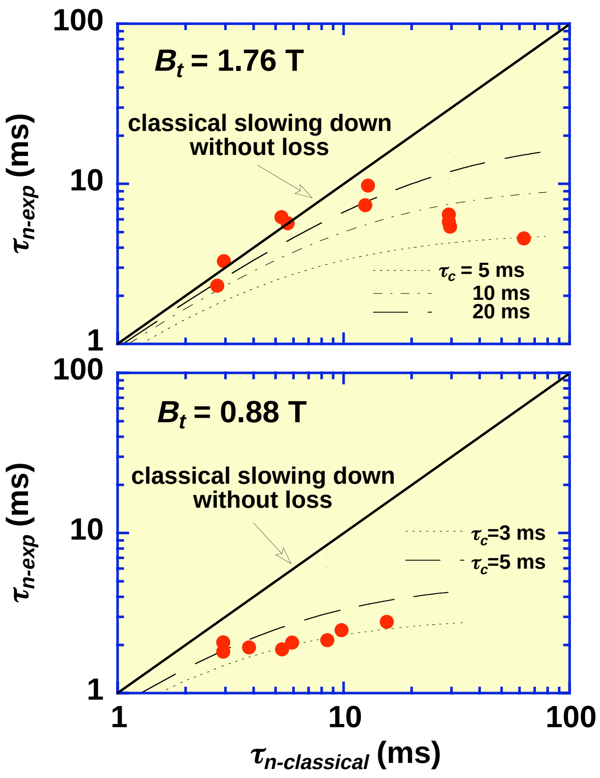


Perpendicularly injected beam ions are not well confined as expected.

Confinement of tangentially co-injected beam ions

D-D neutrons were generated by injecting 1 % deuterium-doped hydrogen NB of which pulse duration was less than 5 ms into deuterium ECRH plasmas at the Higashiyama site.



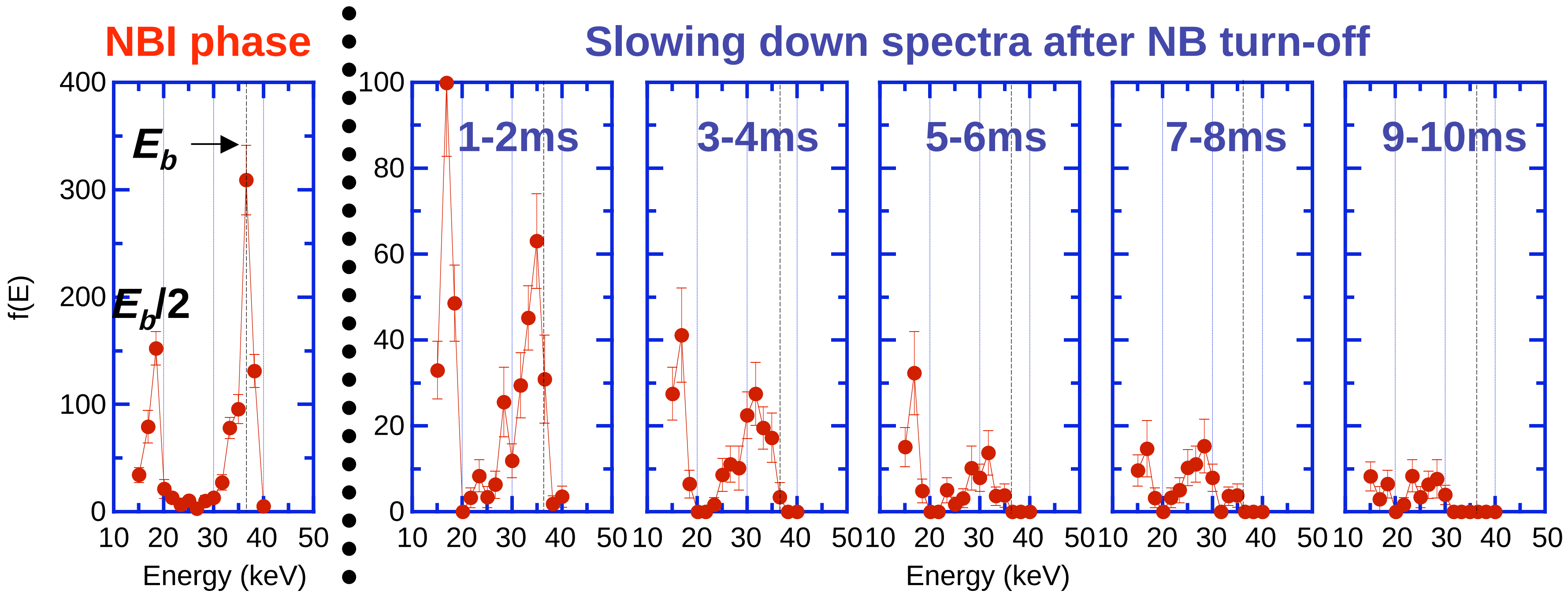


In B_t of 0.88 T, beam ion losses were particularly significant in the long slowing down time regime whereas losses in B_t of 1.76 T were largely suppressed. Losses of co-going transit beam ions were interpreted as the multiplier effects of strong deviation of orbits from the flux surfaces toward the outboard side and resulting high probability of charge exchange loss in a peripheral region where neutral density is high.

M. Isobe *et al*., Rev. Sci. Instrum. **68**, 532 (1997).
M. Isobe *et al*., J. Plasma Fusion Res. SERIES **1**, 366 (1998).

Check of energy loss rate of beam ions

- Short pulse heating NB(~4 ms) is tangentially co-injected into ECRH plasma.
- NPA line of sight is set to be tangential to detect co-passing beam ions.
- n_e ~ $0.3\mathrm{x}10^{19}$ m^{-3}, $B_t = 0.88/R_{ax}$=0.921m(Inward shifted)



After NB turn-off, peak position of full energy component moves to low energy side in time, indicating slowing down of beam ions

M. Isobe *et al*., J. Plasma Fusion Res. SERIES **1**, 366 (1998)

Energy loss rate of beam ions is consistent with Stix formula based on classical theory

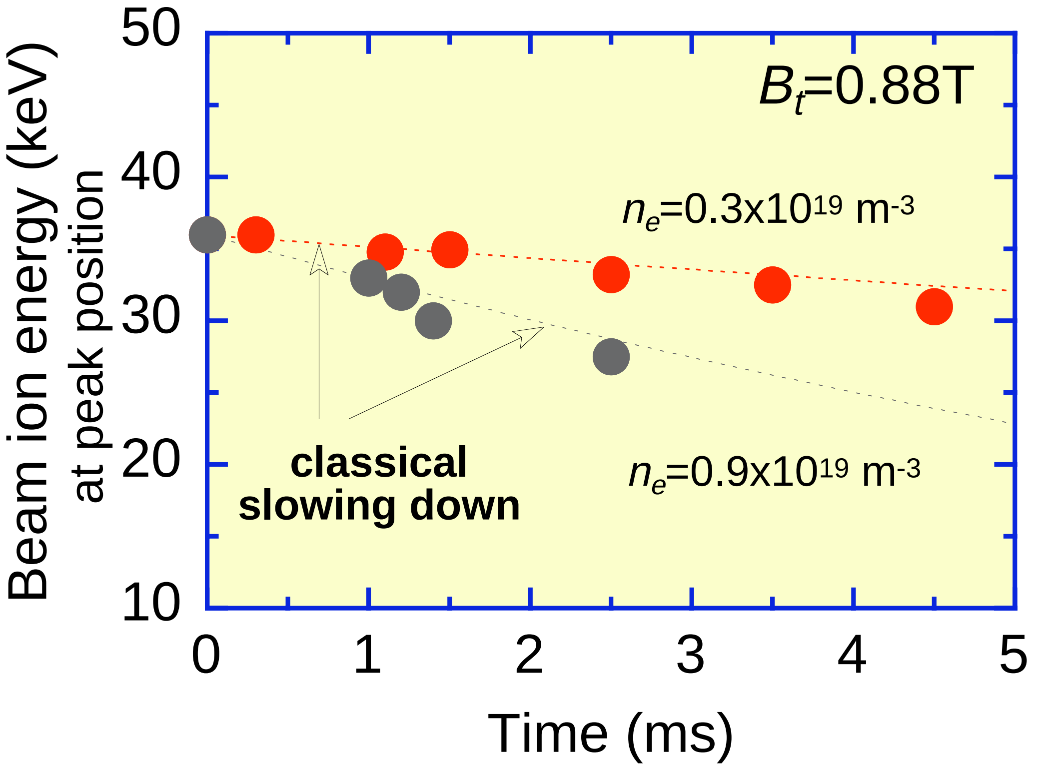
Classical energy loss formula by T.H.Stix (Plasma Physics 14(1972)367)

$$\frac{dE}{dt} = -\frac{\alpha}{\sqrt{E}} - \beta E$$

$$\alpha = 1.81 \times 10^{-7} \ln \Lambda_{ii} A^{1/2} Z^2 \sum_j \frac{n_j Z_j^2}{A_j}$$

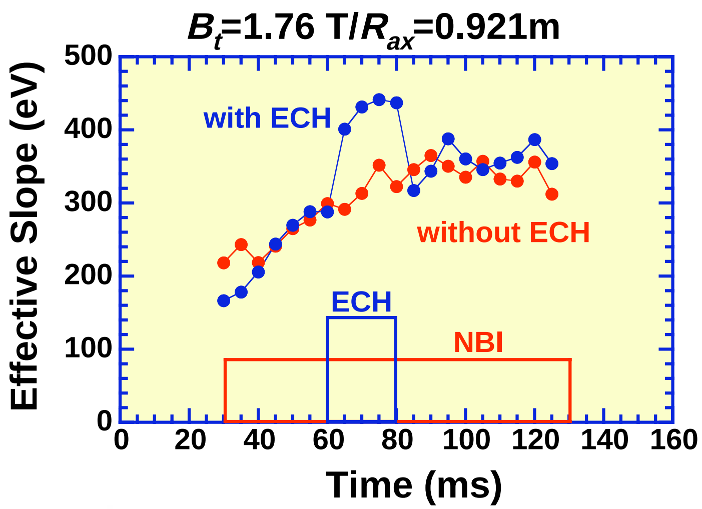
$$\beta = 3.18 \times 10^{-9} \ln \Lambda_{ie} \frac{Z^2}{A} \frac{n_e}{T_e^{3/2}}$$

Comparison between energy loss rate of experiment and classical model

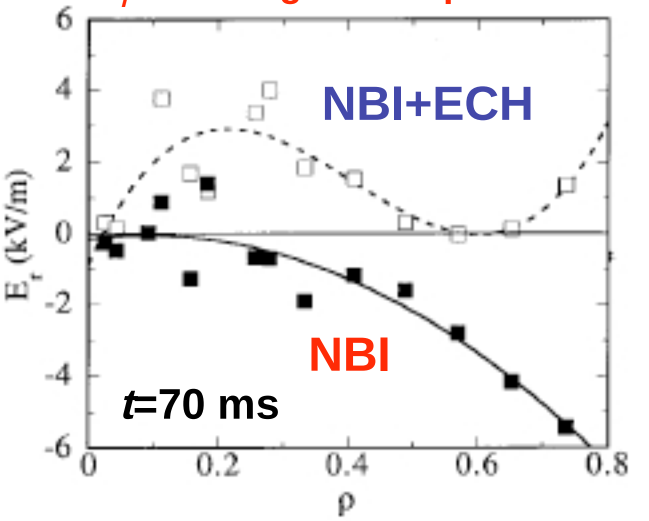


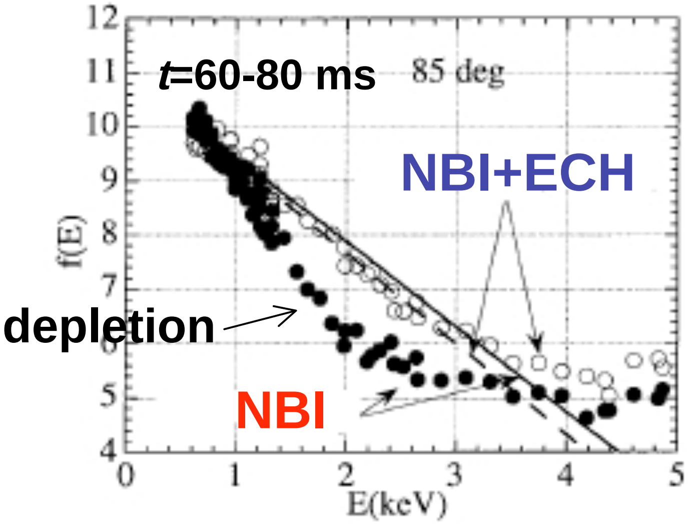
M. Isobe *et al.*,
J. Plasma Fusion Res.
SERIES **1**, 366 (1998)

Effect of radial electric field on trapped ions



The superposition of ECH changes E_r from negative to positive





Positive E_r improved trapped ion orbit, resulting in reducing loss cone domain in the energy range of 1~3 keV.

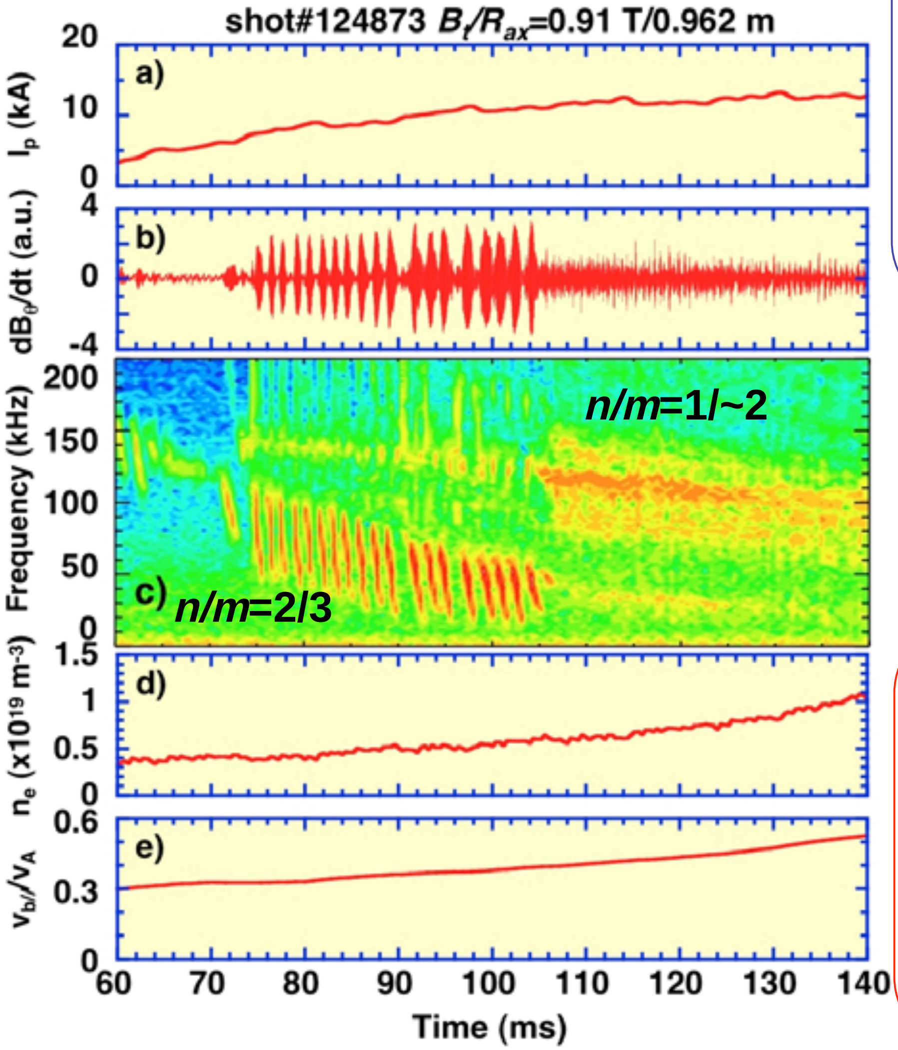
It should be noted that effect of positive E_r on ions having higher energy was not seen.

References

- M. Osakabe *et al.*, Proc. of the 6th IAEA TCM on energetic particles in magnetic confinement systems, October 12-14, 1999, Naka, JAERI-Conf 2000-004, 85
- K. Ida *et al.*, Nucl. Fusion **39**, 1649 (1999).

Fast-ion-driven-MHD instabilities observed in CHS

MHD instabilities excited due to tangentially co-injected NBs (P_{nb}=1.6 MW)



- In the initial half of the discharge (t<105 ms), repetitive bursting magnetic fluctuations are seen.
- This mode is diagnosed to be ***m/n*=3/2**, rotating in **the ion-diamagnetic direction**.
- It is characterized by a **rapid frequency downshift** with a time scale < 1 ms.

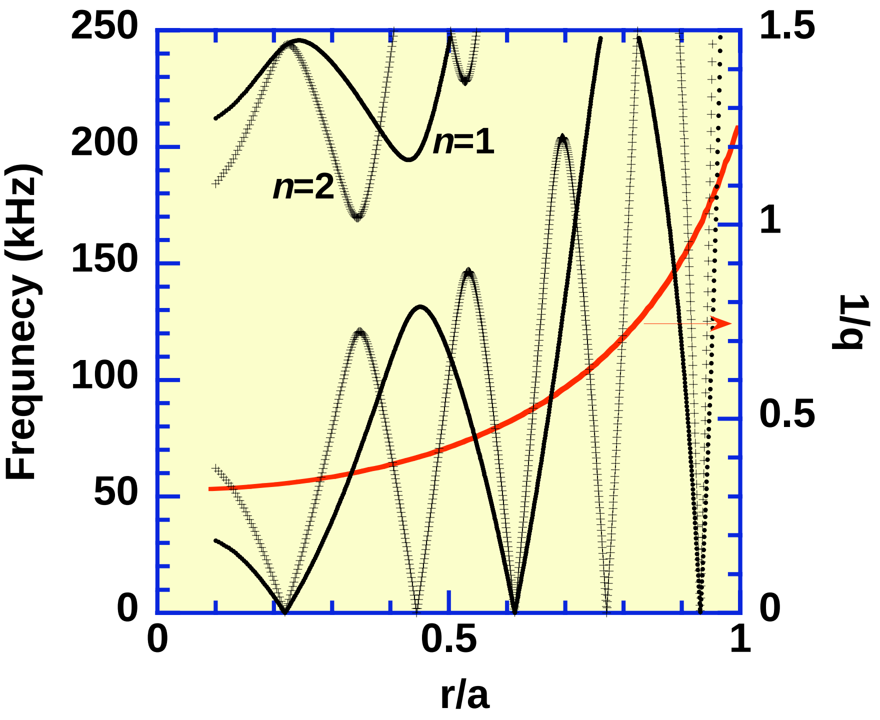
- As $v_{b//}/v_A$ increases, the bursting modes having f<100 kHz disappear and weaker fluctuations having higher frequency (f>100 kHz) become more intense.

- The higher frequency modes are strongly destabilized when the condition of $v_{b//}/v_A>1/3$ is fulfilled.
- The mode numbers are measured as ***n*=1/*m*~2**.
- This mode also propagates in **the ion-diamagnetic direction**.

M. Isobe *et al.*, 21th IAEA fusion energy conference, Chengdu, 16-21 October 2006, EX/P6-8

Shear Alfvén continua

Rotational transform and shear Alfvén continua
for the *n*=1 and *n*=2 modes
in R_{ax}/B_t=0.962 m/0.91 T



- The frequency of repetitive bursting modes is appreciably located below the TAE gap frequency.
- The *m* number is specifically identified without mixing.
- Bursting nature.

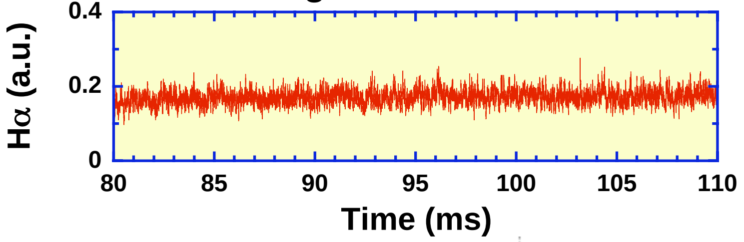
⇨ Observed bursting modes are the so-called EPMs.

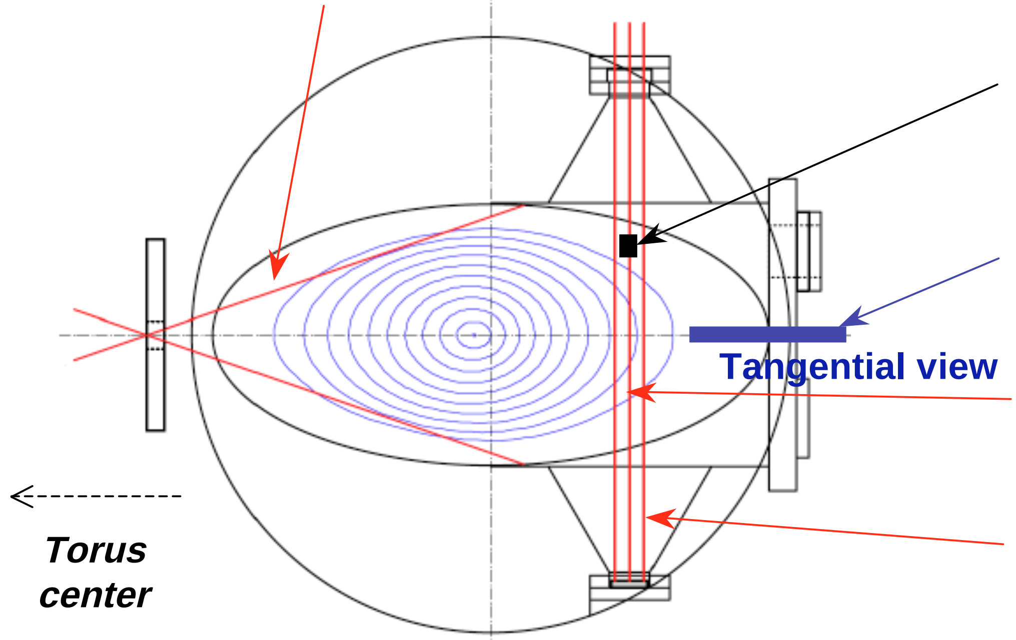
- In regard to higher frequency instabilities (*f*>100 kHz), they are thought to be core-localized TAEs.
- The shear Alfvén spectrum calculated with the experimental parameter range suggests that the observed mode with *f*>100 kHz is *n*=1 TAE.
- The condition of the sideband excitation for TAE, i.e. $v_{b//}/v_A$>1/3 is satisfied.

Fast ion experiments were mainly performed in outward shifted configuration, where EPMs and TAEs are alternately destabilized in the same shot.

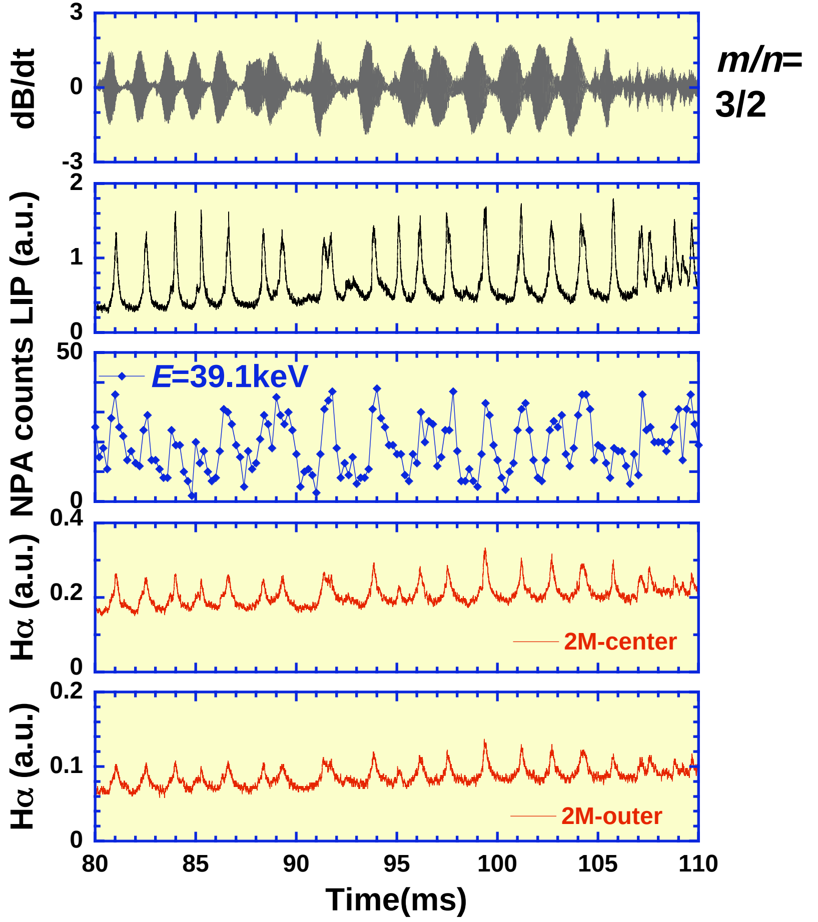
Bursting EPMs enhance lost-fast-ion, fast-CX neutral fluxes and Hα light emissivity at the outboard side of torus

Hα signal from small R side





shot#124868 R_{ax}=0.962 m/B_t=0.92 T
NB#1:E_b=39.5 keV NB#2:E_b=31.9 keV



- Correlated with EPM bursts, LIP, NPA and Hα signals at the large *R* side periodically enhanced.
- No change in Hα light emission from the edge at the inboard side is observed.
- Co-going beam ions diffuse toward the outside and are lost at large *R* side due to EPMs.

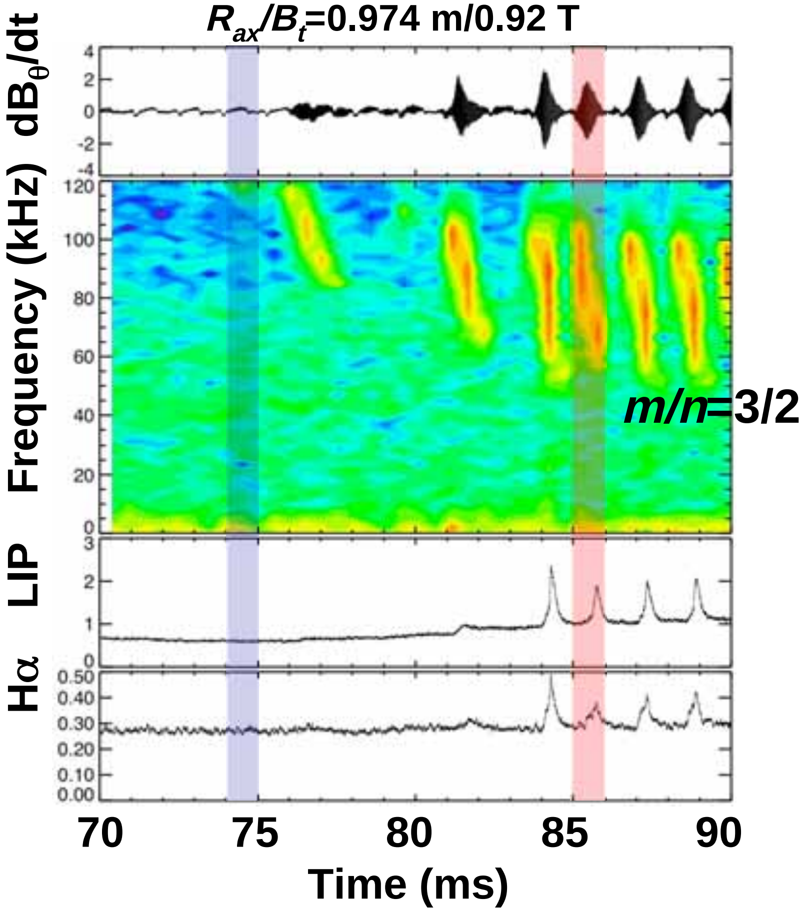
M. Isobe *et al.*, Nucl. Fusion **46**, S918 (2006)

Lost fast ion probe signals measured at large *R* side

- Bright spot appears on the scintillator surface due to impact of fast ions -

shot#122764

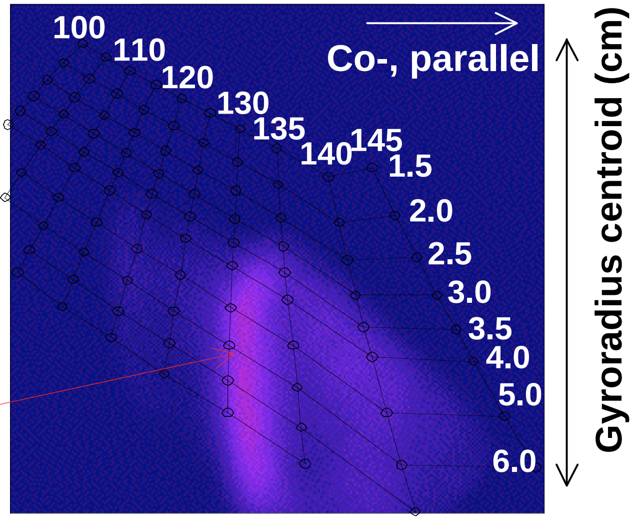
R_{ax}/B_t=0.974 m/0.92 T



Frame rate : 1 kHz

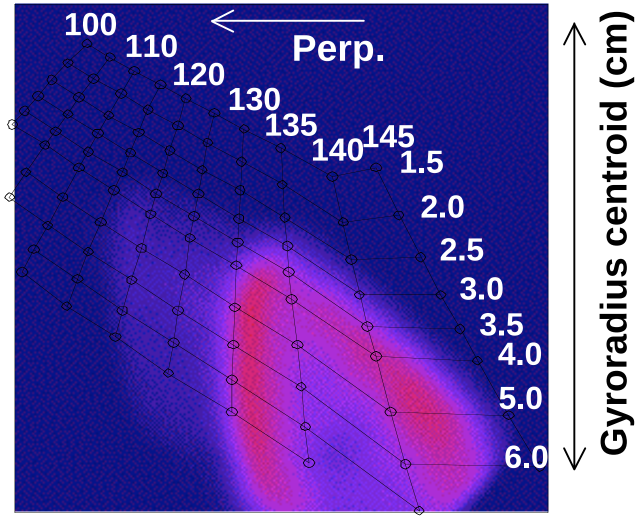
EPM-quiescent phase
***t*=74-75 ms**

Pitch angle (degrees)



Primary spot

EPM phase
***t*=85-86 ms**

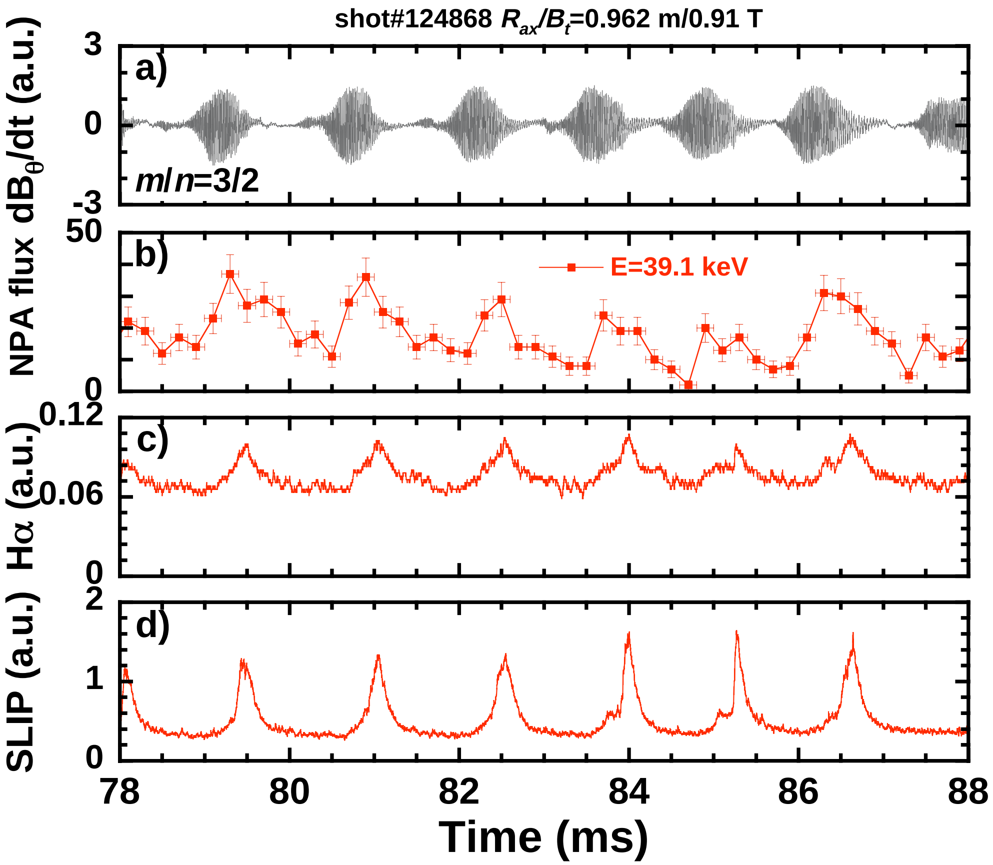


- Primary loss spot appears in pitch angle of 130~133 degrees ($v_{/\!/}/v$= -0.64 ~ -0.68).
- Measured gyro-radius is consistent with that of ions having E_b.
- During EPM, scintillation light intensity in more parallel pitch angle domain significantly increases.

Anomalous transport of fast ions in an interior region of CHS plasma during EPMs

- NPA, Hα light emissivity and lost fast ion signals enlarged -

The increase of NPA flux is always earlier than that of the SLIP



- The NPA flux begins to increase right after the fluctuation begins to evolve whereas the evolution of lost fast ion flux is somewhat delayed.

  This is because the NPA signal contains information of fast ions in the interior region of plasma.

- These observations tell us,

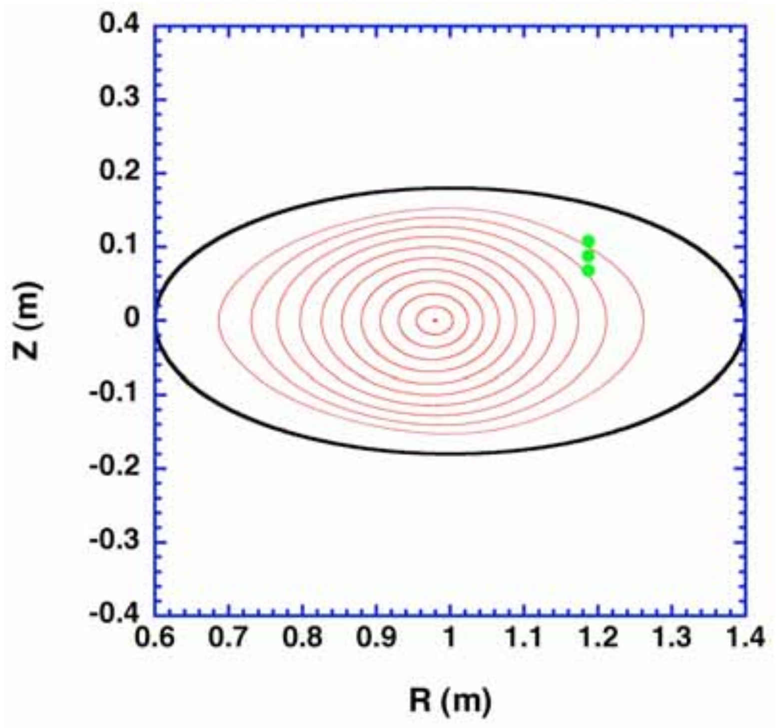
1) Anomalous transport of fast ions begin right after EPM is excited.

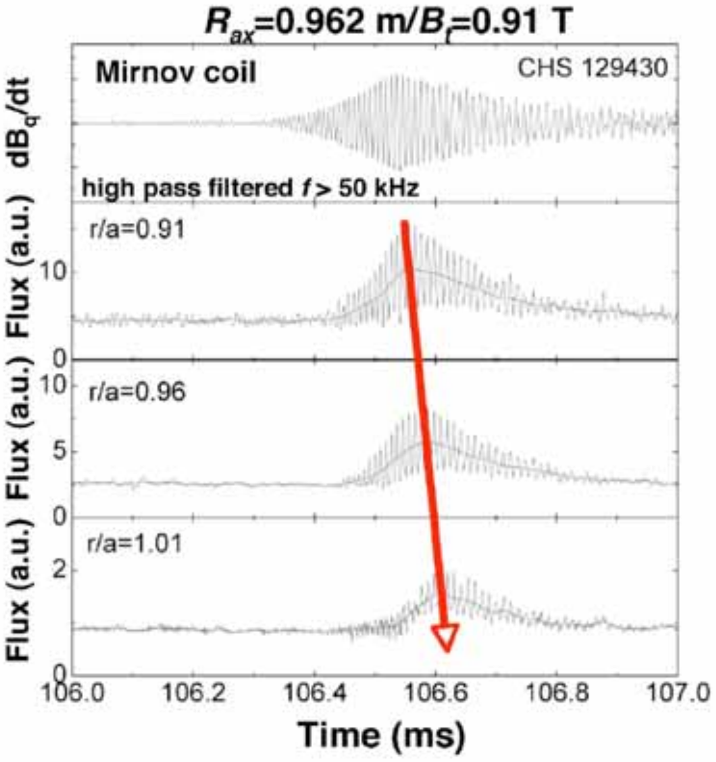
2) EPMs cause significant effects on fast ion transport, leading to rapid loss of fast ions.

3) EPMs are stabilized after an expulsion of fast ions.

Direct observation of radial transport of fast ions in an interior region of CHS plasma during EPMs

DLP Measured points of fast ion flux



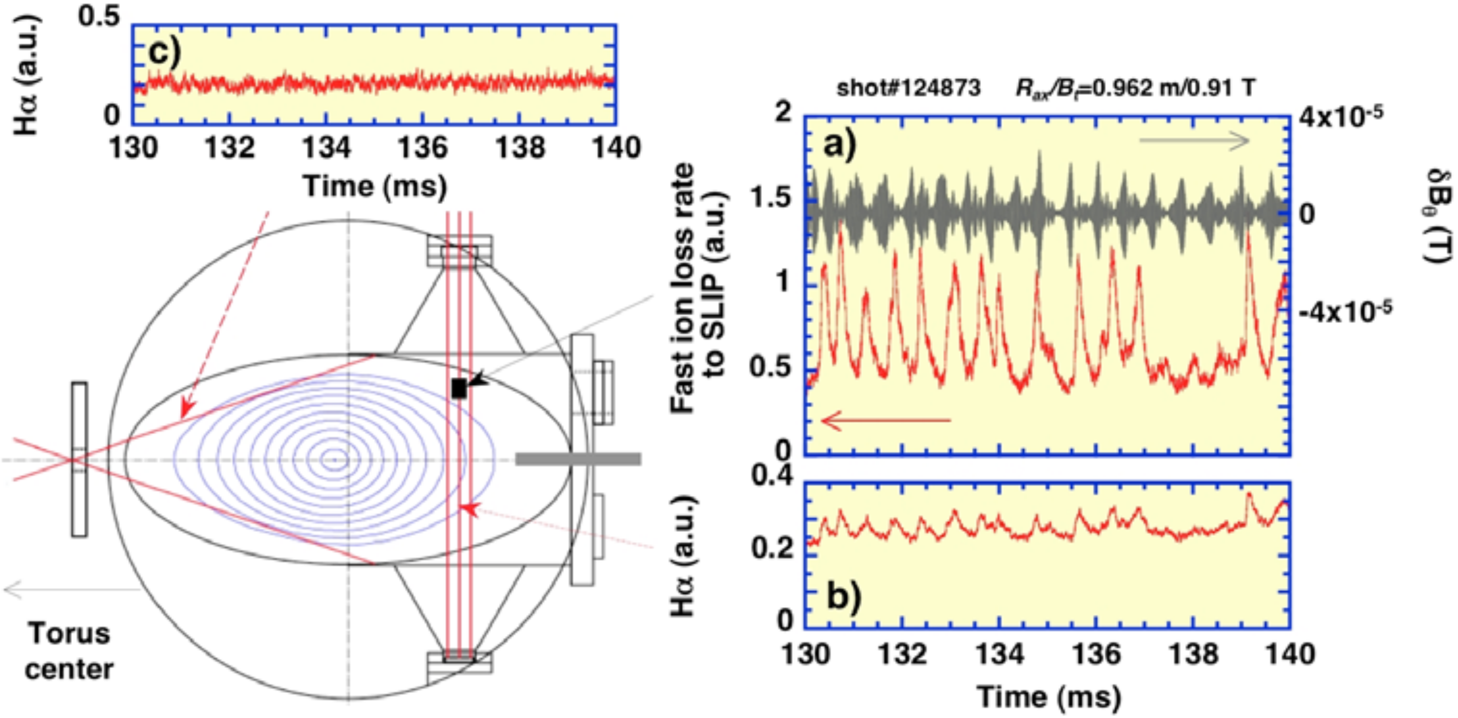


- The time-resolved fast ions transport to the peripheral region due to the EPM has been clearly seen. **Velocity of radial movement of fast ions is evaluated to be ~ 600 m/s.**

- The internal measurement of the fast ions indicates that they are rapidly transported by the EPMs out of the central CHS plasmas in R_{ax}/B_t of 0.962 m/0.91 T.

TAE-induced fast ion transport

The recent experiments reveal that repetitive anomalous losses of fast ions are significantly induced due to *n*=1 TAEs ; the gap for these modes is formed by a coupling of *m*=2 and 3 poloidal modes and results in δB_q over 10^{-5} T when two NBs are tangentially co-injected.



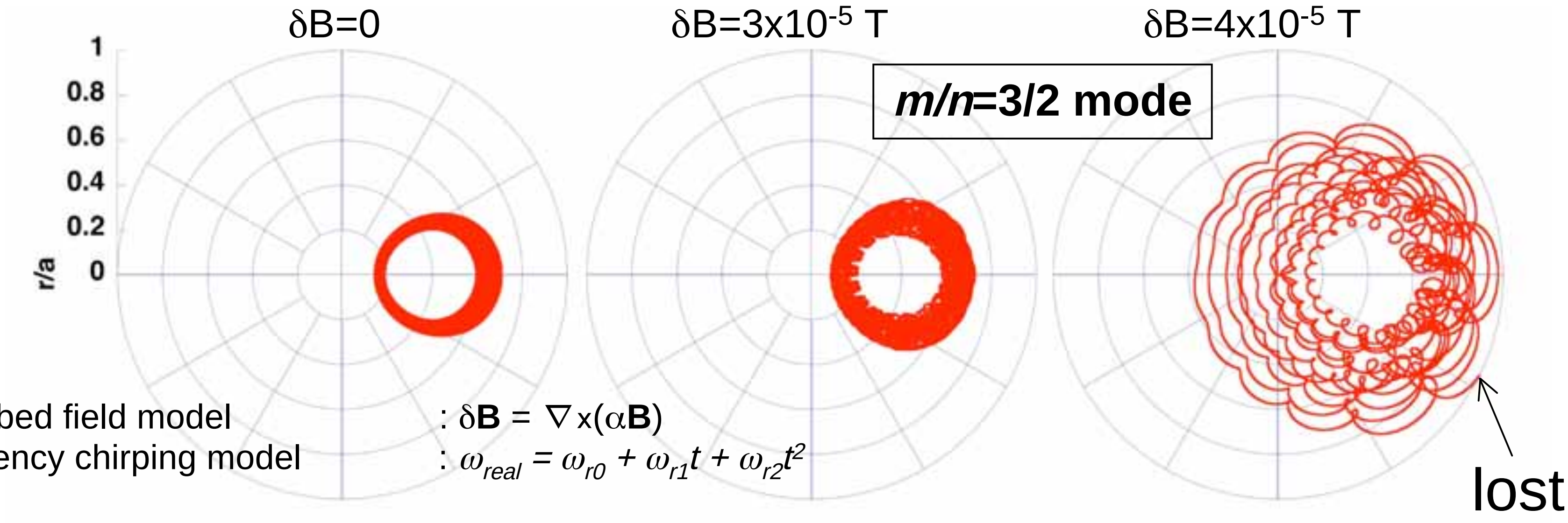
- Correlated with the TAE bursts of $dB_q \sim 2\times10^{-5}$ T, LIPs placed at the large R side show periodic increases of lost fast ion fluxes, indicating that the beam ions are expelled due to the TAE bursts.

- Co-going transit beam ions are transported to the outboard side resulting from the TAE bursts and are lost.

Orbits of co-going transit fast ions in perturbed field

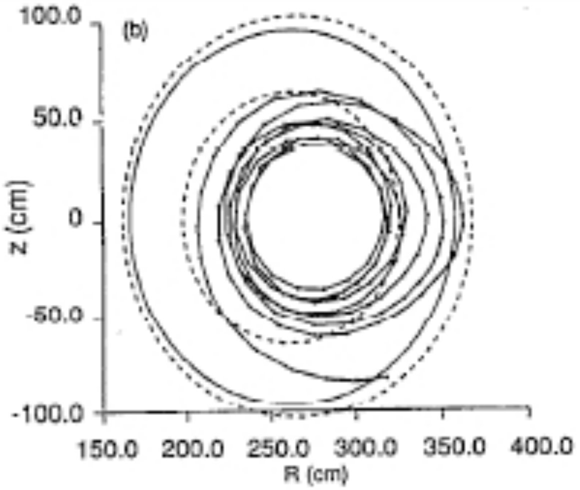
Co-passing fast ion is lost at the outboard side of CHS

R_{ax}/B_t=0.962 m/0.95 T, E=38 keV, s=0.5(birth place), $v_{//}/v$ = 0.8 at birth place



Perturbed field model : $\delta\mathbf{B} = \nabla \times (\alpha\mathbf{B})$
Frequency chirping model : $\omega_{real} = \omega_{r0} + \omega_{r1}t + \omega_{r2}t^2$

Example of TFTR case
***m/n*=2/1 mode assumed**



H.E. Mynick *et al.*,
PoF, B5 (1993)1471.

Summary

The CHS project since June 1988 came to a close at the end of August 2006.

Study of fast ion confinement has been one of key physics targets because of the symmetry breaking of the system and enhanced toroidicity. For this reason, various fast ion diagnostics have been applied to CHS to study fast ion behaviors.

In the early days' experiment of CHS which was in operation at the Higashiyama site of Nagoya University (June 1988 - March 1999), our interest was mainly focused on issues related to fast-ion-orbit/loss cone structure.

In the latter half of CHS project at the Toki site (October 2000 - August 2006), we stressed on the studies on fast-ion-driven MHD instabilities and their effects on fast ion transport although the studies had already been started in the initial half of CHS project.

Helically trapped beam ions : Poor confinement ⇦ W_p, NPA & Neutron

Passing beam ions : Good in Bt of 1.76 T but losses exist in Bt of 0.88 T ⇦ Neutron

Effect of E_r : Epi-thermal ions improved by positive E_r but no effect seen for fast ions
⇦ NPA

EPM/TAE : drastic fast ion transport in the outward shifted configuration at B_t of 0.95T.
⇦ NPA, SLIP, FLIP, DLP