Partial Summary of US-Japan Workshop and
Kyoto University 21st COE Symposium on
"NEW APPROACH IN PLASMA CONFINEMENT EXPERIMENT
IN HELICAL SYSTEMS"
Kyoto University, 2-4 March 2004

Program and presentations available at:

http://www.center.iae.kyoto-u.ac.jp/plasma/usj04/index.html

D. R. Mikkelsen

Stellarator theory teleconference, 15 April 2004

Program of
The Joint Meeting of US-Japan Workshop and Kyoto University 21st COE Symposium on
"New Approach in Plasma Confinement Experiment in Helical Systems"

March 2, 2004

9:00	Registration	
9:30	Opening address	F. Sano & D. Anderson
9:40	Overview of Heliotron J experiment	T. Mizuuchi (Kyoto Univ.)
10:10	Overview of HSX Experimental Operations	D. Anderson (U. Wisconsin)
10:40	Coffee break	
11:00	First experiments in neutral beam heated plasmas in the TJ-II stellarator	M. Liniers (CIEMAT)
11:30	Recent results from the H-1 Heliac	B. Blackwell (ANU)
12:00	Confinement improvement and related profile and fluctuation study in CHS	S. Okamura (NIFS)
12:30	Photo & Lunch	
14:00	MHD properties of high beta plasma and recent results in LHD experiments	K. Y. Watanabe (NIFS)
14:30	The impact of the electron root on helical plasma confinement	M. Yokoyama (NIFS)
15:00	Impurity confinement studies in the Wendelstein 7-AS stellarator	R. Burhenn (IPP, Greifswald)
15:30	Coffee break	
15:50	Measurement and modeling of electrode biased discharges in the HSX stellarator	S. Gerhardt (U. Wisconsin)
16:20	Divertor flow and fast particles behavior in spontaneous change of plasma confinement mode in the Uragan-3M torsatron	E. Sorokovoy (Kharkov Inst.)
16:50	Levy turbulence in the boundary plasma of the torsatron "URAGAN - 3M"	A. Chechkin (Kharkov Inst.)
17:20	Production of helicon wave range RF plasmas in Heliotron DR	S. Morimoto (Kanazawa Inst. Tech.)
19:00	Reception at New-Miyako Hotel	

March 3, 2004

9:00	Wendelstein 7-X at the transition from procurement to assembly	R. Brakel (IPP, Greifswald)
9:30	Progress in analysis and construction of NCSX	D. Mikkelsen (PPPL)
10:00	Overview of the QPS project	J. Lyon (ORNL)
10:30	Coffee break	
10:50	Analyses of MHD equilibrium and stability in CHS-qa	C. Suzuki (NIFS)
11:20	Three-dimensional equilibrium reconstruction in compact stellarators, including application to MHD studies on the compact toroidal hybrid	S. Knowlton (Auburn Univ.)
11:50	The quasi-poloidal symmetry approach to stellarator plasma confinement	D. Spong (ORNL)
12:20	Lunch	
13:50	Theoretical study of the bootstrap current in Heliotron J plasmas	Y. Nakamura (Kyoto Univ.)
14:20	Application of 3D MHD equilibrium codes to helical system plasmas	Y. Suzuki (Kyoto Univ.)
14:50	Neoclassical transport in advanced helical devices	S. Nishimura (NIFS)
15:20	Coffee break	
15:40	Study of magnetic field optimization effect on energetic particle confinement in LHD	S. Murakami (Kyoto Univ.)
16:10	Experimental study on energetic ion behavior in Compact Helical System (CHS)	M. Isobe (NIFS)
16:40	Observation of the high energy ions in ECH/ECCD plasmas in CHS and Heliotron J	S. Kobayashi (Kyoto Univ.)
17:10	LH transition by a biased electrode in the Tohoku University Heliac	S. Kitajima (Tohoku University)

Adjourn

March 4, 2004

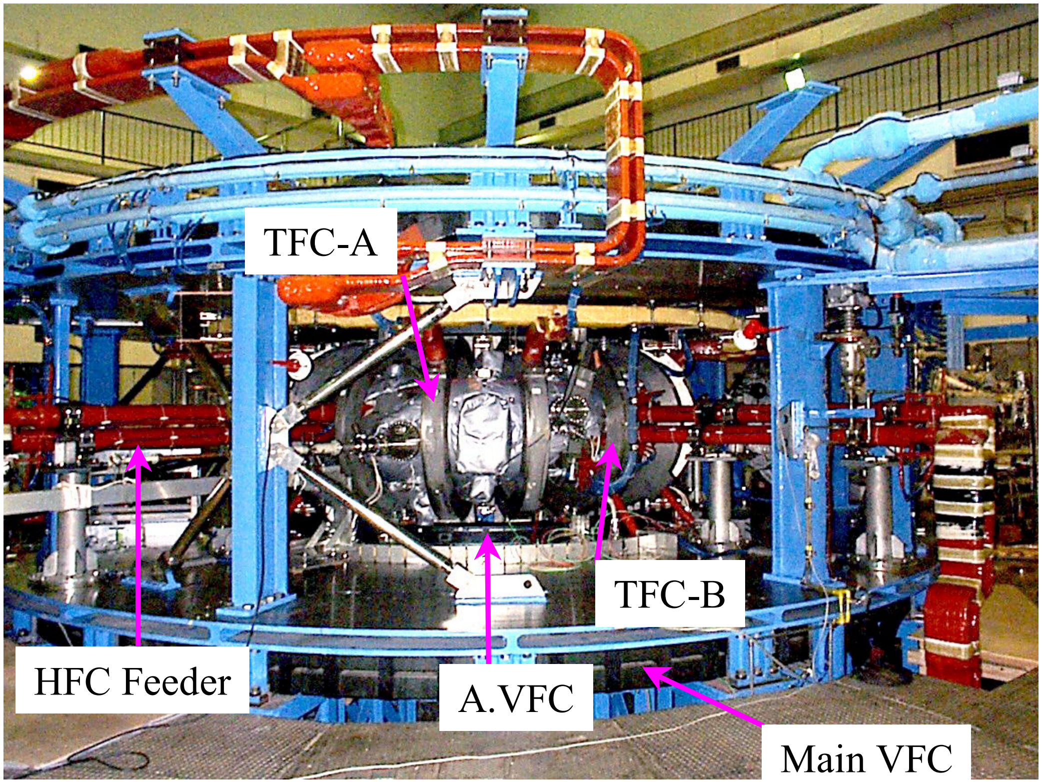
9:00	Steady state operation by LHCD on the superconducting tokamak, TRIAM-1M	K. Hanada (Kyushu Univ.)
9:30	Optimization toward quasi-isodynamicity of stellarators with different numbers of periods experiments	M. Mikhailov (Kurchatov Inst.)
10:00	Helical reactor economics studies	T. Dolan (NIFS)
10:30	Coffee break	
10:50	Discussion	
12:30	Closing	

Overview of Recent Heliotron J Experiments

presented by T. MIZUUCHI *for Heliotron Group*
Institute of Advanced Energy, Kyoto University

- **Introduction**
- **Recent Experiments**
  - **Non-Inductive Toroidal Plasma Current**
    see NF 44 (2004) 47.
  - **H-mode Transition**
  - **High Energetic Particles**
  - **Edge fluctuations**
- **Summary**

Heliotron J Project is aiming at experimental optimization of the helical-axis heliotron concept.

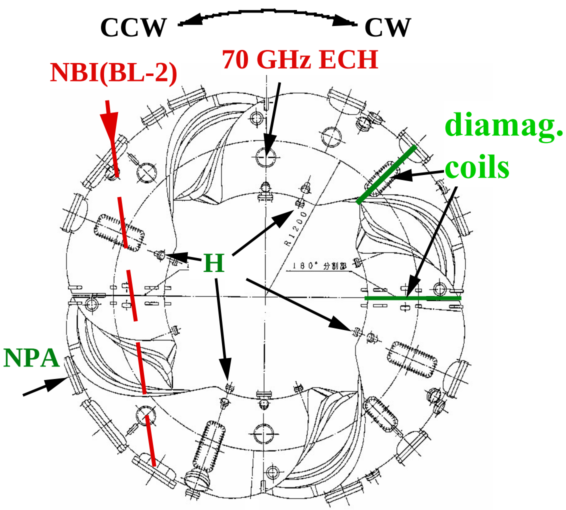


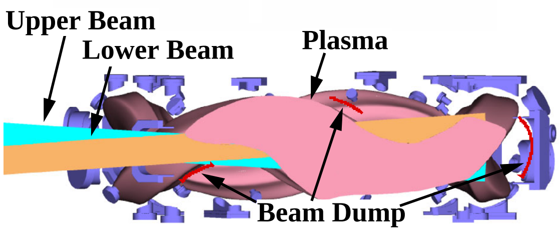
V_{plasma}(STD) ~ 0.17 m^2, A_s ~ 15.4 m^2, V_{CMB} ~ 2.1 m^3

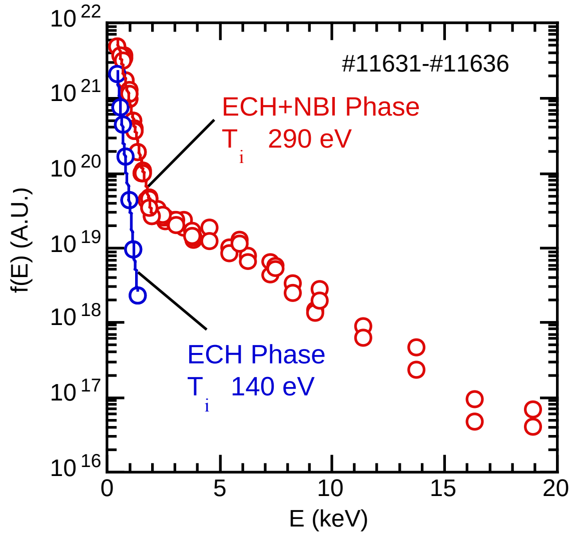
- Coil System
  - **Helical Coil**
    $\theta = \pi + M/L\times\varphi - \alpha\times\sin(M/L\times\varphi)$
    - » L = 1, M = 4, α = –0.4
    - » Major Radius 1.2 m
    - » Coil Minor Radius 0.22 m
  - (8+8) Toroidal Coils
  - 3 pairs of Poloidal Coils
    (*Inner Vertical Coils in the torus center.*)
  - Power Source MG 330MVA
- Confinement Field
  - Max. B 1.5 T
  - Flat-Top Time 0.5 sec.
- **Heating (@ 2003 Campaign)**
  - **ECH ~ 0.4MW/70GHz**
  - **NBI ~ 0.7MW/30kV**
  - **ICRF ~ 0.4MW/19MHz**

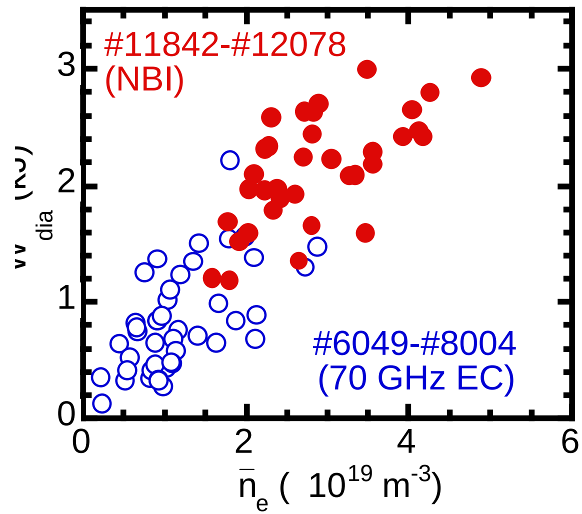
An extent of the operational region was observed by the installation of the Neutral Beam Injection system.

S. Kobayashi, F. Sano
IAE, Kyoto University







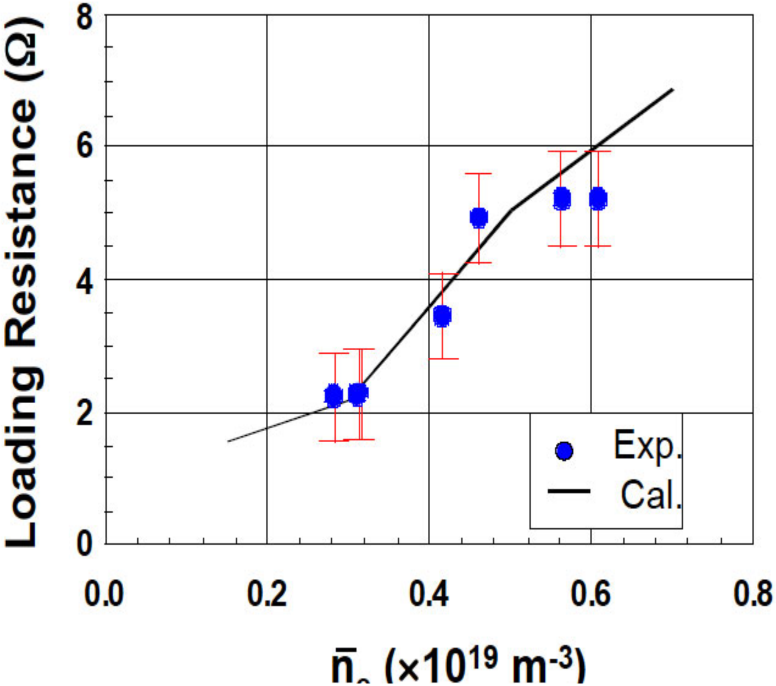


- **An extent of the operational region up to W_{dia} = 3kJ and n_e = 5×10^{19}m^{-3} by NBI.**

- **A 30-keV, 0.7-MW tangential NBI system (BL-2) with its 0.2-s pulse duration was commissioned on Heliotron J.**
- **The beam injector is equipped with two bucket ion sources (V_{acc}<30 kV, P_{inj}<0.7MW).**

The minority (H) heating experiment has started to study the ICRF heating mechanism and high energy ion behavior in Heliotron J

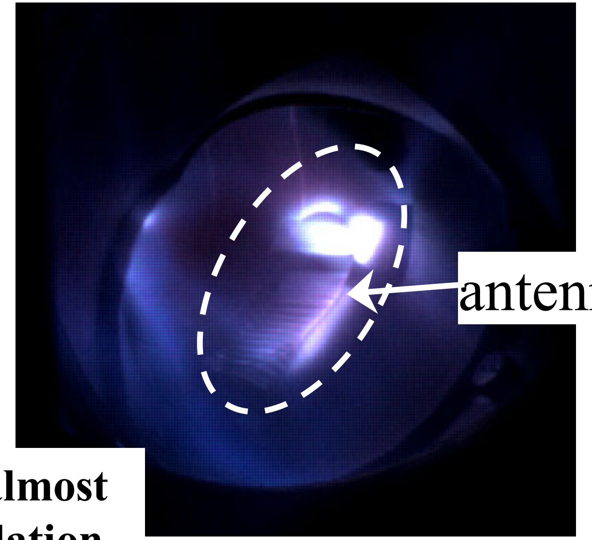
H. Okada, S. Takemoto
IAE, Kyoto University



The antenna resistance due to the plasma loading almost agrees with the expected values by the model calculation.

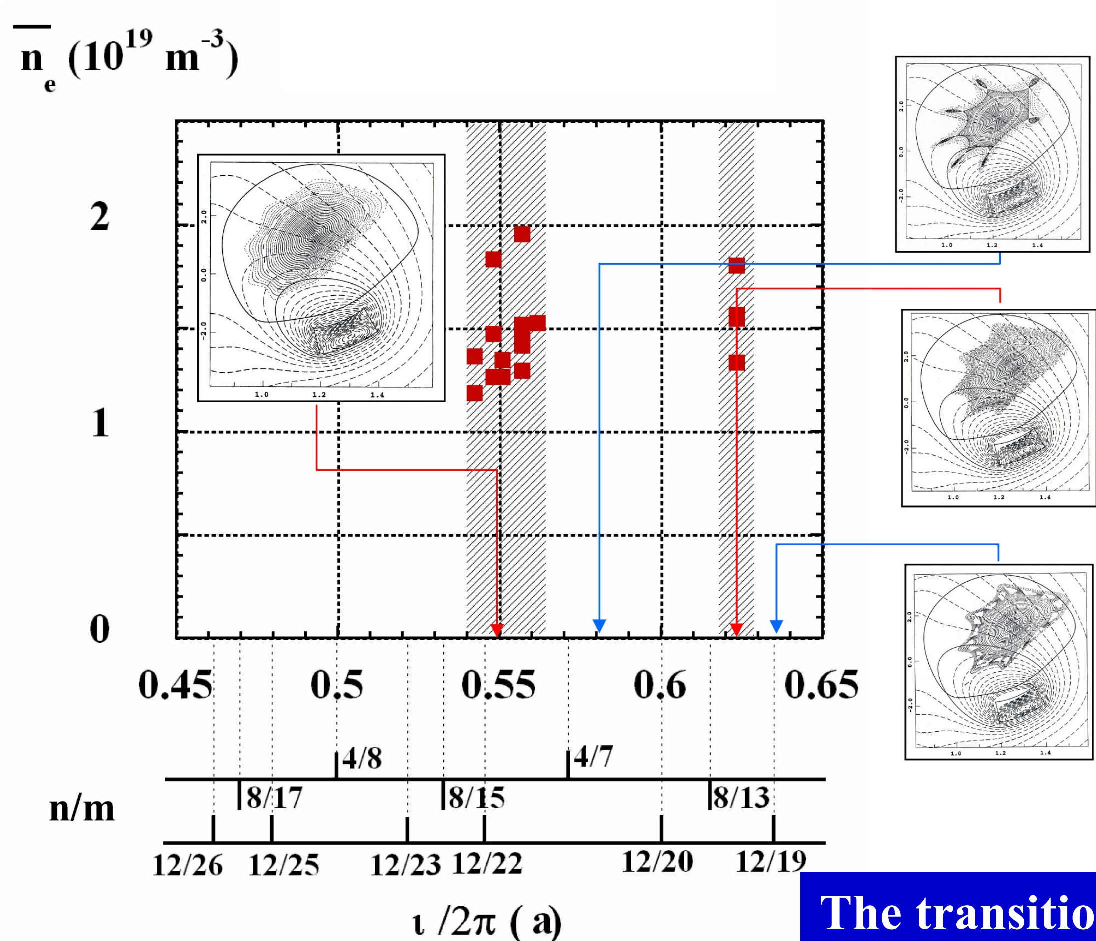
f_{ICRF} = 19 MHz, $P_{ICRF} \leq$ 0.35 MW.

One loop antenna is set on the outboard side at the corner section.



The increase of T_i^D was not observed during the ICRF pulse (~ 10 ms), however, the energetic proton flux was observed up to 8 keV so far.

The transition was discovered in two "windows" of edge iota.



Two windows:

(1) $0.54 < \iota(a)/2\pi < 0.56$
magnetic separatrix configuration

(2) $0.62 < \iota(a)/2\pi < 0.63$
partial wall-limiter configuration

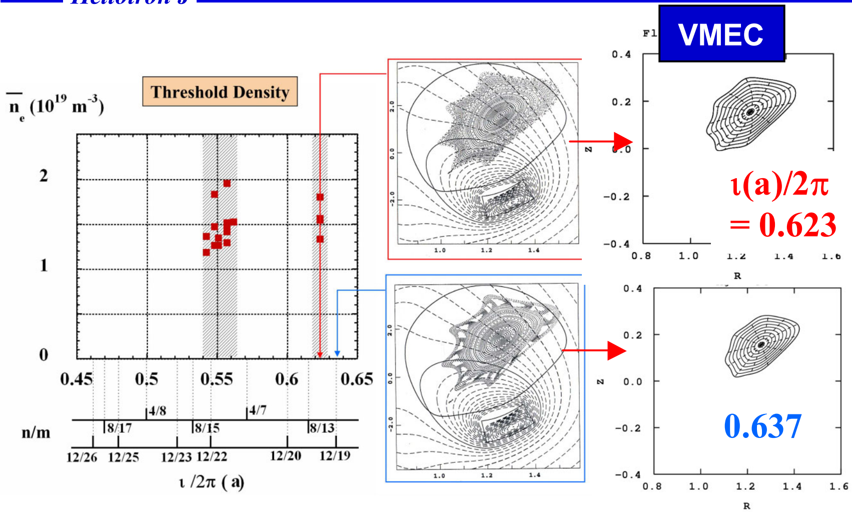
Recently, the transition was observed near $\iota(a)/2\pi \approx 0.61$

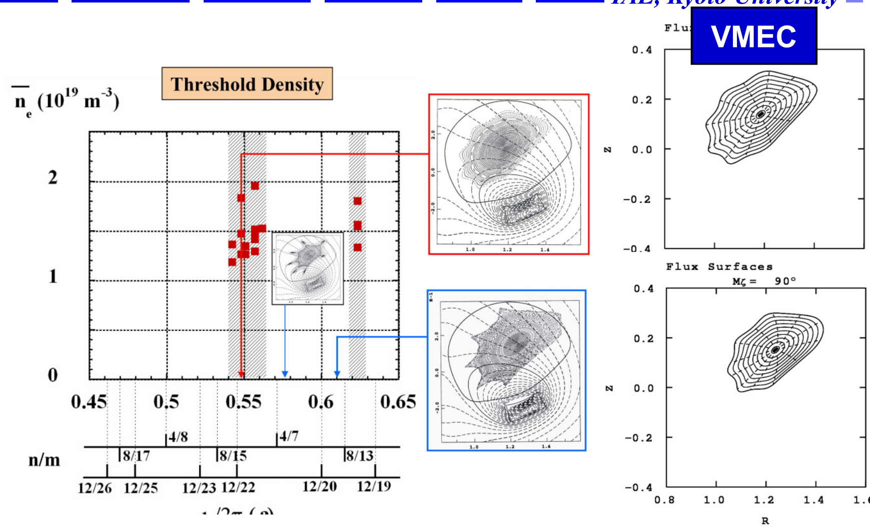
- ECH H-mode seems to be independent of the launching condition of μ-waves.

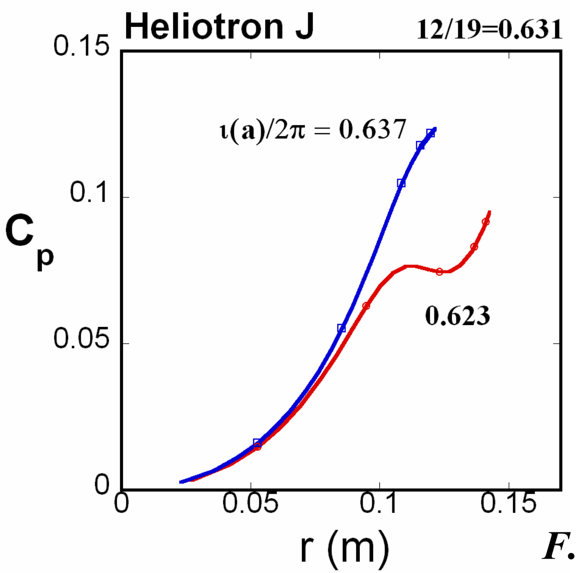
The transition was observed for plasmas with $n_e > n_{ec}$.

F. Sano, et al., EPS2003

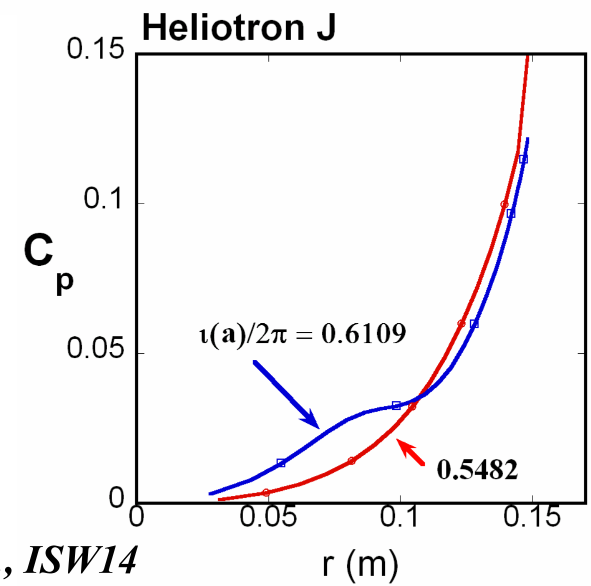
Can the characteristics of the iota-window be explained enough only by the geometrical poloidal viscous damping rate Cp?



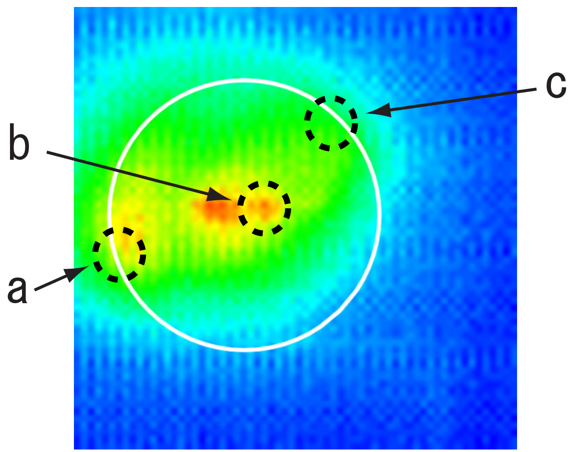




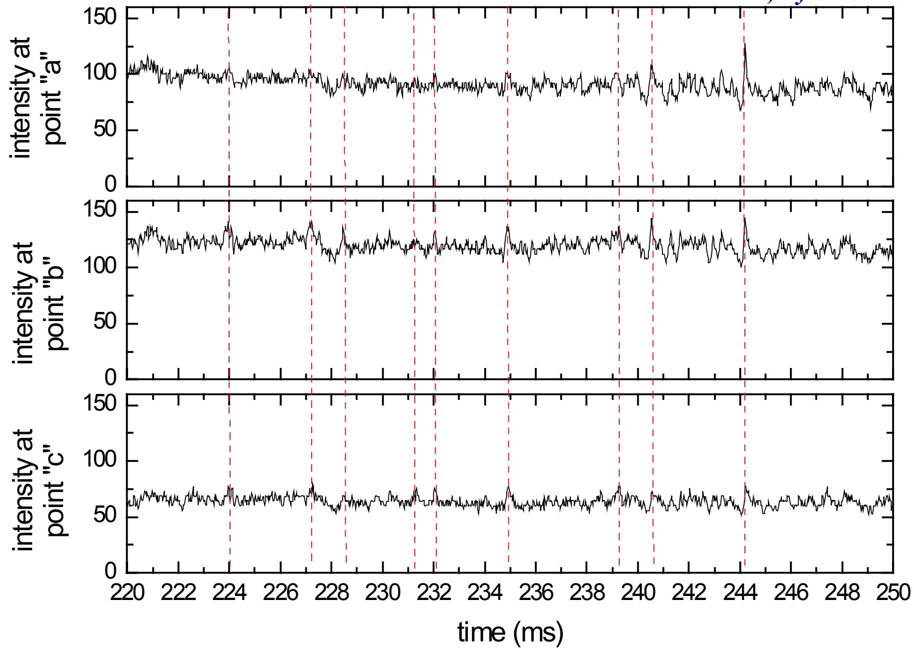
F. Sano, et al., ISW14



"Bursting events" in the edge simultaneously arose in the wide area.



Sampling positions on the target



Hα intensity at three positions

The bursts in the Hα light intensity were simultaneously observed at (toroidally & poloidally) different positions on the target.

→ ***The correlation length of the bursting fluctuation seems to be longer than the target size (9 cm).***

FIRST EXPERIMENTS IN NEUTRAL BEAM HEATED PLASMAS IN TJ-II

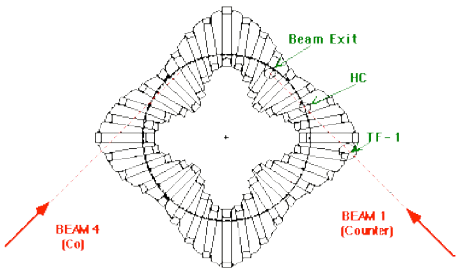
The TJ-II team

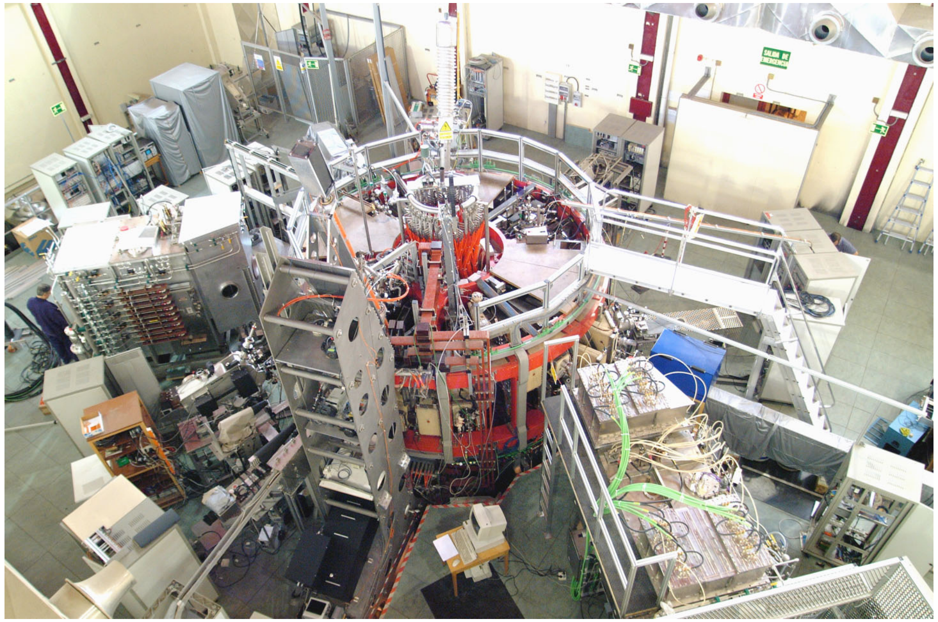
Presented by M. Liniers

Asociacion Euratom-Ciemat para la Fusion
CIEMAT, Av. Complutense 22, 28040 Madrid, Spain

2.- NEUTRAL BEAM INJECTION AT TJ-II

- Two Neutral Beam Injectors from ORNL reinstalled at TJ-II
- Tangential Injection: Co-Counter configuration
- Each Injector:
  - one Ion Source: 40 keV, 100 A
  - 0.9 MW injected Power

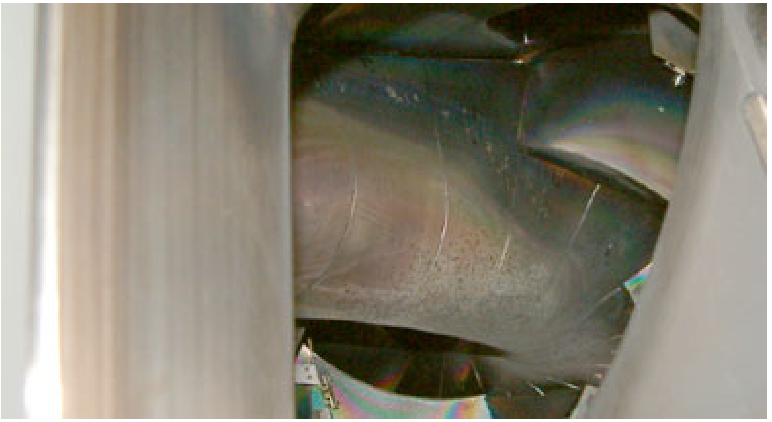


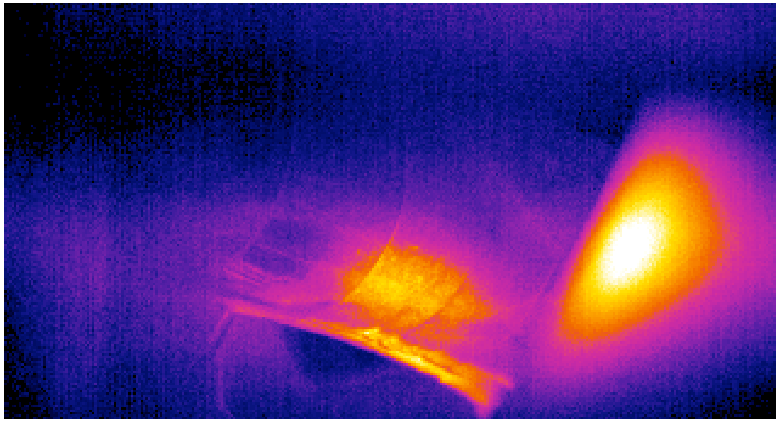


M. Liniers and TJ-II team., Joint US-Japan Workshop and Kyoto University 21st COE Symposium

Laboratorio Nacional de Fusión
Asociación EURATOM-CIEMAT

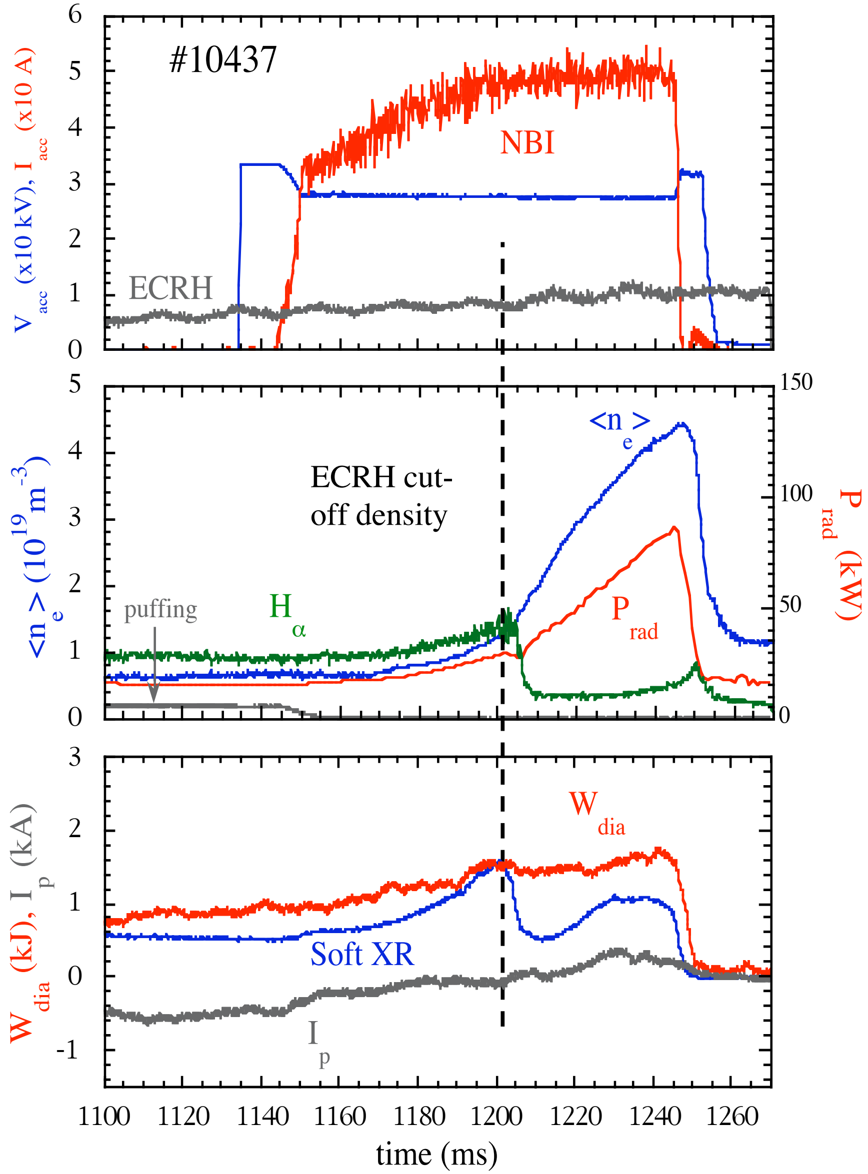
3.- BEAM TRANSMISSION





- 3D beam simulations, combined with finite element thermal calculations led to the design of the thermal load protections on TJ-II vacuum vessel
- An Infrared camera "surveys" the inner vacuum vessel along the beam direction.
- The main expected "hot spots" are at IR sight: TF1 (graphite), the Central Coil groove (SS), and the beam stops (Graphite)

4.- FIRST NBI PLASMAS



- **NBI: 28 kV, 46 A, 100 ms**
- **ECH: two gyrotrons**
  2 x 250 kW
- **ECRH cut-off density:**
  1.7×10^{13} cm^{-3}

M. Liniers and TJ-II team., Joint US-Japan Workshop and Kyoto University 21st COE Symposium

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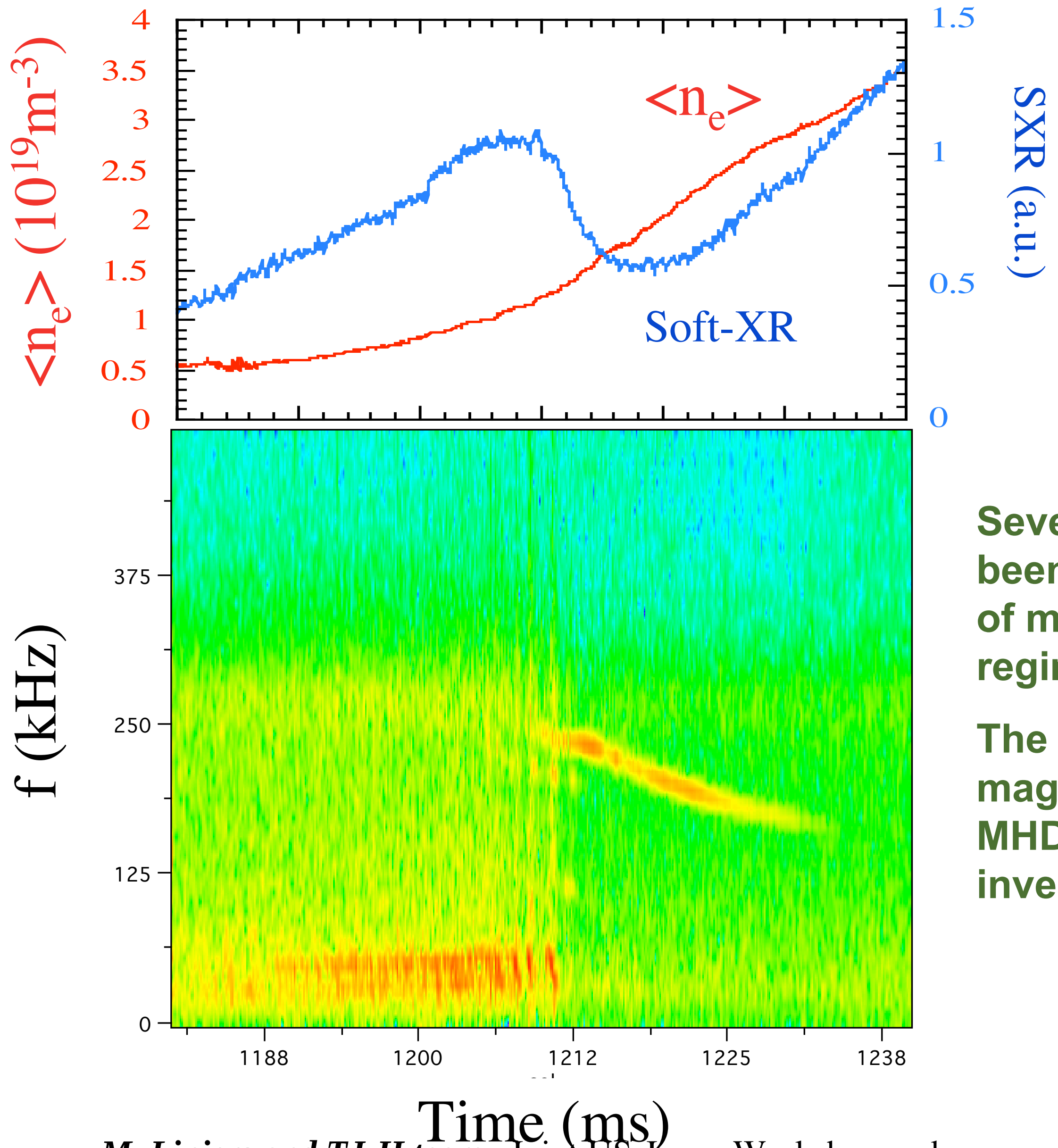
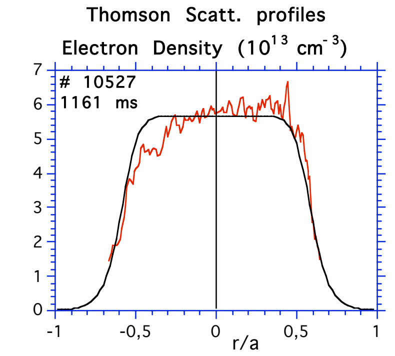
MHD instabilities in NBI plasmas

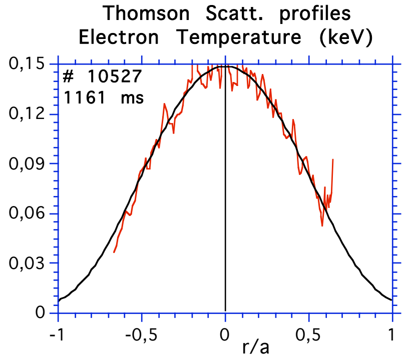


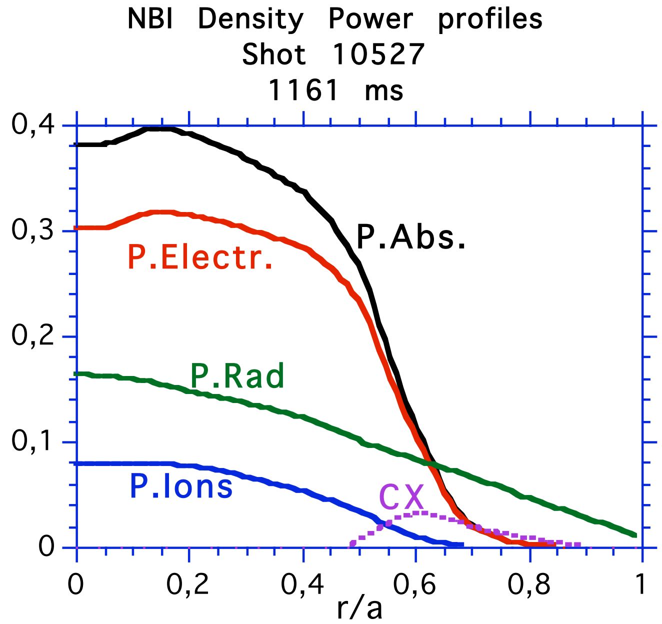
Several modes below 300 kHz have been found in the frequency spectra of magnetic pick-up coils in the NBI regime.

The influence of plasma density and magnetic configuration on these MHD instabilities is under investigation.

NBI computer simulation







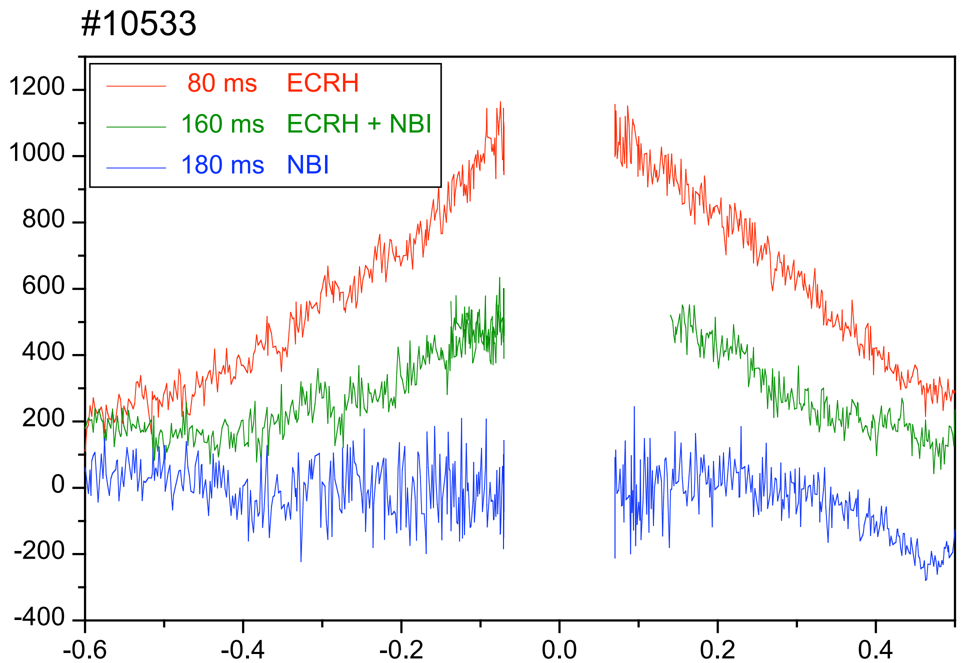
Thomson Scattering profiles were taken at 1061 ms, near de density maximum

We use smoothed and symmetrised profiles in the simulation codes for the discharge analysis: FAFNER-2 for NBI absorption and PROCTR for transport.

Calculated Power absorption profiles are only slightly hollow at axis, rather concentrated and very steep around r/a ~ 0.6

Radiation and CX losses dominate at plasma periphery.

Plasma potential measurements: ECRH and NBI plasmas



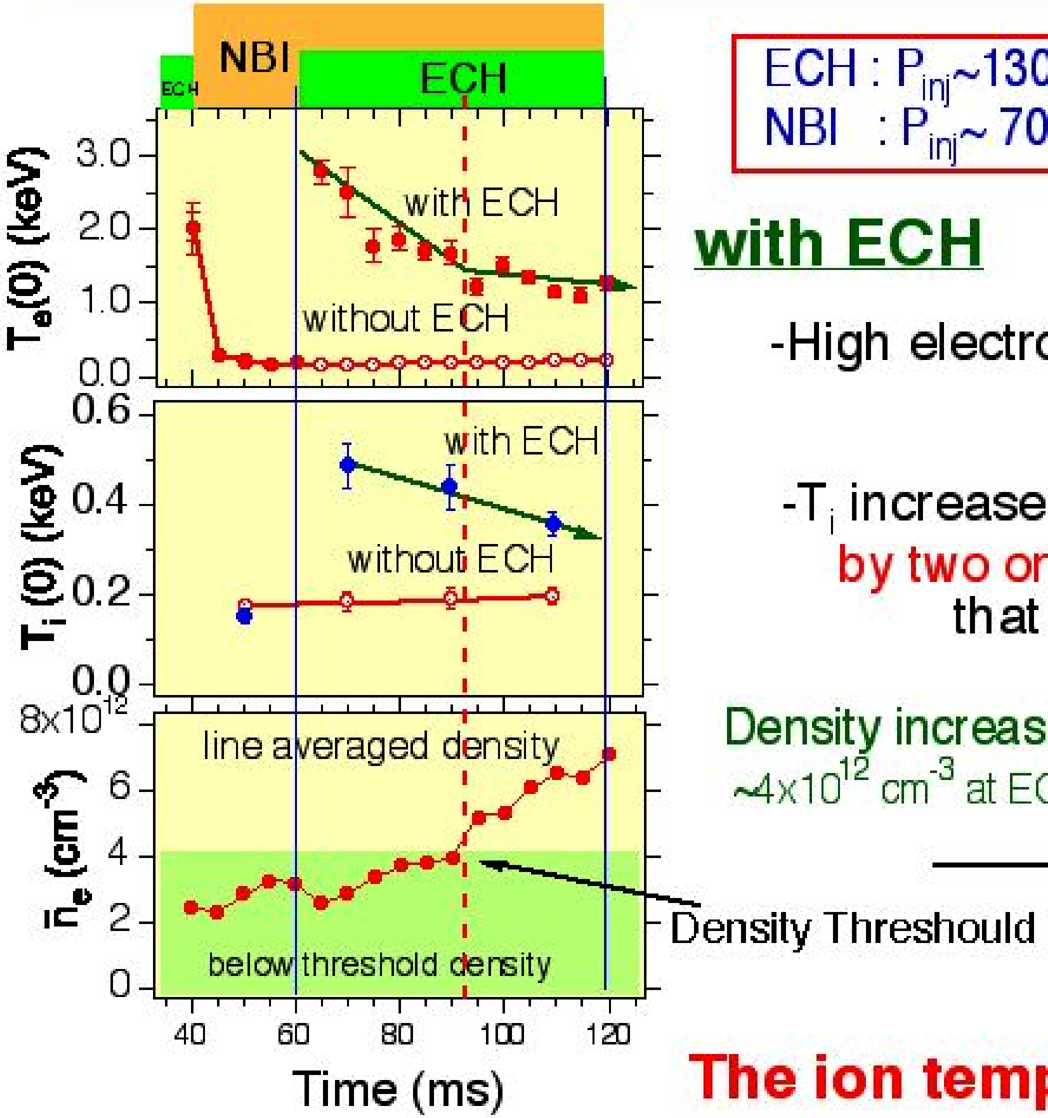
Preliminary plasma potential measurements by the Heavy Ion Beam diagnostic show a strong impact of heating method on radial electric fields.

Confinement Improvement and Related Profile and Fluctuation Study in CHS

S. Okamura
in CHS Experiment

National Institute for Fusion Science
Japan

Operational Condition for N-ITB Formation.



ECH : P_{inj}~130-150kW (53.2GHz, 2nd harmonic)
NBI : P_{inj}~ 700kW

with ECH

-High electron temperature is obtained $T_e(0)$~3 keV

-T_i increases up to $T_i(0)$~500eV by two or three times higher than that of the plasma without ECH

Density increase makes N-ITB disappear.
~4×10^{12} cm^{-3} at EC heating power of 130-150kW.

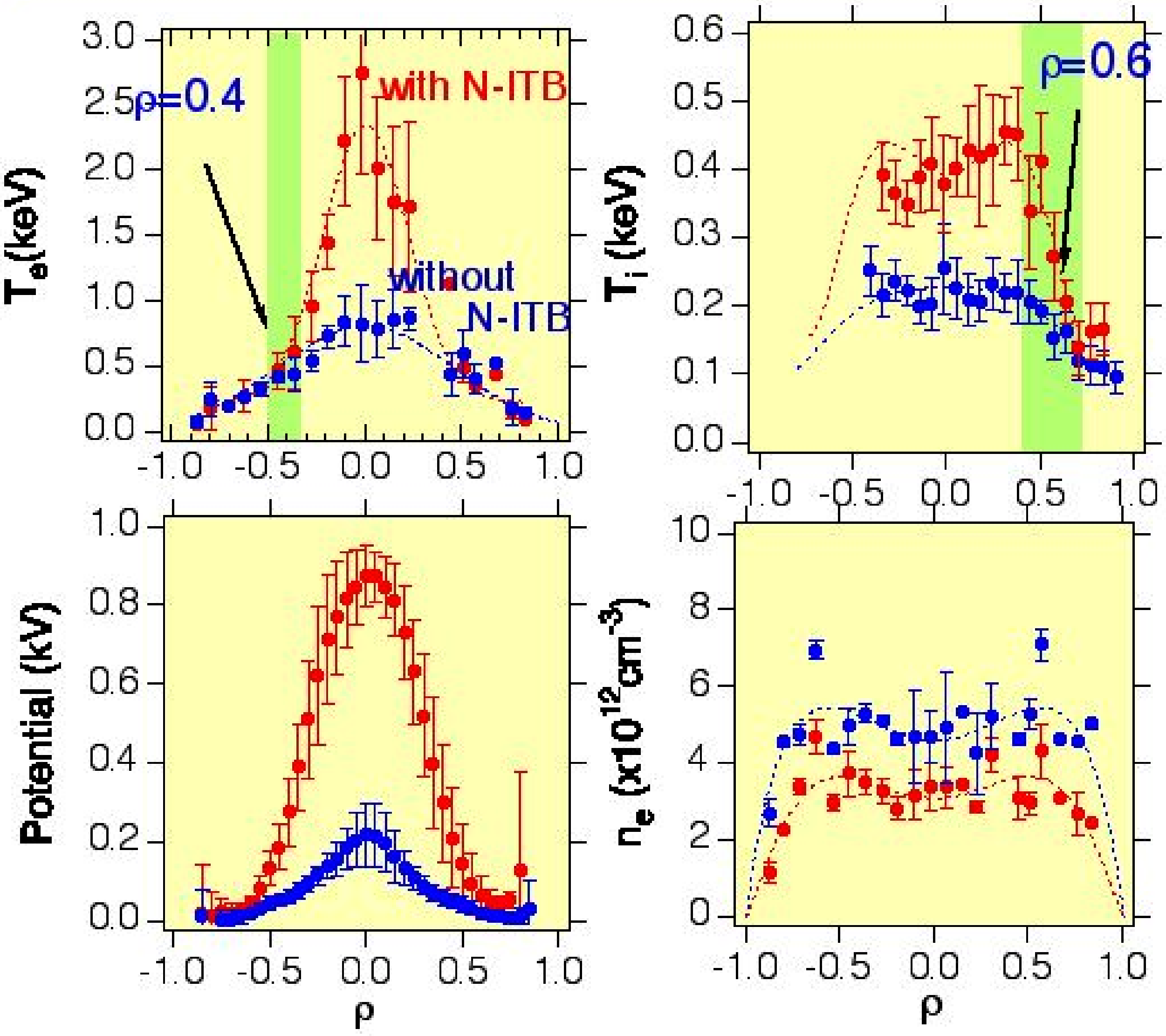
→ Bifurcation nature

The ion temperature increases by ECH application.

Profiles with and without N-ITB

NIFS

CHS



NBI+ECH with N-ITB
NBI+ECH without N-ITB

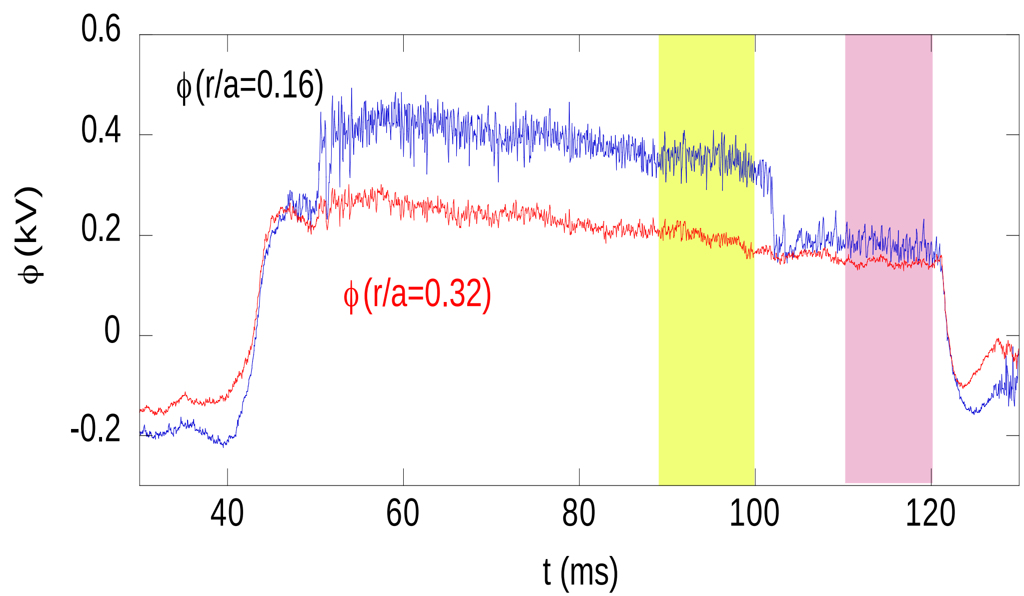
Ion :
The steep gradient increases in the range of $\rho\sim0.4-0.7$

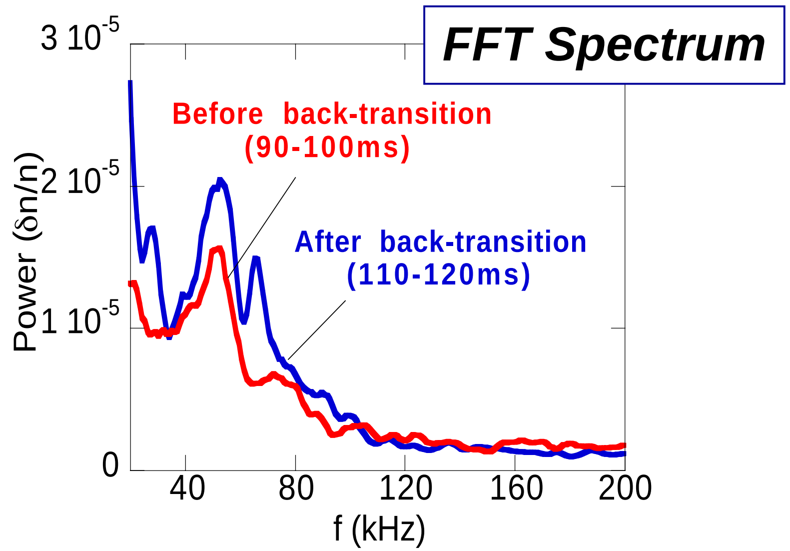
Electron :
The electron temperature gradient also increases inside $\rho\sim0.4$.

Potential :
The electron root is found inside $\rho\sim0.6$ creating the large E_r shear regime.

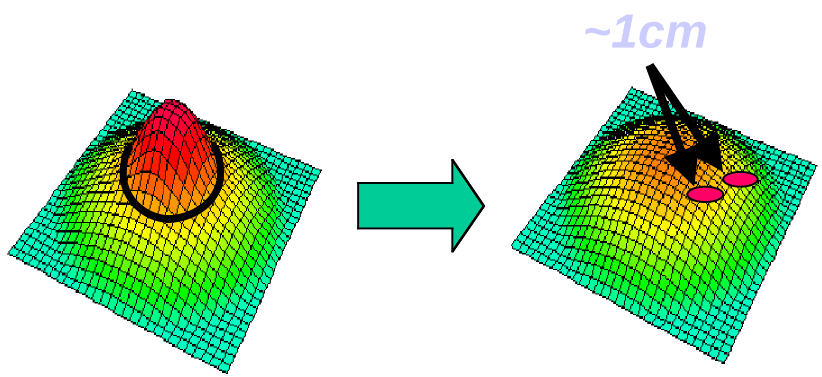
Steep T_i gradient is found in E_r shear regime.

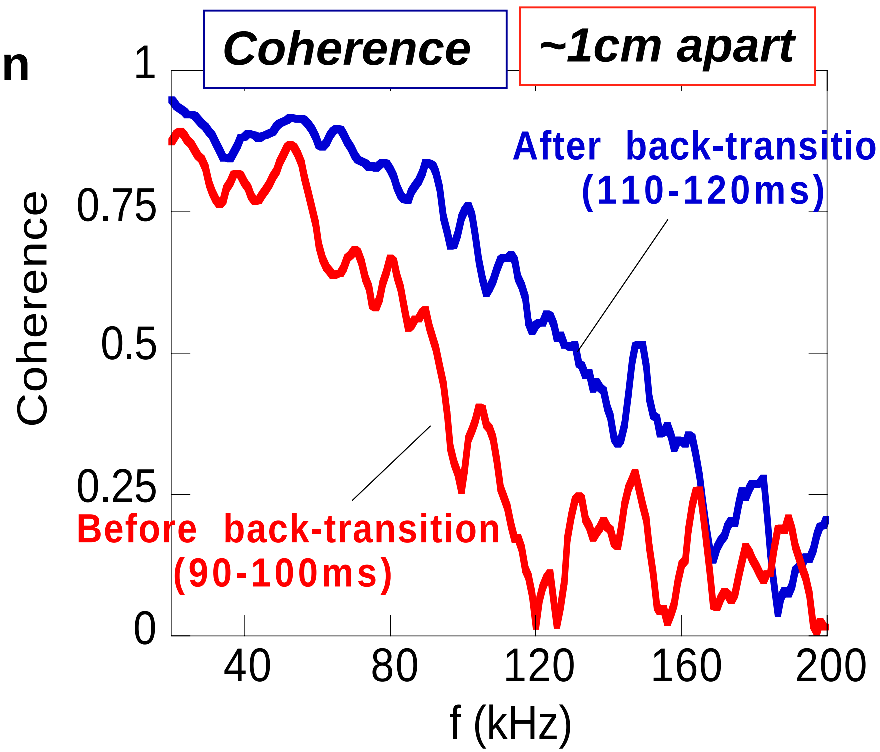
Fluctuation Measurements for ITB Formation





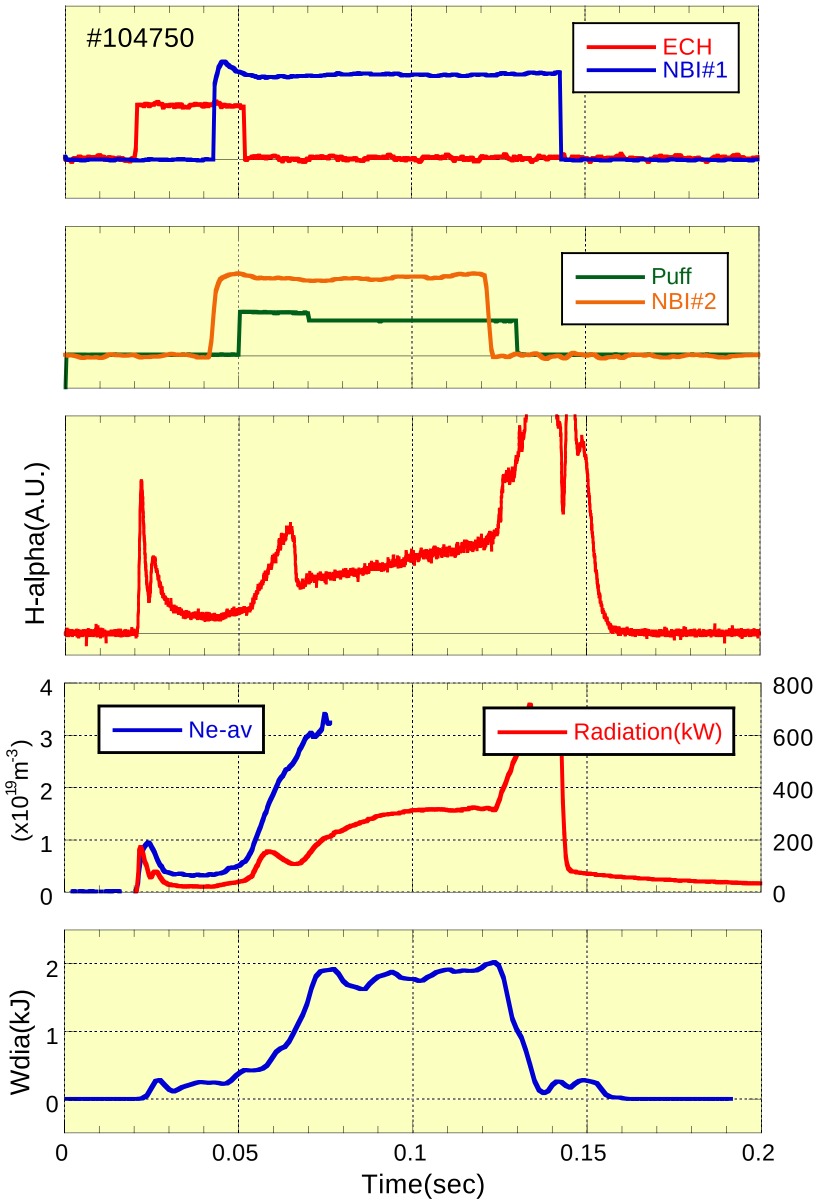
***Dual HIBPs*: measurements of back transition**

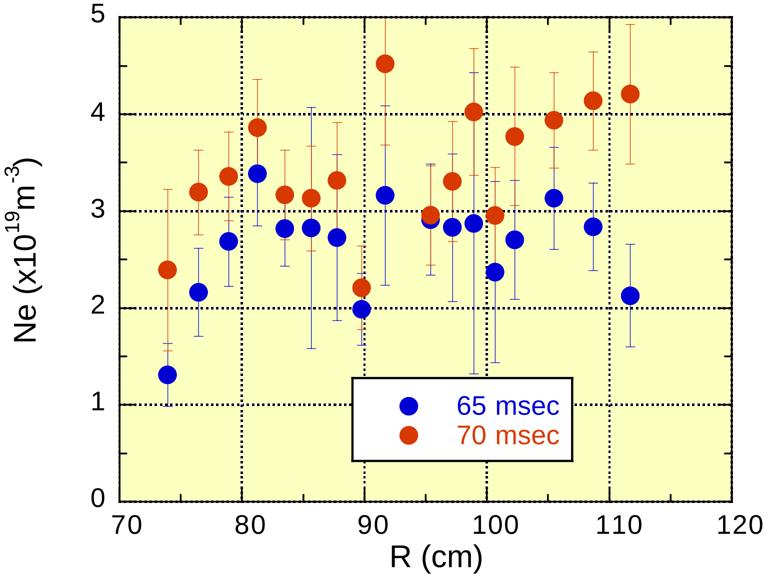


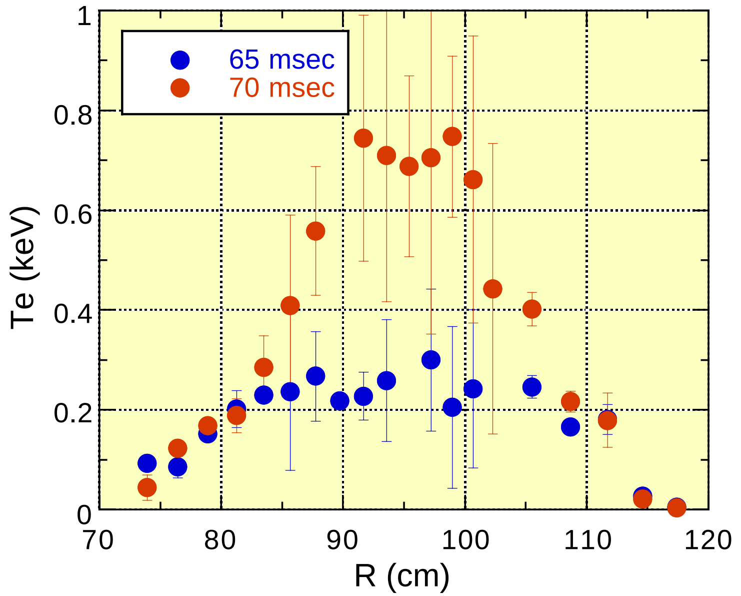


The lost of E_r-shear causes increases in fluctuation amplitude and coherence.

Simultaneous Formation of ETB and ITB



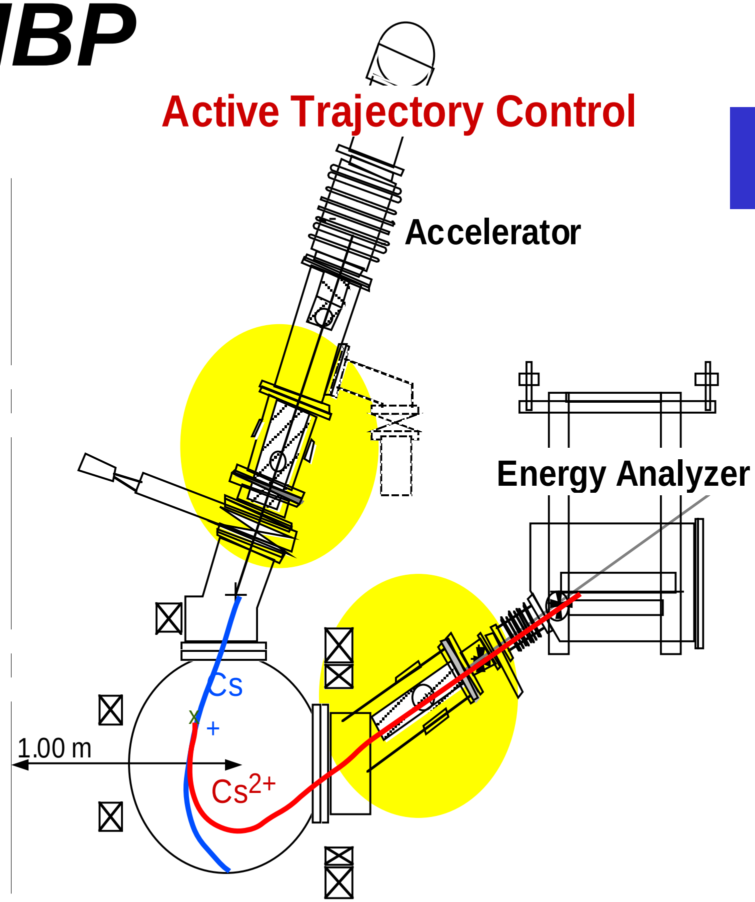




Heavy Ion Beam Probe Measurements

What can be addressed by heavy ion beam probing?

HIBP



Potential Density Magnetic Field

can be simultaneously measured
with highly spatial and temporal resolution.

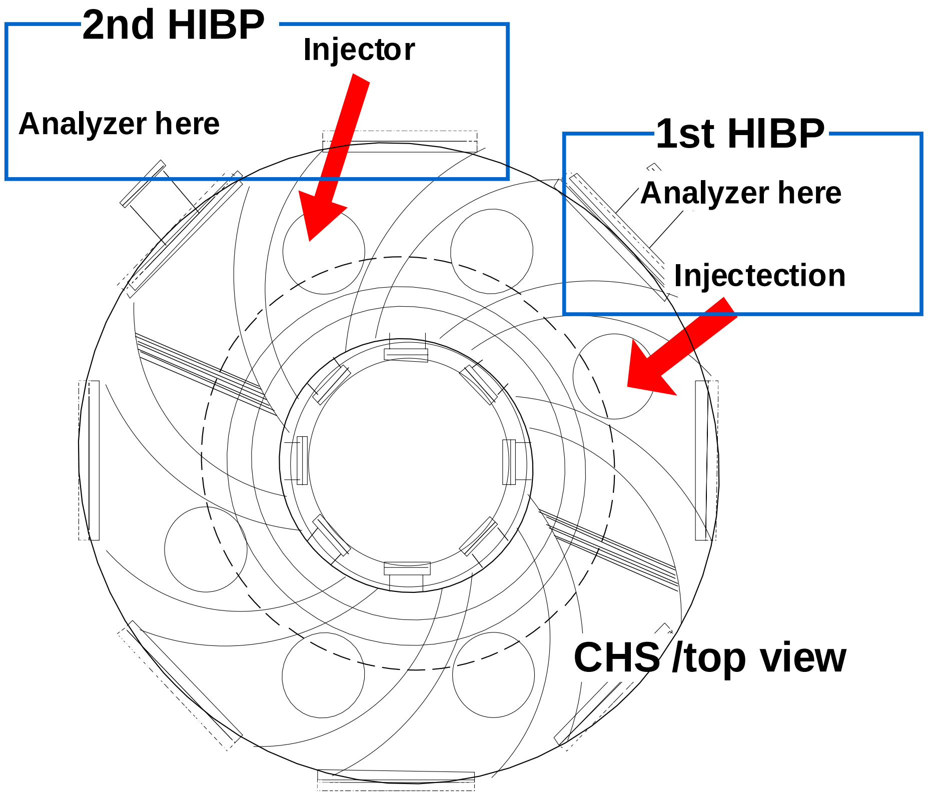
Anomalous transport and barrier

Internal mode structures

Heavy ion beam probe is a power tool for understanding physics of toroidal plasmas.

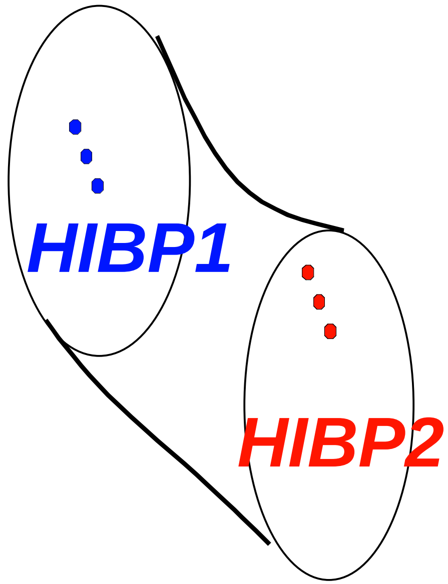
Duo HIBP System in CHS

CHS ***R=1m, a=0.2m m=8, l=2***



90 degrees apart in toroidal direction

Each HIBP has three observable points



Simultaneously 3x3 correlations (between 3 physics quantities) are measurable.

The impact of the electron root on helical plasma confinement

- some examples from LHD experiment and their relationship to neoclassical transport theory-

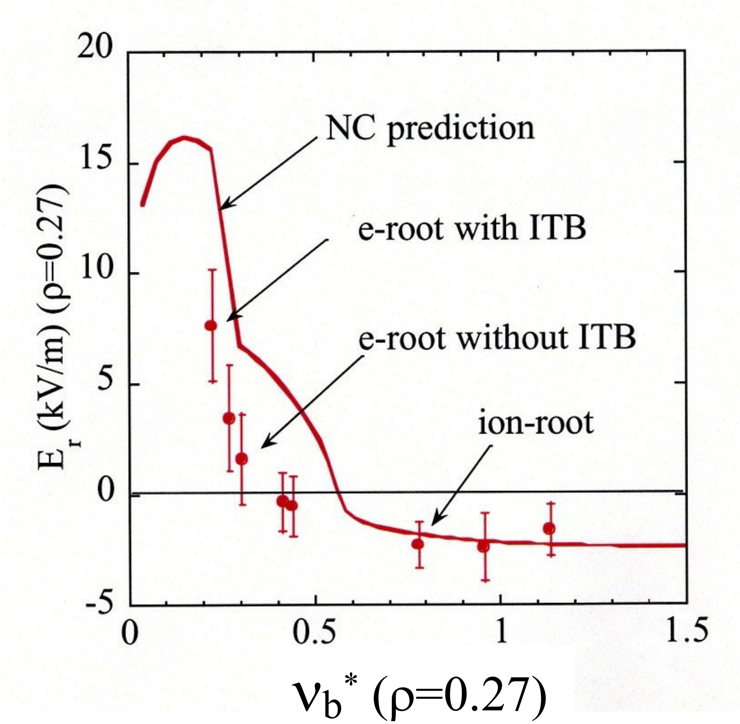
M.Yokoyama, K.Ida, Y.Nakamura, Y.Takeiri, M.Yoshinuma, T.Shimozuma, B.J.Peterson, K.Y.Watanabe, S.Murakami*, A.Wakasa**, S.Kubo, K.Narihara, S.Morita, K.Tanaka, K.Itoh, A.Komori, S.Sudo, O.Motojima
and LHD experimental G

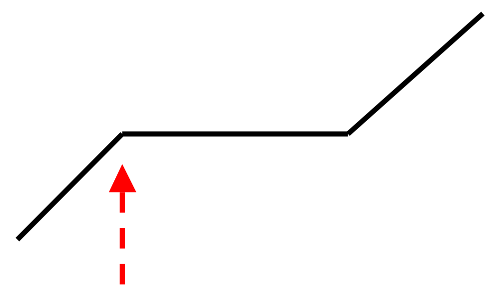
National Institute for Fusion Science, Toki 509-5292, Japan

*Department of Nuclear Engineering, Kyoto Univ., Kyoto 606-8501, Japan**

*Graduate School of Engineering, Hokkaido Univ., Sapporo 060-8628, Japan***

Transition to e-root in the core region



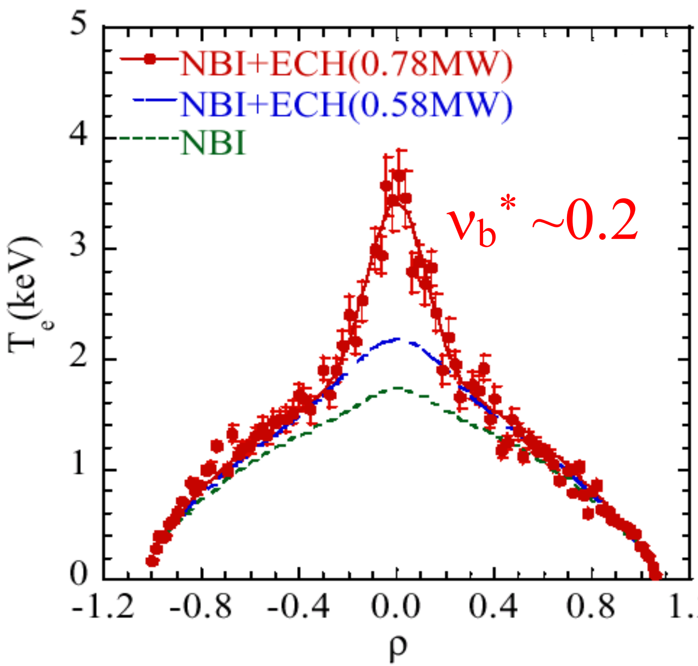


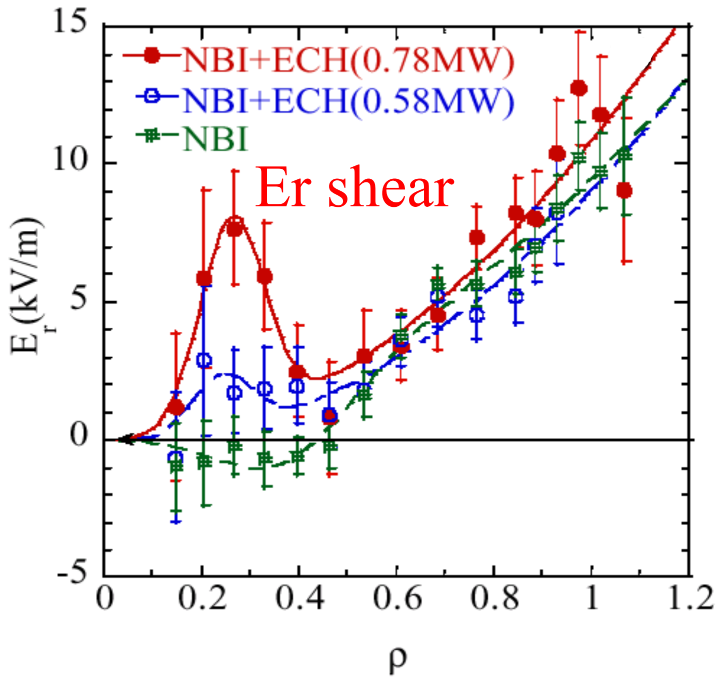
• The threshold collisionality for the transition to e-root is rather well reproduced (NC ambipolar Er)

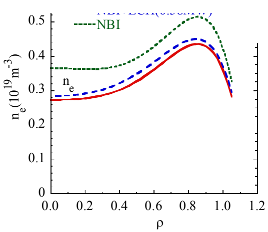
Er and e-ITB formation

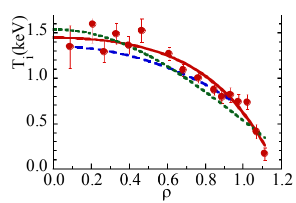
e-ITB formation above critical ECH power
at low enough collisionality

Rax=3.75m, B=1.52T, n_e=(0.3-0.4)x$10^{19}m^{-3}$



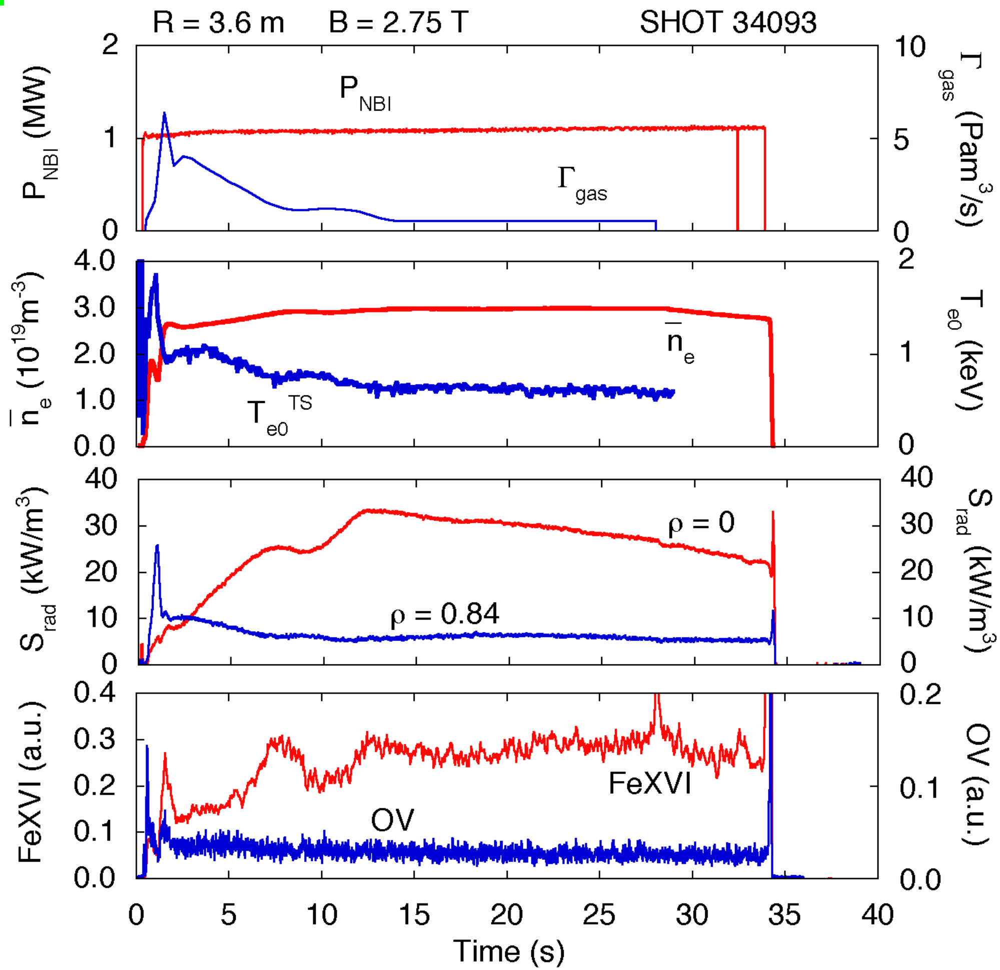






Long timescale impurity accumulation

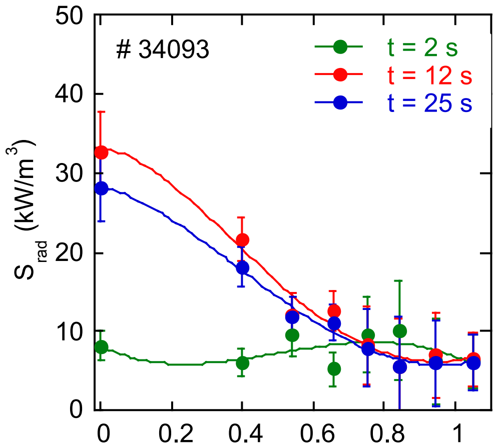
Originating from plasma wall material

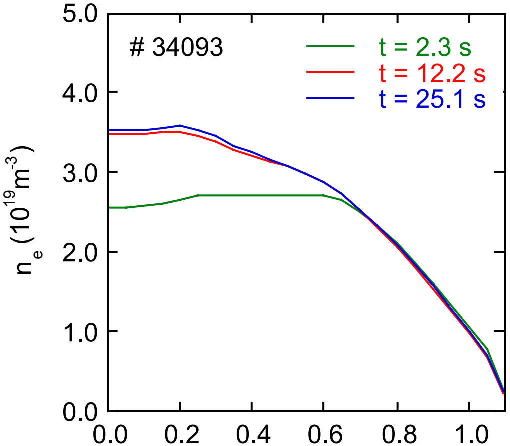


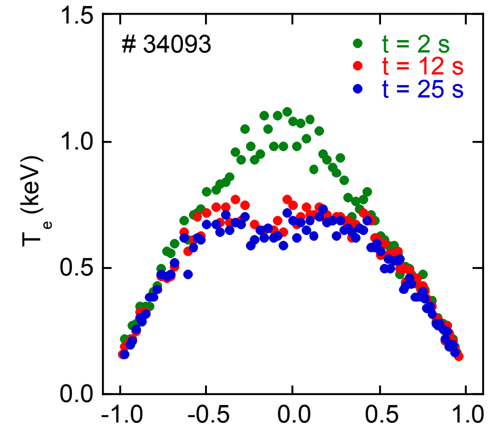
Originating from edge plasma

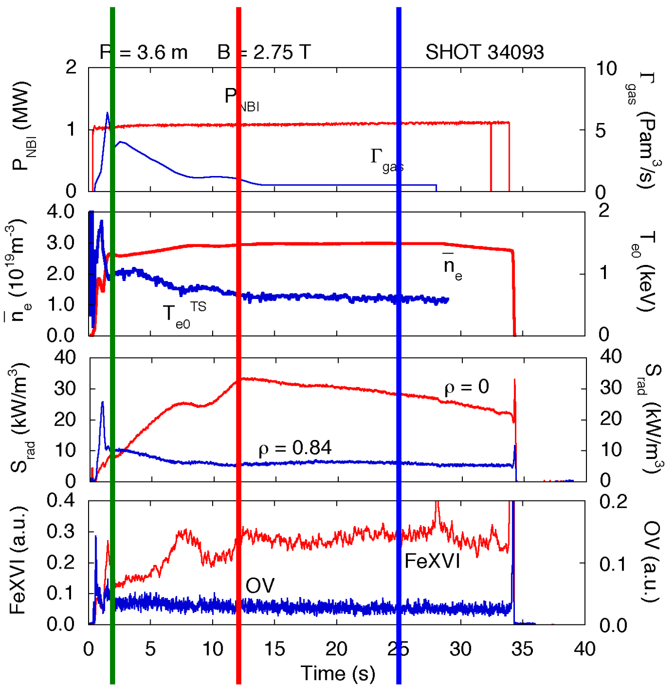
- Constant density with H gas-puff control
- A remarkable increase of core radiation with a long timescale ~O(10s), while remains almost constant at peripheral region
- Heavy metallic (Fe) impurity accumulation

Long timescale impurity accumulation









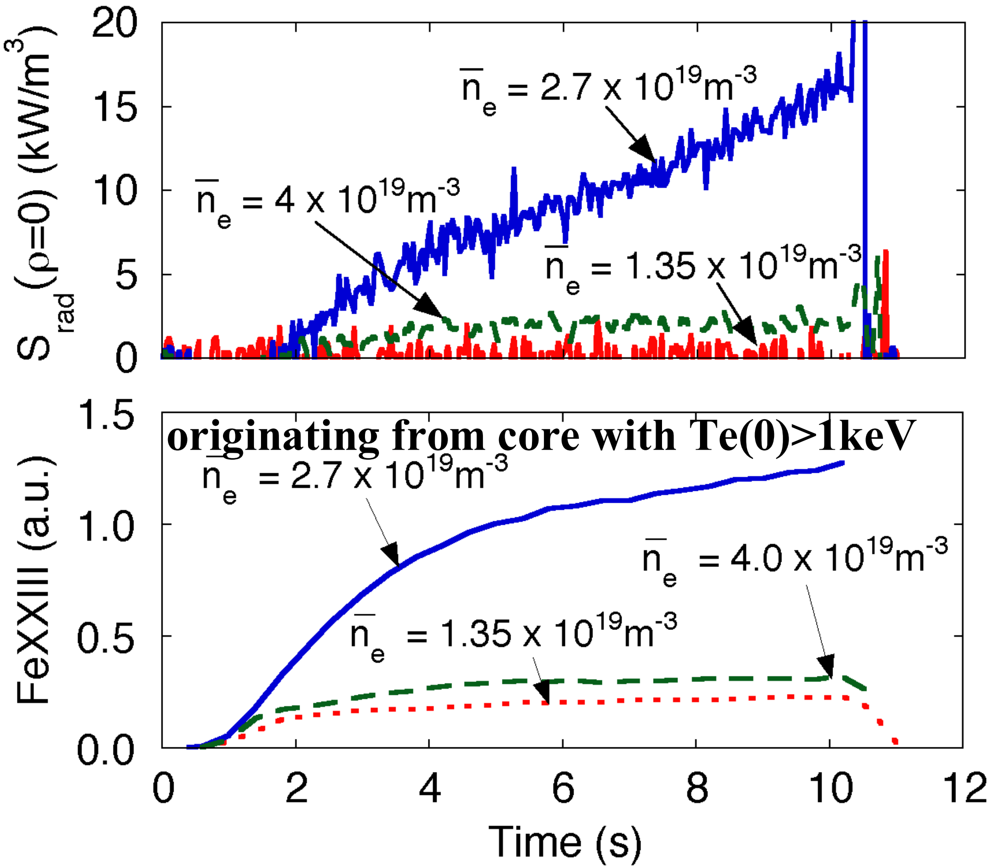
Impurity accumulation $\Leftarrow$ radial profile of Srad

$\Downarrow$

- density peaking
- significant decrease of core Te

Density window for impurity accumulation

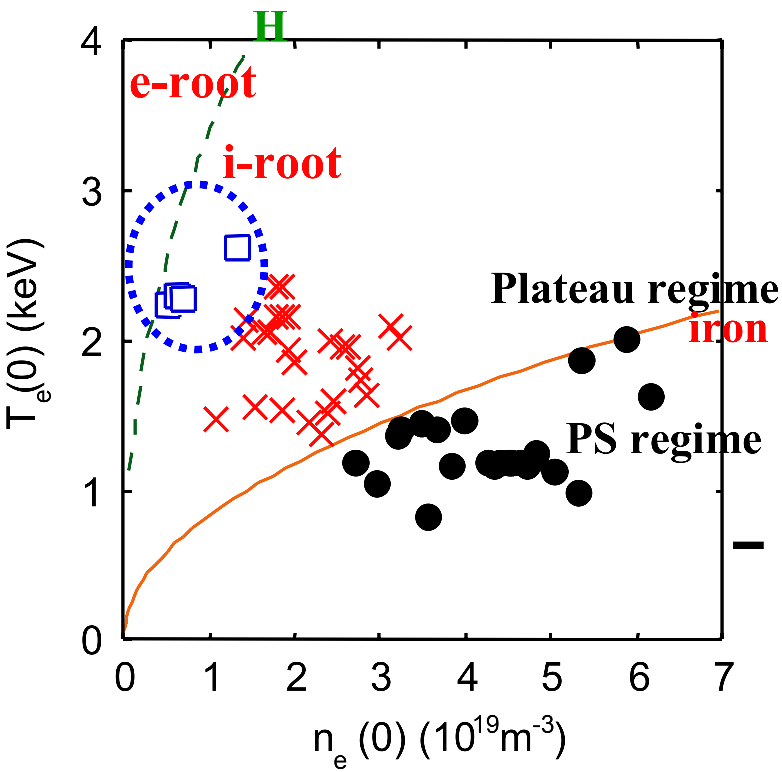
Density scan exp. ⇒ Drastic change of impurity behavior



Remarkable increase of $S_{rad}(\rho=0)$ and line emission only for medium density

⇒ density window for impurity accumulation

Density window for impurity accumulation



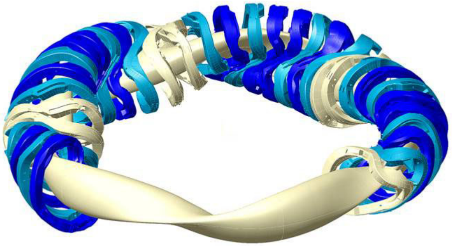
×: accumulation

□: no accumulation

●: pump-out or no accumulation

- High n_e and low T_e region
  - Temperature screening in PS regime : flat n_e profile and ∇T
- Intermediate region
  - Accumulation due to ion root Er
  - Accumulation due to ∇T in plateau regime

- Low n_e and high T_e region **(low collisionality)**
  - Outward convection by electron root Er (due to non-axisymmetric contribution to NC flux)
  - Mitigation of impurity accumulation with e-root in low collisional regime
  - Important finding for high T scenario for helical reactor condition



Wendelstein 7-X
at the transition
from procurement to assembly

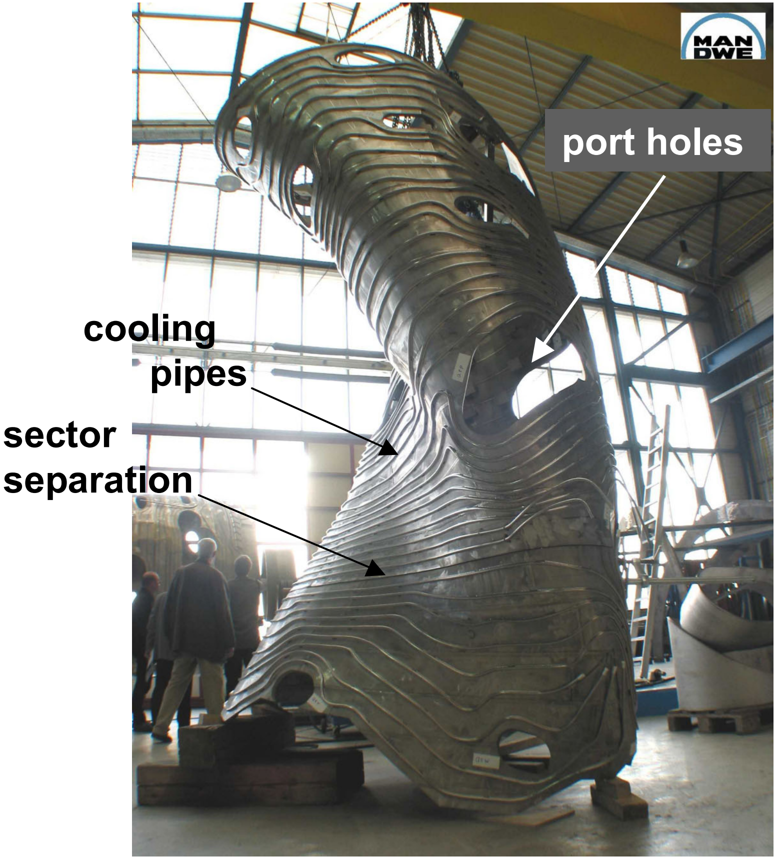
R. Brakel, J. Kisslinger for the W7-X Team

Max-Planck-Institut für Plasmaphysik, Euratom-IPP Association, Greifswald, Germany

Joint Meeting US-Japan Workshop and 21st COE Symposium, Kyoto, 2004

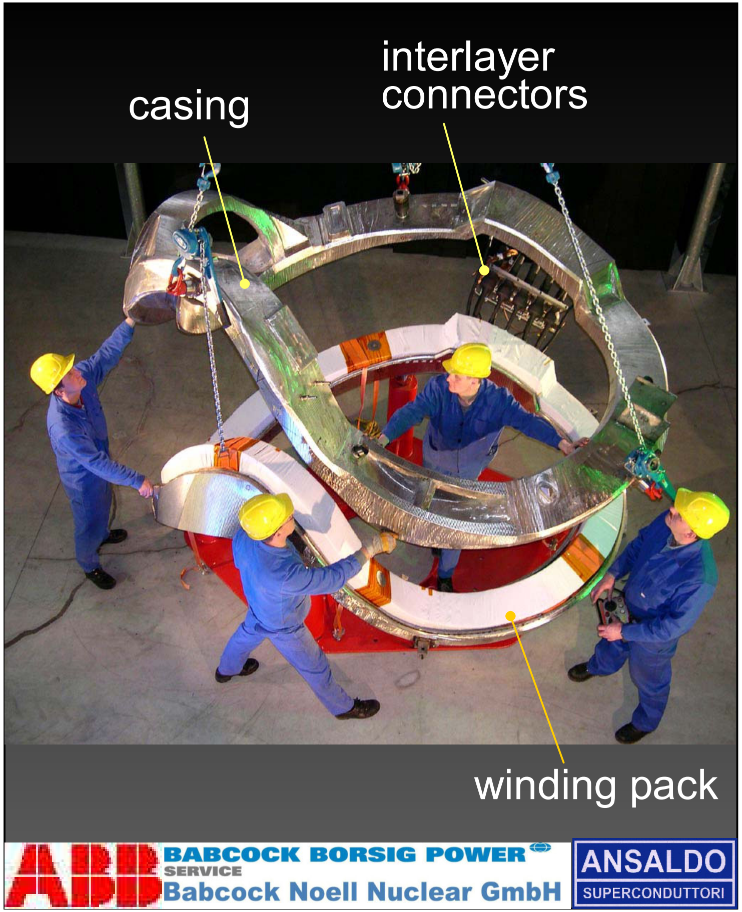
Plasma vessel

- 5 modules with 4 sectors each
- 8 of 20 sectors leak-tested
- 2 sectors delivered (1 half-module) and mounted with diagn. coils



test assembly of the 1st half module

Coil fabrication (non-planar coils)

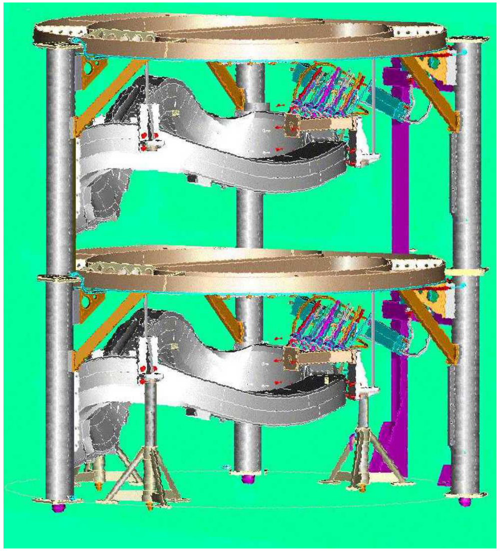


- 50 coils required
- 24 winding packages delivered
- 15 coils embedded
- 7 coils machined
- 3 coils delivered

Coil test facility

cryogenic test facility (CEA/Saclay)

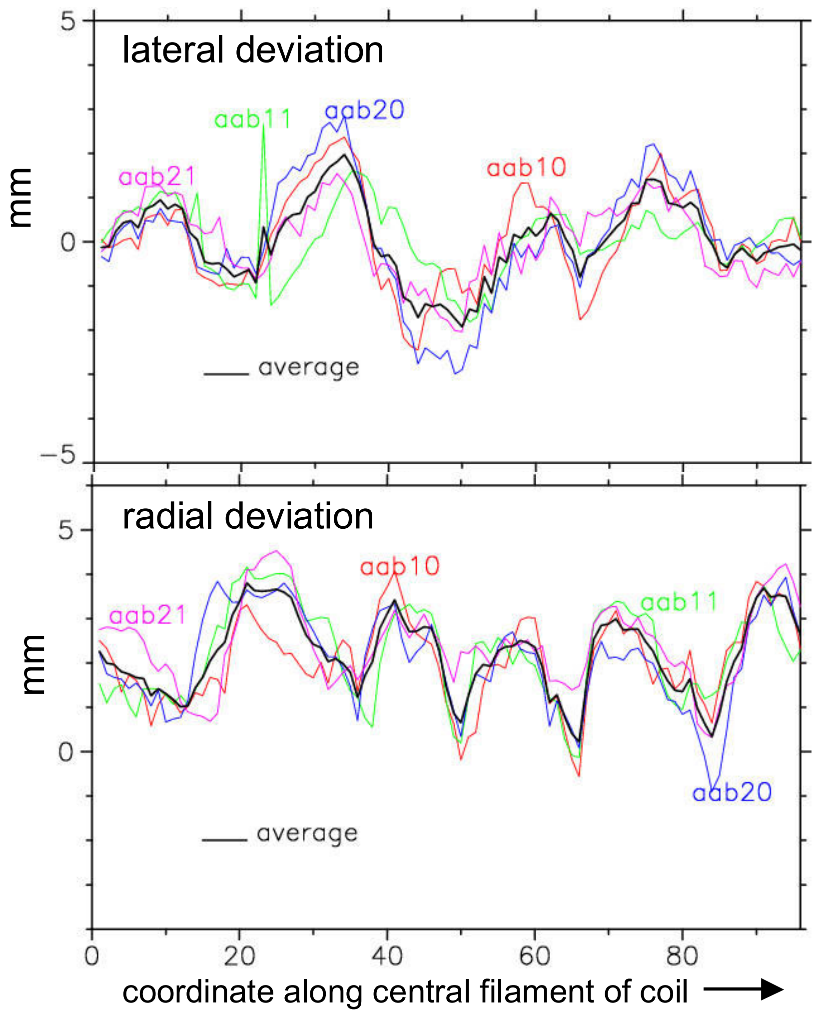
support frame with 2 coils



- 2 non-planar coils and 1 planar coil tested successfully

  (cool-down/warm-up, nominal current, quench, pressure drop, leak rate, mechanical deformations, resistance of joints)

Accuracy of winding pack fabrication (coil type 1)



initial tolerance

average deviation of central filament to CAD-model

aab 10	2.34 mm
aab 11	2.39 mm
aab 20	2.48 mm
aab 21	2.58 mm

⇒ within initial tolerance

average deviation to mean value of the four coils

aab 10	0.65 mm
aab 11	0.73 mm
aab 20	0.66 mm
aab 21	0.65 mm

⇒ small deviation among coils

⇒ small symmetry breaking errors !!

OPTIMIZATION TOWARD QUASI-ISODYNAMICITY FOR STELLARATORS WITH DIFFERENT NUMBER OF PERIODS

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INTRODUCTION (II)

From the initial qi consideration (1996) it followed that there are two classes of reflected particles that can be confined for a long time:

1. deeply to moderately trapped particles, that are always trapped. The approaching to qi leads for these particles to very long time collisionless confinement;

2. barely reflected particles; the second adiabatic invariant is not conserved for such particles, their radial motion is a “diffusive”-like, the character confinement time for reactor-sized parameters (B_0=5T, V=1000m^3) is of the order of 0.05 sec.

One can try to find the configurations with different ratio of the number of particles in these two classes. In particular, the search for “pure” configurations can be made, in which all reflected particles belong to one (first or second) class.

Thus, it was shown that in stellarator with poloidal direction of lines B = const on the magnetic surfaces it is possible to confine for a long time the collisionless α-particles.
The approaching to quasi-isodynamicity leads to diminishing of the effective ripples and bootstrap current.
The requirement of improved fast particle confinement is well compatible with the stability conditions.

Possible directions of further investigations:

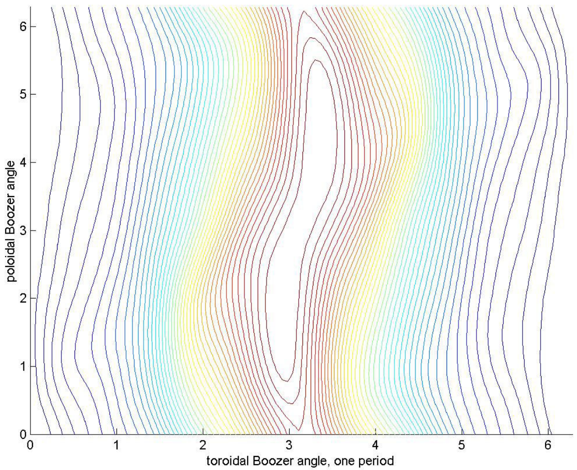
- to try to increase the β value for considered $N = 6$ configuration;
- to consider the configurations with larger number of periods (there is no symmetric analogue for such kind of systems);
- to consider compact configurations with smaller number of periods;
- search for configurations with different shape of plasma column cross-sections.

As a result, it would be useful to receive the dependence $\beta(N)$ for the configurations with improved confinement.

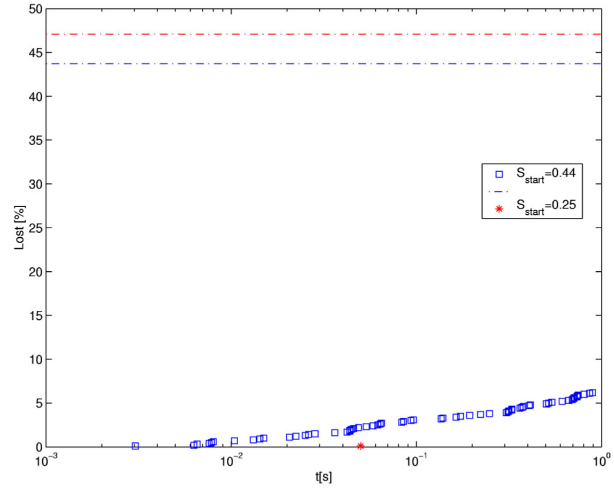
The part of these investigations is under work now.

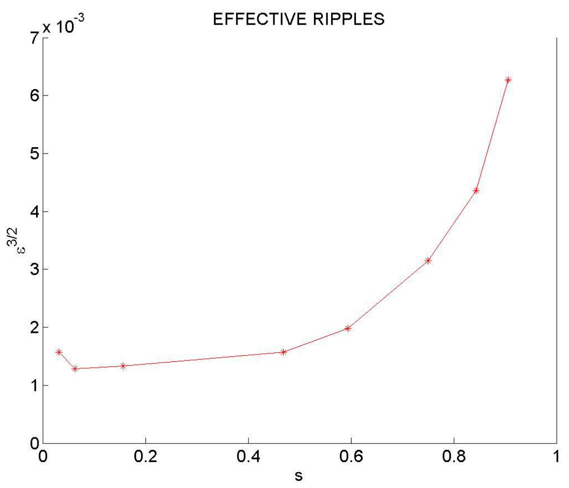
The results of integrated optimization for N=6 configuration for <β>=8.8% (I)

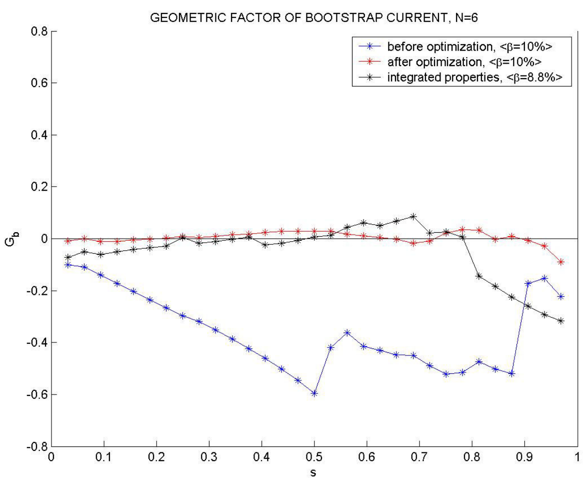
B-contours



Particles confinement

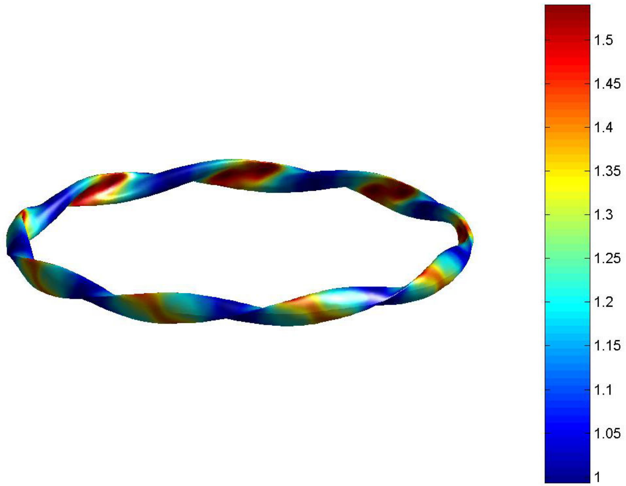




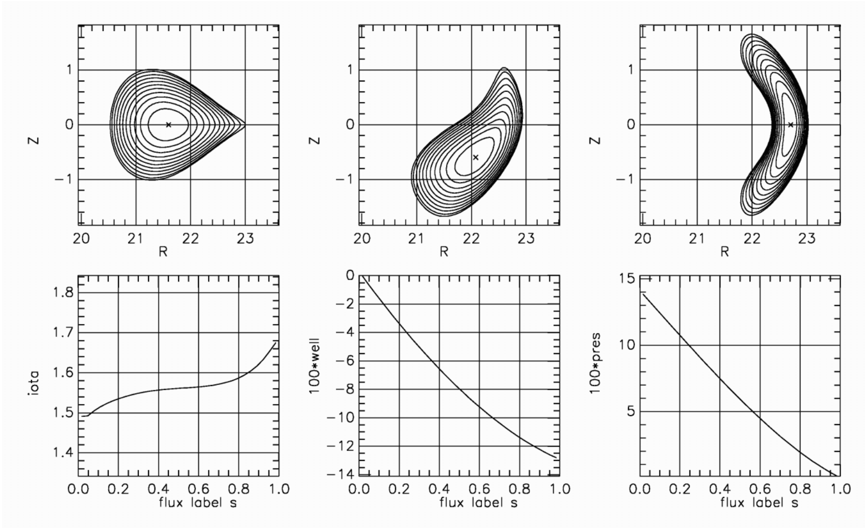


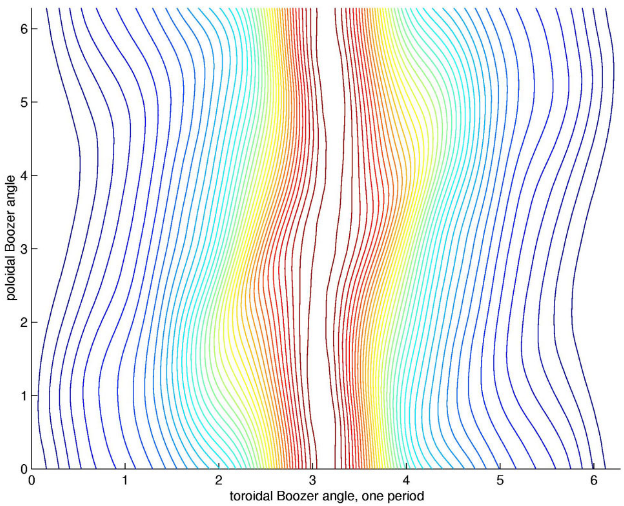
The results of optimization for N=9 configuration for <β>=10% (I)

3D view

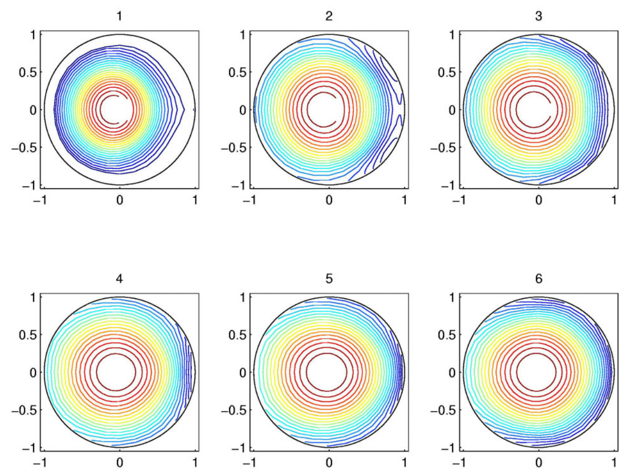


Cross-sections and flux functions



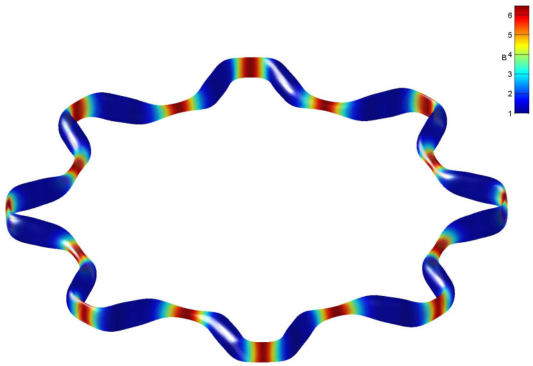


B-contours

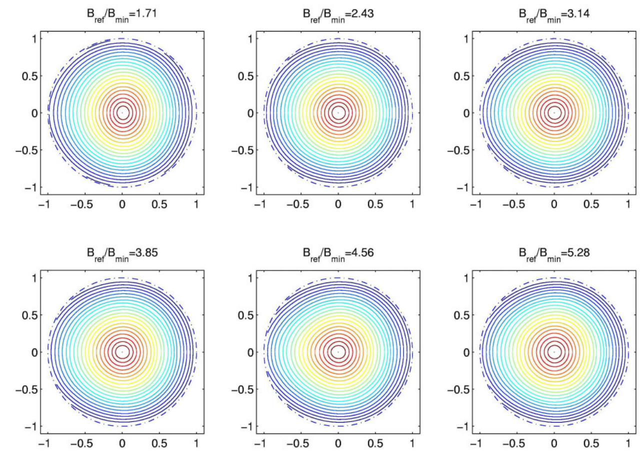


J-contours

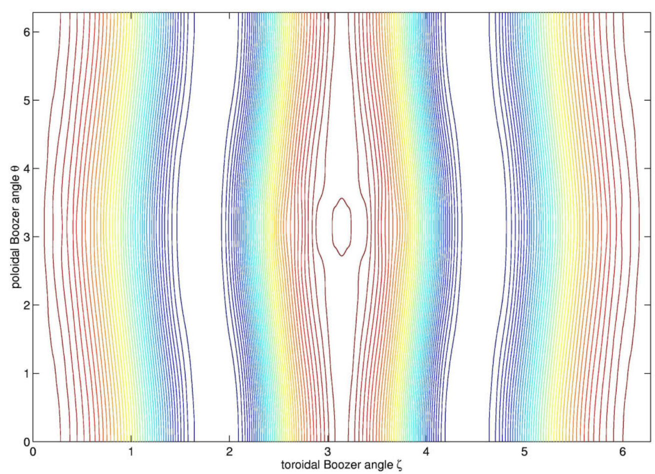
Toroidal mirror-symmetric trap (plane magnetic axis)



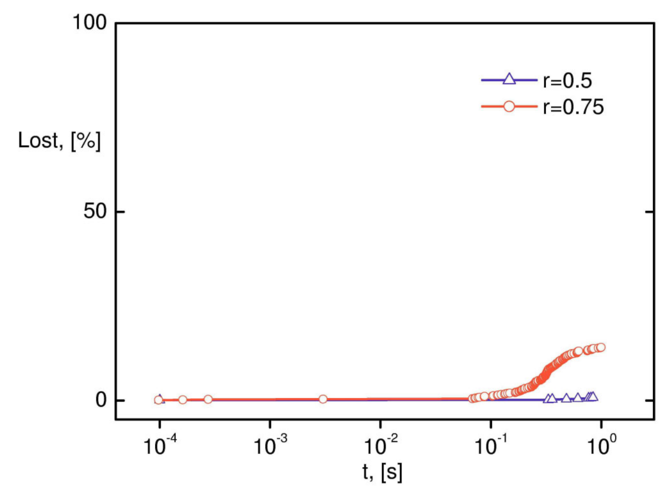
3D view, N=8 configuration



J-contours



Lines B=const on ½ of plasma radius



Particle confinement

CONCLUSIONS

From analytical consideration it follows that in the configurations with poloidal direction of lines *B* = const on magnetic surfaces the secondary current and bootstrap current are small. Due to small connection length the "banana" size of trapped particles is small, too.

These analytical conclusions were conformed by numerical calculations. Computational optimization toward qi (formulated as the requirement of *J*-contours to be closed inside plasma column for all reflected particles started in inner plasma region) of $N = 6$, $\langle\beta\rangle = 5\%$ stellarator leads to good fast particle long time collisionless confinement, small effective ripples and small structural factor of bootstrap current. The qi condition is well compatible with stability requirements.

With increasing the number of periods, the stability β limit increases. The increase of β make it more easy to close *J*-contours inside the plasma column. Thus, for large β the closeness of *J*-contours do not lead automatically to diminishing of effective ripples and bootstrap current; these requirements should be included into optimization procedure.

The preliminary results show that increasing of number of periods from $N = 6$ to $N = 9$ leads to significant increase of plasma pressure limit, from 8.8% to ~15% . Further optimization is required to diminish the effective ripples and bootstrap current for high β stable configuration with good particle confinement.

The β limit for the configurations with larger number of periods is still unclear.