Topics from New Approaches in Plasma Confinement Experiments in Helical Devices

presented by
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2nd Joint Meeting of
US-Japan Workshop and Kyoto University 21st Century COE Symposium on

NEW APPROACHES IN PLASMA CONFINEMENT EXPERIMENTS IN HELICAL SYSTEMS

Nov. 13-15, 2006

Heliotron J — *IAE, Kyoto University*

- **F. SANO, Overview of Recent Experiments in Heliotron J**
- **D. ANDERSON, Overview of HSX Results**
- **S. OKAMURA, Topics from CHS experiment**
- **S. KOBAYASHI, Experimental Studies of NBI-heated plasmas in Heliotron J**
- **W. GUTTENFELDER, Turbulence measurements and theory-based transport modeling of ECRH plasmas in HSX**
- **T. MINAMI, High density edge transport barrier during reheat mode on CHS**
- **Y. SUZUKI, MHD Equilibrium Analyses of Advanced Helical Configurations**
- **T. RAFIQ, Microinstabilities and resistive ballooning modes in helically symmetric stellarators**
- **D. SPONG, Shear flow generation in stellarators - configurational variations**
- **S. KITAJIMA, Dependence of ion viscosity on ripple structures of magnetic configurations in Tohuku University Heliac and CHS**
- **K. MATSUOKA, Effect of magnetic configuration on electron energy transport in CHS**
- **M. ZARNSTORFF, Physics research plans for NCSX**
- **N. POMPHREY, Magnetic Flux Loop Design for NCSX**
- **J. HANSON, Progress in 3-D equilibrium reconstruction in stellarators**
- **R. MAINGI, The edge physics program during initial NCSX operation**
- **T. MIZUUCHI, Dynamic shift of divertor plasma position during a discharge in Heliotron J**
- **T. OISHI, Edge Harmonic Oscillations measured using Beam Emission Spectroscopy in CHS**
- **K. NAGASAKI, ECCD experiments in helical systems**
- **G. MOTOJIMA, Toroidal current control in ECH plasmas on Heliotron J**
- **T. OKADA, Fast ion study using ICRF heating in Heliotron J**
- **C. DENG, Studies of energetic electron-driven Alfvenic modes in HSX**
- **J. BERKERY, Confinement of Pure Electron Plasmas in CNT**
- **S. KNOWLTON, Overview of CTH experiments**
- **W. REIERSEN, Promising Innovations for Future Compact Stellarators**
- **A. WELLER, Progress of W7-X**
- **S. OKAMURA, Discussion on stability and confinement in LHD**

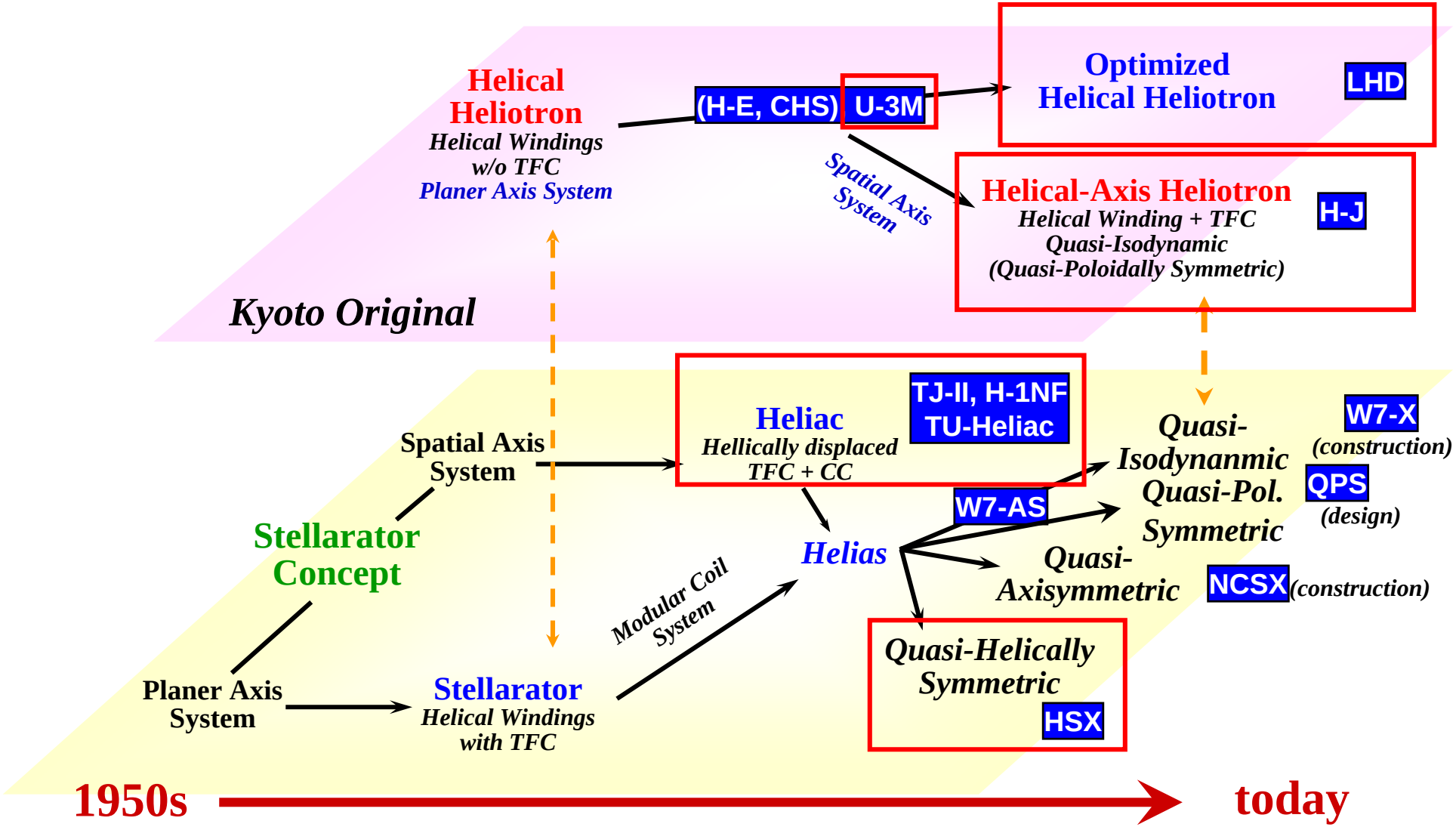
http://www.auburn.edu/cosam/events/plasma/usj06/

– Outline –

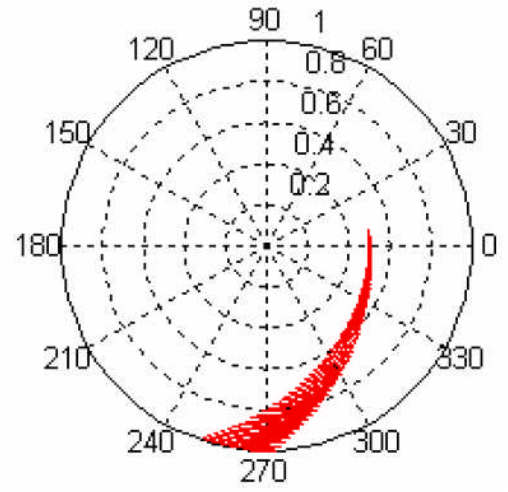
- **Advanced Helical (Stellarator/Heliotron) Concepts**
  - **Quasi-Symmetry**
  - **Quasi-Isodynamic (Quasi-Omnigeneous)**

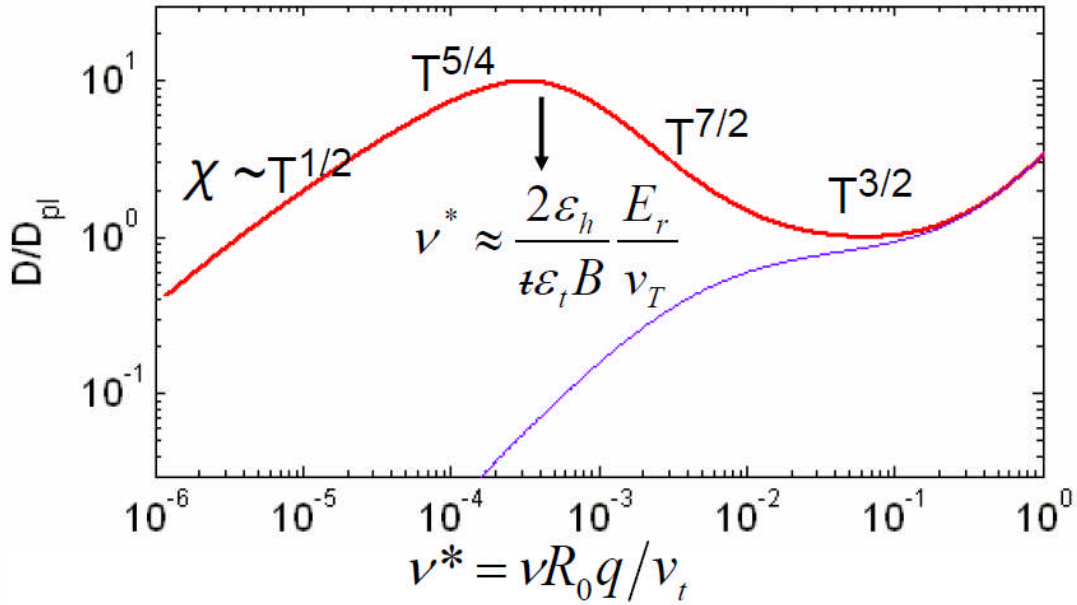
- **Topics from Recent Plasma Experiments in Helical Devices**
  - **Configuration effects on NC/turbulent transport**
  - **Progress in high-β, high density steady state operation**
  - **Divertor relevant experiments**

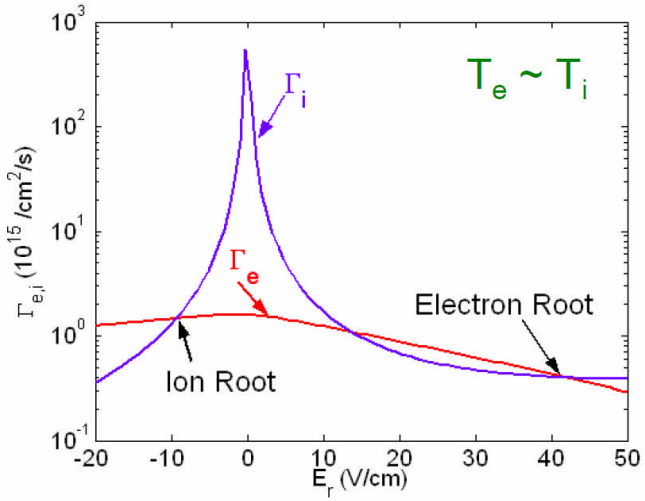
Evolution of Helical (Stellarator/Heliotron) Concepts



Helical ripple leads to high transport in conventional stellarators.
→ *How to reduce it?*





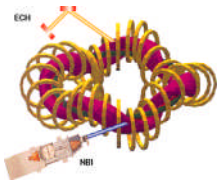
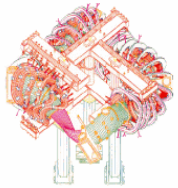
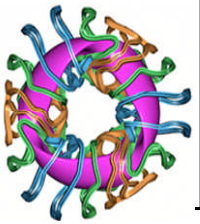
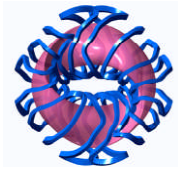


- **Particles trapped in helical ripple have net radial drift in conventional stellarators.**
- **Electric field can mitigate scaling.**
  - ***Ambipolarity constraint on NC fluxes can create E_r.***
- **Advanced helicals reduce the ripple losses through recovering of symmetry or tailoring the field harmonics.**

World-wide research activities for optimization of helical systems

Concept	Modular Coils	Continuous Helical Coil(s)
Quasi-Axisymmetric (Quasi-Toroidally Symmetric)	NCSX (PPPL, 2008?~)	
Quasi-Helically Symmetric	HSX (UW, 1999~)	LHD (NIFS, 1998~) *helical heliotron*
Quasi-Poloidally Symmetric	QPS (ORNL 2010?~)	
Quasi-Isodynamic (Quasi-Omnigeneous)	W7-X (IPP, 2012?~)	Heliotron J (Kyoto, 2000~) *helical-axis heliotron*
Heliac	TJ-II (CIEMAT, 1997~) H1-NF (ANU, 1993~) TU-Heliac (Tohoku, 1988~)	
Others		U-3M (Kharkov,) CTH (Auburn, 2006~)

Helical-Axis Helical Devices in the World

プラズマ装置 国名 研究所	H-1NF オーストラリア オーストラリア国立大学	TJ-II スペイン CIEMAT研究所	HSX 米国 ウィスコンシン大学	Heliotron J 日本 京都大学	NCSX 米国 プリンストン大学	QPS 米国 オークリッジ国立研究所	W7-X ドイツ マックスプランク研究所
スケジュール	1993年～	1997年～	1998年～	2000年～	2008年?～	2010年?～	2012年?～
コイル形式	M＝3 ヘリアック (CR + l=1 HFC x2 + TFC)	M＝4 ヘリアック (CR + l=1 HFC + TFC)	M＝4 ヘリアス (モジュラーコイル)	M＝4／L＝1ヘリカル軸ヘリオトロン	M＝3 準軸対称系 (QA) (モジュラーコイル)	M＝2 準ポロイダル対称系(QPS) (モジュラーコイル)	M＝5 (修正)ヘリアス (超伝導モジュラーコイル)
大半径 R (m)	1.0	1.5	1.2	1.2	1.4	0.95-1.0	6.5
小半径 a (m)	0.22	0.1-0.25	0.15	0.18	0.32	0.3-0.4	0.65
体積 V (m^3)	0.96	1.43	0.44	0.82	3	2-3	54
閉じ込め磁場 B (T)	1.0	1.0	1.37	1.5	1.2 – 1.7	1.0	3.0
パルス幅 Δt (s)	1.0	0.5	0.6	0.5	1.2	1.5	10.0
アスペクト比 R/a	4.5	6-15	8	7	4.4	2.7	10
加熱装置 Heating	ECH : 0.2 MW	ECH : 0.6 MW NBI : 4 MW	ECH : 0.2 MW	ECH : 0.4 MW NBI : 1.5 MW ICRF : 2.0 MW	RF : 6 MW NBI : 6 MW	ECH/EBW : 1 MW ICRF : 1 MW	ECH+NBI 20 - 30 MW
特徴	高回転変換角、低シア、ビーン形状、大きな立体磁気軸回転。	回転変換角(0.96-2.5)、シア、磁気井戸(0-6%)、ビーン形状等の制御が可能。特に、高ベータ実験を目標。	ヘリカル対称性の確保による閉じ込めの向上。	柔軟な磁場配位制御によるヘリカル軸ヘリオトロンの最適化を追求。	準軸対称系(QA)、高自発電流(>50%)のよる閉じ込め性能の原理検証。 <β> ～ 2%	準ポロイダル対称系(QPS)の閉じ込め性能の概念開発。 <β> ～ 2%	ヘリアス配位の改良型。自発電流の低減とヘリアス配位の最適化を追求する超伝導大型実験装置。
装置図							

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- **Advanced Helical (Stellarator/Heliotron) Concept**

- **Topics from Recent Plasma Experiments in Helical Devices**
  - **Configuration effects on NC/turbulent transport**
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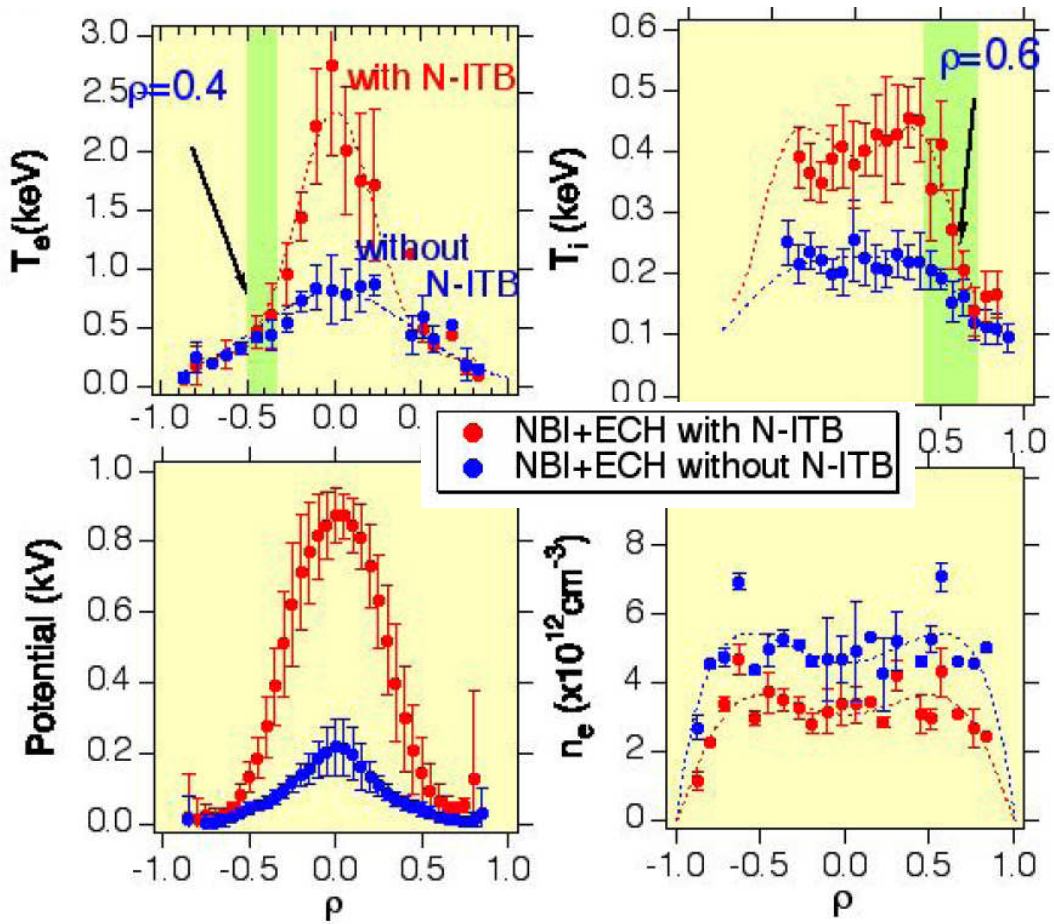
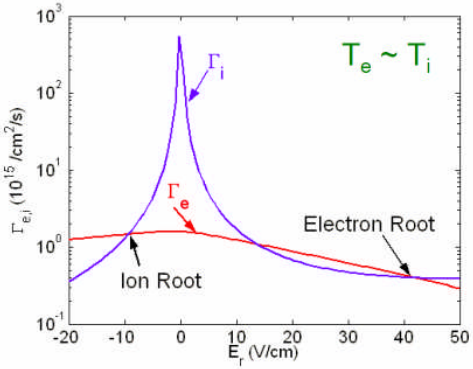
E_r driven by Electron-Root Scenario

Internal transport barrier formation observed in CHS experiments.





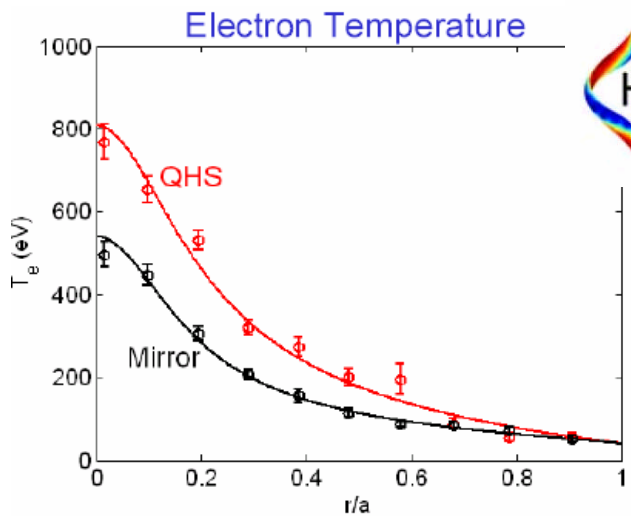
- **The electron-root condition is found inside ρ~0.6 creating the large E_r-shear regime.**
- **Steep T_i-gradient is found in E_r-shear regime.**
- **T_e-gradient also increases inside ρ ~0.4.**
- **HIBP measurements showed suppression of turbulent transport with the internal transport barrier formation.**

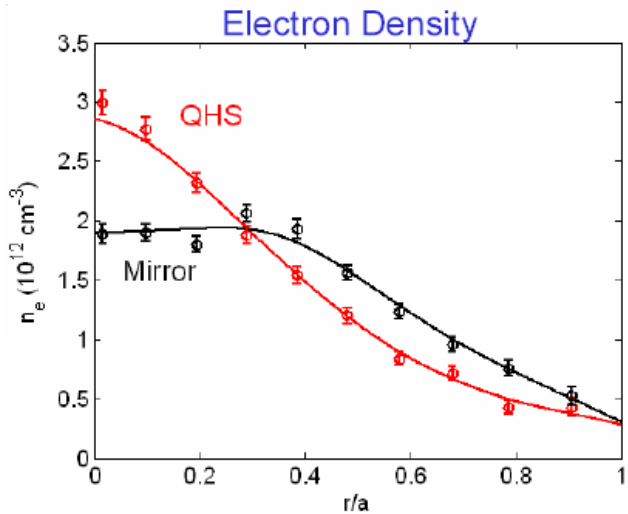
Effects of Configuration on NC transport: Exp. from HSX
Significant differences have been measured between plasma profiles w/ & w/o QHS. (I)

- *Mirror fields are added for symmetry breaking in HSX.*
- **Density profiles are peaked w/ Quasi-Helical Symmetry (QHS), hollow when symmetry is broken.**
  - **Discharges shown: ~50 kW of ECH power, central deposition**
  - **higher temperature, more peaked density profile with QHS.**
- **Hollow/flat n_e-profile in w/o QHS is due to thermodiffusion, which is reduced with QHS**

$$\Gamma = -n\left\{D_{11}\left(\frac{n'}{n} - \frac{qE_r}{T}\right) + D_{12}\frac{T'}{T}\right\}$$

D_{12} is smaller due to quasi-symmetry





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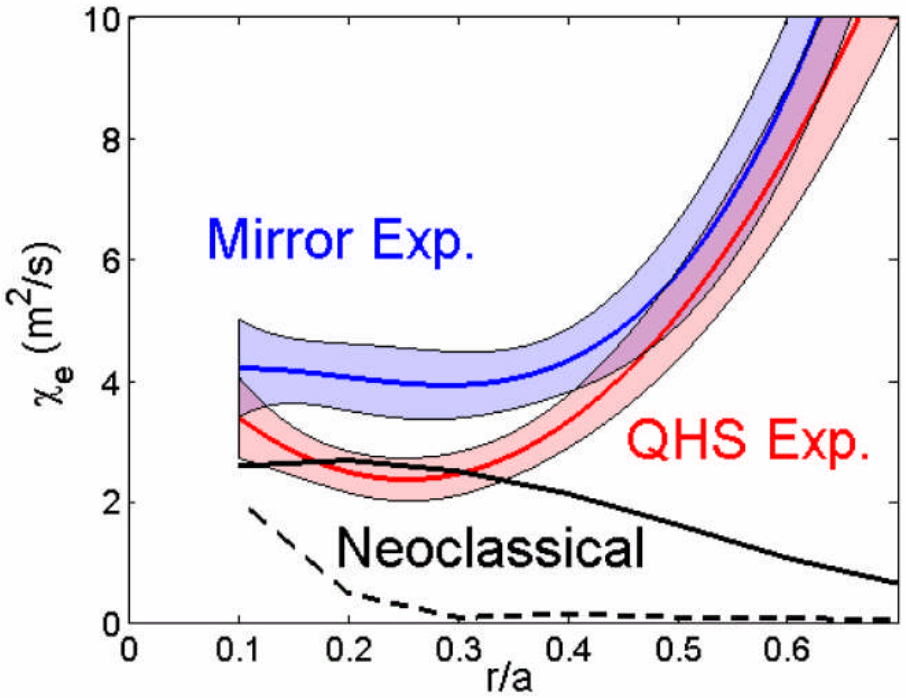
HSX experiment also shows the effectiveness of the symmetry recovering to reduce the thermal diffusivity.

- **Thermal diffusivity is reduced in QHS.**
  - **at r/a ~ 0.25,**
    χ_e : 2.5 m^2 /s in QHS,
    4 m^2 /s in Mirror
  - **Difference is comparable to neoclassical reduction (~2 m^2 /s)**
- **Two configurations have similar transport outside of r/a~0.5.**
  ⇒ anomalous transport dominant



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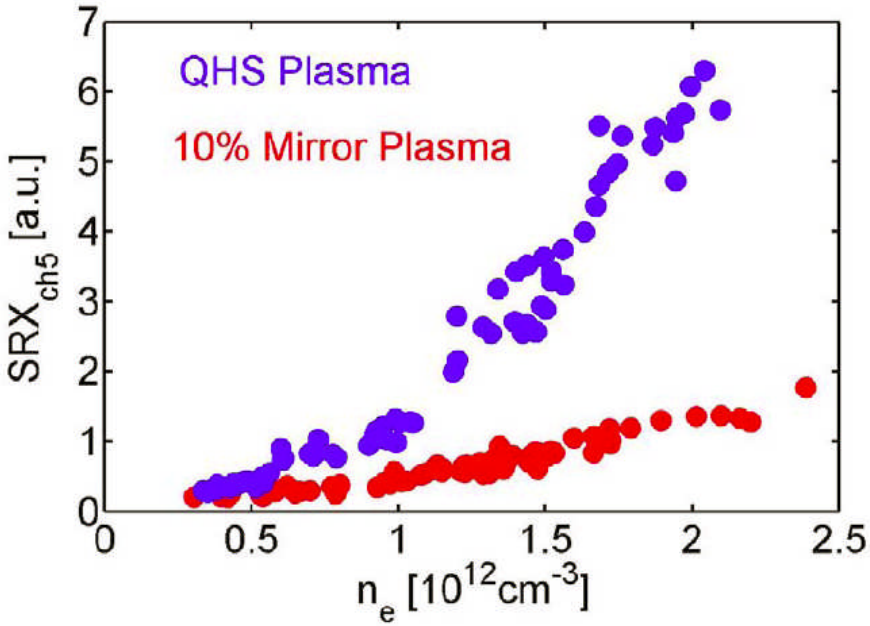
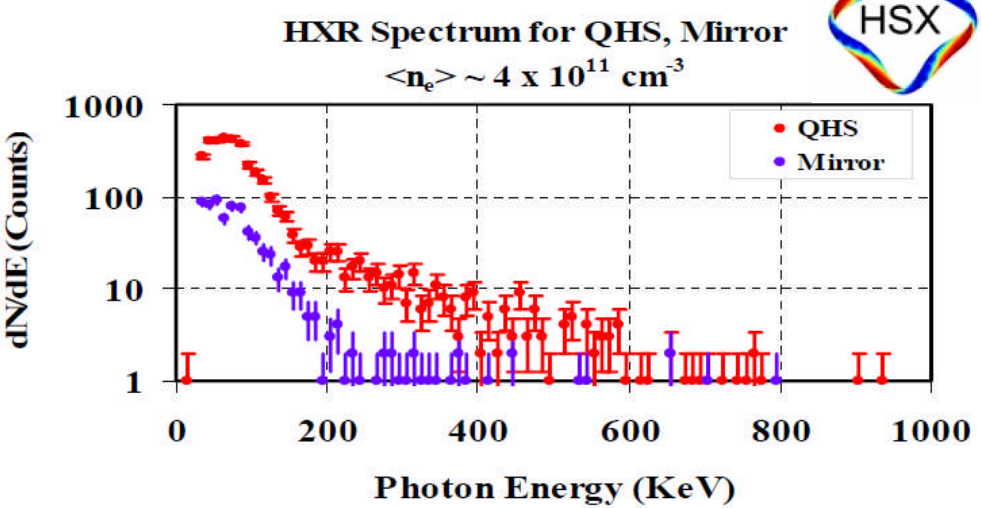
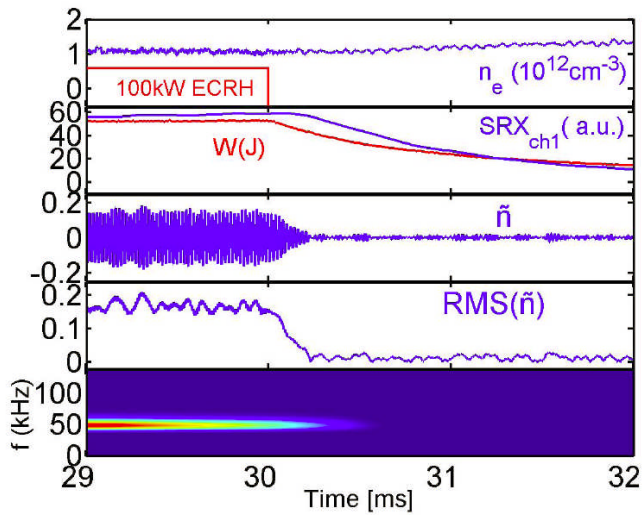
Soft X-ray, Hard X-ray Emissions indicate fast electrons are better confined in QHS.







- **Soft X-ray (600 eV-6 keV) emission; QHS >> Mirror**
- **Hard X-ray flux: QHS>>Mirror; decay time longer**
- **Indicates these fast electrons drive Alfvénic modes.**
  - ***No mode observed in Mirror Configuration.***

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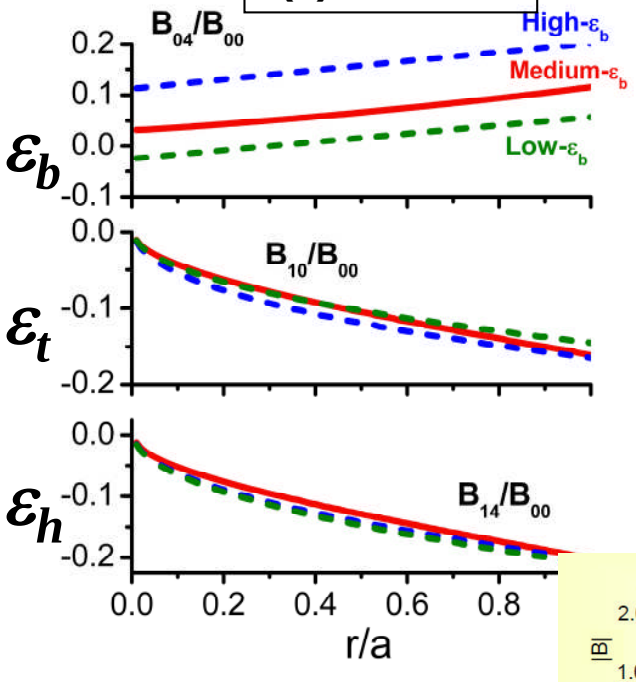
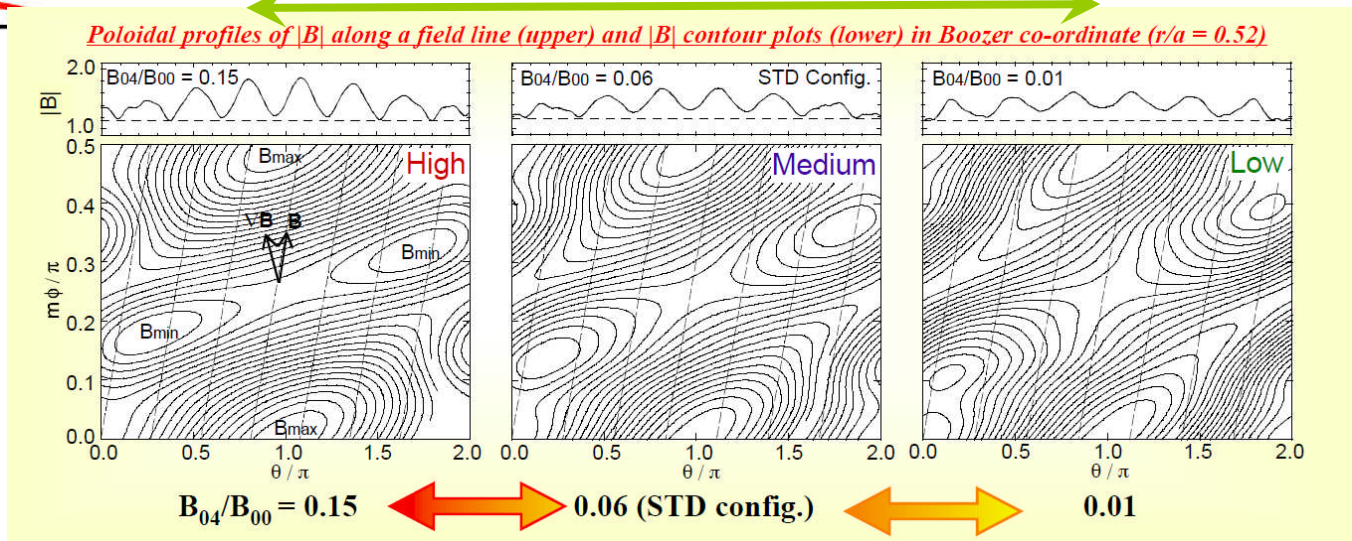
Bumpy (mirror) component is essential to realize the quasi-isodynamic feature in Heliotron J.

$\iota(a)/2\pi \approx 0.56$

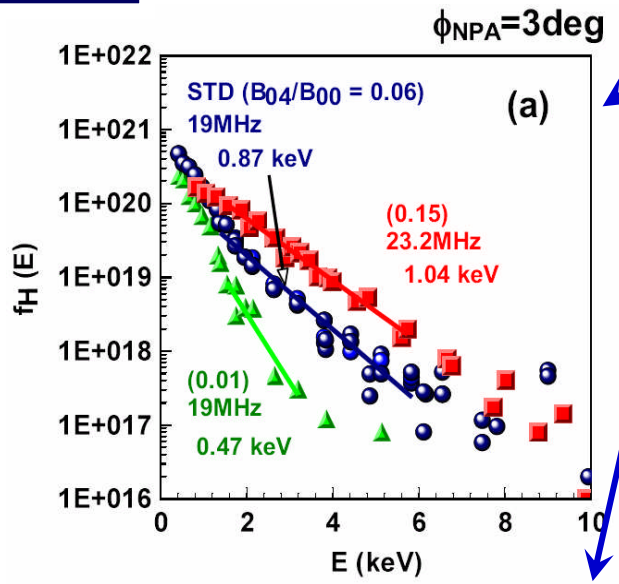


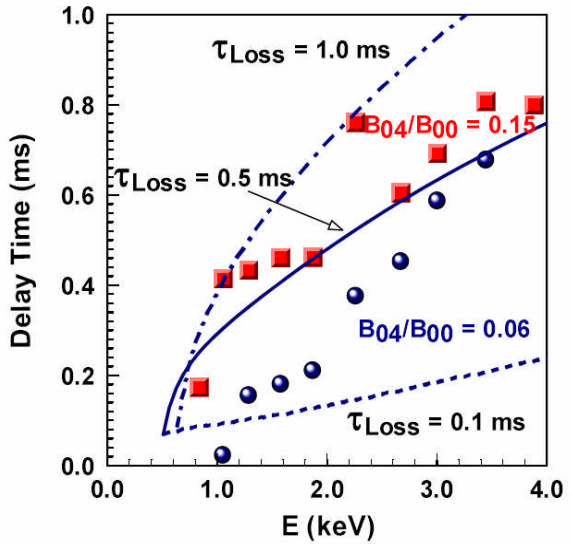
- To investigate the bumpiness effects on fast-ion confinement,
  - the bumpiness was varied by controlling the current ratio of the two toroidal coil sets under the fixed condition of $\iota(a)/2\pi=0.56$.
  - The fast-ions are created by ICRF or NBI.

better ⟷ *worse*

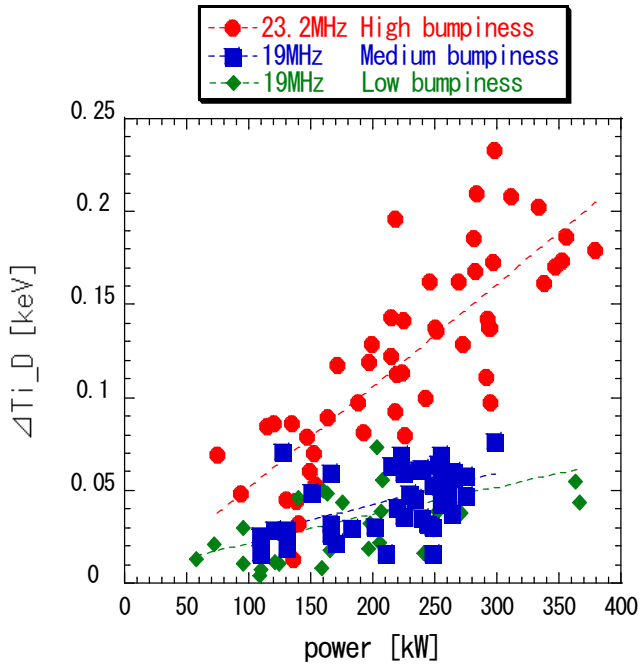


Better confinement of fast ions by ICRF in higher bumpiness configuration





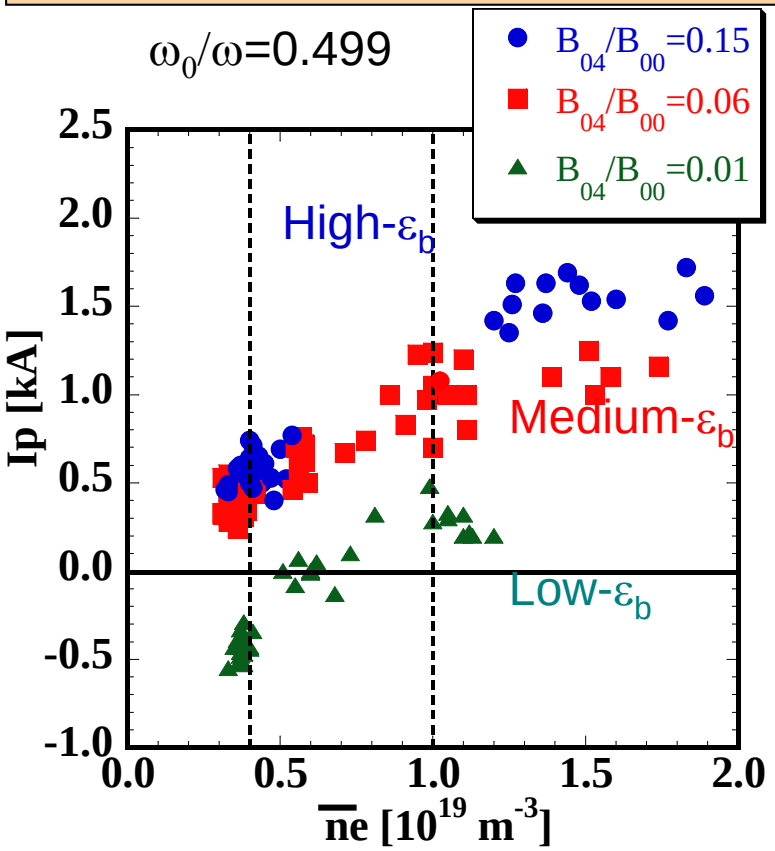
- For ICRF heating, the high-energy ion tail temperature increases with ε_b.
- Power-moderation experiments indicate lower loss-rate for higher ε_b configuration.
- Due to better confinement of fast-ions, higher increment of the bulk ion-temperature is observed for higher ε_b configuration.



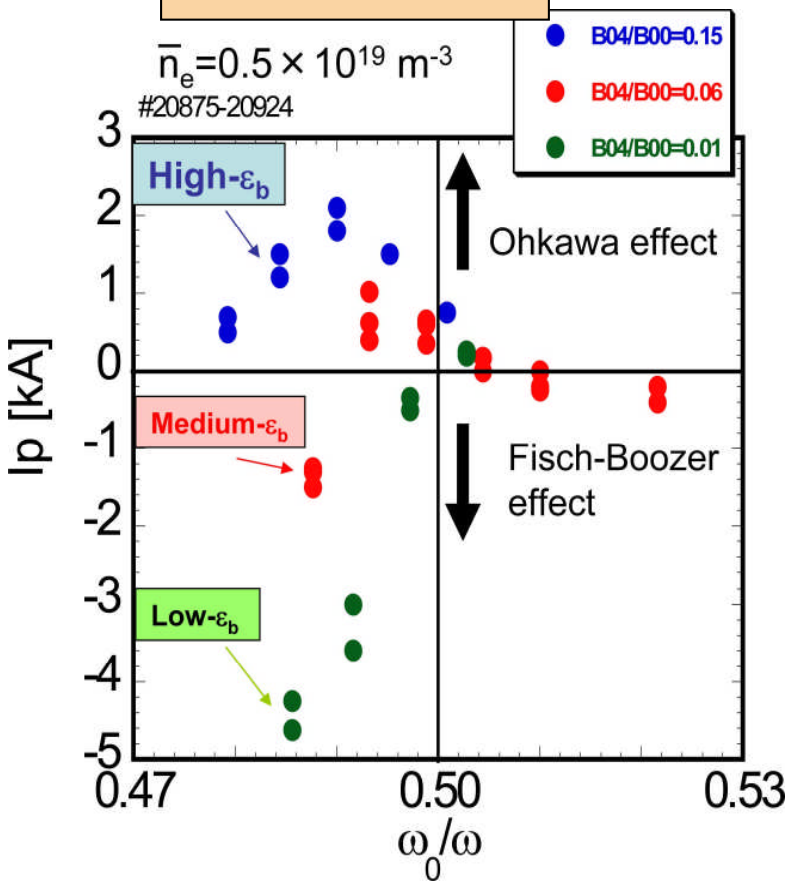
Configuration effects on NC transport

Non-inductive current control
– ε_b dependences –

Bootstrap current control



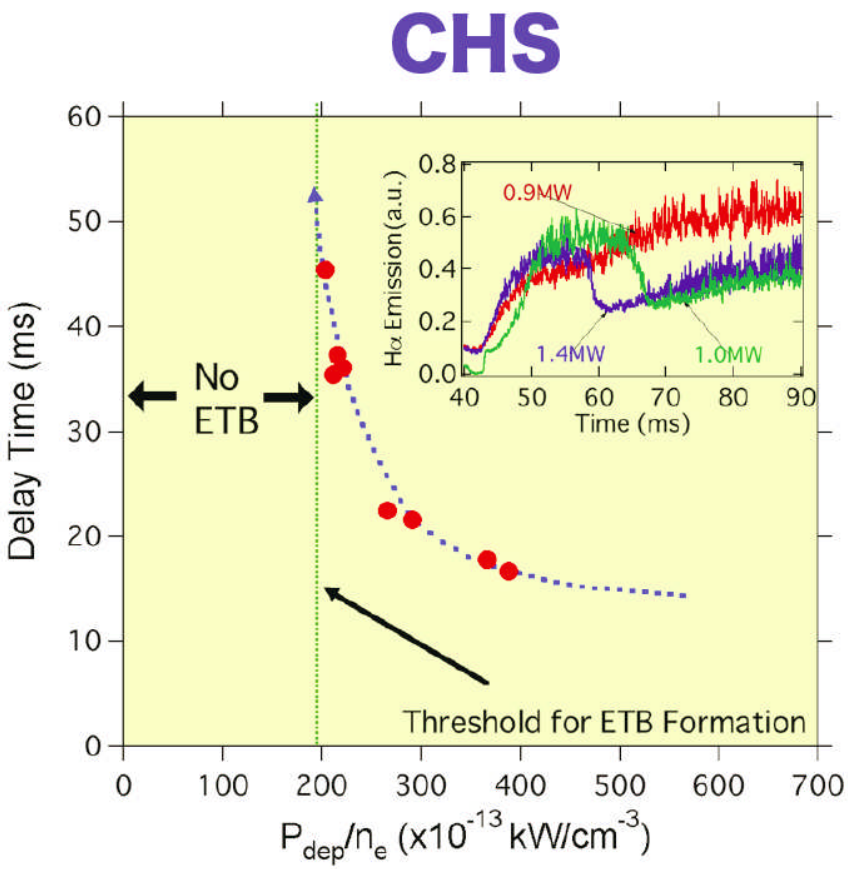
ECCD control

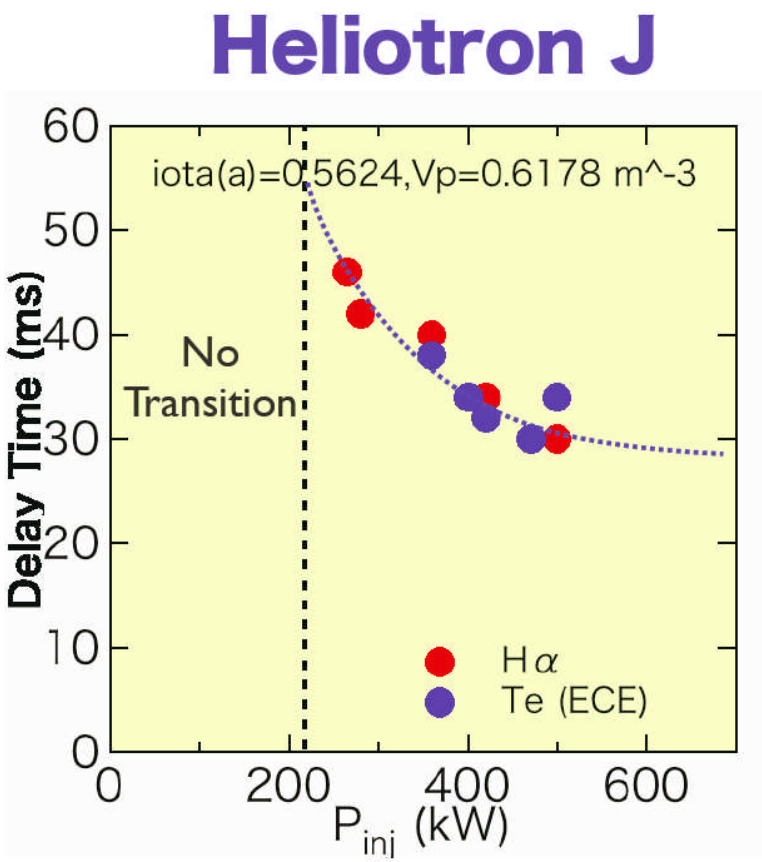


- The ε_b-dependece of BS current is consistent with the predictions from SPBSC calculations.
- For ECCD, the ripple structure at the resonance region is important.

P_{NBI}-Dependence of Delay Time of L-H Transition

Comparison between CHS and Heliotron J





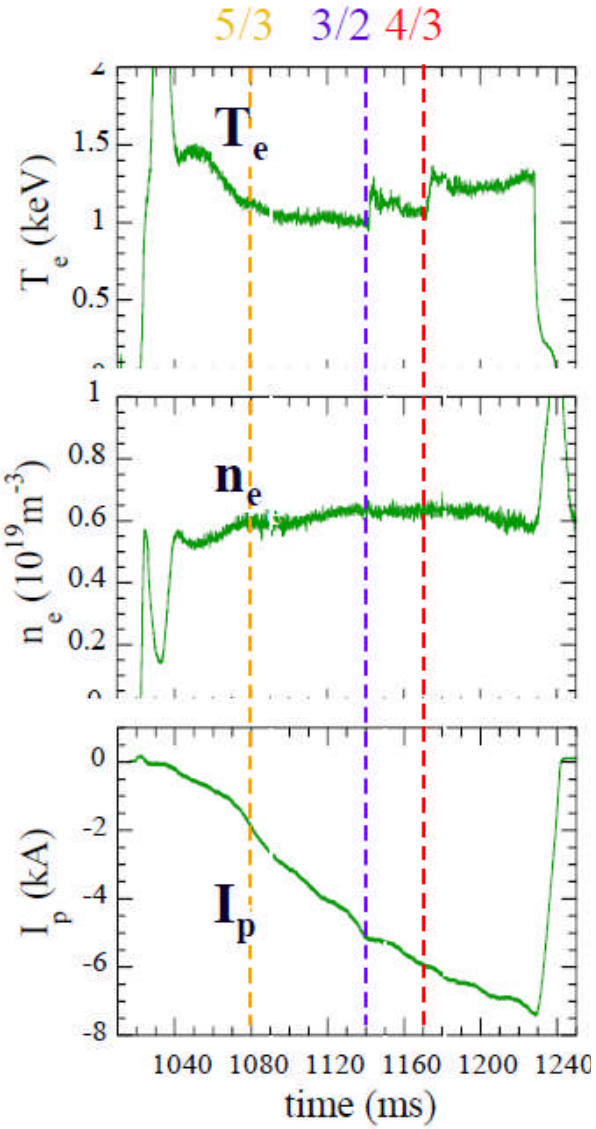
- **Delay time of Hα spontaneous drop after the start of NBI becomes longer as decreasing NBI power.**
- **The edge field structure (rationals?) might be important for the transition.**

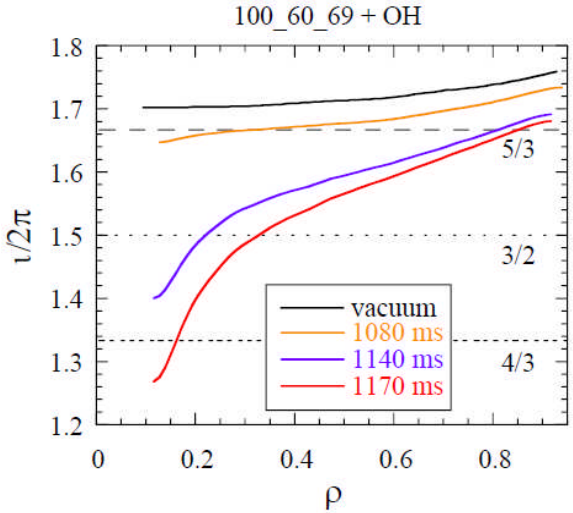
T. Minami, S. Kobayashi, et al

turbulence transport and improved modes

Confinement and magnetic topology

ITB in TJ-II





- **Positioning a low order rational (e.g. 3/2, 4/2, 4/3) near the core (using, e. g., induced OH current or ECCD) triggers an ITB in a controllable way.**
- ***The rational must be inside the plasma to trigger the transition.***
- **Change in E_r is observed near the rational.**
- **So far no cases found where the e-ITB triggered by 5/3.**

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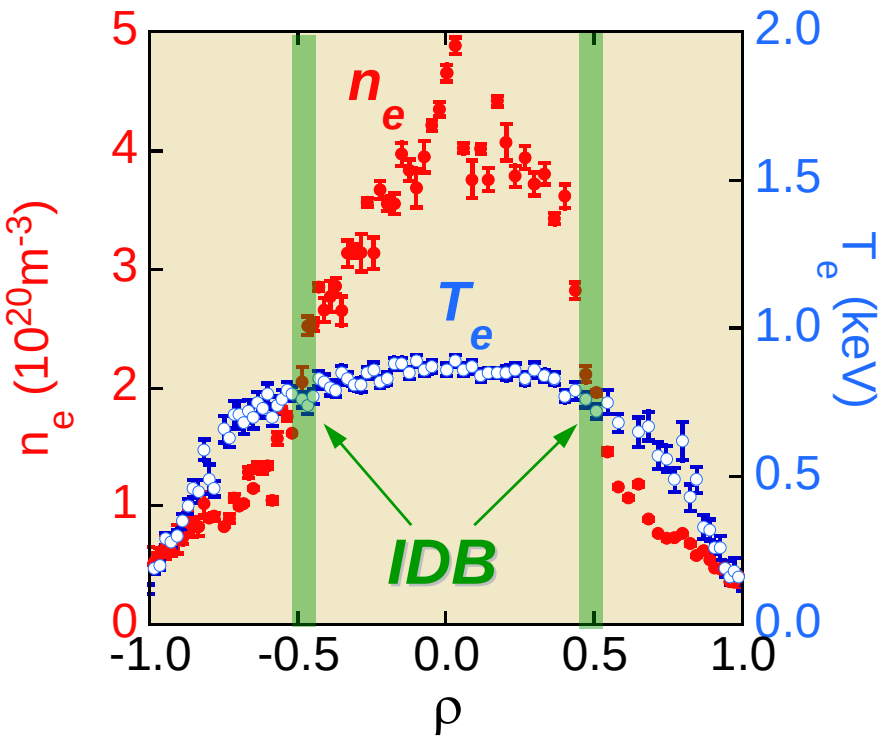
Observation of Internal Diffusion Barrier and *super dense core* plasma in LHD

21st FEC (2006)



Central density : 5×10^{20}m^{-3}

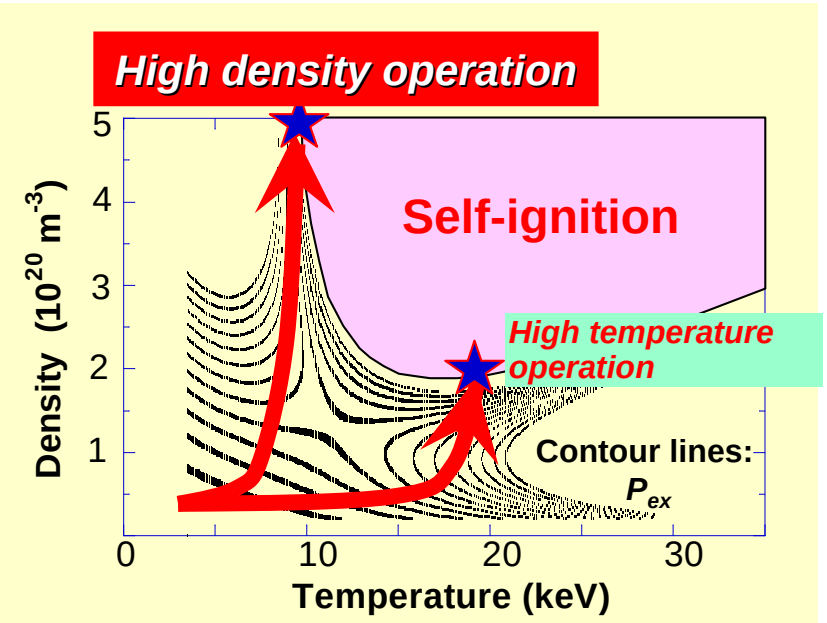
Central temperature : 0.85 keV

➔ exceeding 1 atmospheric pressure

Magnetic field : 2.64 T

➔ Central beta : 4.4 %

: > 5 % at B of 1.5T

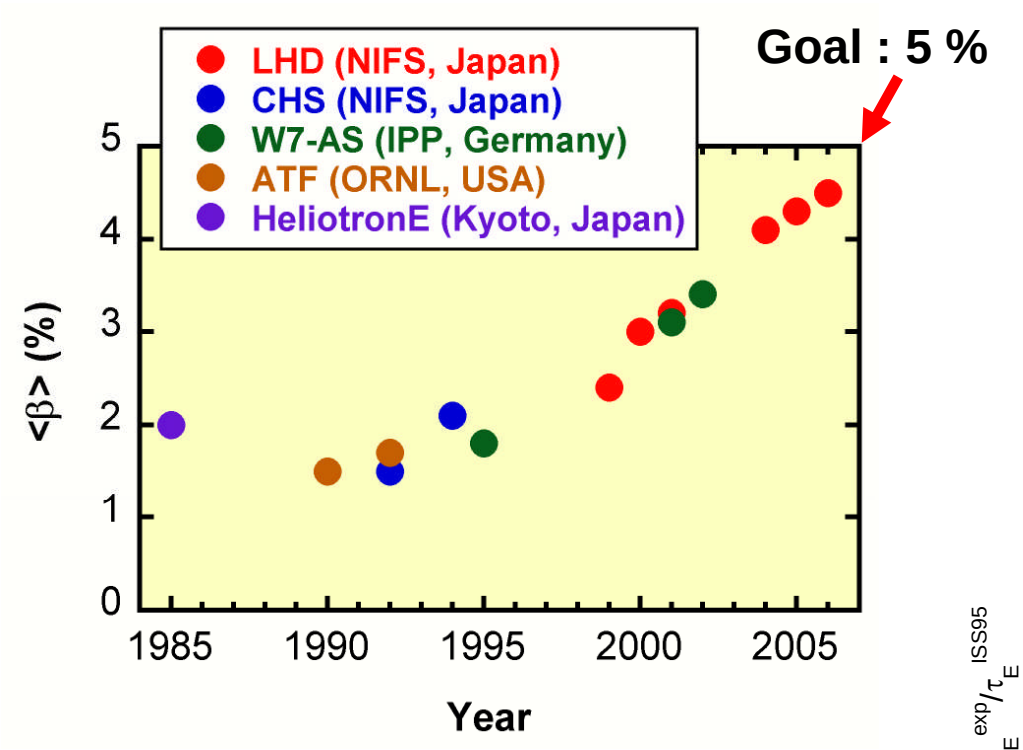


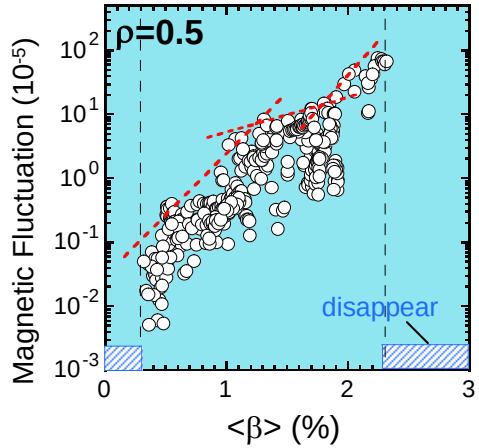
- ***Super Dense Core operation enables a new reactor scenario.***

progress in high-β performance

High β–plasma studies in LHD

21st FEC (2006)

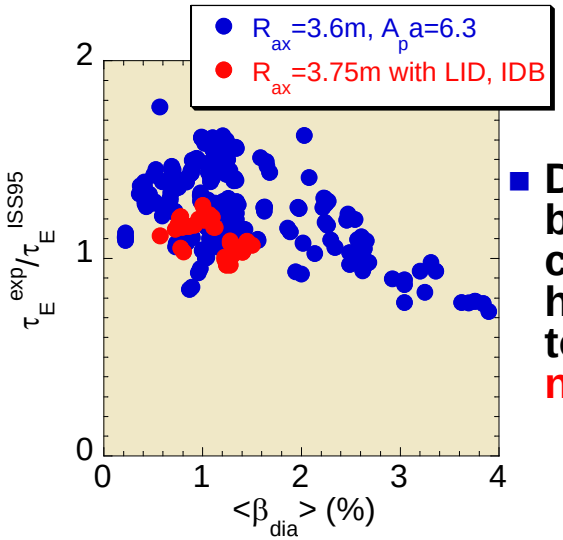




self-stabilization

⇒ realization of high-β plasma,

⇒ ***needs 3D equilibrium reconstruction technique.***



- **Degradation can be attributed to the change of effective helical ripple due to Shafranov-shift, not on MHD effect.**

<β> > 4 % was sustained for >> 10τ_E

- **Degradation in high β regime will be improved by dynamic R_{ax} control in nearest future.**

Request for 3-D Equilibrium Reconstruction is Increasing in Helical Experiments. ⇒ V3FIT

- **Equilibrium reconstruction is invaluable for tokamaks**
  - **Equilibrium Control**
  - **MHD Stability and Confinement Studies**
    ⇒ Example: EFIT code

- **Helical Trends**
  - **Higher beta**
  - **Bootstrap current**

⇒ Equilibrium flux surfaces are not vacuum flux surfaces.

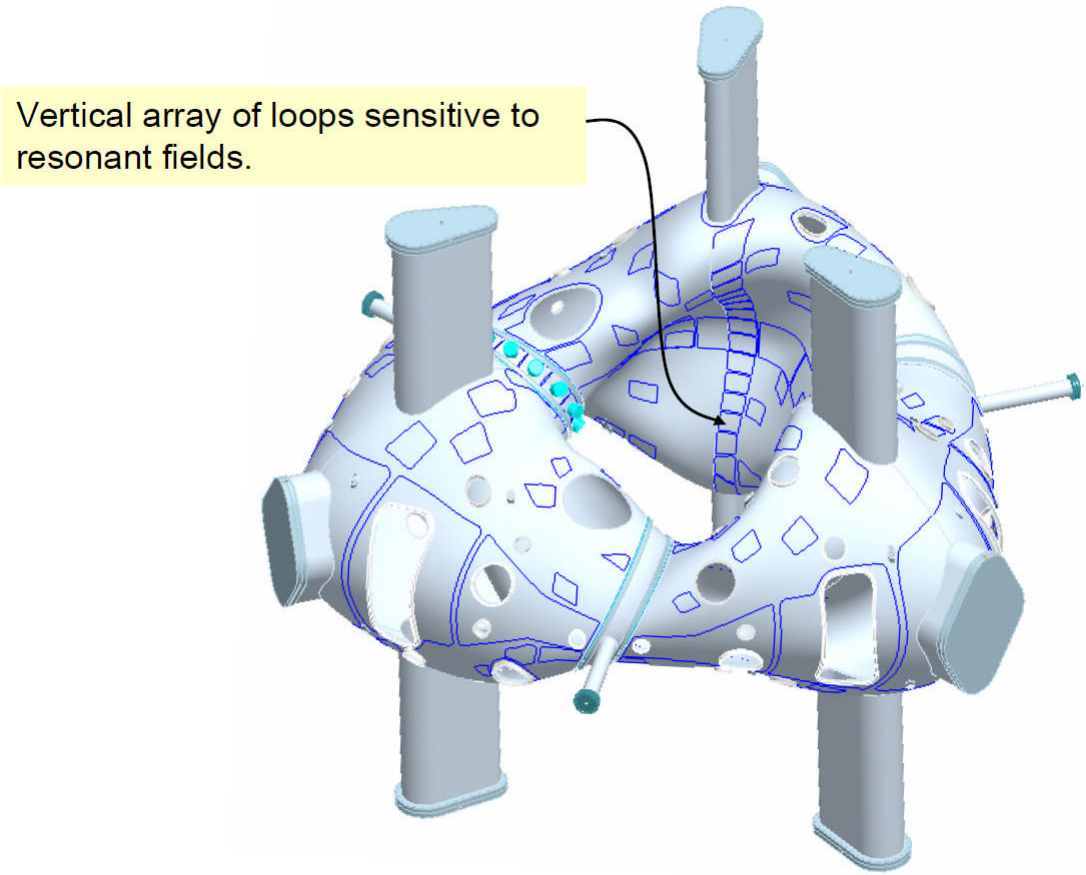
MHD Equilibrium

- **Input:**
  - **External B Field**
  - **Current profile**
  - **Pressure profile**
  - **Toroidal flux**
- **Output:**
  - **Flux surface geometry (*Key to further computations*)**

Equilibrium Reconstruction:

- **Use observed diagnostic signals to determine:**
  - **External B Field**
  - **Current profile**
  - **Pressure profile**
  - **Toroidal flux**

3-D Equilibrium Reconstruction requires a sophisticated flux loop system.



- **Design of Ex-Vessel Flux Loops in NCSX**
- **Both SS fields with n=3·j and periodicity-breaking non-SS fields with |n|=1,2, 4,5, ... must be diagnosed.**

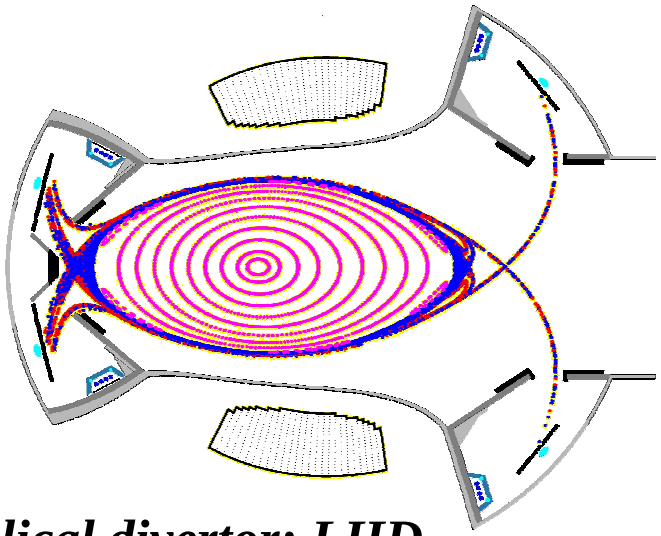
N. Pompherey, et al

– Outline –

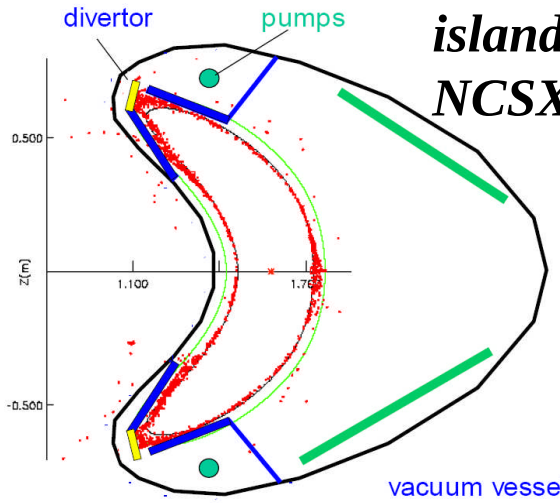
- **Advanced Helical (Stellarator/Heliotron) Concept**

- **Topics from Recent Plasma Experiments in Helical Devices**
  - **Configuration effects on NC/turbulent transport**
  - **Progress in high-β, high density steady state operation**
  - **Divertor-relevant experiments**

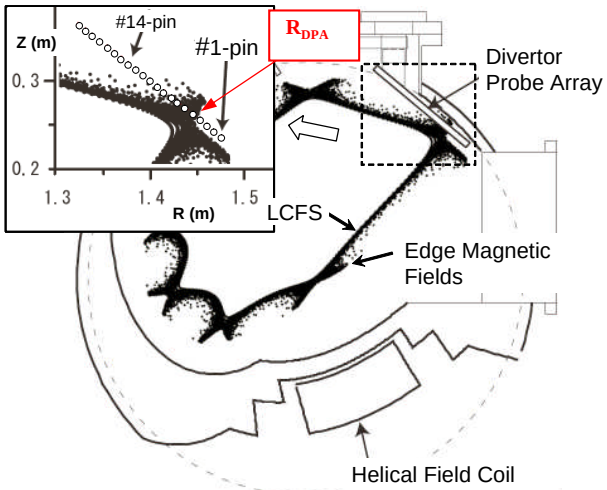
Several Divertor Concepts are proposed for Helical Devices



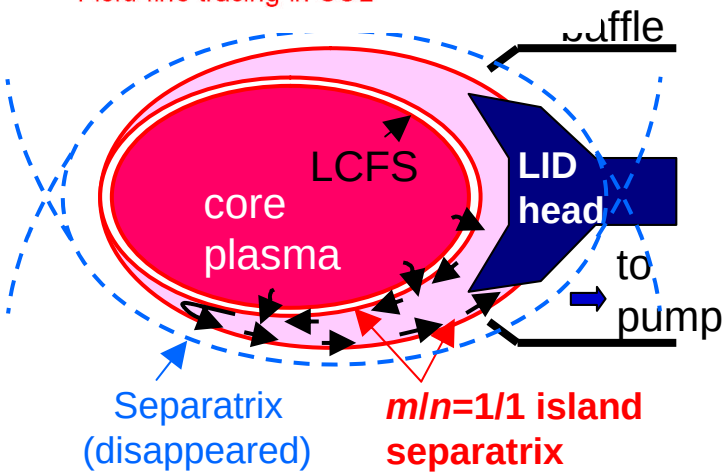
helical divertor: LHD



island divertor: NCSX, W7-X



quasi-helical divertor: Heliotron J

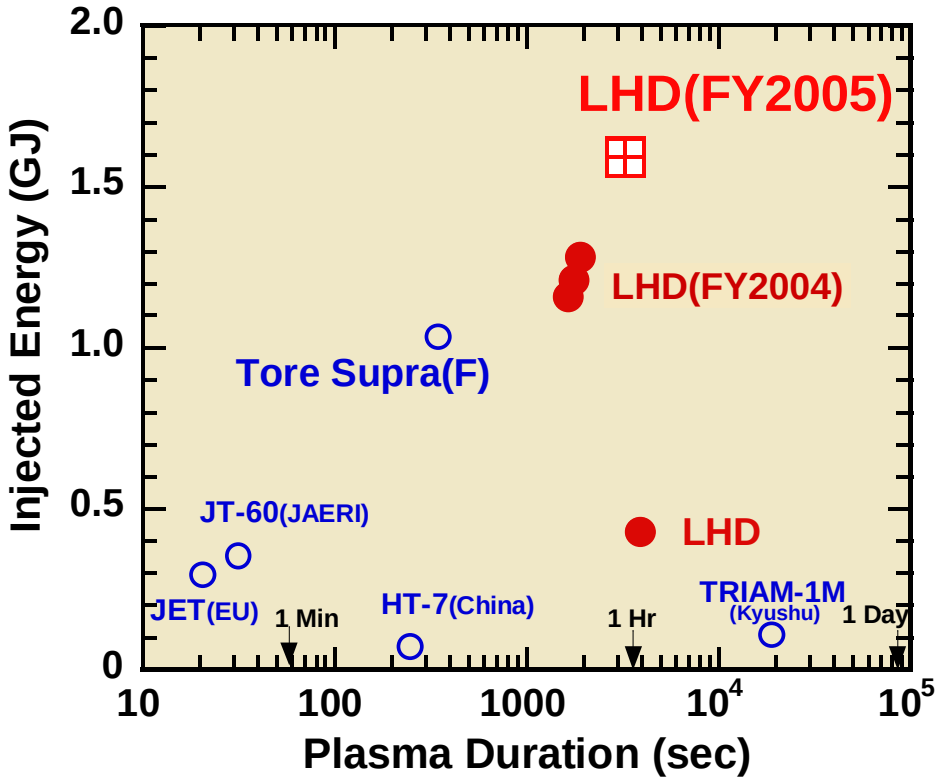


Local island divertor: LHD

progress in long-pulse operation

Steady State Operation in LHD

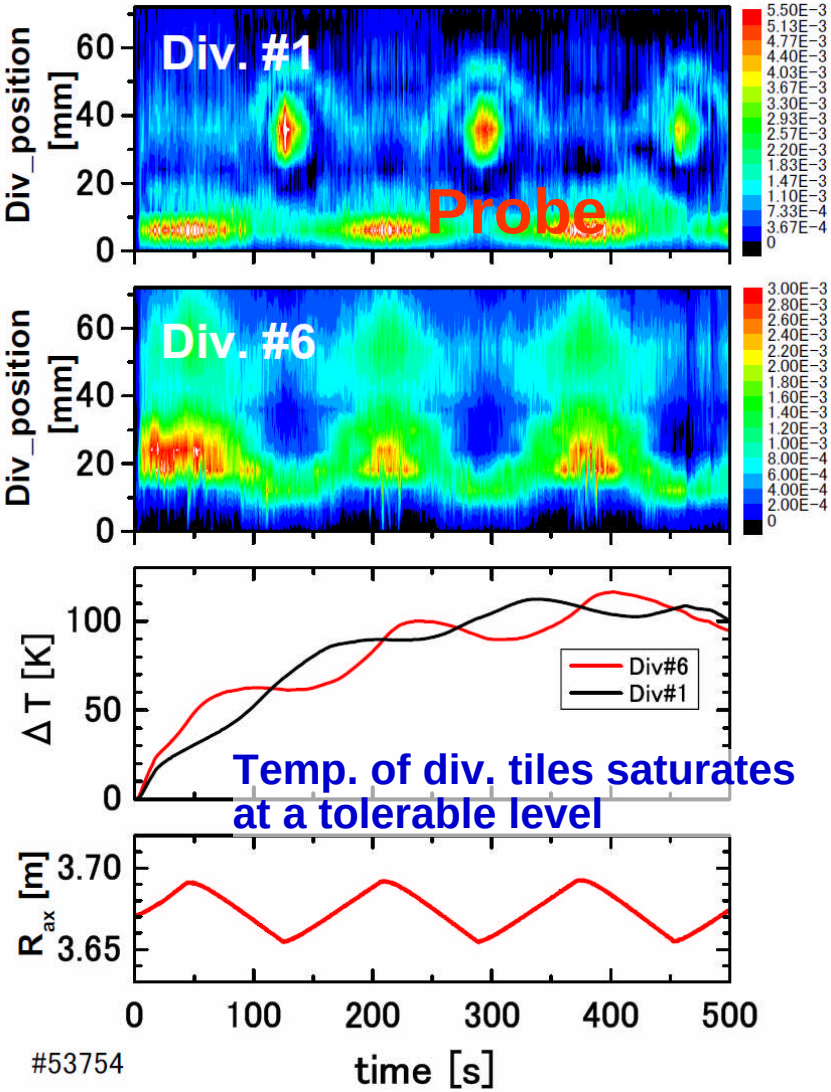
21st FEC (2006)

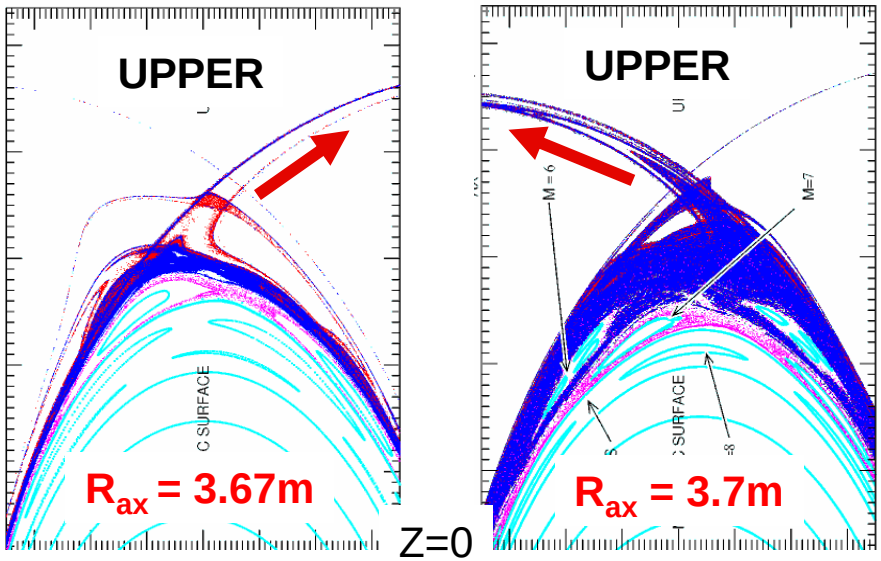


- **Record of input energy to high temperature plasmas in FY2005**
  1.6GJ : 490kW × 3268s
- **Planning longer pulse with higher heating power**
  3 MW for 1 hour

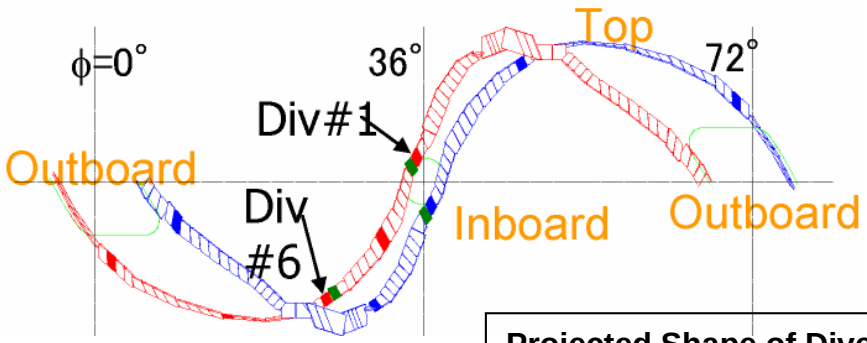
- **Steady state operation by ICRF demonstrates the high potential of helical systems towards a currentless steady state reactor.**
- **Minority heating ICRF accelerates perp. component of ion velocity effectively up to MeV range.**
  - **demonstrates the high capability of LHD to confine high energy ions.**

Particle/heat load on the divertor plates are dispersed by R_{ax} sweeping.



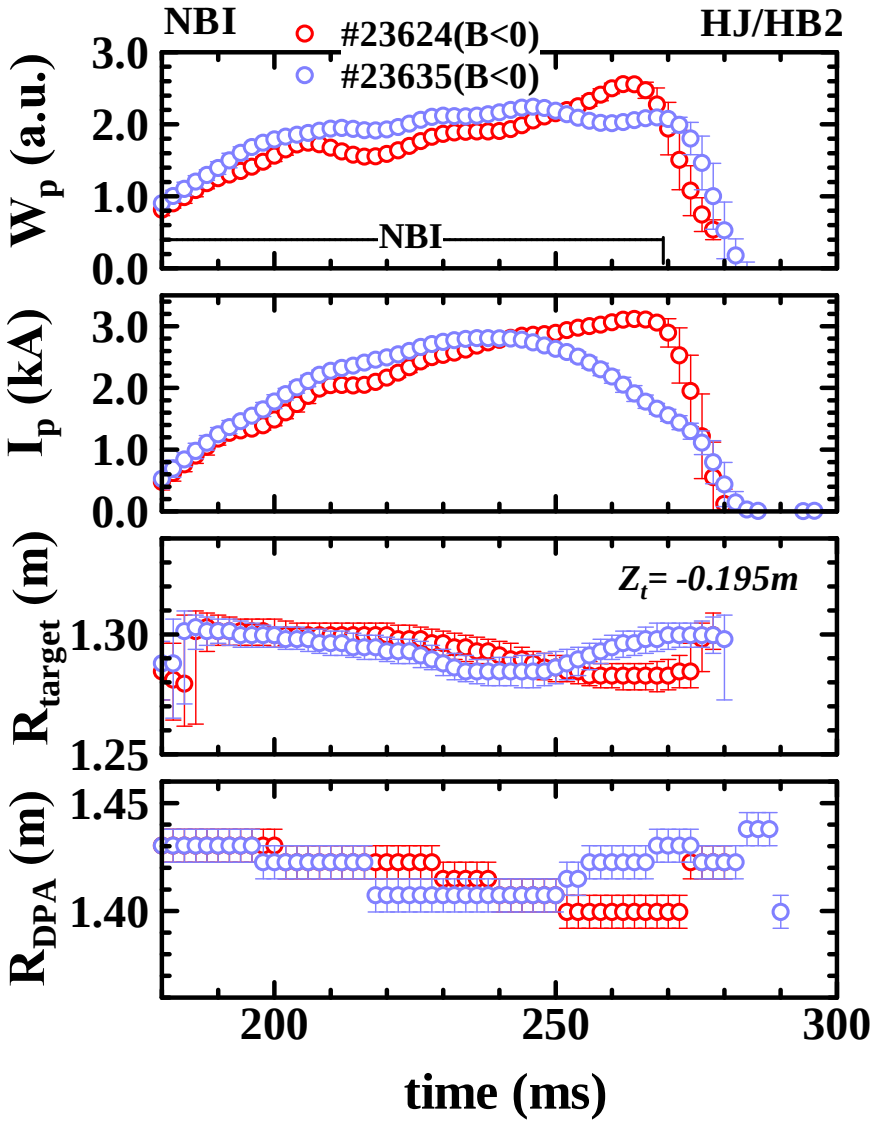


Main divertor trace is switched from inboard to outboard side by a small change of R_{ax} ($\Delta R/R$~0.8%)



Projected Shape of Divertor Tiles

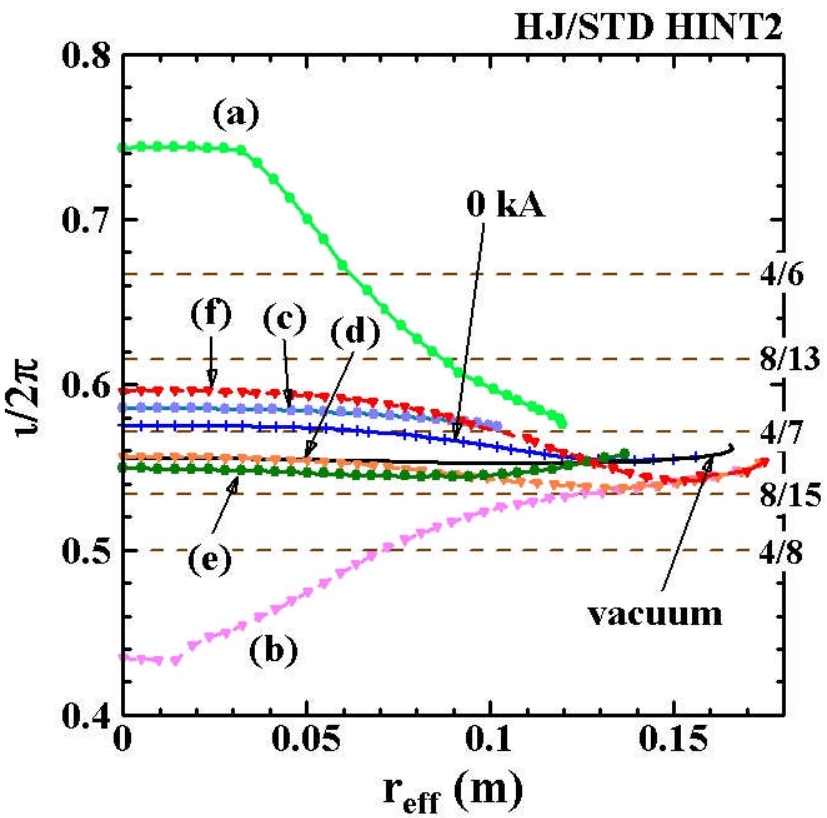
The shift of the diverted plasma footprints is observed during a single discharge.

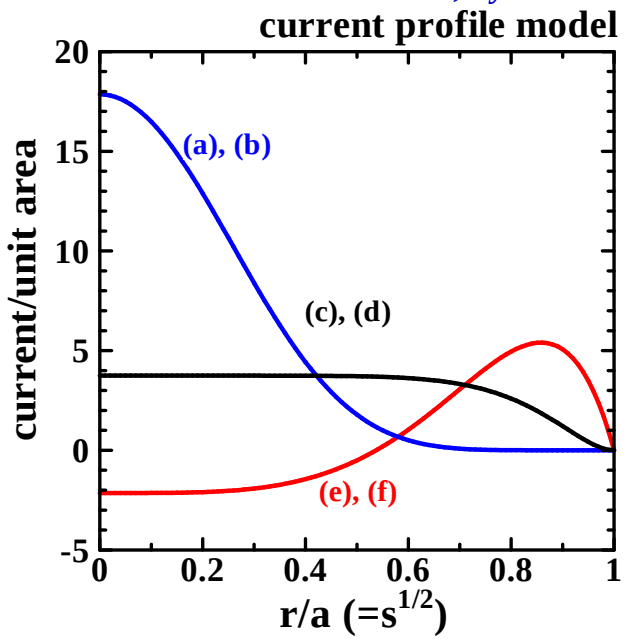


- **The shifts of R_{target} and R_{DPA} are closely related to the change of plasma current.**
  - *In #23624, W_p and I_p were kept increasing up to almost the end of discharge, but in #23635, I_p started to decrease at t ~ 240 ms while W_p did not decrease and was kept almost the same value until the end of the NBI pulse.*
  - *For #23635 discharge, the inward shifts of R_{target} and R_{DPA} were observed until t ~ 240 ms and they started to change the direction of shift for t > 240 ms, i.e. coming back to the values at the initial phase of the discharge.*
- **This experiment points out**
  - *the importance of current control to fix the divertor plasma position in a low shear helical device,*
  - *the possibility of "divertor swing" for the divertor particle/heat load reduction by controlling a small amount of plasma current.*

MODEL CALCULATION (HINT2)

Current Effects on $\iota/2\pi \Rightarrow$ x-point control. Again, we need 3D ER!





$\langle\beta\rangle \sim 0.32$ %, $p=p_0(1-s^2)^2$

(a) $j = j_0(1-s)^8$, $I_{net} = +2.0$ kA

(b) $j = j_0(1-s)^8$, $I_{net} = -2.0$ kA

(c) $j = j_0(1-s^4)^2$, $I_{net} = +2.0$ kA

(d) $j = j_0(1-s^4)^2$, $I_{net} = -2.0$ kA

(e) $j = j_0(60(1-s^2)s^2-5(1-s^2))$, $I_{net} = +2.0$ kA

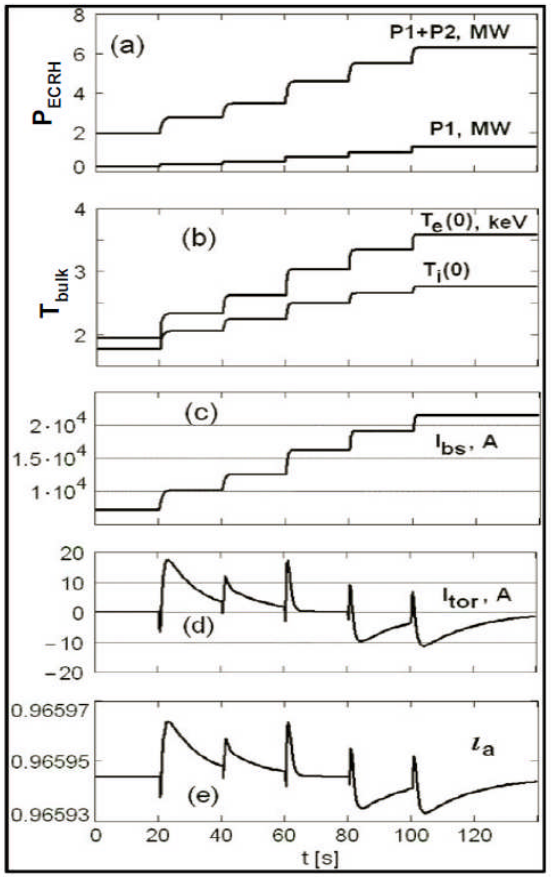
(f) $j = j_0(60(1-s^2)s^2-5(1-s^2))$, $I_{net} = -2.0$ kA

Since the value of vacuum rotational transform is close to the natural resonance condition, even a small change in the edge rotational transform by a small current can make a big change in the plasma radius, i.e. in the x-point.

Divertor swing by a small current drive in W7-X or other helicals?

Predictive Modelling Example

- X-point (thermal load) control by feed forward ECCD... -



...involves various physics software modules :

- Equilibrium recovery
- Flux surface mapping
- Power deposition (ECRH, NBI)
- Transport (neoclassical)
- Current drive

additional modules:

- Thermal loads
- SOL + divertor physics (not yet clear)

Yu. Turkin, A. Werner, ...

– Summary –

- **Advanced Helical (Stellarator/Heliotron) Concept**
  - **Several advanced concepts are experimentally examined.**
    - » **Topics from recent plasma experiments in helical devices are reported.**
      - **Configuration effects on NC/turbulent transport**
      - **Progress in high-β, high density steady state operation**
      - **Divertor-relevant experiments**
- **Helical research activities in the world contribute to**
  - **assess the *attractiveness of helical systems***
    - » **a disruption free, high density (no GW-limit) steady-state reactor**
  - **advance understanding of 3-D plasma**
    - » **for basic fusion science relating also to tokamaks & ITER**
    - » **for physics of non-linear/complex-systems in the natural world**

Thank you very much for your attention!

Please enjoy the Heliotron J tour this afternoon.