Results of JT-60 and JFT-2M in Collaboration with PPPL

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JAERI

Presented at A Celebration of
High Temperature Plasma Physics
50 Years of Scientific Achievement

Princeton Plasma Physics Laboratory

June 5-7, 2002

祝PPPL50周年

Outline

1. Results of JT-60
   - Transport barrier and progress in plasma performance
   - Sustainement of high integrated performance
   - Toroidal Alfvén Eigen mode
2. Results of JFT-2M
3. Theoretical Research
4. Future Direction of JT-60
5. Summary

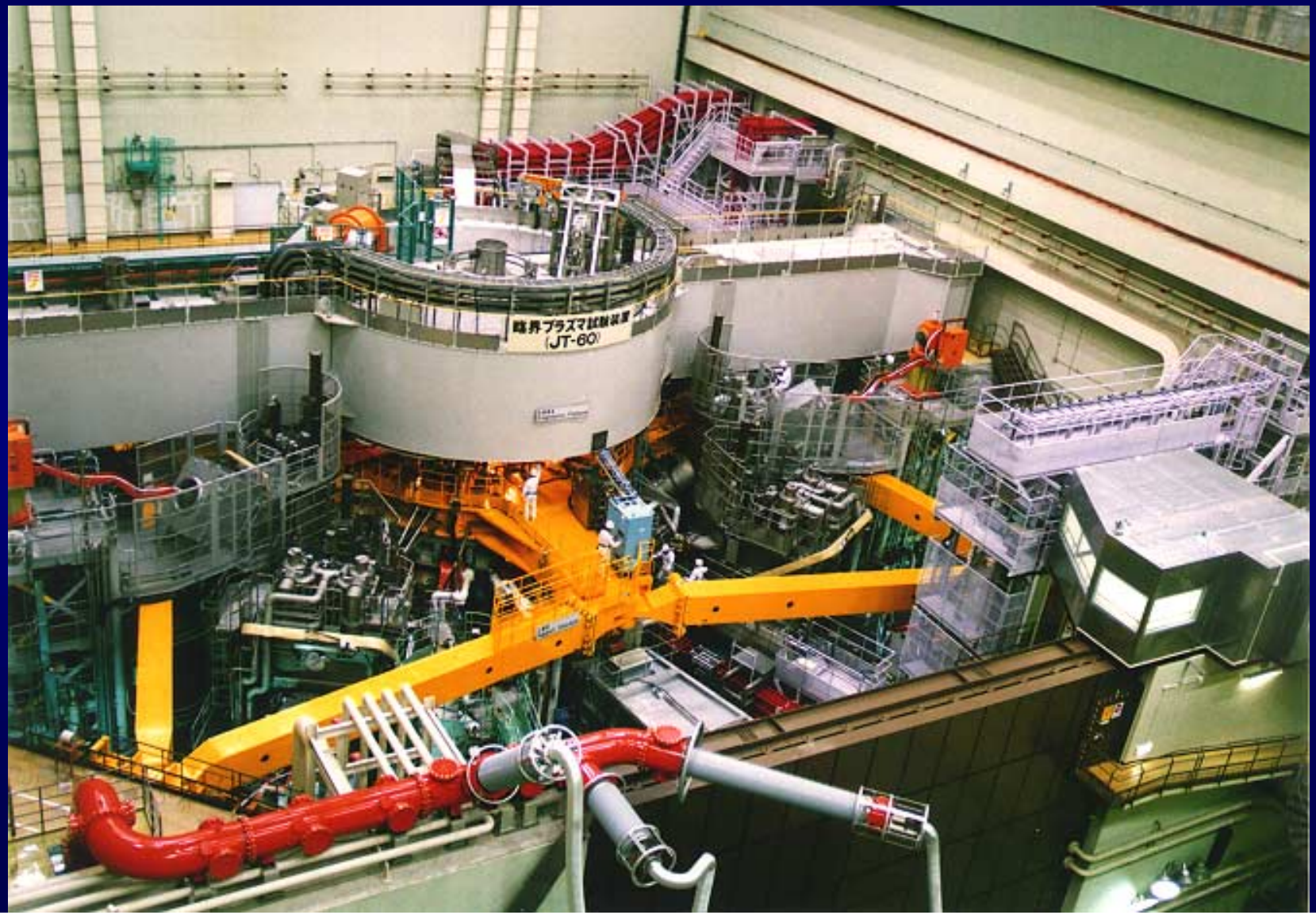
Annals of Fusion Research in JAERI

- 1956 — JAERI established
- 1961 — Fusion research started
- 1972 — JFT-1
- 1969 — JFT-2
- 1975 — Design & construction of JT-60 started
- 1983 — Operation of JFT-2M started
- 1985 — Naka Establishment established
- 1988 — Operation of JT-60 started
- 1992 — ITER CDA started
- 2001 — ITER EDA started
- ITER CTA started

Collaboration enhanced

1986: IEA Co-operation among the Three Large Tokamak Facilities (JET, JT-60 and TFTR) started

1. Results of JT-60



Mission of JT-60

1. Original Mission

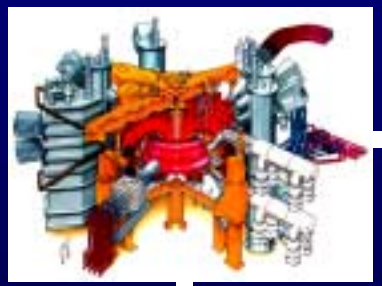
Achievement of equivalent break-even condition

2. New Mission since 1991

to establish scientific and technological basis of ITER and future DEMO reactor

JT-60

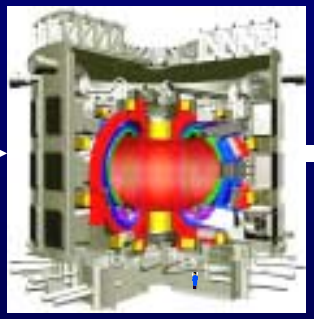
Break-even
Physics R&D



Physics R&D

ITER

Long-burn
Integration
of fusion tech.



DEMO

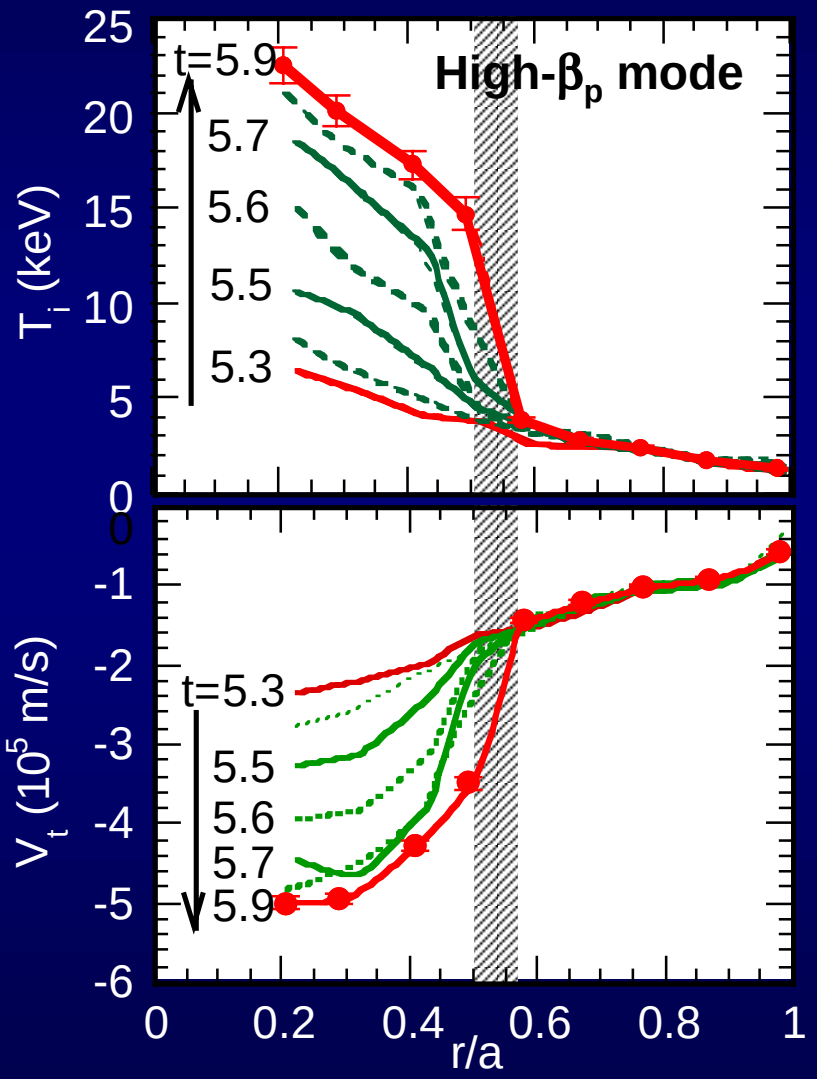
Electricity
Generation

Concept improvement and scientific basis establishment

Transport barrier and progress in plasma performance

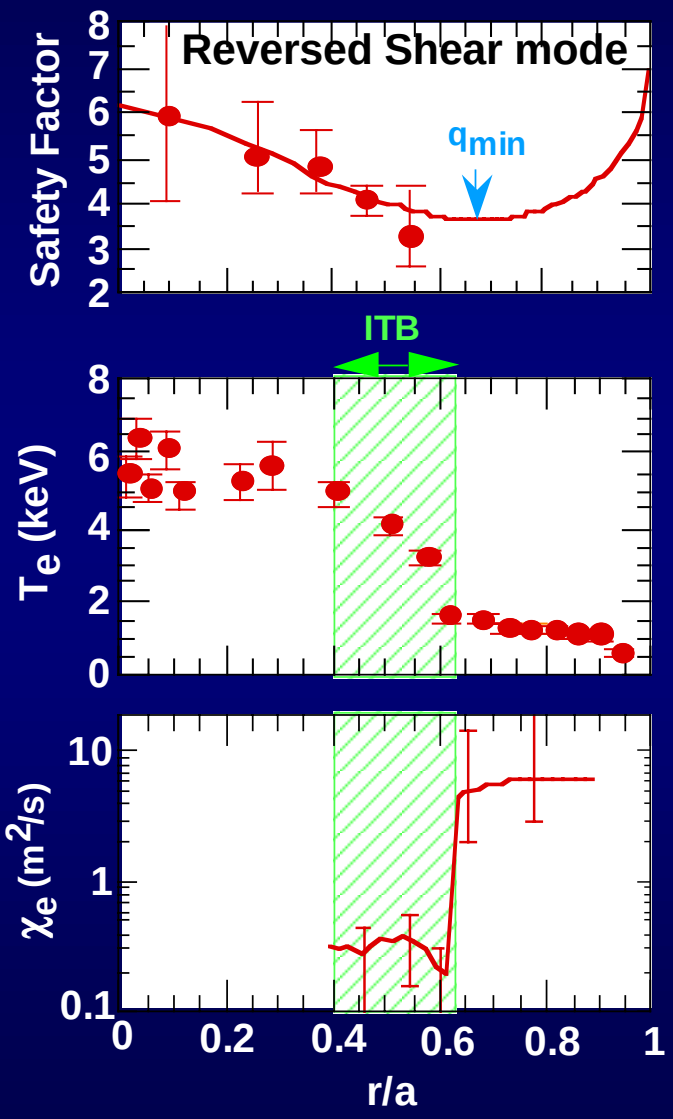
Discovery of Internal Transport Barrier

Formation of ion ITB



Y. Koide, et al., PRL 72 (1994) 3662.

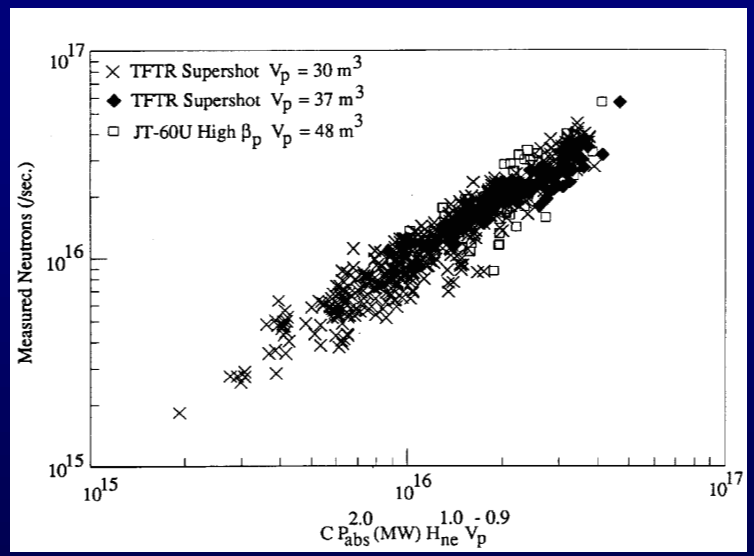
Formation of electron ITB



T. Fujita, et al., PRL 78 (1997) 2377

Finding of Common Scalings for TFTR Supershot and JT-60U High-β_p Plasmas

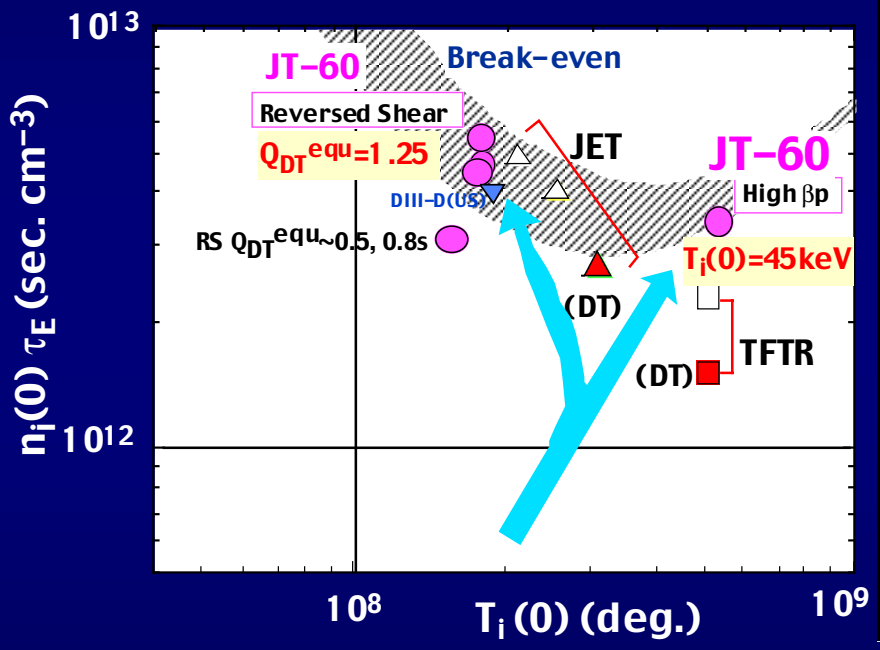
- Collaboration on High-β_p Plasma Research with PPPL started in 1993, which was motivated from the results of high-βp plasmas in JT-60U presented for IAEA conference in 1992
- A joint paper has been presented by Dr. H. Park for the 1994 IAEA conference at Seville.

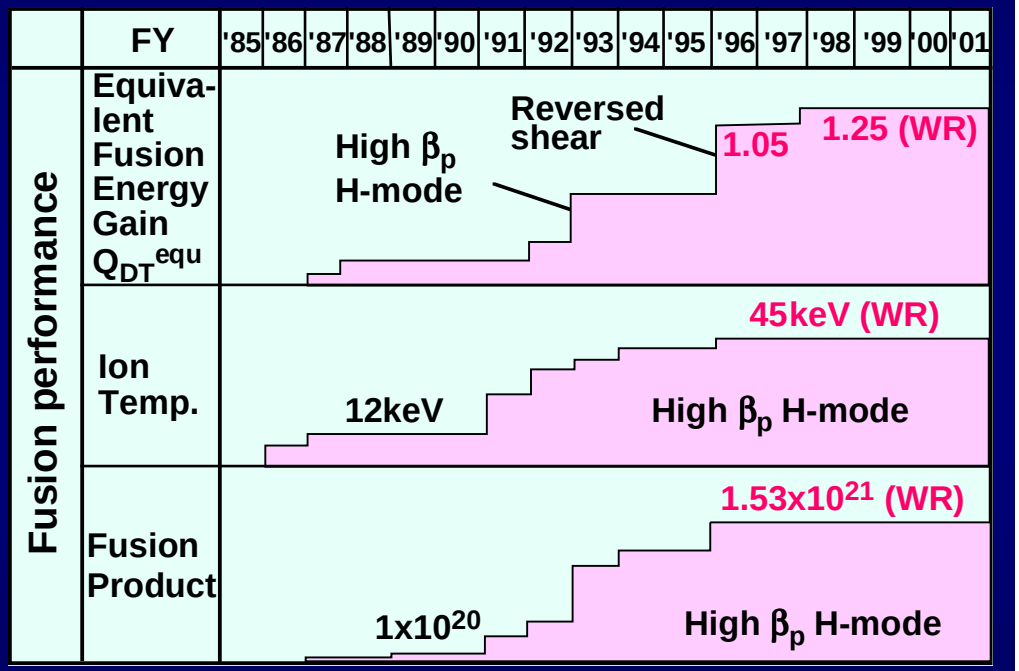


Neutron rate scaling for TFTR supershot and JT-60U high-βp mode

- Significantly improved neutron rate and energy confident have been produced from two different regimes (TFTR supershot and JT-60U high-β_p plasmas) in considerably different machines.
- Common scalings for the DD neutron rate and stored energy are obtained so that the both regimes are characterized by heating power, fueling peaking parameter and plasma volume.

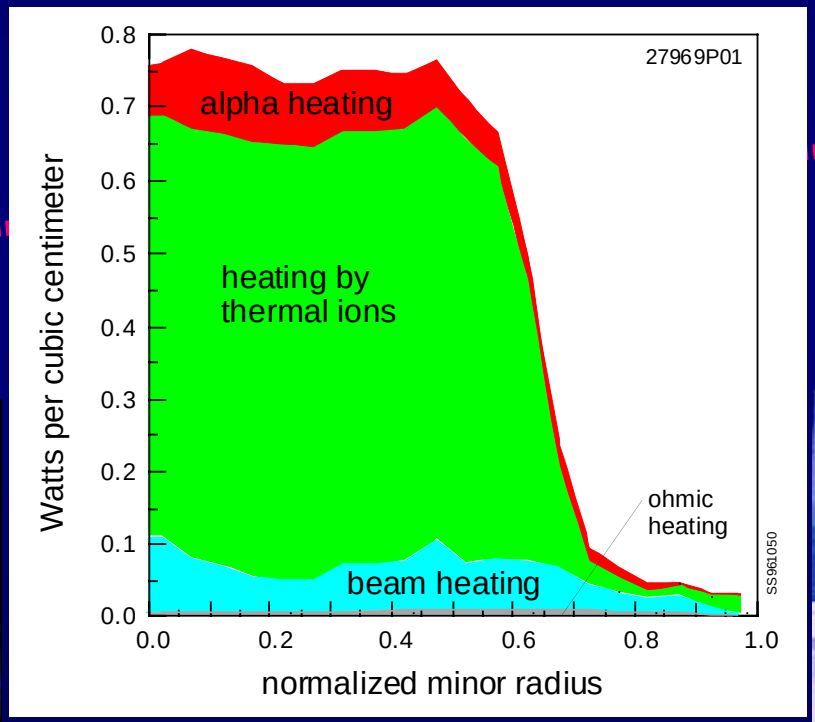
Progress in JT-60 Performance

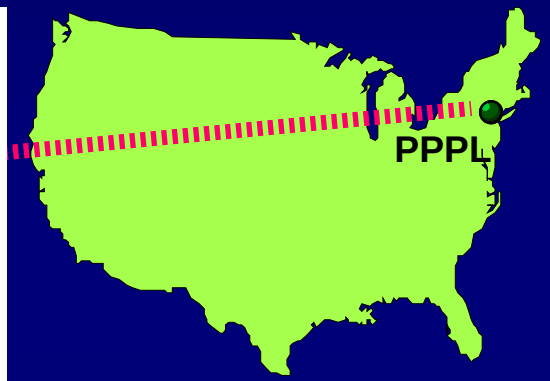




Achievement of equivalent Q_{DT}=1.05 with PPPL in 1996

" In particular, the TFTR group in the PPPL has remotely participated in this campaign and made the TRANSP code analysis for cross-validation. " (*S. Ishida et al., PRL 79 (1997) 3917*)





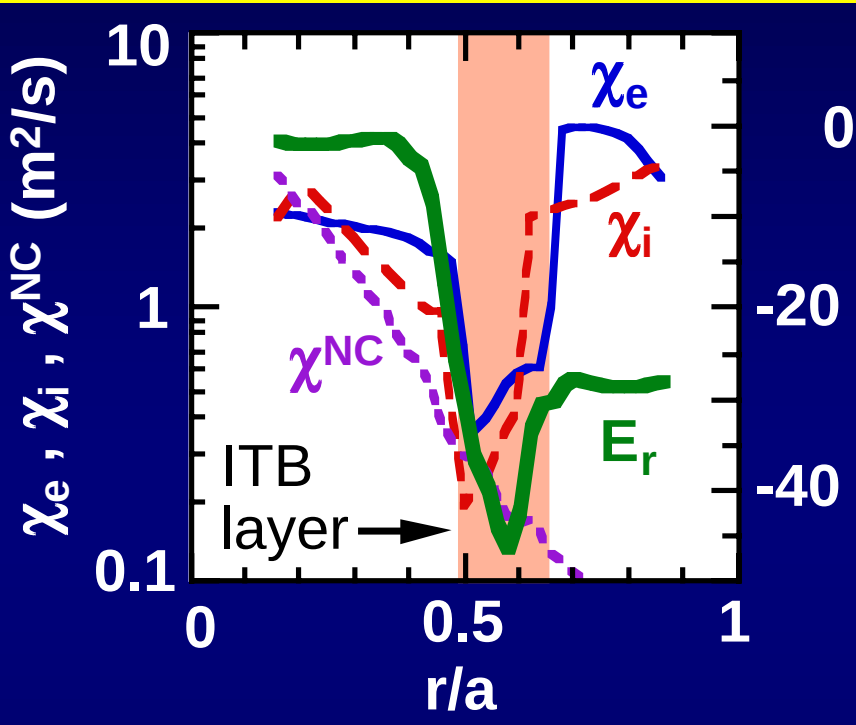
JAERI Naka

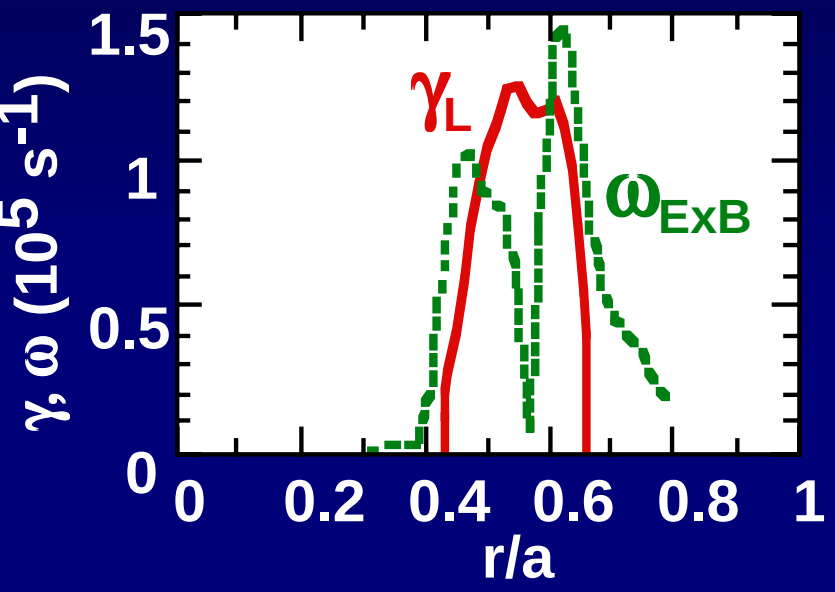
Result from TRANSP code analysis for #27969 of JT-60U

PPPL

Remote participation in the campaign

Significant Reduction of Thermal Diffusivities and Increase in Er Shear in ITB Region





Reversed shear: I_p=1.5 MA, B_t=3.5 T

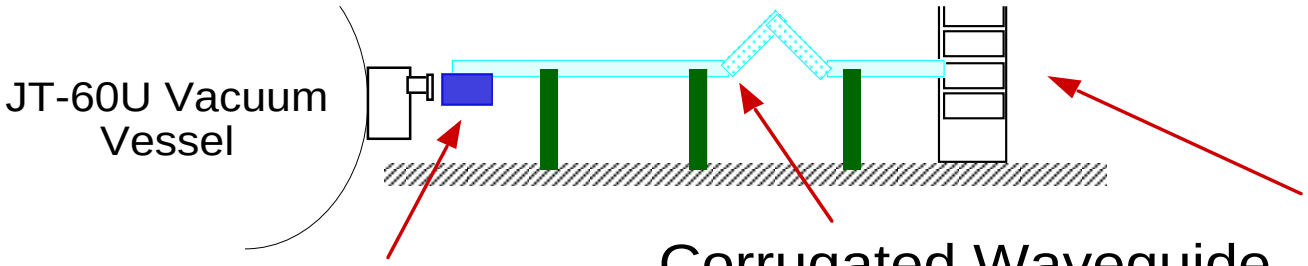
- Internal transport barrier makes:
  - χ^i, χ^e reduced χ^{NC} level
  - Er shear drastically increased

- ExB shearing rate ω_{ExB} comparable to linear growth rate γ_L of microinstabilities (FULL code, PPPL)
- suggested turbulence suppression in ITB region

S. Shirai, et al., Nucl. Fusion, 39 (1999) 1713.

PPPL/JAERI Reflectometer Collaboration for Continuous Correlation Measurements in Transport Barriers on JT-60U

- Main element of a reflectometer system



Mirror System: GA

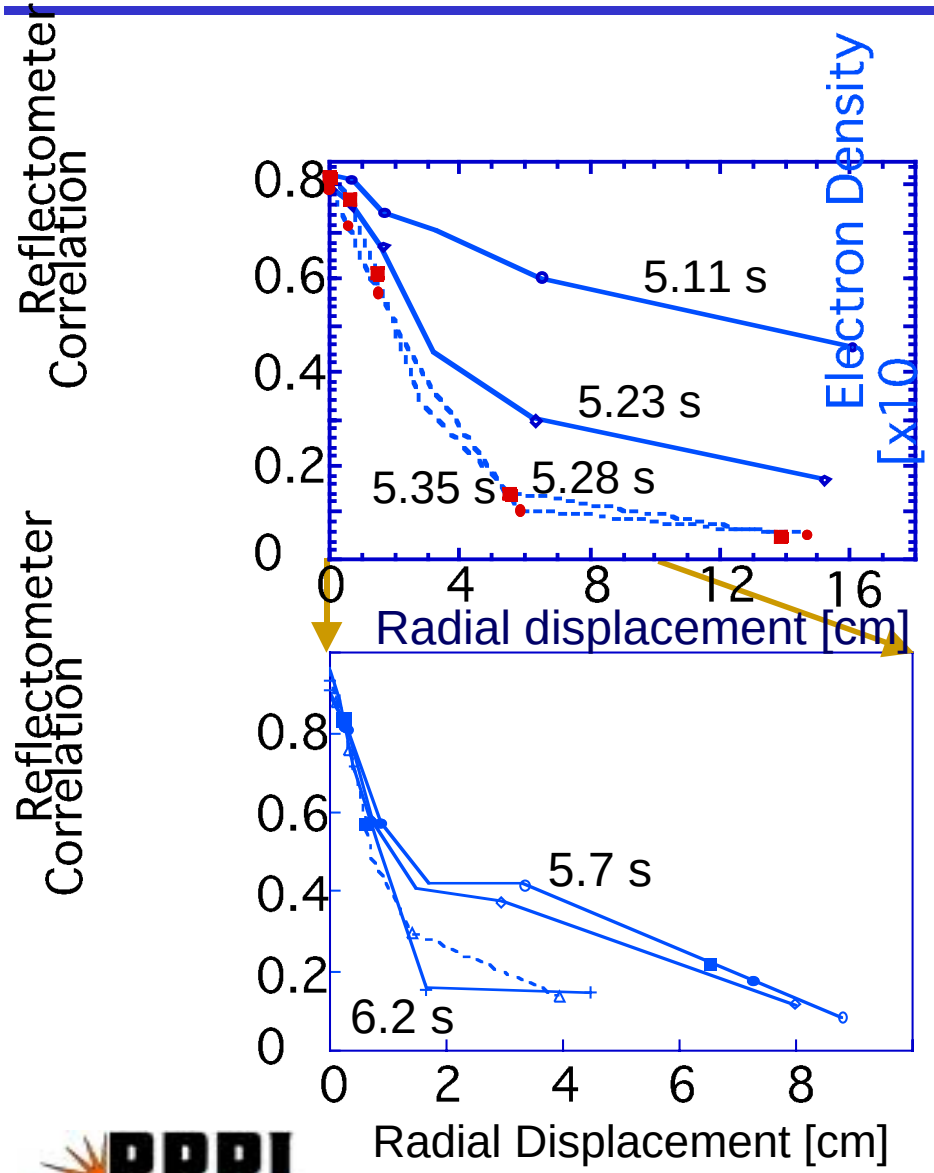
Corrugated Waveguide & Shield Box

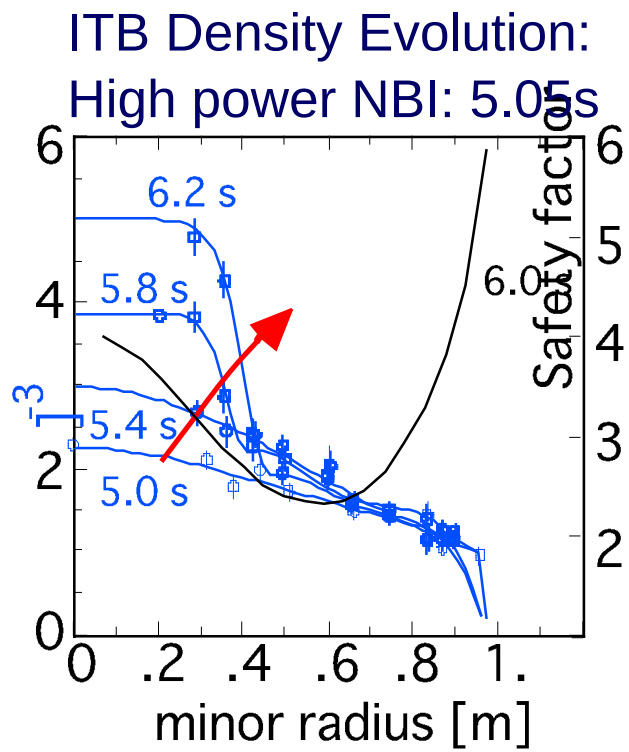
Microwave sources

- Range: 105-140 GHz measures up to magnetic axis:
- Frequency scanning channel allows a radial correlation scan every 60 ms

Main collaborators: Drs. R. Nazikian and K. Shinohara

Reflectometer Measurements Indicate a Reduction of the Radial Correlation Length In the Early Phase of ITB Formation in JT-60U



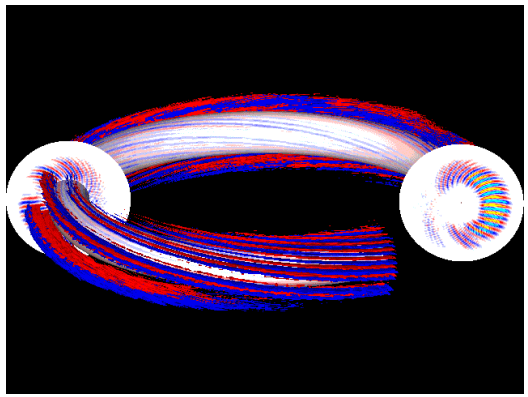


- Very long correlation lengths before ITB formation: $L_c/\rho_i >> 1$!
- Very short correlation lengths inside ITB: close to resolution limit?
- Weak fluctuation change!

Advances in Simulation *and* Visualization Create New Opportunities for Enhanced Theory Experiment Integration

Turbulence simulation in realistic geometry: Gyrokinetic and Gyrofluid codes

Full wave simulation of reflectometry in real geometry



Z. Lin, M. Beer

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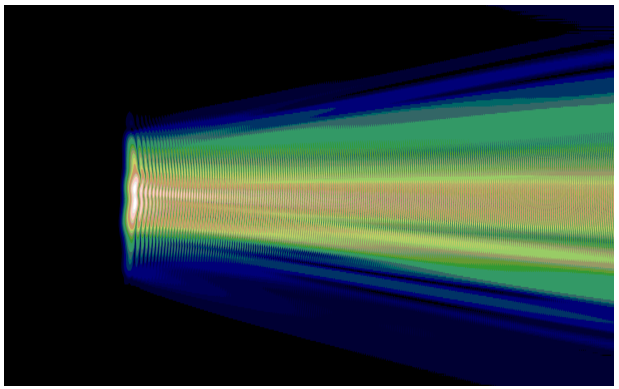


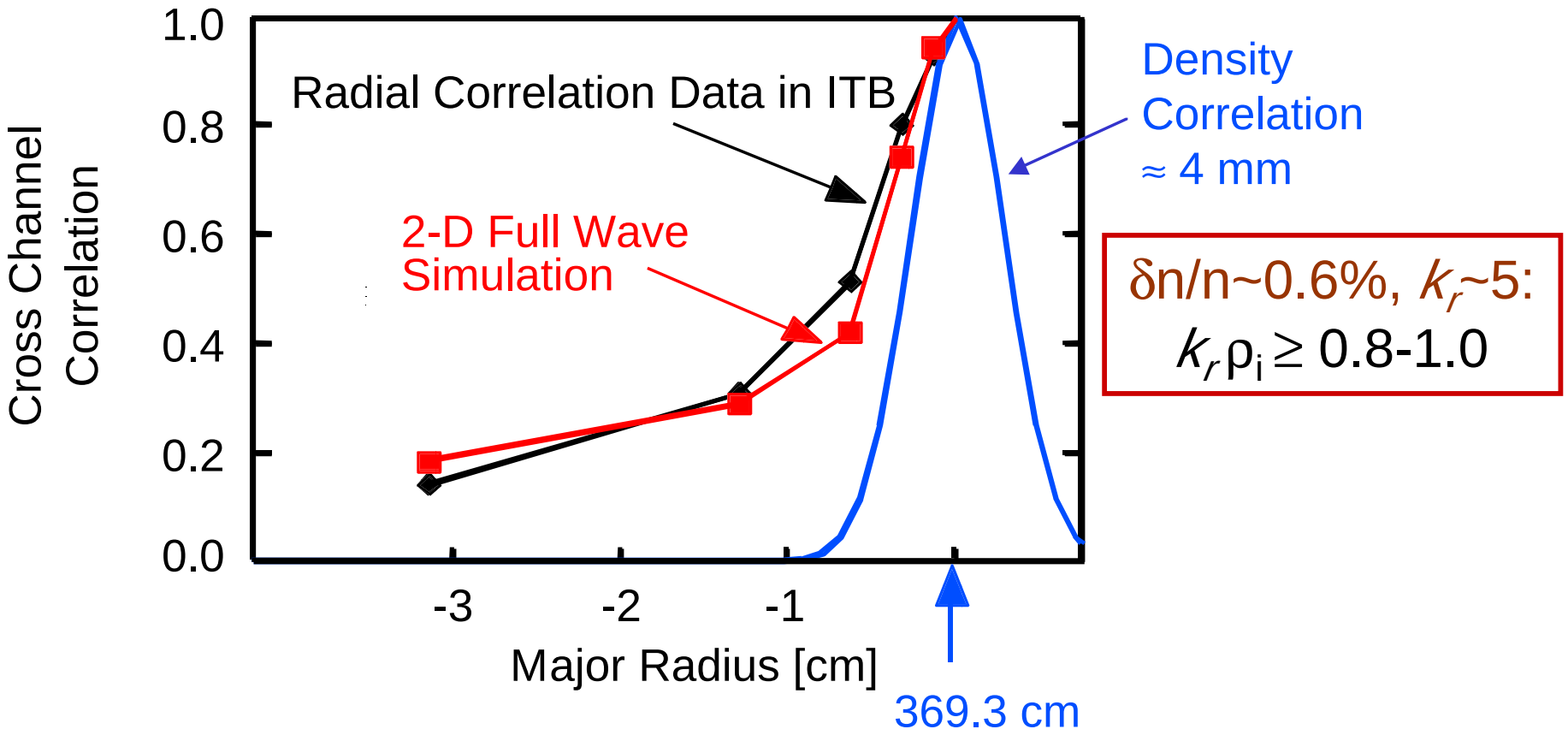
E. Valeo

Major advance in quantitative analysis

New possibilities for experimental design

- PPPL is part of a broad effort to simulate experiment:
  - MIT (Issue of super resolution with curved wave fronts)
  - LLNL (Interpretation of pulse reflectometry with fluctuations)

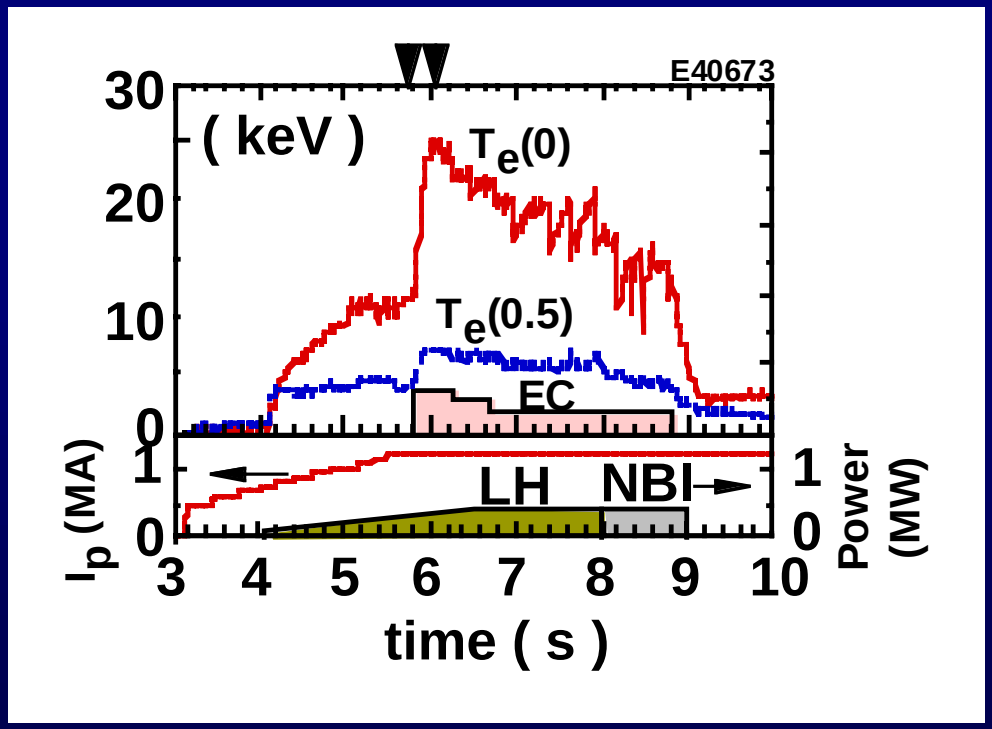
Visualization of Wave Intensity Near the Cutoff Layer: Plasma Curvature and Ripples Revealed in Interference Pattern

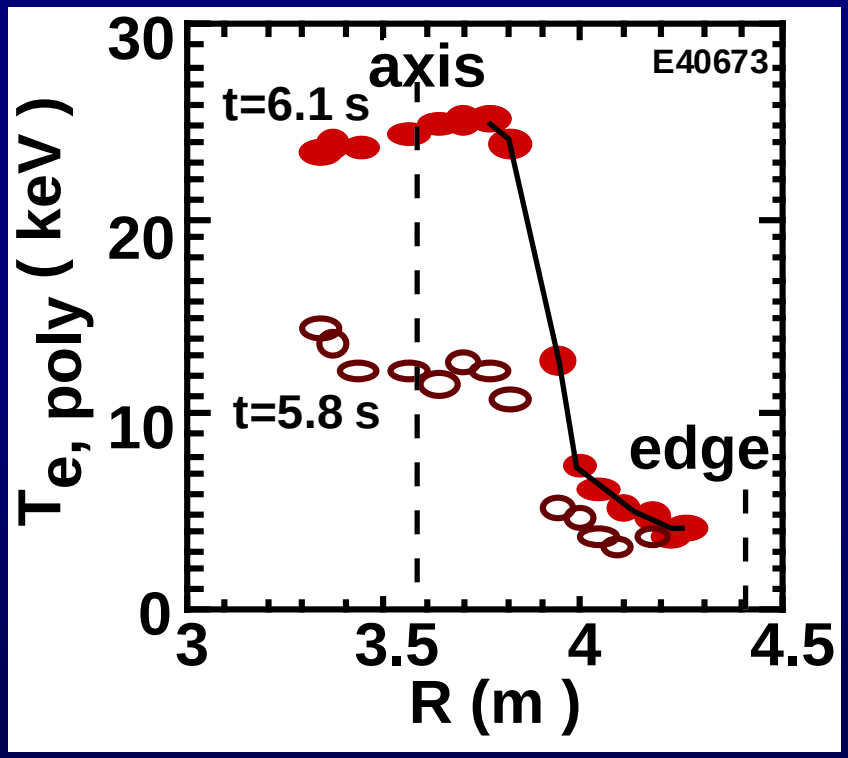


- Gaussian spectrum of test fluctuations, ensemble of 30 runs per correlation
- Higher k_r produce similar result, measurement at spatial resolution limit

Electron ITB Formation with Electron Heating

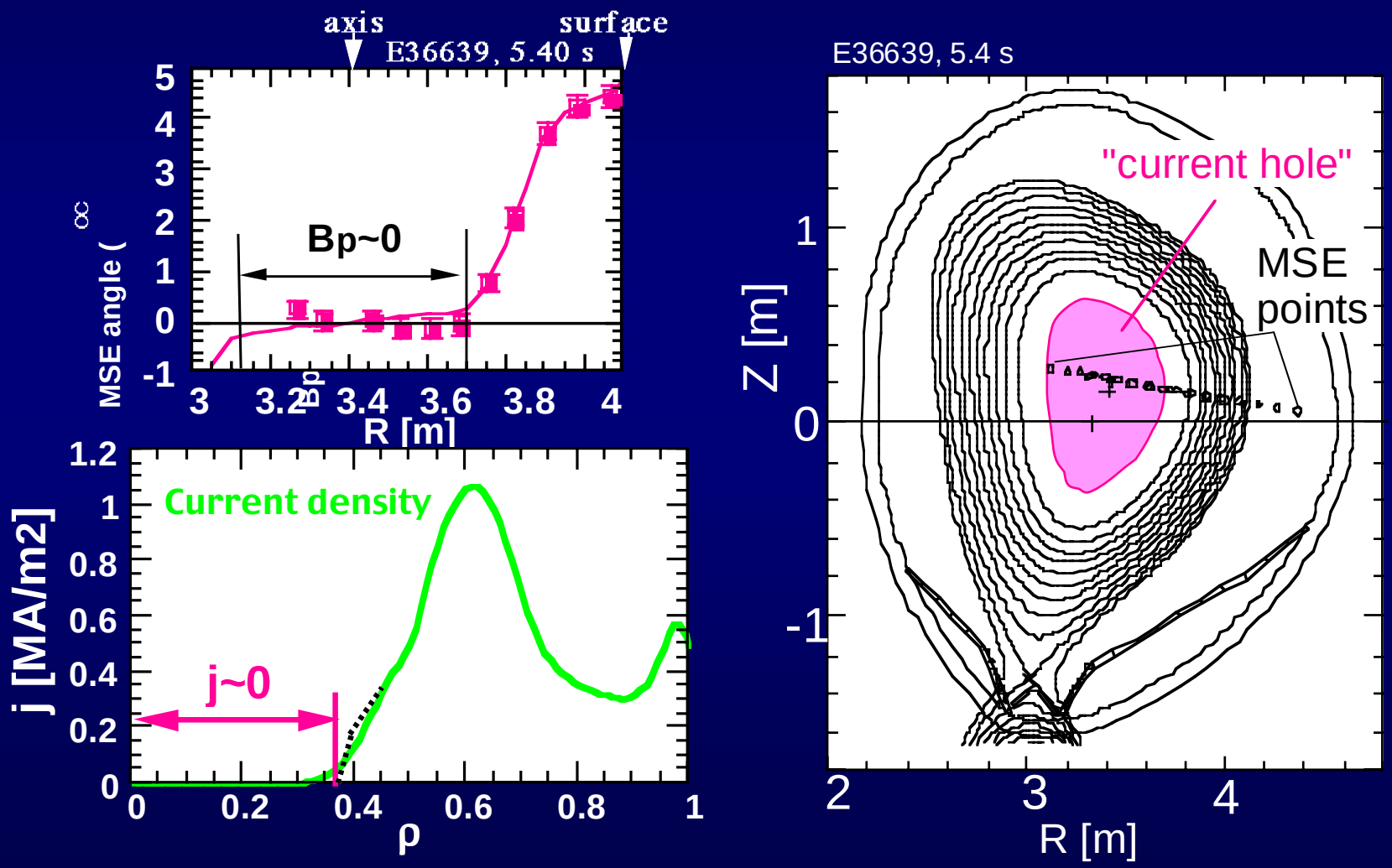
T_e~26 keV was achieved in a wide region within ITB for a reversed shear plasma created with off-axis LHCD and central ECH





New observation : Current Hole

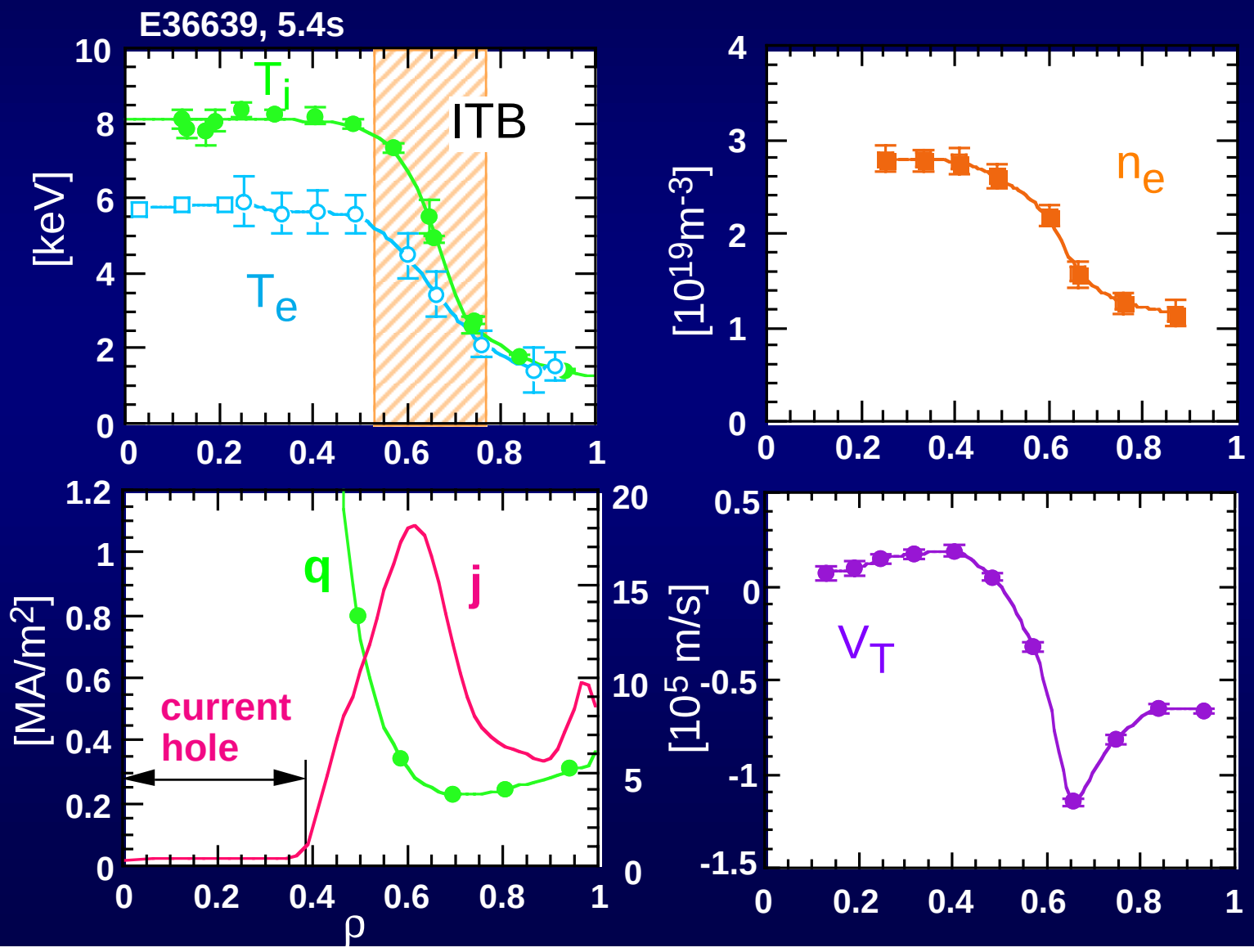
In extreme situation of the hollow current profile, we observed a region of J~0, "Current Hole".



T. Fujita, et al., Phys. Rev. Lett. 87 (2001) 245001

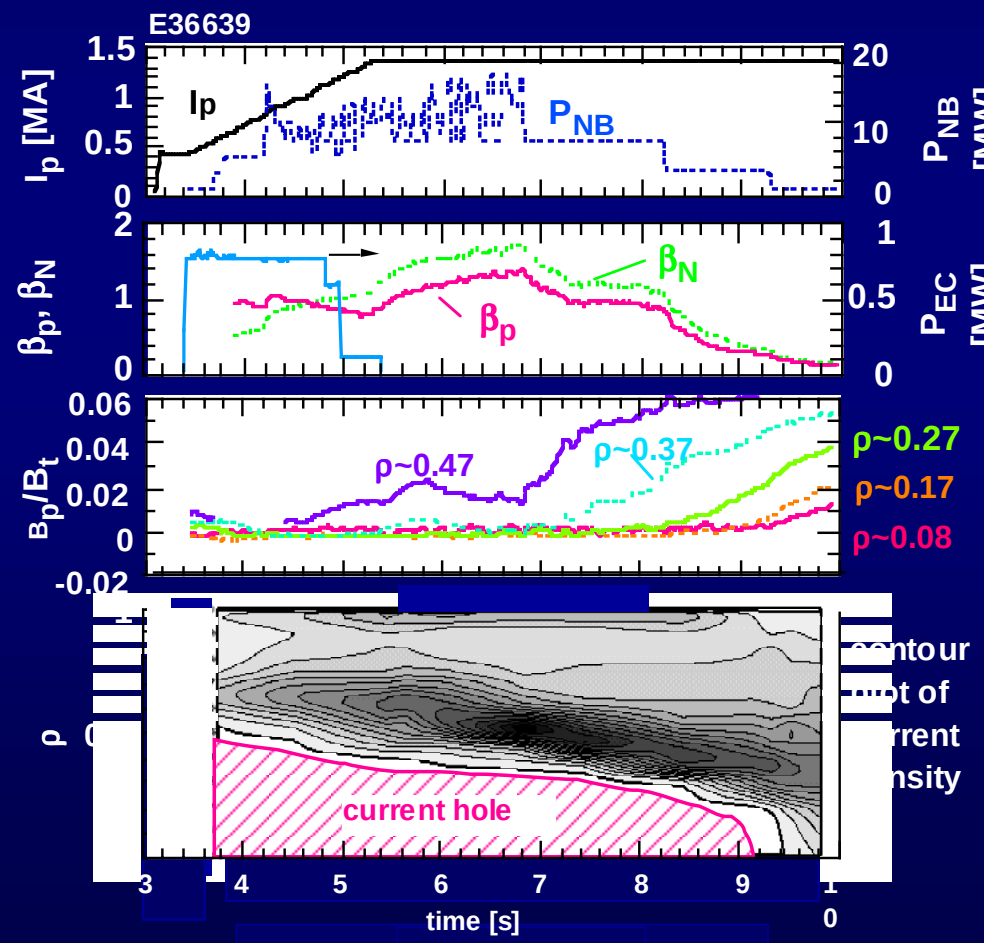
Flat Profile in the Current Hole

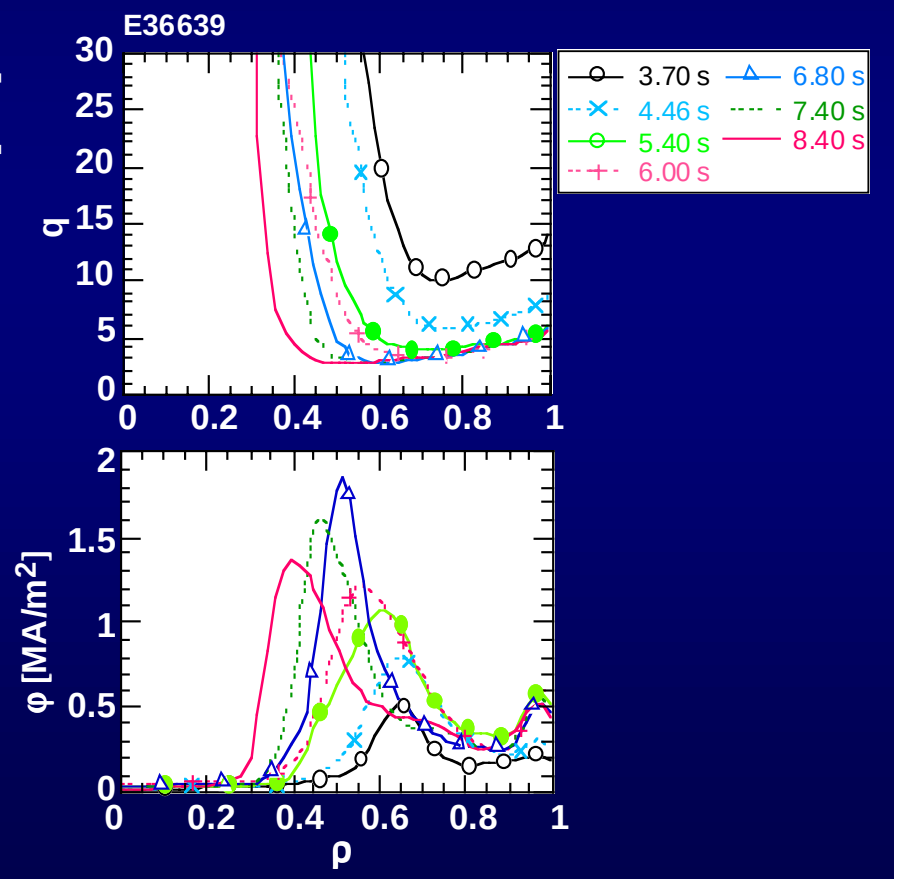
- j(r) is peaked in the ITB layer (bootstrap current).



Persistency of Current Hole

- The current hole was sustained for ~5 seconds without any global instabilities until disappearance of ITB due to the stepdown of heating power.
- High confinement (HH_{98y2}<~1.5) and moderate beta (β_N<~1.7) were obtained, suggesting no necessity of on-axis current in tokamak reactors.





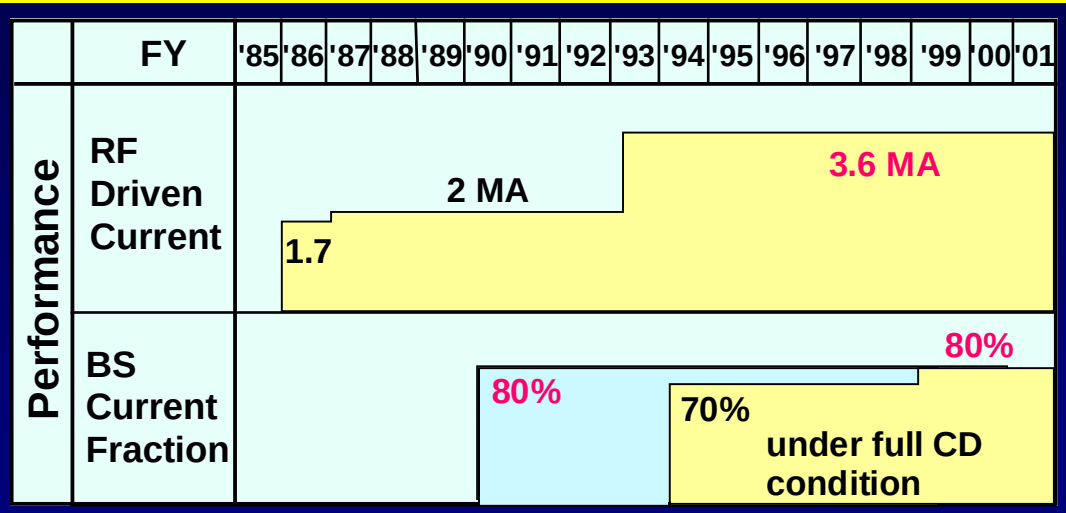
Sustainement of high integrated performance

Typical Requirements for Viable Tokamak Reactor

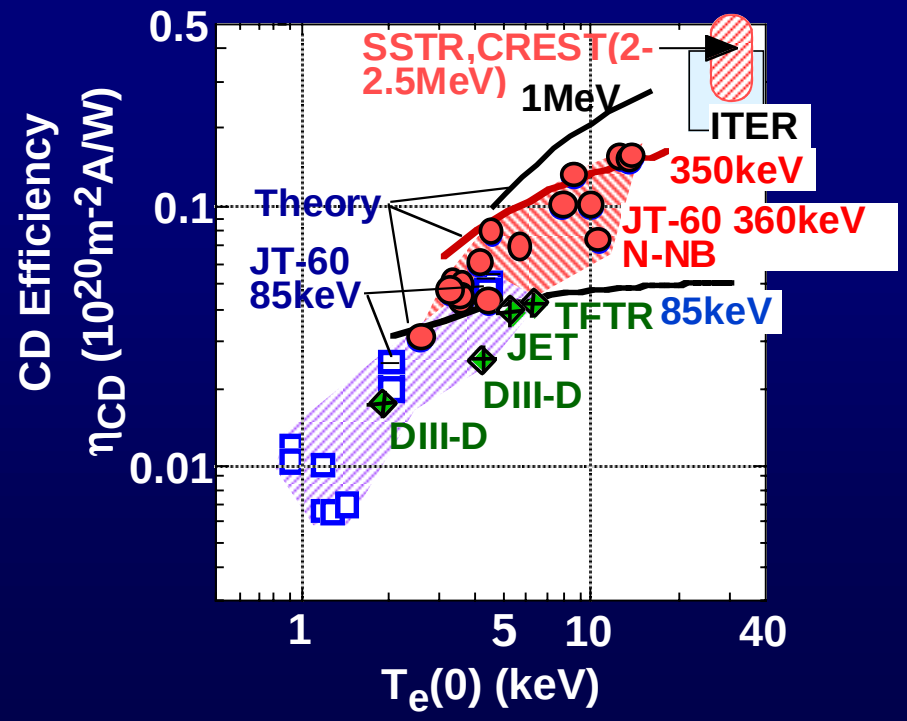
Advanced Scenario

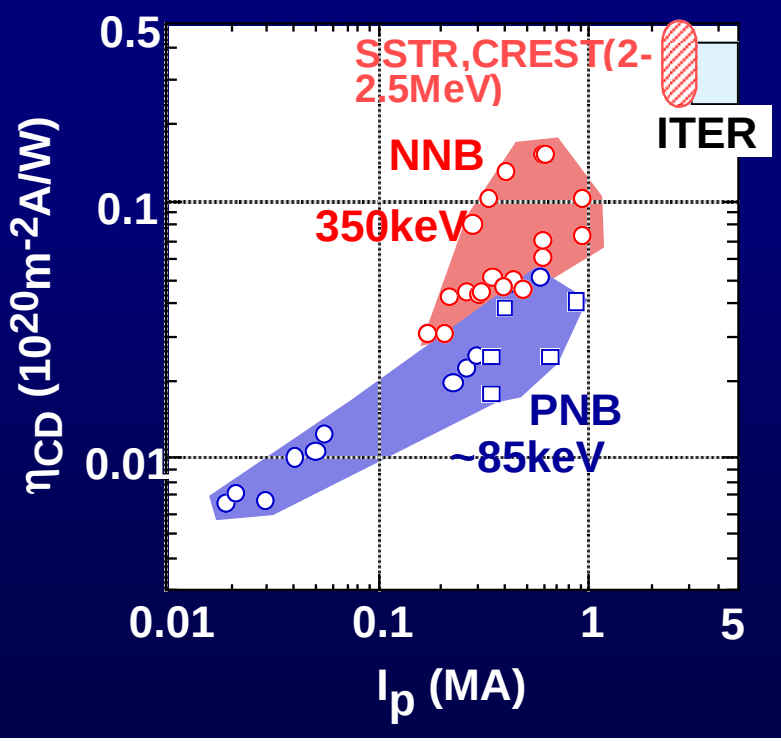
1. **Current drive (CD)**
   - Full non-inductive current drive
   - Bootstrap current fraction; 70-80%
   - CD efficiency; 3-5x10^{19}A/m^2/W
2. **High beta**
   - β_N = 3.5 (SSTR) - 5.5 (CREST)
3. **Confinement**
   - 1-1.4 xIPB98-y2 at $n_e > n_G$
4. **Divertor ; power and particle**
   - Heat : 90-95% radiation
   - Particle: $\tau_{He}^*/\tau_E \sim 5$

Improvement of Current Drive Performance



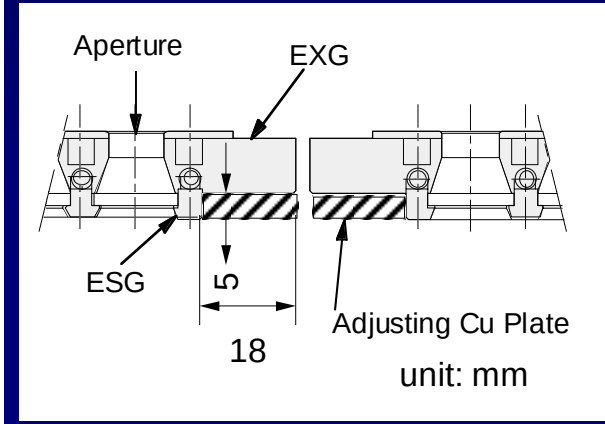
Improvement of N-NB CD efficiency with T_e and E_b(beam energy) was demonstrated that NBCD results are consistent with neoclassical prediction

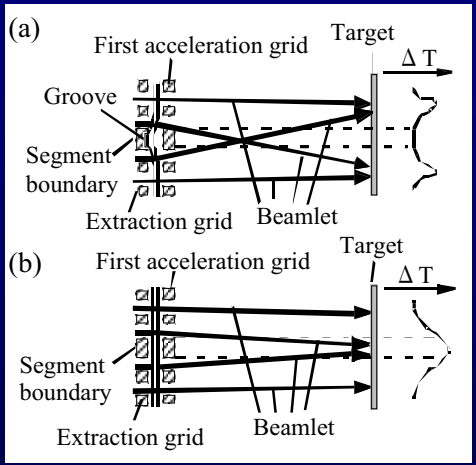


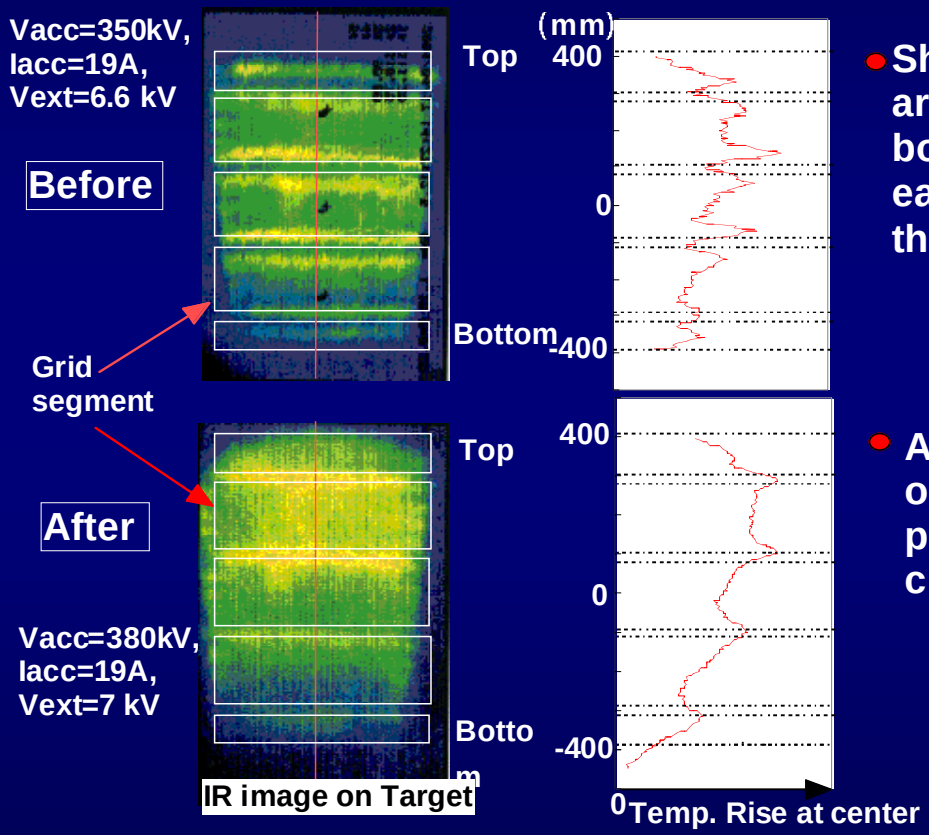


Improvement of N-NB Injection Duration

To make the electric field uniform, a piece of Cu plate was equipped and hence the deflection of the beamlets was corrected.





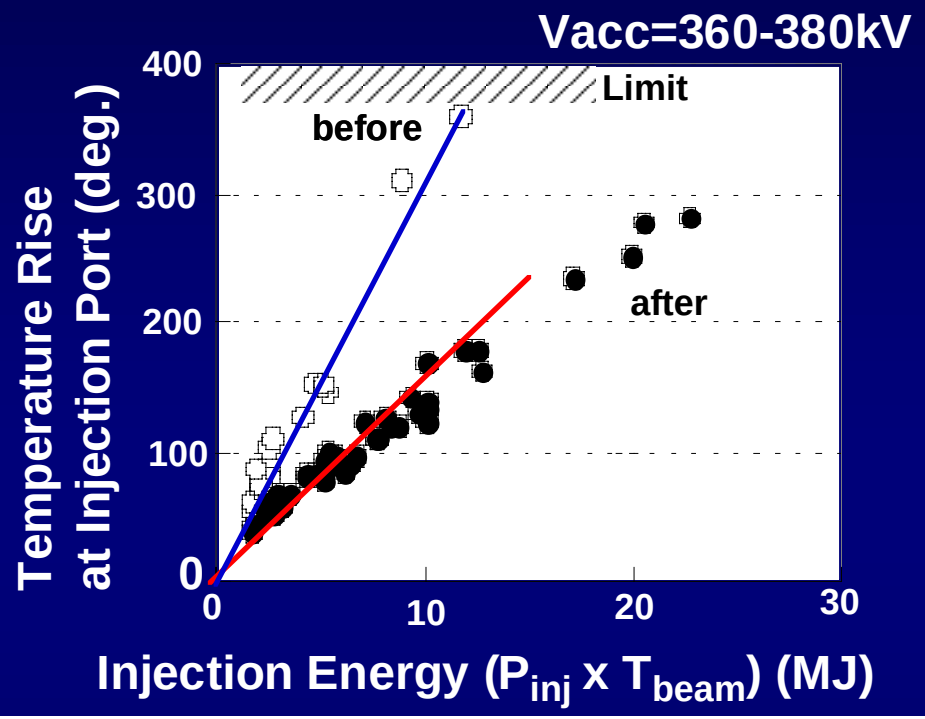


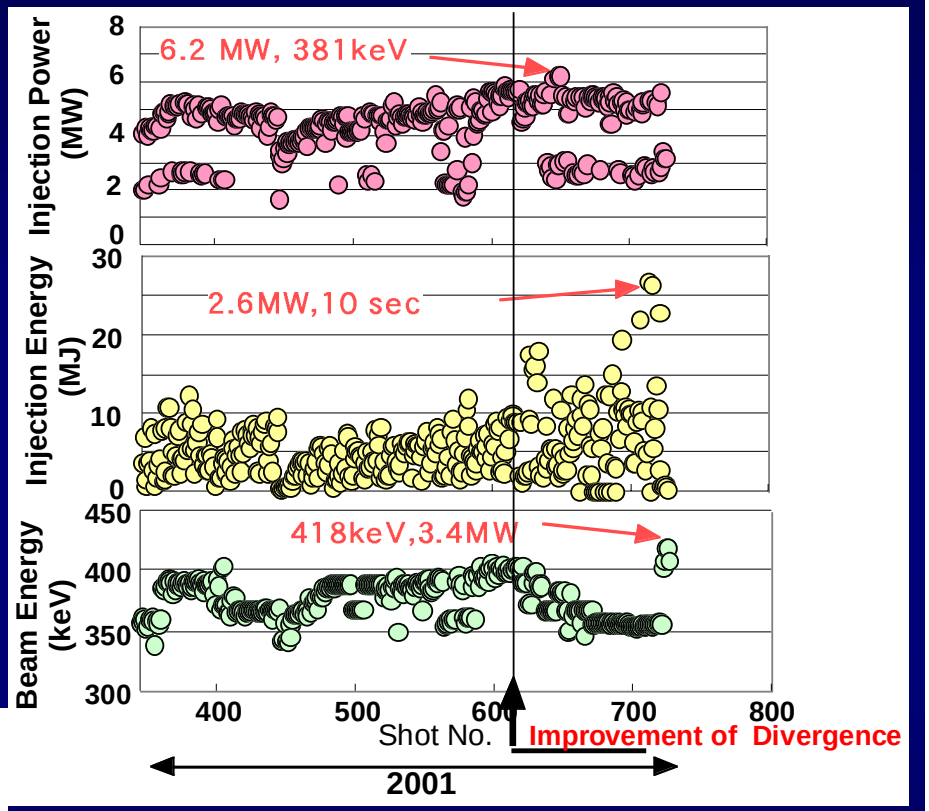
- Short scale peaks are observed at the both edges of the each boundary of the grid segments
- After the installation of the copper pieces, the peaks change.

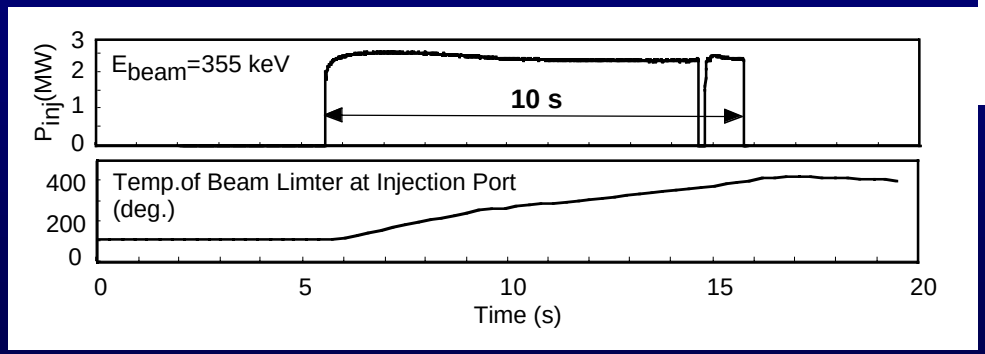
Collaboration with Dr. L. R. Grisham

L. Grisham, et al, Nucl.Fusion, 41 597 (2001)

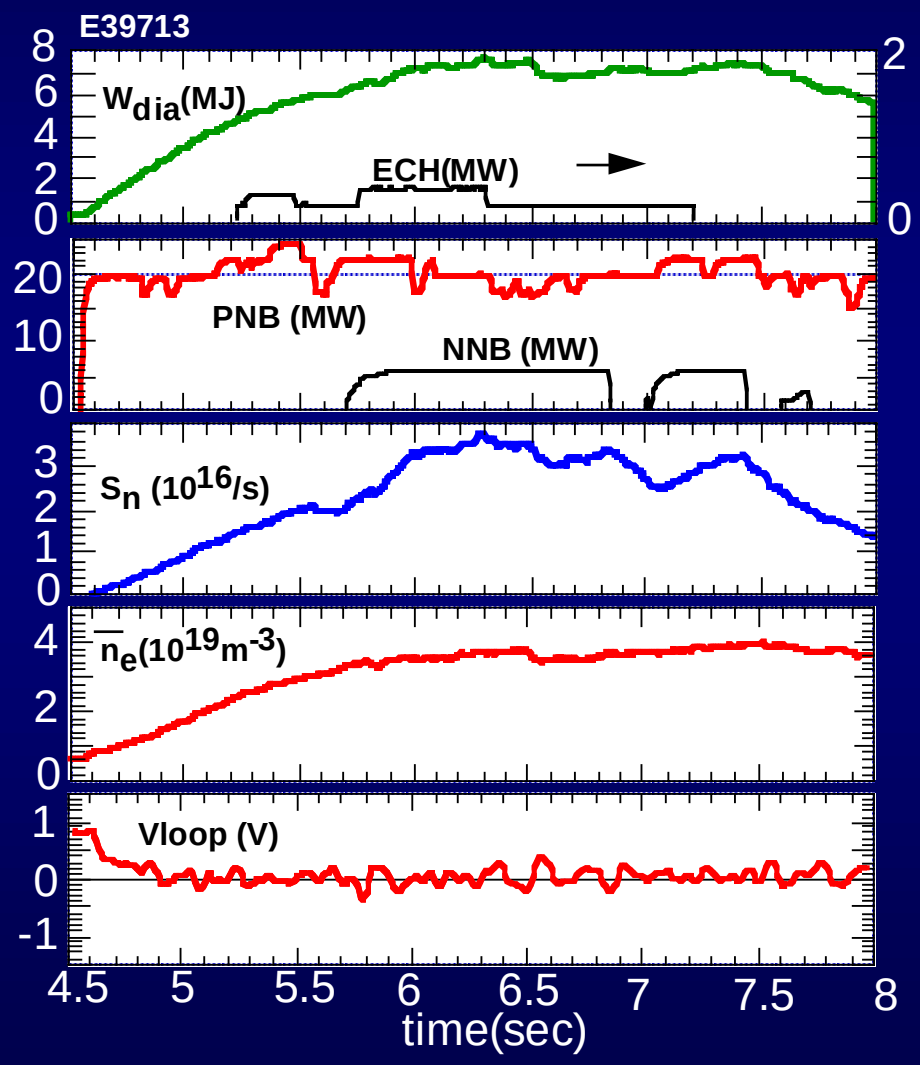
Rsults of Improvement







Improvement of Integrated Performance under Full Non-inductive CD

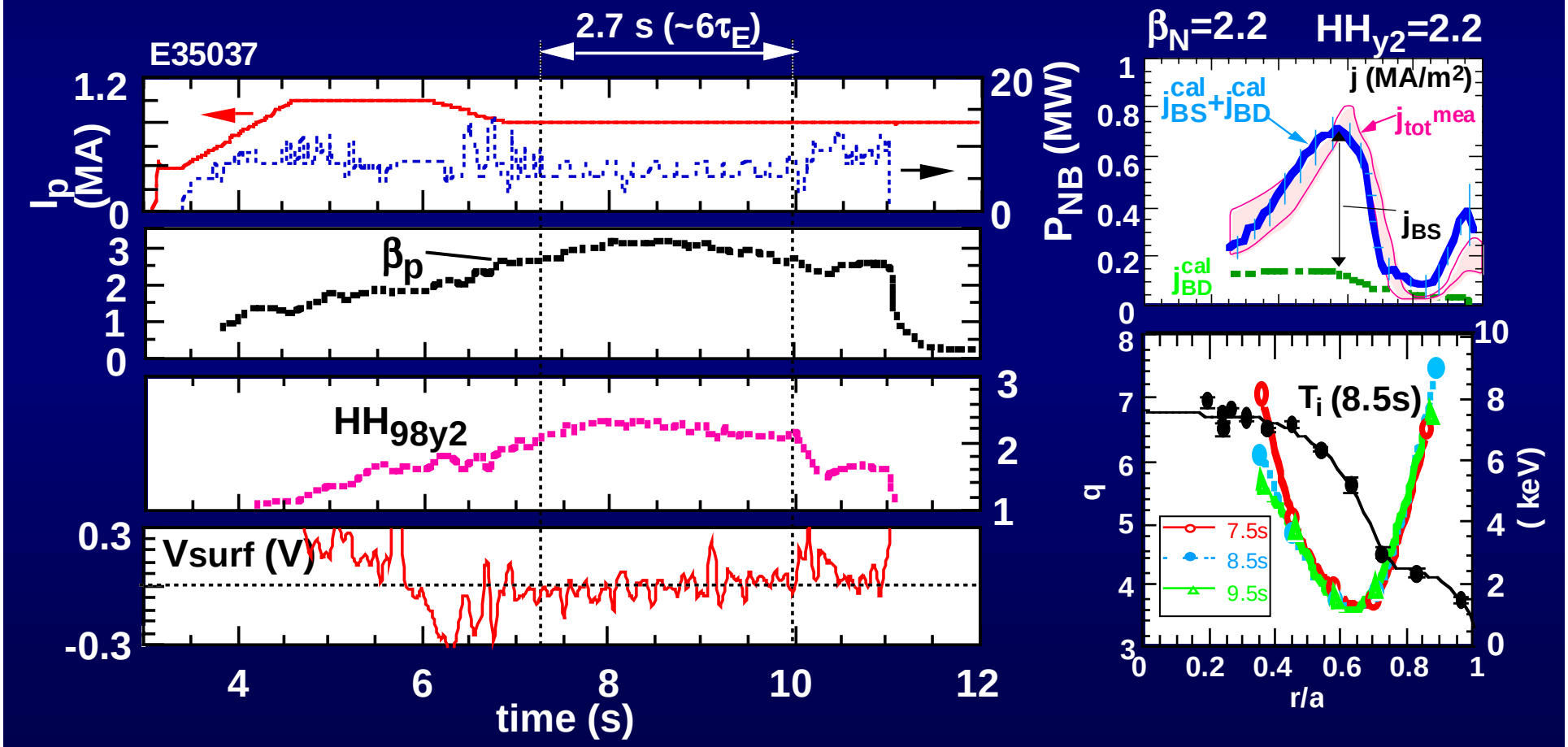


- **Plasma parameters:**
  High β_p H-mode
  β_N=2.3-2.5 at 4.1T,
  1.8 MA, δ=0.34, q_{95}=4.1
- **NNB injection:**
  5.7 MW at 400 keV
- **Plasma performance:**
  HH_{98y2}=1.3
  $n_D(0)\tau_E T_i(0)$ = 3.0 x$10^{20}m^{-3}$skeV
  Full current drive with I_{bs}/I_p=0.50
- Onset of neoclassical tearing mode was avoided by reducing the pressure gradient at q=1.5 and 2 surface

Can We Obtain Steady-state J(r) Solution under Good BS Current Alignment in RS Plasmas?

Quasi-steady high-confinement RS plasma with large BS current fraction under full non-inductive CD

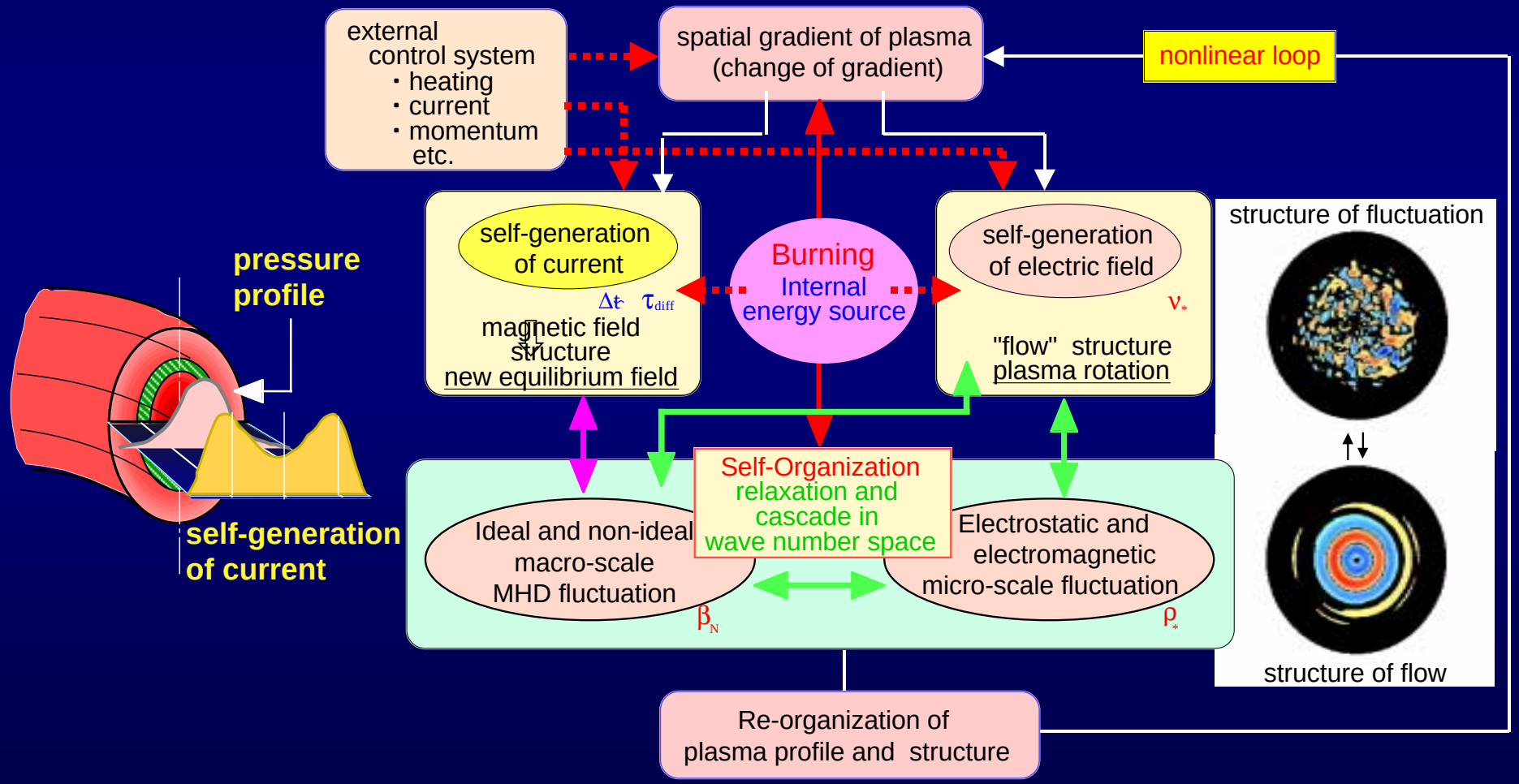
0.8MA/ 3.4T, q_{95}=9.3, off-axis NBCD(25%), BS~80-88%



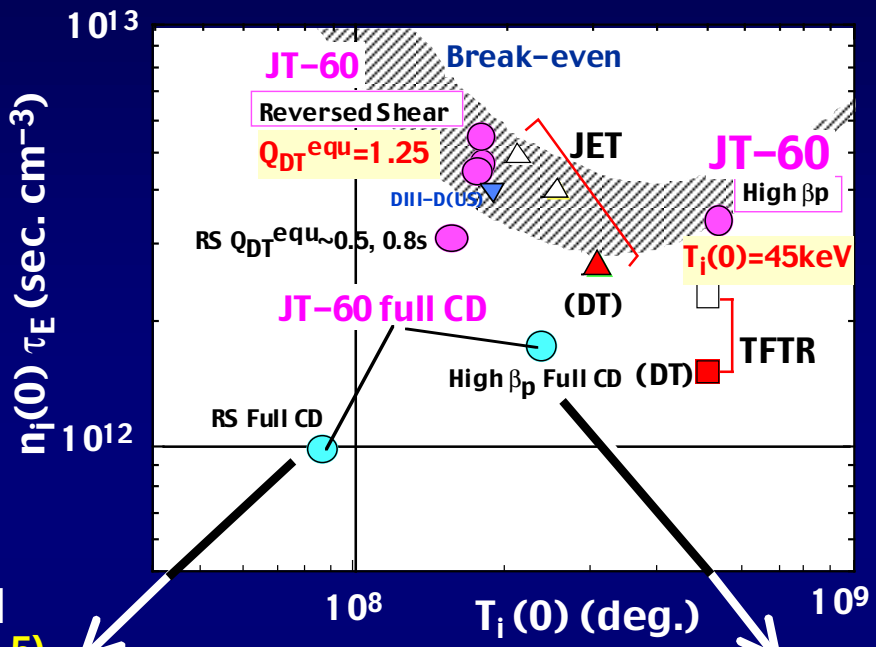
T. Fujita, et al., Phys. Rev. Lett. 87 (2001) 85001

Burning Plasma Physics

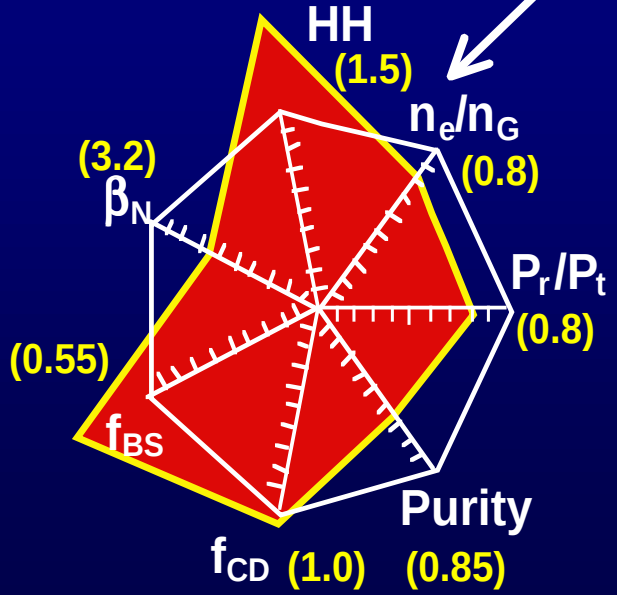
How to control "self-sustained and self-organized autonomous system" where different key factors with different time scales are tightly coupling each other.



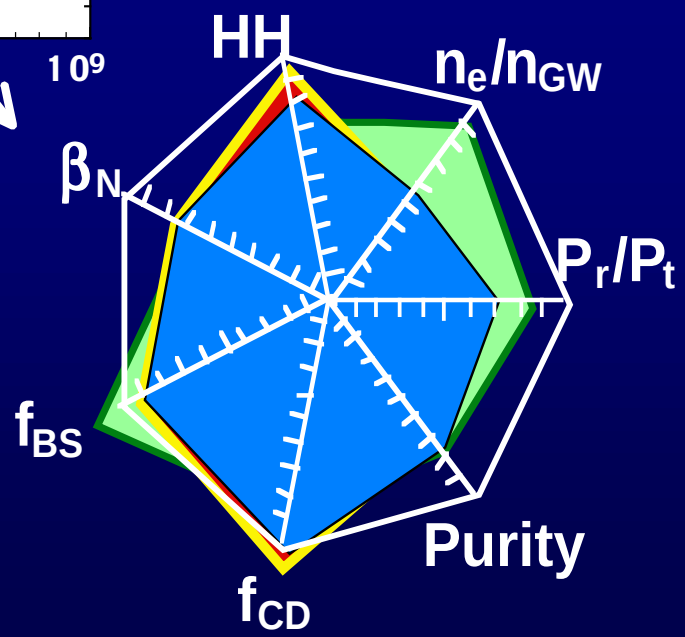
Achievement of Integrated Performance



RS H-mode

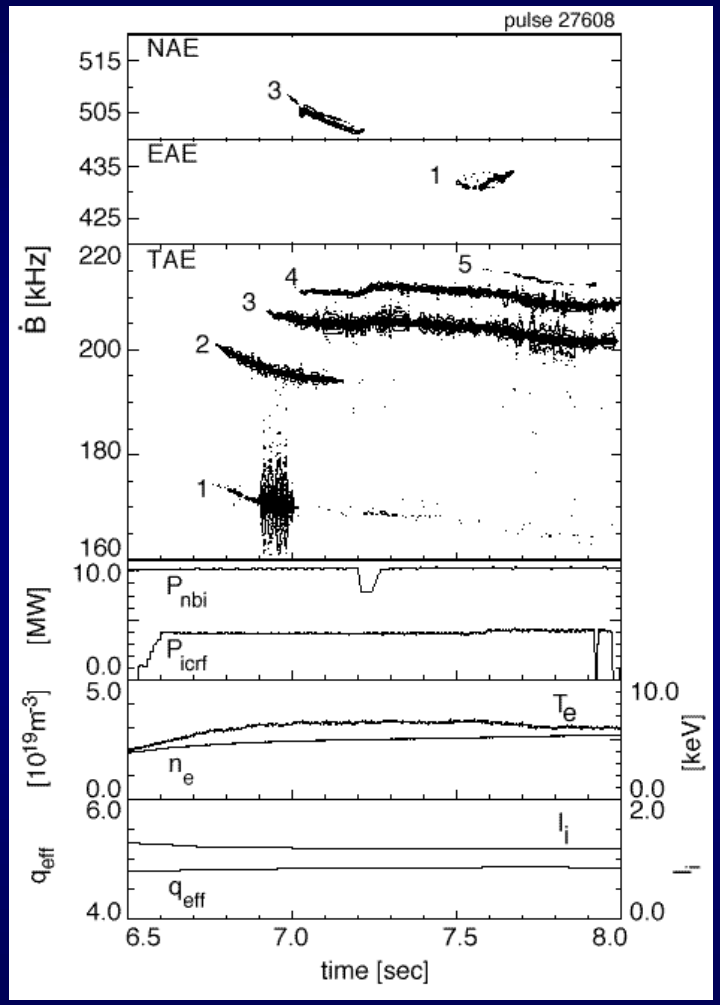


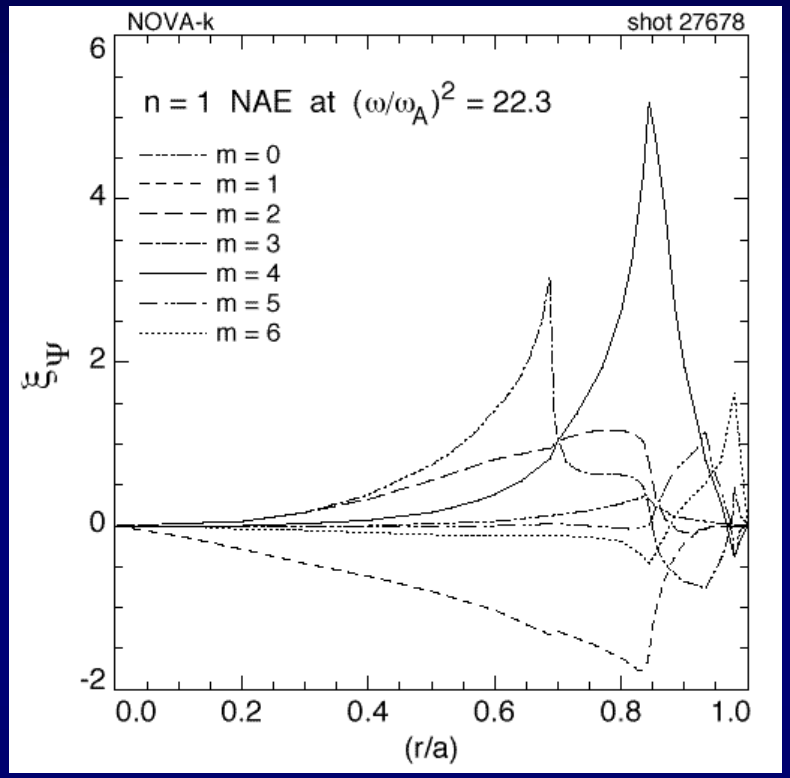
High β_p H-mode



Alfvén Eigenmodes

NOVA-K Code Analysis Leads to Identification of NAE in JT-60U





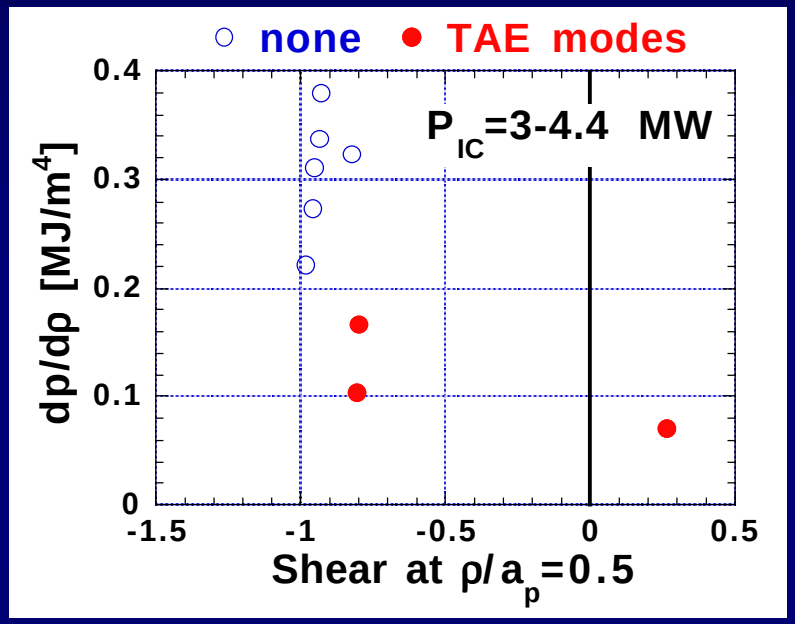
Measured mode frequencies are consistent with NOVA-K calculation.

NAE modes (450-530 kHz) were observed for the first time in JT-60U.

G.J. Kramer, et al., PRL 80 (1998) 2594.

Stability of TAE in Reveased Shear Plasma Can Be Qualitatively Explained by the NOVA-K Code

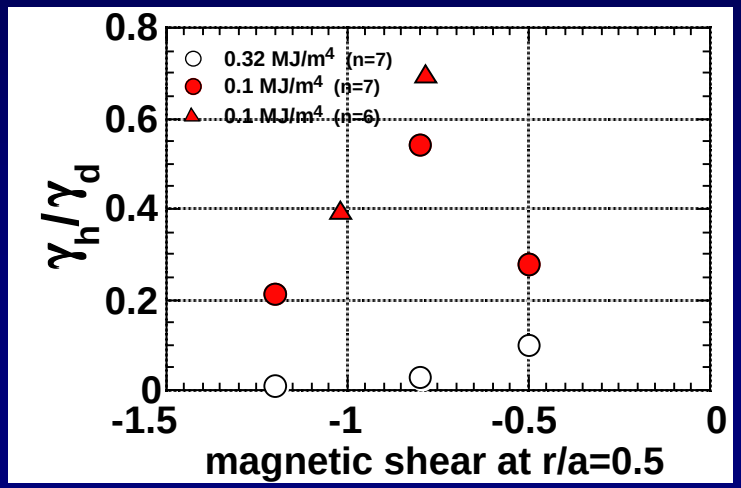
Experiments

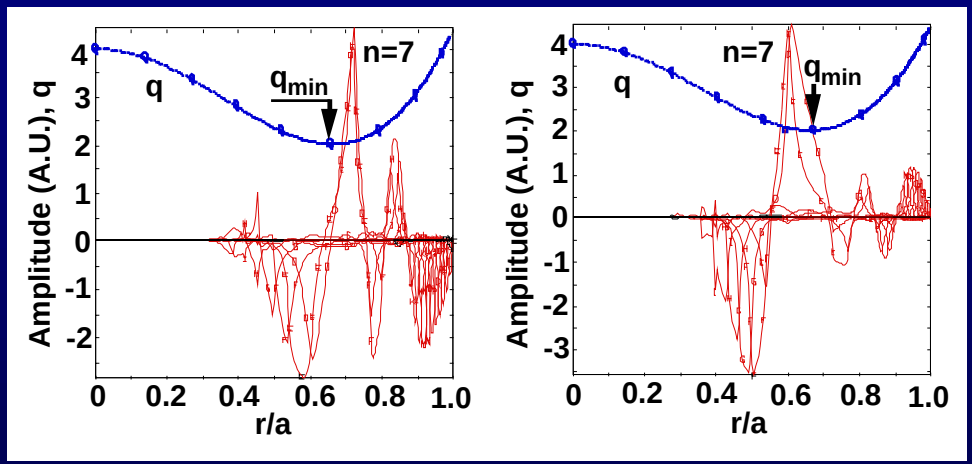


TAE modes are unstable with weak ITB in a reversed shear plasma.

Y. Kusama, et al., Nucl. Fusion, 38 (1998) 1215.

NOVA-K analysis

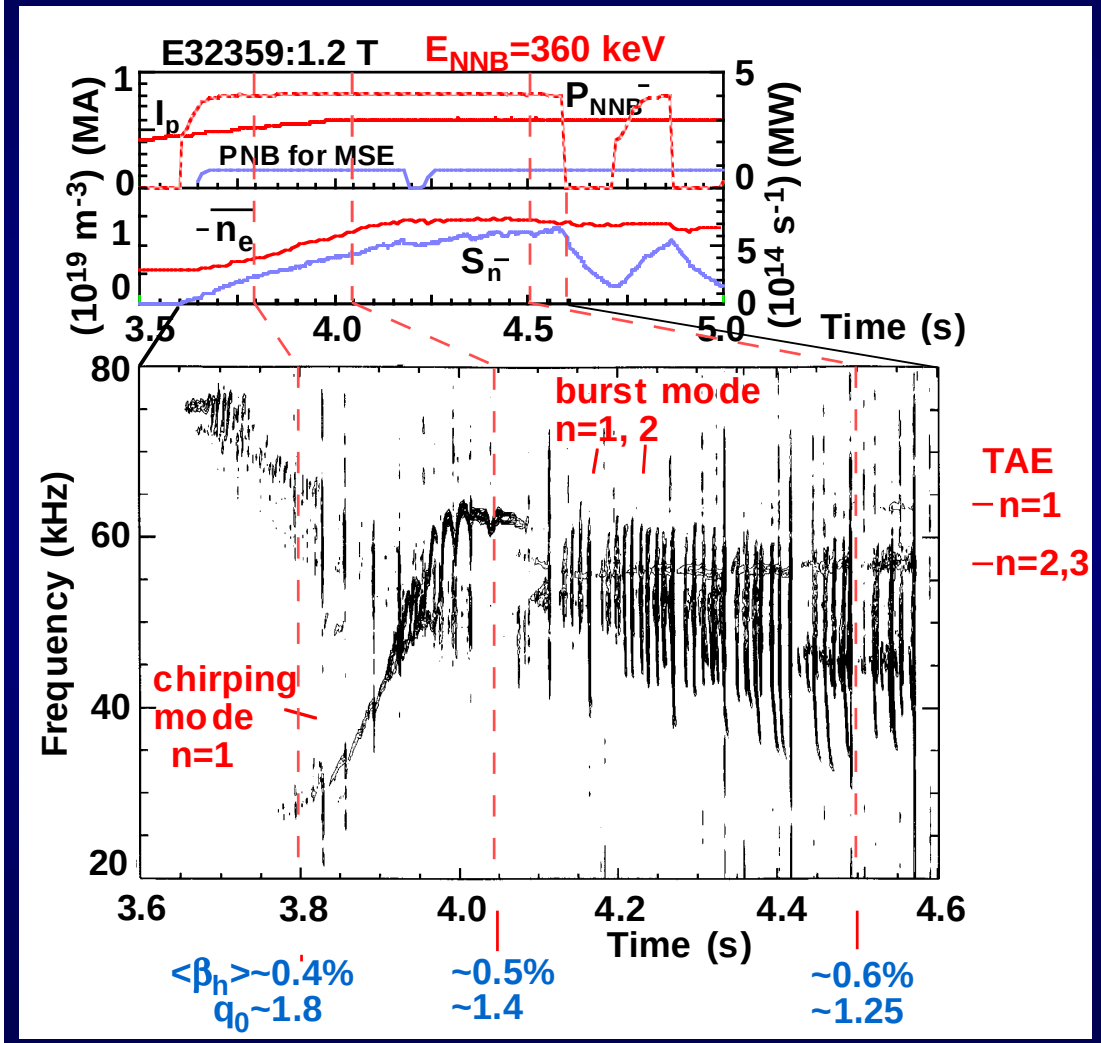




Modes can not peak inside q_{min} for the strong ITB case, resulting in weak fast ion drive.

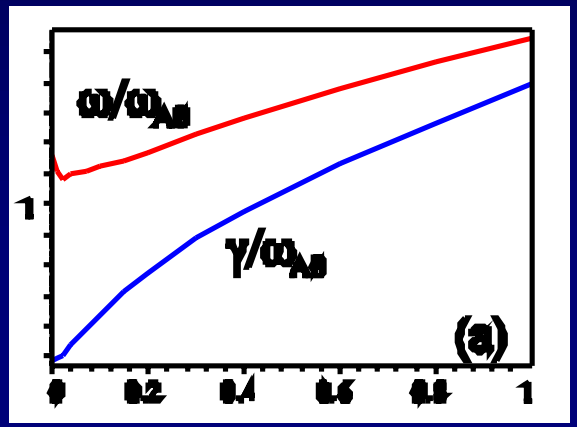
Frequency Chirping Observed during N-NB Injection Is Under Analysis at PPPL

N-NB driven modes



Y. Kusama, et al., Nucl. Fusion, 39 (1999) 1837.

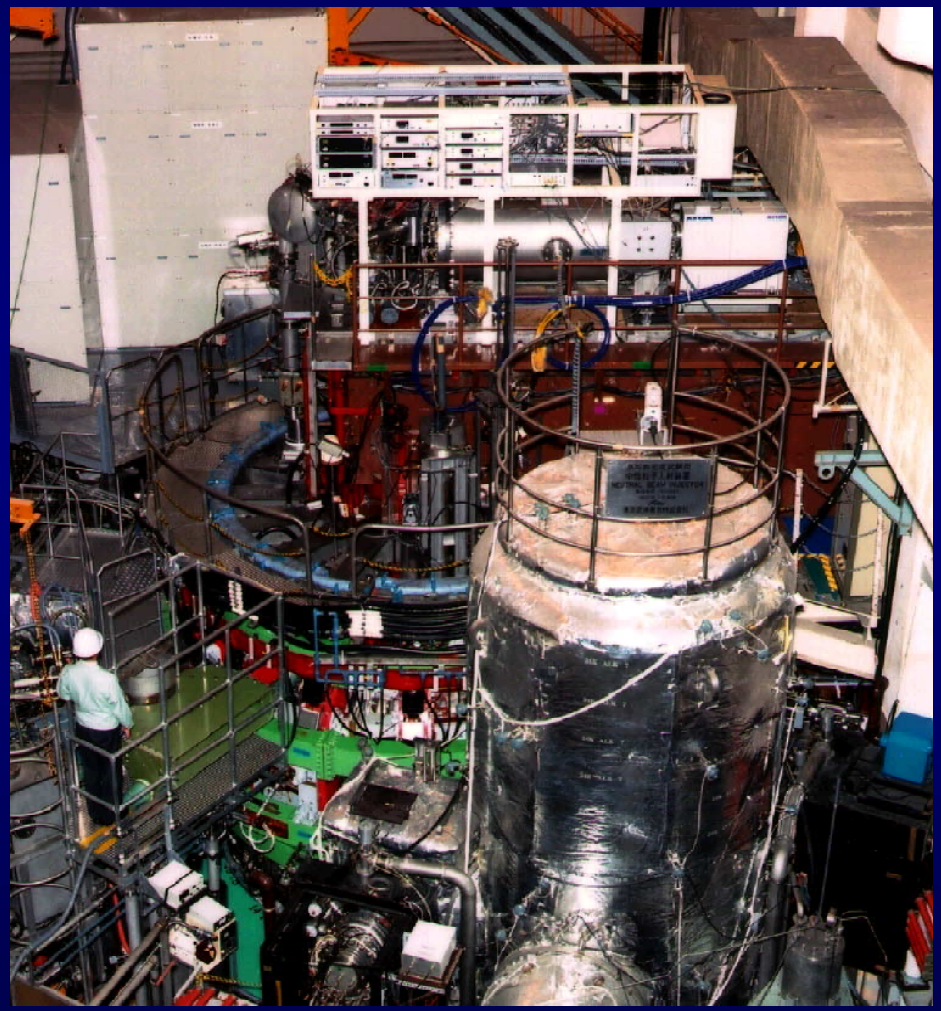
Analysis of n=1 chirping mode with HINST code



- One possible candidate of the chirping mode is Resonant TAE (R-TAE) excited in a high β_h regime.
- Frequency chirping is explained qualitatively due to the increase in β_h.
- More accurate analysis is under way with the NOVA-2 code.

N.N. Gorelenkov, et al., Nucl. Fusion, 40 (2000) 1311.

2. Results of JFT-2M

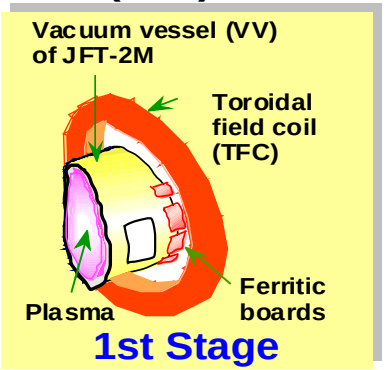


Plasma Applicability Test of Ferritic Material

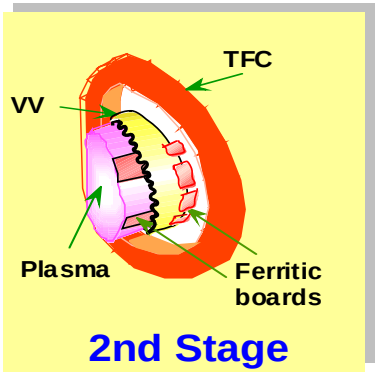
AMTEX (Advanced Material Tokamak EXperiment)

Ripple reduction with ferritic boards (FBs) outside VV

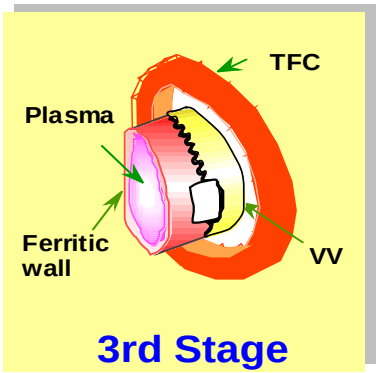
Compatibility between plasma and FBs inside VV



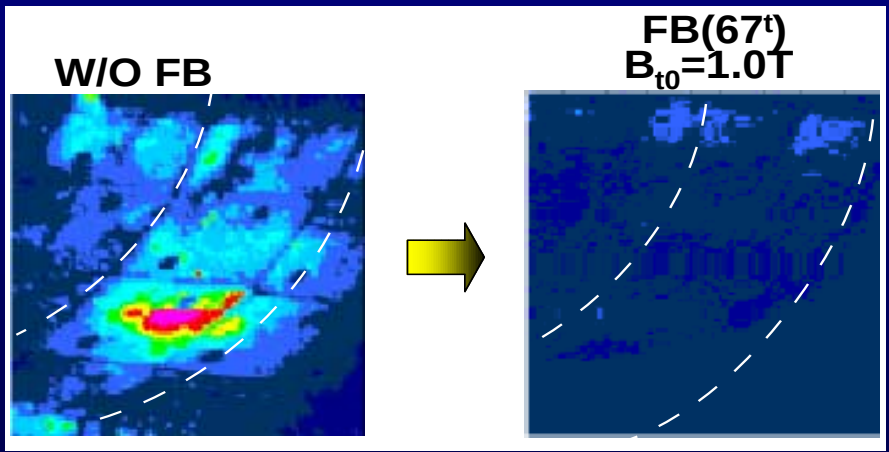
JFY1999



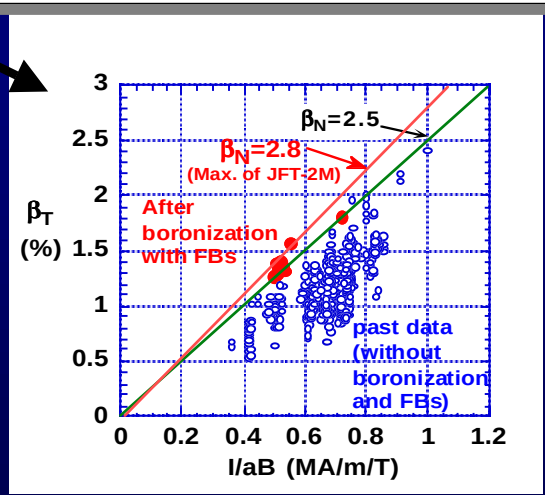
partial covering (JFY2000)



full covering (JFY2001~)



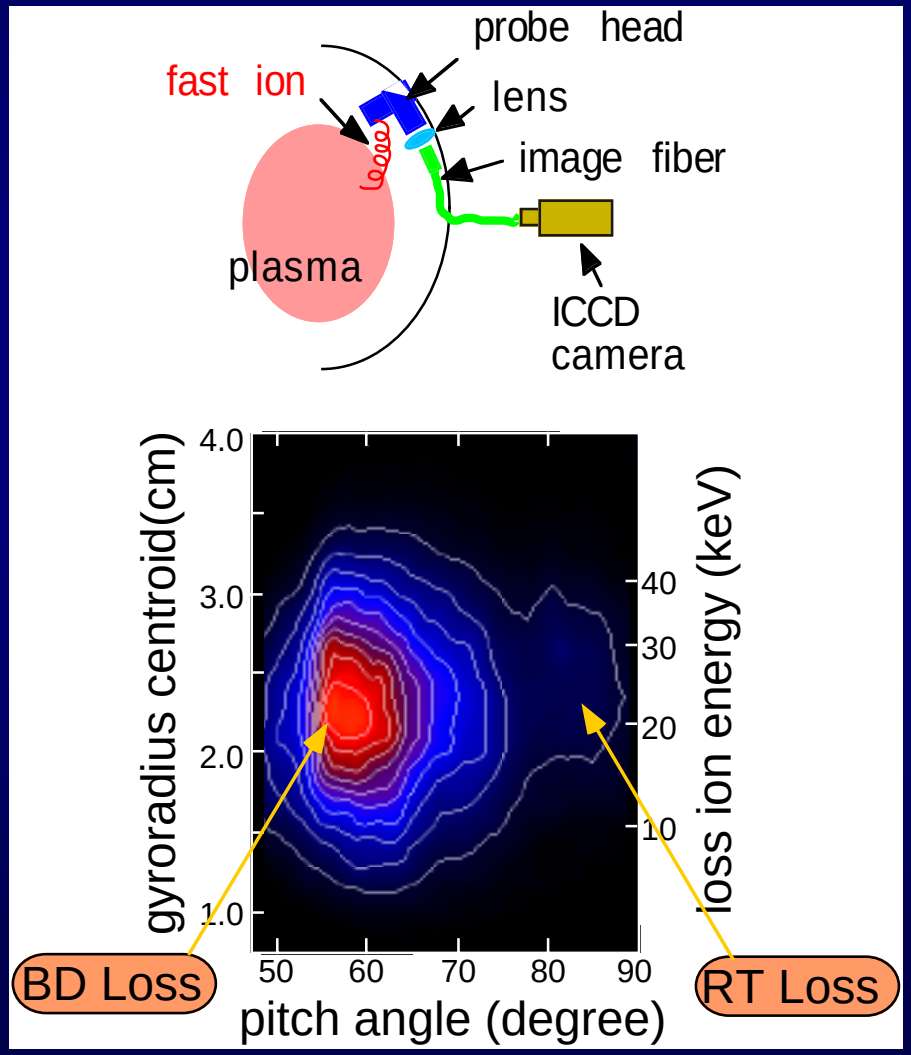
Reduction of ripple loss



No degradation of attainable β_N

The Pitch Angle of BD Loss Corresponds to Loss Cone on the Velocity Space.

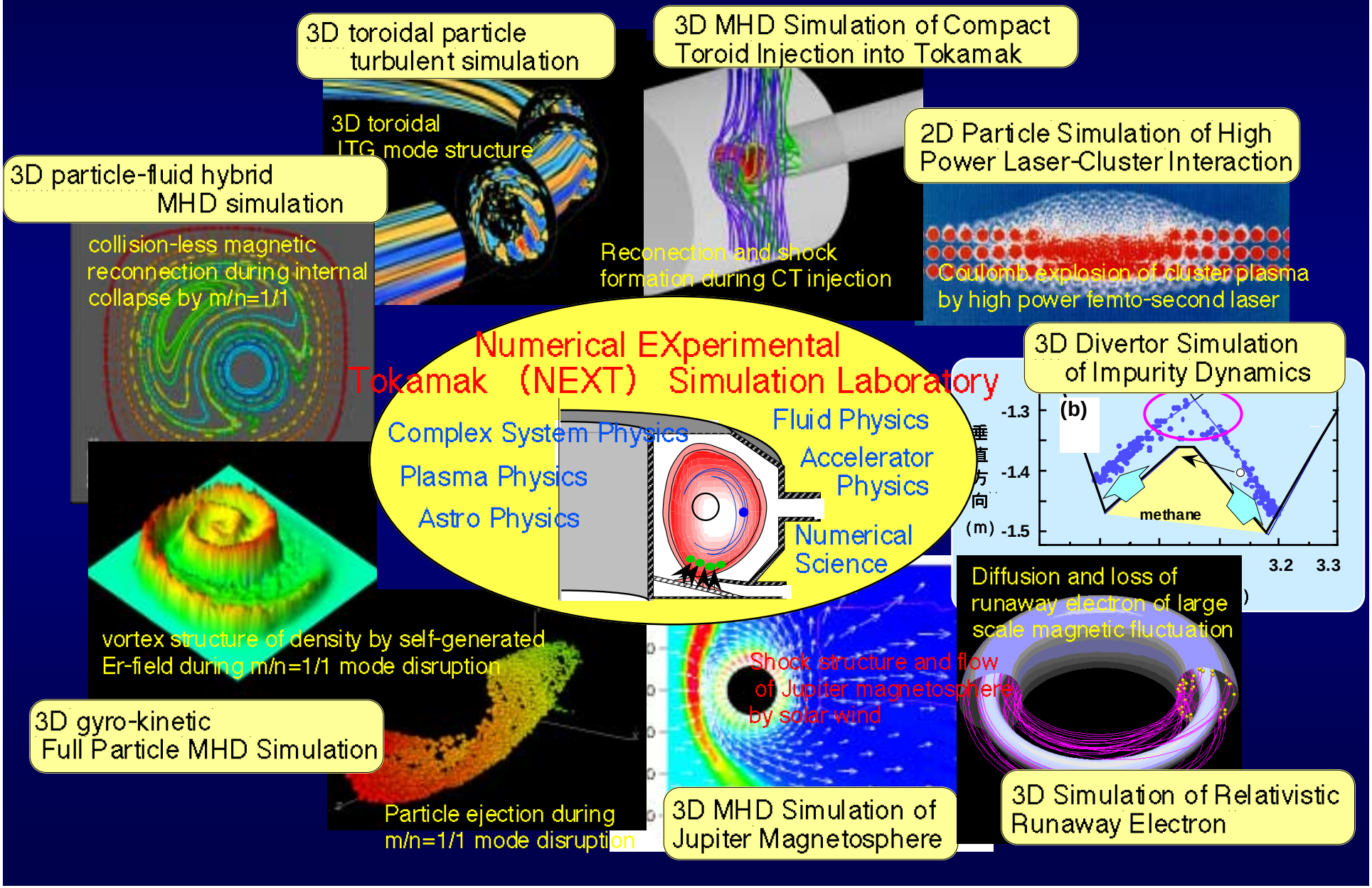
- Lost ion probe was installed in 1999 in order to measure the energy and the pitch angle of energetic lost ions.



Collaboration with Dr. D. Darrow

3. Theoretical Research

Large Scale Simulation Research in NEXT Project



Nonlinear Global Gyro-kinetic Simulation of ETG Turbulence

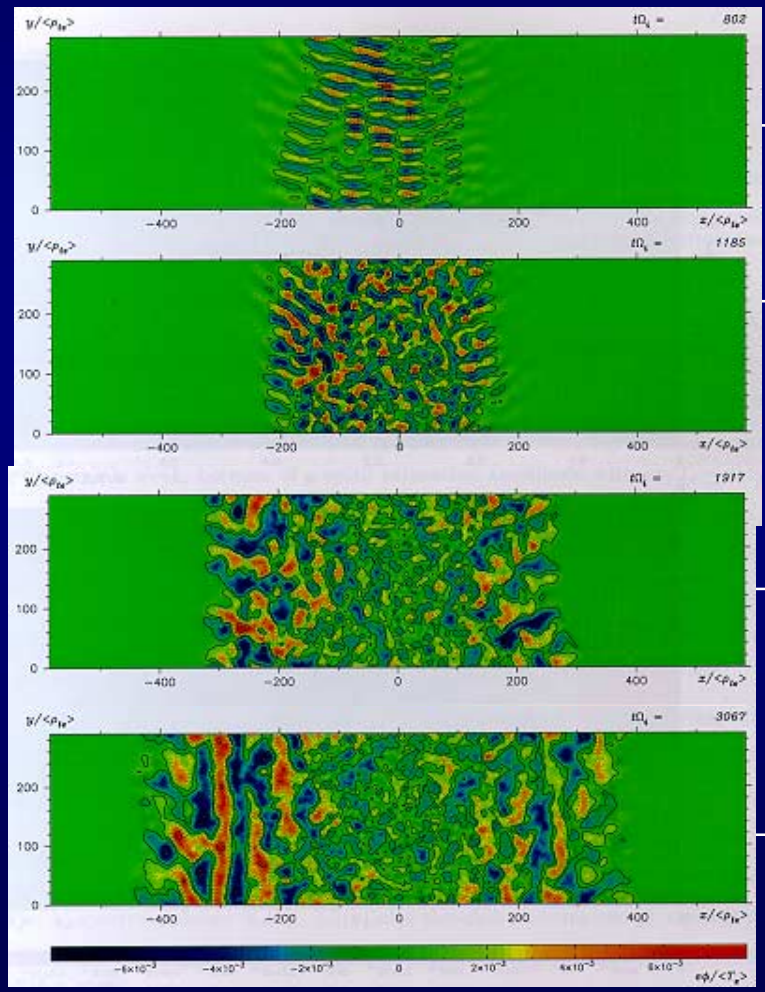
Electron transport barrier is established by the Zonal Flow through the spatial propagation of ETG and Kevin-Helmhoultz turbulence.

① **Linear phase (t=2msec)**

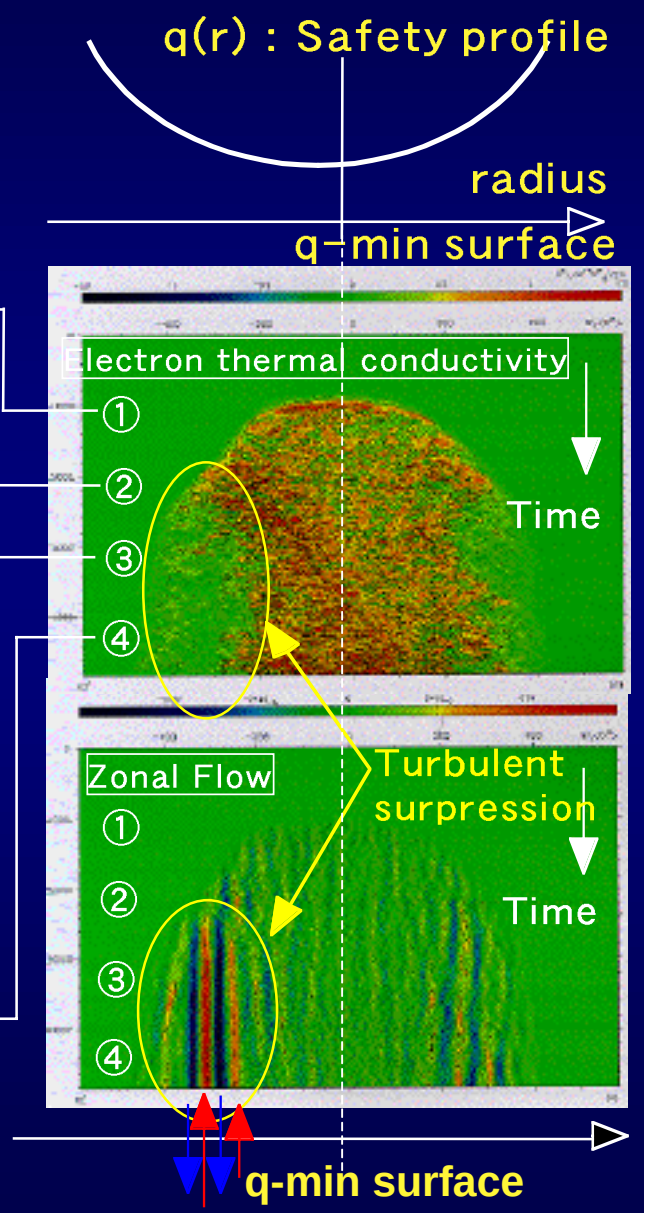
② **Saturation phase (t=4msec)**

③ **Nonlinear phase (t=6msec)**

④ **Quasi-steady state (t=8msec)**

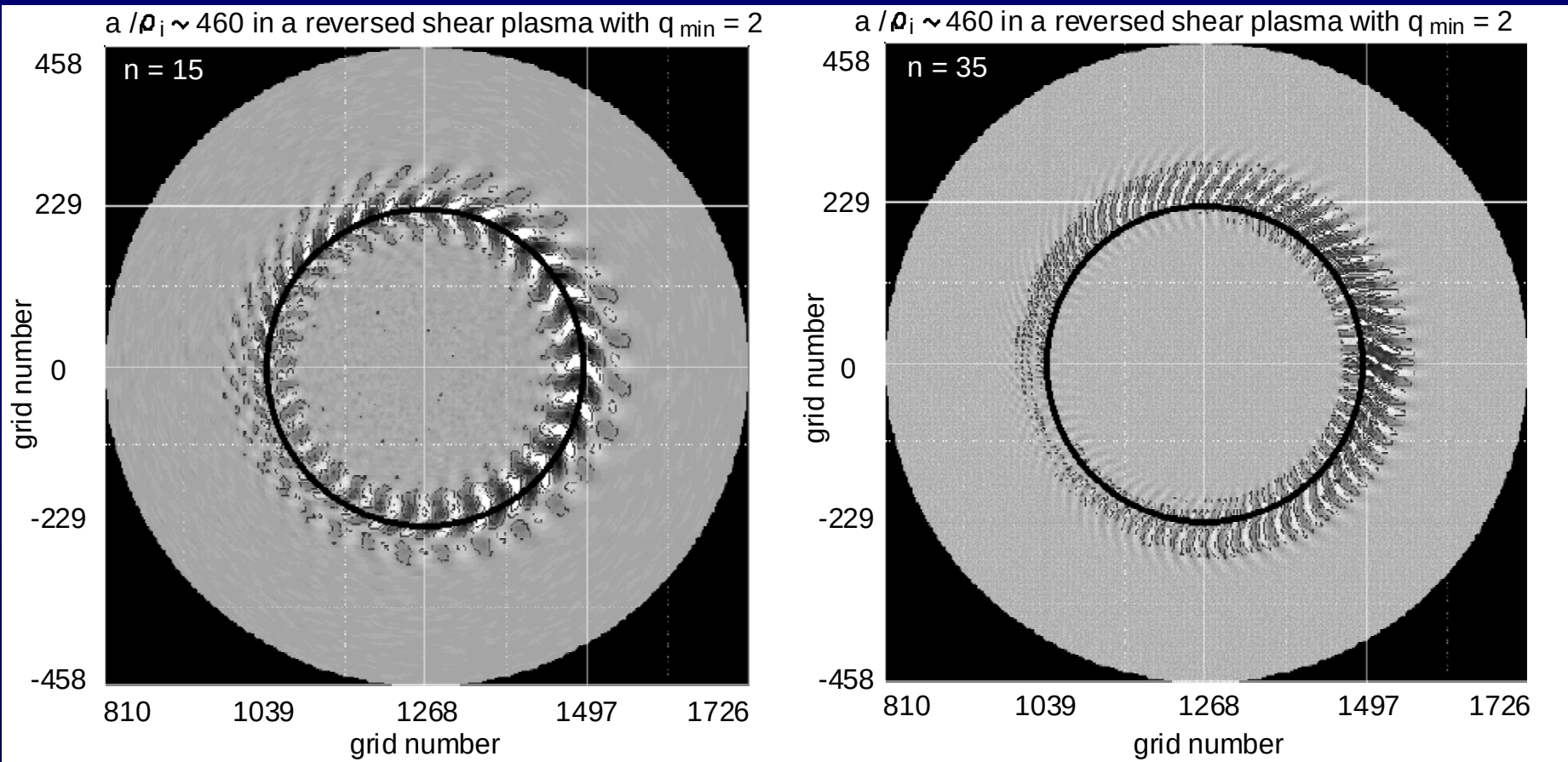


q-min surface



Global Gyro-kinetic Toroidal Particle Code for 3-D Nonlinear Simulation

- **Application of the code for linear calculations before addressing nonlinear simulations**
- **From comprehensive global analyses over a wide range of an unstable toroidal mode number spectrum (n=0～100), it is found that especially in reversed shear tokamaks, properties of the ITG mode are drastically changed through ion heating and density peaking processes.**



R = 2.6 m, a = 0.94 m, B_t = 4.6 T, T_{io} =13 keV, T_{eo} = 4 keV, L_{Ti}/R = 0.1, L_{Te}/R = 0.5, L_n/R = 0.5

Nonlinear Gyro-kinetic MHD Simulation of Reversed Shear Plasmas

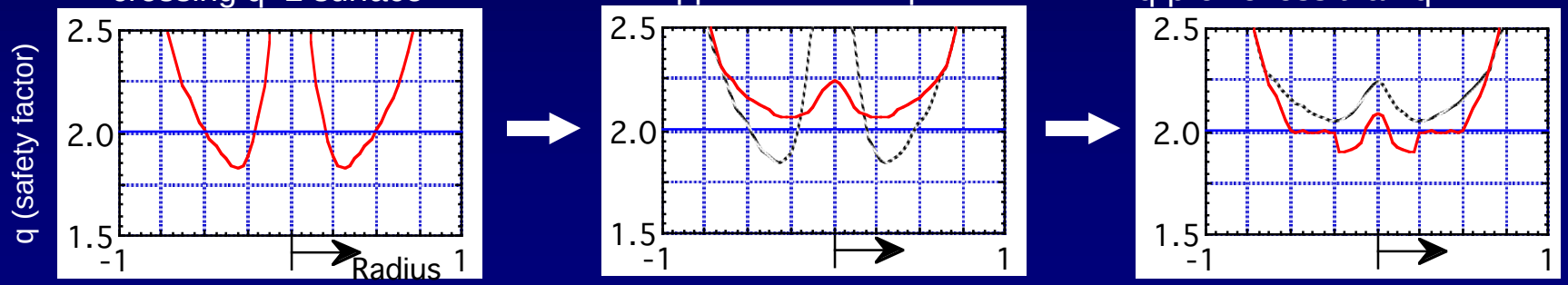
New mechanism that the reversed q-profile crosses the mode rational surface

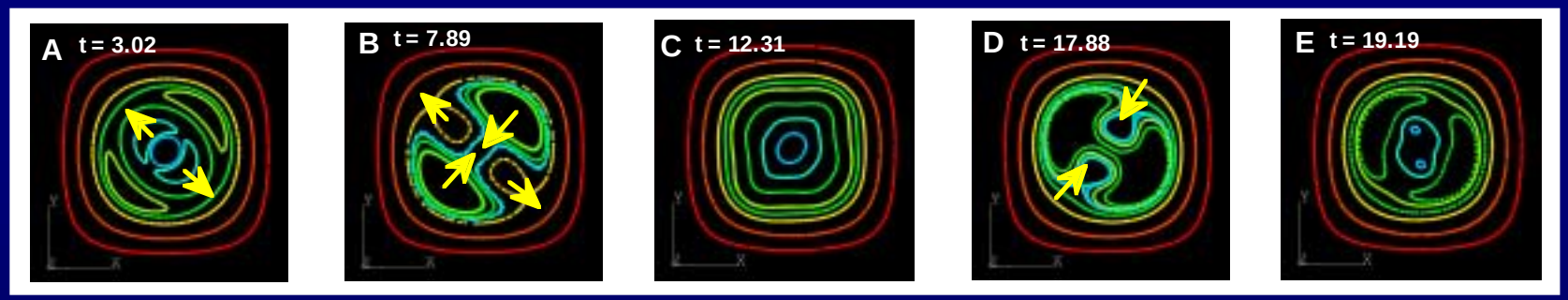
"Electron inertia" is essential for reconnection process in high temperature plasma

Initial q-profile after crossing q=2 surface

flattening of q-profile above q=2

Reconstruction of reversed q-profile less than q=2





growing phase of double tearing mode

flux replacement

nested surfaces

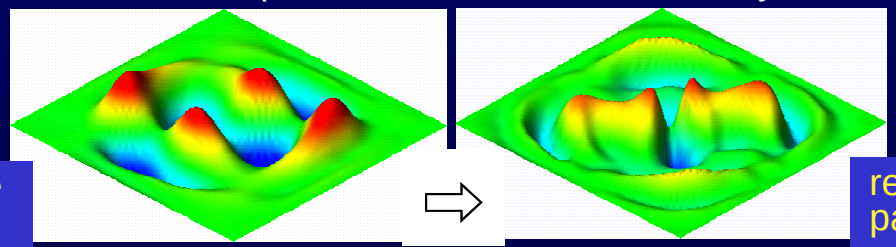
secondary reconnection

recovery of nested surface

↑↓ electrostatic potential

↑↓ current density

Internal collapse due to collisionless reconnection at Alfven time scale

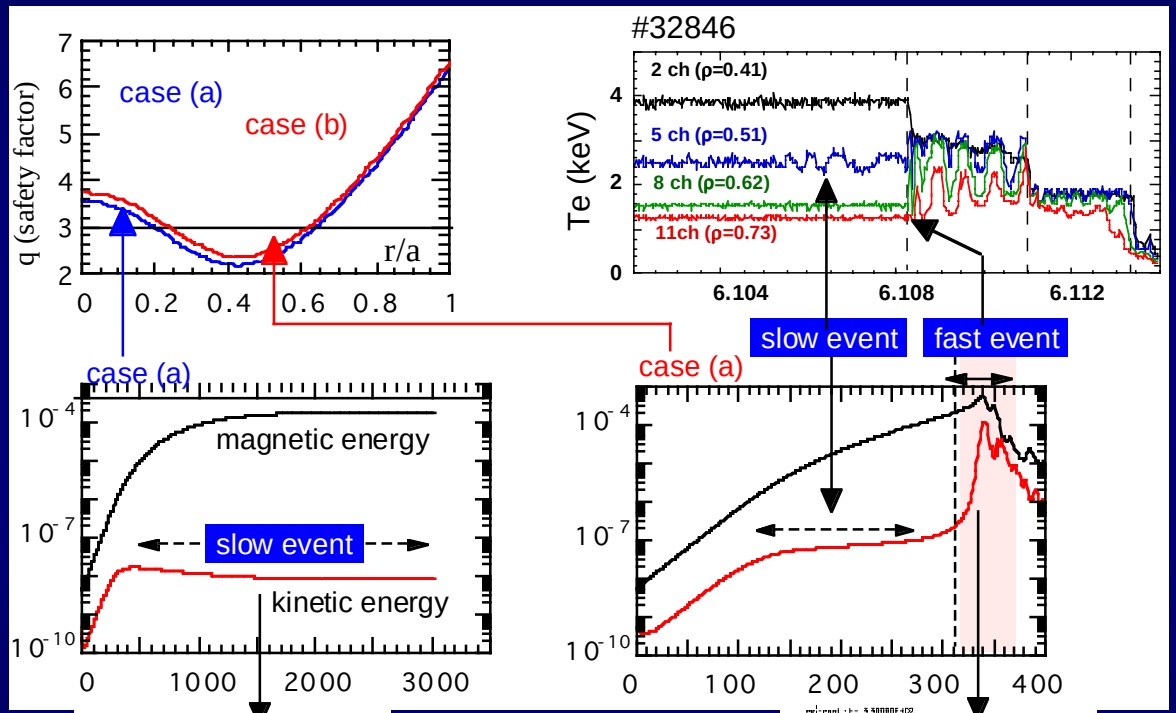


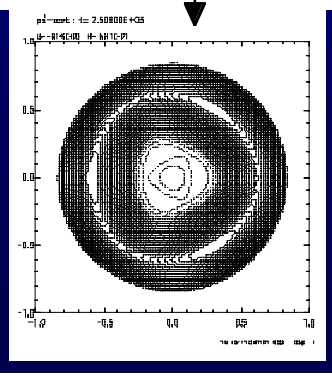
survival of m=2 mode structure due to small dissipation

re-distribution of parallel current

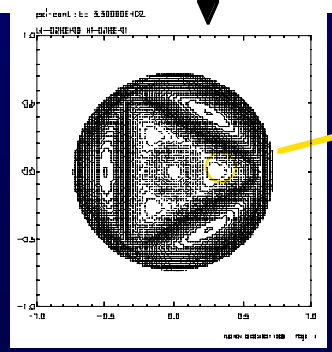
Nonlinear Recuced MHD Fluid Simulation of Reversed Shear Plasmas

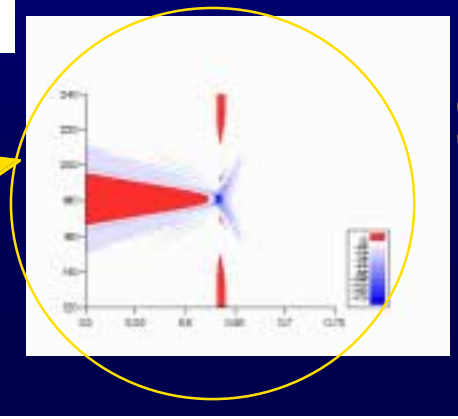
- **New phenomenon of the transition of the mode growth rate from resistive time scale to the fast one**
- **Current point formation within the resistive MHD model**





saturation of two island without disruption





emergence of "current point"

JT-60 exp.
(S.Takeji et al. IAEA-CN-77/EX7/2)

explosive growth after slow time scale evolution

➡ **low beta disruption**

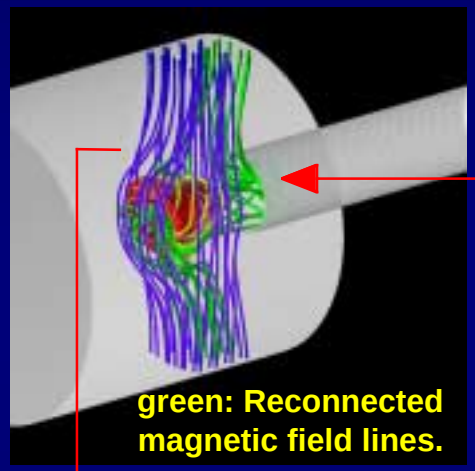
<u>triangular deformation</u> of the islands formed in the slow growth phase

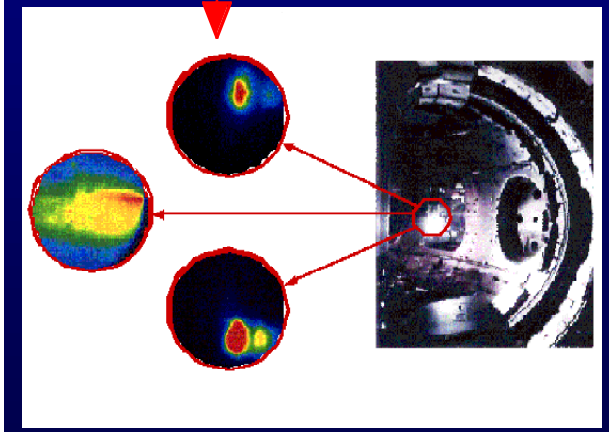
➡ **nonlinear instability**

Nonlinear MHD Simulation of Advanced Fueling by Compact-toroid Injection

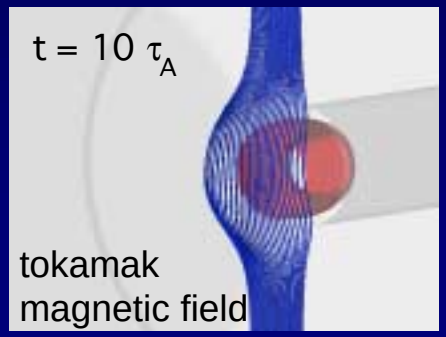
Mechanism of CT penetration into tokamak target plasma through complex magnetic reconnection dynamics

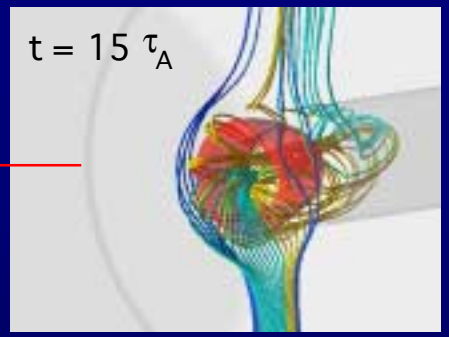
3-D magnetic configuration in the CT penetration process.

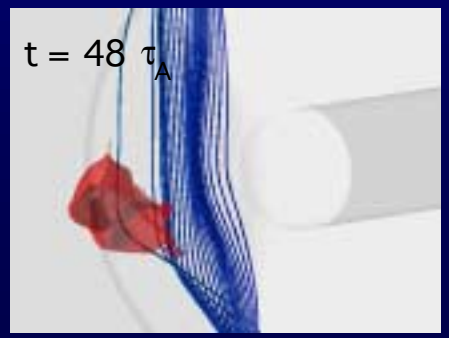




Experiment of the CT injection in JET-2M







High density CT injected with high velocity

First Phase

Mixing and marging between tokamak and CT magnetic field by reconnection

⇨ deceleration of the CT penetration

Second Phase

Unlacing between tokamak and CT magnetic field by second reconnection

⇨ relaxation of the CT deceleration

puzzle ring effect of magnetic field

4. Future Direction of JT-60

Japanese Government Decided on May 29 to Propose Rokkasyo-mura as ITER Candidate Site

Rokkasyo-mura
Aomori prefecture

40 km from Misawa Airport
(Misawa: US Air Force base)
80 km from Aomori Airport

Modification of JT-60U (JT-60SC) (JAERI Proposal)

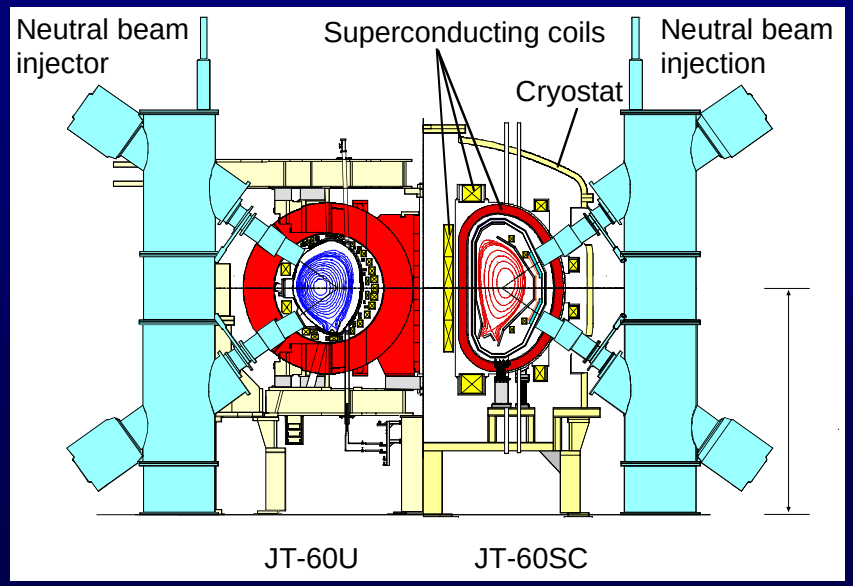
Mission

1) Establishment of high performance steady state operation

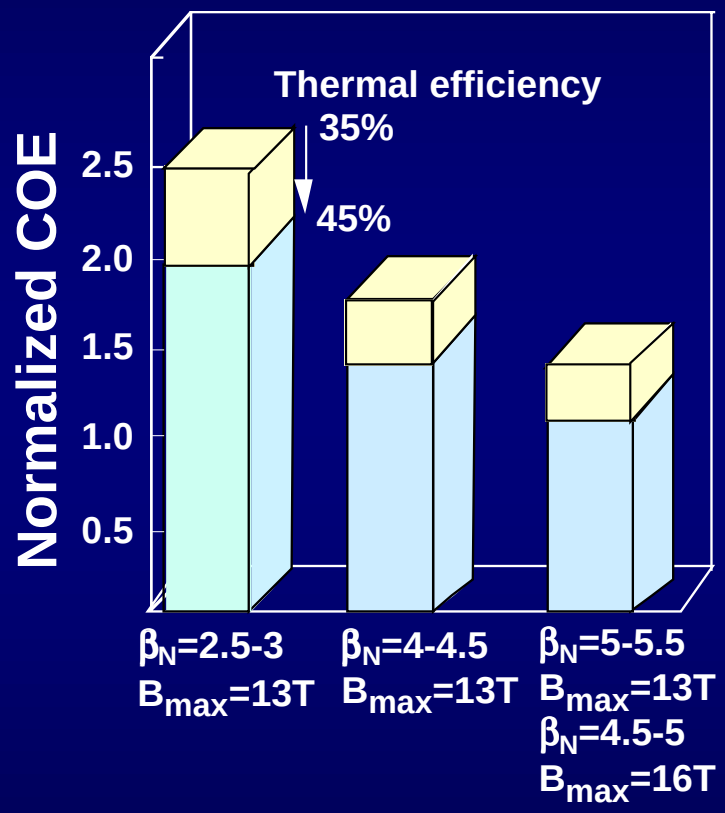
- High beta plasma control (β_N = 3.5 – 5.5)
- Steady state plasma control (f_{BS}=50 – 90%)
- Divertor heat&particle control (f_{rad}～95%、 τ_{He}^*/τ_E~5)
- Disruption control (avoidance, mitigation)

2) Plasma applicability test of advanced materials

- for practical use of the advanced material of low activation ferritic steel

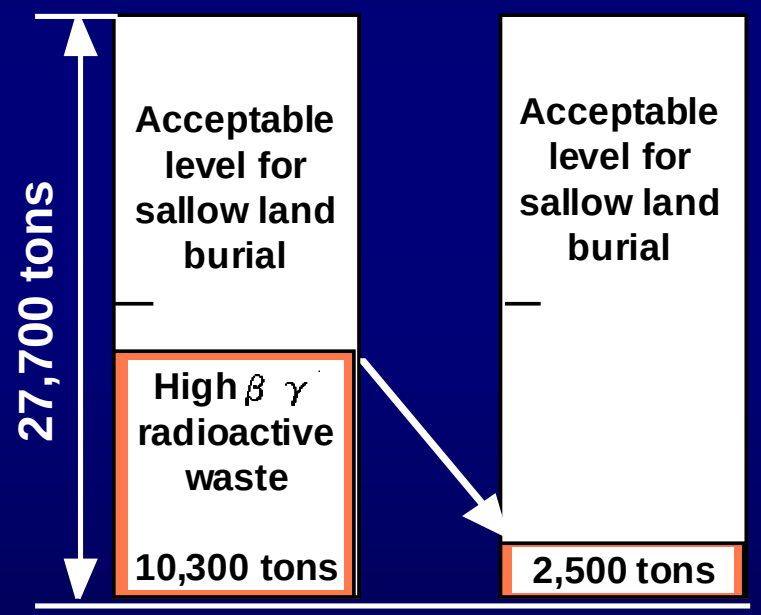


Improvement in Economical and Environmental Attractiveness



Subcommittee for fusion development strategy
May 17. 2000, N. Inoue et al.

Difference of vacuum vessel material



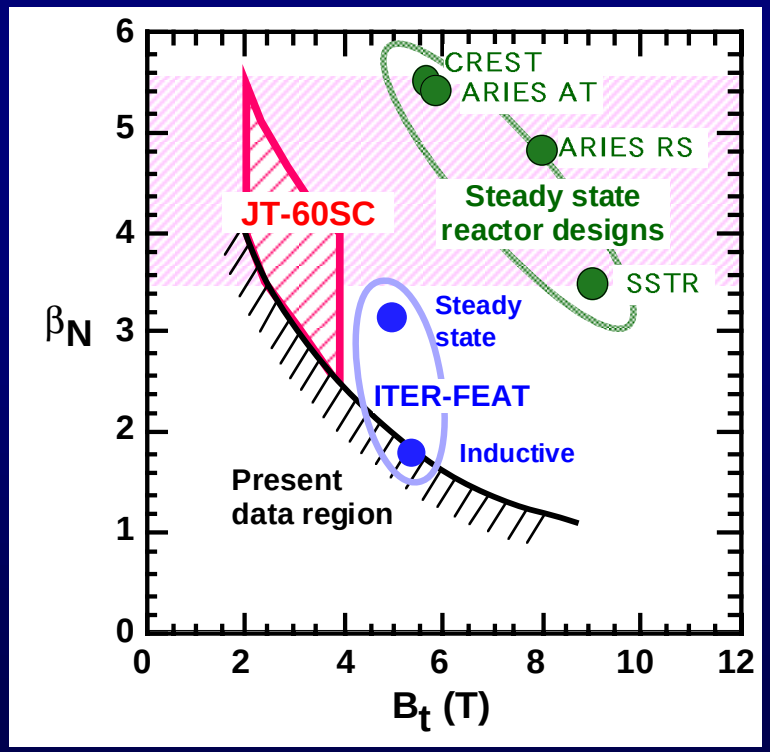
Use of low activation materials increases the acceptable level for sallow land burial

Parameters of JT-60SC

- Sufficiently low (ρ^*, ν^*) plasmas close to DEMO ⇒ R_p ~3 m
- Sufficiently longer duration than current diffusion time ⇒ ~100 s

modification to a superconducting tokamak, JT-60SC.

- JT-60SC pursues plasma parameters deduced from DEMO concepts using **low activation ferritic steel** in the vacuum vessel



Parameter	JT-60U	JT-60SC
Pulse length	15 s	100 s
Max. input power	40 MW (10 s)	44 MW (10 s) 15 MW (100 s)
Plasma current I_p	3 MA	4 MA
Toroidal field B_t	4 T	3.8 T (R_p=2.8 m)
Major radius R_p	3.4 m	2.8 -3 m (2.8 m*)
Minor radius a_p	0.9 m	0.7-0.9 m (0.85 m*)
Elongation κ_{95}	1.8 (δ_{95}=0.06)	≤ 2 (1.8*)
Triangularity δ_{95}	0.4 (κ_{95}=1.33)	≤ 0.5 (0.35*)

* Nominal

Design is progressed in national wide collaboration with **universities, institutes and industries.**

Summary

- JT-60 and JFT-2M will continue to contribute to ITER and establish a scientific basis for attractive steady-state tokamak reactors.
- Collaboration between PPPL and JAERI has created significant results and is increasingly of importance in future.

祈念

PPPLの更なる繁栄