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Summary:

Confinement, Plasma-wall Interaction, and Innovative Confinement Concepts

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Statistics of EX and IC

EX (Magnetic Confinement Experiments)	178
EX-C (Confinement)	~93
EX-D (Plasma-wall Interaction)	22
IC (Innovative Confinement Concept)	22

OV: 28, TH: 92, IT: 28, IF: 19, FT: 69, SE: 5

Total: 441

Outline

1. Tokamak Regimes Extended towards ITER
2. Scenario Optimization
3. Global Confinement Physics
4. Transport Physics
5. Plasma-wall Interaction
6. Innovative Confinement Concepts

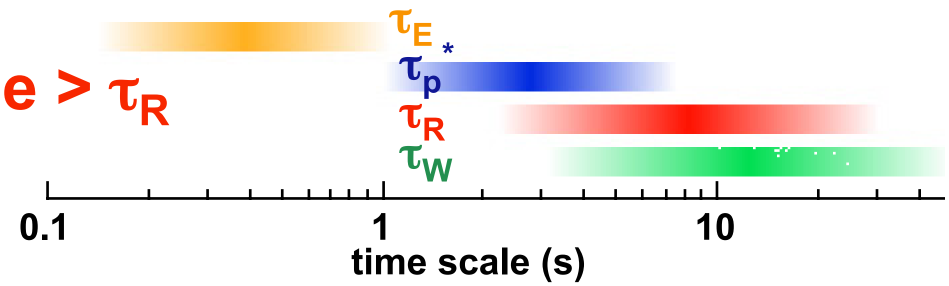
1. Tokamak Regimes Extended towards ITER

Long Pulse Operation

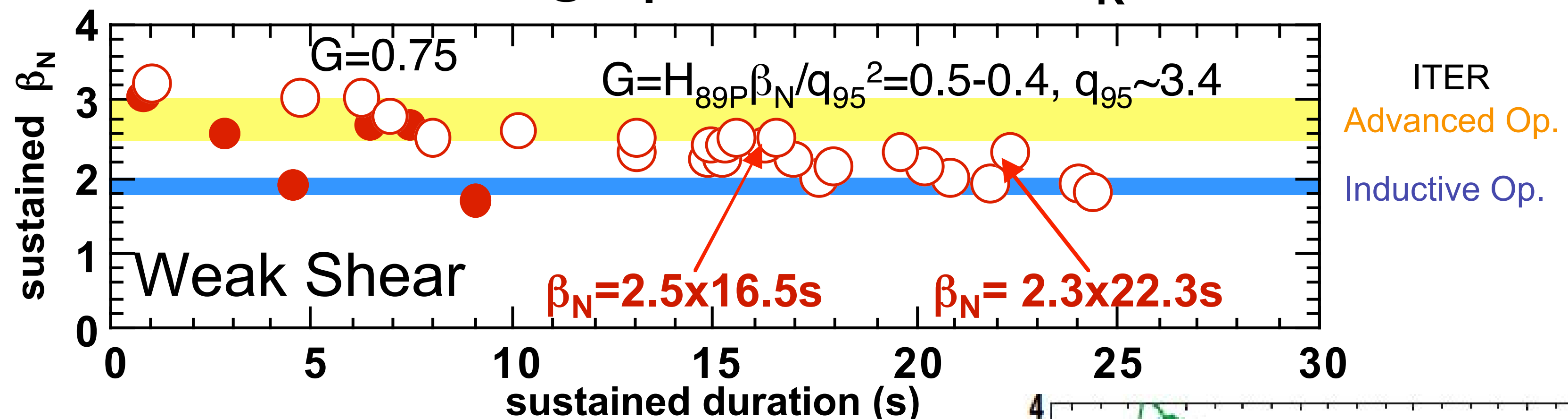
1.1 Long Pulse Operation: high β & G sustained>> τ_R

High β & AT (self regulating) regime > τ_R

Particle control > τ_w

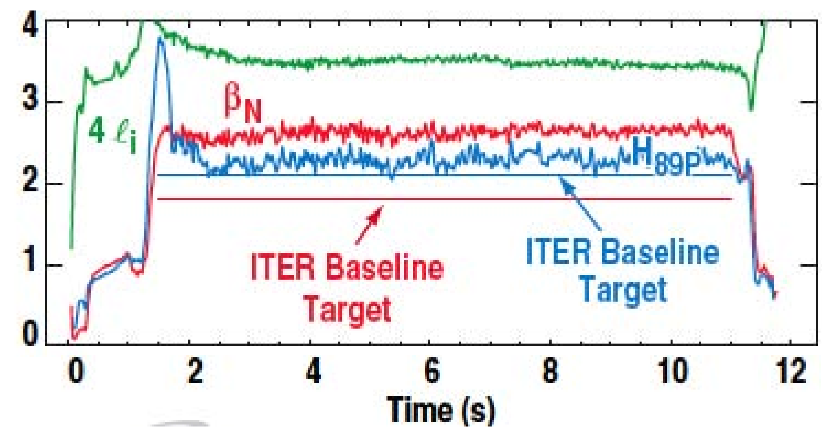


***JT-60U: extended high-β duration =13τ_R**



***DIII-D: 9.5s ITER baseline scenario**
~ 9τ_R, <β>=4%, G~0.55

***JET: 20s reversed shear**



1.2 Long Pulse Operation: Excellent Heat Removal

JET:
- 20s RS, 326MJ

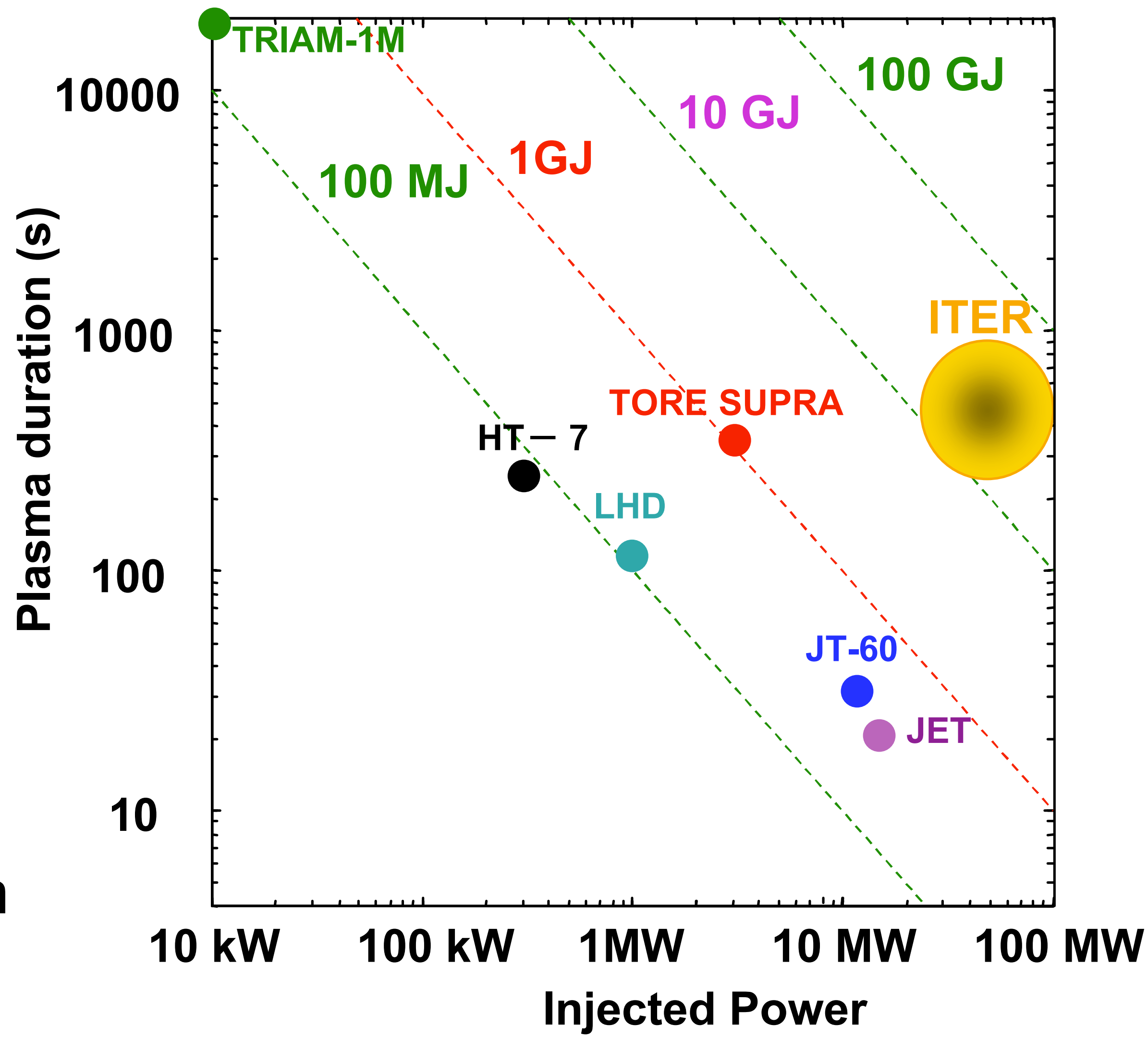
JT-60U:
- 30s ELMy-H, 350MJ

LHD:
- 2min, 115MJ

HT-7:
- 4min, $T_{limiter}$ still rising

TORE-SUPRA:
- 6min, 1GJ

TRIAM-1M:
- 5 hrs, No wall saturation



2. Scenario Optimization & Extrapolation

ITER Baseline Scenario

Long Sustainment: DIIID

Integrated exhaust scenario (Ar + pellet) : AUG, (Ar or N):JET

Steady-state / Hybrid Scenarios

Full CD approaches : JT-60U, DIII-D, JET

WS Long Sustainment: NTM-stabilization: JT-60U, DIII-D, JET, AUG

High Integrated Performance: JT-60U, JET, DIII-D, AUG

High Density & High Radiation: DIII-D, JET, JT-60U

Extension of Improved Regimes

H-mode with small / no ELMs

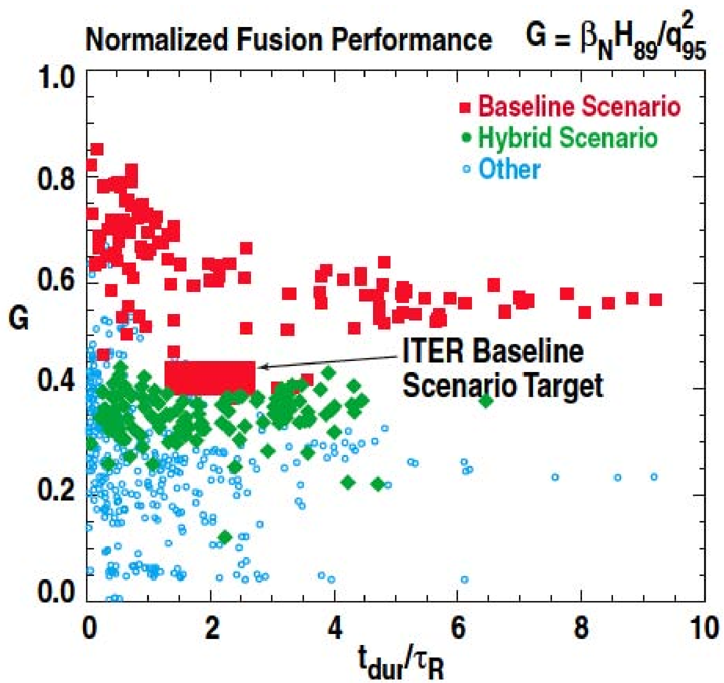
Core Improvement eITB without central heating

etc.

2.1 ITER Baseline Operation

Increased confidence in reaching the ITER performance

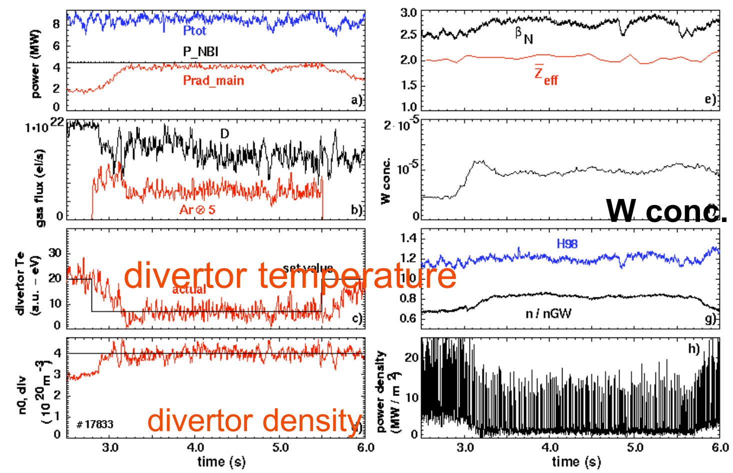
DIII-D: Long sustainment
G~0.55x 9τ_R



Integrated Exhaust Scenario

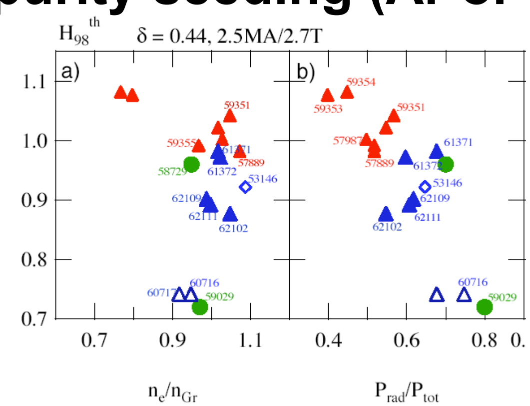
AUG:divertor temperature control by Ar + ELM control by pellet

AUG



JET:impurity seeding (Ar or N)

JET



2.2 Steady-state / Hybrid Scenarios: Full Non-inductive approaches successful

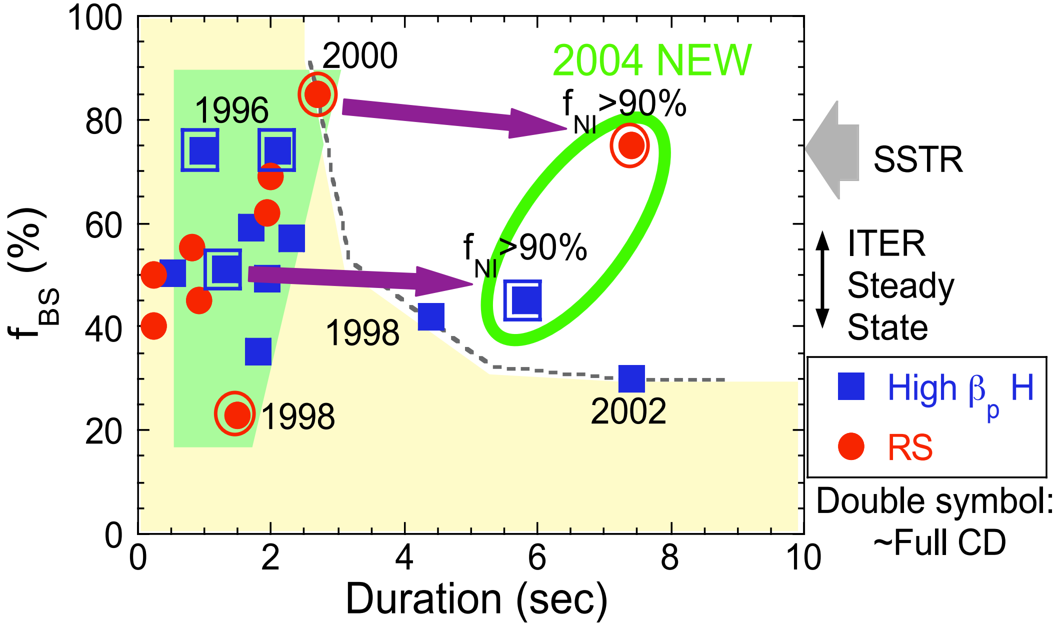
JT-60U (bootstrap+NBCD)

f_{CD}>90%

WS: f_{BS}~45%, 2.8 τ_R

q(r)> ~1.5, q=2 at small ∇ P

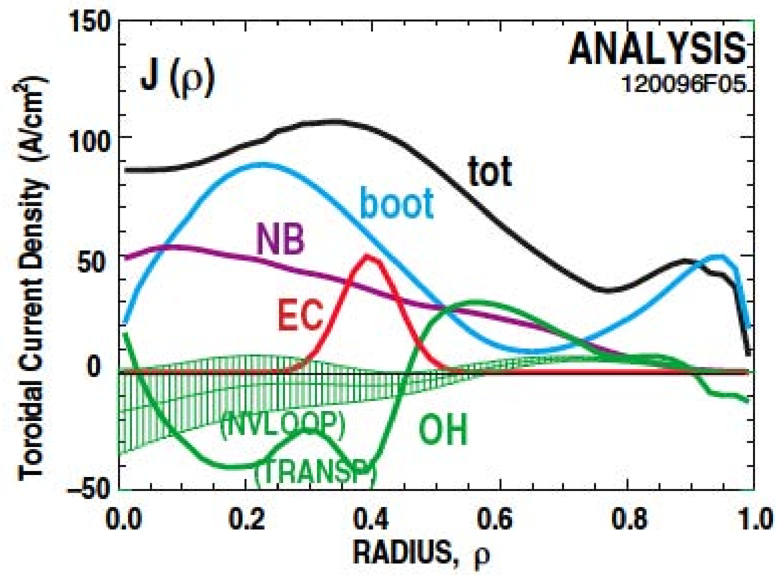
RS: f_{BS} ~75%, 2.8τ_R



DIII-D

(bootstrap+NBCD+ECCD)

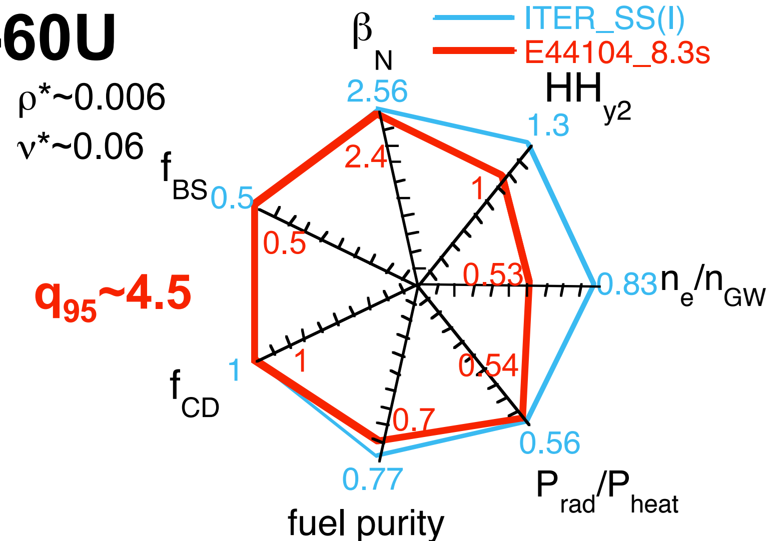
f_{CD} ~100%, β_N<3.5,~1τ_R



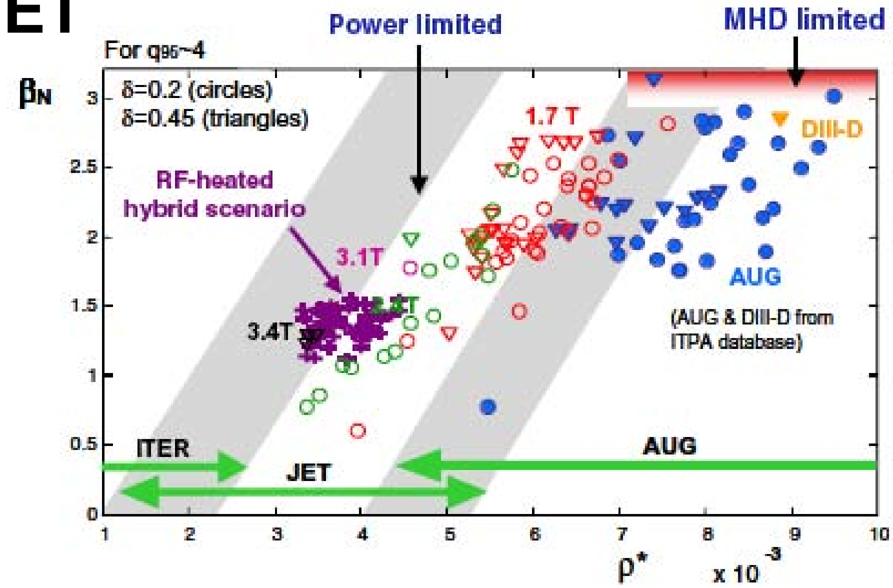
High BS Full CD without inductive current control

2.2 Steady-state / Hybrid Scenarios: Improved Integrated Performance & ITER access

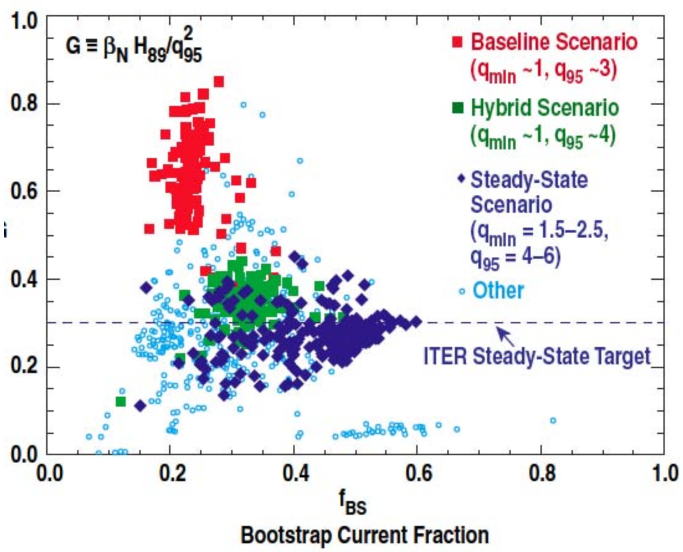
JT-60U



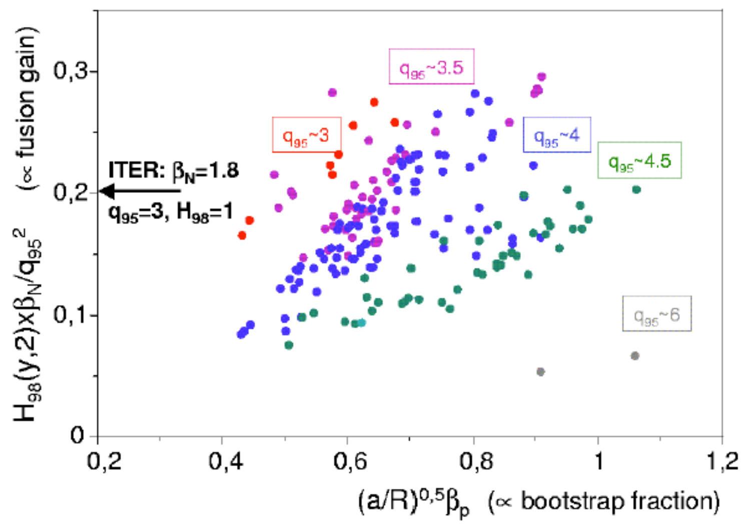
JET



DIII-D



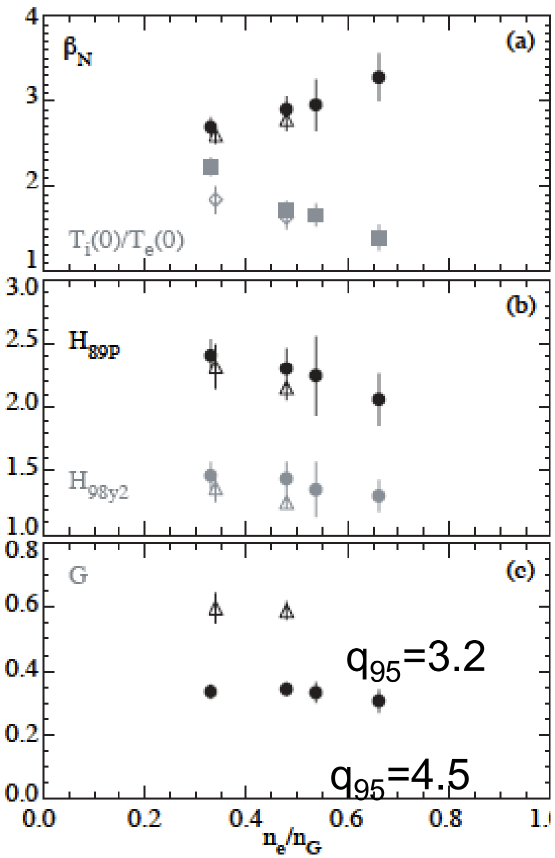
AUG



good probability for achieving high fusion gain in ITER at reduced current (~13MA) with a pulse length longer than 2000s.

2.2 Steady-state / Hybrid Scenarios : Extended to High Density & High Radiation

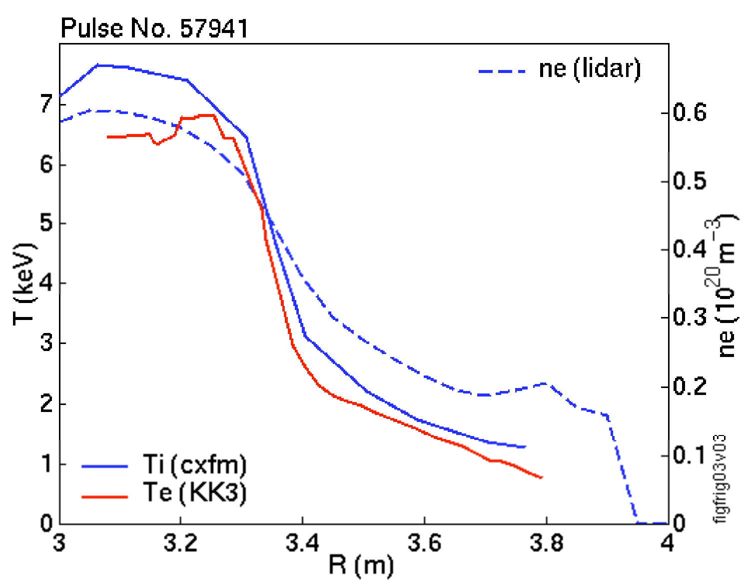
DIII-D



JET

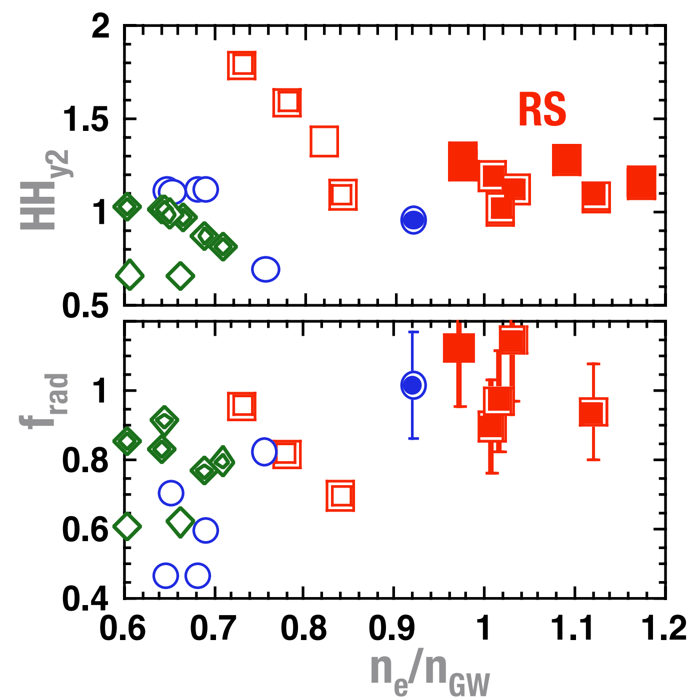
LHCD+Pellet +NBI

=ITB, T_i~T_e, n_{e0}>$\bar{n}_G$, low Rotation



JT-60: n_e/n_{GW}>1, $n_{e(0)}/n_{GW}$ ~1.5

Ne , Ar, D-pellet



2.3 Extension of Improved Regimes

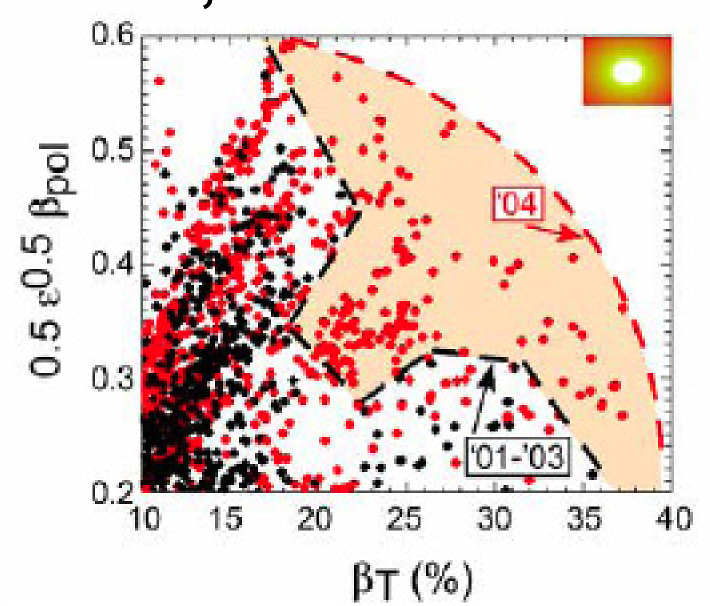
H-mode Improvements

Small - no ELM: AUG, C-Mod, DIII-D,JET, JFT-2M,JT-60U

Low-A MAST: high beta DB, CNTR-NB

NSTX: parametric dependence of confinement established

Helical: CHS, Heliotron-J, Tohoku-Heliac



Core Improvement

Electron ITB without central fueling: TCV, TJ-II

ITB with rotation: MAST

Pellet Enhanced Performance : FTU

2.3 Extension of Improved Regimes(2)

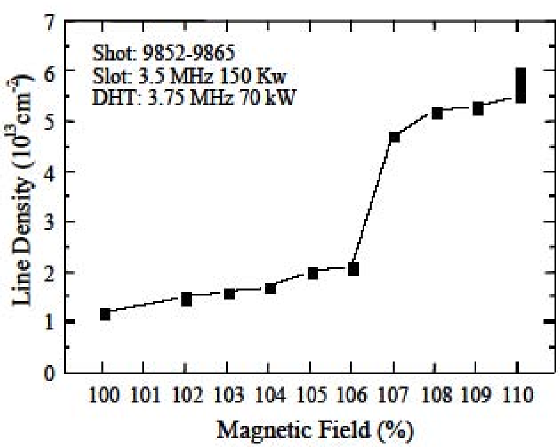
Mirror

HANBIT: A stable high density mode found at $\omega<\Omega_{ci}$.

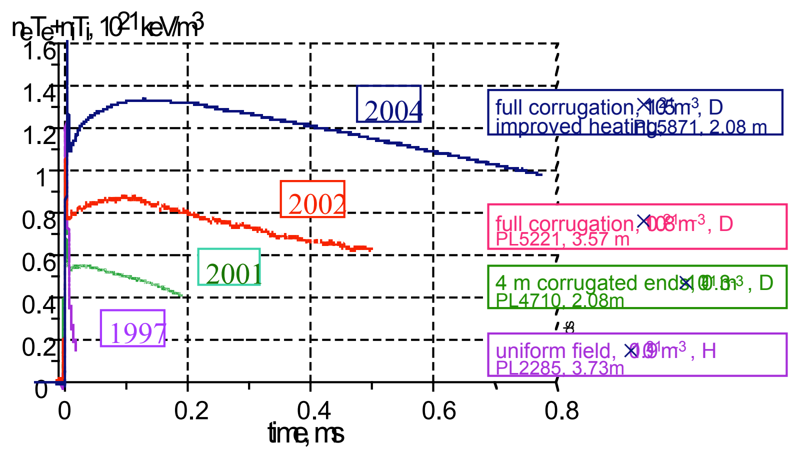
GOL-3: Complete multimirror : $T_e \sim T_i \sim 2keV$ at $10^{21}/m^3$

GAMMA-10: ion-confining potentioal up to 2.1kV

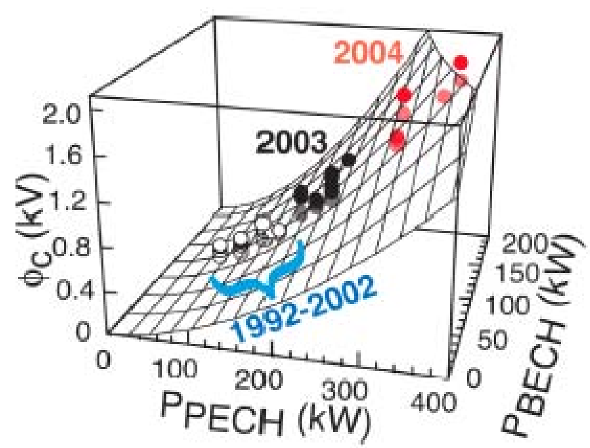
HANBIT



GOL-3



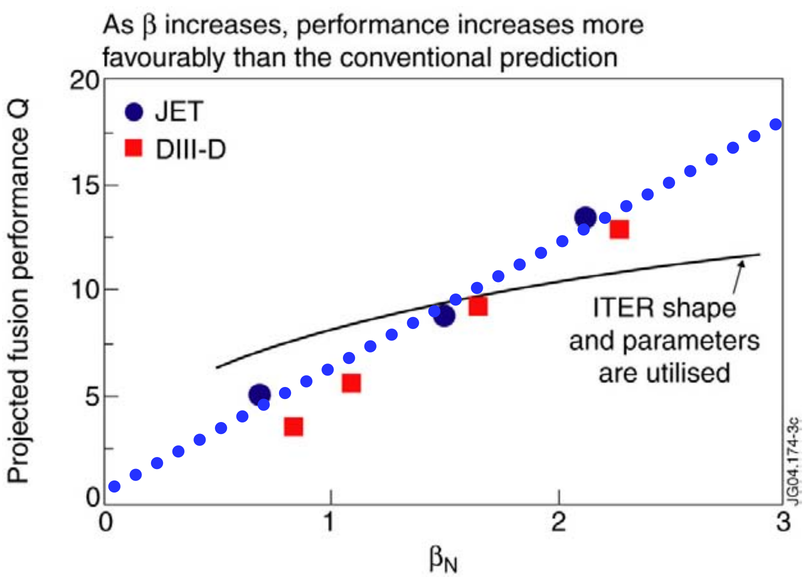
GAMMA-10



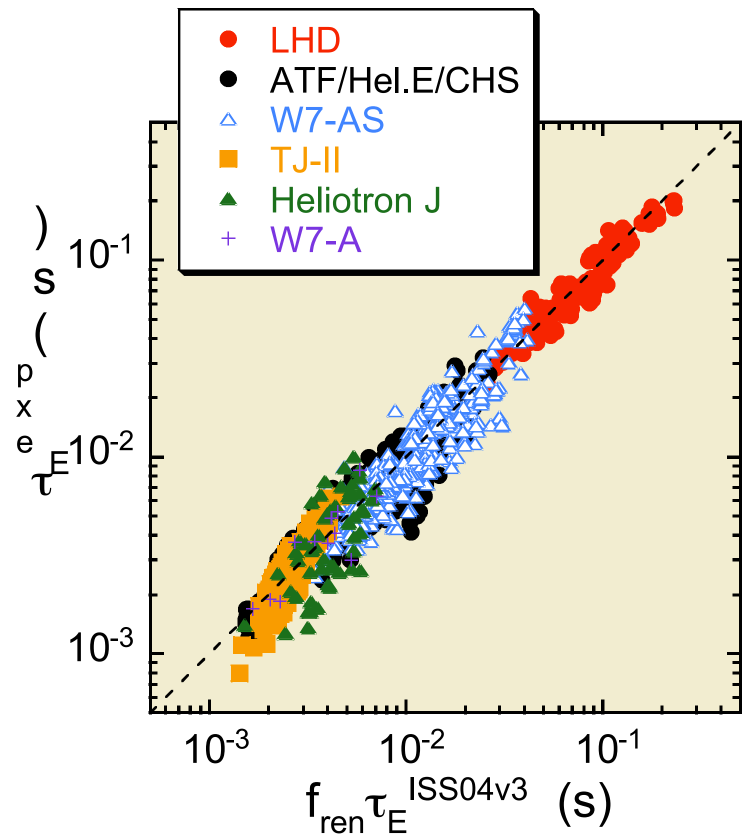
3. Global Confinement Physics

3.1 Scaling Studies of Global Confinement

- **JET and DIII-D: β scan with fixed ρ* and ν* in ELMy H-mode show β independent (electrostatic) energy transport**
- **Would predict improved confinement for high β operation.**

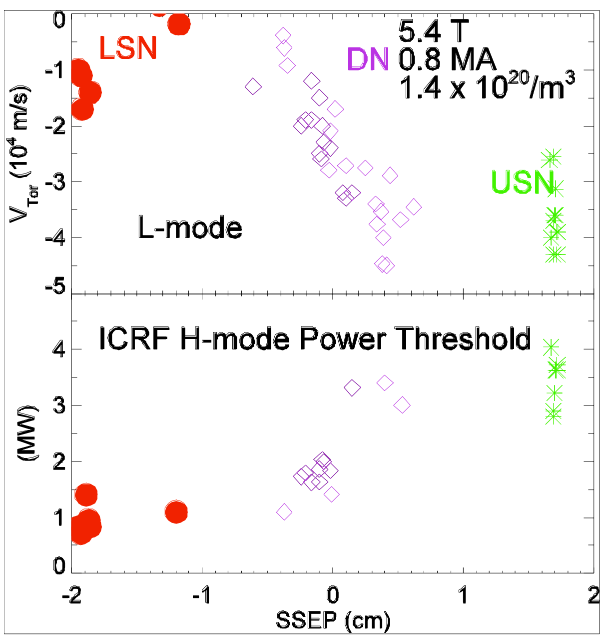


International stellarator database has been extended and new gyro-Bohm scaling has been extracted.

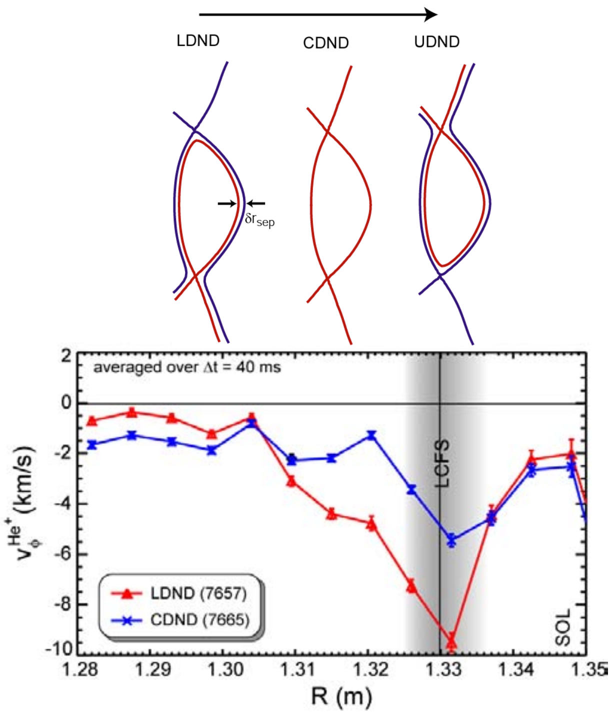


3.2 L/H transition and its power threshold

C-MOD: distance between primary and secondary separatrix has large influence to toroidal rotation and L/H power threshold $P_{L/H}$ (low at LSN).

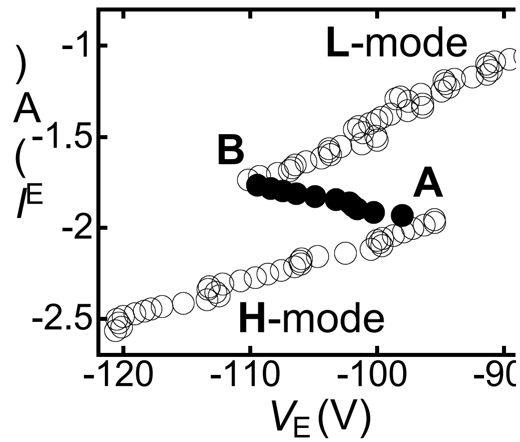


MAST: factor 2 reduction of $P_{L/H}$ in connected DN.



NSTX: HFS gas puffing reduces $P_{L/H}$ (less momentum drag of HFS neutral).

Biased H-mode in TCABR (R=0.615m, r=0.18m) , ISTTOK and TU-Heliac (R=0.48m, r=0.07m).



TU-Heliac

Heliotron J:

H-mode with edge iota windows.

3.3 ITB

Electron ITB (eITB)

MAST: ITB with steep T_e-gradient and peaked n_e profile was formed with counter-NBI where M_ϕ ~ 1 in core.

NSTX: eITB (+ion ITB) formed with early NBI and fast Ip ramp (negative shear).

FTU: high density eITB. T_{e0} up to 5keV at $n_{e0}>1\times10^{20}m^{-3}$ with LHCD+ECRH

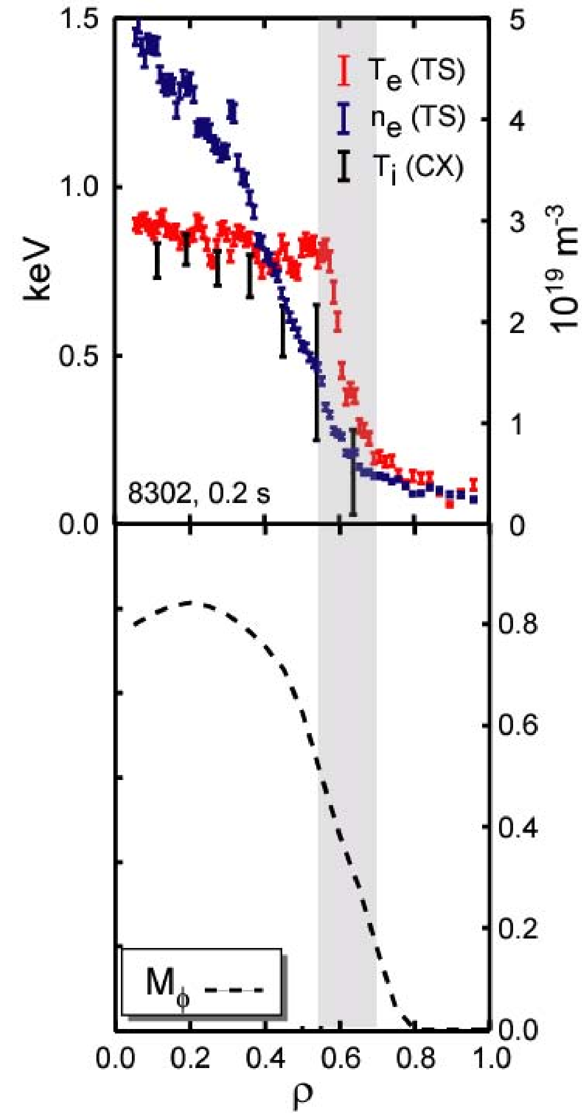
TCV: Control of eITB with inductive CD (negligible power variation).

TJ-II: eITB was formed at low order rational surfaces ($\rho<0.3$) with strong positive Er by loss of ECH superthermal electrons.

JET: ion ITB with small momentum input and ExB shear.

ITB w. no/small momentum input

MAST



4. Transport Physics

4. Transport Physics

Highlighted topics

No.	Topics	Device/paper No.
1	Zonal flow Reynolds stress, GAM, Zonal flow	HT-7, Extrap-T2R JFT-2M, CHS, T-10
2	Electron transport Critical ∇T_e, non-linear $\chi_e \sim (\nabla T_e)^\beta T_e^\alpha$	AUG, JET, JT-60, DIII-D, LHD. TCV
3	Particle transport $G \sim -D[c_q \nabla q/q - c_T \nabla T_e/T_e]$, n_e^* dep.	Tore-Supra, FTU, AUG, JET, LHD, MAST, ET
4	Momentum transport Rotation without torque	Tore-Supra, C-Mod, FTU, DIII-D, TEXTOR
5	Radial electric field E_r control, Flow damping	LHD, GAMMA-10, TJ-II, HSX ISTTOK

4.1 Zonal flow: measurement of Reynolds stress

Direct measurements of Reynolds stress reported from tokamak and RFP

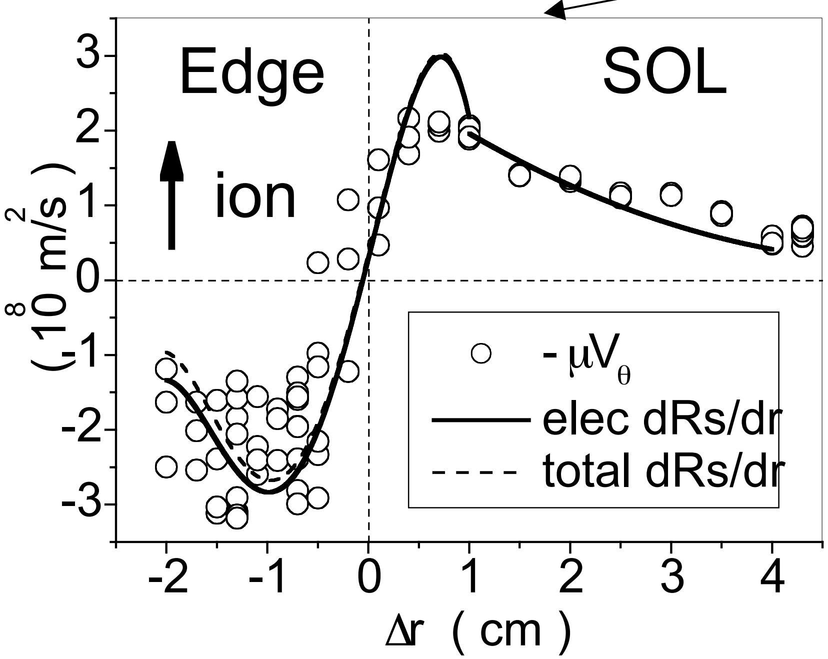
$$\frac{\partial\langle v_E\rangle}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}r^2\langle\tilde{v}_{Er}\tilde{v}_{E\theta}\rangle + \frac{\beta}{n_{eq}}\frac{1}{r^2}\frac{\partial}{\partial r}r^2\langle\tilde{B}_r\tilde{B}_\theta\rangle - \frac{2}{n_{eq}}\frac{a}{R}\langle p\sin\theta\rangle$$

Zonal flow

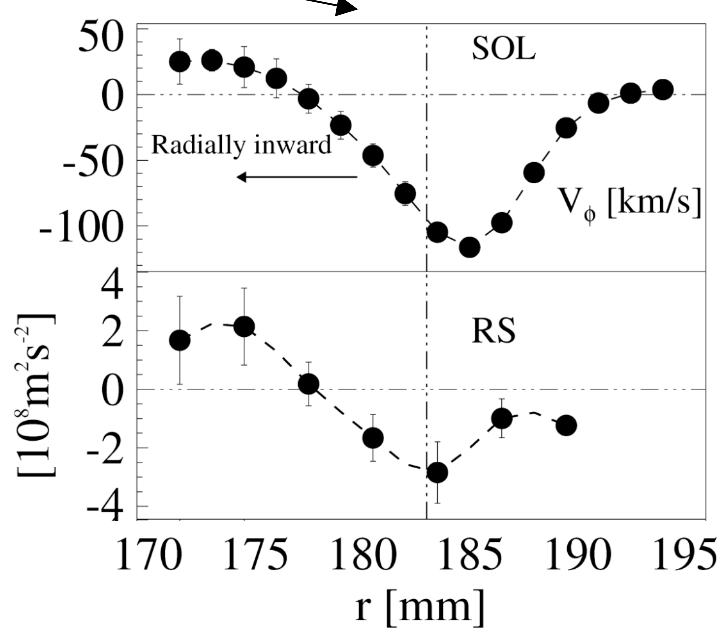
Electrostatic Reynolds stress

Electromagnetic Reynolds stress

GAM term



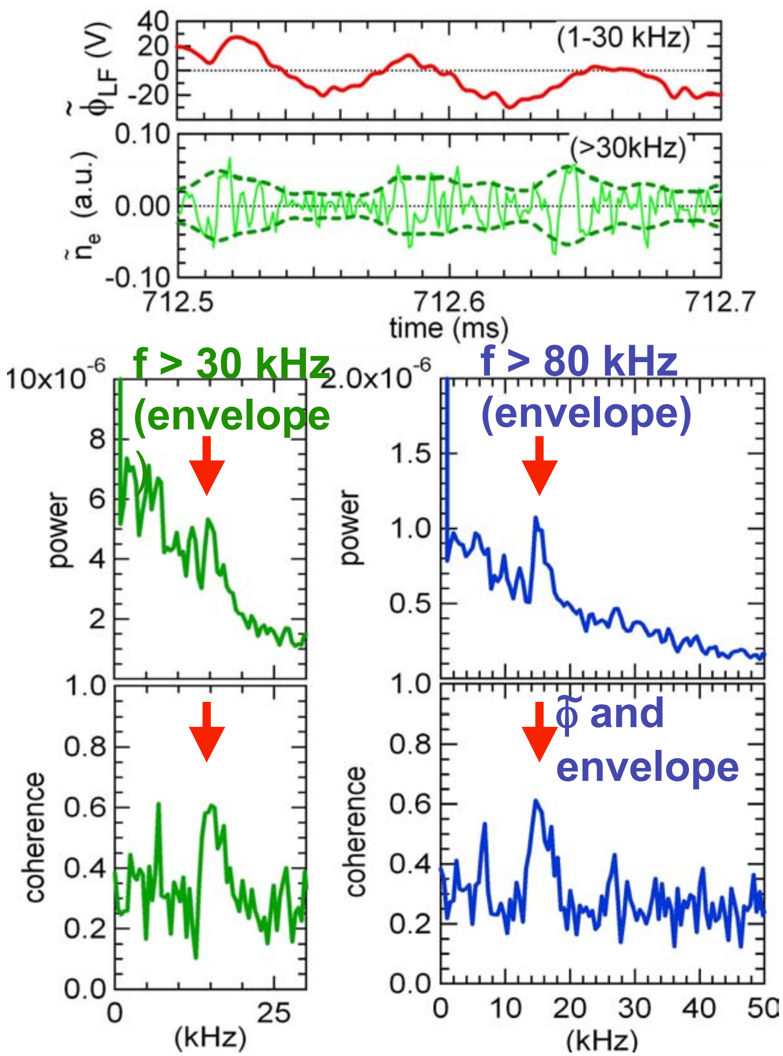
HT-7 (Tokamak)



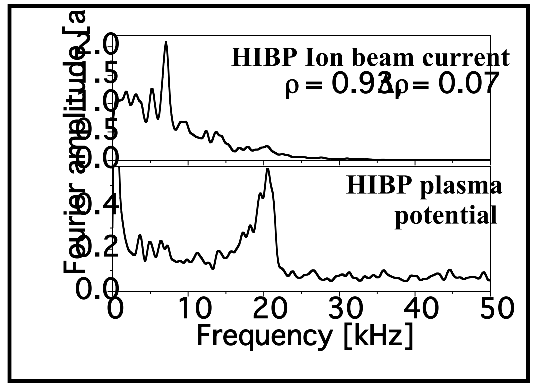
Extrap-T2R (RFP)

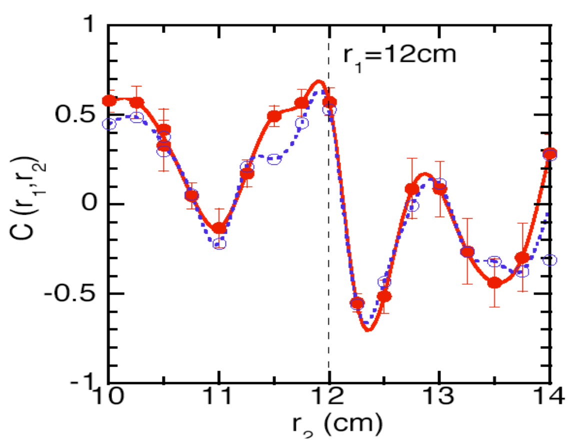
4.1 Measurement of GAM and Low Frequency Zonal Flow

The modulation of $n_{e,ambient}$ correlates with GAM (JFT-2M).



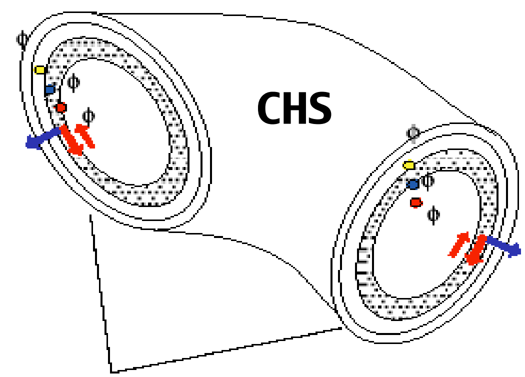
Measurement of GAM (T-10)



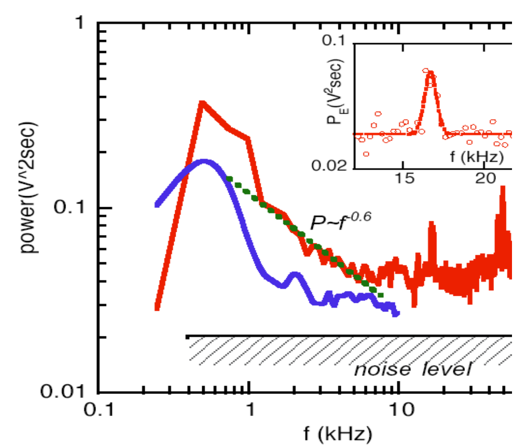


Zonal flow profile

Identification of low frequency Zonal flow (CHS)



Twin HIBP



Zonal flow (f < 1kHz)

4.2 Electron transport: Critical ∇T_e, non-linear $\chi_e \sim (\nabla T_e)^{\beta} T_e^{\alpha}$ (

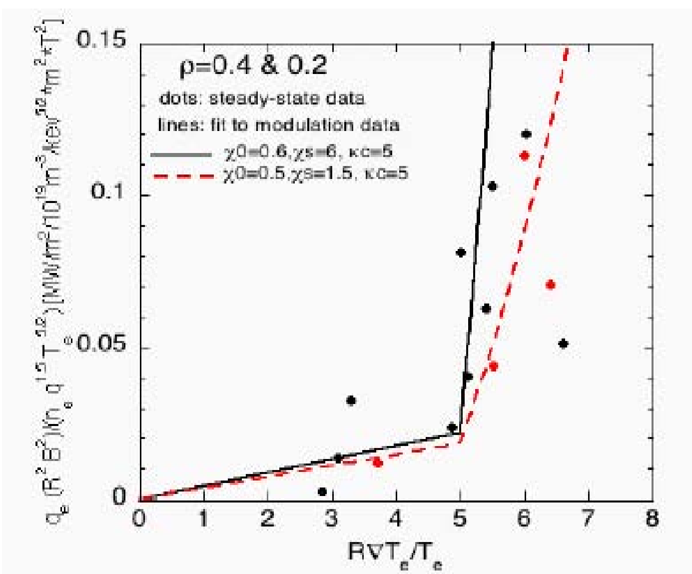
- **Critical ∇T_e**
  JET, JT-60U => YES, DIII-D => NO　　LHD => NO

- **Non-linearity**　　LHD => YES but on Te
  JET, JT-60U => YES, DIII-D => NO

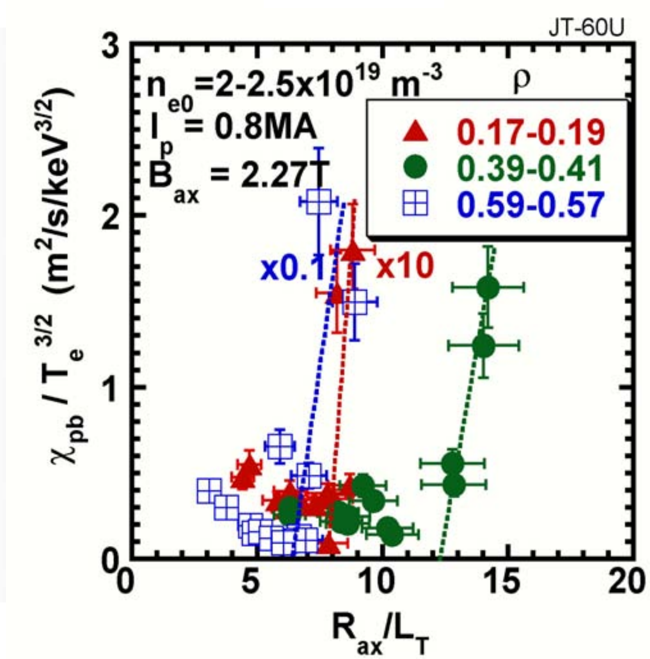
$\chi_e^{tr} = C\, T_e^{\alpha} (\nabla T_e)^{\beta}$

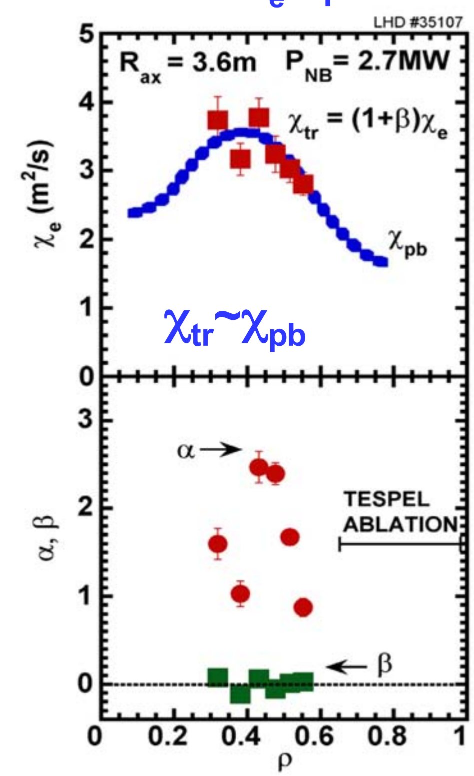
LHD　Strong T_e : $\alpha \sim 1\text{-}2.5$
Weak ∇T_e : $\beta \sim 0$

JET



JT-60U

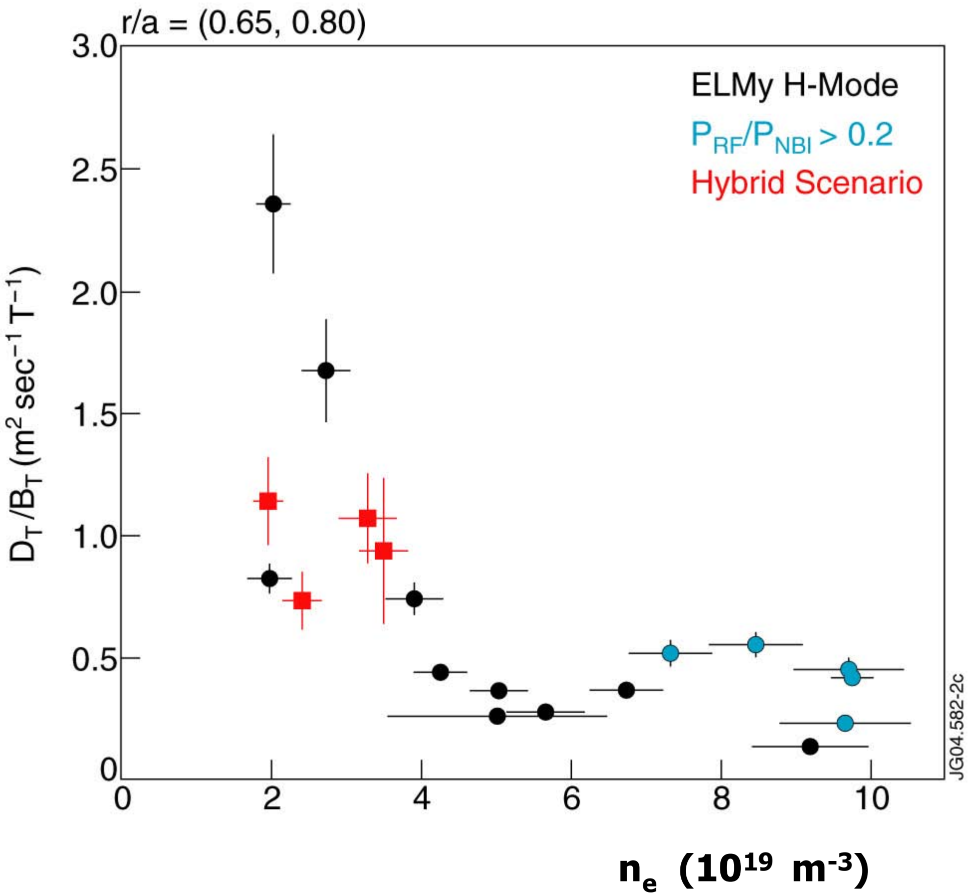




Exp. of effect of plasma shape and shear (TCV)

JET: Thermal Tritium transport

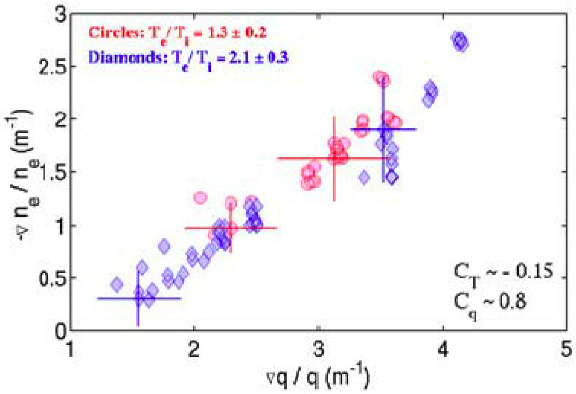
- **Turbulence dominates thermal particle transport for most regimes**
  - –Large inward v_T correlates with high D_T
  - –Neo-classical only for : high n_e ELMy H & in ITBs.
- **Dimensionless parameters scans show:**
  - –Gyro-Bohm particle transport ($D_T \sim \rho^{*3}$) for Inner plasma;
  - –Bohm particle transport ($D_T \sim \rho^{*2}$) for Outer plasma;
  - –when q scans are included scaling is more like Gyro-Bohm in outer plasma ($D_T \sim \rho_{POL}^{*3}$; $\rho_{POL}^{*} = q \times \rho^{*}$);
  - –particle transport has an inverse β and ν^{*} dependence.

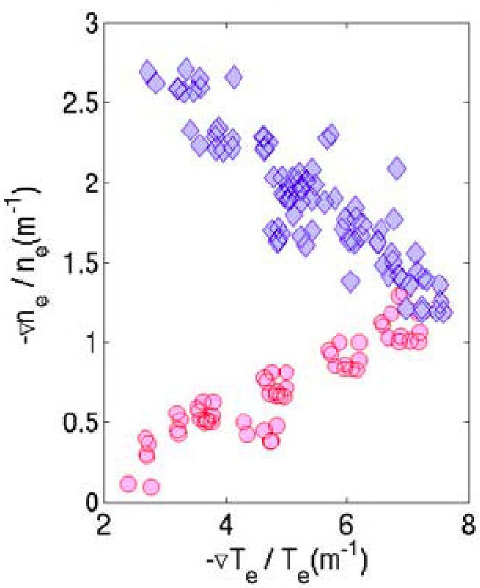


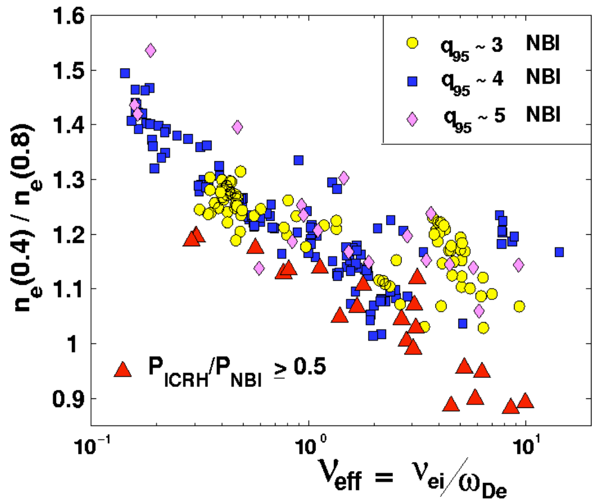
Non-ITB dataset D_T/B_T vs density

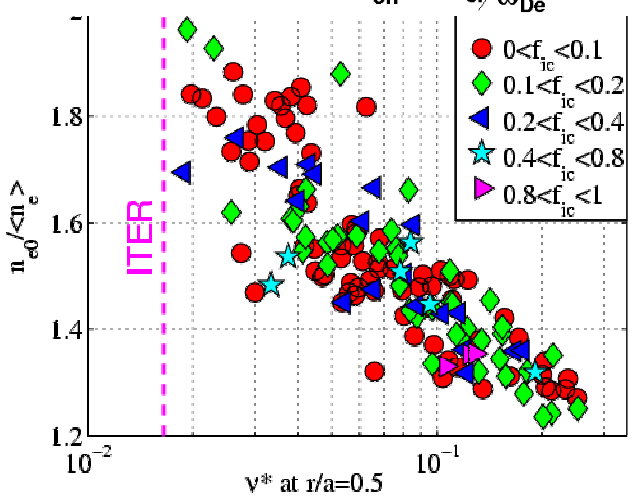
4.3 Particle transport: dependent on $1/L_T, 1/L_q, \nu_e^*$

- **Evident turbulent pinch observed in Tore Supra and FTU.**
  Both the thermodiffusion (∇Te/Te) and curvature (∇q/q) pinches co-exist.
- **Density peaking increases with decreasing collisionality, consistent with quasi-linear ITG/TEM model (AUG, JET)**









⇒ could lead to higher fusion power in ITER

Confirmation of extrapolation to ITER requires further experiments.

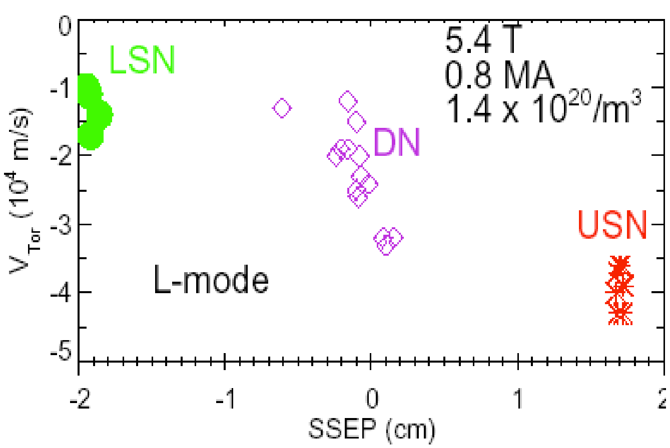
Concern for mpurity accumulation (JT-60U, JET and AUG)

4.4 Momentum transport : Rotation without torque

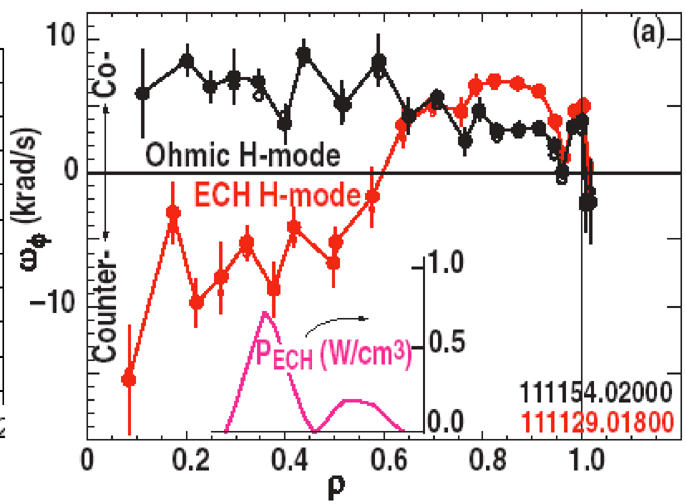
- **Rotation without torque is important for transport and stability (RWM).**

⇒ More reports of rotation without torque input (C-mod, DIII-D, TEXTOR, Tore Supra)

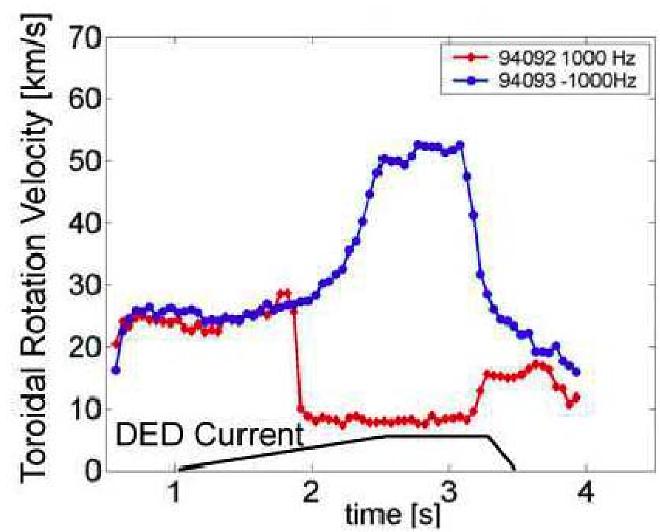
C-Mod: rotation changes with USN,LSN (ICRF)



DIII-D: CTR rotation with ECH



TEXTOR: control by 3/1 DED



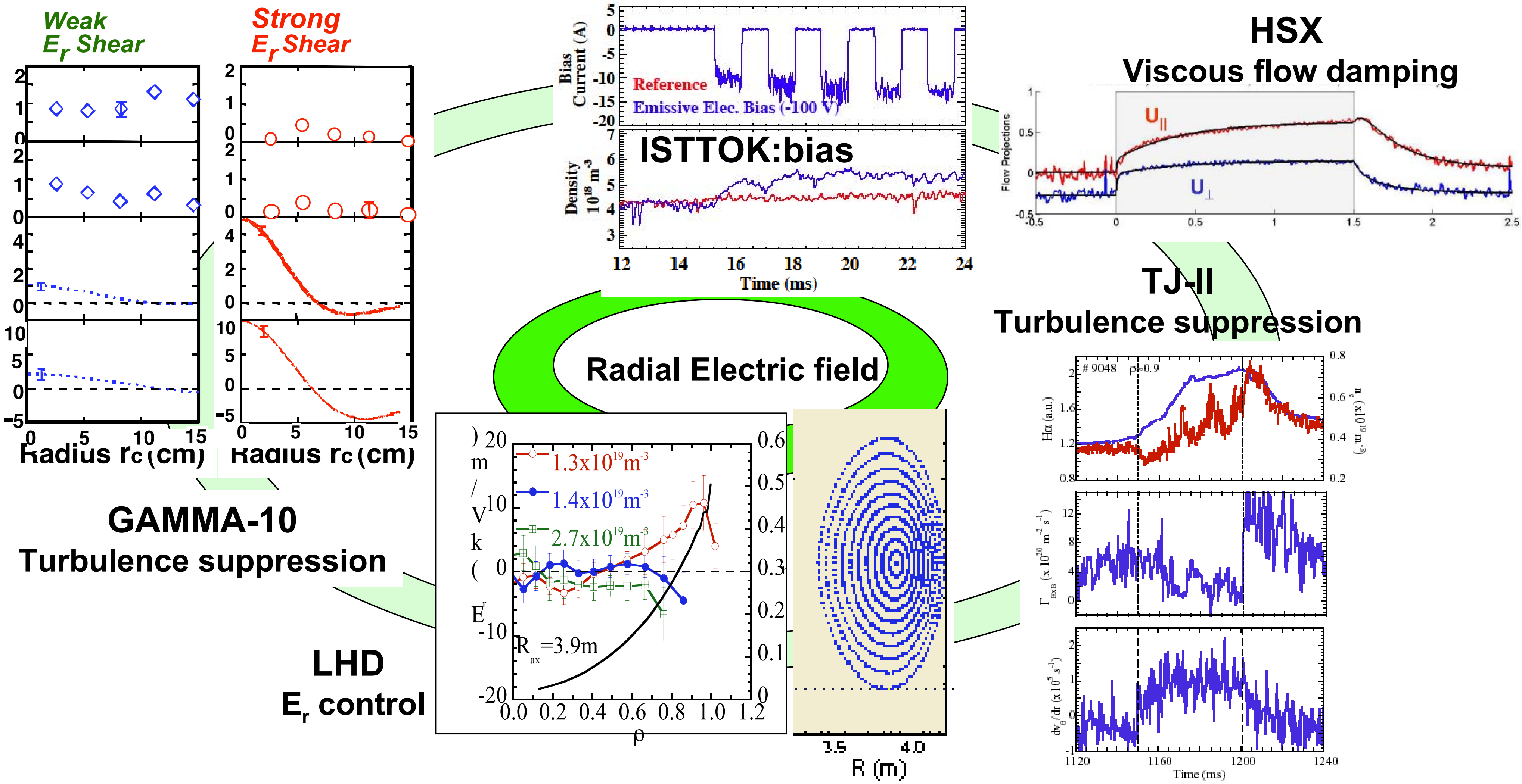
Tore Supra
Co-rotation ~ 80km/s

Cf. AUG; -400km/s for QH mode with counter NBI

4.5 Radial electric field

E_r control, flow damping

Combination of magnetic geometry with E_r produce interesting phenomena (Gamma-X, LHD, TJ-II, HSX, ISTTOK)

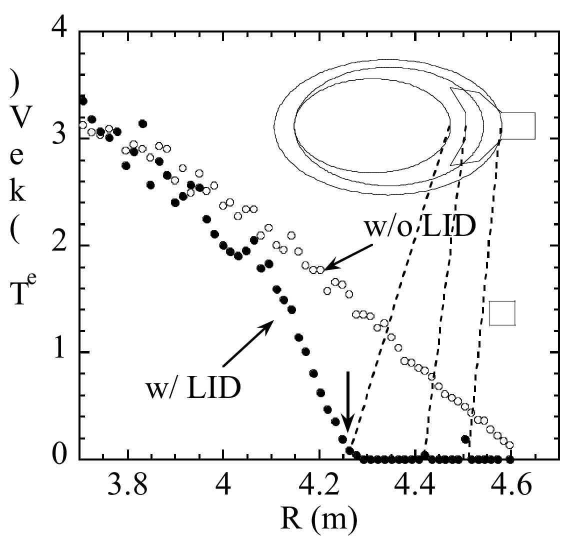


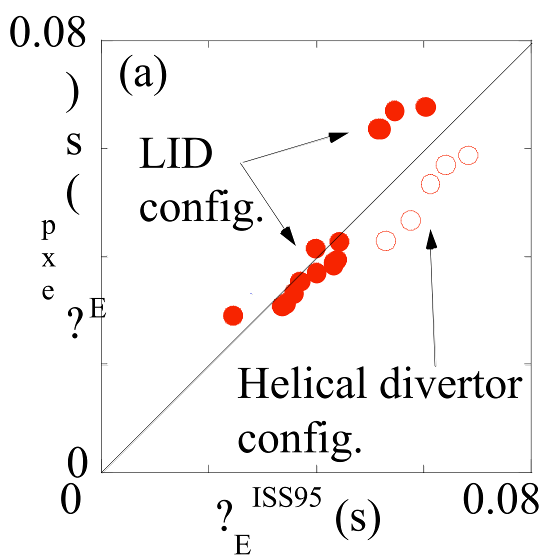
5. Plasma-wall Interaction

5.1 Active Control of Edge Plasma

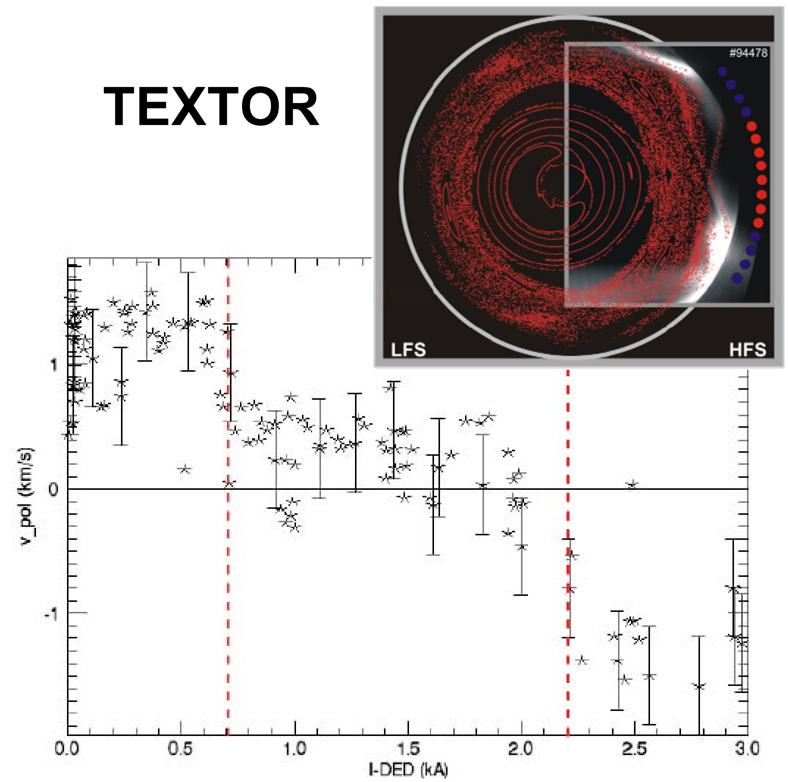
- Higher confinement of τ_E=1.2 τ_E^{ISS95} due to sharp edge (large Te gradient) with a Local Island Divertor (LID) in LHD
- Onset of 2/1 and 3/1 tearing modes by Dynamic Ergodic Divertor (DED) and reduction of the edge poloidal rotation.
- Configuration effects (USN, DN, LSN) on particle control in DIII-D

LHD



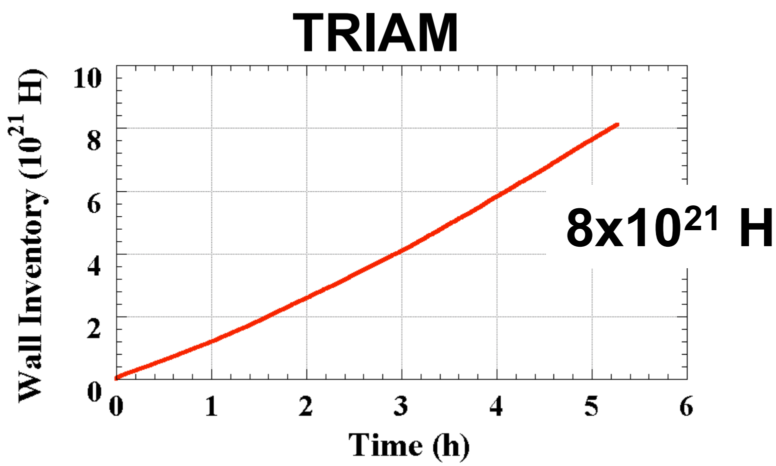


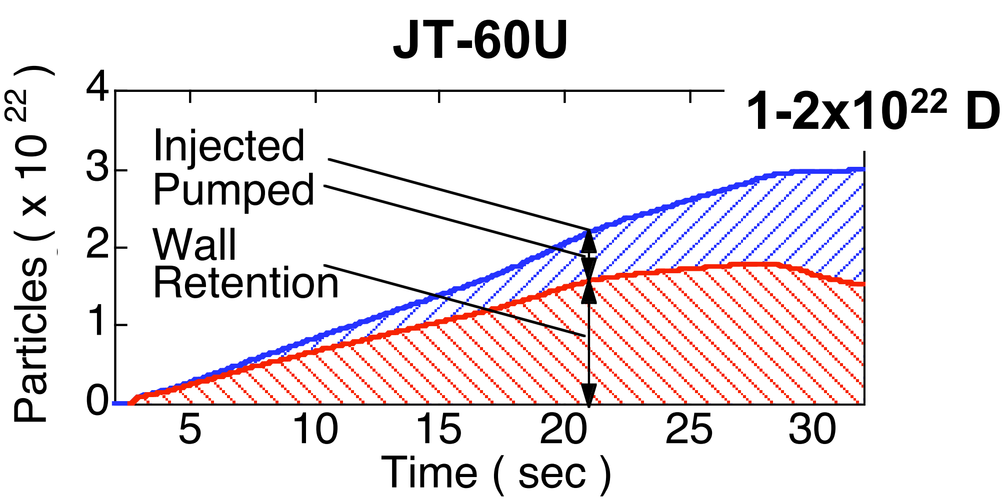
TEXTOR

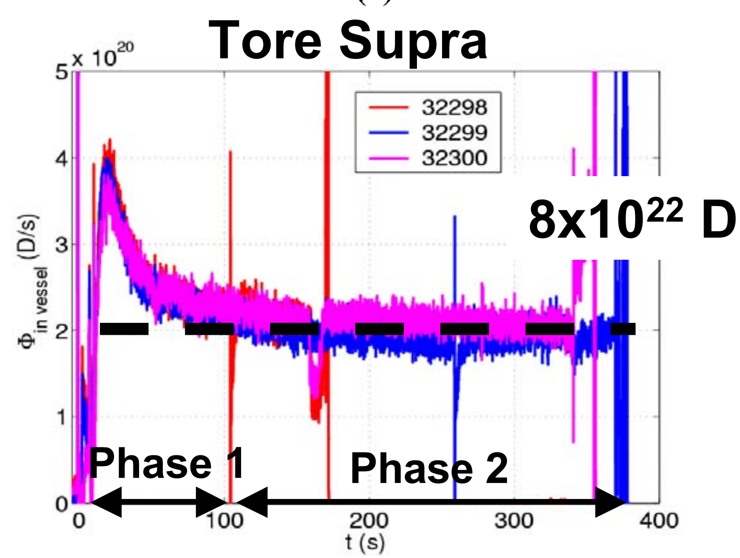


5.2 Recycling/Wall retention

- Wall saturation in JT-60U (30s NB heating, T_{vv}=150, 300°C)
- No wall saturation in TRIAM (5h 16min, T_{vv}=30-40°C) and Tore Supra (6min., $T_{Limiter}$=120°C)
- Wider retention area than the area directly interacted with plasma (JT-60U, TRIAM, Tore Supra, JET, ASDEX-U. TEXTOR).

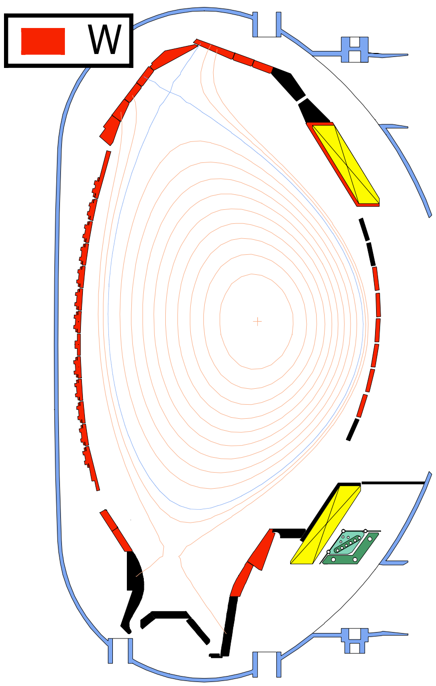


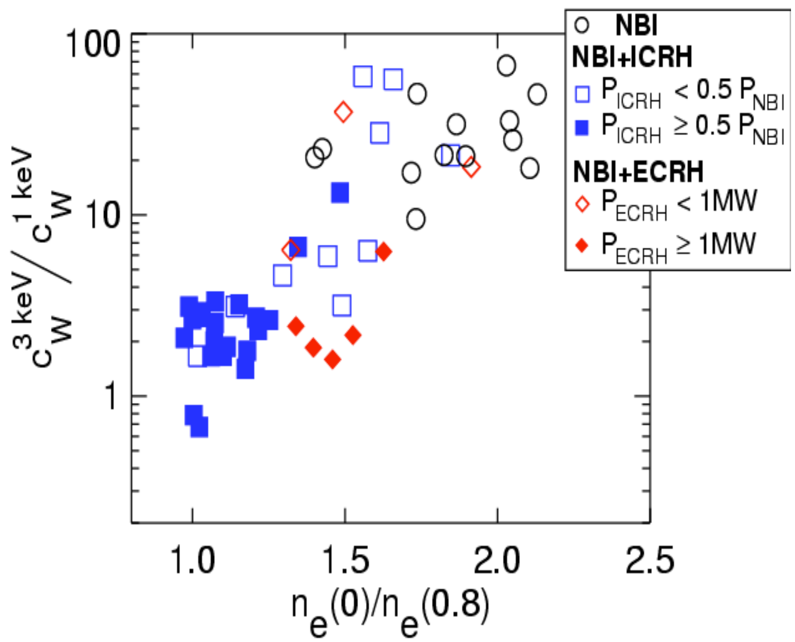


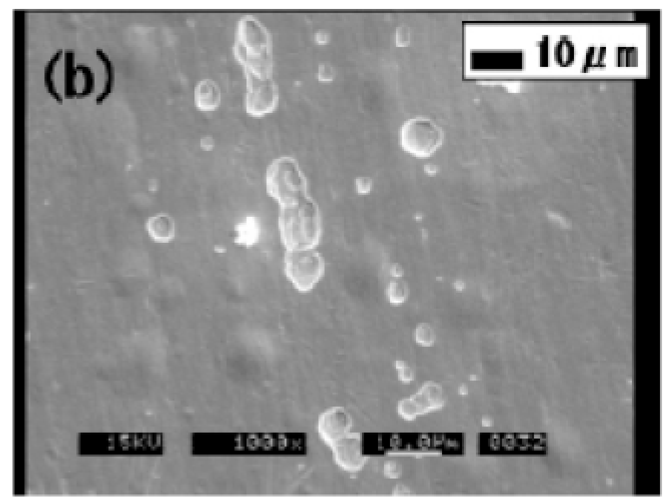


Tungsten Wall

- 65% of all PFC are W coated in ASDEX.
- High performance discharge with moderate W concentrations feasible.
- W concentration is controllable with central ele. heating and pellet triggering of ELMs
- Blisters and bubbles are formed on the surface of W irradiated with low energy (~100 eV) H beam





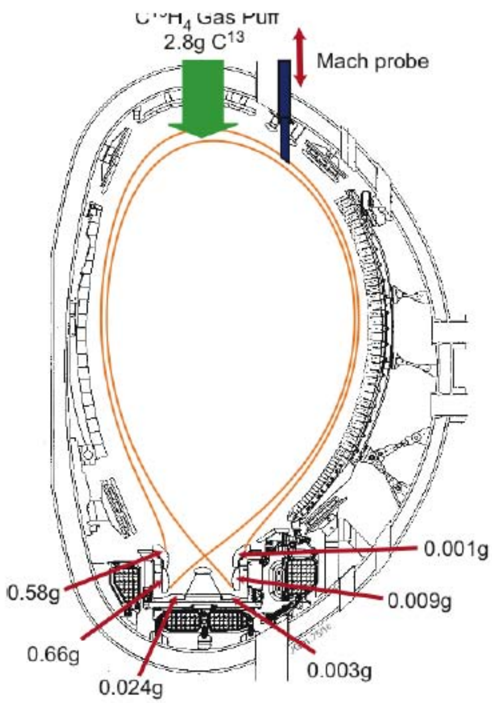


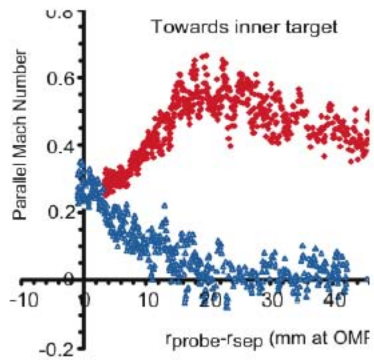
Further experiment in large tokamaks with high power heating

Carbon Migration

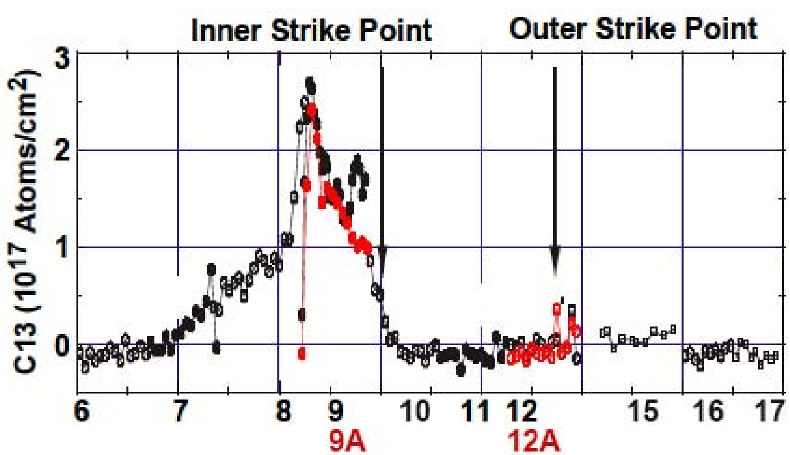
- C migration toward the inner target and its main origin is main chamber (DIII-D, JET, AUG, JT-60U)

$^{13}CH_4$ injection exp.



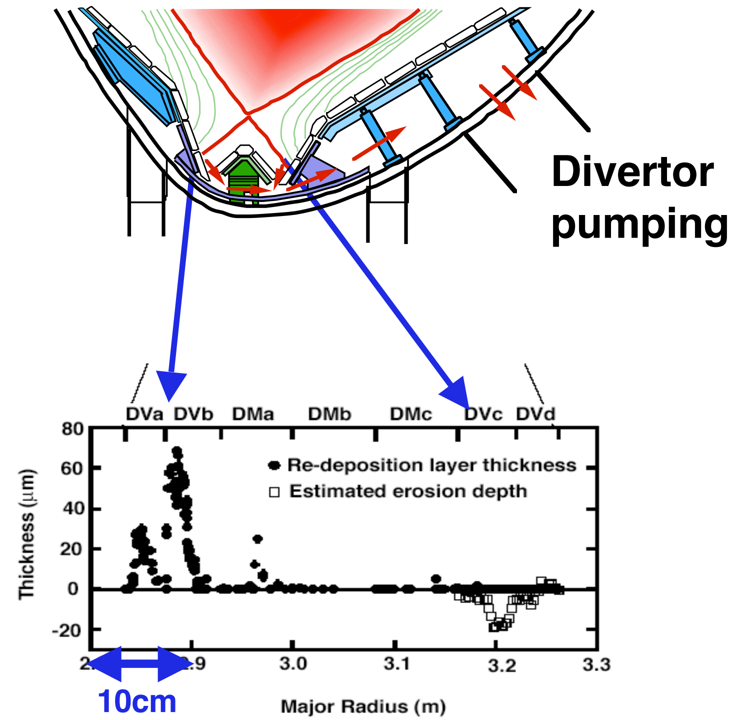


JET



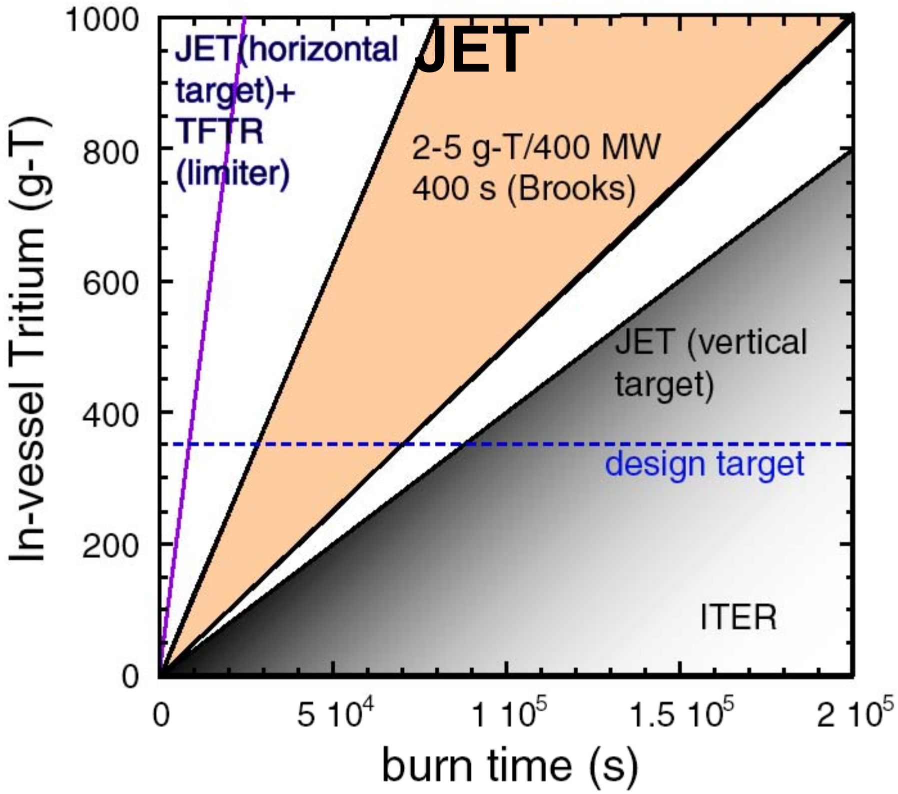
DIII-D

SEM analysis

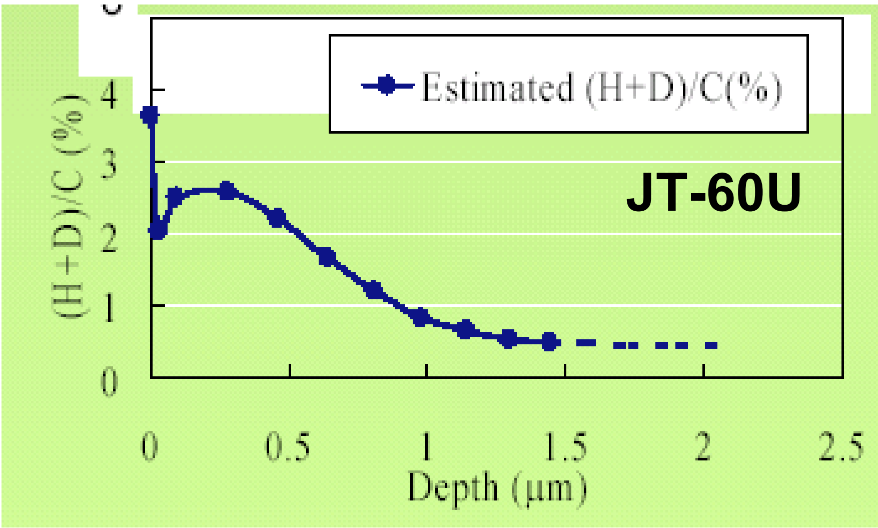


JT-60U

Tritium Retention



	T(D) retention	D/C	dust
JET	3%	0.4 - 1.0	1 kg
ASDEX	3%	0.4 - 1.0	
JT-60		<2%	7 g



T retention much lower with vertical target in JET: Geometry effect?

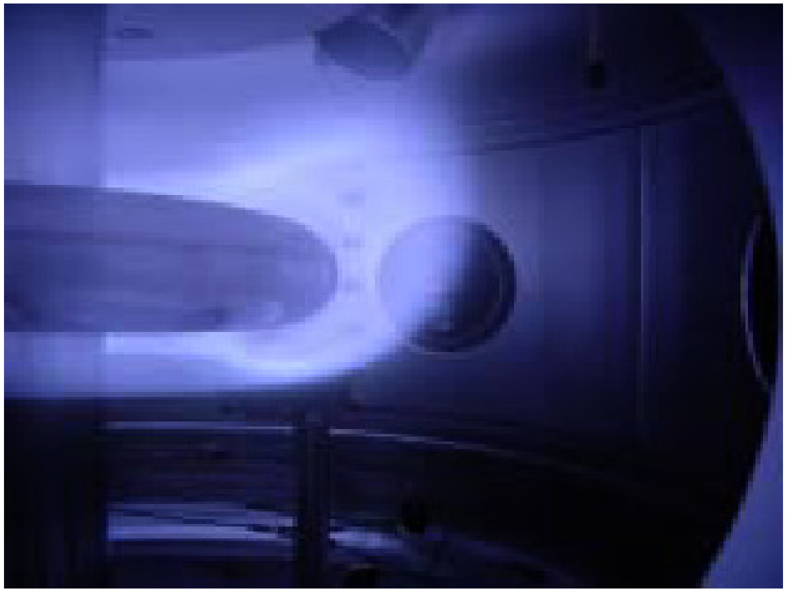
D/C ratio and dust much lower in JT-60: better alignment? Higher temperature?

6. Innovative Confinement Concepts

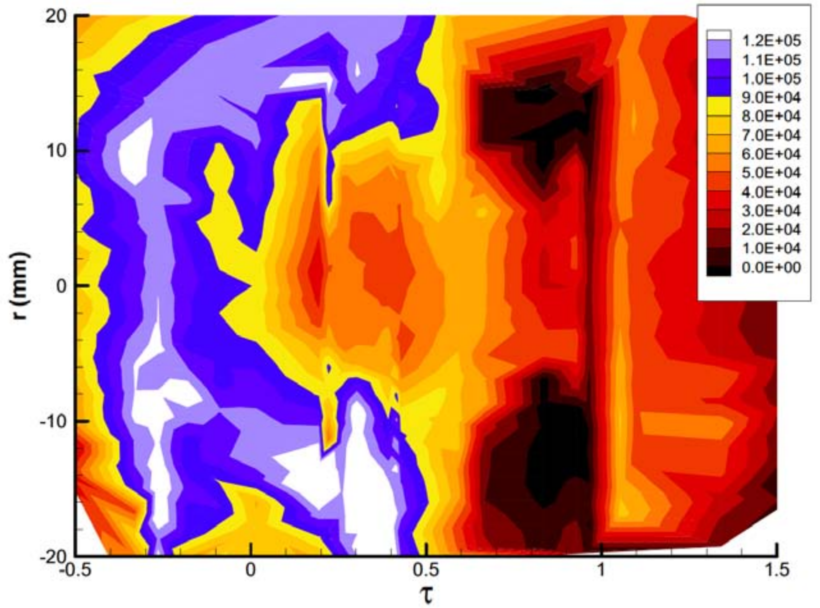
6 Innovative Confinement Concept

Experiments:

- SC levitated internal ring in ECH heated plasma on Mini-RT
- Measurement of axial flow shear in the ZaP flow Z-pinch
- CD by Helicity injection in the HIT-II & HIT-SI
- FRC plasmas, produced and sustained by the RMF, and for MTF (FRX-L, TCS)
- Sequence of spheromak formation (CALTECH), supersonic rotation with centrifugal confinement (MCX)



Mini-RT

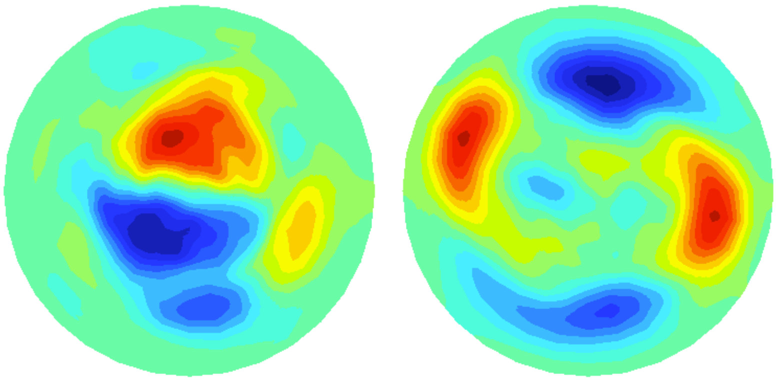


Axial flow shear in ZaP flow Z-pinch

6 Innovative Confinement Concept

Numerical studies:

- Nonlinear evolution of MHD instability in FRC
- Design of magnetic measurement for 3D equilibrium and model of ambipolar plasma flow for NCSX
- Simulation of liner compression using two fluid model
- Optimization of quasi-poloidal stellarator



$t = 60t_A$ $t = 76t_A$

Rotational mode in FRC

New Concept:

- Burning spherical tokamak by pulsed high-power heating of magnetic reconnection
- Selective heating using LH for He ash removal
- Solenoid-free start-up for spherical torus using outer poloidal field coils and conducting center-post
- Spherical tokamak configuration using spherical snow-plug

I am very much pleased that fusion community has made significant progress in confinement and plasma-wall interaction research areas. These results will greatly contribute to ITER.