Summary:

Innovative Confinement Concepts, Operational Scenarios, and Confinement

22nd IAEA Fusion Energy Conference

by

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Key themes of this presentation

- **ITER is our next major fusion energy experiment**
  - ITER's success is our priority
- **Substantial progress has been made in establishing operational regimes required for success of ITER**
  - Many exceed requirements for ITER
- **Understanding of transport is important for confident projection and optimization of all magnetic confinement schemes**
  - Key element is validation of theory and modeling by experiment

Outline

Topical area	Number of papers
Innovative Confinement Concepts	13
Operational Scenarios	16
Confinement experiments	
Particle transport	8
Rotation and momentum transport	10
Energy transport and turbulence	42
L-H transition and pedestal	7

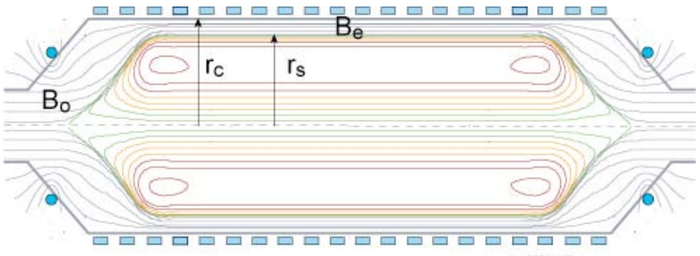
Innovative Concepts Research Is Focused on Novel Solutions to Fusion Challenges

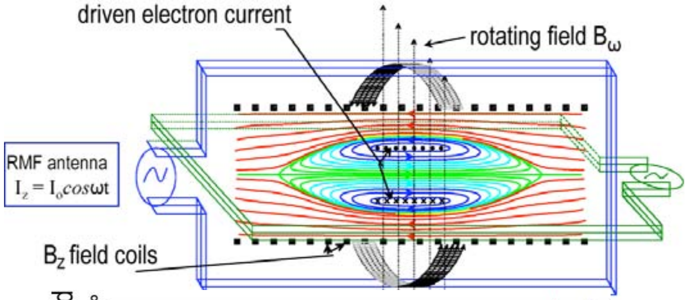
- 13 papers addressing a wide range of topics
  - ✓ Field Reversed Configurations (simply-connected, no TF coils)
  - ✓ Spheromak (simply-connected, no TF coils)
  - – Magnetic mirror (possible neutron source for component testing)
  - – Plasma focus (hot-dense plasma fusion neutron and x-ray sources)
  - – Magnetized Target Fusion for HEDLP (High Energy Density Laboratory Plasmas)
  - ✓ Levitated dipole (high-beta stability and confinement)
  - – Design study for direct- energy conversion
  - ✓ Alternative divertor materials and configurations (power handling and particle control)

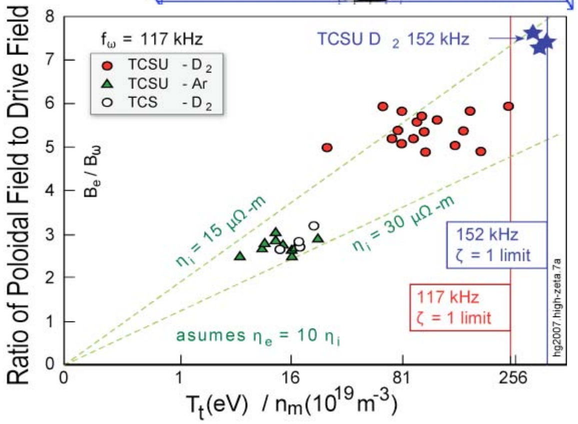
- Progress and excellent science in every area

Field-Reversed Configuration and Spheromak Experiments Are Exploring Sustainment Physics

TCS-U FRC with RMF Drive



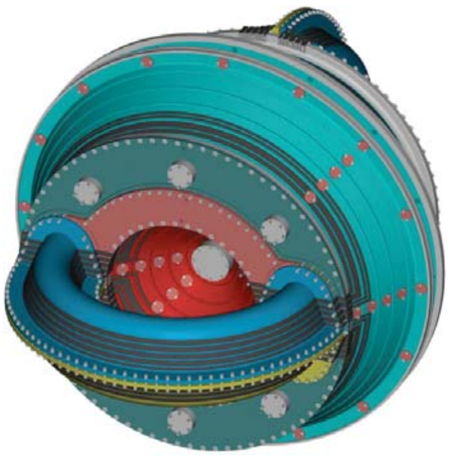


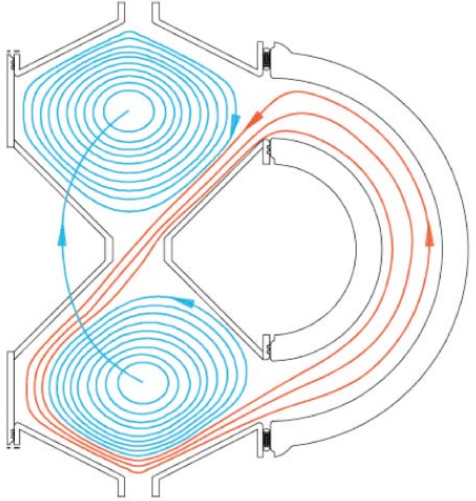


- Sustained FRC
10 msec 250eV

Hoffman, et al. IC/P4 - 1

HIT-SI AC-driven spheromak experiment

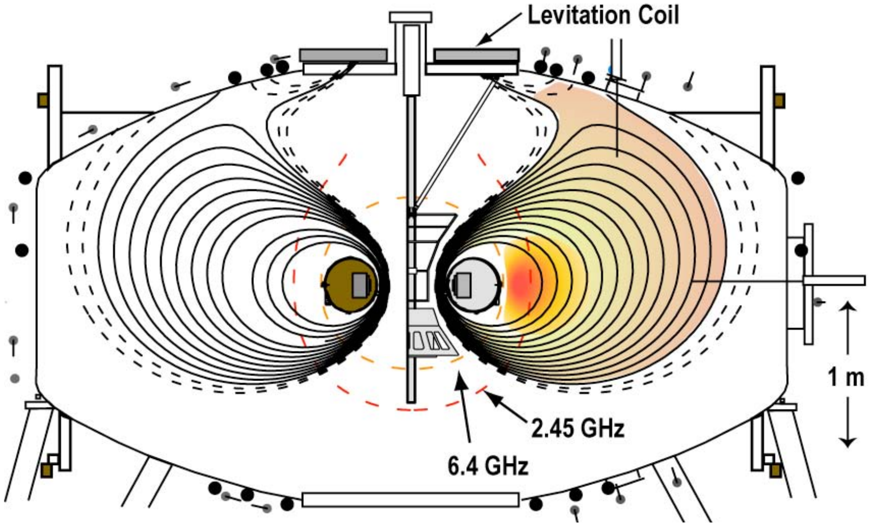


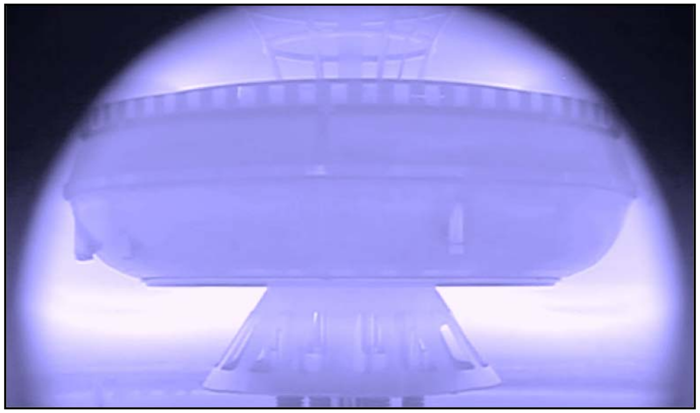


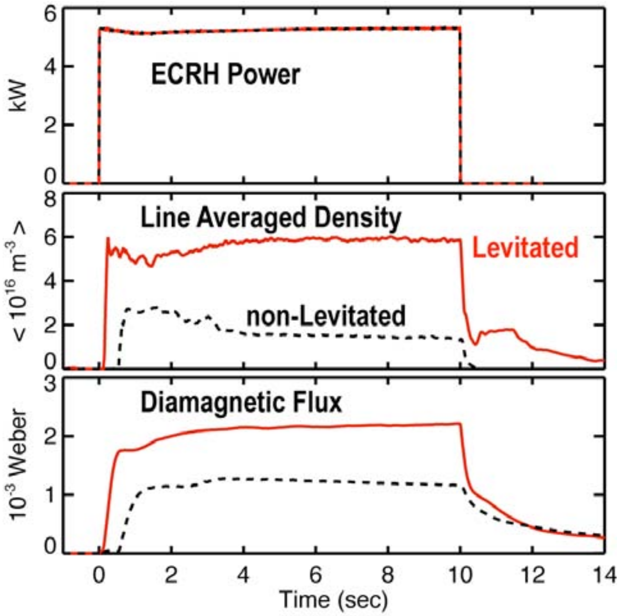
- Two AC injectors 90^0 out of phase yield constant helicity injection:
- 34kA spheromak current

Jarboe, et al. IC/P4 - 5

Levitated Dipole Experiment: High-beta Plasma Confined With Fully Levitated Coil





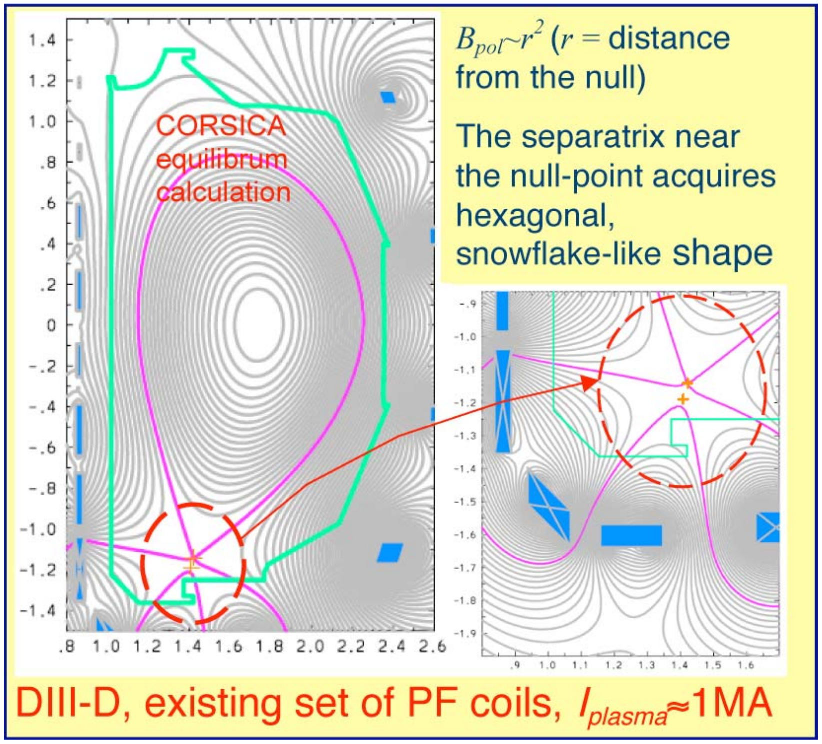


- Increased hot-electron stability
- Density profile varies as expected for marginal stability ($n \propto 1/Vol_{\text{flux tube}}$)
- Fluctuation studies now underway

Garnier, et al. IC/P4 - 12

New Divertor Configurations Seek to Reduce Peak Heat Flux and Improve Edge Stability

“Snowflake” second-order field null



CORSICA equilibrum calculation

$B_{pol} \sim r^2$ (r = distance from the null)

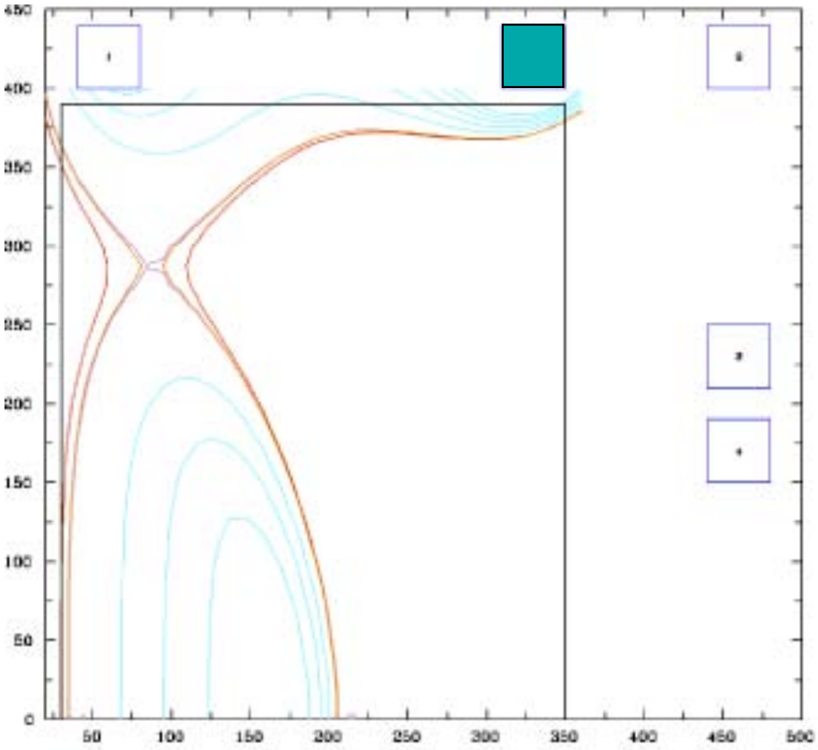
The separatrix near the null-point acquires hexagonal, snowflake-like shape

DIII-D, existing set of PF coils, $I_{plasma} \approx 1$MA

- Increased shear in pedestal (ELMs)
- Increased connection length

Ryutov, et al. IC/P4 - 8

“Super-X” Divertor for an ST-CTF



- Increased area, reduced heat flux
- Increased connection length

Kotschenreuther, et al. IC/P4 - 7

Operational Scenario Development Continues Preparation for Burning Plasma Operation

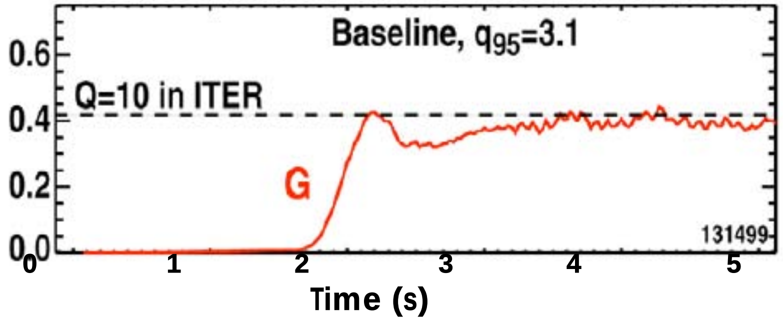
- **ITER scenario development has advanced significantly**
  - Startup scenarios improved
  - ELMing H-mode for Q=10 demonstrations
  - Advanced scenarios lead toward improved performance and long pulse operation
- **Steady-state fusion optimizations are underway**
  - Tokamak experiments reach 100% bootstrap current
  - Stellarator performance improvement seen by configuration optimization
- **Work is starting on the tremendous challenge of coupling the burning plasma core to boundary solutions required for long lifetime of the plasma facing components**

Substantial Progress Reported on the Development and Characterization of Operational Scenarios

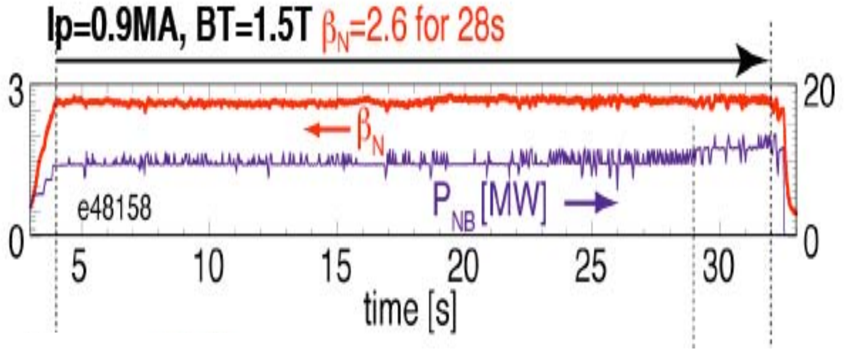
- **Baseline**
  - Reference operating case
  - Q=10 at 15 MA, $\beta_N \approx 1.8$, $q_{95} \approx 3$
- **Advanced inductive**
  - High fusion gain
  - Q=30 at 15 MA, $\beta_N \approx 2.8$, $q_{95} \approx 3$
- **Hybrid**
  - Long pulse, high fluence
  - Q=5 at 12 MA, $\beta_N \approx 2.5$, $q_{95} \approx 4$
- **Steady-state**
  - Reference operating case
  - Q=5 at 9 MA, $\beta_N \approx 3$, $q_{95} \approx 5$

Other contributions from ASDEX-Upgrade and C-Mod

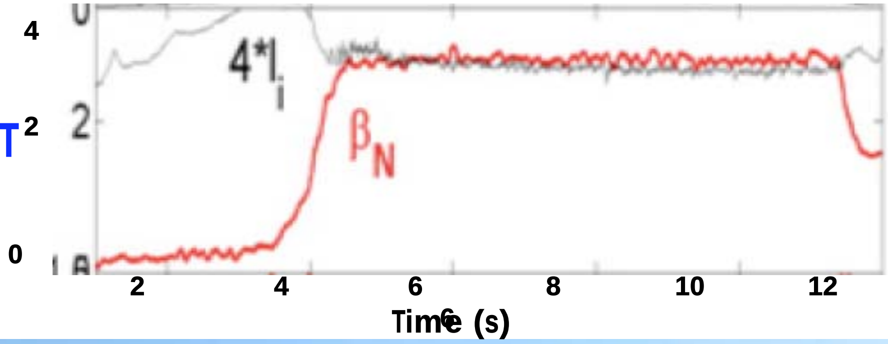
DIII-D



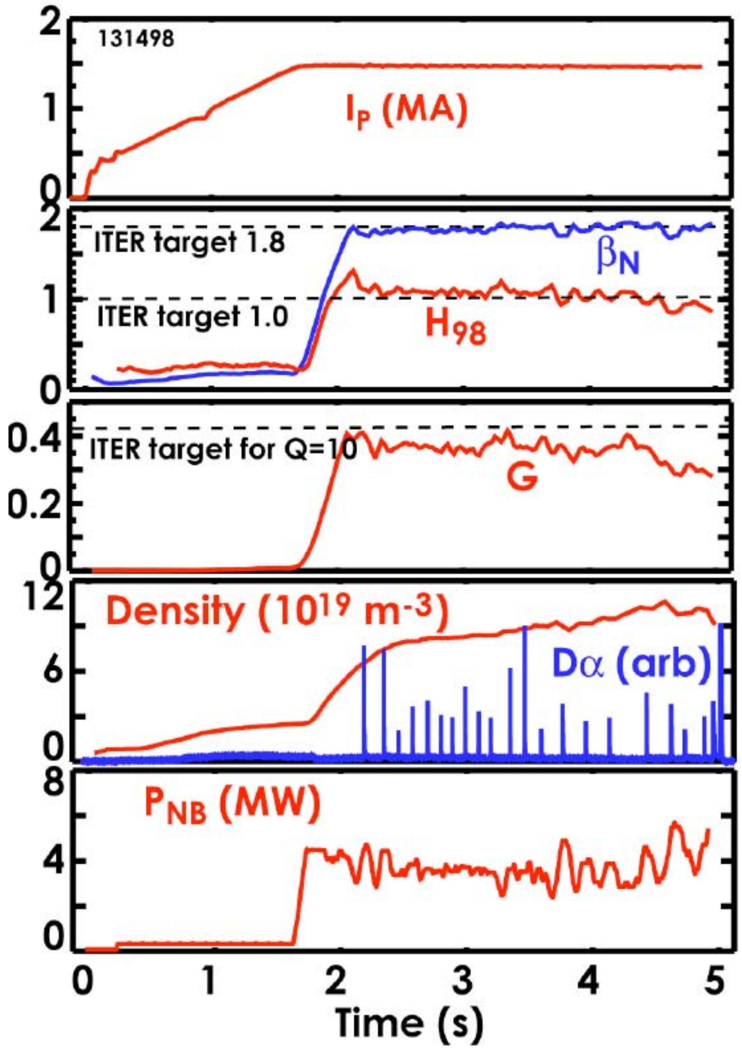
JT-60U



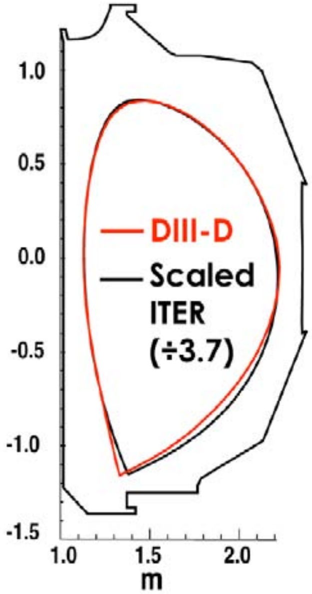
JET



Performance of ITER Baseline Scenario Has Been Validated



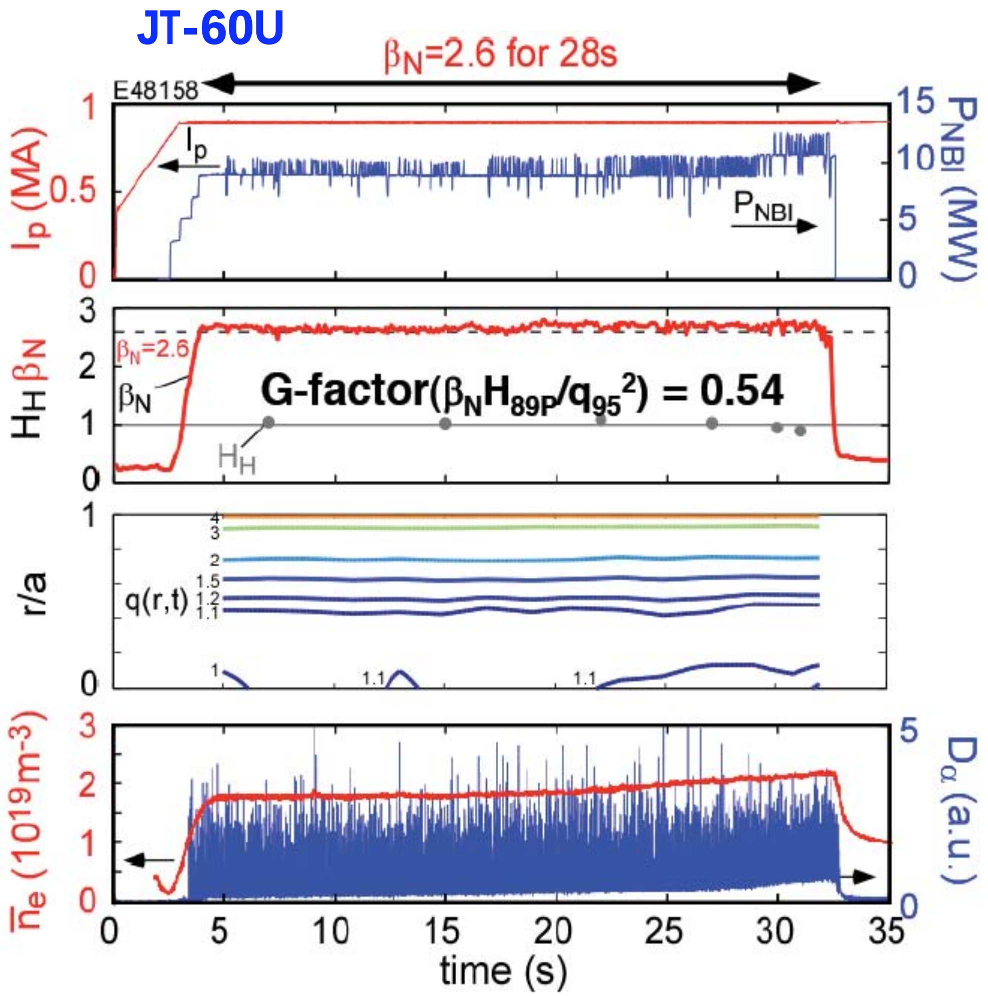
DIII-D



- **Achieved β_N = 1.8, H_{98} = 1.0**
- **Confirms expectations for ITER of:**
  - **Large type I ELMs**
  - **Reduced inductance**

Other contributions from ASDEX-Upgrade, C-Mod, JET, and JT-60U

Stationary Hybrid Plasmas with Performance Well Above the ITER Q=10 Requirements Have Been Demonstrated



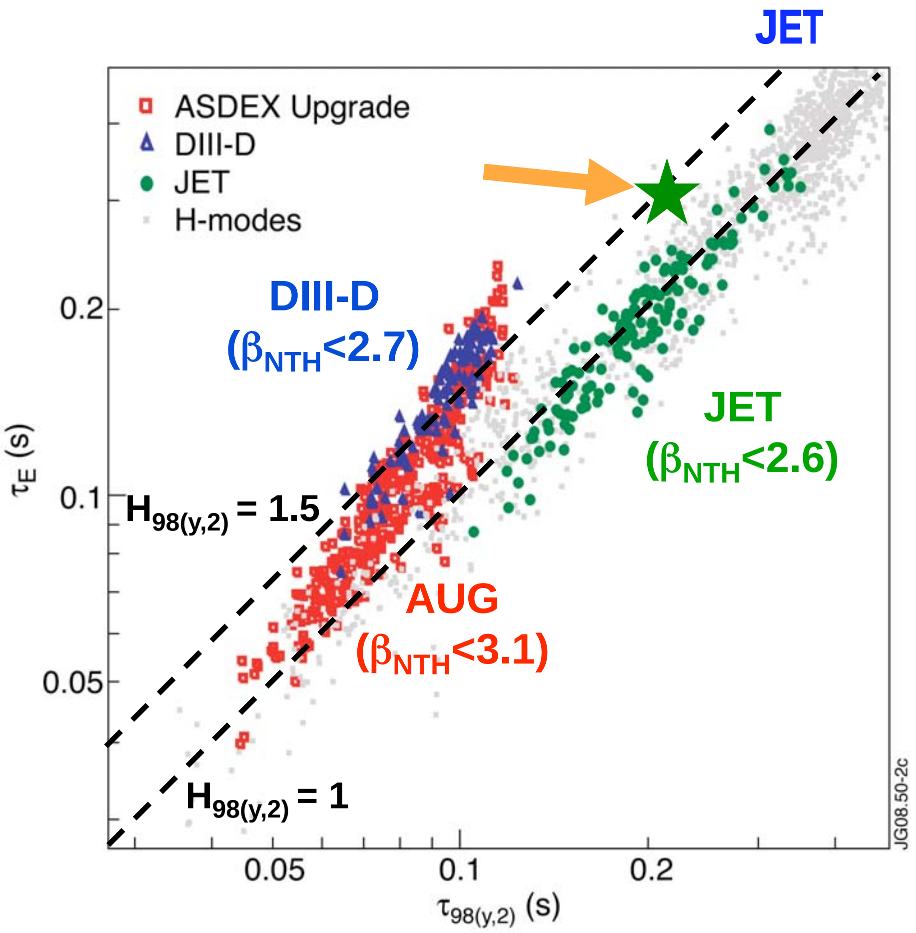
Hybrid Characteristics

- Flat q profile with $q_0 \sim 1$
- $f_{BS} = 0.3 - 0.5$

Long-pulse, high performance operation also demonstrated on JET

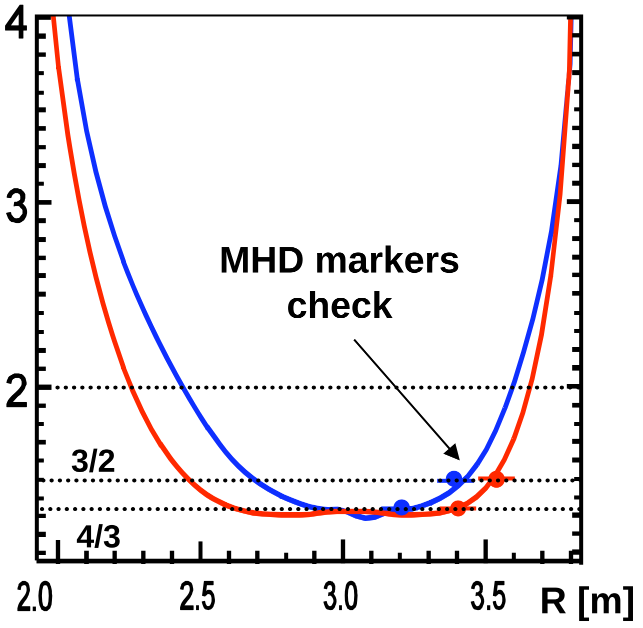
Other hybrid contributions from ASDEX-Upgrade, JET, and DIII-D

High confinement demonstrated in the hybrid regime



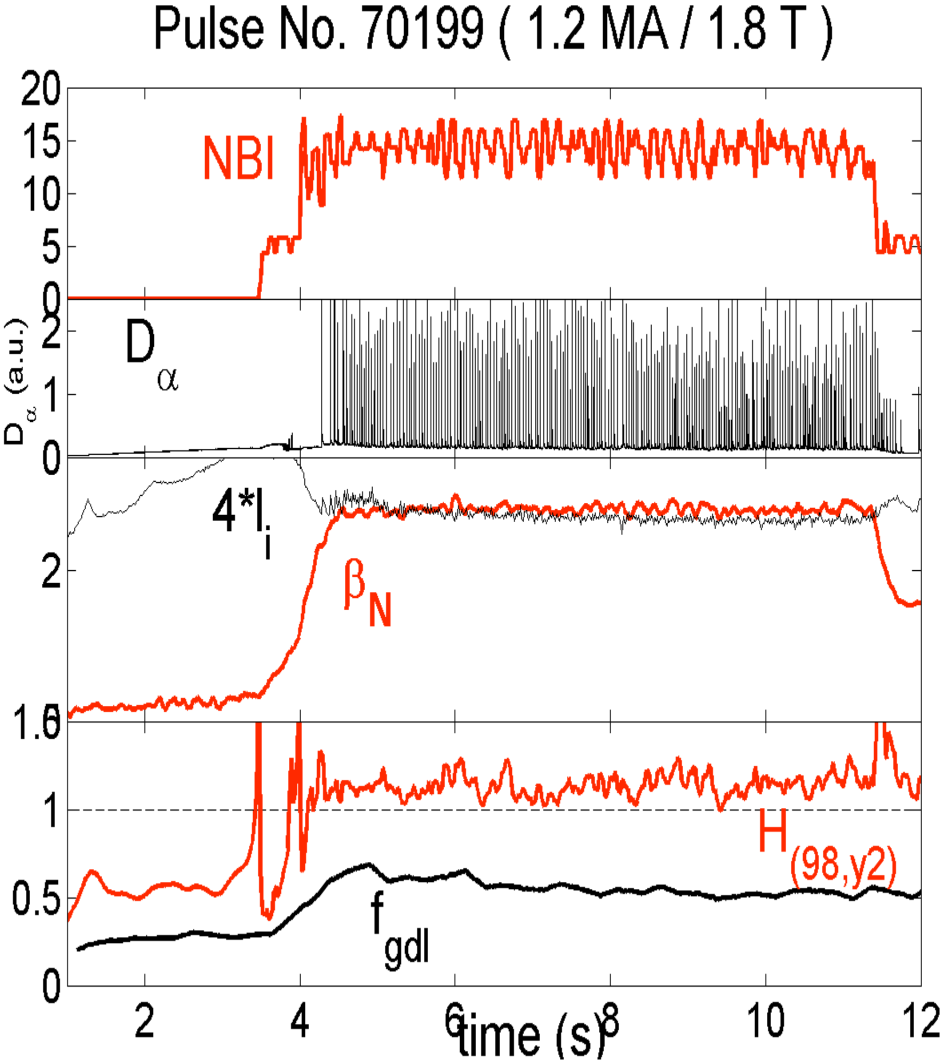
- **Best confinement obtained with broader current profile**

EFIT reconstruction with MSE constraints

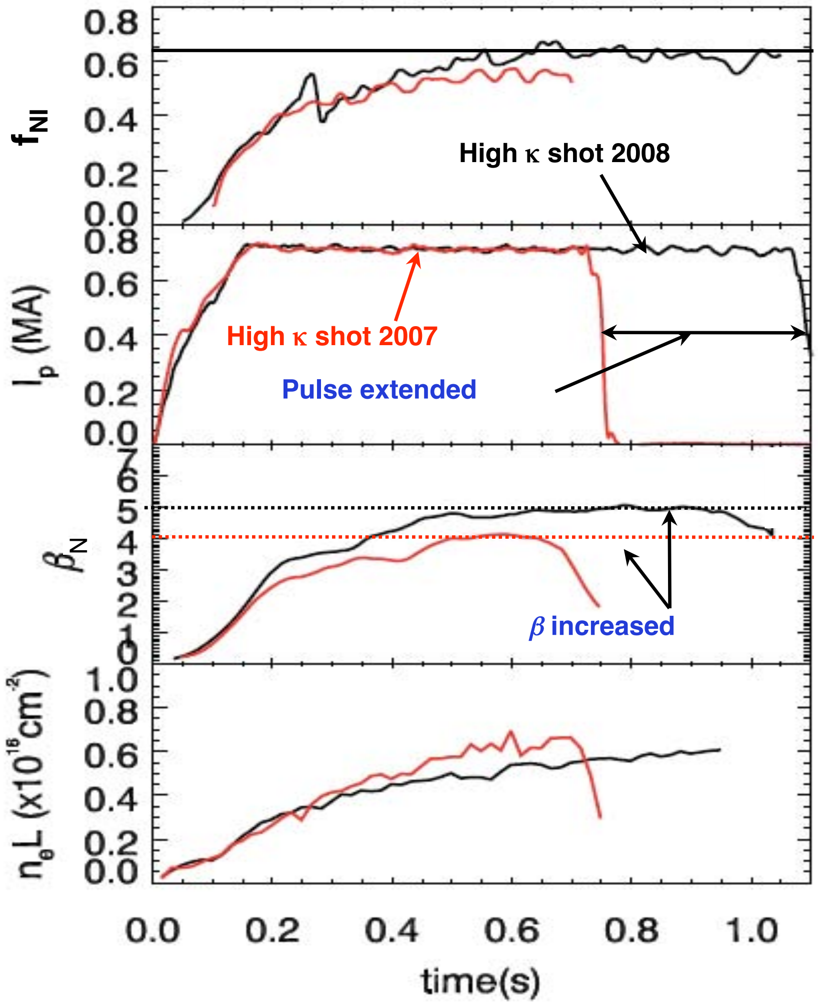


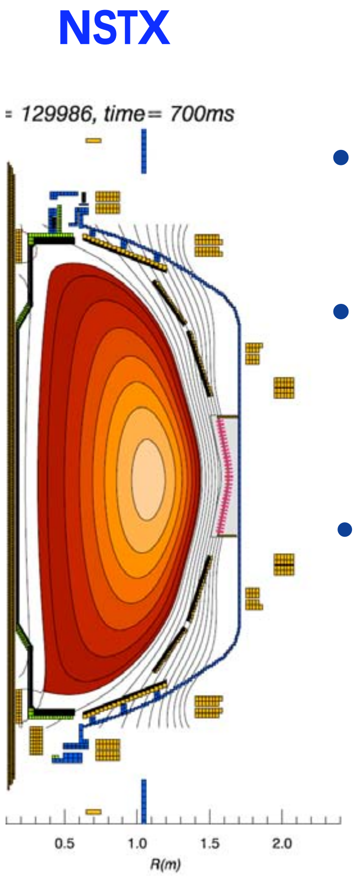
Steady-state Scenario Optimization Shows Great Progress

- **Optimization of shape, current profile, and pressure profiles have been investigated in DIII-D, JET, and JT-60U**
- **Example shown from JET has high β with good performance for ~ τ_R**
- **Contributions also from JT-60U and DIII-D**



Sustained Operation with β_N ~ 5 Achieved Through Plasma Shape Optimization

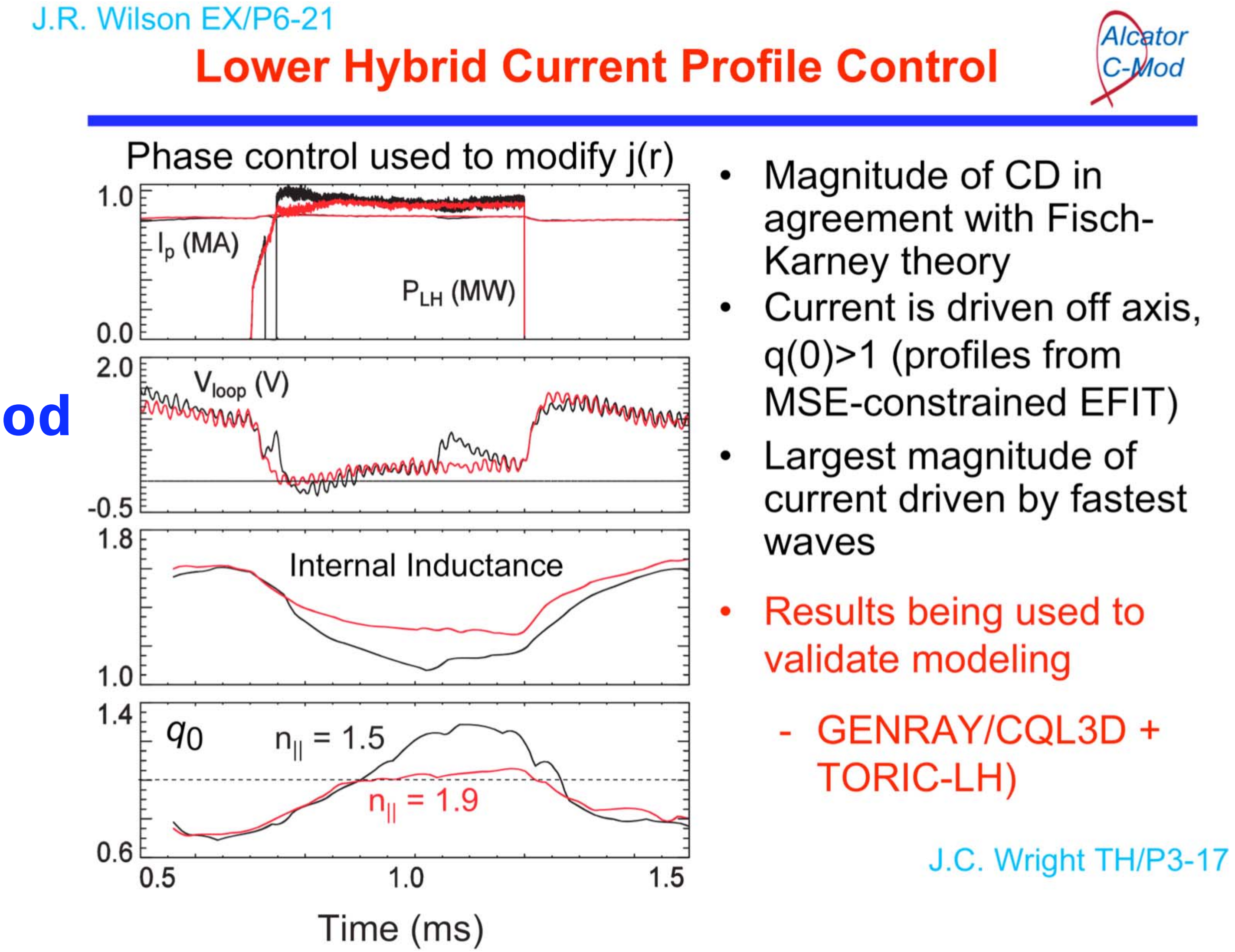




- κ = 2.7
- β_N ~ 5 maintained, well above the no-wall limit
- $\Delta t_{dur} = 1\text{-}2\tau_{CR}$

Tools for current profile optimization are being developed

C-Mod



J.R. Wilson EX/P6-21

Lower Hybrid Current Profile Control

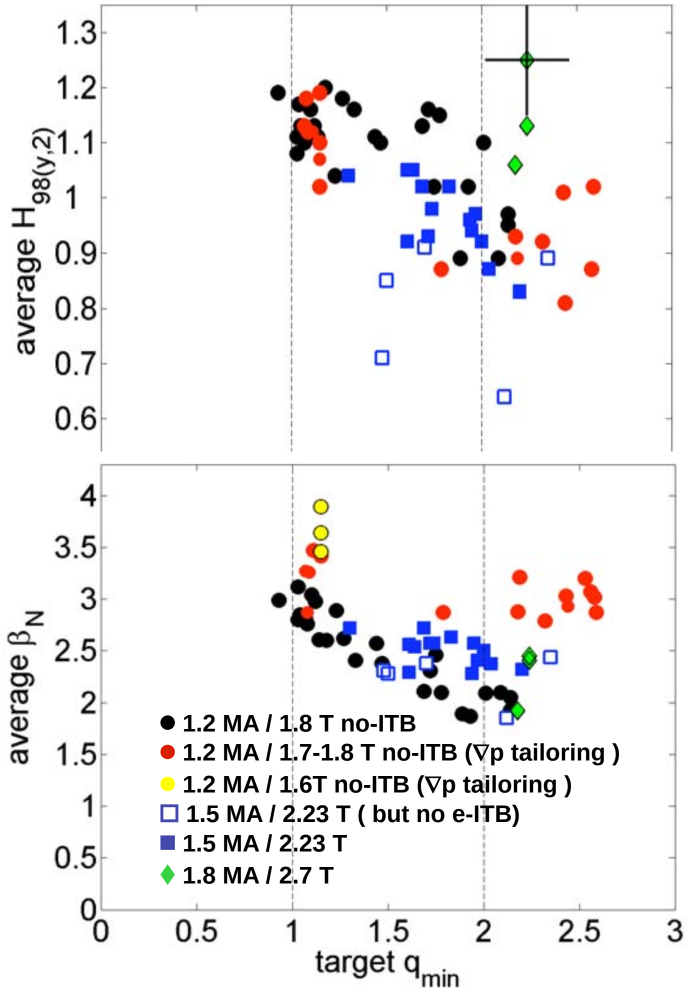
Phase control used to modify j(r)

- Magnitude of CD in agreement with Fisch-Karney theory
- Current is driven off axis, q(0)>1 (profiles from MSE-constrained EFIT)
- Largest magnitude of current driven by fastest waves
- Results being used to validate modeling
    - GENRAY/CQL3D + TORIC-LH)

J.C. Wright TH/P3-17

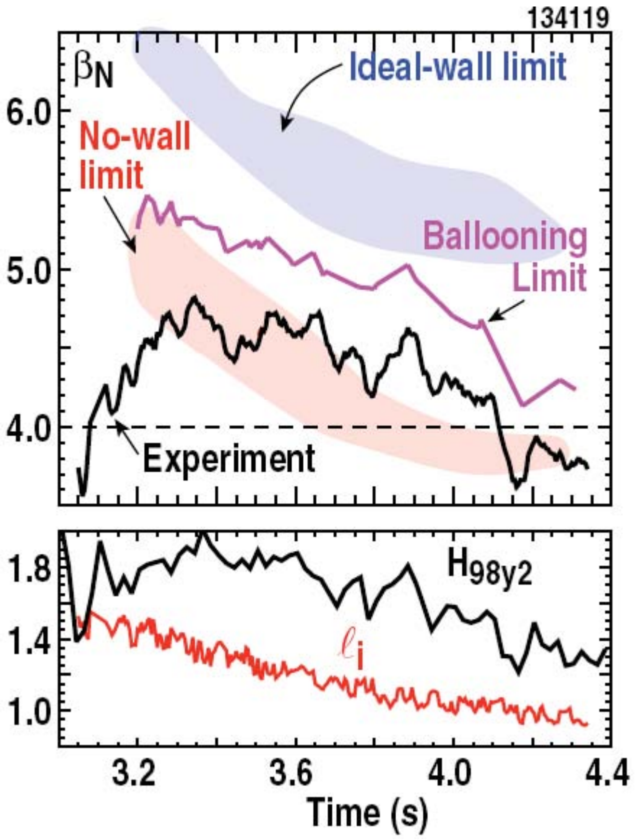
Significant progress has been made towards optimization of the current and pressure profiles for steady-state operation

JET



- Best confinement achieved with ITB
- Highest β_N achieved with profile tailoring

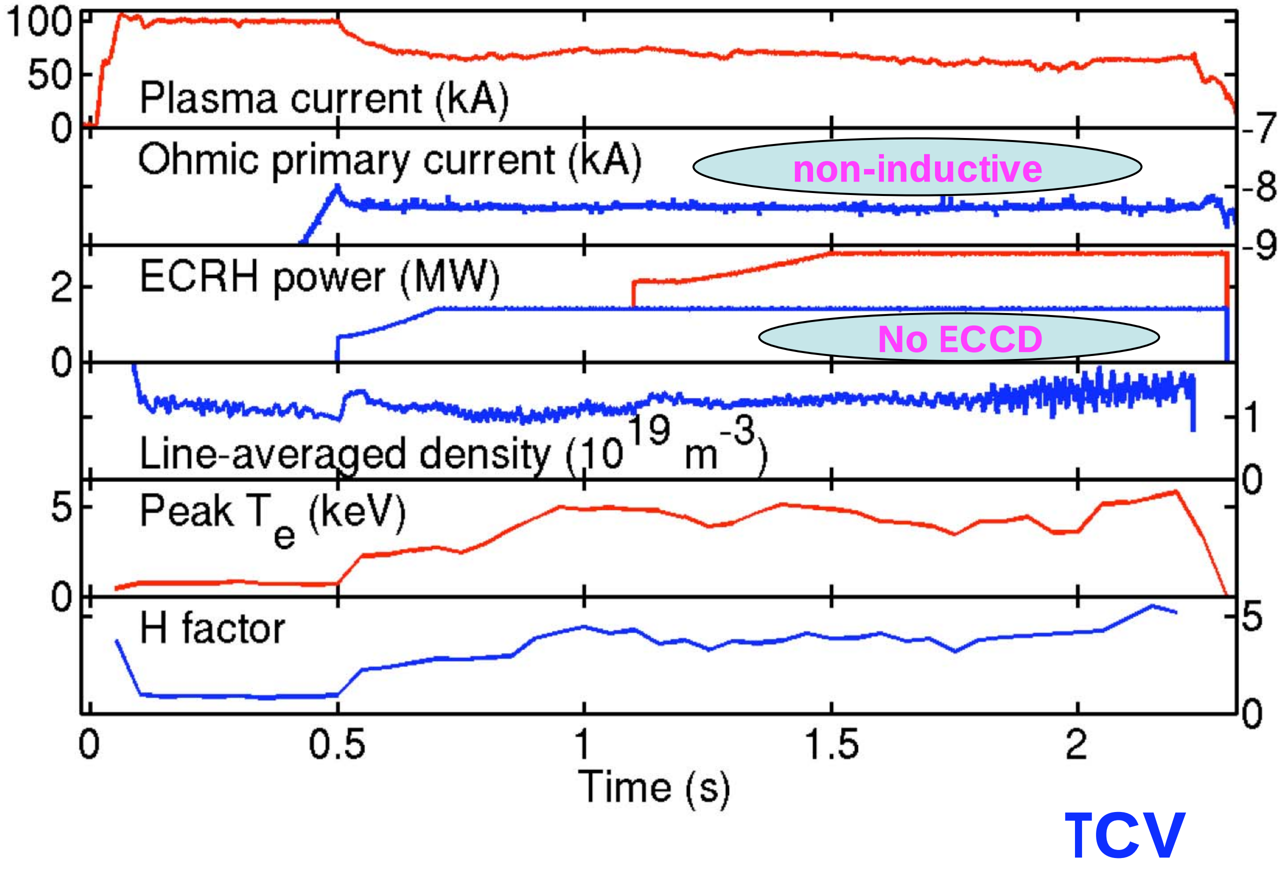
- Strongly peaked current profile leads to simultaneous high β_N and excellent confinement



DIII-D

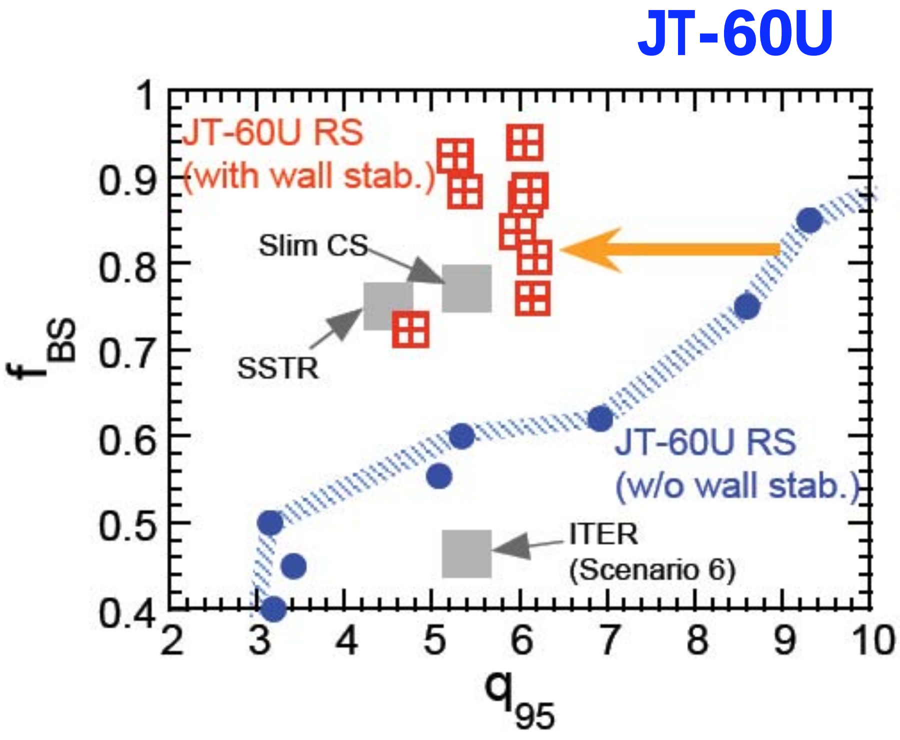
Full Bootstrap Current Operation Demonstrated

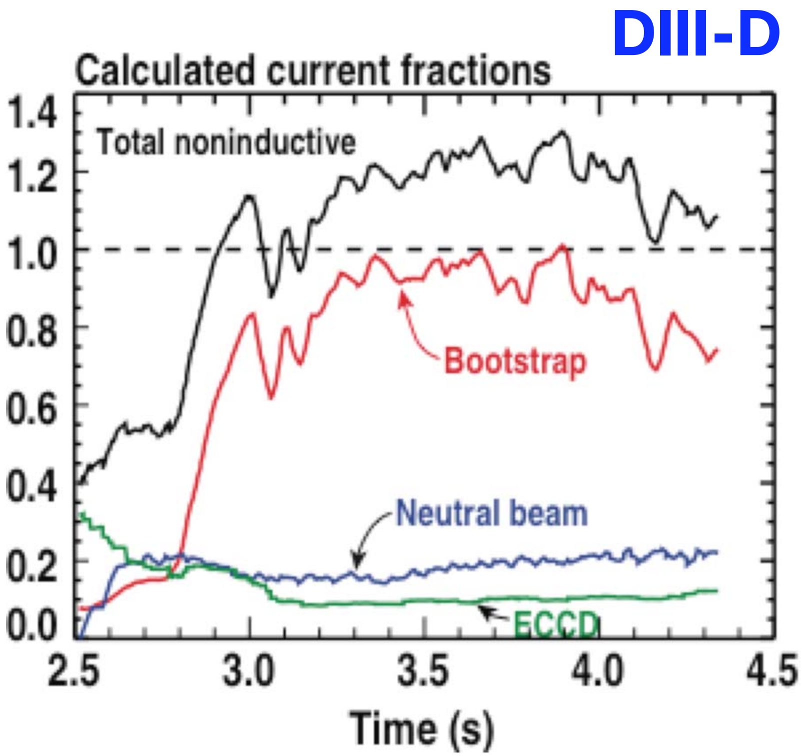
Stationary phase (>>resistive diffusion time)



- **V_{loop} = 0**
- **No external current drive**
- **I_P constant with 2% for 0.8 s**
- **Narrow ITB with H = 2.5-3.5**

High Bootstrap Fraction (>90%) Now Achieved at Relevant q_{95}

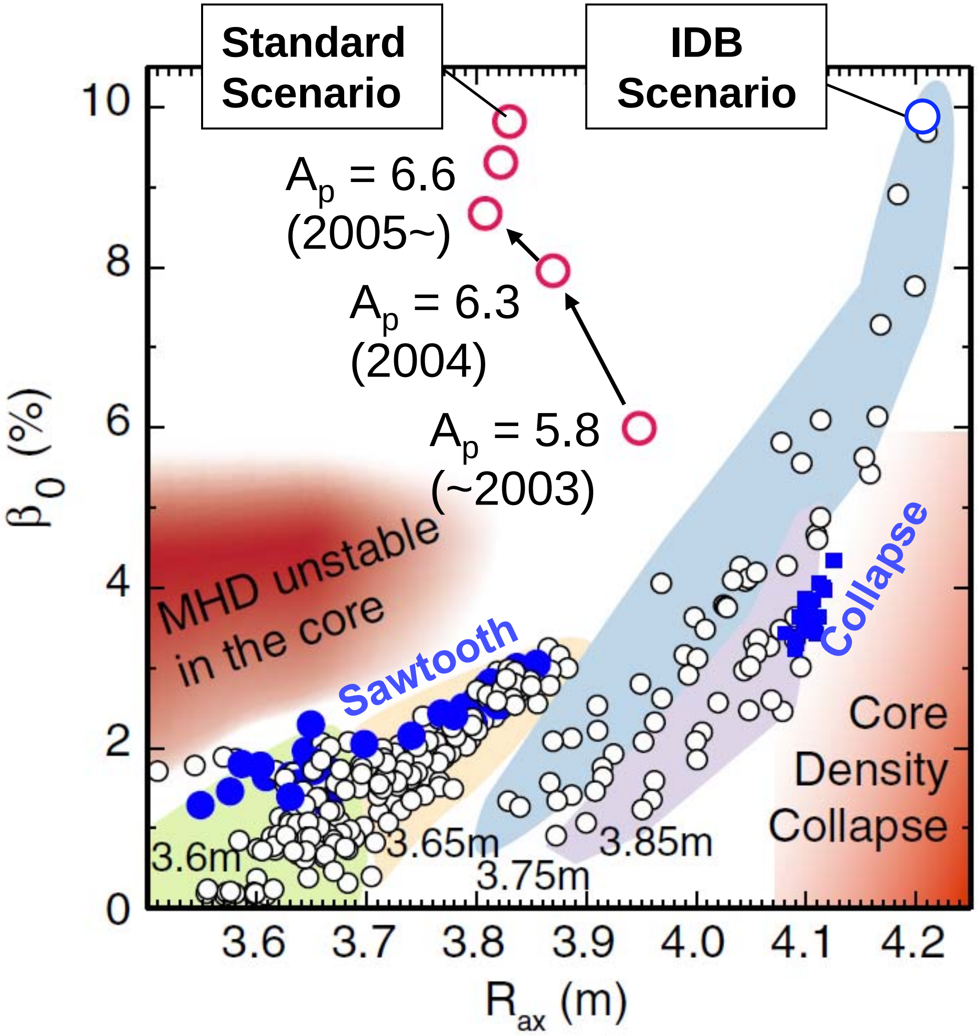




- **Reversed shear with high q_{min}**

- **Positive shear with q_{min}~1**

Stellarator scenario development also utilizing shape and pressure profile control for optimized performance



Magnetic axis position is a key parameter for high-beta

✓ Standard Scenario

(broad pressure profile)

→ **$\langle\beta\rangle$ = 5 %, β_0 ~ 10 %**

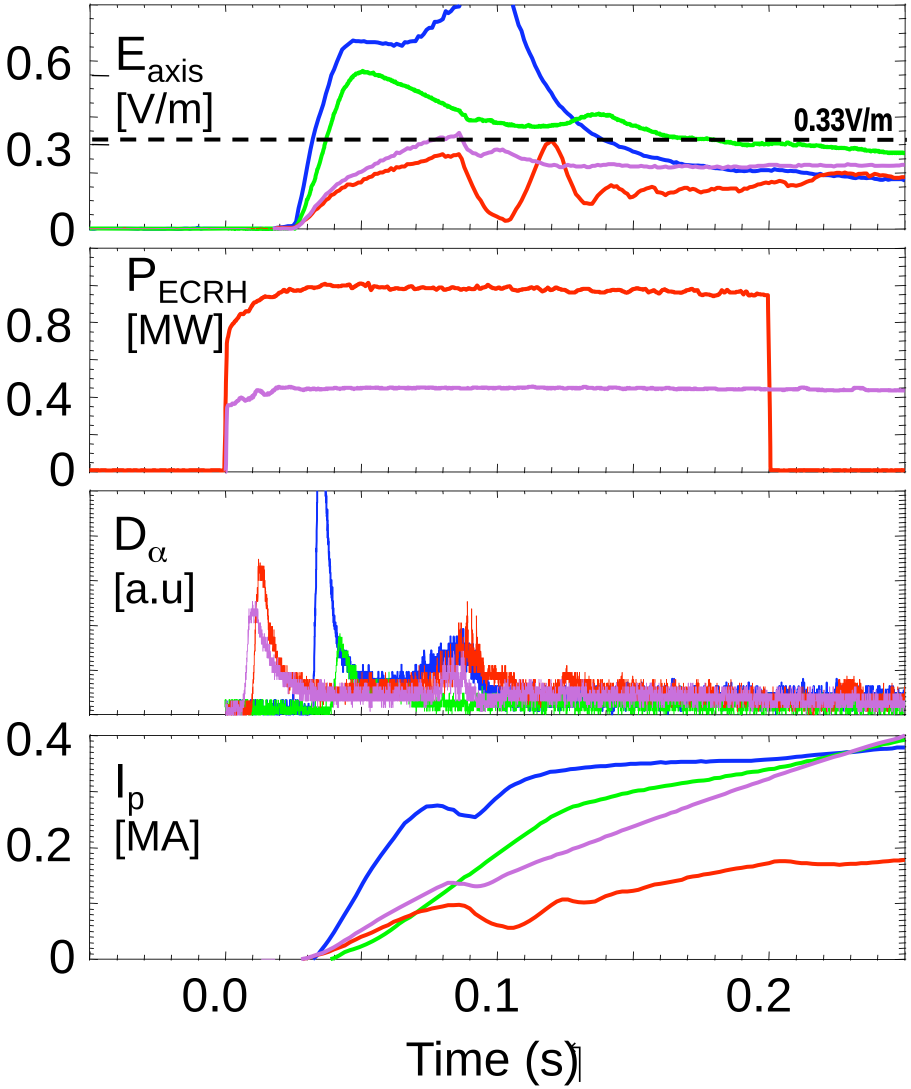
✓ Internal Density Barrier (IDB) Scenario

(peaked pressure profile)

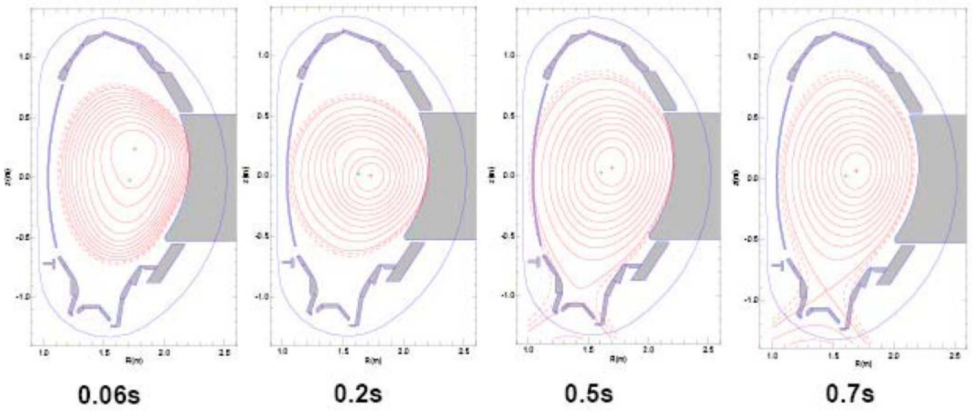
→ **$\langle\beta\rangle$ = 2 %, β_0 ~ 10 %**

LHD

ITER Startup Scenario Improved Through Extensive Collaborative Experiments and Modeling



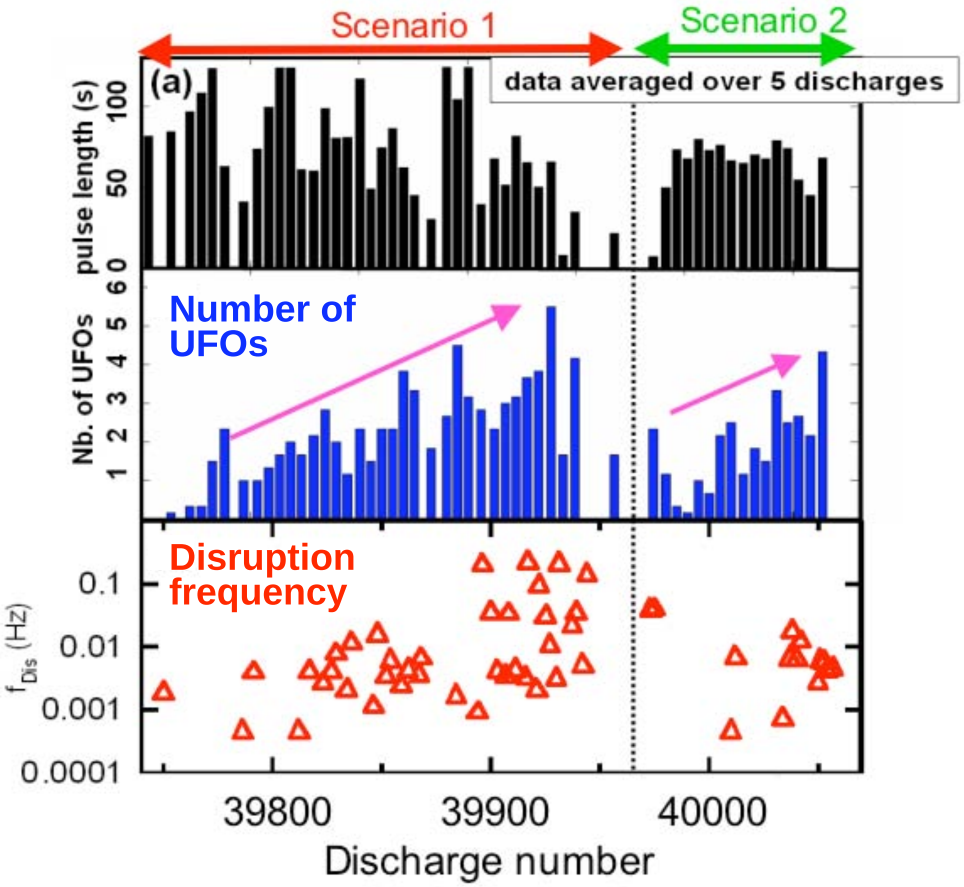
ASDEX-Upgrade

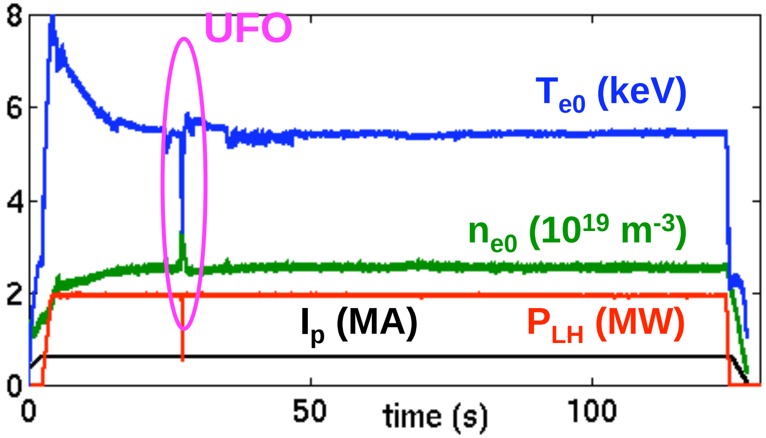


- **EC burnthrough assist at low voltage shown on 5 tokamaks**
- **Large-bore limiter followed by early X-point formation needed for compatibility with ITER coil set and first wall (AUG, DIII-D, JET, C-Mod)**
- **Hybrid performance demonstrated with new ITER startup (DIII-D)**

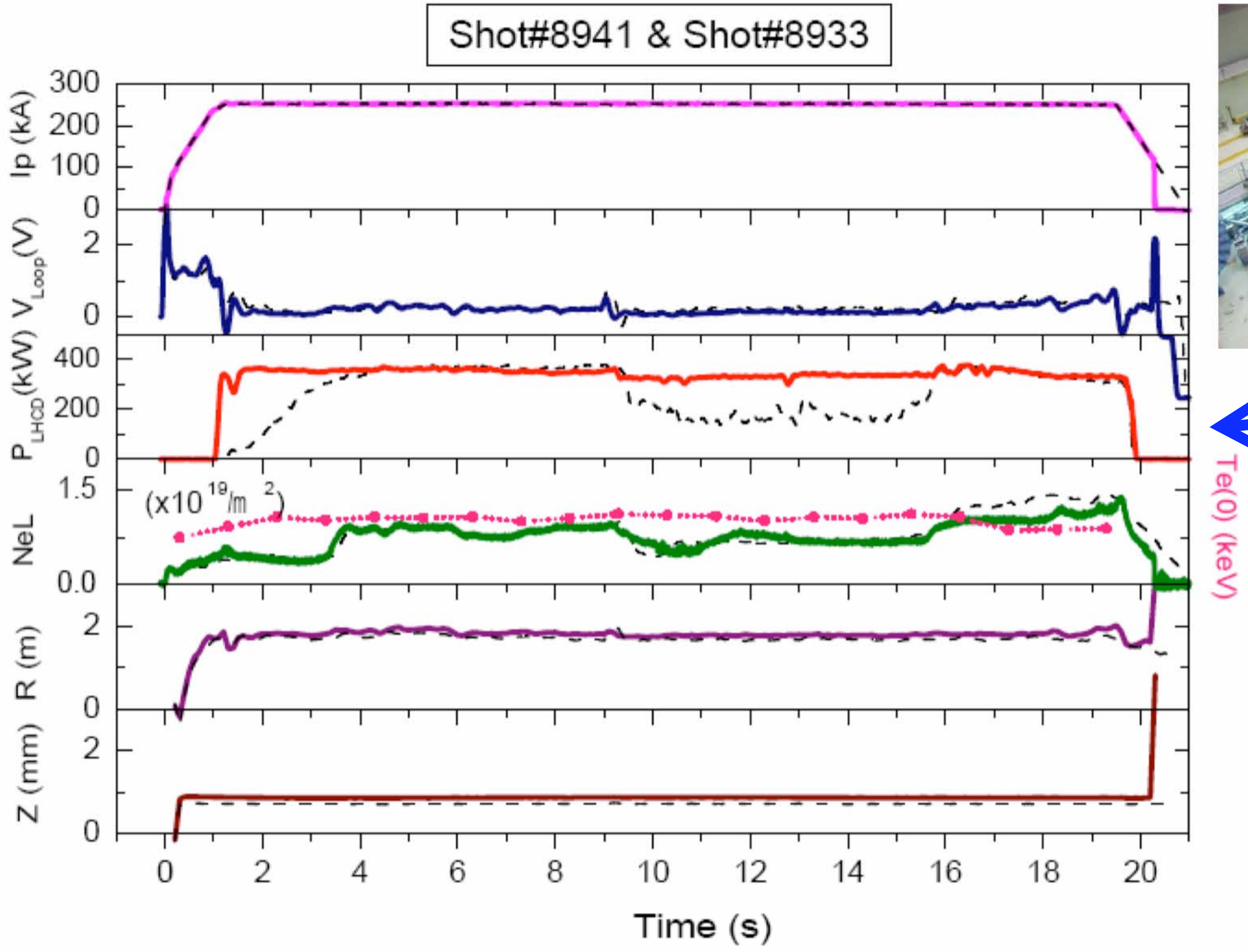
Long Pulse Capability Facilitates Addressing the Integration of Burning Plasmas with Boundary Solutions

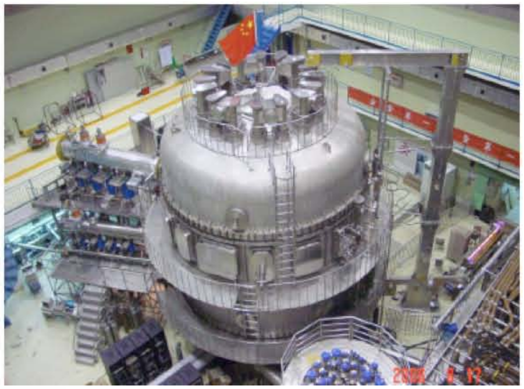
Tore Supra



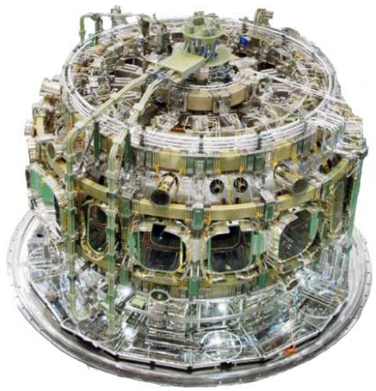


New superconducting divertor tokamaks will advance steady state physics





EAST

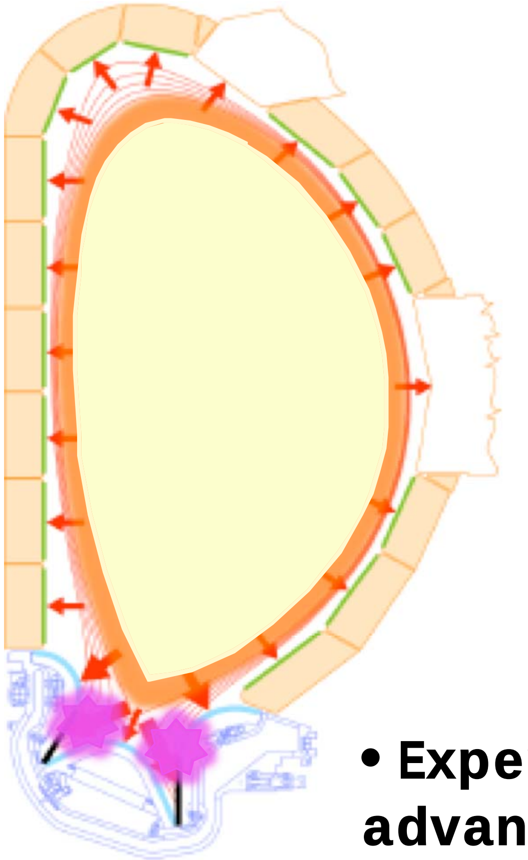


KSTAR

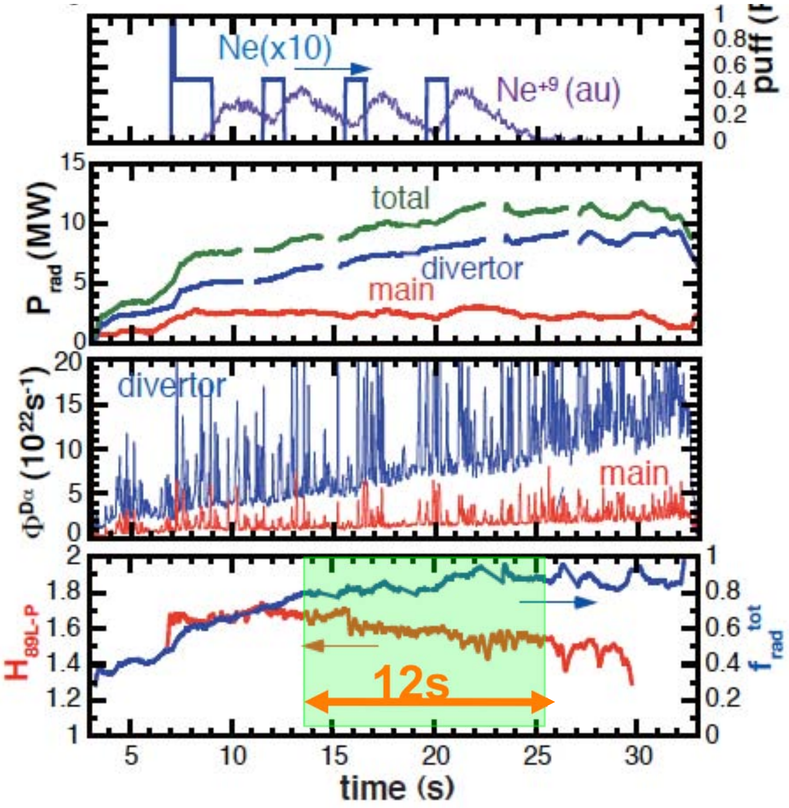
Divertor radiation enhanced by Ne puff in Ar seeding type-I ELMy H plasma with higher H_H = 0.95-0.8

JT-60U

Ar and Ne seeding in ELMy H-mode plasma with ITB

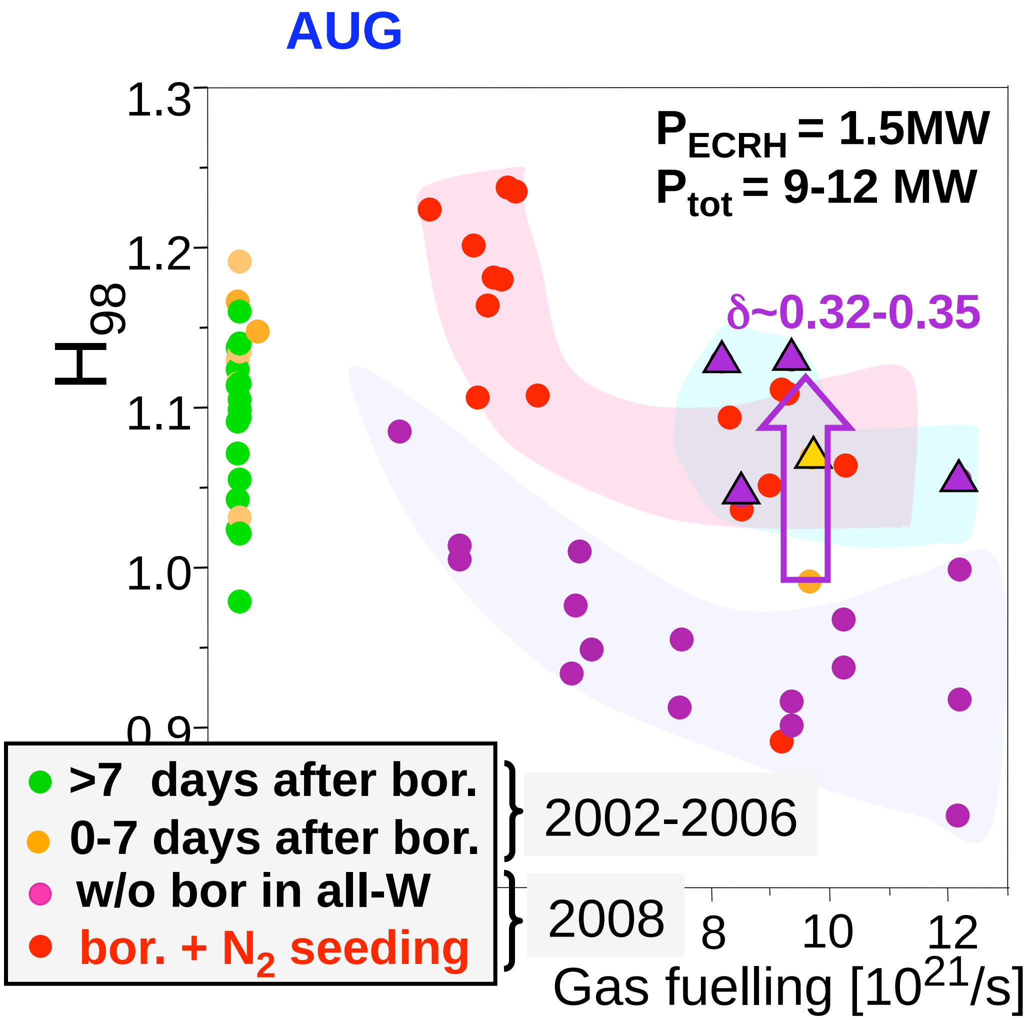


Good confinement (H_{89L}=1.73-1.5, H_{H98y2} = 0.95-0.8) type-I H-mode with large radiation fraction(P_{rad}^{tot}/P_{abs} =0.8-0.9) was sustained.



- **Experiments combining ELM suppression with advanced performance scenarios have started in DIII-D**

Good Performance Obtained with Tungsten Walls When Combined with Radiative Divertor Operation



Nitrogen seeding in boronized full W:

- N_2 seeding controlled by T_{div}
- reduced N “sticking” on W surfaces

→ N content under control

→ low T_{div}, frequent small ELM’s, reduced heat flux to divertor

→ **high W_{mhd}, high $H_{98} \leq 1.25$**

Good perspectives for operation at higher triangularities next year.

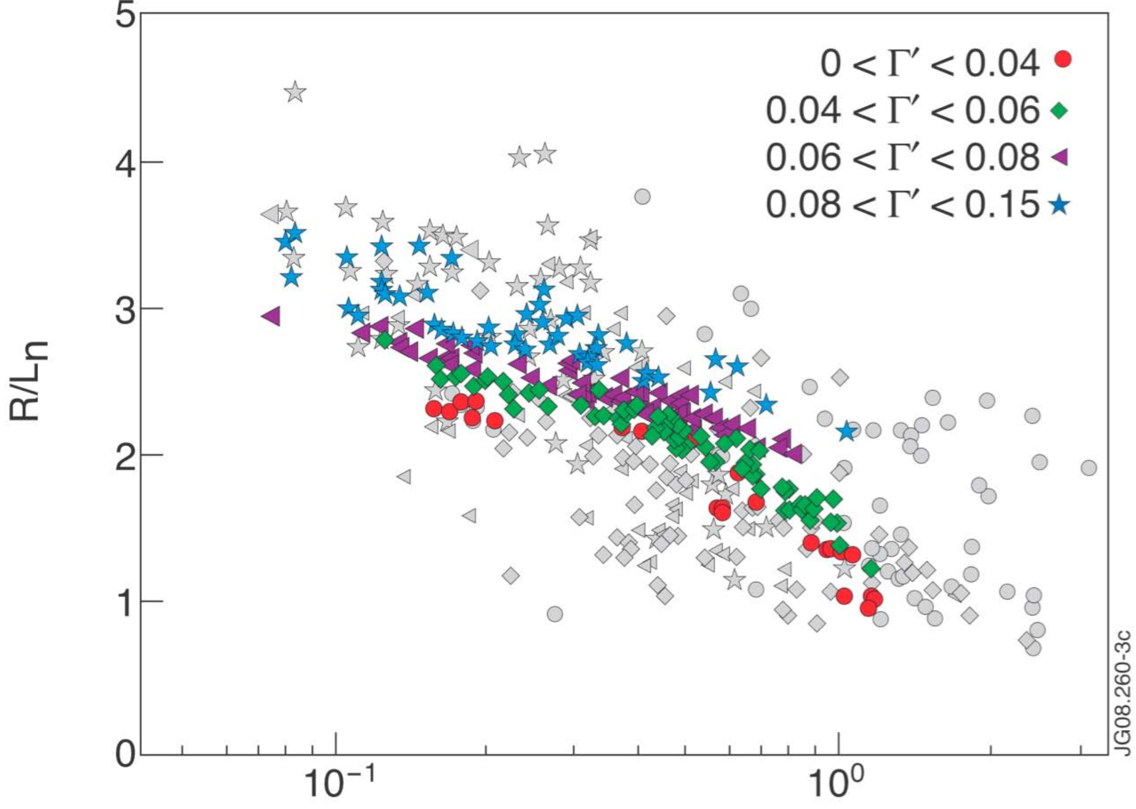
Confinement Experiments Are Addressing Key Issues for Burning Plasma and Fundamental Plasma Physics

Four broad research areas are addressed:

- **Particle transport**
  - Peaking at low collisionality would improve fusion yield in ITER
- **Plasma rotation**
  - Critical issue for confinement and stability
- **Energy transport**
  - Experiments addressing both projection and basic plasma physics of turbulence
- **Pedestal and L-H transition**
  - Progress in prediction of pedestal height – key for performance projections

Progress Reported on Understanding of Particle Transport

Normalized Density Scale Length

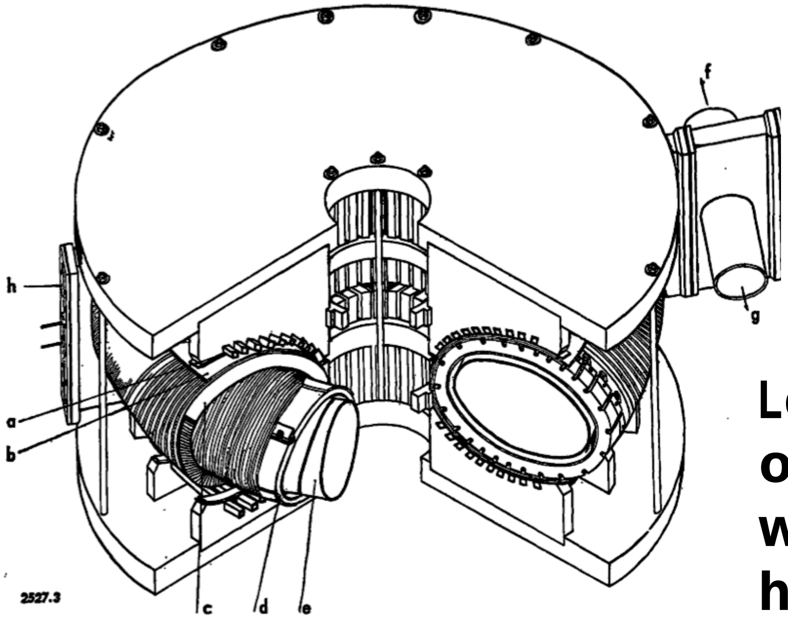


Normalized collision frequency

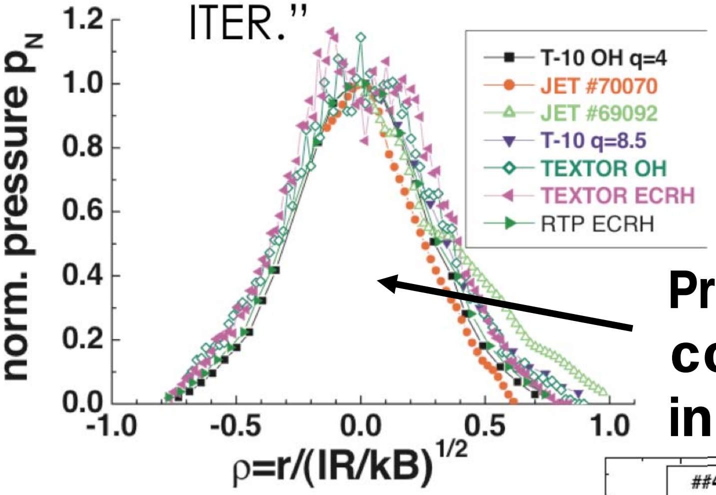
- Results from JET extend work recognized by 2007 Nuclear Fusion prize toward ITER collisionality
- Linear growth rate simulations show good agreement for the dependence of density peaking with collisionality
- Implies ITER could have more peaked density profiles than previously assumed

From Toroidal Chambers (Geneva, 1958) to ITER (Geneva, 2008) - K. A. Razumova

- G. G. Dolgov-Saveliev, D. P. Ivanov, V. S. Mukhovatov, K. A. Razumova, V. S. Strelkov, M. N. Shepelyev, N. A. Yavlinsky, Geneva, 1958, “Investigation of the Stability and Heating of Plasmas in Toroidal Chambers.”

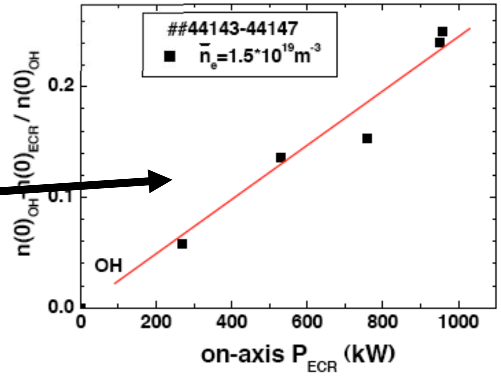


- K. A. Razumova et. al., Geneva 2008, “Tokamak Plasma Self-Organization and Possibility to have the Peaked Density Profile in ITER.”

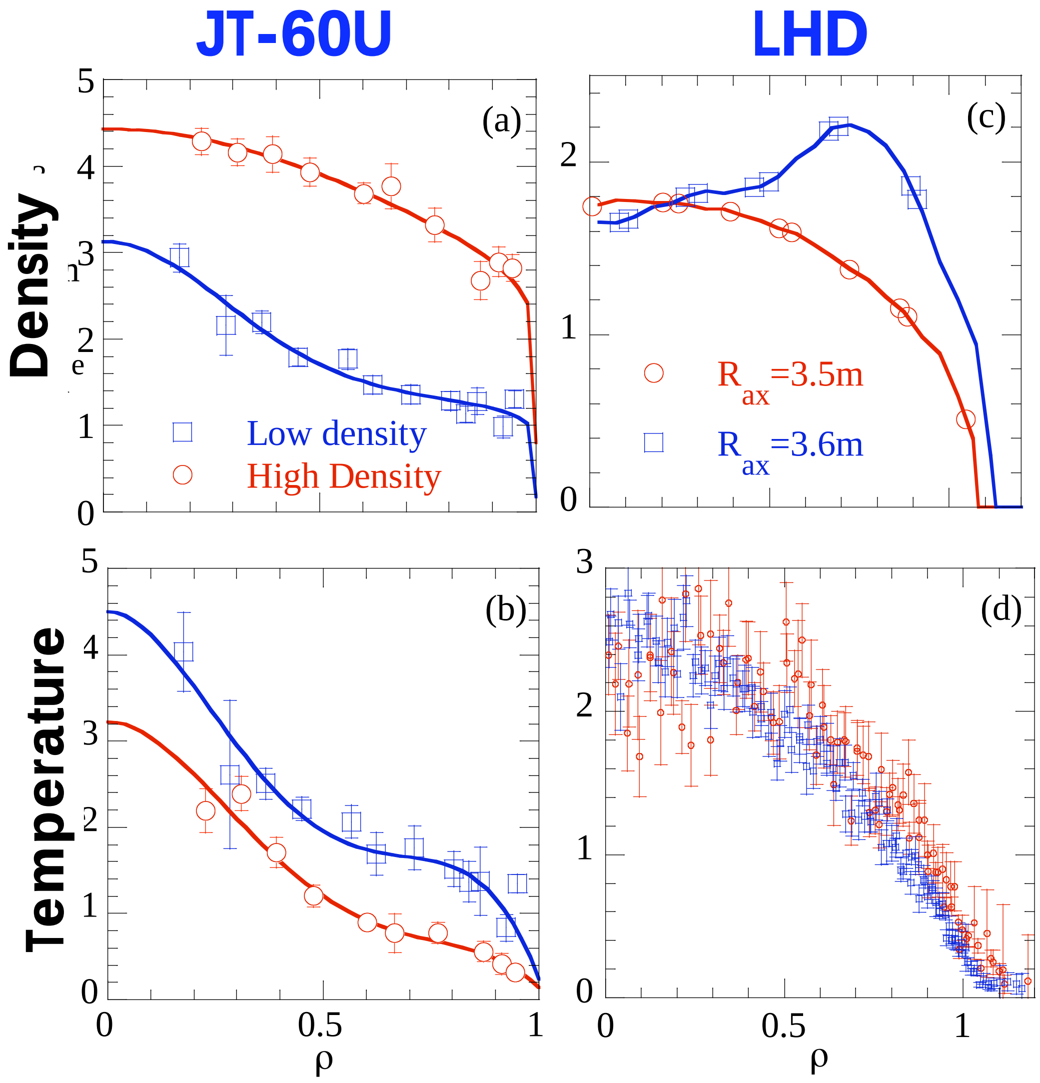


Profile consistency in pressure….

Leads to reduction of density peaking with strong central heating



Progress in Understanding Particle Transport Benefits from Stellarator-Tokamak Comparison



Density transport varies by configuration:

- **JT-60U has large outward diffusion compensated by large inward pinch**
- **LHD has small outward diffusion with almost no pinch**
- **LHD also sees that collisionality dependence varies with the magnetic configuration**

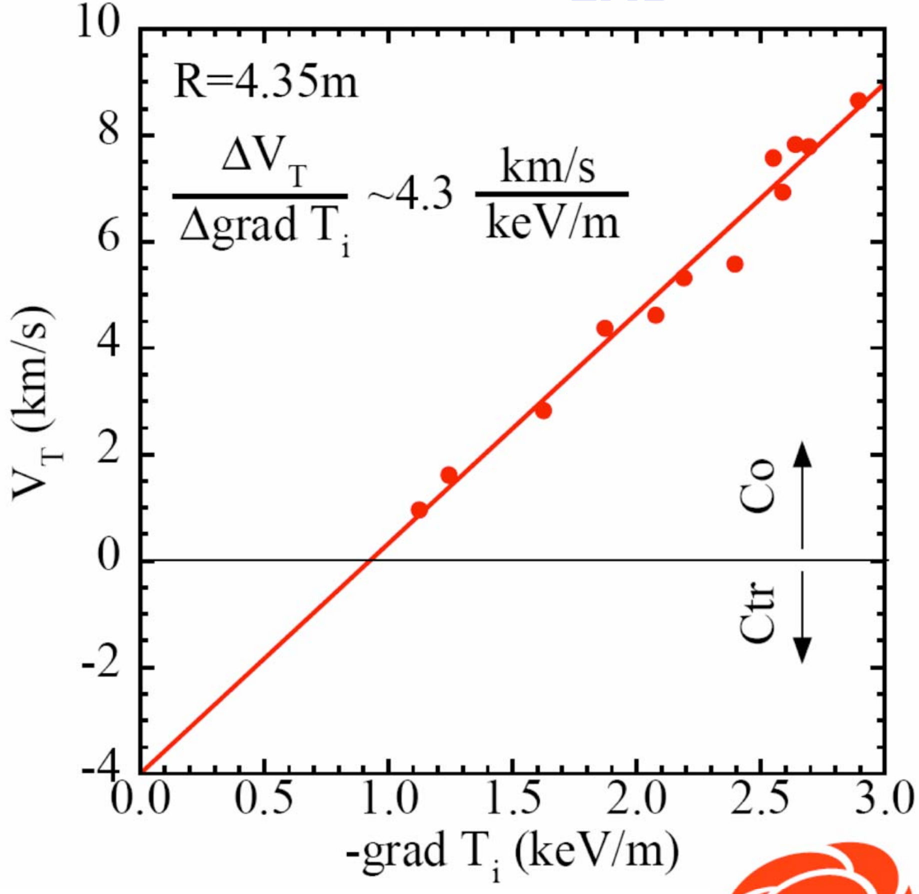
Spontaneous toroidal flow is observed in stellarators

- **Spontaneous toroidal velocity proportional to grad(Ti)**

Continuing work on spontaneous (intrinsic) rotation

- **C-Mod ➔ 100 km/s in ITER**
- **JT-60U**
- **JET**
- **DIII-D**
- **TCV**
- **LHD**

LHD

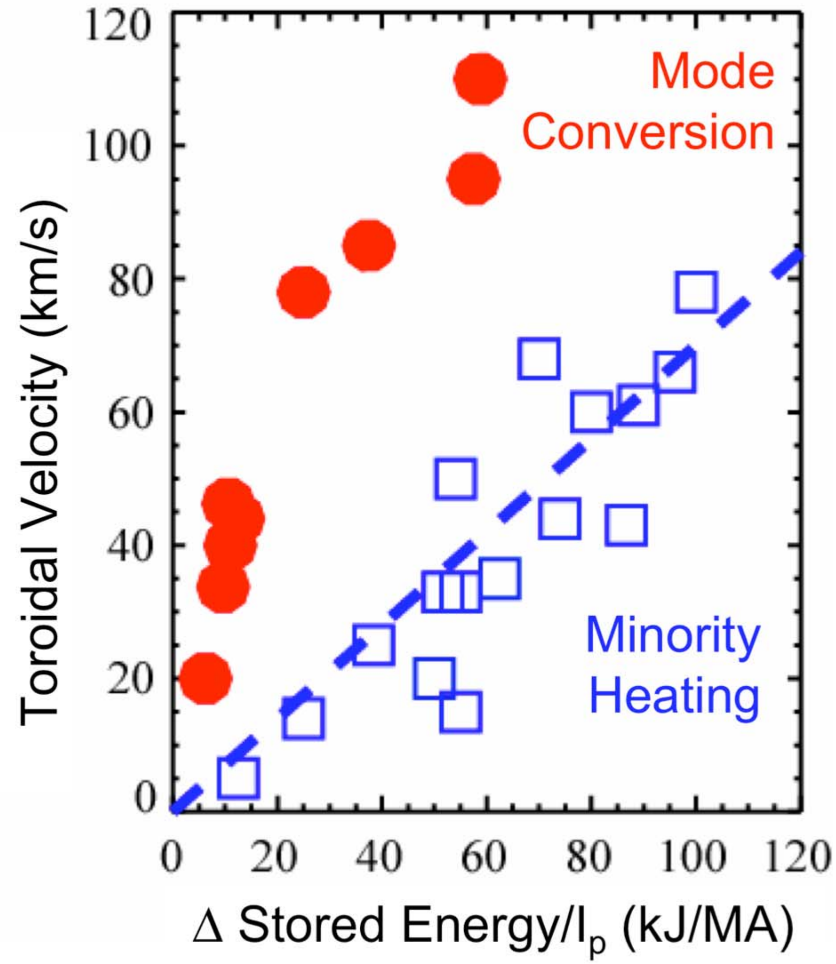


Recent Results Show Direct Flow Drive in ICRF Mode-Conversion Experiments

- Active ICRF Flow Drive
  - At least a factor of 2 above the usual scaling seen with pressure/current
- Use multi-frequency capability
  - 80 MHz, proton minority
  - 50 MHz, ^{3}He mode conversion
  - Both layers near the axis
- Near-axis conversion to Ion Cyclotron Wave (ICW)
  - propagates back toward low field side
  - damps and drives flow at ^{3}He cyclotron layer

Mode Conversion Flow Drive

$B(R_0)$ = 5.1 Tesla; ^{3}He fraction ~ 10%

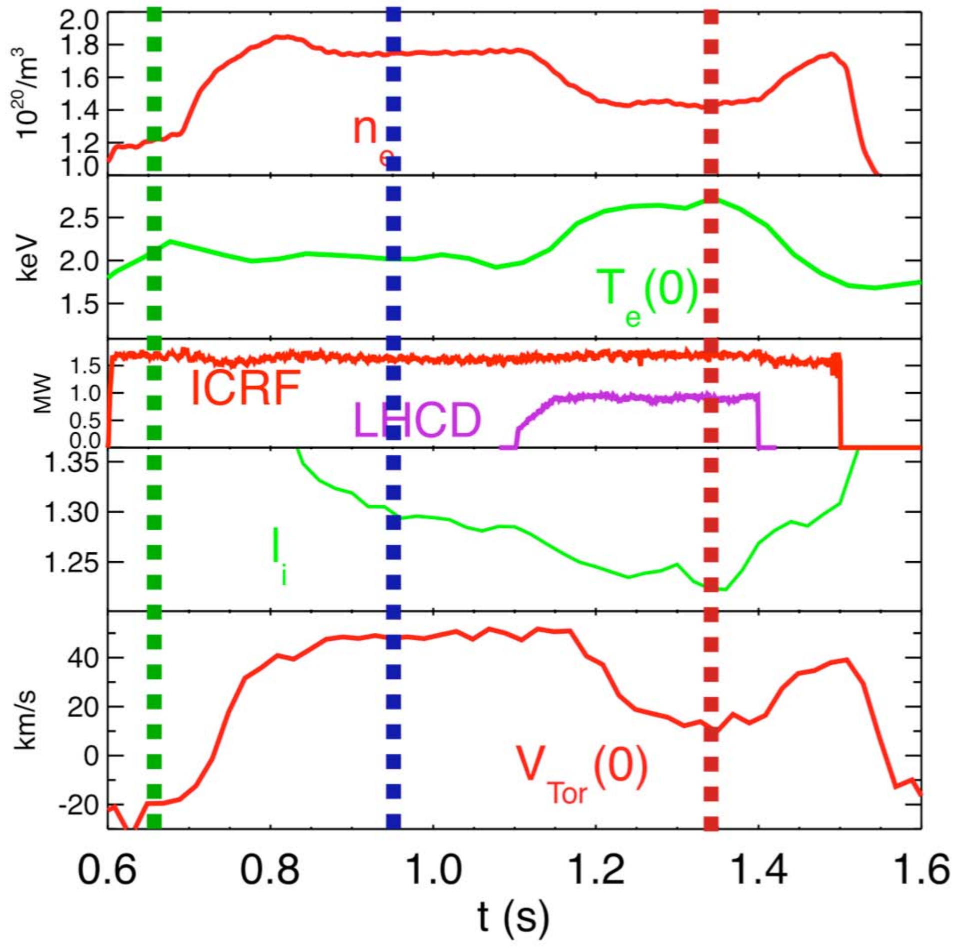


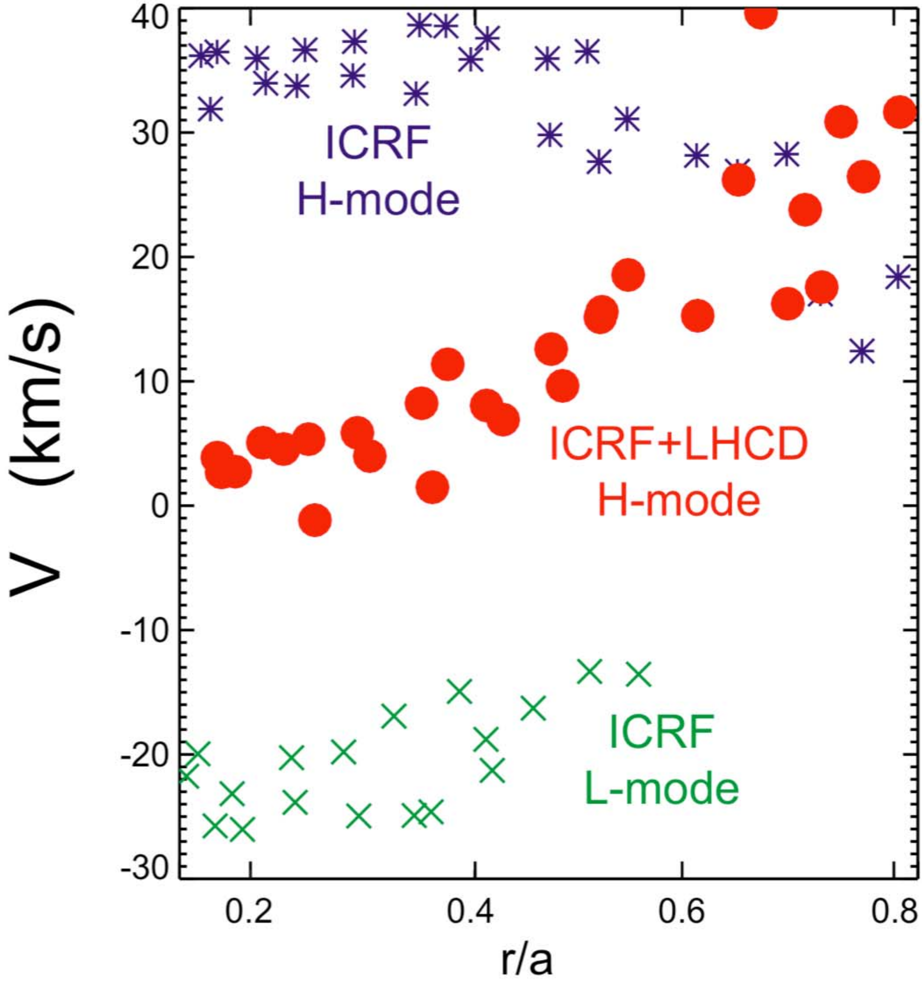
Yijun Lin, Post-Deadline

Effects of LH Counter- and Intrinsic Co-Flows are additive: Flow profile control

Alcator C-Mod

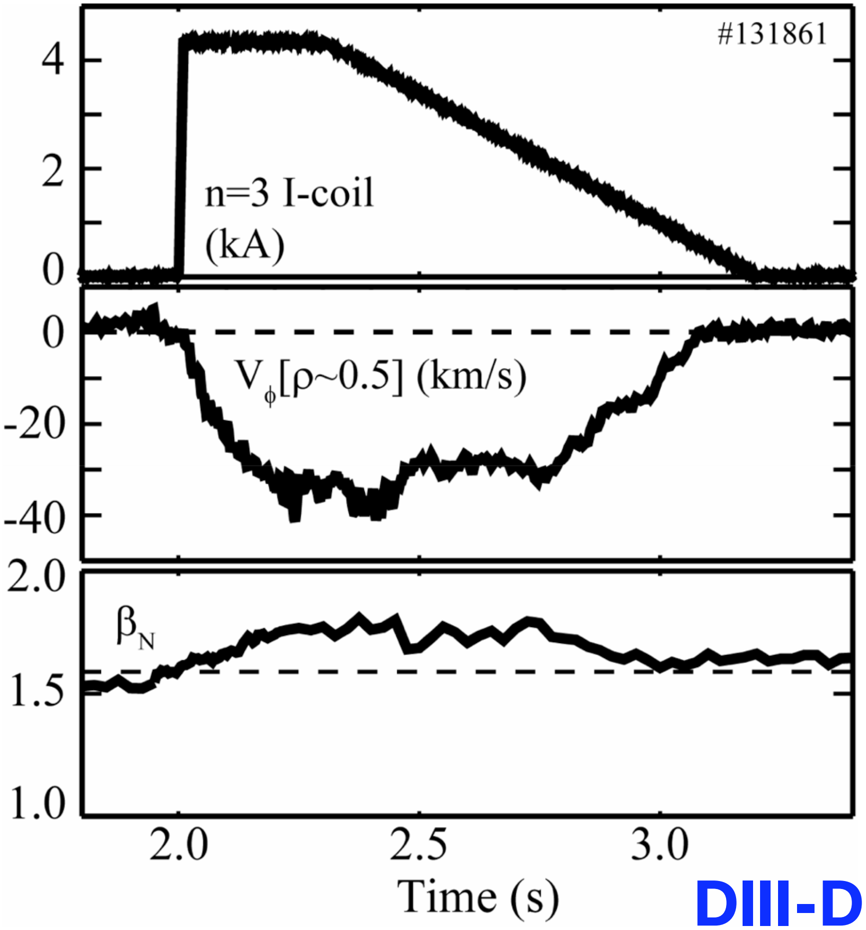
- LHCD counter-current rotation added to intrinsic co-current
  - Hollow rotation profile with strong shear





n=3 Non-Resonant Magnetic Fields (NRMF) Applied to Slowly Rotating Plasma Leads to Rotation Spin Up

- **NBI power and torque constant during time range shown**
- **Rotation acceleration happens at all minor radii**
- **Simultaneous improvement in energy confinement**
- **Evidence for theoretically predicted offset rotation**
  - NSTX has also reported NTV damping



DIII-D

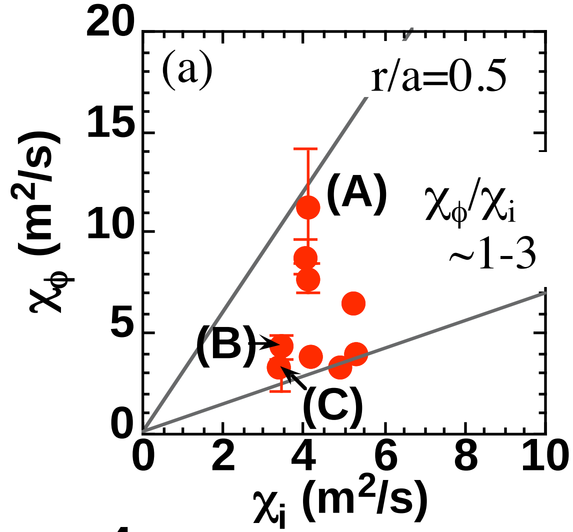
WM Solomon/IAEA/Oct2008

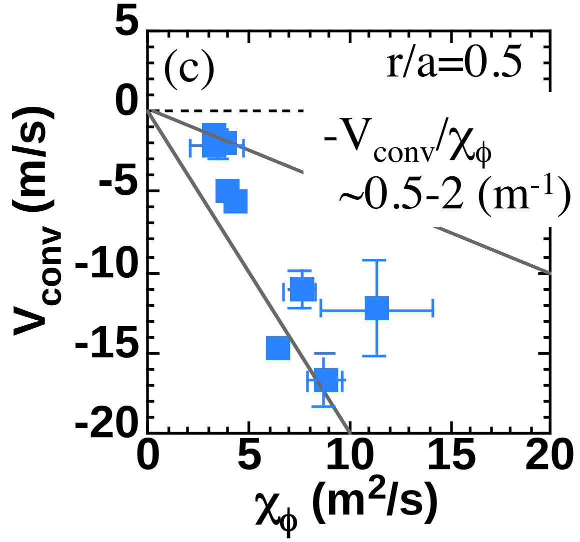
Characteristics of the momentum transport and the intrinsic rotation

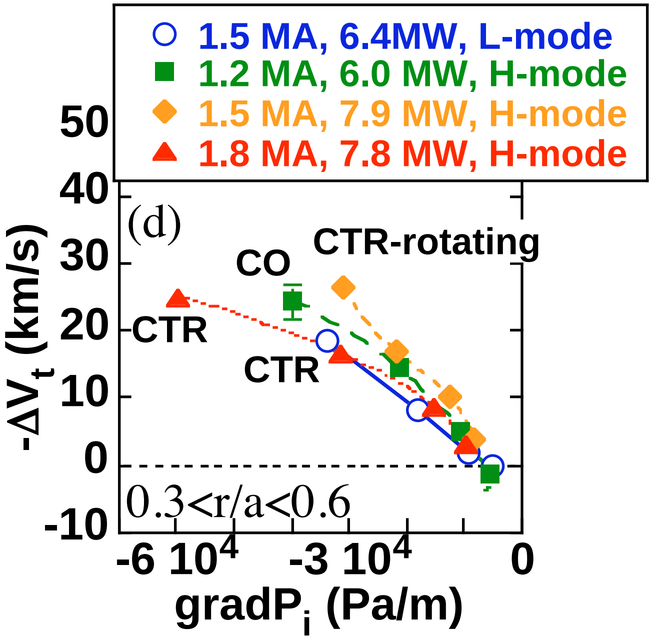
JT-60U

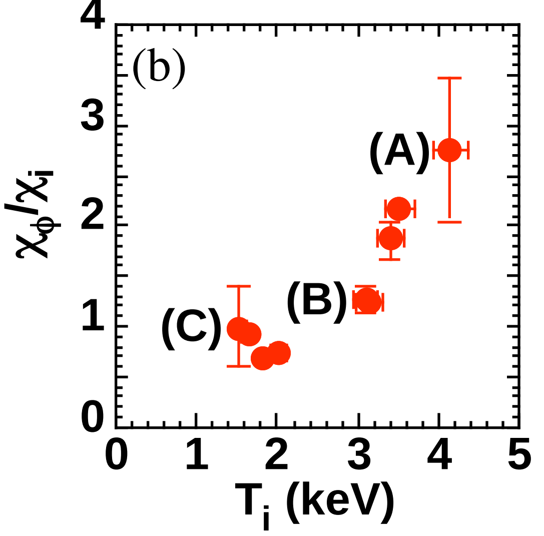
EX/3-1, M. Yoshida

I_p/B_T=1.2 MA/2.5 T, P_{ABS}=5.6-9.1 MW, n_e=2.0-3.0x10^{19} m^{-3}









(a) χ_ϕ increases with χ_i, χ_ϕ/χ_i~1-3 at r/a=0.5.

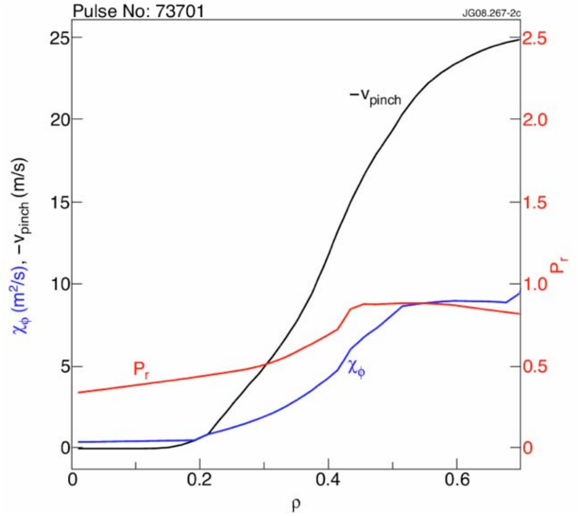
(b) χ_ϕ/χ_i increases with T_i.

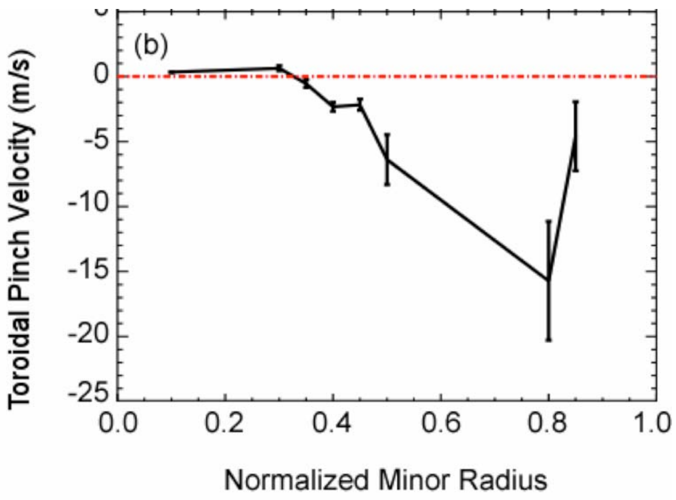
(c) -V_{conv} increases with χ_ϕ, -V_{conv}/χ_ϕ~0.5-2 (m^{-1}).

(d) Intrinsic rotation (ΔV_t) grows with increasing gradP_i. This tendency is almost the same in L-, H-mode, CO-, CTR-rotating plasmas, even in the different I_p, over a wide range of χ_ϕ. -> Local gradP_i causes the local value of intrinsic rotation.

Existence of a Momentum Pinch Observed on Multiple Devices

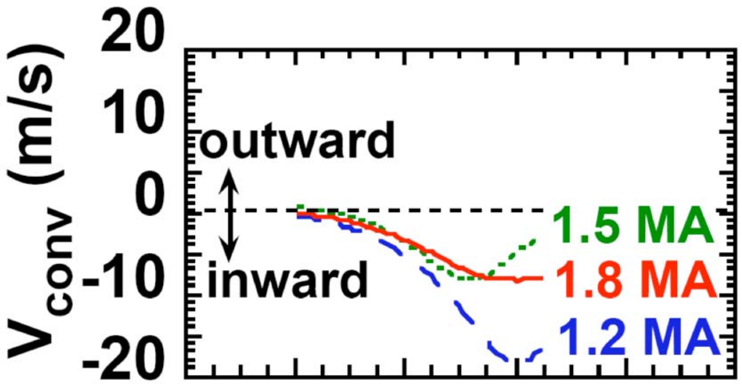
JET

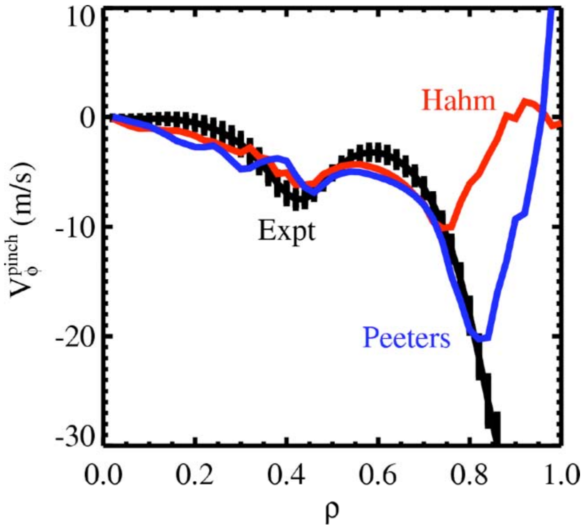




NSTX

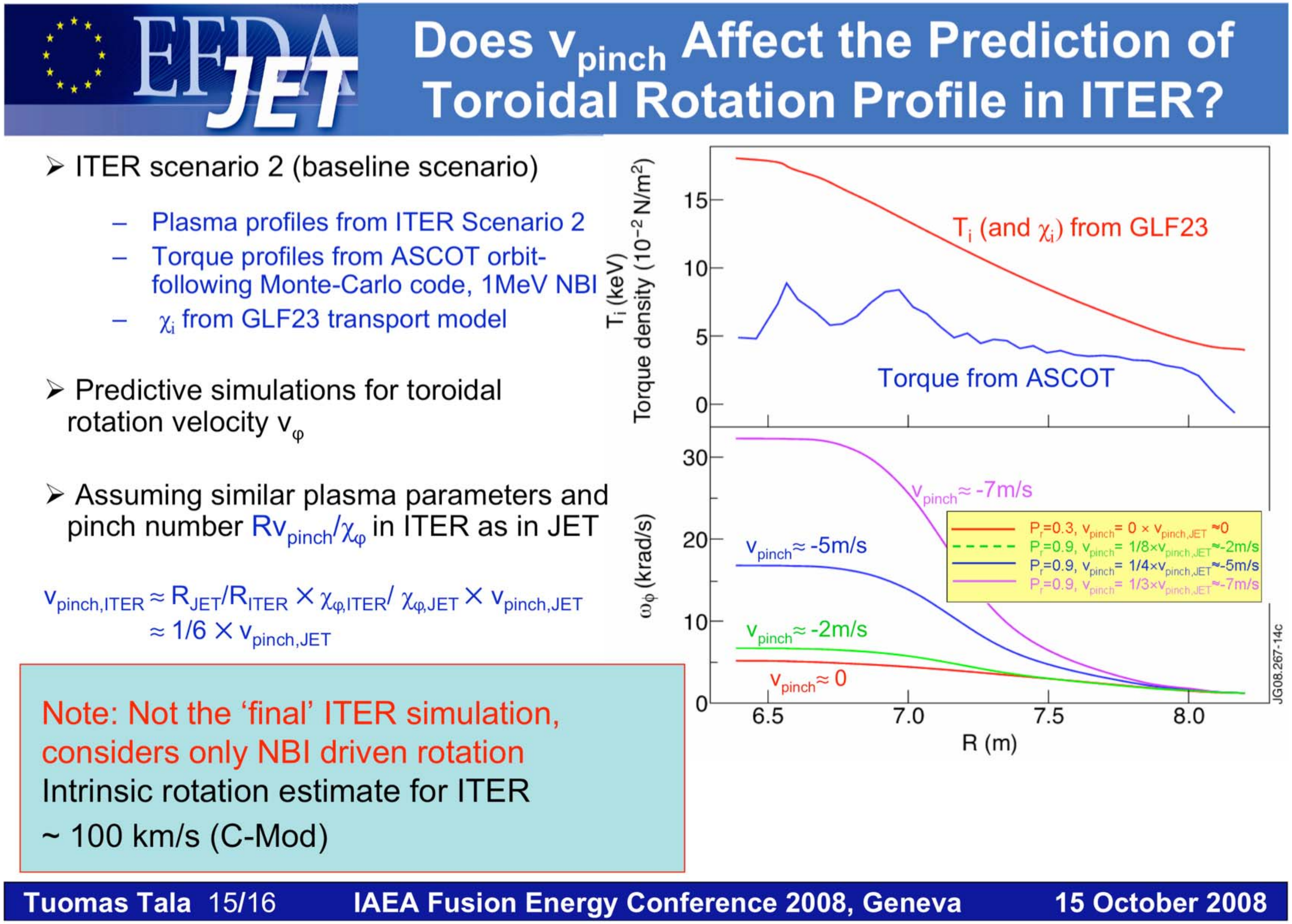
JT-60U





DIII-D

Predictions for rotation in ITER are emerging



Does v_{pinch} Affect the Prediction of Toroidal Rotation Profile in ITER?

- ITER scenario 2 (baseline scenario)
  - Plasma profiles from ITER Scenario 2
  - Torque profiles from ASCOT orbit-following Monte-Carlo code, 1MeV NBI
  - χ_i from GLF23 transport model
- Predictive simulations for toroidal rotation velocity v_φ
- Assuming similar plasma parameters and pinch number Rv_{pinch}/χ_φ in ITER as in JET

$$v_{pinch,ITER} \approx R_{JET}/R_{ITER} \times \chi_{\varphi,ITER}/\chi_{\varphi,JET} \times v_{pinch,JET} \approx 1/6 \times v_{pinch,JET}$$

Note: Not the 'final' ITER simulation, considers only NBI driven rotation

Intrinsic rotation estimate for ITER

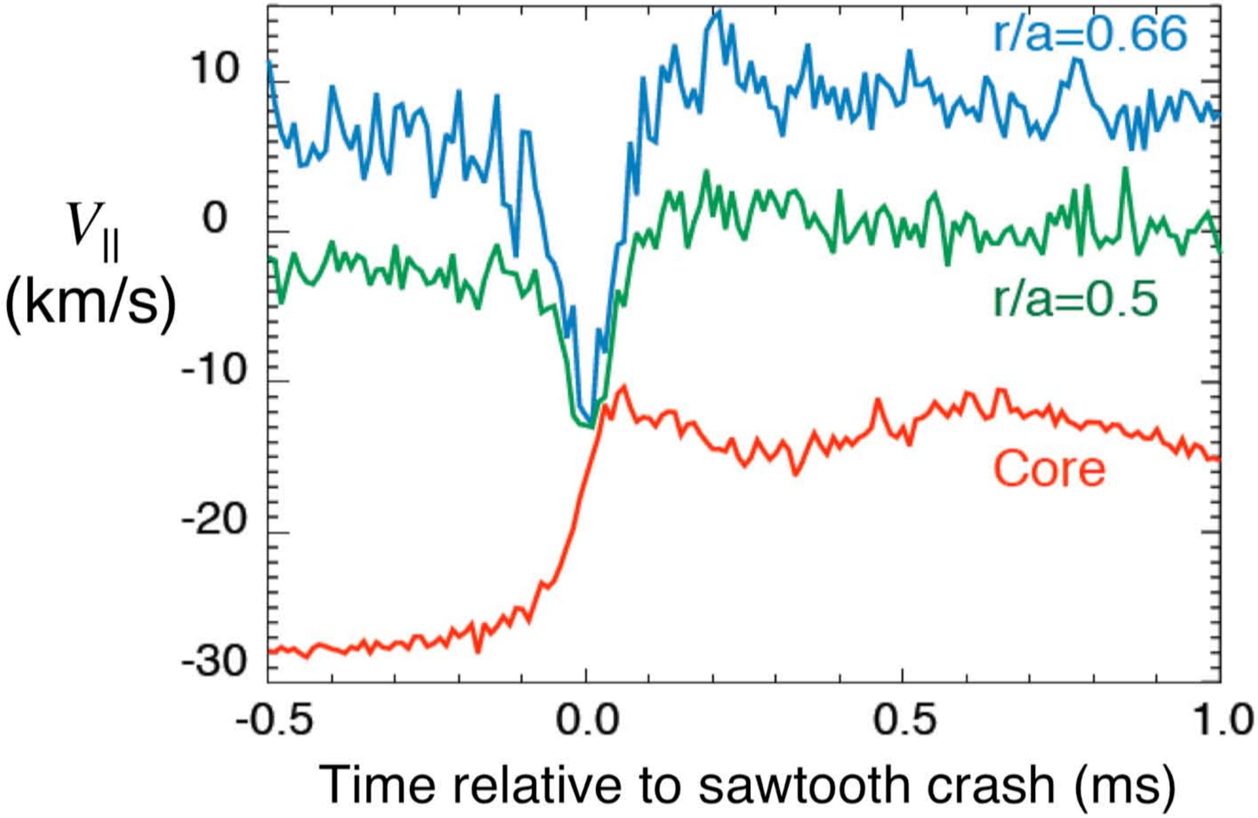
~ 100 km/s (C-Mod)

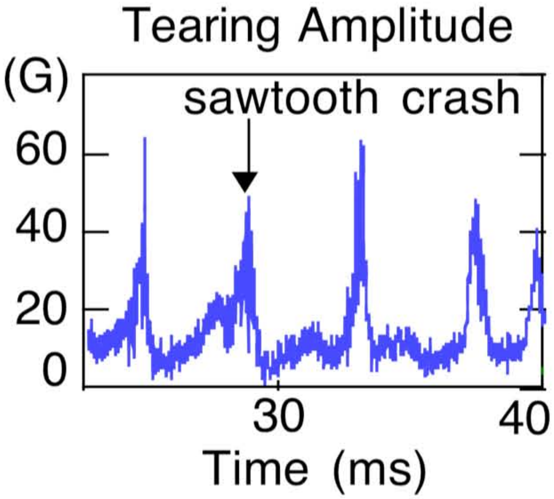
Tuomas Tala 15/16 IAEA Fusion Energy Conference 2008, Geneva 15 October 2008

Momentum transport from MHD tearing instability in the MST reversed field pinch.

- Momentum profile quickly flattens at the sawtooth crash
- Transport much faster than classical diffusion

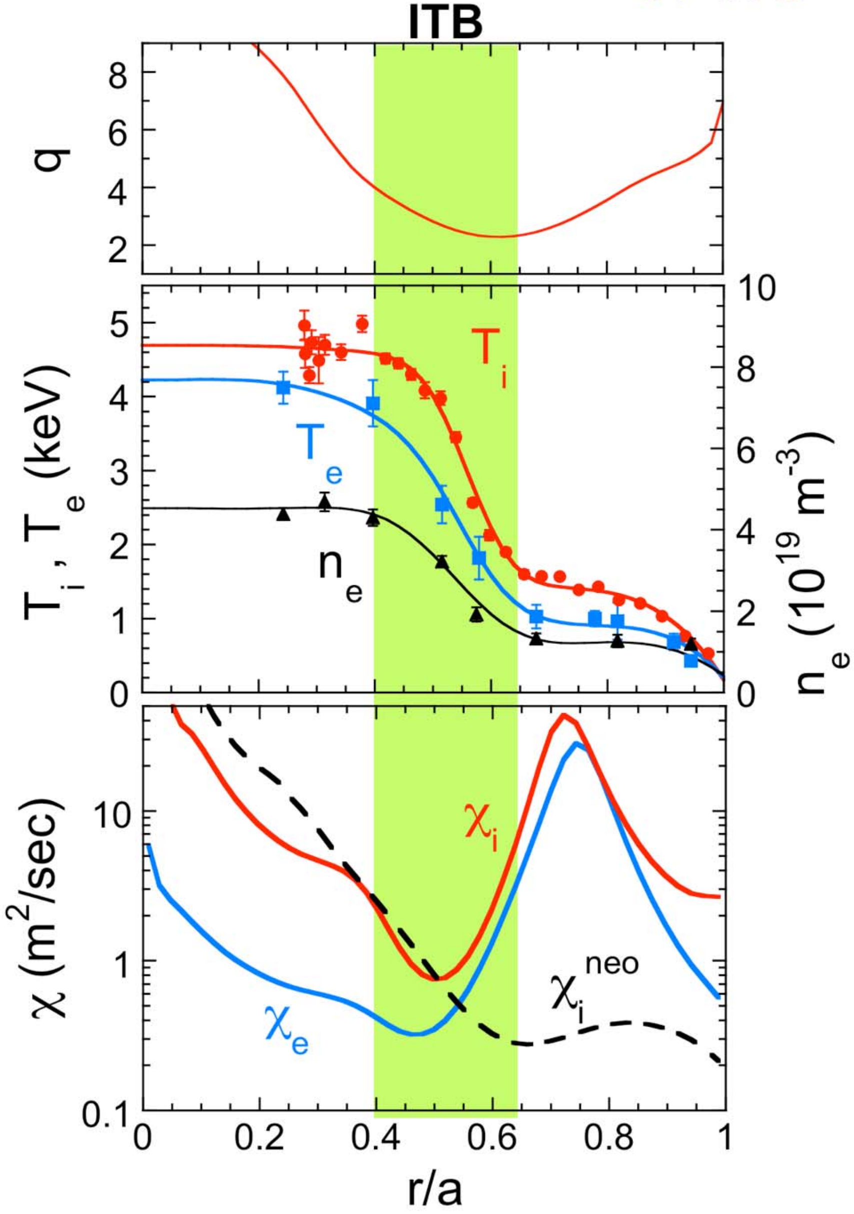
EX/P5-3





Thermal diffusivities down to ion neoclassical level at ITBs

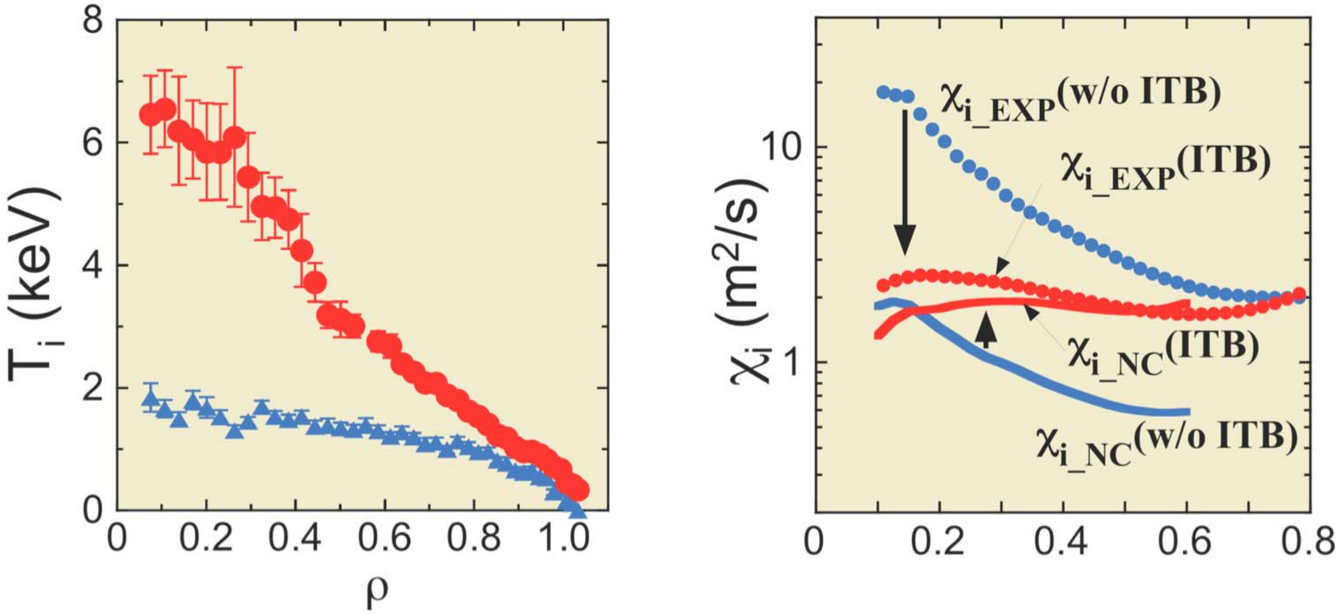
- Strong ITBs for T_i, T_e and n_e profiles were formed around ρ_{qmin} ($q_{min} \sim 2.3$).
- Thermal diffusivities were reduced to ion neoclassical level at ITBs.
- High Confinement ($HH_{y2} \sim 1.7$)
- High density ($n_e/n_{GW} \sim 0.9$)
- Reactor relevant condition
  - – $T_e \sim T_i$
  - – Low momentum input (BAL injection)



Ion neoclassical transport with ITB on LHD

Improvement of ion heat transport realized by upgrade of ion heating power

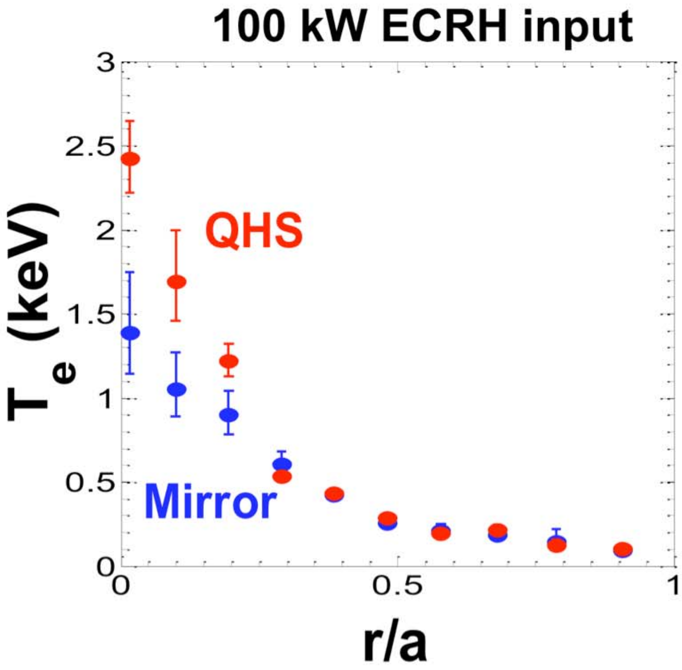
T_i (0) reaches 6.8 keV at $\bar{n}_e = 2\times10^{19} m^{-3}$

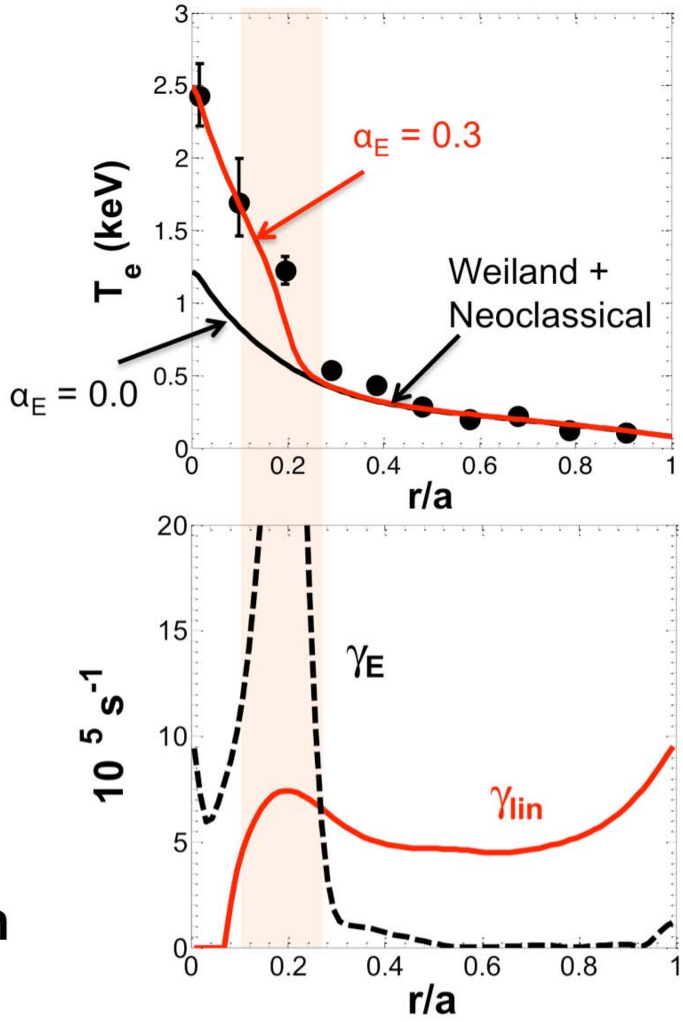


- ✓ Above $P_i / n_i > 4\times10^{-19}$MW m^3
- ✓ T_i Profile exhibits a steep gradient in the core similar to an ITB

➔ EX/8-2Ra by Nagaoka

First evidence of internal transport barrier in HSX





- **Shearing rate greater than maximum linear growth rate inside r/a ~ 0.3**
- **$\alpha_E = 0.3$ gives good agreement with temperature at core**

Talmadge EX/2-5

Improved Confinement with Internal Electron Temperature Barriers in RFX-mod Reversed Field Pinch

Improved confinement up to a factor 2 in Single Helical Axis (SHAx) states: inside the helical structure electron temperature exceeds 1 keV with steep gradients which identify an internal transport barrier ($1/L_{Te}$ of the order of 20 m^{-1}).

The heat conductivity improvement during a SHAx can be more than one order of magnitude and involves about one half of minor radius.

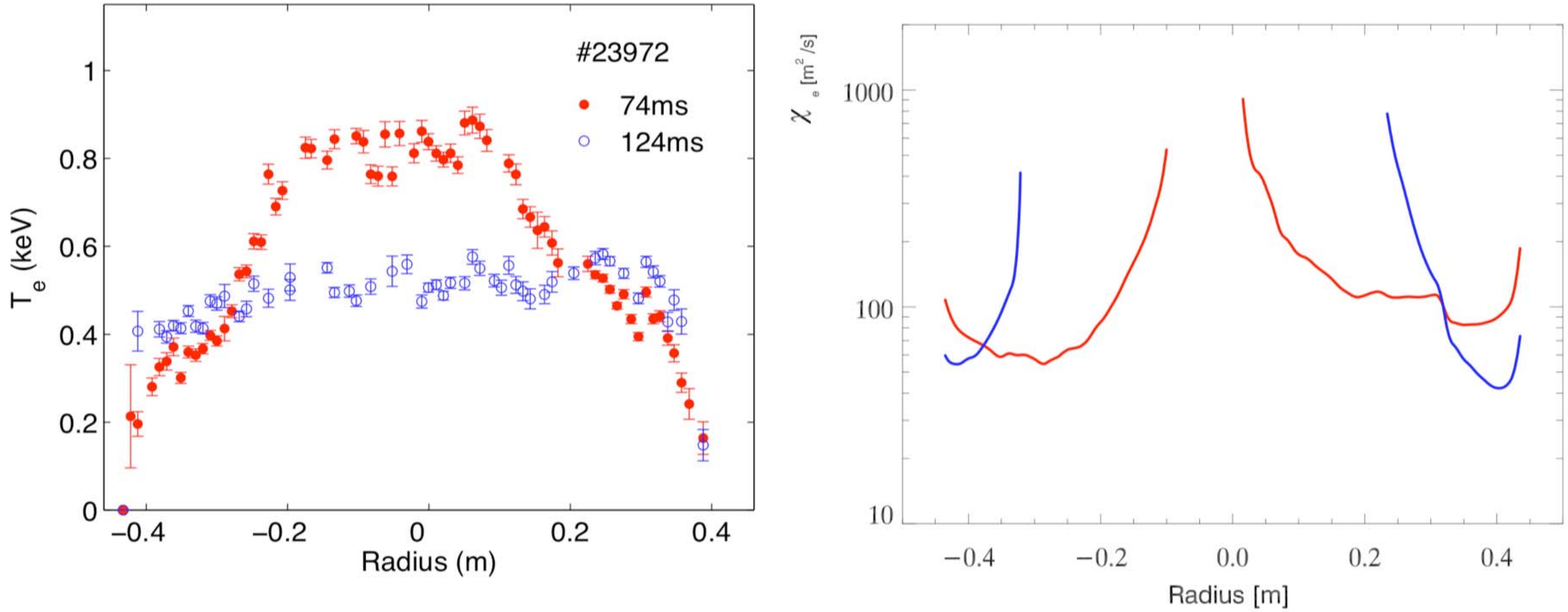
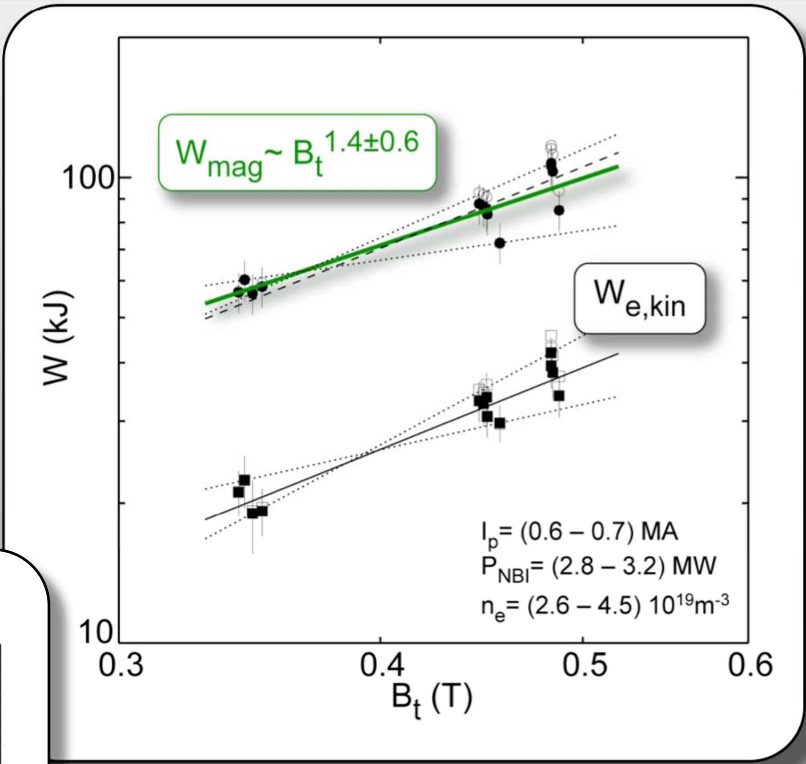


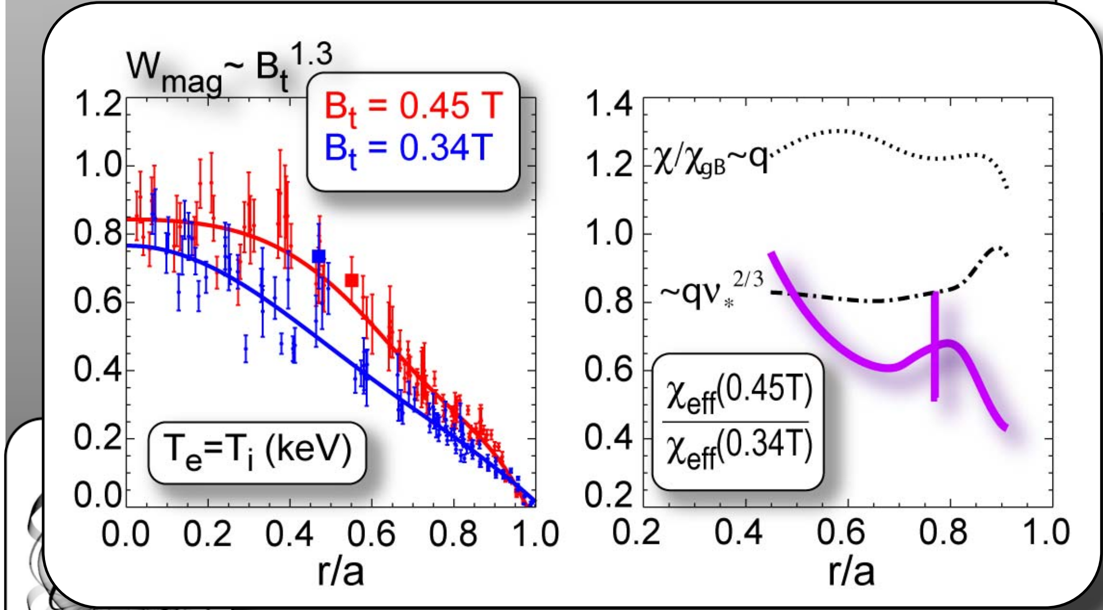
Figure: Measured electron temperature and calculated χ_e profiles during Multiple Helicity and SHAx states in the same RFX-mod discharge.

Stronger B_t and weaker I_p scaling of τ_E than IPB98(y,2)

- On MAST: $W_{mag} \propto B_t^{1.3} I_p^{0.6}$
  - *IPB: $B_t^{0.15}$, $I_p^{0.9}$*
  - *Similar to NSTX (S. Kaye).*

- Can be explained by stronger ν_* and weaker q scaling of χ_{eff} than IPB.





M. Valovic et. al. EX/P5-17

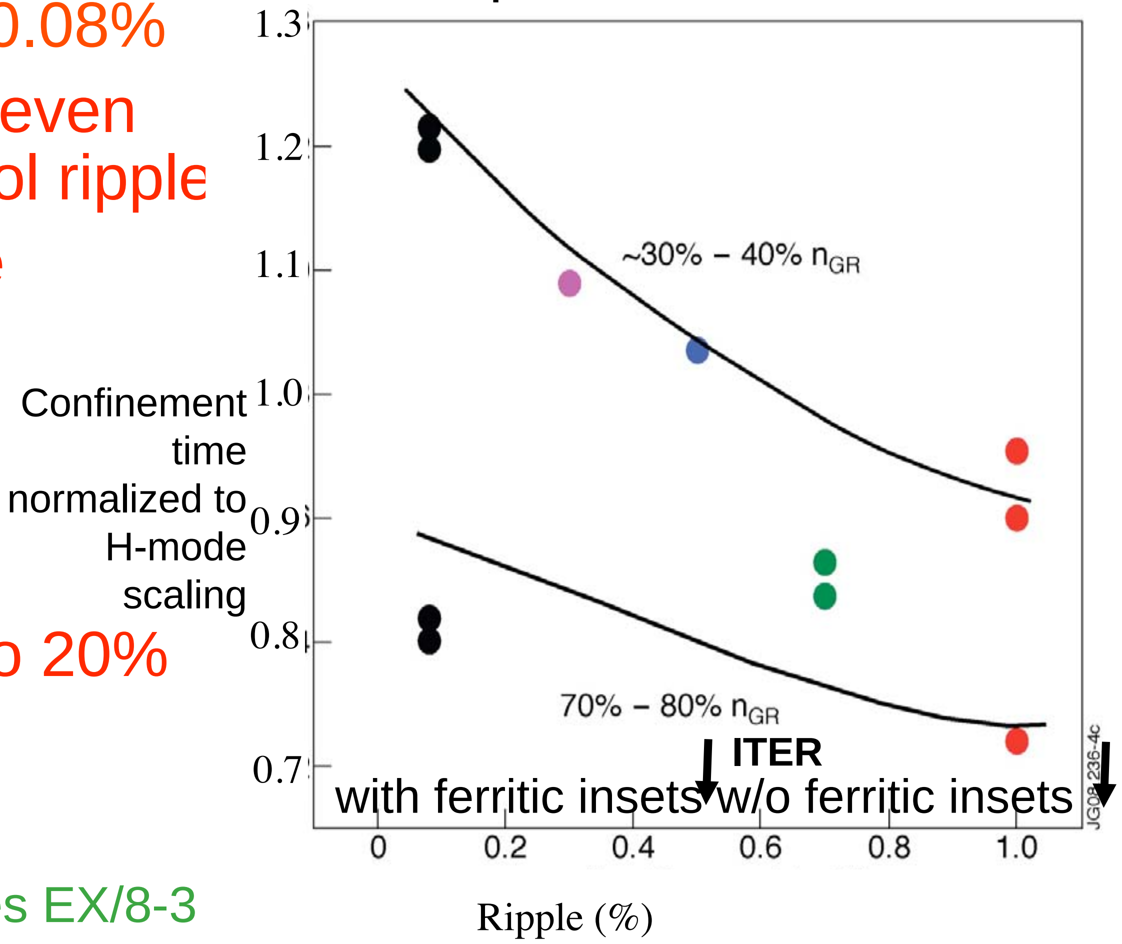
UKAEA Fusion

Working in Europe

Toroidal field ripple studies in JET

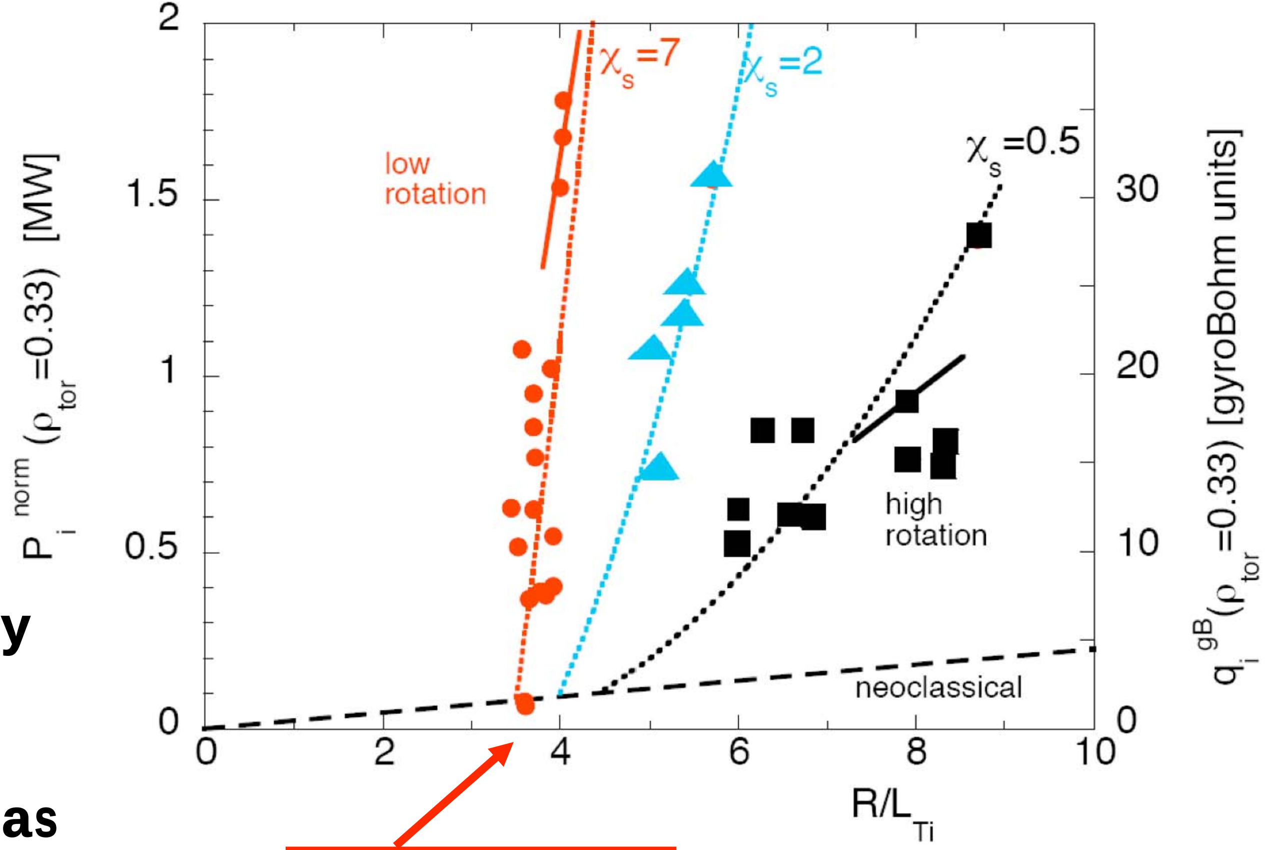
JET results suggests $\delta_{BT} < 0.5\%$ in ITER required to achieve $Q_{DT}=10$ goal
& reduce uncertainty
on confinement extrapolation.

- JET
- 32 coils
  → Intrinsic ripple $\delta_{BT} \sim 0.08\%$
- Separate control of odd/even coils allows to control ripple
- Ripple scan in the range $\delta_{BT} \sim 0.08\%-1\%$ and density scan
- 2.6MA/2.2T
- Neutral Beams only
- Fast particle losses up to 20%



Saibene EX/2-1, Tue. PM, De Vries EX/8-3

First experimental verification of ITG threshold



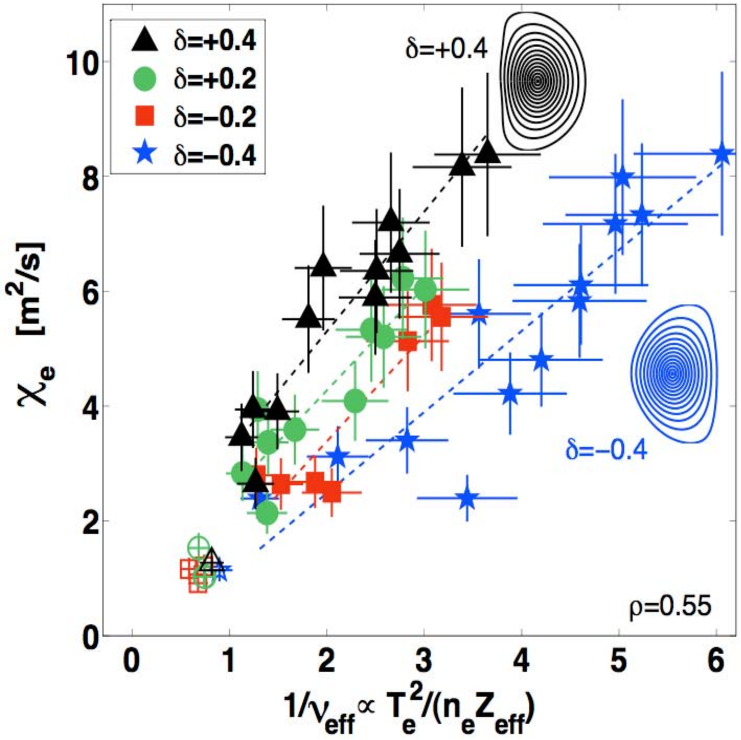
JET

threshold

On JET, ions are very stiff in low rotation plasmas, less stiff in high rotation plasmas (Mantica, EX/2-4)

Dependence of transport on collisionality and triangularity indicative of TEM transport

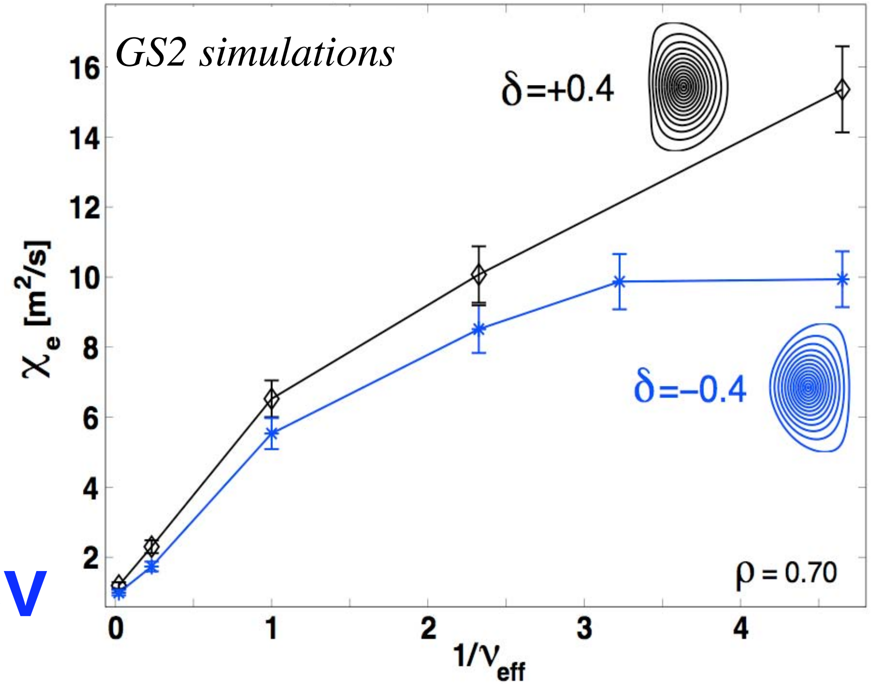
- **χ_e decreases for increasing ν_{eff} and for decreasing δ**
  - L-mode, large T_e gradient: $R/L_{Te}>10$



TCV

Y. Camenen et al., IAEA 2006 EX/P3-20
A. Fasoli et al., IAEA 2006 OV/3-3

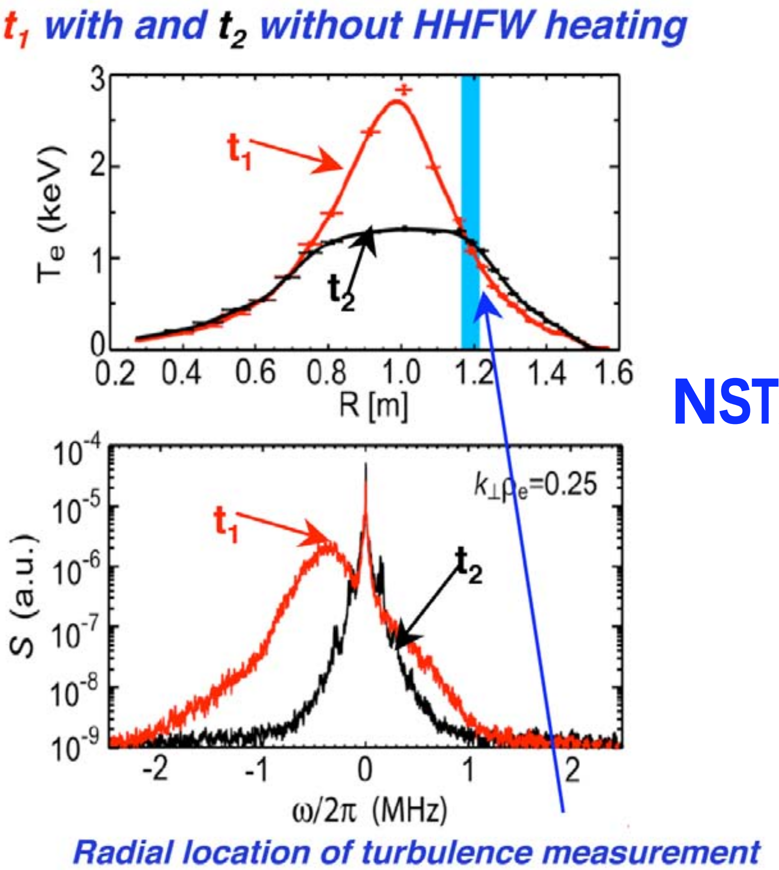
- **Trend confirmed by nonlinear local gyro-kinetic simulations of trapped electron mode (TEM)**



A. Pochelon et al., EX/P5-15

Electron-scale turbulence observed consistent with GS2 predictions

- **High-k ETG-scale spectrum on NSTX increases as T_e profile peaks (Mazzucato EX/10-2Ra)**

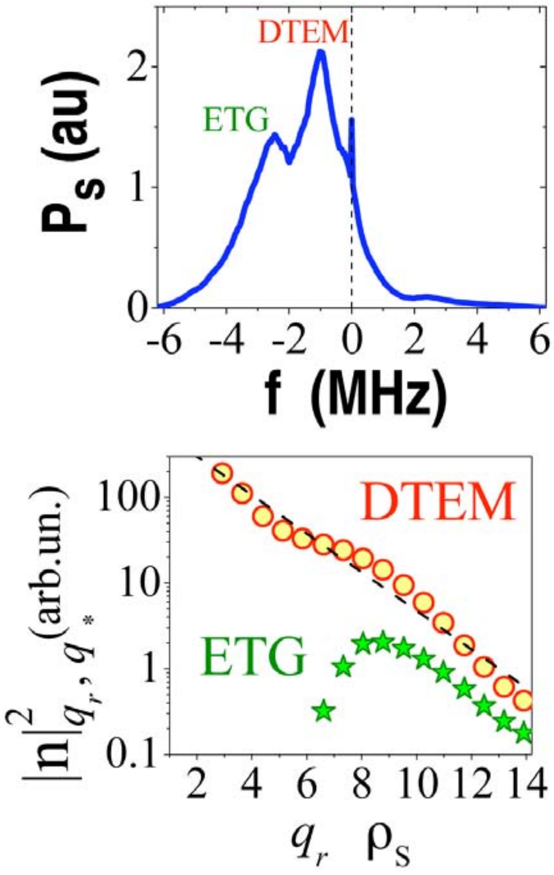


t_1 with and t_2 without HHFW heating

Radial location of turbulence measurement

NSTX

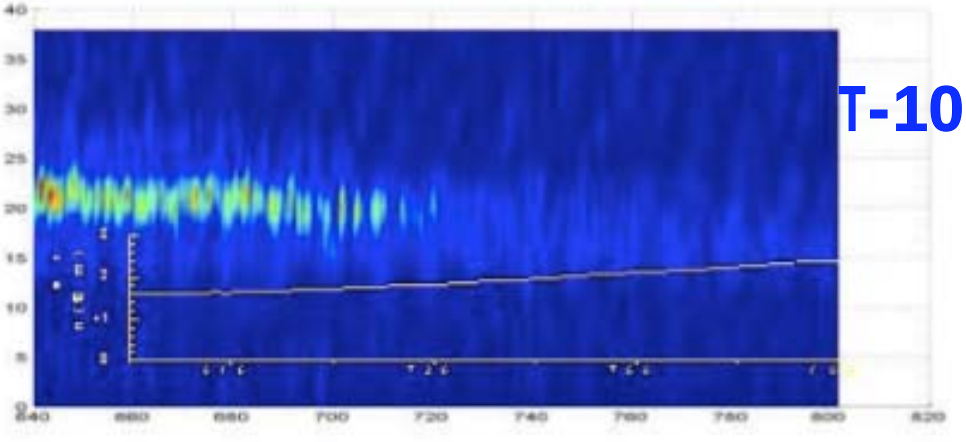
- **FT-2 spectra consistent with GS2 DTEM and ETG predictions (Gusakov, EX/10-2Rb)**

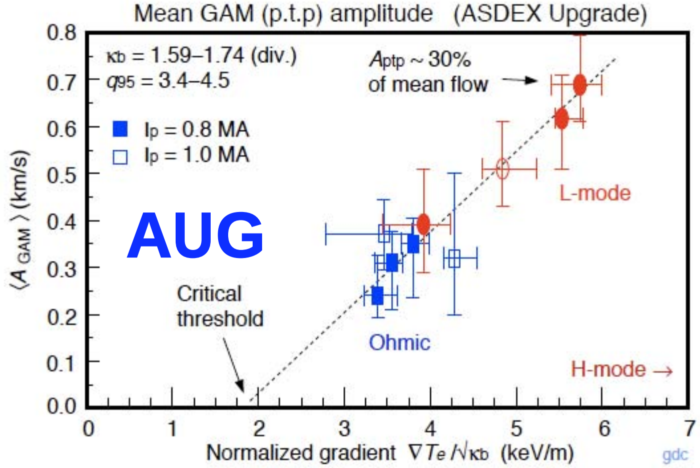


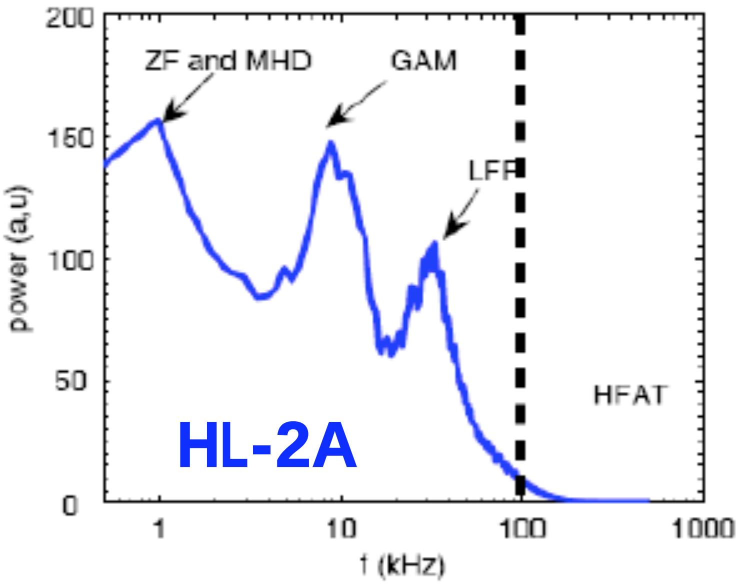
FT-2

Zonal Flows and Geodesic Acoustic Modes (GAM) Characteristics measured on multiple devices

- **T-10, GAM disappears with increasing density (Melnikov, EX/P5-36, Shelukhin EX/P5-37)**
- **HL-2A, Low-frequency zonal flow, GAM and 3-wave coupling to turbulence observed (Liu, EX/P5-32)**
- **AUG, amplitude scaling of GAM is linear with gradient drive (Conway, EX/P5-38)**

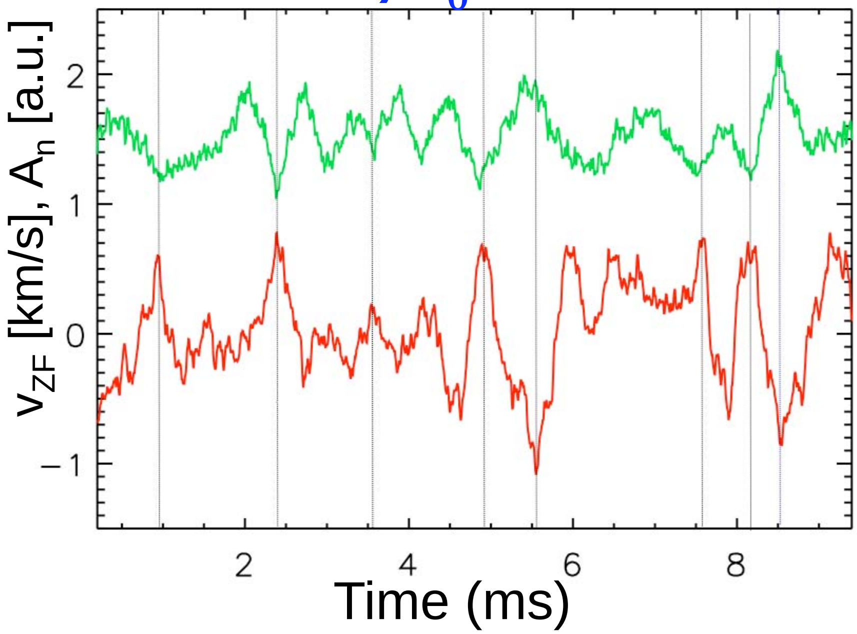




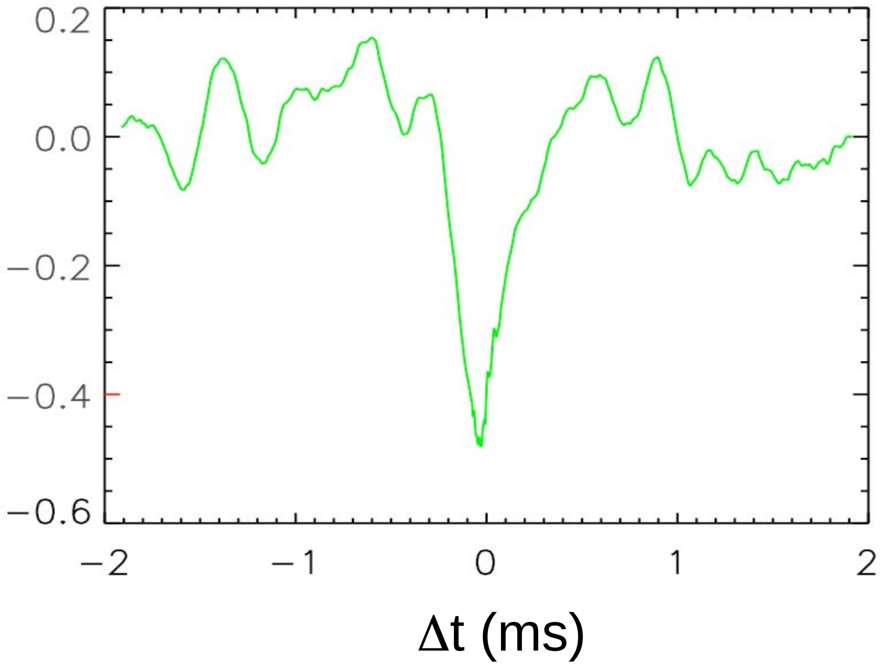


Strong Zonal Flows Reduce Intermediate-scale Density Fluctuations

DIII-D, $k_\theta \sim 5\ \mathrm{cm}^{-1}$



Correlation Coefficient (n,v)

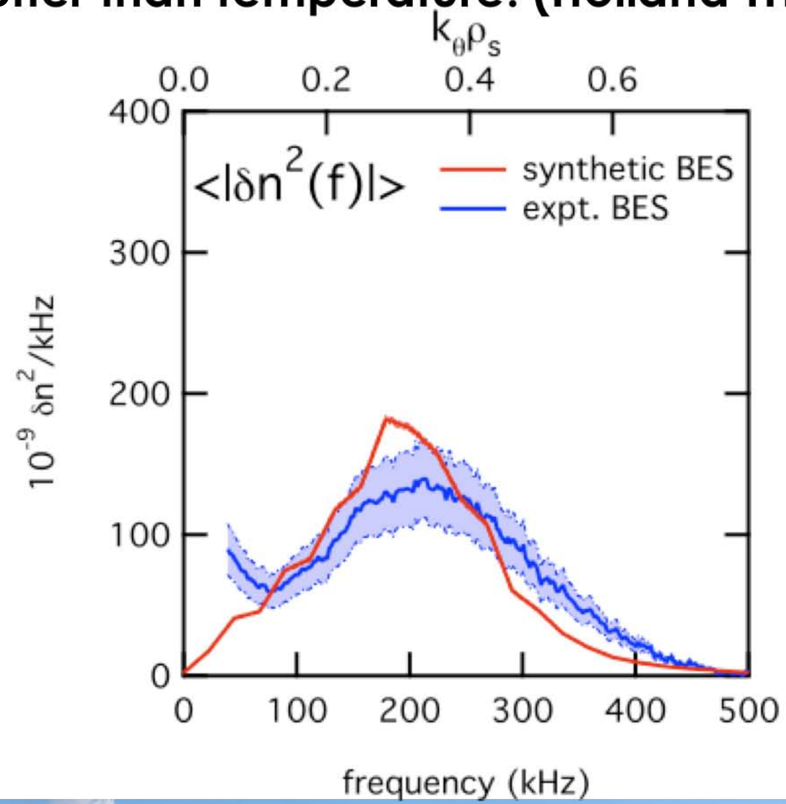


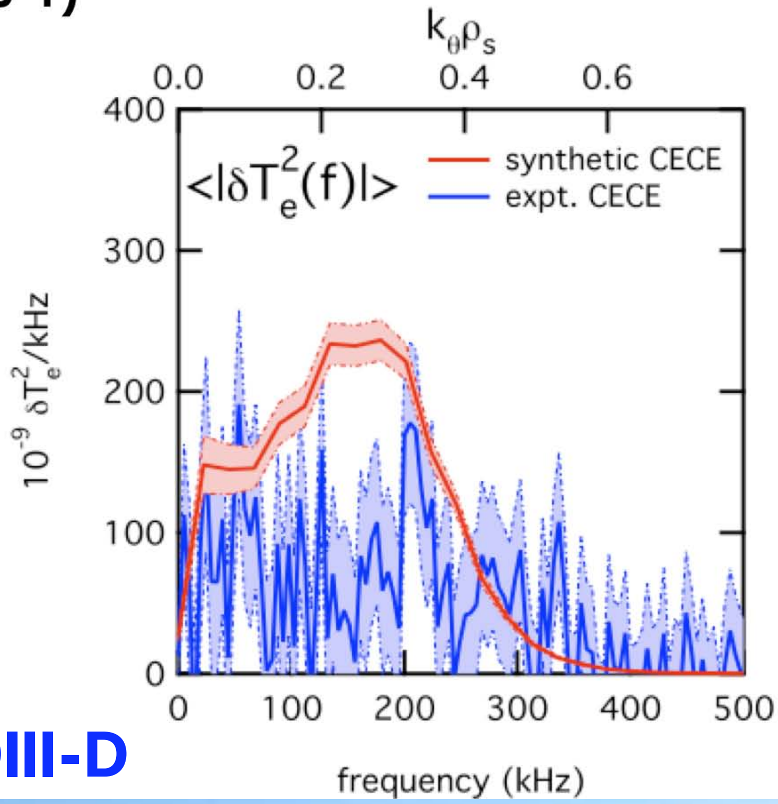
- **Low frequency flow fluctuations**
  v: 0.2-3 kHz
- **High frequency density fluctuation amplitude A_n: 7.5-75 kHz (Schmitz EX/P5-35)**

Strong <u>anticorrelation</u> between flow and density fluctuation envelope in L-mode core plasma

Quantitative comparisons of multi-field measurements to simulations provide stringent test of models

- Simultaneous measurements of density (BES) and temperature (CECE) fluctuations
- Synthetic diagnostics applied to simulation data
- GYRO reproduces both mode spectra and amplitudes, density better than temperature. (Holland TH/8-1)



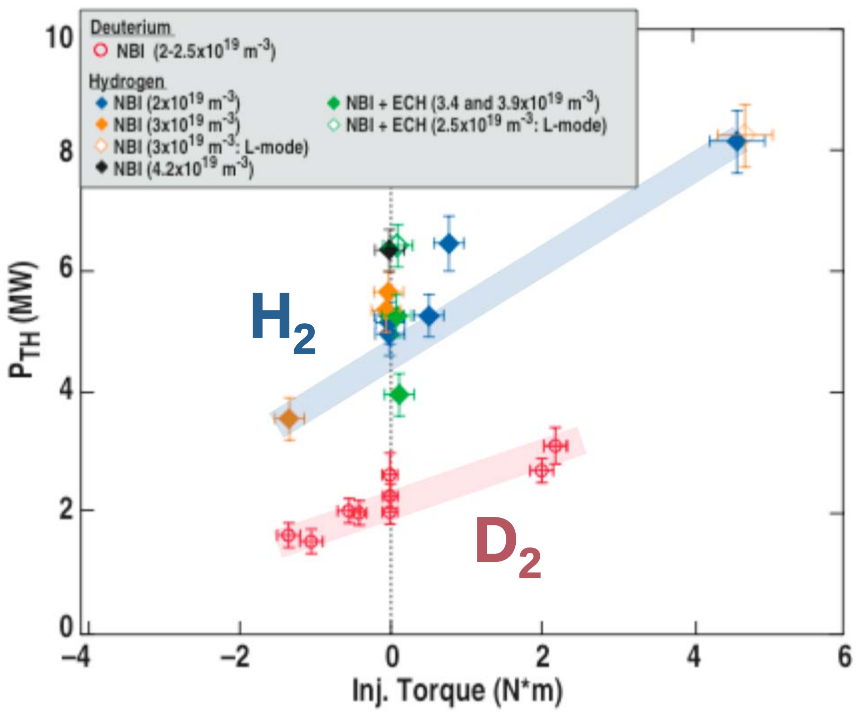


DIII-D

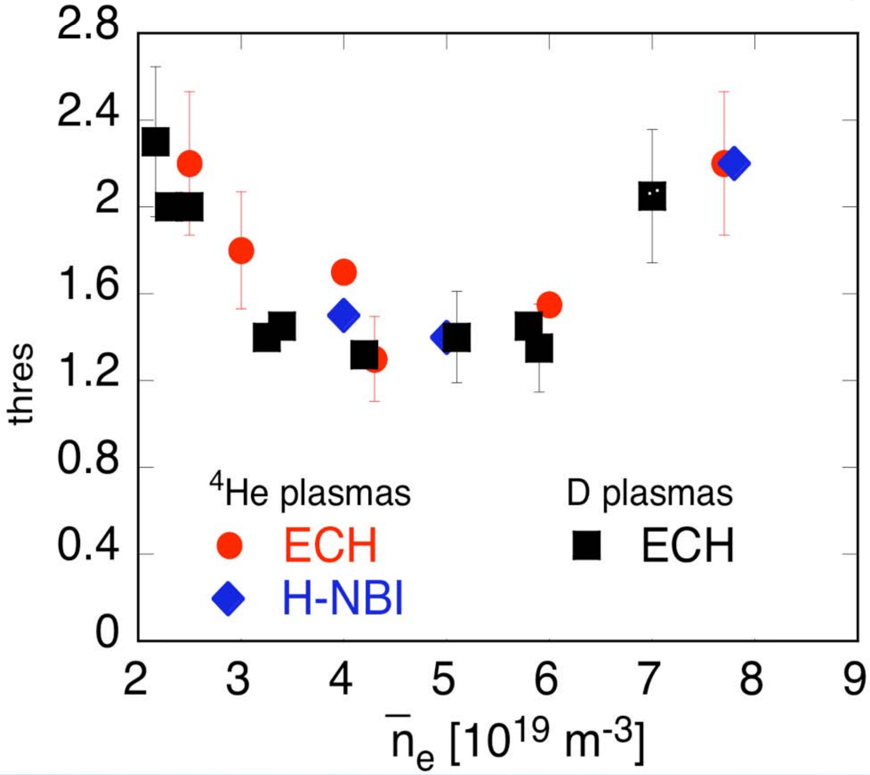
Power threshold for Deuterium and Helium-4 are similar and 2 times lower than Hydrogen

- P_{th} increases with torque in both H and D
- P_{th} minimum similar for ^{4}He and D

DIII-D P_{th}(H,D) vs. Torque



ASDEX Upgrade P_{th} (^{4}He,D) vs. n_e

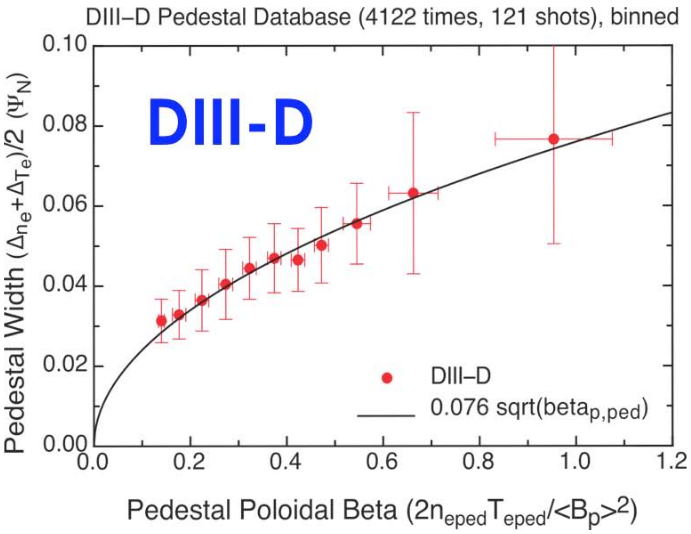


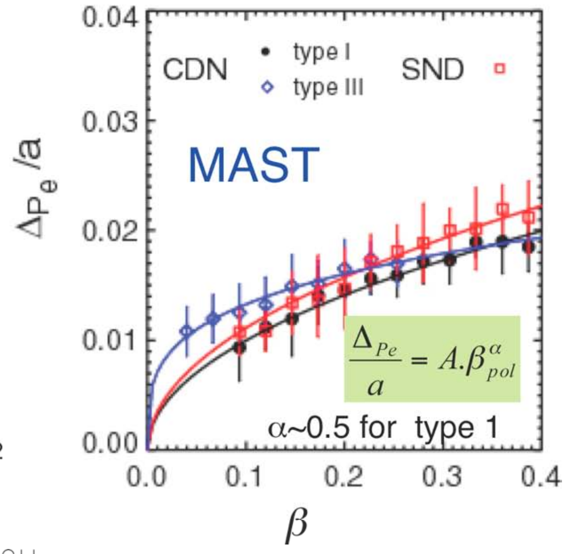
Pedestal Width Scaling with Pedestal Poloidal Beta Observed in Several Devices

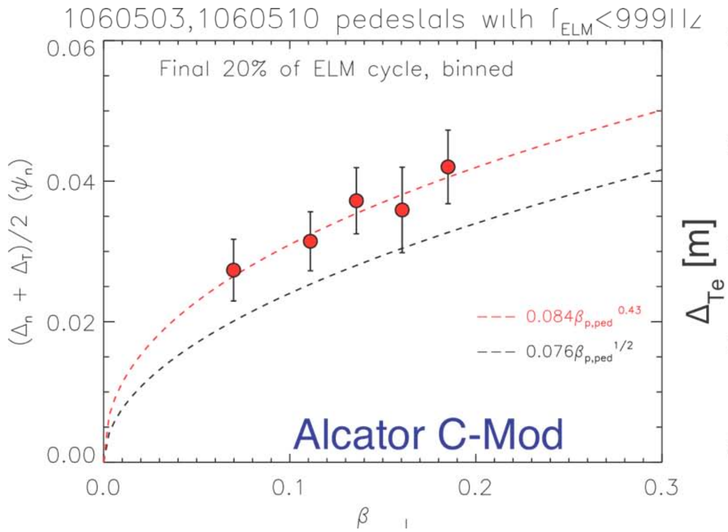
- **Pedestal Pressure width**

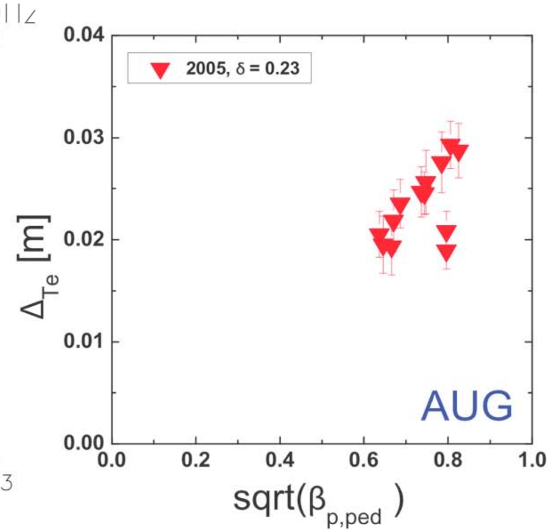
$$\Delta_p(\psi) \propto \sqrt{\beta_{p,pol}}$$

- **Relative width, Δ/a similar across devices**

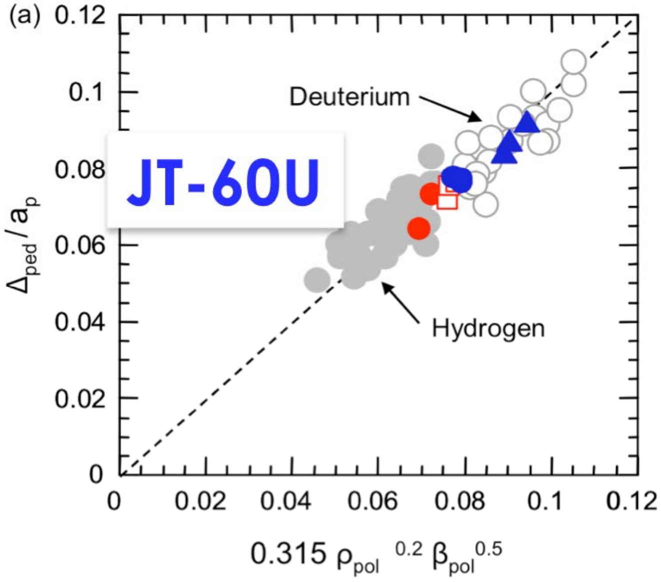


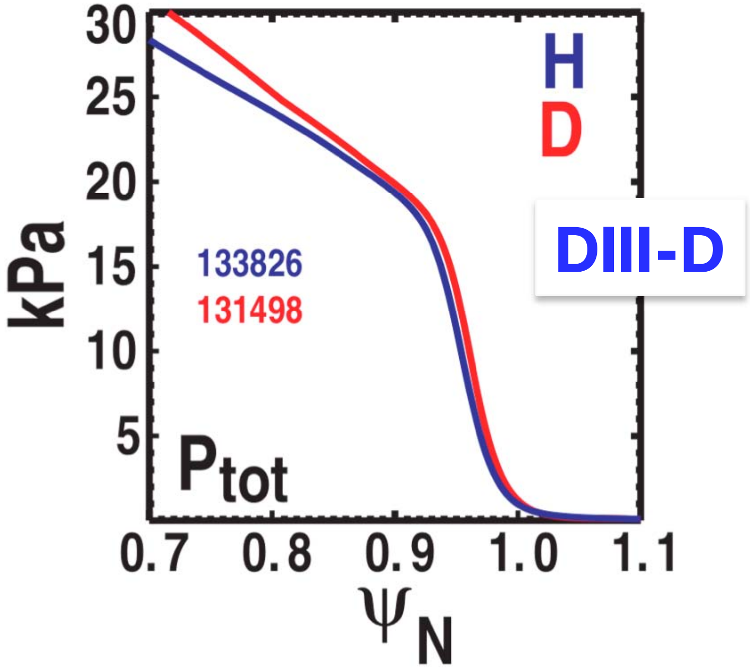






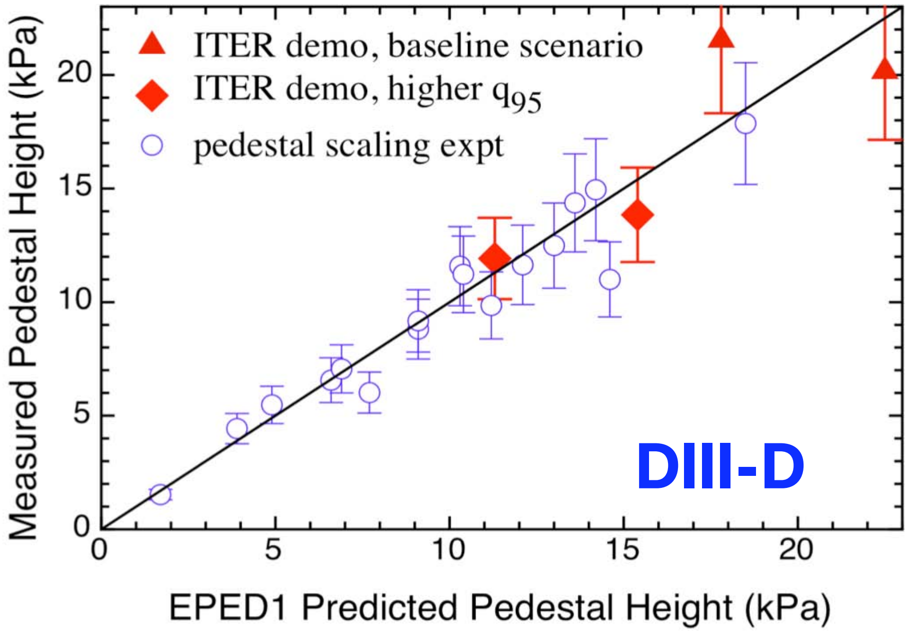
Pedestal width from mass scaling experiments exhibit $(\beta_{\theta,ped})^{1/2}$ and very weak $\rho_{i,\theta}$ dependence

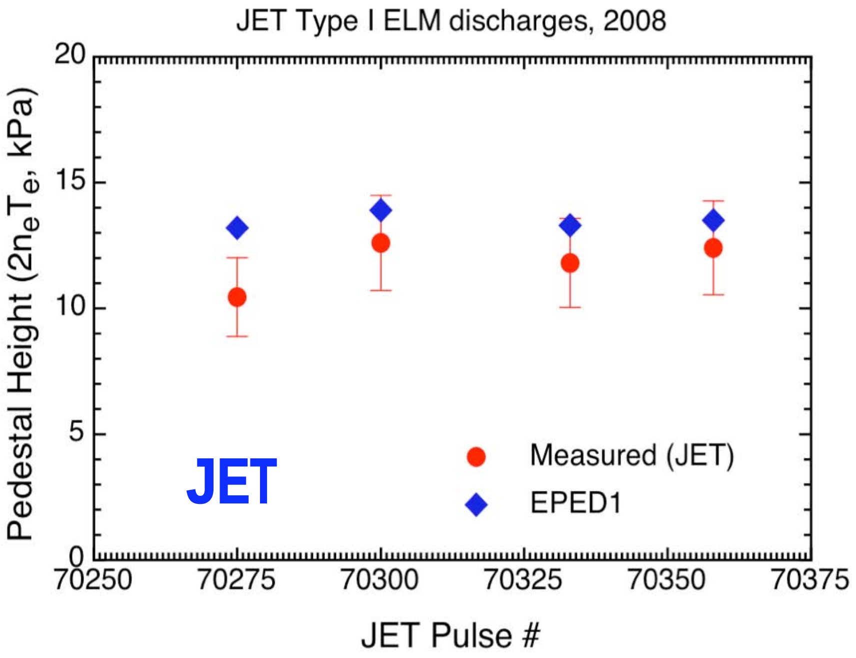




- **JT-60U: Pedestal width (T_i) in H/D experiment scales with $(\beta_{\theta,ped})^{1/2}$, $(\rho_{i,\theta})^{0.2}$**
- **DIII-D: Pedestal width (total pressure) in H/D exhibits dependence on $\beta_{\theta,ped}$ but not on $\rho_{i,\theta}$**

Pedestal Width Scaling Combined with Stability Offers Pedestal Height Prediction





- **Initial prediction for ITER: T_{ped} ~4.6 keV (favorable for Q=10)**

Summary 1: Innovative Concepts Research is Focused on Novel Solutions to Fusion Challenges

- **Levitated Dipole: first full levitation**
  - Increased density, increased beta

- **Progress in sustaining field reversed configurations**
  - FRC -- sustained 10 ms
  - Spheromak -- 34 kA

- **New Divertor Configurations have the potential to reduce peak heat flux**

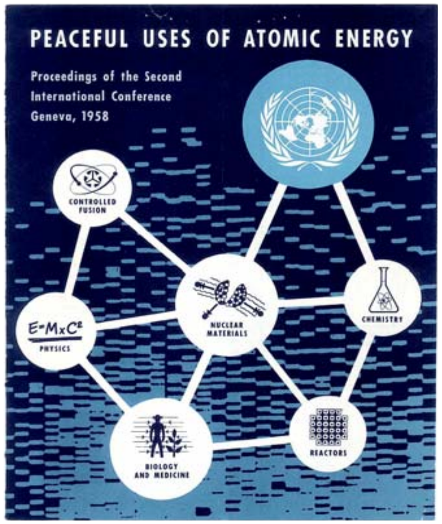
Summary 2: Scenario Research Has Increased Confidence in ITER's Success, but Work Still Remains

- **Several experiments have demonstrated operational scenarios that exceed the requirements of ITER**
- **Performance benefits from conditions not expected in ITER (e.g., low density, $T_i > T_e$, and high toroidal rotation). More work is required to determine acceptability in ITER-like conditions.**
- **Potential of steady-state operation is being realized**
  - Fully non-inductive and 100% bootstrap operation demonstrated
  - Continued improvement in performance achieved through optimization with respect to plasma shape, pressure profile, and current profile
- **Integration of high performance core with boundary solution remains a significant challenge**
  - Performance with metal walls looks promising, but more work to be done
  - ELM suppression achieved but core performance impacted
  - Significant issues with localized heat/particle handling in long pulse discharges

Summary 3: Continued Research in Transport Provides the Basis for Developing Predictive Models

- **Progress in experimental validation of theory-based models for particle transport**
- **New sources of torque are clearly identified: Intrinsic (∇T_i), Mode conversion current drive, lower hybrid, and non resonant magnetic perturbations**
  - Useful for increasing ITER's rotation
- **Inward momentum pinch identified on many experiments**
  - Potentially increasing rotation in ITER
- **Toroidal field ripple decreases the energy confinement**
- **Internal transport barriers are observed on stellarators and RFPs**
- **Clear evidence of critical temperature gradient is demonstrated**
  - Reduced stiffness and rotation increases
- **Evidence of zonal flows reducing turbulence**
- **Pedestal scaling with $\beta_p^{1/2}$ is favorable for ITER**

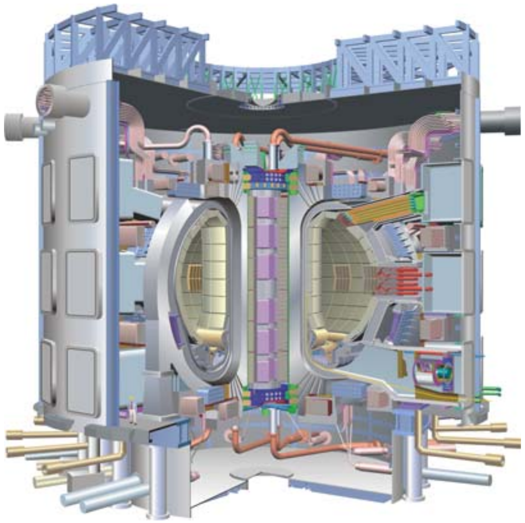
50 Years of Fusion Energy Research



PEACEFUL USES OF ATOMIC ENERGY

Proceedings of the Second
International Conference
Geneva, 1958

- **1958 : The world shared its vision of fusion energy**
- **2008: The world has committed to share the realization of fusion energy**
- **The need for fusion energy is greater than when we started our journey together**



Progress demonstrated at this 22nd IAEA Fusion Energy Conference shows we can move forward – with high and increasing confidence