28th IAEA Fusion Energy Conference

Summary: Magnetic Fusion Experiments - I

Core Confinement	60
MHD & Stability	26
Energetic Particles	17
Divertor & SOL	42

M.C. Zarnstorff

PPPL, USA

15 May 2021

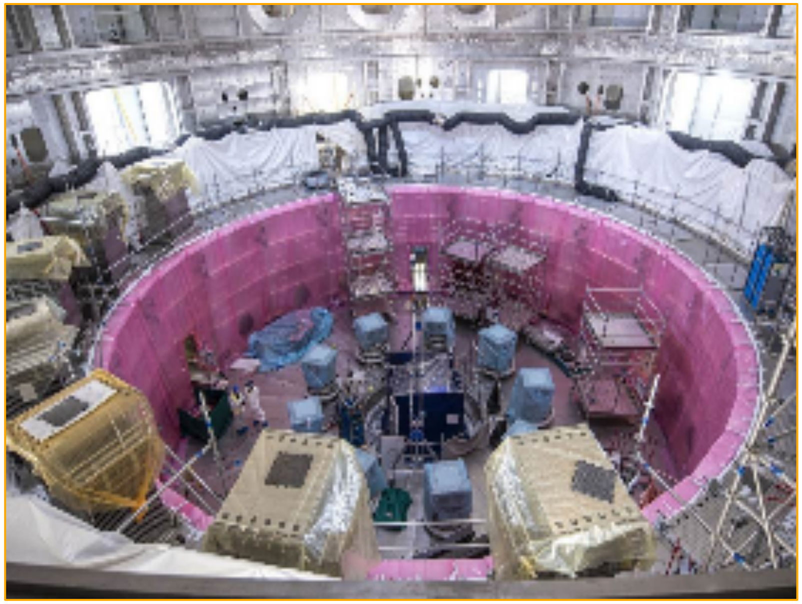
ITER Construction – Fantastic Progress

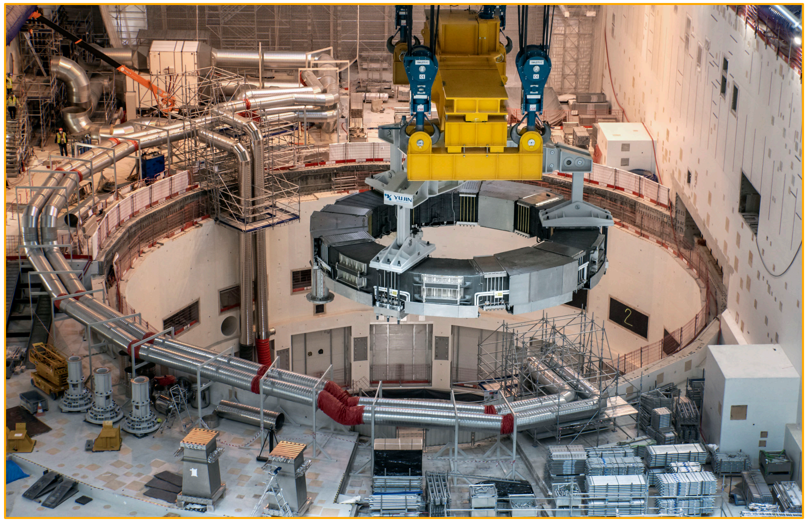
- Major components being delivered
- First sector starting assembly
- Cryostat & coils being installed in pit
- Buildings & infrastructure being completed
- Incorporation of new developments, e.g. shattered pellets DM
- Research prep. progressing

1st plasma: late 2025

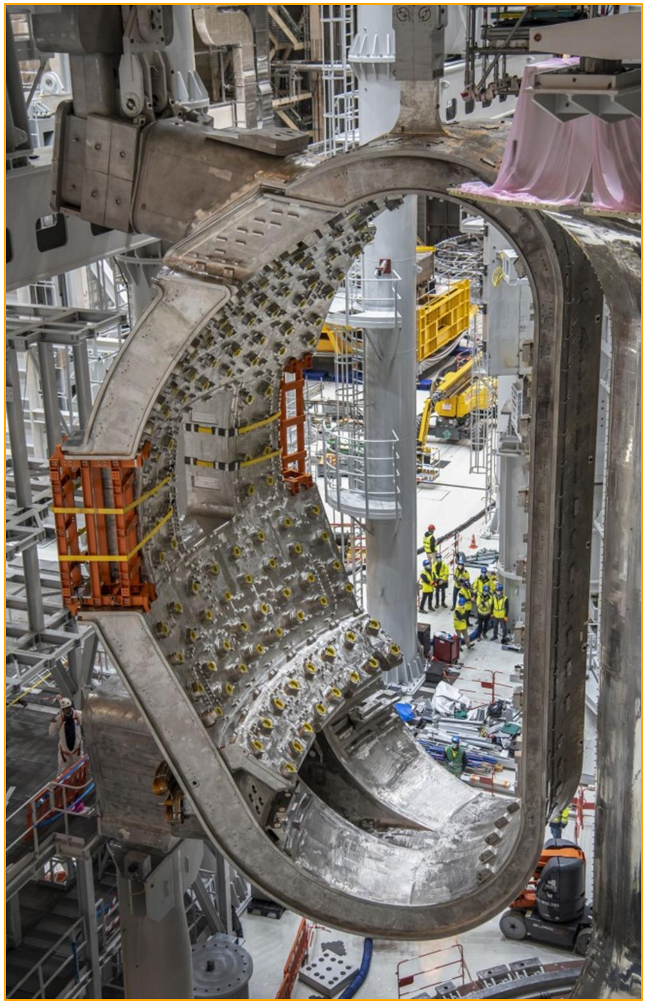
Community support is essential to success.

B.Bigot OV/1-1



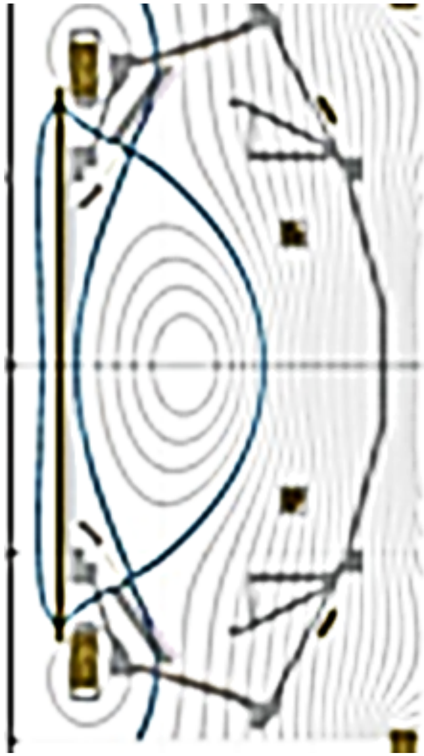


Installation of the cryostat side-wall and PF-coil #6 in the tokamak pit



VV Sector 6 in the sector sub-assembly tool

New & Upgraded Experiments Operating



ST-40 (Tok. Energy)

R=0.4-0.6m,A=1.6-1.8
B_T=3T, I_P=2MA

First plasma: 2019
ST performance,
high T

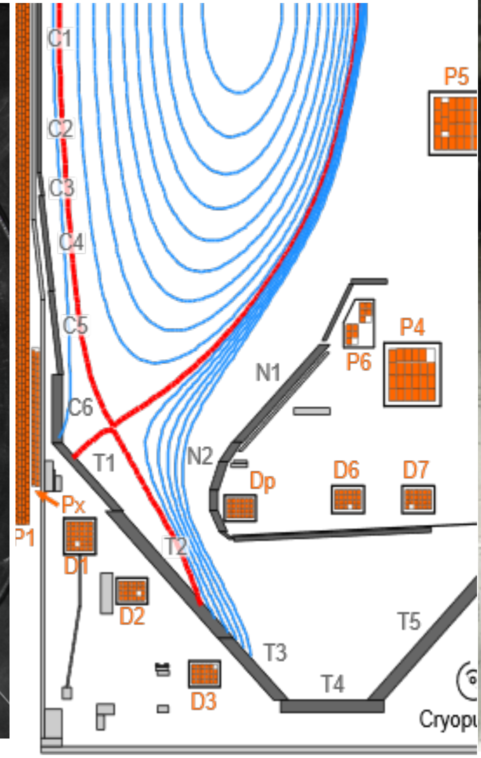
M.Gryaznevich OV/4-5

HL-2M (CN)

R=1.78m, A=2.8
B_T=2.25T, I_P=2.5MA

First plasma: 2020
High performance
w/ adv. divertors

X.Duan EX/4-3

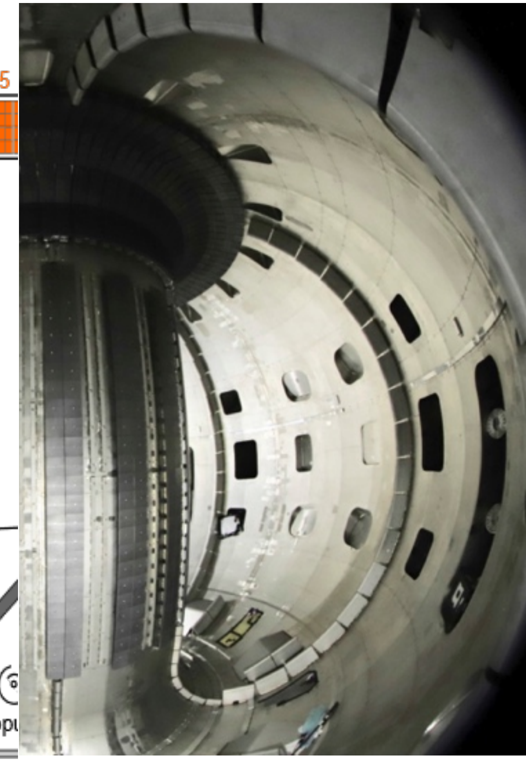


MAST-U (UK)

R=0.85m, A=1.3
B_T=0.92T, I_P=2MA

First plasma: 2020
Super-X Divertor
ST performance

J.Harrison EX/P6-1538

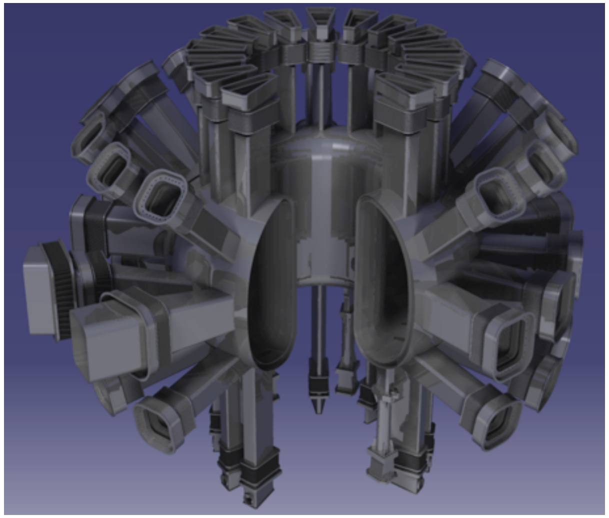


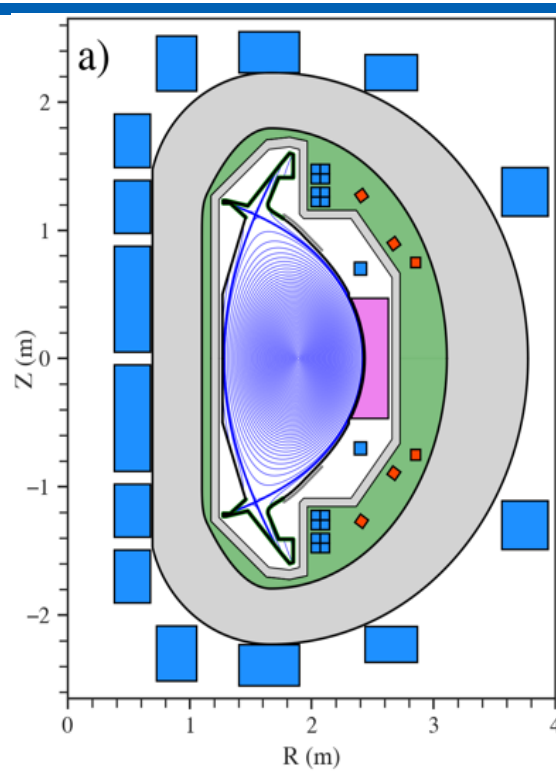
JT60-SA (JP, EU)

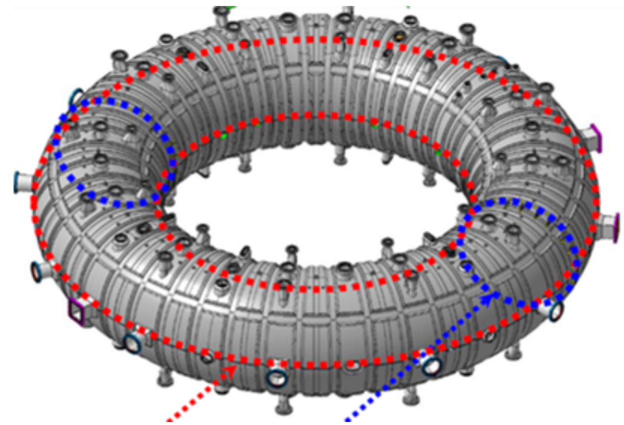
R=3m, A=2.5
B_T=2.25T, I_P=5.5MA
Superconducting
Commissioning
Long pulse adv.
scenarios

Y.Kamada OV/2-4

New Experiment Projects/Upgrades







DTT (IT)

R=2.19m, A=3.1
B_T=6T, I_P=5.5MA

Exhaust physics, core-edge integration divertor test facility

P.Martin EX/P-1053

SPARC (CFS, Inc.)

R=1.85m, A=3.2
B_T=12.2T, I_P=8.7MA

Q > 2 short pulse
Long-leg divertor

P.Rodriguez -Fernandez OV/P-856

RFX-mod2 (IT)

R=2m, A=4.1
I_P=2MA

Closer shell, double poloidal gaps, improved PFCs

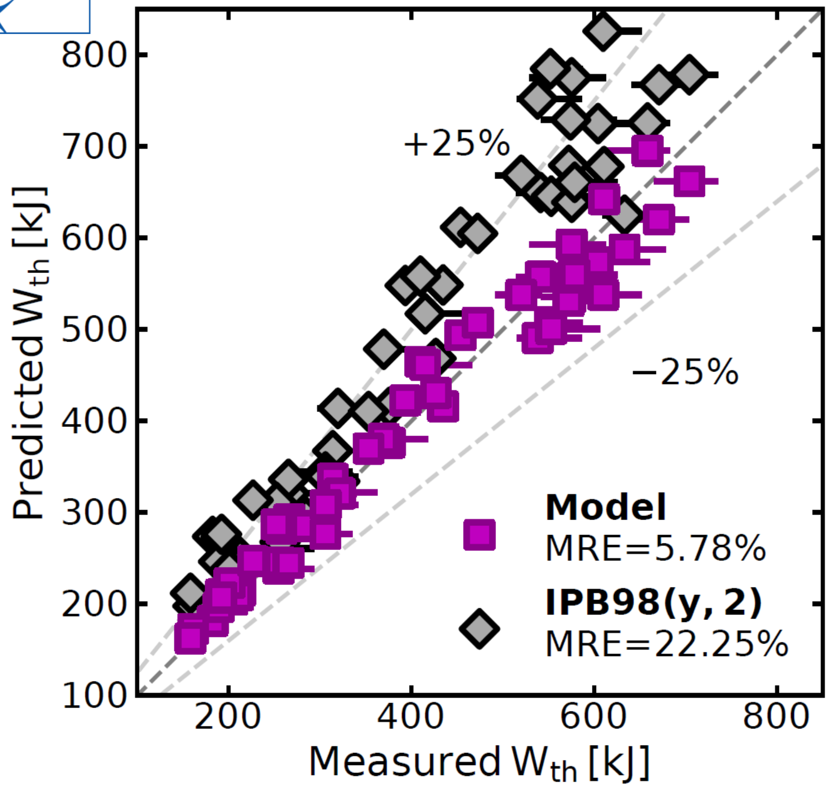
L. Marrelli EX/P-1077

Core Confinement

- Predict-First Modeling
- Impact of fast ions
- Isotope scaling
- Stellarator transport & confinement
- High performance in JET
- ST confinement

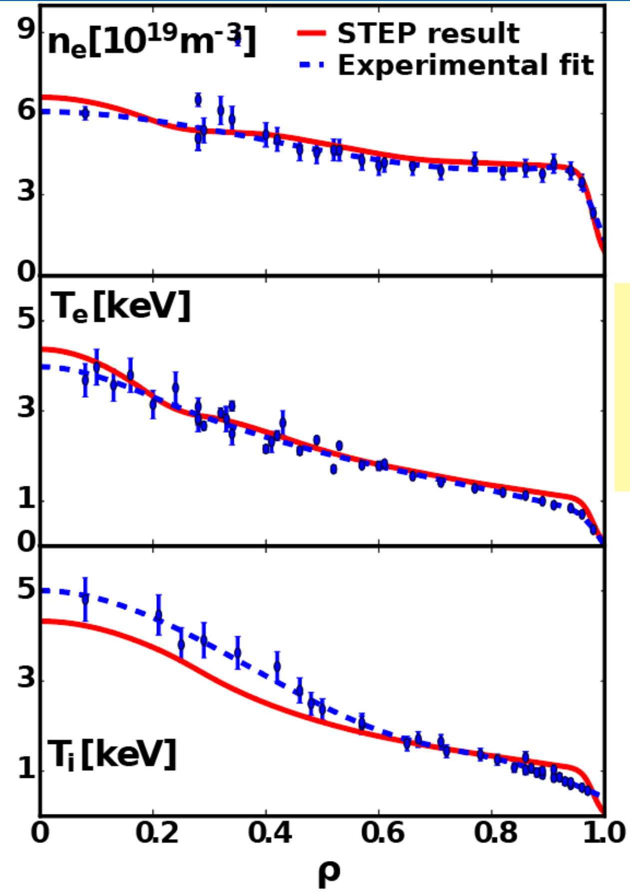
Accurate Predict-First Models Developed

ASTRA/HELENA/MISHKA



- Separatrix parameters from empirical model of gas puff & 2-pt model
- Pedestal from PB-stability & critical temperature gradient model
- Core plasma inside pedestal using TGLF
- More accurate than scaling laws for AUG!

U. Stroth OV2-2; G.Tardini TH/P2-926

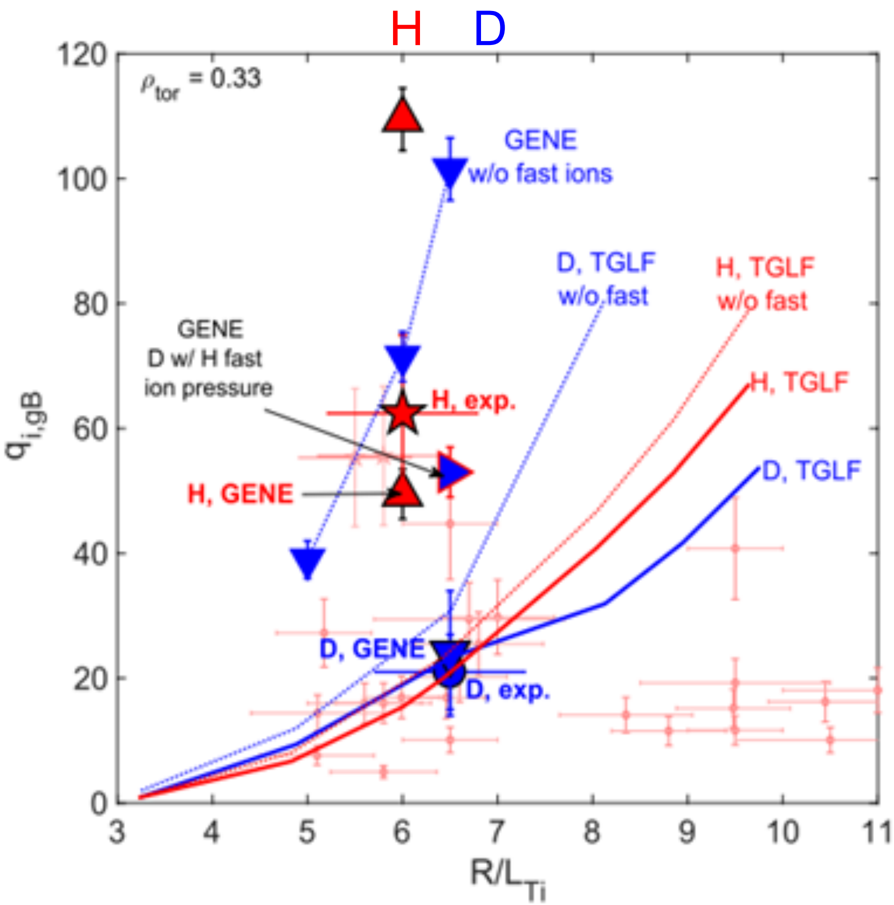


Ding EX/1-3;
J.McClenaghan
TH/P8-1016

- Pedestal from EPED
- Core transport from TGYRO, TGLF, NEO
- NBI and RF sources
- Time evolution from ONETWO
- Successfully designed high β_P scenarios

See also J.Citrin TH/3-2 QuaLiKiz

Impact of Fast Ions on Turbulent Transport Can Differ Between D & H



N. Bonanomi *et al*, NF 2019

J.Mailloux OV/1-2

A.Di Siena TH/4-1

- FI impact studied in JET D and H L-mode by varying ICH ^{3}He resonance
- Fast ion (FI) stabilization of turbulence can produce isotope effects can be large in regimes with high Fast Ion content, beta and rotation [J. Garcia, NF 2018].
- Isotope mass differences affects FI pressure gradient via:
  - Heating deposition profile
  - FI slowing down time
- GENE (GK) modelling shows that **differences in FI in H vs D lead to strong deviations from GB scaling of thermal core transport**

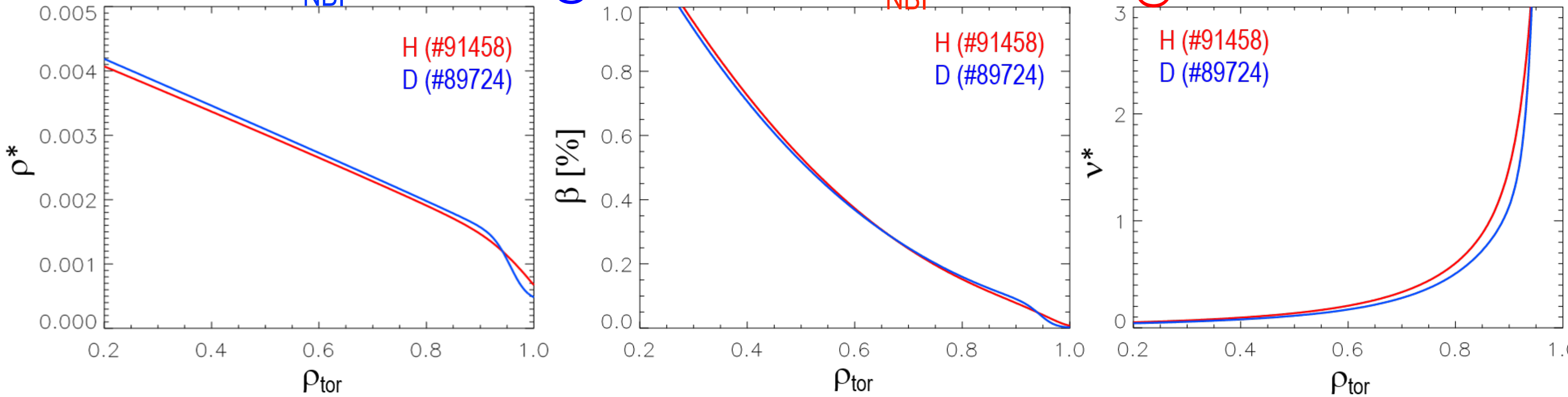
Dimensionless Identity Isotope Effect Experiments

JET

L-mode

D: (3.0T/2.5MA)
P_{NBI} = 6.24 MW @ 82 – 91 keV

H: (1.74T/1.44MA)
P_{NBI} = 2.56 MW @ 64 – 71 keV



Isotope: pulse#	H: #91458	D: #89724
$\Omega_i \tau_{E,th}$ [T s]	0.27	0.28

$\Omega_i \tau_{E,th}$ identical in H and D

L-mode dimensionless energy confinement independent of isotope mass: $\Omega_i \tau_{E,th} \sim A^{0.05\pm0.1}$ where Ω_i is the ion cyclotron frequency.

Dimensionless Isotope Effect Experiments

JET

L-mode

D: (3.0T/2.5MA)
P_{NBI} = 6.24 MW @ 82 – 91 keV

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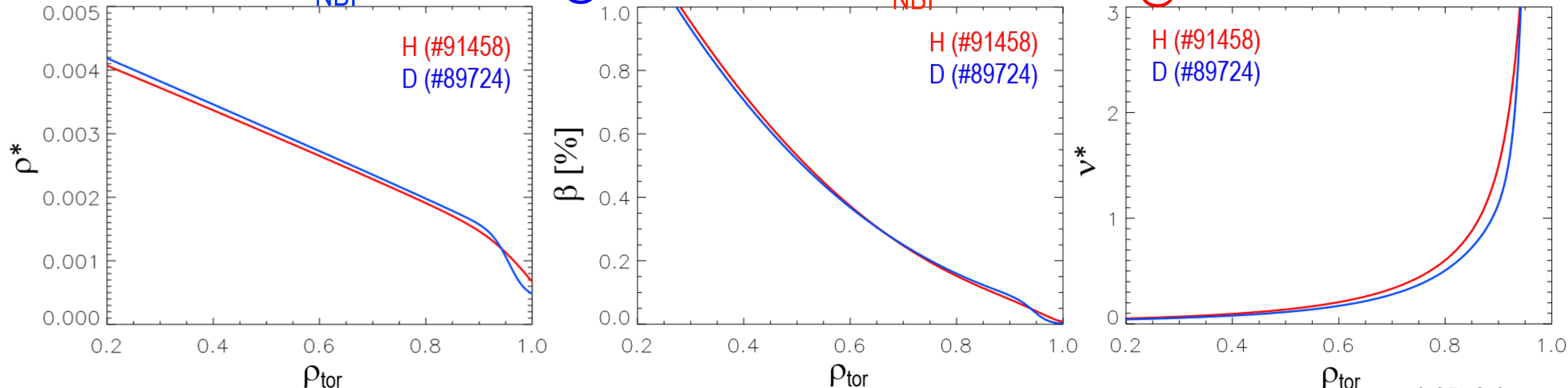
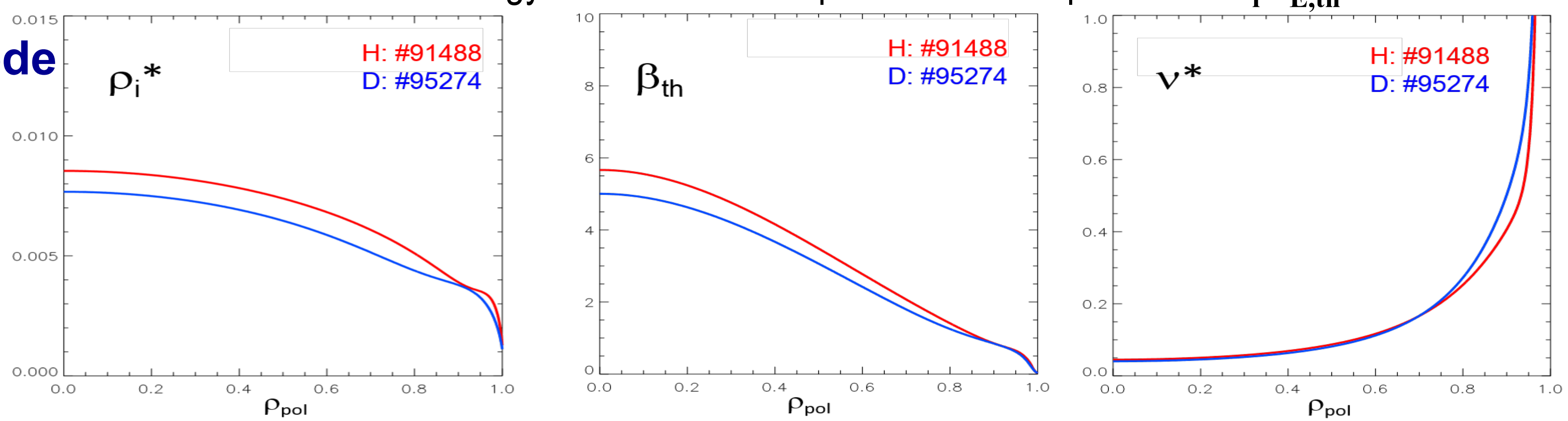


L-mode dimensionless energy confinement independent of isotope mass: $\Omega_i \tau_{E,th} \sim A^{0.05\pm0.1}$

H-mode



$\Omega_i \tau_{E,th}$ [T s]	0.105	0.15

$\Omega_i \tau_{E,th} \sim A^{0.51}$ H-mode
Difference identified as coming from <u>pedestal</u>

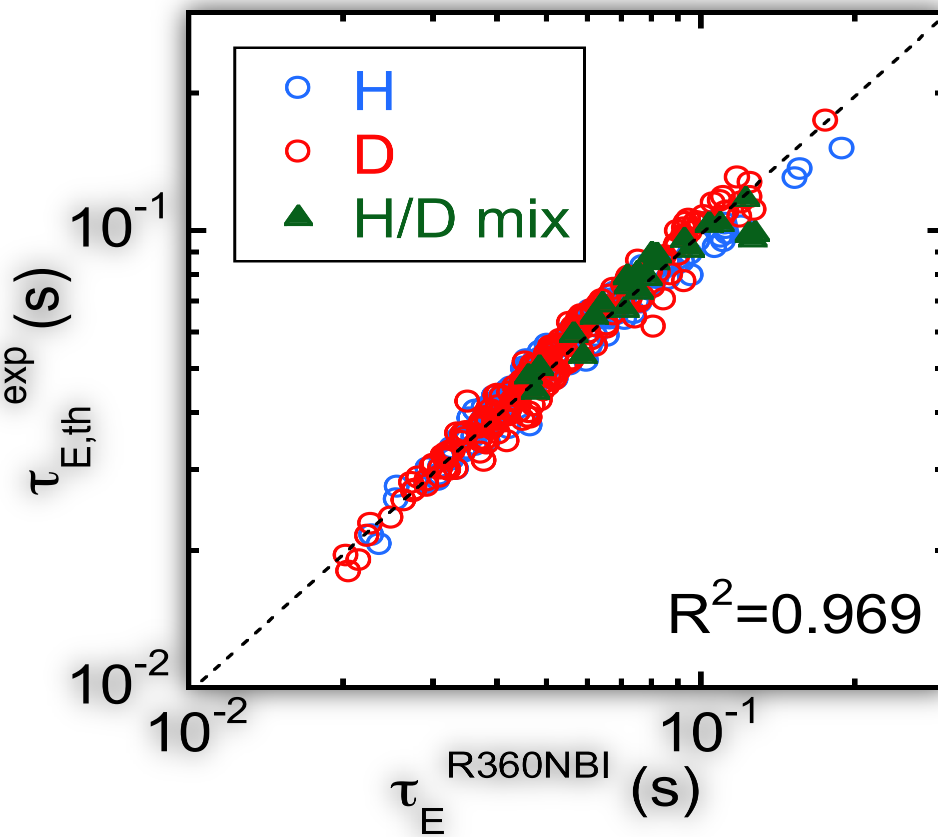
Stellarator Isotope Scaling

LHD

- Database of H and D plasmas at fixed magnetic configuration (R=3.6m)
- NBI heated, dominantly heating electrons

  P_e/P_i=3.9±2.0

  $T_e(0)/T_i(0)$=1.79±0.37



- Fit to operational parameters

$$\tau_{E,th}^{R360NBI} \propto M^{-0.07\pm0.01} B^{0.85\pm0.01} \overline{n}_e^{0.73\pm0.01} P_{abs}^{-0.81\pm0.01}$$

- Fit to dimensionless parameters

$$\tau_{E,th}^{R360NBI}\Omega_i \propto M^{0.94} \rho^{*-3.02} \nu^{*0.15} \beta^{-0.23}$$

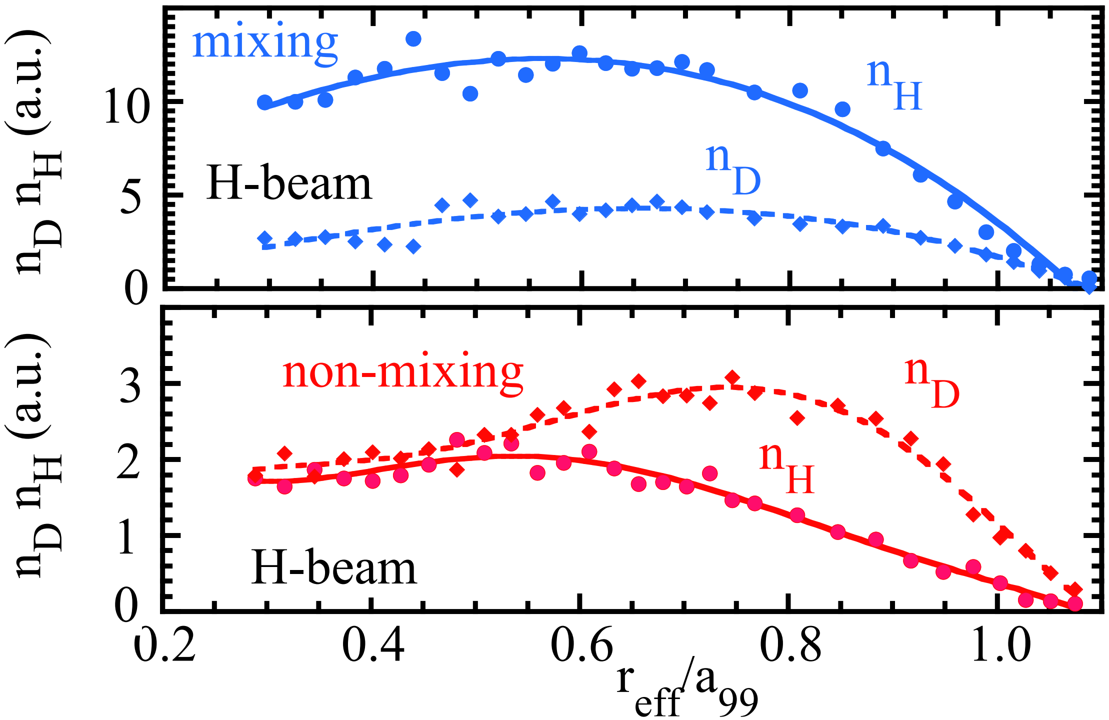
gyro-Bohm with a separate Mass-dependence

H. Yamada EX/P4-1084

Isotope Mixing and Non-Mixing

LHD

- Isotopic densities measured by bulk ion charge-exchange recombination.
- Mixing plasmas have ne > 2-3x10^{19} m^{3}, hollow density profile
- Non-mixing plasmas have low density ne < 2-3x10^{19} m^{3}, peaked density profile

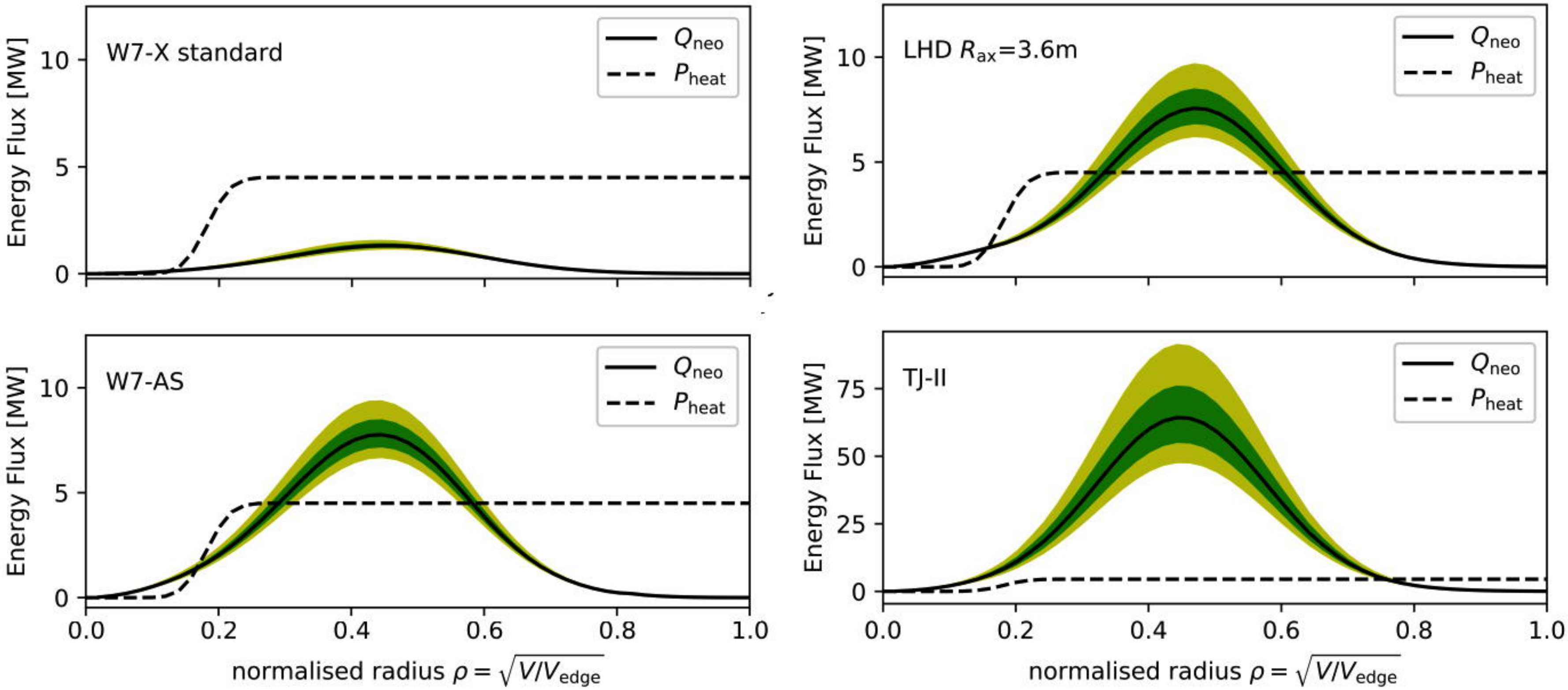


- Gyrokinetic analysis suggests strong correlation with ITG-TEM
  - Mixing: core ITG unstable, TEM stable (ρ = 0.5)
  - Non-mixing: core ITG stable, TEM unstable

K. Ida EX/6-2

W7X: Neoclassical Optimization Successful

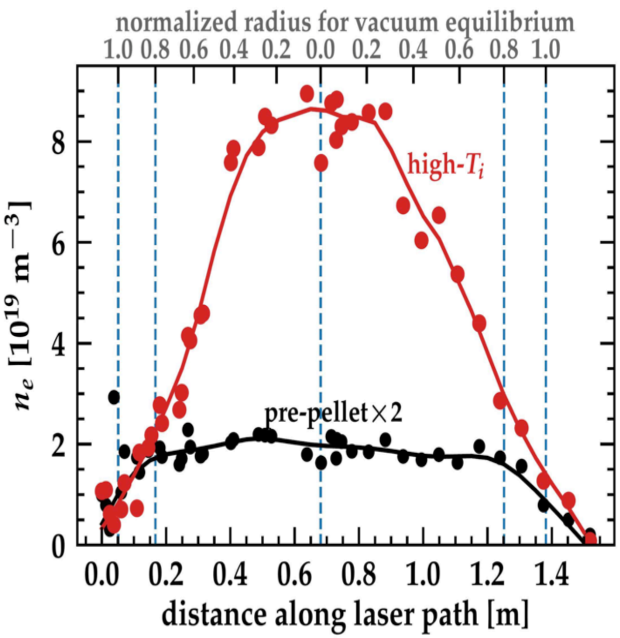
Calculated neoclassical energy transport for W7X profiles in other stellarator shapes

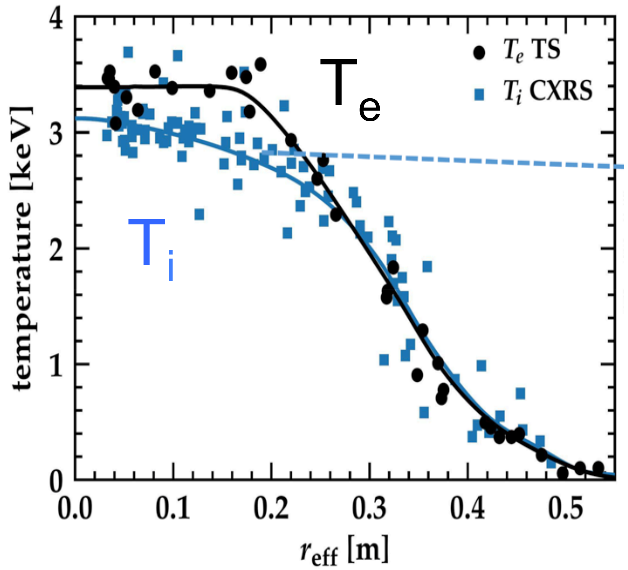


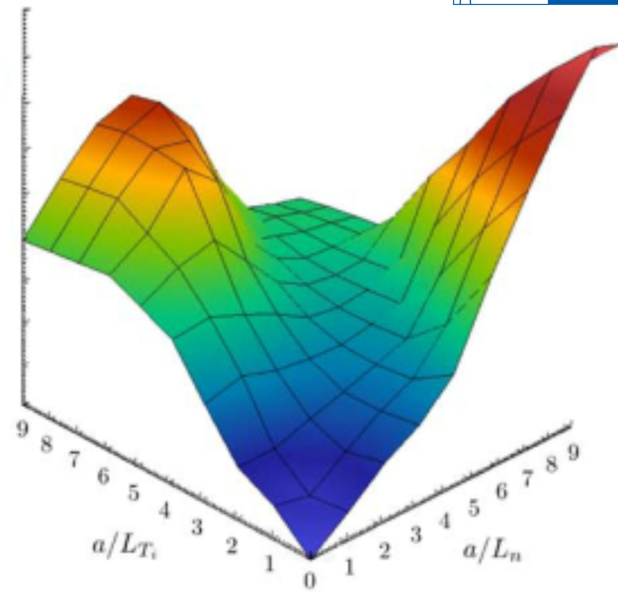
- Pellet peaked density profile to reduce ITG
- Other configurations scaled to same volume and B=2.5T as W7X
- Neoclassical losses calculated using W7X density and temperature profiles
- Other configurations: losses exceed W7X heating power => temperature inaccessible!

T. Pedersen OV/3-2

W7X: Highest Performance with Pellets







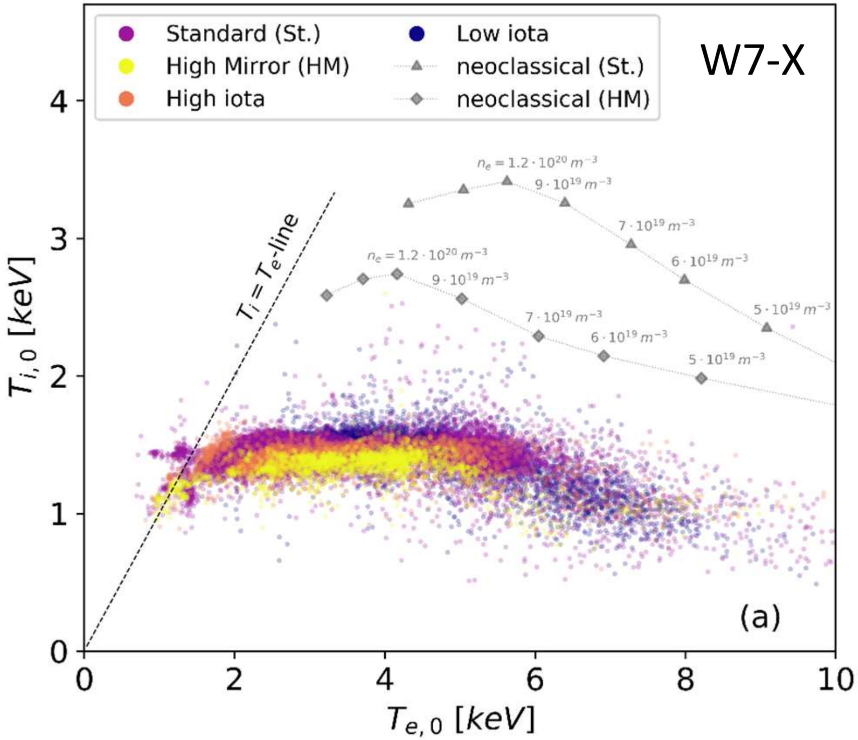
Growth rate vs density and temperature scale lengths

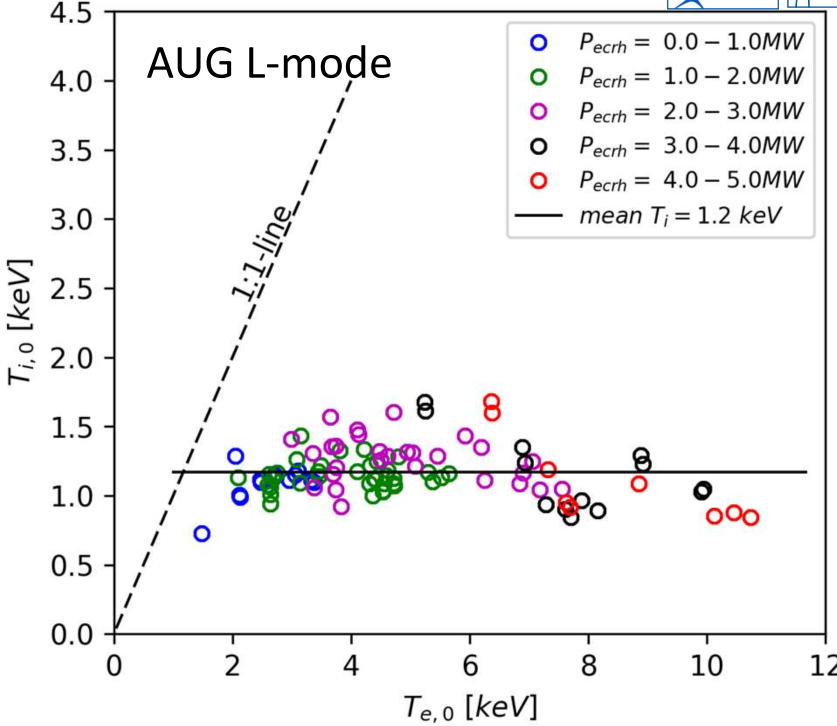
- ECH heating only, 4.9 MW, B=2.5T
- From GENE calculations, need $a/L_n \sim a/L_{Ti}$ to suppress ITG & TEM
- Confinement enhancement of 1.3 x ISS04 scaling
- Accessible using multi-pellet fueling

- Highest n(0) Ti(0) τ_E for a stellarator

M.Beurskens EX/6-3
S.A. Bozhenkov NF 2020

W7X and AUG see T_i ~ 1.5keV clamping for gas-fueled ECH L-mode



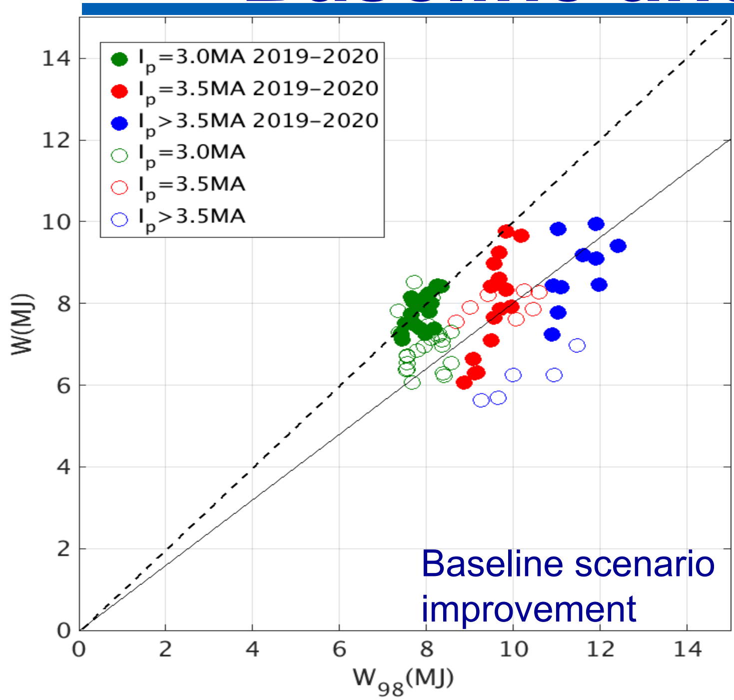


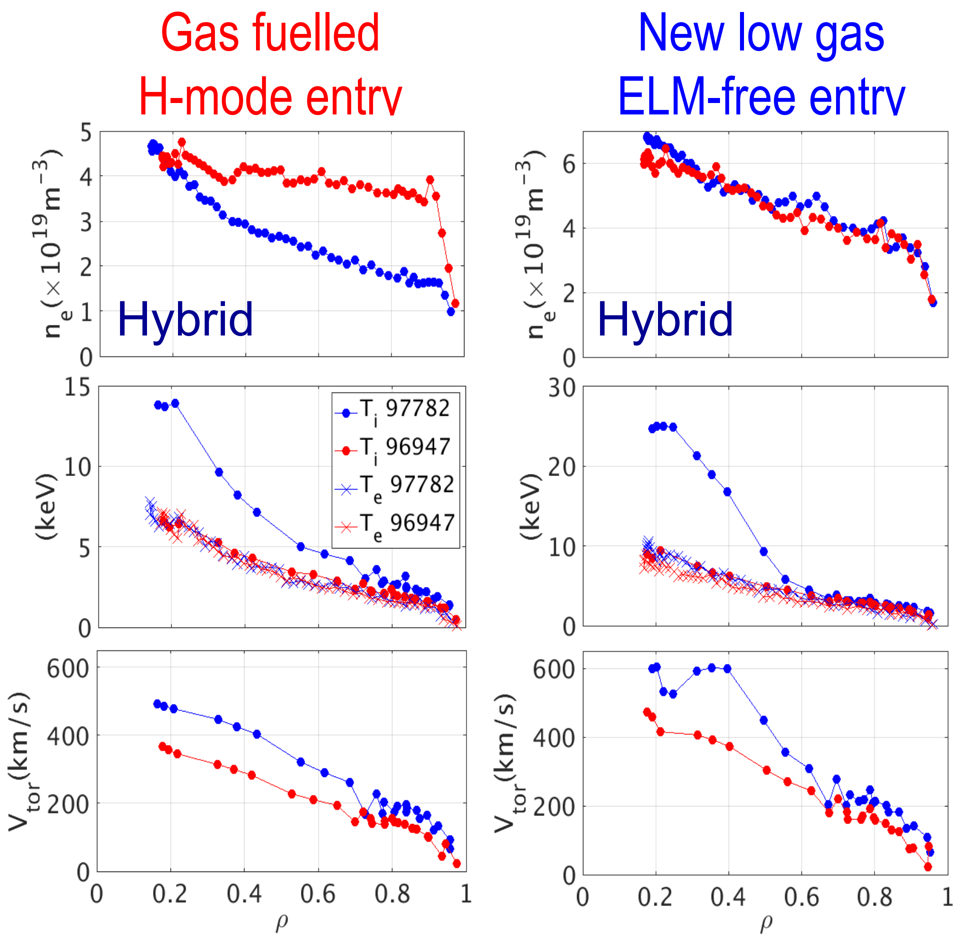
- Ti clamps with only electron heating, independent of magnetic configuration
- ITG stronger for $T_e > T_i$ enforces marginal stability

  Very difficult to increase T_i from an initial condition of $T_e >> T_i$
- Ion-electron thermalization ~ $(T_e-T_i)/T_e^{3/2}$ weakens as T_e increases
- Enhanced confinement usually requires ITG suppression or weakening (ETB, ITB)

M.Beurskens EX/6-3

JET: High Performance for DT Baseline and Hybrid Scenarios





Ion transport reduced by:

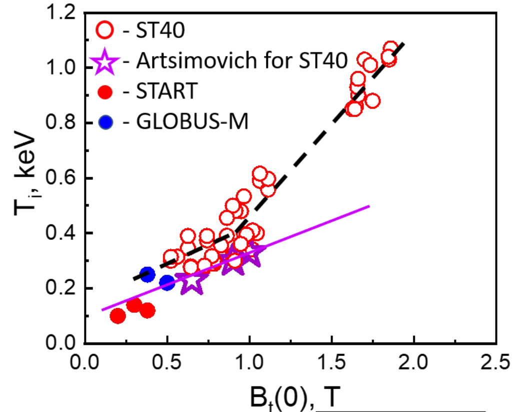
- Edge impurity dilution (reducing n_i)
- Reduced gas puff + pellets (incl. Ne)
- T_i / T_e ~ 1.6 including pedestal top
- Strong ExB shear
- Strong rotation to centrifuge W & Ni

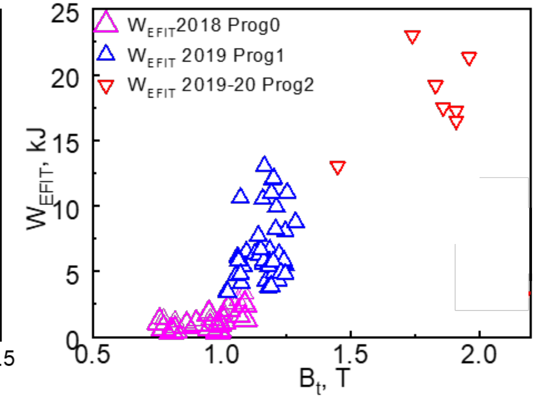
- Core P_{rad} stable
- Pedestal collisionality approaching ITER

- Low-gas puff, ELM-free initial period
- T_i > T_e including pedestal
- Increased rotation
- Core P_{rad} stable
- Record peak and average DD reaction rate

J.Garcia EX/1-2

Spherical Torus Confinement Advances





ST-40

Sharp increase in confinement for B_T > 1T

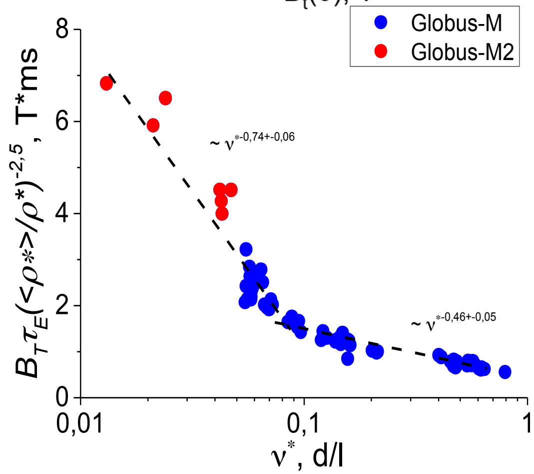
M.Gryaznevich OV/4-5.4

GLOBUS-M2

Extended B_T to 0.8T, Ip to 0.4MA

$B\,\tau_E \sim \nu_*^{-0.74}$ extended to lower ν_*

Yu.Petrov OV/4-5.3

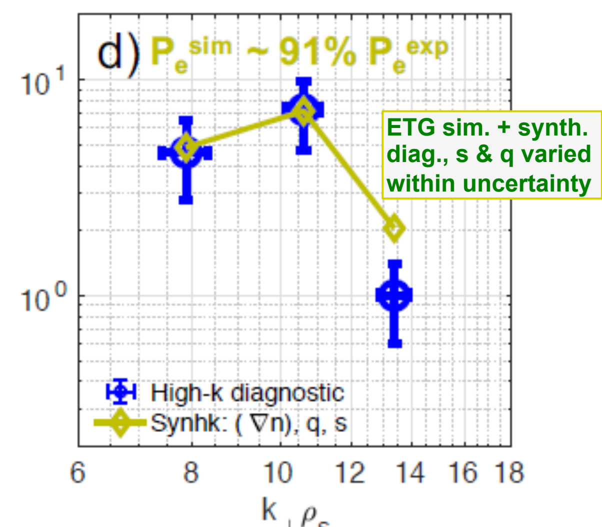


- Consistent with previous ST studies
- Not like IPB98(y,2)

NSTX-U

- Using novel synthetic diagnostic, nonlinear gyrokinetic simulations (GYRO) reproduce electron transport & high-k microwave scattering spectra for moderate-β NSTX H-mode
- Parameter scans (∇n, ∇ T, q, s) used to quantify sensitivity of predicted fluxes and synthetic high-k spectra

W.Guttenfelder OV/4-5.2



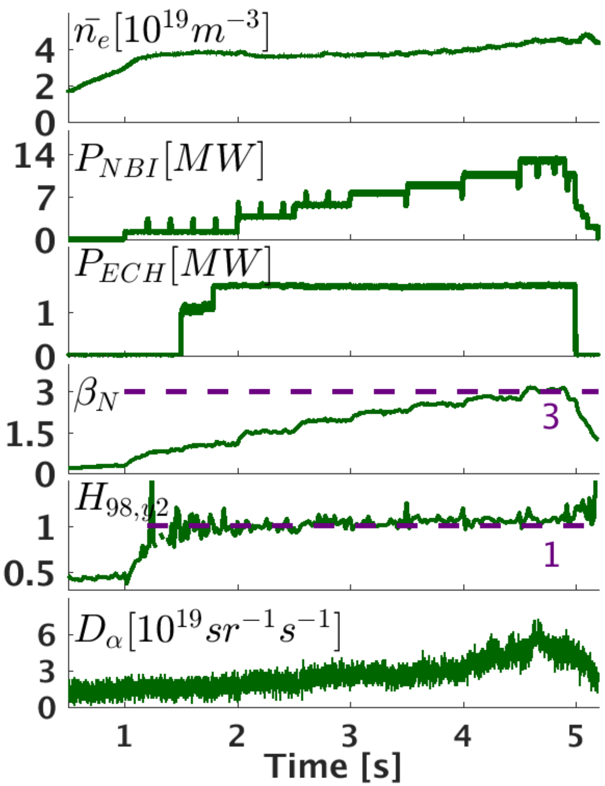
MHD, Stability, and Fast Ion Transport

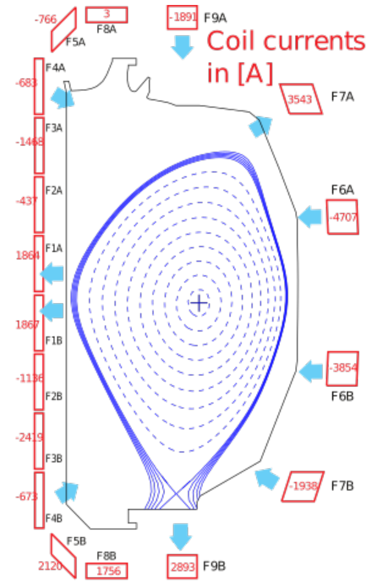
- **Shaping: Reversed Triangularity**
- **Quasi-Symmetric Magnetic perturbations**
- **Magnetic flux pumping**
- **Fast Ion Instabilities & Transport**

Diverted Negative Triangularity Is Advantageous (TCV, DIII-D)

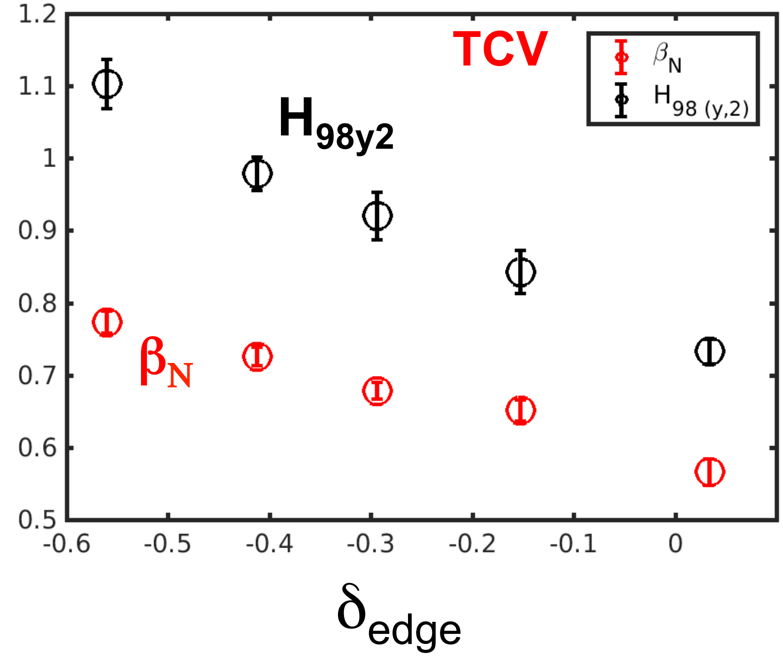
Swiss Plasma Center

DIII-D





avg. δ ~ -0.2



- H(98y,2) ~ 1, β_N=3, without power threshold
- L-mode edge maintained. H-mode threshold drastically higher.
- SOL heat-flux width ~ 1.5 x H-mode width
- $\tau_P \sim \tau_E$ from laser blow-off

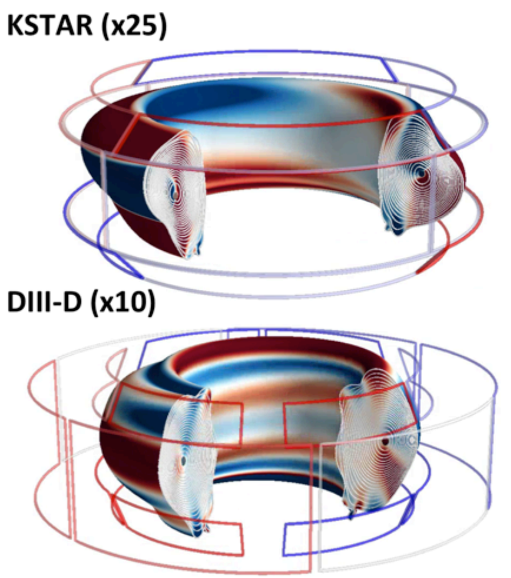
- Energy confinement improves for more negative triangularity, linearly
- Observed for OH, ECH, NBI heating
- Improvement maintained for q_{95} < 3, upto β_N=3
- Density fluctuations reduced inside LCFS
- Reduced SOL turbulence on low-field side, due to shorter connection length

A.Marinoni EX/6-6.1 L.Porte EX/6-6.2

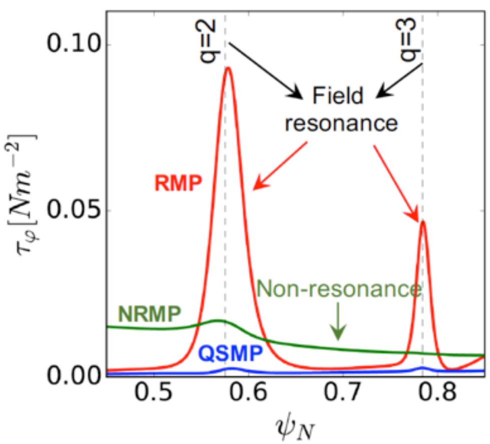
Quasi-Symmetric Magnetic Perturbations (QSMP)

- QSMP in a tokamak: 3D magnetic perturbation that induces the minimum neoclassical 3D torque (NTV) and transport. Compared to RMP (resonant MP) or NRMP (non-resonant MP)
- Optimization for QS perturbation uses self-consistent torque response matrix
- QSMPs do not show confinement degradation in high-β flattop, or impact on L-H transition power in KSTAR and DIII-D, despite large amplitude perturbations
- Thus: Error fields can be modified towards quasi-symmetry, minimizing resonant and no-resonant effects, and minimizing confinement impact.

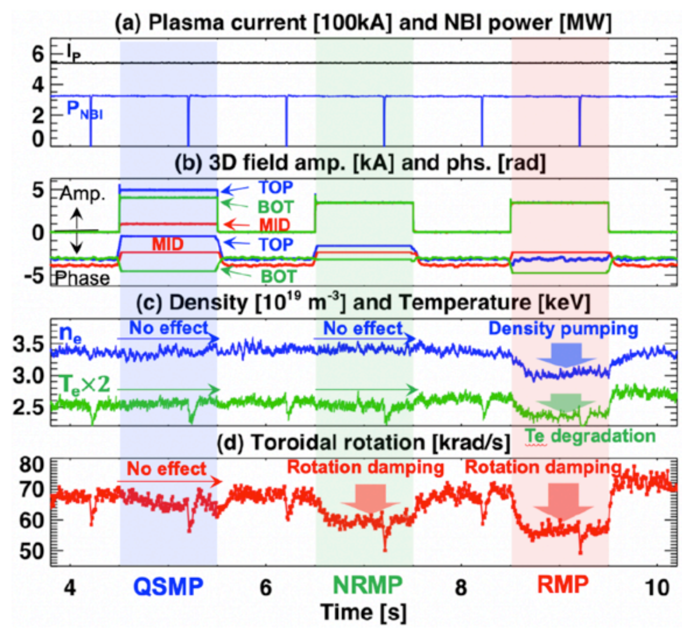
QSMP configuration, with large δB but minimum impact on 3D transport



NTV prediction for QSMP, NRMP, and RMP (KSTAR example)



Experimental Comparison (KSTAR example)



J-K Park EX/4-3

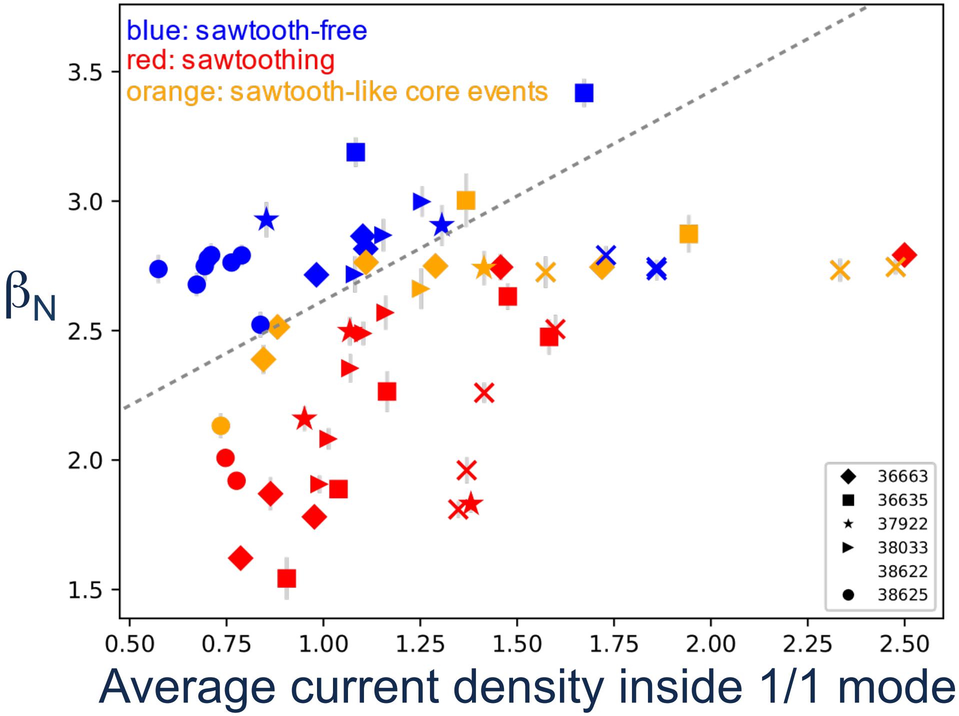
Experimental Evidence of Magnetic Pumping at AUG

- Experimentally test new theoretical model of flux pumping at high β with (1/1) mode [I. Krebs, PoP 2017]
- Possible way to reduce needed current drive in reactors

- Cases where q-profile evolution does follow neoclassical current diffusion
- Or, central co-ECCD cannot drive q(0) down, below q=1 (IMSE measurements, without sawteeth)
- Stronger effect at high β (like theory)

- At high non-inductive current, effect may not be strong enough to keep q(0)=1

- Qualitative agreement with theory, but model gives more peaked current than measurements.



A.Burckhart EX/4-1

Scenario prepared to assess α-driven instabilities in JET-DT

JET

- α-driven instabilities are potentially an issue for burning plasmas, including ITER. Unambiguously identified only in TFTR-DT plasmas so far.
- A dedicated scenario was developed and tested to observe α-Toroidal Alfven Eigenmodes (TAE) in JET-DT, including:
  - Good fusion performance from Internal Transport Barrier
  - Elevated central q-profile, to lower threshold
  - Real-time control trigger to switch to afterglow at peak performance
  - NBI-only before afterglow, to not generate other fast ions
  - ELM pacing by pellets
  - Core-localised TAEs when ICRH heating used (as test)
- Extrapolations to DT using integrated modeling (TRANSP & CRONOS) predict $\beta_\alpha(0)$ ~ 0.15% and ~9 MW of fusion power. This is larger than extrapolations for previous JET pulses, and than the TFTR-DT α-instability experiments.
- JET / TFTR comparisons included in plans for coming JET DT campaign

R. Dumont EX/8-1

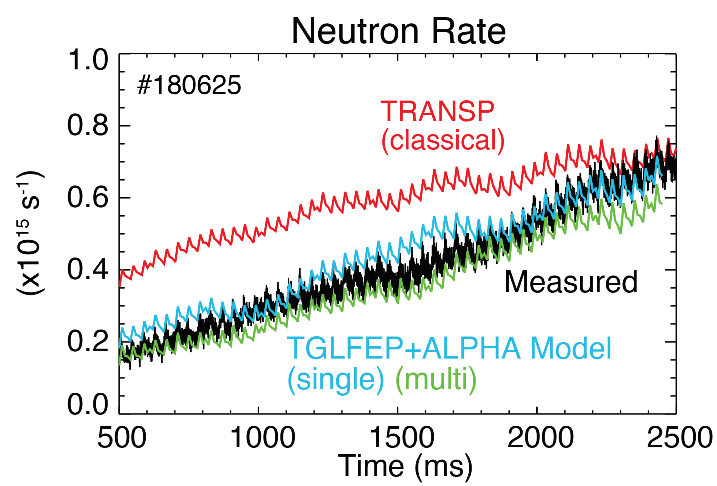
Control of Fast-Ion Alfvenic Modes in Advanced Steady-state Scenarios

- Energetic ion driven Alfvenic Eigenmodes (AE) are common in advanced scenarios with elevated q-min, causing transport of the energetic ions.

- Broadened energetic ion profile gives better control of AE stability in elevated q-min scenarios. Key factor is moving $\rho_{q\text{-}min}$ towards region of reduced $\nabla\beta_{fast}$

- In DIII-D NBI experiments, this was done by switching from central to off-axis neutral beams
  - Accessed 15% higher β_N
  - Ratio of expected to measured neutron emission increased by ~25% in flattop
- TGLF-EP + ALPHA critical gradient model reproduces energetic ion transport trends. Matches measured neutron rate within 12%>

Improved fast-ion transport modeling



- Provides basis for understanding how to avoid AE-induced energetic ion transport in ITER and future burning plasmas.

C. Collins EX/8-2

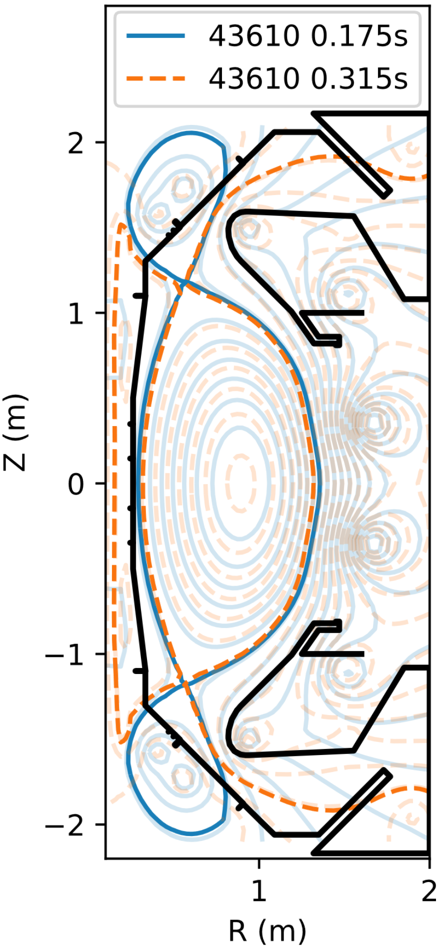
Divertor & Scrape-off-layer

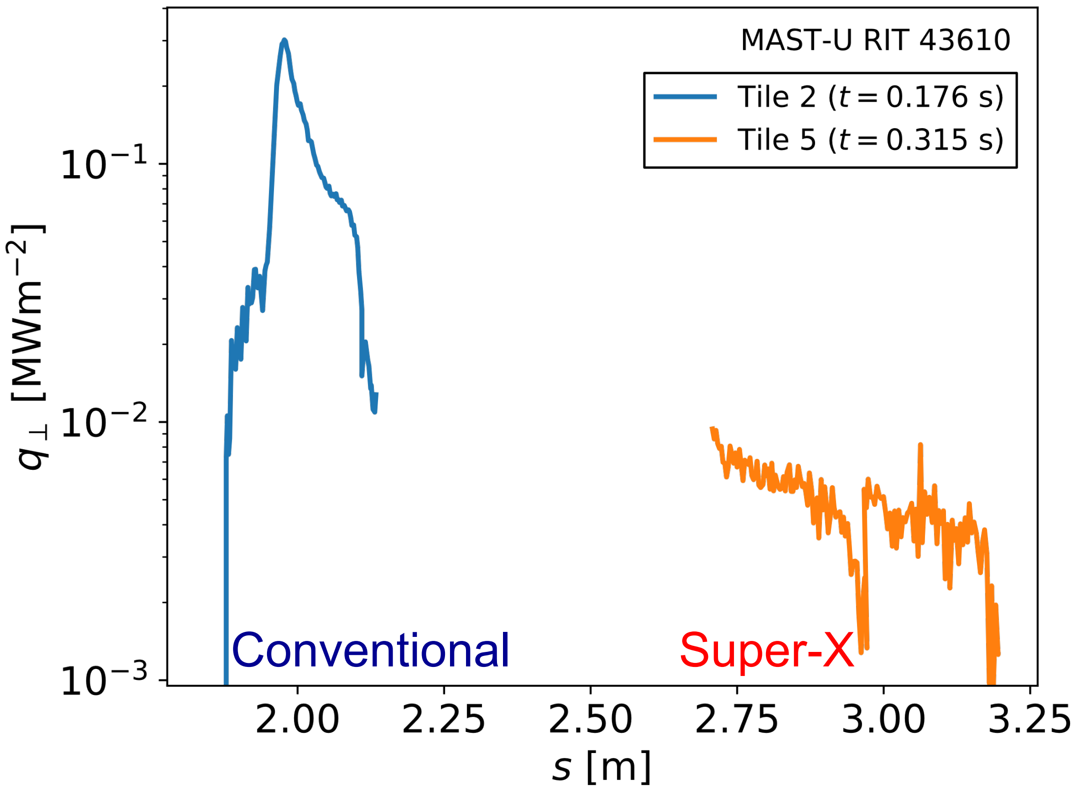
- **Super-X divertors**
- **Controlled Detachment**
- **Stellarator divertors**
- **Divertor experiments and modeling**

Heat Flux Reduced in Super-X Divertor

MAST-U

Substantial reduction in the outer divertor heat flux observed in the Super-X vs. conventional divertor





Initial studies have focused on moving the outer strike points to large major radius and reducing the poloidal field there to produce Super-X configurations.

CCFE CULHAM CENTRE FOR FUSION ENERGY

J.R. Harrison EX/P6-1538

New Methods to Control Detachment

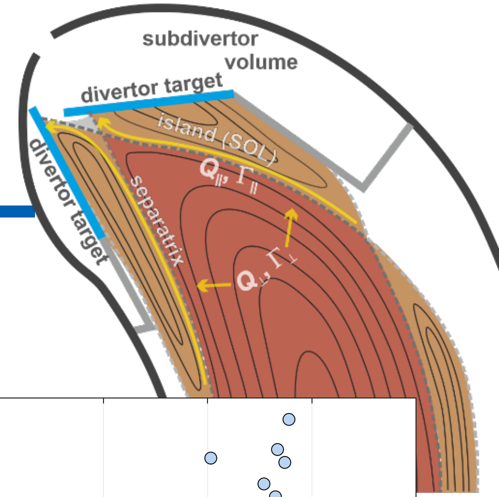
- Metal-wall devices need (low Z) seed-impurity injection for detachment radiator. Previously Nitrogen was best, but:
  - Complicates tritium processing chemistry

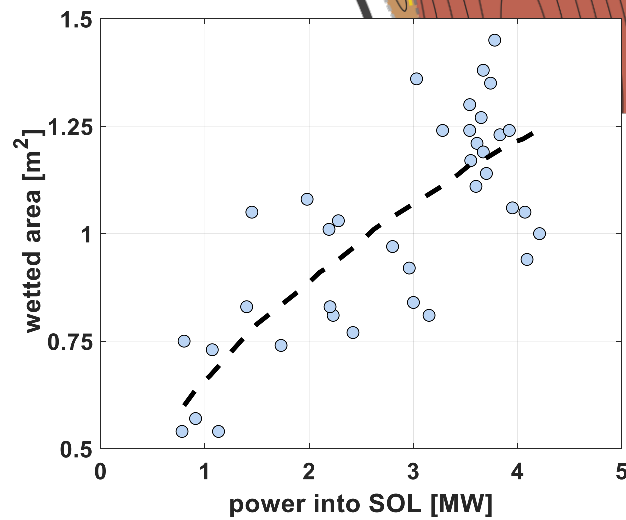
- New gasses are successfully integrating a detached edge with core confinement without confinement degradation
  - Neon — JET High Performance Scenarios — J.Mailloux OV1-2; J.Giroud EX/P3-977
  - Neon — DIII-D High-β_P Scenario — L.Wang EX/7-1
  - Neon,Argon — EAST High-β_P Scenario — L.Wang EX/7-1
  - Argon — AUG EDA H-mode — A.Kallenbach EX/2-5

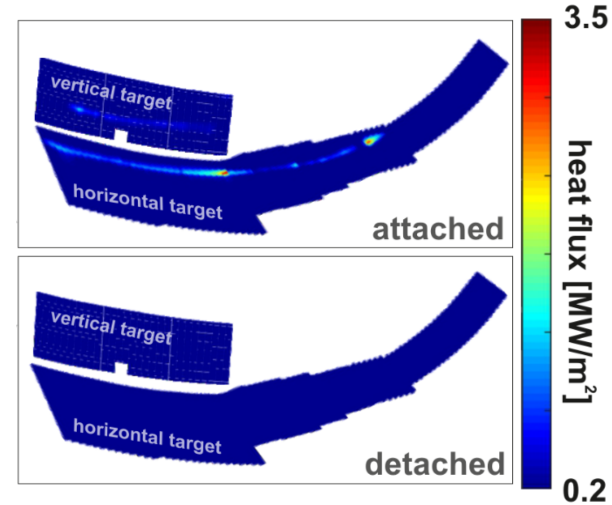
- New feedback control methods of detachment for reliable operation
  - AUG — Location of emission — M.Bernert EX/7-3
  - DIII-D , EAST — J_{sat}, $T_{e,div}$, P_{rad} — L.Wang EX/7-1

W7X Island Divertor Is Highly Effective

- Core plasma surrounded by helical island chain (typ. 5/5) that interfaces to divertor baffles.
- Wetted area up to 1.5 m^2 to spread exhaust heat, increases with P_{SOL}
- Islands shield against impurity sources, e.g. hot spots on divertor tile edges
- Stable, complete detachment in many scenarios achieved, for up to 26 sec. Detachment density ~10^{20} m^{-3}
- Below detachment, observe high recycling regime, enabled by counter-streaming flows in islands.



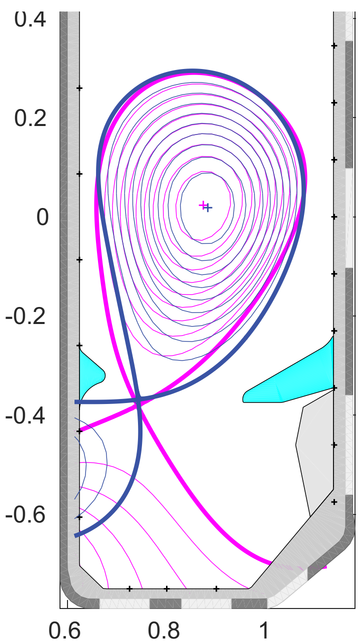


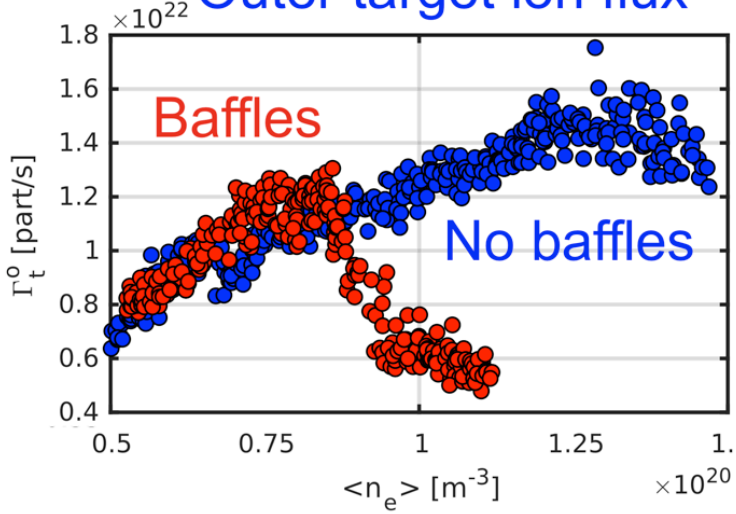


M. Jakubowski EX/7-4

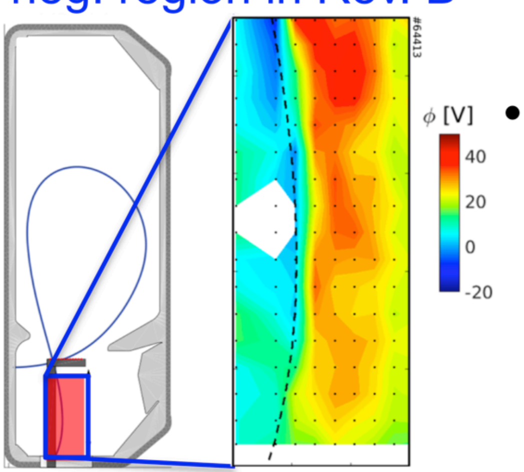
TCV with Baffles – a Divertor Testbed

- Divertor baffles increase neutral pressure ~5x, increase divertor dissipation. Facilitates detachment in L- and H-mode.
- Detachment density ~25% lower with baffles
- Flexible coil-set enables divertor leg steering
- SOLPS drift simulations predicts key features and trends. E.g, potential structure, currents.
- Reduction of detachment threshold for Super-X (large radius target) lower than originally predicted with baffles. May be due to details of geometry.



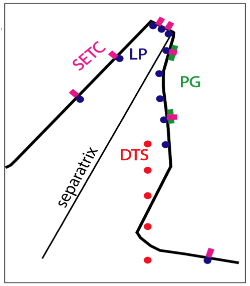


Measured V_{pl} with predicted neg. region in Rev. B

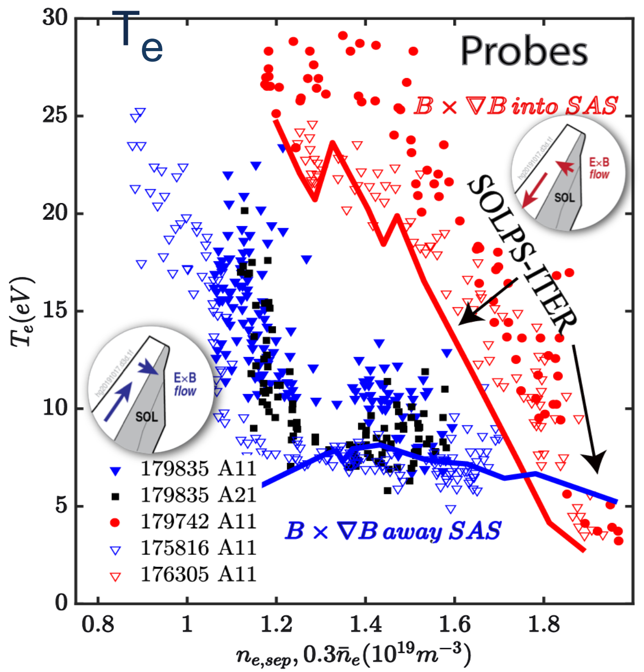


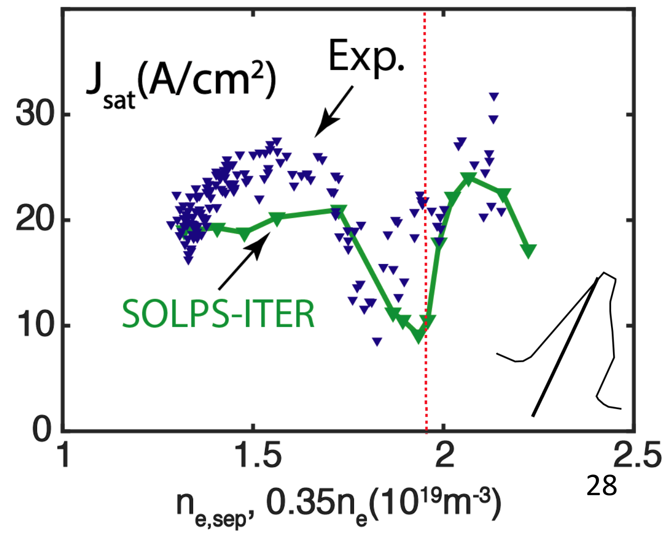
C.Theiler EX/7-5 H.Reimerdes OV4-2

DIII-D SAS is a Divertor Testbed



- SAS: Small Angle Slot divertor
- Interaction between drift flows and divertor geometry has important effects on dissipation
- SOLPS-ITER with drifts reproduces trends found in experiments
  - Lower T_e and detachment density with drift away from divertor.
  - Drifts are comparable to geometry in effects on recycling flux and neutral density
- Experiment and modeling both found that geometry+drift can alter variation of dissipation
  - Including T_e bifurcation and J_{sat} reduction





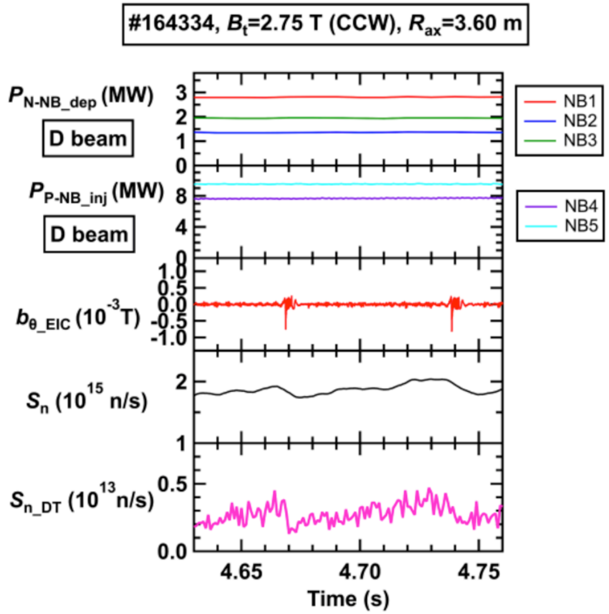
H.Wang EX/7-6

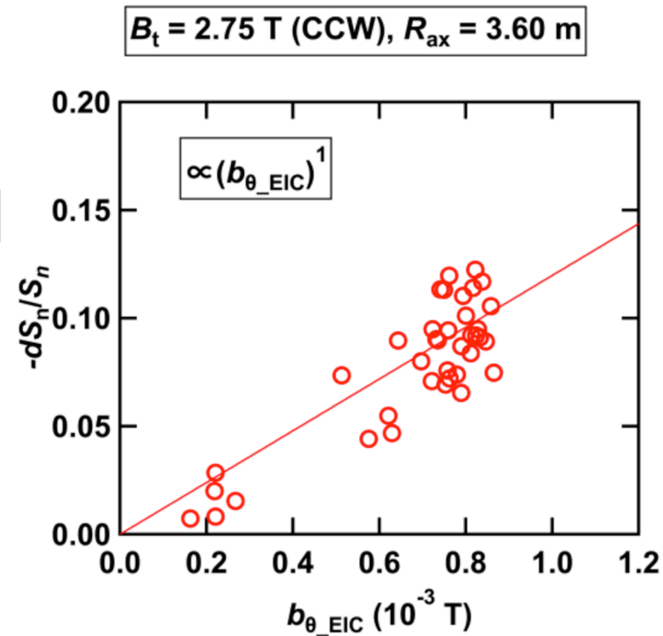
Thank You

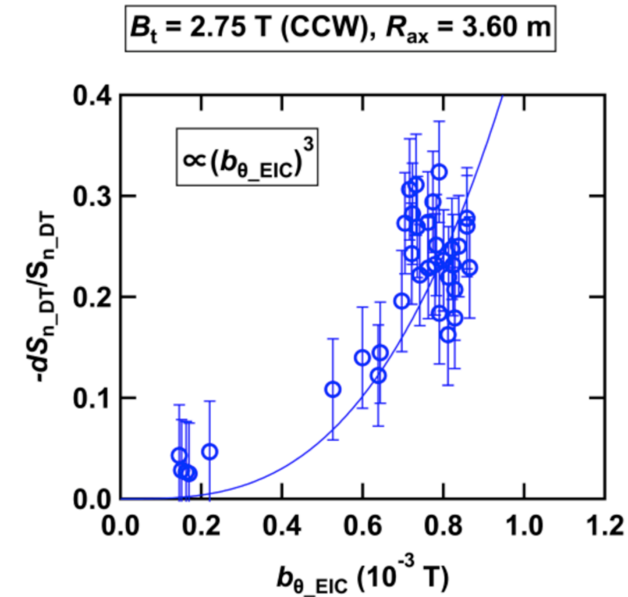
EX/8

K. Ogawa et al.,

A Comprehensive Study of Energetic Particle Transport due to Energetic Particle Driven MHD Instabilities in LHD Deuterium Plasmas







- Beam ion and DD fusion born triton transport due to energetic-particle-driven MHD instabilities (EIC) is simultaneously studied in the Large Helical Device (LHD).
- Drop of total neutron emission rate (S_n) by EIC shows enhanced beam ion transport due to EIC.
  - Experiments in full D and H/D beam conditions shows that EIC induces up to 8% of passing transit beam ion losses and up to 60% of helically-trapped beam ion losses.
- Drop of secondary DT neutron emission rate (S_{n_DT}) increases substantially with the EIC amplitude to the third power and reaches ~30%.
  - 1 MeV tritons are largely transported because the tritons are barely confined in LHD.

Dimensionless-identity comparisons Controlled Pedestal Height (AUG,JET)

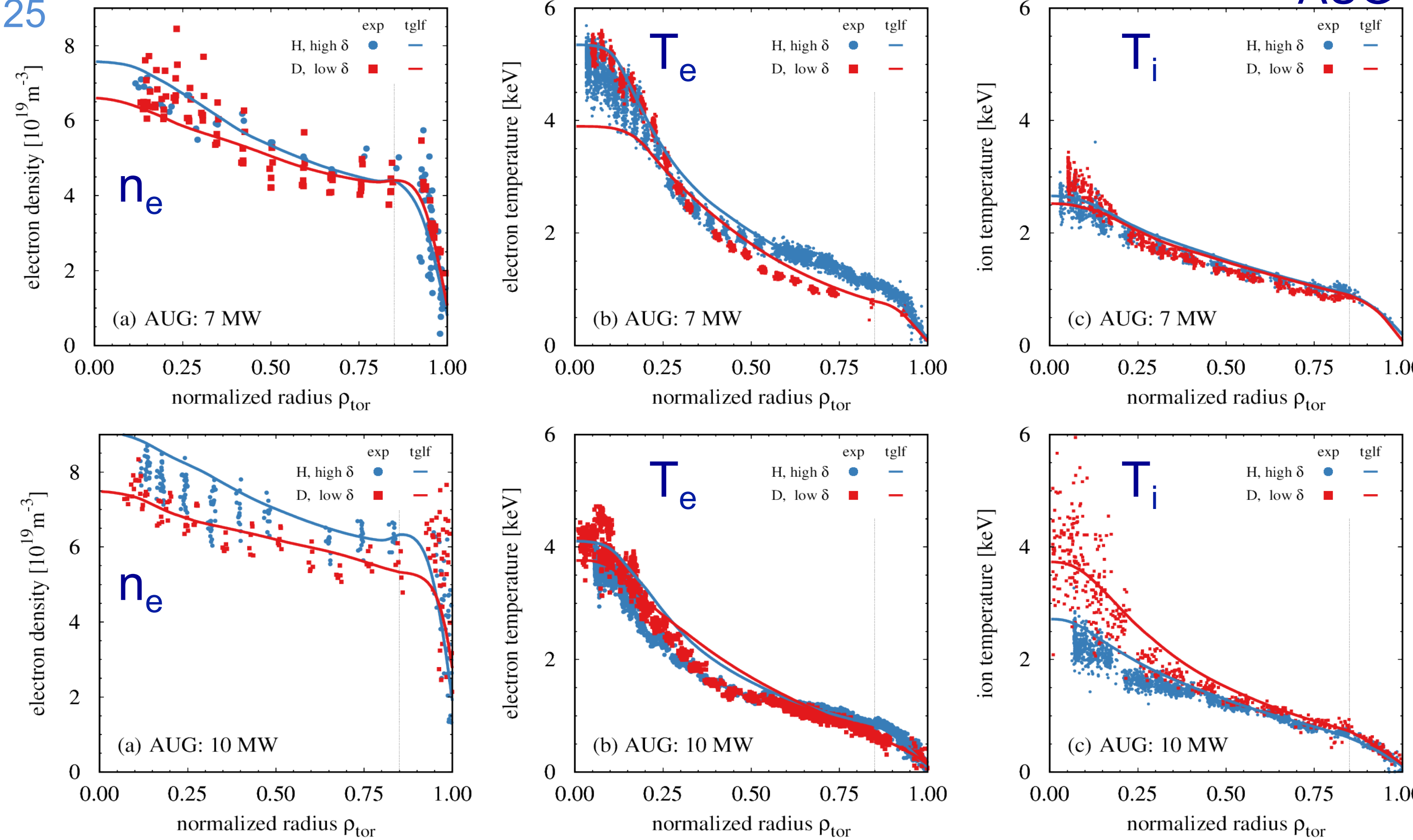
Matched edge profiles by adjusting δ, keeping source profiles similar

H: δ=0.37   D: δ=0.25

AUG

Low NBI power: core profiles similar, good agreement with TGLF

High NBI power: Ti higher in D => reduced ion heat Transport



- Nonlinear GENE simulations: higher fast ions pressure in D-plasmas stabilizes turbulence (slowing-down time)
- Similar experiments in JET

P.A. Schneider EX/P4-1084