NSTX-U is sponsored by the
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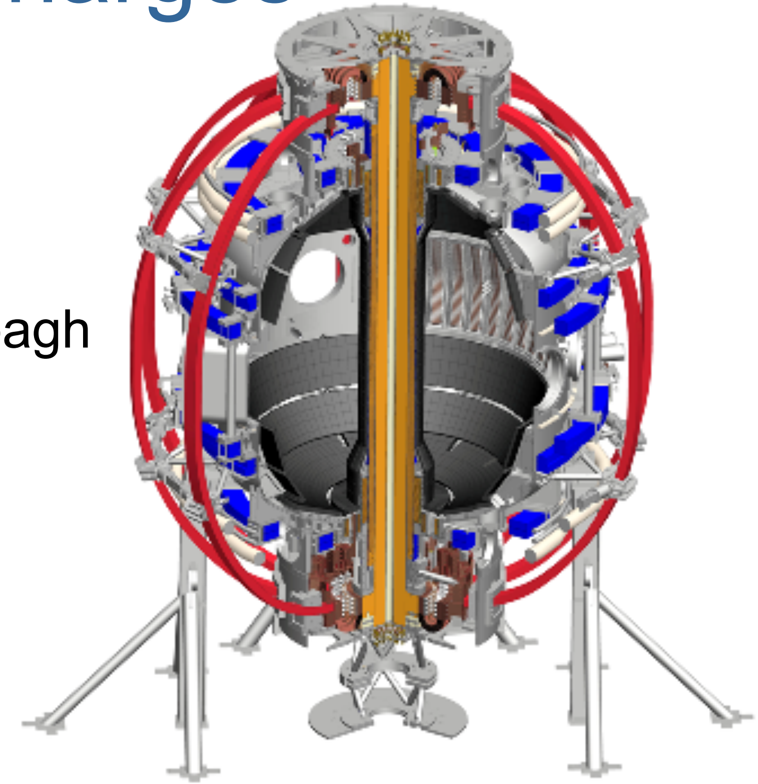
Fusion Energy Sciences

Database of steady discharges without ELMs in NSTX



D.J. Battaglia,
R.E. Bell, S. Gerhardt, B. LeBlanc, S. Sabbagh
and the NSTX team

NSTX-U Monday Science Meeting
January 25, 2021

Database of NSTX has been formed to support the FY22 Joint Research Target (JRT) activities

- FY22 JRT: Enhanced confinement regimes without ELMs
  - Improve projections of non-ELMing regimes to next-step devices

- There are five working groups in the JRT22 (see final slide)
  - Working Group 1 will strive to form a multi-machine database of discharges with steady, ELM-free phases

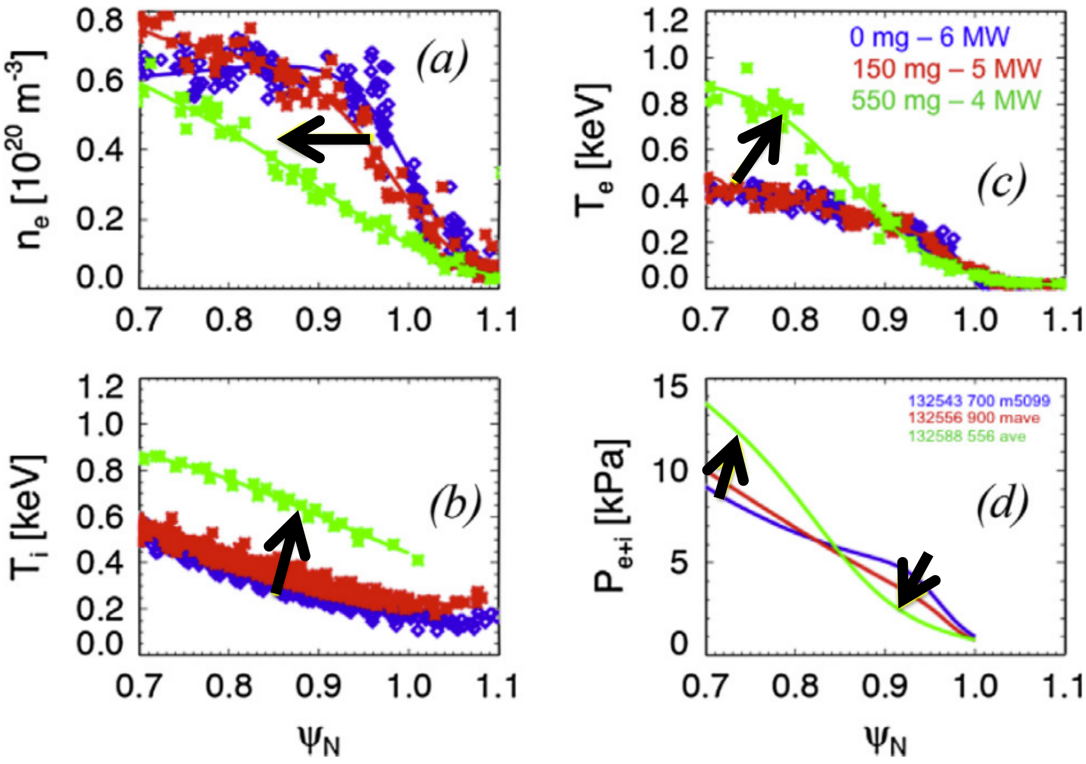
- This talk: database of discharges without ELMs on NSTX
  - Similar to recent effort comparing non-ELMing regimes on DIII-D
    - C. Paz-Soldan et al., PPCF, *submitted* (https://arxiv.org/abs/2012.03339)
  - Valuable for identifying discharges that can be used for detailed analysis in other JRT22 Working Group activities

Review: NSTX achieved Wide Pedestal (WP) H-mode via reduction in recycling with lithium wall coatings

- Lower recycling reduces $n_{e,sep}$ and ∇n_e
  - Lower density gradient changes nature of micro instabilities driving χ_e
  - Improved confinement in **ELM-free** regime

J. M. Canik, et al. Nucl. Fusion 53 (2013)
R. Maingi, et al. Phys. Rev. Lett. 103 (2009)
M. Coury et al. Phys. Plasmas 23 (2016)

	P_{NBI}	Lithium
ELMy H-mode	**6 MW**	**0 mg**
ELM-free H-mode	**5 MW**	**150 mg**
Wide ped. H-mode	**4 MW**	**550 mg**



R. Maingi, et al. J. Nucl. Mater. 463 (2015)

Database aims to find "steady" ELM-free, MHD-free periods in NSTX discharges

- Carbon density almost always has a secular increase in ELM-free regimes on NSTX
  - Z_{eff} and radiated power increase through the discharge
  - Do any regimes approach a "steady" impurity concentration?

- Procedure for forming the "steady" database for NSTX:
  - Identify a 300ms ELM-free and MHD-free time interval in I_p flattop
  - Do linear fit of values over final 200ms
    - 200ms is about 2-5 times a typical energy confinement time
      - DIII-D database uses a 300ms minimum interval
  - Require that …
    - Linear slope of W_{MHD} normalized to the average W_{MHD}: between 0.2 s^{-1} and -0.1 s^{-1}
    - Linear slope of n_{GR} < 0.55 s^{-1}
      - This is about four times larger than what is acceptable in the DIII-D database

Database disclaimers

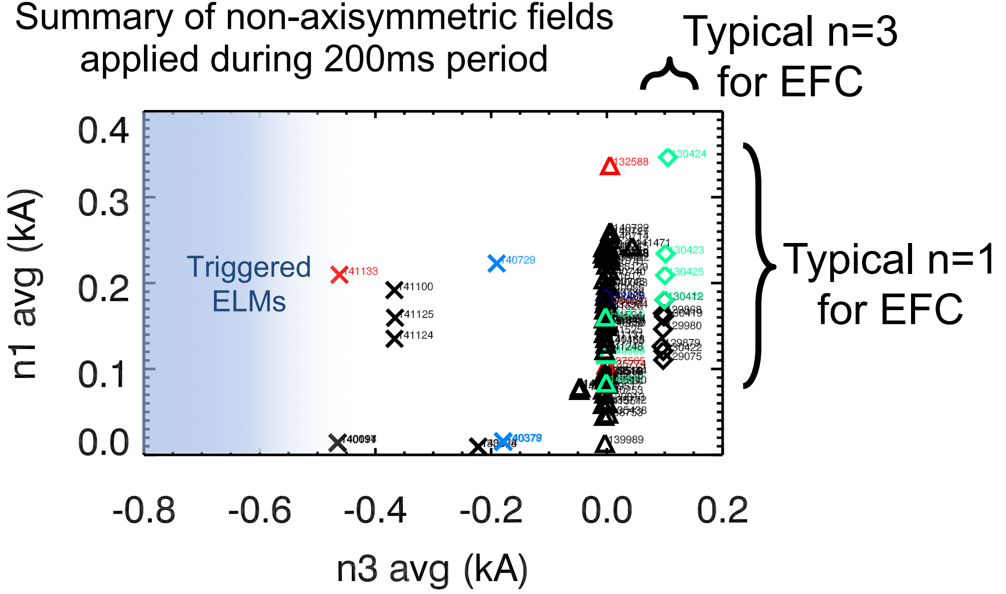
- This is a “trophy shot” database
  - Selectively searched for shots that expand operating space in database
  - May exclude shots that look similar to other shots already in database
  - Database can give a sense of what is possible and what was tried, not always what is inaccessible
- All entries checked manually
  - Shots have to pass the eye candy test (subjective)
  - I may have missed your favorite shot … please send me shot #’s of interest
- Some shots excluded due to data quality and availability
- So far, just ”control room” level analysis (EFIT02 + MPTS + CHERs)

A guide to the plots

- <u>Colors</u>
  - Enhanced Pedestal (EP) H-mode
    - Enhanced thermal confinement at low ion collisionality
  - Lithium dropper
    - Inter- and intra-shot injection
  - Pulsed n=3 fields
    - Small amplitude, ELMs are not triggered
  - Vertical jogs (strike-point sweep)
    - Only one ELM-free pulse so far
  - **All other shots**
    - **Orange:** Highlight on some plots

- <u>Symbols</u>
  - **X:** average n=3 field amplitude is > 0.2 kA outside n=3 EFC
  - **Diamond:** n=3 EFC
  - **Triangle:** all other shots
  - **Small red plus**: 134991. This is "the shot" that achieves really good confinement, but only steady for about 100ms

Summary of non-axisymmetric fields applied during 200ms period



Observation: We could do more to use n=3 below ELM-triggering threshold as an actuator for edge transport and stability

Outline of database results

- Impurity and density accumulation in ELM-free regimes

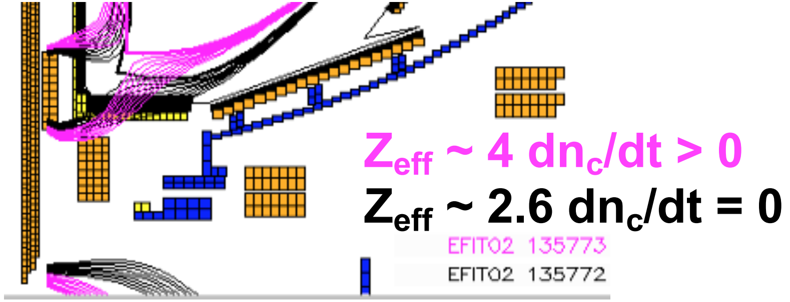
- Operational regime for steady discharges on NSTX

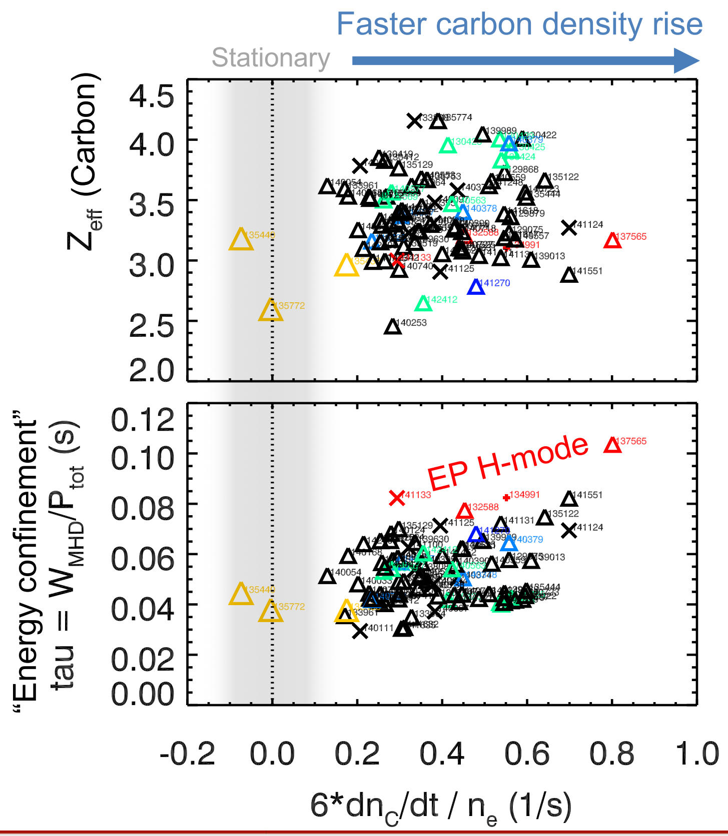
- EP H-mode observations

Accumulation of impurities was the biggest challenge to ELM-free regimes on NSTX

- Orange points are discharges that achieve lower Z_{eff} and rate of carbon accumulation
  - Lower energy confinement with lower I_p and B_T
  - Large flux expansion with shallow incidence angle at lower divertor
    - Smaller X-point height, larger inner gap

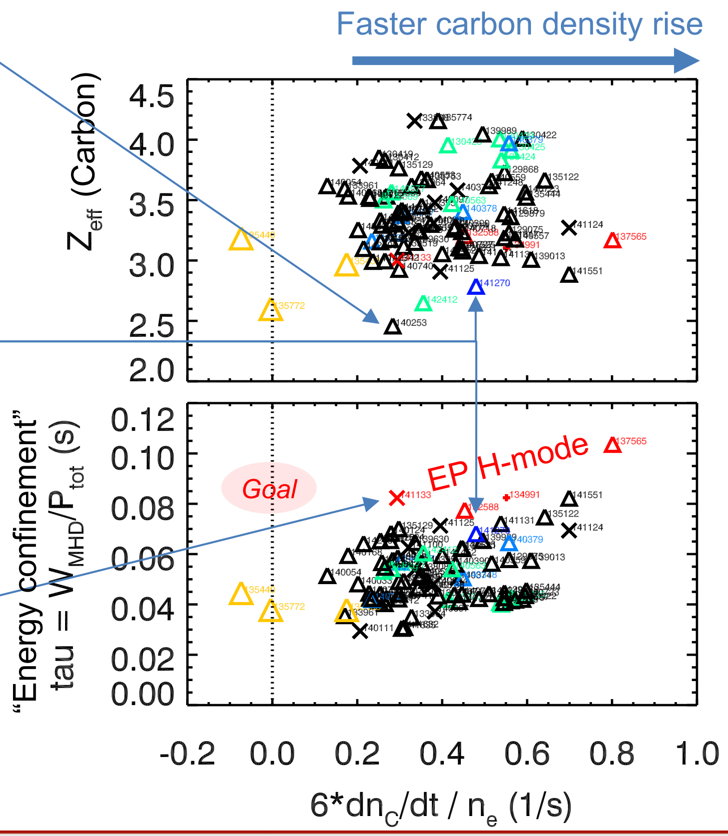
- Pair of sequential shots demonstrate impact of divertor topology on carbon accumulation





Some other shots of interest …

- 140253: First fiducial discharge following "evening helium operations"
  - Z_{eff} ~ 1.5 at start of flattop (CHERS and VB)
  - Why does this help reduce the impurity source?
- 141270: Large flux expansion early in flattop, then vertical jogs that do not induce ELMs
  - Z_{eff} ~ 1.5 at start of flattop (CHERS and VB)
  - Strike point sweeping and/or enhanced transport keeps Z_{eff} lower with good confinement
- 141133: Steady EP H-mode with n=3 fields
  - Enhanced thermal confinement with Z_{eff} = 3
  - Could changes to divertor topology reduce dn_c/dt and maintain enhanced confinement?
    - NSTX-U 5 year plan Thrust 2-1: "Particle control and heat flux mitigation necessary for stationary discharges"

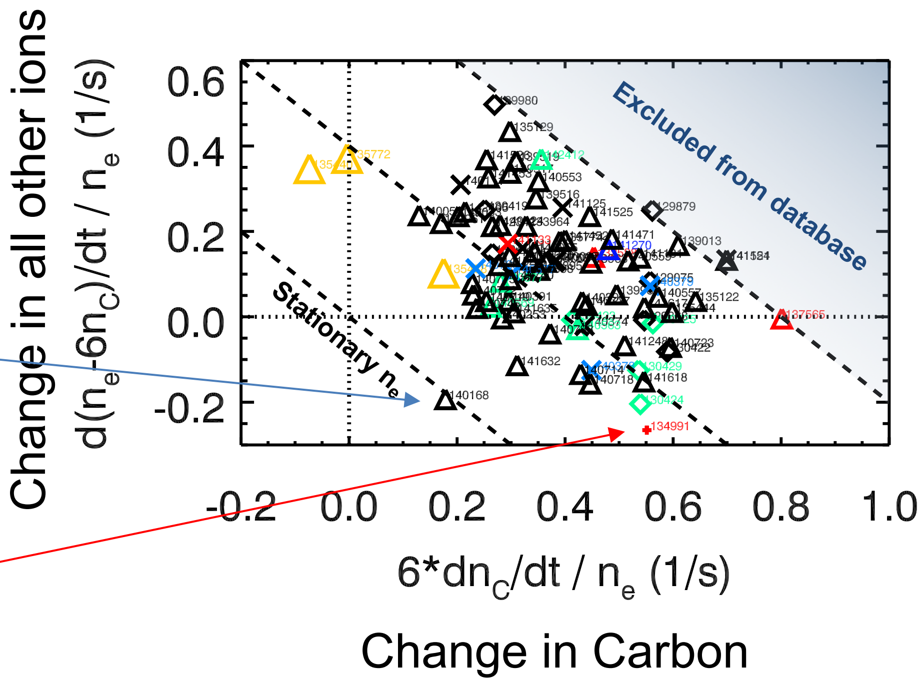


Inferred deuterium inventory can decrease as carbon is increasing

- “Change in all other ions” can be positive or negative
  - No strong correlation with neutral fueling, NBI fueling and/or lithium conditioning was found
  - HFS fueling roughly adjusted with wall pumping conditions

- 140168 achieves stationary n_e
  - Carbon increasing, deuterium decreasing
  - Due to lithium chunk, described in backup

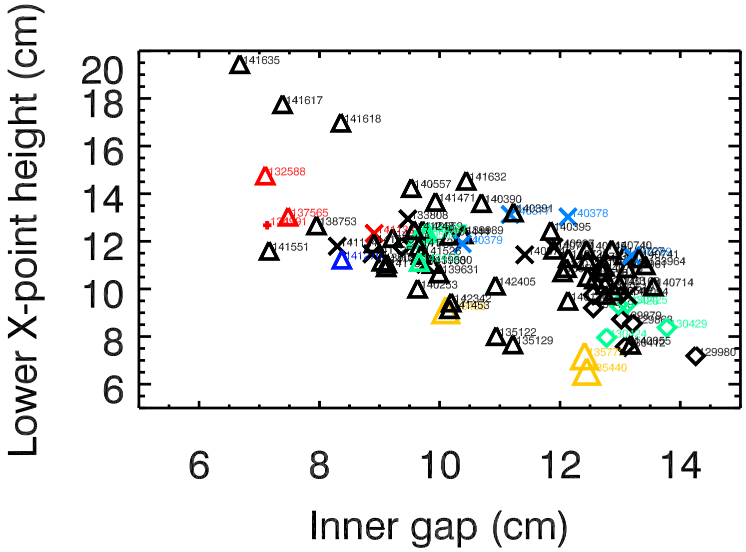
- 134991 has largest decrease in ”ions that are not carbon”
  - Strong SGI fueling, large lithium deposition, strikepoint on LLD



Lower neutral fueling facilitates access to EP H-mode

- EP H-mode observed with low neutral fueling
  - Facilitates access to low edge ion collisionality

- Steady EP H-mode discharges had a larger X-point height and smaller inner gap
  - Greater distance between dominant X-point and divertor floor seems beneficial
    - Perhaps this lowers the neutral source?
  - Large upper/lower gaps lead to discharges with smaller plasma volume



- Motivates combining large flux expansion with larger upper/lower gaps in an open divertor

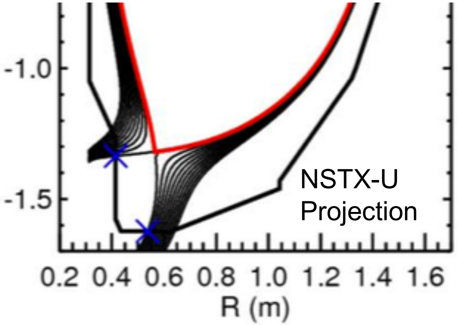
Summary of findings while searching for discharges with "stationary" density

- Discharges with large flux expansion and low incidence angle did achieve stationary carbon density at lower Z_{eff} on NSTX
  - But, discharges had lower thermal confinement

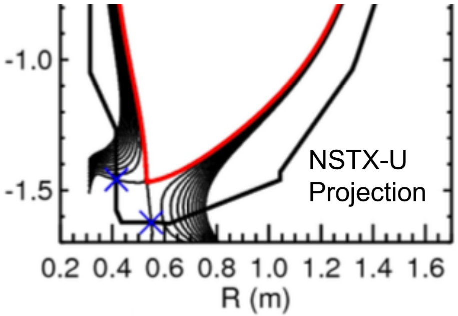
- Lithium wall conditioning facilitated conditions with stationary or decreasing $n_{Deuterium}$ inventory
  - Steady EP H-mode phases seem to favor keeping the X-point away from divertor plates

- NSTX-U goal: Integrate high-confinement regimes with divertor configurations that minimize carbon influx
  - New tools: expanded divertor coils for balanced DN with enhanced flux expansion, divertor and PFR gas injection, fish-scaled tiles

Smaller flux expansion



Larger flux expansion



Outline of database results

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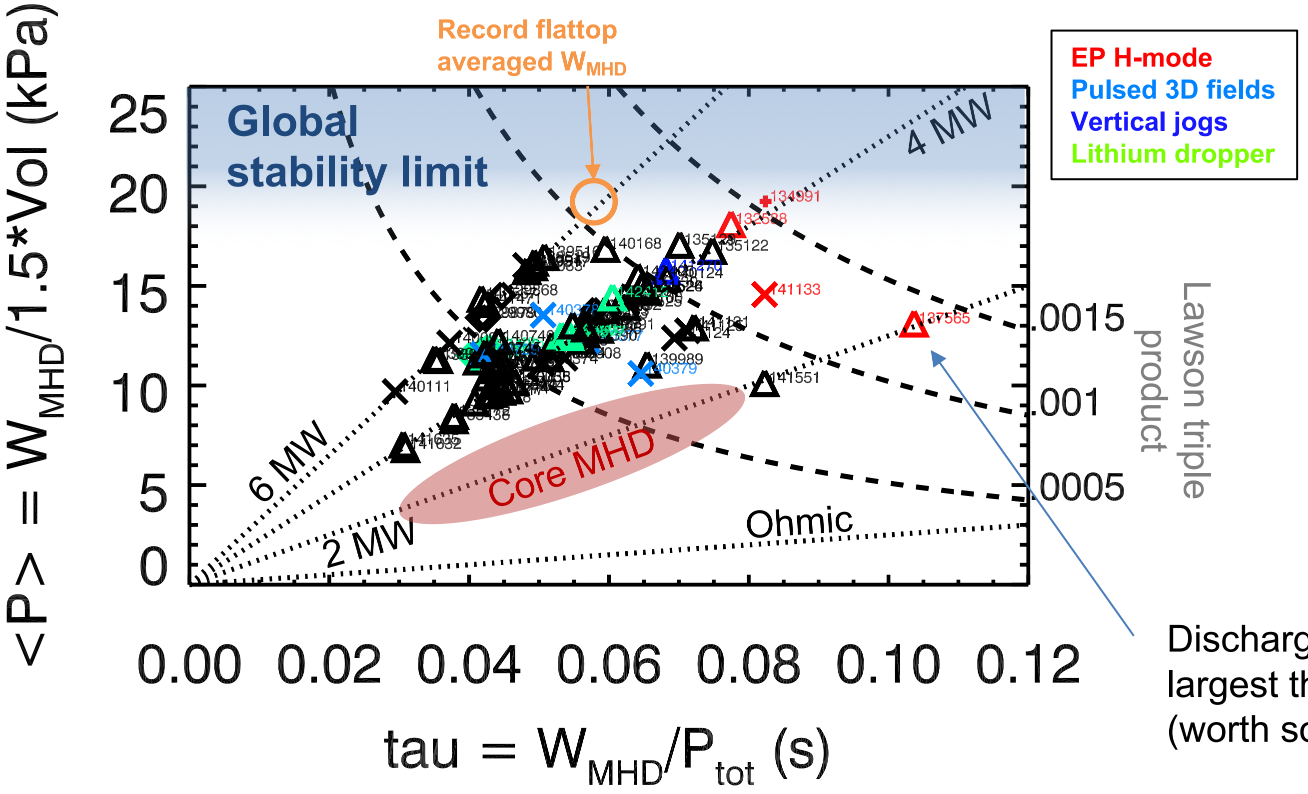
- EP H-mode observations

Most "steady" ELM-free discharges use 4MW of NBI heating



Energy confinement time (not corrected)

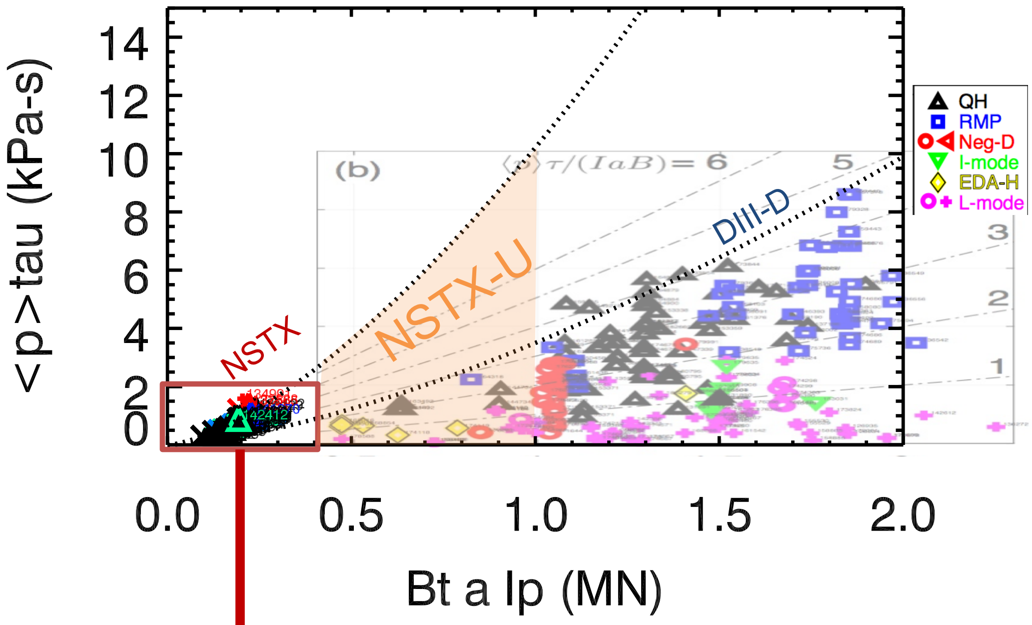
3 beam discharges more likely to have larger density rise at higher confinement

Difficult to avoid core MHD with $P_{NBI} < 3$MW in H-modes

Discharge with LLD at 320℃ has largest thermal confinement (worth some more analysis)

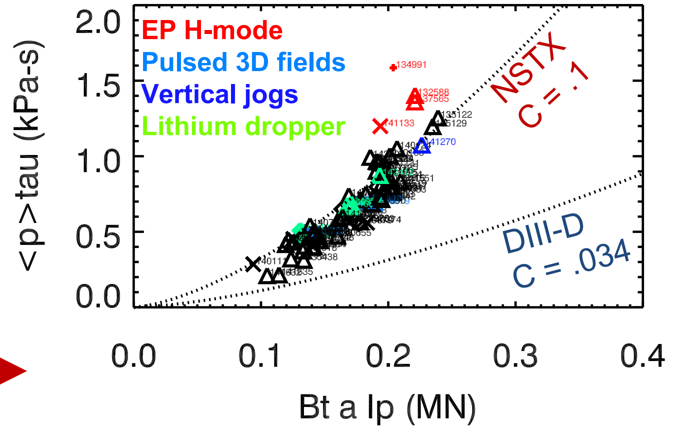
Scaling of triple product with B_t a I_p in ELM-free regimes similar to DIII-D, but with a larger scalar

NSTX-U may achieve similar triple product to DIII-D steady ELM-free scenarios

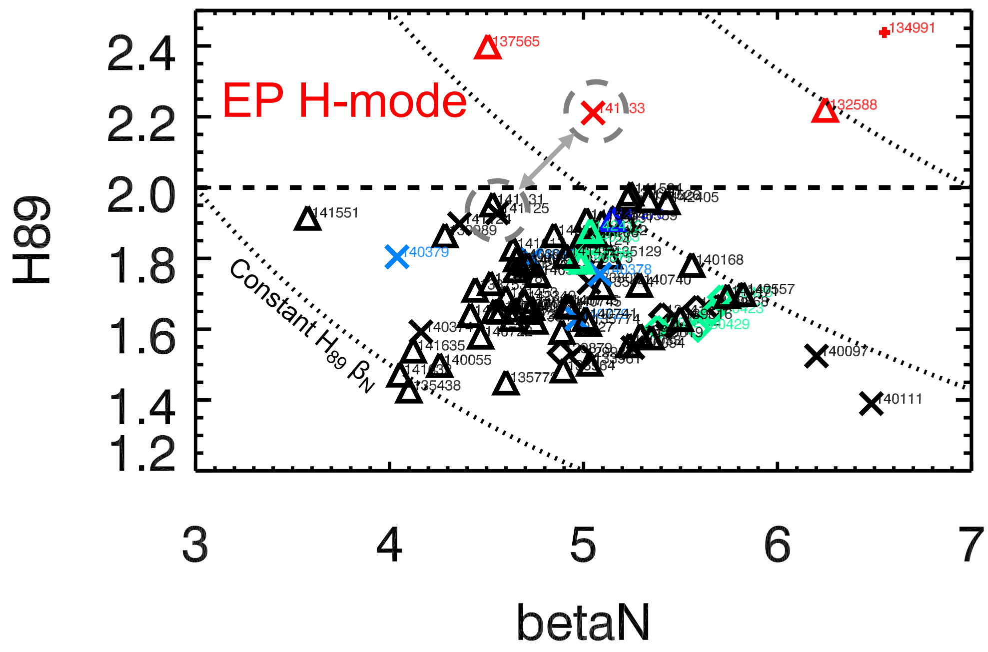


DIII-D data from
C. Paz-Soldan et al. PPCF submitted
https://arxiv.org/abs/2012.03339

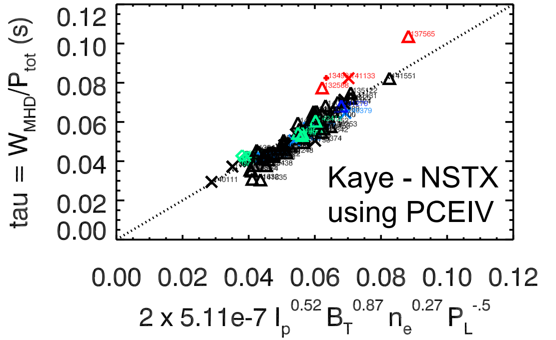
Dotted lines:
$\langle p \rangle \tau = C\,(B_T\ a\ I_p)^{1.5}$

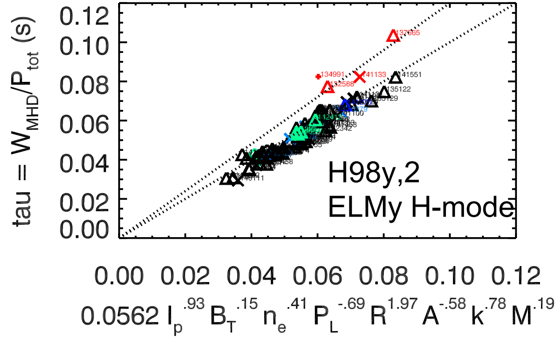


EP H-mode discharges stand out in normalized confinement



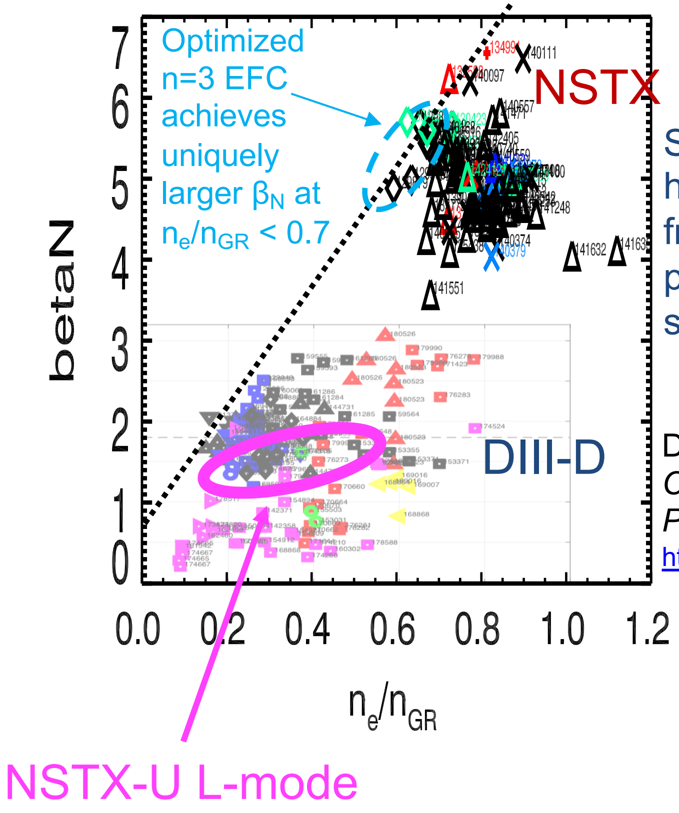
Do not consider these plots as a quantitative comparison to scaling laws: τ_E & P_L are not corrected for NBI efficiency, fast ion component, dW/dt …





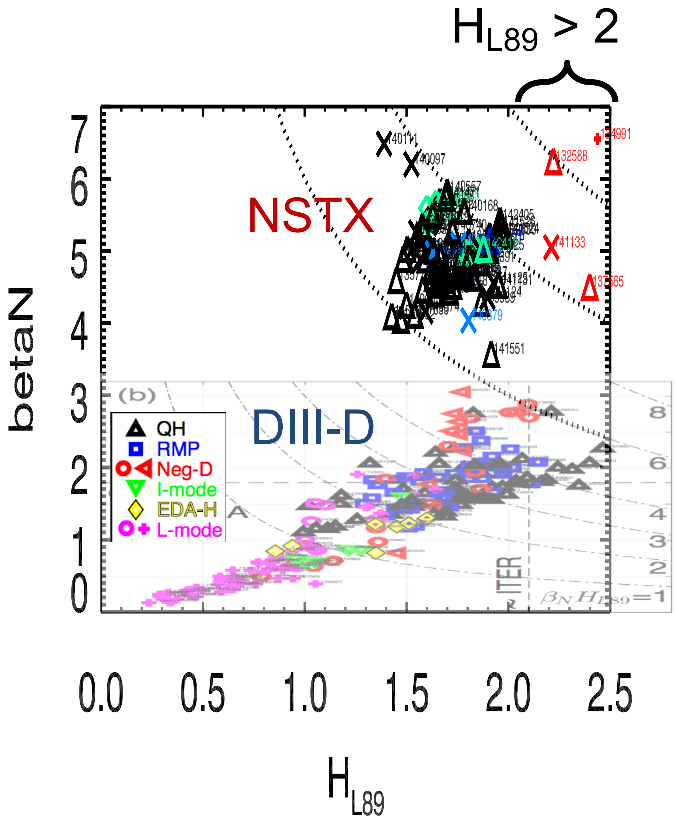
With the caveat that there are only a few EP H-mode discharges in the database ….
The results are consistent with a "bifurcation" in the transport

ELM-free regimes in STs can operate at large β_N with comparable H_{L89} to A~3



Similar trend to DIII-D where high Greenwald density fraction favors broader profiles with improved stability at large β_N

DIII-D data from
C. Paz-Soldan et al. PPCF submitted
https://arxiv.org/abs/2012.03339



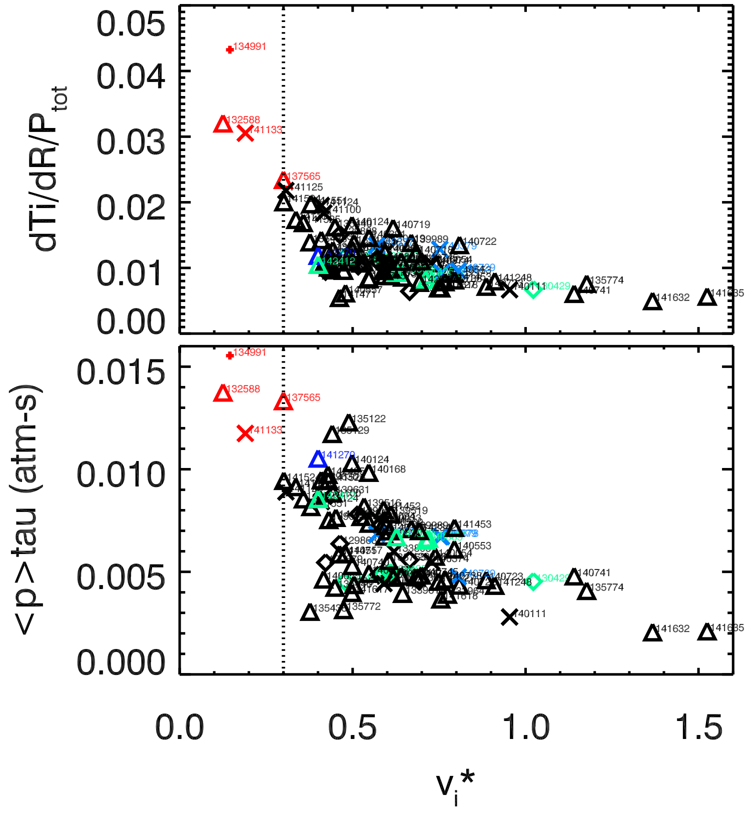
Outline of database results

- Impurity and density accumulation in ELM-free regimes
- Operational regime for steady discharges on NSTX
- EP H-mode observations

EP H-mode: improved neoclassical energy confinement at low collisionality

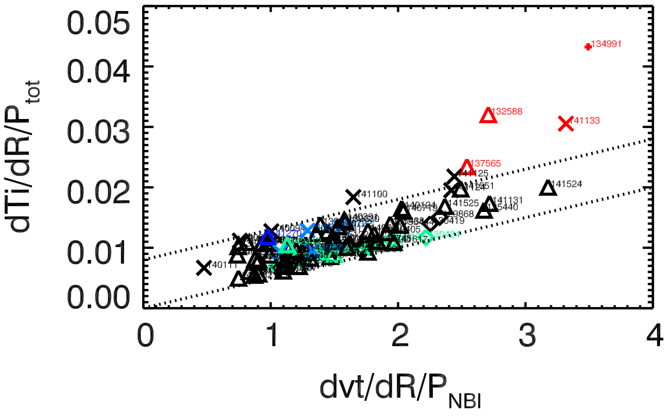
- EP H-mode: bifurcation in transport occurs at low ion collisionality
  - Ion neoclassical transport decreases with ν_i^*
  - Edge ion temperature gradient increases
  - Enhanced anomalous pedestal transport lowers edge density
    - Positive feedback as this lowers collisionality
  - Data consistent with threshold at $\nu_i^* \sim 0.3$

- EP H-mode discharges achieve largest edge T_i gradients normalized to total heating power
  - Generally, triple product improves with lower ion collisionality

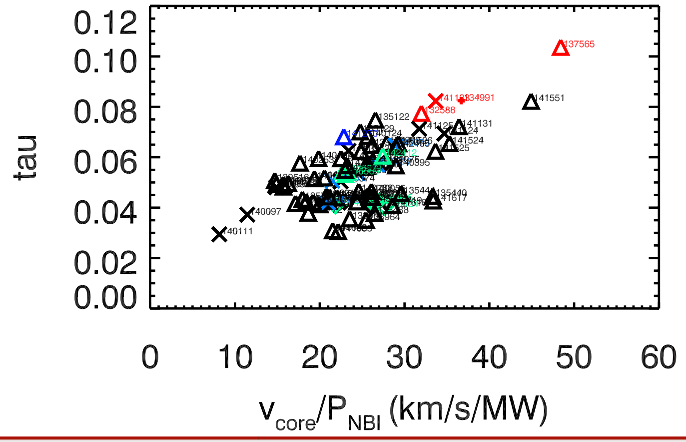


Scaling of edge rotation gradient and core rotation may provide insight to transport mechanisms

- Maximum edge rotation gradient and ion temperature gradient increase together
  - Note that maximum v_t gradient is not always spatially aligned with the maximum T_i gradient
    - Edge E_r shear typically proportional to v_t gradient
  - Discharges with n=3 fields and EP H-mode tend to exhibit stronger T_i gradient compared to v_t gradient



- Energy confinement and a metric for momentum confinement scale together
  - Anomalous electron energy transport is the dominant core transport mechanism



Conclusions

- NSTX database focuses on “steady” discharges void of ELMs and MHD
  - Supports FY22 JRT efforts toward multi-machine comparisons
  - All discharges in the database produced with lithium wall conditioning (increased wall pumping) leading to a wide pedestal
- Very few discharges would clear the bar for “steady” in the DIII-D database
  - Density, namely carbon density, is rising during the ELM-free phase
  - A few discharges with large flux expansion did achieve steady carbon inventory
  - NSTX-U 5 year plan addresses this challenge: (Thrust 2-1) “Particle control and heat flux mitigation necessary for stationary discharges”
- Database further confirms uniqueness of EP H-mode
  - Accessed at lowest edge ion collisionality
  - A distinctive step-up in normalized performance and triple product

Next steps

- Use consistent equilibrium and TRANSP tools for all discharges of interest
  - Most discharges have TRANSP runs, but differ in equilibrium constraints (EFIT, LRDFIT) and/or TRANSP settings
- Continue to comb NSTX results for new entries
  - This has been a nice nostalgic “work-from-home” activity
- Please get involved with the JRT22 Working Groups!

FY22 JRT Working Groups

- Operational space database and 0-D Projections
  - Develop common metrics for comparing regimes and use 0-D scaling to project scenarios to next-step devices
    - Coordinator: Devon Battaglia (dbattagl@pppl.gov)

- Characterization of Edge Transport Mechanisms
  - Apply fluid and gyrokinetic tools to compare edge transport mechanisms in stationary non-ELMing regimes
    - Coordinators: Xi Chen (chenxi@fusion.gat.com), Darin Ernst (dernst@psfc.mit.edu)

- Edge Macro-Stability and MHD-driven transport at strong shaping
  - Characterize scaling of edge MHD stability and associated transport in target regimes
    - Coordinator: Jake King (jking@txcorp.com)

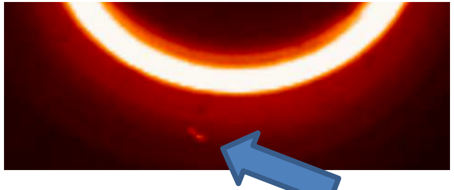
- Role of Wall Conditions and Divertor Compatibility
  - Explore compatibility of regimes with PFC and divertor solutions using experiments and simulation
    - Coordinator: Alessandro Bortolon (abortolo@pppl.gov)

- Expansion of Operating Space toward Burning-plasma Regimes
  - Propose and execute new experiments that extend the operating space on tokamaks operating in FY21-22
    - Coordinators: Darin Ernst (dernst@psfc.mit.edu), Xi Chen (chenxi@fusion.gat.com)

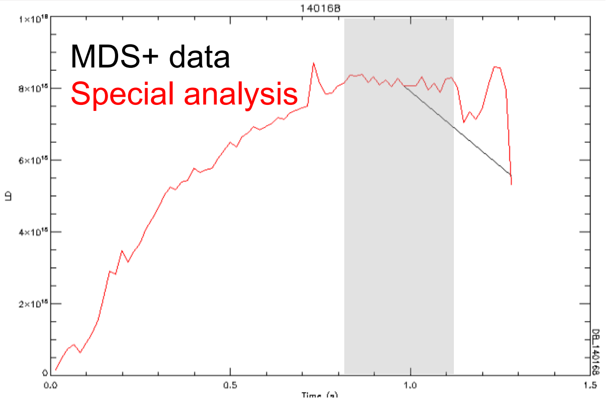
Backup

Discharge with "Lithium chunk" in the divertor achieves $dn_e/dt \sim 0$ (shot 140168)

- Lithium chunk dropped from LITER and fell to the outboard section of the lower divertor
  - Several shots attempting a snowflake divertor vaporized chunk into small chunks
  - Shot 140168: Switch to high-delta shape that avoids the chunk (XP1045)
    - Ran with a lot of lithium deposition
    - Single ELM might have vaporized small chunks
- Achieves constant electron density despite impurity density increasing
  - Ben had to perform special analysis on the MPTS data due to large lithium emission
- One could argue this is an example of intra-shot wall conditioning (i.e. mass injection)

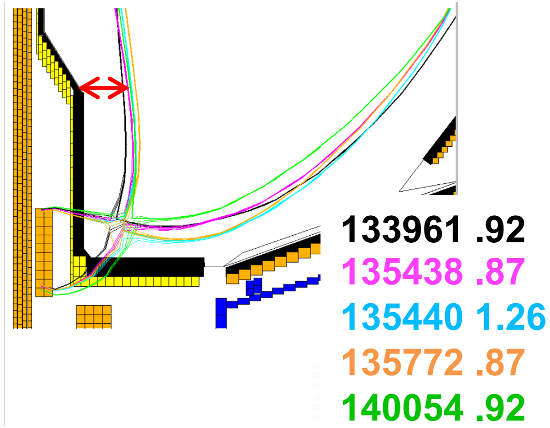


Divertor camera, LLNL



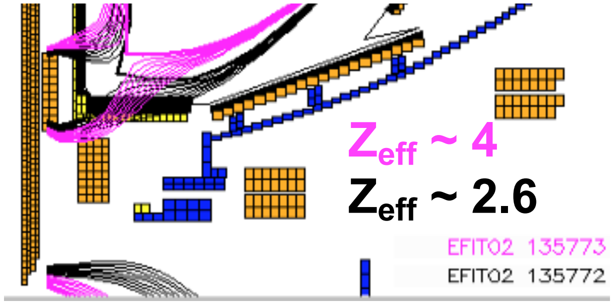
Low carbon accumulation discharges share some similarities

- Shots with the lowest carbon accumulation rate tend to have …
  - X-point close to the lower divertor
  - Large flux expansion
  - Flux surfaces that have a low incidence angle
  - Larger gap between the inner divertor corner
  - Lower energy confinement



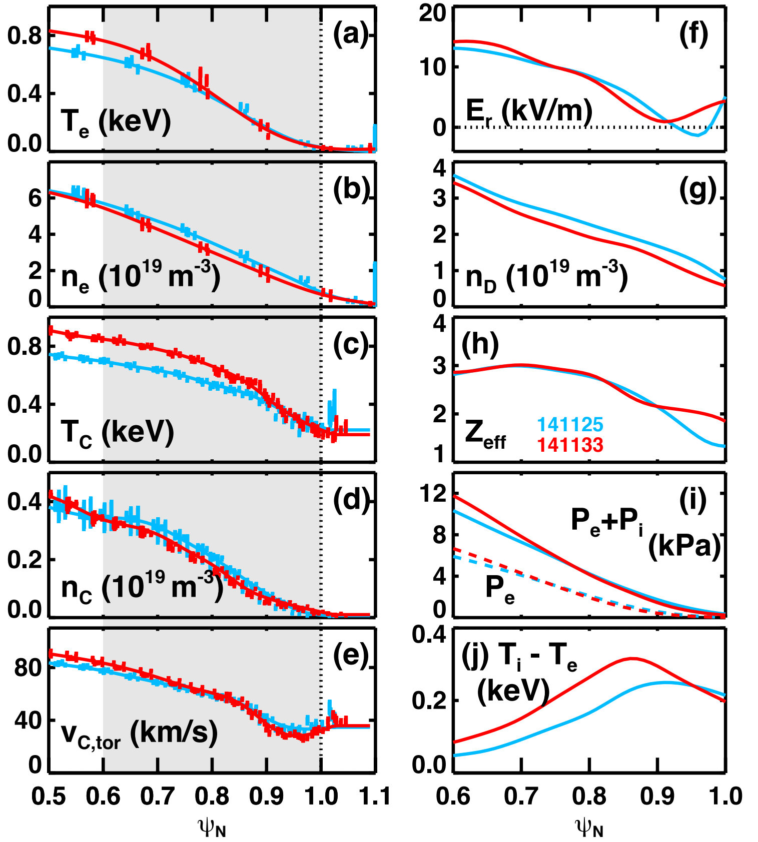
- But, some shots match these conditions and have larger carbon accumulation
  - Needs more investigation

- One pair of shots demonstrates impact of flux expansion and incident angle on the carbon content



EP H-mode has lower edge n_e, larger core T_i and T_e

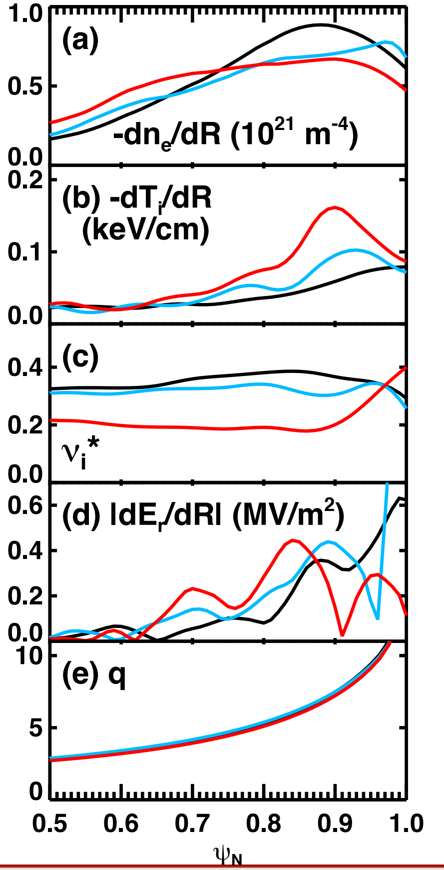
- Edge n_e, n_D is reduced
  - Z_{eff} larger for $\psi_N > 0.9$
- Location of minimum E_r shifts inward
- Pressure similar for $\psi_N > 0.8$
- Characteristic increase in edge ∇T_i
  - Larger core T_i and T_e
  - Bigger increase in core T_i



WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3

EP H-mode realized with more peaked density profile and lower ν_i^*

- EP H-mode: smallest $-\nabla n_e$ for $\psi_N > 0.9$, largest for $\psi_N < 0.7$
  - Density profile is more peaked
- EP H-mode profiles have largest edge $-\nabla T_i$
- $\nu_i^* < 0.3$ near $\psi_N = 0.9$ due to lower density
  - Farther in, smaller ν_i^* due to larger T_i
- E_r shear peaks inside location of maximum $-\nabla T_i$
  - Max $-\nabla T_i$ typically close to E_r minimum in EP H-mode profiles
- Enhanced thermal confinement without reverse q-shear



WP H-mode 141131 EFC only
WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3

Non-resonant 3D fields in WP regime alters edge E_r, Z_{eff}

- Small impact on electron profiles
  - Little change to T_e
  - n_e slightly broader in edge region

- Bigger impact on ion profiles
  - Rotation, E_r reduced via NTV
  - T_i smaller in edge, matched in core
  - n_D broader, n_C pedestal shifts inwards
    - Significant reduction in edge Z_{eff}

- Pressure profiles are similar

WP H-mode 141131 EFC only
WP H-mode 141125 EFC + 400A n=3
EP H-mode 141133 EFC + 500A n=3