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XP-1006: Development of High-Elongation Beam Heated Scenarios with Reduced Impurity Content and Increased Non-Inductive Fraction

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V. Soukhanovskii, any other interested parties.

ASC TSG Group Review

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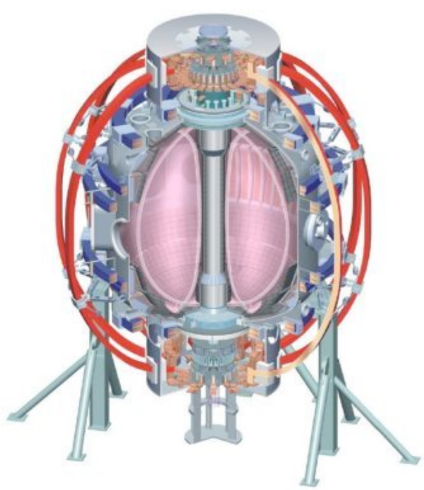

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Overview

- Background:
  - Shots in 2009, XP-836, achieved a reliable scenario with f_{NI}>65%.
  - These shots were full of impurities (Z_{eff}>=3), with ramping radiated power.
- Goal:

  Incorporate advanced impurity control techniques to maintain low Z_{eff} at very high elongation and normalized beta.

  Use these (and any other) techniques to increase the non-inductive fraction.
- Contributes to:
  - Research Milestone R(11-2): Assess the dependence of integrated plasma performance on collisionality.
  - Research Milestone R(11-3): Assess the relationship between lithiated surface conditions and edge and core plasma conditions.
  - PAC "demand" that ASC contribute actively in impurity control research.

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Outline

- Review the high-β_P shots from last year.
- Some “database analysis” of high-κ, high-β discharges.
- TRANSP predictive modeling based on 133964.
- Potential impurity control techniques.
- XP considerations shot list

Highly-Reliable Scenario With High-κ, β_P, and β_N…

2009 High-β_P, 0.48 T, high-κ (2.7)

133961 133963 133964 133994 133996

2009 Long Pulse, 0.38 T high-κ (2.7)

135445

2005 Long Pulse, more standard κ (2.3)

116318

Same plasma current in all cases.

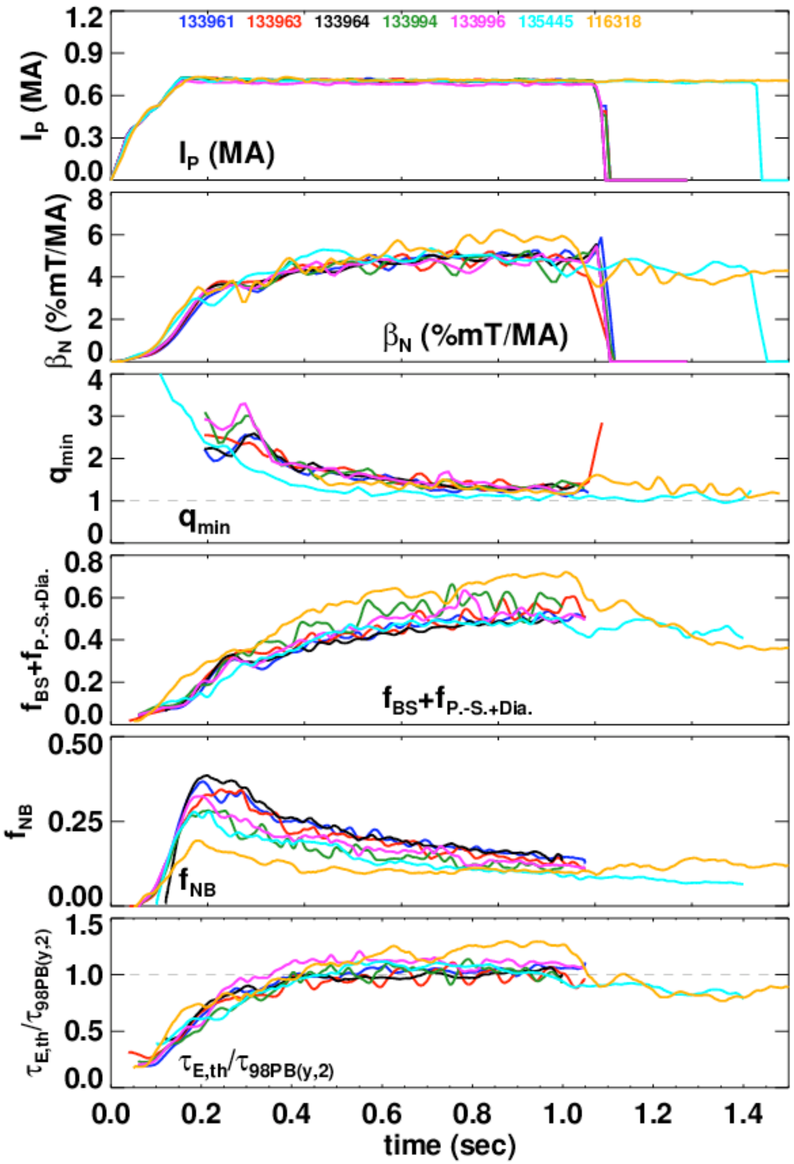
Similar normalized beta values.

Almost (or maybe fully) equilibrated q-profiles.

Bootstrap current was much higher in 2005 trophy shot.

Beam current was lower in 2005 trophy shot.

Confinement was slightly better in 2005 trophy shot.



Highly-Reliable Scenario With High-κ, β_P, and β_N…
…and Lots of Impurities

2009 High-β_P, 0.48 T, high-κ (2.7)

133961 133963 133964 133994 133996

2009 Long Pulse, 0.38 T high-κ (2.7)

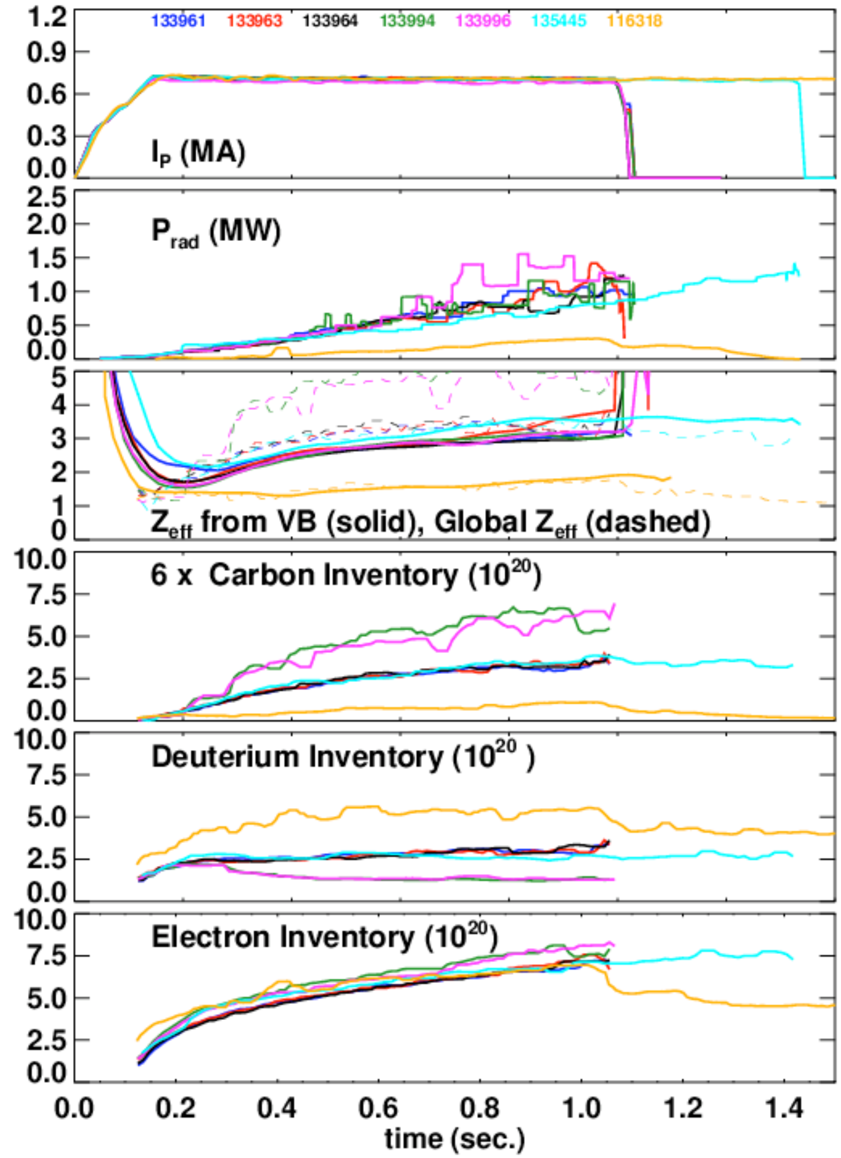
135445

2005 Long Pulse, more standard κ (2.3)

116318

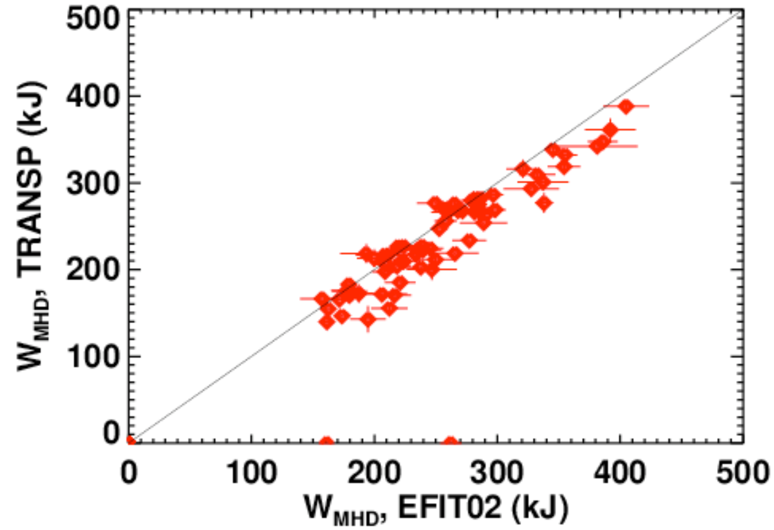
- P_{rad} from bolometers + EFIT.
- N_C=total carbon inventory
  - CHERS + EFIT
- N_D=total deuterium inventory
  - CHERS+EFIT
- N_e=total electron inventory
  - MPTS + EFIT
- Global Z_{eff} defined as

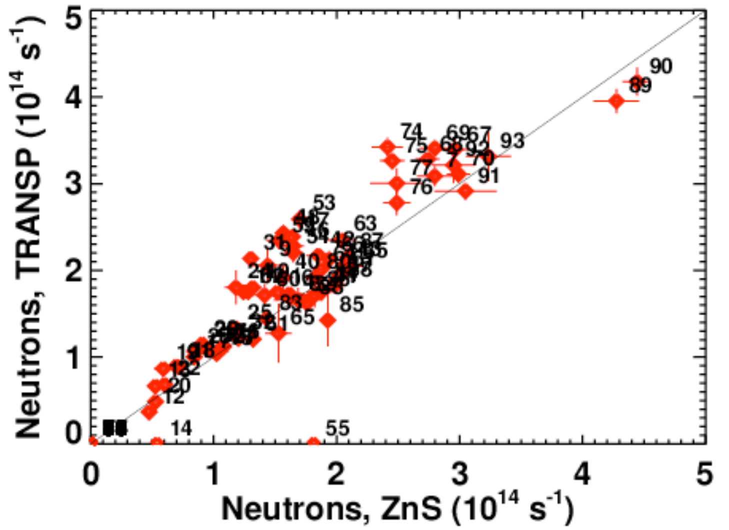
$$Z_{eff,global} = \frac{36N_C + N_D}{N_e}$$



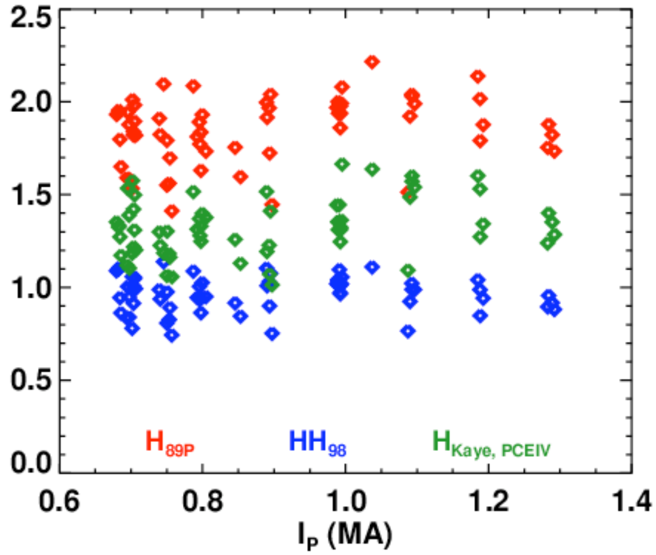
Database Analysis Of High-β Beam Shots

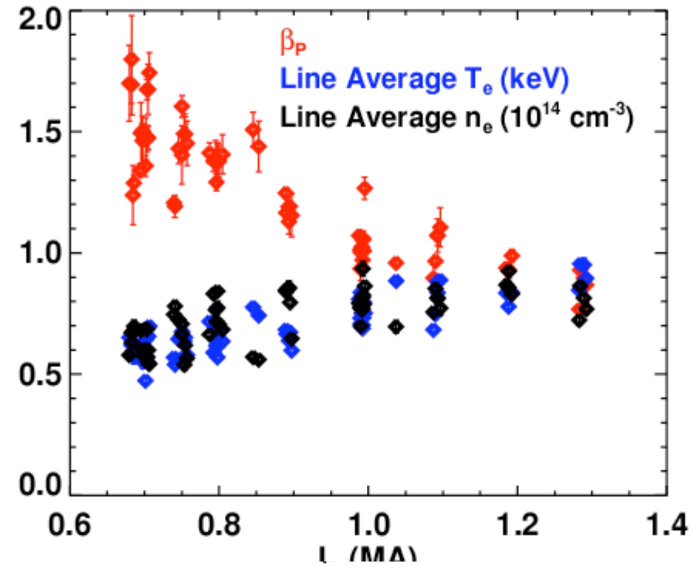
- ~80 discharge with long quiescent periods.
  - All have κ>2 and β_N>4.
- Run TRANSP with LEVGEO=8, mostly lrdfit04 input equilibria.
- For Z_{eff}, use CHERS Carbon or chord VB.
- No fast ion diffusion (yet).
  - Large freedom to match neutron emission through Z_{eff} and dn0out.
- Comparisons to check validity of TRANSP runs:
  - Stored energy
  - Neutron emission.
- Not all TRANSP runs have been fully optimized.
  - Some may require anomalous fast ion diffusion.

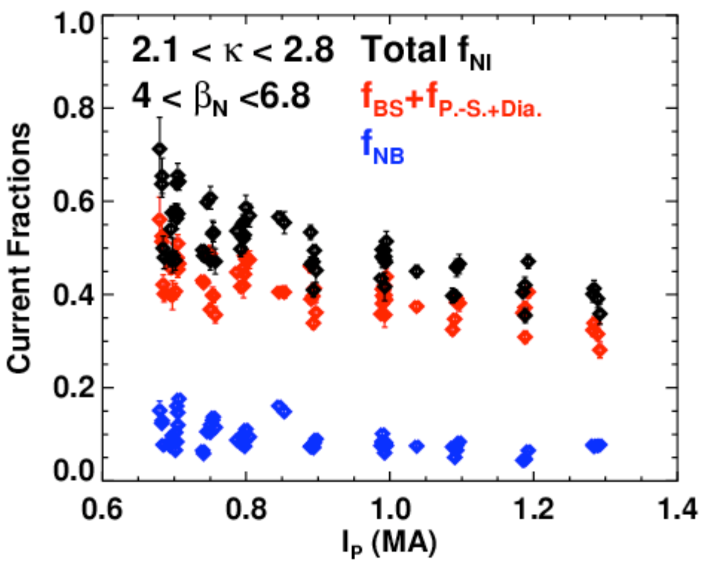


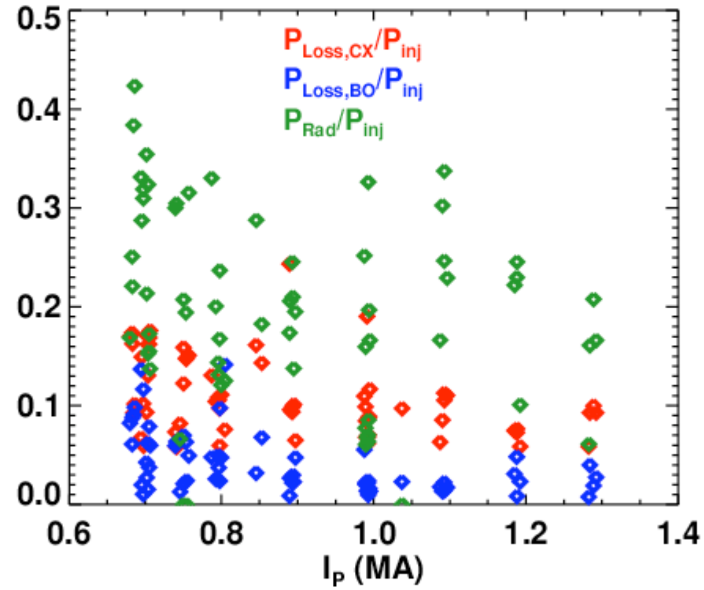


I_P Scaling Of Everything

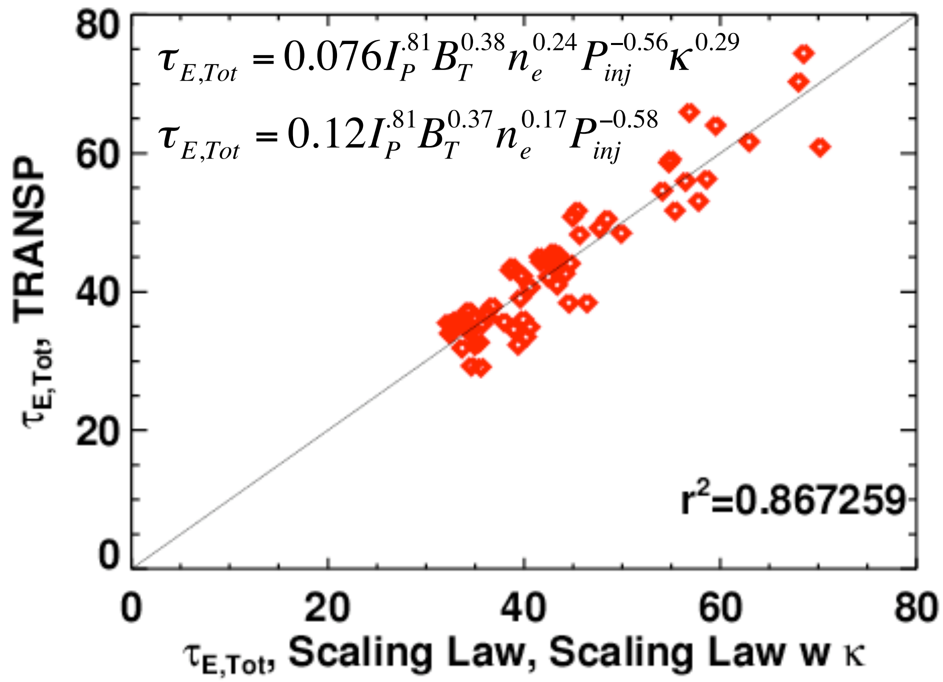


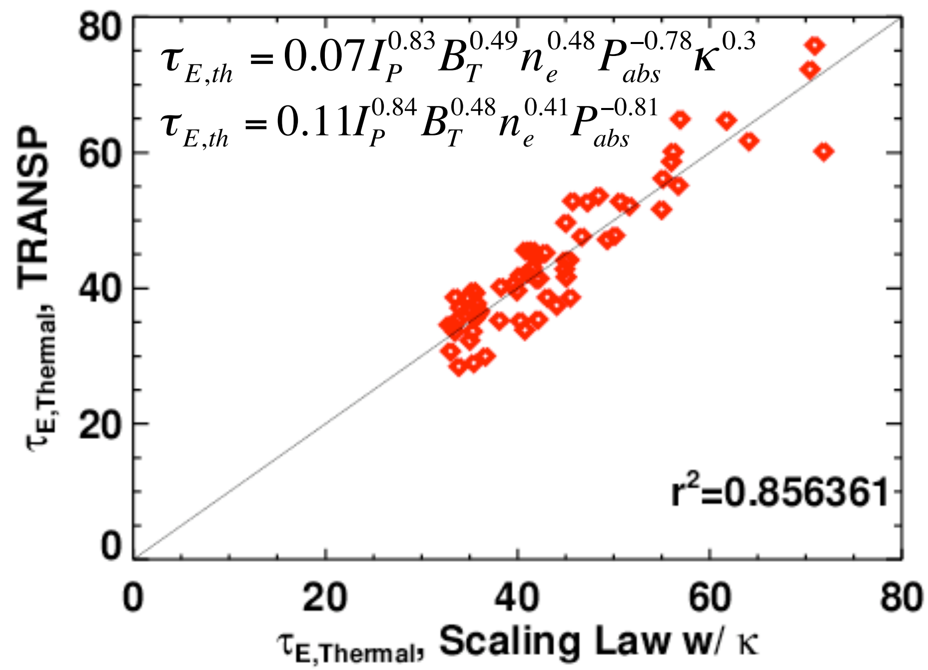






Database Allows a Preliminary Study of Confinement Scaling in the High-κ, High-β Regime





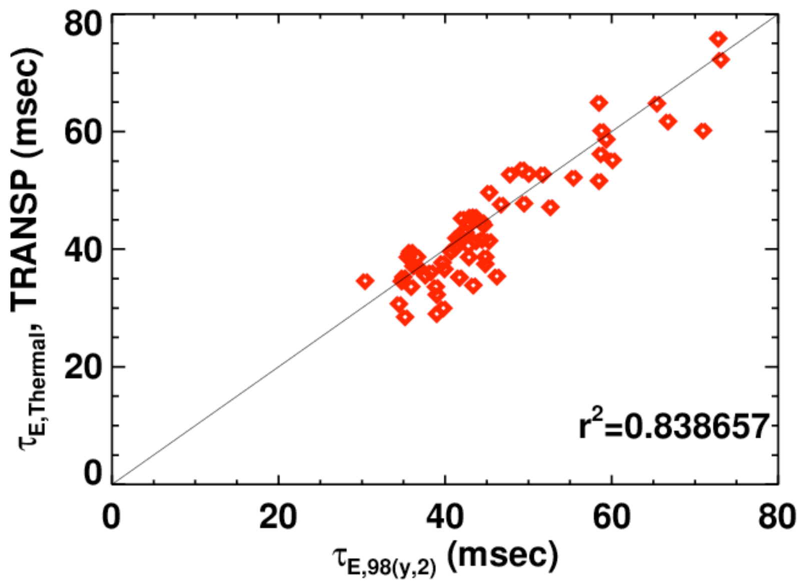
$$\tau_{E,th} = \frac{W_{Th}}{P_{abs}} \qquad \tau_{E,tot} = \frac{W_{Tot}}{P_{Tot}}$$

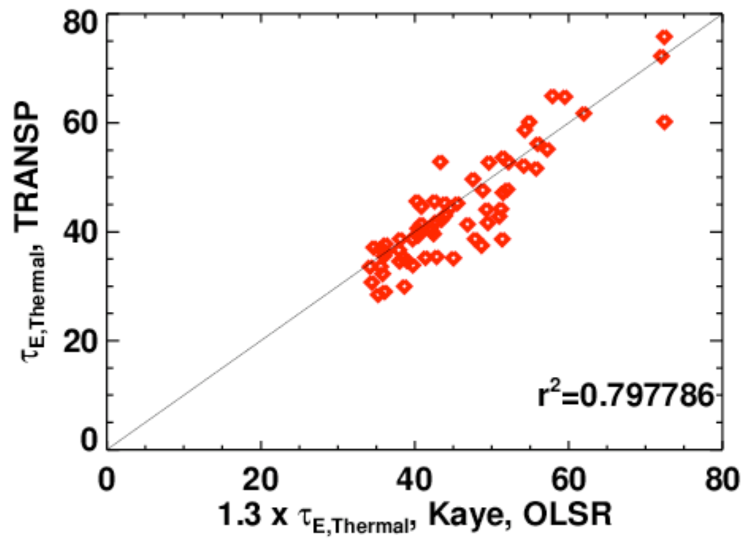
$$P_{Tot} = P_{inj} + P_{OH} - P_{ST}$$

$$P_{abs} = P_{inj} + P_{OH} - P_{ST} - P_{CX} - P_{BO}$$

- Compute regression both w/ and w/o κ as a regression variable.
  - Little change in other exponents when κ is included.
- Largest correlation between any two regressors:
  - Density and current with r^2=0.42
  - Current and field with r^2=0.25
  - Density and Elongation with r^2=0.27

Other Scaling Laws Also Fit the Data Reasonably Well





$$\tau_{E,th,ITER-98} \propto I_P^{0.93} B_T^{0.15} n_e^{0.41} P_{abs}^{-0.69} \kappa^{0.8}$$

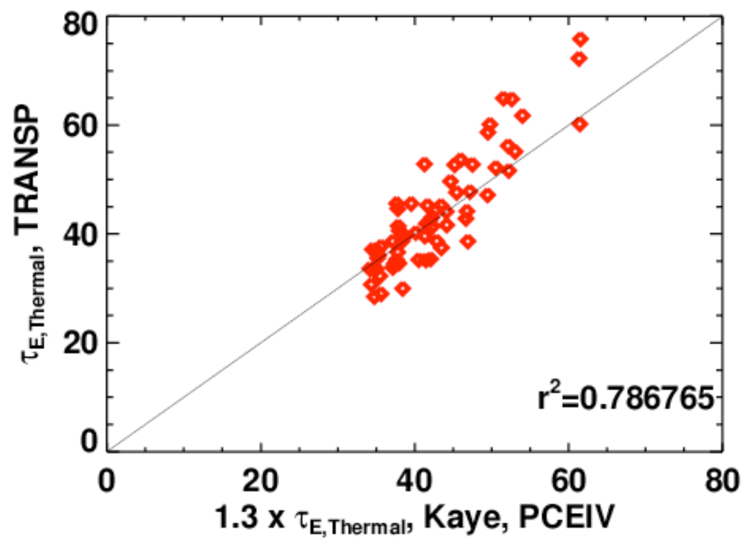
$$\tau_{E,th,Kaye,OLSR} \propto I_P^{0.57} B_T^{1.} n_e^{0.44} P_{abs}^{-0.73}$$

$$\tau_{E,th,Kaye,PCEIV} \propto I_P^{0.52} B_T^{0.87} n_e^{0.27} P_{abs}^{-0.5}$$

$$\tau_{E,th,Gerhardt} \propto I_P^{0.83} B_T^{0.49} n_e^{0.48} P_{abs}^{-0.78} \kappa^{0.3}$$

Data (apparently) does not support very accurate determination of the scaling exponents.

Need to accumulate more data during the 2010 run.



Predictive Simulations

- Take profiles & boundary shape from 133964.
  - High-β_P discharge
- Fix Z_{eff} as a flat profile.
- Scale Z_{eff}, temperature, density as TRANSP input profile.
- Run TRANSP for 3 seconds, to allow profiles to fully relax.
  - Check that the loop voltage profile is flat.
- Not strictly self consistent.
  - TEQ solver liked to crash, so I used LEVGEO=8, but with magnetic diffusion.

TRANSP Shows that Reducing Z_{eff} Can Increase The Non-Inductive Fraction

- Fix:
  - Electron Density
  - Electron and ion temperatures
- Vary:
  - Z_{eff}, but with flat profile, assuming carbon is the impurity.
  - Ion density is adjusted to achieve quasi-neutrality.
- Decreasing Z_{eff}:
  - Decreases beam current drive.
  - Increases bootstrap current.
  - Raises q_{min}

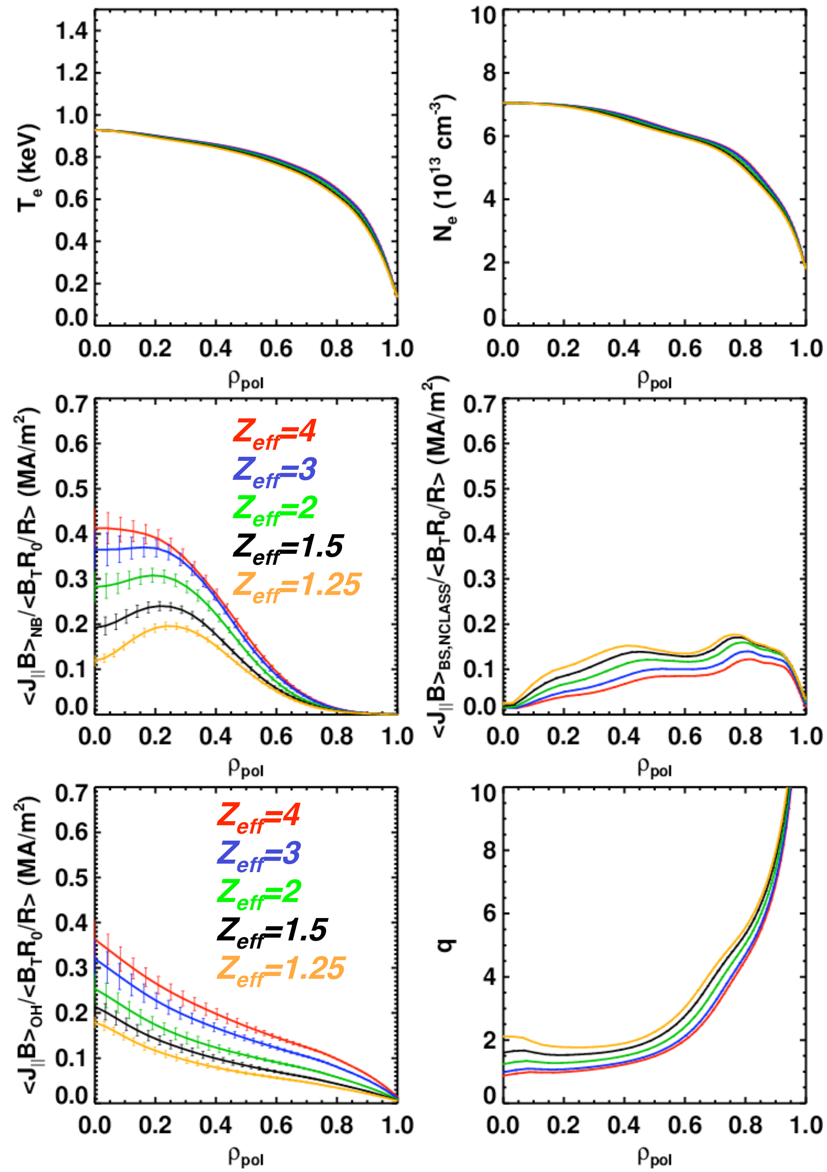
Z_{eff}=4: f_{BS}=40%, f_{NB}=17%, f_{NI}=62%

Z_{eff}=3: f_{BS}=45%, f_{NB}=16%, f_{NI}=67%

Z_{eff}=2: f_{BS}=55%, f_{NB}=15%, f_{NI}=76%

Z_{eff}=1.5: f_{BS}=62%, f_{NB}=13%, f_{NI}=81%

Z_{eff}=1.25: f_{BS}=66%, f_{NB}=12%, f_{NI}=84%

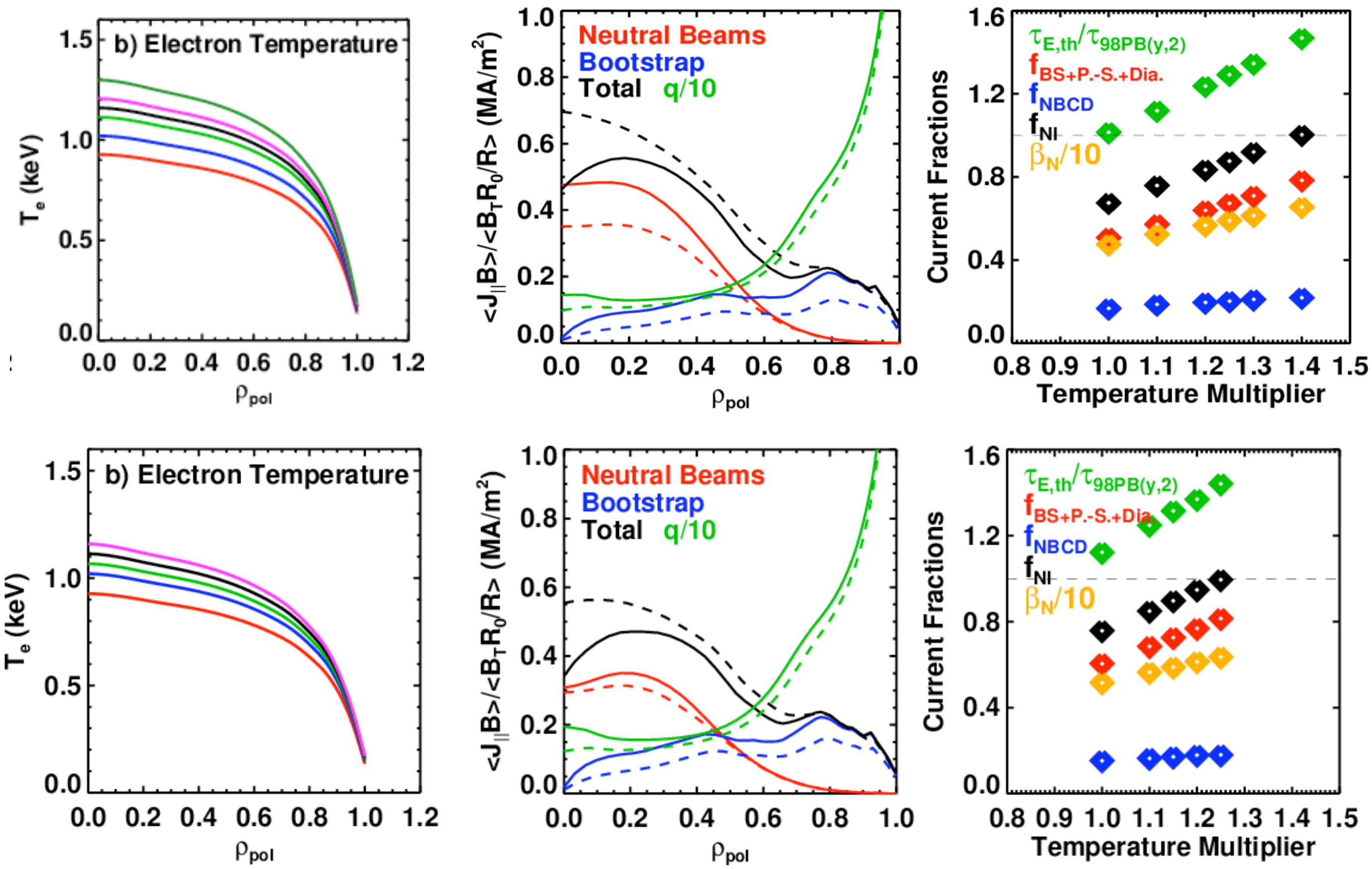


TRANSP Shows that Increasing the Temperature Can Increase the Non-Inductive Fraction

Solid: Experimental Profiles ***Dashed: Non-Inductive Profiles***

Z_{eff}=3

Z_{eff}=2



- Temperature might be increased by:
  - HHFW (not this XP).
  - Eliminating core radiation (this XP).

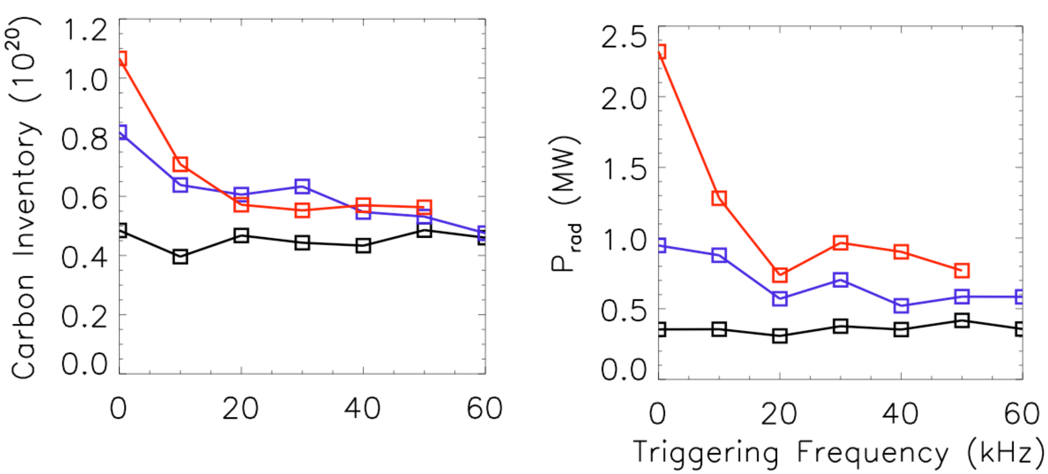
We (May) Have a Number of Tools For Impurity Reduction

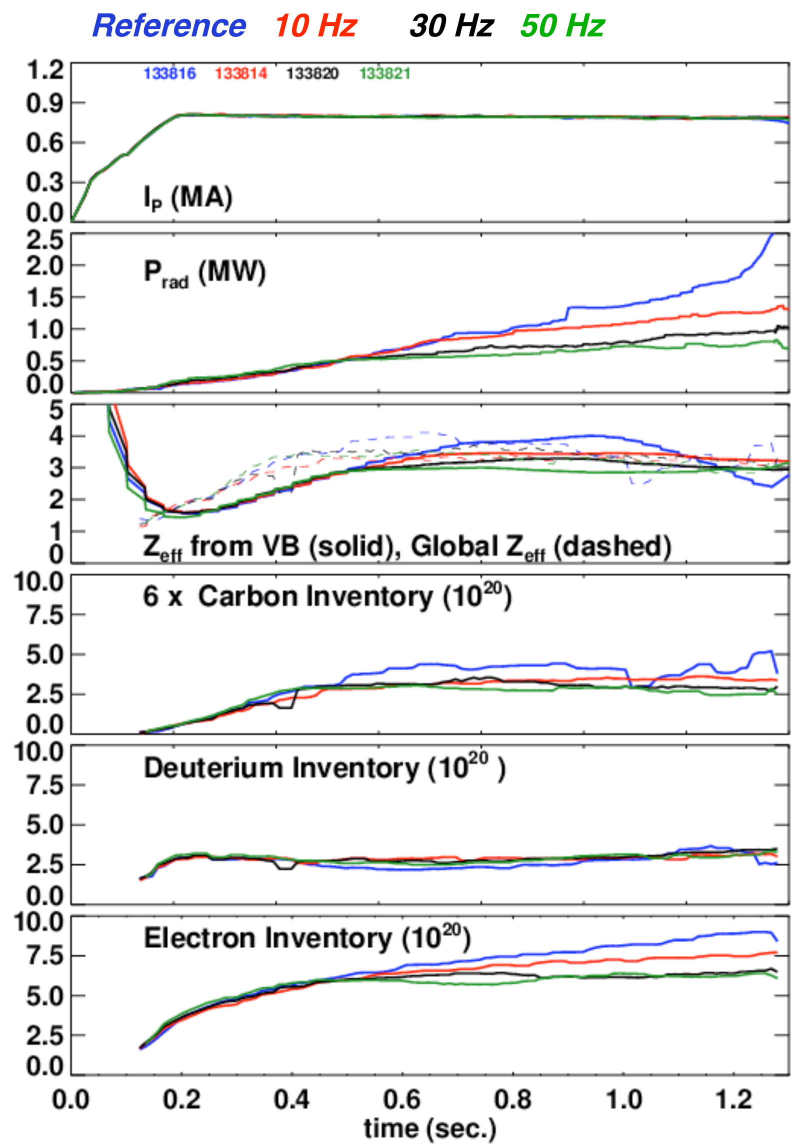
- **ELM Pacing With 3-D Fields**
  - Developed in ASC last year by Canik, Maingi, Sontag, et al.
  - Further studies by Canik, et al. in 2010 coupling these perturbations to vertical jogs.
- **Divertor Gas Injection:**
  - Used in non-lithiated conditions to generate PDD, with resulting reduction in core carbon and divertor heat flux.
  - XP in the Lithium Research TSG by Soukhanovskii
- **Snowflake Divertor:**
  - Under development in BP TSG by Soukhanovskii.
- **Early Shot Optimization:**
  - XP in the ASC TSG by Menard
- **Lithium Powder Dropper:**
  - Method showed reduced radiated power compared to LITER.
  - XP by Mansfield in the Lithium Research TSG
- **Lithium Evaporation Into Diffuse Helium**
  - Showed some signs of impurity reduction.
  - XP in Lithium Research TSG by Skinner and Stotler.
- **Impurity Screening with 3-D fields**
  - Review this next ASC XP by John Canik next Tuesday
- **Additional Impurity Injection**
  - Proposed by Travis Gray at research forum
- **HHFW**
- **Boundary Squareness For ELMs**

Develop these in other XPs, and combine the most reliable methods in this XP.
Focus on integration

ELM Pacing Can Lower Radiated Power and Z_{eff}

- Reliable ELM triggering demonstrated in 2009.
  - Reductions in both P_{rad} and carbon with low-frequency triggering.
  - Low-frequency (20 Hz.) triggering had minimal performance degradation.
- New "AC Compensations" in the mode-ID algorithms should allow RWM feedback and DEFC during rapid n=1 pulses.
- Low-frequency triggering is likely optimal for this XP.





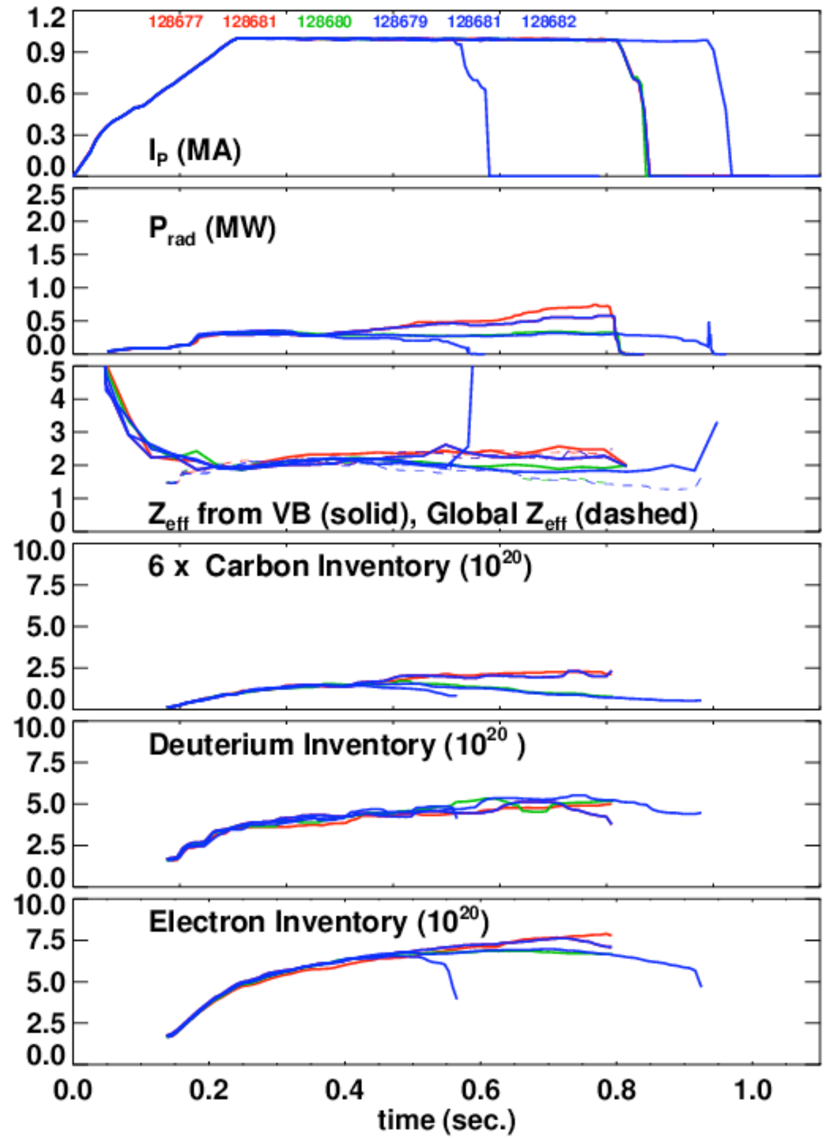
Divertor Puffing May Reduce the Carbon And Impurity Influx 1.0 MA Example

128677 128681: Reference Shots

128680: marginal PDD (1500 torr)

128679, 128682: Good PDD (2000 and 2500 torr)

- Examples with no lithium conditioning.
  - Experiments designed to study heat flux reduction, and so needed calibrated IR camera data.
  - Discharges had ELMs
  - Less P_{rad} and carbon accumulation than in lithiated cases.
- Run at higher plasma current.
  - Experiment designed to maximize the peak heat flux for fixed flux expansion.
- Clear reduction of radiated power and carbon accumulation with puff.
- Interesting to test this with lower plasma current, higher-elongation.
  - Lower X-point may reduce the amount of gas required.



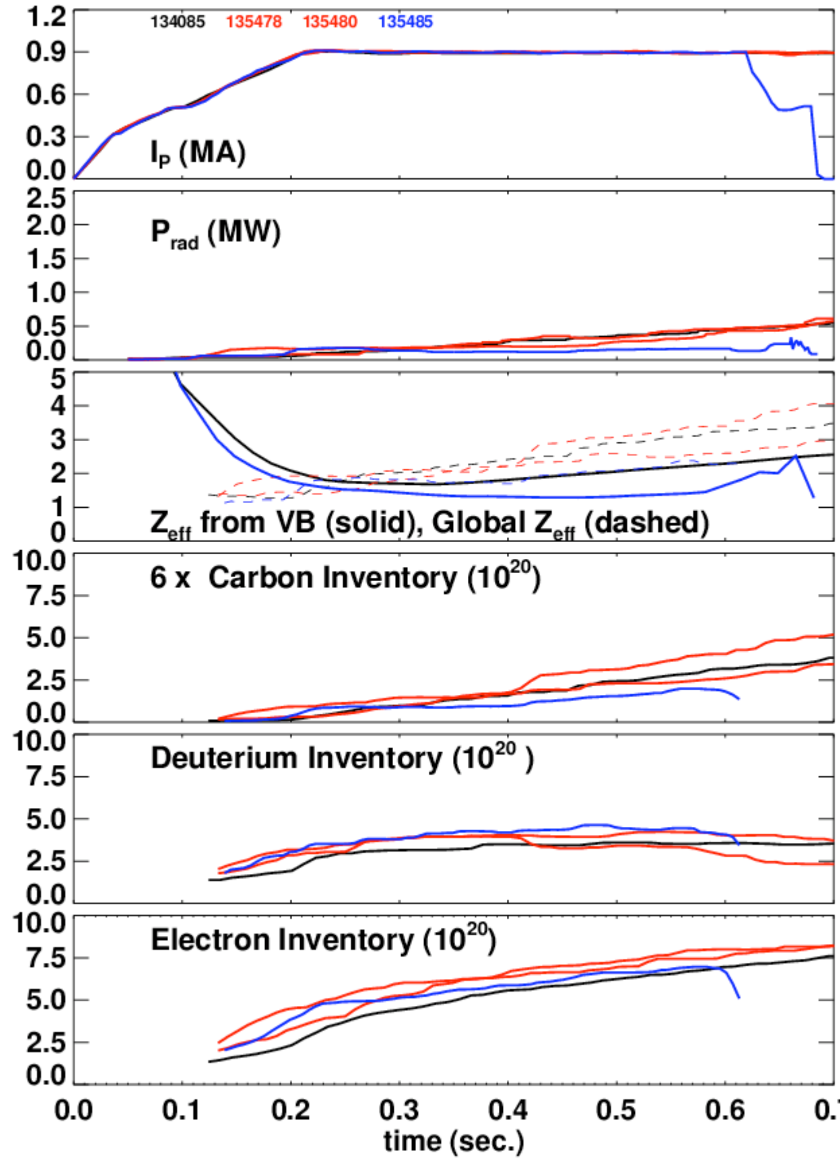
Snowflake Configuration in 2009 Indicates Potential Benefits From PDD

High-Triangularity Reference

Intermediate Triangularity Reference

"Near Snowflake"

- OSP became partially detached when the equilibrium was "near snowflake".
  - Short shots obscures some of the benefits.
- Significant reduction in carbon, radiated power, and $Z_{eff.}$
- Best indicator of what PDD might produce in a lithiated plasma.



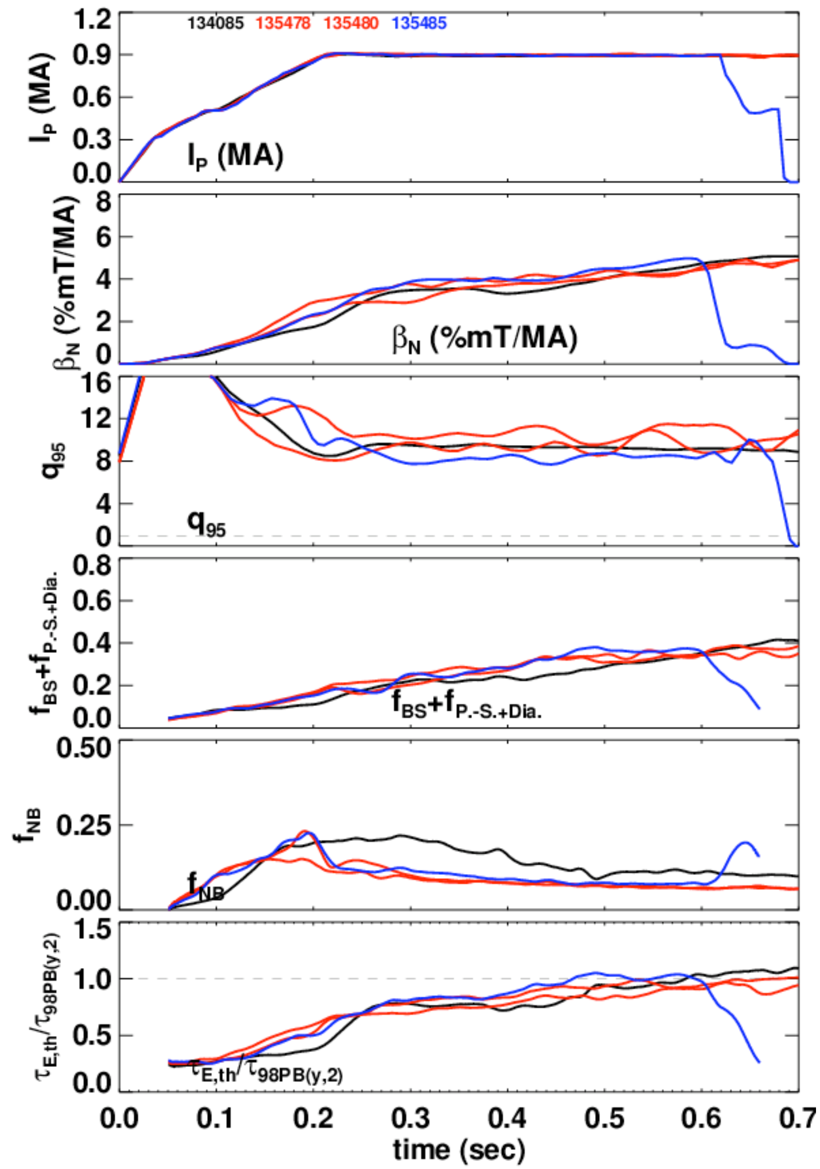
Snowflake Configuration Has Highest Bootstrap Current and Confinement Compared to References

High-Triangularity Reference

Intermediate Triangularity Reference

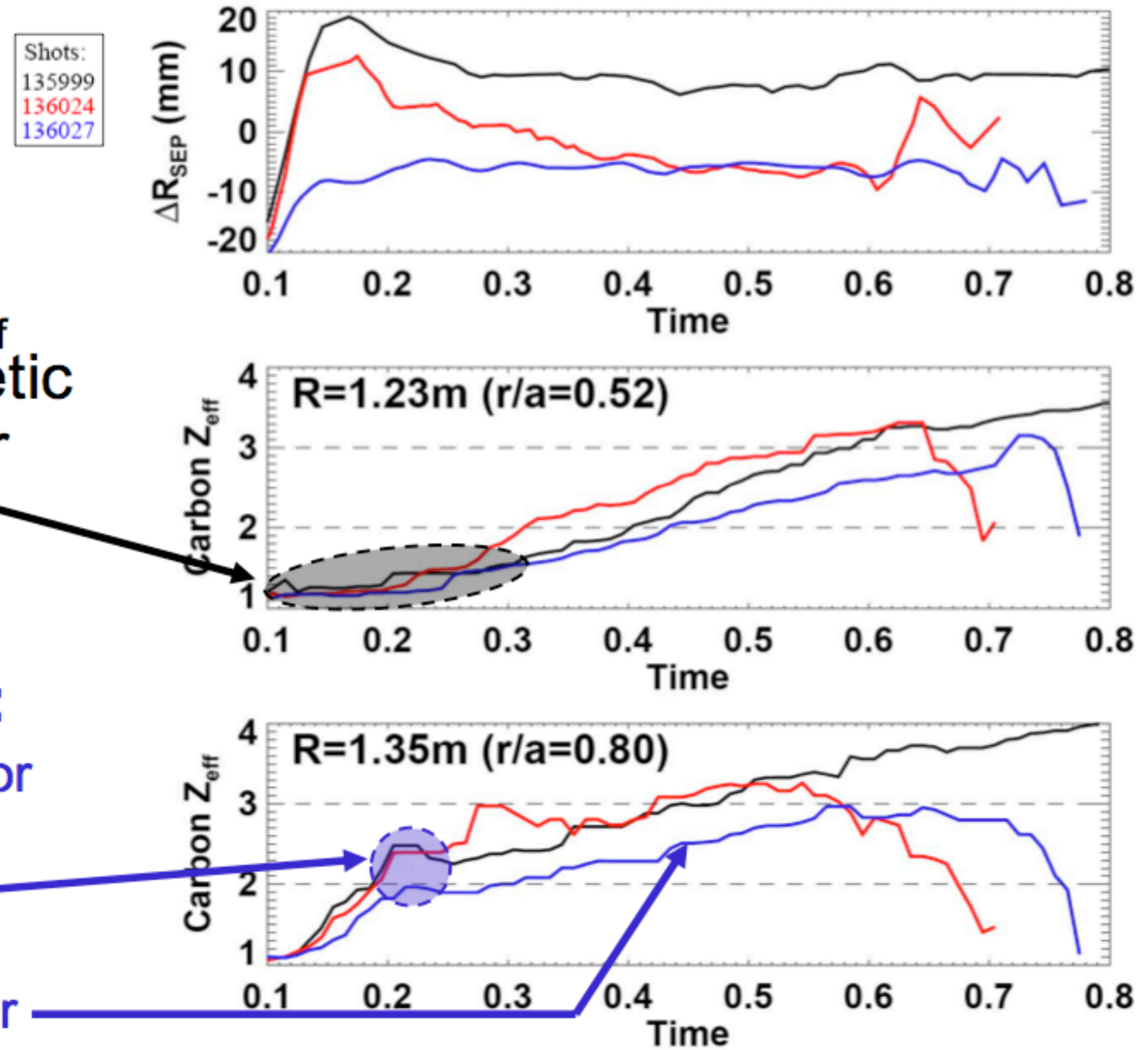
"Near Snowflake"

- Bootstrap +P.-S. + Dia. currents are largest in case with lowest carbon.
  - This despite the somewhat lower q_{95}.
- Normalized confinement is highest in the Snowflake configuration.
- Nothing conclusive, but offers some hope.



Carbon Z_{eff} evolution sensitive to magnetic balance during ramp-up (immediately following early H-mode)

∇B drift down + USN ***∇B drift down, USN → LSN*** ***∇B drift down + LSN***

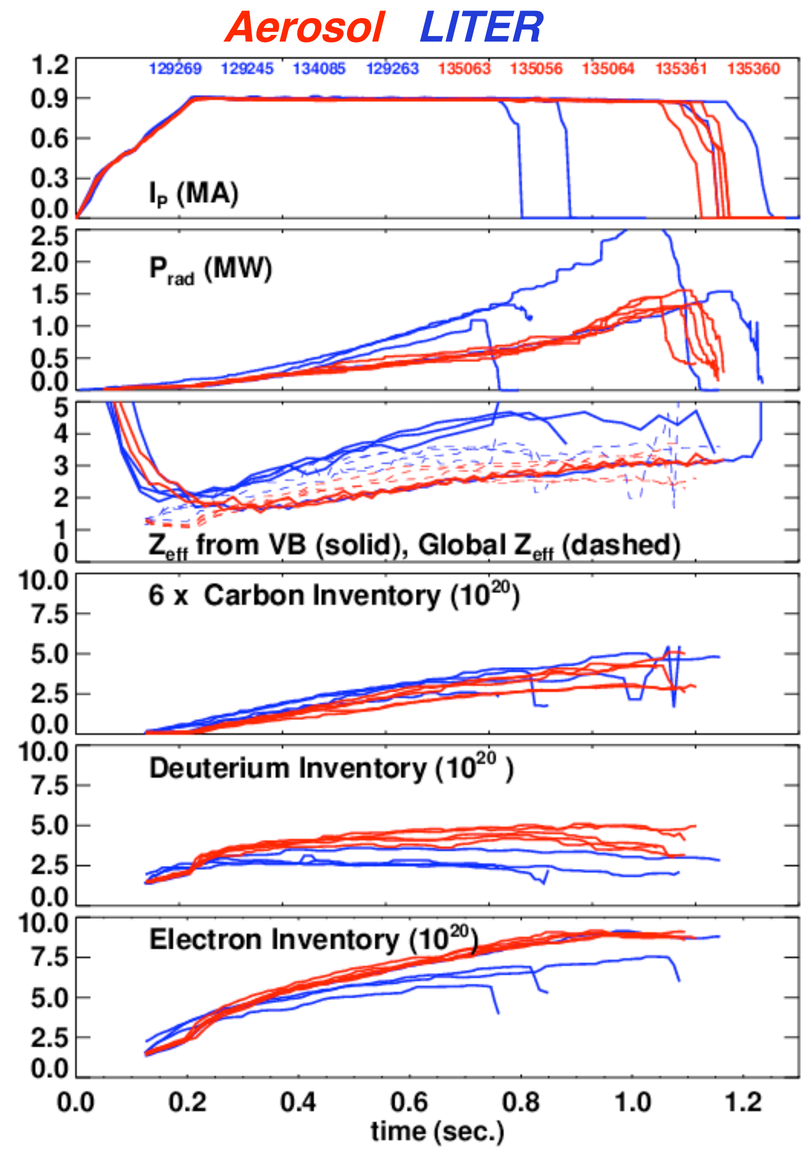


- Core/mid-radius C Z_{eff} similar for all 3 magnetic bias configurations for first ~300ms of shot

- **∇B drift down + LSN:**
  - Reduces C influx and/or confinement **at top of pedestal** immediately after early H-mode
  - Lowers C Z_{eff} thereafter

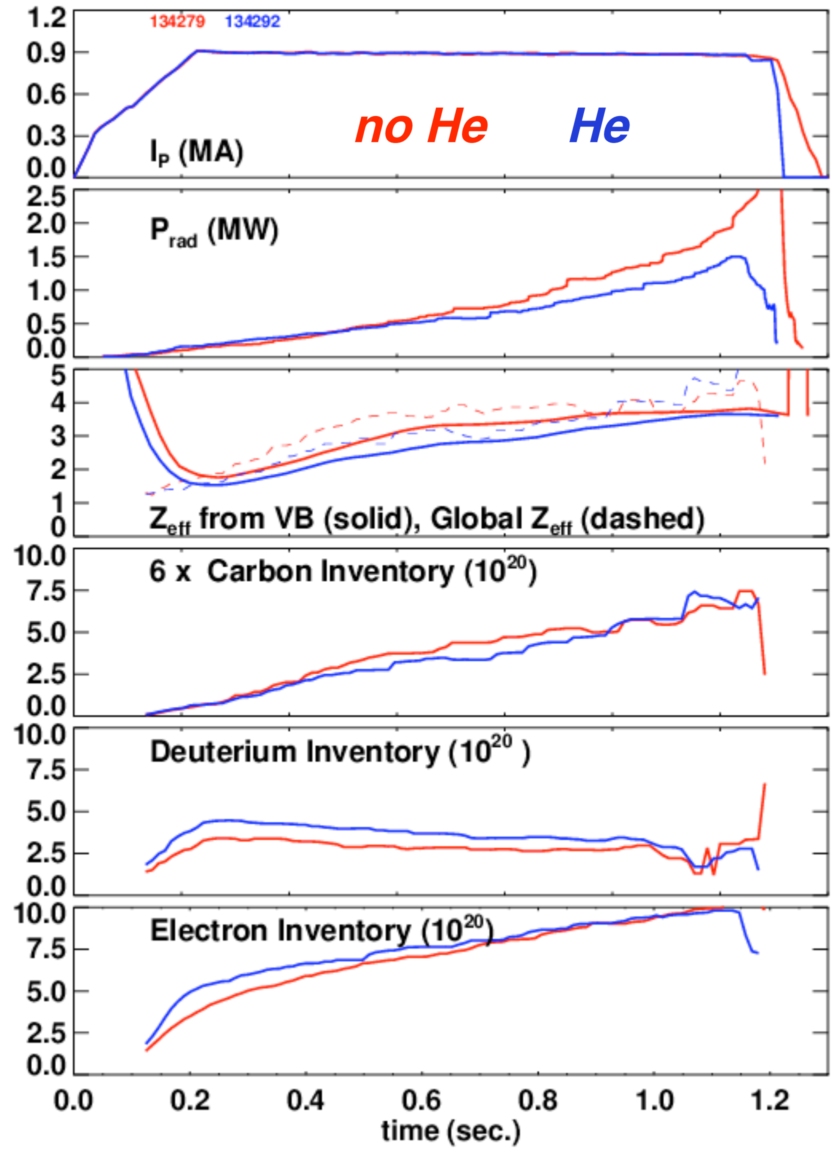
Lithium Dropper May be Useful Tool for this XP

- Shot numbers from D. Mansfield's research forum presentation.
- Compared to LITER, Aerosol has:
  - Reduced radiated power.
  - Reduced carbon inventory.
    - But rate of rise is comparable.
- Fuelling reduced with dropper:
  - LITER cases: 1200-1600 torr in CS
  - Aerosol cases: 800-900 torr in CS
- Dropper shots also:
  - Tended to have some early 'ELMs'.
  - Core MHD was more common in Dropper shots.
    - Not good!



Lithium Evaporation into Diffuse Helium…

- Shot numbers from C. Skinner 2009 results review presentation.
  - 180 mg of LITER between shots in both cases.
- Erosion of lithium at the S.P. may account to minimal difference in carbon accumulation.
- Highly perturbative to operations.
  - Only use in this XP if it shows great promise.



Operations Notes

- Machine must be well conditioned.
- LITER? Yes, I would guess at ~300 mg/shot.
- LLD? Maybe just leave it cold…or maybe not.
  - XP will be run at high-triangularity, where LLD pumping may not be large.
- RWM feedback / DEFC is necessary.
- Fuelling? SGI if we have good recipes for it, otherwise stick to HFS.
- Good to test the other impurity reduction techniques before this XP.
- Diagnostics:
  - Full profile diagnostics.
    - Lithium CHERS would be nice, but not strictly required.
  - X-ray spectrometers are important to monitor metal accumulation.
  - Boundary diagnostics would be helpful as well.

Shot List
Will Change Pending Development of Techniques

- Create reference. Did early front-end modifications reduce or purge impurities?
  - No: Reload shot 133964. (5 shots)
  - Yes: Stretch discharge with modified front end to higher kappa. (7 shots)
- Beam Scan
  - Turn off source C, increase voltage on B (3 shots)
- Add magnetic ELM pacing
  - Start with 20 Hz, 3 msec long, 2 kA amplitude (?)
  - Adjust as necessary, monitoring mhd and confinement (6 shots)
- Add divertor gas puff
  - Parameters as determined by Vlad's LRTSG XP.
  - Try first without pacing, then add best pacing method. (8 shots)
- Add dropper
  - Try first without divertor puff or pacing. (3 shots)
  - Should LITER rate change?…will impact fuelling.
  - Add best of pacing and/or divertor puff. (4 shots)
- Slight kappa scan
  - Modify kappa as +0.15,-0.15,-0.3, study effect on f_{NI} (4 shots)

Total: 35 shots