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Particle and Impurity Control Research and Plans

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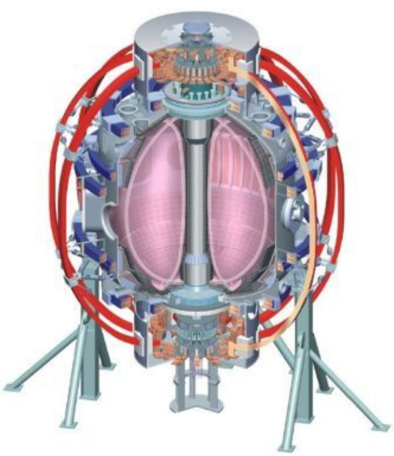
Rajesh Maingi, Oak Ridge National Laboratory

J.E. Menard, A.H. Boozer, and the NSTX Team

NSTX Program Advisory Committee Meeting
Princeton, NJ
Jan. 26-28, 2011



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This talk responds to PAC-27 concerns on impurity control

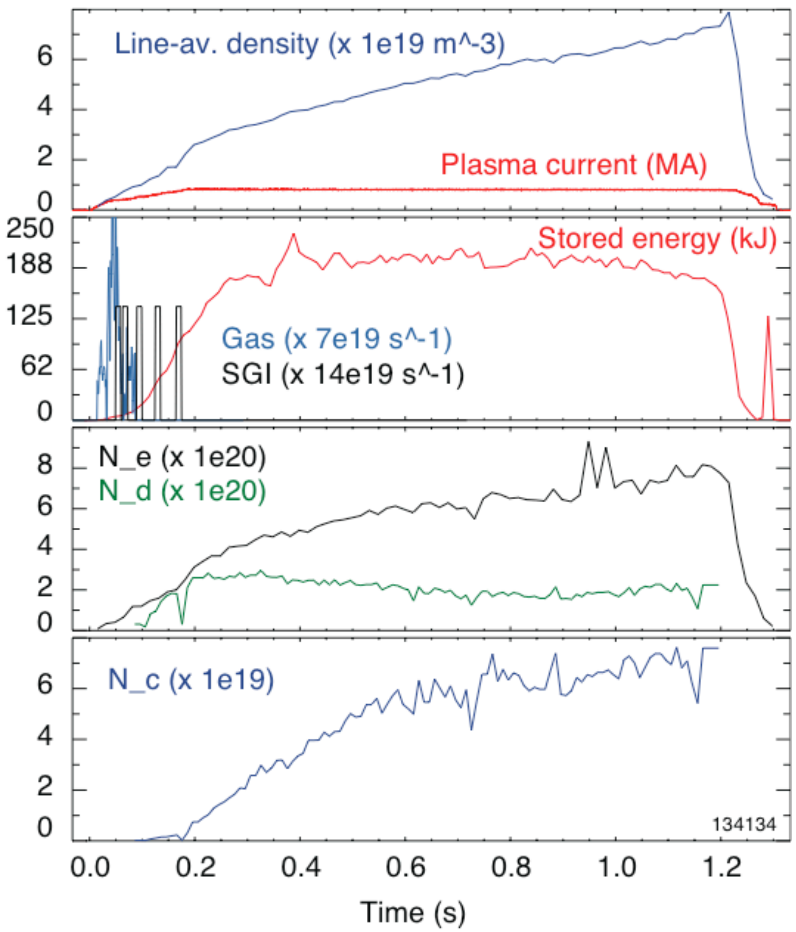
- Since the LLD/Li systems are your primary option for density and impurity control, more effort and planning is needed to develop an alternative if the LLD fails to perform as expected. As part of this effort, to control impurities the PAC supports the plans to install sample molybdenum divertor tiles to gain experience with Li-coated Mo tiles and its effect on carbon impurities in NSTX. **PAC 27-4**
- The PAC urges the NSTX Team to demonstrate density and impurity control, within the next two years, in discharges characteristic of your post-upgrade operation. We suggest you consider combining the forces of several physics tasks groups to address these critical divertor and boundary issues. **PAC 27-5**

Outline

- *Impurity control results and plans (several TSGs)*
- *Impact of 3D fields on edge transport and stability*
- *Preliminary cryopump calculations for NSTX-U*

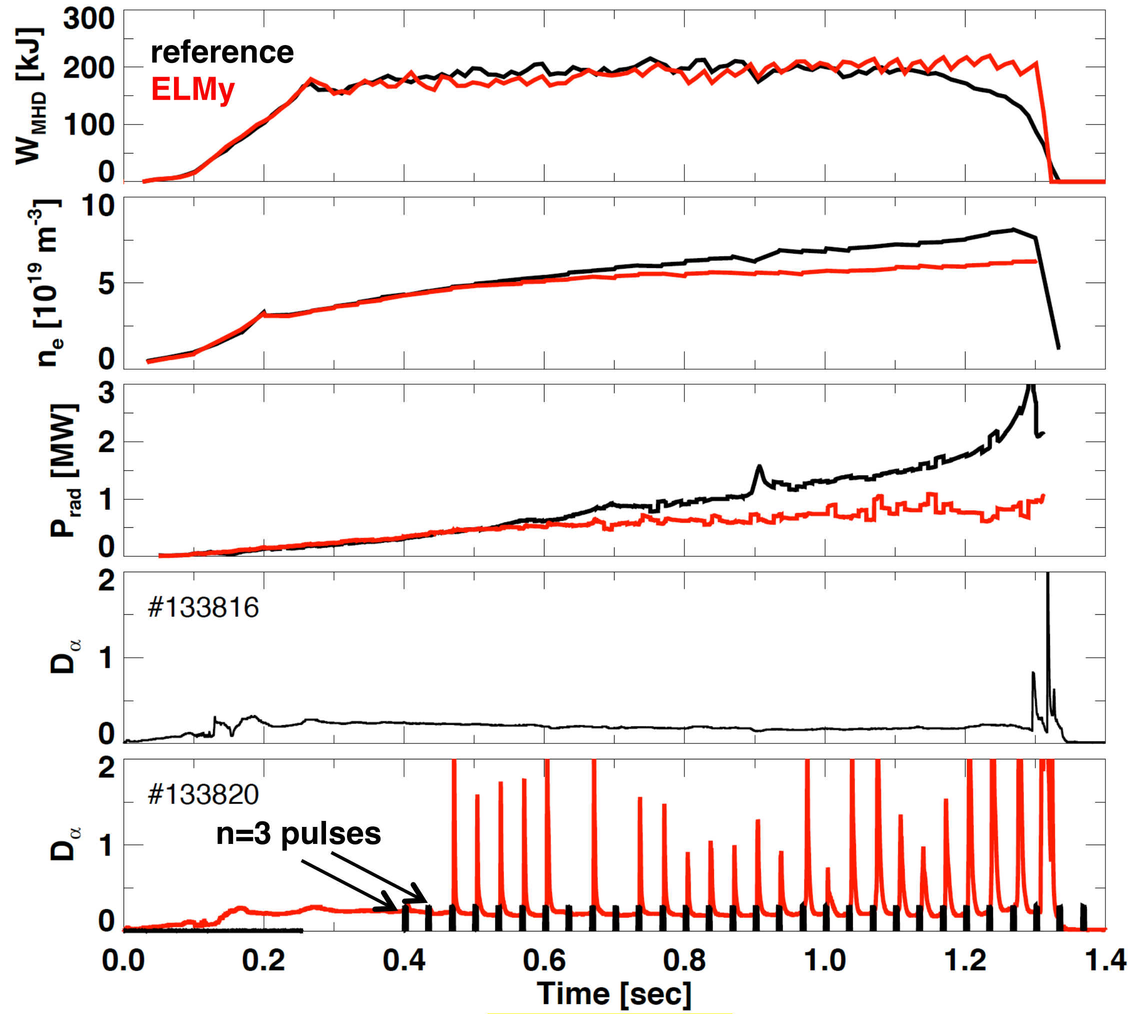
Control of core deuteron typically achievable with Li coatings, but core impurity control more difficult

- *Example with SGI fueling*



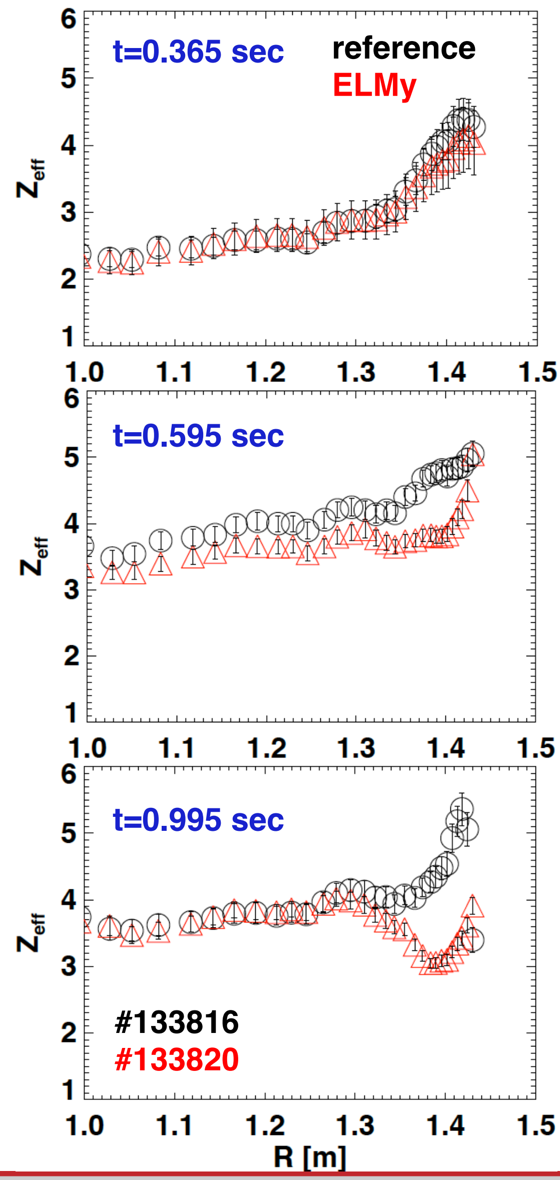
Soukhanovskii, IAEA 2010

- *ELM triggering with n=3 pulses*

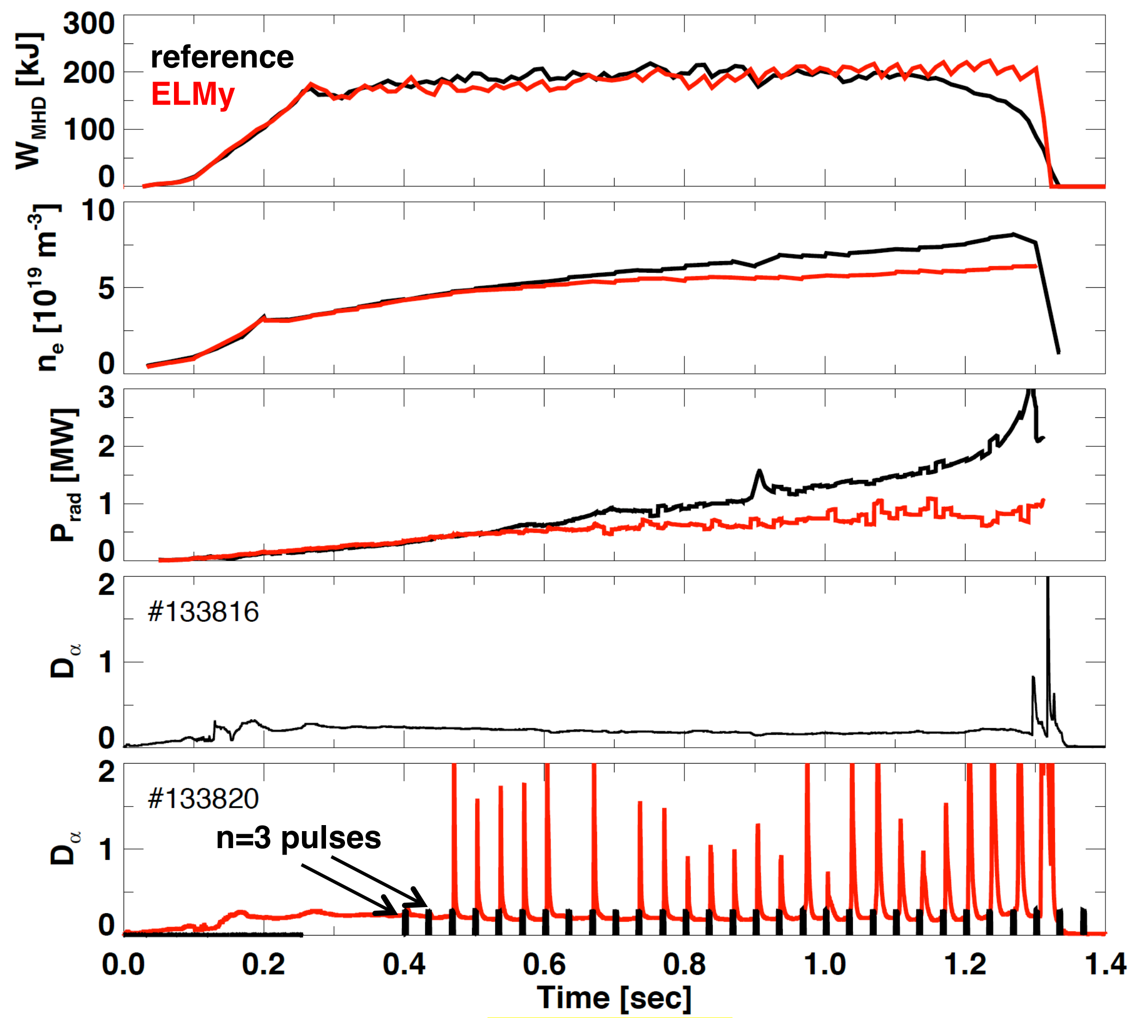


Canik, PRL 2010

ELMs triggered with 3-D fields successful at reducing P_{rad} and edge Z_{eff}, but not core Z_{eff}



- *ELM triggering with n=3 pulses*



Canik, PRL 2010

Impurity control techniques demonstrated transient reductions in core carbon and Z_{eff}

- *No measured reduction of divertor C source with Li -> C*
  - *Possible reduction with hot LLD*
  - Assessment of impurity sources a Ph. D. thesis

Experiments from several TSGs:

✓ Divertor D_2 puffing

✓ Snowflake configuration

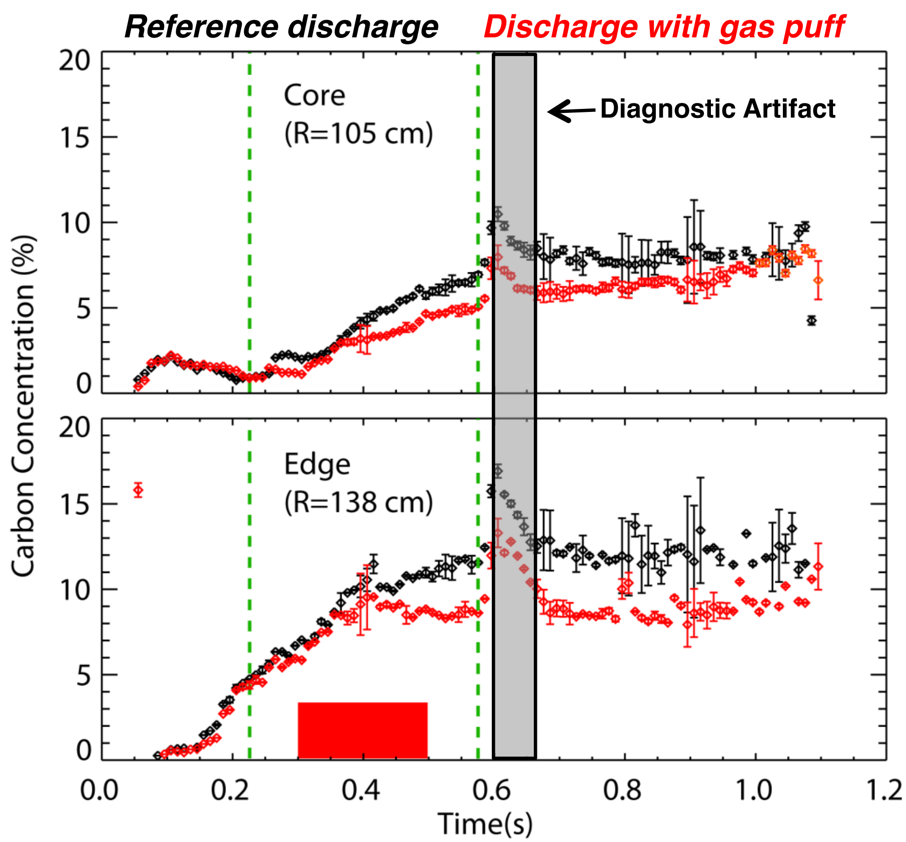
✓ Magnetic balance control – operating at DN

- Combined ELM pace-making techniques: vertical jogs with 3D fields started in FY 2010 – some promise

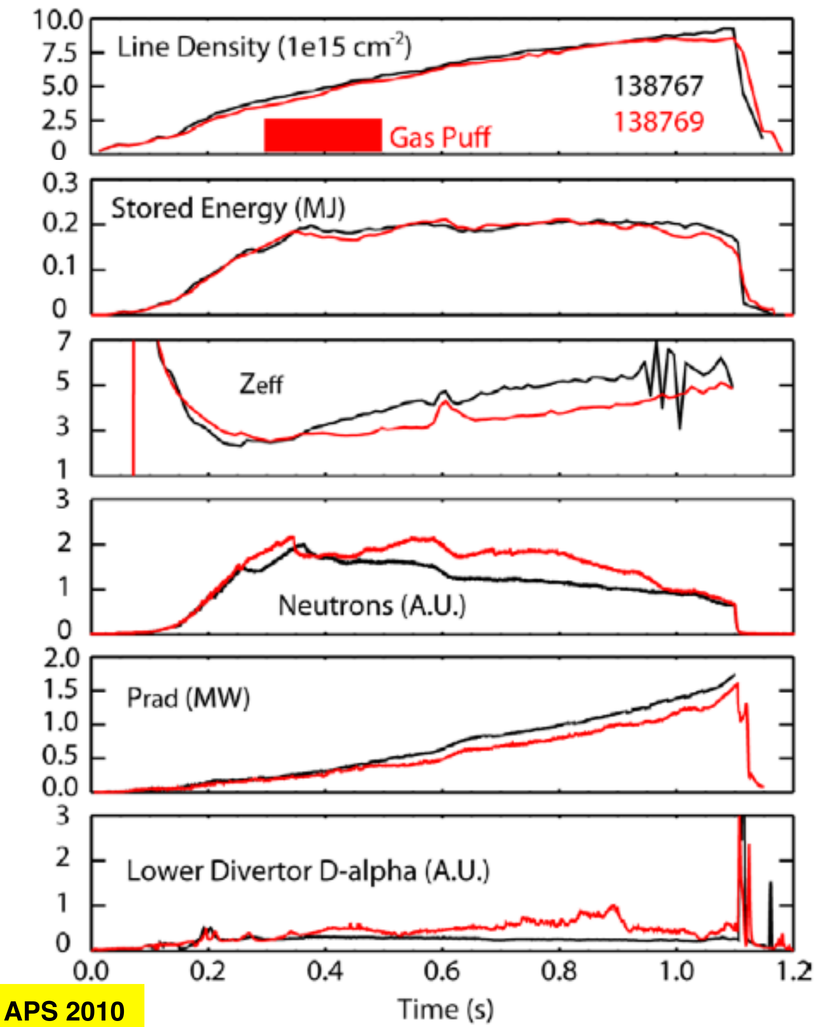
– *Small transients triggered by n=3 pulses below ELM trigger threshold unsuccessful at mitigating impurities*

Divertor D_2 puffing reduces core carbon density and Z_{eff} ramp rate

- Drop attributed to reduced sputtering
- Central f_C and Z_{eff} still rising
  - *Need to develop ways to reduce central impurities*

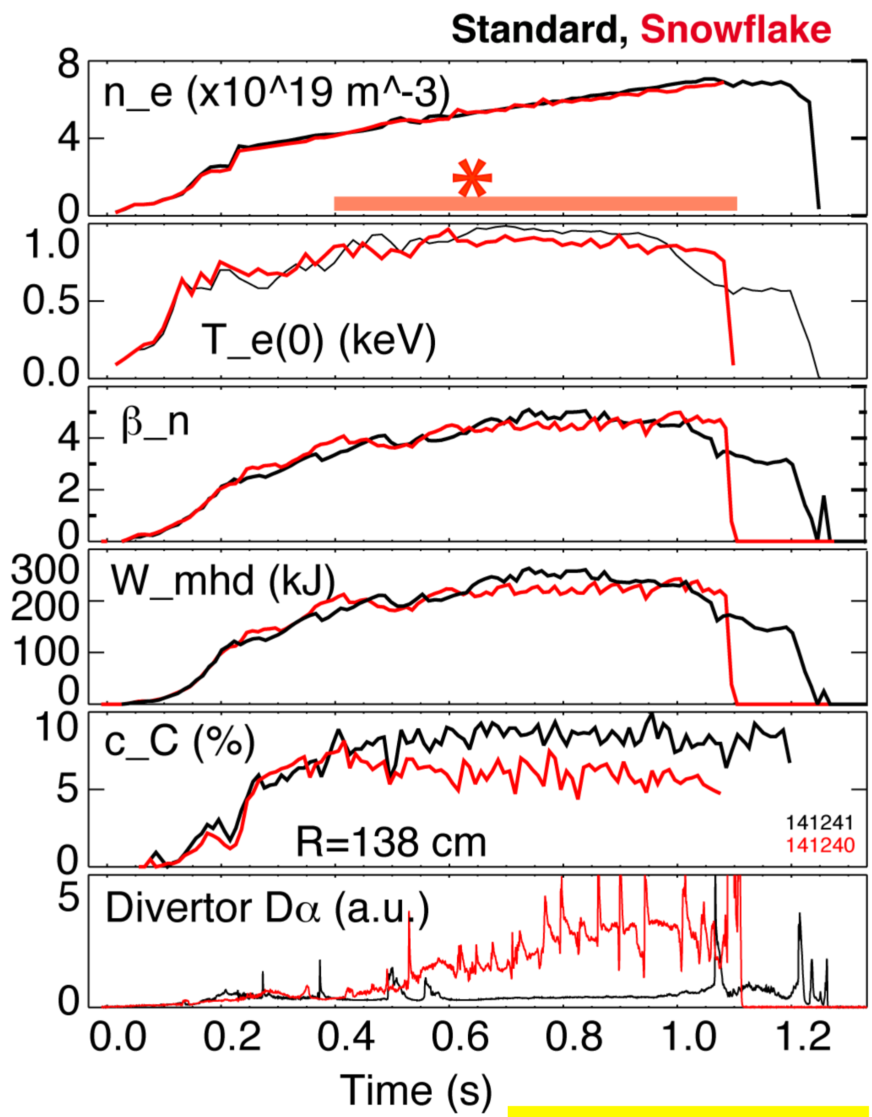


Deuterium Gas Puff From CHI Gap



Scotti, APS 2010

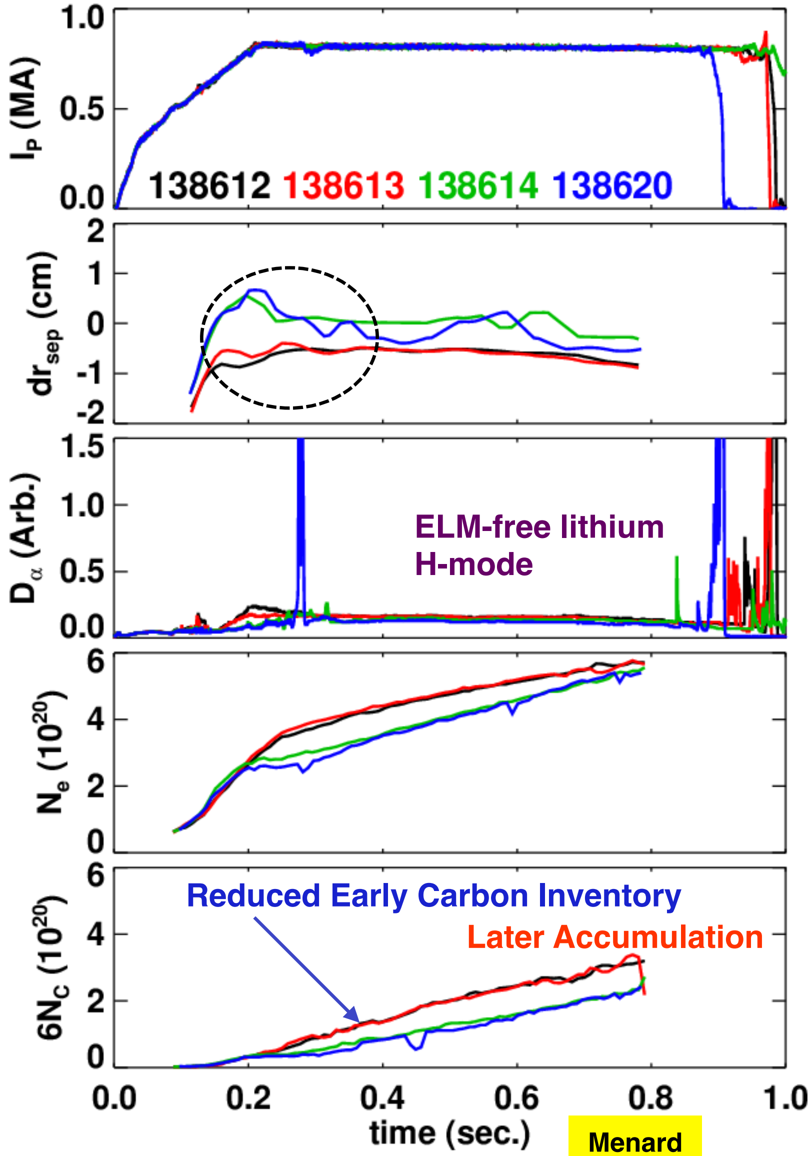
Snowflake configuration also reduces edge carbon



Soukhanovskii, APS 2010

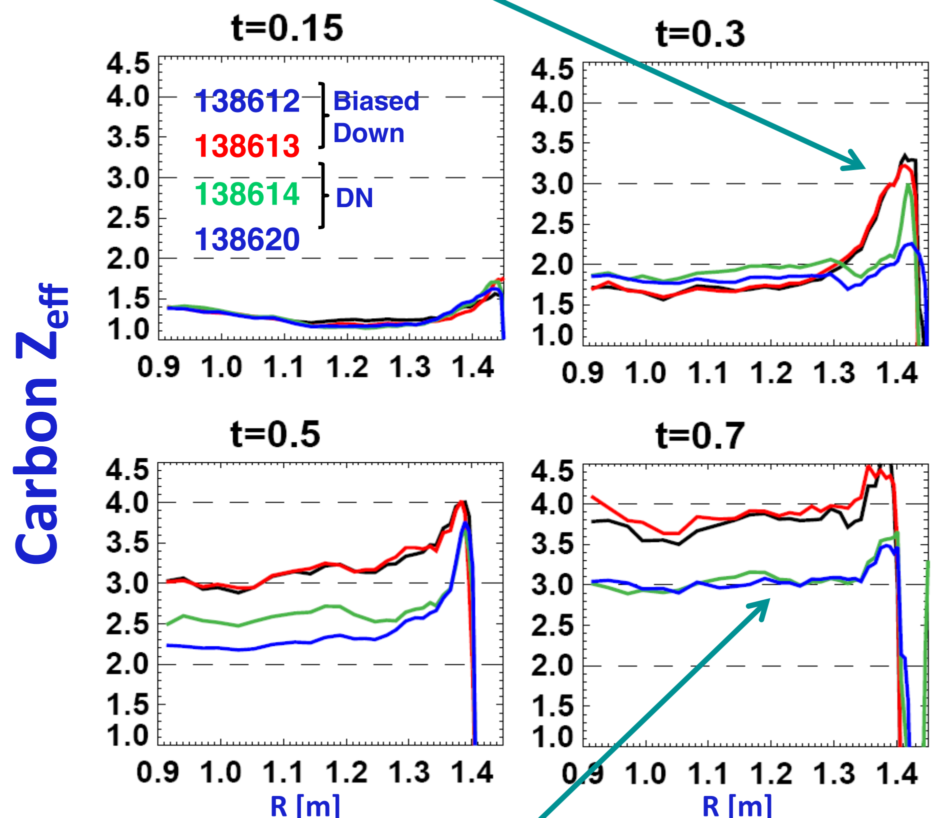
- Snowflake shape facilitates partial detachment
  - Reduces carbon sputtering
- Configuration also brought back ELMs
  - Difficult to separate effect of ELMs vs effect of shape change
- Central carbon still increases, but more slowly
  - *Points again for need for central impurity density control*
- Combined divertor puff and snowflake discharges initiated

Biasing upward (unfavorable ∇B) reduces early carbon, but impurities still increase in time



Menard

Size of H-mode C impurity "ear" near t=0.3s influences late Z_{eff}



Carbon Z_{eff} reduced by ~1 unit late in shot

- *Motivates USN H-mode and I-mode search experiments*

Impurity control research plan will focus on combining techniques

- Envisioned techniques *and hardware changes*
  - Magnetic balance control for early carbon reduction
    - Will look for I-mode as part of ITPA JEX and FY11 JRT
  - Divertor gas puff and/or snowflake for source reduction
  - ELM triggering (3-D fields, vertical jogs) for impurity flushing
  - o Core radiation control with central HHFW
  - o Reduced lithium evaporation rates to keep Type V ELMs
  - *Improved tile to tile alignment*
  - *Mo covers on RWM B_z zensors; removed some CHI gap B_z sensors*
  - *Mo tile upgrade, schedule permitting*
- Priority for NSTX-U:
  - Lower $\langle Z_{eff} \rangle$ with target ≤ 2.5
  - Control P_{rad}^{core}
  - Utilize only small transients
  - * *All must be compatible with heat flux management*

Preliminary erosion modeling for inboard Mo tiles shows low sputtering and plasma contamination

- *Goal: Determine if Mo sputtering and plasma contamination is acceptable*
- *So far [D + 1% C,1% Li] sputtering of bare Mo surface*
- First results encouraging:
  Mo sputtering low (<0.01), little core plasma contamination; two caveats:
  - 1: Mo self-sputtering ok but little margin for one sheath condition
  - 2: if substantial carbon impinges on Mo divertor, from e.g., inner wall C sputtering; re-sputtering of this carbon would tend to reach core plasma (~10% of sputtered flux), thus negating some of the benefit of the Mo
- More thorough analysis in progress
  - WBC analysis of inner Mo divertor, with C, Li on Mo w/ material mixing/ evolution models…
  - High D pumping / low recycling solution
- Possible issue: melting as observed in C-Mod (*no such melting observed on LLD, even with direct strike point plasma flux*)
- Possible issue: rf acceleration and sputtering (*no such effect observed on LLD with HHFW last year, but had limited rf power*)

Brooks

PAC27-17

Outline

- Impurity control results and plans
- Impact of 3D fields on edge transport and stability
- Preliminary cryopump calculations for NSTX-U

Applied non-axisymmetric fields have different responses in different devices

- Density reduced and ELMs suppressed in DIII-D
  - Density reduction related to enhanced particle transport
- ELMs mitigated but not suppressed in JET (and ASDEX-U?)
- ELMs modified in NSTX and MAST with matched Chirikov criterion
  - Density pumpout in certain MAST configurations, when plasma 3-D displacement is large near X-point
  - ELM routinely triggered in ELM-free H-modes in NSTX, with threshold field dependent on q_{95}
  - Plasma response changes result of Chirikov calculations

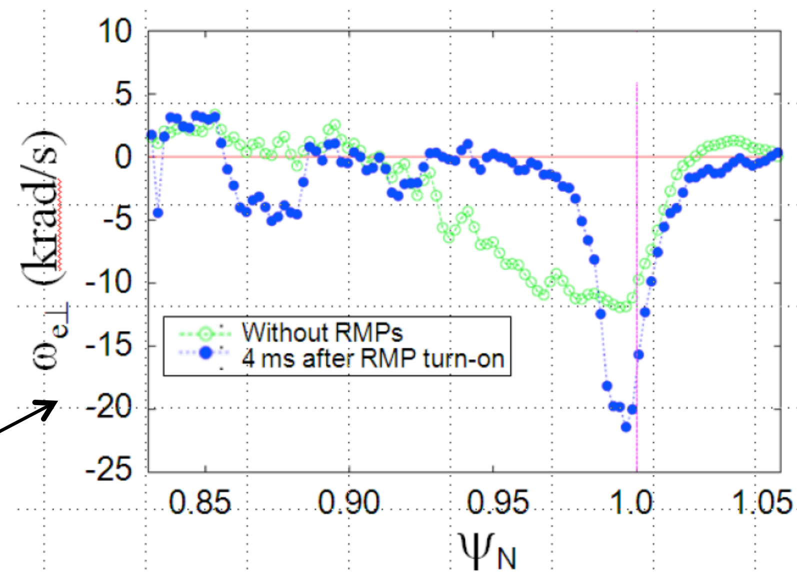
- *Uncertainty for ITER, which is considering this as a very important ELM control tool*

➢ More emphasis on this area in NSTX: R11-4 milestone

Models for increased transport with 3D fields being assessed

- NSTX/DIII-D brainstorming video conf. on 11/19/10

- Examining several theoretical ideas of increased transport
  - Increased E X B convection
  - Role of diffusion, convection when edge particle dominated by NBI fueling (i.e. low recycling)
  - Increased banana diffusion or ripple loss
  - Rotation screening reduction and enhanced transport when ω_e^{perp} -> 0 ($\omega_e^{perp}=\omega_e^{*}+\omega_{ExB}$)
    - Preliminary testing done on DIII-D

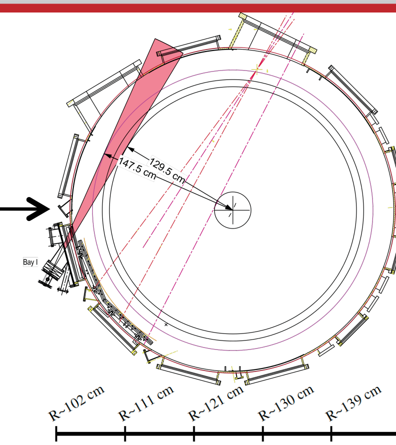


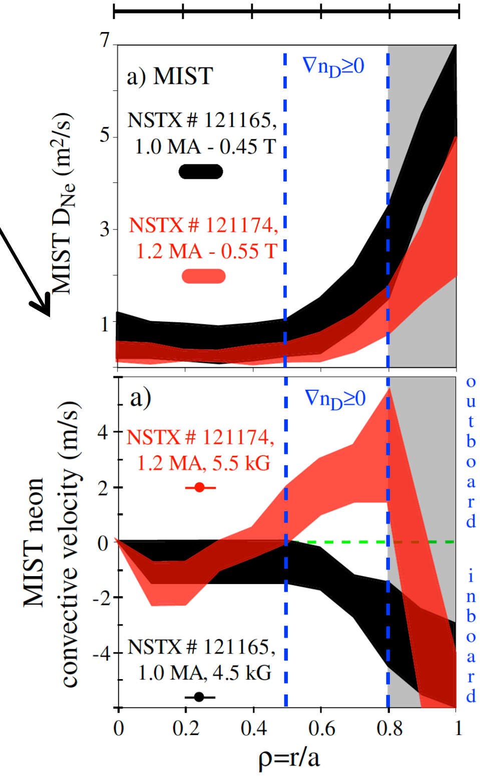
Chang, DIII-D 3D physics seminar, 1/5/11

Particle Transport can be measured via X-ray Emission from Plasma Impurities with new high-resolution SXR array

- 5 photodiode arrays with different filters
- 20 spatial channels with ~1 cm resolution of plasma edge, time resolution >10 kHz
  - Older array can not assess edge transport
  - Preliminary data obtained in 2010
  - Synergy with pulsed Thomson (8 add'l edge channels) plus supersonic gas injector

- Transport studies
  - Carbon build up in ELM-free discharges: separation of diffusion and convection
  - Transport variation in pedestal region: how does the particle transport change with lithium and/or with applied 3D fields?

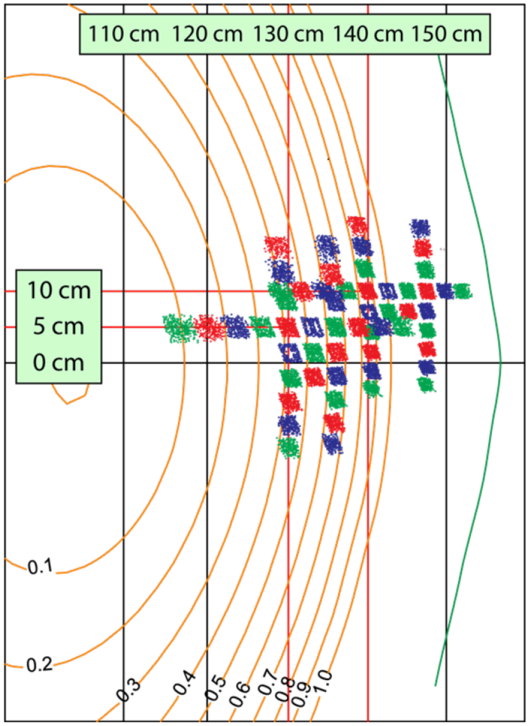




Clayton

Models for increased transport with 3D fields and measurement capabilities being assessed

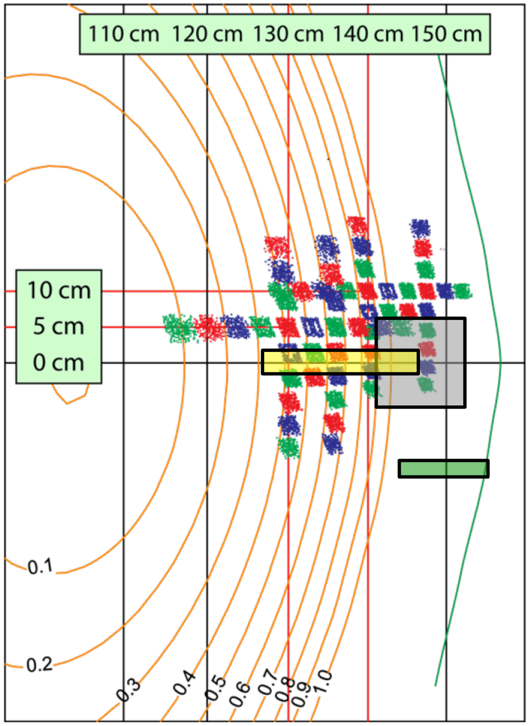
- Turbulence change with applied 3D fields
  - Radial/poloidal coverage with BES; compare and contrast with results on DIII-D
  - Midplane separatrix and SOL with GPI; no obvious differences so far)
  - Midplane edge with new high resolution SXR
  - Tunable radius with high-k scattering
  - Midplane separatrix and SOL with reciprocating probe
  - Divertor with high density divertor Langmuir probe (requires particular geometry)



- Look for pumpout in L-mode plasmas
- Increase divertor turbulence with divertor biasing
- Probe edge stability with new SPA (more spectral control)
- Use Snowflake and 3D fields to probe edge stability

Models for increased transport with 3D fields and measurement capabilities being assessed

- Turbulence change with applied 3D fields
  - Radial/poloidal coverage with BES; compare and contrast with results on DIII-D
  - Midplane separatrix and SOL with GPI; no obvious differences so far)
  - Midplane edge with new high resolution SXR
  - *Tunable radius* with high-k scattering
  - Midplane separatrix and SOL with reciprocating probe
  - *Lower divertor* with dense Langmuir probe array (requires particular geometry)



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- Increase divertor turbulence with divertor biasing
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Outline

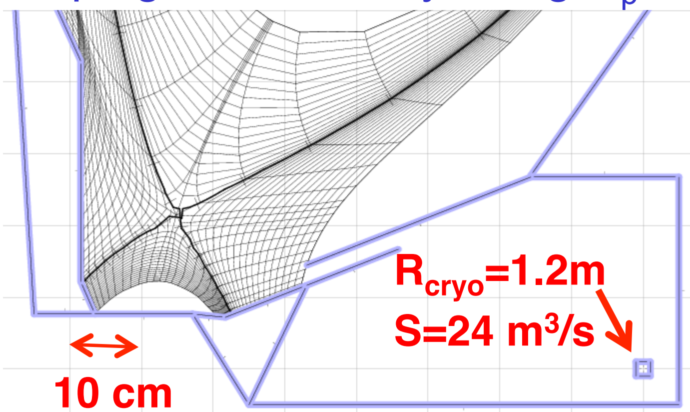
- Impurity control results and plans
- Impact of 3D fields on edge transport and stability
- Preliminary cryopump calculations for NSTX-U

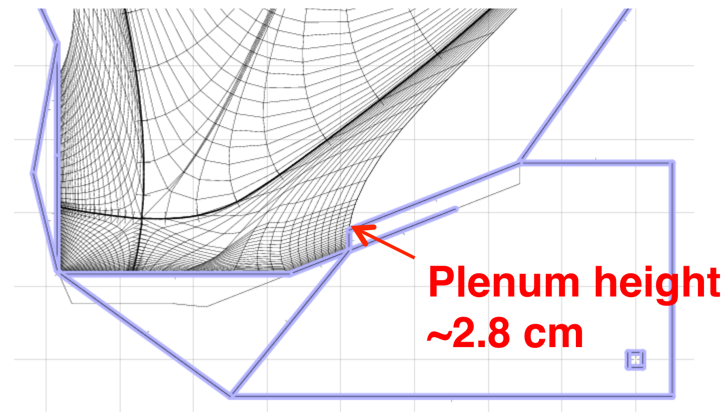
Preliminary assessment of cryopump for NSTX-U has started

- Two calculations: SOLPS (2-D fluid plasma, Monte Carlo neutrals), and analytic model
- Four different geometries examined with SOLPS; entire pump plenum modeled
  - Standard divertor with three different plenum geometries, and one snowflake equilibrium
- Analytic first flight model with standard divertor
  - Plenum pressure computed from plenum geometry, equilibrium and divertor n_e, T_e, and Γ profiles
- Peliminary conclusion: plenum pressure needed to exhaust NBI fueling should be achievable over range of SOL/pedestal n_e

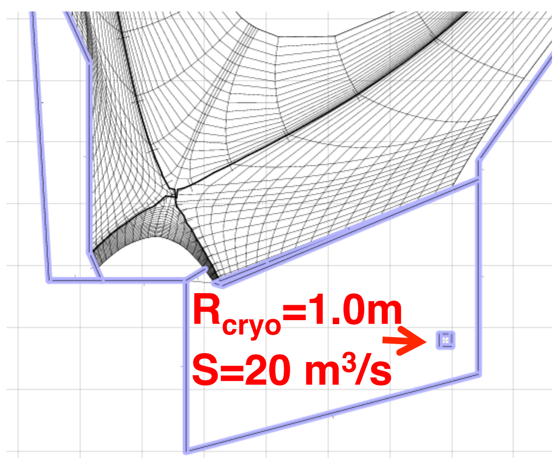
Four geometries scoped with SOLPS for NSTX-U shapes, but with fictitious pump plenums

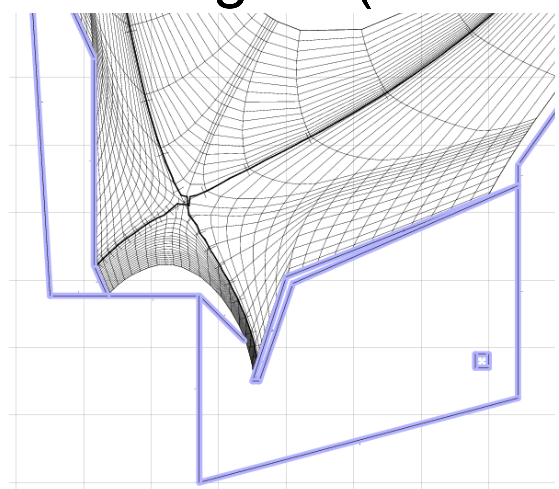
- Pumping in SOL: standard and snowflake geometries
  - n_e scan simulated by varying target recycling coefficient R_p
  - Pumping simulated by using R_p=1.0 and pump sticking fraction=1





- Pumping in PFR: horizontal and vertical targets (near OSP)



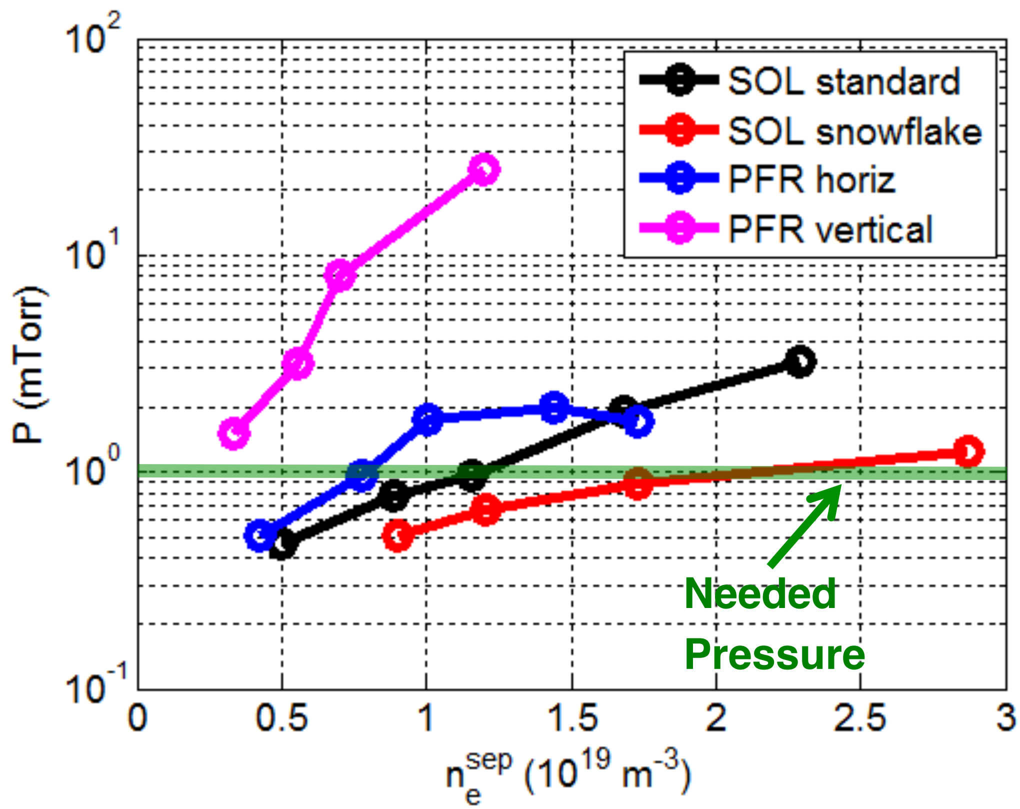


Canik

Neutral pressure needed to exhaust NBI fueling sets the minimum achievable separatrix n_e

- Γ_{NBI}=7.5x10^{20} D+ /s (6 MW)
  - S_{NBI}~12 torr-L/s
- D=0.5, χ=1.0 m^2/s in all cases
- Divertor recycling coefficient varied to yield a density scan
- D_2 pressure at cryo pump monitored
- To pump NBI flux at 6 MW, ~ 1 mTorr is needed in plot
  - S_{pump}=24,000 L/s

SOLPS (no pumping)



Canik

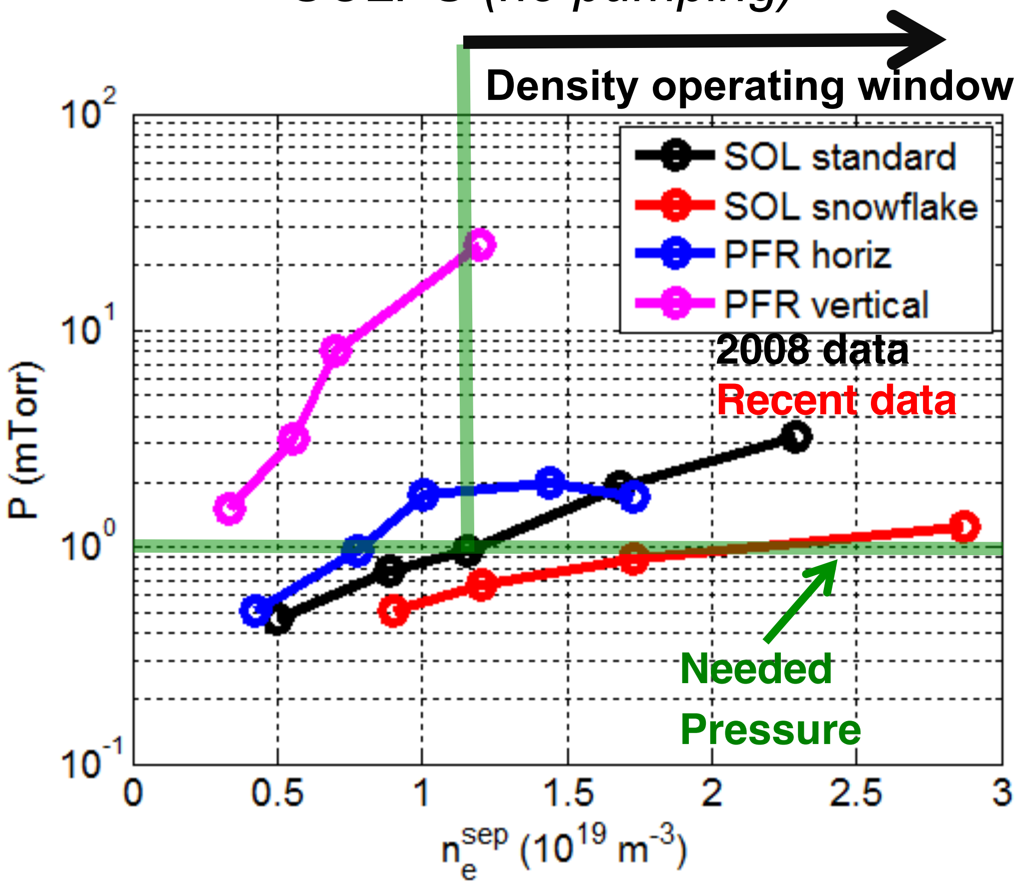
Neutral pressure needed to exhaust NBI fueling sets the minimum achievable separatrix n_e

- *Pressures shown are with no pumping*
  - *With pumping, pressure will be reduced by C/(C+S) ~ 50%*
- n_e operating window obtained by additional gas puffing
- Relation to scenarios

Scenario	n_{max} $/n_{GW}$	n_{max}^{ped}	n_{max}^{sep}
Long pulse	$\leq$1	9e19	4.5e19
High NI	$\leq$1	7e19	3.5e19
Max I_p	$\leq$0.7 - 1	1.3e20	6.5e19

- P_{NBI}=10 MW case in progress

SOLPS (no pumping)



Canik

Detailed cryopump design calculations with 2D plasma/neutrals codes planned for NSTX-U

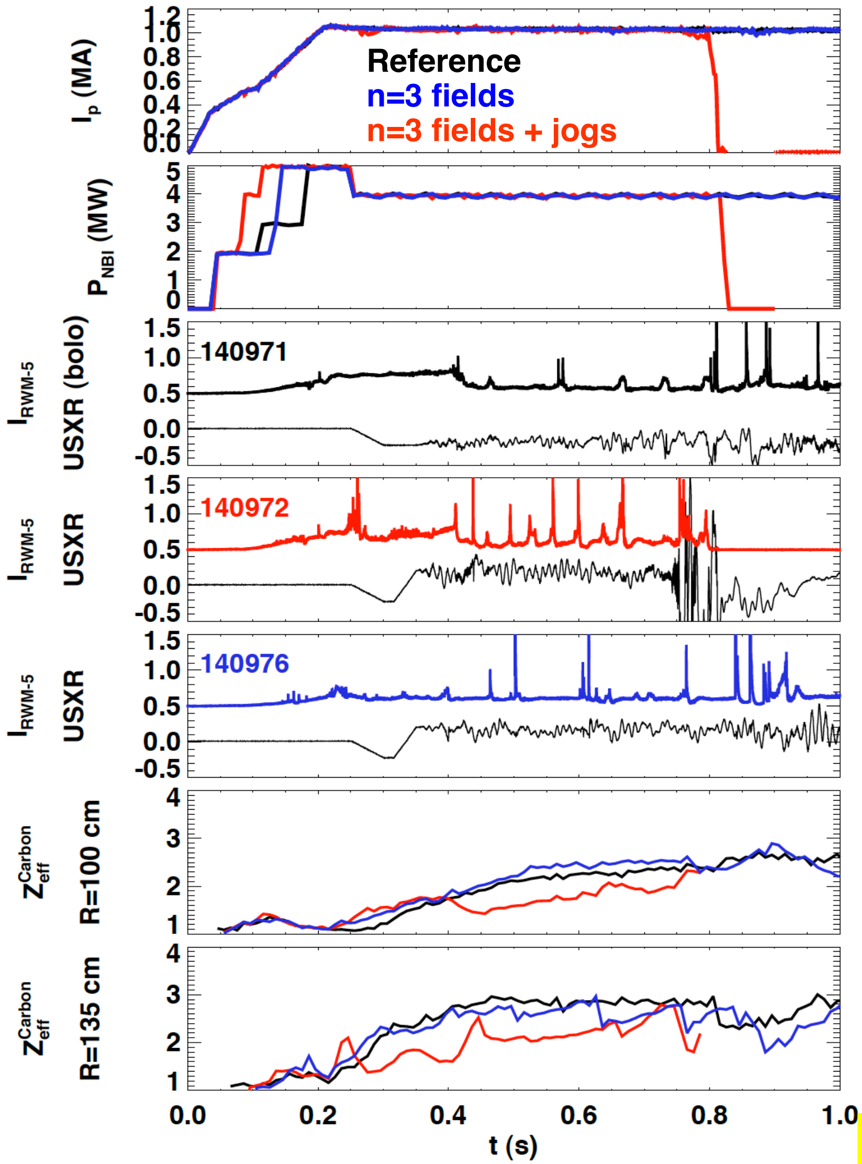
- Higher heating: P_{NBI}=10 MW
- D, χ consistent with I_p = 2 MA, B_t = 1 T operation
  - Present values from 1.2 MA, 0.55 T, 6 MW case
- Up/down symmetric double-null calculation
  - Only lower divertor considered presently
- Compatibility with power exhaust and snowflake divertor operation
- Actual NSTX-U PFC geometry and space constraints
- Iterate for compatibility with core scenario calculations

Summary

- Increasing emphasis on core impurity control techniques, including combinations
- Increasing emphasis of the effect of 3D fields on edge transport and stability, for NSTX-U and ITER
- Cryopump design calculations commencing
  - Initial studies show promise in pumping of NBI fueling
  - Next step will consider machine space constraints

BACKUP

Combination of n=3 triggered ELMs and vertical jogs show promise for carbon impurity control



Canik

- ELM frequency higher with combined ELM pace-making techniques *(n=3 DC)*
  - Reference has a few ELMs
  - Z_{eff} from carbon appears to be flattening during ELMy phases
  - May need to combine with other techniques, e.g. divertor gas puff, snowflake, δ_r^{sep} control
- Limited run time in 2010, more in 2011-2012
  - Do jogs reduce minimum n=3 field to trigger ELMs?
  - Jogs + pulsed n=3 fields

Preliminary erosion modeling of Mo tiles shows low sputtering and plasma contamination

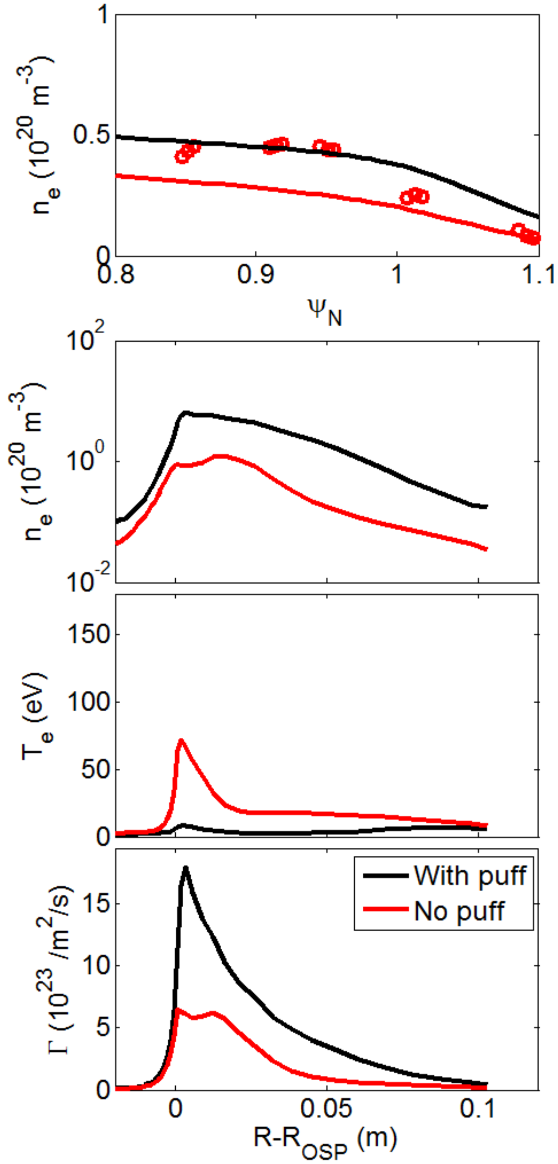
- WBC modeling of SOLPS background plasma
- Debye (normal sheath) model near self-sputtering limit, grazing sheath model acceptable

Parameter	Reference sheath model (Debye-only)	Alternative sheath model (Magnetic+Debye)
Mean free path[a], mm	0.24	0.58
Charge state[c]	3.1	1.8
Energy[c], eV (standard deviation. eV)	491 (303)	213 (212)
D^+ sputtering fraction	0.47	0.77
Self-sputtering fraction	0.53	0.23
Sputtered Mo current/incident D^+ current	9.6×10^{-4}	3.6×10^{-4}
Sputtered Mo to core plasma	-0-	-0-
Peak gross erosion rate, nm/s	5.2	2.8
Peak net erosion rate, nm/s	0.46	0.23

Brooks

SOLPS simulations with cryo-pumping: SOL standard

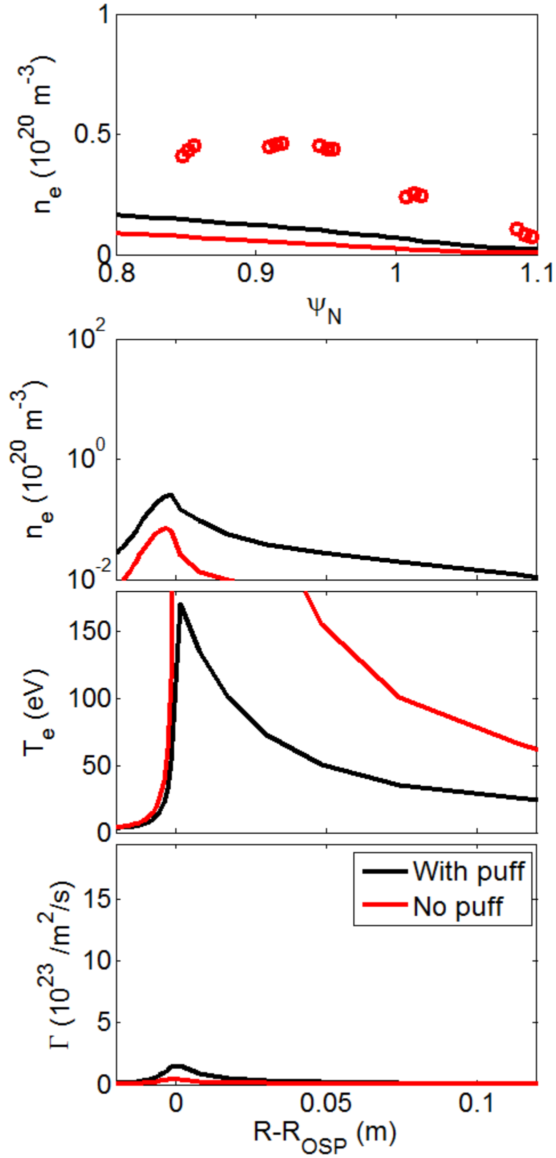
- Particle balance
  - Input with puff: 1.85e21 D+/s ~29 torr l-s (of D_2)
    - Pressure in plenum: 1.1 mTorr
    - Pumped flux: 26.4 torr l-s
  - Input w/o puff: 7.5e20 D+/s ~ 11.7 torr l-s
    - Pressure in plenum: 0.53 mTorr
    - Pumped flux: 12.7 torr l-s
- Separatrix densities
  - 2.0×10^{19} m^{-3} without puff
  - 3.7×10^{19} m^{-3} with puff
  - Beam input (for 6 MW) can be pumped at a reasonable nesep, but no much leeway for having a strong density pedestal and keeping low Greenwald fraction



Canik

SOLPS simulations with cryo-pumping: PFR vertical

- Particle balance
  - Input with puff: 1.85e21 D+/s ~29 torr l-s (of D_2)
    - Pressure in plenum: 1.5 mTorr
    - Pumped flux: 29.7 torr l-s
  - Input w/o puff: 7.5e20 D+/s ~ 11.7 torr l-s
    - Pressure in plenum: 0.61 mTorr
    - Pumped flux: 12.1 torr l-s
- Separatrix densities
  - 0.23×10^{19} m^{-3} without puff
  - 0.67×10^{19} m^{-3} with puff
  - Much more room for having good pumping at low densities



Canik