NSTX

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Connecting the X-transport model with LH power threshold studies on NSTX

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

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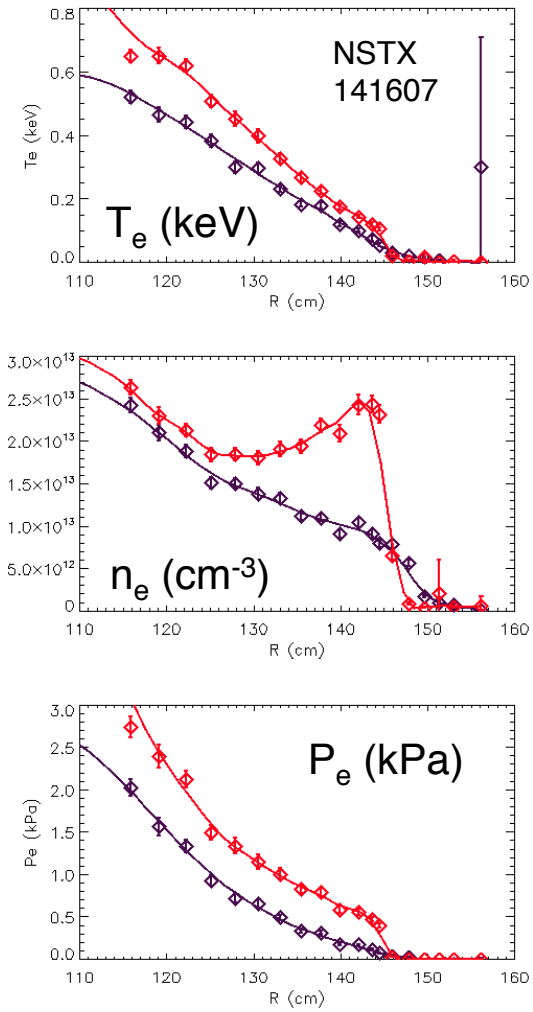
Outline

- LH transition physics
  - Critical E_r or E_r shear may trigger LH transition
- X-transport model
  - E_r must be large enough to prevent non-ambipolar loss of ions following neoclassical orbits
- Dependence of P_{LH} on R_X
  - Recent experiments on NSTX demonstrate dependence of P_{LH} on X-point radius, consistent with X-transport model
- Other connections between X-transport and experiment
- Conclusions

The transition from L- to H-mode confinement is a hallmark of advanced tokamak (AT) regimes

- Characteristics of the L-H transition
  - Observed in all high-power magnetic confinement devices
  - Abrupt (sub-ms) reduction in the energy and particle transport near the plasma boundary
    - Pedestal in electron and ion density and temperature profiles
    - Increased core plasma pressure (Increased global energy confinement)
    - Enhanced confinement of impurities
  - Reduction in edge (and maybe core) turbulence is observed
  - New equilibrium can be unstable to edge localized modes

13 ms before LH transition
23 ms after LH transition



Identifying the conditions that trigger LH transition is a priority for ITER and future AT reactors

- First principles model of LH transition
  - Still under development after ~25 years of research
  - Experimentally: approaching diagnostic resolutions and coverage needed to test theories
  - Computationally: approaching computing power needed to run self-consistent models with a large range of temporal and spatial scales

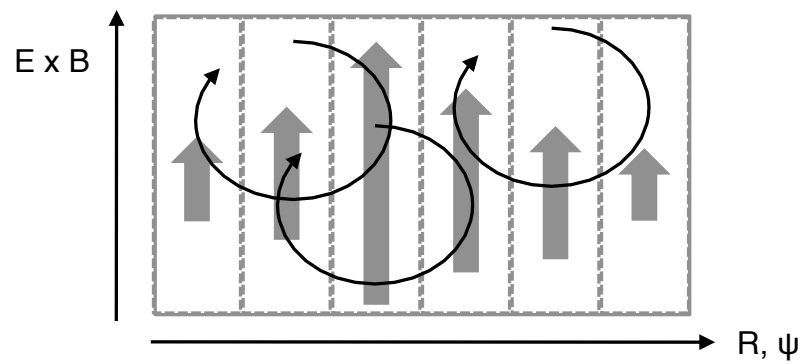
- Scaling relations of P_{LH} versus global parameters
  - Early observation: Power threshold for triggering LH transition (P_{LH})
  - P_{LH} is a global quantity that is fairly easy to measure routinely on many experiments
    - Database indicates P_{LH} scales strongly with B_t, n_e and S
  - Does not capture relevant physics, but guides designs while first principle models are being developed

LH transition may be triggered by a critical E_r or E_r shear that suppresses turbulent transport

- From MHD force balance: $E_r = v_\theta B_\phi + v_\phi B_\theta - \nabla(n_i T_i)/Z_i e n_i$

- Hypothesis: LH transition at a critical E_r x B shearing rate
  - *E_r x B* shear rate increases prior to the formation of a pedestal
  - Sufficient cross-field flow shear can break up turbulent cells
  - Achieve critical flow shear → suppress turbulence → larger gradients → gradients enhance E_r → flow shear increases
  - Not the full story, but a component of most LH transition theories

$$\omega_{ExB} = \frac{(RB_\theta)^2}{B}\left(\frac{\partial}{\partial\psi}\right)\frac{E_r}{RB_\theta}$$



Equations from: K.H. Burrell, *Phys. Plasmas,* **4** (1997) 1499

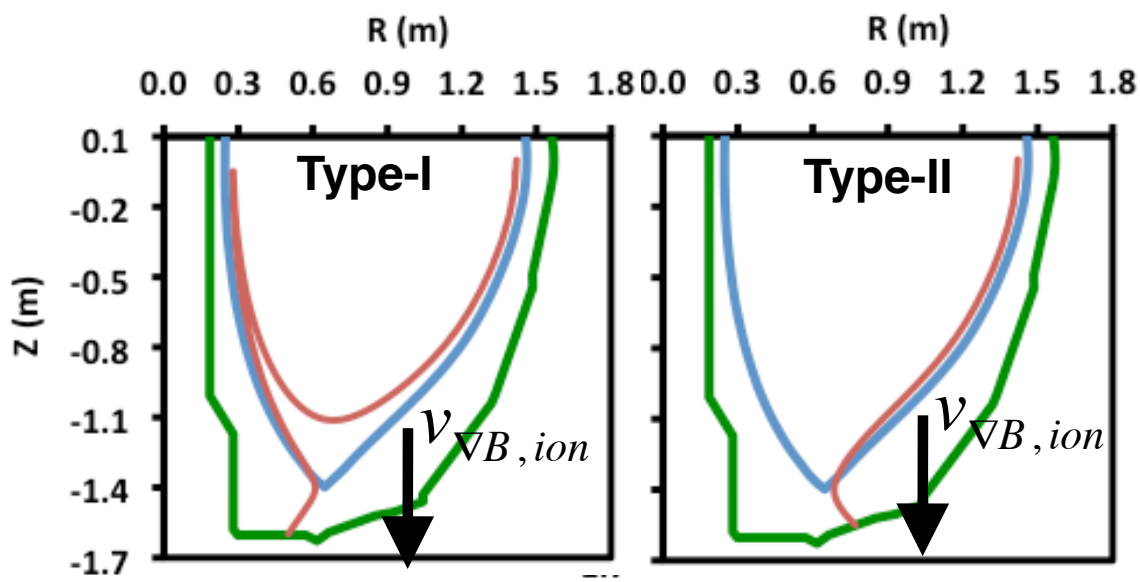
X-transport model: E_r must be large enough to prevent non-ambipolar ion orbit loss

- Neoclassical orbits can transport particles out of plasma
  - Banana width of ions is larger than electrons
    - Orbits lost through X-point in diverted geometry
    - Non-ambipolar: more ions lost than electrons

$$\Delta r \sim v_{\parallel 0}\ m/B_\theta$$

  - E_r quickly develops to alter orbits, maintain quasi-neutrality
    - Rotation and/or ion gradients change on slower timescale for force balance
    - E_r ~ ion orbit loss current

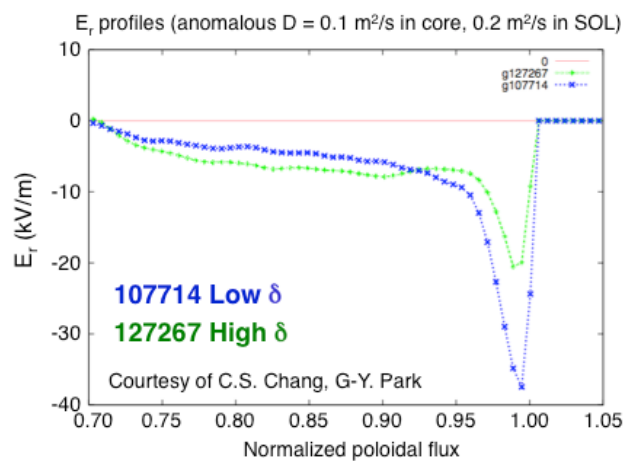
- Ion loss orbits:
  - Type-I: Bounce inboard of X-point
  - Type-II: Lost on single pass



Neoclassical ion orbit code used to predict ion loss cone in velocity space

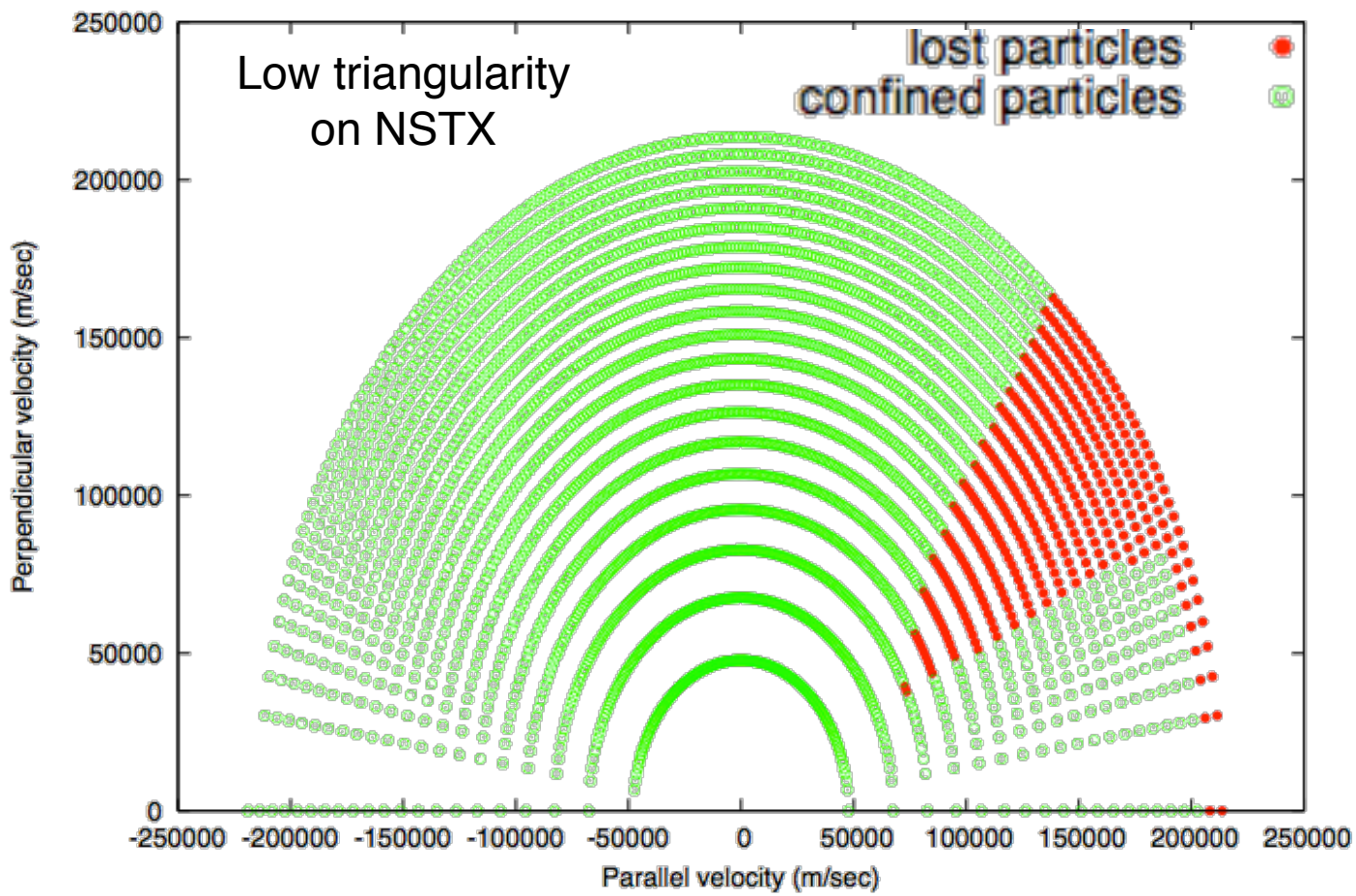
- Calculate ion orbits without electric fields, flows or collisions
  - Single-particle guiding-center motion
  - Fast calculation that depends only on the magnetic geometry
  - Identifies "loss cone" in ion velocity space
  - Provides tool for comparing the ion loss cone (~ E_r) for different geometries

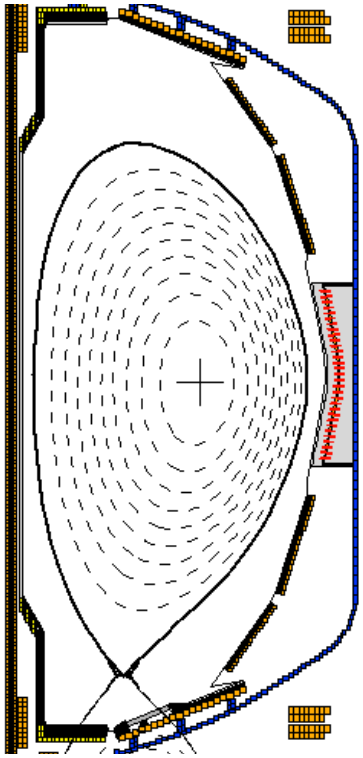
- XGC-0: Self-consistent calculation including collisions
  - Experimental profiles of electron and ion parameters constrain solution
  - Electric fields computed self-consistently
  - Ion, electron and neutral collisions
  - Large computation requiring ~ 1 day to run



Non-ambipolar loss hole in ion velocity space in absence of E_r, flows, and collisions

1,000 ions launched from a single point on outboard midplane at psi_N = 0.96
(Each ring is a contour of constant energy)





Non-ambipolar loss hole in collisionless ion velocity space in absence of E_r and flows

1,000 ions launched from a single point on outboard midplane at psi_N = 0.96
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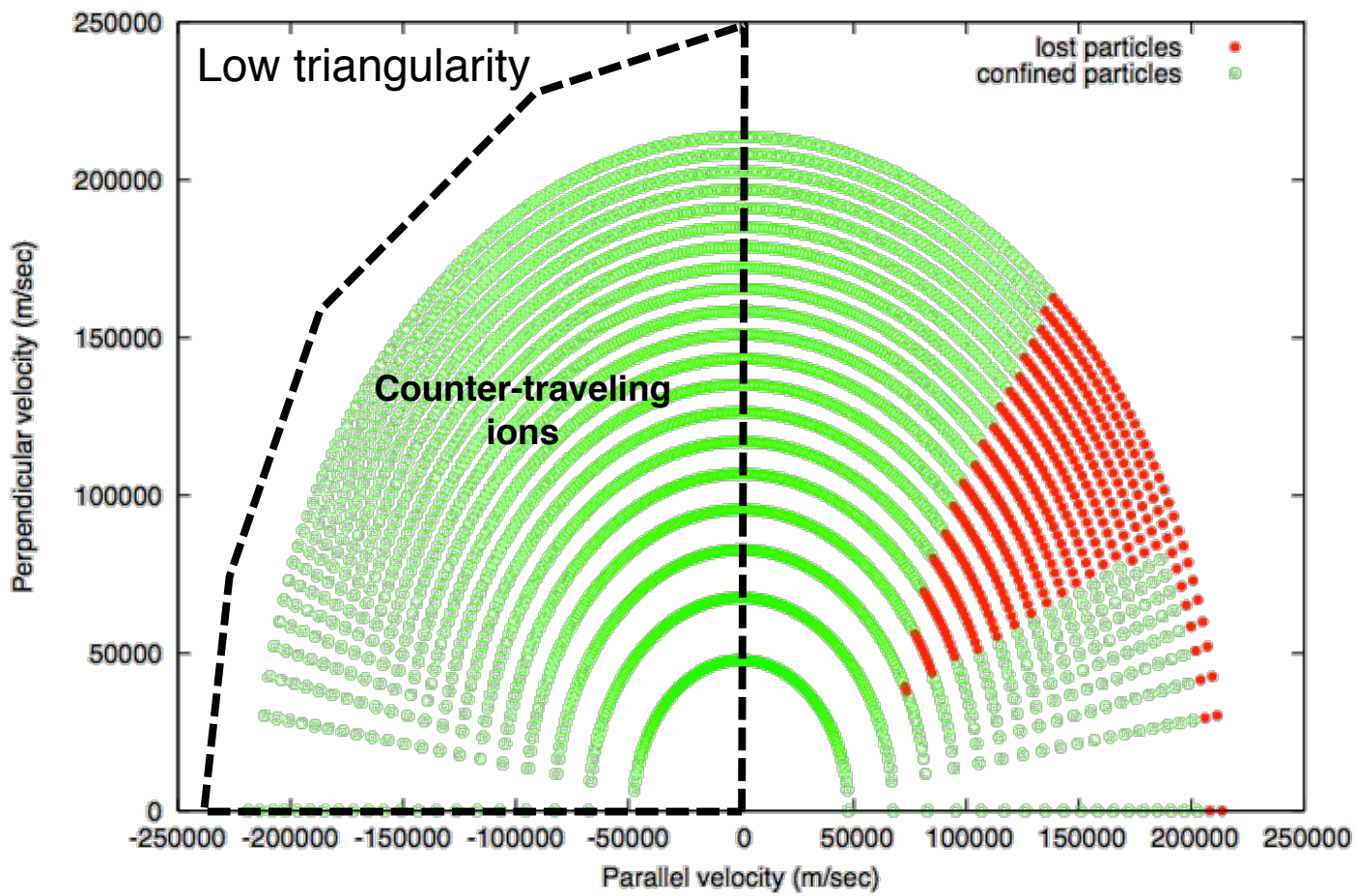

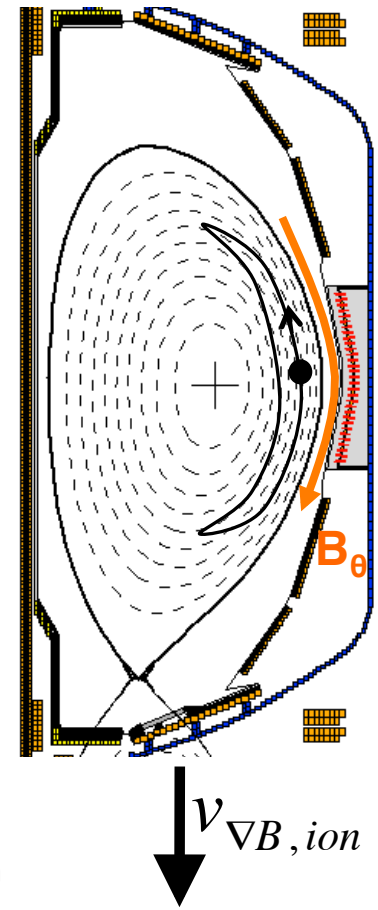

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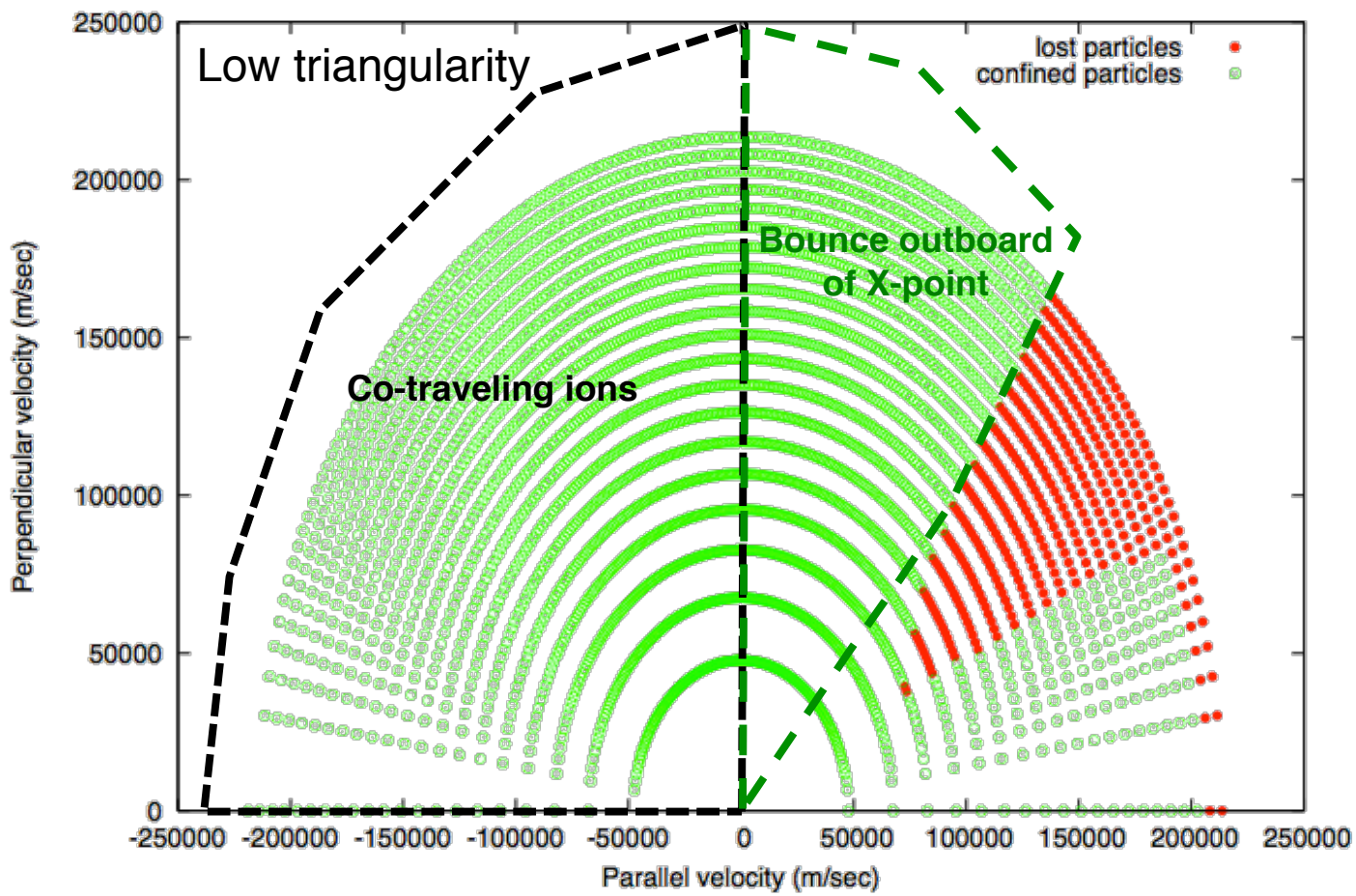

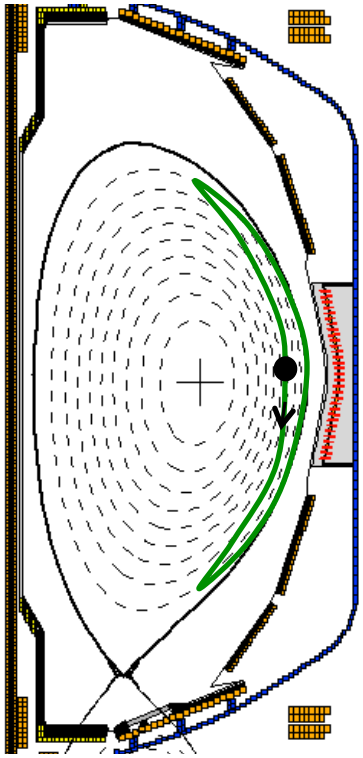

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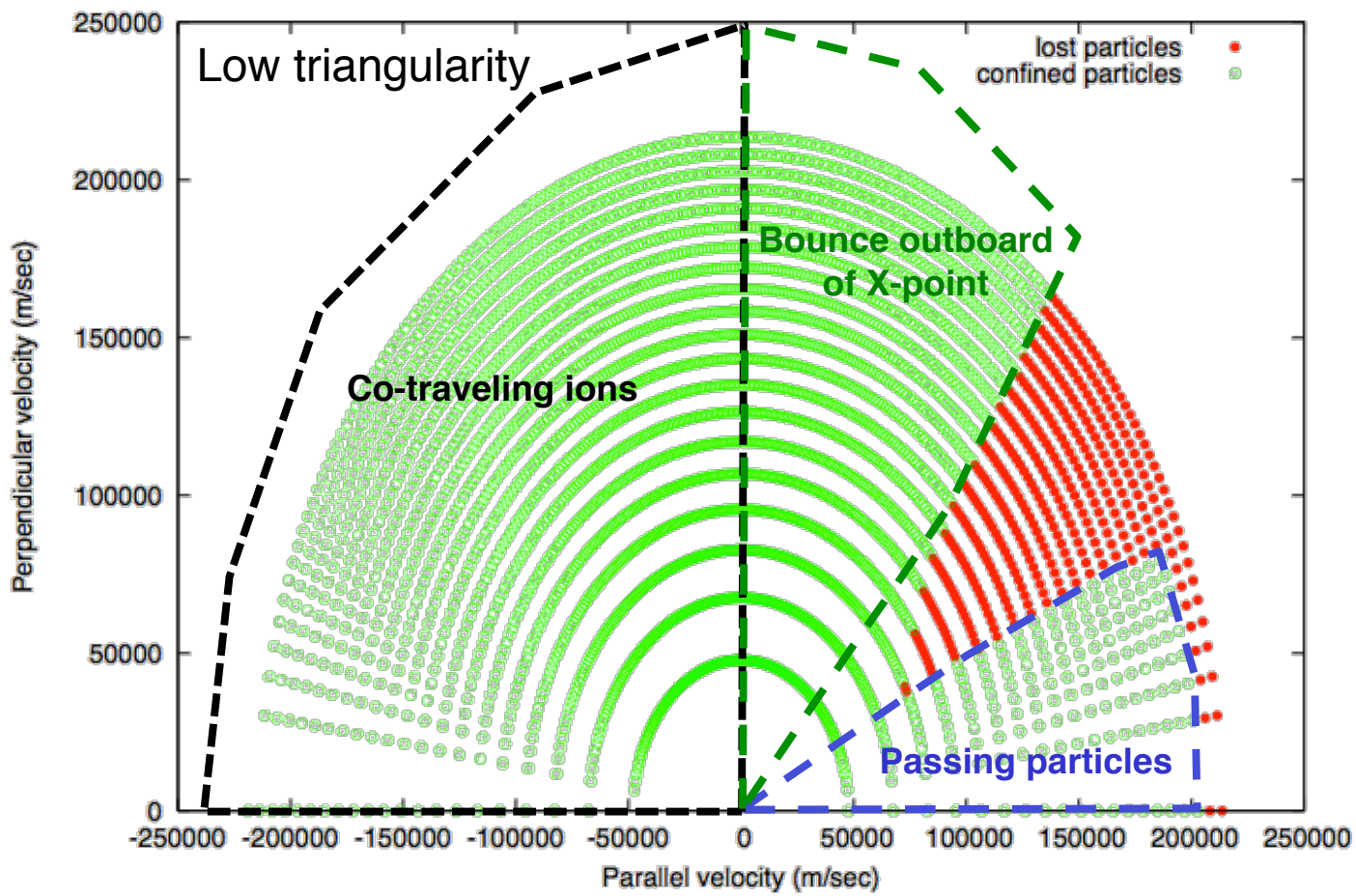
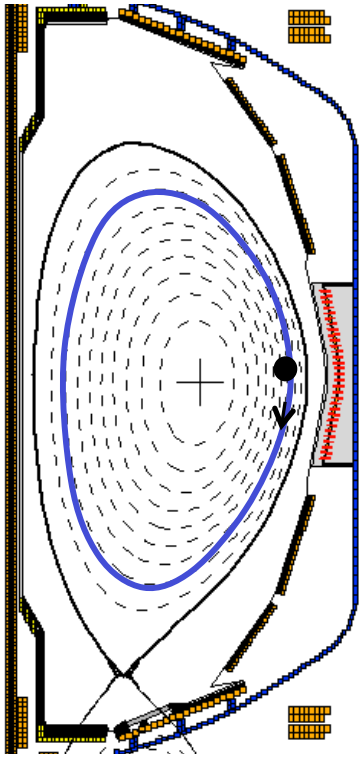
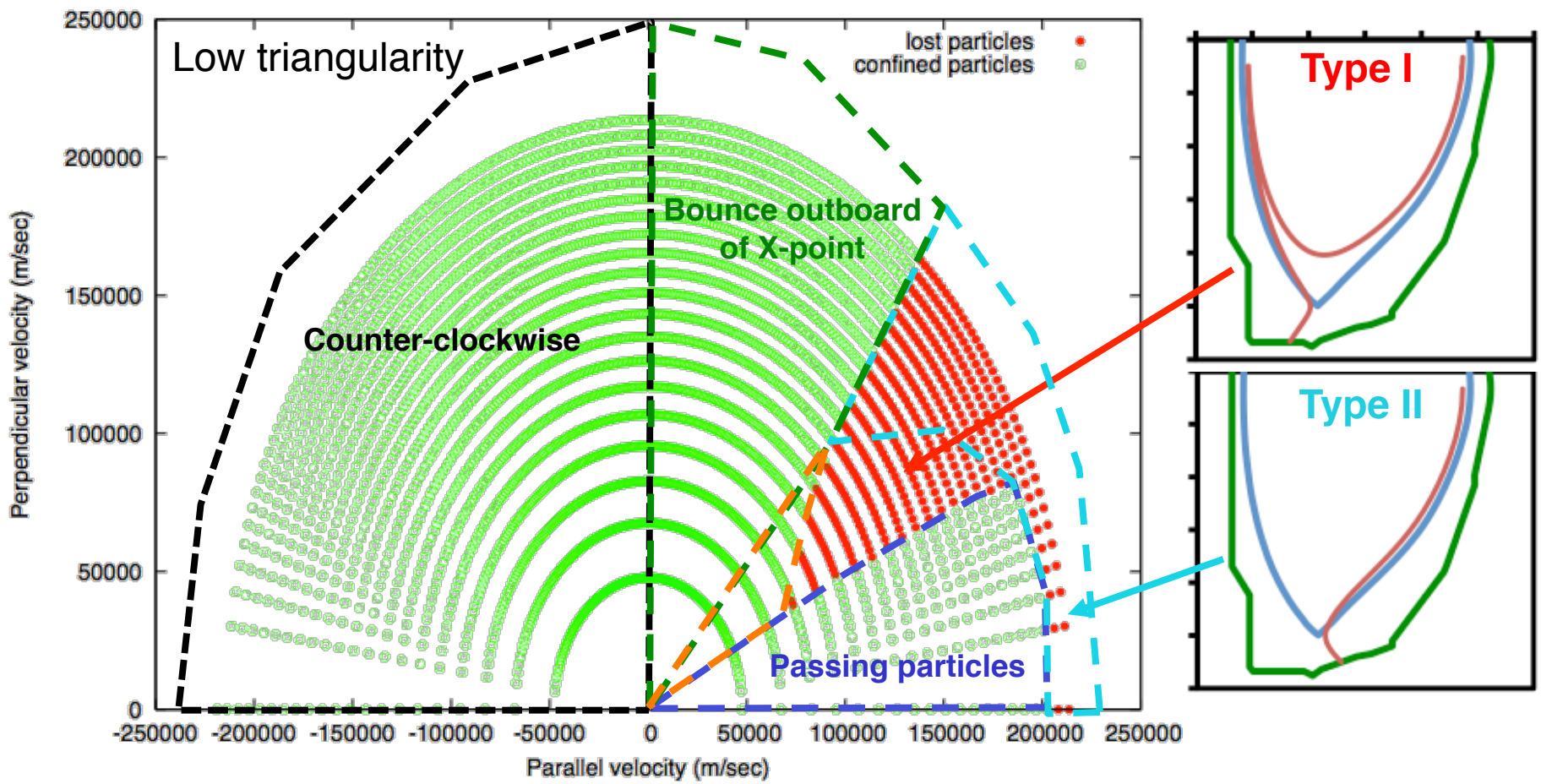




Non-ambipolar loss hole in ion velocity space in absence of E_r, flows, and collisions

1,000 ions launched from a single point on outboard midplane at psi_N = 0.96
(Each ring is a contour of constant energy)



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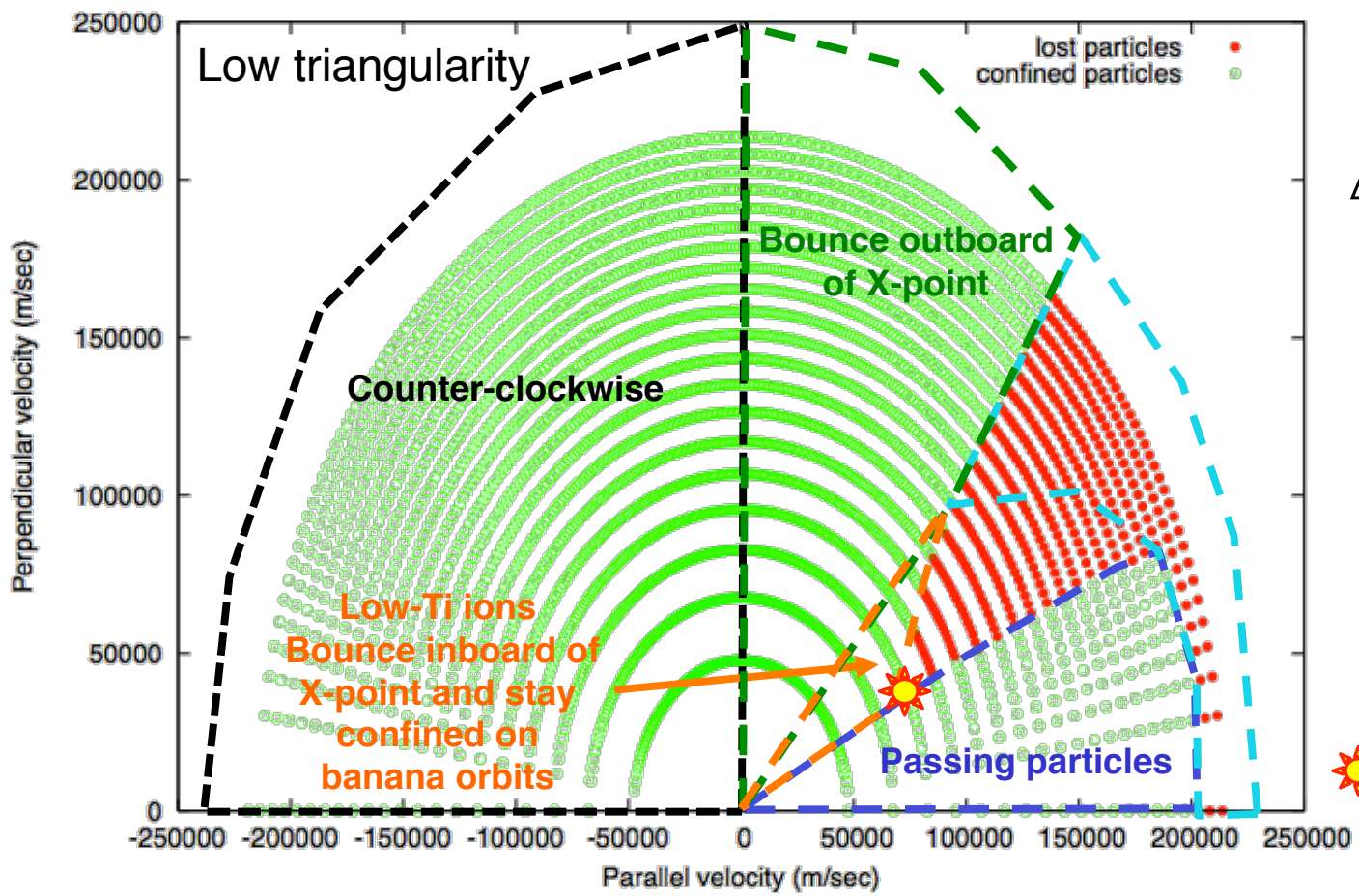


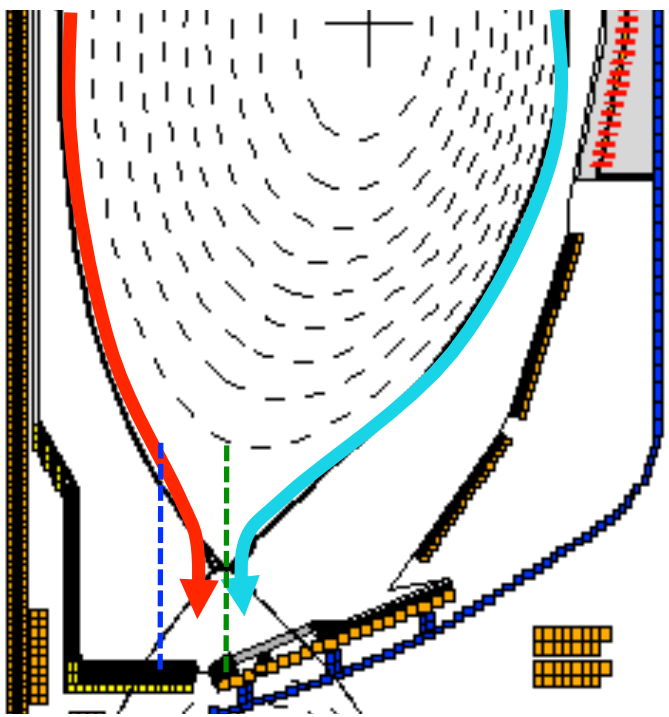
$$\Delta Z_{drift} \approx \bar{v}_{\nabla B} \Delta t_{loss}$$
$$\sim E_i / L_{orbit}$$

Lowest Ti ion on lost orbit is on passing/ trapped boundary

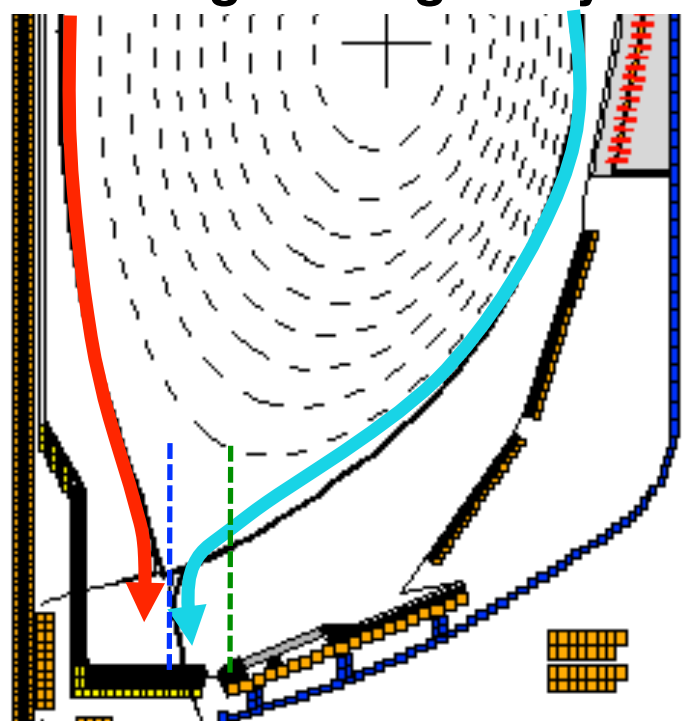
Shape of velocity hole depends on X-point radius

- Move large R_X (δ_{low} ~ 0) to small R_X (high δ_{low}) …
  - Shorten type-I orbits → increase critical T_i for type-I loss
  - Lengthen type-II orbits → decrease critical T_i for type-II loss
  - More ions will bounce inboard of X-point

Low Triangularity

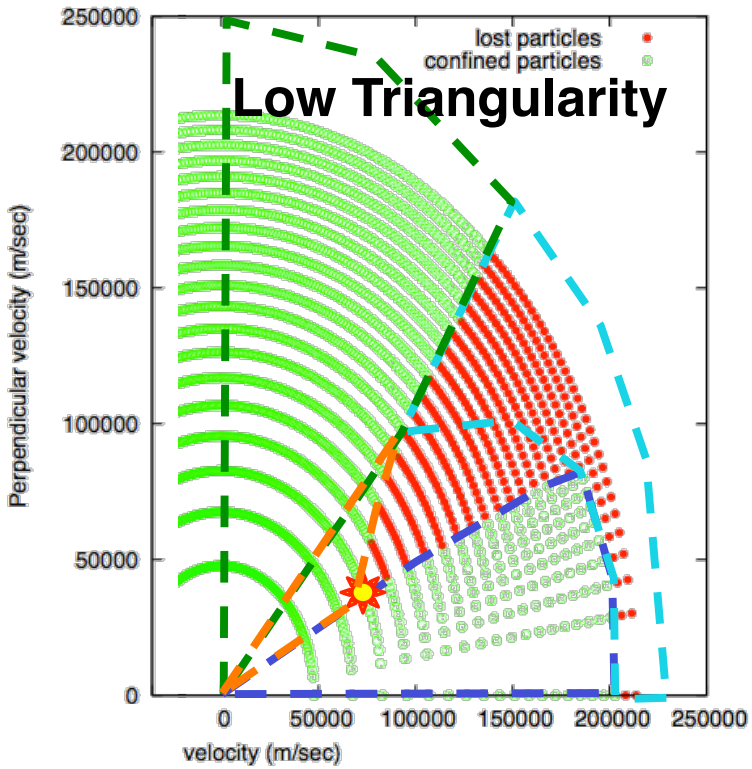


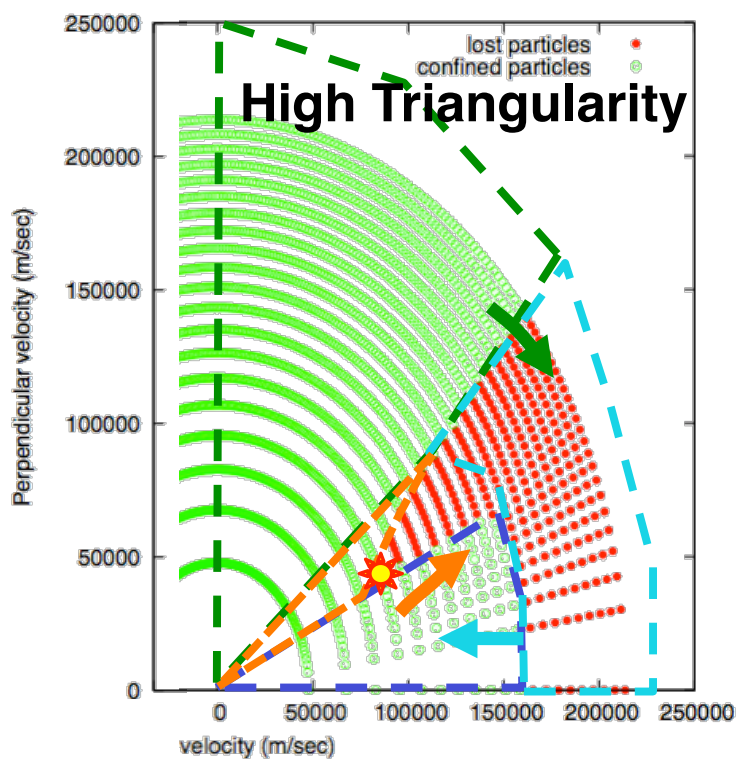
High Triangularity



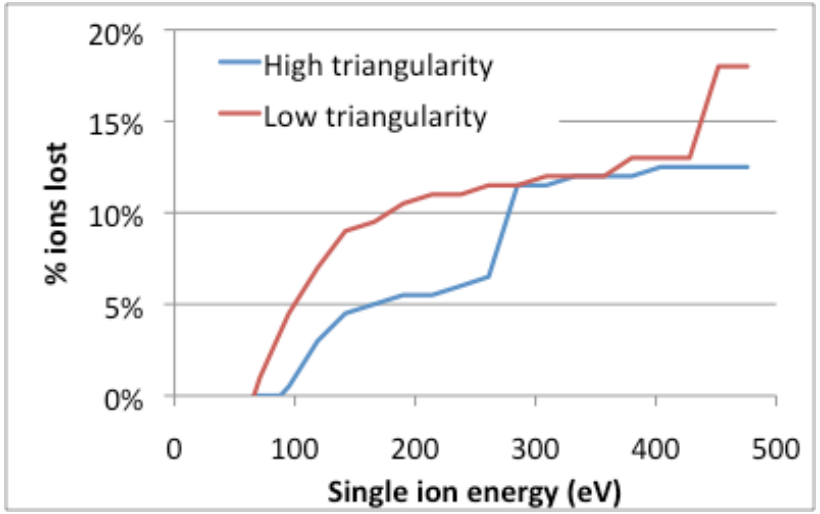
High-δ shape has a larger critical T_i and smaller loss cone for type-I orbit loss

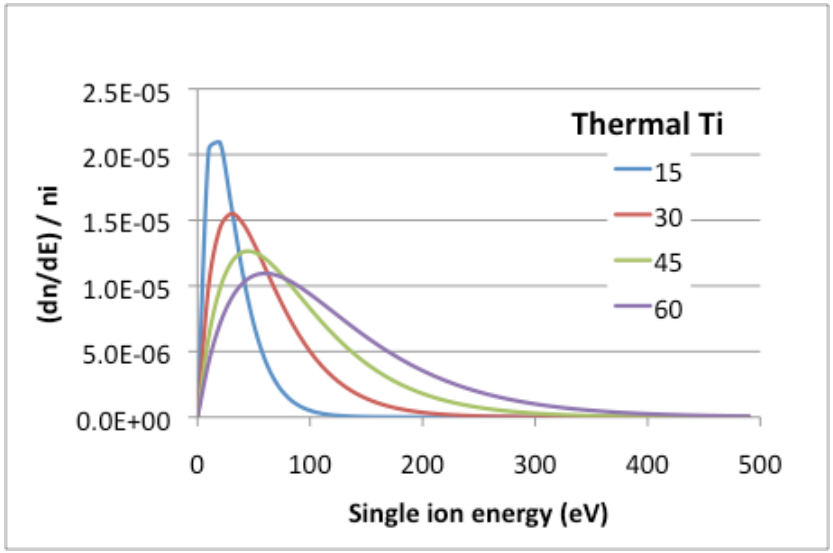
- Move large R_X (δ_{low} ~ 0) to small R_X (high δ_{low}) …
  - Shorten type-I orbits → increase critical T_i for type-I loss
  - Lengthen type-II orbits → decrease critical T_i for type-II loss
  - More ions will bounce inboard of X-point



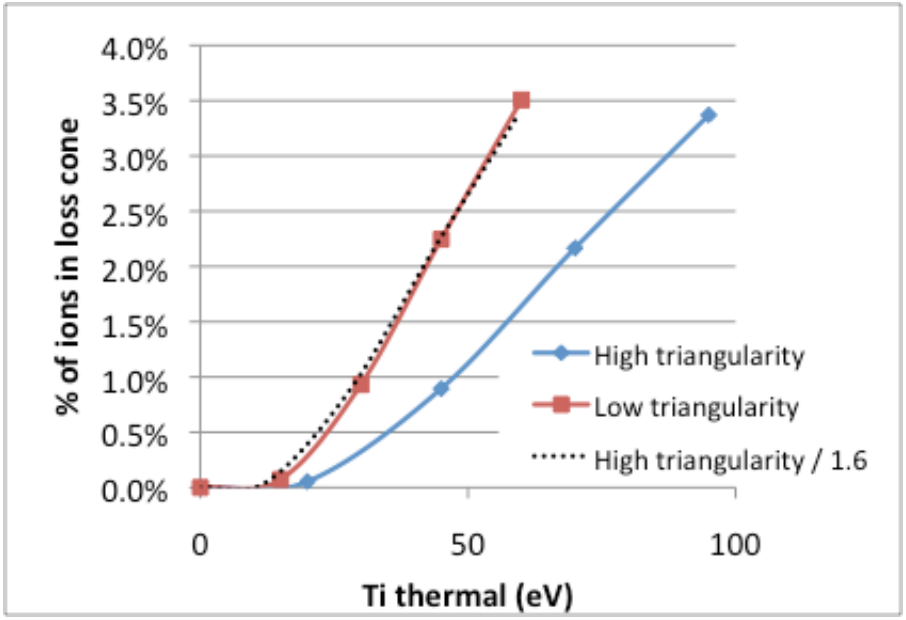


The number of ions in the loss cone for a given local thermal T_i is largest for the low-δ shape





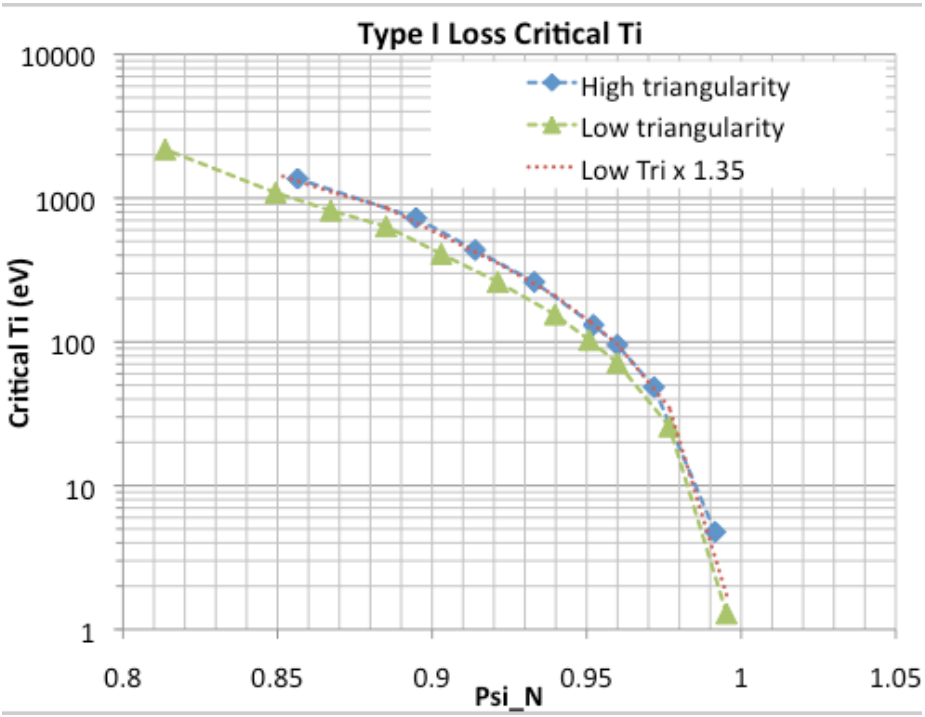
n_{loss} / n_i at psi_N = 0.96

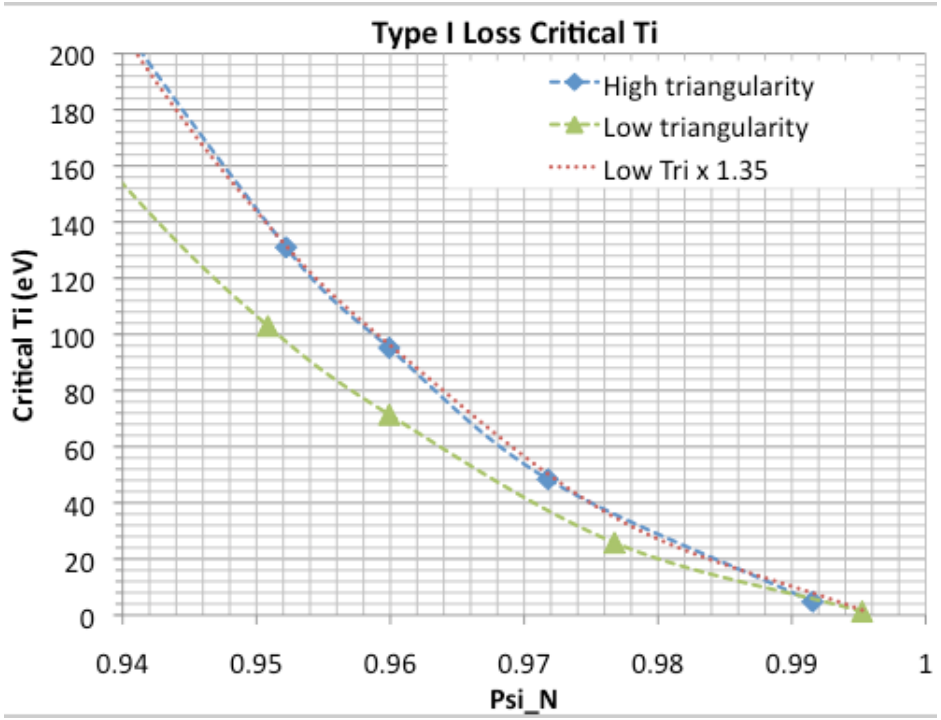


The thermal T_i needs to be 1.6 times larger in the high-δ than low-δ to get an equivalent ion loss

Critical T_i for type-I orbit loss is about 1.35 times larger for high-δ than low-δ

Lowest T_i ion that starts on the midplane and is lost via type-I orbit

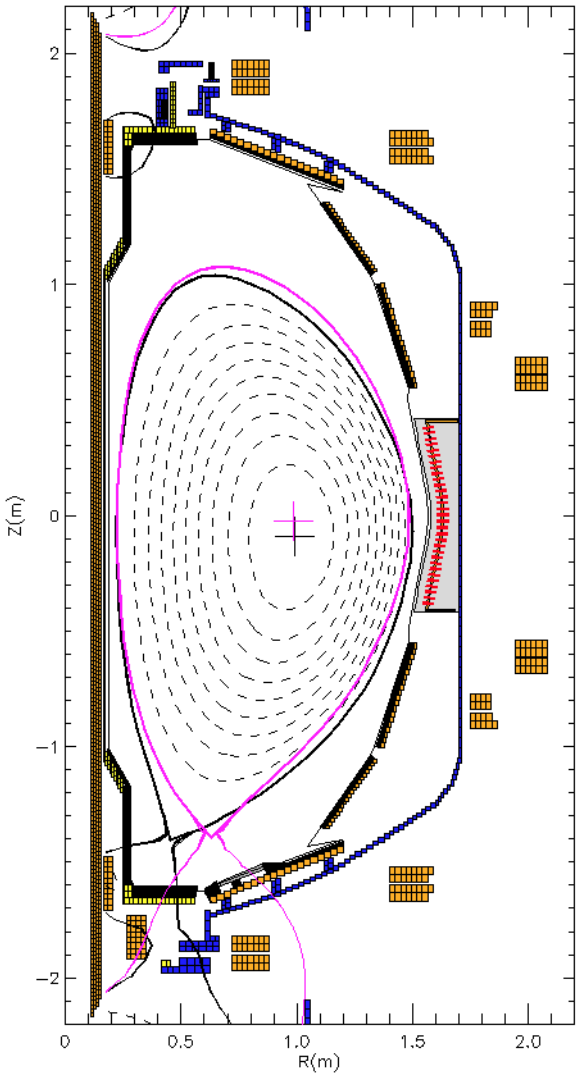




Goal: Examine conditions leading to LH transition for different R_X shapes on NSTX

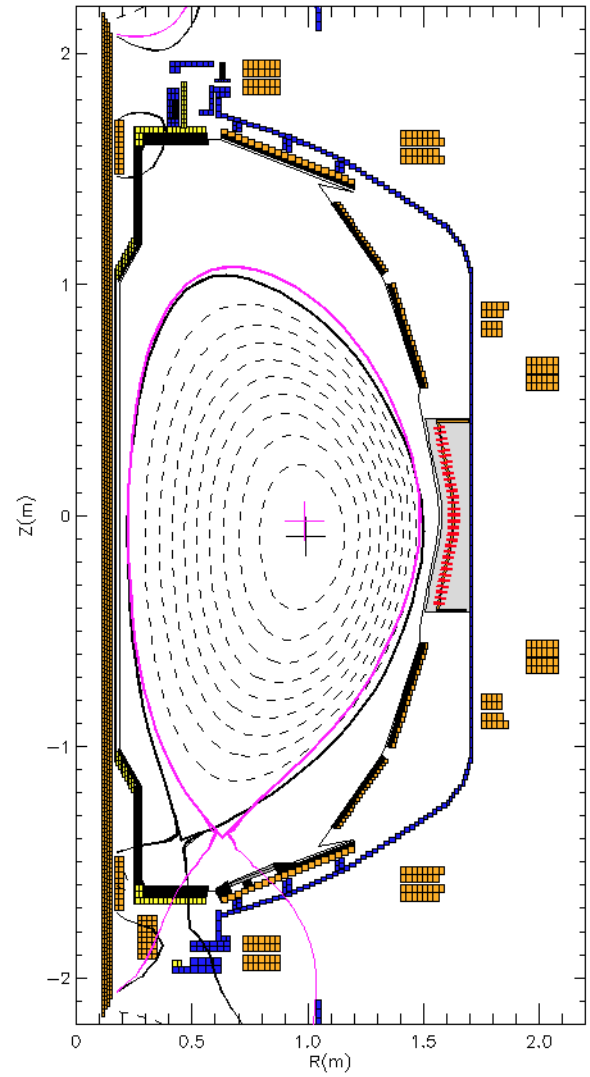
- Expect T_i (~ P_{LH}) to be higher at LH transition for high-δ than low-δ

- NSTX is an ideal device to test this dependence
  - Low aspect ratio geometry (A ~ 1.4)
    - Large grad-B_t, low collisionallity
    - Large trapped particle fraction
    - Enhanced grad-B drift
  - Edge neutral density control with lithium coatings relaxes constraints on divertor strike points
  - State-of-the-art diagnostics
  - Advanced plasma shape control



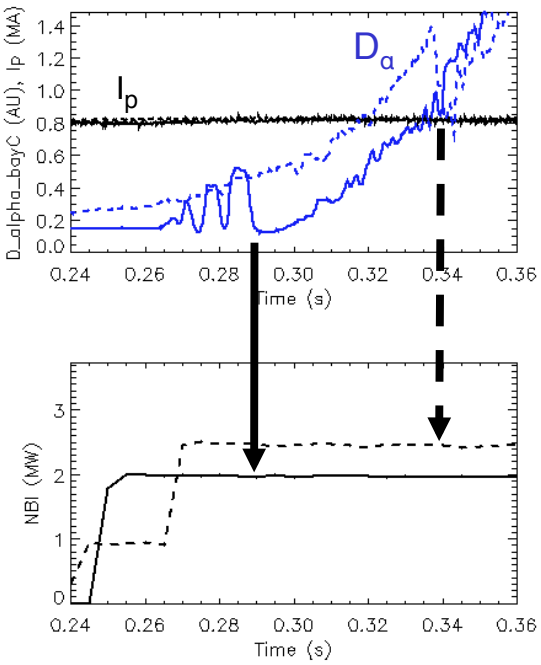
Experiments build on previous results from 2009*

- With the same TF coil current …
  - Match inboard B_t (i.e., inner gap)
  - Match outboard |B| (i.e., outer gap and I_p)
  - Match B_{t0} (same R_0)
- Try to match other P_{LH} variables . . .
  - Line-averaged density
  - X-point height
  - Plasma surface area
- Aim for transition > 40 ms after NBI power increase
  - Avoid time of large dW/dt and evolving P_{OH} to improve P_{LH} calculation



* R. Maingi et. al., *Nucl. Fusion,* **50** (2010) 064010

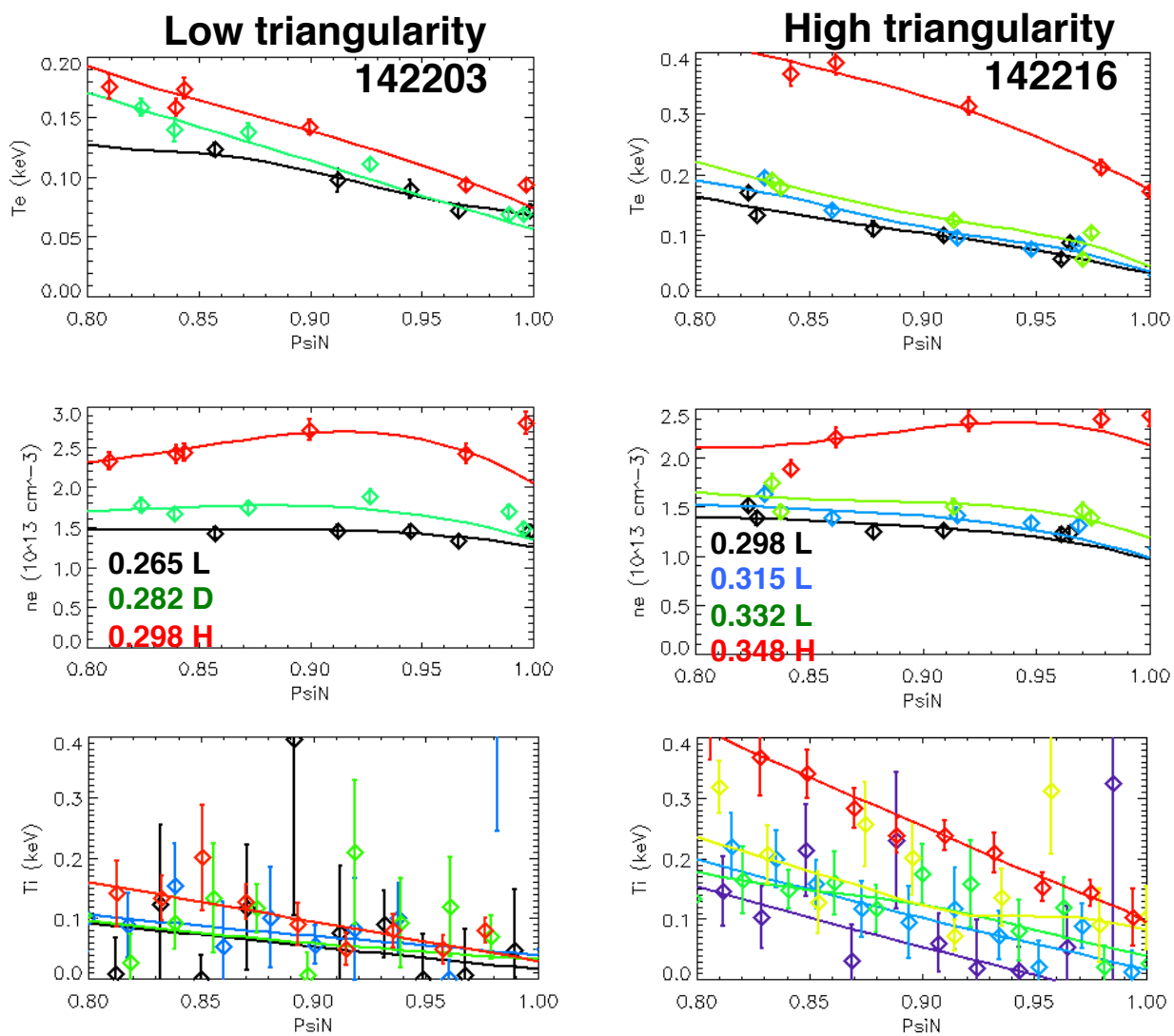
P_{LH} and (rough) T_i measurements are consistent with X-transport predictions



High triangularity – dotted
Low triangularity – solid

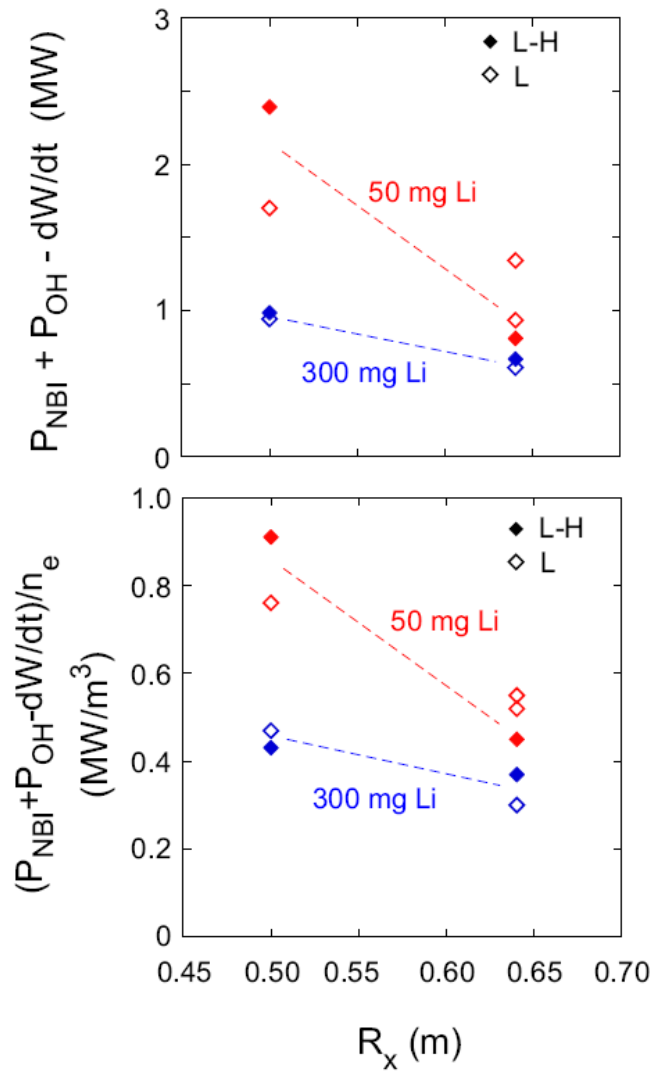
High-δ P_{loss} ~ 2.1 MW
Low-δ P_{loss} ~ 1.3 MW

Ratio: 2.1 MW / 1.3 MW ~ 1.6



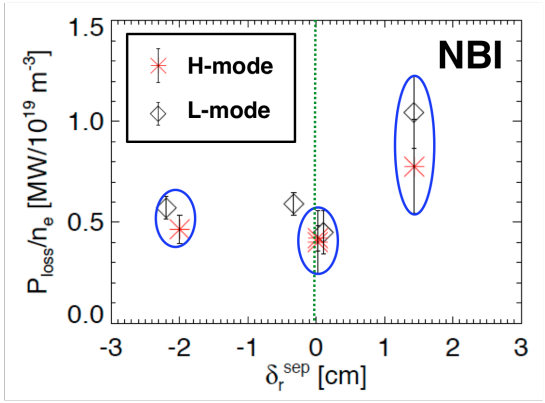
P_{LH} for both shapes strongly influenced by edge fueling and pumping

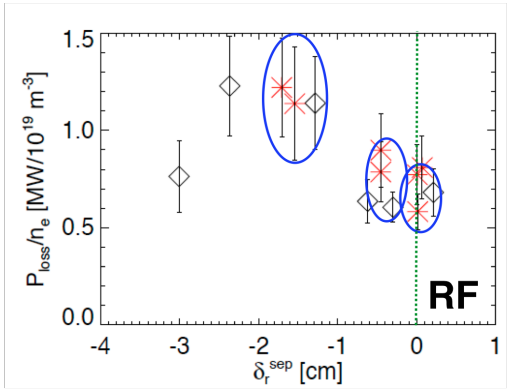
- Scan R_x and neutral fueling / pumping
  - Low triangularity: $R_x = 0.64$ ($\delta_L = 0.36$)
  - High triangularity: $R_x = 0.47$ ($\delta_L = 0.64$)
- Full TRANSP analysis of six discharges to get NBI heating power
  - Matched B_t, I_p, Z_X
  - Nearly matched n_{el}
    - Required more fueling for high Li shots
- Edge fueling and R_X both have a significant effect on P_{LH}
  - 20% - 40% change with geometry
  - 30% - 40% change with edge fueling



Some other interesting connections between experiment and X-transport model

- Toroidal electric field → Ware pinch of trapped ions
  - P_{LH} increases with larger $|V_{loop}|$
    - Induce LH transition with V_{loop} spike toward zero
  - Contributes to scaling of P_{LH} with I_p
- X-point balance
  - Ion loss cone could double in size for balanced double null
  - Grad-B in unfavorable direction
    - Ion loss cone moves to higher energy due to up-down asymmetry of plasma
    - Loss time at least twice as large → more sensitive to collisions

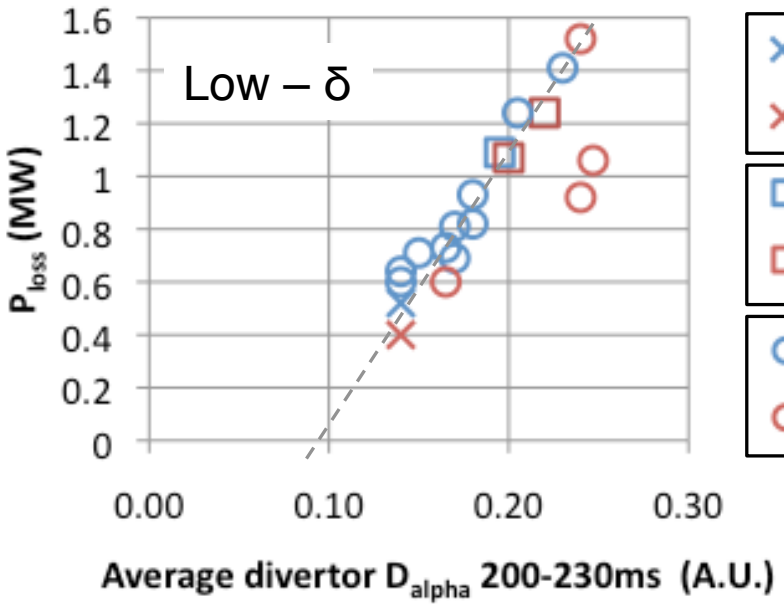




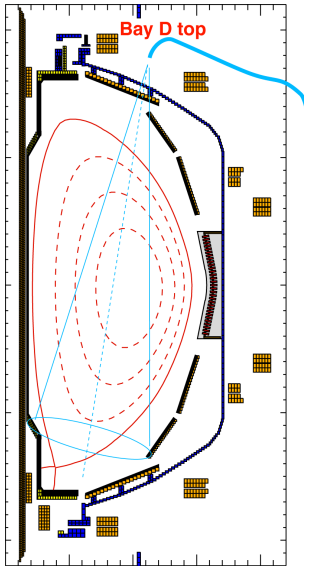
R. Maingi et. al., *Nucl. Fusion,* **50** (2010) 064010

- P_{LH} decreases with less divertor recycling
  - Ion-neutral interactions near X-point detrap and thermalize ions

Preliminary observation: P_{LH} scales linearly with initial divertor D_α intensity



× LH × L	300 mg lithium inter-shot (High pumping, high fueling)
□ LH □ L	50 mg lithium inter-shot (Med. pumping, med. fueling)
○ LH ○ L	No lithium inter-shot (Low pumping, low → med. fueling)



- P_{LH} increases with pre-NBI divertor D_α signal
  - May be proportional to initial edge neutral density (n_N)
- Indicates n_N is important in P_{LH} calculations
  - NBI heating efficiency depends on n_N
  - Neutrals impact LH trigger (ion – neutral collisions)

Some other interesting connections between experiment and X-transport model

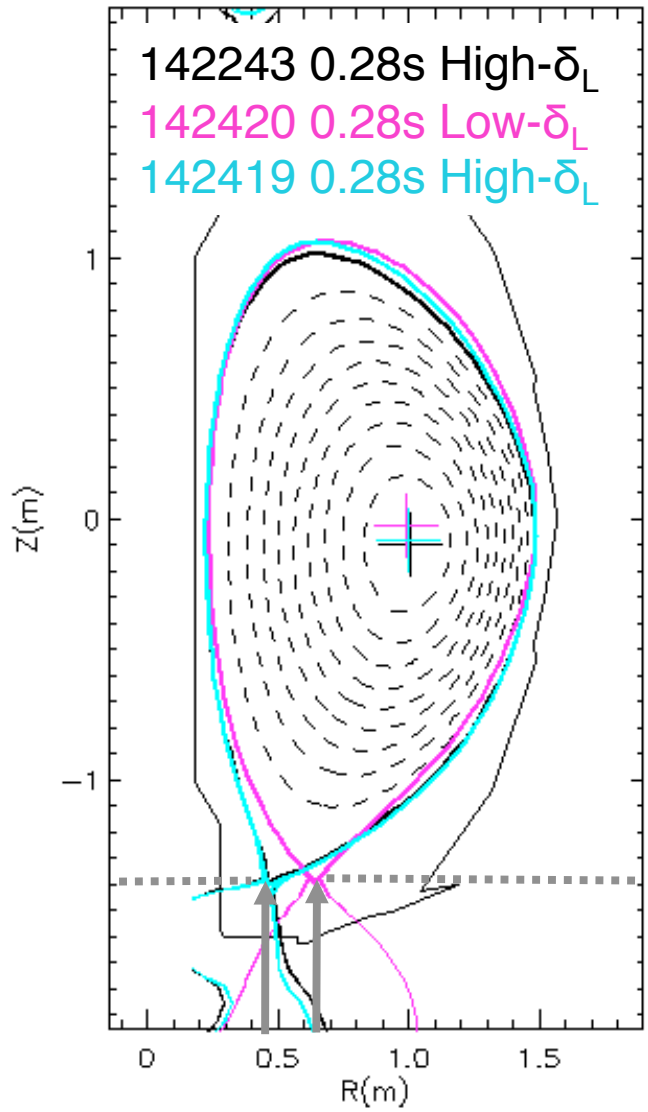
- Mass dependence
  - Critical energy for ion loss ~ $Z_i / m_i^{1/2}$ → $P_{LH} \sim m_i^{1/2}$ for $Z_i \propto m_i$

- As I_p decreases . . .
  - B_{out}/B_{in} decreases in an ST, more trapped particles (lowers P_{LH})
  - Banana widths become larger (lowers P_{LH})
  - Loss time increases (increases P_{LH})
  - E x B shearing rate decreases (increases P_{LH})

$$\omega_{ExB} = \frac{\left(RB_\theta\right)^2}{B}\left(\frac{\partial}{\partial\psi}\right)\frac{E_r}{RB_\theta}$$

- Near linear B_t dependence
  - E_r x B_t shearing rate linearly depends on B_t at edge
  - Ion loss time is shorter as B_t is decreased

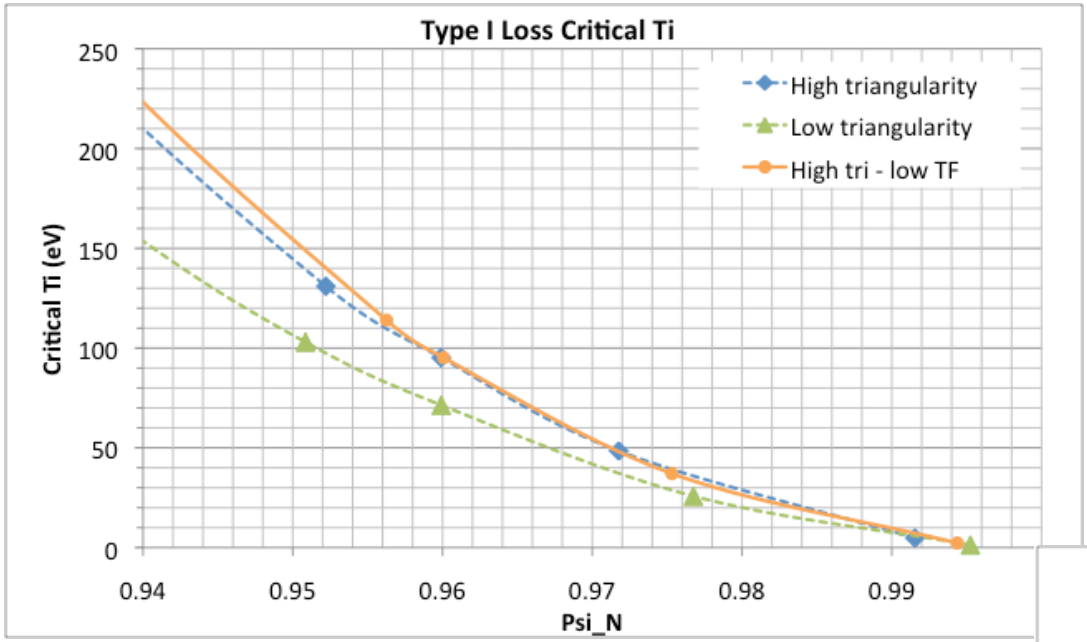
P_{LH} is similar for both shapes when B_{tX} is matched



- TF current reduced for high-δ shape to match B_{tX}
  - P_{LH} very similar to low-δ shape
- Dataset implies $P_{LH} \sim B_{tX}^{1.0-2.0}$
  - 22% - 27% reduction in B_{tX} gives …
  - 22% - 45% reduction in P_{LH}

B_{t0} (T)	R_X (m)	B_{tX} (T)	P_{NBI} (MW)	P_{LH} (MW)
0.55	0.47	0.86	1.9	1.1
0.55	0.64	0.63	1.0	0.7
0.40	0.47	0.63	1.0	0.6

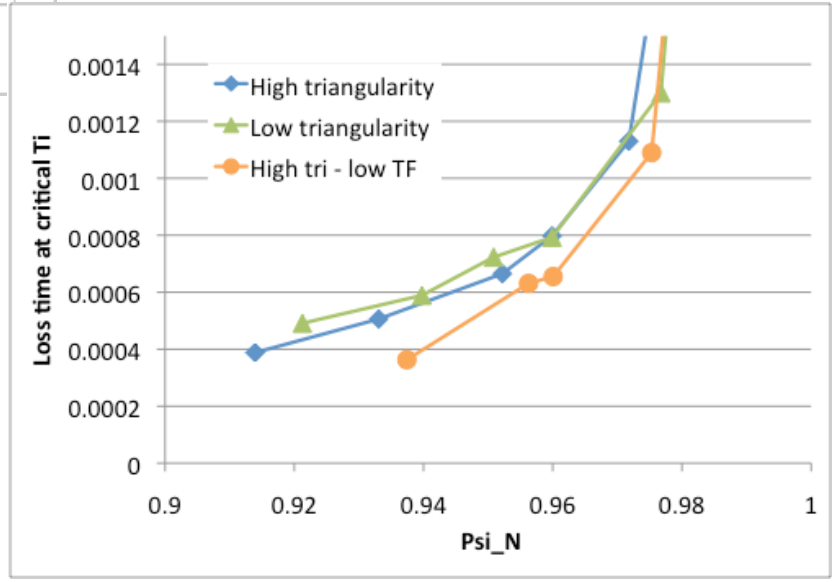
Reducing B_T by ~30% does not change the critical T_i for the high triangularity shape



Critical T_i and loss hole size does not have a strong B_t dependence

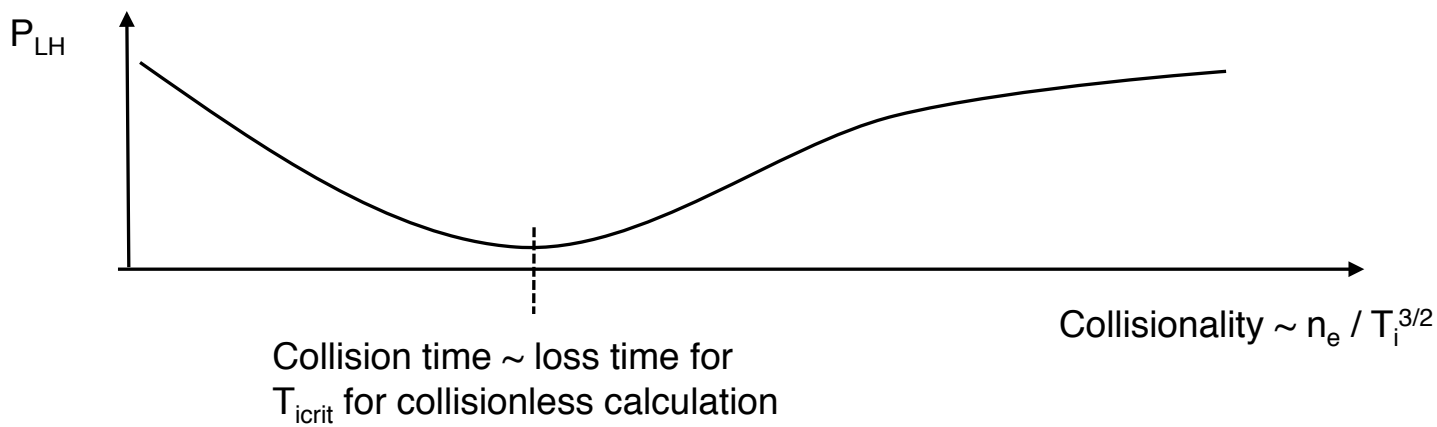
(Banana widths are independent of B_t)

But the lower q_{95} reduces the loss orbit length and loss time. Thus, the ions are less susceptible to collision effects.



Some other interesting connections between experiment and X-transport model

- Effect of collisions can be complicated
  - Ion-electron collisions slow down ions → push loss cone to higher T_i
    - Could manifest as a threshold in T_e
  - Ion-ion collisions
    - Low density: Larger density increases rate of ions scattered into loss cone and number of ions in loss cone
    - High density: Collisionality large enough to detrap ions in loss cone → larger density raises the loss cone to larger energies
    - Very high density: All ions detrapped, no X-transport effect



Summary

- X-transport: E_r must be large enough to prevent non-ambipolar loss of ions following neoclassical orbits
  - Build-up of E_r increases E x B flow shear rate, may trigger LH transition at some critical level
  - Number of ions on loss orbits very sensitive to the local thermal T_i
- P_{LH} observed to decrease with R_X on NSTX
  - Consistent with ion loss hole calculations that predict a lower thermal T_i is needed for the low-δ shape than the high-δ to achieve a given ion loss rate
- X-transport model predicts trends that are consistent with other experimental observations
  - X-transport is only one of the ways to build-up E_r, but could be a dominant contribution, especially in STs

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