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ABSTRACT

1S 32 - Investigation of Collisional Nonprompt Alpha Loss using Major Radius Shifts on TFTR*

H. W. Herrmann, D. S. Darrow, M. C. Herrmann, H. E. Mynick, S. J. Zweben, and the TFTR Group, Princeton Plasma Physics Laboratory

A major radius shift experiment has been conducted on TFTR to look for experimental evidence of collisional nonprompt loss [1] of charged fusion products. Pitch angle scattering of marginally passing charged fusion products across the passing/trapped boundary in velocity space can cause particles to be nonpromptly lost. Under steady state conditions, collisional nonprompt loss is predicted to contribute an insignificant amount to the total fusion product loss. An inward major radius shift should, however, transiently enhance this loss mechanism. To test this theory, the plasma major radius was shifted inward in ~80 msec from 2.6 m to 2.35 m and then shifted back out at the same rate after a delay of ~320 msec. These shifts were conducted at various plasma currents and in DD and DT plasmas. Enhancement of nonprompt loss was not apparent in the signals of the lost alpha detectors during the shifts. The results of this experiment will be compared to code calculations.

*Work supported by US DoE contract DE-AC02-76-CH03073

[1] C.S. Chang, et al., Phys. Plasmas **1** (1994) 3857
N.N. Gorelenkov, Sov. J. Plasma Phys. **16** (1990) 241
C.T. Hsu and D.J. Sigmar, Phys. Fluids B **4** (1992) 1492

Summary & Conclusions

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- A Major Radius Shift experiment was conducted on TFTR with the expectation of increased α loss, which would have provided insight into the physics of α's near the Passing/Trapped Boundary (Collisional Nonprompt Loss in particular).

- Performance of the experimental procedure was warranted by the agreement between a simple theorectical model and prelimary experimental results.

- The experiment failed to produce the expected increase in α loss, although it did produce an unexpected loss of partially thermalized α's at the Passing/Trapped Boundary which is not yet understood.

- An improved theoretical model based on more realistic assumptions has aided in the understanding of α physics and explains the lack of increased α loss during an R Shift.

- Previous experimental results were most likely corrupted by MHD induced by the R Shifts.

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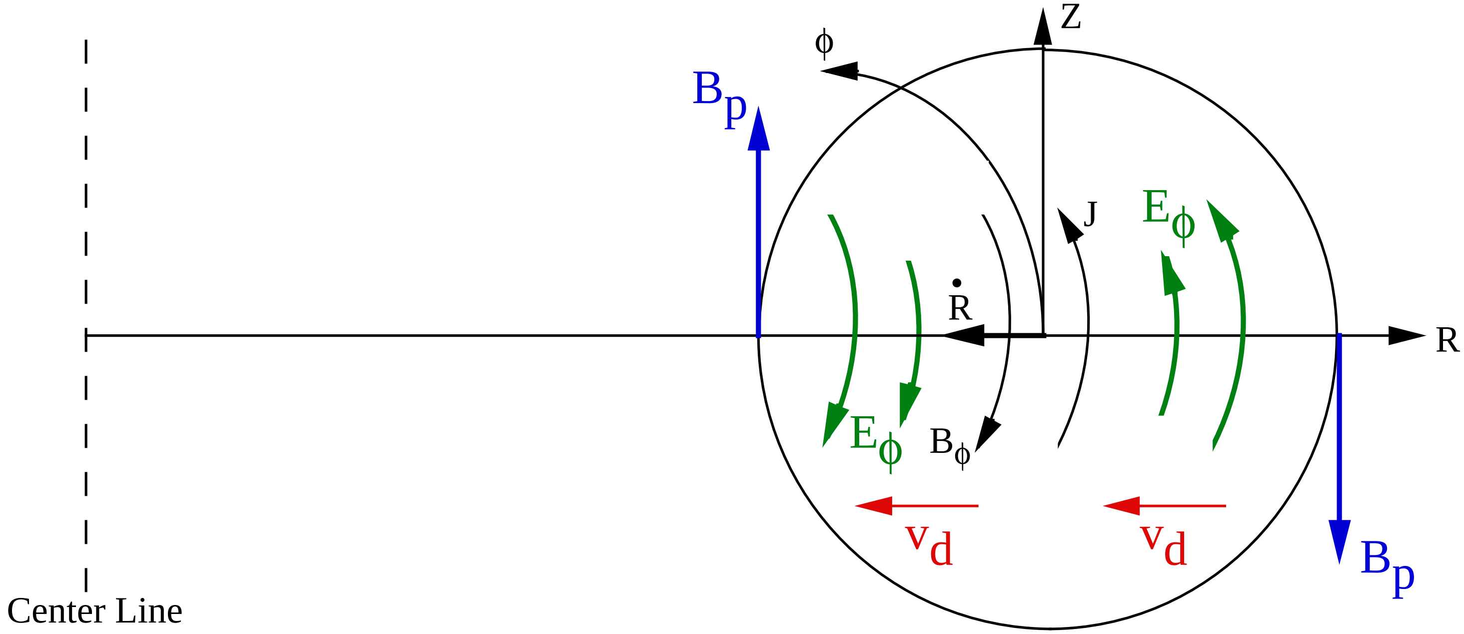
Hypothesis: Inward Major Radius Shift might deconfine marginally passing alphas

α trajectories shift along with plasma during R Shift

TFTR



- R shift causes Ψ_p at a fixed point in space to change in time ⇒ induced E_ϕ

$$E_\phi = \left(\frac{d\Psi_p}{dt}\right) \Big/ 2\pi c R \quad , \qquad \Psi_p = \int B \cdot dS_p$$

- E_ϕ ⇒ Inward drift of α's in direction of R Shift

$$v_d = \left(E_\phi \times B_p\right) \Big/ B^2 = -\hat{R} \left|E_\phi\right| \left|B_p\right| \Big/ B^2$$

- E_ϕ ⇒ heating of α's

$$\frac{dv}{dt} = \frac{v_\phi}{v} \frac{ZeE_\phi}{m} \cong \frac{v_{||}}{v} \frac{Ze}{2\pi mcR} \left(\frac{d\Psi_p}{dt}\right) \geq 0 \text{ for all } \alpha\text{'s}$$

Ref: N.N. Gorelenkov

Shift of α trajectory to higher B field should cause marginally passing α's to mirror and become trapped ⇒ increased α loss

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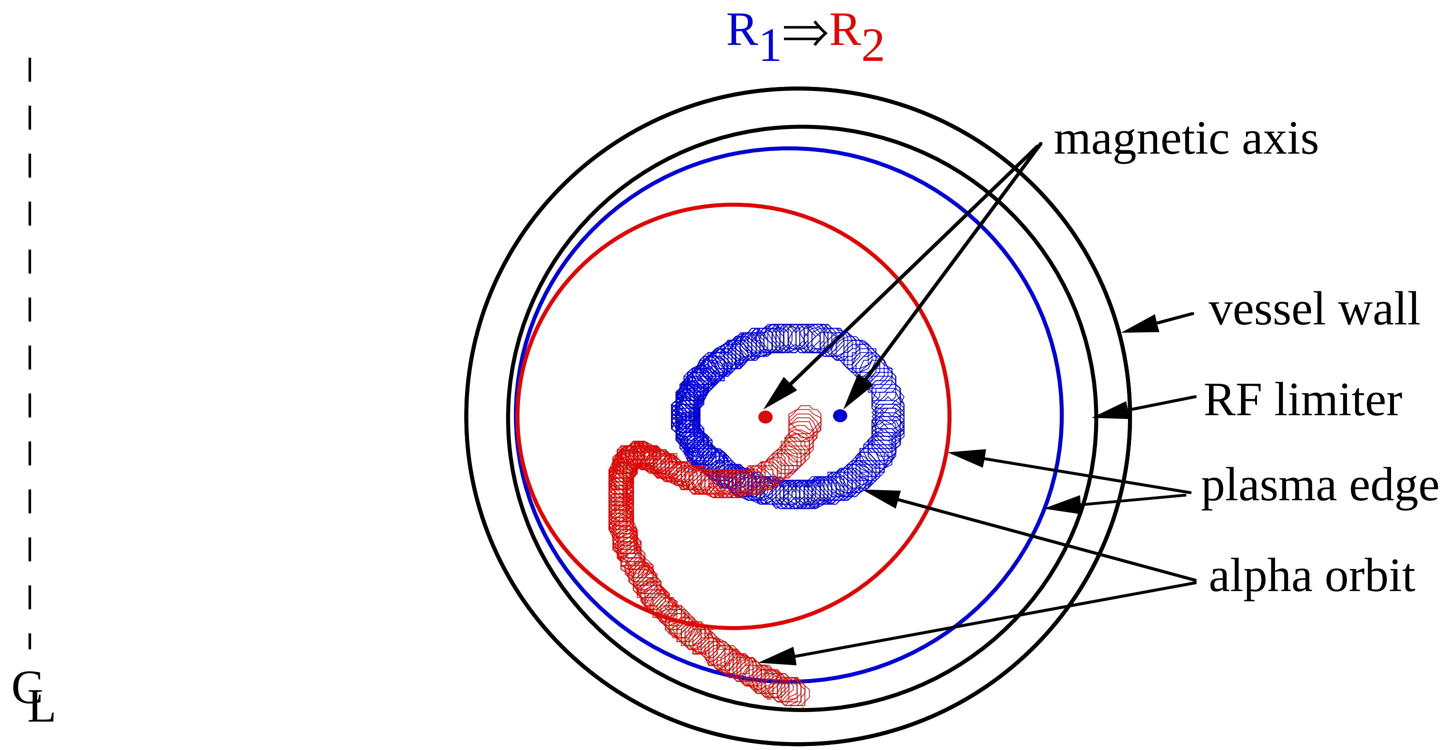

Original Working Model Assumptions (revised for improved model later):

- α follows flux surface throughout R shift (⇒ r/a of outer midplane crossing point remains fixed)
- α Energy (E) increase from R Shift is small
- α magnetic moment (μ) is conserved (since $\frac{1}{B}\frac{dB}{dt} = \frac{1}{R}\left|\frac{dR}{dt}\right| << \Omega$)

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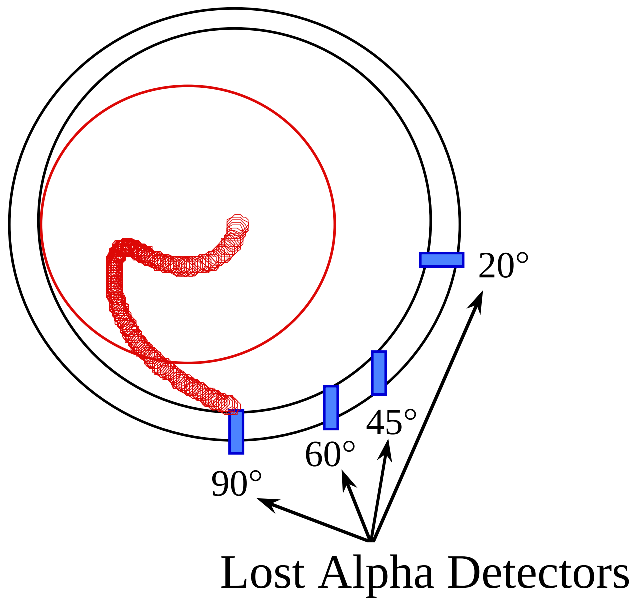
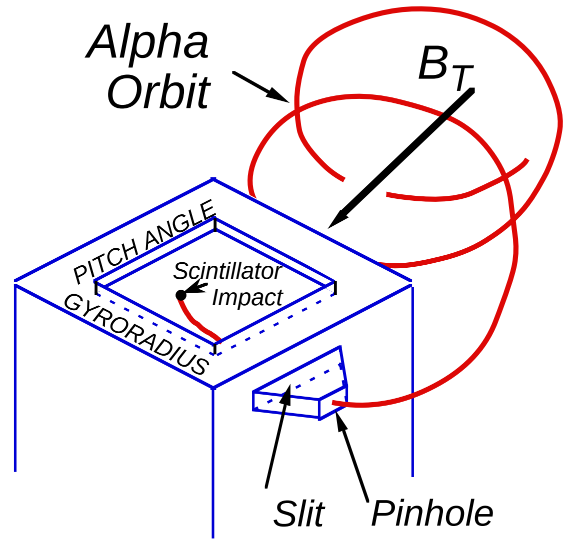
Increased α loss should be detected by the Lost Alpha Detectors





- Scintillator detectors located at 20°, 45°, 60°, and 90° below outer midplane at one toroidal location
- Detectors measure α flux and ρ, χ distributions as a function of time
- All results shown are from 90° detector

Physics Model: R Shifts might reveal physics of alphas near the Passing/Trapped Boundary

Pitch Angle Scattering of α's across the Passing/Trapped Boundary results in Collisional Nonprompt Loss (CNPL)

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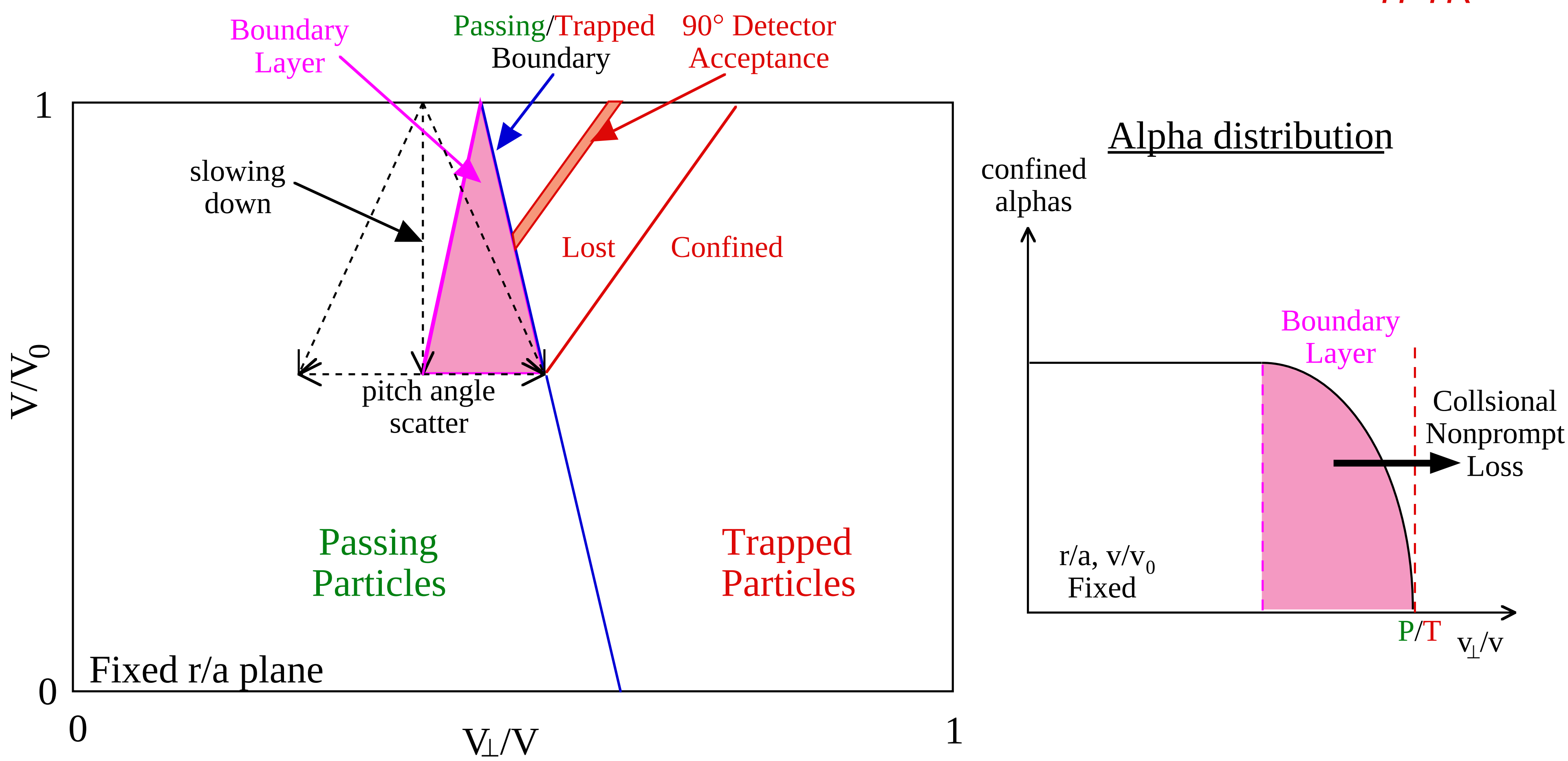
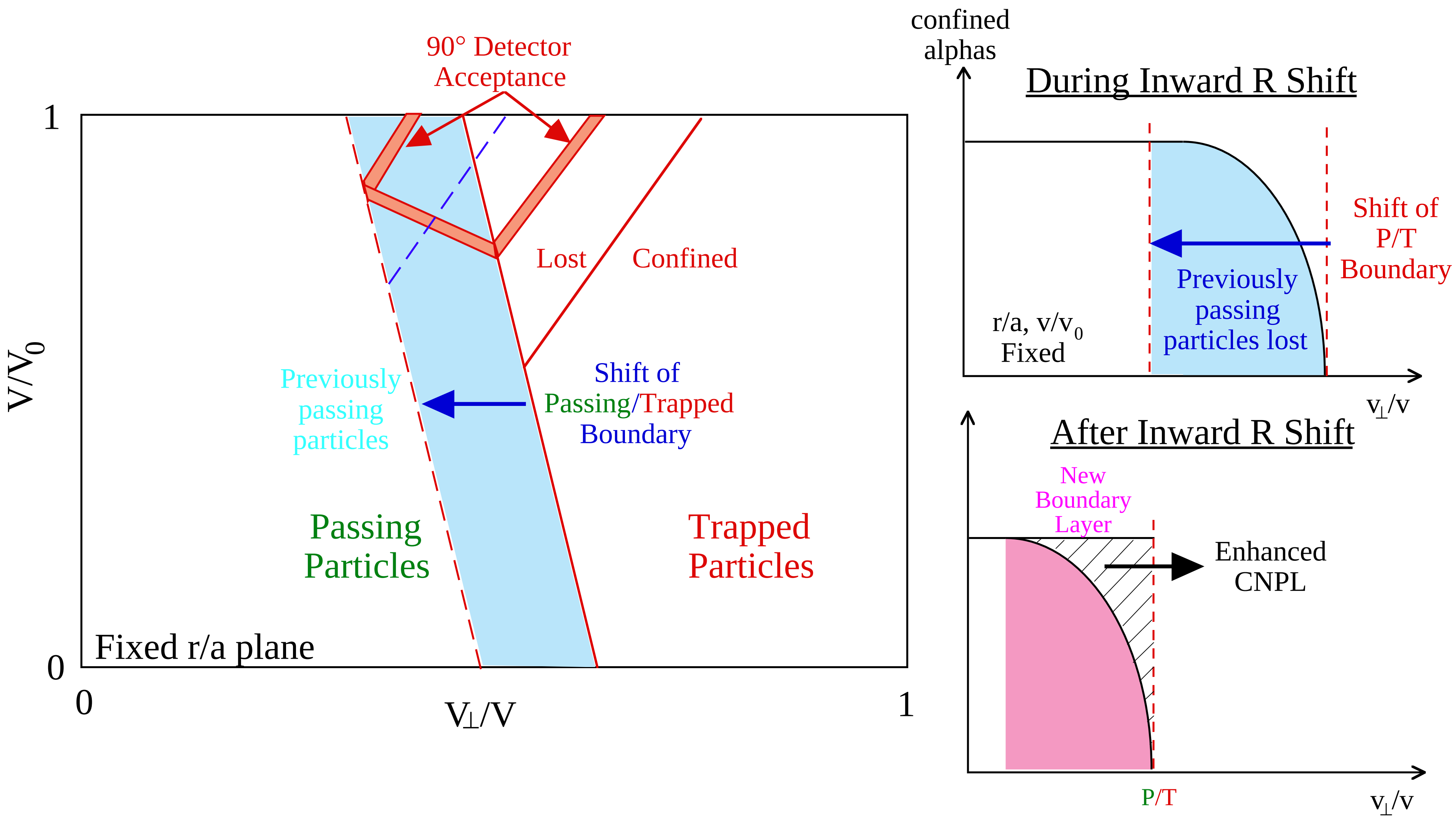


- Paramaters plotted for α's **Outer Midplane Crossing Point** of counter-going α's
- Although $\nu_{SD} \gg \nu_{90^\circ}$, small angle scattering is sufficient for marginally confined particles to cross the P/T Boundary
- Slope in the particle distribution function inside Boundary Layer leads to a diffusive flux of Collisional Non-prompt Loss

Ref: C.S. Chang

Inward R shift might allow experimental verification of CNPL



- Model assumes E & (r_{mp}/a) remain constant during shift (where r_{mp} is the minor radius at the outer midplane crossing point)
- Inward R Shift $\Rightarrow$ shift of P/T Boundary releasing previously confined passing particles
- After Inward R Shift $\Rightarrow$ more fully populated Boundary Layer leading to an enhanced CNPL

Comparison of model and actual R Shift showed reasonable agreement

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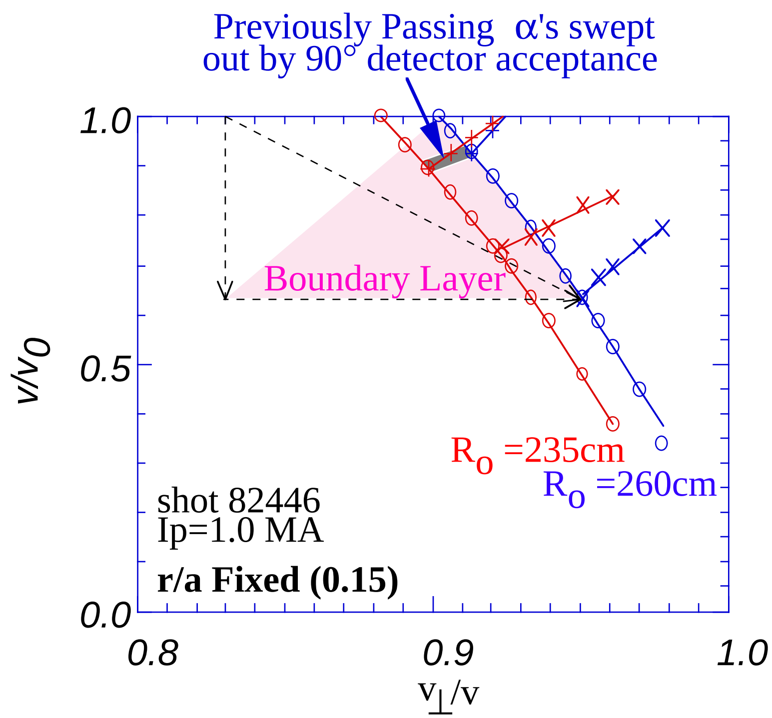

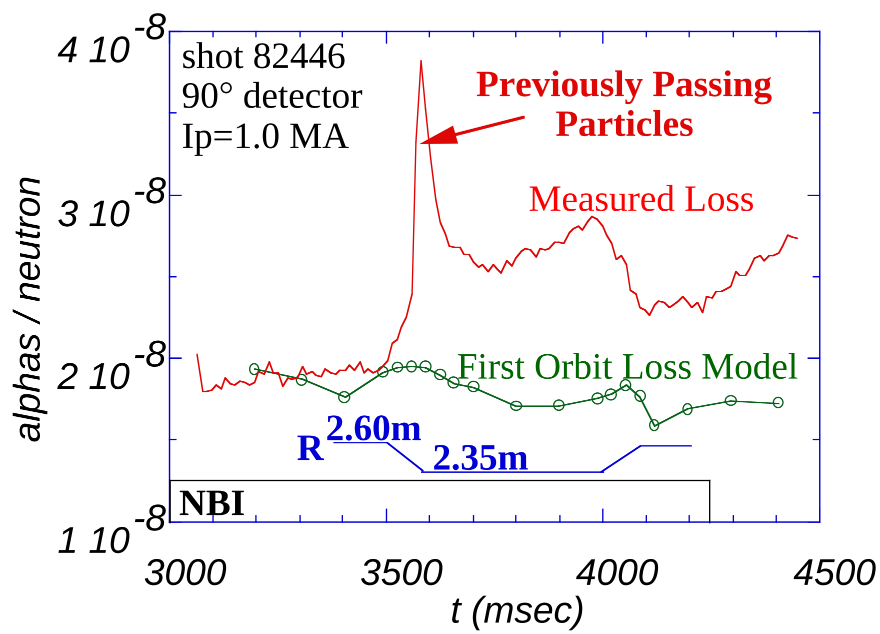

- Loss estimates using r/a=0.15
  - Max loss increase ≈ 100% (~ 50% increase measured)
  - Energy of nonprompt loss ≈ 0.8 E_0 $\Rightarrow$ ~3% drop in $\bar{\rho}$ (consistent with measured drop)

- However, strong MHD during R Shift might also explain observations

R Shift experiment developed to test model

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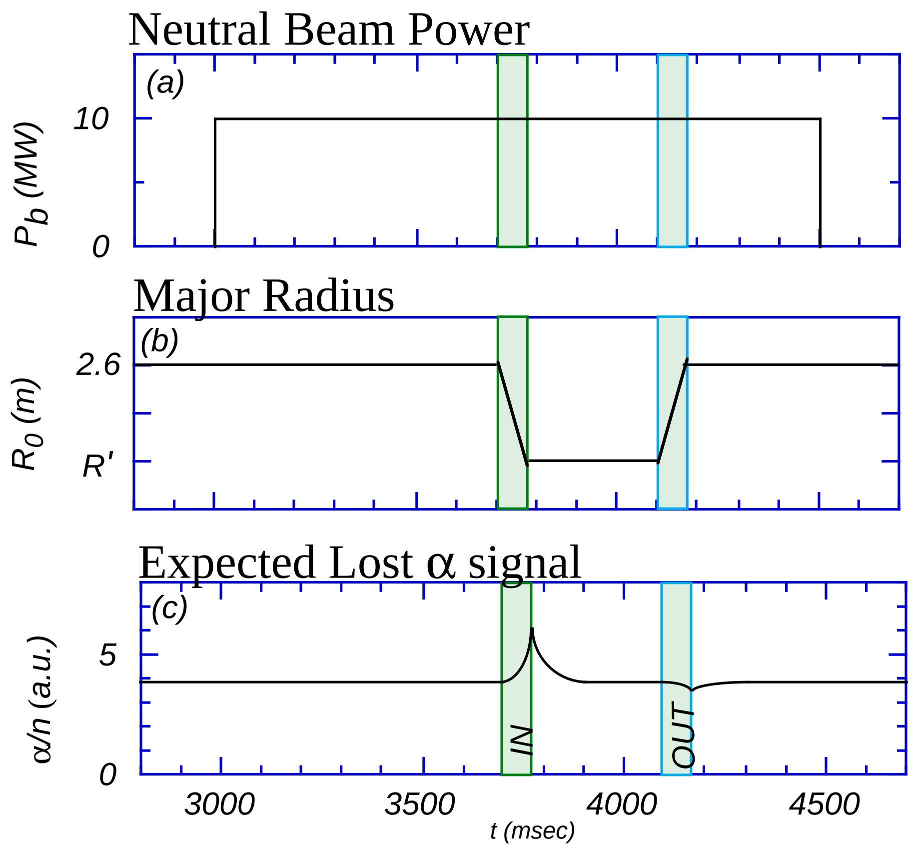

- 80 ms R shift from 2.6 m to R' during IN at 3.7 s, & back to R' during OUT at 4.1 s
  R' = 2.4 m for I_p = 1.0 & 1.4 MA
  R' = 2.5 m for I_p = 1.8 MA (to avoid disruption)
- Current Scan (1.0, 1.4, 1.8 MA shifts)
- Baseline shots without R shifts done for comparison
- Primary Expectation: to see increase in loss of partially thermalized α's at the Passing/Trapped Boundary during IN shift

Experimental Results: Disagreement with original model

Results of R shift experiment do not agree with original expectations

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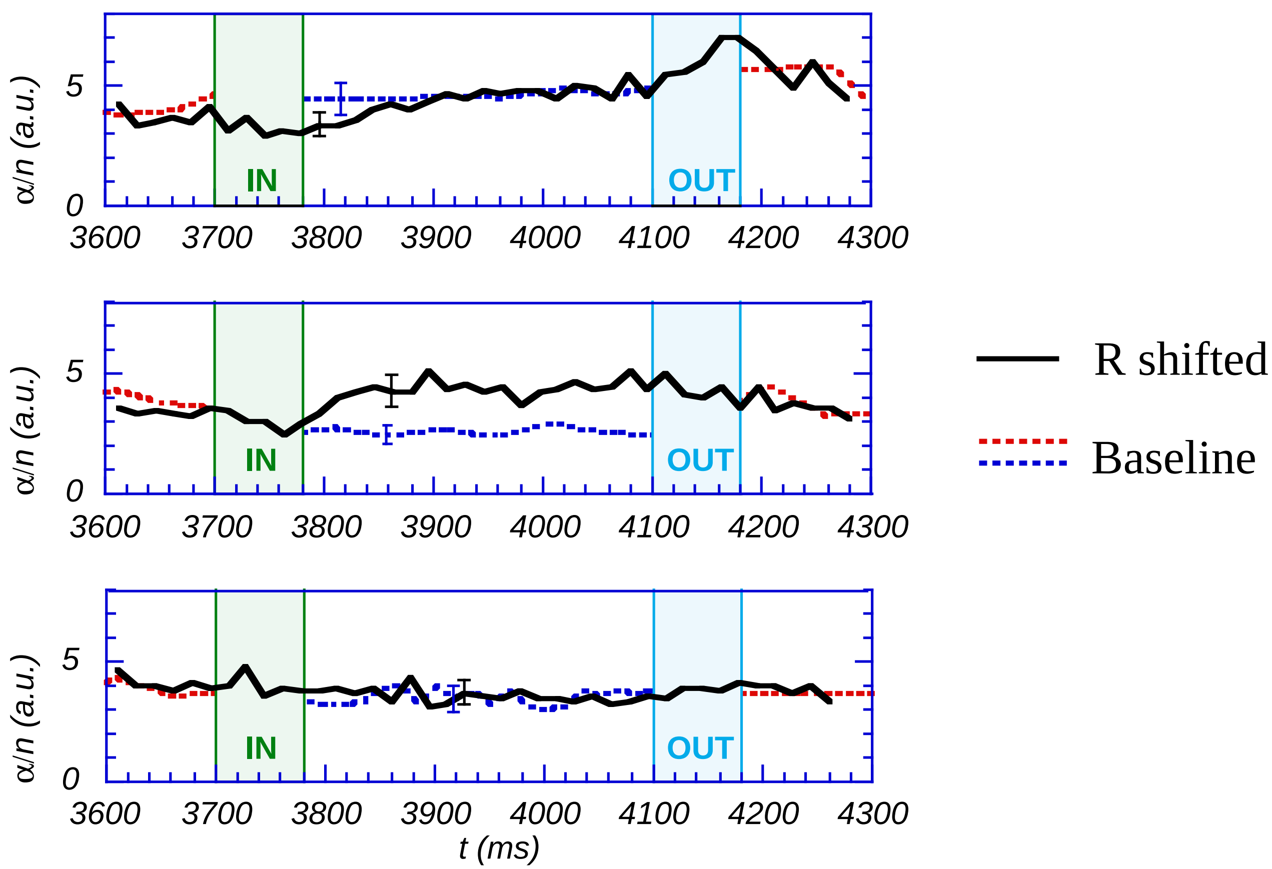
90° Lost Alpha signals

Ip

1.0 MA

1.4 MA

1.8 MA



- The expected increase of neutron normalized α loss during the IN shift was not observed
- Unexpected increase of α loss between IN & OUT shift was observed at 1.4 MA

Gyroradius measurements support existence of anomalous loss at 1.4 MA

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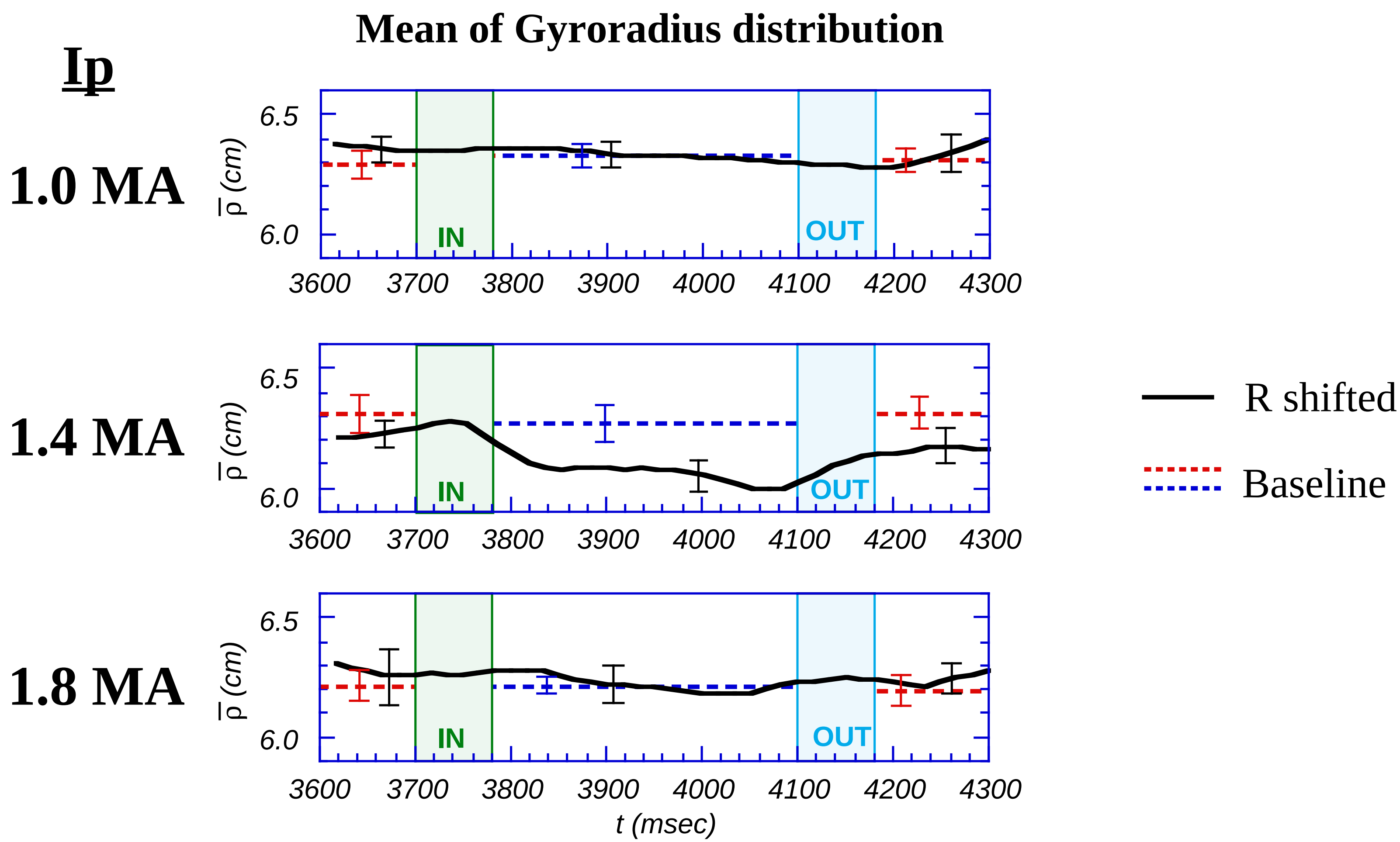

- Mean of gyroradius distributions ($\bar{\rho}$) as measured with the 90° Lost Alpha detector shows the existence of a partially thermalized loss between the IN & OUT shifts at 1.4 MA

Pitch Angle measurements also support anomalous loss at 1.4 MA

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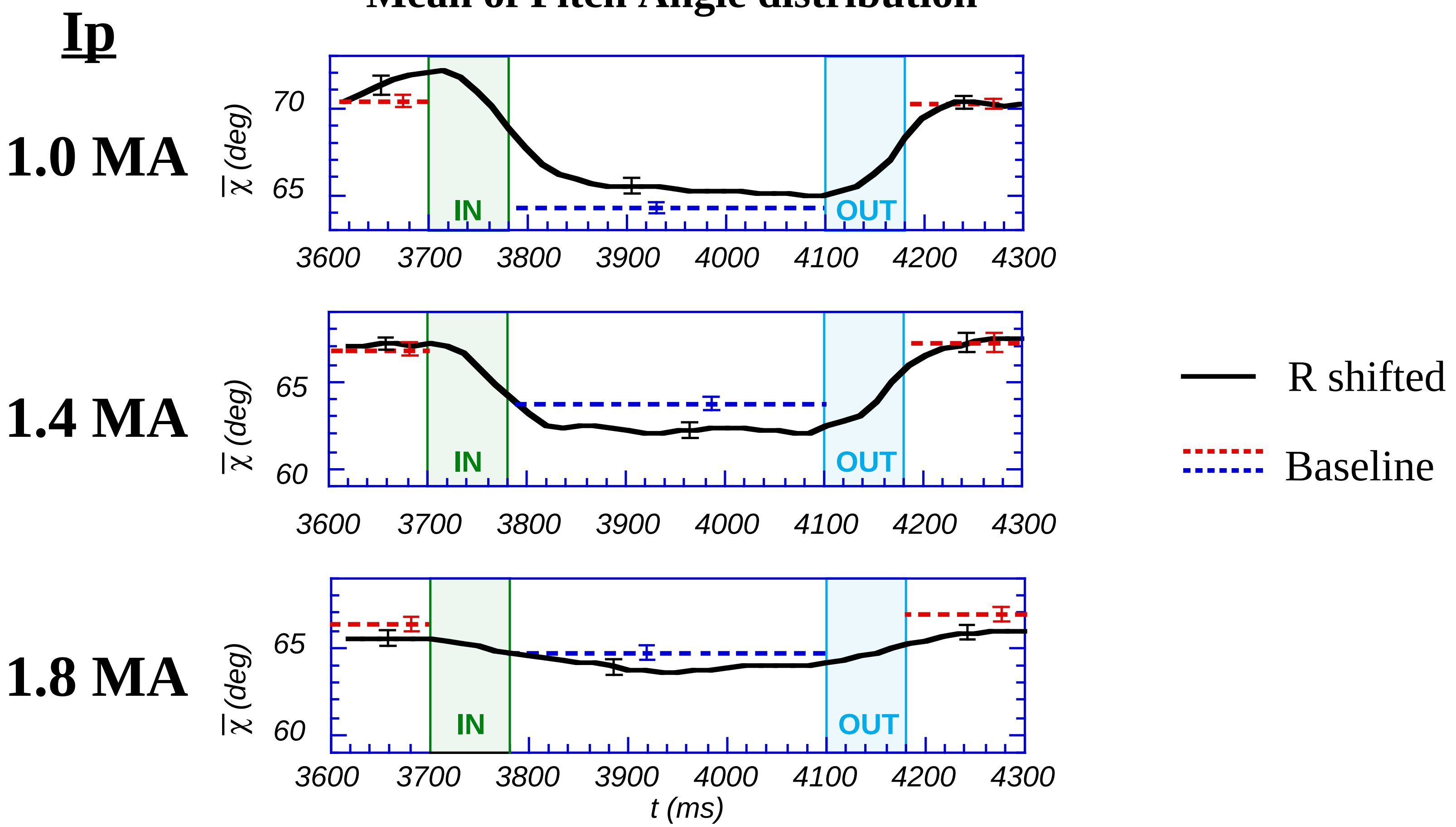
Mean of Pitch Angle distribution



- Mean of pitch angle distribtions (χ) as measured with the 90° Lost Alpha detector shows the existence of a loss between the IN & OUT shifts at 1.4 MA with a reduced χ
- Inspection of χ distributions between shifts shows that anomalous loss is consistent with loss at the Passing/Trapped boundary $\Rightarrow$ Collisional pitch angle scattering across boundary

Summary of Experimental Results

Results disagree with original model:

- R Shifts produced insignificant changes in α loss during shifts

- 1.4 MA R Shift produced unexpected α loss $\Uparrow$ between the shifts
  - $\Uparrow$ accompanied by $\Downarrow$ in $\bar{\rho}$ & $\bar{\chi}$
  - $\Uparrow$ takes ~ 70 ms to reach steady state ($\approx$ collisional time scale)

$\Rightarrow$ Anomalous loss of partially thermalized α's crossing the Passing/Trapped Boundary at 1.4 MA

Improved Model: *Revised assumptions and improved theoretical tools help to explain the disagreement*

Invariants (μ,P_ϕ) provide ideal phase space to study R shifts

TFTR

- New formalism based on **Guiding Center** equations of Hsu & Sigmar & M.C. Herrmann's Fast Orbit Solver
- α's remain **stationary** in (μ,P_ϕ) space
- **E and r/a** no longer assumed to be conserved
  - Change in r/a implicit in new formalism
  - Change in E estimated from Gorelenkov

≈0 for marginally passing α

$$\Delta E \approx E\,\frac{\Delta R_{\text{mag axis}}}{R_{\text{mag axis}}}\left(1+\frac{\langle E_{\|}\rangle}{E}\right)$$

- A **fixed point in real (R,Z) space** transforms into an **inverted parabola in (μ,P_ϕ) space**:

$$\mu = \frac{E_\perp}{B} \quad , \; P_\phi = mRv_\phi - \frac{e}{c}\Psi_p$$

$$\Rightarrow \; \mu = \frac{E}{B(R,Z)} - \frac{B(R,Z)}{2\,mR^2 B_\phi^2(R,Z)}\left(P_\phi - \frac{e}{c}\Psi_p(R,Z)\right)^2$$

  - Parabola apex at v_ϕ=0
  - Right (Left) leg of parabola $\Rightarrow$ v_ϕ>0 (v_ϕ<0)

Boundaries in (μ,P_ϕ) space delineate various orbit classes

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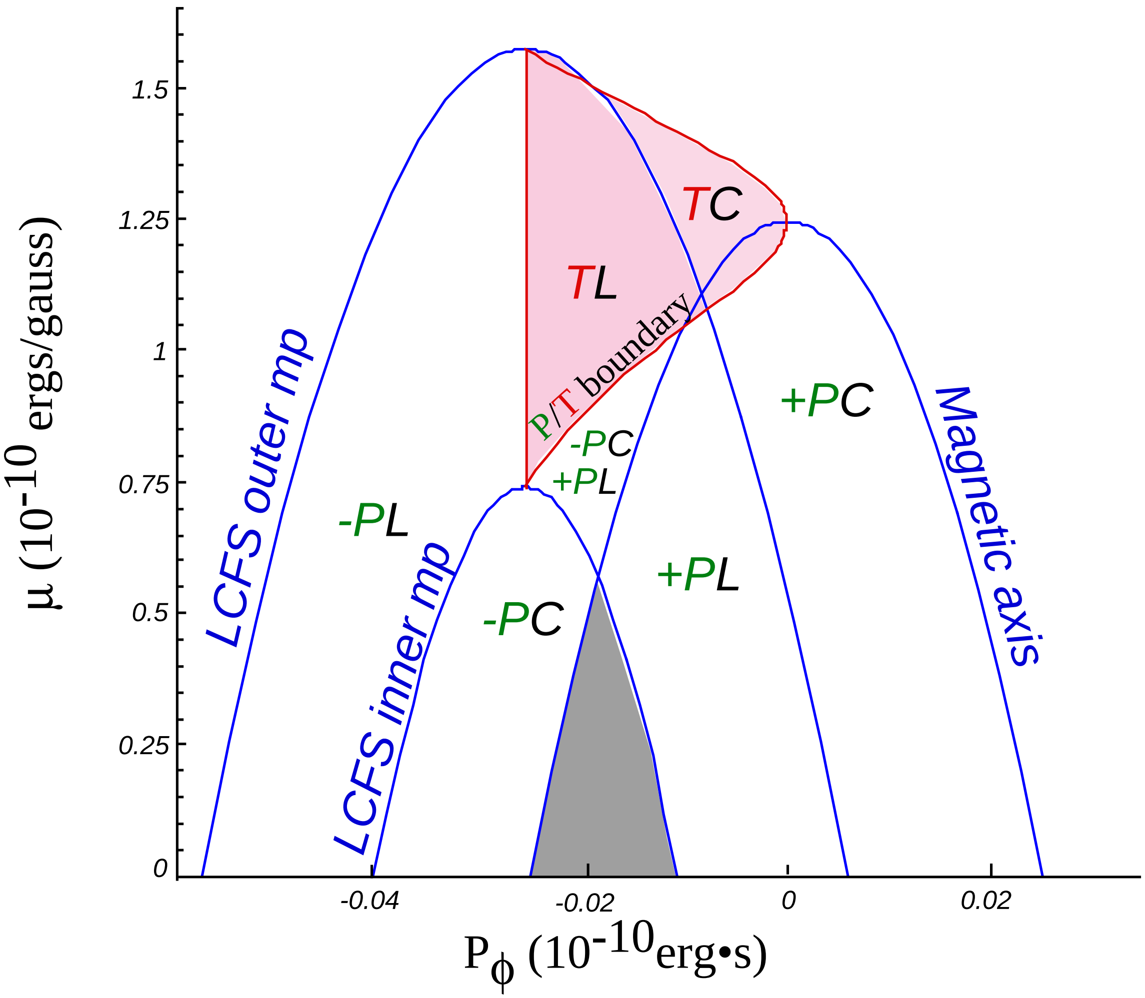

Orbit classes:

T ⇒ Trapped
+P ⇒ co-going Passing
-P ⇒ counter-going Passing

C ⇒ Confined
L ⇒ Lost

- Fixed (R,Z) parabolas bounded by those of Magnetic axis, and inner & outer midplane (mp) of Last Closed Flux Surface (LCFS), such that the apexes of all fixed (R,Z) parabolas lie within the locus of v_ϕ=0 points along the midplane
- Passing/Trapped boundary formed by locus of v_ϕ=0 points along inner midplane from the magnetic axis to the LCFS

magnetic axis to the LCFS

Shift of Passing/Trapped boundary depends on E Shift as well as R Shift

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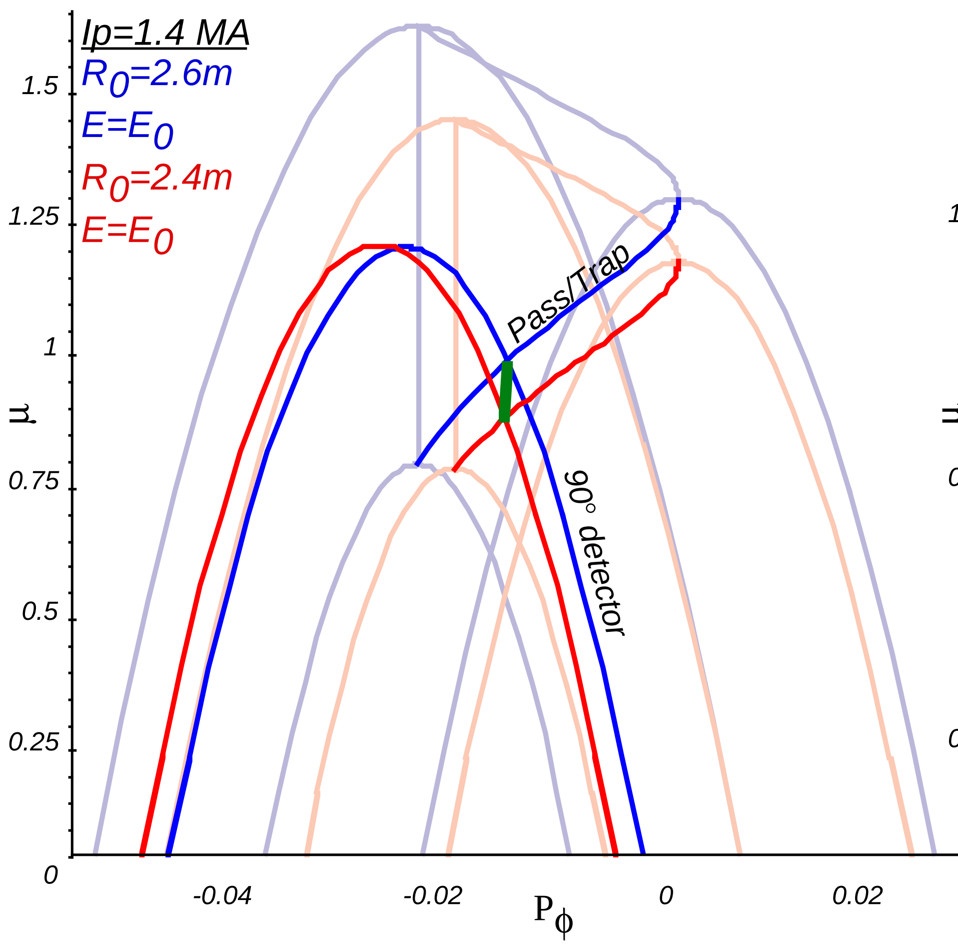
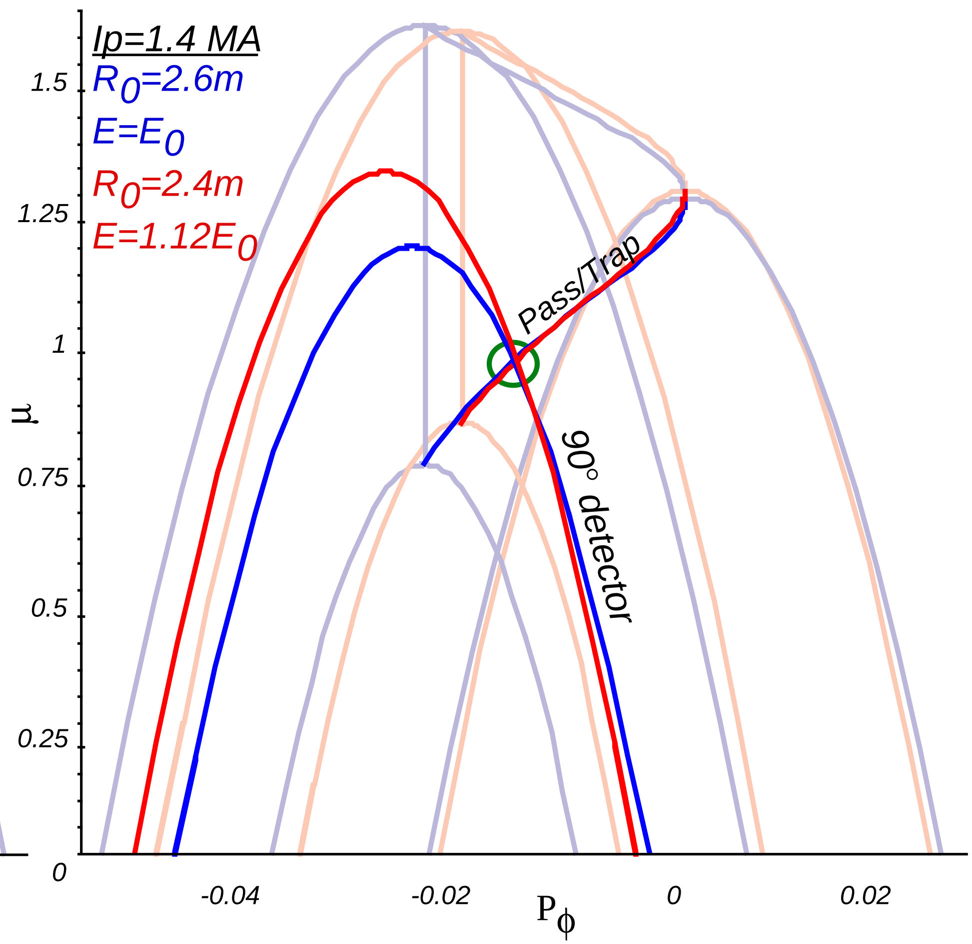
$\Delta E=0$



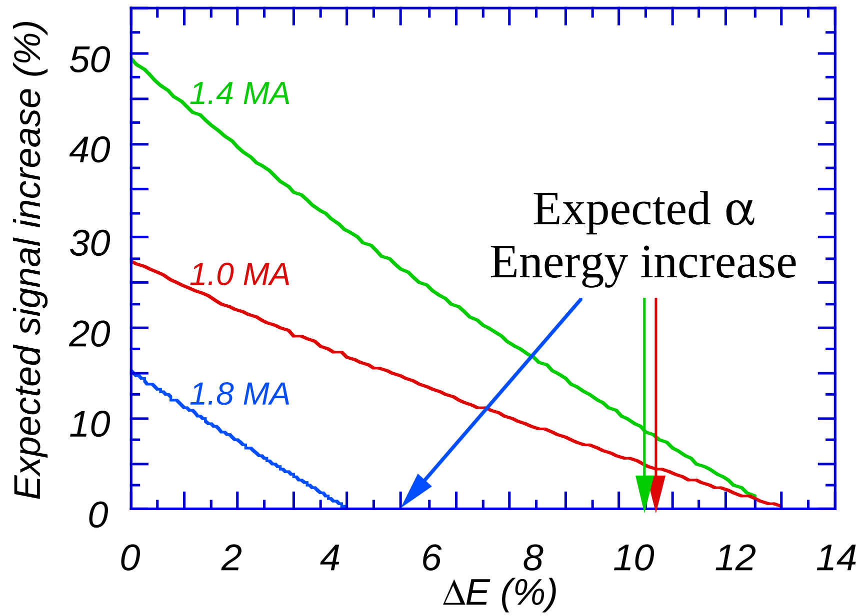
$\Delta E=12\%E_0$



- Assuming alphas gain no energy from R shift, the Passing/Trapped boundary sweeps across previously passing alphas releasing them to the 90° detector

- Energy gain that results in no sweeping of the Passing/Trapped boundary can be found
- In this 1.4 MA case, a 12% energy gain results in no additional loss of α's

Energy increase during R Shift explains disagreement with original model



- The expected 90° Lost Alpha detector increase is estimated by comparing the region swept out by the Passing/Trapped Boundary due to the R Shift and the First Orbit Loss region, weighting each region by the source profile and taking into account the α build up time vs the Shift rate
- 1.0 MA expectation reduced by the fact that the α energy must be below ~$0.8E_0$ before the banana width is small enough for fattest bananas to strike the wall at $\theta_p \leq 90°$
- Collisional Nonprompt Loss tends to make the possibility of increased α loss even less likely due to the partial depletion of marginally passing α's