Fast Ion Loss During Applied 3D Magnetic Perturbations on DIII-D

by

M.A. Van Zeeland[1]

with X. Chen[1], N.M. Ferraro[1], M. Garcia-Munoz[3], W.W. Heidbrink[2], G.J. Kramer[5], C.J Lasnier[8], D.C. Pace[1], S.L. Allen[8], T.E. Evans[1], J.M. Hanson[4], L. Lao[1], M.J. Lanctot[1], W.H. Meyer[8], R. Nazikian[5], R.A. Moyer[6], D.M. Orlov[6], C. Paz-Soldan[1], M. Shafer[7], A. Wingen[7]

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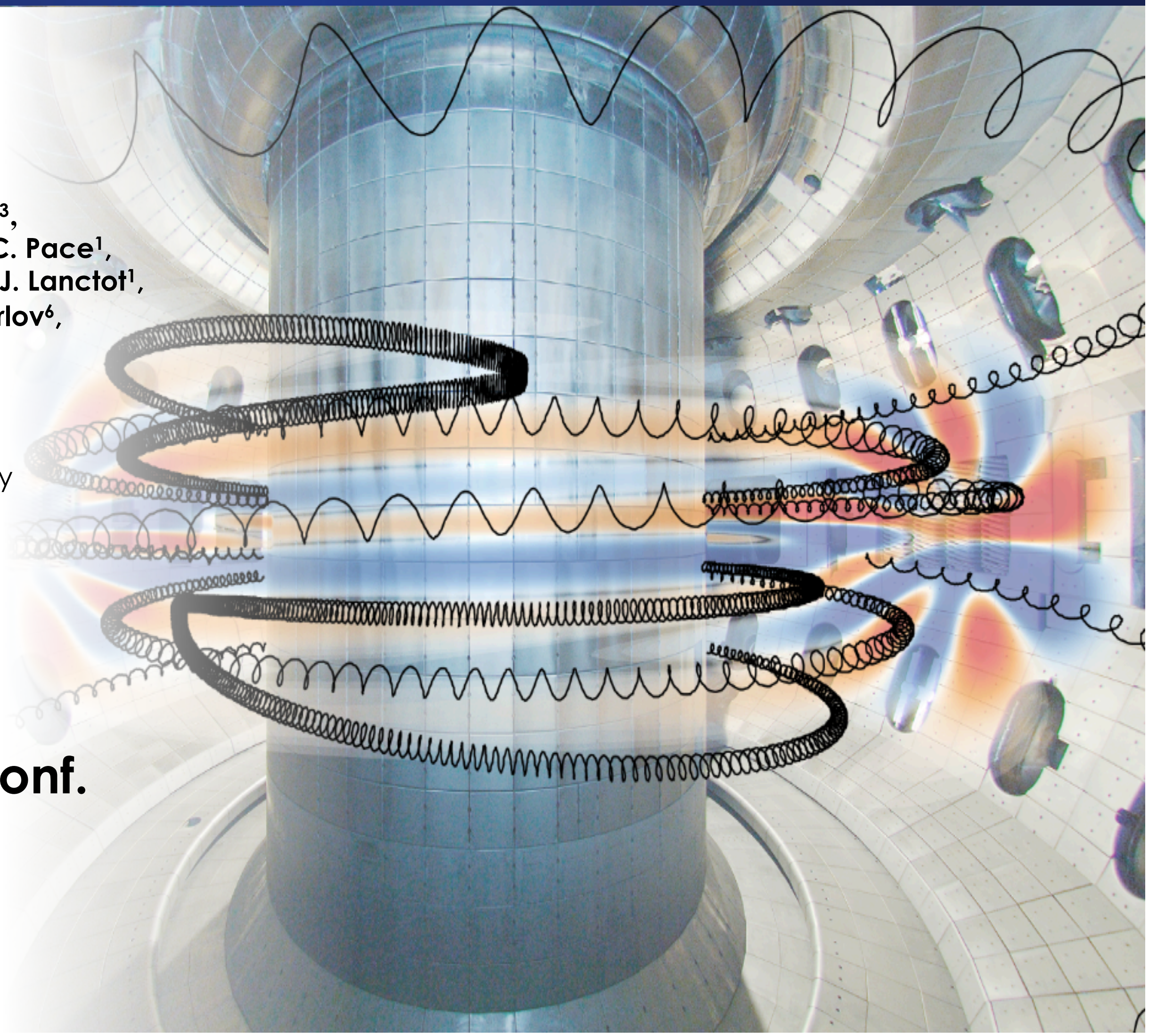
[4]Columbia University, New York, NY, USA
[5]PPPL, Princeton, NJ, USA
[6]University of Calif.-San Diego, CA, USA
[7]ORNL, Oak Ridge, TN, USA
[8]LLNL, Livermore, CA USA



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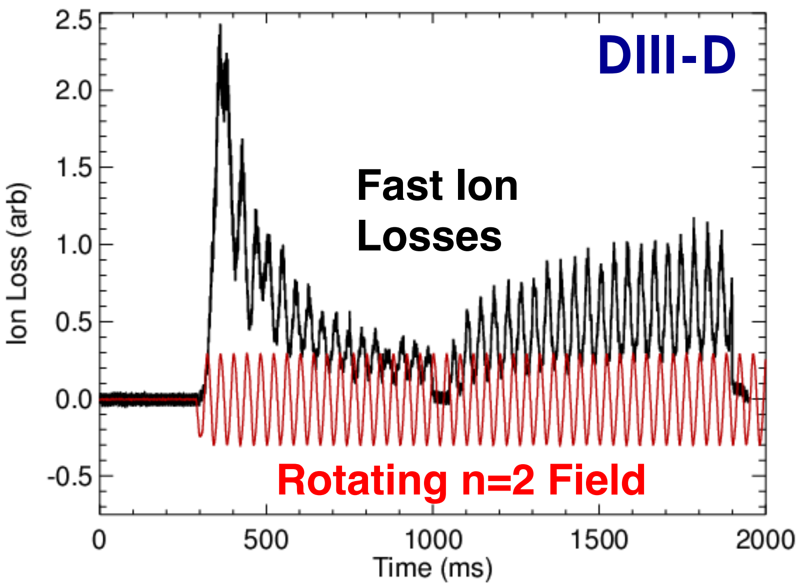
October 13–18, 2014

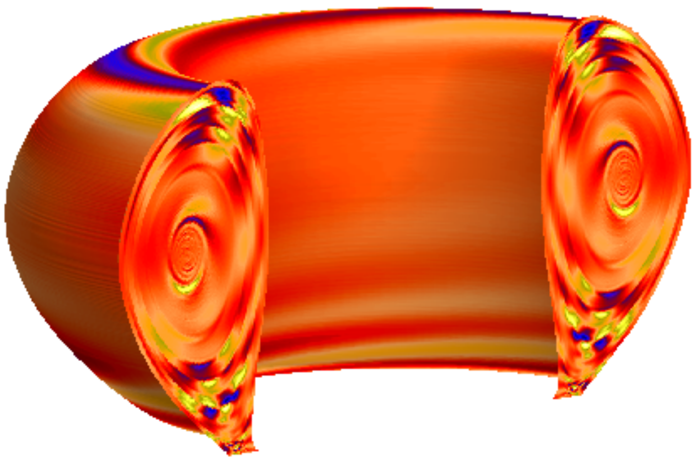
3D Fields Such as Those from ELM Coils or Test Blanket Modules Can Significantly Alter Fast Ion Confinement



- **Simulations show ELM mitigation coils can induce 5% (or more) loss of beam ions in ITER[1,2]**
  - Potential source of wall damage
- **3D fields can also increase losses from core MHD that would otherwise only cause redistribution[6]**
- **On DIII-D, 3D field induced losses have been observed from several sources – TBM[3] and internal coils[4]**
- **Besides obvious negative consequences, potentially positive use as a energetic particle (EP) control tool[5]**

[1]K. Shinohara, et al., NF **51** (2011)
[2]T. Koskela et al., PPCF **54** 105008 (2012)
[3]G.J. Kramer, et al., NF **53** (2013)
[4]M.A. Van Zeeland, et al., PPCF, **56** (2014)
[5]A. Bortolon, et al. PRL (2014)
[6]M. Garcia Munoz, NF (2013)

Goal is to Measure, Understand, and Be Able to Predict Impact of 3D Fields on Fast Ion Confinement in DIII-D & Future Devices



M3D-C1 δB, n=2

Outline

- Introduction to relevant diagnostics, hardware, and modeling approach
- Modulation of prompt beam ion loss by rotating 3D fields
- Evidence for the importance of plasma response in modeling of 3D field induced EP losses
- Large edge EP transport in RMP ELM suppressed plasmas
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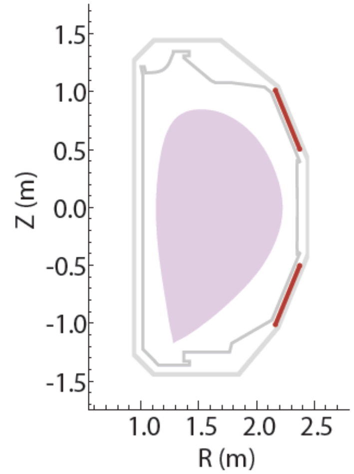
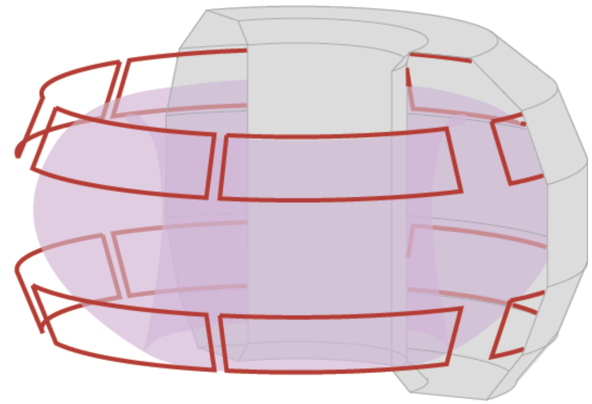
In These Experiments an Array of Fast Ion Diagnostics is Employed to Measure the Impact of I-Coil Induced 3D Fields

3D Fields

- **I-coils (6+6 coils above/below midplane)**
- **n=1-3 (can rotate n=1 and n=2, convenient for toroidally localized diagnostics)**
- **Typical peak $\delta B/B$ in plasma ~10^{-3}**





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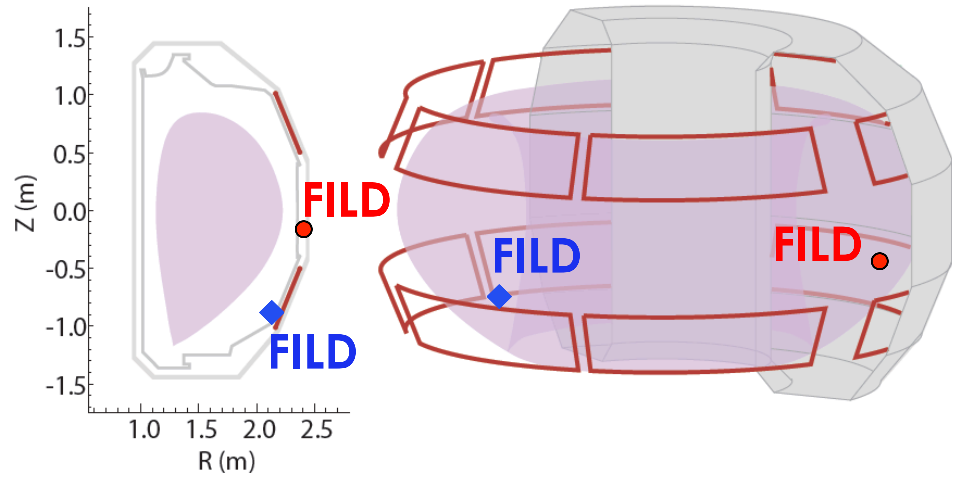
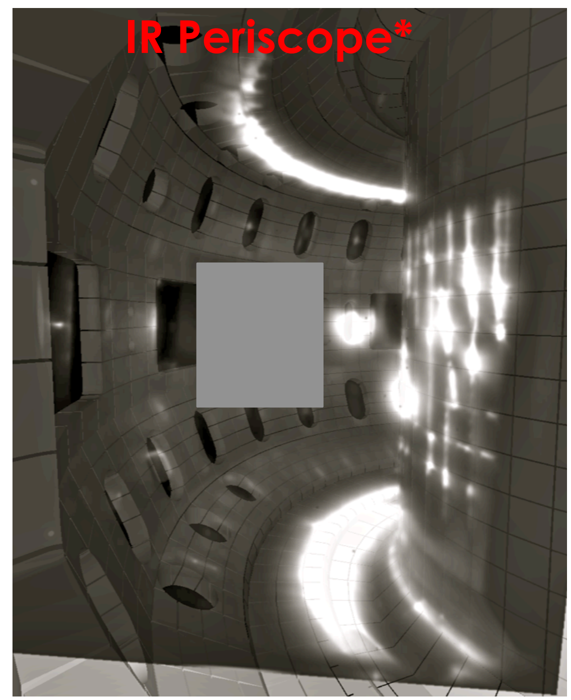


Fast Ion Measurements

- Fast Ion Loss Detectors (FILD)
- IR Imaging - heat load of lost EPs
- Fast Ion D-alpha (FIDA) – Impact on confined fast ion profile



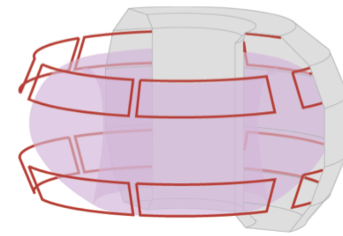
*C. Lasnier, et.al. RSI 2014

Modeling Uses Full Orbit Following Combined with M3D-C1* Calculated Fields and Monte Carlo Birth Profile Calculations

*N.M. Ferraro and S.C. Jardin, J. Comput. Phys. 228, 7742 (2009)

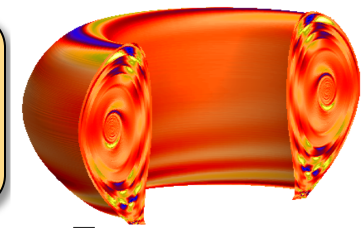
Single Timestep:

Applied Coil Currents, Equlibrium and Measured Profiles of n_e, T_e, T_i, etc



M3D-C1

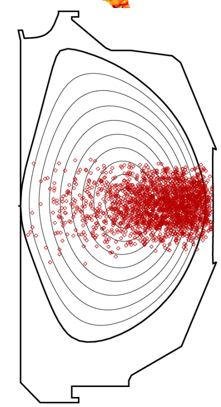
Calculate vacuum δB spectrum, plasma response to single-n including δB, δn_e, δP, etc.



B+ δB

Equil. kinetic profiles + δn_e

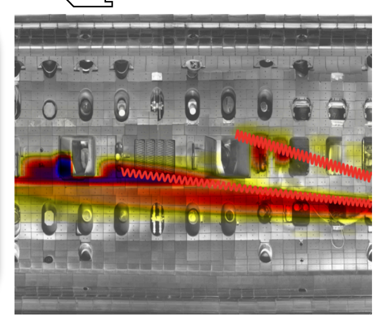
Calculate beam ion birth profile



Full Orbit Following

Prompt loss: Follow particles >1 bounce period, no scattering. Collect particles at FILD and wall.

Long timescale: Follow particles w/ SPIRAL[1] ~slowing down time, include scattering, drag. Gives impact on confined and lost.



[1]Kramer G..J., et al., Plasma Phys. Control. Fusion **55** (2013) 025013

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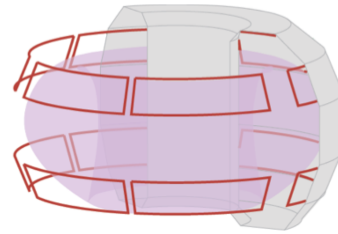

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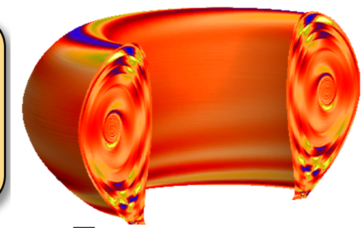


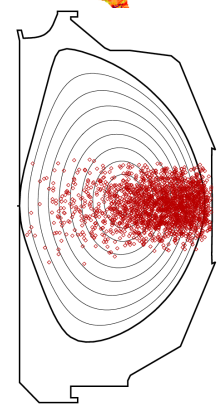
Repeat for:

- **Several different phases of applied field**
- **Different beams**
- **Different amplitudes**
- **Different energies**
- **Vacuum fields or w/ plasma response**

B+ δB

Equil. kinetic profiles + δn_e

Calculate beam ion birth profile



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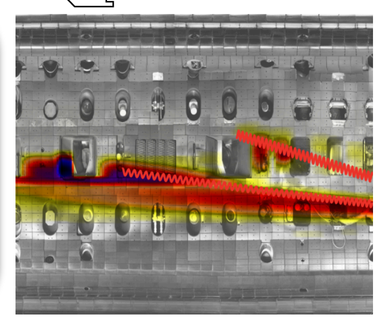

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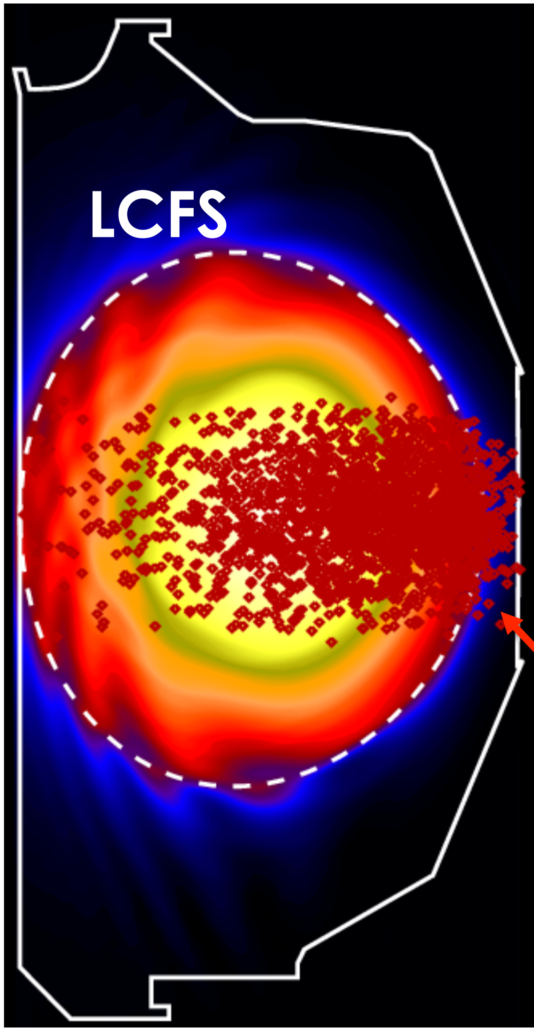
New Beam Ion Birth Profile Calculator Developed For Analysis of 3D Field Induced EP Transport Experiments



- **3D fields distort kinetic profiles[1] causing change in beam deposition**
- **Density, temperature, and impurity density interpolated on several rays representing neutral beams**
  - Profiles can have arbitrary 3D spatial dependence
  - Example: M3D-C1 calculated density during n=2 (*Amp x2.5*)
- **Significant deposition can occur outside of last closed flux surface (LCFS)**

[1]R.A. Moyer, et.al. Nucl. Fusion 52 (2012) 123019

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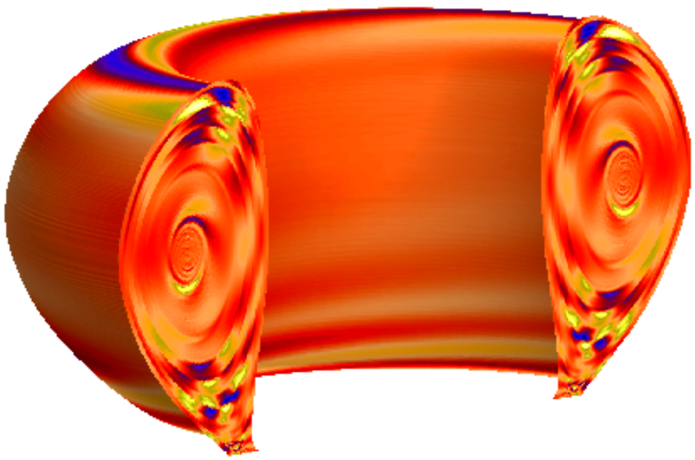

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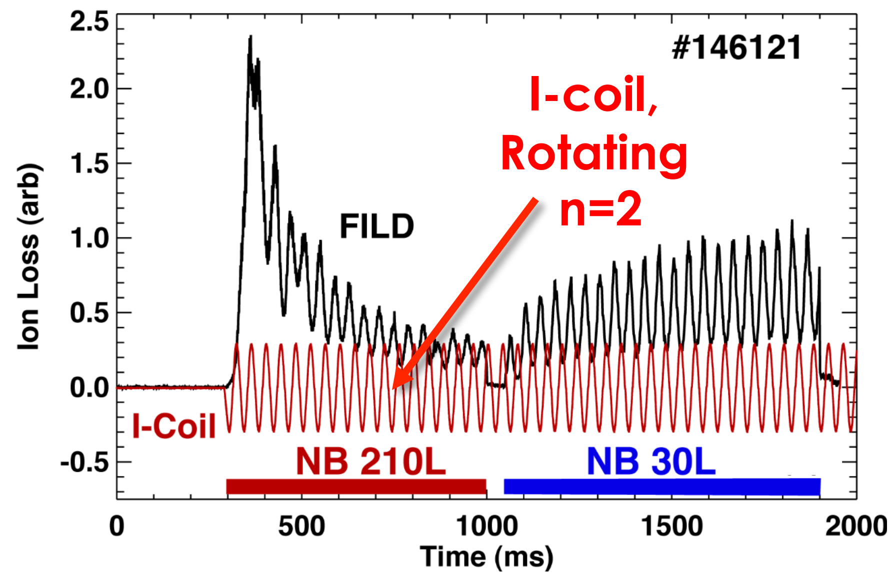
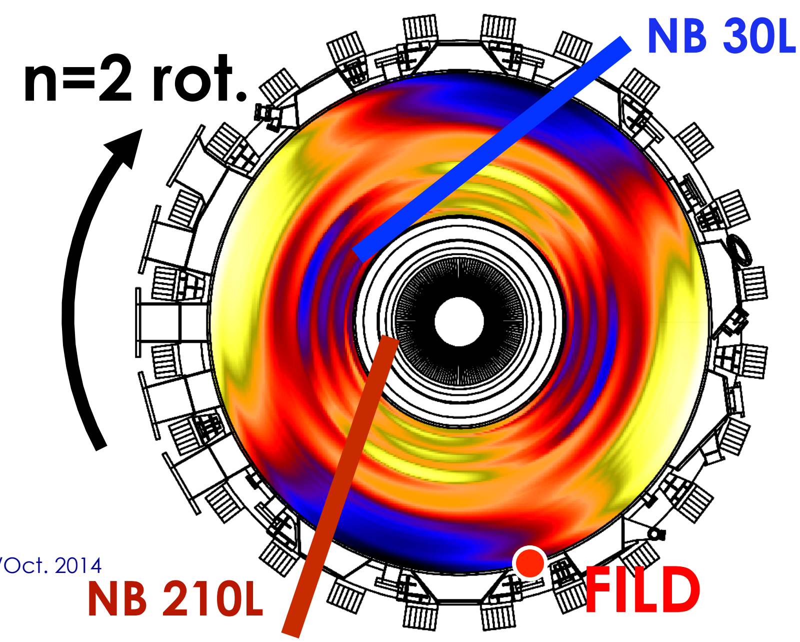
FIELD Measurements Show Modulation of Losses at I-coil Rotation Frequency in Low-Current L-mode Discharge

- **L-mode discharge with 25Hz rotating n=2 field**
  - Two separate beams: co-current NB30L, counter-current NB210L
  - Perturbation rotates past beams and FILD ➔ many points for comparison





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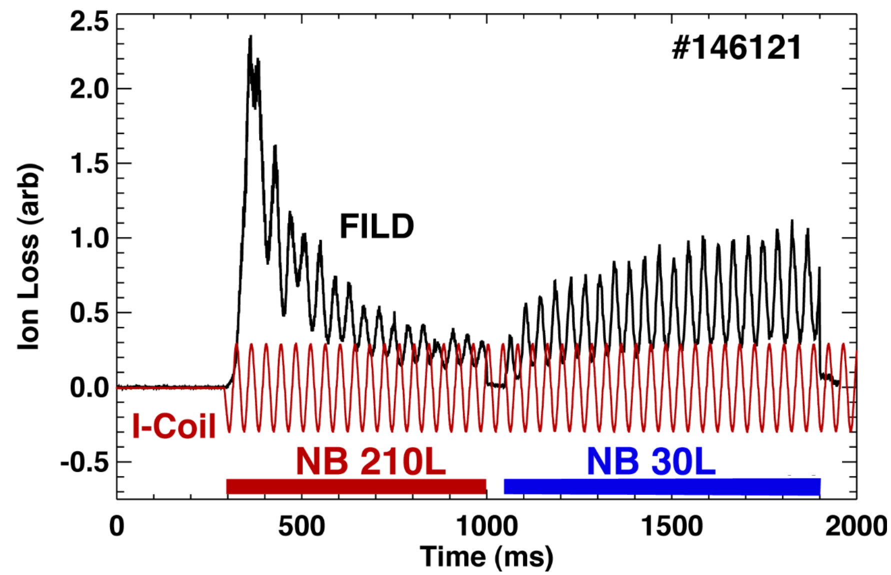
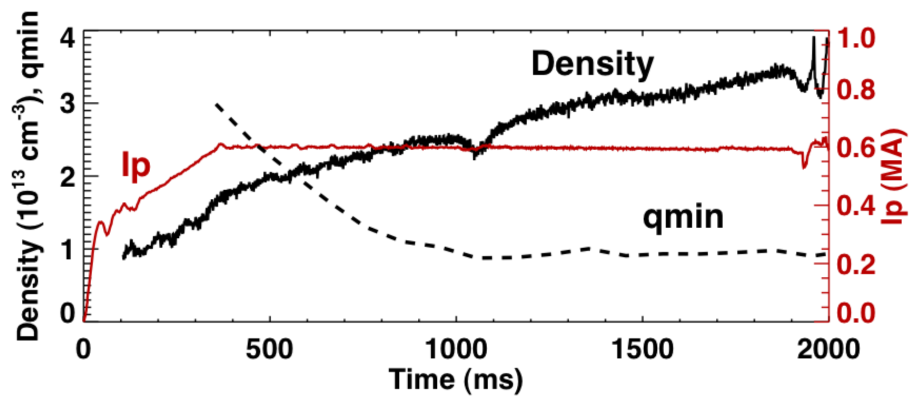
- **Modulated FILD signal changes with beam and as current and density profile evolve**





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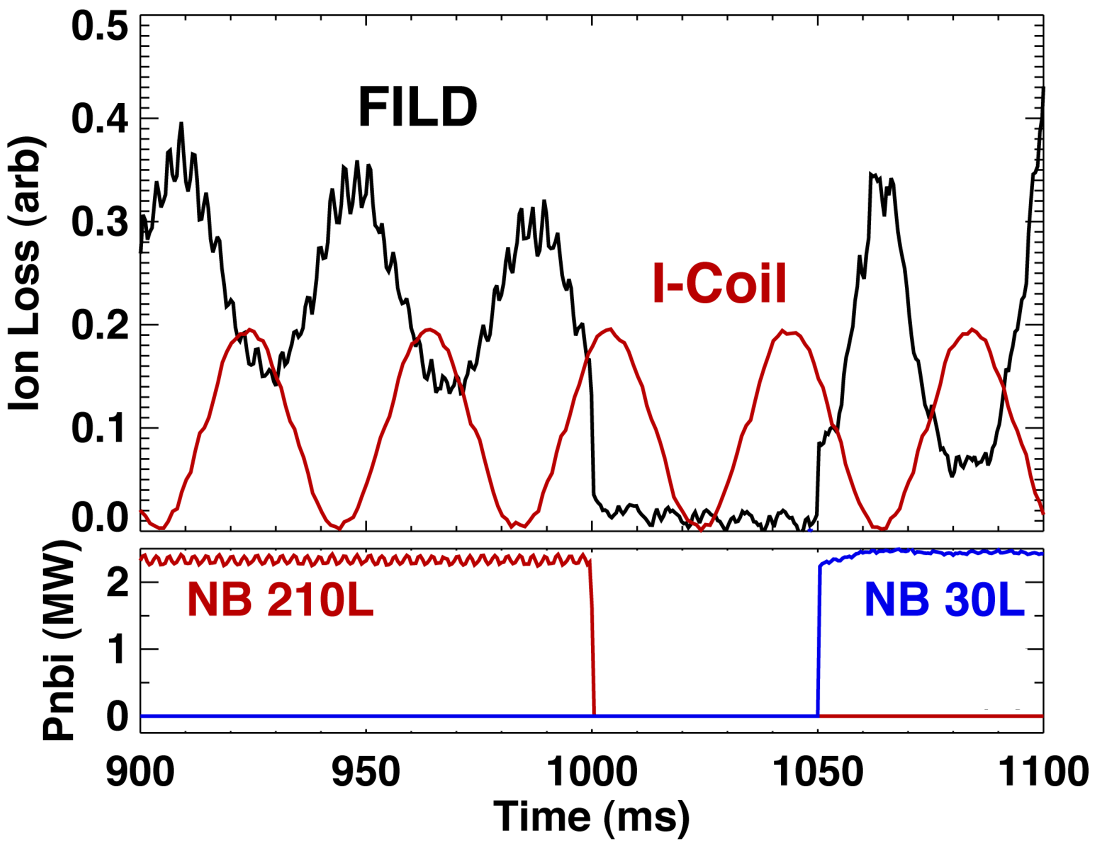
Measured Loss at FILD in These Plasmas Is Dominated By Prompt Loss (First Orbit Loss)



- **Loss decays within 20μs after beam turn-off (~1 Bounce Period)**
- **210L power fluctuations show up directly in loss signal**

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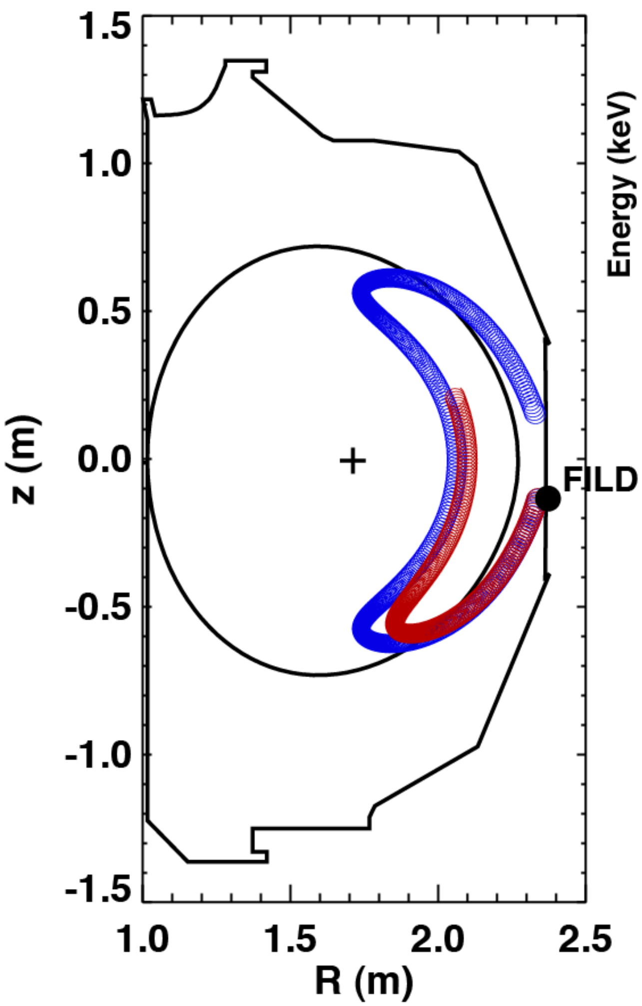
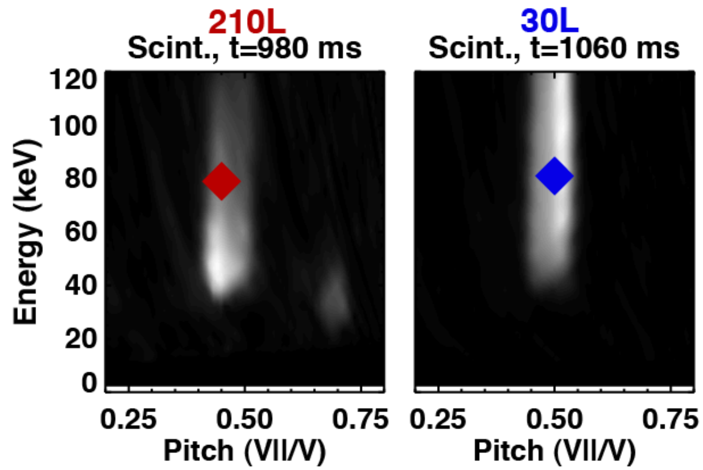
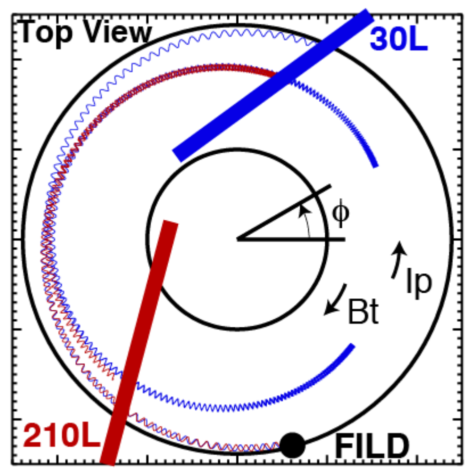
Using Measured Energy and Pitch of Losses, Reverse Orbit Tracing Shows Approximate Trajectories



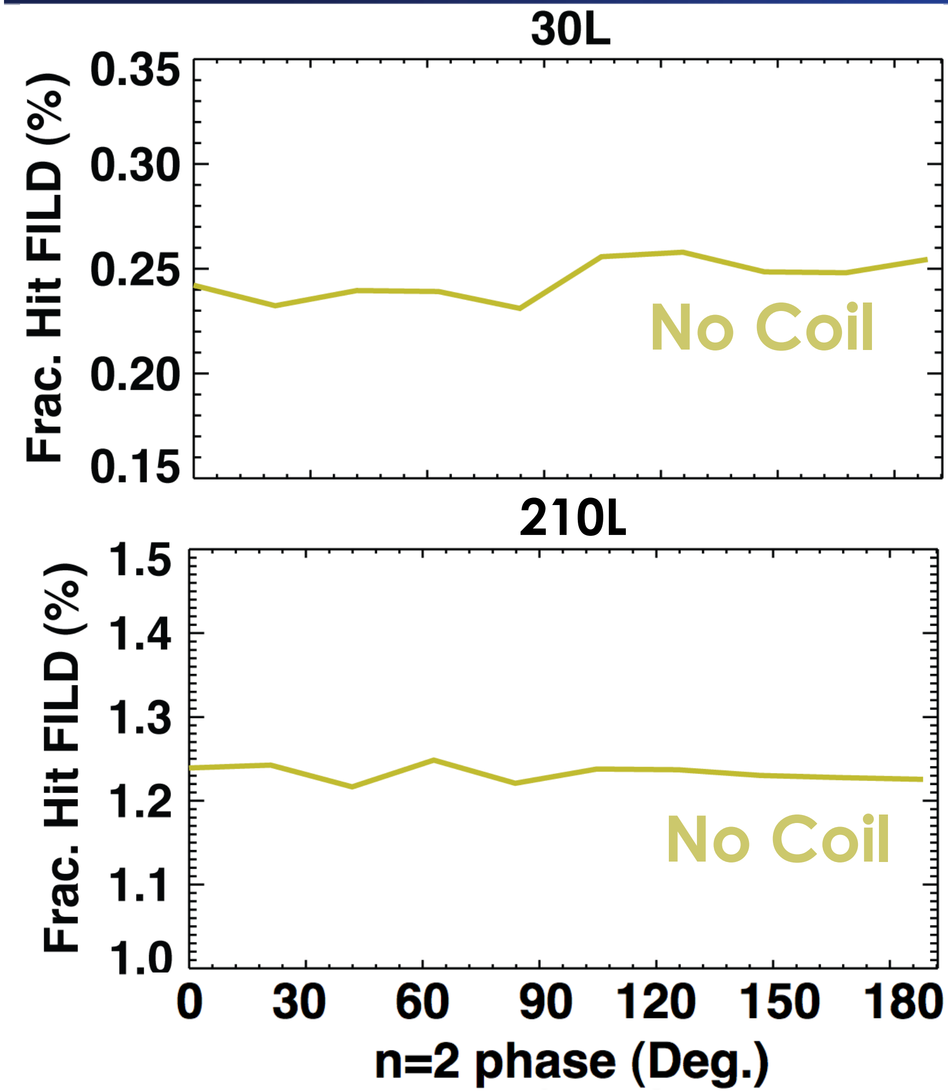




- Full-energy (~80kV) orbits are followed backward until they overlap the corresponding beam
- 210L ions born at mid-radius in core
- 30L ions come from outboard midplane in scrape-off-layer
- To properly model observed signals, *must* include SOL ionization

M. Van Zeeland/IAEA/Oct. 2014

Particles From Each Beam Followed at Several Phases of n=2 and Collected at Wall or FILD



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- **No Coil case shows statistics and prompt loss levels**

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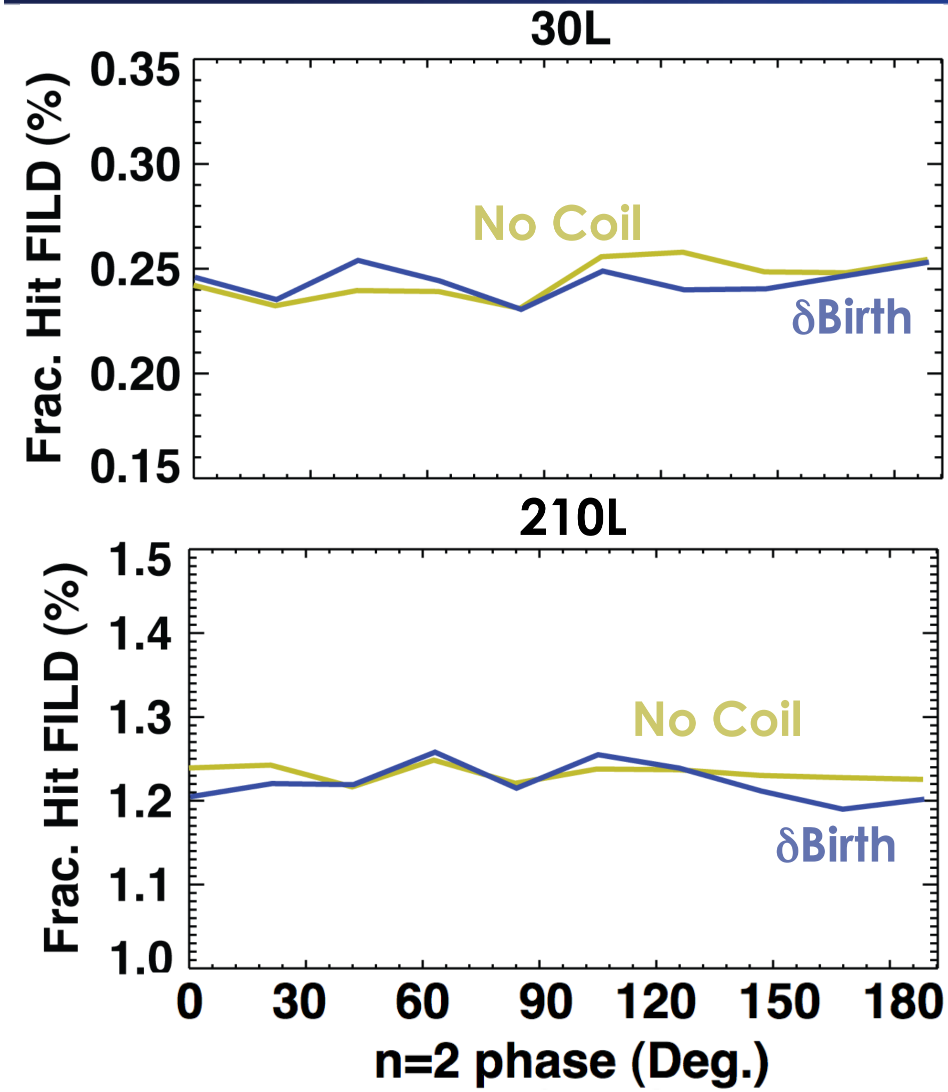

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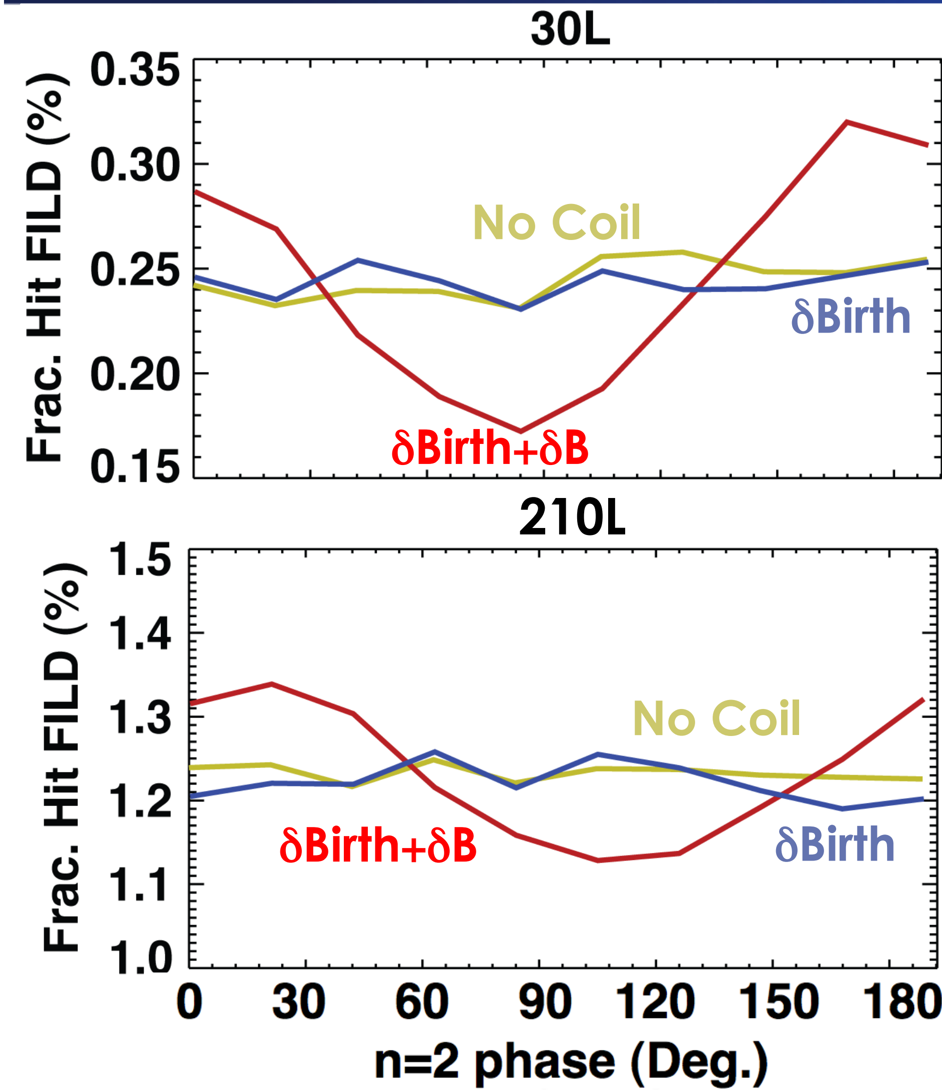

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- **δBirth+δB – Perturbed fields and birth profile**
  - clear modulation of losses with different phase for 210L and 30L losses

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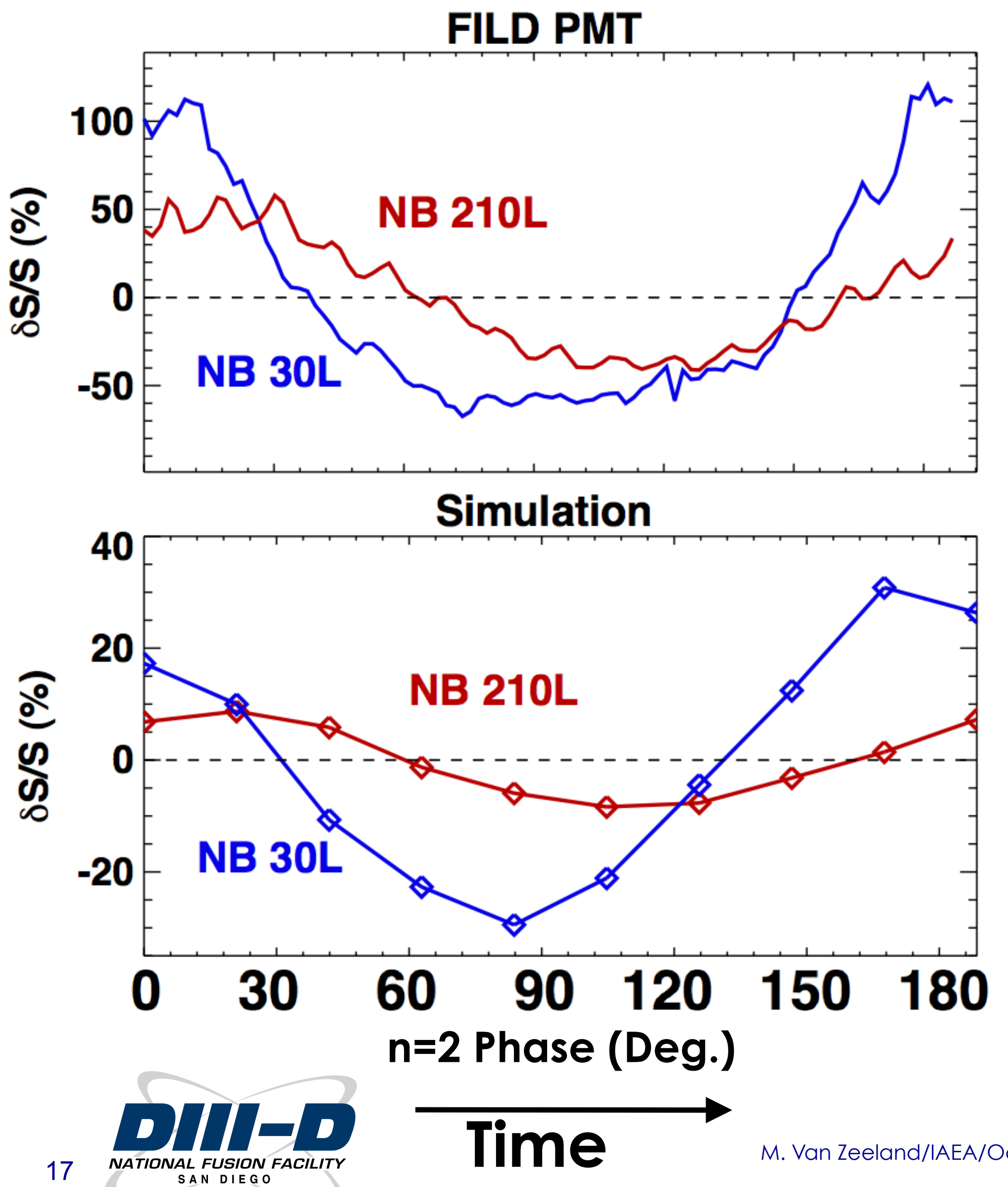
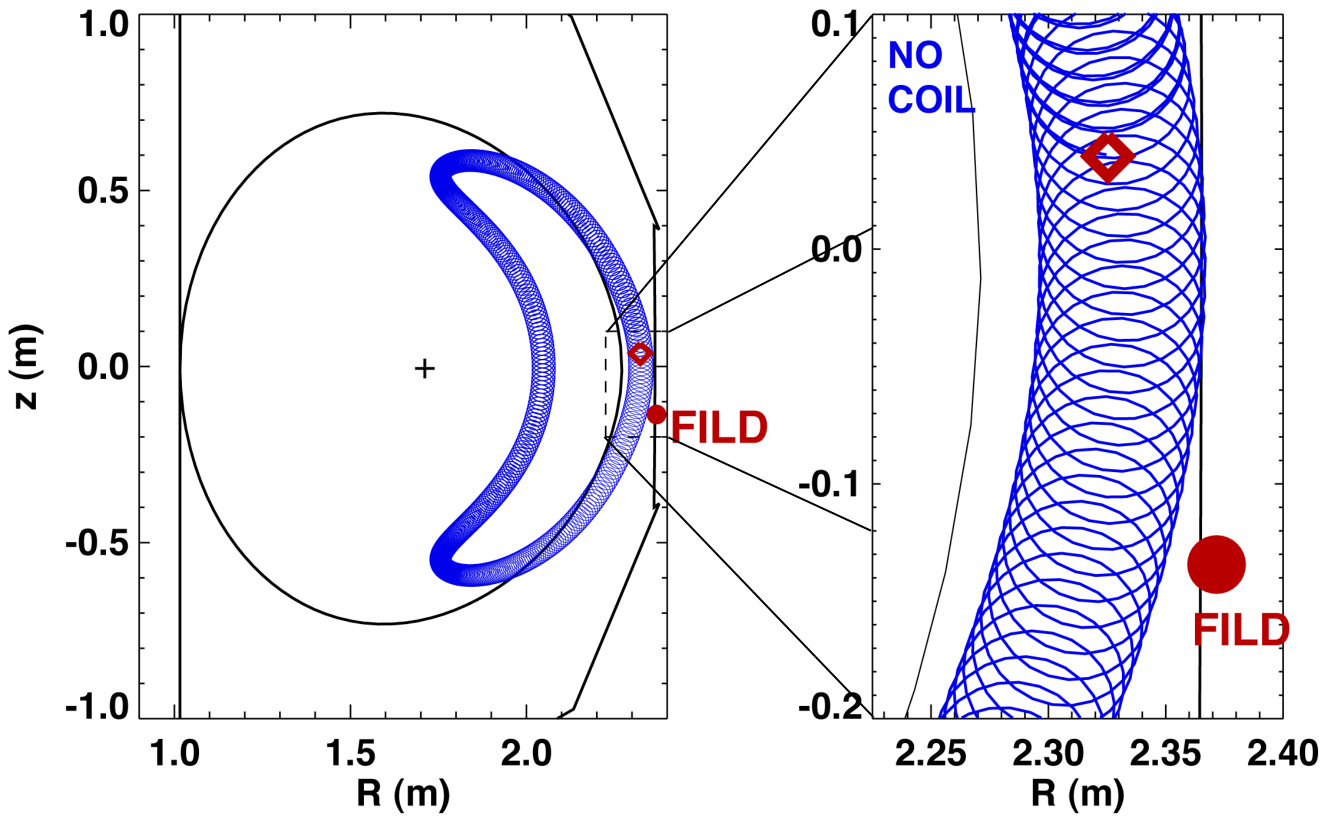
Phase and Relative Amplitude of Loss Modulation is Reproduced By Modeling



- **FILD time series remapped to phase shift of n=2 perturbation**
- **Consistent with FILD data, modeling shows:**
  - Larger modulation of 30L losses than 210L
  - 30L peaks near n2phase=0
  - ~30 Deg. phase shift between 30L and 210L modulation
- **Predicted δS/S smaller than experiment**

Simulations Show Typical Trapped Orbits To FILD Oscillate Radially by ~ +/-1 cm in First Bounce Period



- **Example unperturbed orbit that just misses wall**

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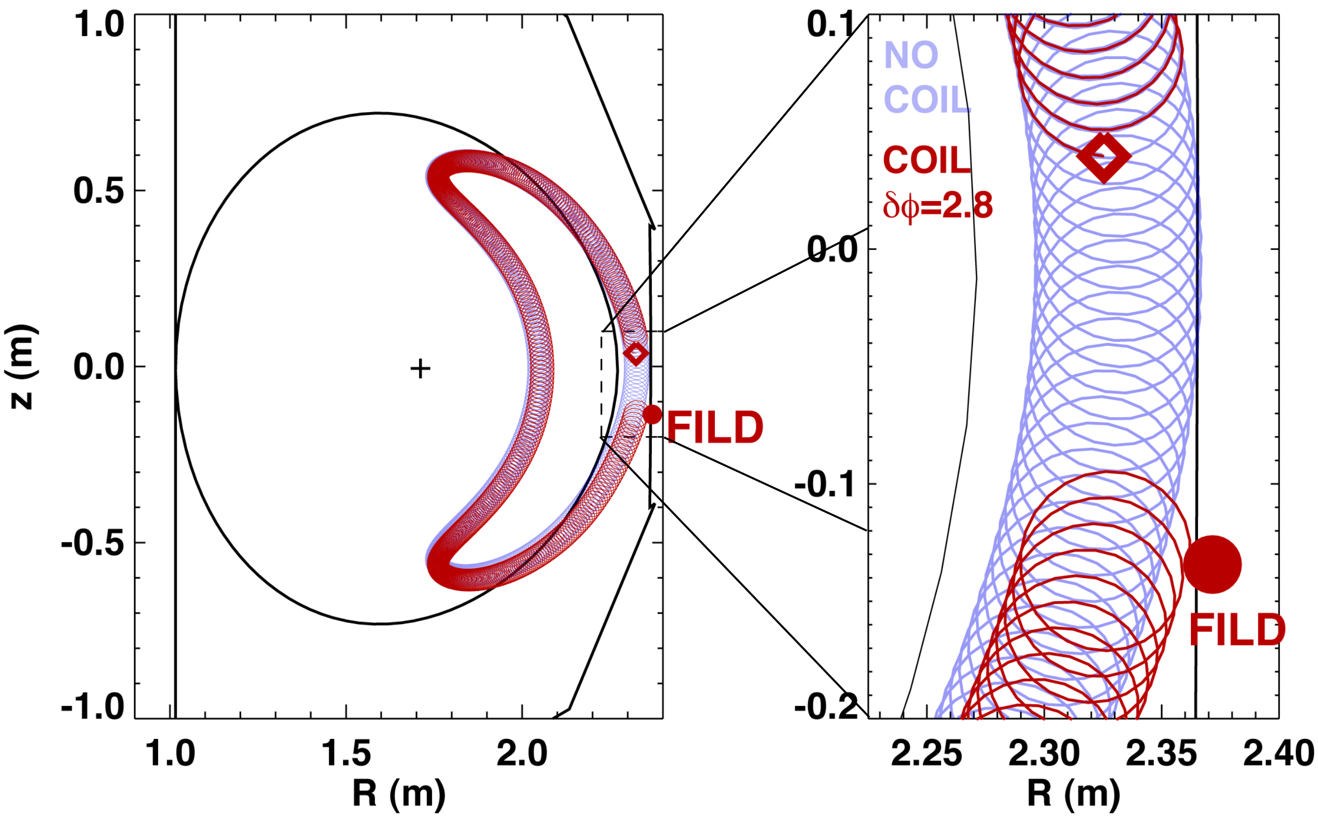

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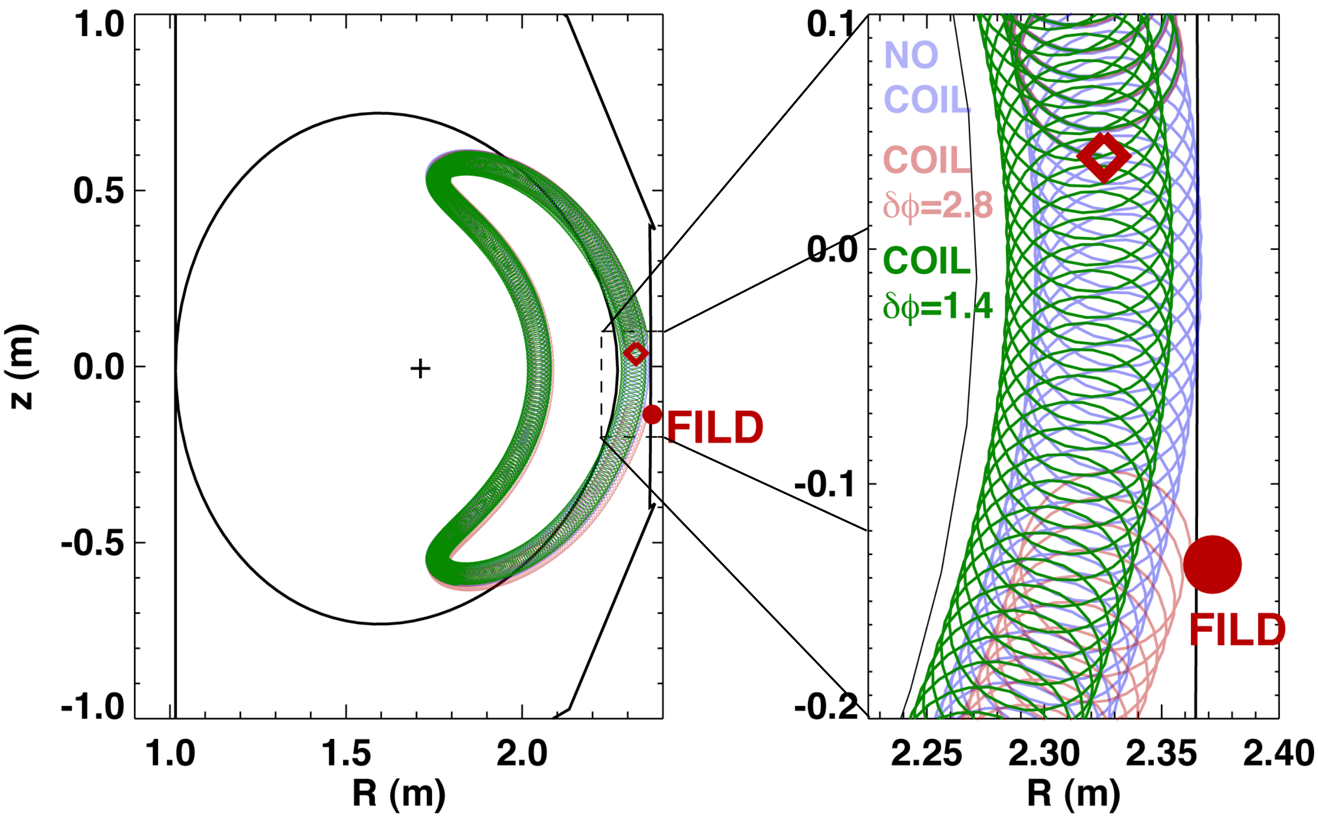

- Example unperturbed orbit that just misses wall
- At one phase of perturbation, orbit is shifted out and *strikes FILD*
- For another phase, orbit is shifted inward on first poloidal transit (later, moves out and strikes wall)
- Modulation of signal occurs when orbits hitting FILD originate from regions of varying birth rate

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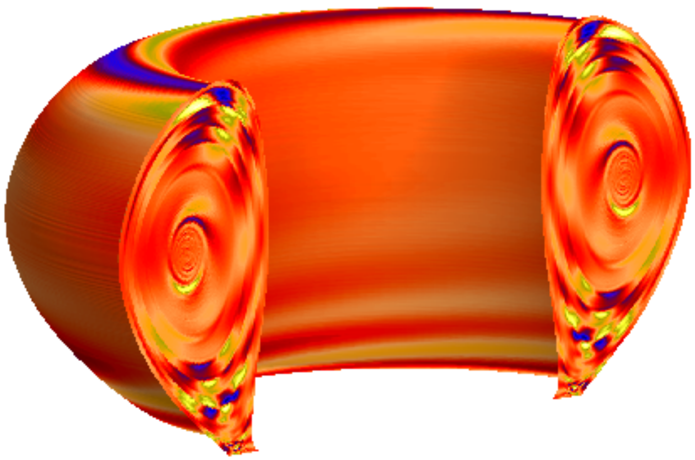

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Scan of Plasma Beta Combined with Rotating I-coil Fields Used to Investigate Role of Plasma Response

- **n=+1 / n=-1 traveling wave with f=25Hz applied**
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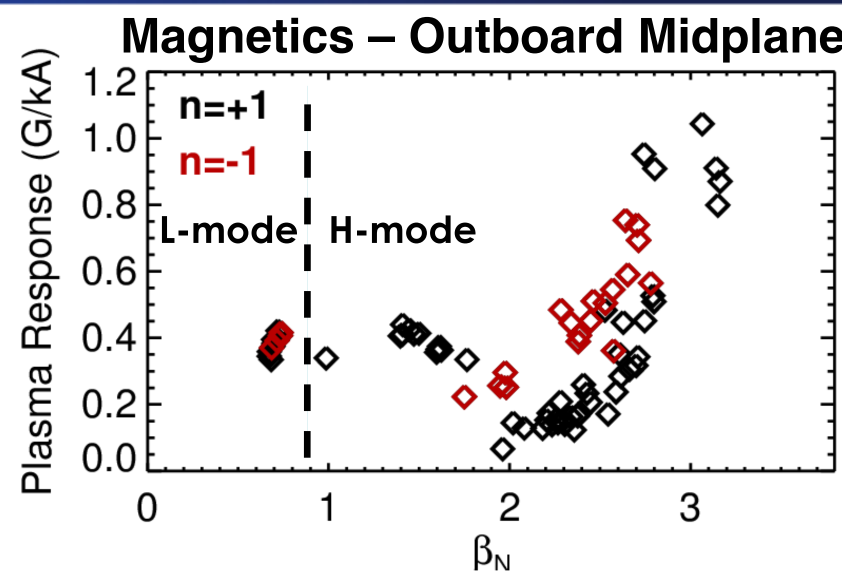

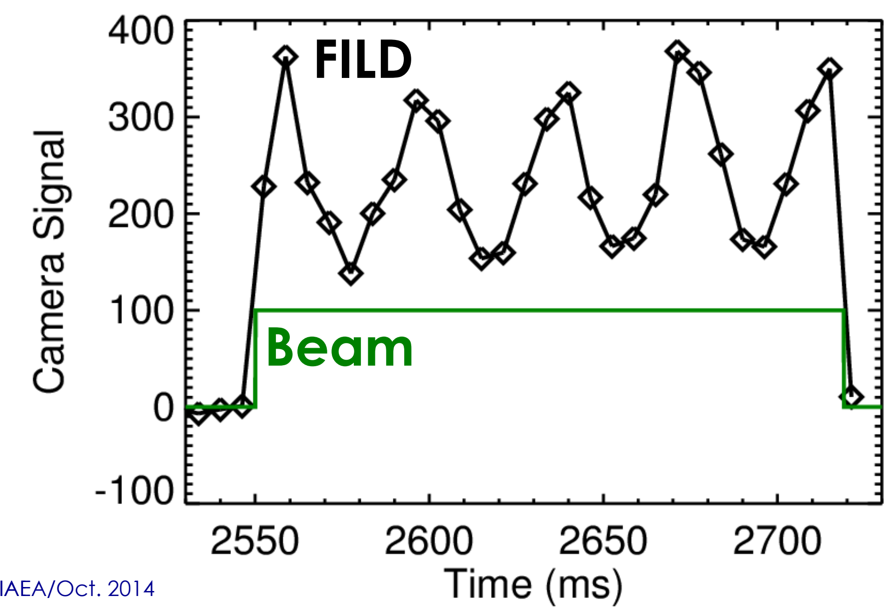

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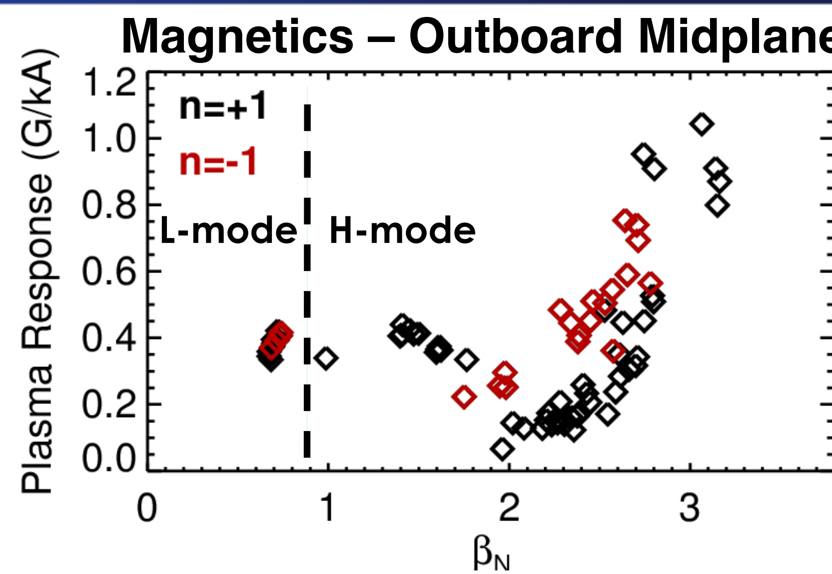

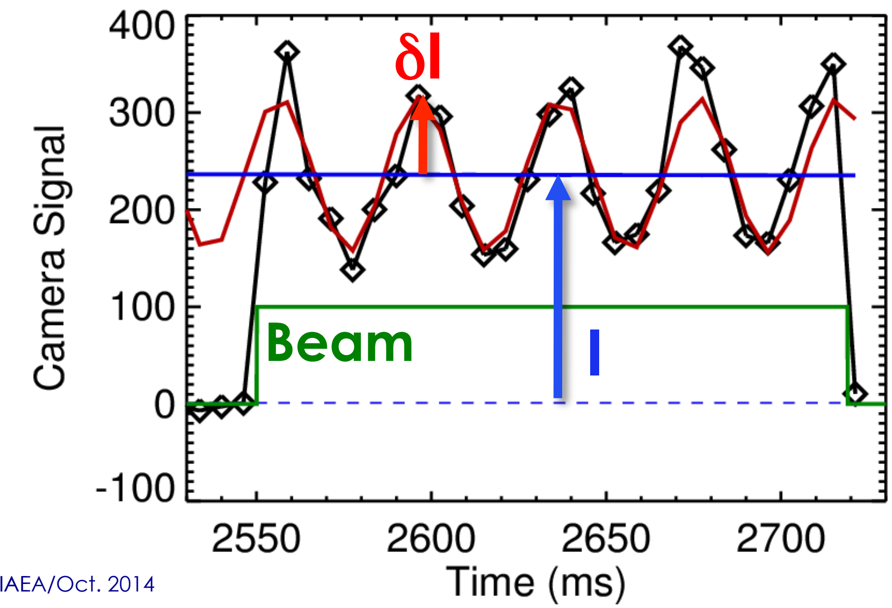

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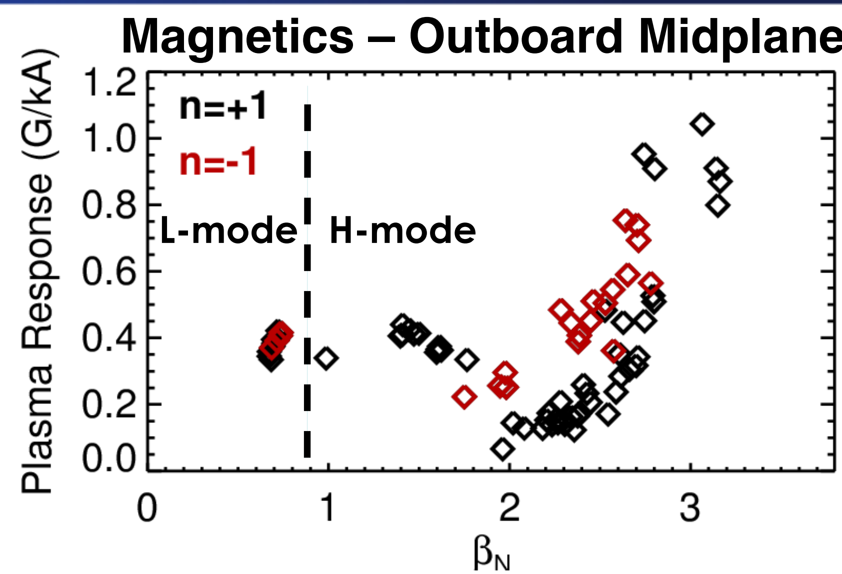
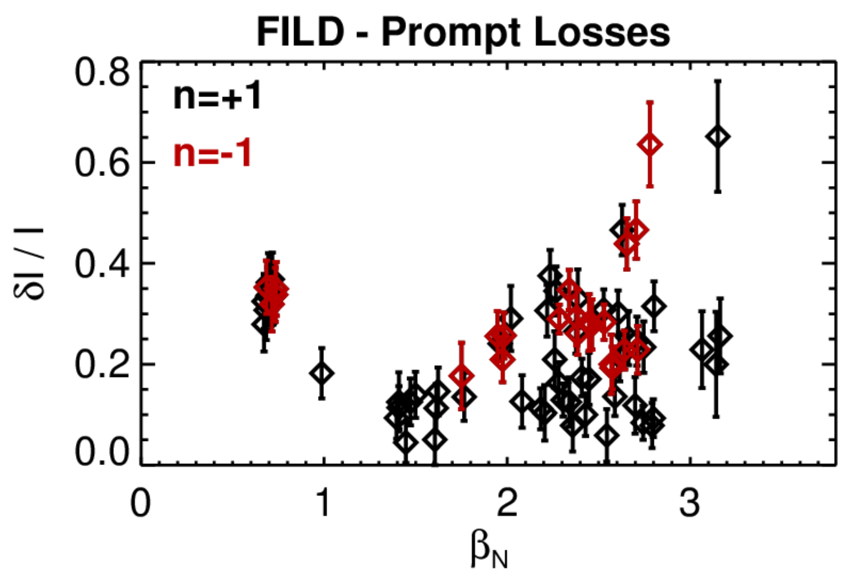
- **Fit to modulated prompt loss level gives n=1 impact on EP loss**
- **n=1 induced loss to FILD changes significantly with β_N**
  - Approx. x10 difference between minimum and maximum δI/I
  - Similar behavior to plasma response from magnetic probe
  - Would never be captured with n=1 vacuum fields alone





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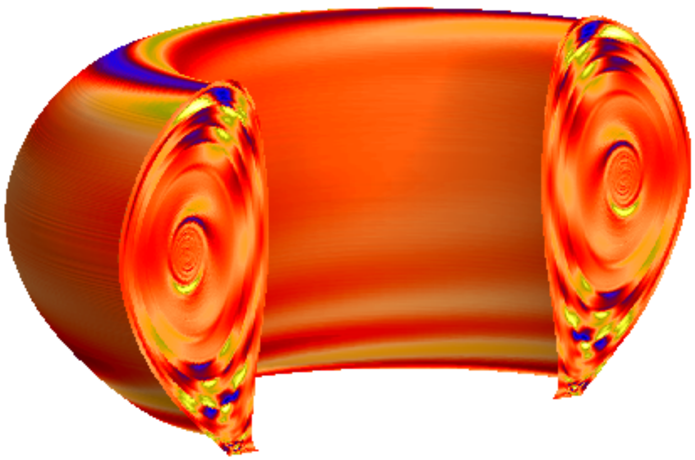

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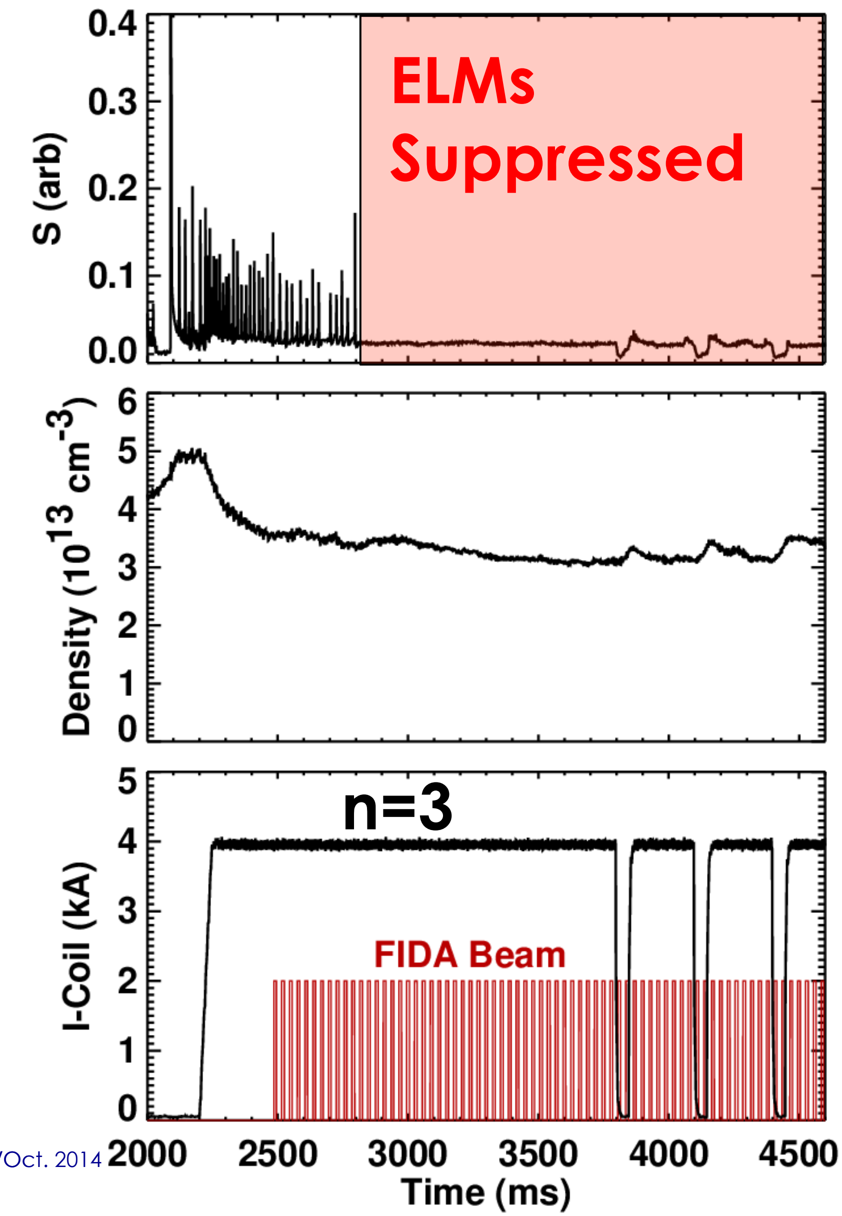
- **Conclusions**

Short I-coil Off Periods Were Used To Measure Change In Fast Ion Confinement Due to n=3 Fields in RMP ELM Suppressed Plasmas

- ***Experiments carried out in response to SPIRAL predictions showing large expected transport***
- **ITER Similar Shape Plasmas (ISS)**
- **50 ms I-coil off periods shorter than time for ELMs to return but *predicted to be sufficient for EP profile to recover***
- **Maintaining ELM suppression important**
  - ELMs cause EP transport
  - Compromise edge FIDA



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FIDA Data Shows Recovery of Edge EP Profile During I-coil Off Periods

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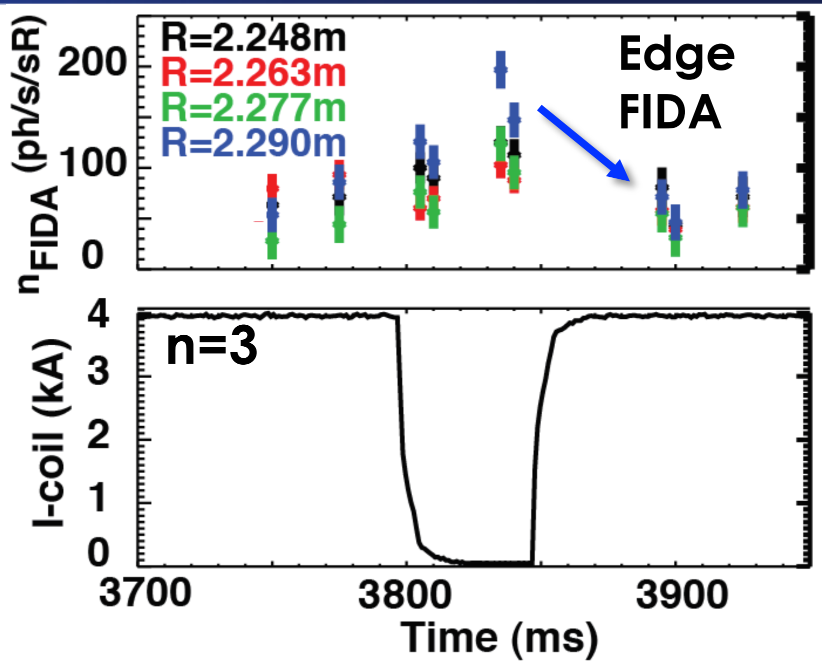
- **FIDA emission increases steadily throughout n=3 off periods then drops rapidly after turn-on**



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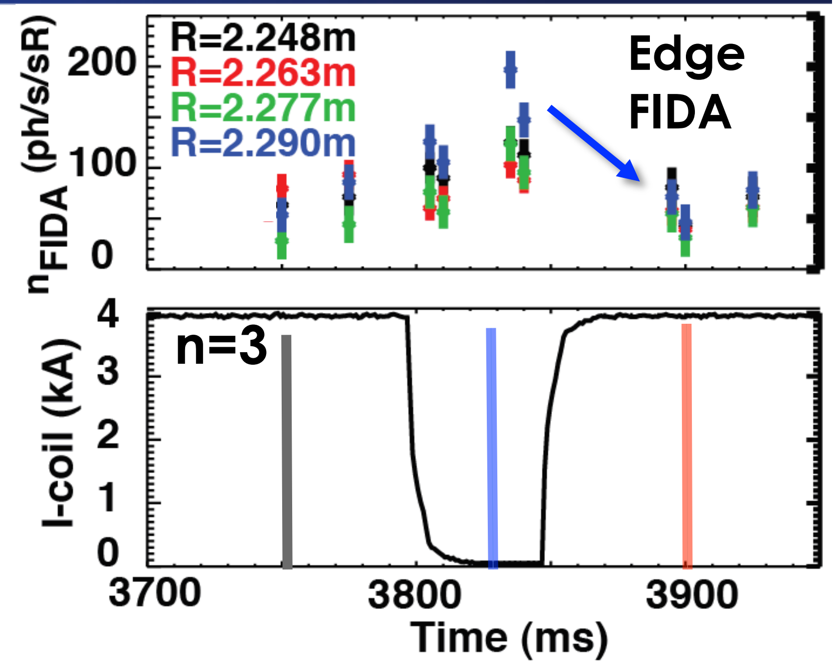
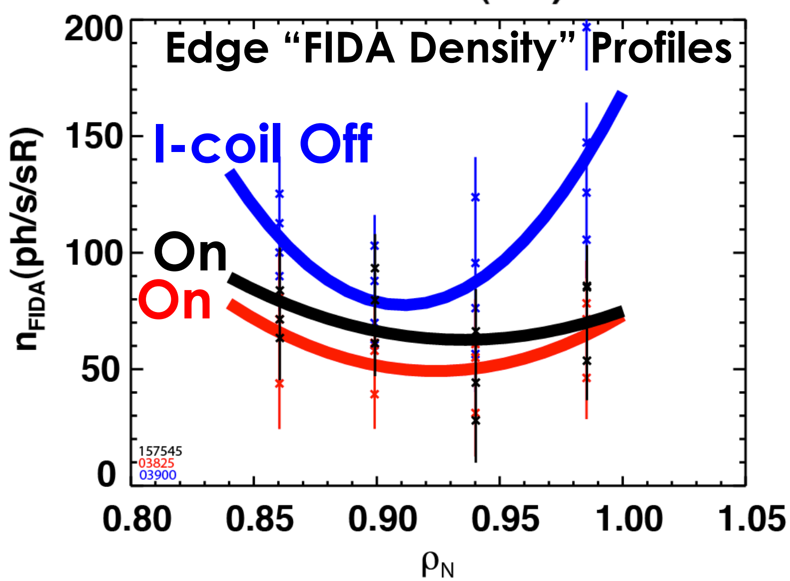
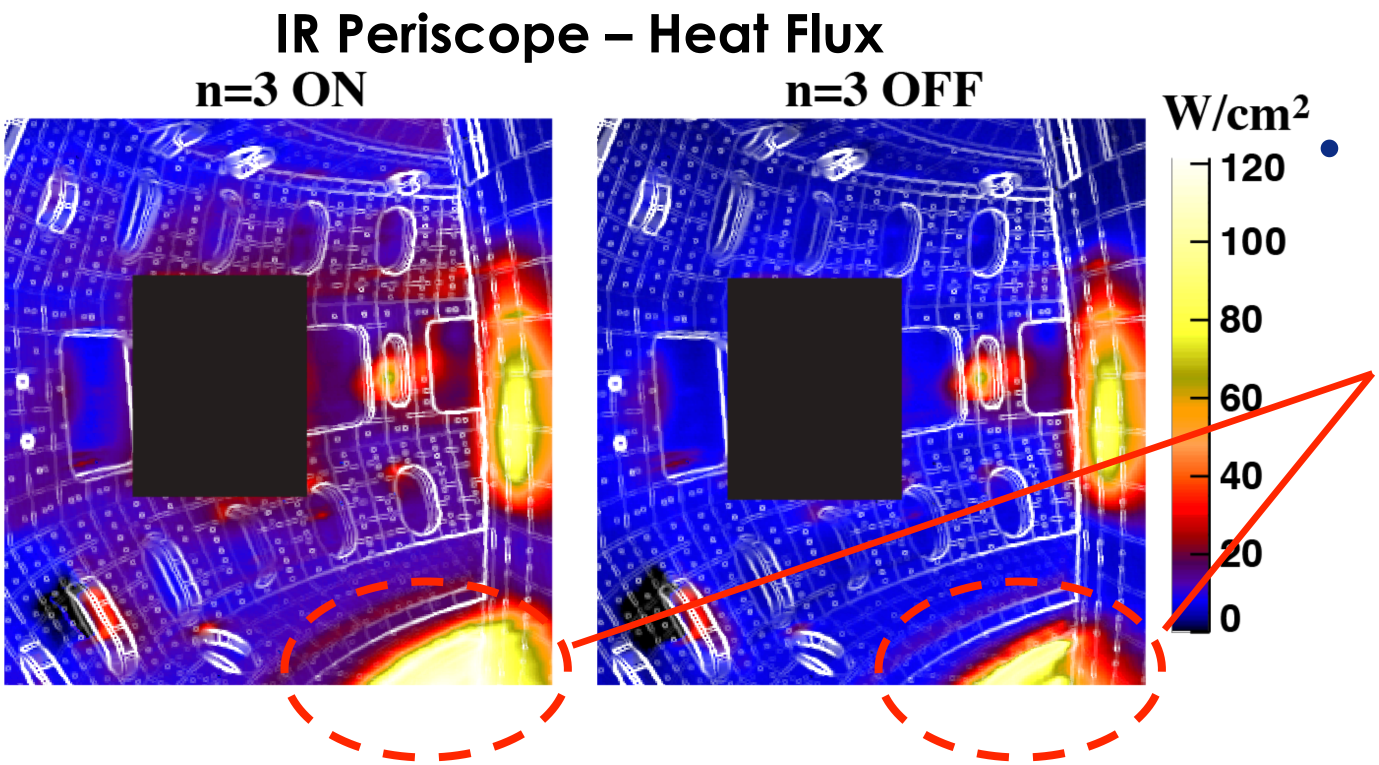




IR Periscope Shows Heat Flux Due to Prompt Beam Ion Loss and Divertor Heating Due to n=3



- **Largest change in heat flux during n=3 turn-off is in divertor region**
  - Heating likely due to combination of thermal[1] + fast ion loss

1. A. Wingen NF 21, 012509 (2014)

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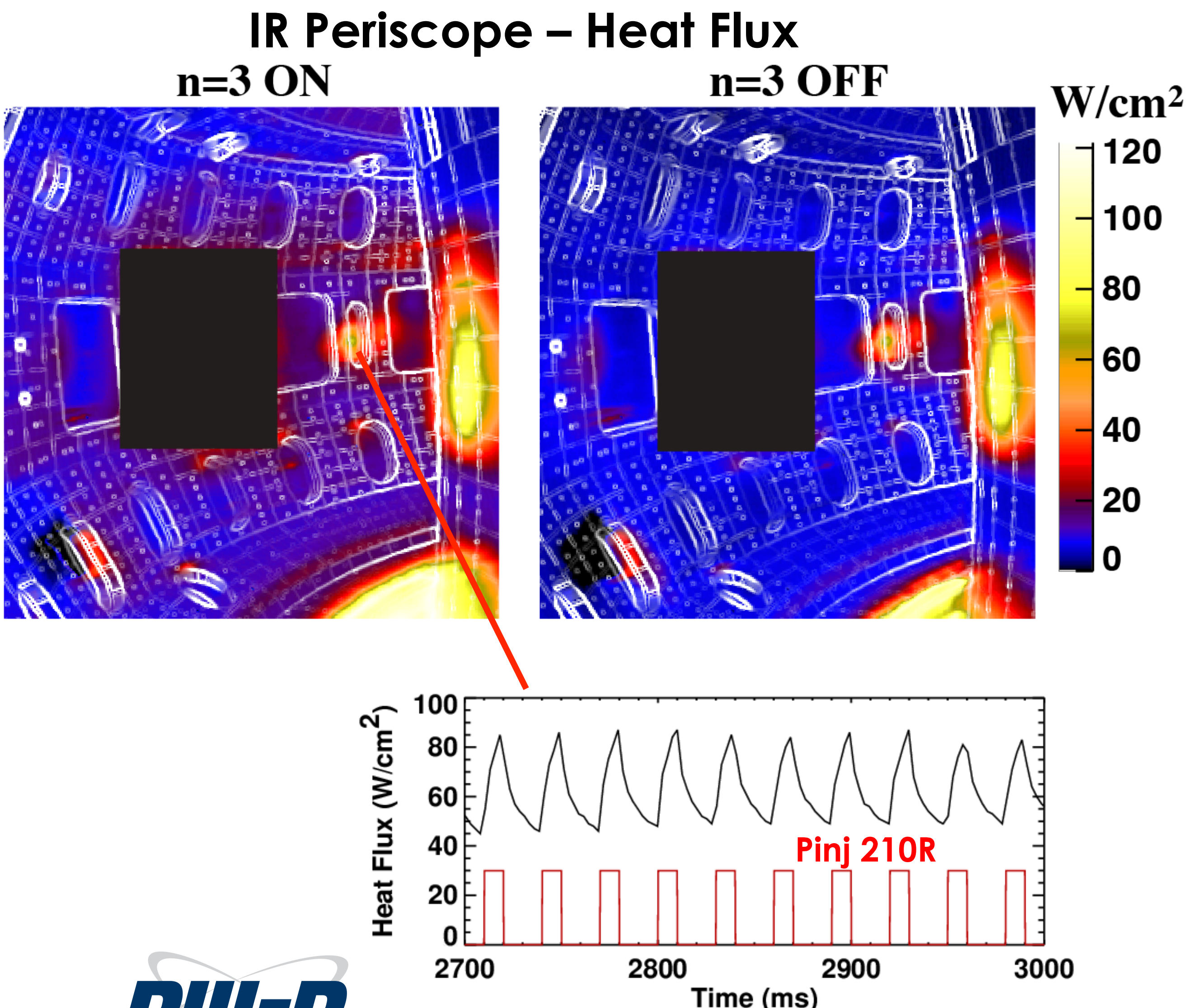


- **Largest change in heat flux during n=3 turn-off is in divertor region**
  - Heating likely due to combination of thermal[1] + fast ion loss

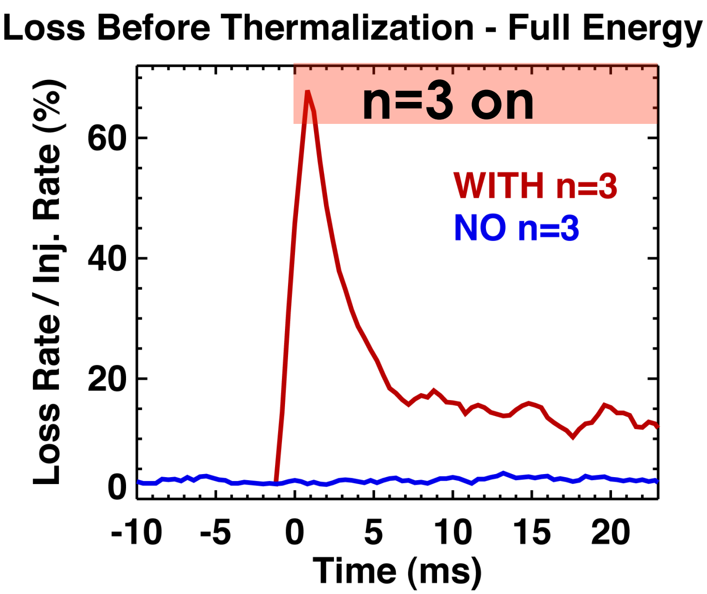
- **Also observable is prompt loss footprint due to counter beam blips**

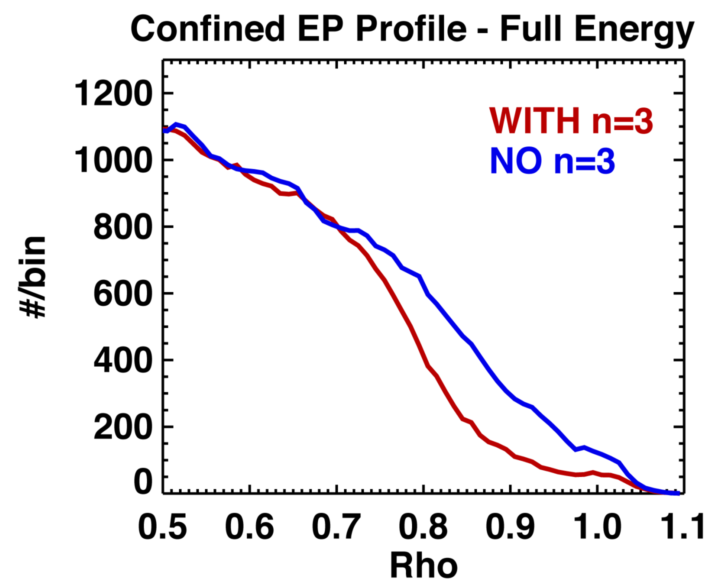
M. Van Zeeland/IAEA/Oct. 2014

1. A. Wingen NF 21, 012509 (2014)

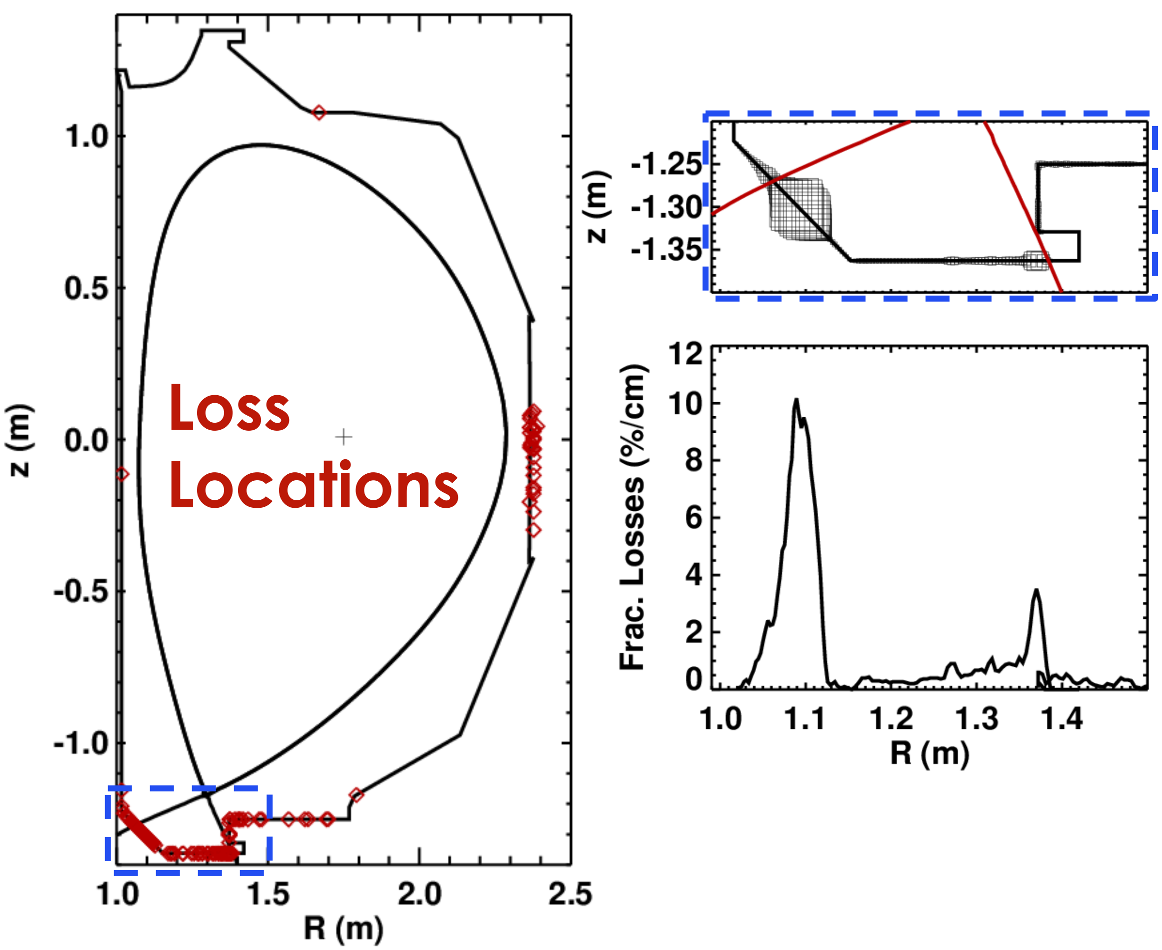
SPIRAL Simulations Find a Significant Increase in EP Losses Due to Application of n=3 RMP

- **Beam ions are injected at constant rate and followed with slowing down and pitch-angle scattering**
- **EPs are followed until lost or thermalized**
- **After steady state distribution created (t~70 ms) n=3 applied**
- **Significant loss of injected particles occurs due to n=3**
  - Losses are from particles born near edge
  - Edge EP profile (ρ>0.7) shows drop consistent with FIDA data





Fast Ion Loss Simulations Predict Large Fraction of EP Losses Are Concentrated in Divertor



- ~85% of lost particles strike divertor region
- Losses peak near unperturbed separatrix locations - similar to IR camera
- Estimates indicate peak EP heat flux ~100W/cm^2
  - Can reduce by slowly ramping on coils

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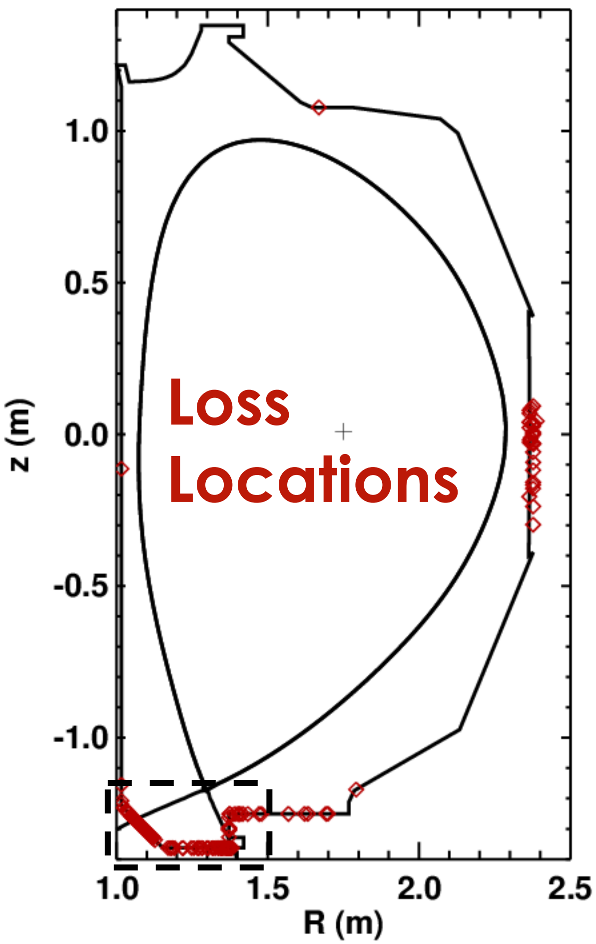
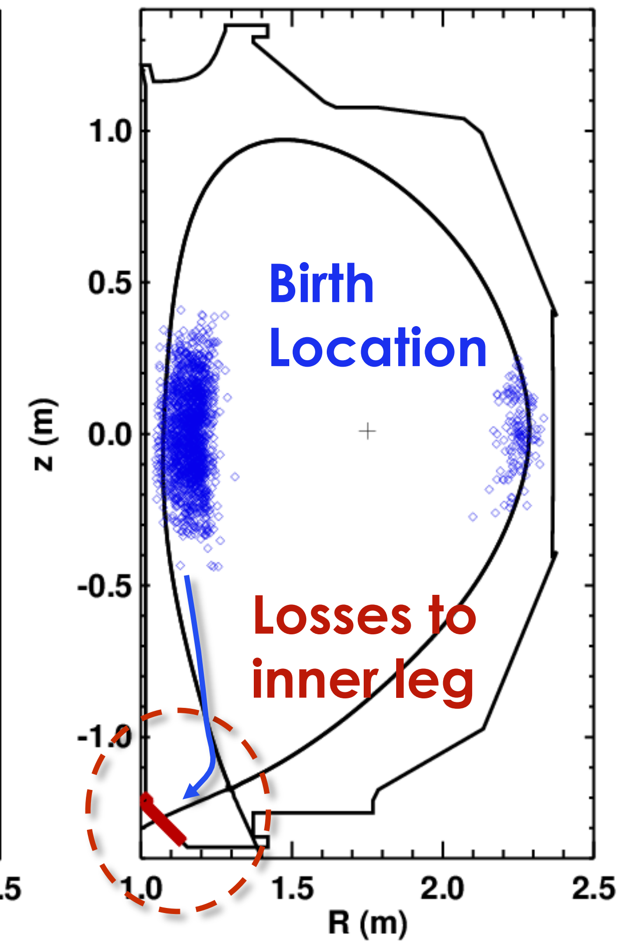
Fast Ion Loss Simulations Predict Large Fraction of EP Losses Are Concentrated in Divertor





- **~85% of lost particles strike divertor region**
- **Losses peak near unperturbed separatrix locations - similar to IR camera**
- **Estimates indicate peak EP heat flux ~100W/cm^2**
  - Can reduce by slowly ramping on coils
- **Inner divertor losses primarily particles born at small major radius**
  - Increased density will help reduce this

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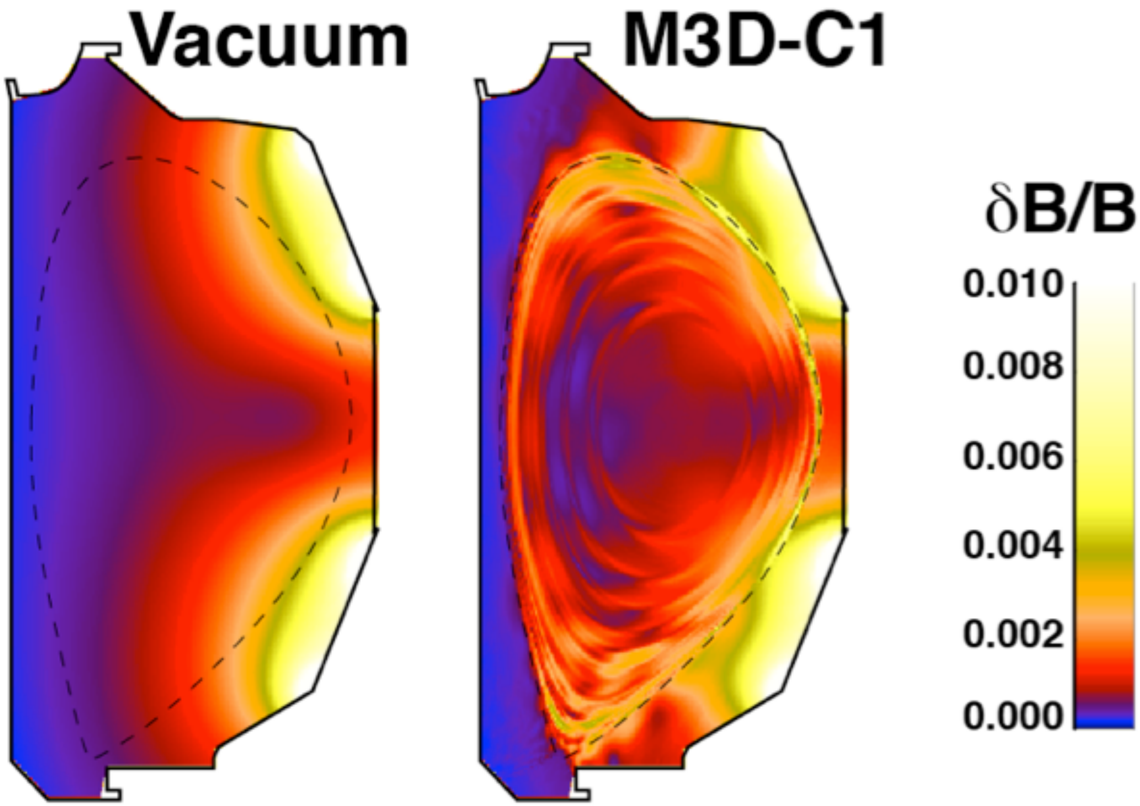
Conclusions

- **Full orbit following combined with M3D-C1 and new beam deposition code employed to model 3D field induced EP transport in DIII-D**
- **Model captures many of the important features in range of conditions including**
  - Modulation of prompt beam ion loss
  - Large impact of n=3 fields on edge EP profiles in n=3 RMP ELM suppressed plasmas
- **Experiment using prompt beam ion loss and rotating n=1 field indicates plasma response can play a significant role in EP loss**
- **Provides physics basis for predicting 3D field induced EP transport in DIII-D and future devices as well as potentially exploiting it as a control tool**

Additional Slides

Perturbed Magnetic Field Can Be Significantly Different with Inclusion of Plasma Response

- Typically in core, peak $\delta B/B \sim O(10^{-3})$
- Plasma response adds structure and can increase field significantly in core



n=3 RMP ELM suppressed case, 146626

Simulations Show Fast Ions Can Resonate with 3D Field Perturbations For Typical Operating Conditions

- **Resonance condition:**

  $\omega = n_{tor}\omega_{prec} + N\omega_{bounce}$

  For $\omega=0$, $N=1$

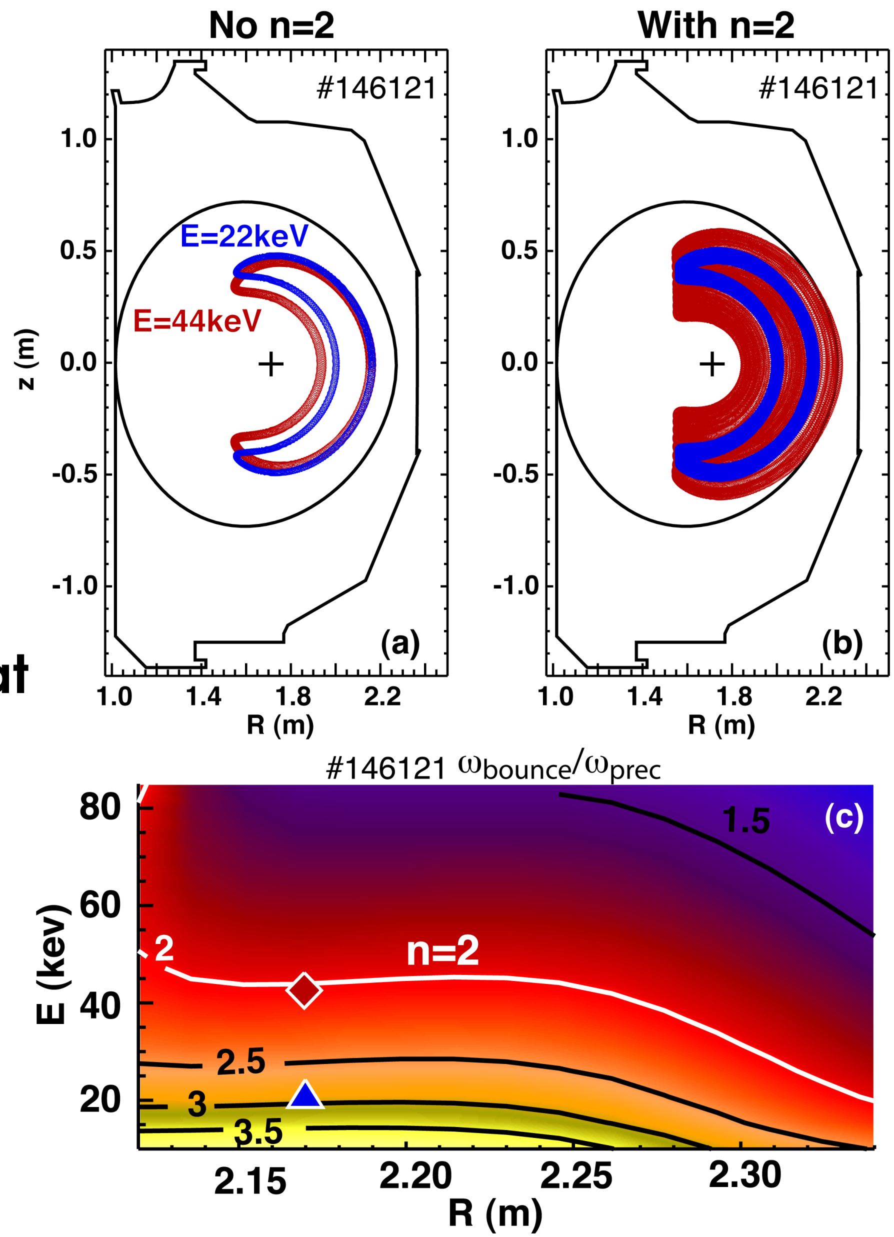
  $\omega_{bounce}/\omega_{prec} = n_{tor}$

- **Difficult for thermal ions to fullfill low-n resonance condition – *fast ions can***

- **Example orbit shows 44keV ion that fulfills resonance with n=2 field**

  $\omega_{bounce}/\omega_{prec}=2$

- **Resonance location can be tuned (Ip, Bt, etc.) to coincide with difft. Regions of phase space**



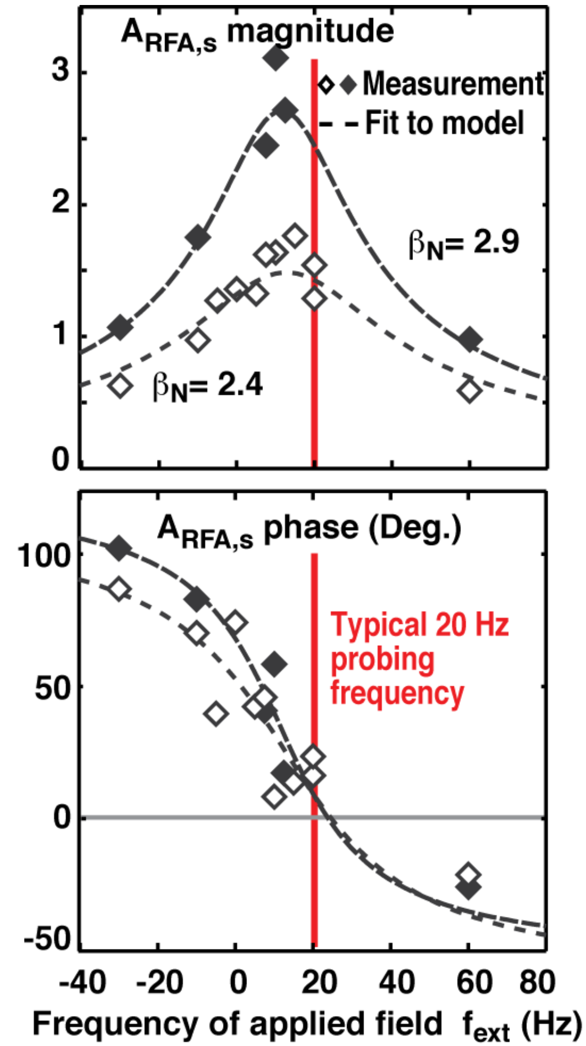
Single-mode plasma response model has resonance at stable RWM rotation rate

- Fourier analysis of ***single-mode response model*** at applied frequency ω_{ext} gives

$$\frac{B_{plas}}{B_{vac}} = c\frac{1 + (\gamma_{RWM} + i\omega_{RWM})\tau_w}{i(\omega_{ext} - \omega_{RWM})\tau_w - \gamma_{RWM}\tau_w}$$

- ***Strongest response expected*** when perturbation frequency is ***resonant*** with stable mode rotation rate $\omega_{ext} = \omega_{RWM}$

- Natural RWM rotation frequency is determined by plasma rotation and dissipation (kinetic effects), and wall eddy current torque



[H. Reimerdes, PRL 2004]

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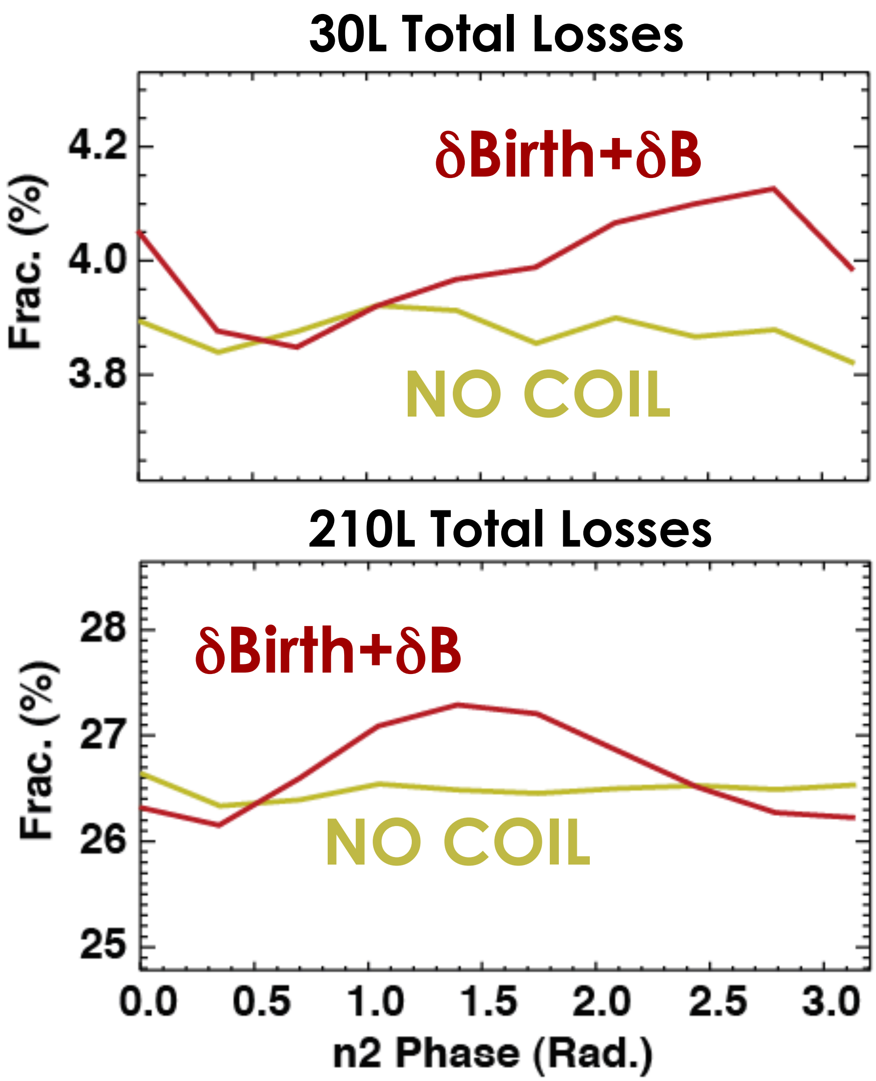
Modeling of n=2 L-mode Case Shows Total Prompt Loss To Wall Increases With Applied 3D Field



- **Change in total prompt loss depends on phase of perturbation**
- **Prompt loss increases for both beams at almost all phases of n=2 perturbation**
  - Peak increase ~7% 30L and 3% for 210L

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