Simulation of Observed EGAM Induced Beam-ion Losses in DIII-D

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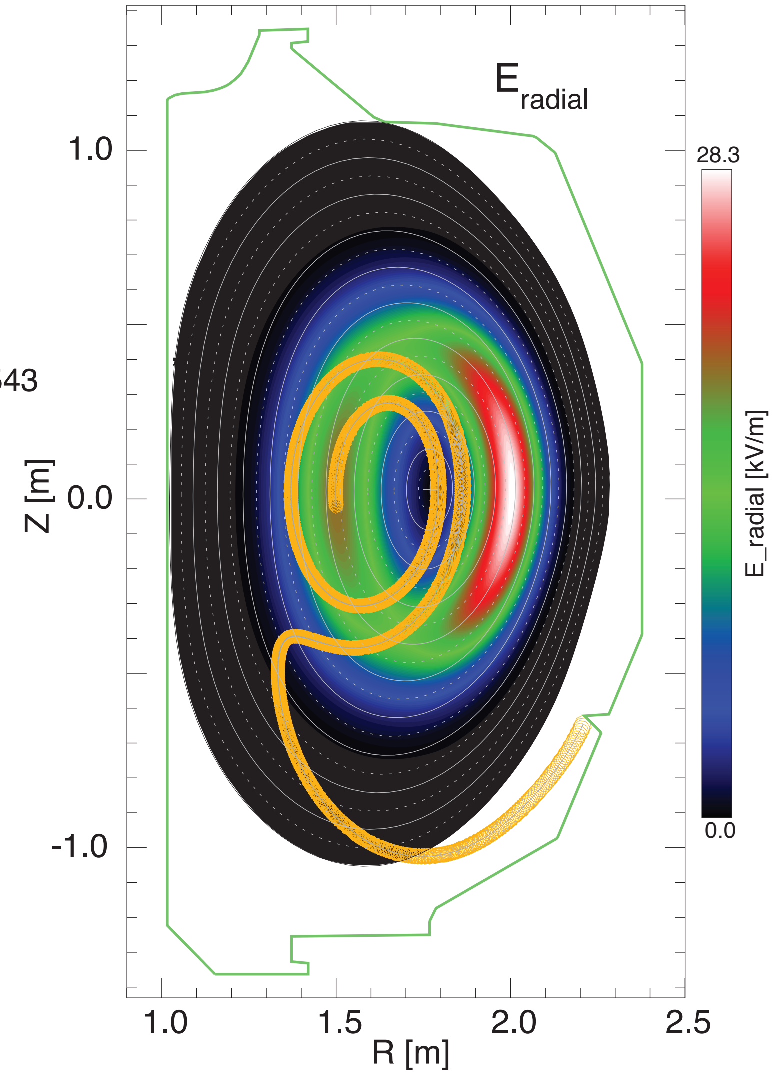

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Introduction and Outline

- The Energetic particle Geodesic Acoustic Mode (EGAM) [1] is often observed early in DIII-D discharges with counter-Neutral beam injection (NBI) [2]
  - Core localized
  - Frequency range: 10 to 30 kHz
  - Effective in inducing fast ion losses
- When the EGAM is present significant amounts of beam ions are found to be lost as observed on the Fast Ion Loss Detector
- This motivated us to study those losses with the full orbit-following code SPIRAL and find out where those losses arise from
- It will be found that the losses occur because particle-EGAM resonances are aligned well with the loss-cone boundary over a large particle energy range

[1] G.Y. Fu **Phys. Rev. Lett. 101** 185002 (2008)
[2] R. Nazikian et al. **Phys. Rev. Lett. 101** 185001 (2008)

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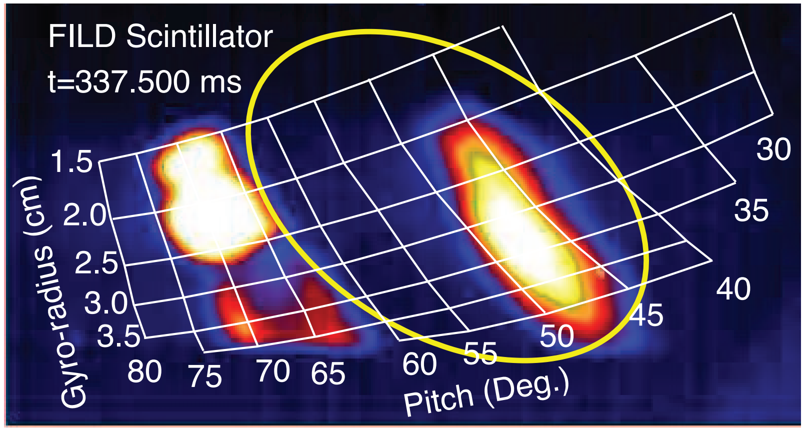
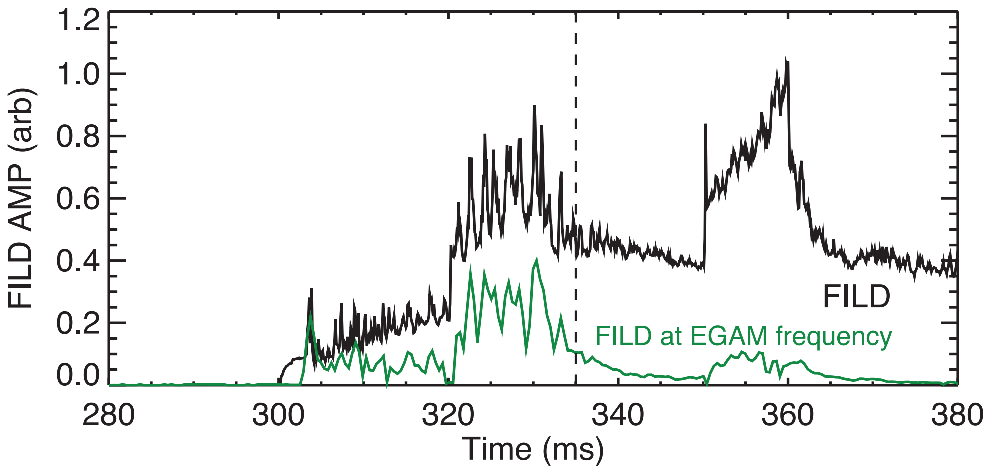
Pitch Angle and Gyro-radius Resolved Measurements Motivate the Loss Simulations

- The Fast Ion Loss Detector (FILD) measures the gyro-radius and the pitch angle of the lost ions
- The fast evolution of the losses is measured as an integral over an area indicated with the yellow ellipse
- These measurements motivated us to simulate the EGAM losses and investigate the loss mechanism





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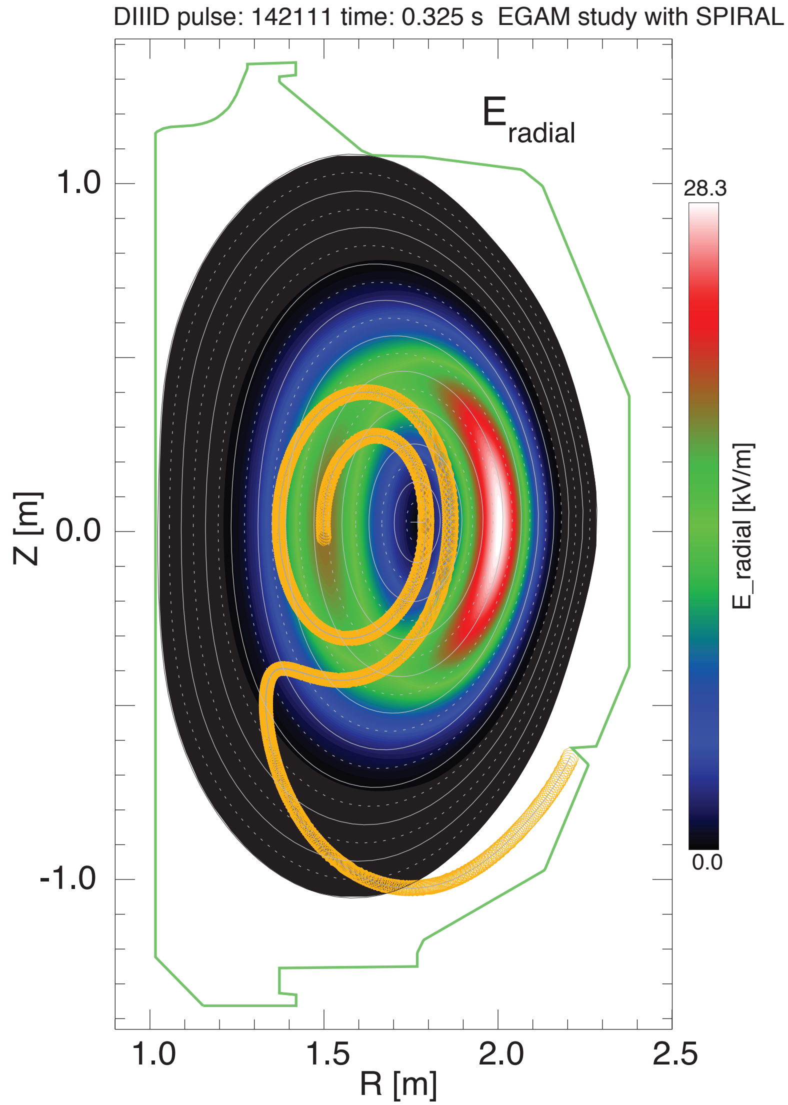
The Full Orbit Following Code SPIRAL was used to Simulate EGAM Losses

- The SPIRAL code follows the particle orbits by solving the Lorentz equations:

$$\vec{v} = \frac{d\vec{r}}{dt} \qquad \frac{d\vec{v}}{dt} = \frac{q}{m}(\vec{v} \times \vec{B} + \vec{E})$$

- The magnetic field $\vec{B}$ and electrical field $\vec{E}$ are usually given on an (unstructured) mesh
- A robust interpolation procedure is used based on Chebyshev polynomials so that Maxwell's equations are satisfied for all interpolated points
- Ripple fields, slowing-down, and pitch angle scattering can be included together with MHD modes and rf fields
- Realistic walls are included to calculate heat loads
- Particle deposition profiles from amongst others TRANSP can be used



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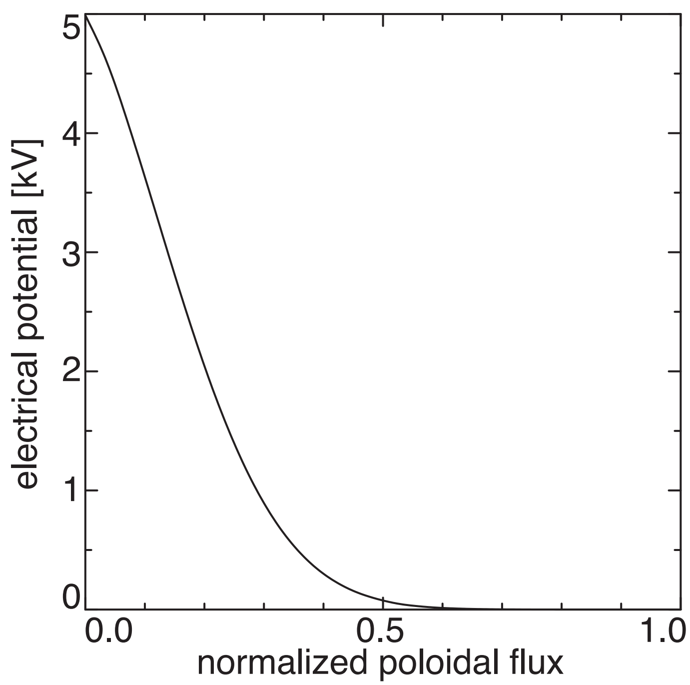
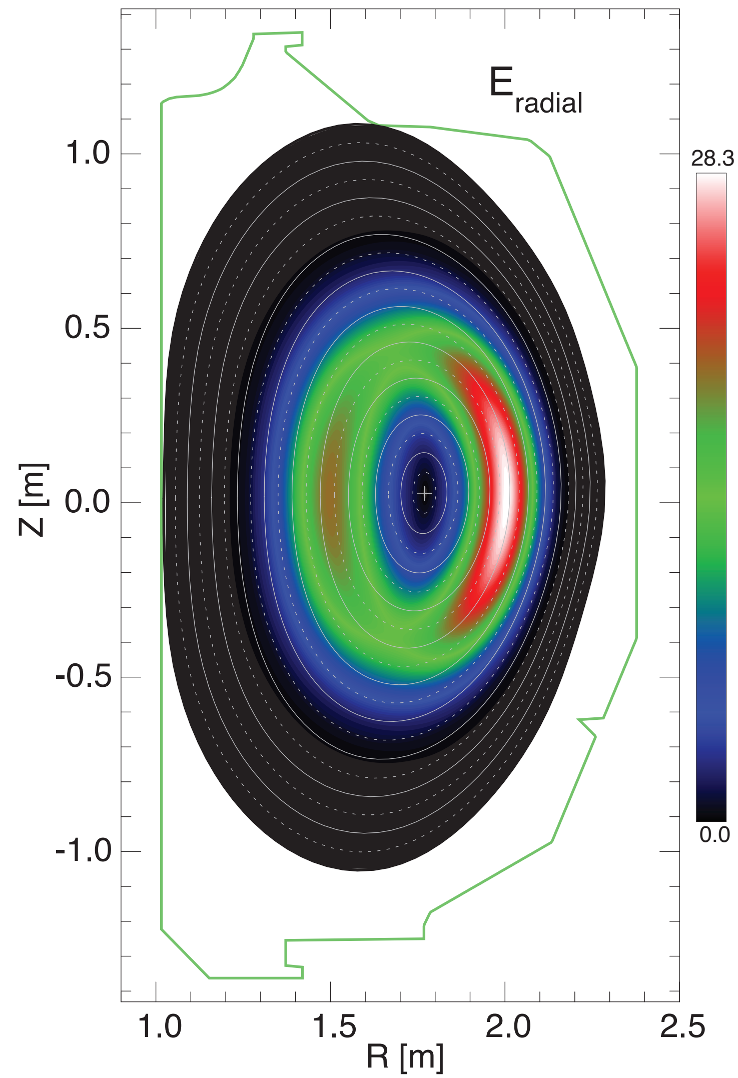
The EGAM was Modeled as a n=0 m=0 Time-varying Electrostatic Potential

- The mode structure of the EGAM was modeled along the lines presented in G.Y. Fu, **Phys. Rev. Lett. 101** 185002 (2008)
- From an electrical potential the radial electrical field obtained



$$E_r = -\nabla\Phi \longrightarrow$$



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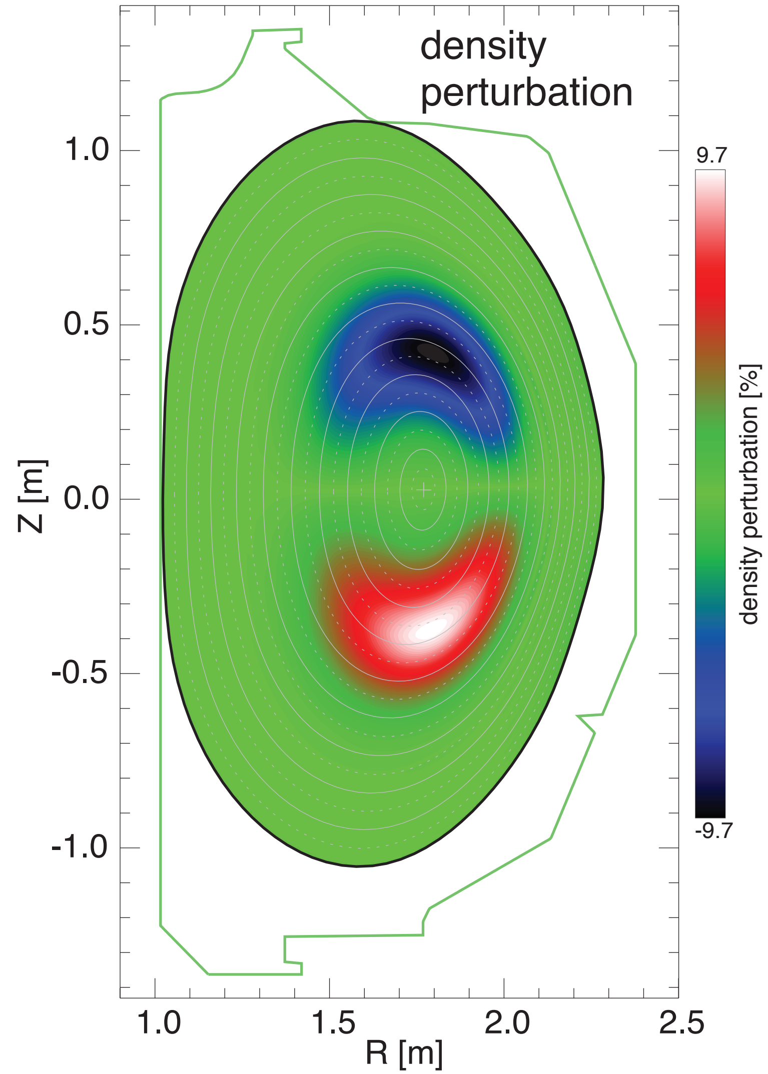
The EGAM Amplitude in the Simulations was Adjusted to Match the Experimental One

- From the plasma displacement
$$\xi = \frac{E \times B}{i \omega B^2}$$
the density fluctuations are calculated

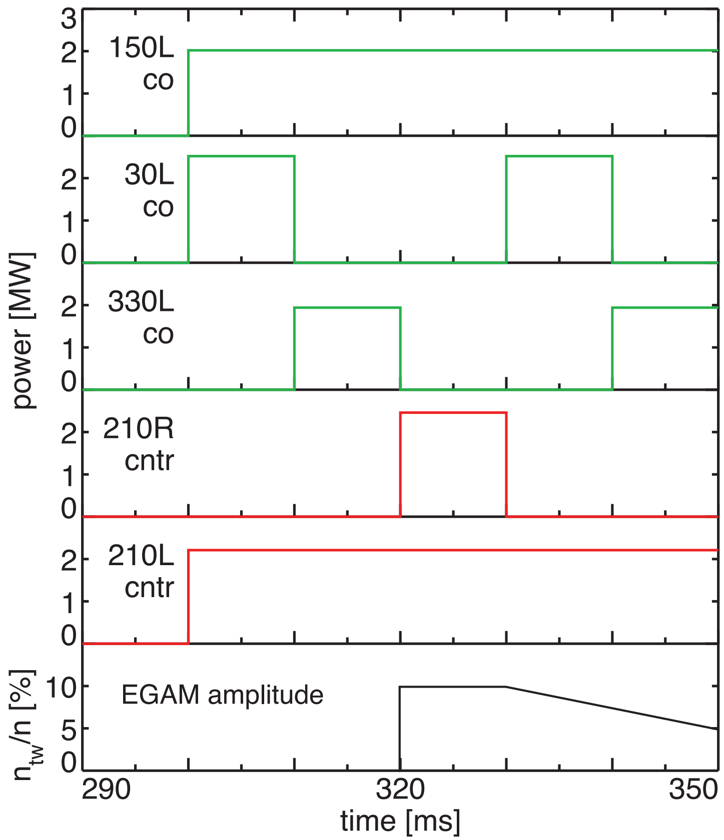
- The width and height of the electrical potential were adjusted so that the the calculated density fluctuations matched the measuremented ones that were obtained from the Beam Emission Spectroscopy (BES) diagnostic

- The resulting density perturbation has an n=0 m=1 character similar to what was found experimentally



Beam-ions were Loaded in Accordance with the Experiment and Followed for up to 50 ms

- Particles were taken from the TRANSP 3-D beam birth profiles and distibuted uniformly during the times that the beams were injected
- The particles we followed until they got lost or reached 350 ms
- Slowing-down and pitch angle scattering were included in the simulations
- The EGAM was turned on at 320 ms when the 210R counter beam was injected



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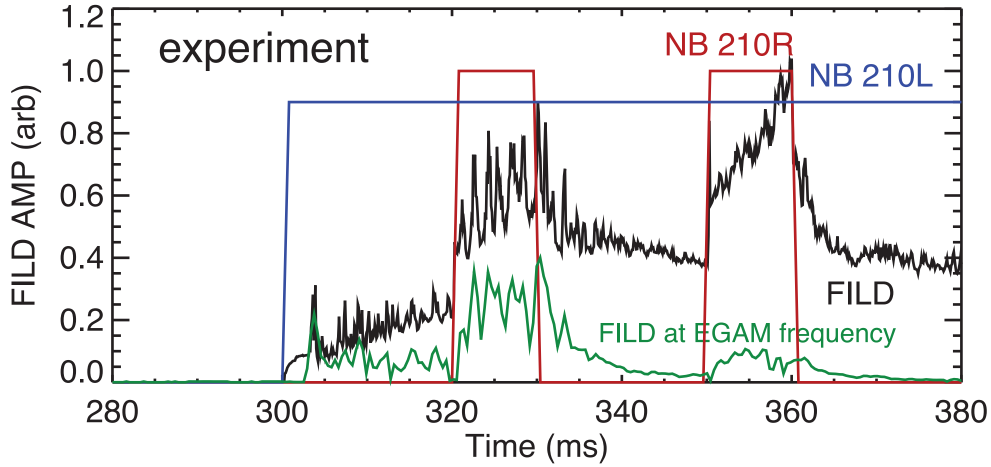
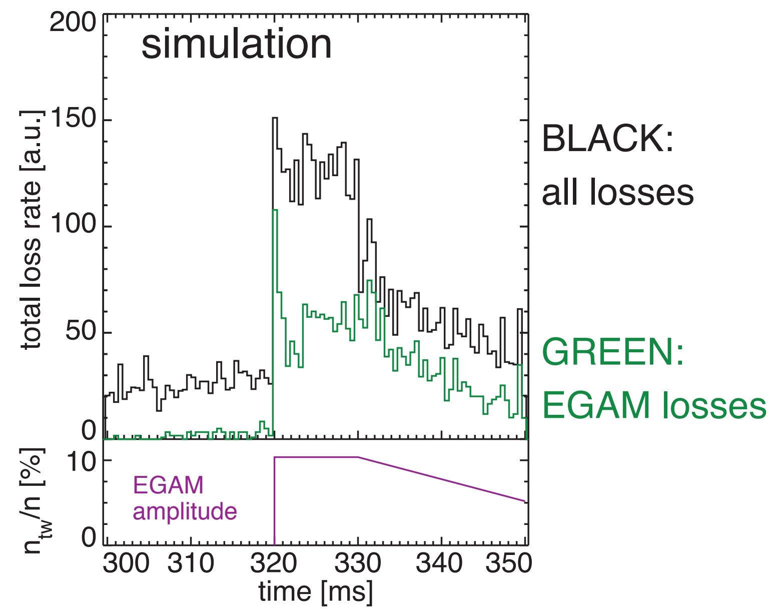
The Experimental and Simulated Loss Rates Agree Qualitatively Very Well

- Experimentally:
  - When the 210R counter beam is injected the losses at the FILD detector increase



- The same behavior is found in the SPIRAL simulations



- The simulated losses are due to
  - First-orbit losses before 320 ms
  - EGAM-induced and first-orbit losses after 320 ms

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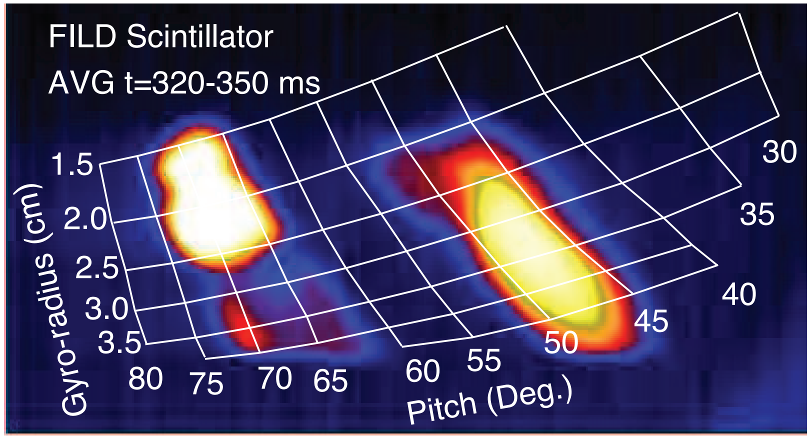
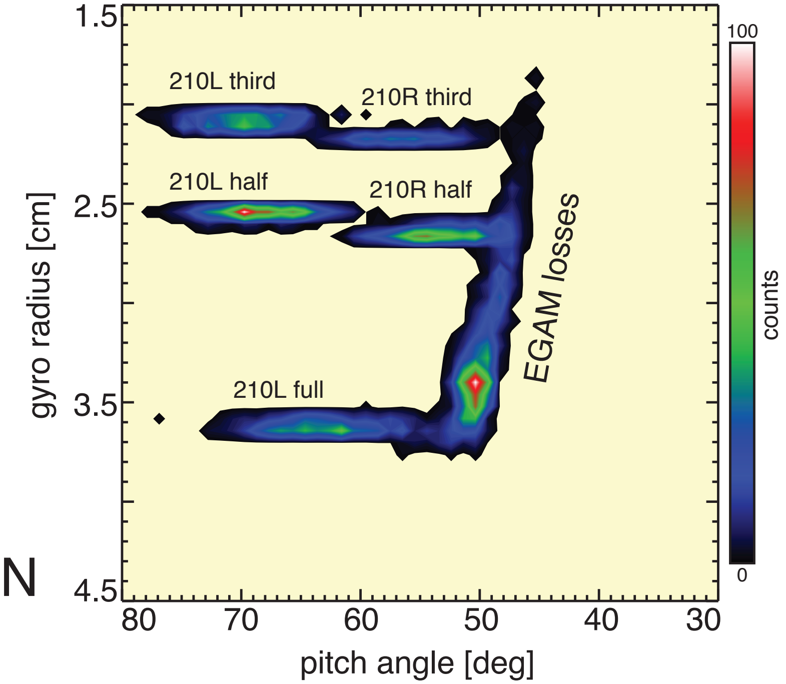
The 2-D FILD Image of Gyro-radius and Pitch Angle is also Reproduced in the Simulations

EXPERIMENT



SIMULATION



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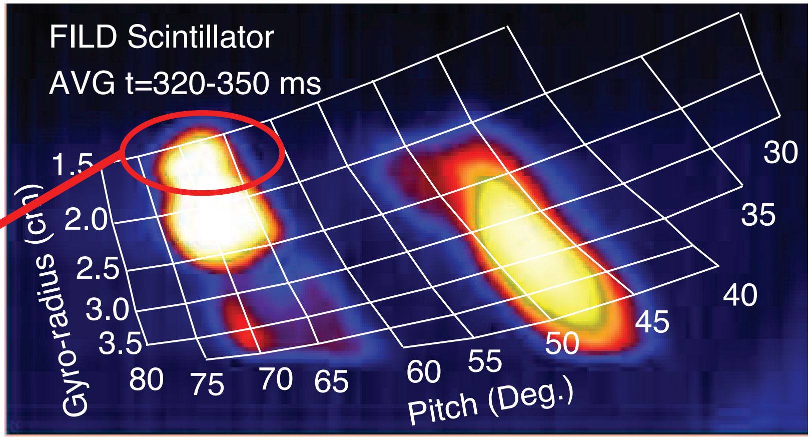
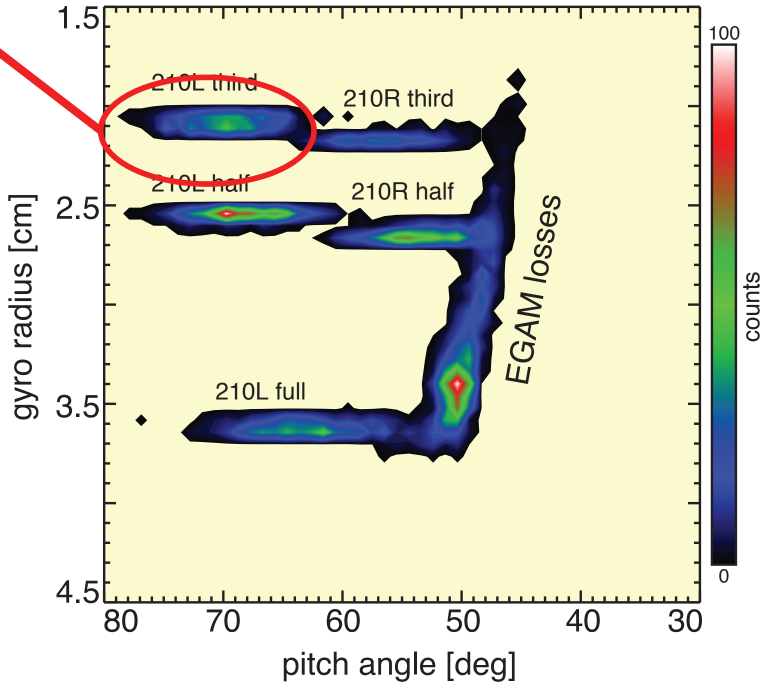


- First-orbit losses from:
  210L third-energy fraction



SIMULATION

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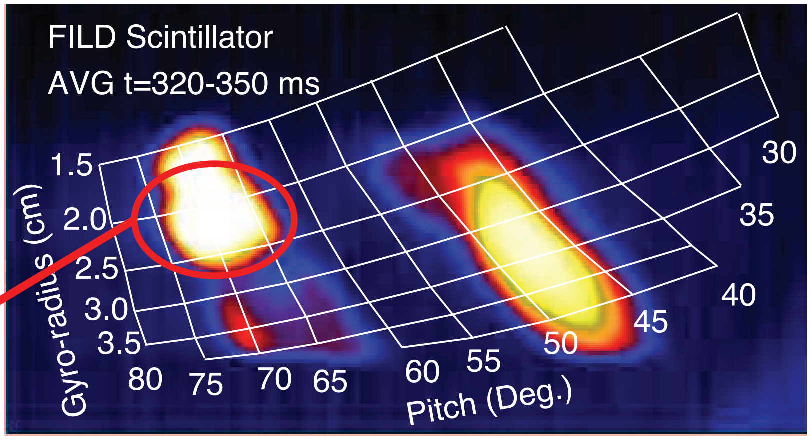
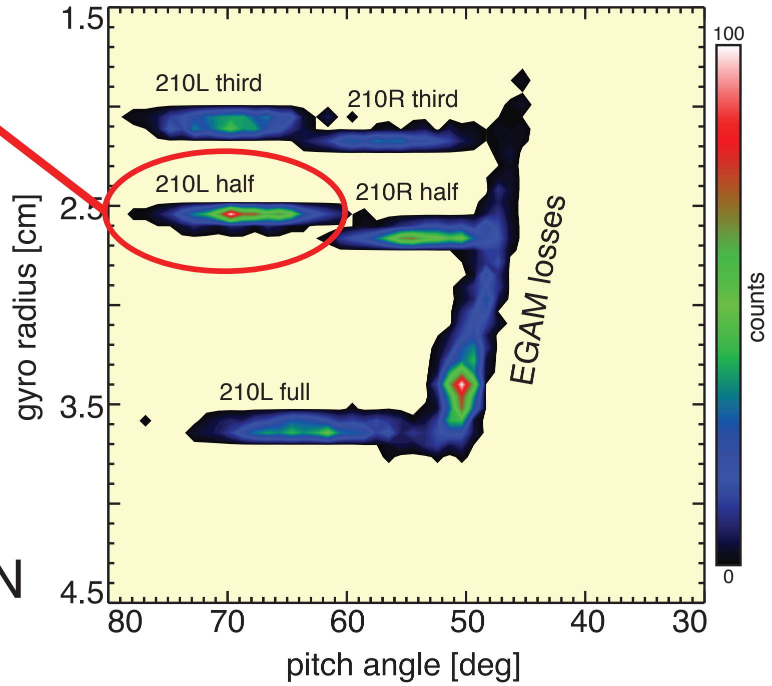


- First-orbit losses from:

  210L third-energy fraction

  210L half-energy fraction

SIMULATION



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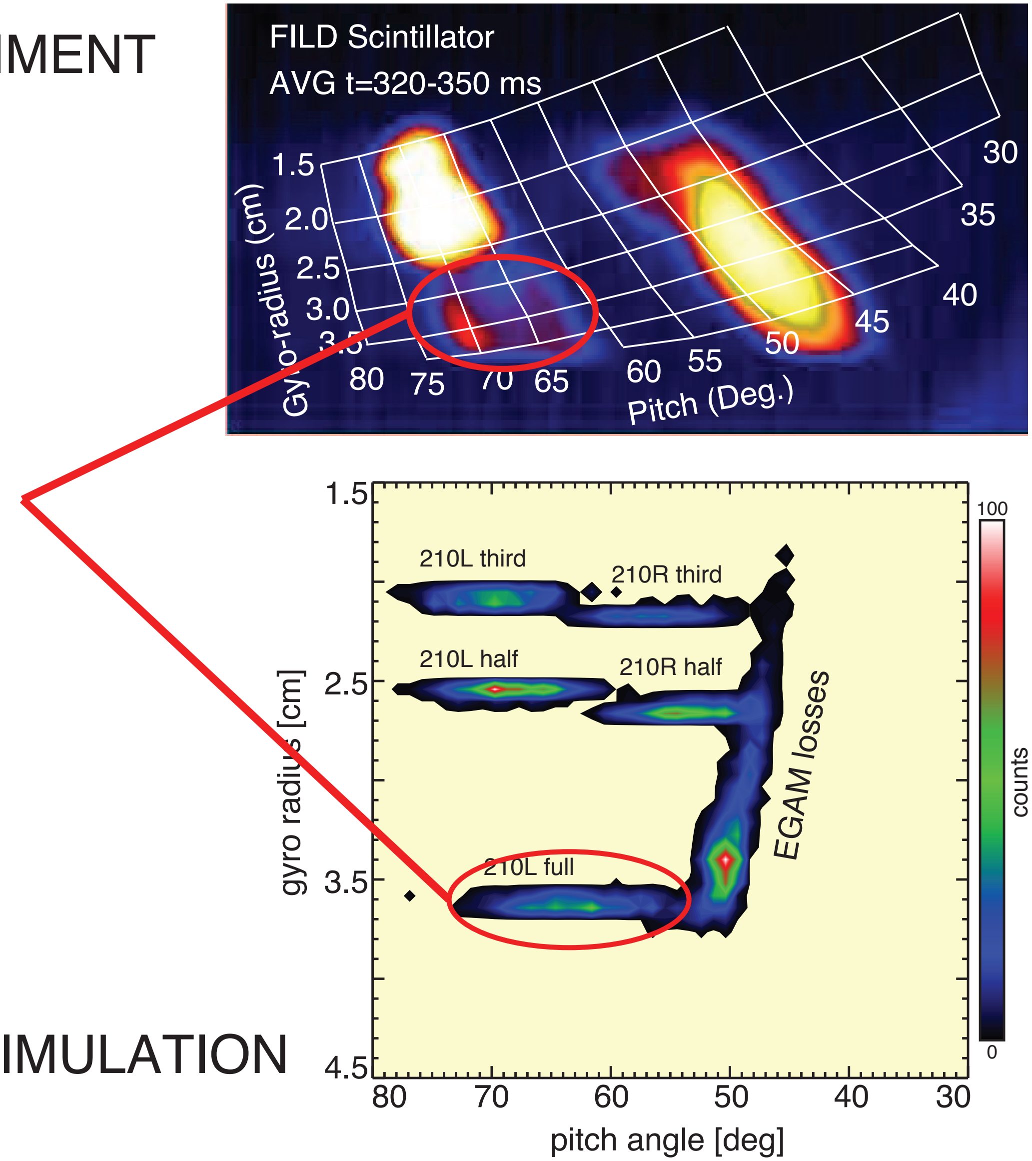
The 2-D FILD Image of Gyro-radius and Pitch Angle is also Reproduced in the Simulations

EXPERIMENT

- First-orbit losses from:
  - 210L third-energy fraction
  - 210L half-energy fraction
  - 210L full-energy fraction



SIMULATION

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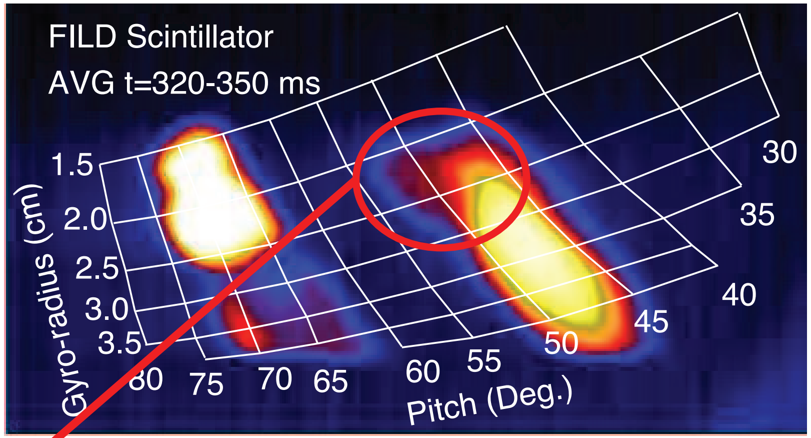
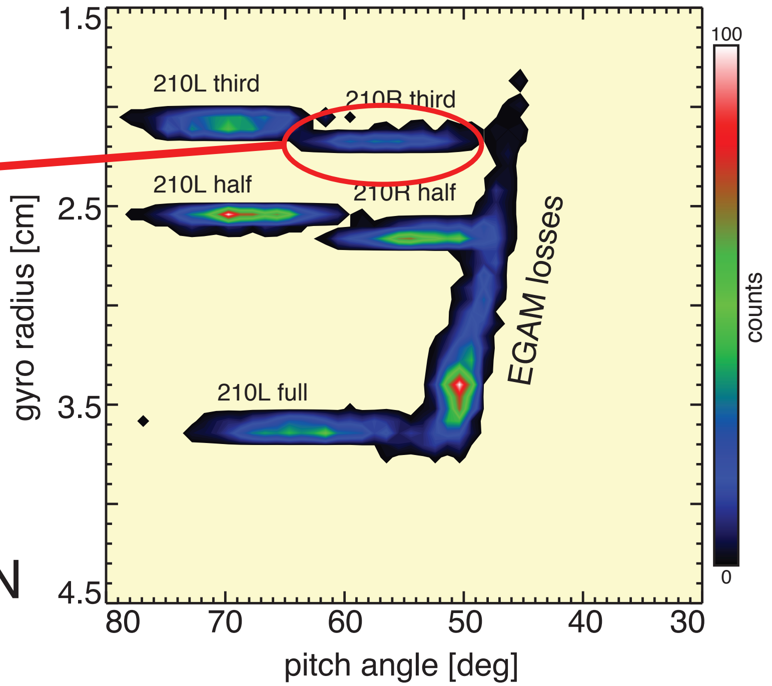
EXPERIMENT



- First-orbit losses from:
  - 210L third-energy fraction
  - 210L half-energy fraction
  - 210L full-energy fraction
- First-orbit losses from:
  - 210R third-energy fraction

SIMULATION



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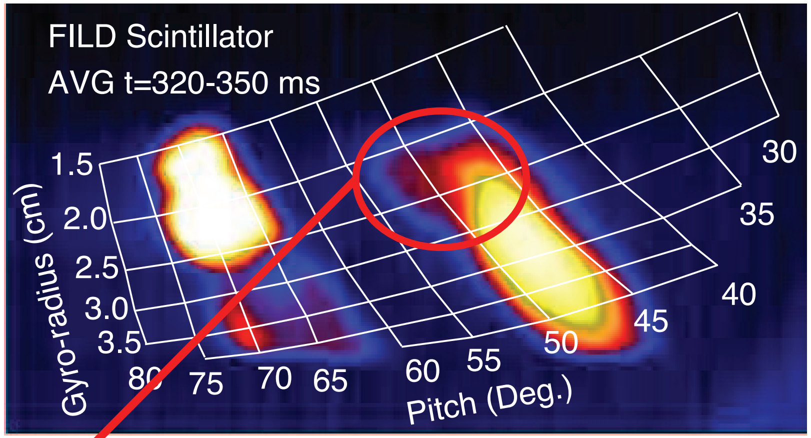
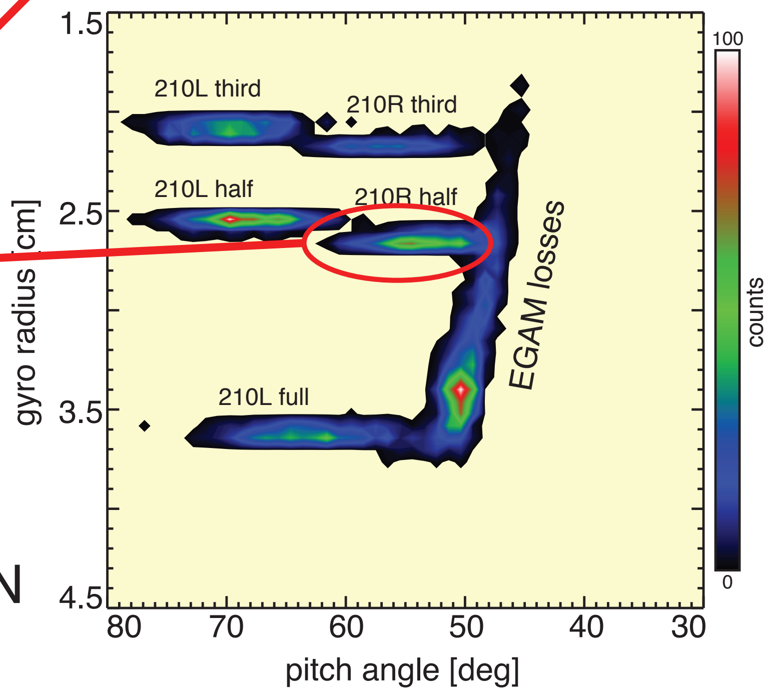


- First-orbit losses from:
  - 210L third-energy fraction
  - 210R half-energy fraction
  - 210L full-energy fraction
- First-orbit losses from:
  - 210R third-energy fraction
  - 210R half-energy fraction

SIMULATION



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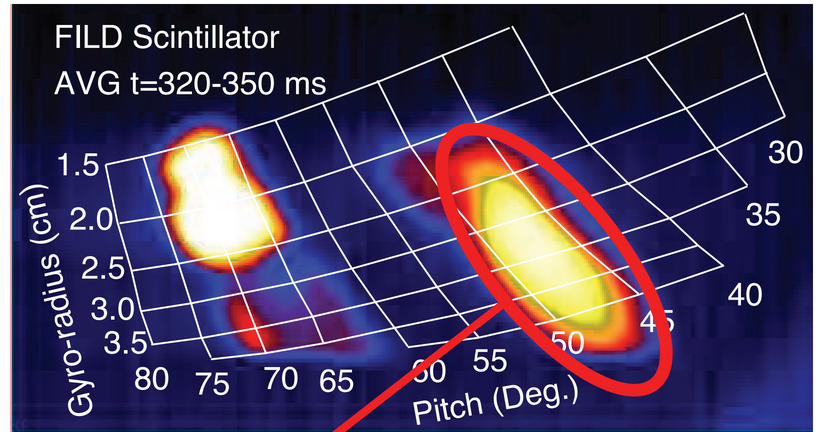
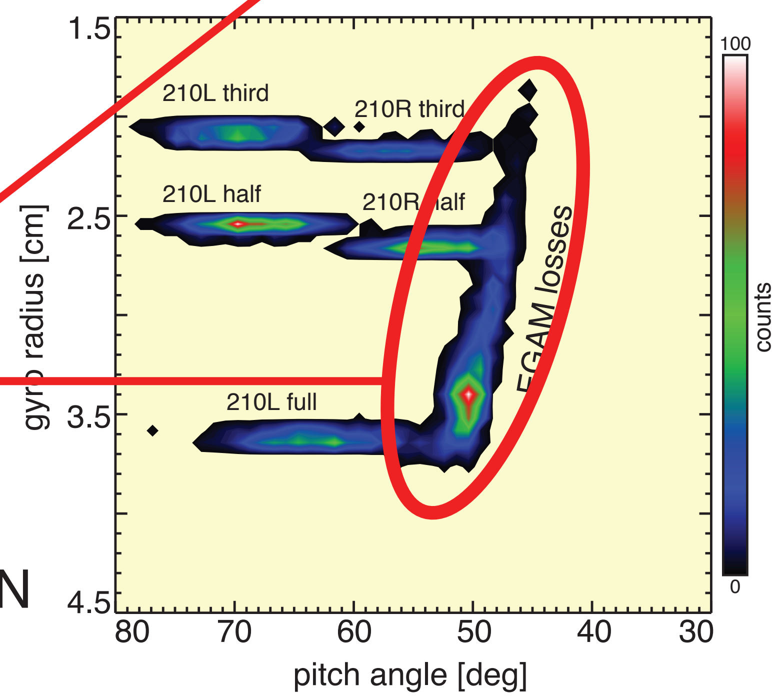


- First-orbit losses from:
  - 210L third-energy fraction
  - 210R half-energy fraction
  - 210L full-energy fraction
- First-orbit losses from:
  - 210R third-energy fraction
  - 210R half-energy fraction
- EGAM induced losses

SIMULATION



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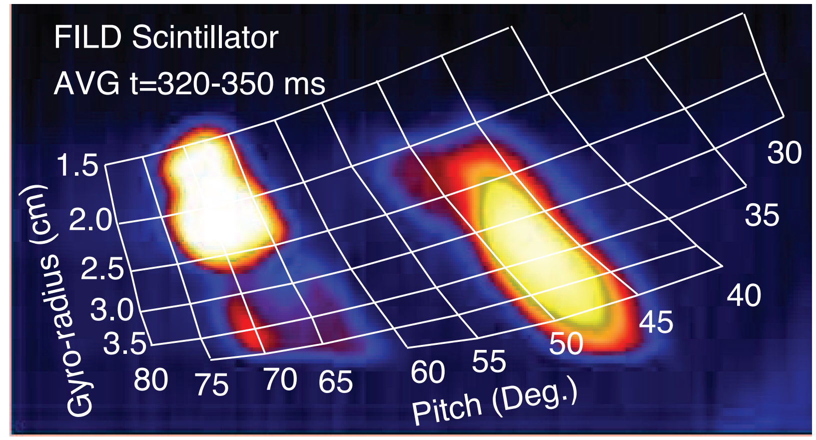
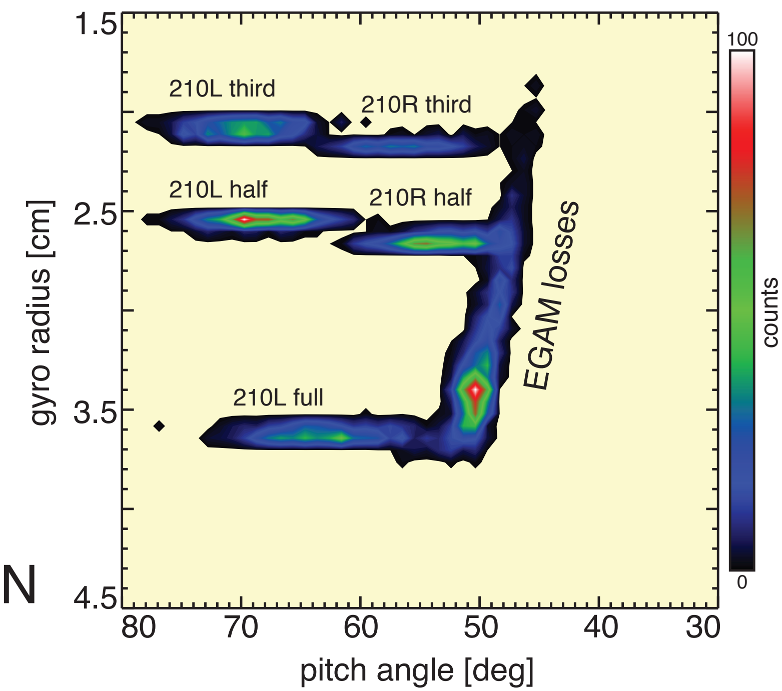
The 2-D FILD Image of Gyro-radius and Pitch Angle is also Reproduced in the Simulations

EXPERIMENT



- First-orbit losses from:
  - 210L third-energy fraction
  - 210R half-energy fraction
  - 210L full-energy fraction
- First-orbit losses from:
  - 210R third-energy fraction
  - 210R half-energy fraction
- EGAM induced losses
- Experiment and simulations agree well with each other

SIMULATION



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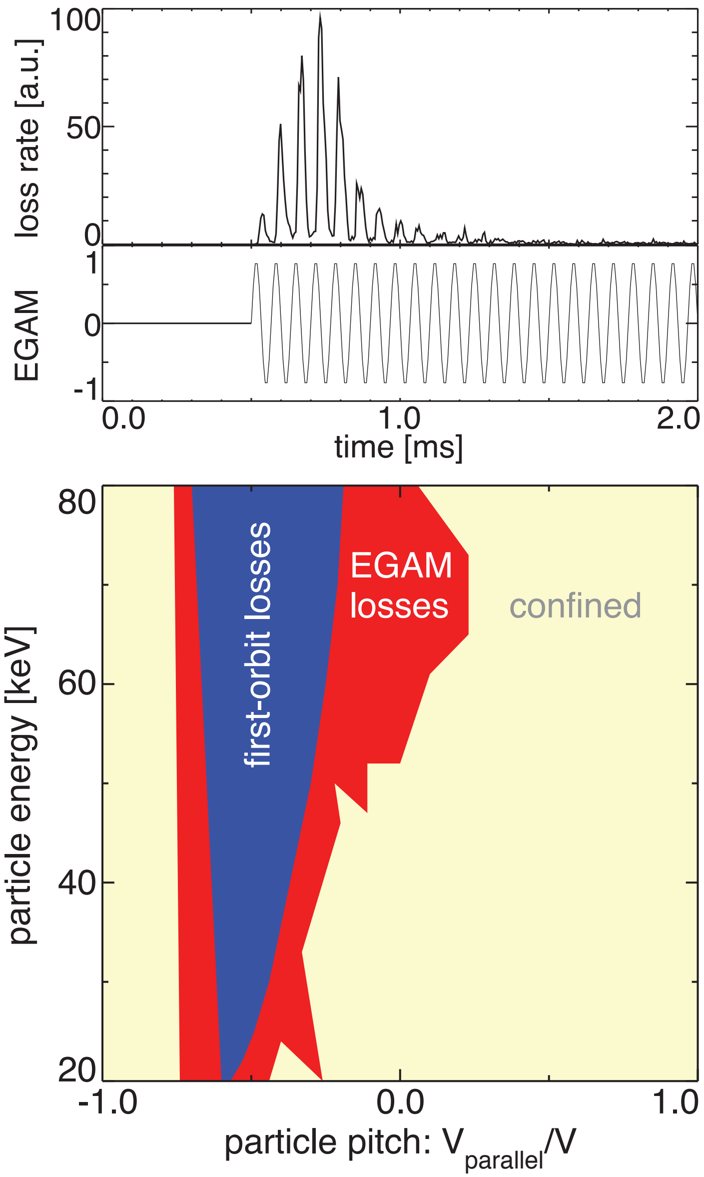
Coherent EGAM Losses are Found in the Simulations

- Particles were loaded at R=2.0 and Z=0.0 m uniformly in energy between 20 and 80 keV and pitch between -1 and 1
- First-orbit losses were removed before the EGAM was switched on
- Coherent losses were found as soon as the EGAM was switched on
- Those losses arise from:
  – Counter-going particles (pitch < -0.6) and trapped particles (pitch > -0.6)



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Particle-mode Resonances are Aligned with the Edge of the Loss Cone

- The resonance condition for particles with the n=0 EGAM is given by:

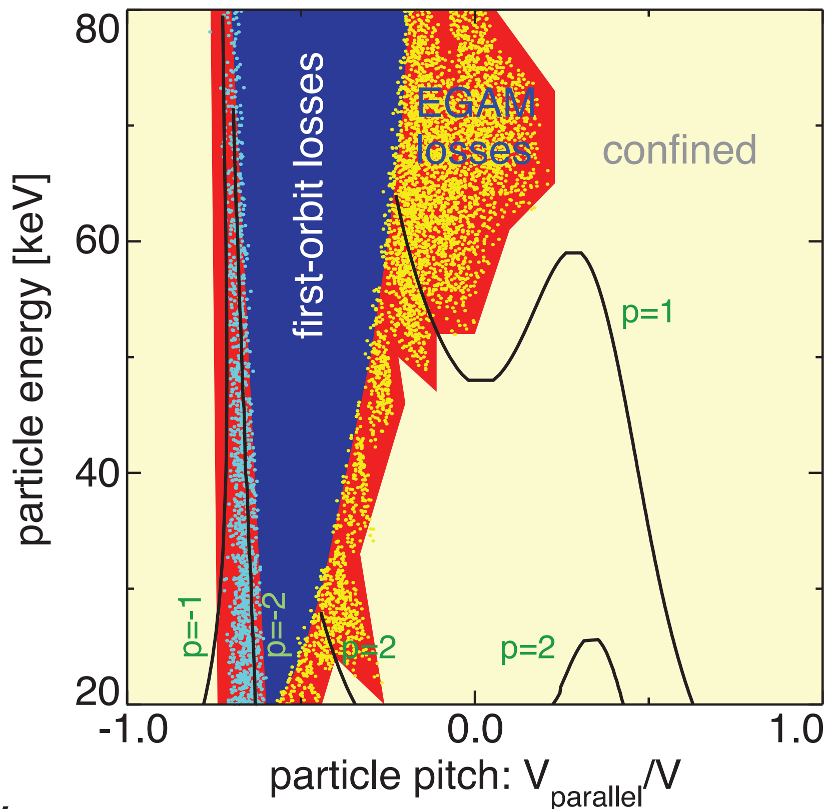
$$\omega_{EGAM} = p\,\omega_{pol}$$

  with integer p the bounce harmonic

- The p=-1 and p=-2 resonances are aligned with the edge of the loss cone

- Losses occur when a resonance is close to the loss boundary

- In this case:
  Slowing down near the left loss boundary keeps the particles in resonance for a long time and therefore, have a high change of getting lost



blue dots: lost particles that give >1% of its energy to the mode

yellow dots: lost particles that gain >1% of its energy from the mode

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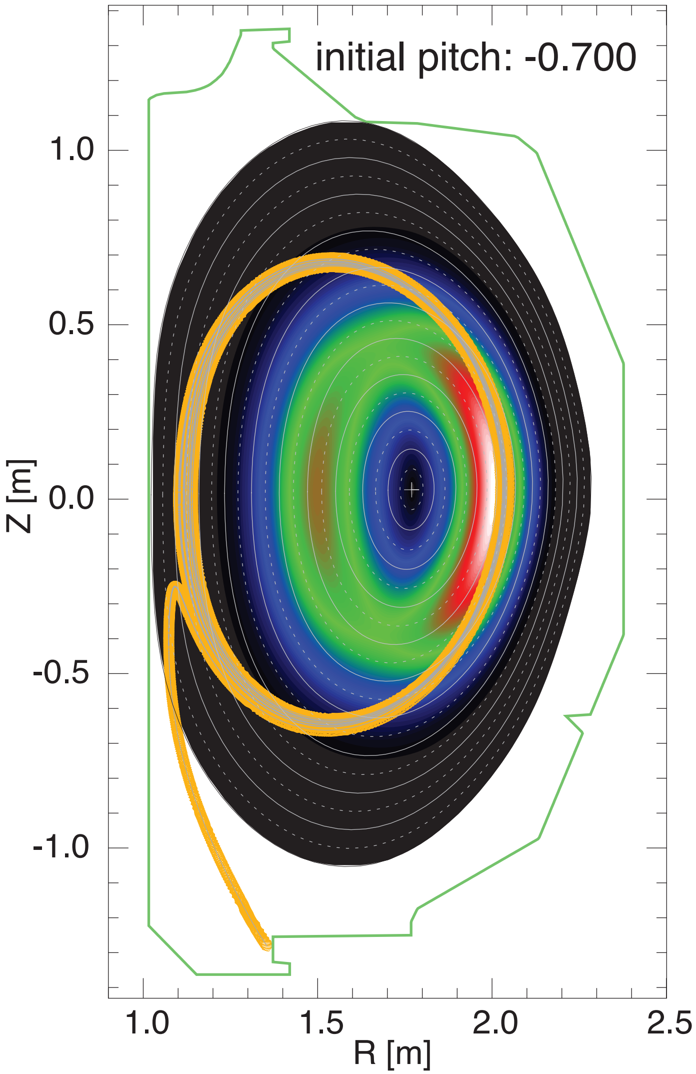
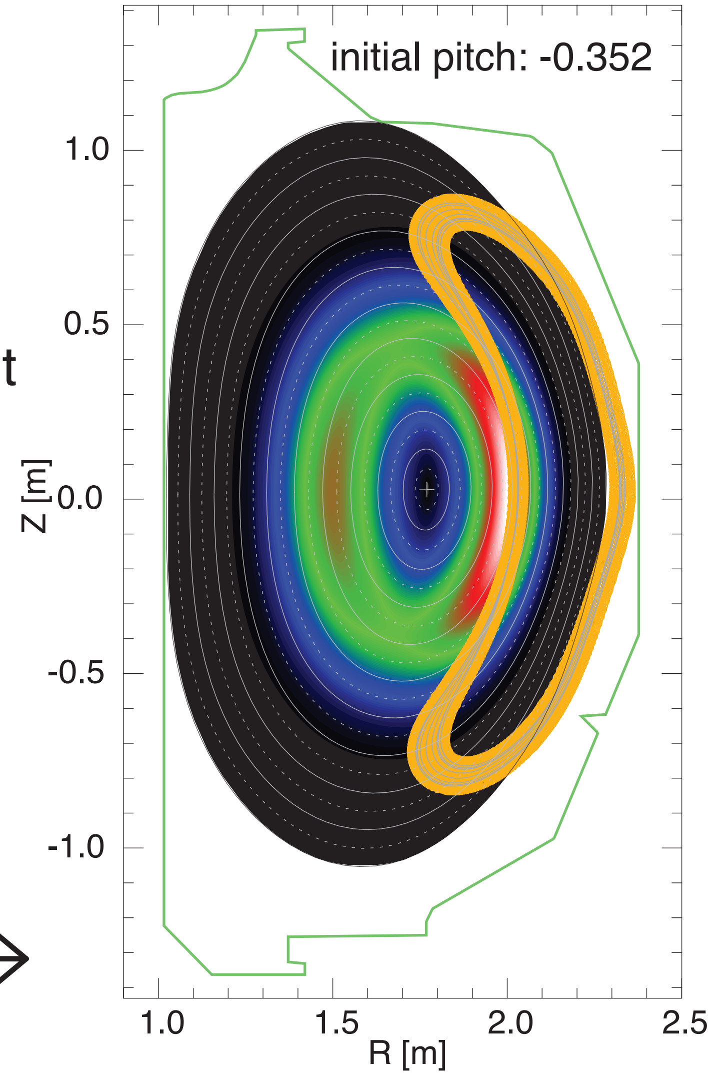
The EGAM Transfers Particles from Confined Orbits to Lost Orbits



- A 60 keV deuteron:

  launched on a counter passing orbit:
  looses 2.2 keV energy
  transits to trapped orbit
  and is lost

  launched on a trapped orbit:
  gains 1.1 keV energy
  the orbit expands and is lost



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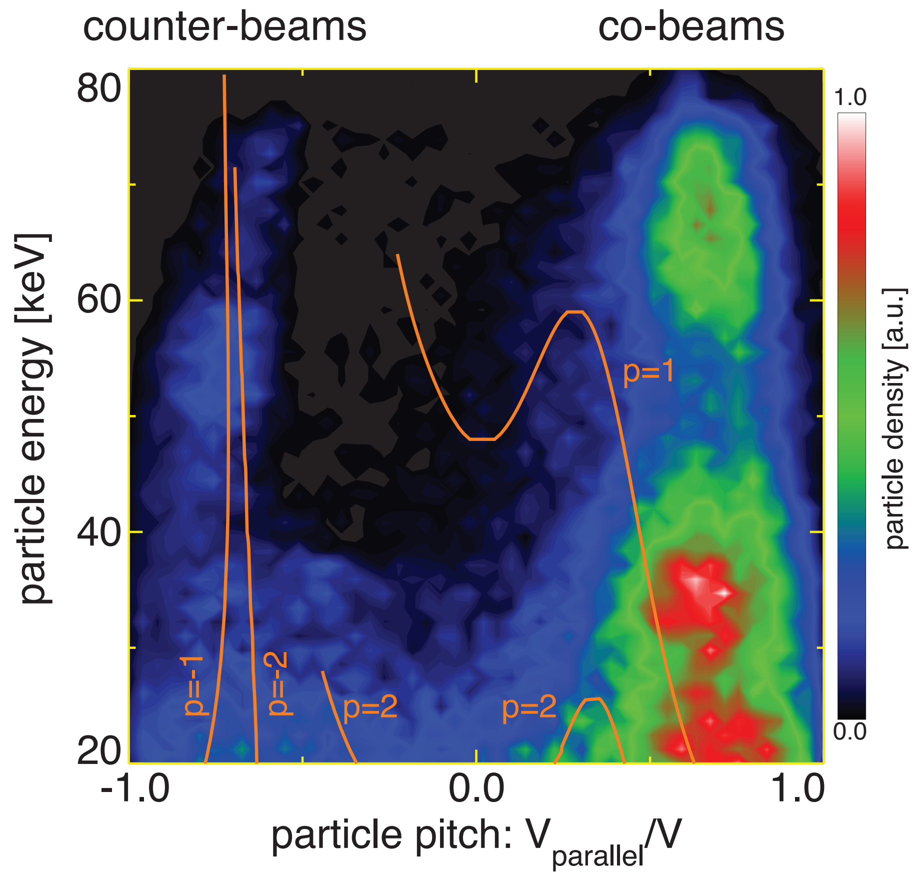
The Slowing-down Distribution of the Counter Beams Coincides with the EGAM Resonances

- After 50 ms of beam injection slowing down distributions have developed for for the co- and counter-beams
- The counter-beam distribution coincides with two EGAM resonances for the whole slowing-down trajectory
- This creates favorable conditions for losing a significant amount of counter-beam ions due to the EGAM



Particles shown for all R and Z

Resonances at R=2.0 m Z=0.0 m

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Summary and Conclusion

- Observations with the Fast Ion Loss detector in DIII-D have shown that significant amounts of beam ions are lost when the EGAM is present
- A good qualitative agreement was found between the FILD observations and simulations performed with the full orbit code SPIRAL
- The code was then used calculate the particle-EGAM resonances which were found to be aligned with the edge of the loss cone
- Counter injected beams populate this region of phase space and when those beam ions slow down they have ample time to interact with the EGAM and moved into the loss cone