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

by

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In collaboration with

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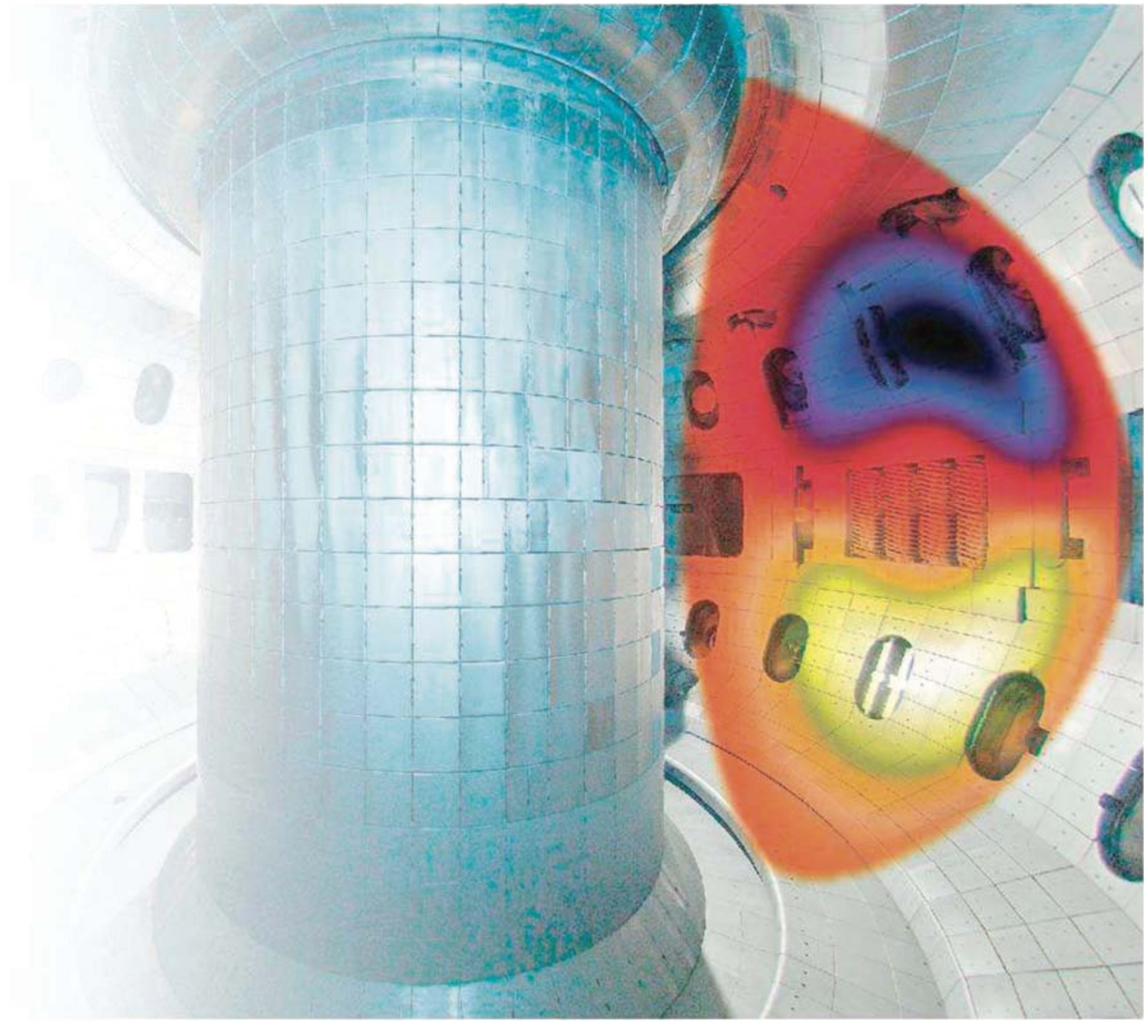

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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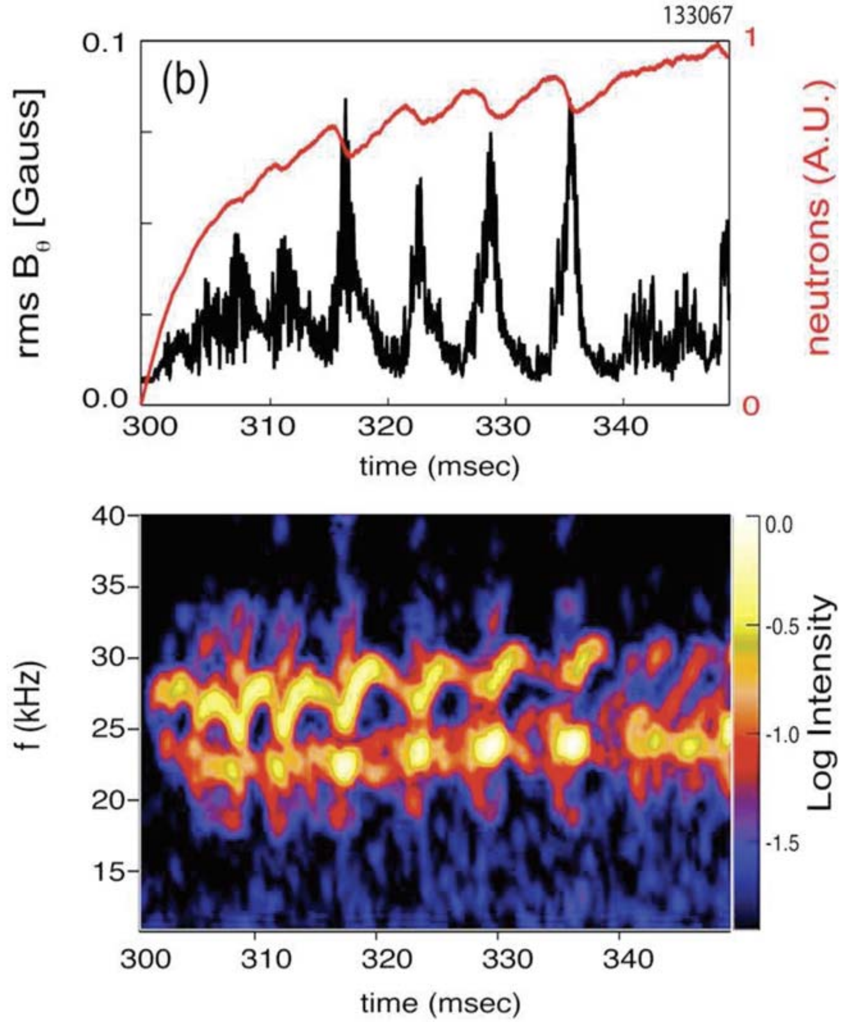
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Geodesic Acoustic Modes can be Driven by Energetic Particles — the EGAM

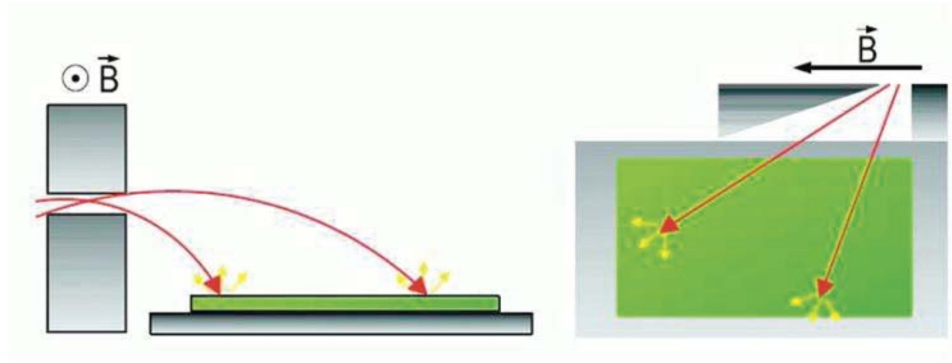
- Geodesic Acoustic Modes are zonal flows with n=0 and $\omega_{GAM}=C_s/R$
- Recently, macroscopic GAMs were discovered that are driven by energetic ions[1,2]
- EGAMs are excited strongly by counter-injected neutral beams
- EGAMs can be driven to large amplitudes leading to large beam-ion losses
- Detailed measurements of the mode properties and losses allow the validation of nonlinear dynamical model for fast-ion transport



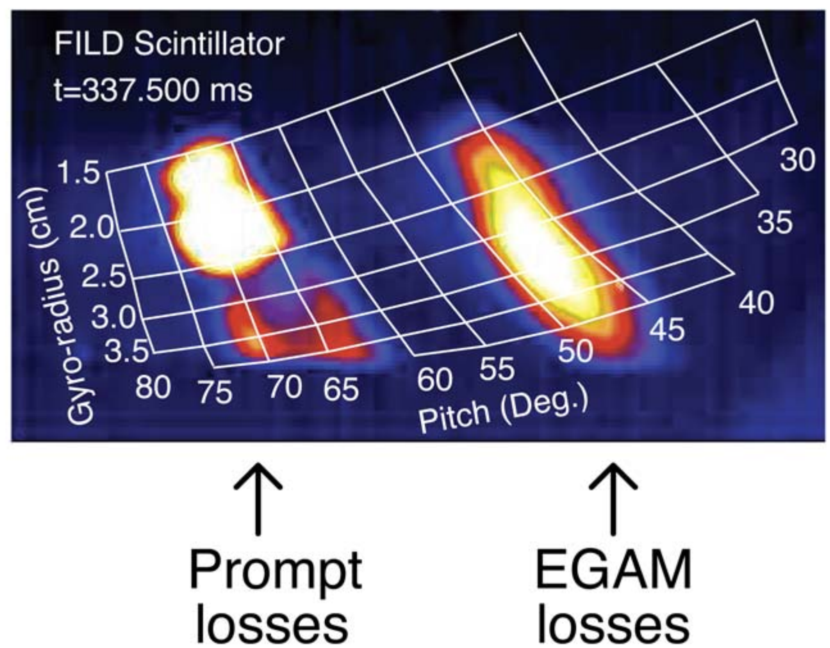
[1]G.Y. Fu, *Phys. Rev. Lett.* **101**, 185002 (2008)
[2]R. Nazikian, et al., *Phys. Rev. Lett.* **101**, 185001 (2008)

The EGAM Induces Losses Over an Extended Energy Range

- **The Fast Ion Loss Detector (FILD) measures the pitch angle and energy of lost fast ions**
  - A collimator and the magnetic field give energy and pitch discrimination



- **FILD reveals that the EGAM-induced losses occur over an extended energy range (or gyro-radius)**
- **The losses arise from the counter-going beams**
- **Can we simulate the EGAM losses and understand why they occur over such a broad energy range?**



For more information on FILD, see: X. Chen et al., UP9.00059 on Thurs. afternoon

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

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

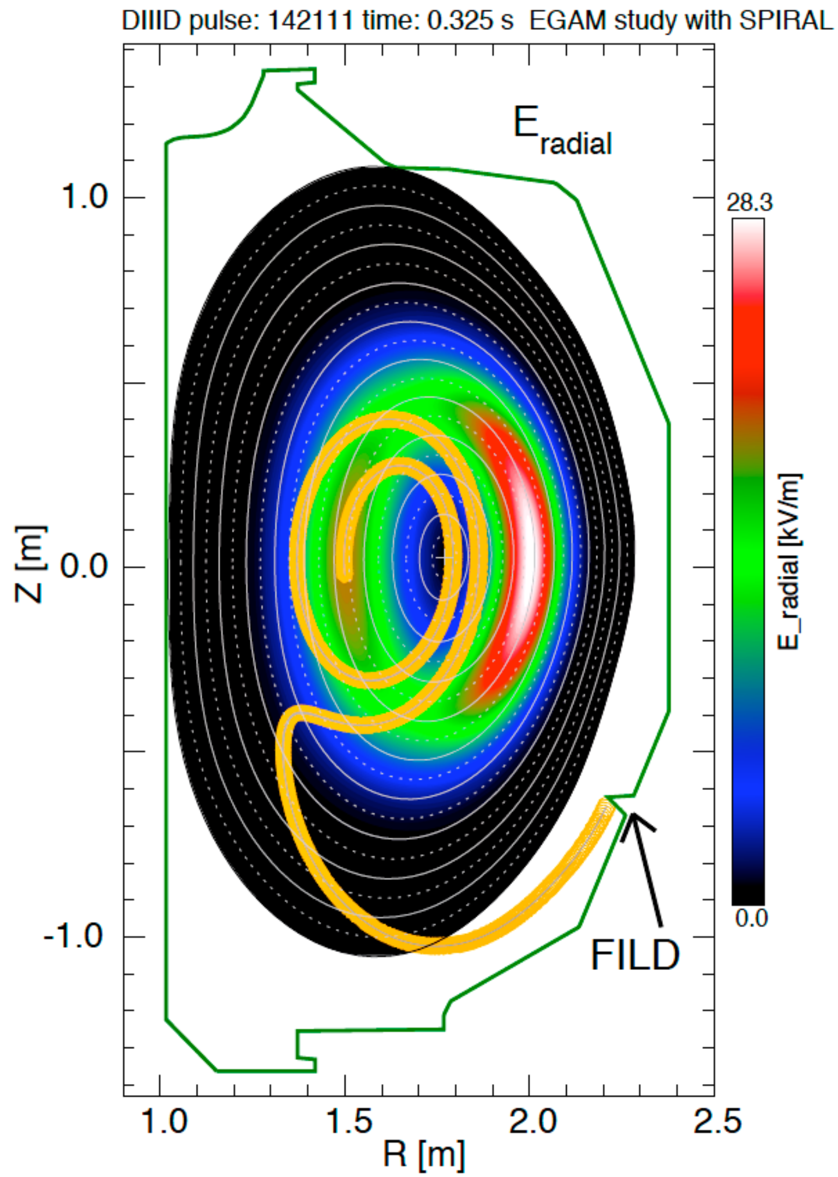
$$\vec{v} = \frac{d\vec{r}}{dt} \qquad \frac{d\vec{v}}{dt} = \frac{q}{m}(\vec{v} \times \vec{B} + \vec{E})$$

- **Ripple fields, slowing-down, and pitch angle scattering can be included together with MHD modes and rf fields**

- **The EGAM is modeled as time-varying electrical potential:**

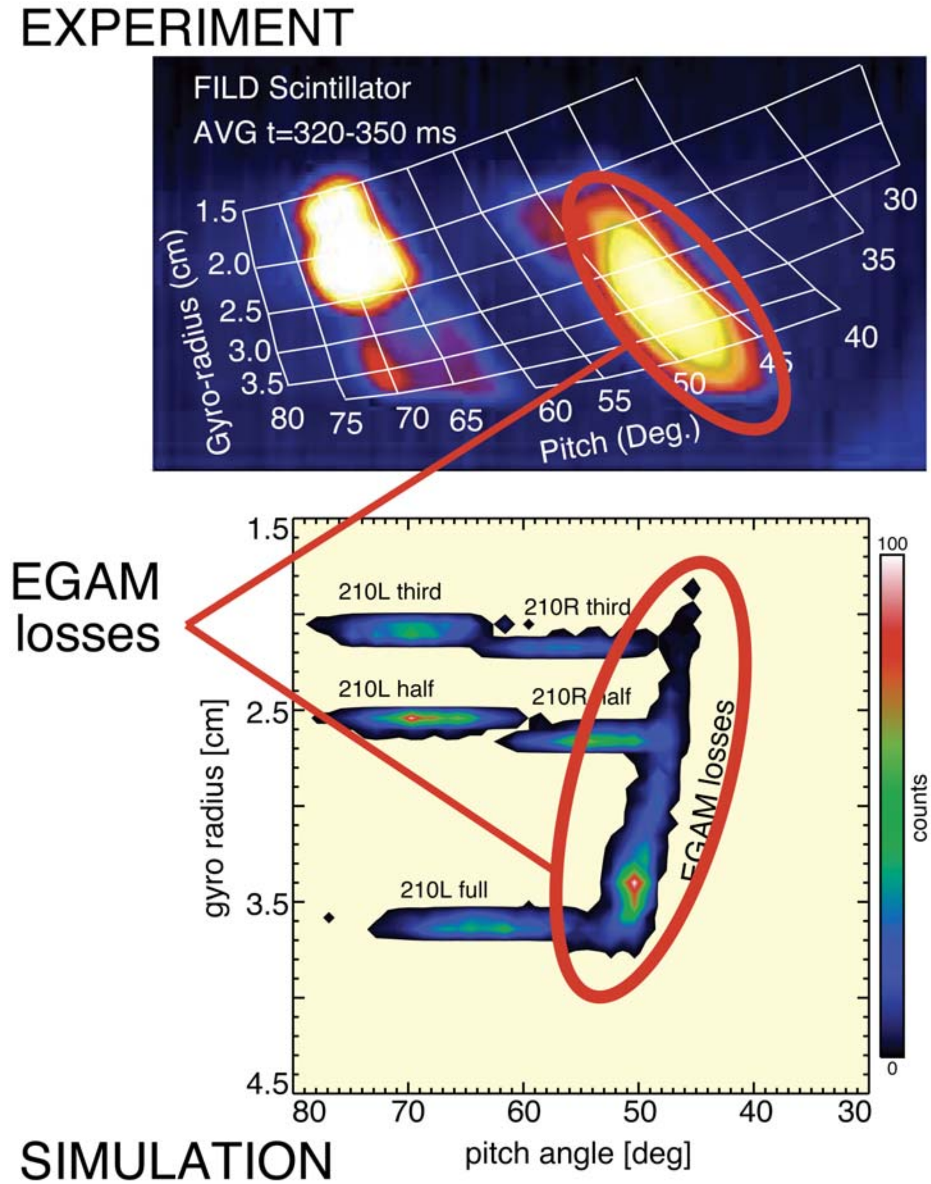
$$E_r = -\nabla\Phi \sin(\omega t)$$

- **Realistic walls are included to calculate fast ion losses**



EGAM-Induced Losses From the FILD Detector are Reproduced With the SPIRAL Code

- **In the simulations the experimental conditions were closely matched**
  - EFIT equilibrium
  - TRANSP/NUBEAM beam birth profiles
  - Experimental EGAM mode width and amplitude: density fluctuations of ~10%
- **The EGAM-induced losses are reproduced well in simulations with the full orbit SPIRAL code**
- **Why are the EGAM losses occurring over such a wide energy range?**



Particle-Mode Resonances and Loss Cone Are Aligned Well With Counter Beam Injection

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

  $$\omega_{EGAM} = P\omega_{pol}$$

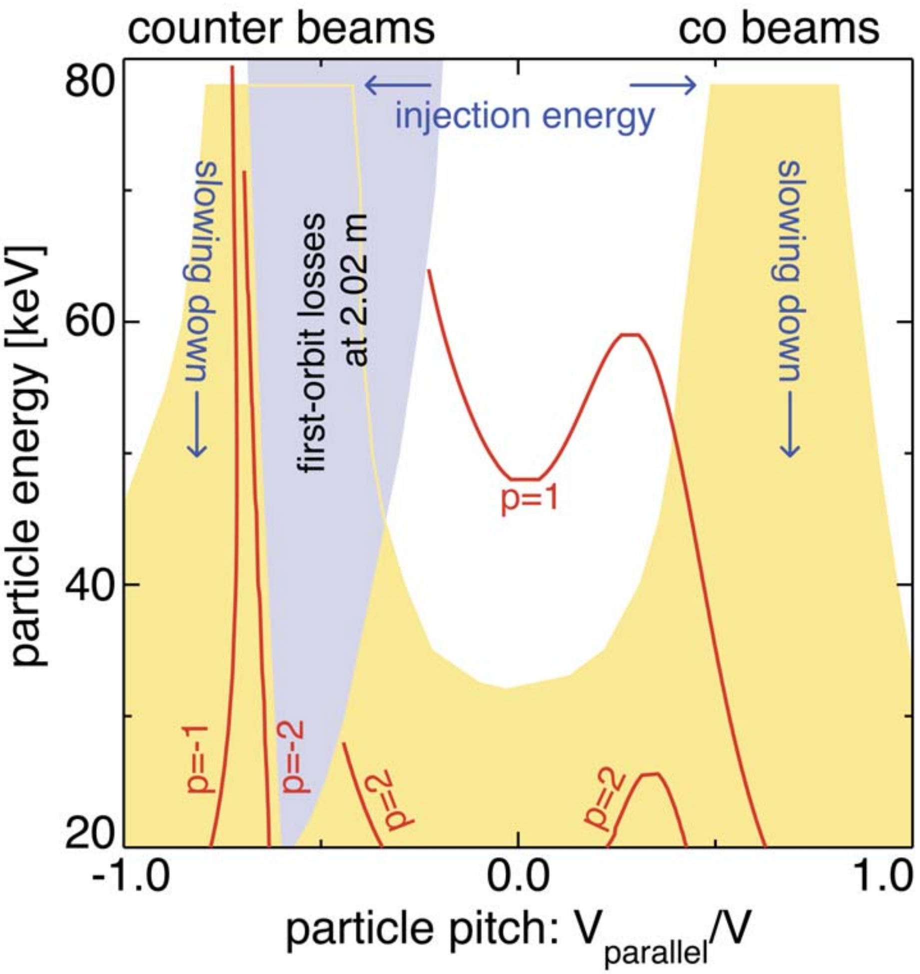
  with integer P the bounce harmonic

- **The P=-1 and -2 counter resonances**
  - Are aligned with the edge of the loss cone
  - In the slowing-down distribution of the counter beams

- **Hence, losses are found over a wide range of particle energies**

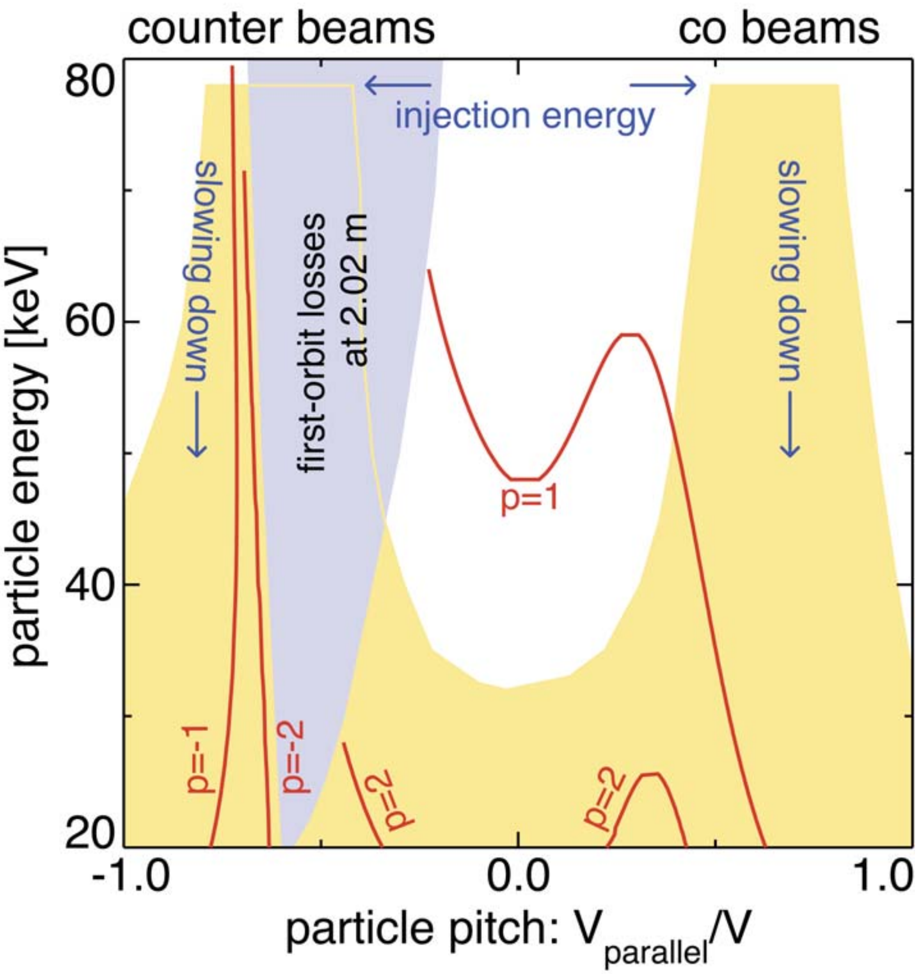
- **Particles lose energy to the mode before getting lost**

- **This provides a strong drive for the EGAM**



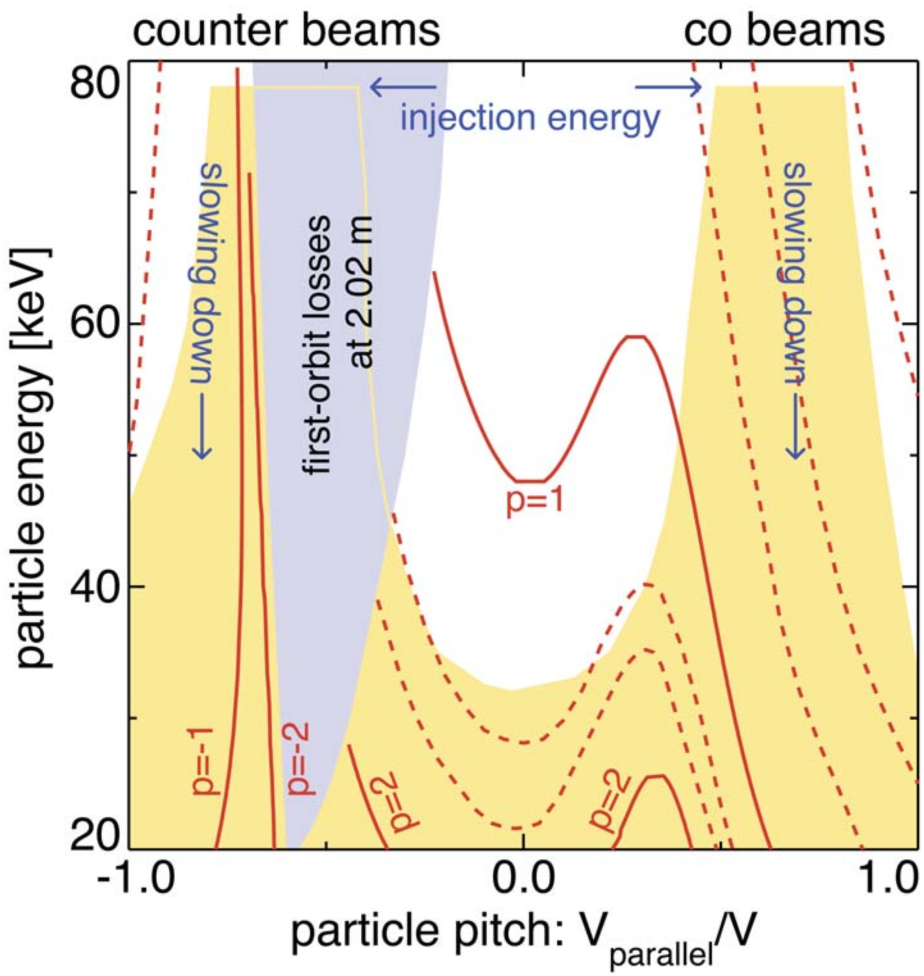
At Large EGAM Amplitudes, a New Set of Resonances Was Found in the Simulations

- **No resonances are present in the co-beam slowing down distribution**



At Large EGAM Amplitudes, a New Set of Resonances Was Found in the Simulations

- **No resonances are present in the co-beam slowing down distribution**
- **At the experimental mode amplitude in the simulation resonances appeared in the co-beam slowing down distribution**
- **In the following, we will**
  - Explore the nature of those resonances
  - Look for effects on the fast-ion distribution



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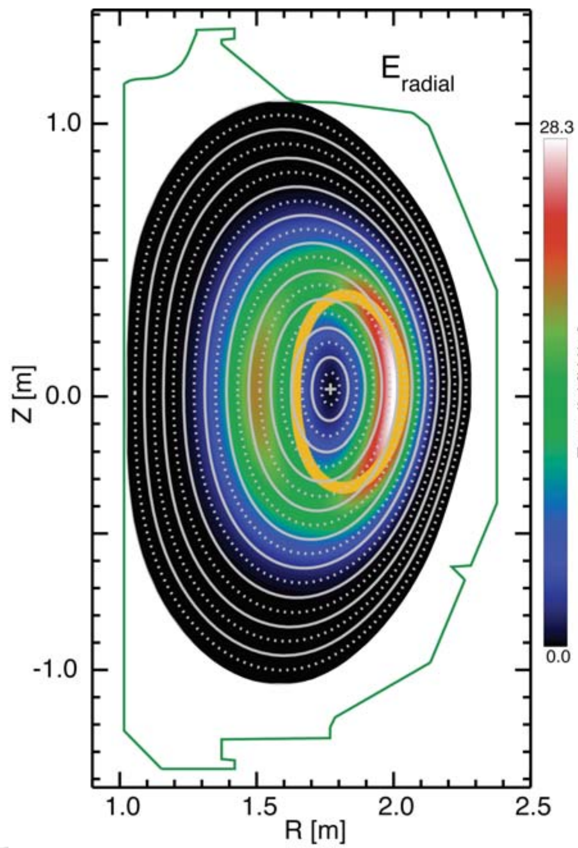
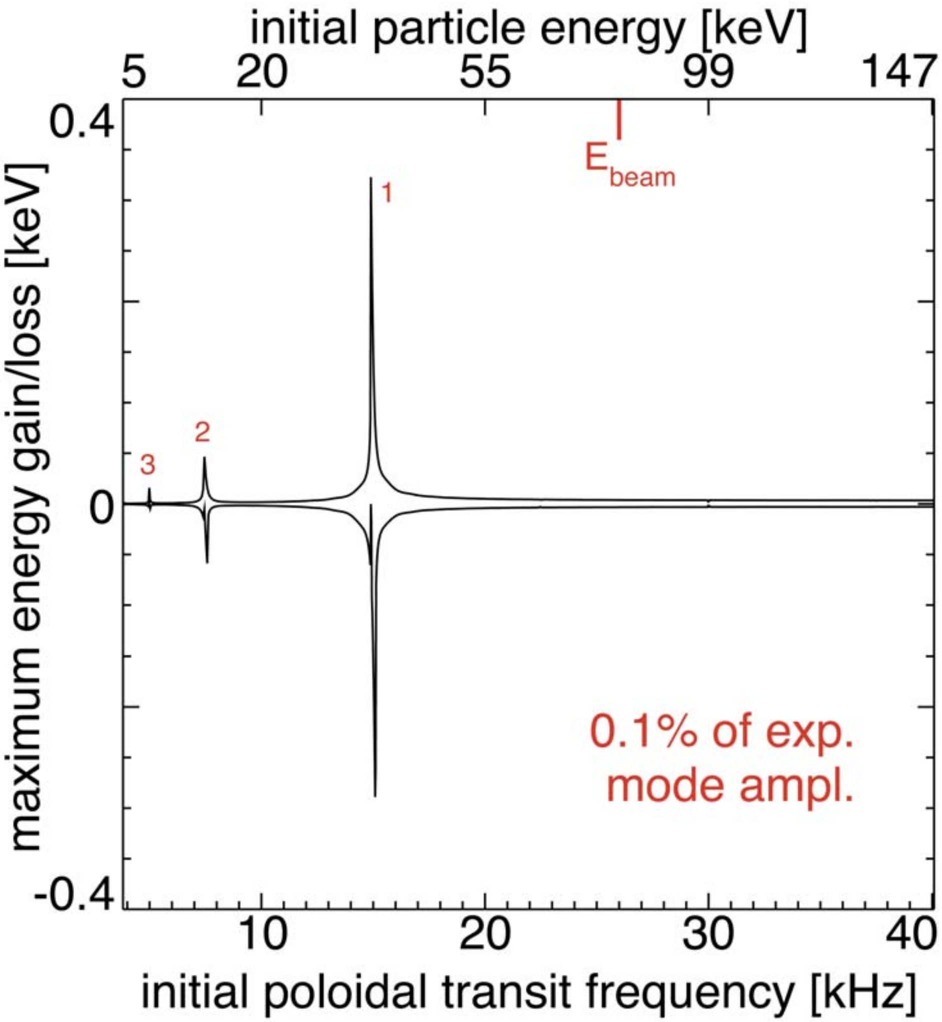
Identification of Nonlinearly-Generated Fractional Resonances for the Measured Mode Amplitude

- **The linear resonance condition:**

$$\omega_{EGAM} = P\omega_{pol}$$

is fufilled for amplitudes of 0.1% of the experimental amplitude





EGAM frequency: 15.0 kHz
particle pitch: 0.5

Identification of Nonlinearly-Generated Fractional Resonances for the Measured Mode Amplitude

- **The linear resonance condition:**

$$\omega_{EGAM} = P\omega_{pol}$$

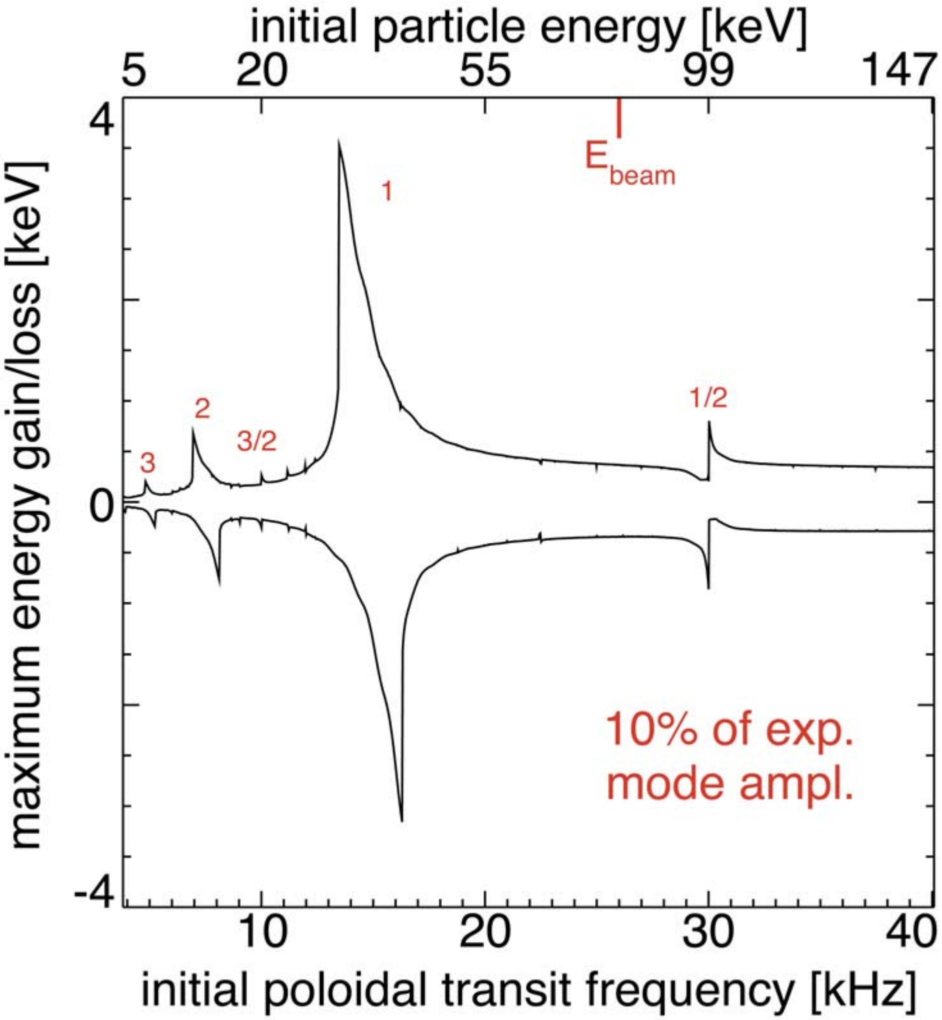
is fufilled for amplitudes of 0.1% of the experimental amplitude

- **Fractional resonances:**

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

occur when the mode amplitude is larger than 1% of the experimental amplitude

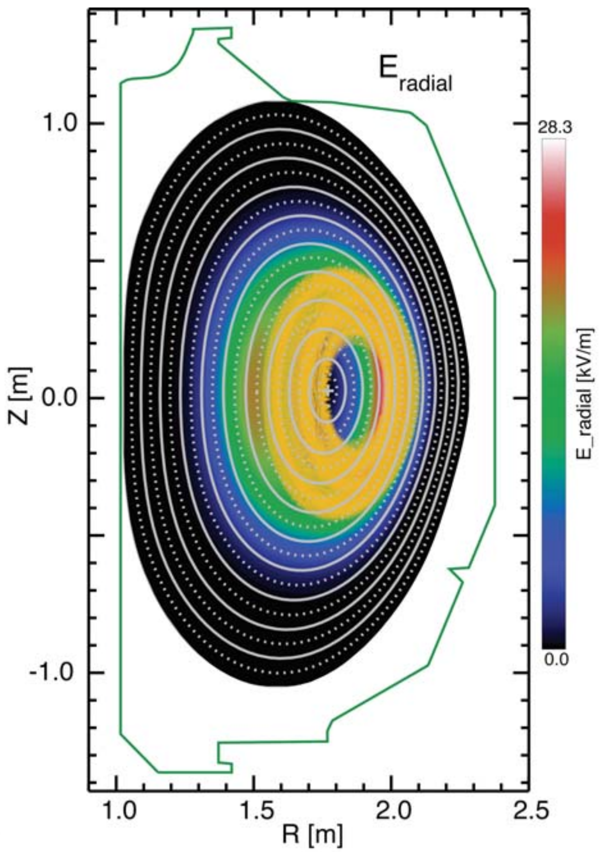
- **The fractional resonances arise from a nonlinear interaction between the particle orbit and the mode**

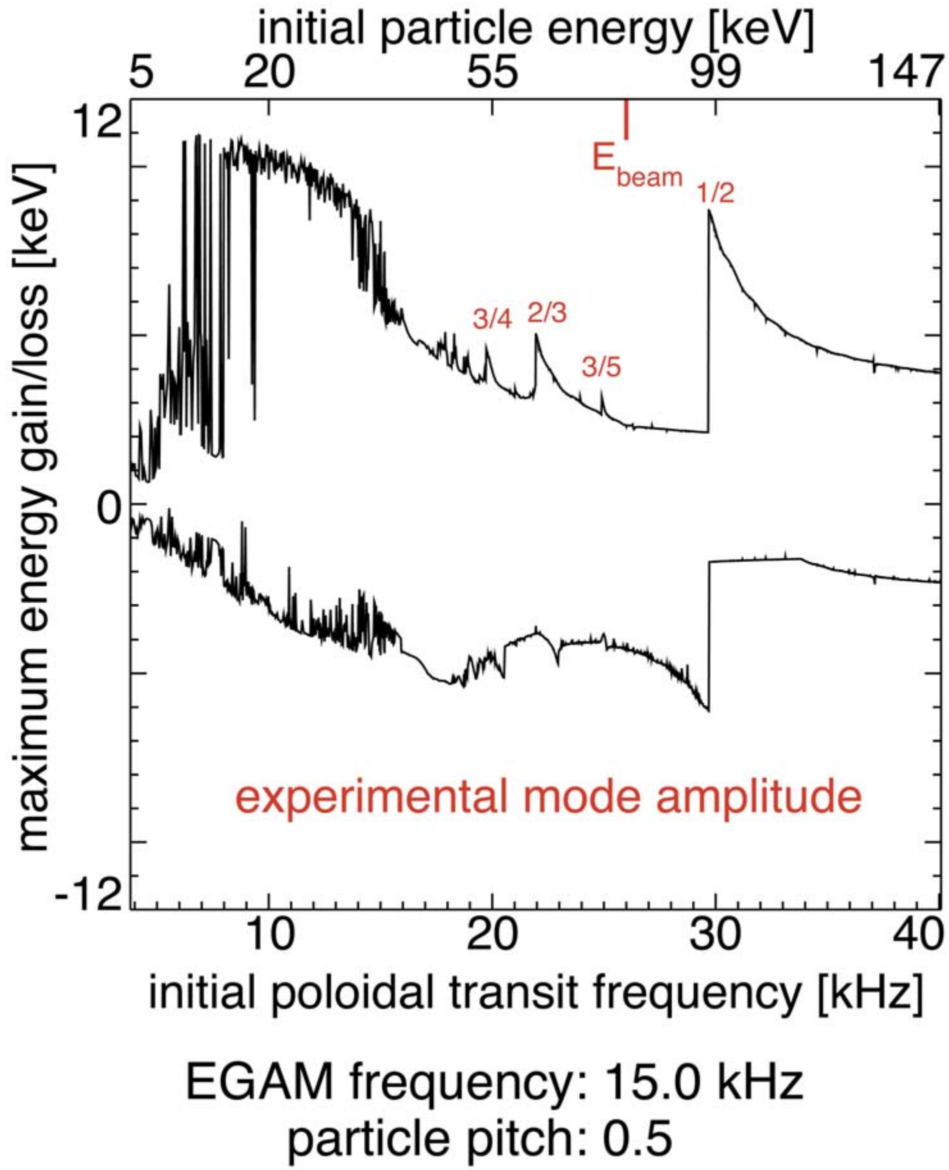


EGAM frequency: 15.0 kHz
particle pitch: 0.5

Identification of Nonlinearly-Generated Fractional Resonances for the Measured Mode Amplitude

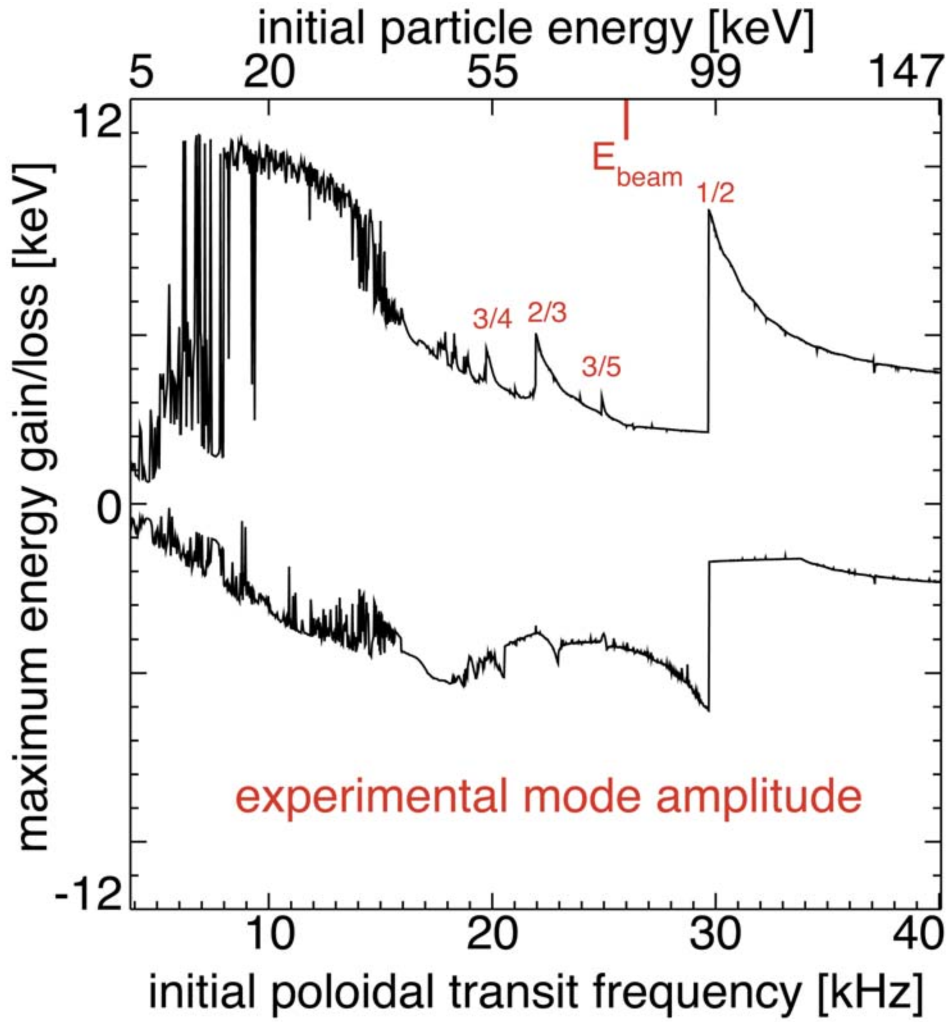
- **At the experimental mode amplitude, an extended region is formed where resonances overlap**
- **The orbits in this region have become stochastic**





Identification of Nonlinearly-Generated Fractional Resonances for the Measured Mode Amplitude

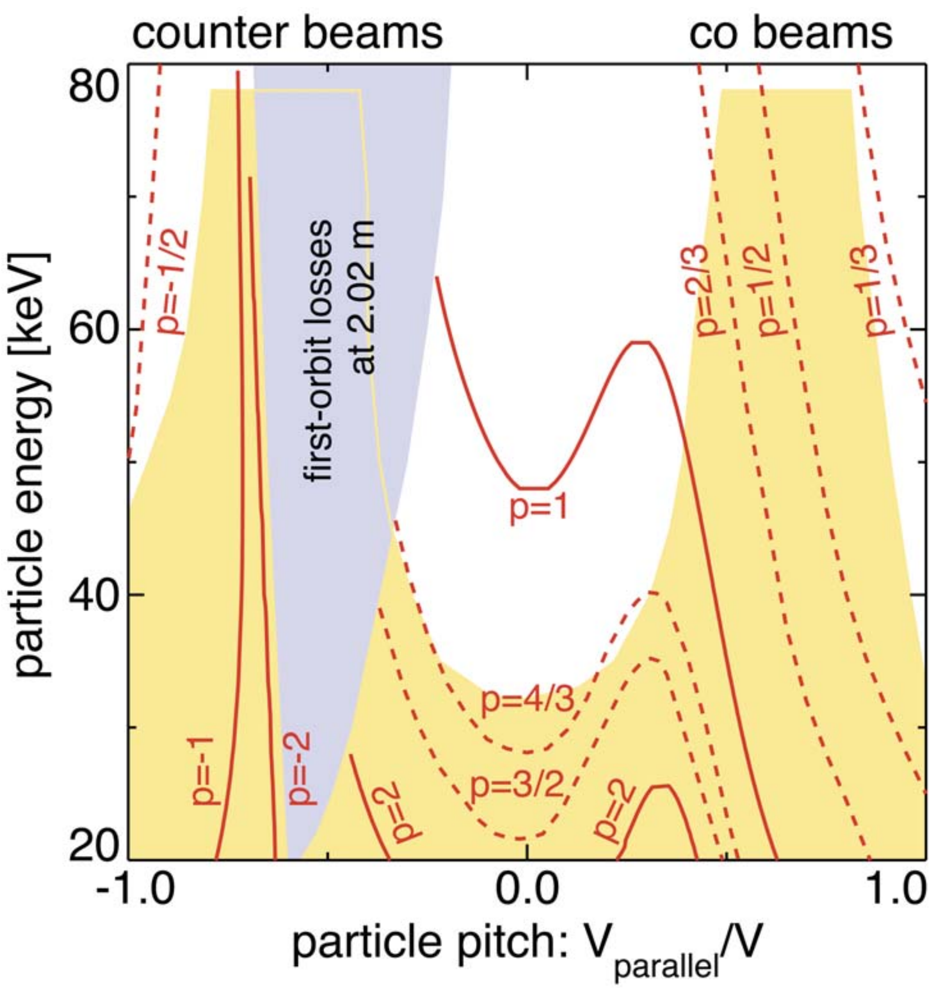
- **At the experimental mode amplitude, an extended region is formed where resonances overlap**
- **At the measured EGAM amplitude the particles gain more energy from the mode than they lose to the mode**
- **Hence, the simulations predict that co-beams contribute to the damping of the EGAM which can be investigated experimentally**



EGAM frequency: 15.0 kHz
particle pitch: 0.5

Co-Beams Can Interact Strongly With Large Amplitude EGAMs Via Fractional Resonances

- **Fractional resonances are found to coincide with the co-beam phase space**
- **When the resonances overlap, the particle orbits become stochastic which can lead to enhanced fast-ion transport**
- **In carefully designed experiments, such transport might be observed on the fast-ion D_α (FIDA) diagnostic**



Summary and Future Work

- Simulations have revealed that the observed EGAM-induced losses can be explained by counter resonances that are aligned well at the edge of the loss cone over a substantial energy range
- Those lost particles provide a strong drive for the EGAM
- At the experimental EGAM amplitude, a nonlinear interaction between the mode and the particle orbits was found in the simulations
- This interaction leads to fractional resonances
- The increased resonance density leads to stochastic orbits at the observed EGAM amplitude and, hence, an increased fast-ion transport

Future Work

- Identify signs of enhanced fast-ion transport with the FIDA diagnostic when the EGAM is excited
- Study the influence of co-beams on the stability of the EGAM