Modeling of ELM-pacing by Lithium Granule Injection (LGI) on NSTX-U with the M3D-C1 code

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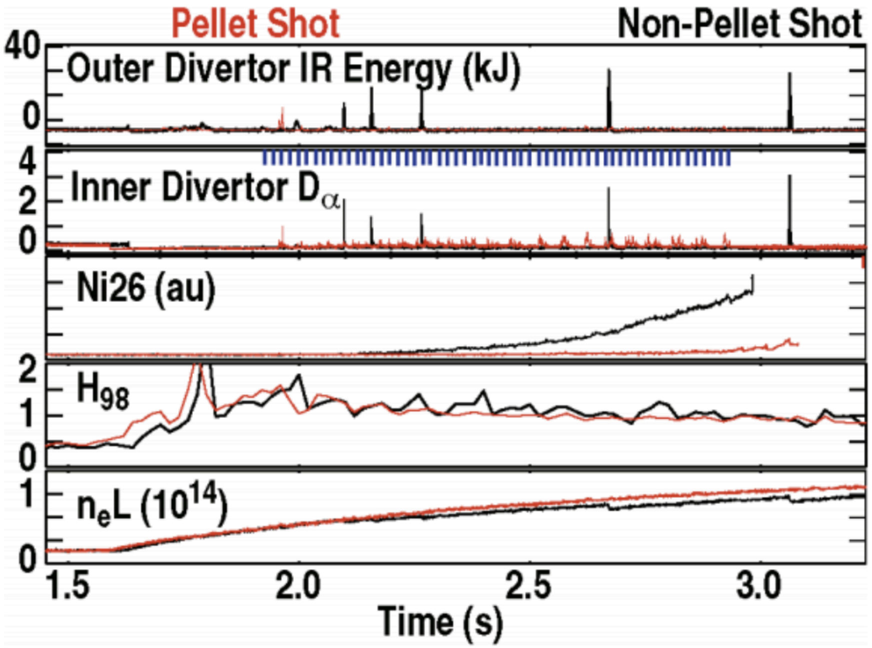
Introduction and motivation

- The control and pacing of ELMs is needed in ITER
  - Need to have a tolerable peak heat flux on the divertor plates
  - Prevent impurity contamination, especially W
  - Need a larger ELMs frequency than “natural” one

- ELM pacing by D_2 pellet injection has been tested and proved to be effective in several devices



ELM pacing on DIII-D

Introduction and motivation

- However, D_2 pellets also fuel the plasma
    - Need to decouple plasma fueling and ELM control
- ELM pacing by Lithium Granule Injection (LGI) has been demonstrated on EAST, DIII-D and NSTX and has potential for high injection rates
- Lack of physical understanding of the processes at play
- A modeling effort is needed to support next NSTX-U experiments

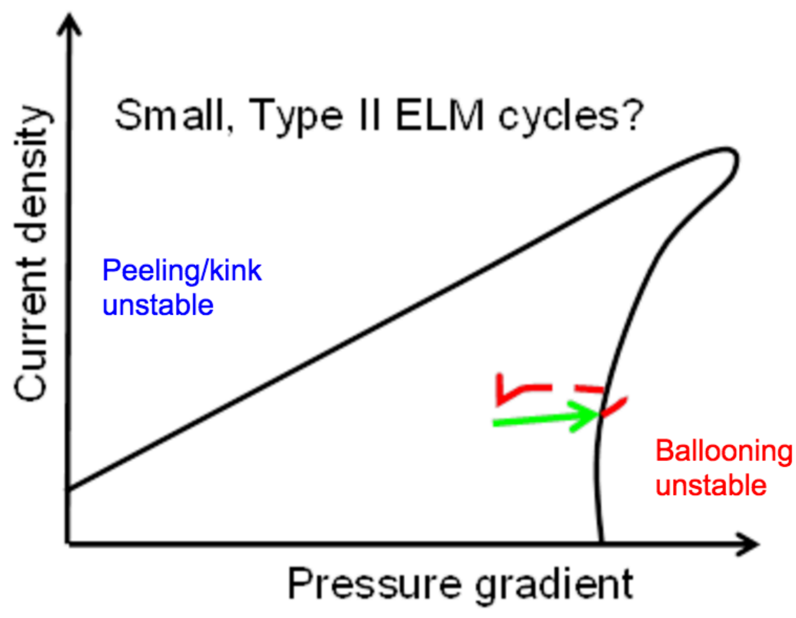
Outline

1. LGI principle and experiments
2. Pellet injection models
3. M3D-C1 modeling

ELM pacing principle

- Because of the 3D pressure perturbation due to the pellet ablation, medium/high-n ballooning modes become unstable.
- The ballooning modes are destabilized by the large local pressure gradients of the pressure perturbation.

Peeling-ballooning diagram



Link between pellet parameters and profiles perturbation

- Need to link the pressure perturbation needed to trigger an ELM and the pellet parameters
  - Pellet size
  - Species (pure D_2, Li or even LiD)
  - Pellet velocity
  - Injection location (HFS vs. LFS)

Lithium Granule Injection principle

- **Top part: granule dropper**

– four separate reservoirs, 0.3-0.9 mm

– vibrating piezoelectric disk

– Average drop rate function of applied voltage (0-1000Hz)

- **Bottom part: granule impeller**

– rotary motor + ferro-fluidic feed-though, f_{rot} < 250 Hz

– Two-paddle impeller imparts 10-100 m/s f_{inj}=500 Hz

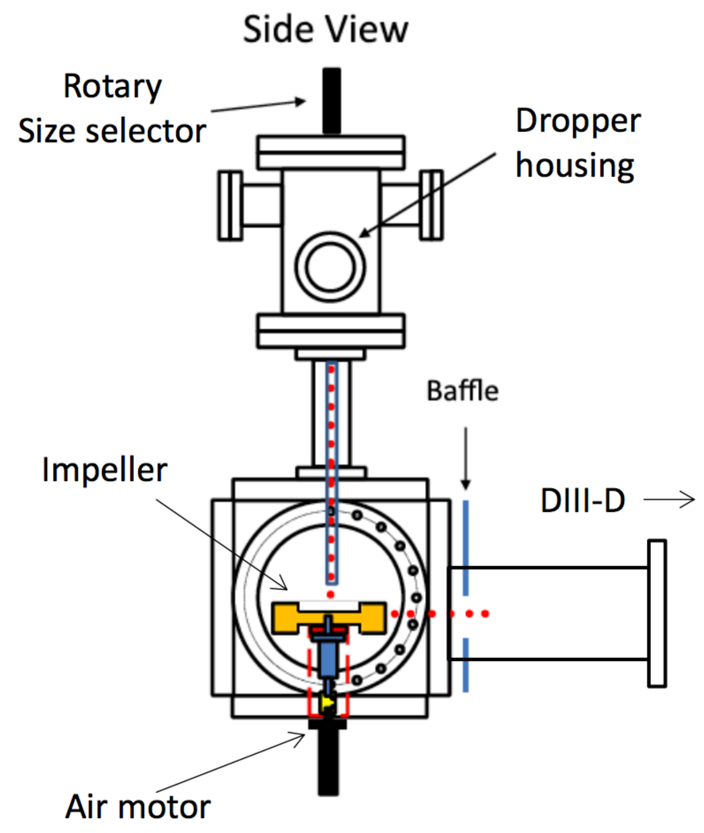


Figure from [A. Bortolon et al.]

Examples of edge perturbations induced by Lithium injection on NSTX

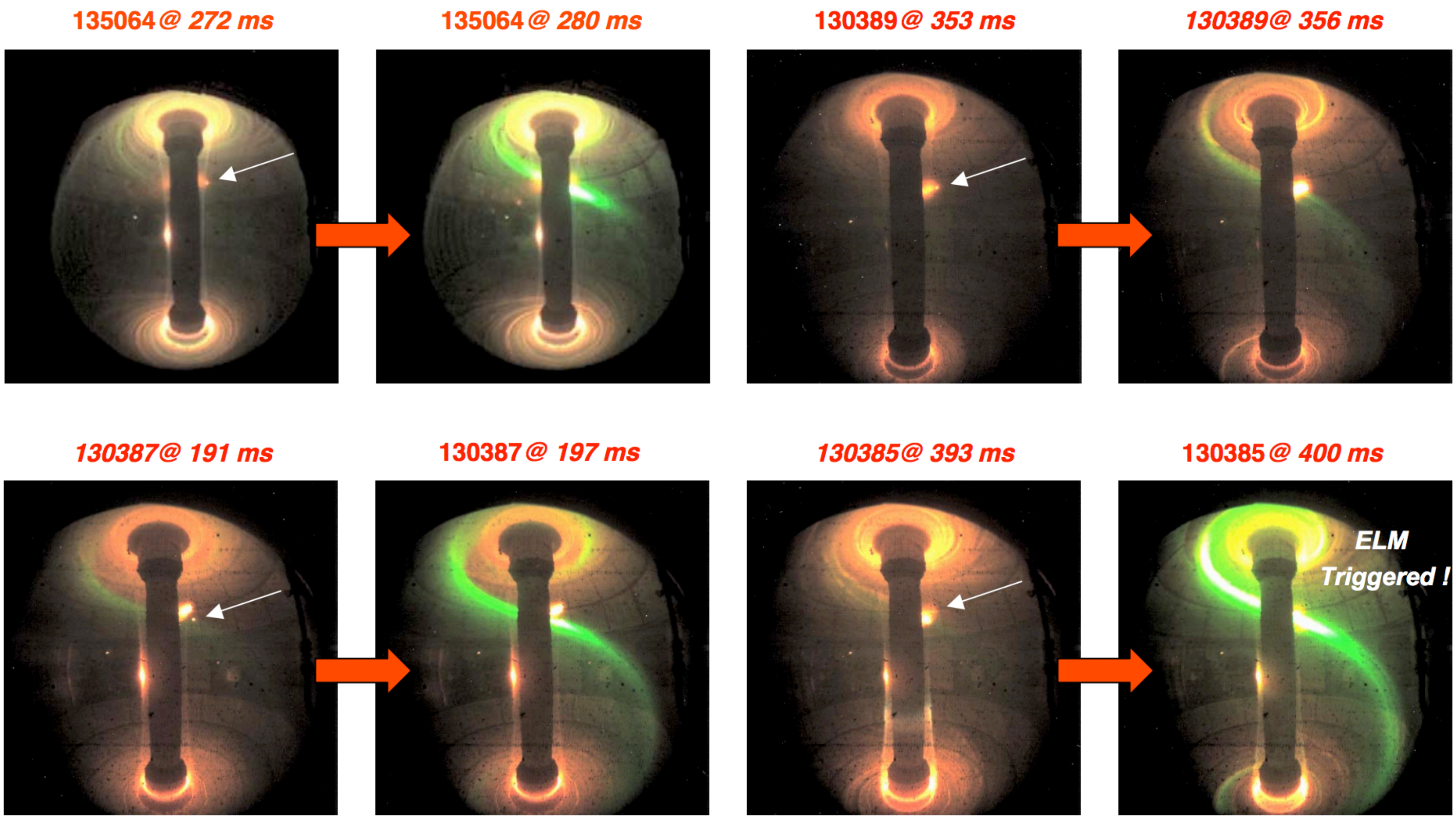


Figure from *[D. K. Mansfield et al.]*

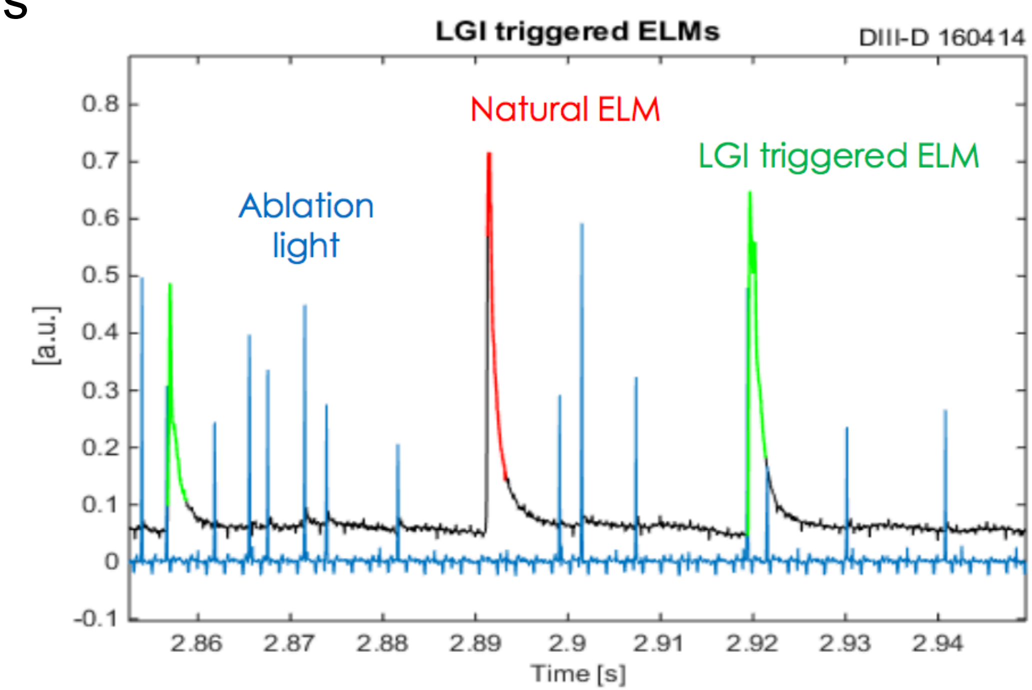
LGI triggered ELMs in DIII-D

Its key to identify which ELMs are associated with LGI

– Not all ablations are followed by ELMs

– ELMs can occur naturally during LGI phases

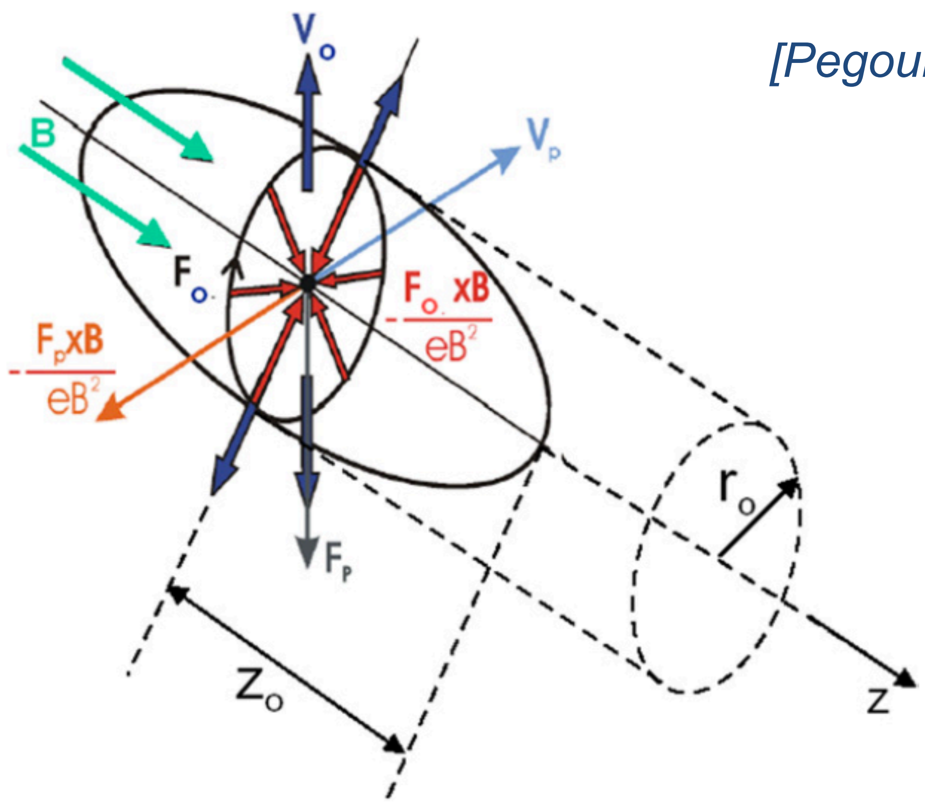
Modeling can provide some insight



LGI triggered ELMs in DIII-D

Pellet models: Shielding mechanisms

For both hydrogen or impurity pellets, ablation is a self regulated process, in the sense that the ablation cloud self-adapts for the heat flux at the pellet surface to be just enough to maintain the shielding capability of the cloud at the adequate value



[Pegourie]

Different types of shielding

- **Gas dynamic shielding (dominant mechanism for D_2)**
  - Due to the collisions between the incident plasma particles and that of the cloud, which is responsible for the ionization and heating of the ablatant.
- Electrostatic shielding
  - Due to the negative charge of the cloud with respect to the background plasma.
- Magnetic shielding
  - Due to the partial expulsion of the magnetic field from the cloud interior by the expanding plasma, and the associated reduction of the incident heat flux.

Pellet ablation model

- Neutral Gas Shielding (NGS) model:

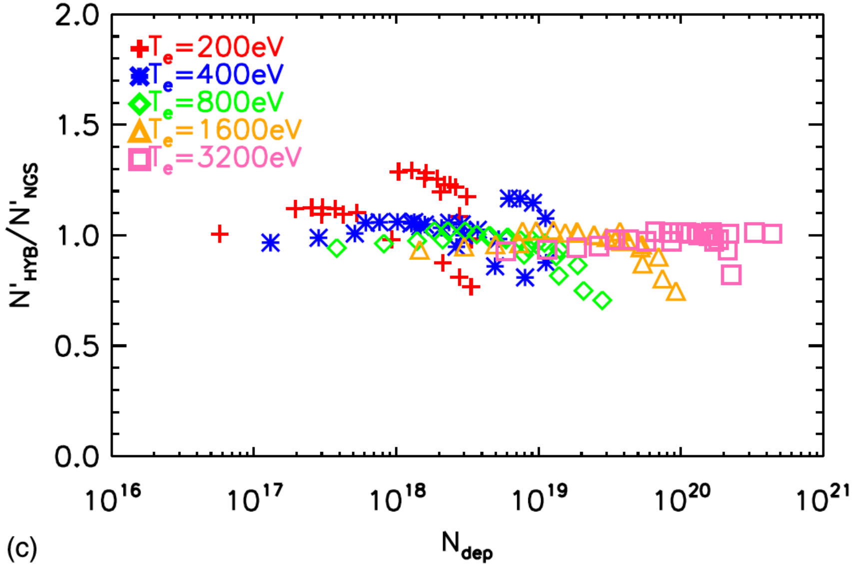
  - Assume that the neutral gas shielding is the dominant process
  - Assume a constant pellet velocity
  - Gives a pellet ablation rate which depends on background plasma parameters

$$N' = 4.12 \times 10^{16} \cdot r_{\mathrm{p}}^{1.33} \cdot n_{\mathrm{e}}^{0.33} \cdot T_{\mathrm{e}}^{1.64}.$$

Pellet model comparison [Gal2008]

- Comparison of Hybrid model, LLP model and NGS model
  - LLP model: takes into account channel flows and double electrostatic shielding
  - Hybrid model: same as LLP but assumes a spherical cloud

N': ablation rate

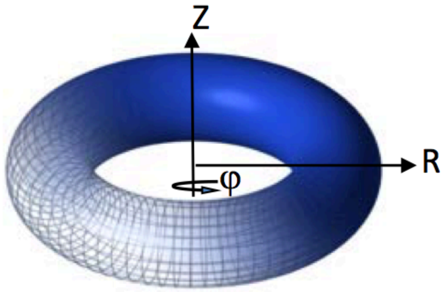


Additional shielding effects counteract each other.
Ablation rate comparable to the NGS model, comparable to the experiment

M3D-C1 solves the 3D two-fluid MHD equations in a magnetized torus

$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \mathbf{B} = \nabla \times \mathbf{A} \qquad \mathbf{J} = \nabla \times \mathbf{B}$$



$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla \mathbf{V}\right) + \nabla \bullet \mathbf{P} = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_{GV} + \mu \nabla^2 \mathbf{V}$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \mathbf{R}_c + \frac{1}{ne}(\mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{P}_e) - \lambda_H \nabla^2 \mathbf{J}$$

$$\frac{3}{2}\frac{\partial p_e}{\partial t} + \nabla \bullet \left(\frac{3}{2} p_e \mathbf{V}\right) = -p_e \nabla \bullet \mathbf{V} + \eta J^2 + \frac{\mathbf{J}}{ne} \bullet \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n\right] - \nabla \bullet \mathbf{q}_e + Q_\Delta$$

$$\frac{3}{2}\frac{\partial p_i}{\partial t} + \nabla \bullet \left(\frac{3}{2} p_i \mathbf{V}\right) = -p_i \nabla \bullet \mathbf{V} + \mu \left|\nabla V\right|^2 - \nabla \bullet \mathbf{q}_i - Q_\Delta$$

[S. Jardin, N. Ferraro]

Resistive MHD

2-Fluid terms

Features of M3D-C1

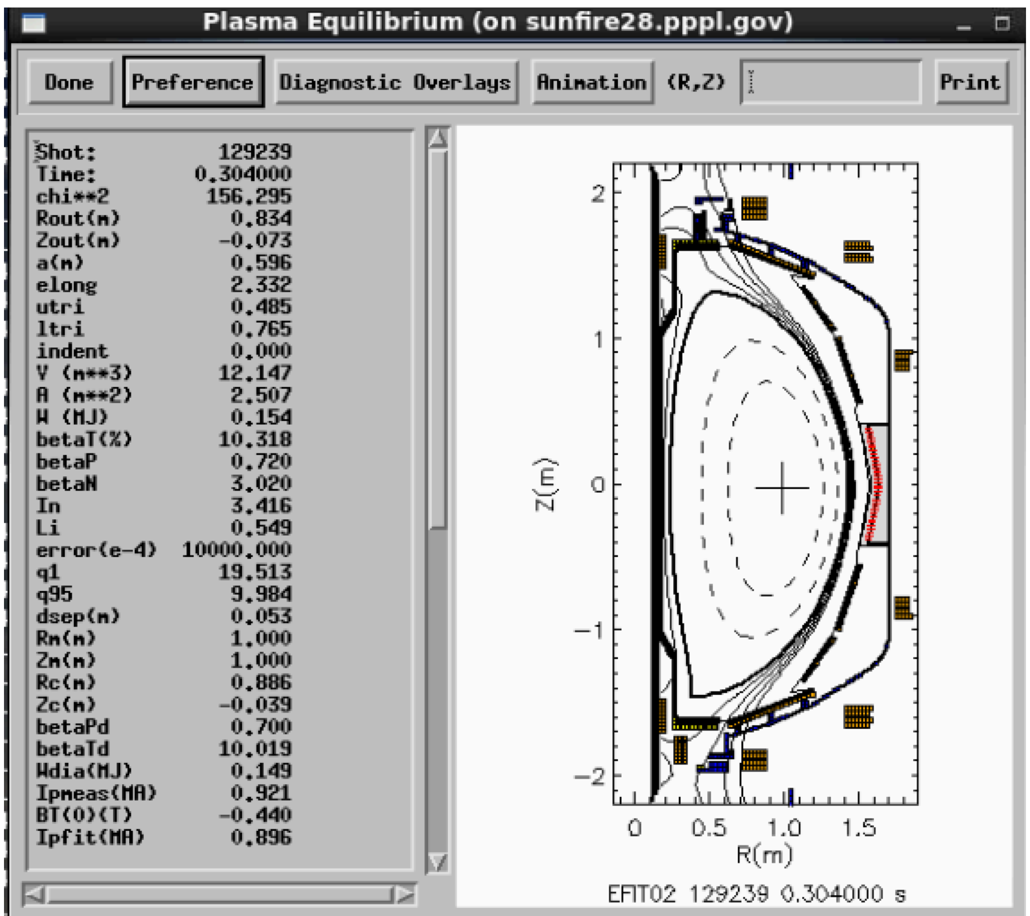
- High accuracy
  - High order 3D finite elements: crucial to get a spatially localized pellet
  - Full 2F MHD equations: diamagnetic terms very important for ELMs dynamic
- Can perform long-time simulations: ~ 10 ms
  - Fully implicit time-advance algorithm
  - Study of stability on the transport timescale
- Geometrical flexibility: mesh packing, realistic wall geometry

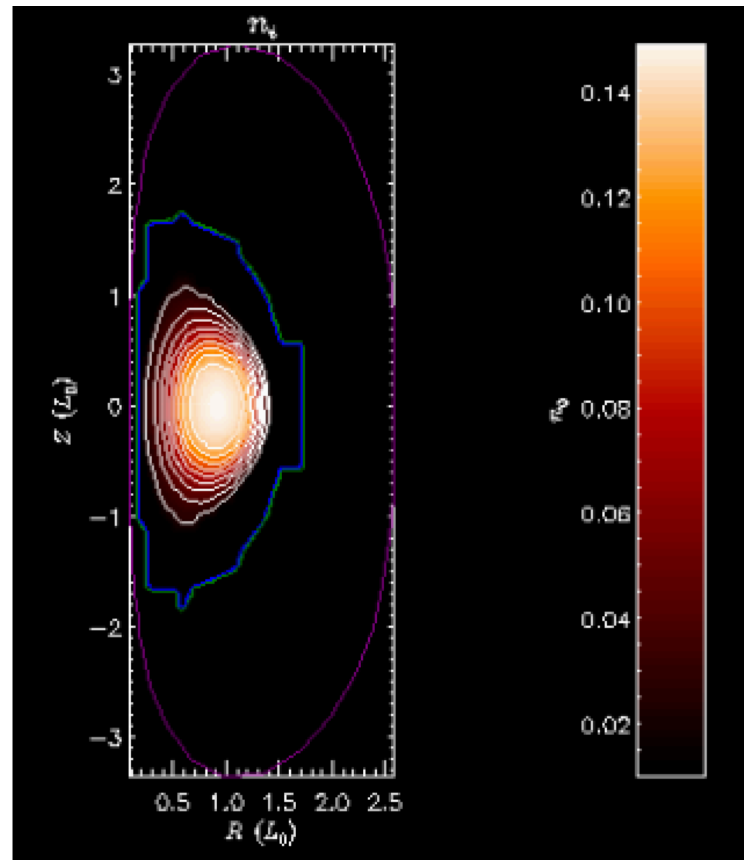
Pellet model in M3D-C1

- Neutral Gas Shielding (NGS) model currently being implemented in M3D-C1:
    - Density source term taking into account the pellet ablation
    - Pellet ablation process is approximated to be adiabatic: no heat sink in the temperature equation
- First simulations on-going
- Maxwellian model also being tested

Plan: to be able to make prediction for NSTX-U operation (pellet size, velocity, …)

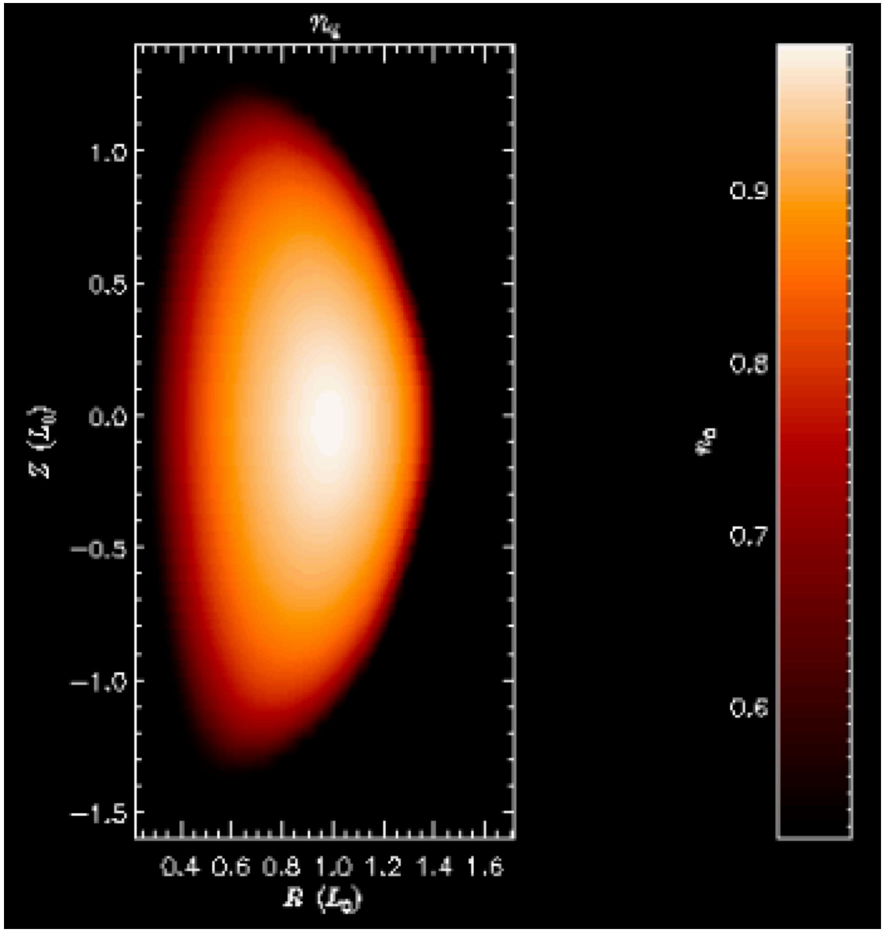
- Start from a NSTX-U high performance stable equilibrium and turn on pellets in the simulation.



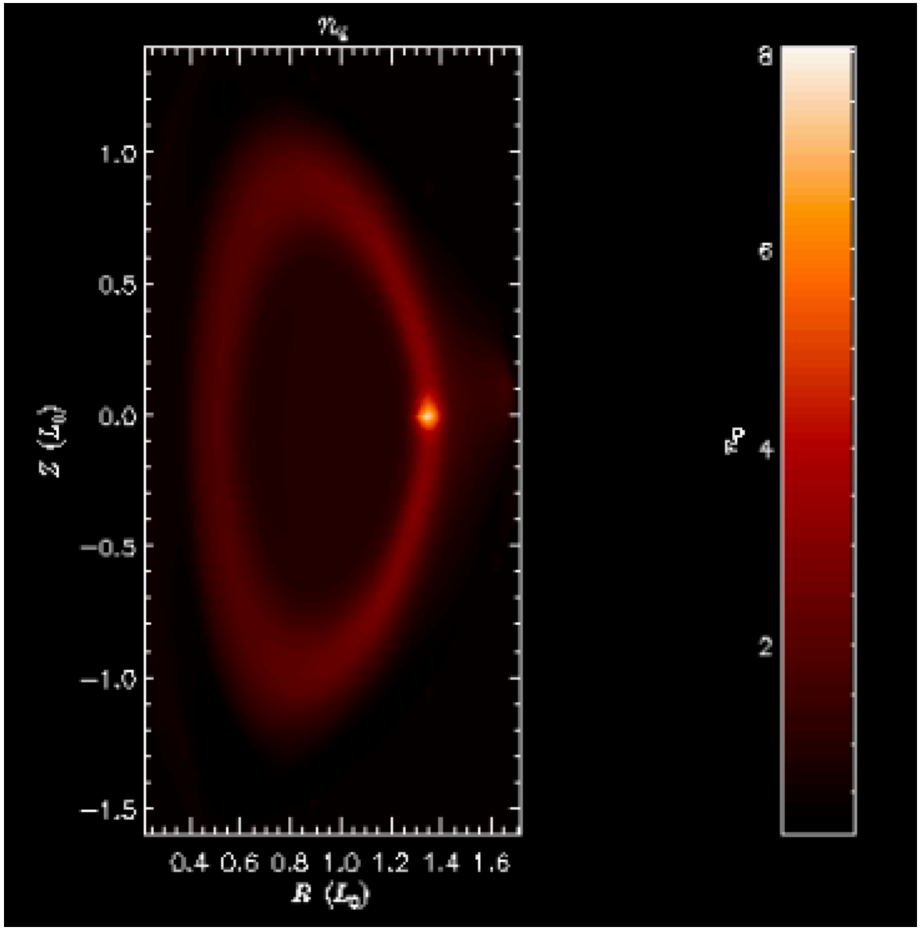


First pellet injection test: 2D simulation
Edge density increase

Ion density



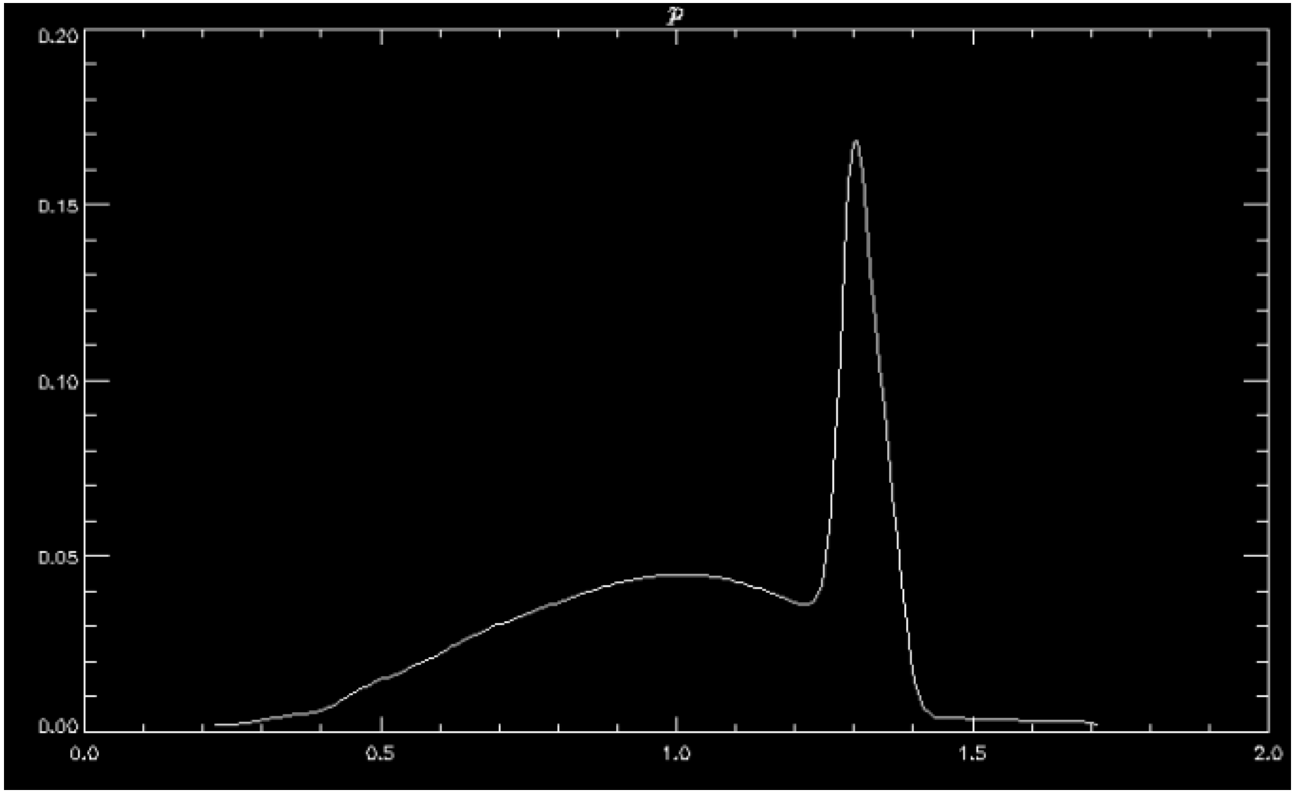
Equilibrium



During pellet injection

Pressure profile

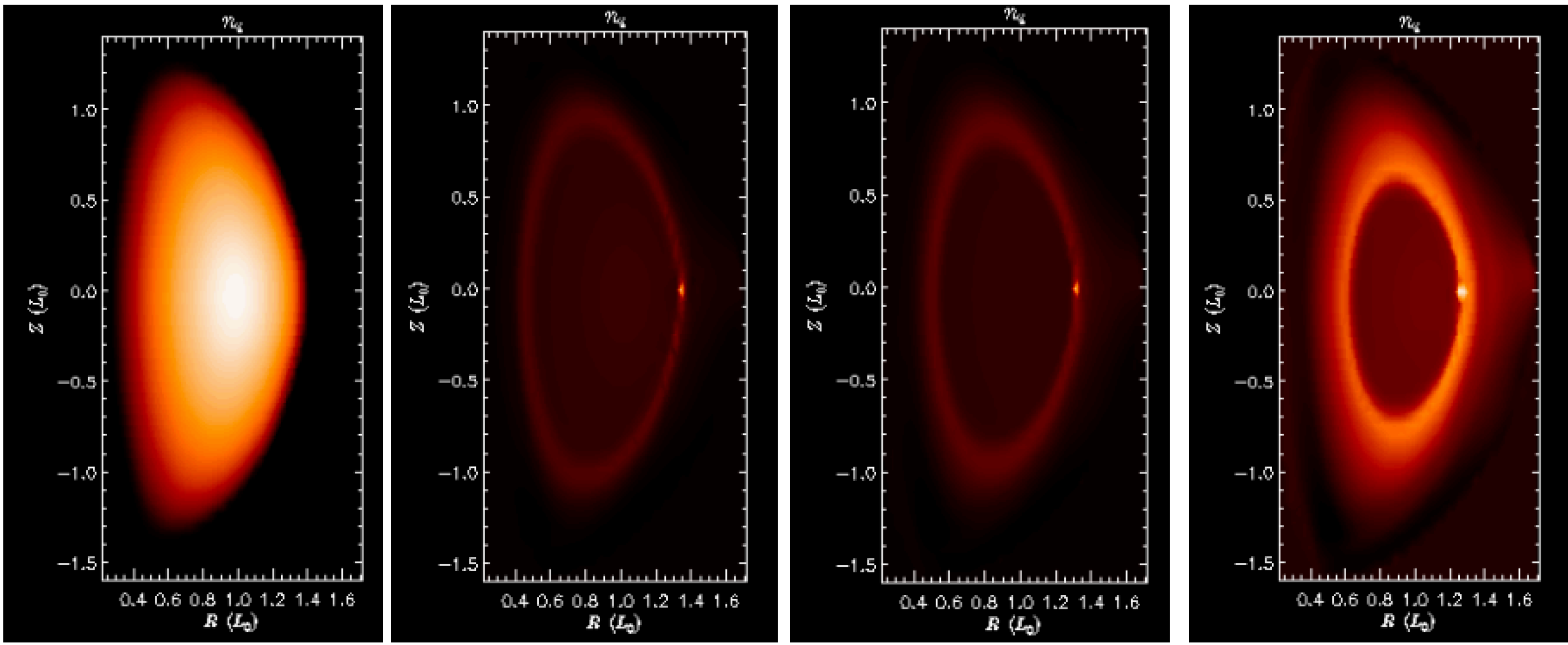
P[norm. units]



R[m]

Density time evolution

Parameter scan on-going: pellet size, velocity



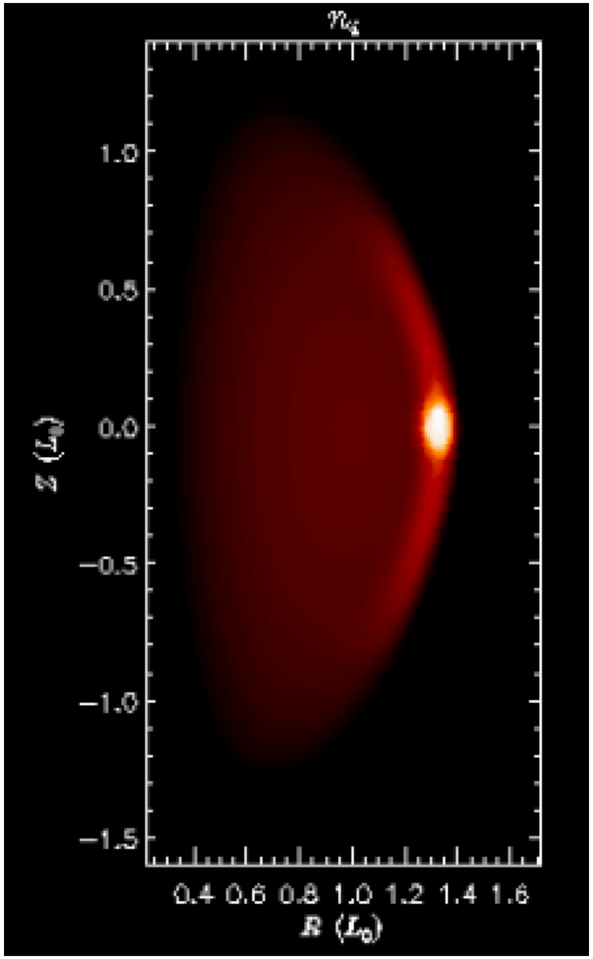
Pellet radius ~ 5 mm,
pellet velocity ~ few 100m/s

Conclusion

- Lithium Granule Injection is a promising ELM pacing method
- New tool for ELM control
- First experimental results on several devices
- Modeling started with M3D-C1
    - First implementation of a deuterium moving pellet

Perspectives

- Implement a full LGI model in M3D-C1
  - Need a model including radiation, ionization, etc for Lithium.
  - Possibly taking into account additional shielding effects
  - Is NGS model good enough approximation for LGI or should we use a more complex model?
  - Comparison with experimental data
  - Application to NSTX-U scenarios and ELM control



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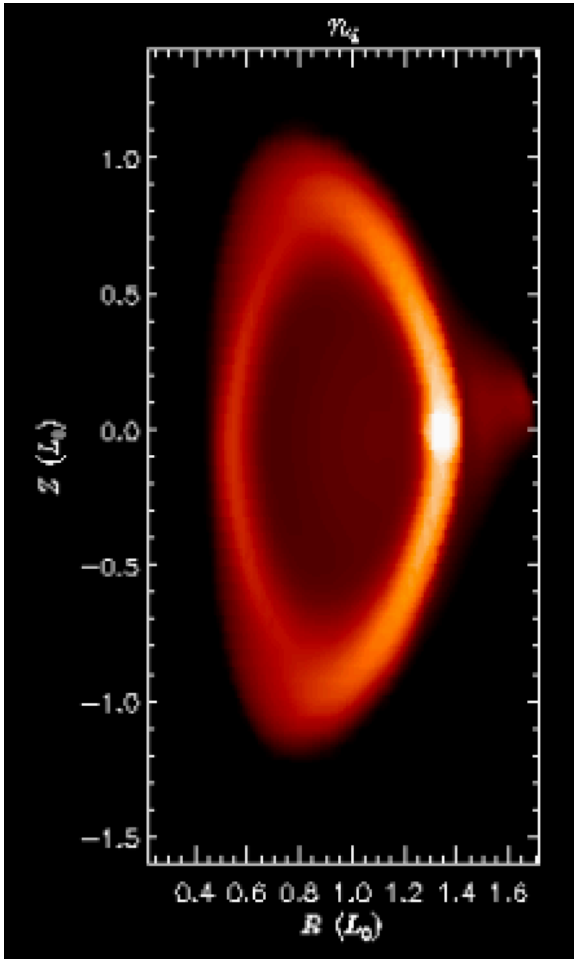
0.5
0.0
−0.5
−1.0
−1.5
Z (L₀)
0.4 0.6 0.8 1.0 1.2 1.4 1.6
R (L₀)



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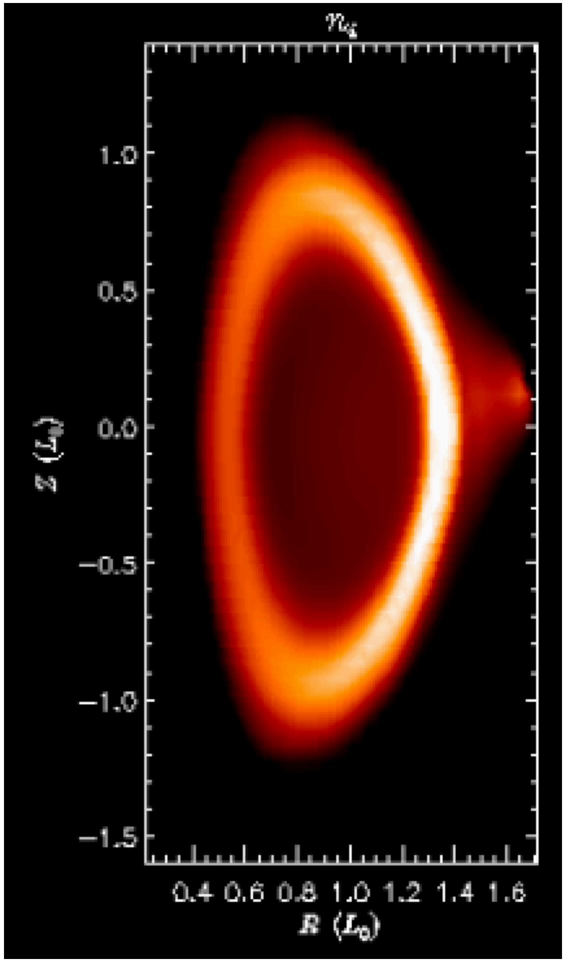

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