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Deuterium gas puff z-pinch simulation with LSP

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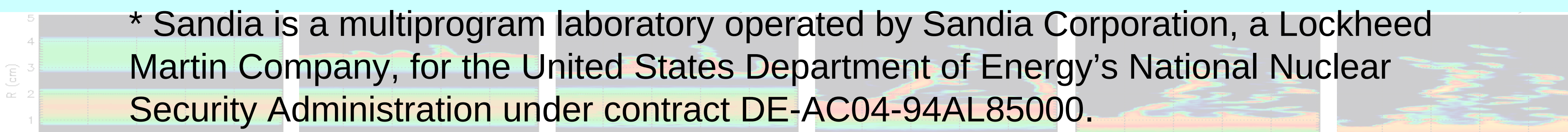

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Goal: Address 50 year old question of neutron production mechanism in z-pinch

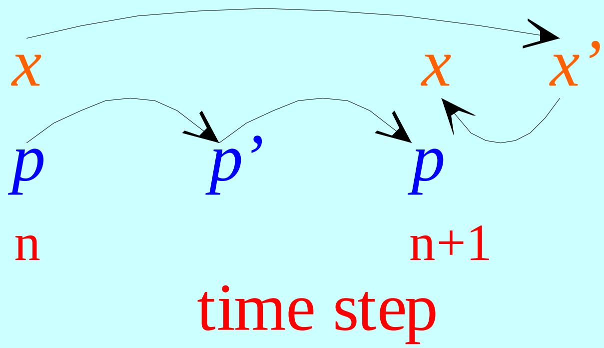
- **Thermonuclear neutron production scaling as I^4 is quite promising for fusion energy***
- **Deuterium pinches have been examined experimentally for many years**
  - **Significant neutron production**
  - **Early conclusions had been that the majority of neutron yield is from non-thermal deuterium population that does not scale favorably**
- **We have built a fully kinetic electromagnetic model that includes both nonthermal and thermal processes to address this question**

*J. Ise, Jr. and R. V. Pyle, in Conference on Controlled Thermonuclear Reactions, Princeton Univ., 17-20 October 1955 (TID-7503, USAEC, 1955), p.218; Velikovich, et al. Phys. of Plasmas 14 022701 (2007).

Elements of LSP computational model

- **Fully electromagnetic solution to allow non neutral plasmas (Rayleigh Taylor bubble and spike potentials)**
  - **EM energy-conserving direct-implicit algorithm**
- **Electron and ion inertial effects**
  - **Fully kinetic particle-in-cell treatment**
- **Plasma interpenetration**
  - **Coulomb scattering between all particles**
  - **binary ion-ion Coulomb collisions**
  - **approx. e-ion, e-e based on drifting Maxwellian**
- **Fusion reaction calculation for arbitrary reactant energy distribution function**
  - **Binary fusion model**

Direct Implicit Algorithm*



particle *p* advance using half of the old and new electric field

- **First, particle *p* and *x* advance with $E_{n+1}(x_{n+1}) = 0$**
- **The EM fields are then pushed using linear correction terms to predict the effect of $E_{n+1}(x_{n+1})$ on the perturbed current $\delta J = \langle S \rangle \bullet E_{n+1}(x_{n+1})$ ($\langle S \rangle$ is the susceptibility)**

$$\frac{\partial \boldsymbol{E}}{\partial t} = \frac{1}{\varepsilon}\left(\nabla \times \frac{\boldsymbol{B}}{\mu}\right) - \boldsymbol{J} - \langle \boldsymbol{S} \rangle \cdot \mathbf{E}$$

- **Particle *p* and *x* are then corrected in final push**

*See D. W. Hewitt and A. B. Langdon, J. Comp. Phys. **72**, 121-155 (1987); D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell, and T. A. Mehlhorn, Phys. of Plasmas **13**, 063105 (2006)

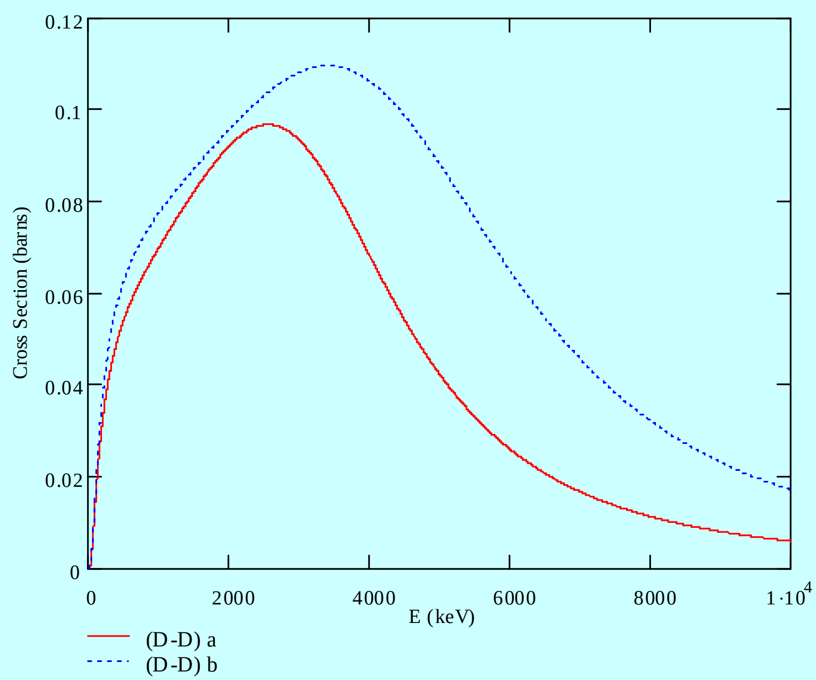
Binary collision algorithm* adapted for Coulomb, fusion reactions

- **Particles are sorted to respective cells and each pair is scattered with only assumption that of Coulomb logarithm**

Here we consider fusion reactions:

D + D -> He^3(0.82 MeV) + n (2.45 MeV)
Q = (0.82 + 2.45) MeV
D + D -> T(1.01 MeV) + p(3.02 MeV)
Q = (1.01+3.02) MeV
D + T -> He4(3.5 MeV) + n (14.1 MeV)
Q = (3.5 + 14.1) MeV

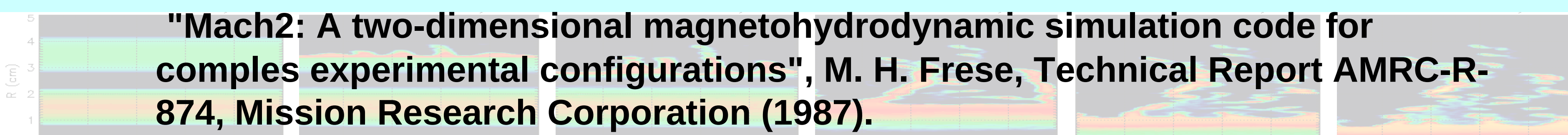
***Non-relativistic* kinematics good for E < 10 MeV**



*K. Nanbu and S. Yonemura, “Weighted Particles in Coulomb Collision Simulations Based on the Theory of a Cumulative Scattering Angle” JCP 145, 639-654 (1998)

Detailed PIC comparison with MHD

- MHD simulations with Mach2 code*
- Same numerical spatial grid (100 μm resolution)
- Internal Mach2 timestep longer than LSP
- D-D neutron production assuming Maxwellian ion temperature
- Electrode effects ignored (periodic BC in *z*)



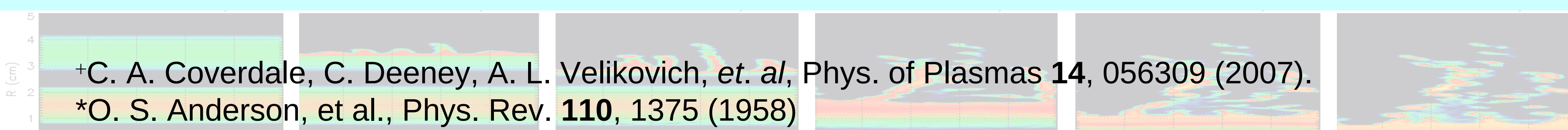
"Mach2: A two-dimensional magnetohydrodynamic simulation code for comples experimental configurations", M. H. Frese, Technical Report AMRC-R-874, Mission Research Corporation (1987).

1D, 2D simulations with varying current test neutron yield scaling

- **Pinch experiments on Z performed in the 15 MA range offer a good starting point[+]**
- **Consider same 2 ring configuration**
  - **Outer puff 222.5 mg, 3-4 cm radius**
  - **Inner puff 222.5 mg, 1-3 cm radius**
  - **Assuming I_o = 15 MA with a linear τ = 100ns rise, R = 4cm**
  - **Keep time to first bounce* fixed at 100 ns to pinch**
  - **Lengths scale as $I_0^{1/2}$ with fixed gas density**

$$t = 1.43R\left[\frac{100\pi\rho\tau^2}{I_o^{\,2}}\right]^{1/4}$$

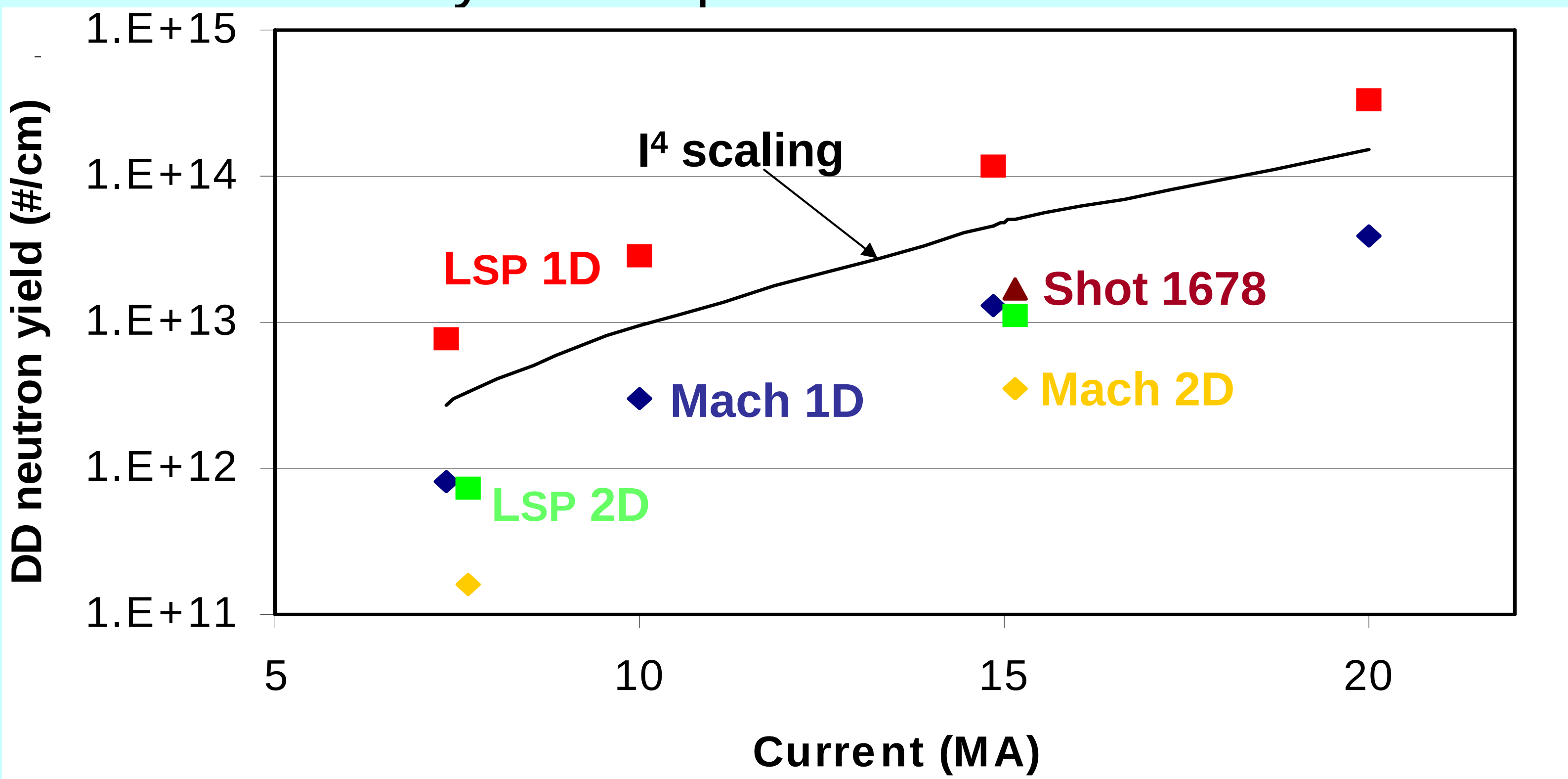
Assumes uniform distribution of gas density ρ with R



[+]C. A. Coverdale, C. Deeney, A. L. Velikovich, *et. al*, Phys. of Plasmas **14**, 056309 (2007).
*O. S. Anderson, et al., Phys. Rev. **110**, 1375 (1958)

Neutron yield scaling roughly I^4

- Roughly thermonuclear scaling from 7-20 MA regardless of dimensionality or computation model

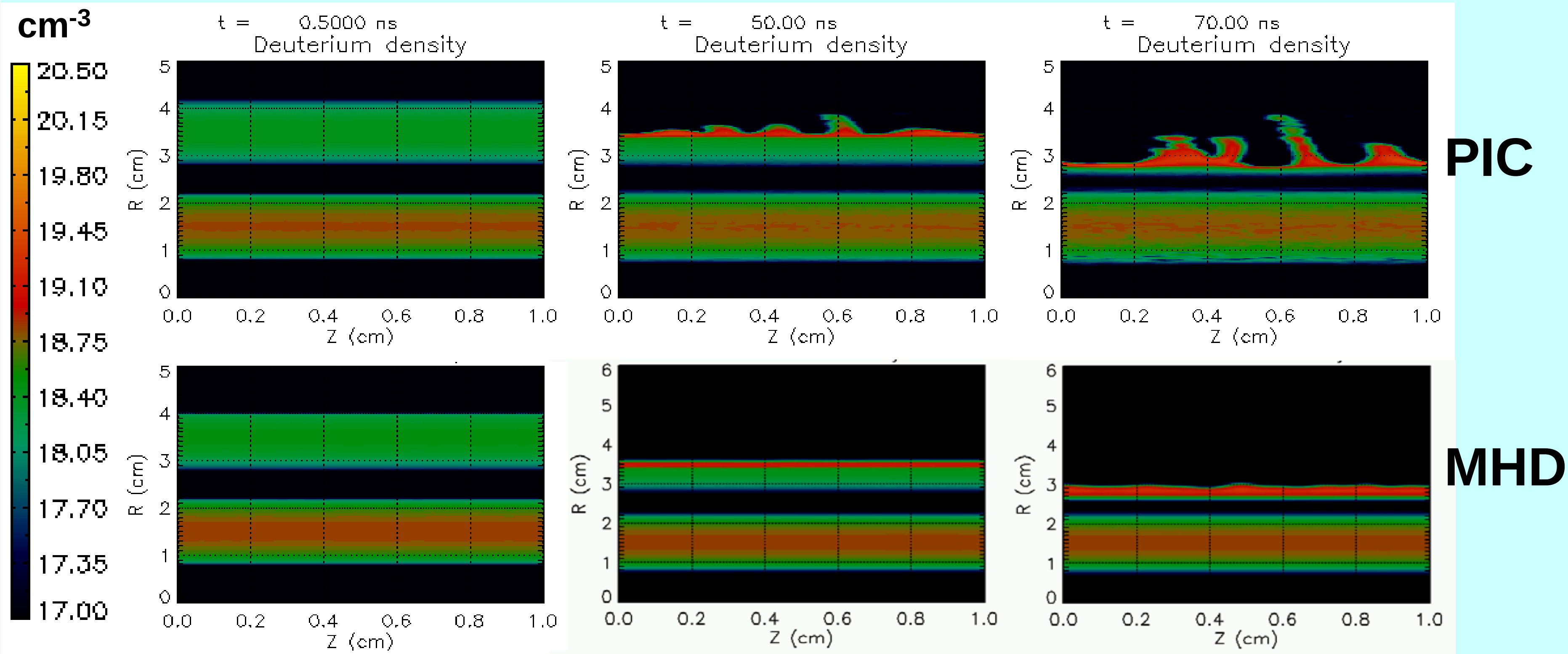


PIC model predicts order of magnitude higher yield

Careful 2D comparison at 15 MA between PIC and MHD

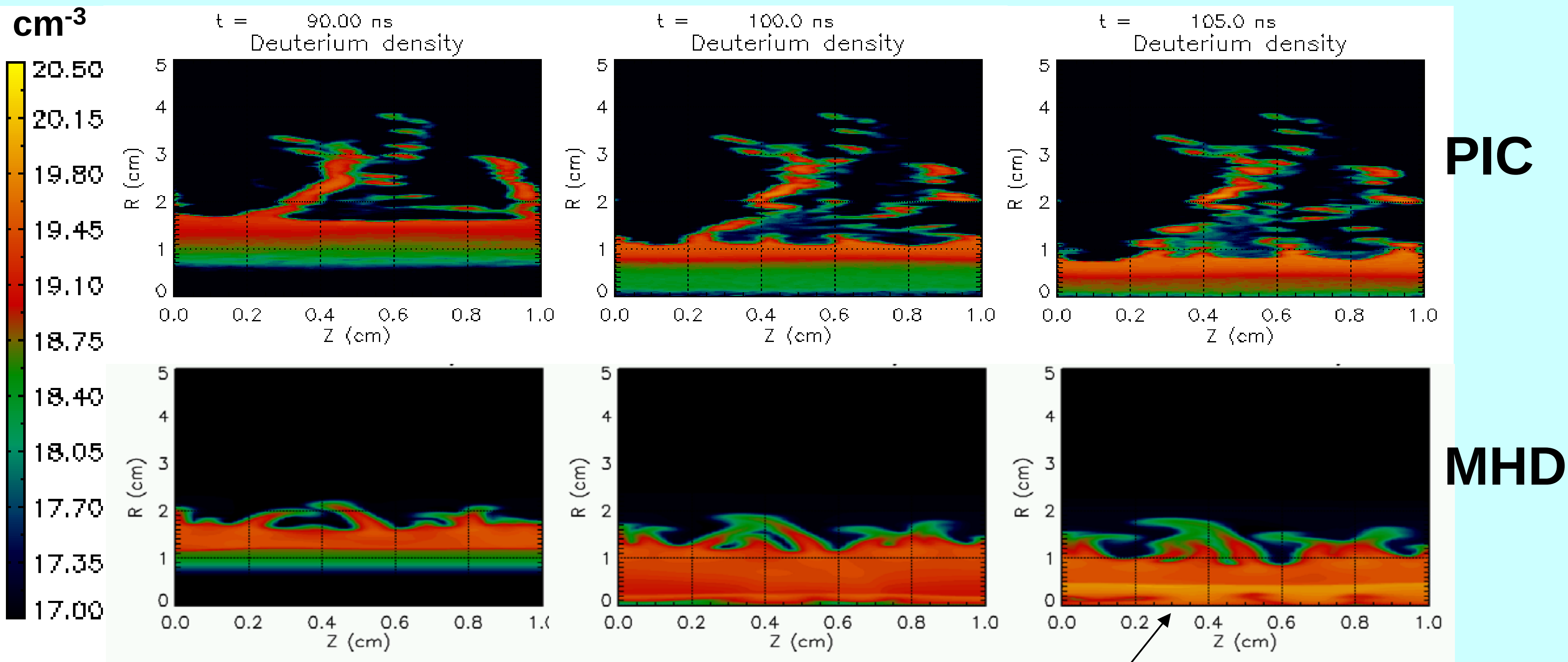
- 1% random axial mass variation drives more rapid Rayleigh Taylor growth in PIC
- PIC shows annular character of plasma maintained thru coalesce on axis, no shocks as seen in MHD
- PIC has larger current near axis, drives stronger electric fields, fast ions

Early phase – PIC exhibits rapid Rayleigh Taylor growth



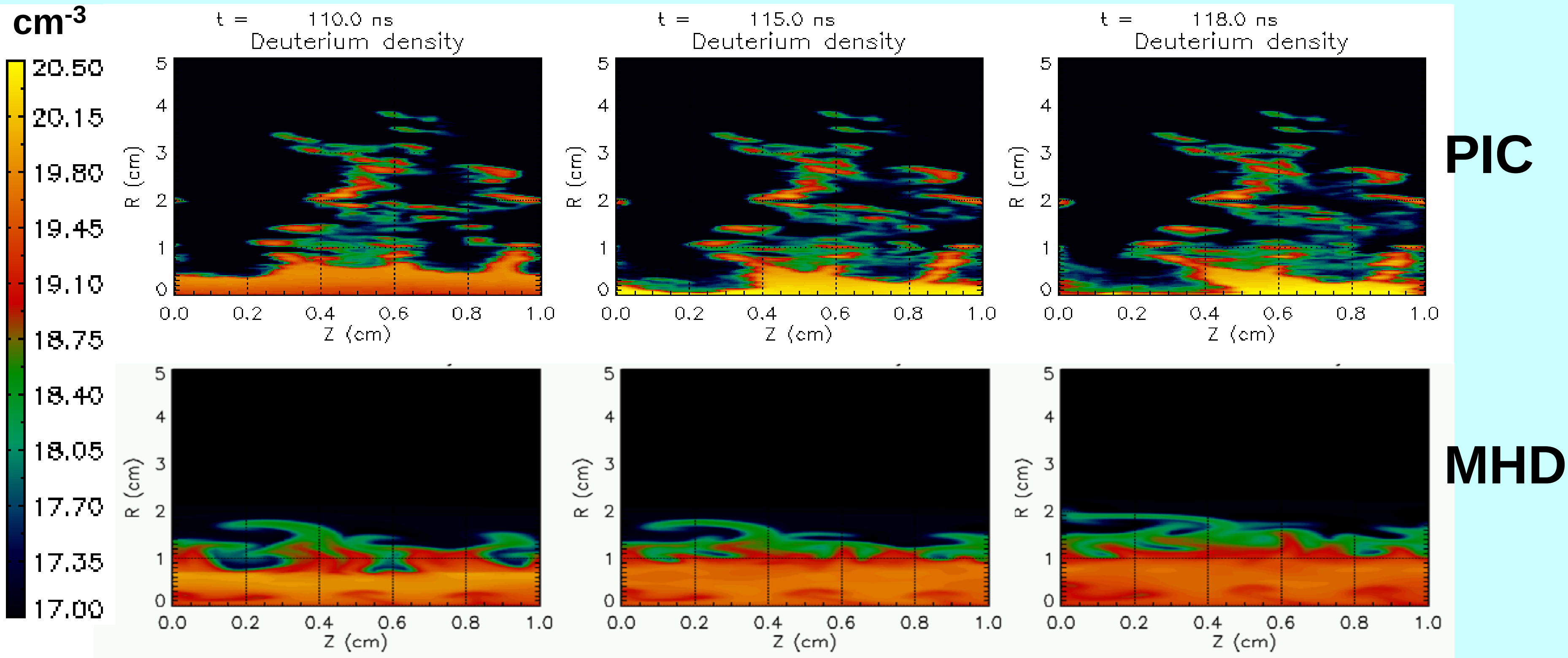
PIC growth could be enhanced by particle noise

Pinch phase – coalescence in PIC is delayed



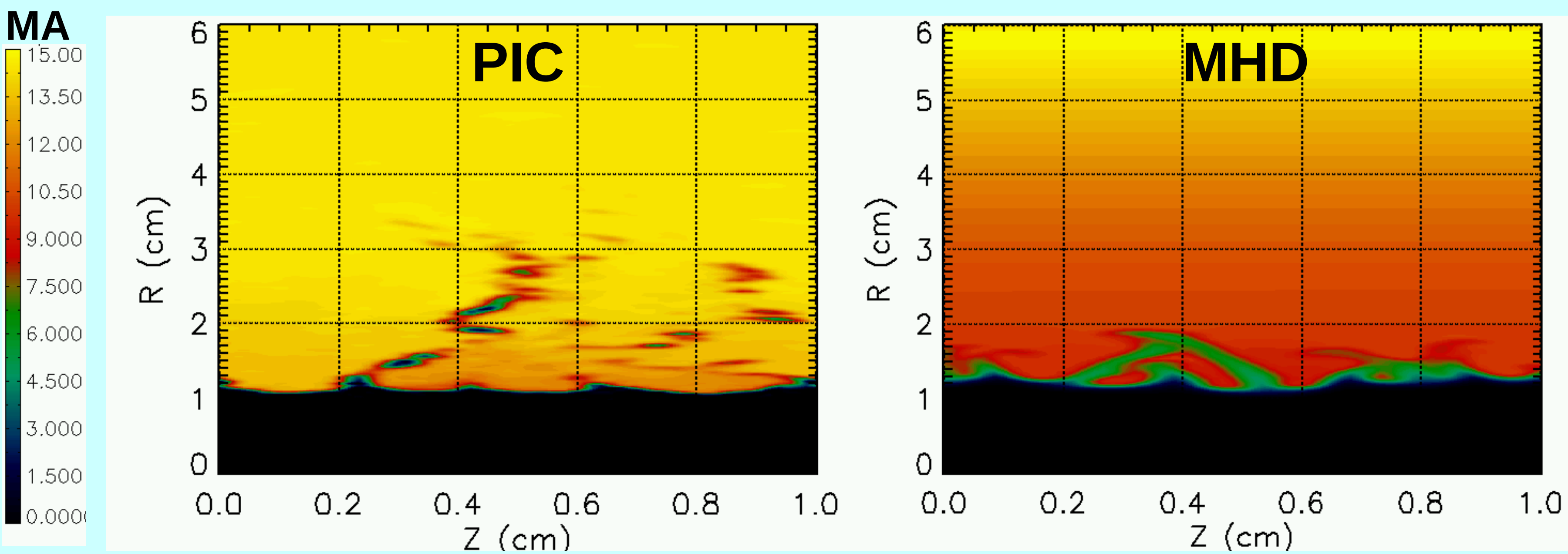
MHD exhibits a shock behavior not observed in PIC

Late time – some mass still coalescing, filament forms in PIC

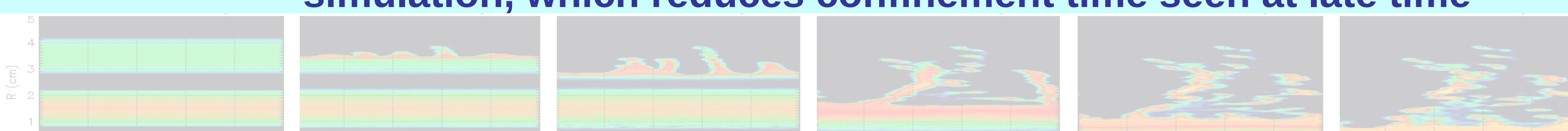


Hotter corona region carries more current in MHD

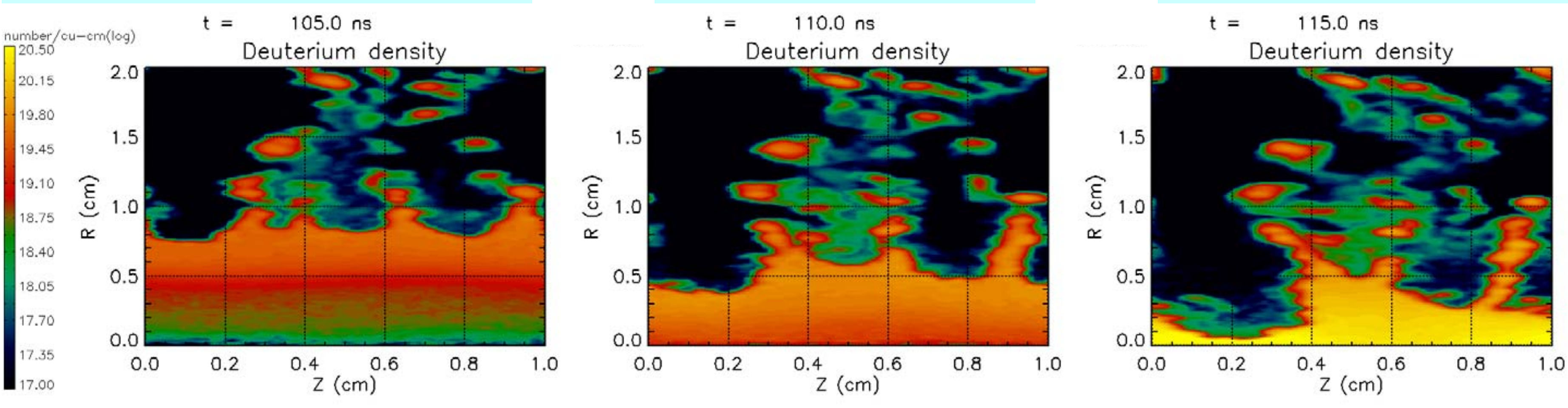
- Comparison is at 100 ns into implosion



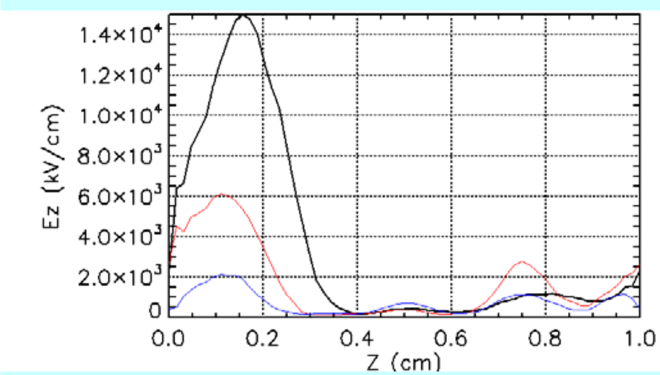
The effective pinch current at 2 cm is 2 MA less in MHD simulation, which reduces confinement time seen at late time

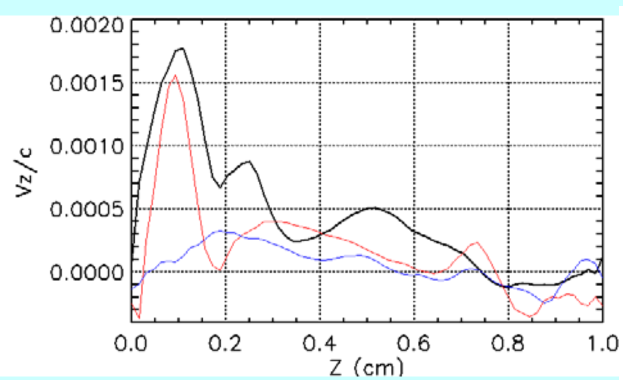


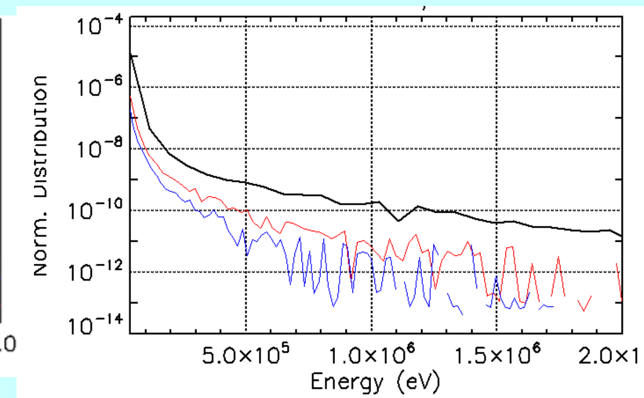
Electric fields large between spikes, drive ions to higher energy



105 ns 110 ns 115 ns





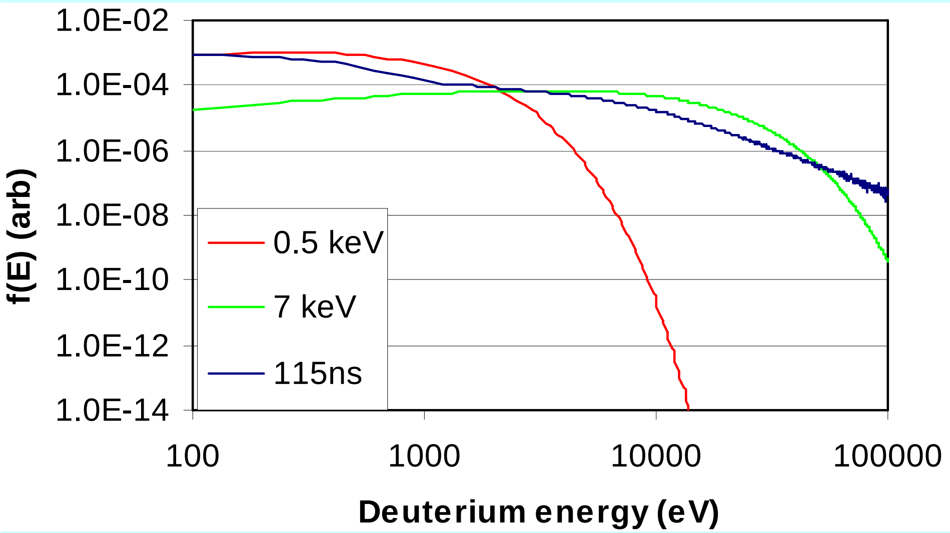


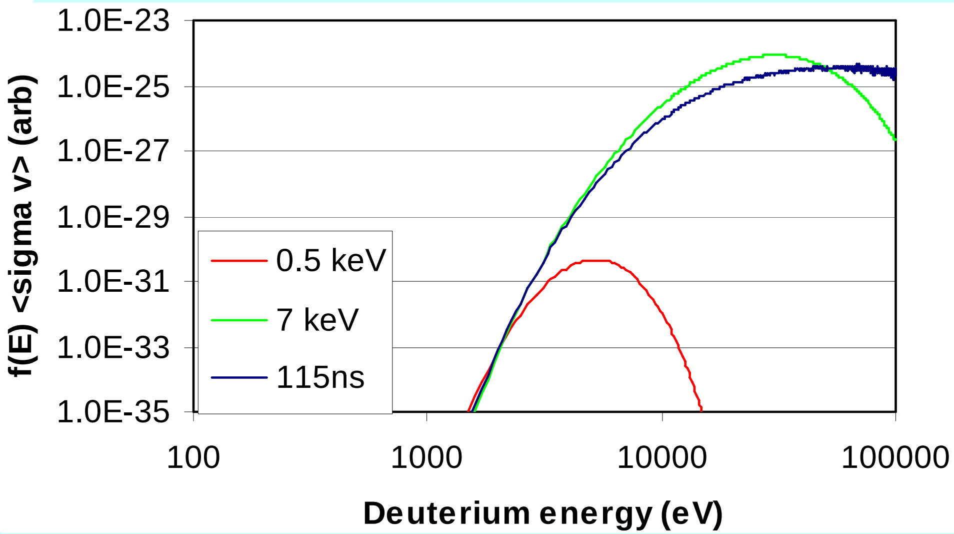
Average Ez within 1.5 cm radius

Average ion Vz within 1.5 cm radius

Deuterium energy distribution

Deuterium energy distribution exhibits high energy tail

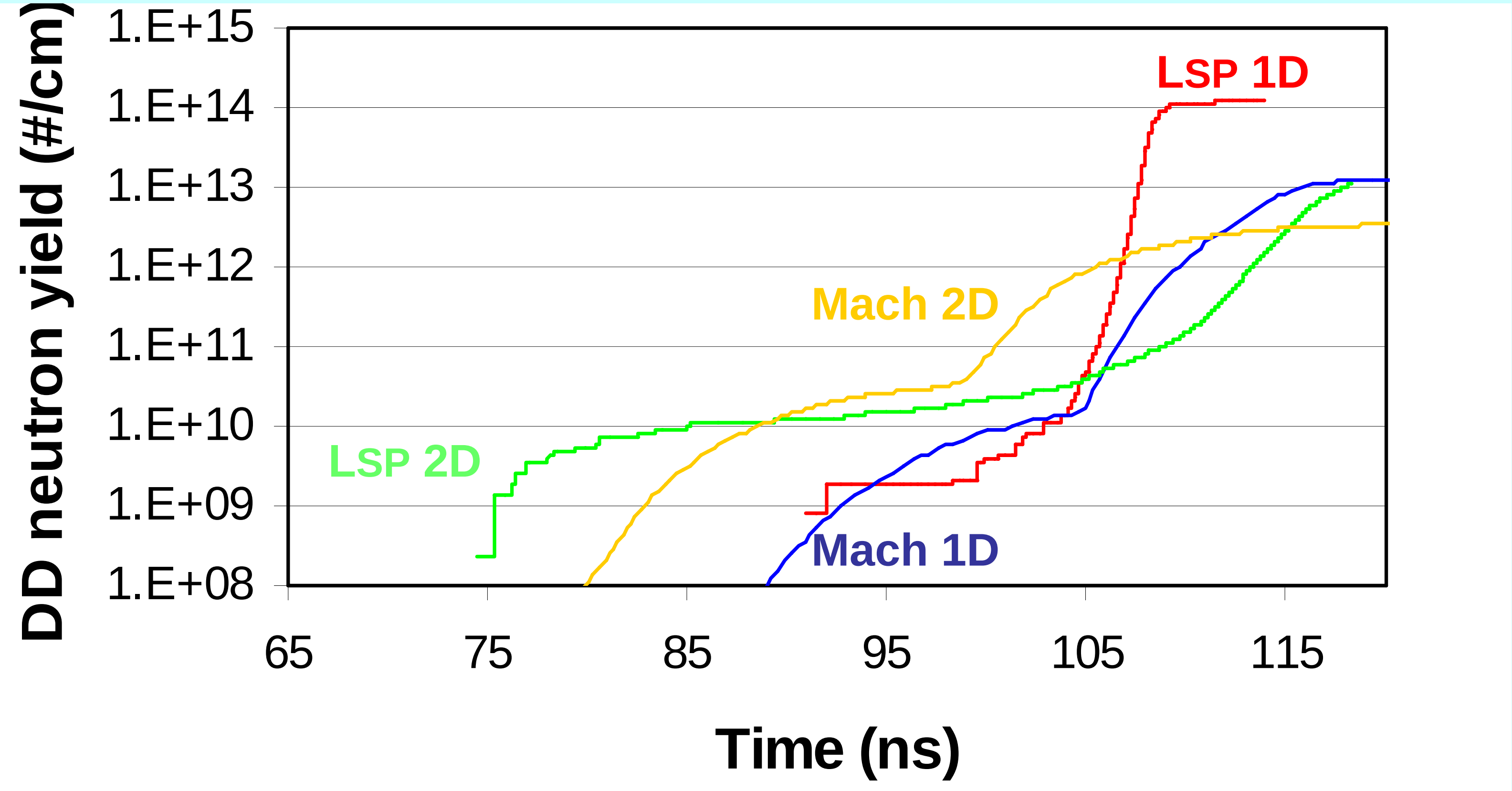




Distribution tail accounts for half the neutron production by 115 ns

Neutron production at 15 MA

- As in experiment, neutron production in PIC is somewhat longer then MHD with significant nonthermal component at late time



Kinetic, electromagnetic simulation reveals nonideal pinch behaviors

- Non Maxwellian distributions, mean free path effects, non neutral assumption results in strong differences in pinch characteristics
- Strong E fields drive energetic ions which enhance neutron production late in time – may account for half the yield
- Electrode, 3D effects subject of future work