PROGRESS IN MAGNETIZED TARGET FUSION DRIVEN BY PLASMA LINERS

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Outline

- Why Magnetized Target Fusion (MTF)?
- The plasma liner driven MTF concept
- Implosion dynamics
- 0-D model and results
- Research issues
- Plasma interpenetration
- Flux compression
- 3-D modeling of the implosion dynamics
- Experimental plan and status

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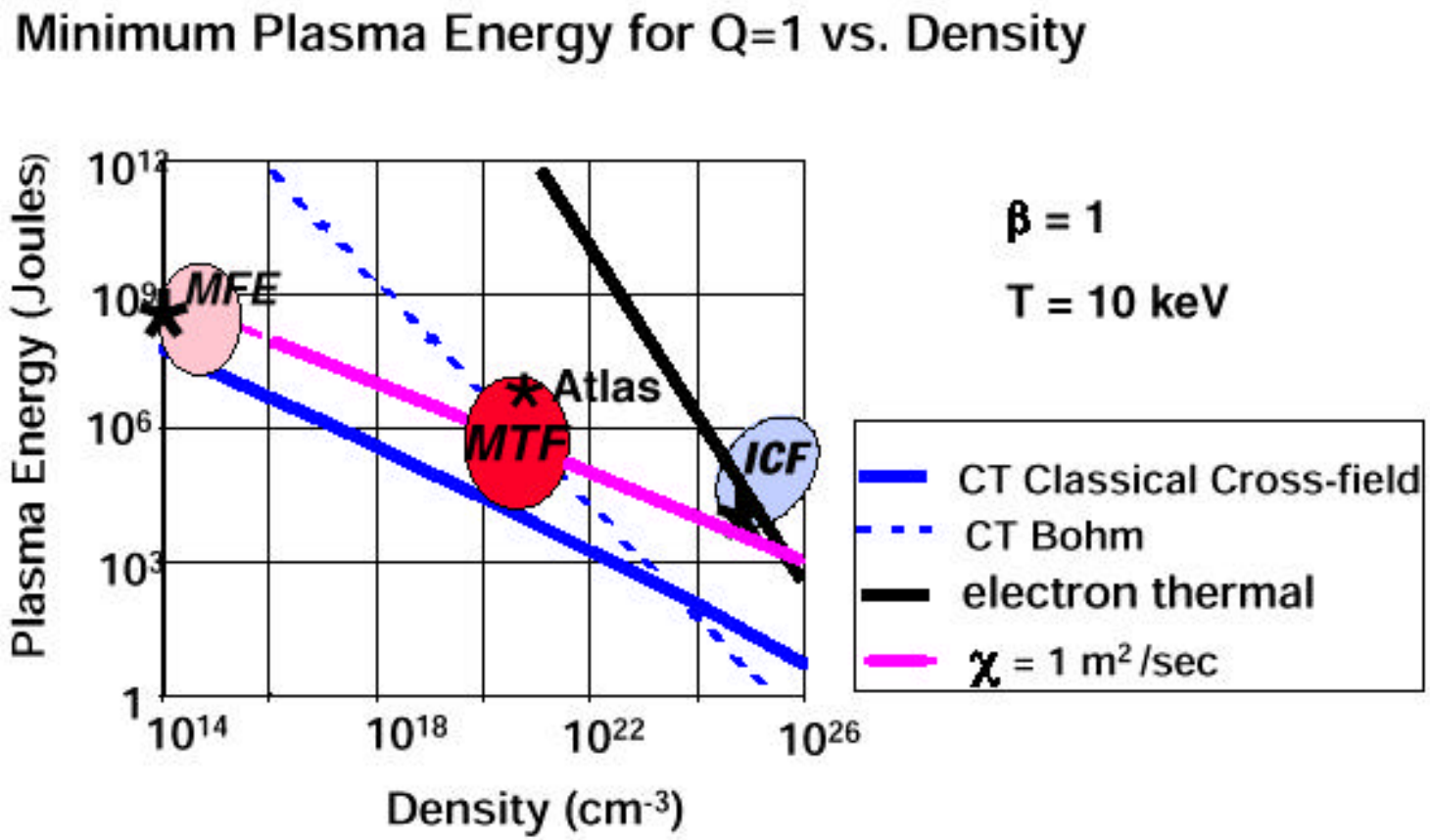
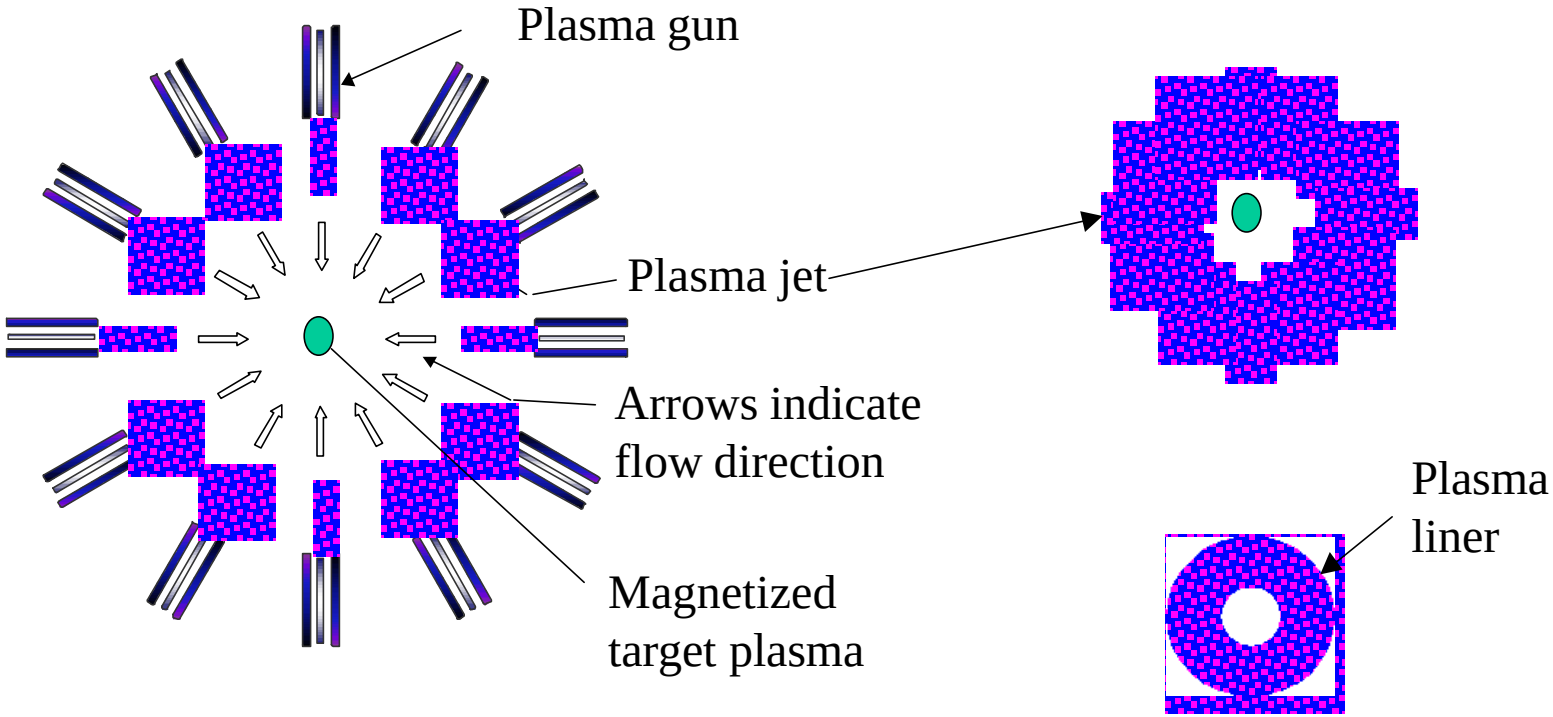
Why Magnetized Target Fusion (MTF)?
Parameter Space for Fusion



Plasma Liner Driven Magnetized Target Fusion



- **An approximately spherical distribution of jets are launched towards the compact toroids at the center of a spherical vessel**
- **The jets merge to form a spheroidal shell (liner), imploding towards the center**

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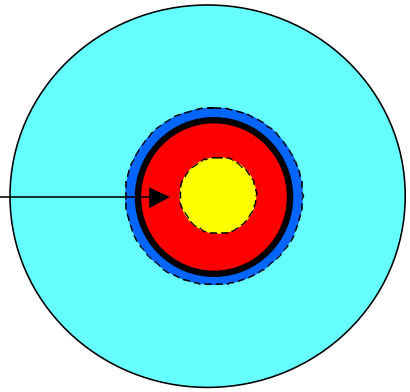
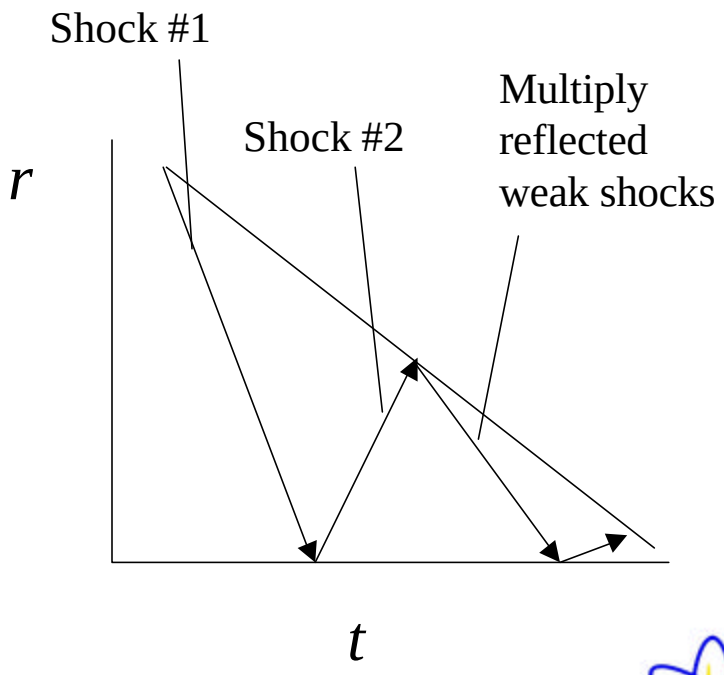
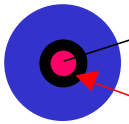
Implosion Dynamics

- When the liner meets the target, a contact surface is formed
- A shock propagates into the target converging spherically towards the center
- The shock heats the plasma to a sufficiently high temperature for the plasma to have sufficient conductivity to trap the magnetic flux
- When the shock reaches the center, it turns around giving rise to a reflected shock, until it meets the contact surface
- Compression proceeds by multiple reflections of the shock
- The magnetic flux is compressed with the plasma leading to an increase in magnetic field intensity





Target and Liner Confinement and Burn



Target peak magnetic field > 500 T

- Suppresses thermal conduction ⇒ Nearly adiabatic compression
- The target ignites - batch burn
- α-particles released from the fusion reactions heats and burns a thin inner layer of the liner, thus amplifying the fusion gain
- Fusion neutrons moderated by the dense hydrogen layer of the liner by more than 50%

Target and inner liner confinement time is the sum of

- Transit time of the stagnation shock through the liner
- Twice the transit time of the rarefaction wave

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0-D Code for Modeling Fusion Performance

- A 0-D code has been developed to model the implosion dynamics and the fusion yield.
- Model the first two shocks using Richtmyer-Lazarus theory
- Model the acoustic compression phase, taking account of bremstrahlung, synchrontron, electron and ion thermal conduction losses with B field
  - **Uses Braginskii's transport coefficients**
- Assume magnetic flux frozen with the plasma
- Uses a quasi-static 1-D fluid flow model for the liner
- Fusion burn physics in the target and the liner
- Uses Kirkpatrick model for the magnetic field enhancement of α-particle energy deposition in the target plasma
- Uses Evan's theory for α-particle energy deposition in the liner in the absence of magnetic field
- Model the confinement time by computing the transit times of the stagnation shock and the rarefaction wave

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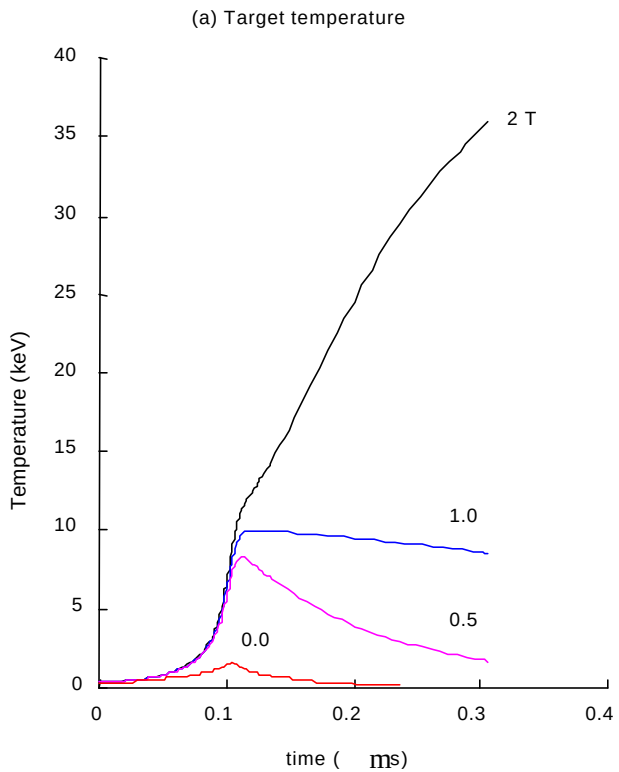
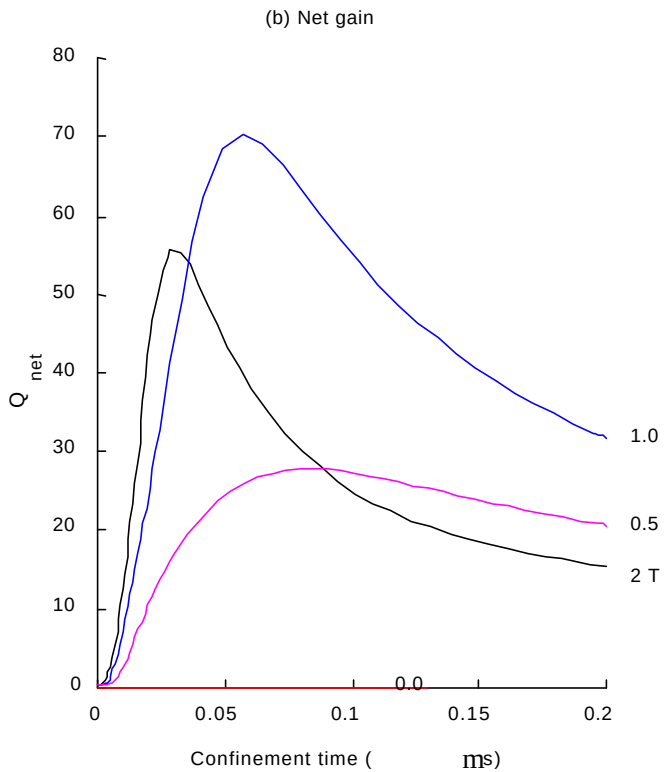
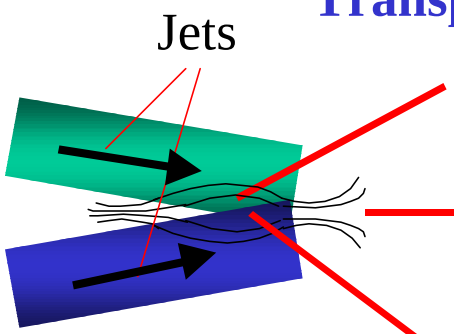
0-D Modeling Results





Dynamic Plasma Liner Formation - Research Issues

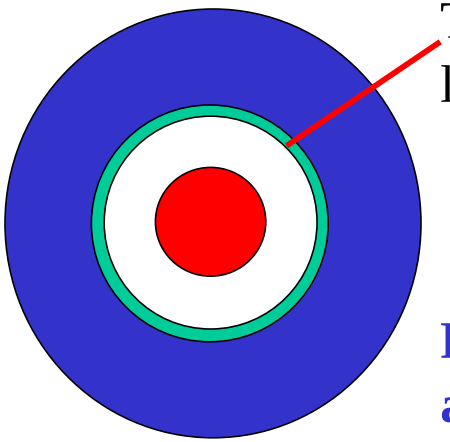
Plasma jets with sufficient density and velocity are required
Spatial and temporal precision of the jets
Transport of the jets



Compressed region between the jets

Material squeezed forward giving rise to “precursor jets”. These may be swept up by the jets following them forming a “diffused edge region”

Instabilities could grow in the presence of velocity differentials between the jets



The liner has a diffused edge region. The density of the liner rises sharply behind this edge region.

The diffused edge engages the target first
- **Some plasma interpenetration may occur**

Rayleigh-Taylor and Richtmyer-Meshkov instabilities are considerations during target implosion

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Stability of the Merging of Two Jets

- **If there is a velocity differential between the two jets, instabilities (flow irregularities) will grow**
- **Issues:**
  - Time scale of liner formation?
  - Growth rate of instability?
- **Jets: 100 km/s - 200 km/s (10 cm/ms - 20 cm/ ms)**
- **Transport distance: 2 to 4 m**
- **Liner formation time scale: 10 ms to 40 ms**
- **Needs to ensure that instability growth rate be small on this time scale**

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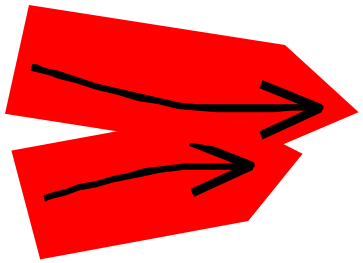
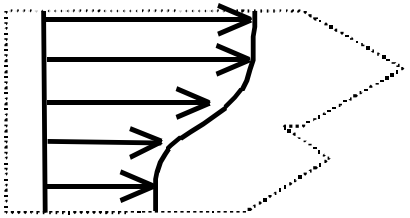
Stability Analysis of Merging of Two Jets

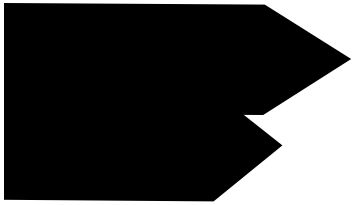


The flows have both transverse and parallel components

Transverse coordinate (y)

Axial, or parallel coordinate (x)





<u>Cases considered</u>

Transverse component is negligible (small angle impact)

Sound speed in jets is relatively high, so that the perturbing flow is incompressible

Approximate resulting shear layer as hyperbolic tangent function

$$U = U_0 \tanh \frac{y}{L}$$

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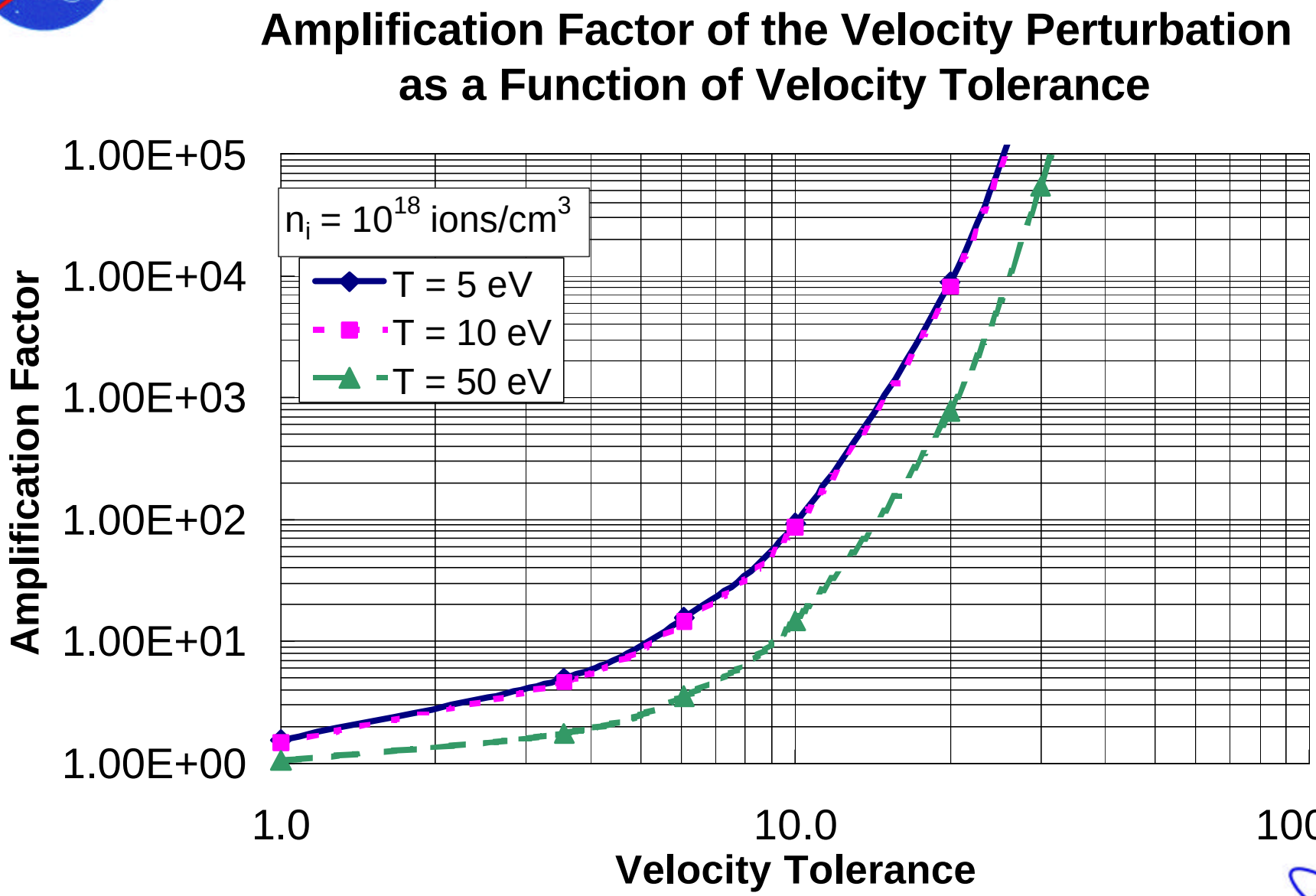
Amplification Factor over 40 ms



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Formation of the Contact Surface

- **Issue: Interpenetration of plasmas (IP)**
- **Penetration of target plasma into the liner is a more important issue than liner into the target**
  - Penetration of target plasma into the liner would result in reduced compression of the target
- **Determining factor: Ion-ion Collision length and the ion Larmor radius**

$$l = \frac{25pe_0^2(kT)^2}{Z^4 ne^4 \ln\Lambda} \qquad r_L = \frac{\sqrt{2kTm_i}}{ZeB}$$

$$\text{For adiabatic compression}: \; T \propto \frac{1}{r^2},\; B \propto \frac{1}{r^2} \Rightarrow \; l \; \propto \frac{1}{r},\; r_L \propto r$$

- **At peak compression, target radius typically ~ 5 mm**
- **Acceptable thickness of the IP region ~ 1 mm**

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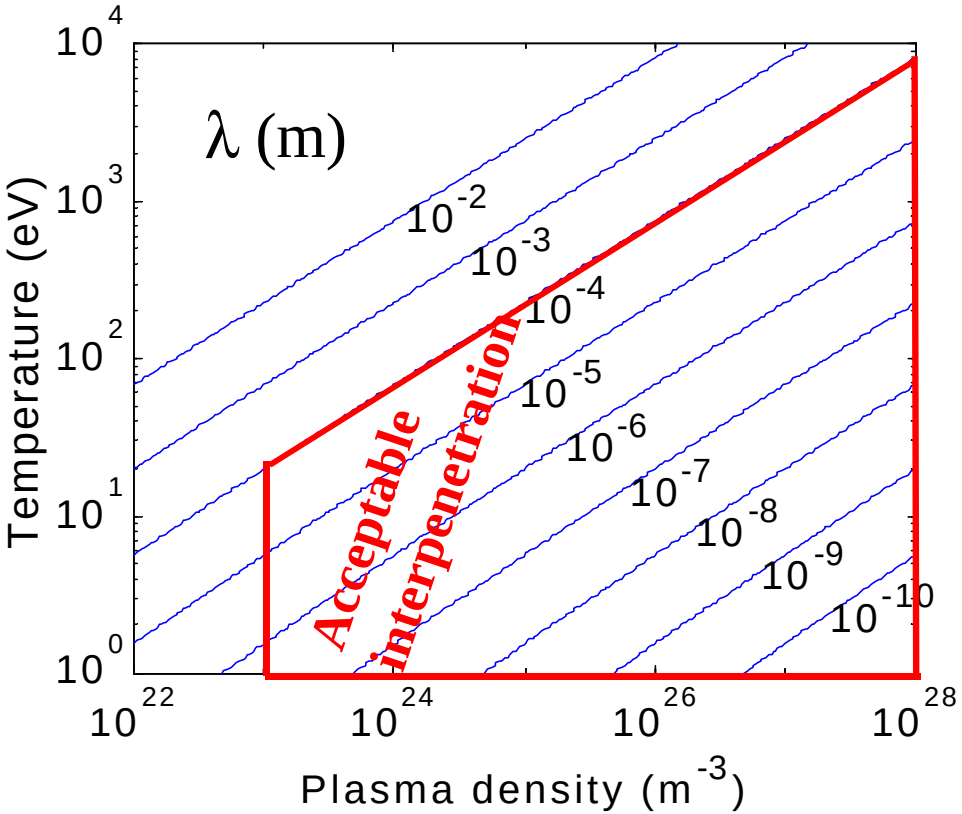
Interpenetration from the Viewpoint of the Ion-Ion Collision Length

- **A 10-times radial convergence gives a 10 times amplification of the ion-ion mean free path l**
- **l < 1 mm at final compression Þ l < 0.1 mm at the beginning of compression**
- **Example: a liner "diffused" edge or a target with *kT* ~ 10 eV, *n* > 10^{23} m^{-3} Þ l < 10 mm (Interpenetration should be insignificant)**
- **The parameter subspace (n, T) in which the IP is acceptable is conveniently large from a practical point of view**



More detailed exploration requires particle simulation for the ions

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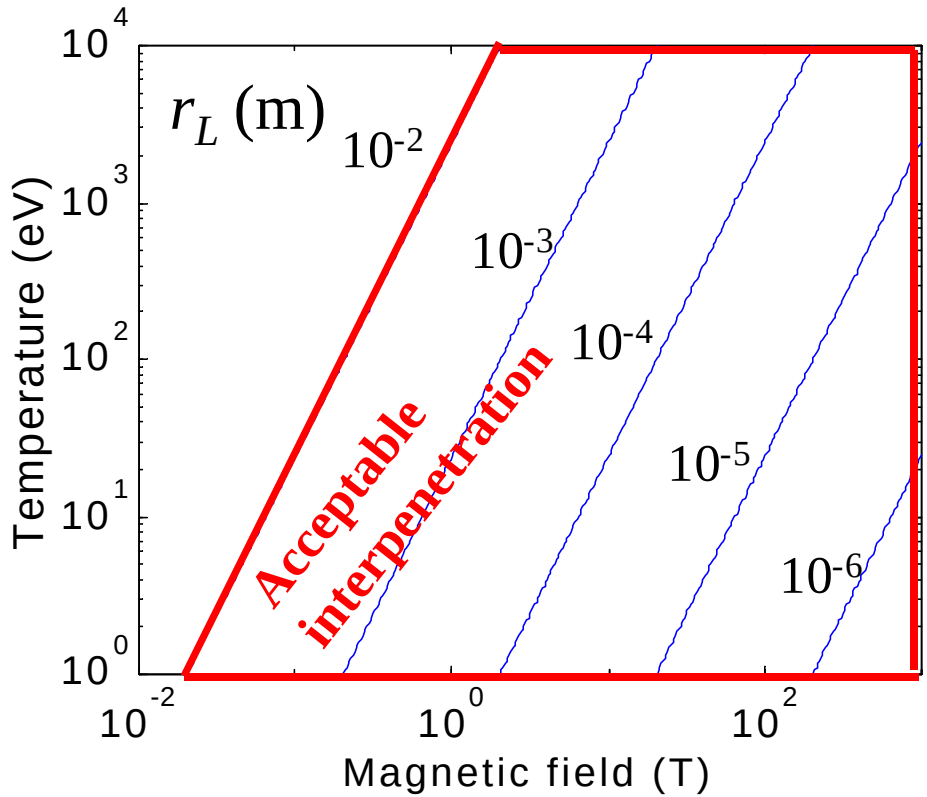
IP from the Viewpoint of the Larmor radius

- **A 10-times radial convergence gives a 10 times shrinking of the ion Larmor radius**
- **r_L < 1 mm at final compression Þ r_L > 10 mm at the beginning of compression**
- **Example: a target with an initial kT ~ 10 eV, B > 1 T Þ r_L < 1 mm (Interpenetration effect expected to be insignificant)**
- **Acceptable parameter subspace (B, T) is conveniently large**
- **Union of the two subspaces**



More detailed exploration requires particle simulation for the ions

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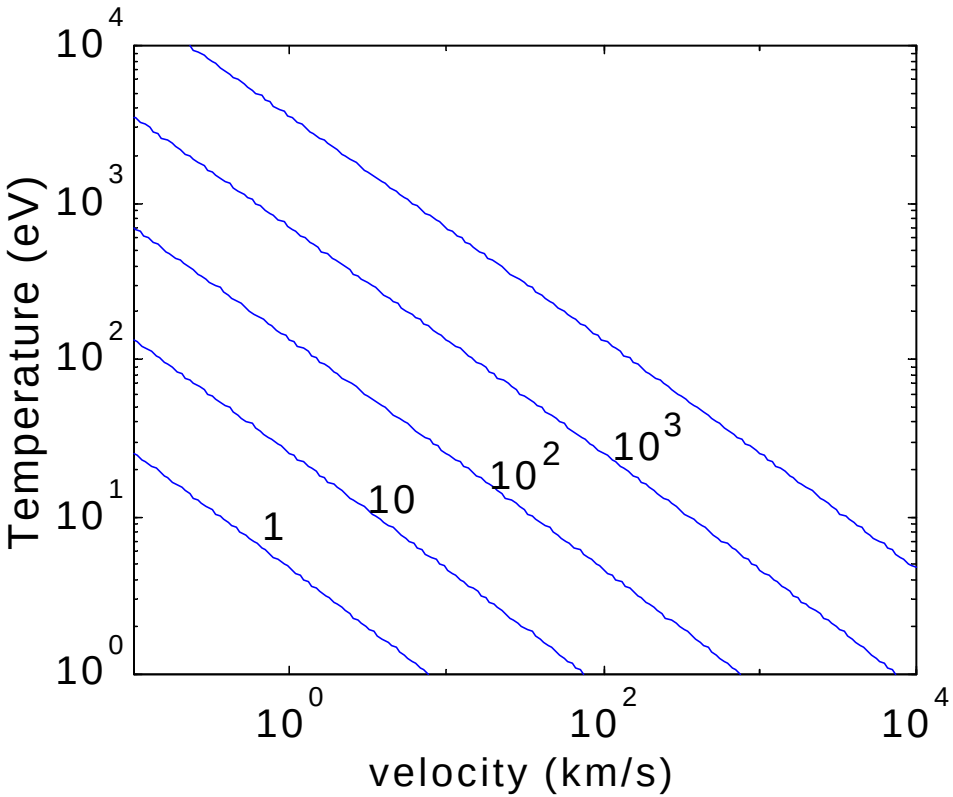
Target Flux Compression

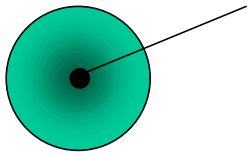
- **Determining factor is the magnetic Reynold's number of the contact region**
  - $R_m = m s v \ell$
- **R_m > 100 for favorable flux compression**
- **Practical realizations of the acceptable parameter subspace are possible**
- **Example: kT = 100 eV, v > 100 km/s, R_m > 500**



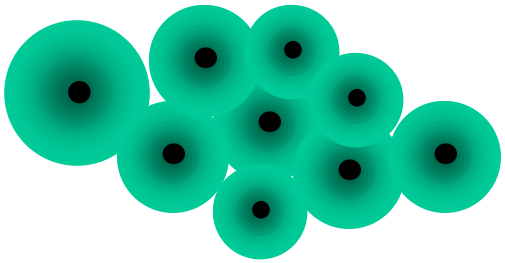
More detailed exploration requires particle simulation for the ions

3-D *Simulation of the Liner Formation and Target Compression with SPHINX*

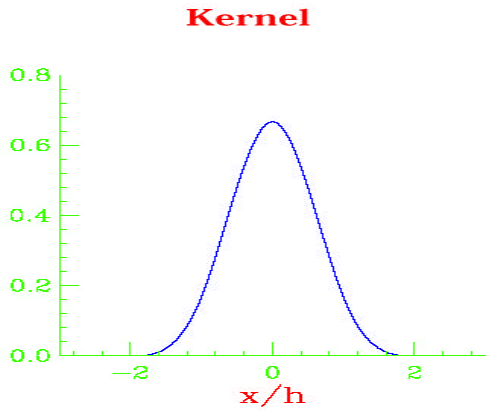
- **A Lagrangian cell is represented by a freely moving "point" particle with a "sphere of influence"**

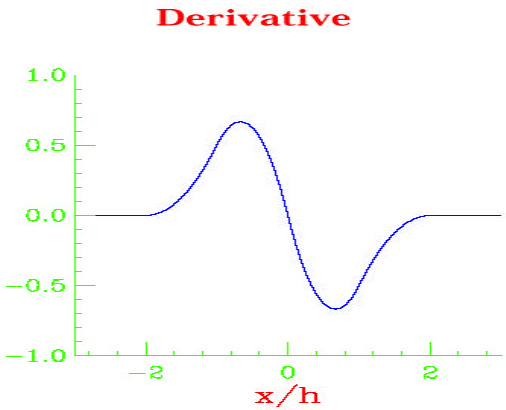


Particle centered at $\mathbf{r}'$,
velocity $\mathbf{v}$, density r,
internal energy e



- **The sphere of influence is modeled by a smoothing function, called kernel function,** $W(|\mathbf{r}-\mathbf{r}'|, h)$





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The Los Alamos SPHINX Fluid Equations

Exact | **SPH Discretization**

$$A(\mathbf{r}) = \int A(\mathbf{r}')d(\mathbf{r}-\mathbf{r}')d\mathbf{r}' \rightarrow A_i(\mathbf{r}) = \sum_{j=1}^{N} A(\mathbf{r}'_j)W(|\mathbf{r}_i - \mathbf{r}'_j|, h)\Delta\mathbf{r}'_j, \quad \Delta\mathbf{r}'_j = \frac{m_j}{r_j}$$

Momentum: $$\frac{d}{dt}\vec{v} = -\left(\frac{1}{\rho}\right)\nabla P \rightarrow \frac{d\mathbf{v}_i}{dt} = -\sum_j m_j \left(\frac{P_i + P_j}{r_i r_j}\right)\nabla_i W_{ij}$$

Energy: $$\frac{de}{dt} = -\left(\frac{P}{\rho}\right)\nabla\bullet\vec{v} \rightarrow \frac{d\boldsymbol{e_i}}{d\boldsymbol{t}} = \sum_{\boldsymbol{j}} \boldsymbol{m_j}\frac{P_{\boldsymbol{j}}}{\rho_{\boldsymbol{j}}^2}(\vec{v}_{\boldsymbol{i}} - \vec{v}_{\boldsymbol{j}})\bullet\nabla W(|\vec{\boldsymbol{r}}_{\boldsymbol{i}} - \vec{\boldsymbol{r}}_{\boldsymbol{j}}|, \boldsymbol{h})$$

Mass: $$\frac{d}{dt}\rho = -(\rho)\nabla\bullet\vec{v} \rightarrow \frac{d\rho_{\boldsymbol{i}}}{d\boldsymbol{t}} = \rho_{\boldsymbol{i}}\sum_{\boldsymbol{j}}\frac{\boldsymbol{m_j}}{\rho_{\boldsymbol{j}}}(\vec{v}_{\boldsymbol{i}} - \vec{v}_{\boldsymbol{j}})\bullet\nabla W(|\vec{\boldsymbol{r}}_{\boldsymbol{i}} - \vec{\boldsymbol{r}}_{\boldsymbol{j}}|, \boldsymbol{h})$$

No thermal conduction

Or, $$\rho = \sum_{\boldsymbol{k}=1}^{\boldsymbol{N}} \boldsymbol{m_k} W(\bar{\boldsymbol{r}} - \vec{\boldsymbol{r}}_{\boldsymbol{k}}, \boldsymbol{h})$$

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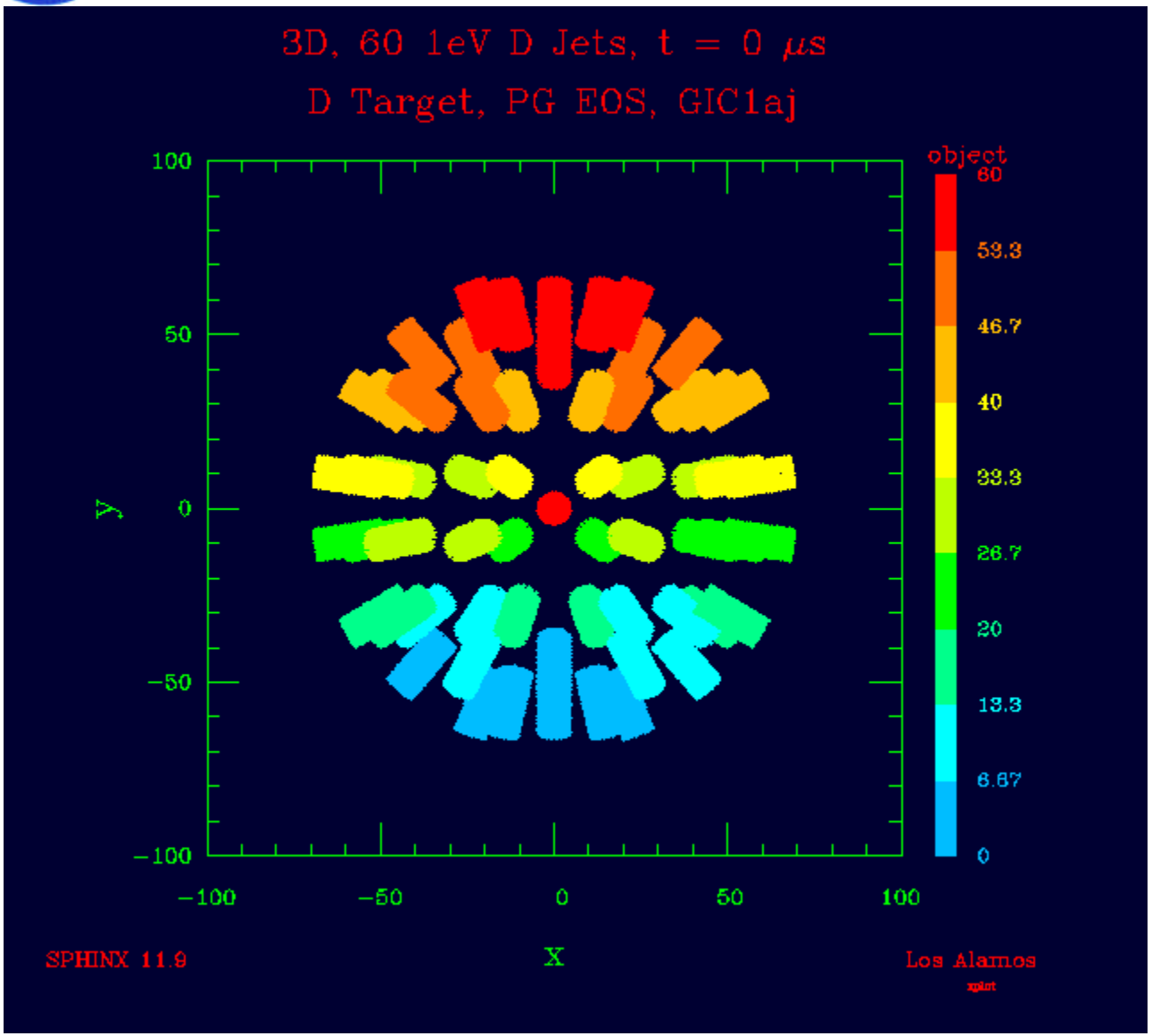
SPHINX - Case G1C1a



Jet:
Cylindrical column
Deuterium plasma
Diameter: 10 cm
Length: 20 cm
jet material:
deuterium
125 km/s, 30 mg, 1 eV

Target:
D-T spherical plasma
5 cm radius
1e24 ions per m^3
10 eV

The computation started with the jet front 0.5 m from the center.

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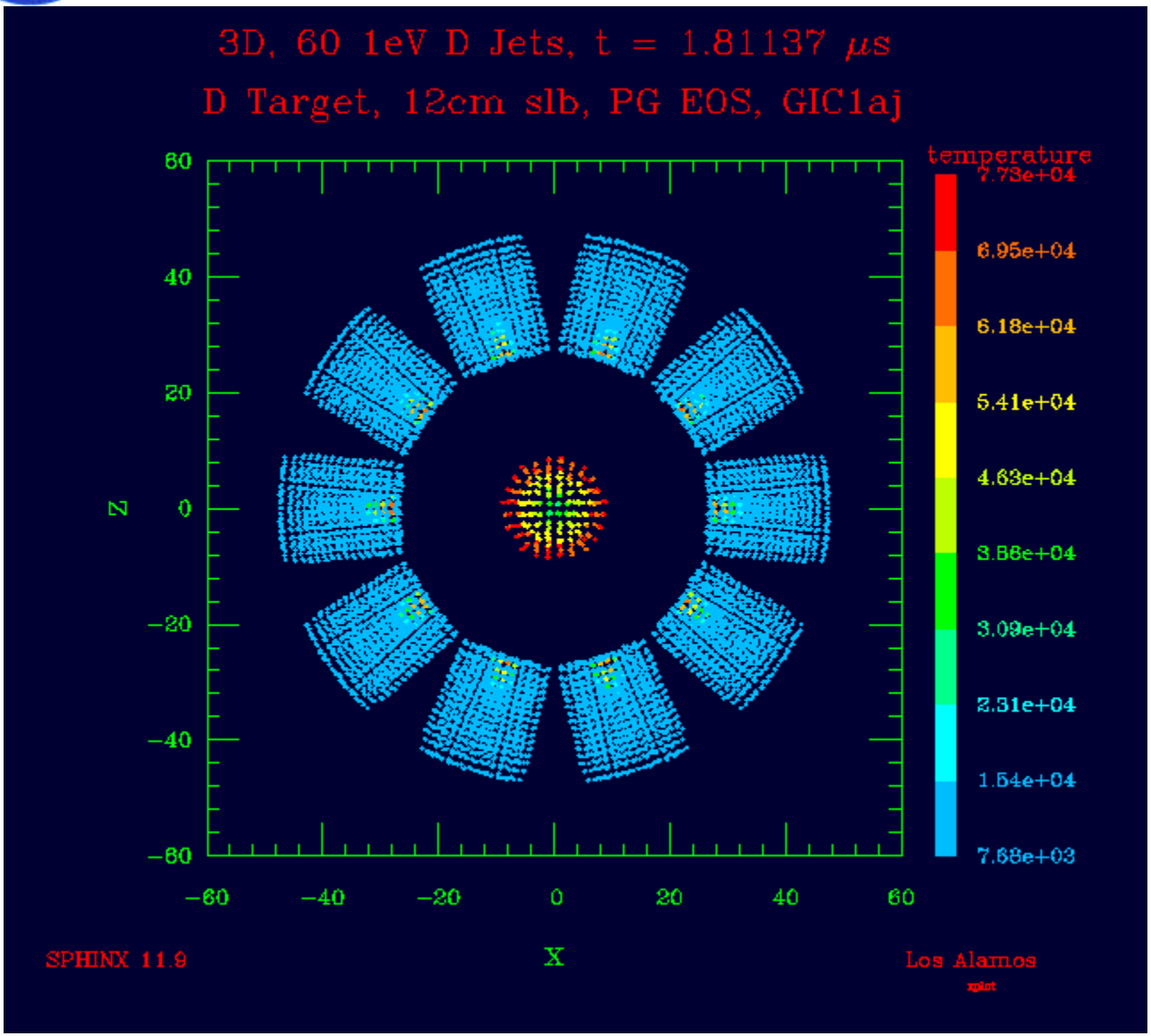
SPHINX - Case G1C1a



- Jets just collided
- Looking at a slab 12-cm thick along the y-axis
- Two layers of jets are depicted
- Each block has two jets
- Looking at 20 jets
- Compression in the contact region may be seen
- Some precursor jets are formed

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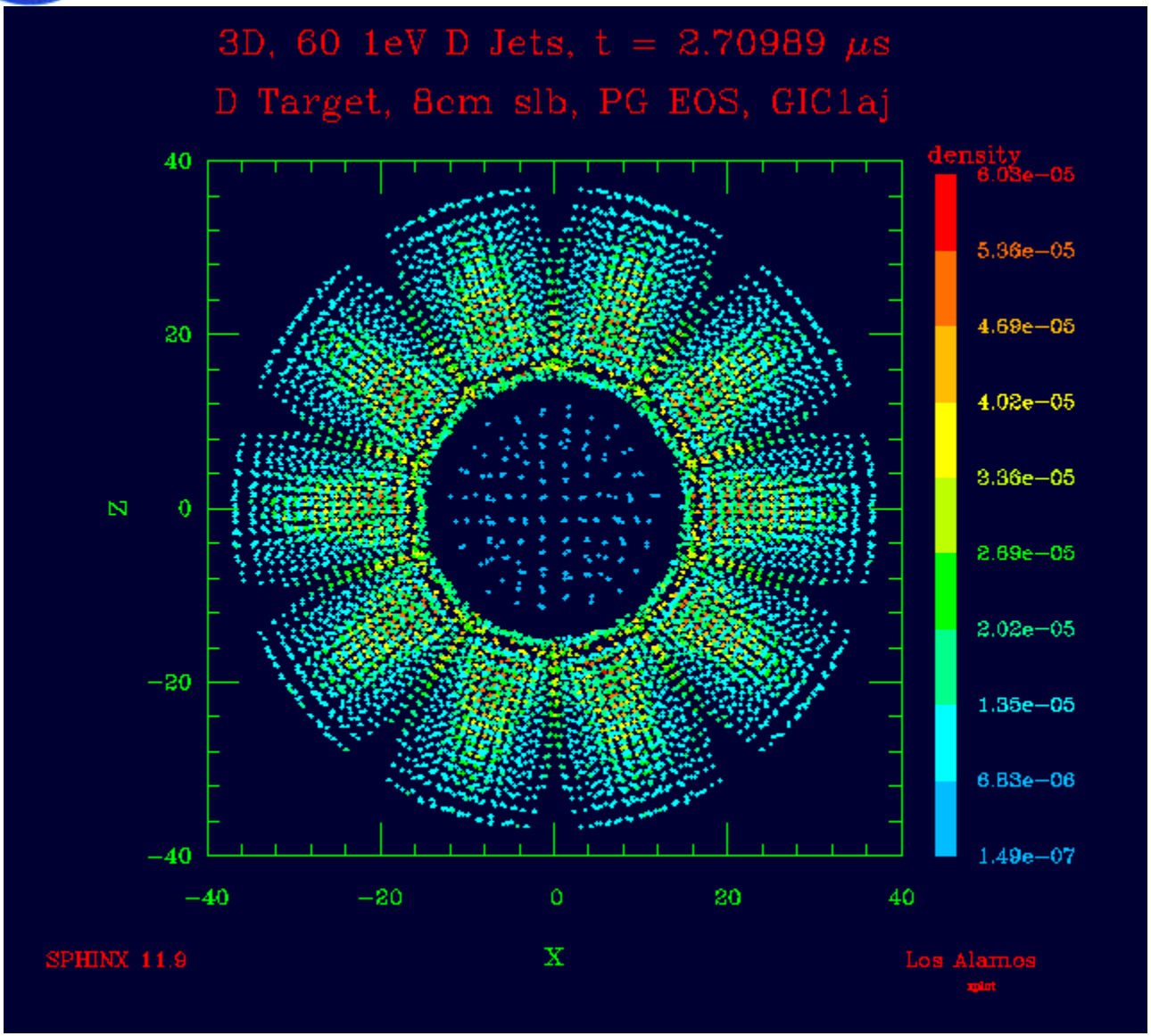
SPHINX - Case G1C1a



- Precursor jets are swept up by the main jets
- Liner is beginning to form
- Just about to engage the target
- Very little precursor jets in front of the liner
- Density increases sharply towards the front of the liner

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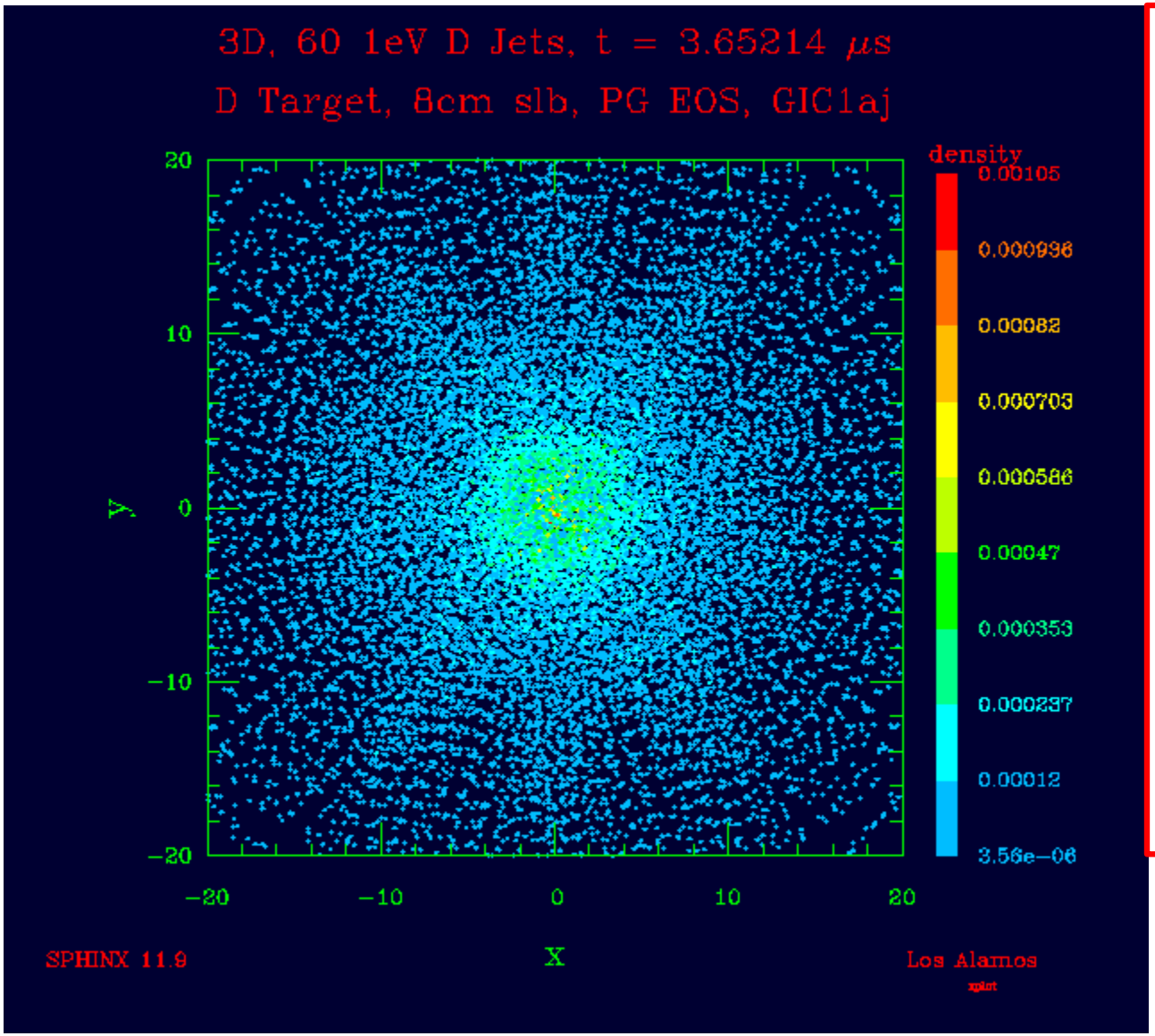
SPHINX - Case G1C1a (j74xyd20)



Peak compression reached at 3.65 ms

$n \sim 3 \times 10^{26}\ m^{-3}$

State of compression persists for > 1 ms

Temperature > 8 keV, consistent with 0-D

The density is ~ 1/10 calculated with 0-D

The confinement time is about 10 times more

Expect fusion yield to be comparable

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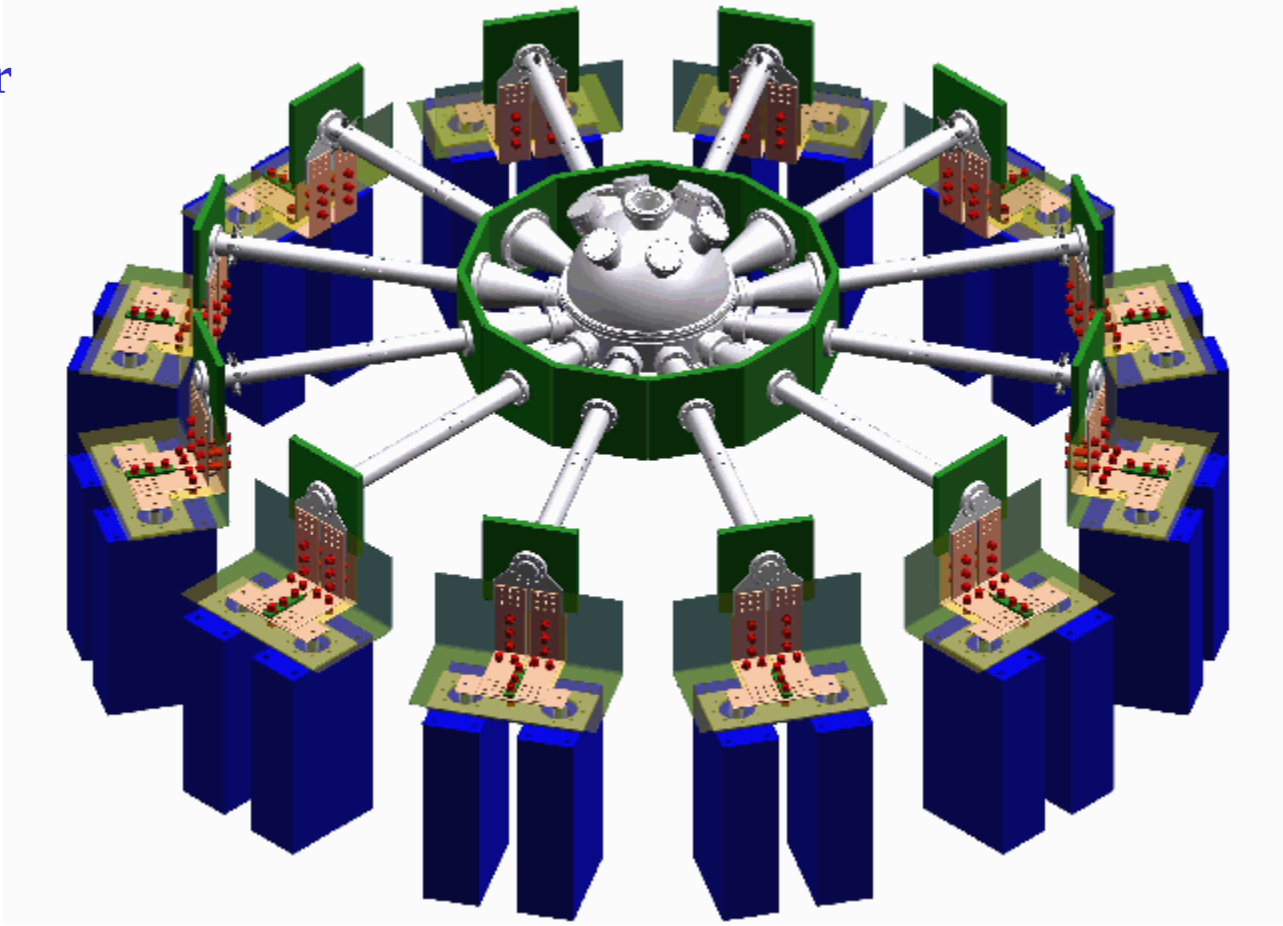
Plasma Liner Physics Exploratory Experiment PLX-1

- **Study formation of a 2-D (cylindrical) liner**
- **Uses 12 plasma guns in a circular array to form a cylindrical liner**
- **Use the 2-D liner to implode a plasma to achieve 100 eV**
- **4-year project**



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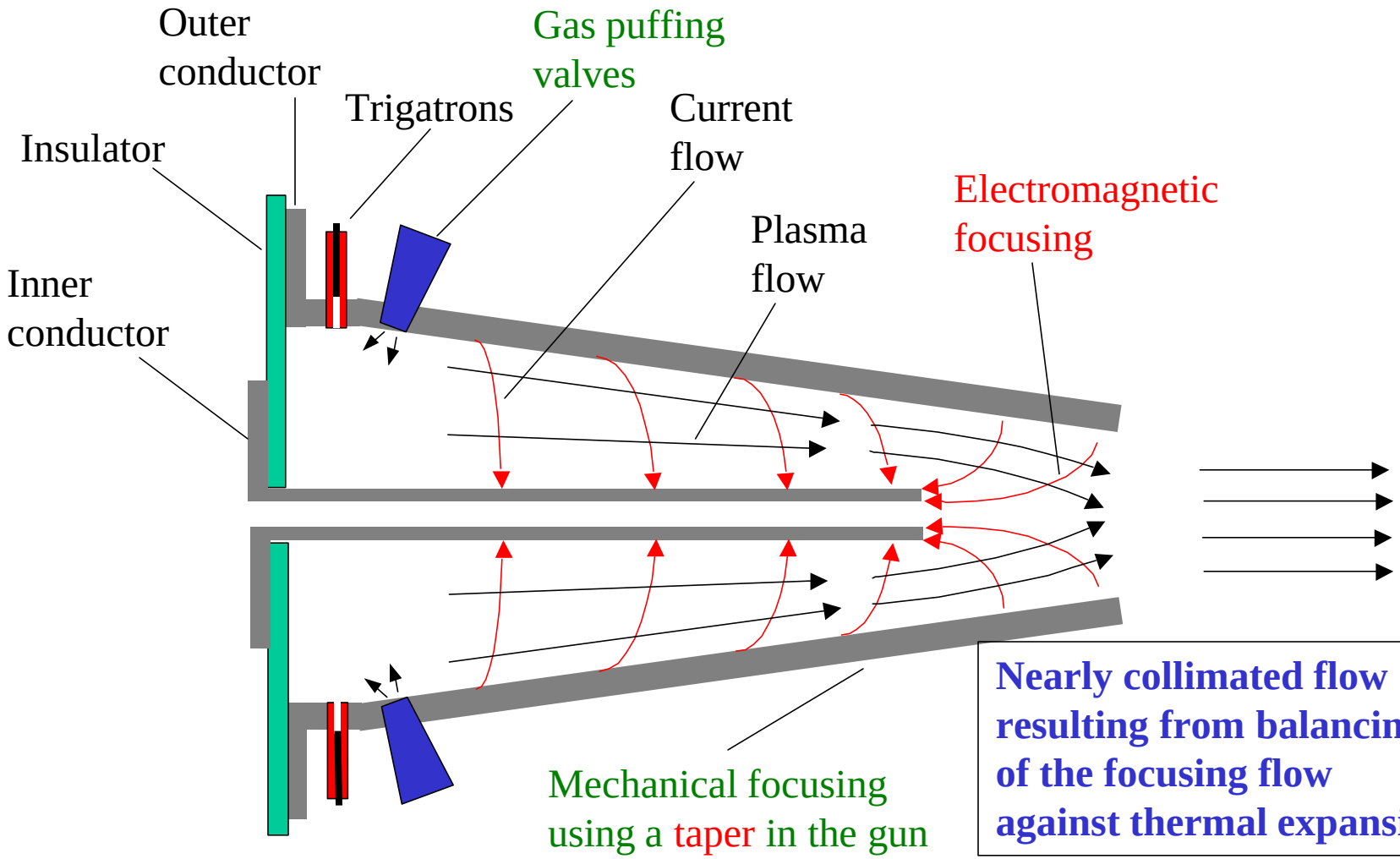
The Coaxial Plasma Accelerator Concept



Nearly collimated flow resulting from balancing of the focusing flow against thermal expansion

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PLX-1 Project Plan

Address timing and spatial precision of plasma initiation in a coaxial gun

- Develop pulsed power experimental infrastructure
- Develop trigger for 1 gun
- Develop triggering system for multiple guns (up to 12)

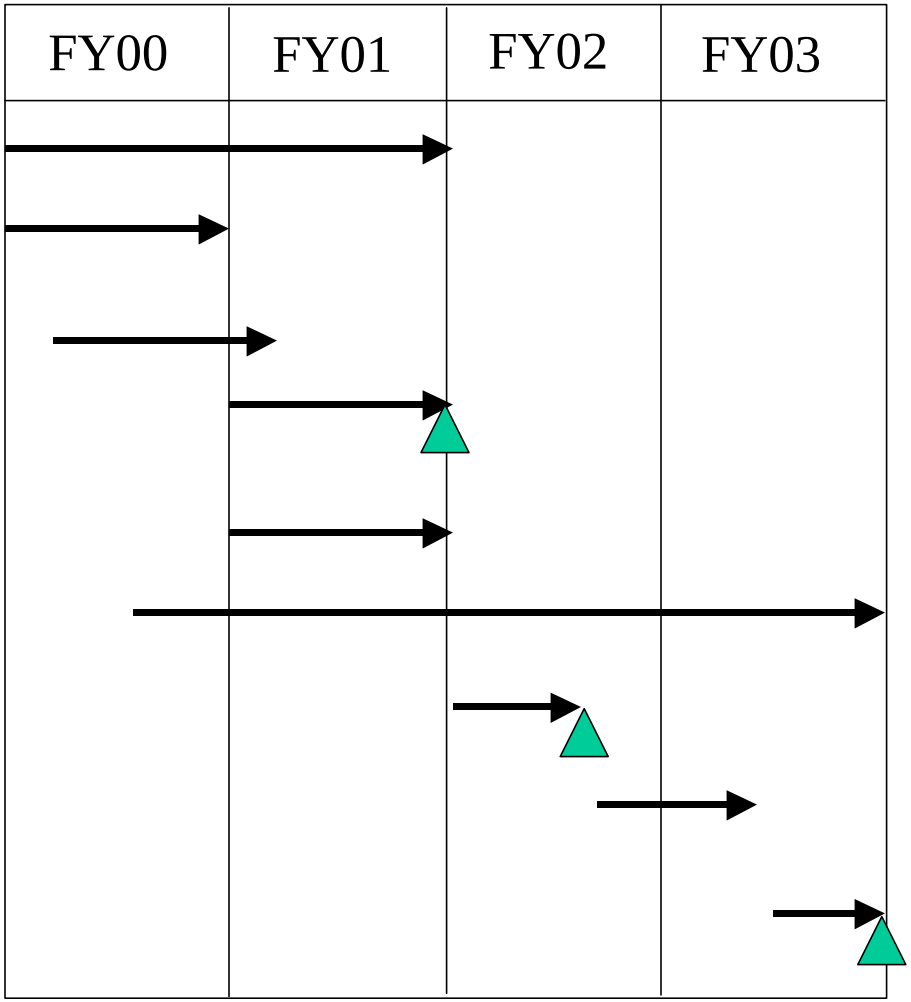
Model and design one plasma gun

Develop diagnostics

Build and test one plasma gun

Build a 12-gun experimental system for producing a 2-D liner

Experimentation with the 12-gun system to form a liner



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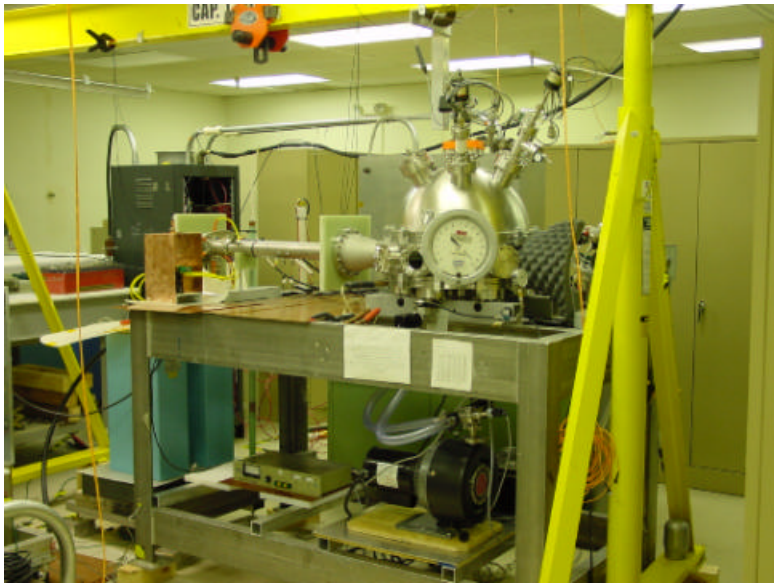
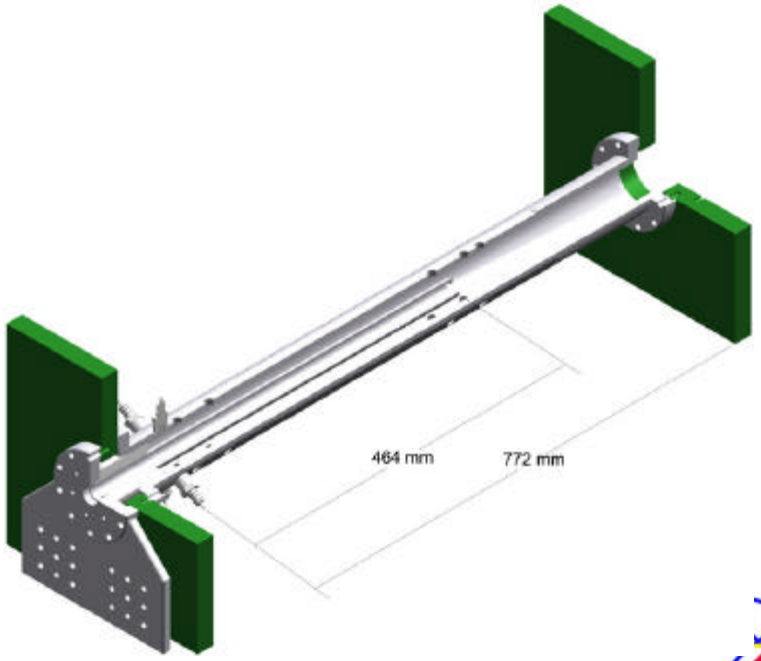
Year 1

- **Objective**
  - Develop pulsed power experimental infrastructure
  - **Validate the performance of the trigatrons for 1 gun to obtain:**
    (1) Timing and spatial precision of plasma initiation
    (2) Reproducibility
- **Status:**
  - Pulsed power experimental infrastructure completed.
  - Triggering system for one gun developed and tested.





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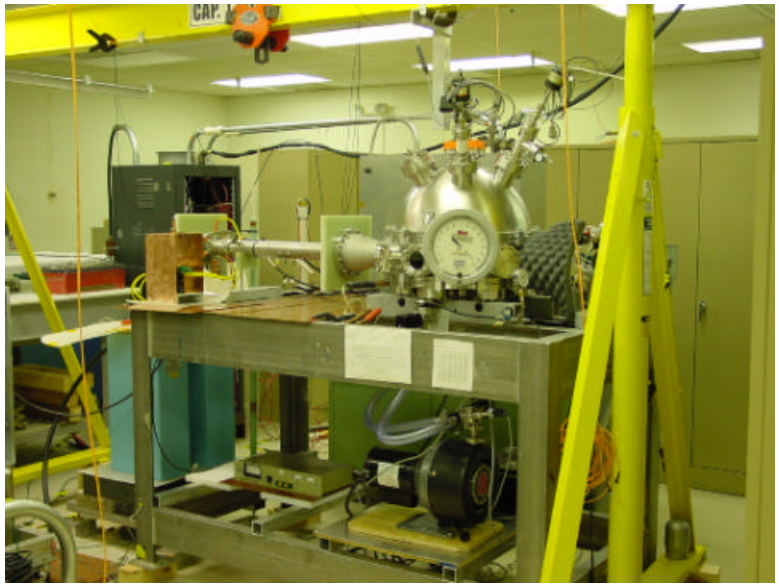

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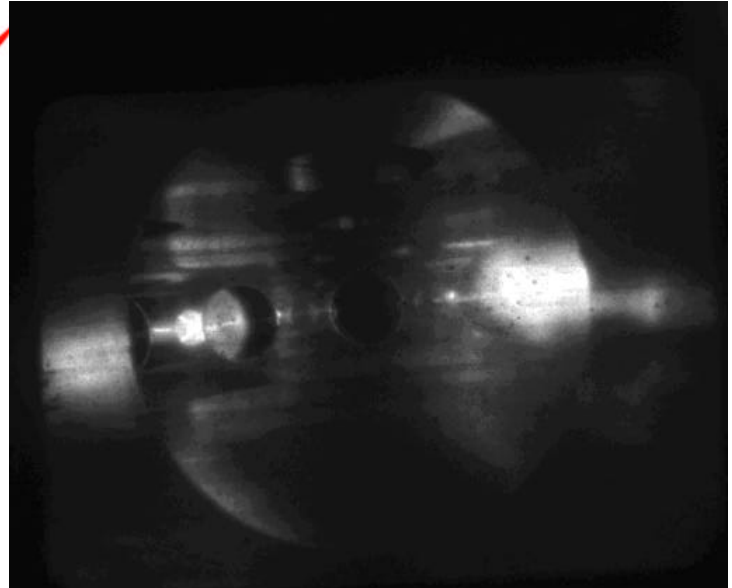

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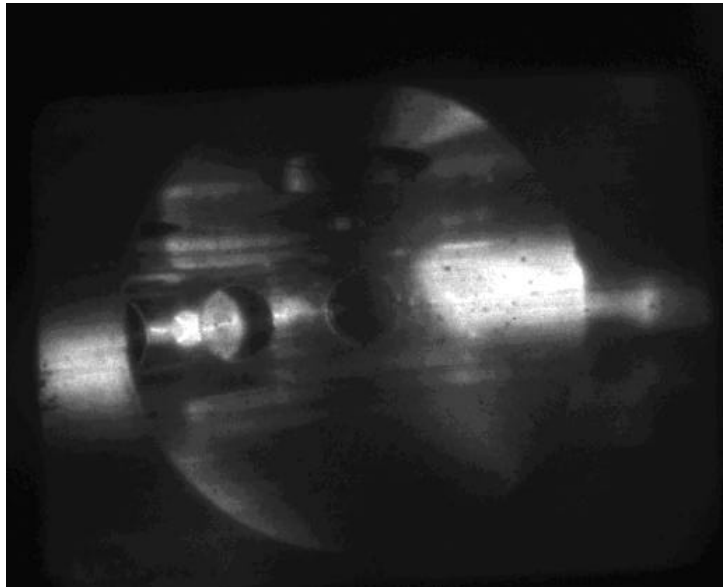

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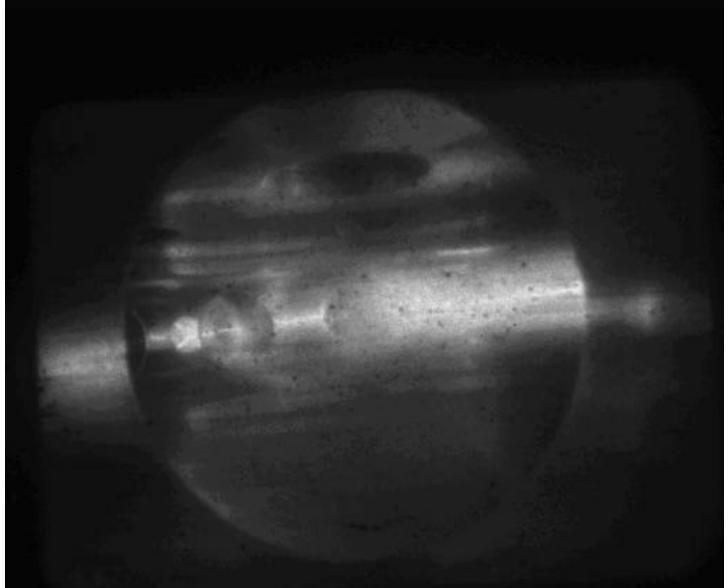

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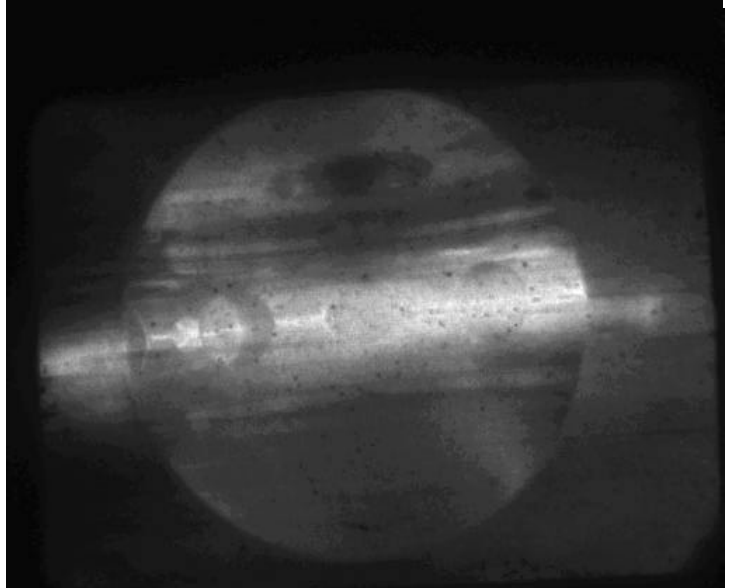

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Summary

- **Review progress made in plasma-liner driven MTF**
- **Overall 0-D system performance of the concept modelled**
- **Linear, incompressible stability of the interaction of the jets analysed**
- **Parametric subspaces in which plasma interpenetration is not an issue identified**
- **3-D plasmadynamics of the liner formation and target compression attempted**
- **First experimental step towards studying the dynamics formation of a 2-D liner and the 2-D compression of a target plasma taken with some preliminary success**

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Flow Structure of the Liner

- **1-D analytic, quasi-static model**
- **Mass and momentum conservation equations**

$$\frac{\partial}{\partial r} r^2 r u_r = 0, \quad \frac{\partial p}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r} r r^2 u_r^2 = 0$$

- **Assume flow in the liner to be polytropic with polytropic index G, the equations reduce to:**

$$\frac{x}{2y}\frac{dy}{dx} = \frac{1}{M^2 - 1}, \quad M^2 = \left(\frac{u_r}{c}\right)^2 = M_b^2 y^{\Gamma+1} x^{2(\Gamma-1)}, \quad y = \frac{u_r}{u_b}, \quad x = \frac{r}{r_b}, \quad y(1) = 1,$$

$$\frac{r}{r_b} = \left(y x^2\right)^{-1}, \qquad \frac{p}{p_b} = \left(\frac{r}{r_b}\right)^{\Gamma}, \qquad \frac{c}{c_b} = \left(\frac{r}{r_b}\right)^{(\Gamma-1)/2}$$

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Liner Velocity and Density Profiles

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Acoustic Compression of the Target

- **Energy equation**

$$\frac{d}{dt}(kT_t) = \frac{1}{6N}\left\{\Delta E_a \dot{N}_r - \dot{Q}_c - \dot{Q}_{rad} - p\dot{V} - \dot{E}_B - \dot{E}_k\right\}$$

$$\dot{N} = -\dot{N}_r = -\frac{N^2}{V}\langle s v\rangle,$$

$$\dot{Q}_c = 4pr_b^2 gk\left(\frac{T_t - T_b}{r_b}\right),\ k = k_{\perp e} + k_{\perp i},\ k_{\perp e} = \frac{n_e k(kT_e)t_{ee}}{m_e}\frac{4.66w_{ce}^2 t_{ee}^2 + 11.92}{w_{ce}^4 t_{ee}^4 + 14.79w_{ce}^2 t_{ee}^2 + 3.77},$$

$$k_{\perp i} = \frac{n_i k(kT_i)t_{ii}}{m_i}\frac{2w_{ci}^2 t_{ii}^2 + 2.64}{w_{ci}^4 t_{ii}^4 + 2.7w_{ci}^2 t_{ii}^2 + 0.68},\quad t = \frac{25pm^{1/2}e_0^2(kT)^{3/2}}{\sqrt{3}Z^4 ne^4 \ln\Lambda},\quad w_c = \frac{eB}{m}$$

$$\dot{Q}_{rad} = \dot{Q}_{bremsstrahlung} + \dot{Q}_{synchrotron},$$

$$\frac{\dot{Q}_{bremsstrahlung}}{V} = 1.445\times10^{-40} g_{ff} n_e T_e^{1/2}\sum n_i Z_i^2,\quad \frac{\dot{Q}_{synchrotron}}{V} = 6.2\times10^{-17} B^2 n_e T_e(keV)\left[1 + \frac{T_e(keV)}{204} + \ldots\right],$$

$$\dot{E}_B = \left(\frac{2p}{3m}\right)\left(\frac{r_0}{r_h}\right)^2 (B_0 r_0)^2 u_b,\quad E_k = \frac{3}{10}m_t u_b^2,\quad p\dot{V} = \frac{3N_p kT_t u_b}{r_b},\quad N_p = 4N.$$

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Confinement: The Stagnation Shock

- **At peak compression ("the turn-around"), a stagnation shock propagates outwards halting the converging flow in the liner**
- **Local speed of the stagnation shock =** $(g+1)u_r/2.$

  u_r - local flow speed

- **Transit time of the stagnation shock**

$$t_s = \left(\frac{2}{g+1}\right)\int_{r_b}^{r_a}\frac{dr}{u_r} = \left(\frac{r_b}{u_b}\right)\left(\frac{2}{g+1}\right)\int_{1}^{x_a}\frac{dx}{y(x)} \equiv \frac{r_b}{u_b}t_s(x_a).$$

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Confinement: The Rarefaction Wave

- **When the stagnation shock reaches the outer boundary, a rarefaction wave propagates backwards**
- **Transit time**

$$t_r = \int \frac{dr_s}{c_s(r_s)}, \quad r_s(r_s) = \left(\frac{g+1}{g-1}\right) r(r), \; p_s(r_s) = \left(\frac{g+1}{2}\right) r(r) u_r^2(r),$$

$$t_r = \left(\frac{r_b}{u_b}\right)\left(\frac{g-1}{g+1}\right)^{1/3}\left(\frac{2}{g(g-1)}\right)^{1/2} \int_1^{x_a} \frac{x^2}{\left(x^3 + \frac{2}{g-1}\right)^{2/3} y} dx \; . \equiv \left(\frac{r_b}{u_b}\right) t_r(x_a)$$

- **Confinement time:** $t_{conf} = t_s + 2t_r = \frac{r_b}{u_b}(t_s(x_a) + 2t_r(x_a)).$

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Charged Particle Energy Deposition

- **In a magnetic field (after Kirkpatrick, 1998)**

$$f_a(Br, rr; f_0) = f_0(rr)\left[\frac{1+3(Br)^2}{1+3(Br)^2 f_0(rr)}\right],$$

- **In the absence of magnetic field (Evans, 1973)**

$$-\left\langle \frac{dE}{dx} \right\rangle_j = 2pZ^2 Z_j^2 \left(\frac{e^2}{4pe_0}\right)^2 \frac{m}{m_j E} F_j(y_j) \ln \Lambda_j,$$

$$F_j(y_j) = erf(y_j) - \left[1 + \frac{m_j}{m}\right] y_j \left(\frac{2}{\sqrt{p}}\right) \exp\left(-y_j^2\right), \quad y_j^2 = \frac{m_j}{m}\frac{E}{kT_j}.$$

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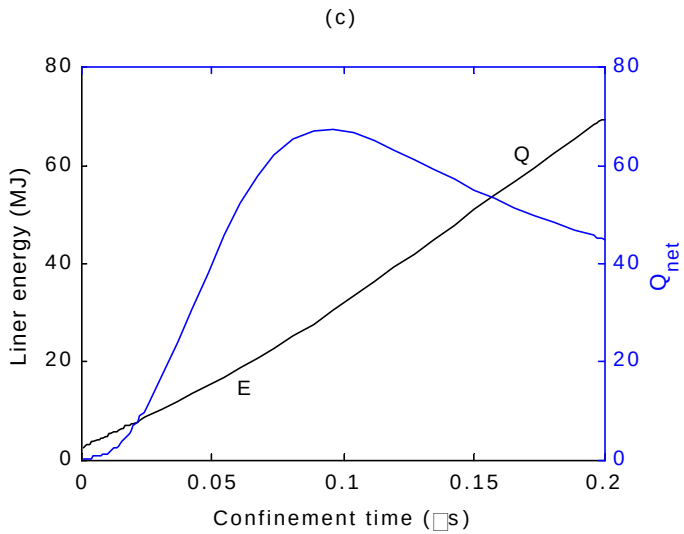
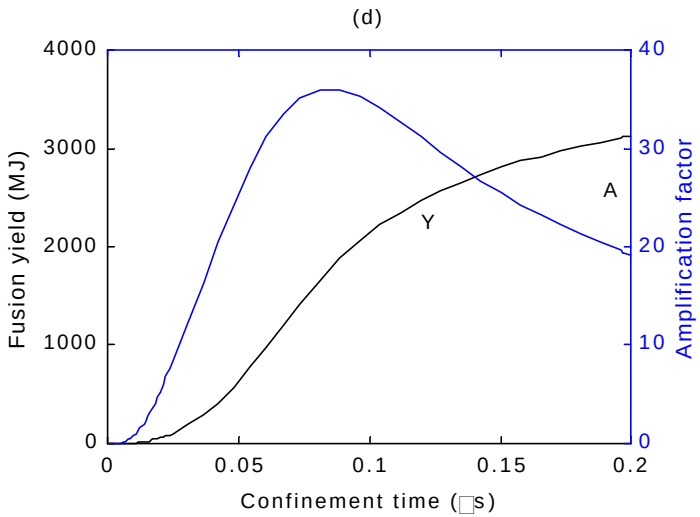
0-D Modeling Results





Initial conditions: Target, 50 mm, 2 eV, 1.5 T, 10^{24} m^{-3}
Implosion velocity: 125 km/s
Peak compression: Target 2.5 mm

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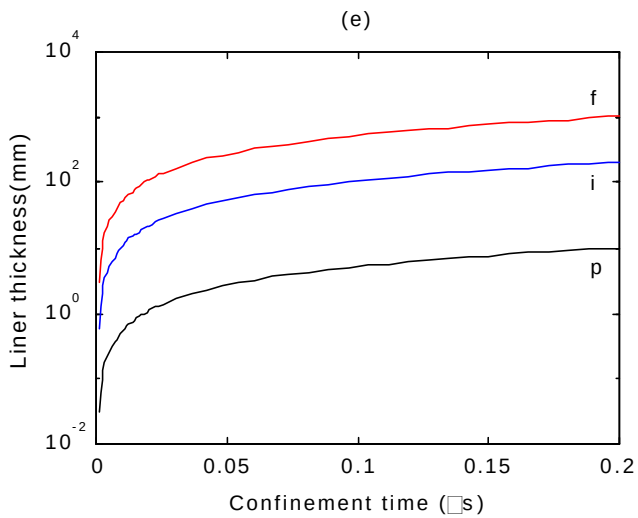
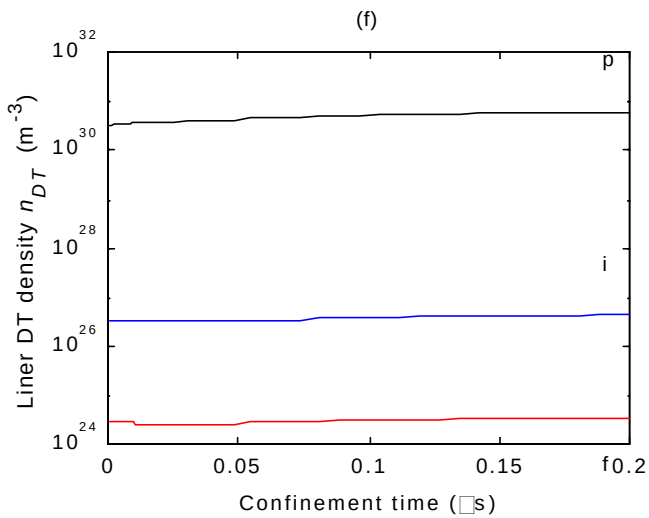
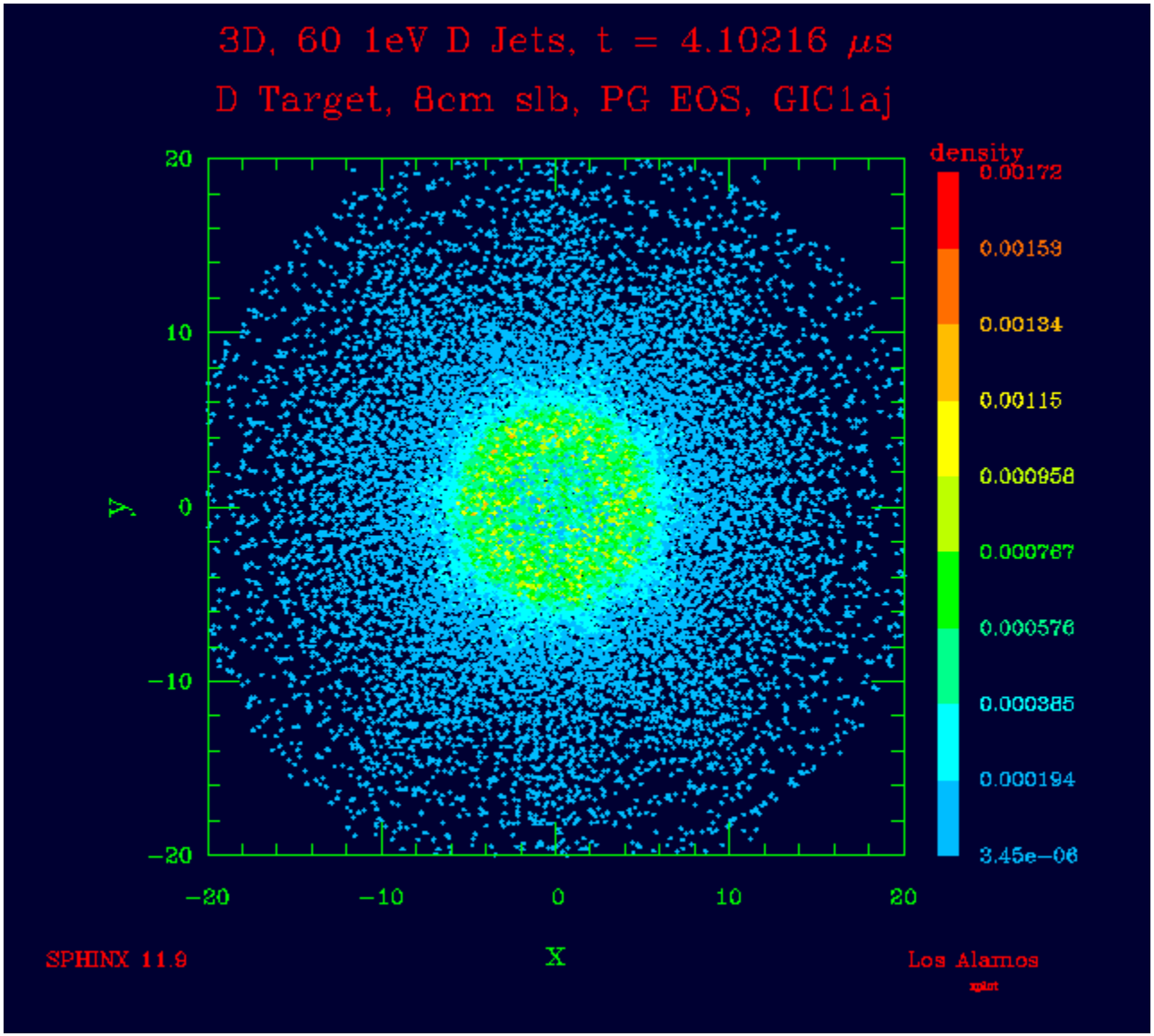

(e)
Liner thickness(mm)
Confinement time (□s)
f
i
p


(f)
Liner DT density n_{DT} (m^{-3})
Confinement time (□s)
p
i
f

SPHINX - Case G1C1a (j83xyd20)



Temperature and density of target and liner persisted for > 0.7 ms

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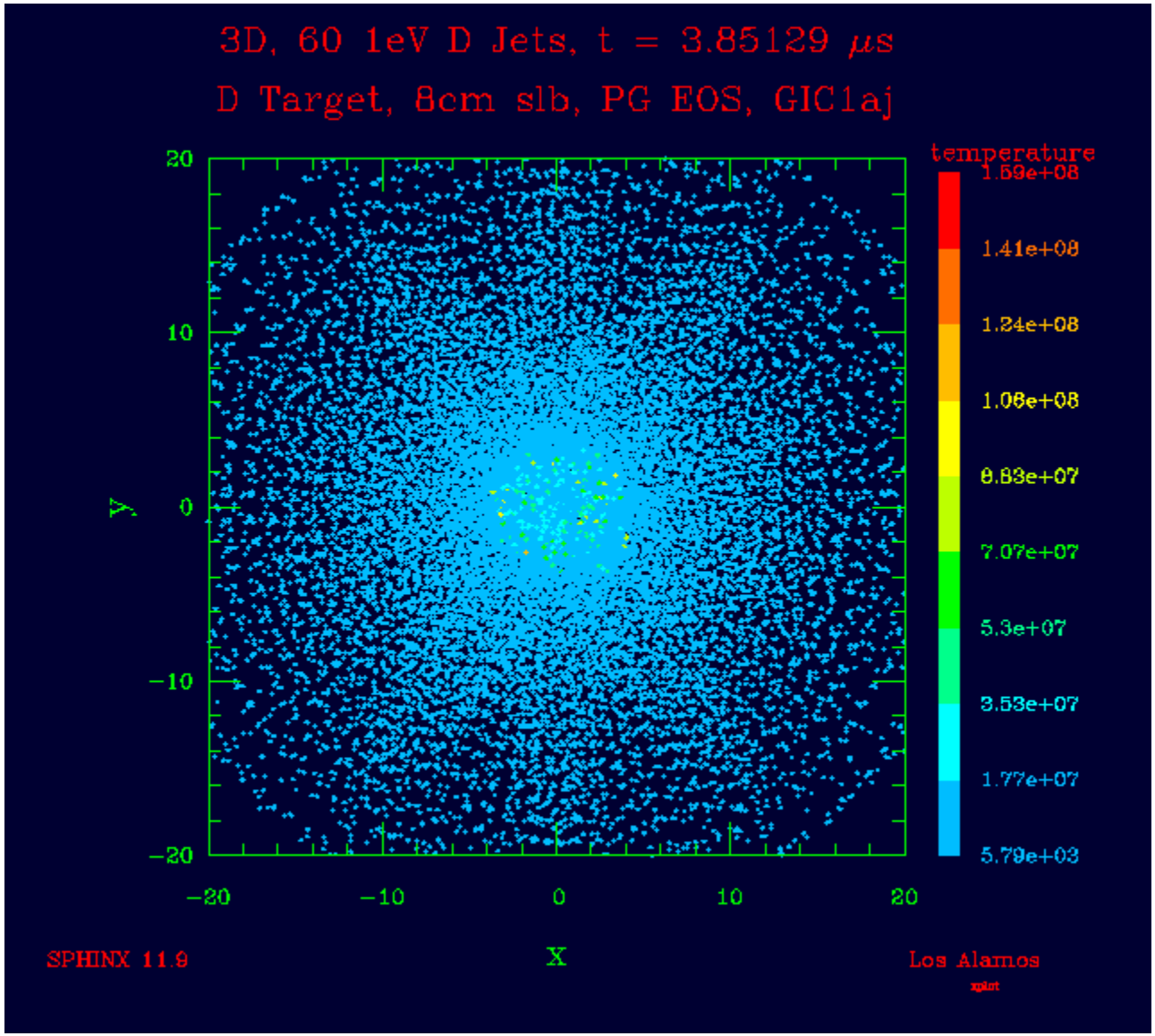
SPHINX - Case G1C1a (j78xyT20)



Peak temperature > 8 keV, when fusion reactions can be expected to accelerate (not modeled)

Consistent with the 0-D calculation

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