Supersonic Plasma Jet Driven MIF Fundamentals

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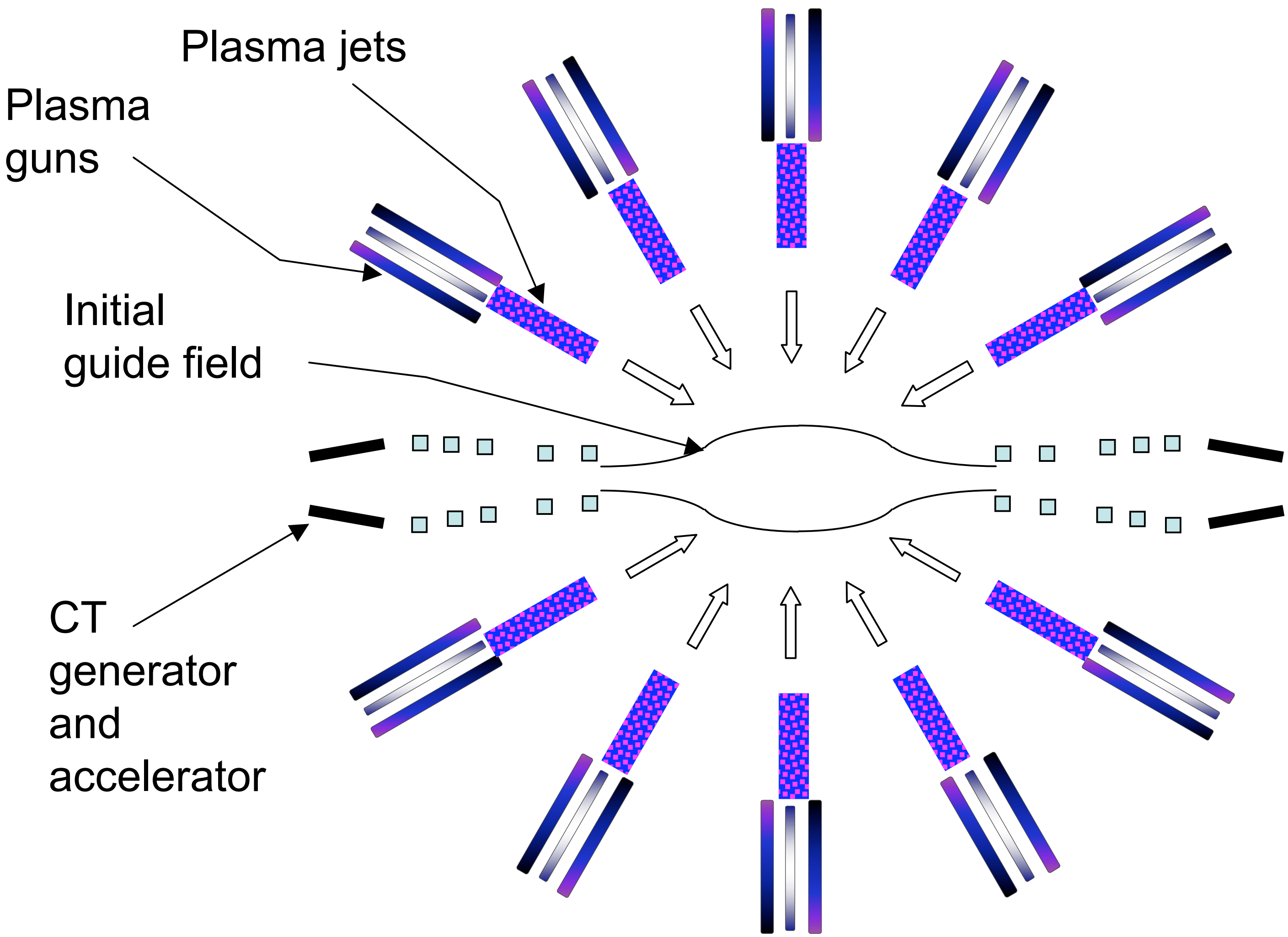
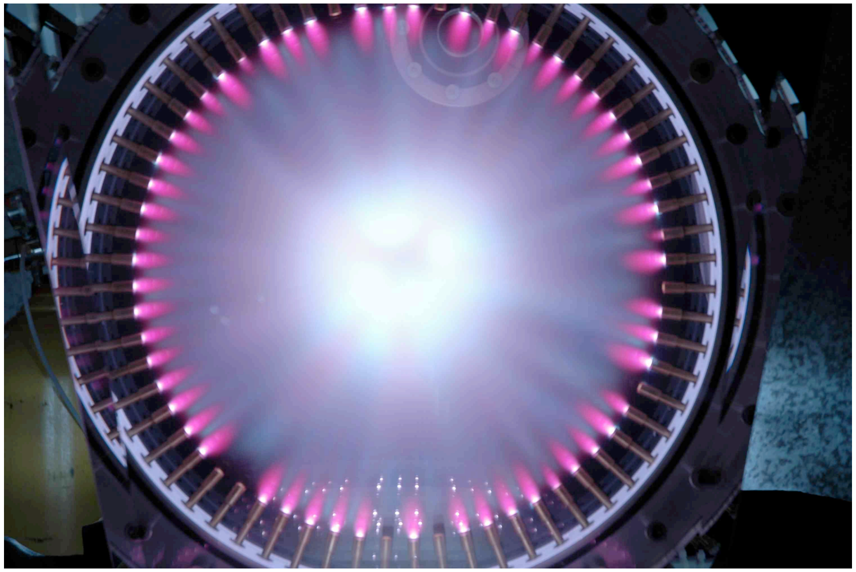
Supersonic plasma jets as drivers for MIF

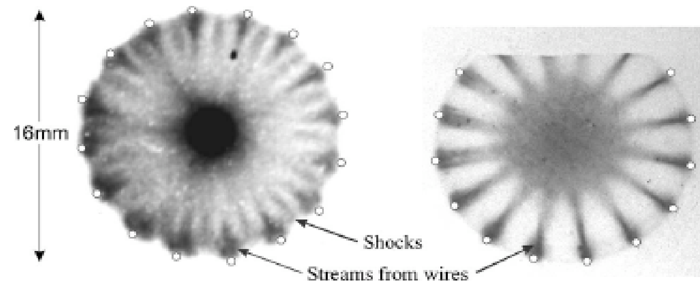


Options for plasma jets



Wire-array Z-pinch produces HED plasma jets

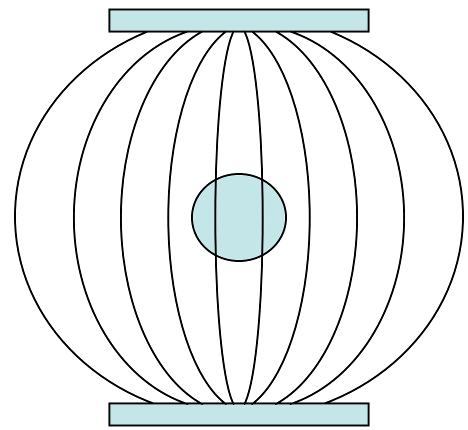
(Bott et al.)



2-D Convergence of 64 plasma jets demonstrated at HyperV

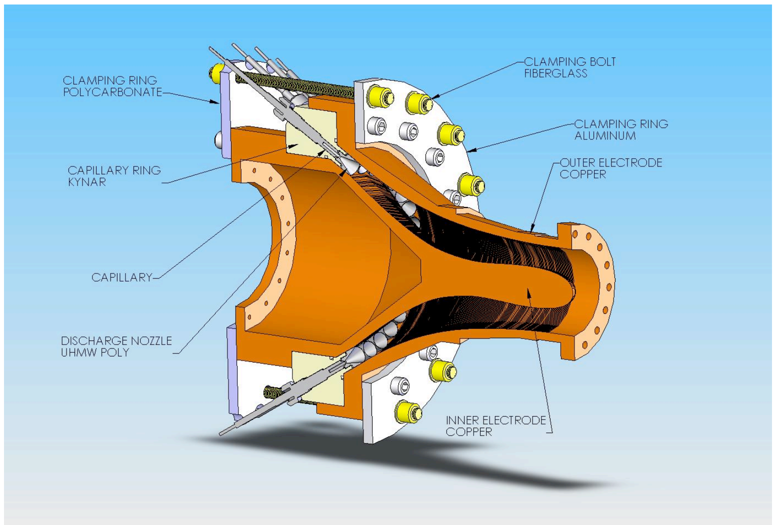
For spherical 3-D arrays:

- Why not 192 jets?
- Why not 300 jets?

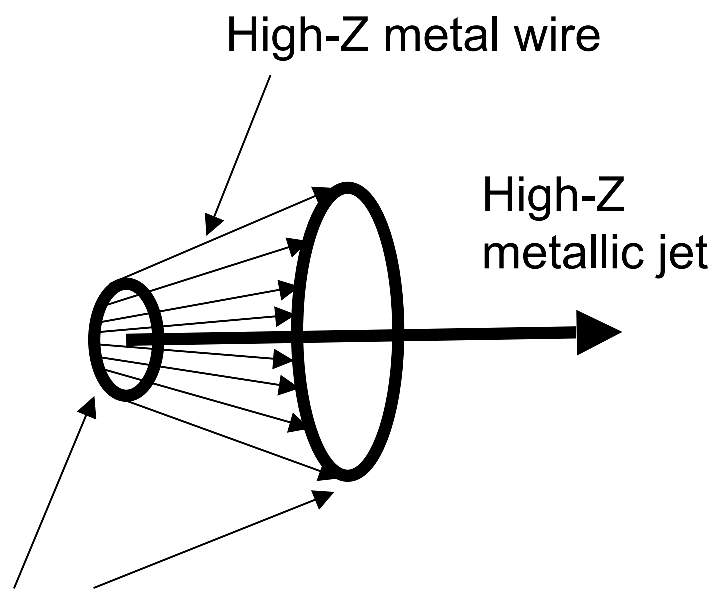


Spherical wire-array Z-pinch

Plasma guns possibilities



Coaxial plasma guns with shaped electrodes

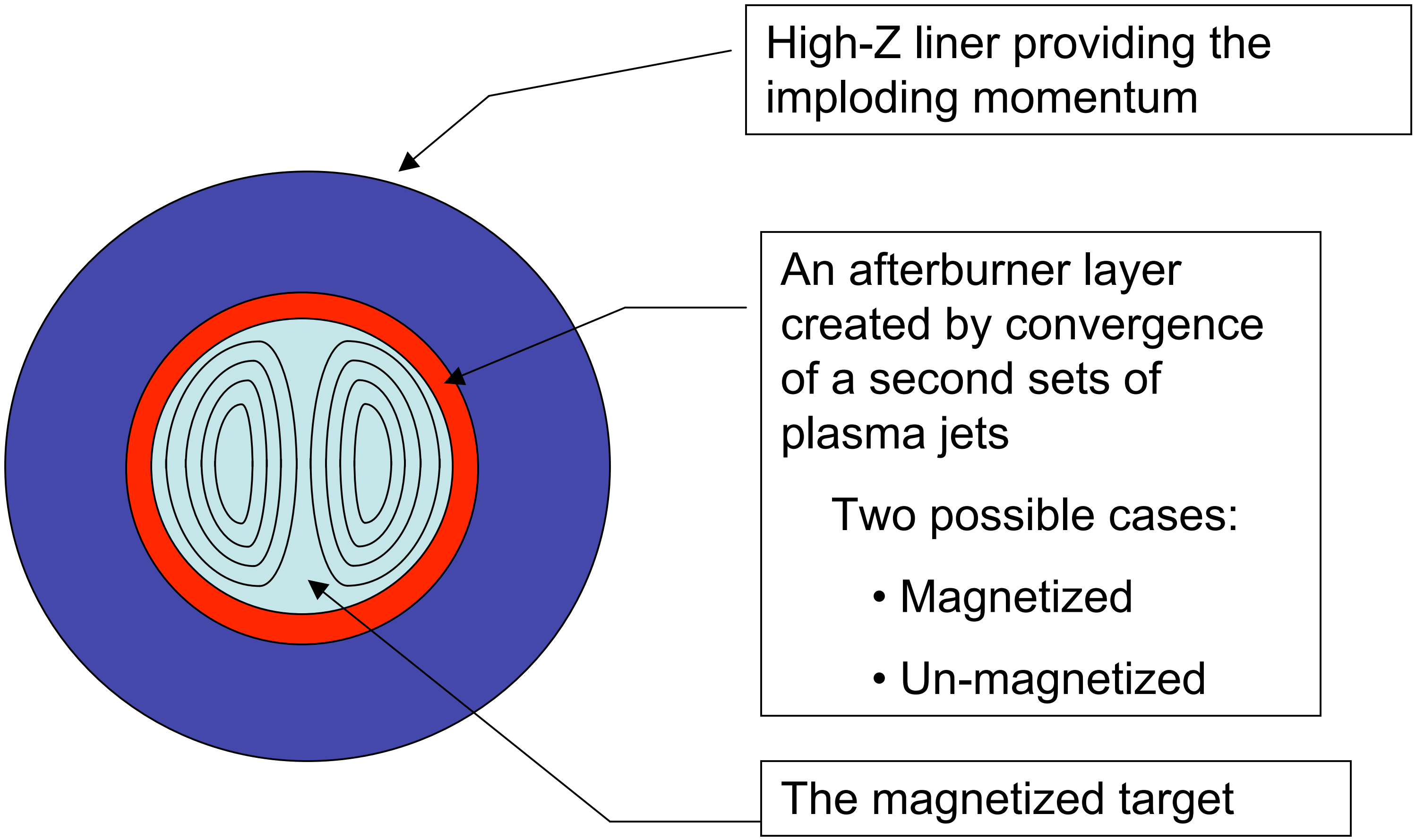


Cartridge containing conical wire array and ring electrodes to be inserted into a plasma gun

Conical wire-array plasma gun

Advanced PJMIF

Idealized mathematical models



High-Z is needed for the imploding liner

- Pressure and density amplification by factors of 10^4 to 10^5 are required
  - Requires high Mach number flows
- As the liner implodes, it compresses on itself, heating itself up, losing compressibility and compressing power
  - Sound speed goes up, depressing the Mach number
- By using high-Z species in the liner, ionization and radiation helps to clamp the liner temperature
  - Lowers the effective Γ of the liner

$$p \rightarrow \frac{1}{\Gamma} \alpha^{-\frac{\alpha+1}{2}} M_i^{\alpha-1} \rho_i u_i^2$$

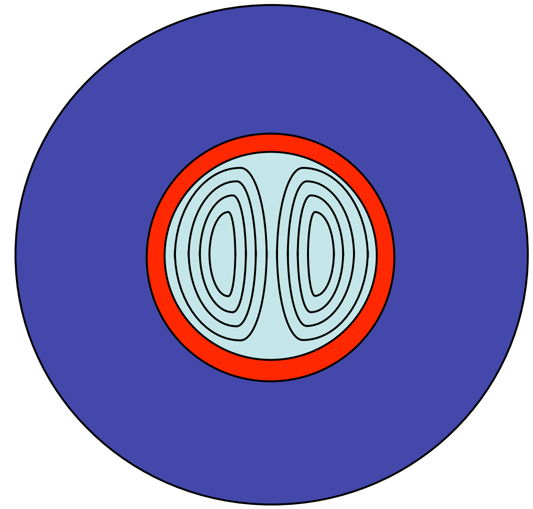
$$\rho \rightarrow \alpha^{-\frac{\alpha-1}{2}} M_i^{\alpha-1} \rho_i$$

$$\alpha = \frac{\langle\Gamma\rangle + 1}{\langle\Gamma\rangle - 1} \qquad \alpha - 1 = \frac{2}{\Gamma - 1}$$

Γ	Pressure limit	Density limit
5/3	$p \rightarrow 1.875 \times 10^{-2} M_i^3 \rho_i u_i^2$	$\rho \rightarrow 0.125 M_i^3 \rho_i$
5/4	$p \rightarrow 1.355 \times 10^{-5} M_i^8 \rho_i u_i^2$	$\rho \rightarrow 1.5 \times 10^{-4} M_i^8 \rho_i$

Confinement and burn: The strategy

- Batch burns
  - Not looking for self-propagating burn, target or in the afterburner
- For this discussion, high gain means G > 30
  - Requires advanced PJMIF schemes
  - Very high density burn the in target and the afterburner
- Intermediate gain means 5 < G < 30
  - Lower density burn
  - Still makes use of the afterburner
  - The target needs to burn to produce sufficient alphas to heat the afterburner layer to fusion temperatures
- Low gain means G < 5
  - No afterburner burn



Present focus:

- Low gain and intermediate gain schemes

A Framework for Analysing the Performance of the Reactor Concept

- The overall performance of the reactor scheme is very sensitive to the choice of the target parameters: radius, density and magnetic field
- Starting with a bad combination of these parameters often leads to a performance envelop that could preclude the attainment of desired performance goals
- The following slides aimed at presenting a framework that would avoid the pitfalls of picking the bad combination of design parameters from the beginning.
- It does so by working backwards from the desired performance and setting up the physics conditions that need to be satisfied in reaching the desired performance goal in a self consistent manner.
- The framework separates out the physics parameters as critical parameters to be attained through further analysis, and thus helps to focus on the physics issues for further research

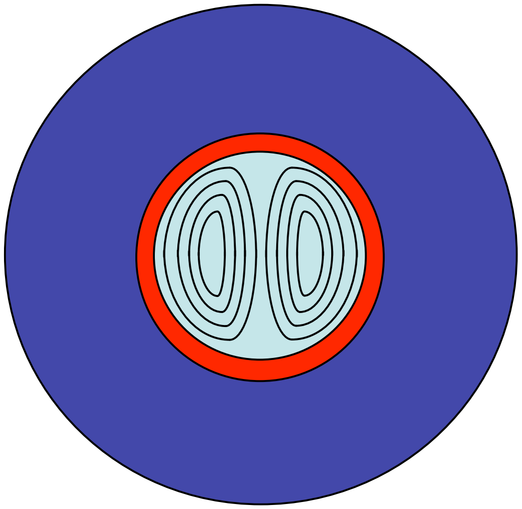
Confinement

After peak compression, the inner surface of the outer liner will begin to retreat

Because the outer liner is much colder and denser, the retreat of the inner surface is governed by the flow in the outer liner

The inner surface is accelerated by the pressure gradient against the high density in the outer liner

Motion takes time to develop



$$\text{Confinement time} = \frac{\text{Relaxation length}}{\text{Characteristic speed}}$$

The characteristic speed = sound speed of the outer liner

Relaxation length?

Confinement

Relaxation length?

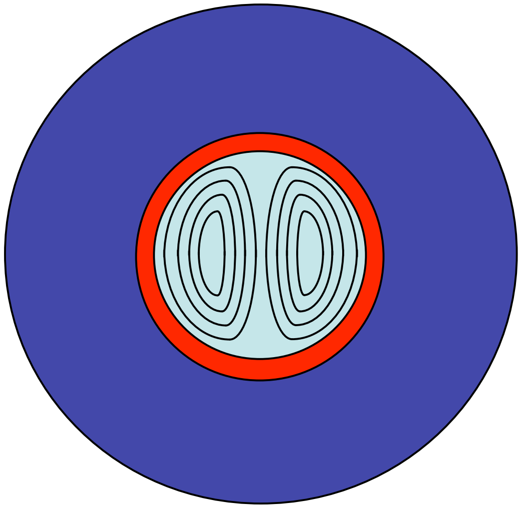
$$r_c = b_2 r_a,\ 1 \le b_2 \le 2,\ r_a \text{ is target radius at peak compression}$$

$$c_L = \frac{u_i}{\sqrt{\alpha}},\ u_i \text{ - initial speed of plasma liner (jet)}, \alpha = \frac{\Gamma + 1}{\Gamma - 1}$$

Confinement time

$$\tau_c = \frac{\sqrt{\alpha}\, r_c}{u_i},$$

$$\Gamma = \frac{5}{3} \to \alpha = 4,\quad \Gamma = \frac{5}{4} \to \alpha = 9$$



Burn considerations: Target

$$\text{Fusion burn fraction}: \ f_b = \frac{\frac{1}{2}\langle \sigma v \rangle n\tau_c}{1+\frac{1}{2}\langle \sigma v \rangle n\tau_c} \approx \frac{1}{2}\langle \sigma v \rangle n\tau_c$$

$$\text{Target fusion yield}: E_{f,T} = \varepsilon_f f_{b,T} N_{DT}$$

N_{DT} = Number of DT pairs

$$E_{f,T} = \frac{\pi}{3}\langle \sigma v \rangle \varepsilon_f \left(\frac{\sqrt{\alpha}}{u_i} \right) b_2 n_a^2 r_a^4, \ n_a - \text{Target density at peak compression}$$

Some of the alpha energy is deposited in the target

For most scenarios considered, $0.1 \le f_{\alpha,T} \le 0.3$ where $f_{\alpha,T}$ is the fractional alpha deposition in the target.

The B field in the target needs to satisfy the ignition requirement, and determines the fractional alpha deposition in the target. (Basko, 2000).

Burn considerations: Afterburner

To obtain burning from the afterburner layer, the layer needs to be heated up to the fusion temperature, kT_b

Assume the burning of afterburner occurs at an average radius of $b_4 r_a$. The thermal energy to bring the afterburner to the fusion condition is:

$$E_{b,th} = 12\pi\left(\frac{kT_b}{m_{DT}}\right)b_4^2 r_a^2 n_b^2 \Delta r_b$$

$n_b, \Delta r_b$ – particle density and thickness of afterburner during burn

$b_4 r_a$ – average inner radius of the afterburner layer during burn

A fraction (b) of this energy needs to be supplied by the alphas produced from the fusion burn of the target

$$bE_{b,th} = \frac{1}{5} f_{\alpha,b}\left(1 - f_{\alpha,T}\right)E_{f,T} \qquad (1)$$

Where $f_{a,b}$ is the alpha deposition fraction in the afterburner. Specifying a ρr for the after burner: $\rho_b \Delta r_b \geq h_\alpha$ (2) determines the magnetic field needed in the afterburner to produce the required degree of alpha deposition:

$$\frac{B}{\rho_b} \geq g_\alpha$$

Burn considerations: Total fusion yield and gain

$$E_{f,b} = \pi b_2 b_4^2 \langle \sigma v \rangle \varepsilon_f \frac{\sqrt{\alpha}}{u_i} b_5 n_b^2 r_a^3 \Delta r_b,$$

The burn time of the afterburner = b_5 *x the confinement time of the target-liner assembly*

$$\text{Total fusion yield, } E_f = E_{f,T} + E_{f,b} \qquad (3)$$

$$\text{Fusion gain, } G = \frac{E_f}{E_{jet}} = \frac{\eta_H E_f}{E_a} = \frac{\eta_H E_f}{\frac{8\pi}{3}\left(\frac{3}{2} + \frac{1}{\beta}\right) n_a k T_b r_a^3} \qquad (4)$$

η_H = hydro efficiency of jet energy into target energy

Equations (1) – (4) provides 4 equations in the 4 unknowns: r_a, n_a, n_b, Δr_b given G, E_f, η_H, together with the physics parameters b, b_2, b_4, b_5, $f_{\alpha,T}$, $f_{\alpha,b}$

For a given fusion gain G and total fusion yield E_f, the equations can be solved for target radius, target density, afterburner thickness and density during burn

$$r_a = \left(\frac{D_2^2}{D_1}\right)^{1/4}, \quad n_a = \frac{D_2}{r_a^3},$$

$$\Delta r_b = \frac{3b_2 b_4^2 b_5 h_\alpha^2 r_a}{\left\{\frac{3m_{DT}^2 E_f u_i}{\pi\langle\sigma v\rangle\varepsilon_f\sqrt{\alpha}\,r_a^2} - b_2 m_{DT}^2 n_a^2 r_a^2\right\}}, \quad n_b = \frac{h_\alpha}{m_{DT}\Delta r_b}$$

where,

$$D_1 = \frac{180\left(\frac{kT_b}{m_{DT}}\right) b b_4^2 h_\alpha}{\langle\sigma v\rangle\varepsilon_f\left(\frac{\sqrt{\alpha}}{u_i}\right) b_2 f_\alpha}, \quad f_\alpha = f_{\alpha,b}\left(1 - f_{\alpha,T}\right) \qquad D_2 = \frac{\eta_H E_f}{\frac{8\pi}{3}\left(\frac{3}{2}+\frac{1}{\beta}\right) kT_b\, G}$$

An Example: G=20 (plasma gun eff = 50%), Yield = 2 GJ

- Assumptions: (1) relaxation length = 1 x target radius; (2) fusion burn temperature = 10 keV; (3) Jets-to-target hydro efficiency, η_H = 20% (Pecheck, Colgate, and Kirkpatrick have estimated efficiencies in the range of 20% to 25% in similar situations)
- Results from solving the system equations (1-4) follow:
- Jets: Zn, 1 eV, 27 km/s, Mach number = 20
- With initial jet density > 10^{24} m^{-3}. maximum stagnation pressure > 143 Mbar
- Target at peak compression:
  - radius 5.93 mm, density 4.47 x 10^{27} m^{-3}
  - Target confinement time = 66 ns
  - Burn fraction = 0.17, pressure 143 Mbar
  - Target fusion yield: 914 MJ
  - Target alphas: 182 MJ
  - Prescribe a B field of 2.17 MG (217 T) in the target to be above the ignition threshold (Basko or Kirkpatrick)
  - Results in alpha deposition of 0.3 in the target
  - 128 MJ of alphas escapes, available to heat the afterburner
  - Plasma energy: 20 MJ
  - Total jet energy required = 100 MJ
- Number of plasma guns required for assembling the outer liner: 300 - 500

An Example: G=20, Yield = 2 GJ

- Afterburner during burn
  - Thickness 9.68 mm, density 2.5 x10^{27} m^{-3}
  - Burn time: 33 ns
  - Burn fraction: 0.046
  - Thermal energy: 80 MJ
    - 80% is assumed to be provided by the alpha heating
      - Need to verify this with the hydro consideration
    - 64 MJ needs to be provided by alpha heating, out of 128 MJ of alpha energy escaped from the target
    - Alpha fractional deposition required = 0.5
      - Minimum B field in afterburner required = 2.7 MG (270 T)
  - Fusion yield from afterburner: 1.1 GJ
  - Burn amplification of 4.7
- Total yield = (0.9 + 1.1) GJ = 2 GJ
- Gain = Yield/jet energy = (2 GJ/100 MJ) = 20

Magnetized compressional heating of the target

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

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

$$\dot{Q}_c = 4\pi r_b^2 g \kappa \left(\frac{T_t - T_b}{r_b}\right), \ \kappa = \kappa_{\perp e} + \kappa_{\perp i}, \ \kappa_{\perp e} = \frac{n_e k(kT_e)\tau_{ee}}{m_e} \frac{4.66\omega_{ce}^2\tau_{ee}^2 + 11.92}{\omega_{ce}^4\tau_{ee}^4 + 14.79\omega_{ce}^2\tau_{ee}^2 + 3.77},$$

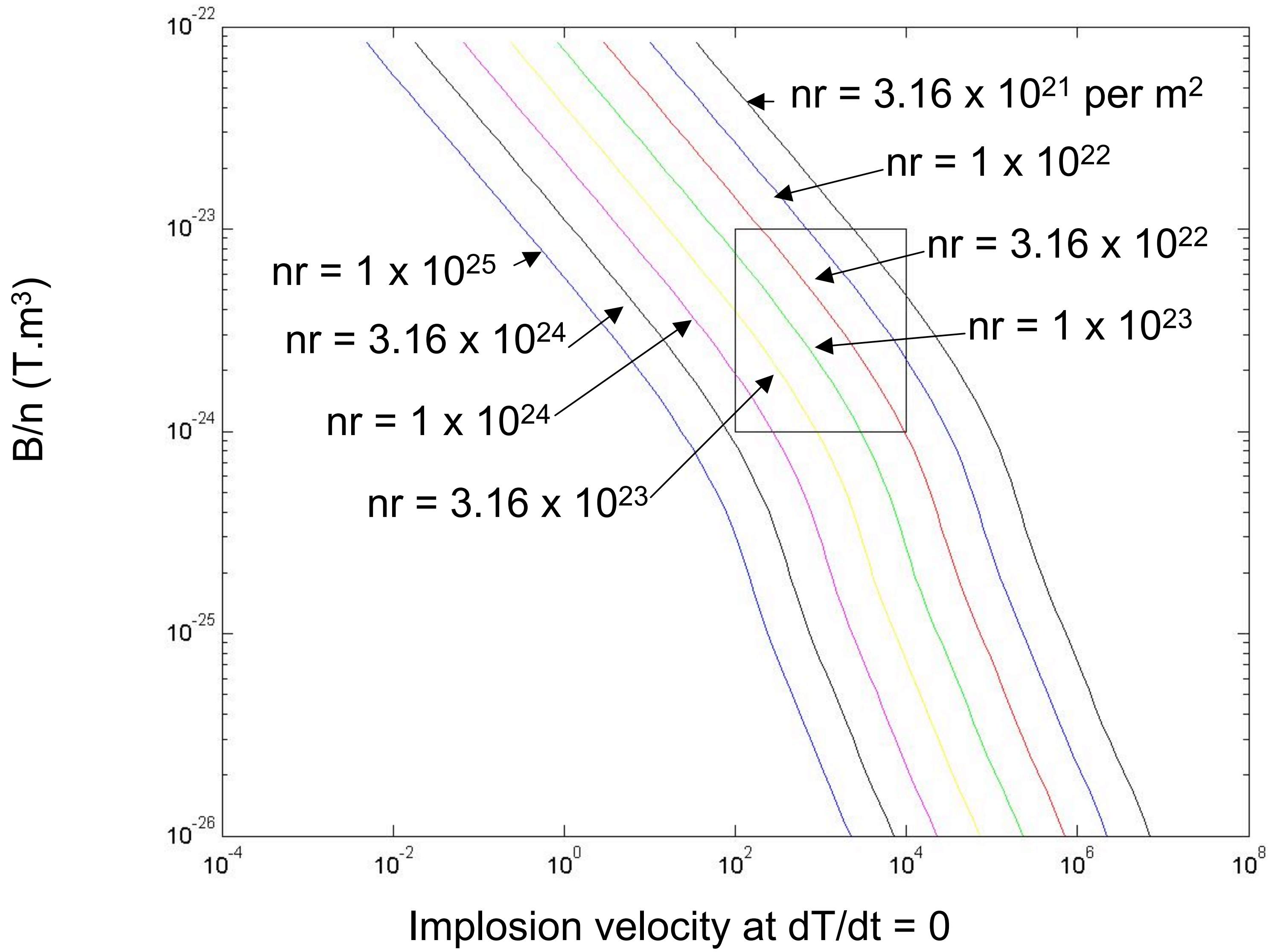
$$\kappa_{\perp i} = \frac{n_i k(kT_i)\tau_{ii}}{m_i} \frac{2\omega_{ci}^2\tau_{ii}^2 + 2.64}{\omega_{ci}^4\tau_{ii}^4 + 2.7\omega_{ci}^2\tau_{ii}^2 + 0.68}, \quad \tau = \frac{25\pi m^{1/2}\varepsilon_0^2 (kT)^{3/2}}{\sqrt{3}Z^4 n e^4 \ln\Lambda}, \quad \omega_c = \frac{eB}{m}$$

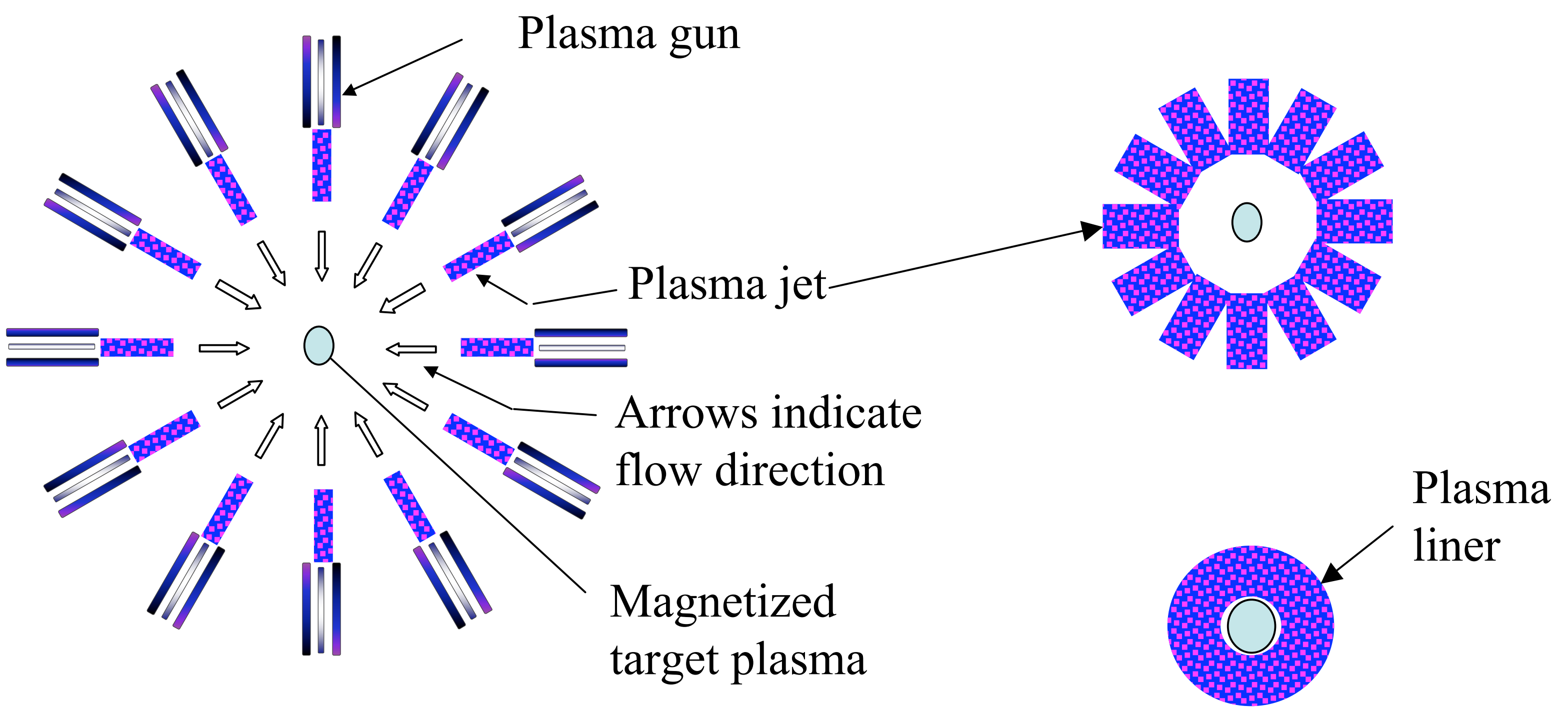
$$\dot{Q}_{rad} = \dot{Q}_{bremsstrahlung} + \dot{Q}_{synchrotron},$$

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

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

Minimum Imploding velocity to overcome all the thermal losses: For adiabatic heating, the imploding velocity needs to be several times larger




Plasma gun
Plasma jet
Arrows indicate
flow direction
Magnetized
target plasma
Plasma
liner