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Nuclear Fusion

A nuclear reaction in which light nuclei fuse together and form a heavier one.

Fusion Reactions

\[ _1^1D^2 + _1^1D^2 \rightarrow _1^3T^3 (1.01 \text{MeV}) + _1^1H^1 (3.02 \text{MeV}) \]

\[ _1^1D^2 + _1^2He^3 \rightarrow _2^4He^4 (3.6 \text{MeV}) + _1^1H^1 (14.7 \text{MeV}) \]
Lawson Criterion

The relation which relates the density and energy confinement time for the fusion fuel plasma at a given temperature is known as Lawson criterion

\[ E_{fusion} \geq E_{th} \]

\[ n\tau > 10^{14} \text{ sec/cm}^3 \quad \text{for 10 keV D-T reaction} \]

\[ n\tau > 10^{16} \text{ sec/cm}^3 \quad \text{for 100 keV D-D reaction} \]
Z-pinch

A plasma column in which current $J_z$ is driven in the axial ($z$) direction by an electric power source producing an azimuthal ($\theta$) magnetic field $B_\theta$ which confines the plasma by a $(J_z \times B_\theta)$ force.
θ-pincher

In a θ-pincher device the current flows in the azimuthal direction of cylindrical plasma column. The interaction of the current and axial magnetic field is through \((\mathbf{J} \times \mathbf{B})\) force.
Instabilities in Pinch Devices

Unfortunately, Pinch devices suffer with number of instabilities such as: sausage, kink and Rayleigh-Taylor instabilities.

Sausage Instability:
The sausage instability arises due to a wave like perturbation in the equilibrium state of a plasma column. The perturbation is symmetric about the axis, crests and troughs appears on the surface. The column appears constricted at some locations and expanded at others. The strength of the magnetic field varies as $B_\theta \sim \frac{1}{r}$, therefore, its magnitude is different at different locations.

![Diagram of sausage instability](image)
Kink Instability

The kink instability arises due to the formation of bend or kink in the plasma column, though it maintains its uniform circular cross-section. The density of the magnetic field lines increases on the concave side and decreases on the convex side.
Effect of axial **Magnetic field** to suppress the sausage and kink instabilities
Rayleigh-Taylor Instability

Rayleigh-Taylor instability occurs when a heavy fluid is supported by a light fluid in the presence of gravitational field. In pinch devices plasma being heavy fluid is compress by mass-less magnetic field. The instability occurs only if the plasma is accelerating or decelerating.

The growth rate of R-T instability is given by

$$\gamma = \sqrt{kg_{\text{eff}}}$$

where $k$ is the wave number of the perturbation and $g_{\text{eff}}$ is the acceleration of the plasma.
Possible Ways to Mitigate R-T in Z-Pinches

R-T instability can be reduced with different stabilization techniques like.

• Spin of the outer shell,

• Thick shells

• *Multi-cascade liner systems*

alongwith the inclusion of axial magnetic field $B_z$. 
Other Pinch Devices

• Cylindrical Liners
• Gas Puff Configurations
• Wire Array Loads,

Major Applications of Z-Pinches

• Controlled Thermonuclear Fusion
• Generation of High Magnetic Fields
• Sources of high energy, high intensity charged particles
• Studies of Material Properties
• X-Ray Lasers etc.
Numerical Model for Z-pinch dynamics

• **Snow plow model**

In this model one assumes that

1. Plasma is a good conductor; initially the discharge current form a **thin current sheath** on the outer surface of the plasma column.

2. Plasma ahead of the current sheath is in initial state.

3. The current sheath **sweeps all the mass on its way** as it moves.
The equation of motion is

\[ \frac{d}{dt} \begin{bmatrix} M \\ \frac{dr}{dt} \end{bmatrix} = -2\pi r \left( P_{mag} \right) \]

\[ \frac{d}{dt} \left[ \rho_0 \pi \left( r_0^2 - r^2 \right) \frac{dr}{dt} \right] = -2\pi r \left( \frac{B_\theta^2}{8\pi} \right) \]

for

\[ B_\theta = \frac{I_z(A)}{5r \text{ (cm)}} \]

and the discharge current

\[ I_z = I_0 \omega t \]

The normalized equation of motion for the current sheath is given by

\[ \frac{d^2 R}{d\tau^2} = \frac{2R}{(1 - R^2)} \left( \frac{dR}{d\tau} \right)^2 - \frac{\tau^2}{R(1 - R^2)} \]

with

\[ \tau = t \left( \frac{I_0^2 \omega^2}{100\pi \rho_0 r_0^4} \right)^{\frac{1}{4}} \]

\[ R = \frac{r}{r_0} \]
If we also include the effect of kinetic pressure, then the above equation will become

\[
\frac{d}{dt} \left[ \rho_0 \pi \left( r_0^2 - r^2 \right) \frac{dr}{dt} \right] = -2\pi r \left( P_{mag} - P_{kin} \right)
\]

\[
\frac{d^2 R}{d\tau^2} = \frac{2R}{1 - R^2} \left( \frac{dR}{d\tau} \right)^2 - \frac{\tau^2}{R (1 - R^2)} + \frac{\beta R^{\frac{7}{3}}}{(1 - R^2)}
\]

with

\[
\beta = \frac{P_{kin}}{P_{mag}} \quad R'[0] = 0, \quad R[0] = 1
\]
Staged Pinch (Z- \( \theta \) pinch) (UCI-Experiment)

The configuration embodies a conventional Z-pinch, imploding onto a co-axial cryogenic fiber (\( \theta \)-pinch) plasma. This configuration is also called as Z- \( \theta \) pinch.

Addresses the problems of effective compression and large current rising rate.

The inductive heating induces \( \theta \)-pinch discharge on the fiber surface with rise time of few nanosecond and the combined configuration of Z- \( \theta \) pinch is found stable.
Strong magnetic field generation by imploding gas-puff plasma

\[ B_z = B_0 \left( \frac{r_0^2}{r^2} \right) \]
Thin Shell Model for the Z-Pinch (Rahman et al., 1989)

With cylindrical symmetry, the radial component of the equation of motion for the imploding thin plasma shell is

\[ M_0 \left( \frac{d^2 r}{dt^2} \right) = -2\pi r P_{mag} \]

Where:

- \( M_0 = 2\pi r \rho \Delta r \) (mass per unit length of the plasma, \( \Delta r \ll r \) is shell thickness)
- \( P_{mag} = \frac{B_{\theta}^2}{8\pi} - \frac{1}{8\pi} \left( B_z^2 - B_0^2 \right) \) (Total magnetic pressure)
- \( B_z = B_0 \left( \frac{r_0^2}{r^2} \right) \) (Magnetic flux conservation)
- \( B_{\theta} = \left( \frac{I(A)}{5r(cm)} \right) \) \( I = I_0 \sin \left( \frac{2t}{\pi t_0} \right) \) (Sinusoidal Current profile)
Equation of motion in dimensionless form

\[ \frac{d^2 R}{dt^2} = - \frac{1}{R} \left( \frac{I_0^2}{100 \ M_0 r_0^2} \right) \sin^2 \left( \frac{\pi t}{2 t_0} \right) - R \left( \frac{B_0^2}{4 \ M_0} \right) \left( 1 - \frac{1}{R^4} \right) \]
\textbf{\(\theta\)-pinch (Fiber Plasma Dynamics)}

Continuity equation

\[
\frac{\partial n}{\partial t} + \nabla \cdot (nV) = 0
\]

Mass conservation equation

\[
m n \left( \frac{\partial}{\partial t} + V \cdot \nabla \right) V = -\nabla \left( P_{\text{mag}} + P_{\text{kin}} \right)
\]

\[
P_{\text{kin}} = (1 + Z)nT
\]

\[
P_{\text{mag}} = \frac{B_0^2}{8\pi} \left[ \frac{1}{R^4} + \left\{ 1 - \left( \frac{a_0}{a} \right)^4 \right\} \right]
\]

\(Z\) being the charge state of the plasma ions. \(n\) is number density.

The energy equation under the adiabatic condition

\[
\frac{d(Pn^{-\gamma})}{dt} = (\gamma - 1)n^{-\gamma} \left[ P_{\Omega} + P_{\alpha} - P_{\text{brem}} - P_{\text{cycl}} \right]
\]
These equations in normalized parameters can be written as

\[
\frac{d^2 \hat{a}}{dt^2} = -\frac{200 B_0^2}{n_0 a_0^2} \left[ \frac{\hat{a}}{R^4} - 800 \left( \frac{n_0 T_0}{B_0^2} \right) \frac{\hat{T}}{\hat{a}} + \hat{a} \left( 1 - \frac{1}{\hat{a}^4} \right) \right]
\]

\[
\frac{d\hat{T}}{dt} = -2(\gamma - 1) \frac{\hat{T}}{\hat{a}} \frac{d\hat{a}}{dt} + (\gamma - 1) \frac{10^{22} \hat{a}^2}{2n_0 T_0} \left[ P_\Omega + P_\alpha - P_{\text{brem}} - P_{\text{cycl}} \right]
\]

\[
\hat{a} = \frac{a}{a_0}, \quad \hat{T} = \frac{T}{T_0}
\]

\[
P_\Omega = 1.29 \times 10^{21} \left( \frac{B_0^2 (MG)}{T_0^{3/2} (keV) a_0^2 (\mu m)} \right) \left( \frac{1}{\hat{a}^2 \hat{T}^{3/2} R^4} \right)
\]

\[
P_\alpha = 3.22 \times 10^{26} n_0^2 \left( \frac{1}{\hat{a}^2} - 2 \hat{n}_\alpha \right)^2 \frac{1}{[\hat{T} T_0 (keV)]^{3/2}} \exp \left[ -\frac{19.94}{(\hat{T} T_0)^{1/3}} \right]
\]
\[ P_{\text{brem}} = 3.32 \times 10^{20} n_0^2 \frac{\hat{T}\hat{T}_0(keV)}{\hat{a}^4} \text{ keV/cm}^3\text{-nsec} \]

\[ P_{\text{cycl}} = 3.88 \times 10^{16} \frac{n_0 B_0^2 (MG)\hat{T}\hat{T}_0(keV)}{\hat{a}^2 R^4} \text{ keV/cm}^3\text{-nsec} \]

Although Rahman et al., Model successfully explains to achieve controlled fusion with the help of Z-θ pinch. But unfortunately the thin shells are found unstable against the R-T instability.
Rotation or Spinning of thin shell

The stabilization effect comes from the centrifugal force that is directed opposite to the effective gravity force near the stagnation point. In the early works, it was supposed that rotation would be introduced by mechanical means. The concept of centrifugal stabilization was recently reconsidered by Rostoker et al., (1995), who suggested spinning of thin shell in Z-pincho. To overcome R-T instability he calculated following value of spin velocity.

\[ \Omega_0 = 3.8 \times 10^{-3} \, n \, \text{sec}^{-1} \]
Spinning thin shell Model for the Z-Pinch Dynamics
(Rostoker et al. (1995))

With cylindrical symmetry, the radial component of the equation of motion for the imploding thin plasma shell is

$$M_0 \left( \frac{d^2 r}{dt^2} - r \dot{\theta}^2 \right) = -2 \pi r P_{mag}$$

$$M_0 = 2 \pi r \rho \Delta r$$ (mass per unit length of the plasma and $\Delta r << r$ is shell thickness)

$$P_{mag} = \frac{B_\theta^2}{8\pi} - \frac{1}{8\pi} \left( B_z^2 - B_0^2 \right)$$ (Total magnetic pressure)

$$B_z = B_0 \left( \frac{r_0^2}{r^2} \right)$$ (Magnetic flux conservation)

$$B_\theta = \left( \frac{I(A)}{5r(cm)} \right)$$

$$I = I_0 \sin \left( \frac{2t}{\pi t_0} \right)$$ (Current profile)
Equation of motion in dimensionless form

\[ \frac{d^2 R}{dt^2} = \frac{\Omega_0}{R^3} - \frac{1}{R} \left( \frac{I_0^2}{100 M_0 r_0^2} \right) \sin^2 \left( \frac{\pi t}{2 t_0} \right) - R \left( \frac{B_0^2}{4 M_0} \right) \left( 1 - \frac{1}{R^4} \right) \]
Radiative collapse in an impurity-seeded spinning gas-puff staged pinch


\[ \frac{d^2 R}{dt^2} = \frac{\Omega_0}{R^3} - \frac{1}{R} \left( \frac{I_0^2}{100 M_0 r_0^2} \right) \sin^2 \left( \frac{\pi t}{2 t_0} \right) - R \left( \frac{B_0^2}{4 M_0} \right) \left( 1 - \frac{1}{R^4} \right) \]

Solutions of the above nonlinear differential equation are plotted by considering the initial conditions; \( I_0 = 10 \, \text{MA} \), \( M_0 = 38 \, \mu \text{g/cm} \), \( B_0 = 0.02 \, \text{MG} \), \( r_0 = 4 \, \text{cm} \) and \( t_0 = 50 \, \text{nsec} \).
Impurity Seeded θ-pincho (Fiber Plasma Dynamics)

Equations in normalized parameters can be written as

\[
\frac{d^2 \hat{\alpha}}{dt^2} = f^2 \frac{\Omega_0^2}{R^4 \hat{\alpha}^3} - \frac{200 B_0^2}{n_0 a_0^2} \left[ \frac{\hat{\alpha}}{R^4} - 800 \left( \frac{n_0 T_0}{B_0^2} \right) \frac{\hat{T}}{\hat{\alpha}} + \hat{\alpha} \left( 1 - \frac{1}{\hat{\alpha}^4} \right) \right]
\]

\[
\frac{d\hat{T}}{dt} = -2(\gamma - 1) \frac{\hat{T}}{\hat{\alpha}} \frac{d\hat{\alpha}}{dt} + (\gamma - 1) \frac{10^{22} \hat{\alpha}^2}{2n_0 T_0} \left[ P_\Omega + P_\alpha - P_{\text{brem}} - P_{\text{cycl}} - P_{\text{imp}} \right]
\]

For 100 Megagauss magnetic field the gyro-radius for 3.5 MeV alpha particle in the present case is about 20 μm.

\[
P_\alpha = 3.22 \times 10^{26} n_0^2 \left( \frac{1}{\hat{\alpha}^2} - 2\hat{n}_\alpha \right)^2 \frac{1}{[\hat{T}T_0(\text{keV})]^\frac{3}{2}} \exp \left[ -\frac{19.94}{(\hat{T}T_0)^{\frac{1}{3}}} \right] \text{ keV/cm}^3\cdot\text{nsec}
\]
To determine $n_\alpha$, we use the rate equation

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha V) = \frac{1}{4} n^2 \langle \sigma V \rangle_{D-T}$$

In normalized parameters

$$\frac{d\hat{n}_\alpha}{dt} = 9.2 \frac{n_0}{\hat{\alpha}^4} \left[ \hat{T}_0 (keV) \right]^{2/3} \exp \left[ -\frac{19.94}{(\hat{T}_0)^{1/3}} \right] - 2\hat{n}_\alpha \frac{d\hat{\alpha}}{dt}$$

$$P_{brem} = 3.32 \times 10^{20} n_0^2 \frac{\left[ \hat{T}_0 (keV) \right]^{1/2}}{\hat{\alpha}^4} \text{ keV/cm}^3\text{-nsec}$$

$$P_{cycl} = 3.88 \times 10^{16} \frac{n_0 B_0^2 (MG) \hat{T}_0 (keV)}{\hat{\alpha}^2 R^4} \text{ keV/cm}^3\text{-nsec}$$
\[ P_{imp} = \tilde{P}_{brem} + \tilde{P}_{rec} + \tilde{P}_{line} \]

\[
P_{imp} = 3.32 \times 10^{20} Z^2 \frac{f^2 n_0^2}{\hat{a}^4} \left[ 1 + \frac{0.033 Z_{eff}^2}{\hat{T}T_0 \text{(keV)}} \right] + 7.9 \times 10^{21} Z^2 \frac{f n_0}{\hat{a}^2} \left[ \hat{T}T_0 \text{(keV)} \right]^\frac{5}{2} \]

Z is the charge state of the impurity ions. \( f \) being the fraction of impurity (0.01 of the D-T fuel density) and \( Z_{eff} \) is the effective charge of the impurity (Kr) ion. The calculation of \( Z_{eff} \) is a complicated factor depending on the temperature and ionization rate equation. For simplicity we have used \( Z_{eff} \) for Kr without going into the detailed calculation of line width and opacity.

By solving equations with initial values of \( I_0=10 \text{ MA}, r_0=4 \text{ cm}, t_0=50 \text{ nsec}, M_0=38 \mu\text{g/cm}, T_0=20 \text{ eV}, B_0=20 \text{ kG}, a_0=0.02 \text{ cm} \) and \( n_0=10^{22} \text{ cm}^{-3} \) for two cases namely with and without impurity.
Without impurity losses
<table>
<thead>
<tr>
<th>$\Omega_0$</th>
<th>$\tau_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0$</td>
<td>$0.0 \times 10^{-3}$ nsec$^{-1}$</td>
</tr>
<tr>
<td>$0.8 \times 10^{-3}$</td>
<td>$3.2 \times 10^{-3}$ nsec$^{-1}$</td>
</tr>
<tr>
<td>$4.0 \times 10^{-3}$</td>
<td>$4.0 \times 10^{-3}$ nsec$^{-1}$</td>
</tr>
</tbody>
</table>

With Kr-impurity
**Conclusion:**

Although large spin velocities are needed to suppress the R-T instability growth rate, but the fusion parameters can not be easily achieved even with impurity seeding.

**Problems**

In number of experiments it has been observed that thin gas-puff implosions are extremely unstable and specially Rayleigh-Taylor instability is unavoidable.
The radial component of equation of motion, in normalized units, under the snow-plow model

\[
\frac{d^2 R}{dt^2} = \frac{\Omega_0^2 (1 - R^2)}{R^3} - \left[ \frac{I_0^2}{100 M_0 r_0^2 R} \sin^2 \left( \frac{\pi t}{2t_0} \right) + \left( \frac{B_0^2}{4M_0} \right) \left( \frac{R^4 - 1}{R^3} \right) - 2R \left( \frac{dR}{dt} \right)^2 \right] \frac{1}{(1 - R^2)}
\]

At the inner boundary the snow-plow effect ceases and the current sheath moves like a thin annular shell.

\[
\frac{d^2 R}{dt^2} - \frac{\Omega_0^2}{R^3} = -\frac{I_0^2}{100 M_0 r_0^2} \frac{1}{R} \sin^2 \left( \frac{\pi t}{2t_0} \right) - R \left( \frac{B_0^2}{4M_0} \right) \left( 1 - \frac{1}{R^4} \right)
\]
For puff thickness $L_p=0.01$

$\Omega_0=0$

$\Omega_0=1.0 \times 10^{-3} \text{ nsec}^{-1}$

$\Omega_0=4.0 \times 10^{-3} \text{ nsec}^{-1}$
Conclusion:

Although large spin velocities are needed to suppress the R-T instability growth rate, but the fusion parameters can not be easily achieved even thick-puff.
Multi cascade liner system
Multi-cascade liner system


The dynamical equation, in dimensionless parameters under the snow-plow approximation for the first cascade

\[ \frac{d^2 R}{dt^2} = - \left[ \frac{A}{M_{01} r_{01}^2} f^2(\tau) + \left( \frac{B_0^2}{4M_{01}} \right) \left( \frac{R^4 - 1}{R^3} \right) - 2R \left( \frac{dR}{dt} \right)^2 \right] \frac{1}{(1 - R^2)}, \]

\[ A = \frac{i_0^2}{100R}, \quad R(= r/r_{01}) \quad M_{01}(= \pi r_{01}^2 \rho_{m1}) \]

The equation of motion for the current sheath in the region of second cascade under the snow-plow assumption will become

\[ \frac{d^2 R}{dt^2} = - \left[ \frac{A}{M_{02} r_{01}^2} f^2(\tau) + \left( \frac{B_0^2}{4M_{02}} \right) \left( \frac{R^4 - 1}{R^3} \right) - 2BR \left( \frac{dR}{dt} \right)^2 \right] \frac{1}{(1 - BR^2)}, \]

\[ B = (\rho_{m2}/\rho_{m1})[1 - (r_{02}/r_{01})^2 + (r_{02}/r_{01})^2 \rho_{m2}/\rho_{m1}]^{-1} \]

\[ M_{02} = \left[ \pi \rho_{m1}(r_{01}^2 - r_{02}^2) + \pi \rho_{m2}r_{02}^2 \right] \]
At the inner boundary of the second cascade, the snow-plow effect ceases and the current sheath moves like a thin annular shell given by

\[
\frac{d^2 R}{dt^2} = -\frac{A}{M_{03}r_{01}^2} f^2(\tau) - \left( \frac{B_0^2}{4M_{03}} \right) \left( \frac{R^4 - 1}{R^3} \right)
\]

\[
M_{03} = \pi \rho_{m1}(r_{01}^2 - r_{02}^2) + \pi \rho_{m2}(r_{02}^2 - r_{03}^2)
\]
For different puff thickness and for mass ratios ($M_{02}/M_{01}=1-10$).
For the mass ratio $M_{02}/M_{01}=1$ and for the second puff thickness $= 0.07$ cm.
Conclusion:

We may conclude that the multi-cascade system is good for achieving thermonuclear fusion conditions. For the optimum choice of puff-thickness and mass ratio, one may achieve a pinch plasma close to thermonuclear fusion conditions.
MHD Model for the Z-Pinch Plasma

(Zahoor Ahmad, N.A.D. Khattak, G. Murtaza and A. M. Mirza, to be submitted)

Continuity equation
\[
\frac{\partial n}{\partial t} + \nabla \cdot (nV) = 0
\]

Momentum equation
\[
\rho \left( \frac{\partial}{\partial t} + \nabla \cdot V \right) V = -\nabla p + J \times B
\]

Energy or temperature equation
\[
\frac{3}{2} \left( \frac{\partial p}{\partial t} + \nabla \cdot (PV) \right) = -p
\nabla \cdot V + \eta J^2 - P_{\text{loss}}
\]

\( n \) is the ion density, \( V \) velocity, \( p=(1+Z)nT \) is the pressure (\( T \) is the plasma temperature in energy units) and \( \rho \) is the mass density.

\( P_{\text{loss}} = P_{\text{endloss}} + P_{\text{brem}}. \)

\( \eta \) is the plasma resistivity and \( B \) is the magnetic field.
End losses to the electrodes is estimated as

\[ P_{\text{endloss}} = -\frac{5T}{2\epsilon l} J_z \]

\[
\frac{d}{dt} \left[ B_z(t) r_{\text{out}}^2 R^2(t) \right] = \frac{c^* \eta}{2\pi} \left[ B_0 - B_z(t) \right]
\]

The zero dimensional MHD equations in normalized form are

\[
\frac{d^2 R}{dt^2} = (1 + Z) \frac{2\pi n_0}{M} \frac{T(t)}{R(t)} - \frac{I_0^2 \sin^2 \left( \frac{\pi t}{2t_0} \right)}{50 M r_{\text{out}}^2 R(t)} \frac{1 - \beta^2 + 2\beta^2 \ln \beta}{(1 - \beta^2)^2} \]

\[-\frac{R(t)}{4M} \left[ B_0^2 - B_z^2(t) \right] \]

\[
\beta = \frac{r_{\text{in}}}{r_{\text{out}}} \]

\[
\frac{dT}{dt} = -\frac{4T(t) dR}{3R(t) dt} - \frac{2\pi r_{\text{out}}^2 R^2(t)}{3 N_0 (1 + Z)} P_{\text{loss}} + \frac{2\pi r_{\text{out}}^2 R^2(t)(1 - \beta^2)}{3 N_0 (1 + Z) \eta \theta} \]

\[+ \frac{2\eta I_0^2 \sin^2 \left( \frac{\pi t}{2t_0} \right)}{3\pi r_{\text{out}}^2 R^2(t) N_0 (1 + Z) (1 - \beta^2)} \]
Normalized radius of gas puff for Snow Plow Model (red line) and MHD model (Black line) vs time.

\[ I_0 = 10 \text{ MA}, \ r_0 = 4 \text{ cm}, \ t_0 = 50 \text{ nsec}, \ M_0 = 38 \mu\text{g/cm}, \ T_0 = 20 \text{ eV}, \ B_0 = 20 \text{ kG}, \ a_0 = 0.02 \text{ cm} \text{ and } n_0 = 10^{22} \text{ cm}^{-3} \]
Axial Magnetic field for Snow Plow Model (red line) and MHD model (Black line) vs time.
Plot of normalized fiber radius, density and temperature against time for Snow Plow Model.

Plot of normalized fiber radius, density and temperature against time for MHD model.
Conclusion and Summery of the Results

1. Although large spin velocities are needed to suppress the R-T instability growth rate, but the fusion parameters can not be easily achieved even with impurity seeding.

2. Fusion parameters can not be easily achieved with spinning the thick-puff.

3. Multi-cascade system is good for achieving thermonuclear fusion conditions. For the optimum choice of puff-thickness and mass ratio, one may achieve a pinch plasma close to thermonuclear fusion conditions.

4. The MHD model is more consistant. The value of number density in MHD model is approximately 1000 times the initial density and is achieved in the nsec time scale which fulfills $n \tau$ criterion. We can achieve temperature $\sim 80$ keV which is sufficient for the fusion reaction to take place.
List of Publications and Conference Proceedings

1. Plasma Dynamics in a Staged Pinch Device
   7th National Symposium on Frontiers in Physics QAU (Nov 1998) Islamabad, Pakistan
   N. A. D. Khattak, Arshad M. Mirza, Zahoor Ahmad and G. Murtaza

2. Radiative collapse in an impurity-seeded spinning gas-puff staged pinch
   Arshad M. Mirrza, Zahoor Ahmad, N. A. D. Khattak and G. Murtaza

3. Study of Plasma Parameters in a Spinning Thick-Gas-Puff Staged Pinch
   N.A.D. Khattak, Zahoor Ahmad, Arshad M. Mirza and G. Murtaza

4. Staged pinch dynamics driven by multicascade liner system
   Zahoor Ahmad, N.A.D. Khattak, Arshad M. Mirza, and G. Murtaza

5. Implosion Dynamics of a Dense θ-Pinch Plasma Driven by Multi-cascade liner System
   Laser and Particle beams 19, 657 (2002)
   Zahoor Ahmad, Arshad M. Mirza, N.A.D. Khattak, and G. Murtaza
6. Magnetohydrodynamic (MHD) Model for the Staged Pinch Plasma to Study Fusion Parameters
   Zahoor Ahmad, N. A. D. Khattak, Arshad M. Mirza, W.J. Goedheer and G. Murtaza

7. Study of Fusion Parameters in a Multicascade Liner System.
   27th International Nathiagali Summer college on physics and contemporary Needs (June 24-July 6, 2002), Pakistan.
   Arshad M. Mirza, Zahoor Ahmad, NAD khattak and G. Murtaza

8. Thermonuclear Fusion with Multicascade Liner Staged Pinch Plasmas
   International conference on Models and Methods in Fluid Mechanics (23-26 June 2003), COMSTATS Institute of information Tech. Abbottabad, Pakistan
   Arshad M. Mirza, Zahoor Ahmad, NAD khattak and G. Murtaza

9. Magnetohydrodynamic (MHD) Model for the Staged Pinch Plasma to Study Fusion Parameters and comparison with Snow Plow model
   Zahoor Ahmad, N.A.D. Khattak, G. Murtaza, and Arshad M. Mirza (to be submitted)
Thank you very much for your attention