



# A Space Physics Inspired Approach to Magnet Confinement Fusion: Converging Plasma Pistons

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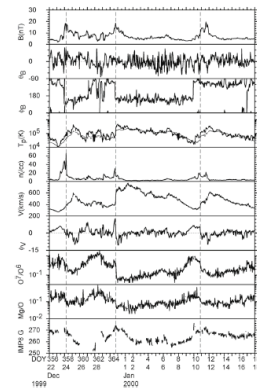


## Abstract

A novel approach to Magnetic Confinement Fusion (MCF), first published in US Patent #11,744,002. "System of Converging Plasma Pistons" (also patent pending U.S. 2024/0015876 A1) is presented. The concept is a linear machine suitable for high- $\beta$  D-T pulsed nuclear fusion reactors wherein plasma "pistons" form part of the confinement system at either end of the fusing plasma, resulting in a unique magnetic configuration. In the process of formation, the pistons compress and heat a "target plasma" that becomes the fusion core. The physics is partially inspired by observation of plasma phenomena in the Heliosphere such as corotating interaction regions (CIRs). The plausibility of a reactor is explored in a "back-of-the-envelope" study based, where possible, on relevant experimental results and, where necessary, extrapolation of those results. Insights developed subsequent to the patent disclosure are described, particularly the interface between pistons and the fusion core. The goal is to determine what further study is justified and point towards modeling and experimentation needed to bring the concept to fruition, or to determine if it is a dead end so far as a practical energy producing fusion reactor is concerned, as with so many concepts before it. While the physics is decidedly high risk/high reward, the underlying technologies are relatively well developed, reducing technical risk.

## Corotating Interaction Regions (CIRs) in the Heliosphere

Fig. 18 Observations of three high-speed streams with interaction regions at their leading edges made near the Earth during a 27-day period in December 1999-January 2000. The vertical dashed lines indicate the stream interfaces. Solar wind plasma and magnetic field data are from the ACE spacecraft, while the bottom panel shows the modulations in the galactic cosmic-ray intensity indicated by the counting rate of the anti-coincidence guard (G) of the IMP 8 GME instrument. Image reproduced with permission from Richardson (2006), copyright by AGU



Richardson, Ian G., *Living Reviews in Solar Physics*, 15, 1614-4961 (2018)

Fast plasma overtakes slow plasma in Heliosphere

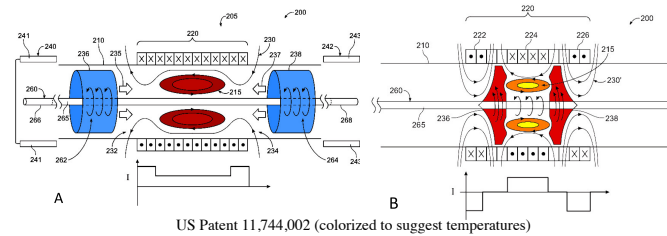
- Plasma compressed by ram pressure
- Density increases
- Temperature increases
- Magnetic field increases

Different plasma components remain largely distinct over long time scales.

Appealing for magnetic confinement fusion IF it can be applied to a reactor.

CIRs eventual merge, so such a reactor would be a pulsed rather than a steady-state reactor and use D-T fusion.

## An Embodiment of Converging Plasma Pistons



(A) a "target plasma" is formed, here taken as a Field Reversed Configuration (FRC), and held in a mirror field (230) produced by external coils (220). The direction of current is indicated using the "x and dot" convention with a notional illustrative plot of current (I) in the coils as a function of axial position. Coaxial railguns (240, 242) project plasmoid "pistons" (236, 238) at the target plasma. These pistons' azimuthal (toroidal) magnetic fields (262, 264) are a product of the guns' operation. Central structure (260) is optional.

The plasma pistons are analogous to CIRs. As they enter the central chamber, the current in the external coils (220) is adjusted so the pistons (236, 238) can contact the target plasma (215). The pistons are also compressed in the process, initially by ram-pressure, increasing the toroidal magnetic field and pressure.

(B) the plasma pistons have stalled against the target plasma. On the outer side of the pistons, the field is increased as they stall, but the current in the end coils (222, 226) is reversed compared to the central coils (224) (as shown in the notional current plots and the x's and dots). The pistons are thus in a cusp magnetic field (230) modified on the inner side by the presence the target plasma. This cusp configuration pins the pistons in place while fusion proceeds in the target plasma (now the fusion core). Moving an outer cusp field (230) inward using can compress a piston, raising or helping sustain its magnetic field, density and temperature. Similarly, the pistons can be moved to further compress the target plasma. This may be done to maintain fusion conditions in the target plasma against losses. It may also be used to bring the target plasma to fusion conditions where the initial kinetic energy of the pistons is insufficient. The result is a unique magnetic configuration: the fusion assembly. Besides providing compression, the plasma pistons inhibit end losses, providing a partial end plug.

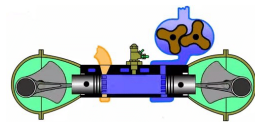
## A Thermonuclear Diesel

Note, the plasma pistons are part of the confinement system, NOT the fusion core.

No significant fusion occurs in the pistons.

"A unique magnetic configuration"

The pistons are analogous to the metal pistons in a opposed piston two-cycle Diesel engine. A whimsical but helpful perspective (and inspiration).



<https://www.researchgate.net/publication/330361590/figure/fig1/AS:714953254244360@1547469547624/Schematic-of-an-opposed-piston-engine.ppm>

## Pulsed Reactor Optimization

$$E_{out} = \frac{1}{4} n_i^2 Q_{dt} \langle \sigma v \rangle \tau_{conf}$$

$$E_{in} = 3Tn_i$$

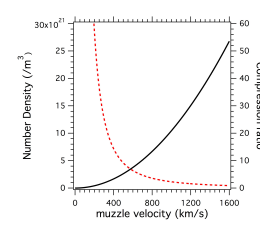
$$n_i = \frac{\beta B^2}{4\mu_0 T}$$

$$X = \frac{E_{out}}{E_{in}} = \frac{n_i Q_{dt} \langle \sigma v \rangle}{12T} \tau_{conf}$$

$$= \frac{\beta B^2 Q_{dt} \langle \sigma v \rangle}{48\mu_0 T^2} \tau_{conf}$$

IF confinement time,  $\tau_{conf}$ , is independent of temperature, get the usual optimal temperature of ~14 keV.

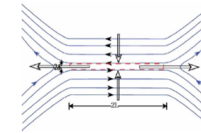
## Piston Requirements



The compressed pistons taken as:  
The same  $B$  for confinement  
Same density (to avoid Rayleigh-Taylor instabilities)  
The pistons' compression ratio,  $C_{pa}$ , determined by the muzzle  $B_{pm}$   
$$C_{pa} = \frac{B_{ta}}{B_{pm}}$$
  
The initial density is determined by  $C_{pa}$   
$$n_{ipa} = C_{pa} n_{ipm}$$
  
Plot assumes magnetic energy =  $0.5 * \text{kinetic energy}$ ,  $B = 12 \text{ T}$ ,

## Magnetic Reconnection at Core-Pistons Interfaces and Merger

Antiparallel Sweet-Parker reconnection in neutral sheet.



$$\frac{V_{in}}{V_{out}} = \frac{V_{in}}{V_A} = \frac{\delta}{L}$$

$$V_{in} = \frac{\delta}{L} V_A$$

Standard Sweet-Parker (MHD)

$$\delta_{sp} = \frac{L}{\sqrt{S}} = \sqrt{\frac{L\eta}{\mu_0 V_A}}$$

$$S = \frac{\mu_0 V_A L}{\eta}$$

$$V_{in} = \frac{\delta}{L} V_A = \sqrt{\frac{\eta V_A}{L \mu_0}} \sim T^{-3/4}$$

$S$  being the Lundquist number

Sweet-Parker Generalized to Two-fluid  
Yamada, et al. *Phys. Plasmas*, 13, 052119 [2006]

$$\delta_{gen} = \left( \frac{m_i}{4m_e} \right)^{1/4} \left( \frac{\lambda_{emfp}}{L} \right)^{1/2} \left( \frac{V_A}{V_{thi}} \right)^{1/2} \delta_{sp}$$

$$= 4.6 \left( \frac{m_i}{m_H} \right)^{1/4} \left( \frac{\lambda_{emfp}}{L} \right)^{1/2} \left( \frac{V_A}{V_{thi}} \right)^{1/2} \delta_{sp}$$

$$= 5.8 \left( \frac{\lambda_{emfp}}{L} \right)^{1/2} \left( \frac{V_A}{V_{thi}} \right)^{1/2} \sqrt{\frac{L\eta}{\mu_0 V_A}}$$

$$= 5.8 \sqrt{\frac{\lambda_{emfp}\eta}{\mu_0 V_{thi}}}$$

Giving.

$$V_{in} = \frac{5.8}{L} V_A \sqrt{\frac{\lambda_{emfp}\eta}{\mu_0 V_{thi}}}$$

For anti-parallel reconnection. Divide by 3 for perpendicular.

$$V_{in} = \frac{1.9}{L} V_A \sqrt{\frac{\lambda_{emfp}\eta}{\mu_0 V_{thi}}}$$

$$\tau_{merge} = \frac{E_{sa} R_{ta}}{V_{in}} = \frac{E_{sa} R_{ta} L}{1.9 V_A} \sqrt{\frac{\mu_0 V_{thi}}{\lambda_{emfp}\eta}}$$

Where  $R_{ta}$  is the radius of the assembled target plasma (core) and  $E_{sa}$  is its elongation.

### Optimizing Core Temperature

$\tau_{merge}$ , and hence  $\tau_{conf}$ , has a temperature dependence. Effectively,  $\delta_{gen} = 0.5d_i$  (ion inertial length)

$$V_{in} \sim \frac{\delta_{gen}}{L} V_A \sim \frac{V_A}{L \omega_{pi}} \sim \frac{1}{L \sqrt{n_i}} \frac{B}{\sqrt{n_i}} \sim \frac{T}{L \beta B}$$

$$\tau_{merge} \sim \frac{E_{sa} R_{ta}}{V_{in}} \sim E_{sa} R_{ta} L \frac{\beta B}{T}$$

$$X = \frac{E_{out}}{E_{in}} = \frac{\beta B^2 Q_{dt} \langle \sigma v \rangle}{48 \mu_0 T^2} \tau_{merge} \sim \frac{\beta^2 B^3 \langle \sigma v \rangle}{T^3}$$

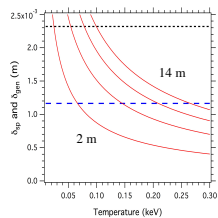
Optimal temperature  $\sim 7\text{keV}$  (not  $\sim 14\text{keV}$ ) due to cube instead of squared temperature dependence.

### Optimal Fusion Conditions

#### Fiducial fusion core conditions

Assume  $B_{ta} = 12\text{ T}$   
 $T_{ta} = 7\text{ keV}$   
 $\beta_{ta} = 94\%$   
 $n_{ta} = n_{eta} = 2.4 \times 10^{22}/\text{m}^3$   
 $(n_i = n_d = 1.2 \times 10^{22}/\text{m}^3)$   
 Power density:  $1.6 \times 10^{10}\text{ W/m}^3$   
 Plasma energy density:  $8.1 \times 10^7\text{ J/m}^3$   
 Scientific breakeven  $\sim 5\text{ ms}$

### Assembled Piston Temperature



Blue dashed is  $\delta_{gen}$ ; Red is  $\delta_{sp}$  for  $L = 2, 6, 10$  and  $14\text{ m}$  left to right. Horizontal dotted black is ion inertial length.

Pistons must be in the two-fluid state. Effectively, this occurs when  $\delta_{sp}$  reaches the  $\delta_{gen}$  in the fusion core. This occurs at higher temperature for larger  $L$ . The plot shows the temperatures where  $\delta_{sp}$  intersects  $\delta_{gen}$ .

Note: the pistons have  $B = 12\text{ T}$  for confinement and same density as the core. For small  $L$ , higher temperatures are required to slow the resistive decay of the field.

### By The Numbers

$$X = \frac{\beta B^2 Q_{dt} \langle \sigma v \rangle E_{sa} R_{ta} L}{91 T^2 V_A} \sqrt{\frac{V_{thi}}{\mu_0 \lambda_{emp} \eta}} \sim \frac{\beta^2 B^3 \langle \sigma v \rangle E_{sa} R_{ta} L}{T^3}$$

If we take  $L = R_{ta}$  and  $E_{sa} = 0.5$  so tilt instability external between pistons [Steinhauer, *Phys. Plasmas*, 18, 070501, 2011]

$$X = \frac{R_{ta}^2}{4.12\text{ m}^2} \quad (\text{Note favorable scaling with radius})$$

$$\tau_{merge} = (5\text{ ms}) X$$

$$\text{Burn fraction: } (0.24\%) X$$

#### Tantalizing

ITER volume =  $830\text{ m}^3$  [M. Shimada et al. *Nucl. Fusion*, 47 S1(2007)]  
 For same volume,  $L = R_{ta} = 6.4\text{ m}$   $E_{sa} = 0.5$ ,  $X = 9.9$   
 Cycle time of  $\sim 2.5\text{ min}$  gives  $\sim 4400\text{ MWt}$  for a 1000 MWe power plant. Average fusion power and neutron flux would be  $\sim 7$  times that of an ITER scale reactor, but comparable to a similar tokamak plant of the same electrical output.

#### For Perspective

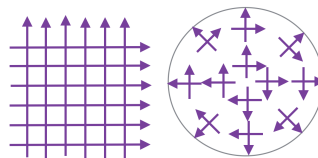
Fusion core diameter of 12.8 m.  
 Typical PWR internal diameter  $\sim 4\text{ m}$   
 Typical containment dome diameter  $\sim 40\text{ m}$

#### Caveat: Large L

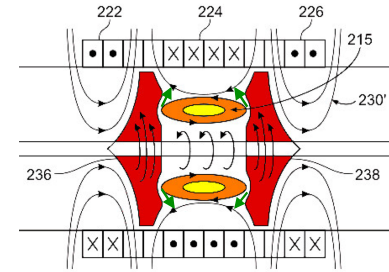
Ji & Daughton [*Phys. Plasmas*, 18, 111207 (2011)] put reconnection in "Multiple X-line collisionless" regime as opposed to the "Single X-line collisionless" regime used in the calculations above. The multiple X-line implies the intermittent formation of magnetic islands and flux ropes (very broadly defined) which flow out of the neutral sheet with the plasma and increase the average speed of reconnection.

MRX experiments [Dorfman et al. *Phys. Plasmas*, 21, 012109 (2014)] observe such flux ropes with  $L \gg \delta_{gen}$  in anti-parallel reconnection.

Cartoon shows magnetic configuration used for calculations, and actual configurations. Not only are the fields perpendicular, but they change orientation continuously with angle. What then is the coherence length and what is the impact on islands and/or flux ropes?



### Plasma Outflow



Green arrows suggest reconnected plasma outflow from the neutral sheets between the pistons and core. The ram pressure of an Alfvén flow equals the magnetic pressure, here, of the external field. Backpressure slows reconnection. How the system evolves is unclear.

#### Smaller Reactor?

Assumed  $E_{sa} = 0.5$  for core (tilt stability) but  $X$  scales with  $E_{sa}$

Can external stabilization increase  $E_{sa}$ ?

Does violence of reconnection and plasma mixing slow growth of instabilities in an FRC? [Itagaki, et al., *Phys. Plasmas*, 21, 030703 (2014)].

Shear angle is  $90^\circ$ , but pistons with a parallel poloidal component (e.g. spheromaks) would reduce the angle and slow reconnection.

#### Beyond Backs of Envelopes

Modeling with codes such as NIMROD and kinetic codes one important path.

Among the many existing experimental systems, some (perhaps with suitable additions or modifications) may be another important path.

The value of such research likely would extend beyond this particular application, illuminating plasma physics.

A small-scale prototype converging piston system may be the best avenue of research, particularly if it can be based upon an existing system.

"IT'S SO CRAZY, IT JUST MIGHT WORK!"