ADVANCES TOWARDS PB11 FUSION WITH THE DENSE PLASMA FOCUS

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HYDROGEN BORON FUSION

Advantages:

Charged particles only, direct conversion to electric power

Potential large reduction in cost of energy

$$p + B^{11} \Rightarrow 3\ He^{4}$$

Only 0.2% Energy in neutrons,

$$He^{4} + B^{11} \Rightarrow n + N^{14}$$

too low energy for activation,
no long- or medium-term radioactivity

TWO BASIC CHALLENGES

1) Achieve $E_i > 300$keV
$n\tau > 2x10^{15}$ sec/cm^3

2)Fusion power> x-ray bremsstrahlung

DPF AS ROUTE TO PROTON-BORON FUSION

SUMMARY

Experimental results indicate high particle energy and $n\tau$ can be achieved

New theoretical results indicate high magnetic field achievable with DPF suppress ion-electron heating reduce T_e and thus x-ray emission

DPF's low cost means this route can be examined experimentally with modest resources

Potential gain is environmentally benign power production an order of magnitude cheaper than at present

MAGNETIC FIELD EFFECT

1970's: Strong magnetic field reduces ion-electron energy transfer--McNally and others

Applied to neutron stars, fusion at moderate fields

Classical effect: For ions colliding with electrons with gyrofrequency ω_g , energy transfer drops rapidly for impact parameter

$$b > v_i/\omega_g$$

Less than λ_D by a factor of $v_i\, \omega_p/ v_{eth}\, \omega_g$

So Coulomb log is reduced to Ln $(mv_i^2/h\ \omega_g)$

Valid for collisions where ions lose energy to SLOWER electrons

But for electrons with $v_{eth} >> v_i$, which LOSE energy to ions, Coulomb log is much larger Ln $(mv_e^2/h\ \omega_g)$

Ignoring momentum transfer parallel to field, steady state occurs when

$$T_i/T_e = \mathrm{Ln}\,(mv_e^2/h\ \omega_g)/\mathrm{Ln}\,(mv_i^2/h\ \omega_g)$$

QUANTUM EFFECT
LANDAU LEVELS

Angular momentum quantized, Landau energy levels:

$$E_b = (n+1/2)\, ehB/mc = 11.6\text{eV}B(\text{GG})$$

Since maximum momentum transfer is mv, where v is relative velocity, for $mv^2/2 < E_b$ very little excitation from ground level, very little energy transfer.

$$E_i < (M/m)\, E_b$$

For E_i =300keV,

B>14GG for p

B>3.5GG for α

B>1.3GG for ^{11}B

RESULTS

For $T=2T_i/(M/m)\ E_b > 1$ rapid convergence on Ln(T)
(More accurately $\Gamma(0,1/T)$ averaged over Maxwellian distribution)

For T<1 numerical integration yields:

T	LnΛ
1.0	0.238
0.8	0.177
0.6	0.121
0.4	0.0724
0.2	0.0308
0.1	0.01316

Very large effect compared with non-magnetic LnΛ~15.
For $p^{11}B$ protons with T>1 contribute nearly all the electron heating.

CAN SUCH HIGH FIELDS BE ACHIEVED IN DPF?

Theory gives scaling law:

$$B_c=4z(\mu M/m)B$$

B is peak field at cathode

For Texas experiment, predicts B_c = 0.43 GG-- observed 0.4 GG

For decaborane peak I = 2.3 MA, r_c =3.3 cm
B_c = 14 GG

Large extrapolation-- must be tested by experiment

Theory gives:

$$n\tau=304\mu^{4/3}z^{1/3}I^2/rR_B$$

Texas prediction: 4.6×10^{13} sec/cm^3
Best : 9×10^{13} Average 0.9×10^{13}

Decaborane at above conditions:
$n\tau= 4.2\times10^{15}$

ANODE STRESS STUDIES:

LIMITS ON INITIAL B FIELD

Thermal and pinch stress studies of anodes show peak initial magnetic field at anode base (hollow anode) must be:

< 200KG for Cu (1 MA/cm)

< 380KG for Be (~2 MA/cm)

Tapered anode 2-1

$r_a/r_c=2.5$

Maximum plasmoid B field 15 GG

PRELIMINARY SIMULATION OF PLASMOID

Assumes: Homogenous, stable, Maxwellian plasmoid
no collective heating

Includes:

production of electron and ion beams

heating of plasmoid electrons by e-beam

emission of x-rays by electrons

energy exchange between ions and electrons
including magnetic effect

generation of α by TN reactions

heating of ions by α particles

transfer of energy from ions, electrons to B field

PRELIMINARY SIMULATION RESULTS

			Rx1.5	R/1.5	nx1.5	n/1.5
Peak I (MA)	**3.0**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**
B(GG)	**6.0**	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**
Gross Input (kJ)	**89.6**	**17.5**	**17.5**	**17.5**	**17.5**	**17.5**
X-ray/Input	**0.55**	**0.71**	**0.70**	**0.73**	**1.29**	**0.27**
Beam/Input	**0.71**	**0.93**	**1.01**	**0.83**	**0.77**	**0.83**
Beam+X-ray/Input	**1.26**	**1.64**	**1.71**	**1.56**	**2.06**	**1.22**

DIRECT CONVERSION OF ION BEAM AND X-RAY PULSE TO ELECTRIC POWER--APPLICATIONS

For power production: 80% conversion efficiency yield 49% overall efficiency of conversion of fusion energy to output power.

UV losses minimized by >1 kHz pulsing

5-20 MW/ electrode limited by cooling of electrodes ~ 2% total

For space propulsion, ion beam produces thrust at 10^6 sec ISP(10,000 km/sec)

With 80% x-ray recovery + 46% efficiency beam recovery: 78% energy to useful thrust

Thrust-to-mass ratios of 0.1 N/kg, specific power of 500 kW/kg

Six month transit time to Jupiter, 2-1 total mass/payload ratio

NEED FOR HIGH EFFICIENCY OF ENERGY TRANSFER TO PLASMOID

EXISTING ROUTE:

REDUCE ANODE RADIUS OR TAPER TO INCREASE SPEED OF RUN-DOWN, COLLAPSE—HIGHER dB/dT, INDUCES LARGER AZIMUTHAL CURRENT

POSSIBLE NEW ROUTE:

INDUCE INITIAL ANGULAR MOMENTUM WITH HELICAL ELECTRODES TO GENERATE AZIMUTHAL BULK FLOW

NEW SIMULATIONS

1) **Plasmoid formation to increase energy efficiency**

2) **Plasmoid burn to study stability with α generation and collective heating: inhomogeneous, non-Maxwellian, 3D PIC**

MHD assumptions do not hold—non-collisional plasma. But huge range of scales defeat conventional PIC approaches.

Plasmoid Particle Methods

1. Used here are drift kinetic fluid particles (DKFP) that track precisely the evolving distribution function — under the action of the drift velocity $\mathbf{C}(x)$ and acceleration $\mathbf{A}(x)$,

$$\mathbf{C} = \mathbf{V} + \mathbf{x} \cdot \delta / h \ , \mathbf{a} = \mathbf{A} + \mathbf{x} \cdot \alpha / h \ .$$

With the time varying scale parameters,

$$D(t) = (1 + \frac{t\,\delta}{h} + \frac{1}{2}\frac{t^2\,\alpha}{h}) \ ,$$

$$h_{\pm}(t) = \pm h + (V \pm \delta)\, t + \frac{1}{2}\,(A \pm \alpha)\, t^2 \ .$$

2. The distribution functions are simple products on space and velocity,

$$f(\mathbf{x}, \mathbf{v}) = \Pi_i^3 \mathcal{B}_{wi}(X, x) \mathcal{G}_{ui}(V, v)$$

and solve

$$(\partial_t + \mathbf{V} \cdot \partial_{\mathbf{X}} + \mathbf{A} \cdot \partial_{\mathbf{V}}) f \equiv \mathcal{L}_0 f = 0 \ ,$$

using the characteristics,

$$\mathbf{X} = \mathbf{x} + \int^t dt_1 \mathbf{v} + \int^{t_1} dt_2 \mathbf{a} \ \mathbf{V} = \mathbf{v} + \int^t dt_1 \mathbf{a} \ .$$

3. The expected profile for number density (per unit length, area, or volume) $n(X,t) \equiv < N > /\ell$ is then:

$$n(X,t) = \frac{N}{2hD(t)} \left(\operatorname{erf}\left(\frac{h_+(t) - X}{\sqrt{2}U\,t} \right) + \operatorname{erf}\left(\frac{X - h_-(t)}{\sqrt{2}U\,t} \right) \right),$$

with similar expressions for momentum P and enthalpy H, e.g.

$$P(X,t) = \frac{mN}{2hD^2(t)} \left(\operatorname{erf}\left(\frac{h_+(t) - X}{\sqrt{2}U\,t} \right) + \operatorname{erf}\left(\frac{X - h_-(t)}{\sqrt{2}U\,t} \right) \right)$$

$$(V + \frac{\delta\,X}{h} + \frac{1}{2}\,t\,(A + \frac{\alpha\,X}{h})) + \frac{mNU}{\sqrt{2\pi}2hD^2(t)}$$

$$(e^{(-1/2\,\frac{(h_+(t)-X)^2}{U^2\,t^2})} - e^{(-1/2\,\frac{(X-h_-(t))^2}{U^2\,t^2})})\ .$$

The enthalpy or total kinetic energy content profile $H(X,t) \equiv <\rho v^2>/2$ is given by:

$$H(X,t) = \frac{mN}{2hD(t)} \times \left(\operatorname{erf}\left(\frac{h_+(t) - X}{\sqrt{2}U\,t}\right) + \operatorname{erf}\left(\frac{X - h_-(t)}{\sqrt{2}U\,t}\right)\right)$$

$$\left(U^2 + \frac{(V + \frac{\delta\,X}{h} + \frac{1}{2}\,t\,(A + \frac{\alpha\,X}{h}))^2}{D(t)^2}\right)$$

$$+ \frac{mN}{\sqrt{2\pi}2hD^3(t)}U\left(V + \frac{1}{2}\,A\,t + X\,\left(\frac{1}{t} + 2\,\frac{\delta + \frac{1}{2}\,\alpha\,t}{h}\right)\right)\cdot$$

$$(e^{(-1/2\,\frac{(h_+(t)-X)^2}{U^2\,t^2})} - e^{(-1/2\,\frac{(X-h_-(t))^2}{U^2\,t^2})})$$

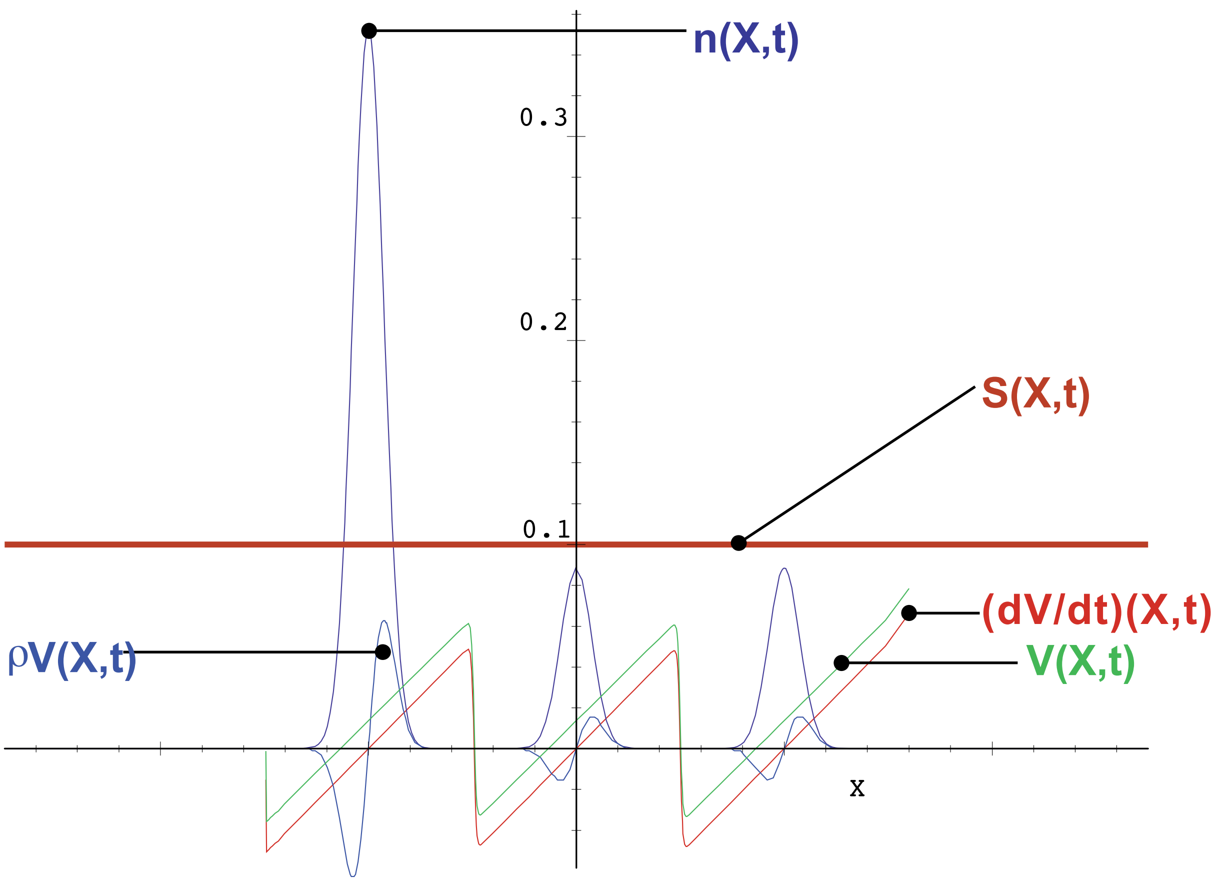
$$- \frac{mN}{\sqrt{2\pi}2hD^3(t)}U(\delta + \frac{h}{t} + \frac{1}{2}\,\alpha\,t)(e^{(-1/2\,\frac{(h_+(t)-X)^2}{U^2\,t^2})} + e^{(-1/2\,\frac{(X-h_-(t))^2}{U^2\,t^2})})\ ,$$

including both thermal and drift energies and the changes in these energies provided by the external forces.

4. The momentum change due to pressure gradients is *built in* and *self similar*, viz.

$$\sum_{i=1}^{N}\left(\frac{\frac{tkT}{2ND(t)}\partial_X n(X,t)}{(P(X,t)-n(X,t)(V+(\delta X/h)+(t/2)(A+\alpha X/h))/D(t))}\right)_i = 1\ ,$$

for each particle on all space and time domains.



Three Fluid Particles Collide - the acceleration and velocity fields are everywhere proportional, the similarity variable S(X,t) is everywhere constant.

5. The fluid properties, needed by the electrodynamics to support the evaluation of a magnetic Reynolds number

$$\mathcal{R}_m = 1.2184 \cdot 10^{-2} \ell_B V_r T_{eV}^{3/2} / \ln \Lambda Z \alpha_\perp (Z \omega \tau_e)$$

or field diffusion scale lengths,

$$(\frac{\lambda_o}{\delta_o})^2 = \frac{\mathcal{R}_m}{2} \left(\frac{\lambda_o^2}{\ell_B V_r t_o} \right) ,$$

are then easily projected into each node or cell of the field solution grid with virtually no error.

6. The influence that each fluid particle brings to any other region can be tabulated by projecting any observable moment over any remote domain of interest. The projection factors,

$$\mathcal{P}_L(X_<, X_>, t) = (\frac{N}{2h}) \frac{1}{U\sqrt{2\pi}} \int_{X_<}^{X_>} dX \int_{-h}^{h} (\frac{dx}{t}) \left(\frac{X - x}{t} \right)^L$$

$$\times \exp(-\tfrac{1}{2}(\tfrac{(((X-(A+\alpha x/h)t^2/2-x)/t)-(V+\delta x/h))}{U})^2)$$

are then the means for collecting information out of the particles.

CLOSING POINTS

DPF extremely economical, equipment costs ~$150,000

Two-to-three-year, two million dollar program can accomplish next steps, test theoretical predictions, scaling laws, determine if break-even feasible

Goal-- if break-even obtainable, DPF can produce energy output in ion beam. With inductive and electrostatic conversion, cost of energy conversion could be slashed.

Conceptual design of DPF reactor indicates capital cost of <$200,000 for >5MW unit

Energy costs less than 1/10 of present