The PJMIF Concept
Plasma Jet Magneto-Inertial Fusion Tutorial

A presentation

By

EnergyCite®

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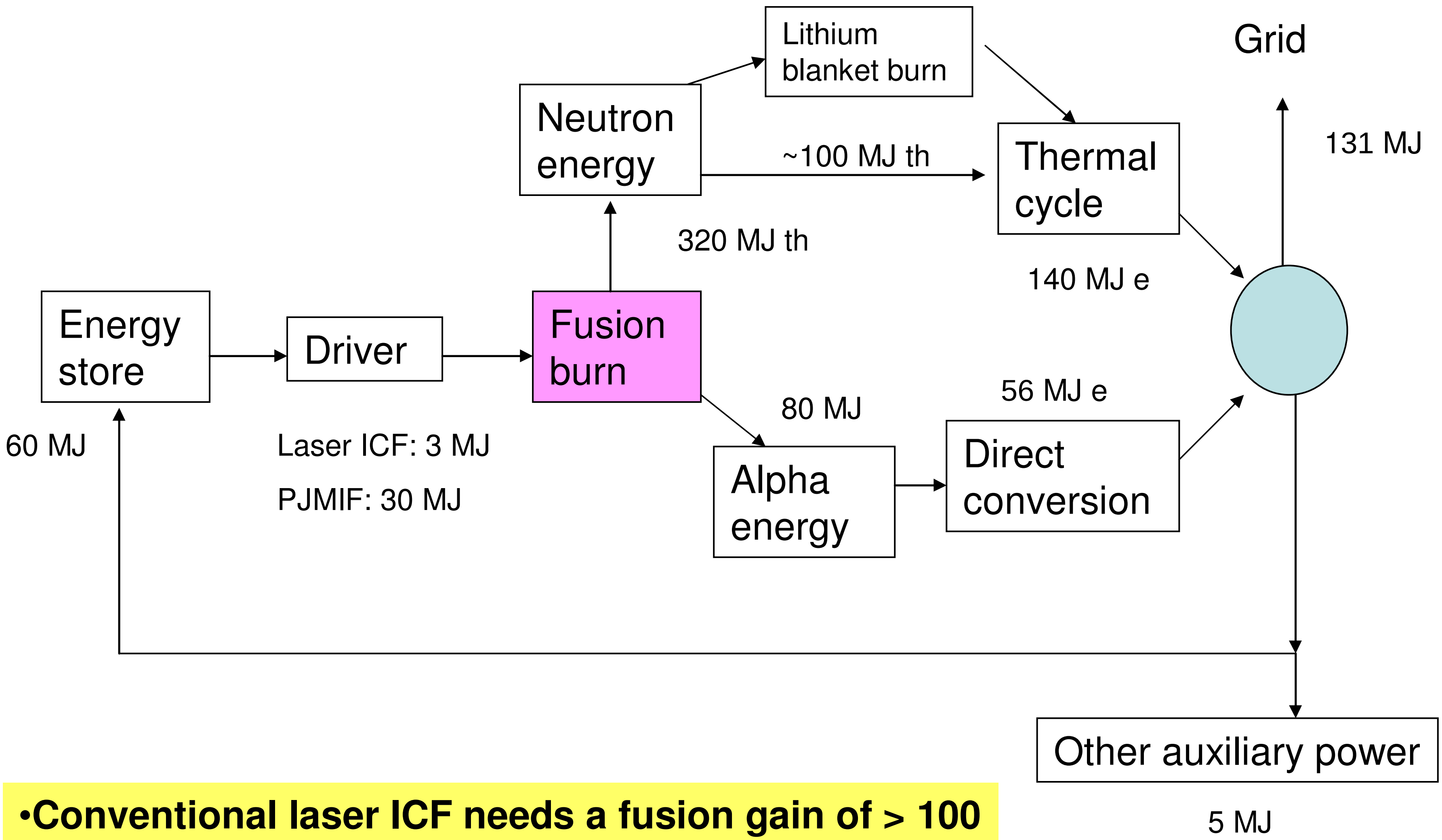
Outline

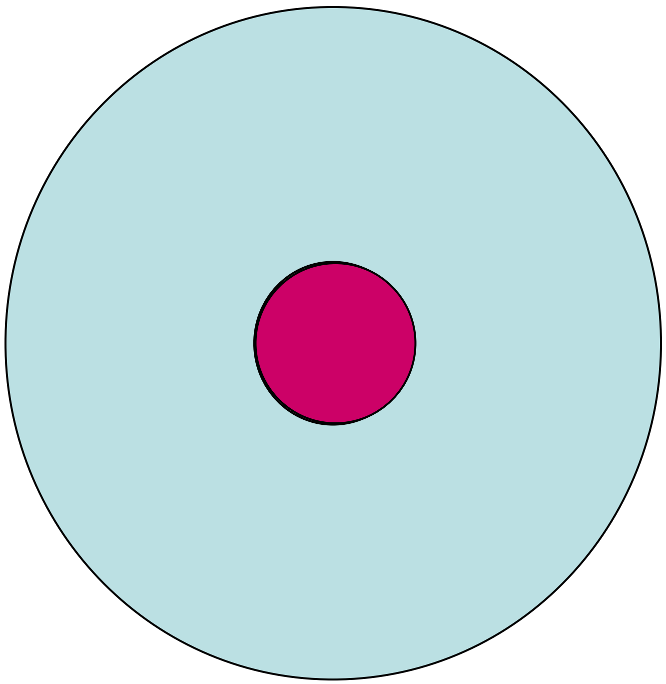
- Discuss the fusion power flow chart to determine the fusion gain required by any given inertial fusion scheme in order to produce net power on the grid
  - Compare PJMIF against laser ICF
- Explain the fusion burn configuration for PJMIF
- Explain how this is achieved in PJMIF → a discussion of the implosion scheme
- Explain how the target is magnetized
- The plasma guns
- Concluding remarks

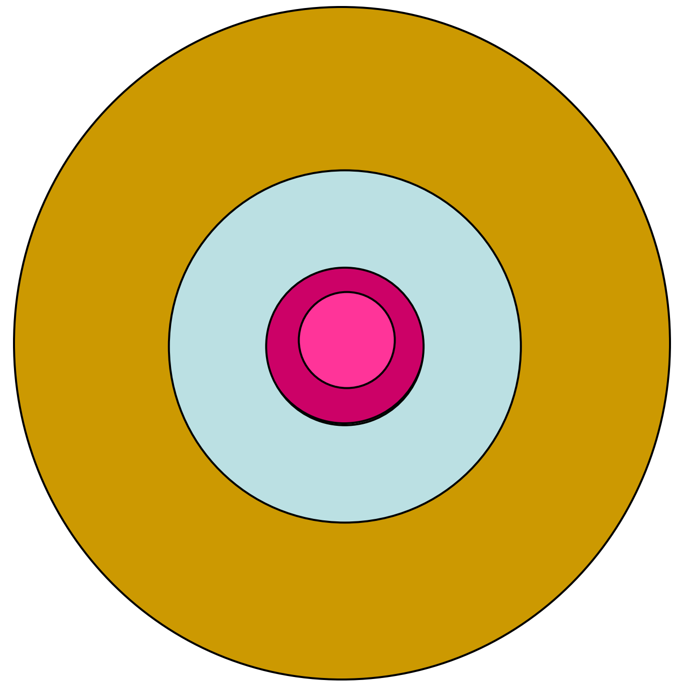
The Fusion Power Flow Cycle



- **Conventional laser ICF needs a fusion gain of > 100**
- **PJMIF needs only a gain of ~ 10**

The PJMIF Fusion Burn Configuration





Simple PJMIF burn configuration

Typical values:

Target ~ 1 cm diameter, 10 mg D-T

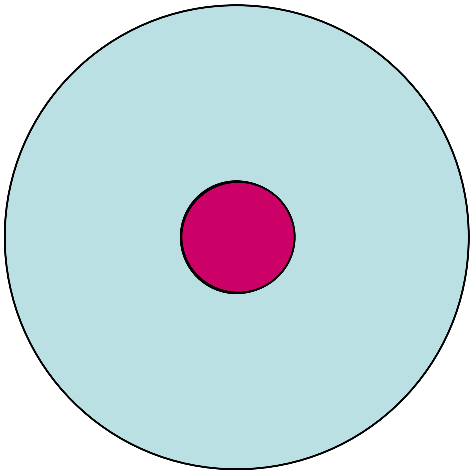
Liner ~ 5 cm thick, 10 g – 30 g, high Z

Proprietary PJMIF Configuration

Structured target

Composite and structured liner

The PJMIF Fusion Burn Configuration



Simple PJMIF burn configuration

Typical values:

Target ~ 1 cm diameter, 10 mg D-T

Liner ~ 5 cm thick, 10 g – 30 g, high Z

Target density ~ 4.6×10^{21} per cm^3.

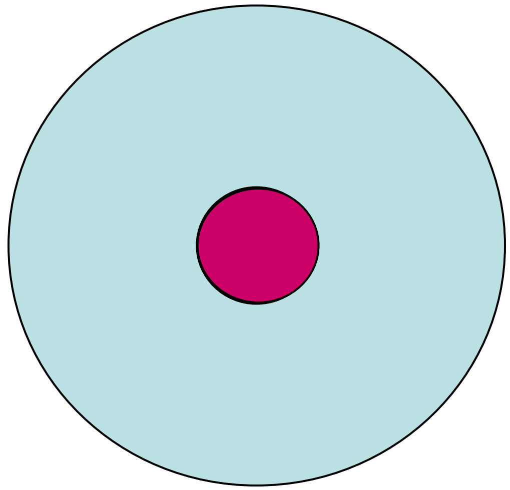
Let the target has a temperature of 10 keV and let it be contained by the liner for about 0.5 microsecond, the total fusion energy produced by the fusion burn is 444 MJ.

During the burn, the target pressure is 147 Mbar.

This pressure needs to be created by the liner.

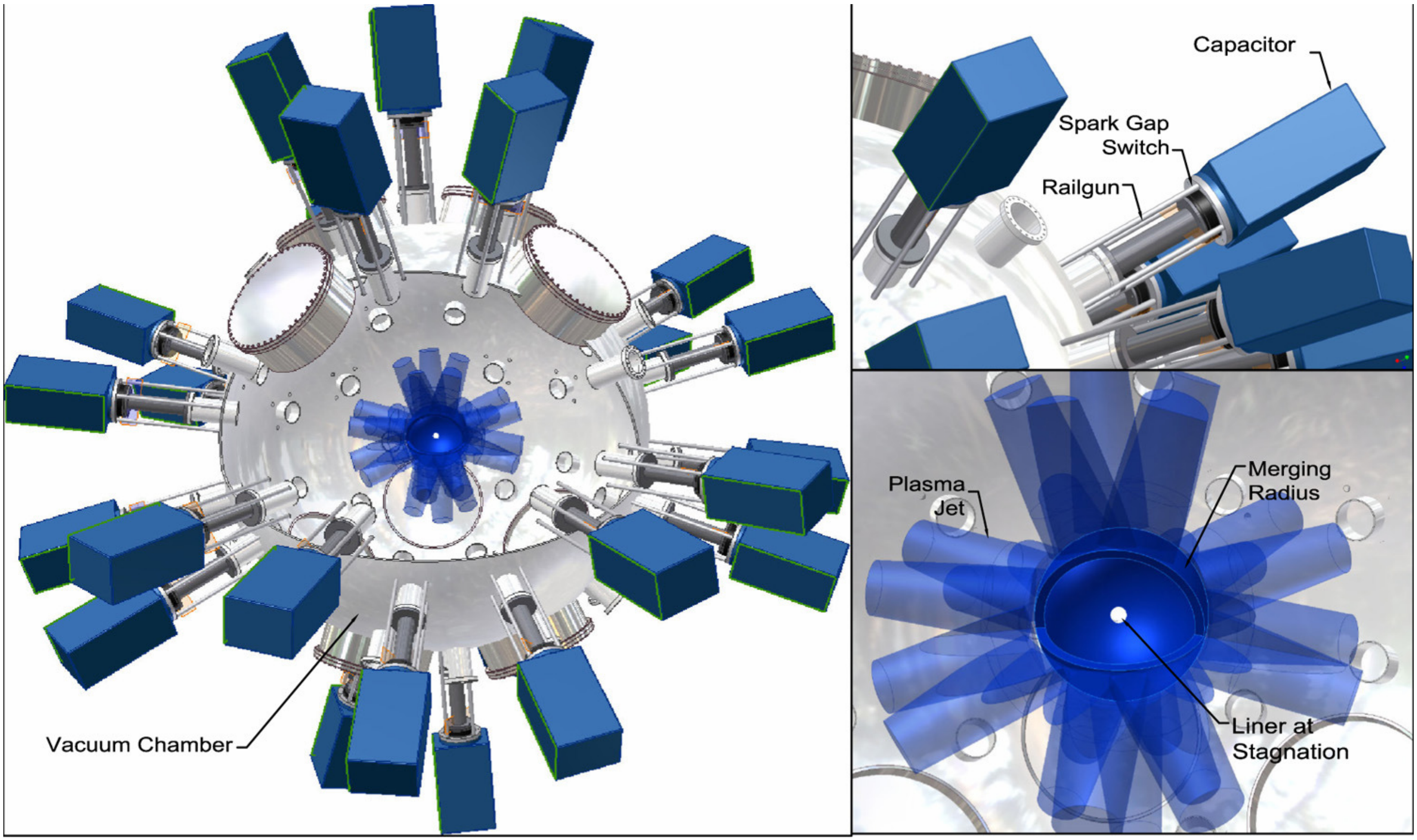
PJMIF needs to accomplish two things

- Create the target and liner configuration for fusion burn using plasma liners formed by plasma jets
  - Density ~ 5 x 10^{21} per cc
  - Pressure ~ 150 Mbar
  - Temperature ~ 10 keV
- Maintain this configuration for about 0.5 μs

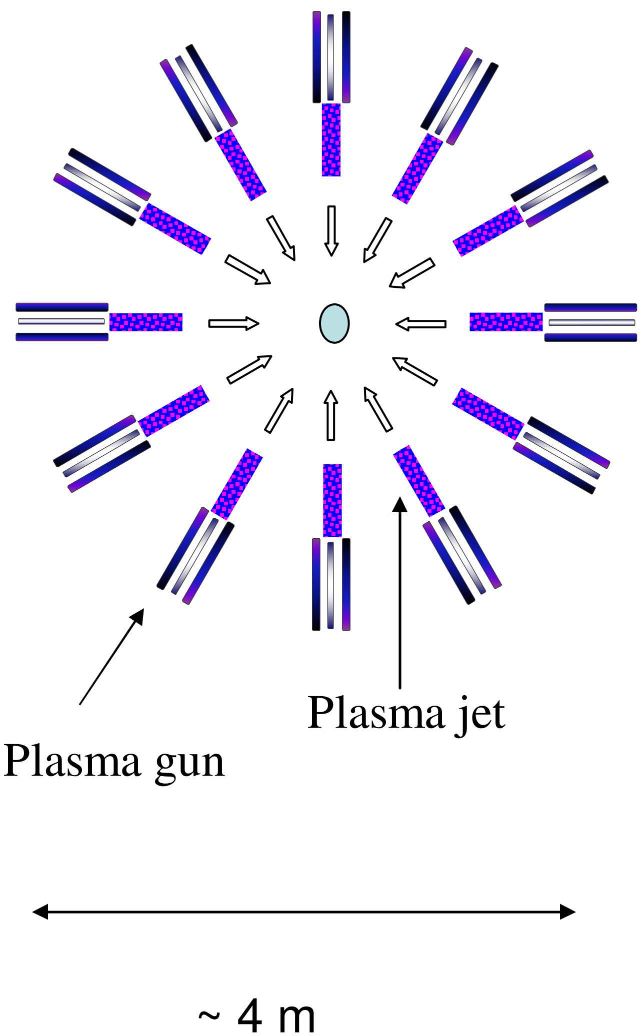


Simple PJMIF burn configuration

A spherical chamber with one or more sets of plasma guns



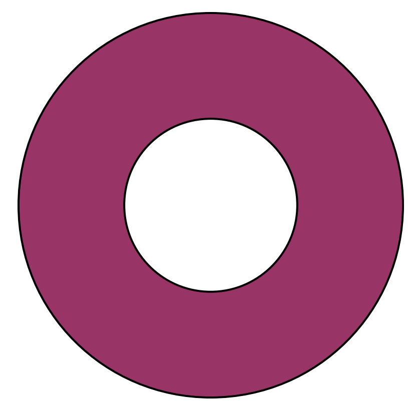
Two sets of jets are launched by the plasma guns



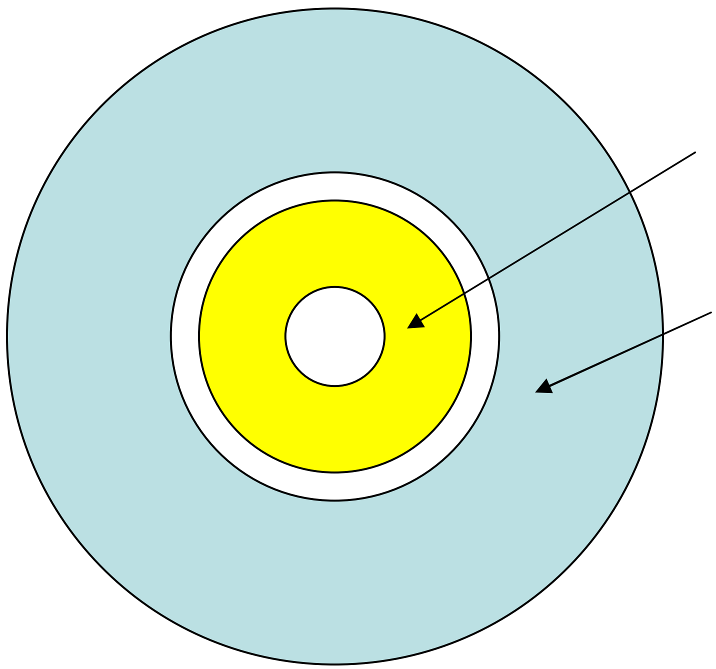
Jets launched and propagate towards the merging radius, r_m ~ 0.6 m

At the merging radius, jets merge to form a shell (liner)

Shell converges towards the center



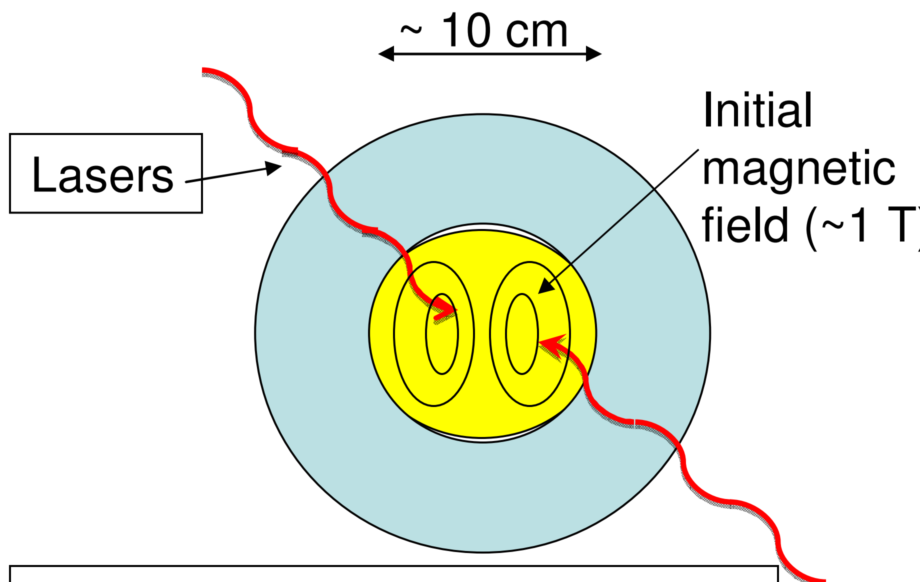
The target, the imploding liner, and the magnetization of the target



The first set of jets carrying a mixture of D-T (~ 5 mg) forms the target.

The second set of jets carrying a high atomic-weight species forms the heavy imploding liner (10 g – 30 g)

The desired initial temperature of the target is ~ 1 million deg K. It is then compressed by the heavy liner to the required density and thermonuclear temperatures.



Lasers are used to drive currents in the target to generate the seed magnetic field

The Dynamics of the Converging Liner

- The pressure of implosion is provided by the momentum flux density, ρv^2, of the liner (commonly called its ram pressure).
- As the liner converges towards the center, its density increases rapidly inversely as the square of the radius (inverse square law), so does its ramp pressure (ram pressure amplification, A)
- The ram pressure amplification is limited by
  - the convergence ratio
  - the self heating of the liner, creating self internal pressure that works against its inward motion towards the center.
  - Hydrodynamic instabilities, such as the Rayleigh-Taylor instability

Assessment of the Potential of PJMIF

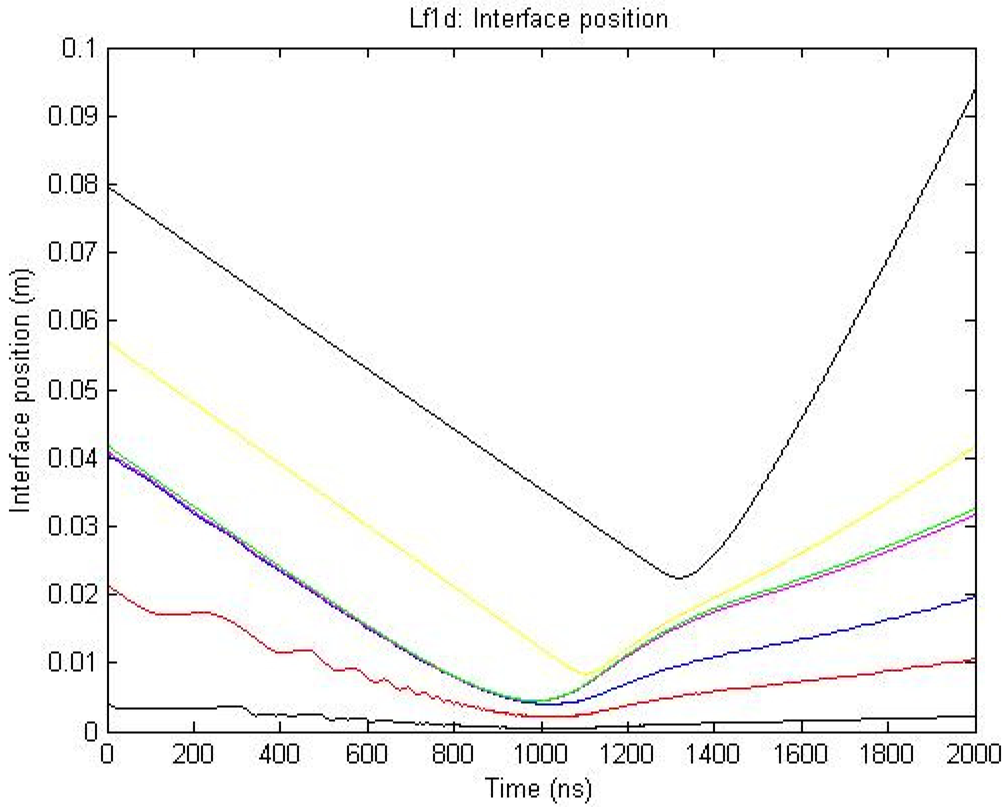
- We have used analytical and lumped parameter models to assess the potential of PJMIF
  - Assessments are not unanimous among all authors
  - Generally there are more favorable assessments
- We have reasonably advanced computer codes for modeling the implosion dynamics of PJMIF
  - 1D Lagrangian fluid dynamics for parametric scan
  - 1D Radiative Hydrodynamics codes (RAGE of LANL)
  - 3D Smoothed Particle Hydrodynamics for study of asymmetric effects, preliminary studies of Rayleigh-Taylor instabilities

Ref: Thio et al. (1999); Cassibry let al. (2009); Awe et al. (2011);
Hsu et al.(2011); Parks (2008); Samulyak (2010)

An illustrative computer modeling example

Case Lf1d-thio-ab-54: 30 MJ liner energy

1D Lagrangian plasma dynamics with ideal gas EOS, fusion burn, fixed-parameter alpha energy re-deposition, no radiative transport.



Cells #2-21 inner target, #22-26 afterburner, #27-51 liner.

Shown are interfaces #52, #39, #27, #24, #22, #12, #3

Target and liner jets merge at a radius of 60 cm

Target is structured – inner and afterburner layer

Liner has kinetic energy of 30 MJ

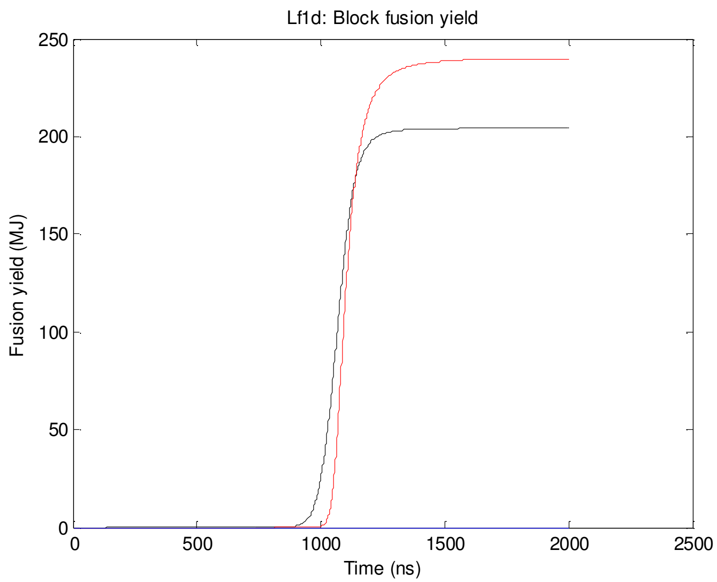
An analytic model is used to compute the flow down to a radius of 8 cm

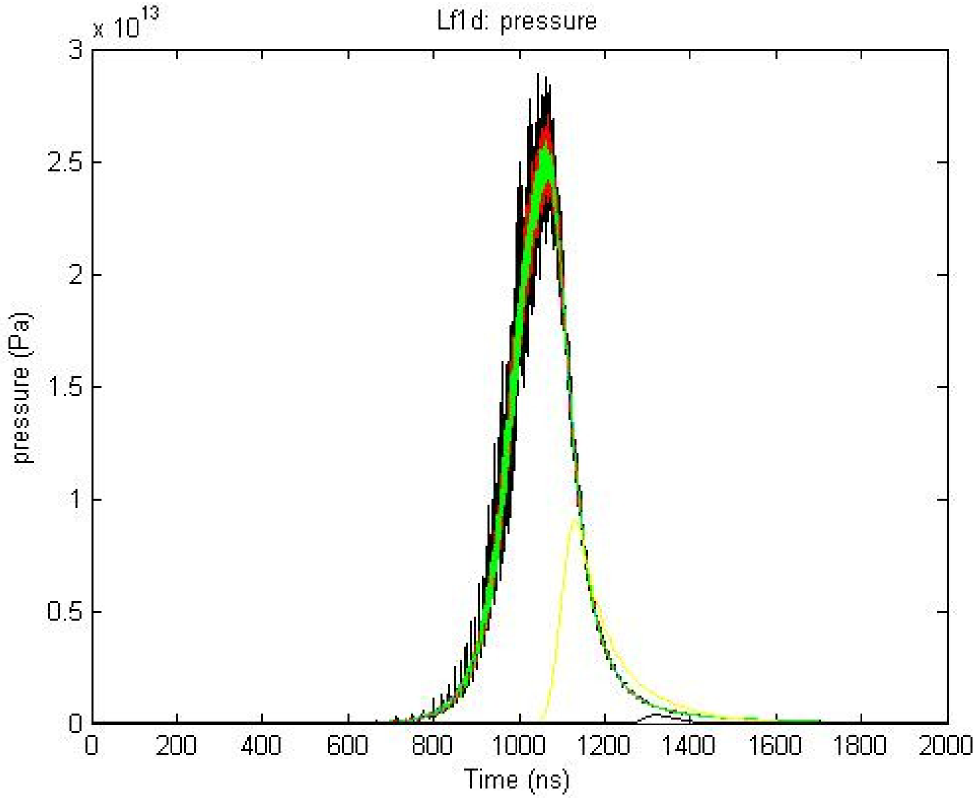
The 1D computer code then takes over and simulates the detailed dynamics and fusion burn

An illustrative computer modeling example

Case Lf1d-thio-ab-54: 30 MJ liner energy

Fusion yield: 440 MJ (DT) + 120 MJ (Li burn)





- The example is not optimized.
- Optimization will improve yield.
- Simulation has idealized assumptions
- Realistic physical effects will degrade yield

Liner convergence and implosion dynamics

- The implosion dynamics is sensitive to the details of the physics assumptions:
  - Equation of state
  - Radiative transport
  - Plasma interpenetration
- Our computer codes at present make reasonable assumptions about these physics details, but are not exact, and have not been validated against experiments
- They serve to give qualitative expectations of the potential of the concept and scoping of the magnitudes of the key parameters.

Liner Convergence and Implosion Dynamics: What remains to be done

- The equation of state, the radiation properties (opacities), the collisionality, the growth rates of instabilities need to be accurately measured, modeled, or characterized using a combination of experiments and computational modeling
- This physics needs to be captured in the most advanced 3D, hybrid particle-in-cell and smoothed particle hydrodynamics codes, complete with radiative magnetohydrodynamics, fusion burn physics with energetic particle energy deposition.
- The codes need to be validated against further experiments so that they can be relied upon as being predictive rather than hind-casting.
- Apply the codes systematically to search for and design the most optimum set of initial conditions and implosion trajectory.

The company that pays for this development owns the know-how and the computer codes

- The combination of computer model development and experimental validation, leading to predictive computer models and using them in engineering design is common in the development of advanced technology today.
- This is a peta-flop-scale supercomputing effort.
- Supercomputing modeling is a key enabling tool for our program
  - It is a key strategy for my proposed program
  - A state-of-the-art supercomputing cluster based on GPU parallel computing is planned for our proposed program.

Target Magnetization

- Our favorite technique for target magnetization is the use of lasers, but we are open to other possibilities.
- The basic principle is based on the beating of two plasma waves to produce a beat wave which is optimally coupled to the electron thermal motion, resulting in a net acceleration of the electrons in the direction of the plasma beat wave.
- The plasma waves are excited by electromagnetic waves in the form of laser beams.
- Prior to the firing of the lasers, a pre-initial magnetic field is set up to guide the accelerated electrons.

Target Magnetization: What has been done and what remains to be done

- The principle has been demonstrated in the microwave regime in plasmas with densities several orders of magnitude less than what we plan in PJMIF.
- The use of lasers to produce plasma beat waves to drive currents in dense plasma is a new and innovative technology to be developed on the program. The technology might have other scientific and industrial applications.
- Advanced 3D particle-in-cell (PIC) plasma code with accurate laser-plasma interaction physics and EM field calculation need to be developed.
- Experiments need to be conducted to validate the code, so that it has a predictive capability.
- The computer codes and the lessons learned in developing the technique is the technological know-how to be owned by the company, and which cannot be acquired in any other way.
- The code need to be apply to search for and design the most optimal way of establishing an initial seed magnetic field in the target plasma.

The Key to PJMIF is the ability to produce plasma jets of high density, high Mach number and high velocity

- Typical characteristics
  - Length ~ 5 cm
  - Density ~ 10^{17} particles (ions) per cm^3
  - Velocity ~ 40 km/s – 80 km/s
  - Mach number ~ 10 – 60
- Mach number = jet velocity/jet sound speed

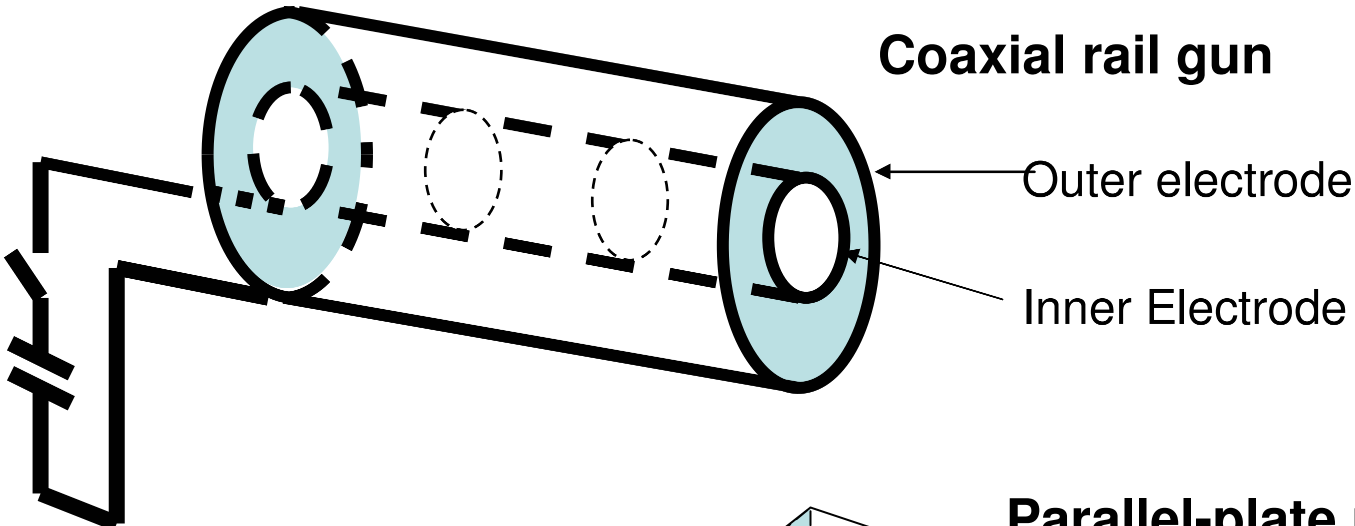
$$\text{Sound speed (ions)} = \sqrt{\frac{\gamma kT}{m_i}}$$

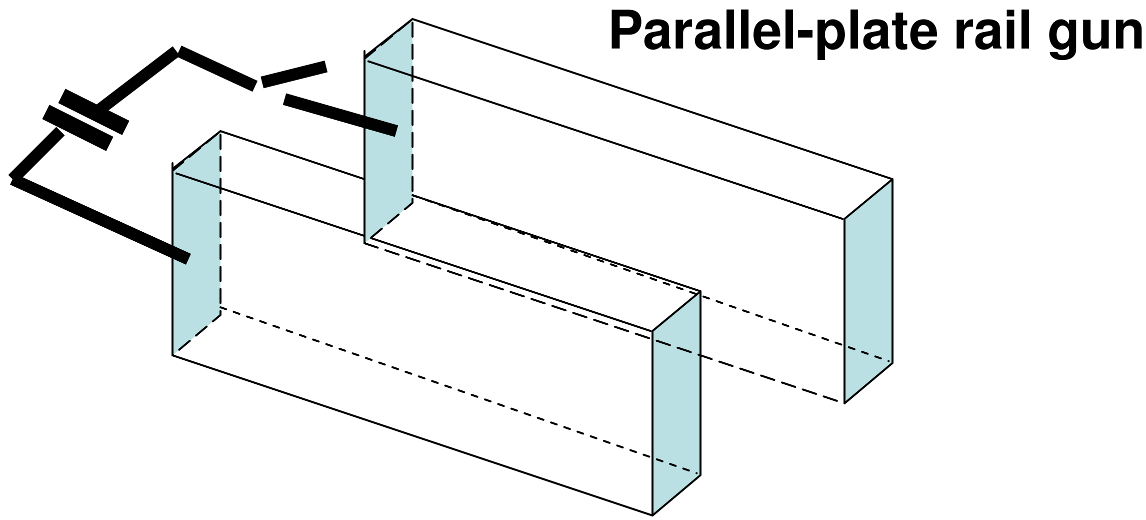
$$\gamma = \text{ratio of specific heats of the plasma} = \frac{c_p}{c_v}$$

γ is a complicated function of the atomic physics of the plasma

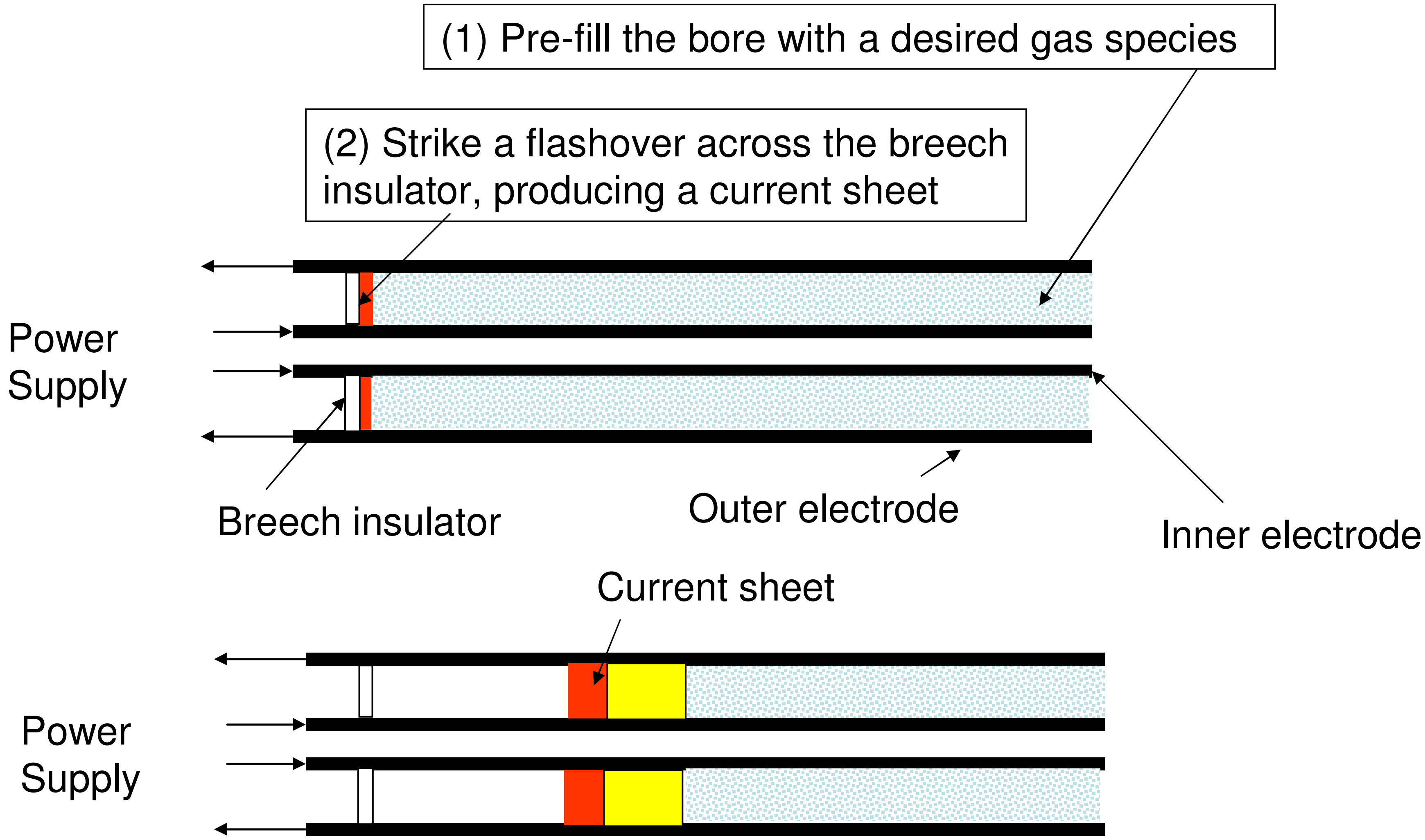
How are these plasma jets produced?

- They are produced by using plasma guns





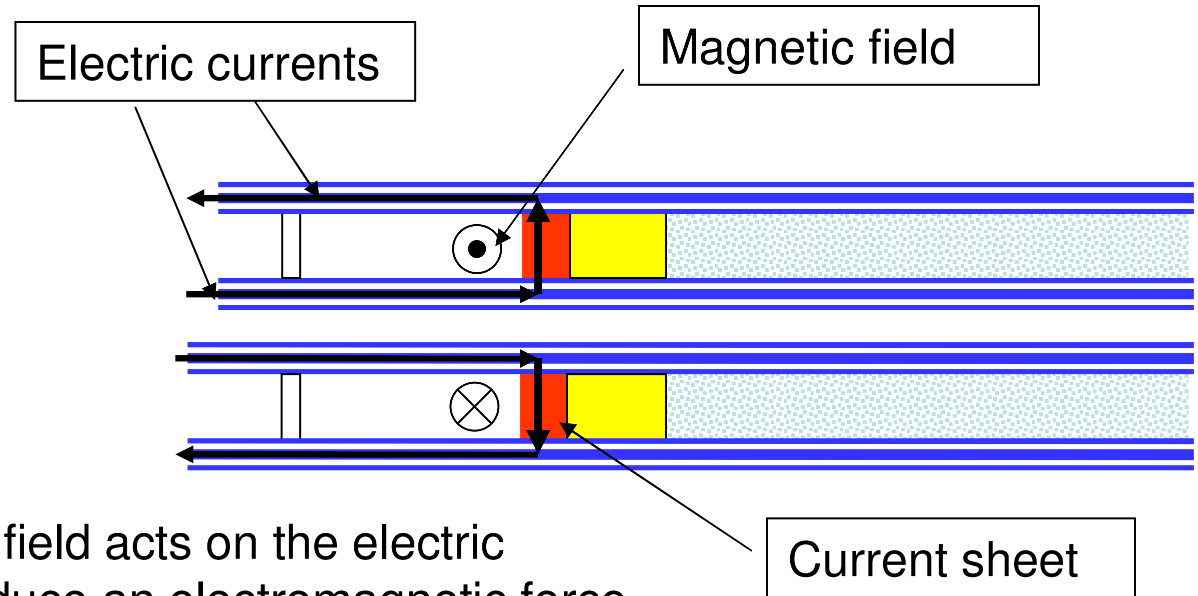
Conventional mode of operating pulsed plasma guns



Current sheet propagates down the electrodes, snow-plowing the gas ahead of it

What generates the accelerating force in an electromagnetically driven plasma gun

Electrical currents flowing in the electrodes induce magnetic field in between the electrodes by Ampere's Law



The magnetic field acts on the electric current to produce an electromagnetic force (the Lorentz force) on the current sheet. This is the force that accelerates the plasma.

$$\boxed{F_L = \frac{1}{2} L' I^2}$$

L' – the instantaneous inductance gradient experienced by the current sheet

40+ years of research based on this snow-plow mode of accelerating the plasma

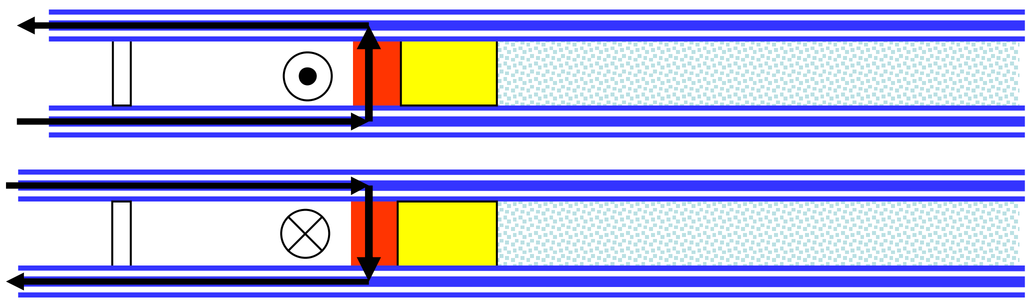
- Plasma guns were researched since the 1960's mainly by NASA (or its predecessor) and the Air Force as pulsed plasma thrusters (PPT) for space applications.
- The snow-plow mechanism was formulated by Marshall Rosenbluth in a 1952 paper to explain the acceleration of plasma in a theta pinch.
  - Researchers then apply it to accelerate plasma in plasma guns instead.
- PPTs have been flown by NASA and the Air Force on many satellites for station keeping
- Very well developed technology

However, there was an inherent performance barrier of the conventional PPTs

- Performance improvements on these PPTs grind to a halt in the mid-1990’s
- Thio reviewed the field and concluded the performance barrier was rooted in the pre-fill and the snow-plow mechanism of accelerating the plasma (Thio, 2000)

There were two major flaws in the snow-plow mechanisms

- Critical ionization velocity barrier
  - When the current sheet reaches a velocity sufficient to cause ionization of the neutral atoms in front of it, the neutral atoms are ionized, and energy is taken out of the current sheet, slowing it down
- The snow-plow was found to be leaky
  - Not all of the neutral atoms get entrained by the current sheet
    - Some leak past the current sheet
    - As bad as 10% to 20%
  - Neutrals left behind become seeds for arc re-strike behind the main plasma.
    - The restrike arc draws current away from the main current sheet, causing a reduction in the force of acceleration.



A paradigm shift is required: No pre-fill, no snow-plow, no surface flashover

- To produce plasma jets with the required density, velocity and Mach number required for PJMIF, a new mode of operating the plasma gun was proposed by Thio (2000) with the following prescription:
  (1) Evacuate the gun
  (2) Inject the plasma to be accelerated with sufficient density supersonically
  (3) Turn on the voltage across the injected plasma, producing a controlled current sheet over the back of the conducting plasma – no surface flashover.
    – The plasma has a well defined initial condition, making controlled acceleration of the plasma slab possible
  (4) The electrodes are shaped so that the plasma is accelerated as a compact slab

What happens when the electrodes are not shaped?

By Ampere's law, the magnetic field between the electrodes acting on the current sheet is given by:

$$B = \left(\frac{\mu}{2\pi}\right)\left(\frac{I}{r}\right)$$

In a plasma, the magnetic field exerts a pressure given by:

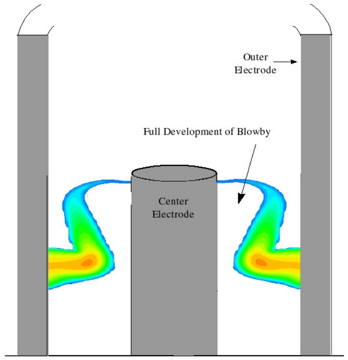
$$P_B = \frac{B^2}{2\mu}$$

The magnetic pressure on the plasma is thus:

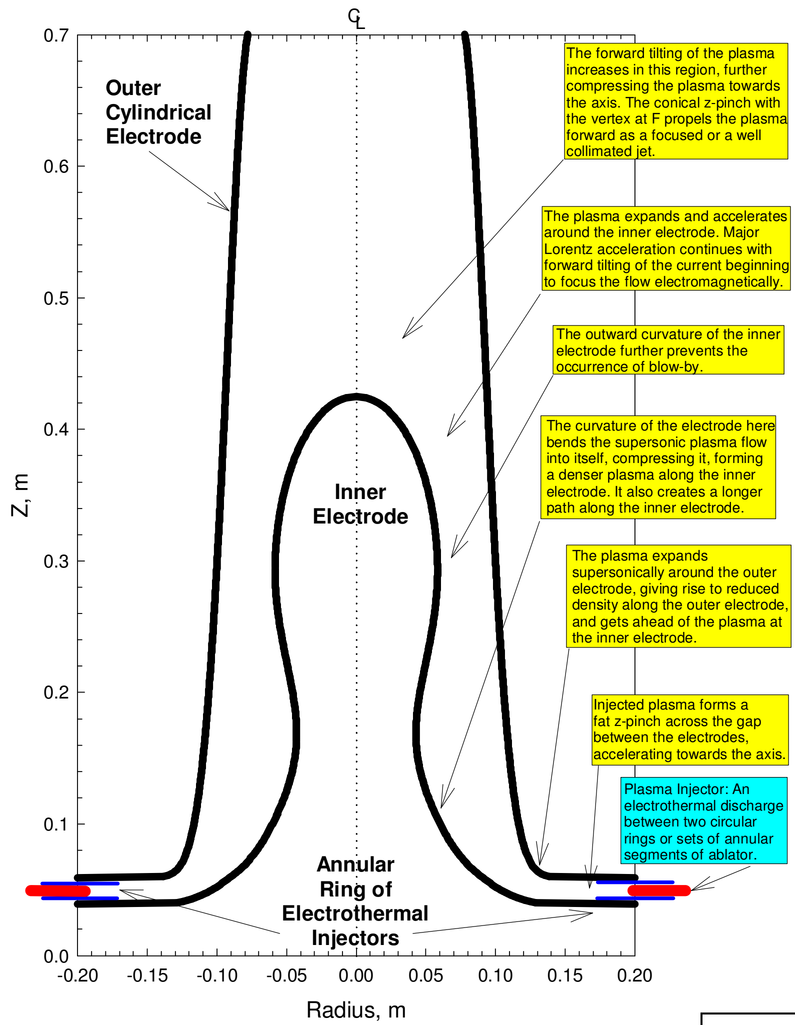
$$P_B \propto \frac{1}{r^2}$$

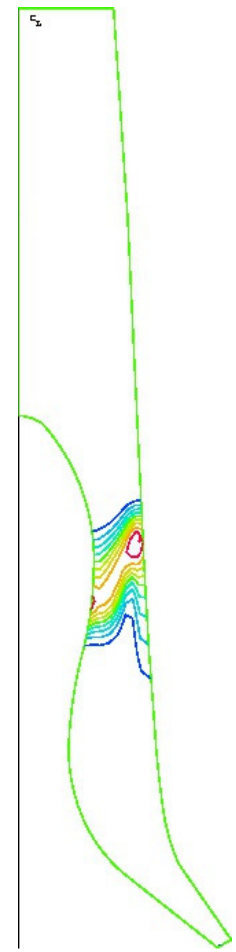
2D Magnetohydrodynamics simulation reveals what happens:

The magnetic field blow-by near the inner electrode and left most of the main plasma behind.



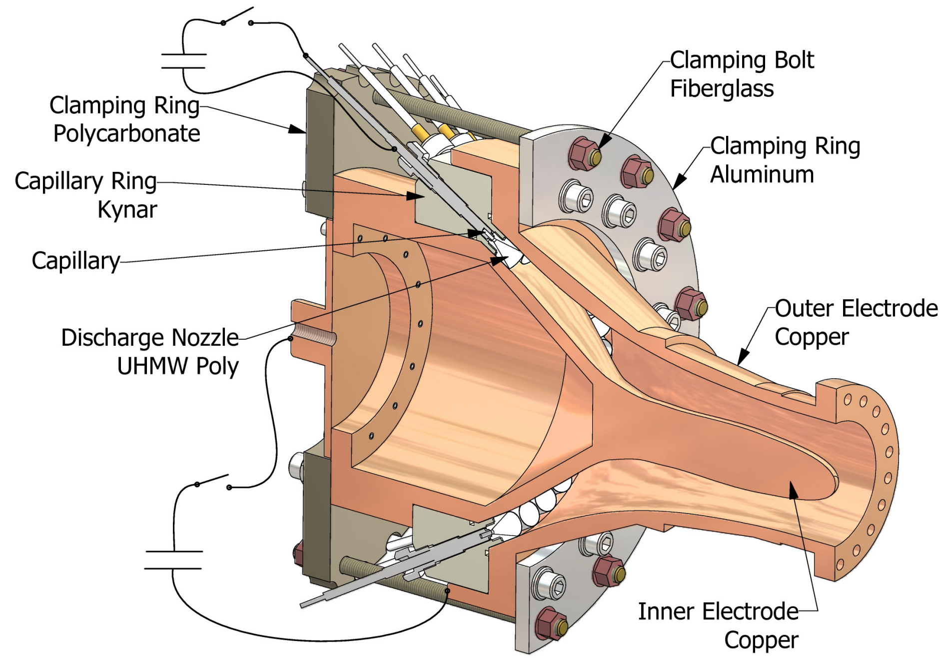
MHD shaping of the electrodes stabilize the acceleration of the plasma as a slab





2D MHD simulation showing no blow-by

Engineering implementation of the new plasma gun concept



Engineering implementation of the contoured coaxial plasma gun at HyperV Technologies Corporation

Parallel-plate mini-railgun plasma injectors at HyperV

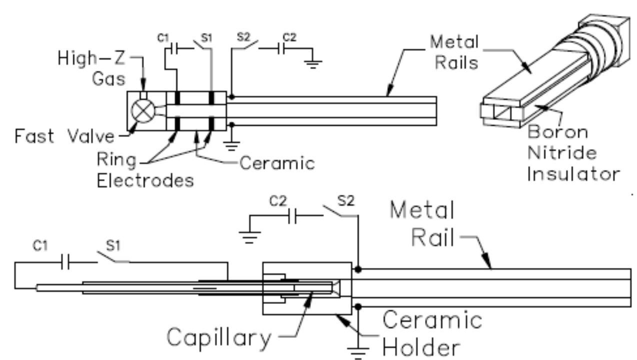
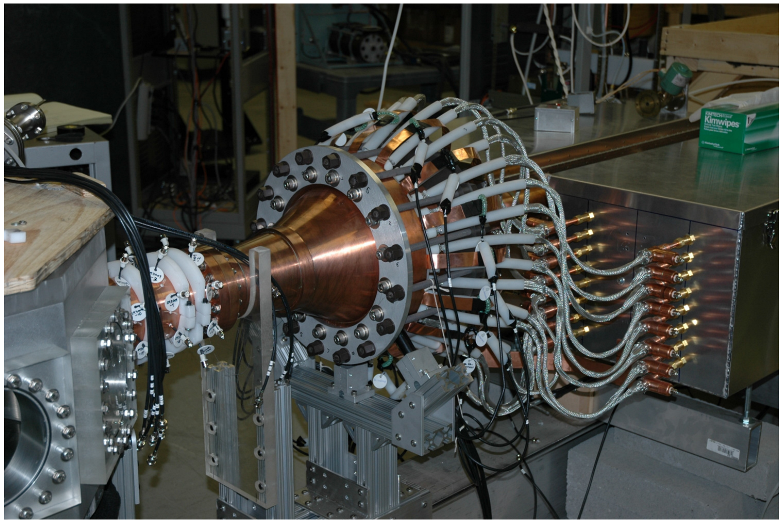
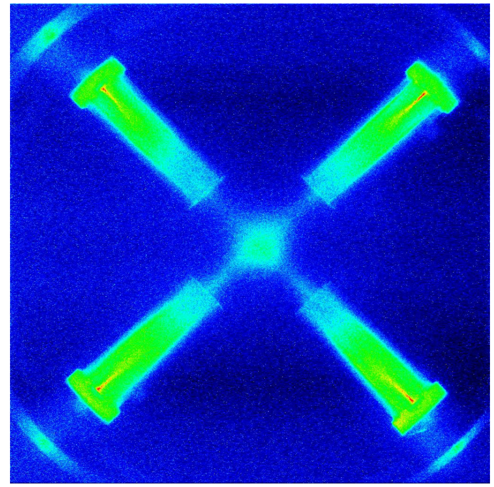
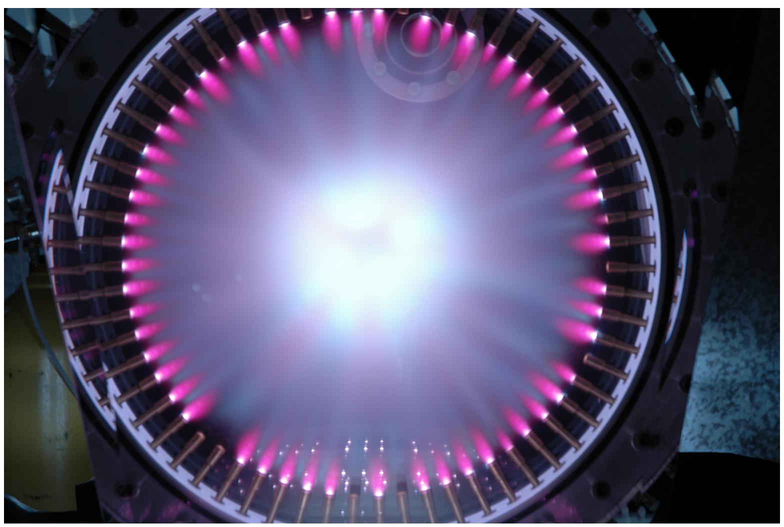


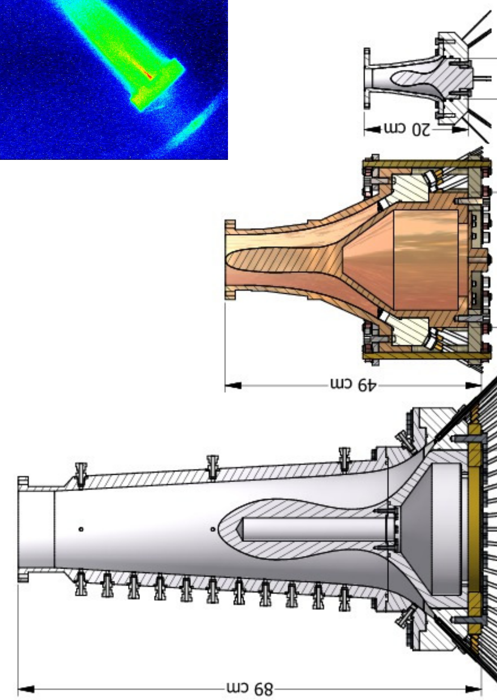
Figure 12 *Railgun with two versions of plasma injector, (top) ceramic capillary with fast valve gas injection, (bottom) polyethylene ablative capillary. The dimensions of the railgun relative to the injectors are not quite to scale here.*

We have now routinely produce plasma jets with these devices

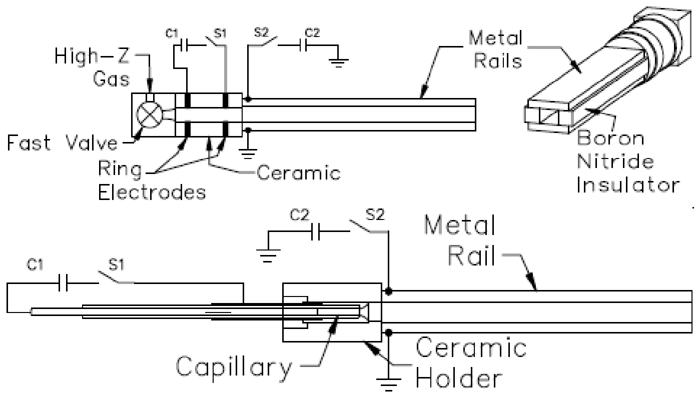








For expediency, in the LANL PLX experiment, we are using plasma railguns with cylindrical nozzle



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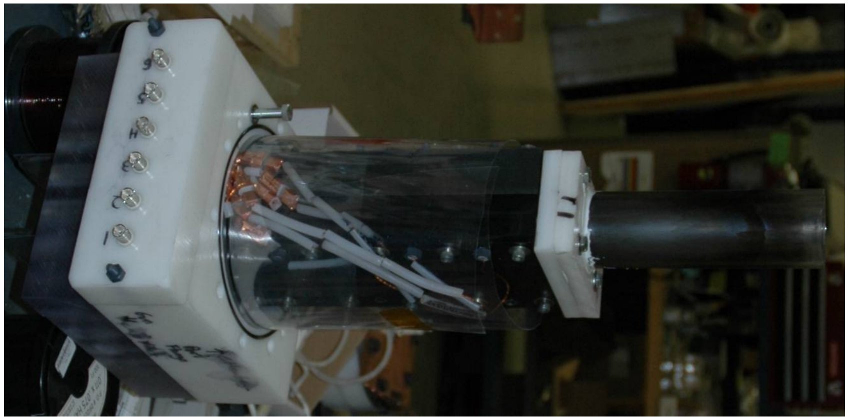
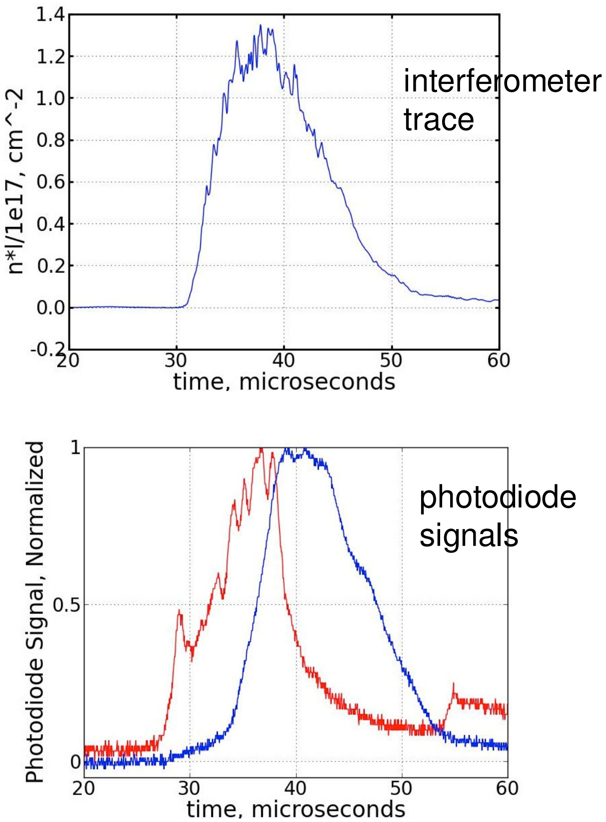


Latest measurements show:

- **Peak electron density ~ 10^{17} cm^{-3}**
- **Peak velocities > 40 km/s**
- **Total argon mass up to 4 mg**



*F. D. Witherspoon et al. (2011)

What remains to be done for the Plasma Guns

- *The overall objective is to deliver the required density, Mach number, velocity and degree of purity, and electric-to-kinetic efficiency*
  – Learn to inject two or more gaseous materials into the same gun
  - Demonstrate the ability to attain the required degree of purity
  - Demonstrate the attainment of the required jet density and mass
  - Demonstrate the attainment of the required jet Mach number (temperature)
  - Learn to operate the gun repetitively and demonstrate its lifetime between maintenance
  - Advanced 3D hybrid, 2-fluid, Hall PIC-MHD
- Development will be assisted by the development of predictive computer codes for modeling the gun.

Concluding Remarks

- PJMIF is an attractive fusion concept with relatively low-cost development path
- But development nonetheless
- Q: Can PJMIF produce economic fusion power?
  - There are a number of learning curves and uncertainties in the physics data to be acquired
  - The resolution of these uncertainties and learning curves is the objective of Phase I of the program, and will provide a definitive answer to the question
  - There is no guarantee what the answer will be at this point. It requires a minimum amount of research, pure and simple. It is part of what I meant by "seed funding."
  - By the same token, the company that pays for Phase I will own all the computer codes and the engineering experience and lessons, which collectively is the technological know-how.
  - This technological know-how might still be valuable in spin-off applications if the answer is "No", or it might be worth billions if it is "Yes". To the best of our knowledge, we believe the answer is likely to be "YES".