Simulation-Guided Design of a MegaJoule Dense Plasma Focus


September 18th, 2019
Outline

- Introduction to dense plasma focus (DPF)
- Neutron generation physics
- PIC modeling & benchmarks to measurements
- Simulation movies and restrikes
- Two ways current is diverted from pinch location:
  - Restrikes in plasma
  - Arcing behind gun
- Trends in the simulations → reduced order model
- Using the model to improve experiments
- Next questions to answer
Dense Plasma Focus: A coaxial plasma railgun

The “Mather” DPF: an open ended coaxial gun

DPFs make
• energetic (keV to MeV) beams
• x-rays
• neutrons (for D or DT gas)
DPFs can be sized for relevant yield

- **Anode length (cm)**
  - 5
  - 10
  - 30

- **Yield (DD)**
  - $1e^5-1e^6$
  - $1e^7$
  - $1e^{11}-1e^{12}$

**Legend**
- **90 kA** Portable active interrogation
- **200 kA** Accelerator-based AmBe replacement
- **2-3+ MA** Potential: survivability, neutron imaging
MegaJOuLe Neutron Imaging Radiography (MJOLNIR) design & build team

Now: 1 MJ/2.7 MA
Upgrade: 2 MJ/4+ MA
Stages of a DPF discharge

1) insulator flashover
2) run-down
3) run-in
4) pinch
Stages of a DPF discharge

1) insulator flashover
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Stages of a DPF discharge

1) insulator flashover
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3) run-in
4) pinch

Magnetic field fills volume where gas has been swept up
Stages of a DPF discharge

1) insulator flashover
2) run-down
3) run-in
4) pinch
Physics of neutron generation during z-pinch phase (according to 2D PIC simulations)
Physics of neutron generation during z-pinch phase (according to 2D PIC simulations)

\[ \text{Yield} = \int N_{\text{beam}} n_{\text{target}} L_{\text{target}} f(E)\sigma(E)\,dE \]

- \( N \) = number
- \( n \) = number density
Kinetic (particle) code captures anomalous resistivity and beam formation in plasmas

Fluid picture: each “pixel” is a fluid element with a density, temperature, and velocity

Kinetic picture: each “pixel” is a collection of particles; density, internal energy, and velocity are derived from collection

Kinetic model needed to get correct neutron yields in dense plasma focus (DPF)

- Each “pixel” in the pinch region is really 1,000-10,000 particles
- 100-500 million particles per simulation
- We resolve electron cyclotron motion (~femtosecond time-steps)
- ~1 million time steps

<table>
<thead>
<tr>
<th>Model</th>
<th>Neutrons</th>
<th>Agrees with experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic</td>
<td>$8.6 \times 10^6$</td>
<td>✓</td>
</tr>
<tr>
<td>Hybrid</td>
<td>$3.6 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>Fluid</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

A. Schmidt, V. Tang, D. Welch, PRL 2012
Details of LLNL PIC modeling

Simulations are performed in two coupled stages:
1. Single Fluid with MHD which establish the initial conditions and circuit dynamics
2. Kinetic PIC with Full Maxwell’s equations starting 10-20 ns prior to the pinch phase

Fluid to Kinetic Transition
- Maps Local plasma distribution function to a drifting Maxwellian of kinetic particles
- Preserve during transition
  1. Currents and Fields
  2. Plasma Conditions

Note: A typical 3 MA simulation takes 60-120 days of wall time. A few million cpuHrs

Resolution
Δx, Δz = 100–400 μm
Δt = 0.25–250 fs

Physics Models
- Collisions
- D-D/T Fusion packages

Circuit Driver
- Full Maxwell Equations
- Implicit Particle advance
  - Direct Implicit Scheme
  - Full Matrix Inversion for Field Advance
  - Currently resolving ωc across most of the simulation

Distribution Function in the Sheath

Ti ≈ 800 eV
Ni ≈ 5x Ambient
How a Dense Plasma Focus produces Neutrons

Beam Target dominates the total yield over thermonuclear
Model agrees within a factor of 2 with experimental yields

We have typically observed overall fairly good agreement but typical under predict the yield by roughly a factor of 2x for higher current MJ DPF shots

Similar scaling to Experiment but at half the coefficient
Near/far nToF agreement indicates that simulated pulse shape/neutron energies are reasonable.

Pulse shape agreement:
- Down-scattered neutrons (not in model)

Energy spread agreement:
- We get time offset?

Particle Model
5/16/2013 Shot 13 data
Example of a 200 kA fluid-to-kinetic simulation including restrikes
Particles accelerated across the gap to >1 MeV
DPFs show variable measured yields and kinetic simulations reproduce variability/stochasticity

Challenge: Find ways to increase average yield and simultaneously improve shot-to-shot consistency
High-yield pinches always exhibit strong $m=0$ instability in simulations.

High-yield pinch

ion density
log(cm$^{-3}$)

$rB_\theta$
Amps

$m=0$ instability

-4  0  4  8  12
time after stagnation [ns]

zoom region
4mm x 4mm
Electric field sets up in the gap between two separated blobs of plasma

- Electric field: \( \log(\text{kVcm}^{-1}) \)
- Ion density: \( \log(\text{cm}^{-3}) \)
- \( rB_\theta \)
- Amps

Zoom region
4mm x 4mm

Time after stagnation [ns]

-4 0 4 8 12

High-yield pinch

M=0 instability
Beam forms on axis when electric field sets up there

Beam creation
\[ \text{cm.s}^{-2} \]

Electric field
\[ \log(\text{kVcm}^{-1}) \]

Ion density
\[ \log(\text{cm}^{-3}) \]

\( rB_\theta \)
Amps

Zoom region
4mm x 4mm

High-yield pinch

\[ \text{m=0 instability} \]

-4 0 4 8 12
time after stagnation [ns]
In a low yield simulation, a full m=0 never sets up, possibly due to restrike currents.

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**Beam Creation**
- [cm.s⁻²]

**Electric Field**
- log(kV cm⁻¹)

**Ion Density**
- log(cm⁻³)

**rB_θ**
- Amps

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**Zoom Region**
- 4mm x 4mm

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**High-Yield Pinch**

**Low-Yield Pinch**

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**m=0 Instability**

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**Same Scales**

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**Cathode Flashover**
- Run down

**Anode Pinch**
- Insulator
Similar to restrikes, current arcing behind the gun diverts current from pinch

- Mystery: why wasn’t LLNL mini DPF producing expected yields?
- Hypothesis: current is flowing behind the gun

We can add a parasitic current path in the simulation behind the gun to simulate arcing behind the gun

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>$C_b$</td>
<td>400 nF</td>
</tr>
<tr>
<td>$L_b$</td>
<td>50.3 nH</td>
</tr>
<tr>
<td>$R_b$</td>
<td>80 mΩ</td>
</tr>
<tr>
<td>$V_s$</td>
<td>80 kV</td>
</tr>
<tr>
<td>$R_s$</td>
<td>1 mΩ – 1 kΩ</td>
</tr>
<tr>
<td>$L_{DPF}$</td>
<td>4.5 nH</td>
</tr>
</tbody>
</table>
Arcing behind the gun can introduce significant reduction in neutron yield

<table>
<thead>
<tr>
<th>Case</th>
<th>Trigger Voltage [kV]</th>
<th>Yield ($10^6$ Neutrons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>restrike</td>
<td>80</td>
<td>.02</td>
</tr>
<tr>
<td>no restrike</td>
<td>8000</td>
<td>0.9</td>
</tr>
</tbody>
</table>
The earlier the arcing, the worse the yield

![Graph showing the relationship between Rs turn on time (ns) and n yield.](image-url)
Simulations indicate that anode-to-sheath restriking is common

Trailing mass left behind by hydrodynamic instabilities create lower-inductance current pathways that divert current from the pinch region
Hollow anode mitigates anode-to-sheath restrikes
Lower yield shots show evidence of parasitic current diversion from pinch region
Lower yield shots show evidence of parasitic current diversion from pinch region

Vary resistance of a 5 nH current path (represents restrike near the insulator) to match low yield shot current trace in snow-plow model.

Ideal: measure location of restrike with b-dot or other probe.
Insights from PIC modeling to be applied to lower order model

- Beam temperature for a given DPF current doesn’t change much
- For a given stored energy class of DPFs, conversion efficiency of gun energy to beam energy is somewhat constant
  → Main influence on yield is through aerial density and temperature of target
- Large radius anode/long implosion time leads to hydrodynamic instabilities that appear early in run-in
  - We can mitigate these hydro instabilities with a tapered anode, where the taper stops at a particular radius. Mass is swept up starting from the radius where the taper stops (the “implosion radius”).
- Plasma target needs to be hot to minimize stopping power (increases aerial density average cross-section)
  - Too much mass in the implosion (high gas fill or large implosion radius) can cause target to be cold
- A hollow anode can help mitigate anode-to-sheath restrikes

From analytic shock physics: maximum achievable convergence ratio appears to be about 10 in a shock-driven cylindrical implosion
With a few assumptions, we can make a reduced order model to explore wide parameter space

\[ Yield = \int N_{beam} n_{target} L_{target} f(E)\sigma(E)dE \]

Simple Model:
- Assume the hydrodynamic disassembly time of the “target” >> duration of ion beam and acceleration time of ion beam
- Assume beam can’t miss the target, i.e. partially magnetized
  - Getting to sufficient areal density will probably mostly guarantee this
  - Larmor Radius for 1 MeV D\(^+\) near the pinch is about 0.5-1 mm
- Useful pinch length is ≈ 2 cm long
- Beam spectrum is decaying exponential
  \[ f(E) = e^{-E/E_b} \]
Anode design evolution influenced by both kinetic and reduced order models

Hollow anode
Reduce anode-to-sheath restrikes

Tapered anode
Delay hydrodynamic instabilities

Smaller radius hollow
Hotter plasma target
Example of how modeling insights helped improve anode design

- First anode fielded on MJOLNIR was unsuccessful at high current
- Modeling gave us insight that plasma target was not getting hot enough
- We reduced the hollow radius and recovered performance at high currents
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Key future questions

- In MJOLNIR, where do restrikes occur?
  - At base of DPF/insulator
  - In A-K gap
  - From anode-to-sheath

- How do we avoid restrikes?
  - Operating pressure
    - Could be problematic since high pressure is needed for high yields
  - Increase A-K gap
    - Increases head inductance, lowers peak current – what is effect on pinch current?
  - Anode shape

- What limits performance at higher pressures?