Simulation-Guided Design of a MegaJoule Dense Plasma Focus

A. Schmidt, E. Anaya, M. Anderson, J. Angus, S. Chapman, C. Cooper, C. Goyon, D. Higginson, I. Holod, E. Koh, A. Link, D. Max, Y. Podpaly, A. Povilus

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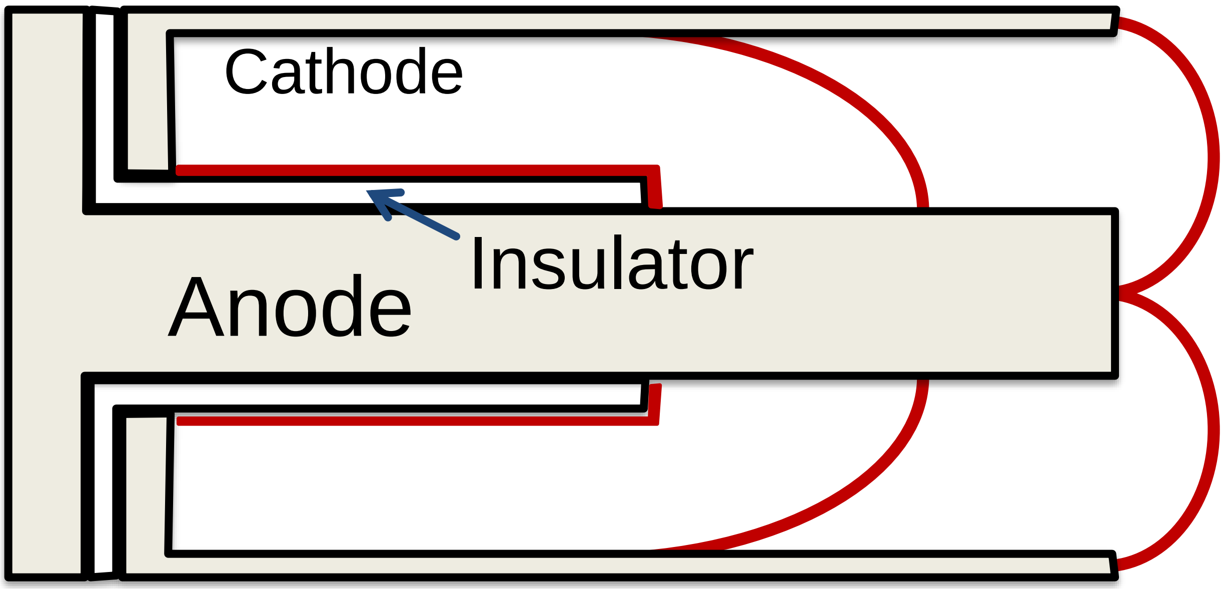
Outline

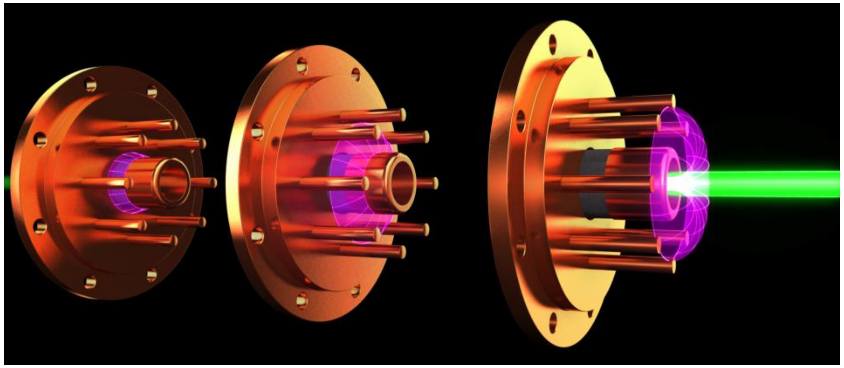
- Introduction to dense plasma focus (DPF)
- Neutron generation physics
- PIC modeling & benchmarks to measurements
- Simulation movies and restrikes
- Two ways current is diverted from pinch location:
  - Restrikes in plasma
  - Arcing behind gun
- Trends in the simulations→ reduced order model
- Using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

Dense Plasma Focus: A coaxial plasma railgun

The “Mather” DPF: an open ended coaxial gun

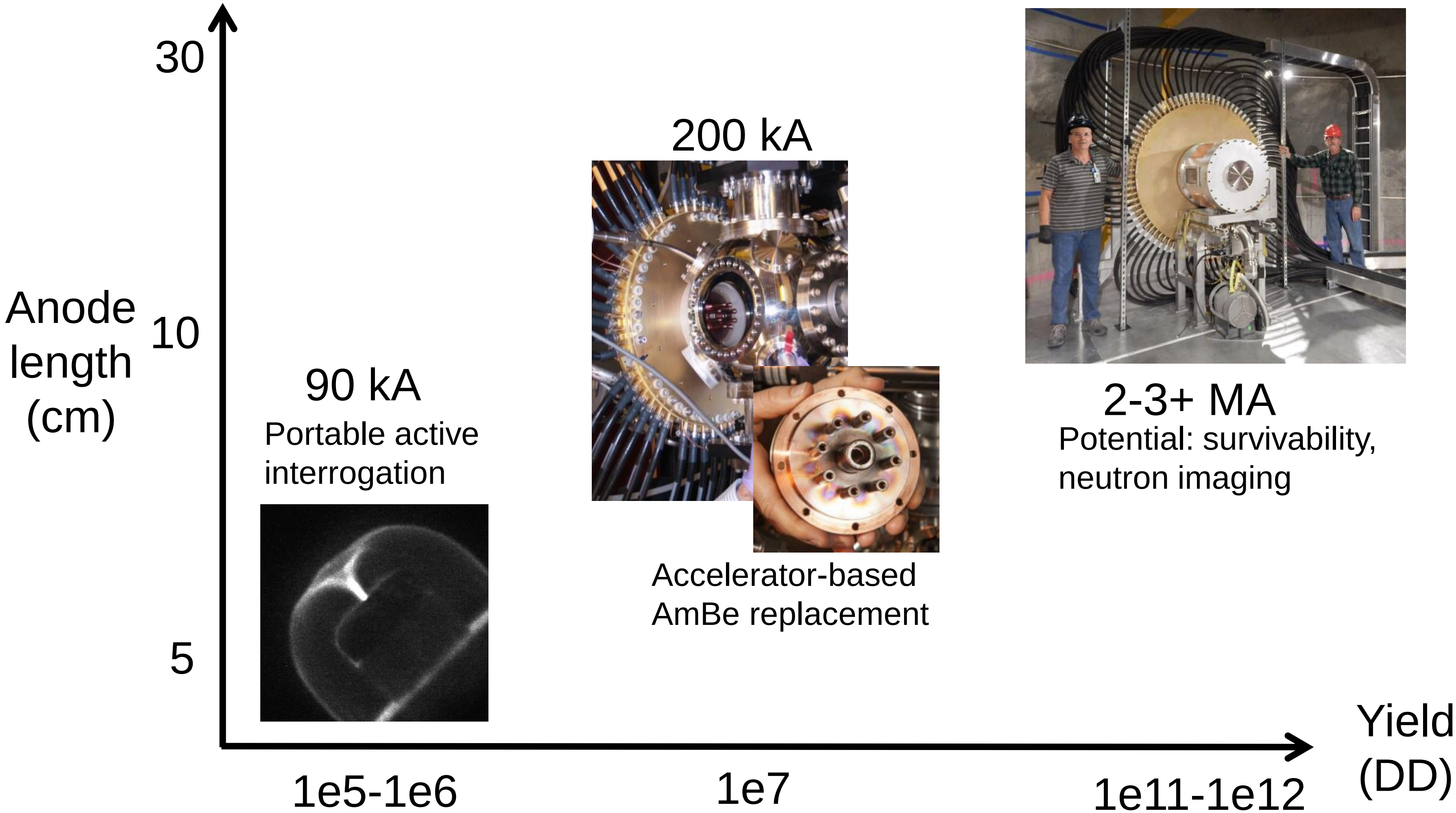


LLNL DPF

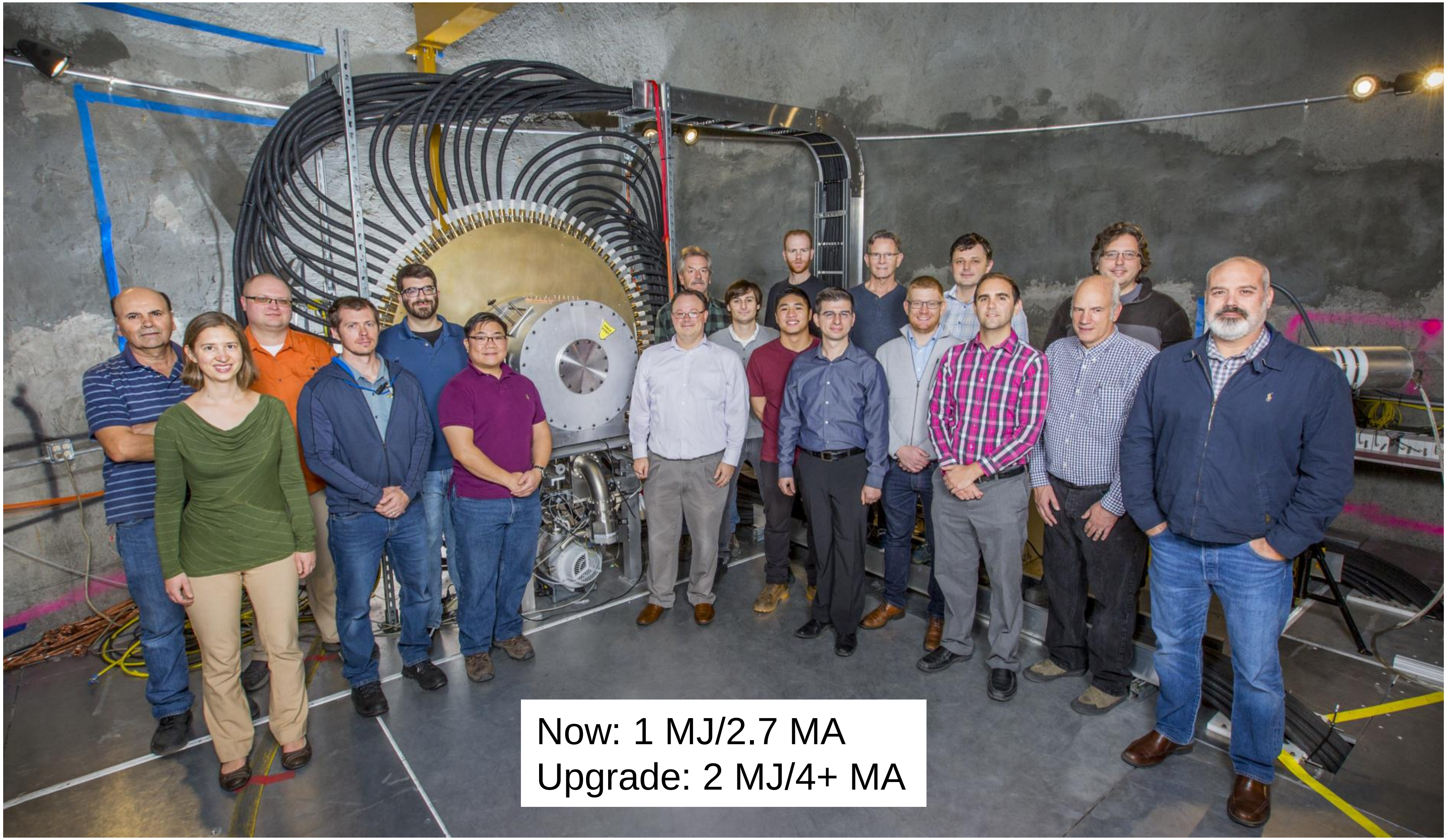


DPFs make
- energetic (keV to MeV) beams
- x-rays
- neutrons (for D or DT gas)

DPFs can be sized for relevant yield

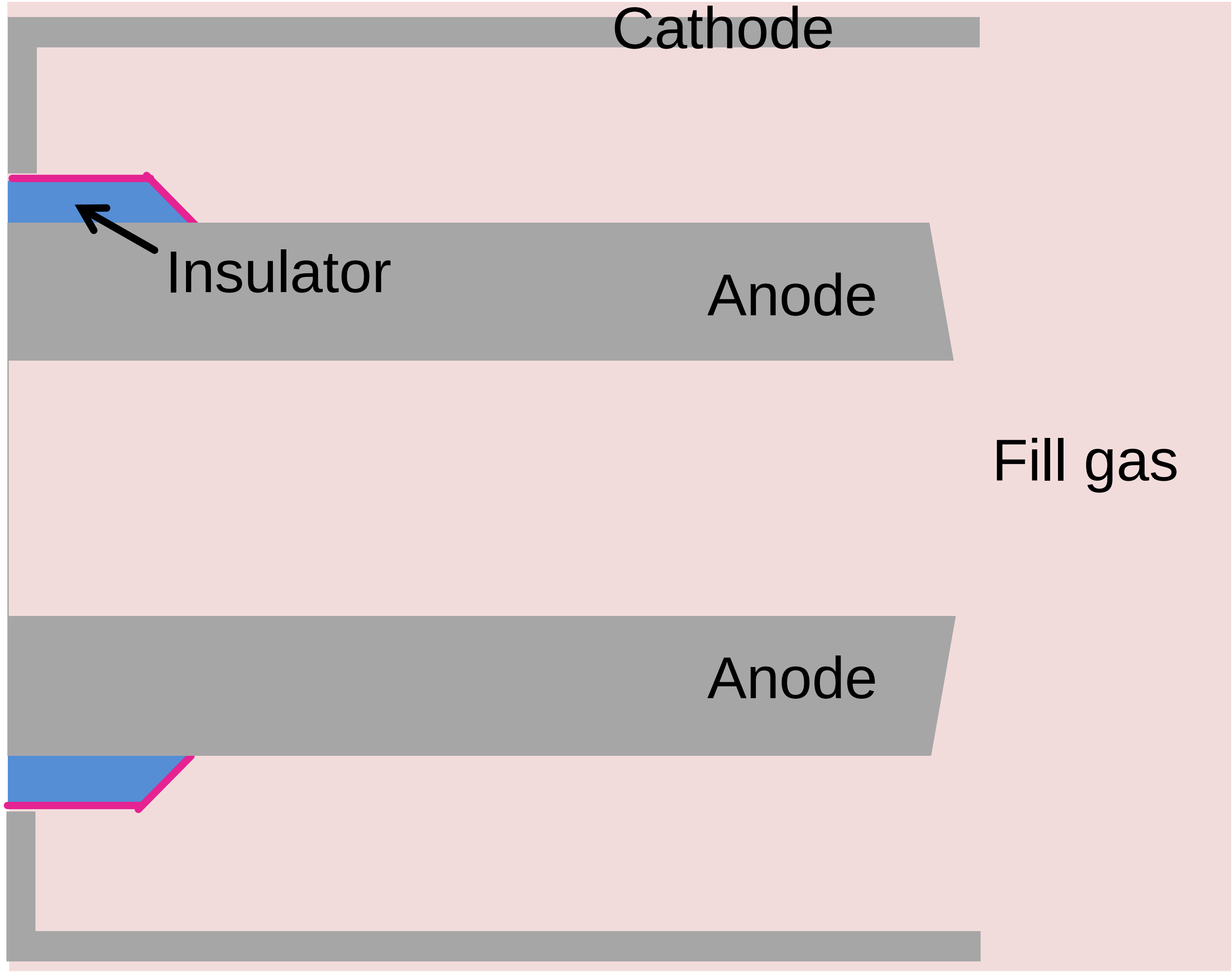


MegaJOuLe Neutron Imaging Radiography (MJOLNIR) design & build team



Now: 1 MJ/2.7 MA
Upgrade: 2 MJ/4+ MA

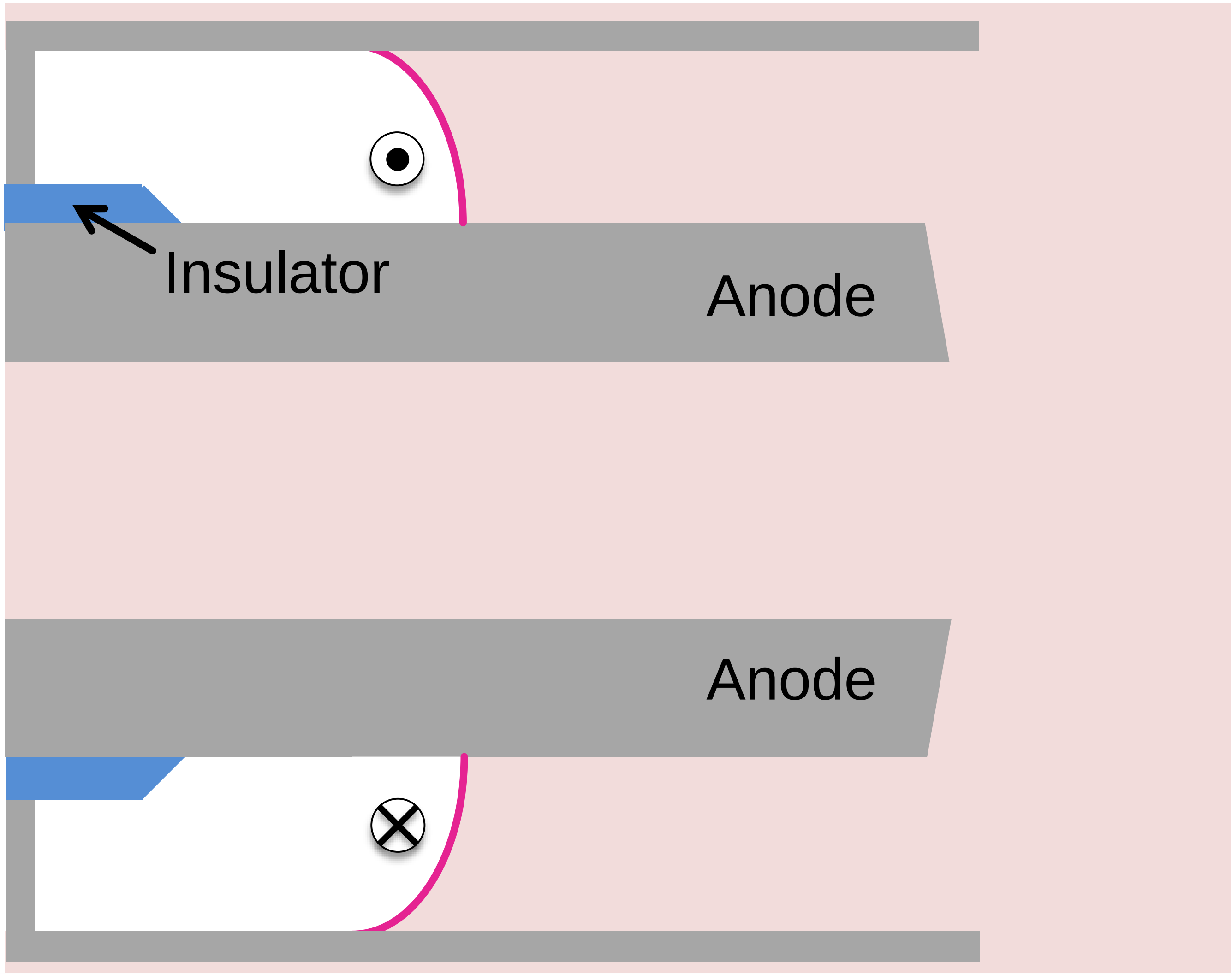
Stages of a DPF discharge



Stages of a DPF discharge

1) **insulator flashover**
2) run-down
3) run-in
4) pinch

Stages of a DPF discharge



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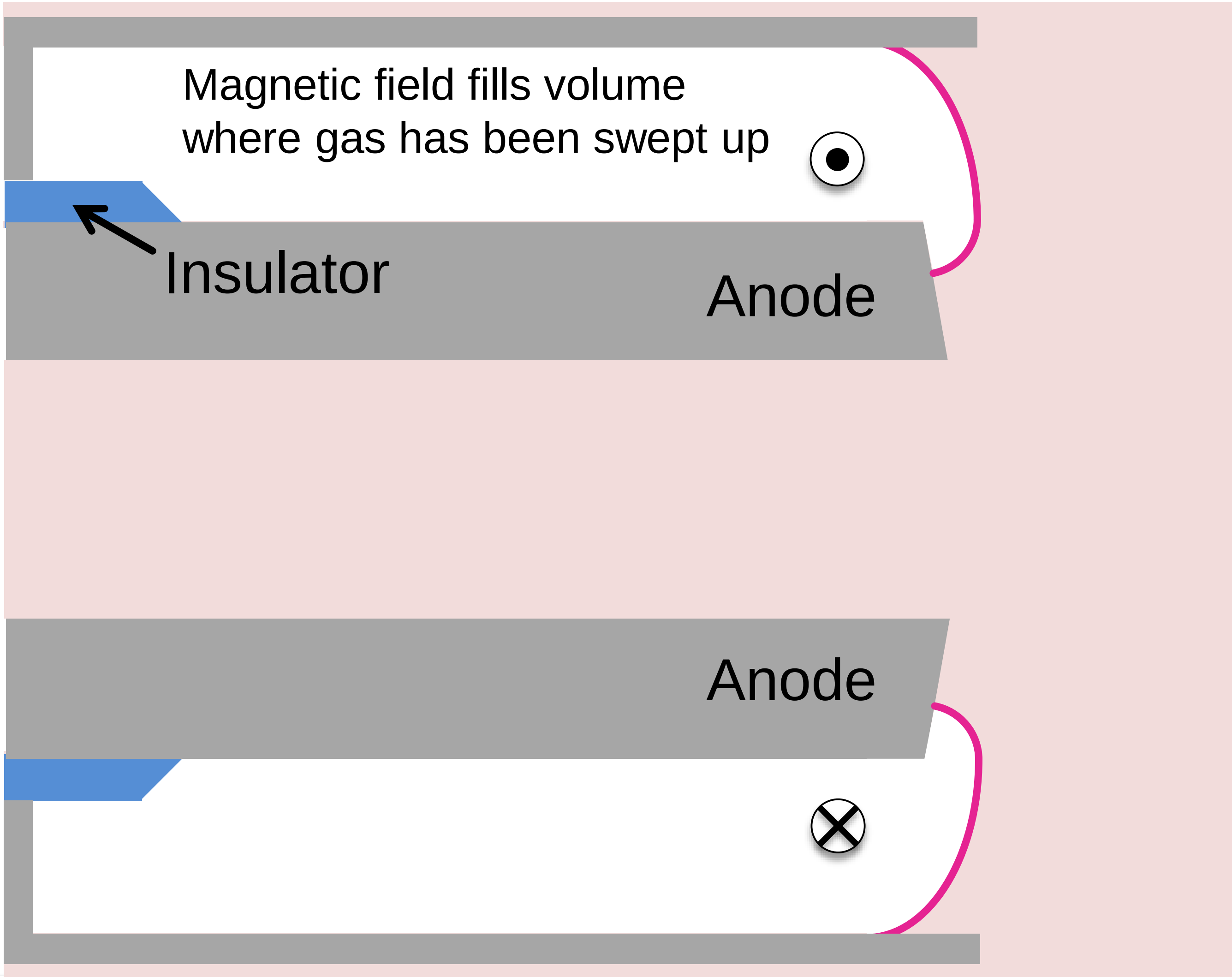

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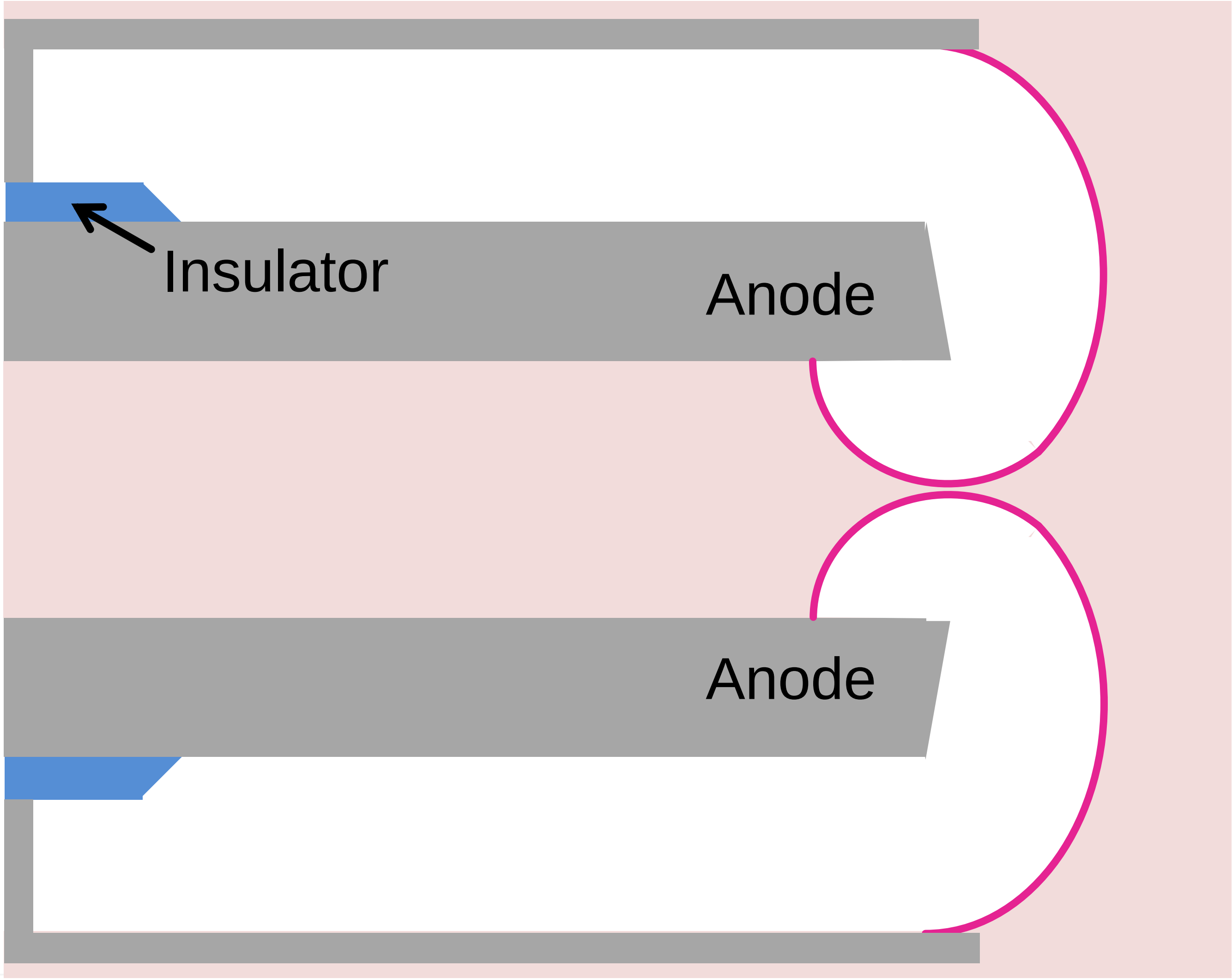
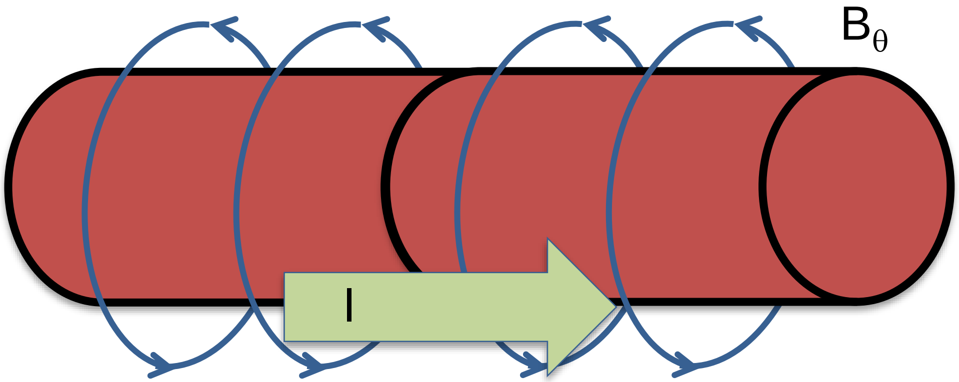


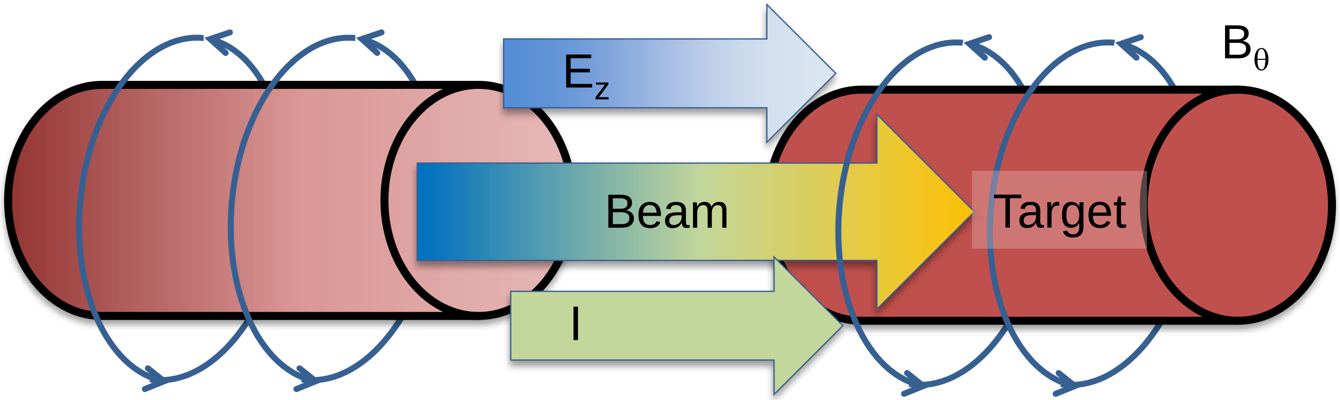
Stages of a DPF discharge

1) insulator flashover
2) run-down
3) run-in
4) **pinch**

Physics of neutron generation during z-pinch phase (according to 2D PIC simulations)

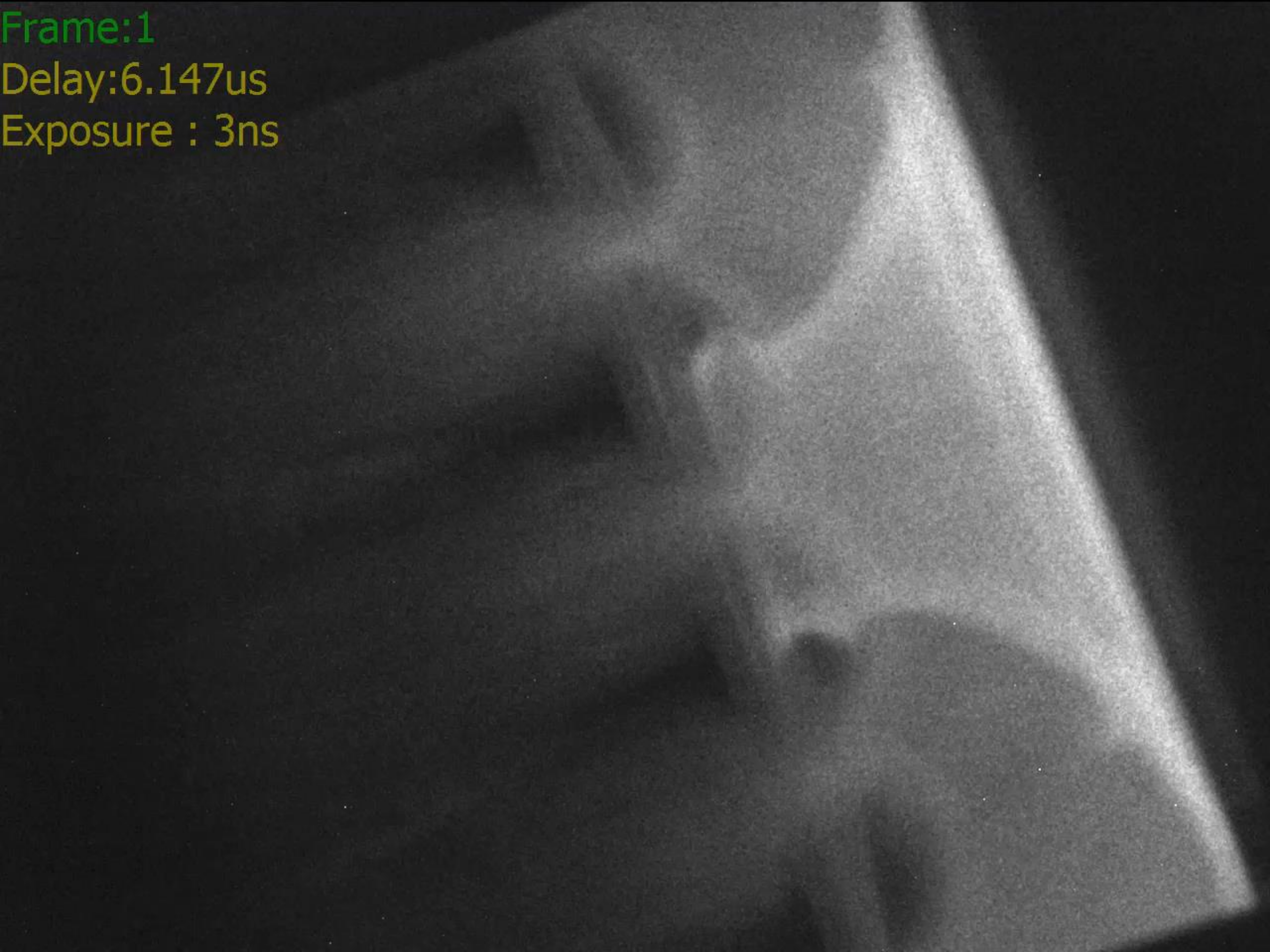


Physics of neutron generation during z-pinch phase (according to 2D PIC simulations)

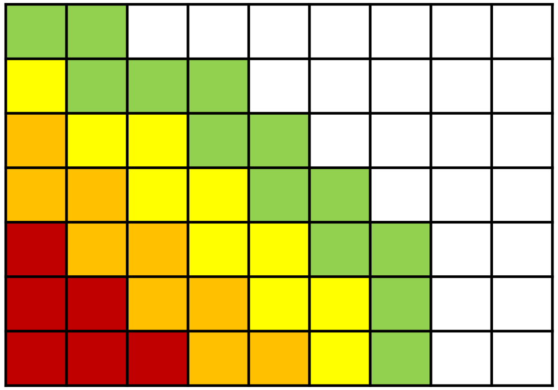


$$Yield = \int N_{beam} n_{target} L_{target}\, \mathrm{f(E)} \sigma(E) dE$$

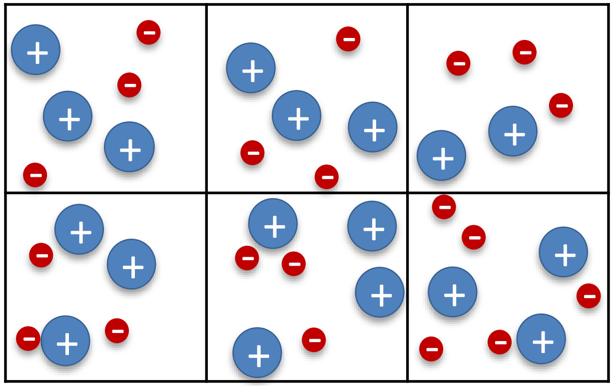
N = number
n = number density


Frame:1
Delay:6.147us
Exposure : 3ns

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)

Kinetic	8.6×10^6
Hybrid	3.6×10^4
Fluid	0

Agrees with experiment

A. Schmidt, V. Tang, D. Welch, PRL 2012

- 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

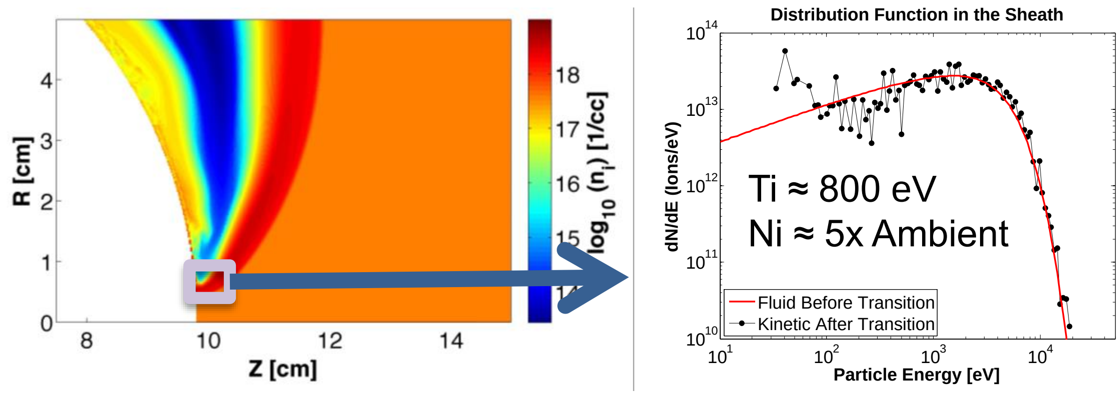
Details of LLNL PIC modeling

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

$\Delta x, \Delta z$ = 100–400 μm

Δt = 0.25–250 fs

Physics Models

- Collisions
- D-D/T Fusion packages

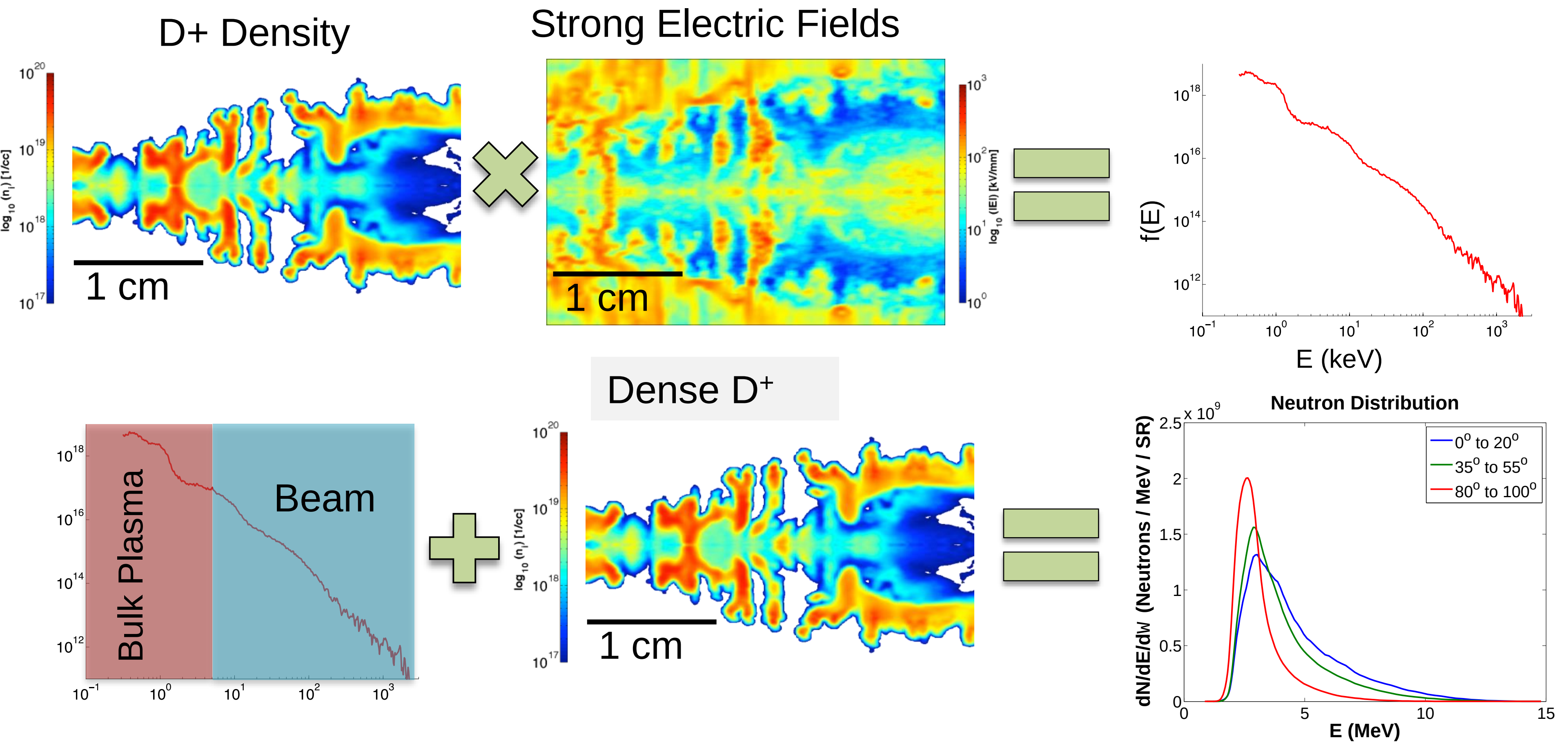
Circuit Driver

Full Maxwell Equations

Implicit Particle advance

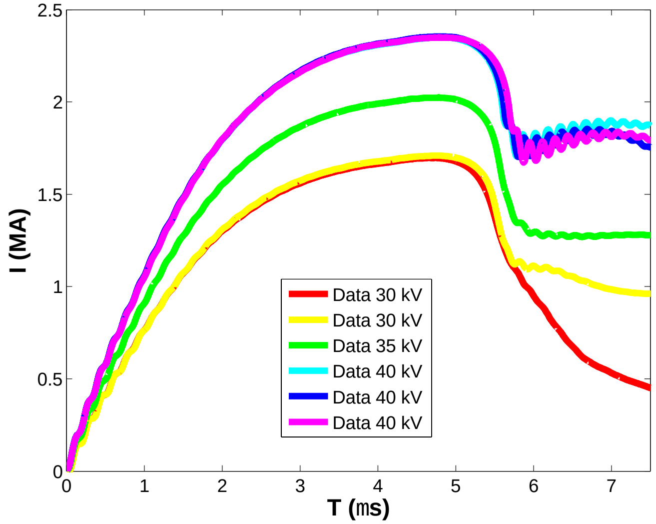
- Direct Implicit Scheme
- Full Matrix Inversion for Field Advance
- Currently resolving ω_c across most of the simulation

How a Dense Plasma Focus produces Neutrons

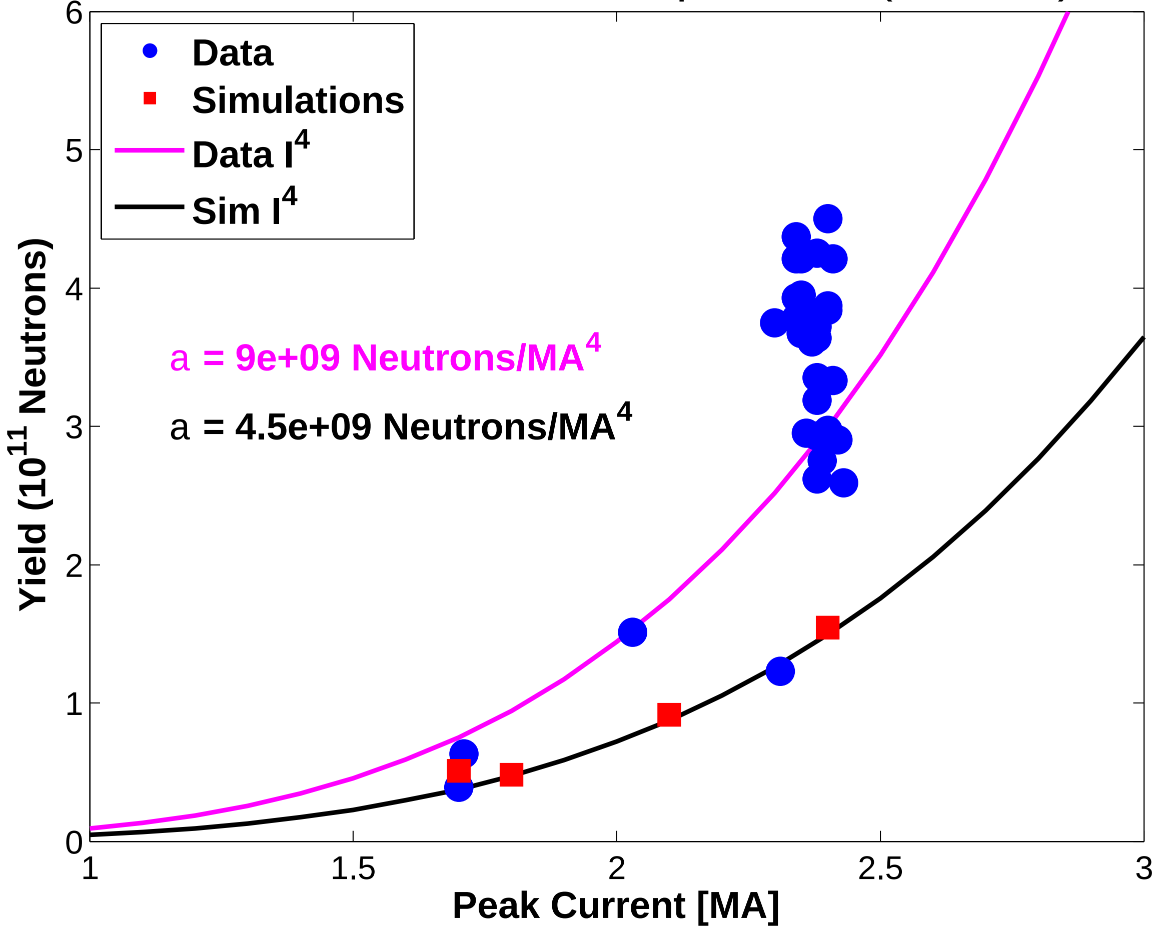


Beam Target dominates the total yield over thermonuclear

Model agrees within a factor of 2 with experimental yields



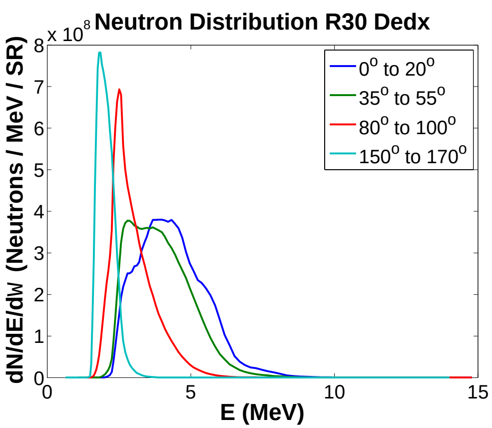
Data taken from Gemini experiment (Nevada)

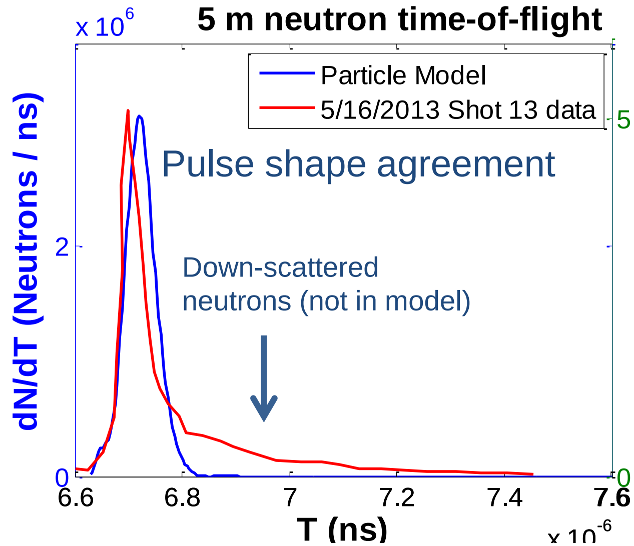


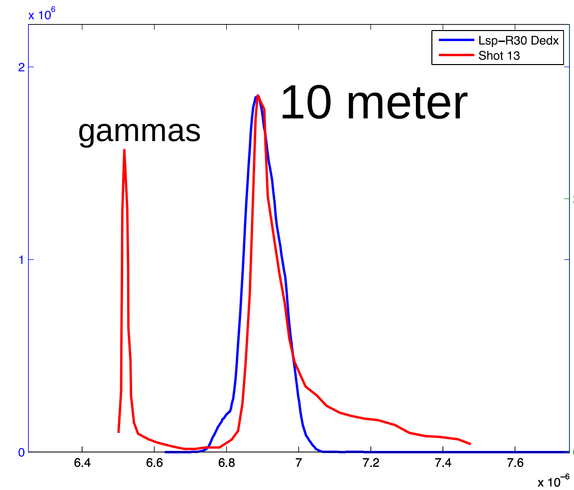
We have typically observed overall fairly good agreement but typical under predict the yield by roughly a factor of 2x for higher current MJ DPF shots

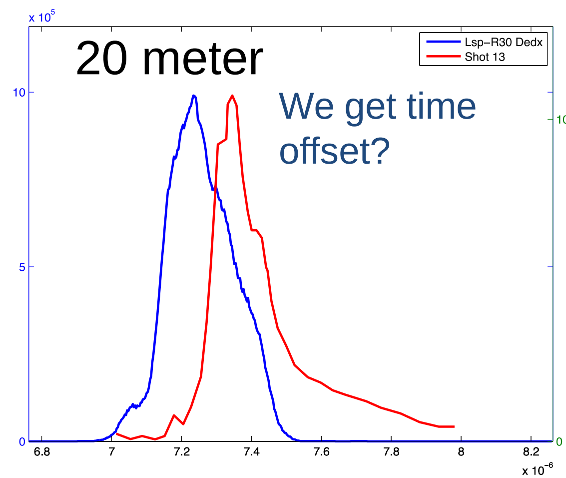
Similar scaling to Experiment but at half the coefficient

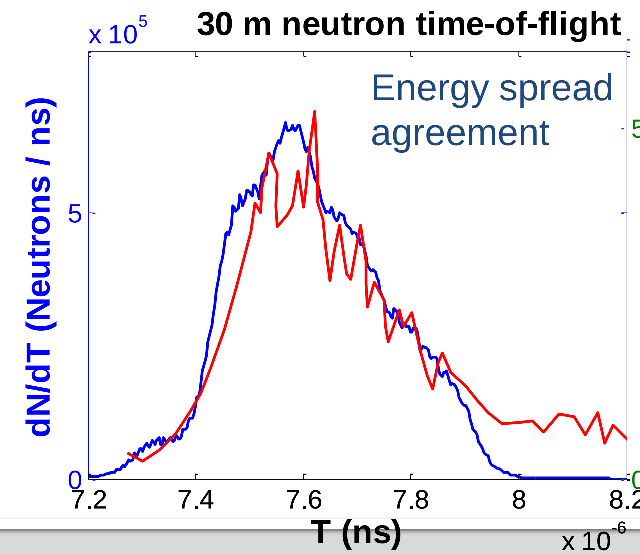
Near/far nToF agreement indicates that simulated pulse shape/neutron energies are reasonable



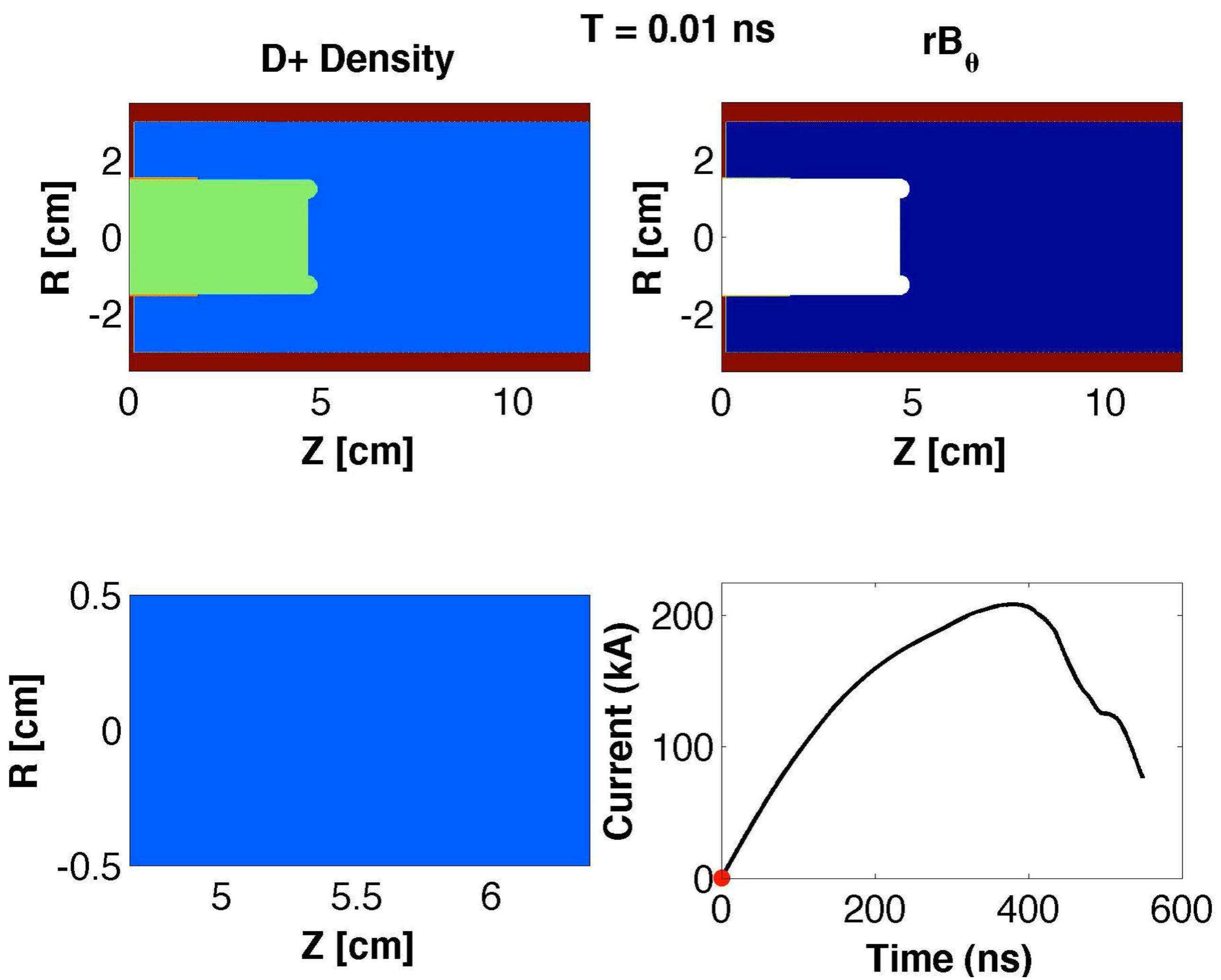




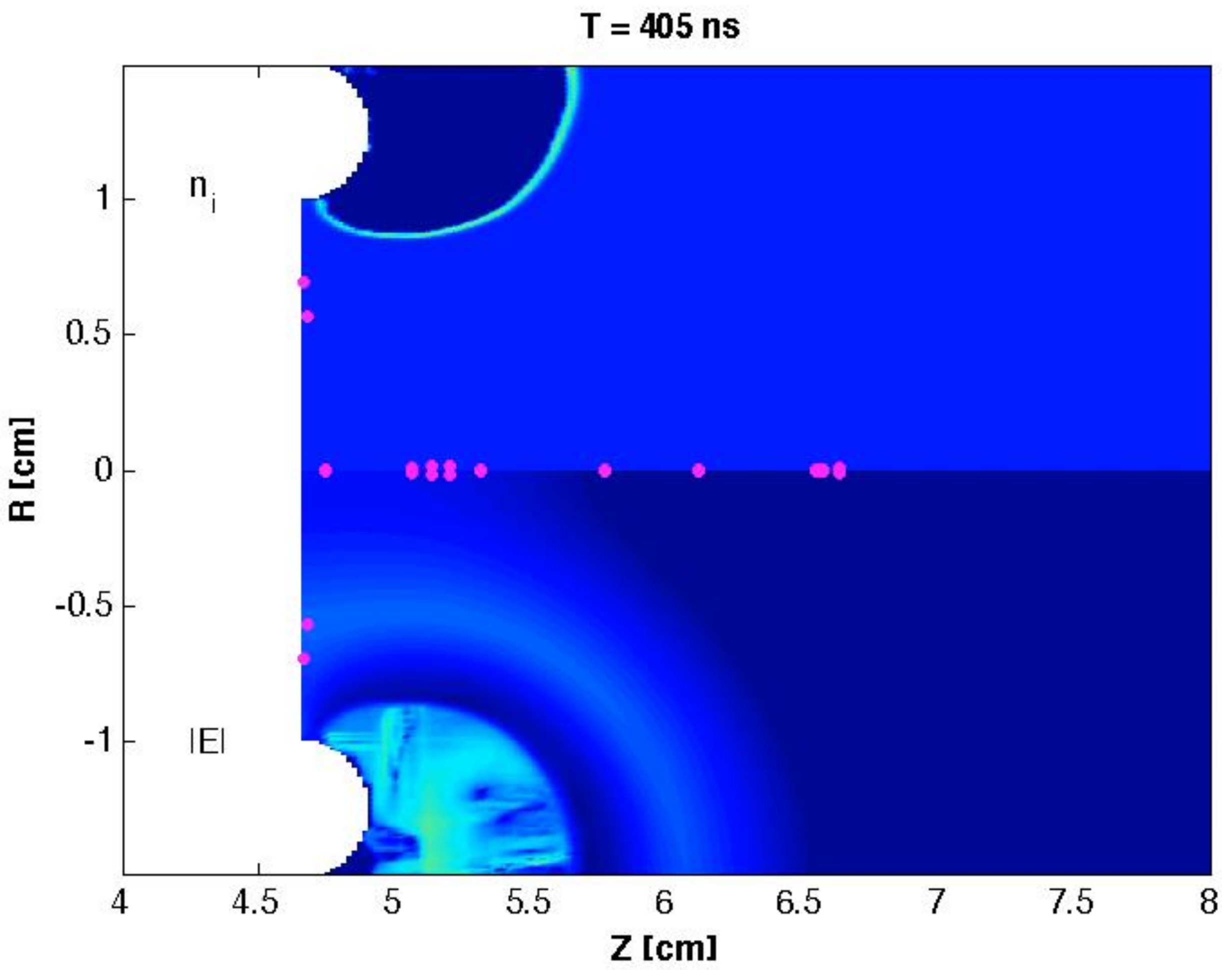




Example of a 200 kA fluid-to-kinetic simulation including restrikes

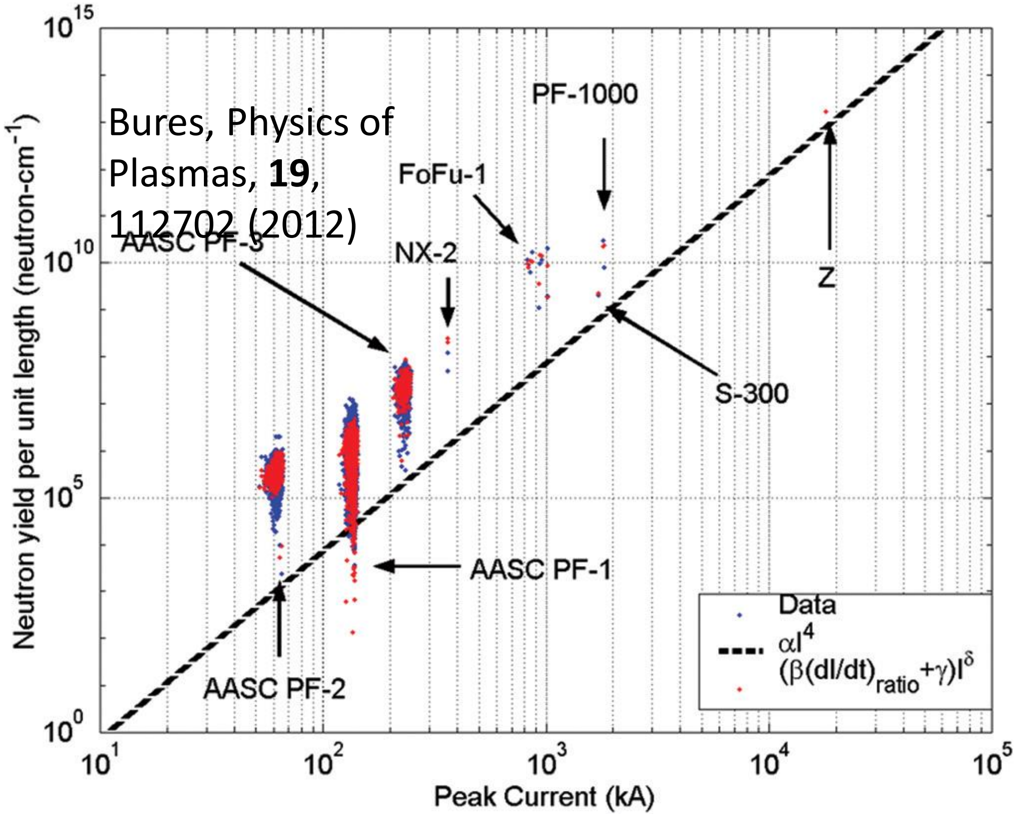


Particles accelerated across the gap to >1 MeV

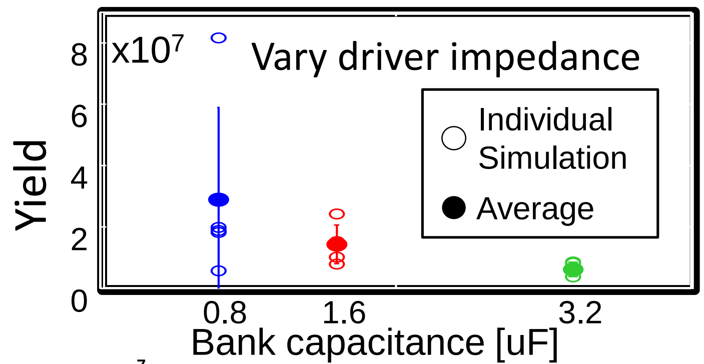


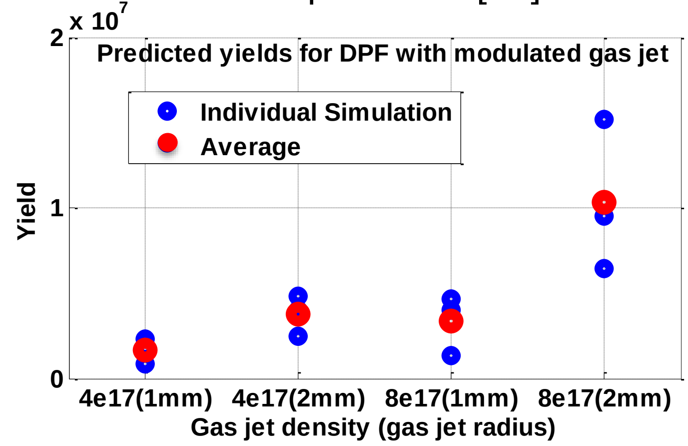
DPFs show variable measured yields and kinetic simulations reproduce variability/stochasticity

Data



Simulations

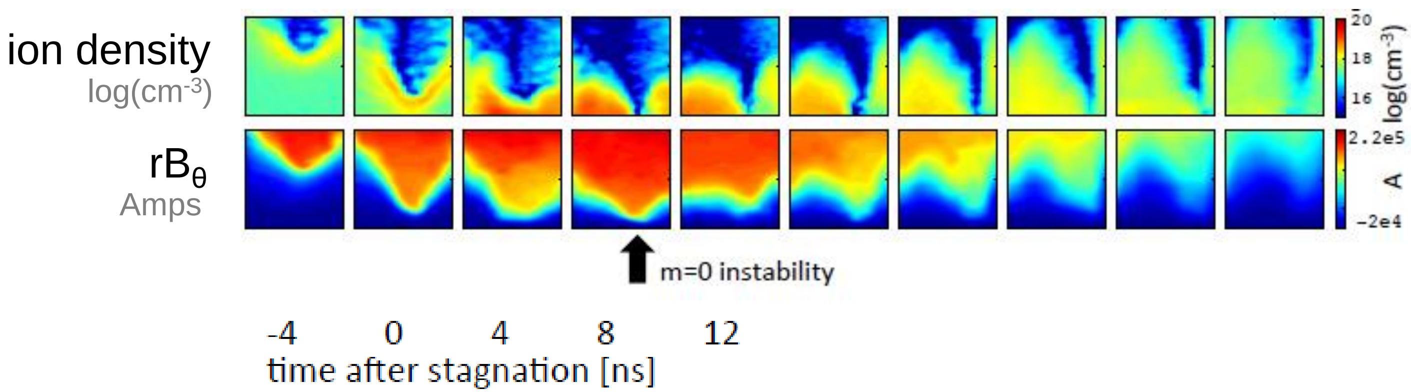




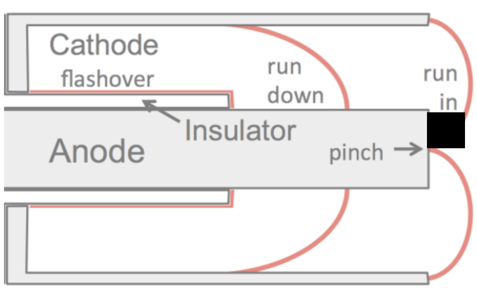
Challenge: Find ways to increase average yield and simultaneously improve shot-to-shot consistency

High-yield pinches always exhibit strong m=0 instability in simulations

High-yield pinch



zoom region
4mm x 4mm



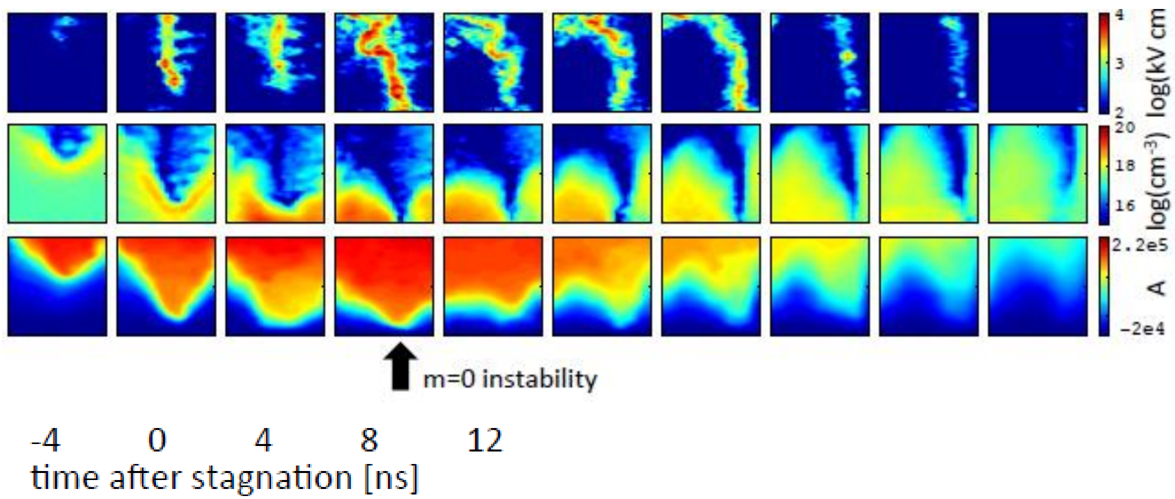
Electric field sets up in the gap between two separated blobs of plasma

High-yield pinch

electric field
log(kVcm[-1])

ion density
log(cm[-3])

rB_θ
Amps



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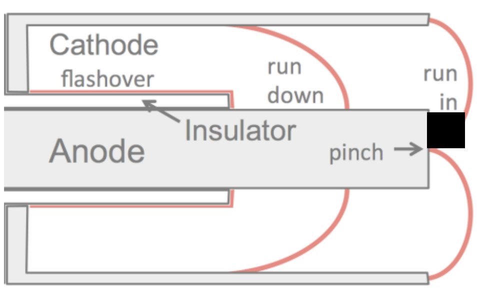
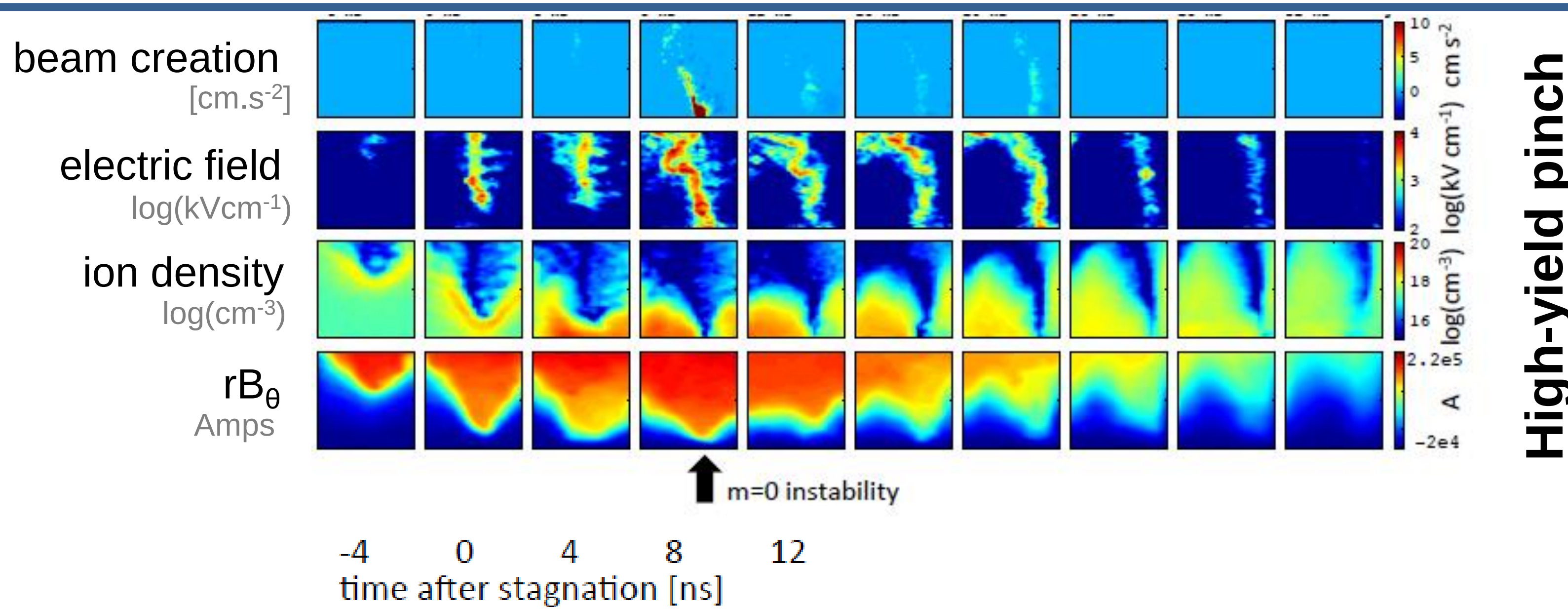
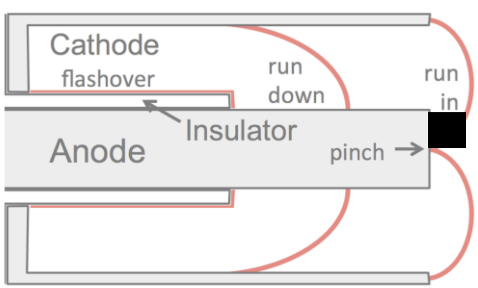


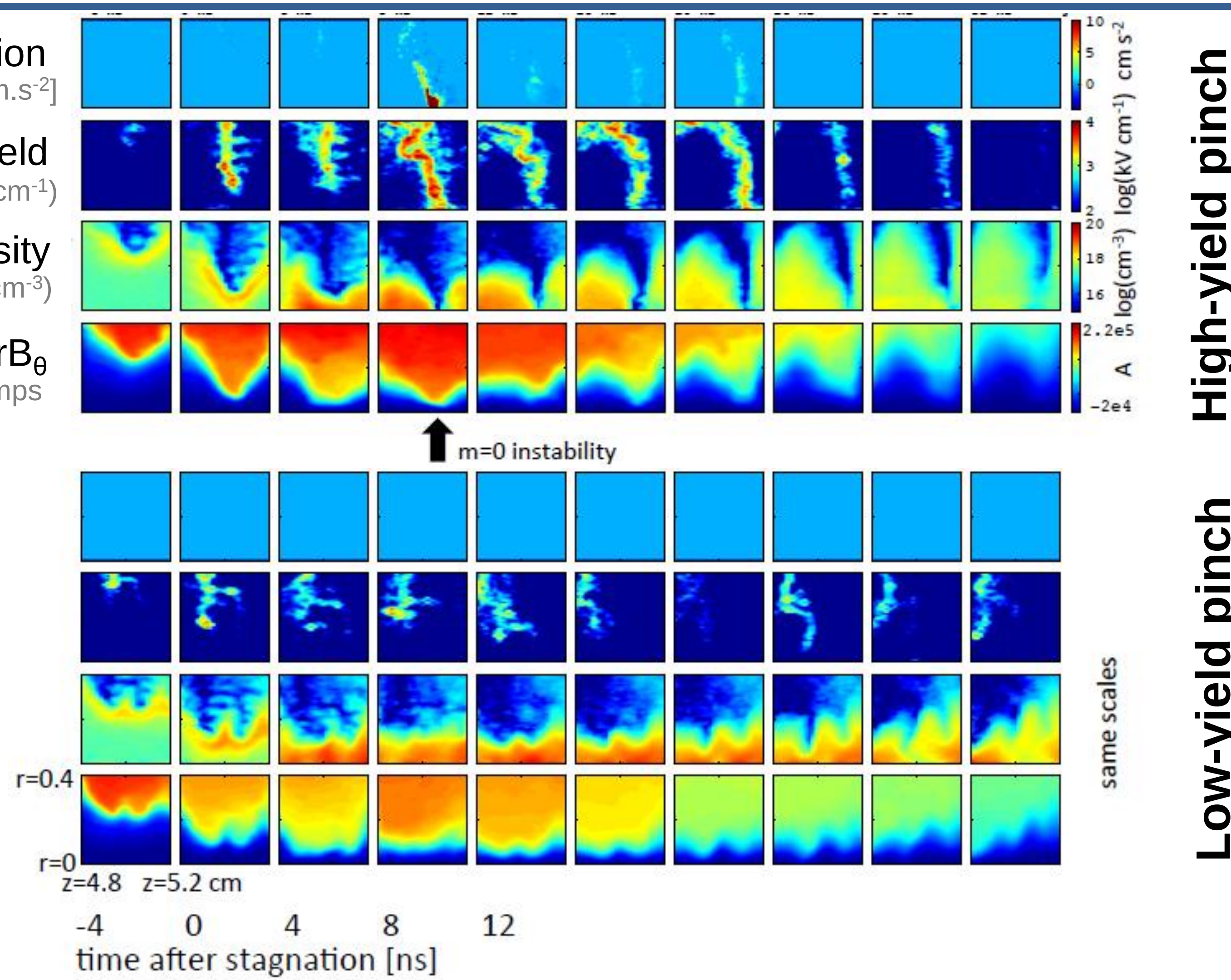
Beam forms on axis when electric field sets up there



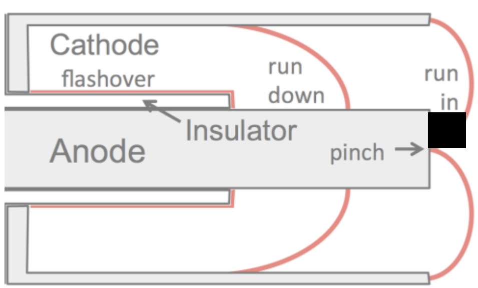
zoom region
4mm x 4mm



In a low yield simulation, a full m=0 never sets up, possibly due to restrike currents

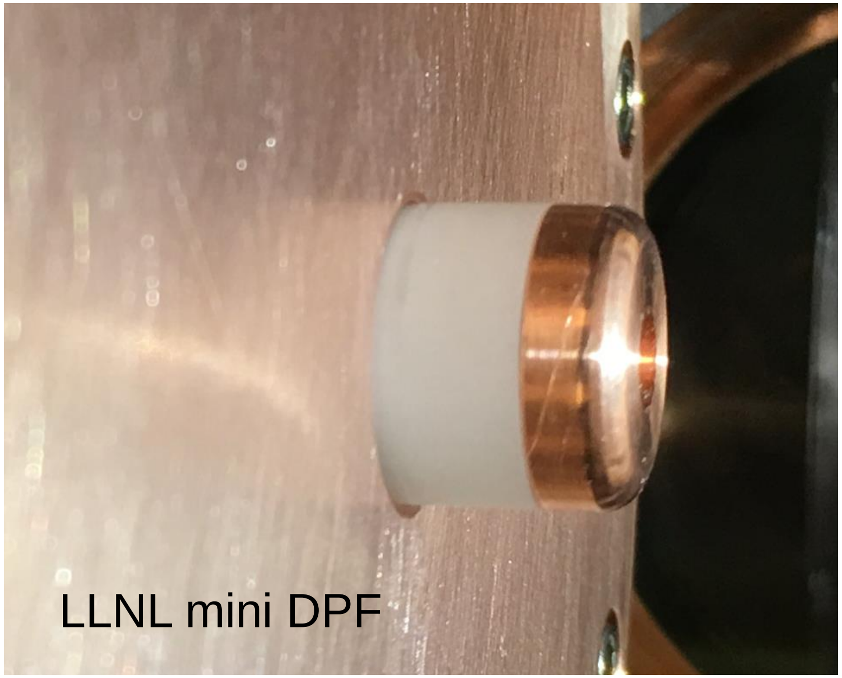


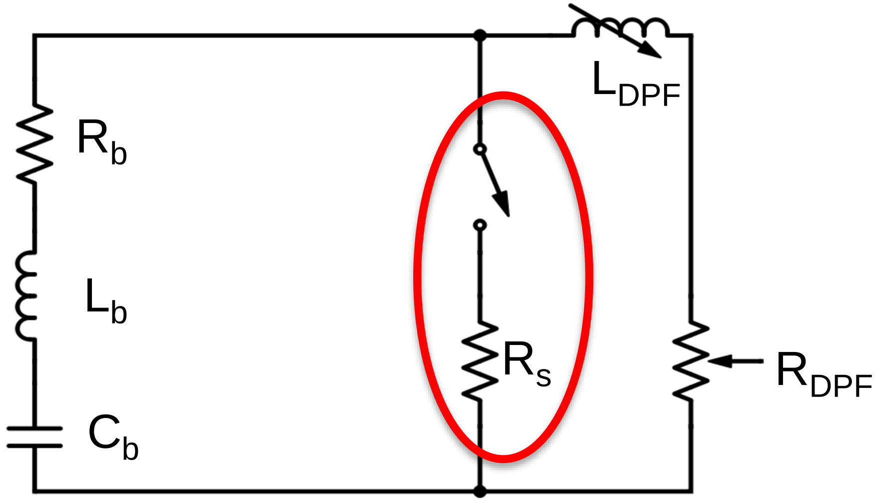
zoom region
4mm x 4mm



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

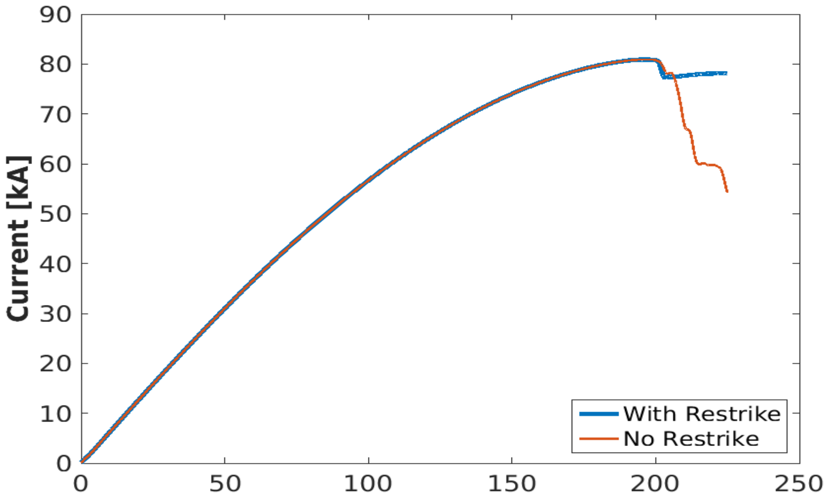


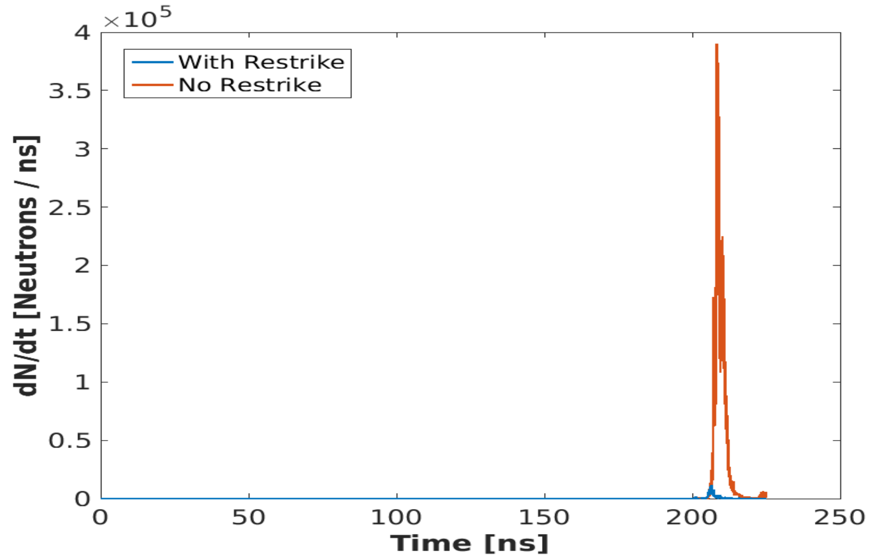


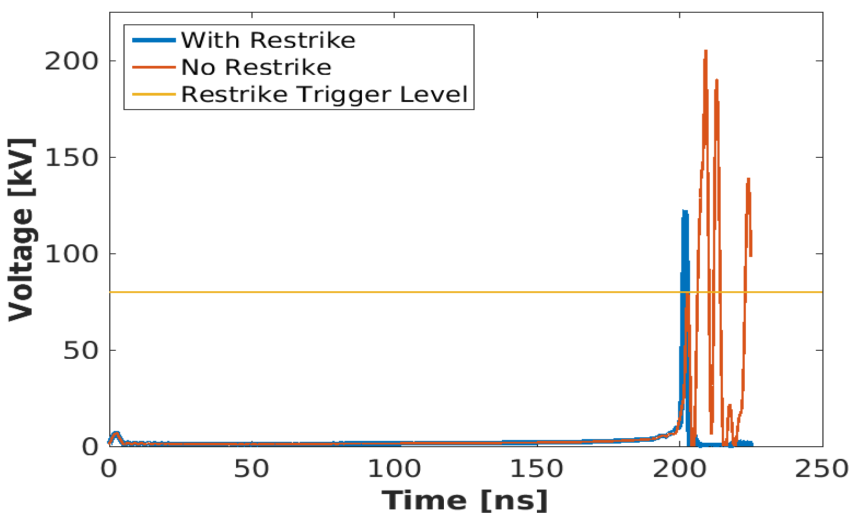
C_b	400 nF
L_b	50.3 nH
R_b	80 mΩ
V_s	80 kV
R_s	1 mΩ – 1 kΩ
L_{DPF}	4.5 nH

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

Arcing behind the gun can introduce significant reduction in neutron yield

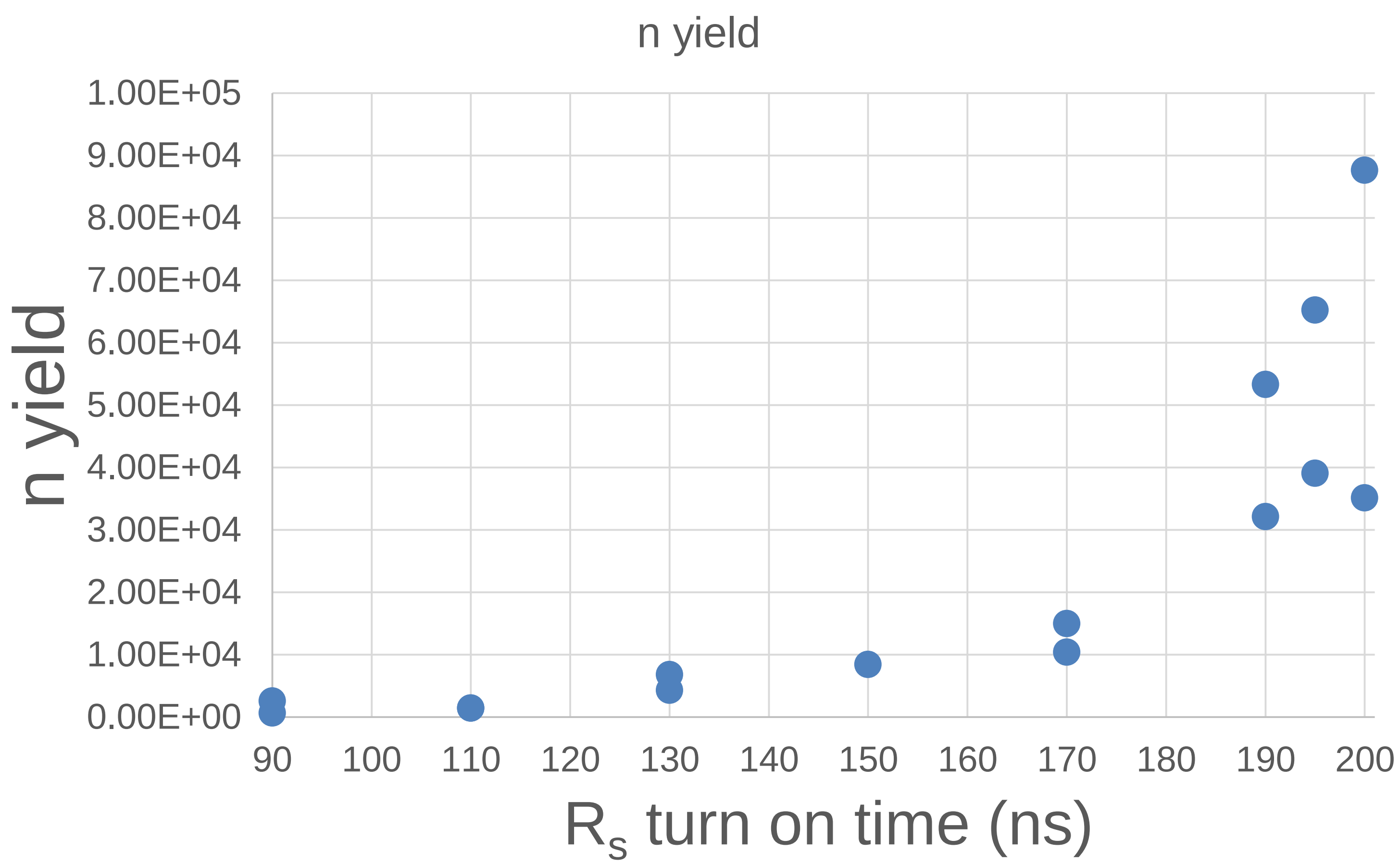




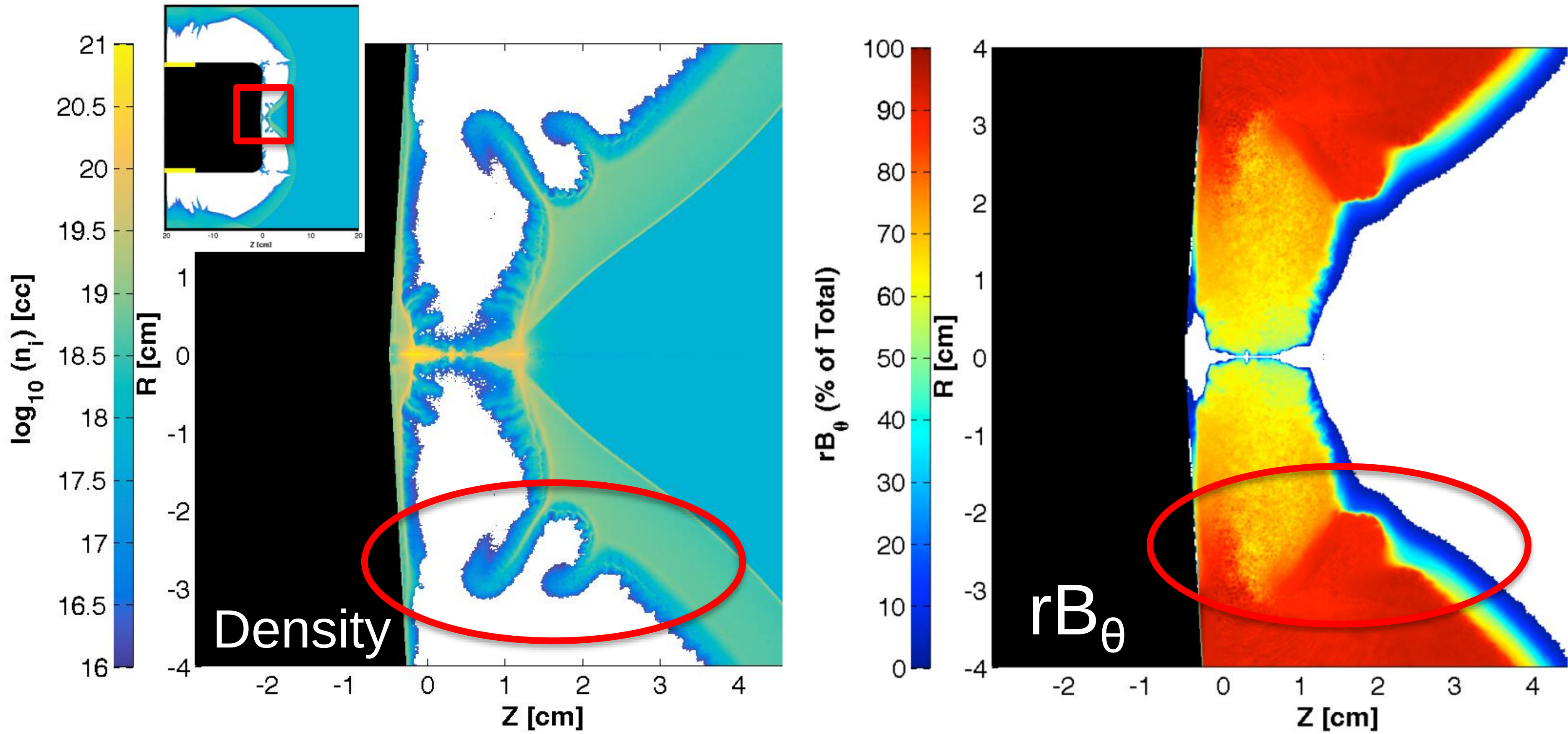


Case	Trigger Voltage [kV]	Yield (10^6 Neutrons)
restrike	80	.02
no restrike	8000	0.9

The earlier the arcing, the worse the yield

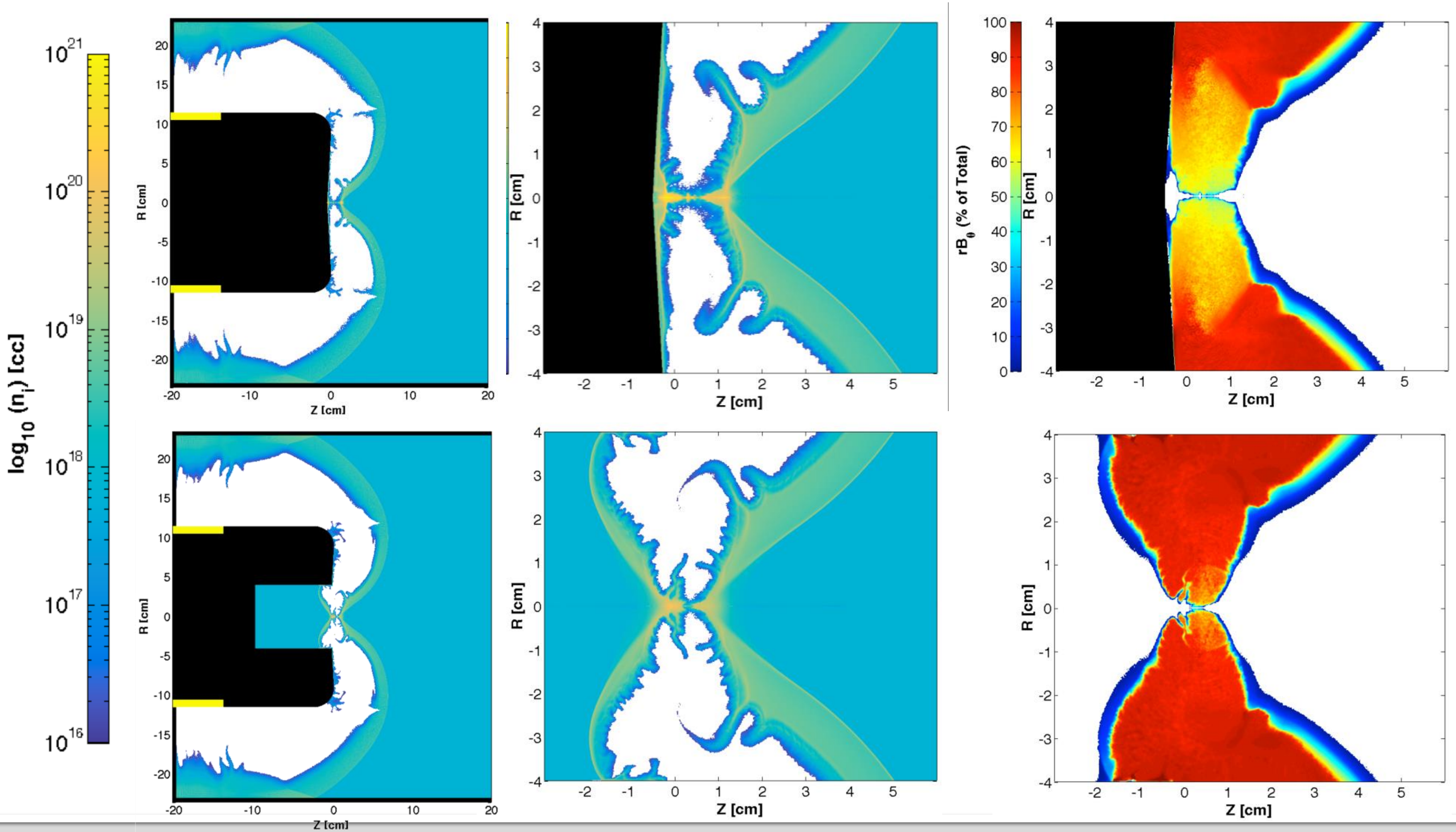


Simulations indicate that anode-to-sheath restriking is common

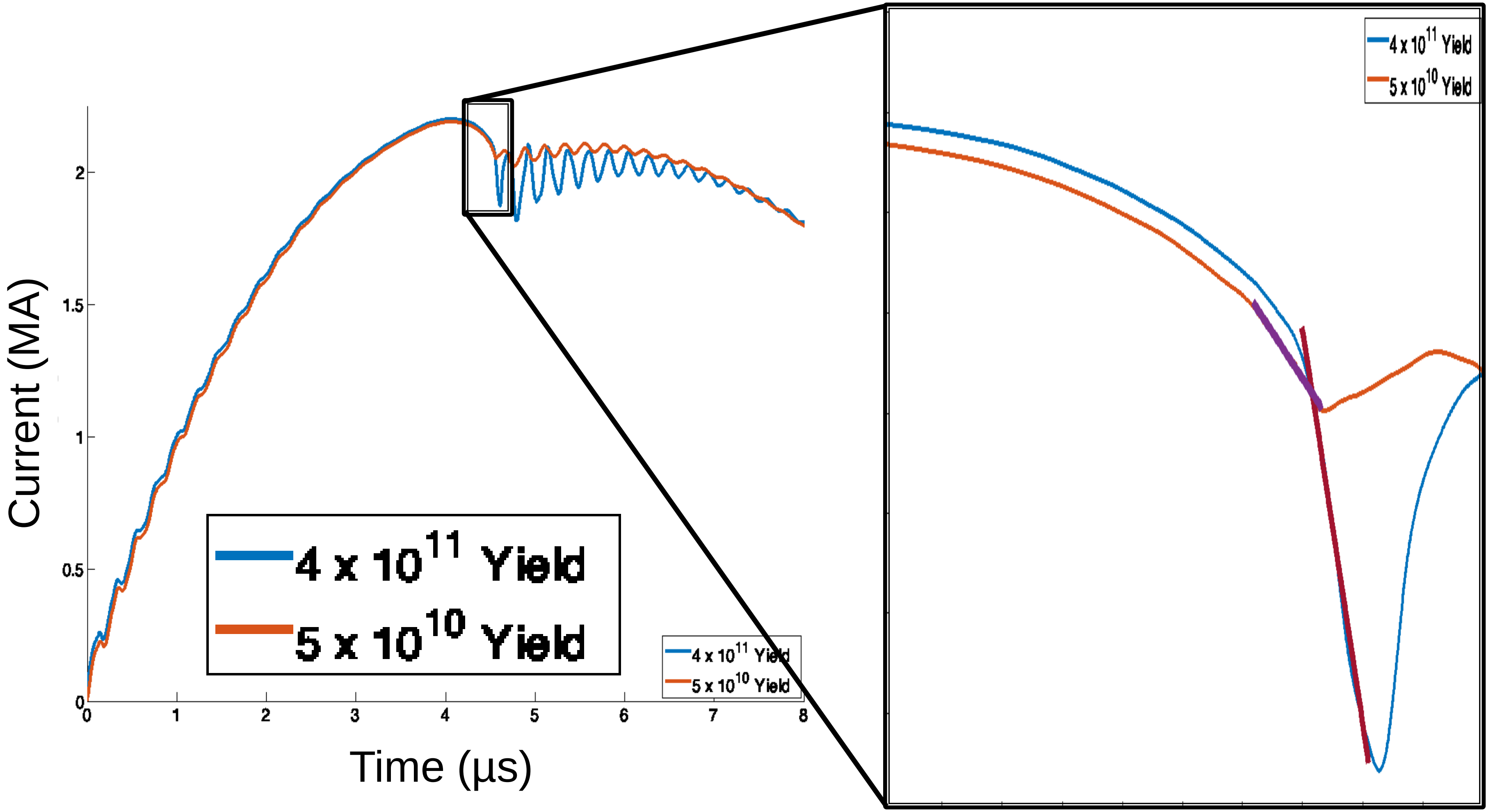


Trailing mass left behind by hydrodynamic instabilities create lower-inductance current pathways that divert current from the pinch region

Hollow anode mitigates anode-to-sheath restrikes



Lower yield shots show evidence of parasitic current diversion from pinch region



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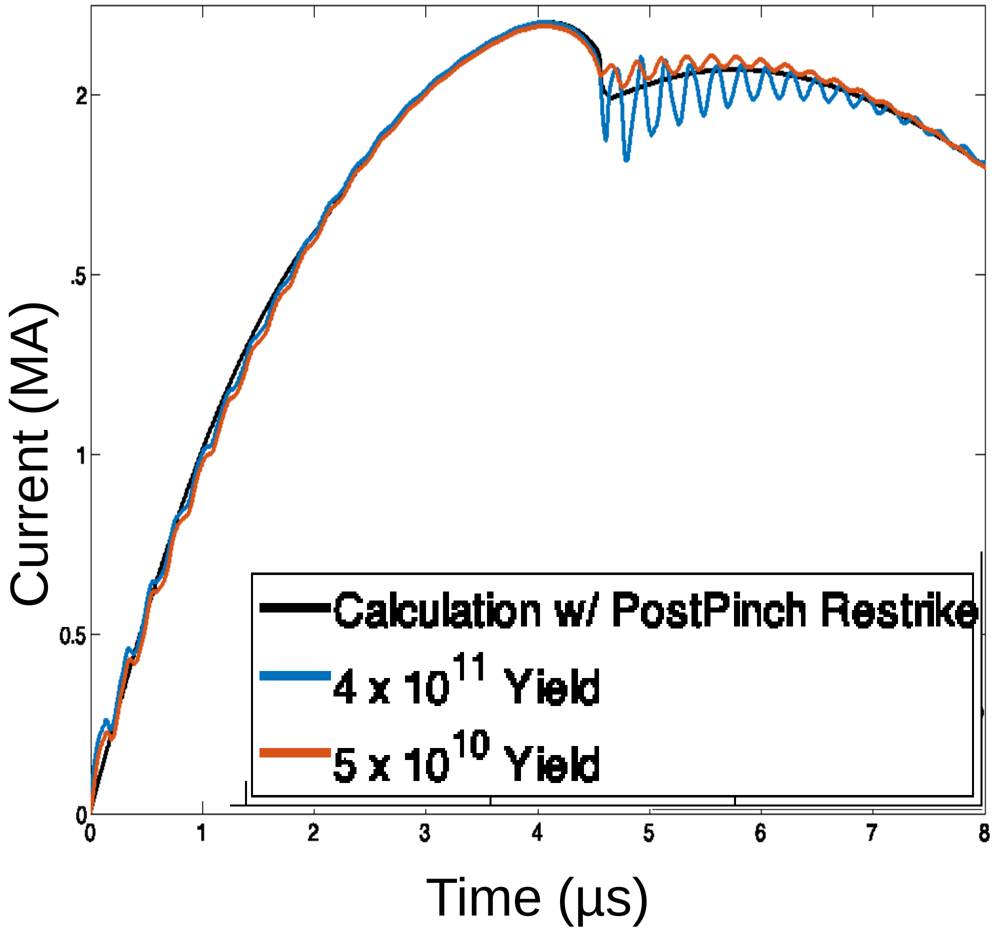


Vary resistance of a 5 nH current path (represents restrike near the insulator) to match low yield shot current trace in snow-plow model

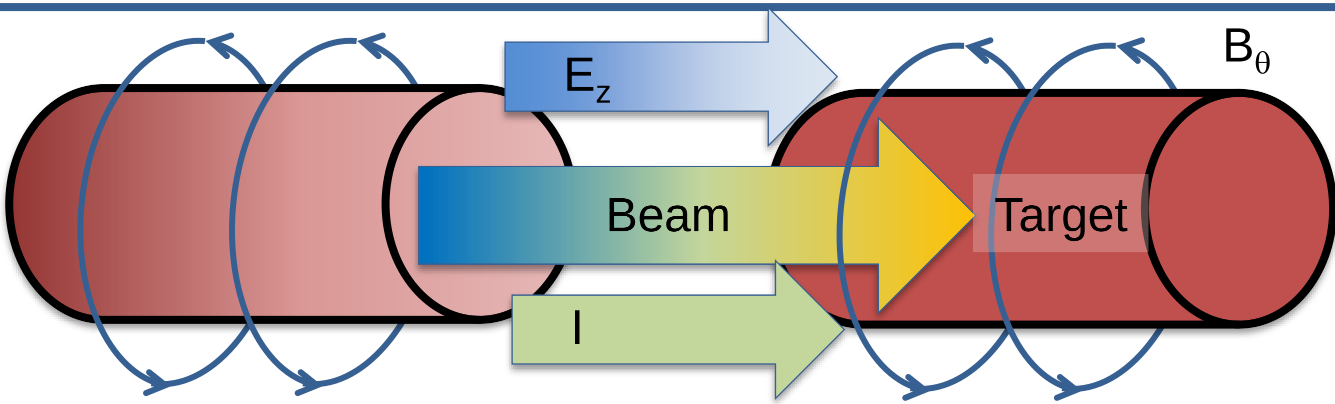
Ideal: measure location of restrike with b-dot or other probe

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



$$Yield = \int N_{beam} n_{target} L_{target} \, \mathrm{f(E)} \sigma(E) dE$$

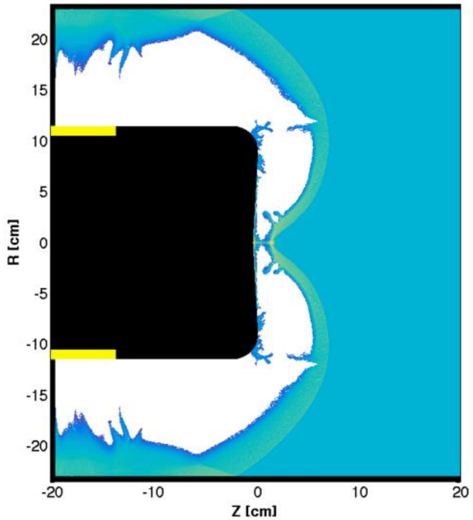
N = number
n = number density

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

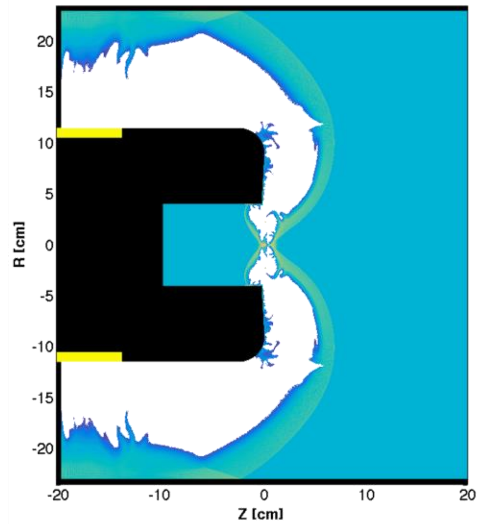
$$f(E) = e^{-E/E_b}$$

Anode design evolution influenced by both kinetic and reduced order models



Hollow anode

Reduce anode-to-sheath restrikes

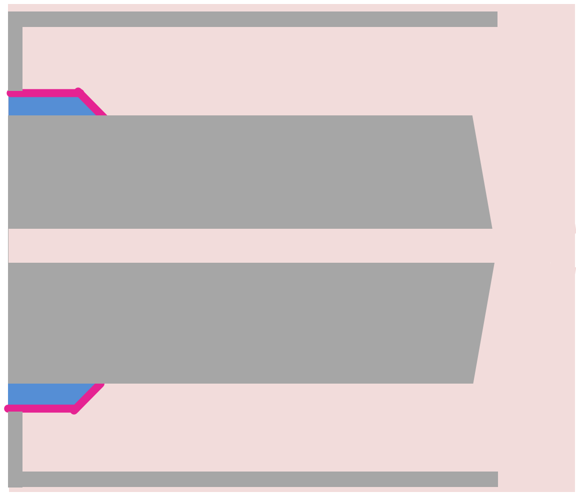


Tapered anode

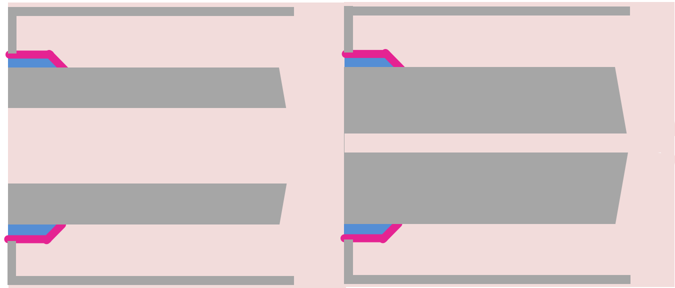
Delay hydrodynamic instabilities

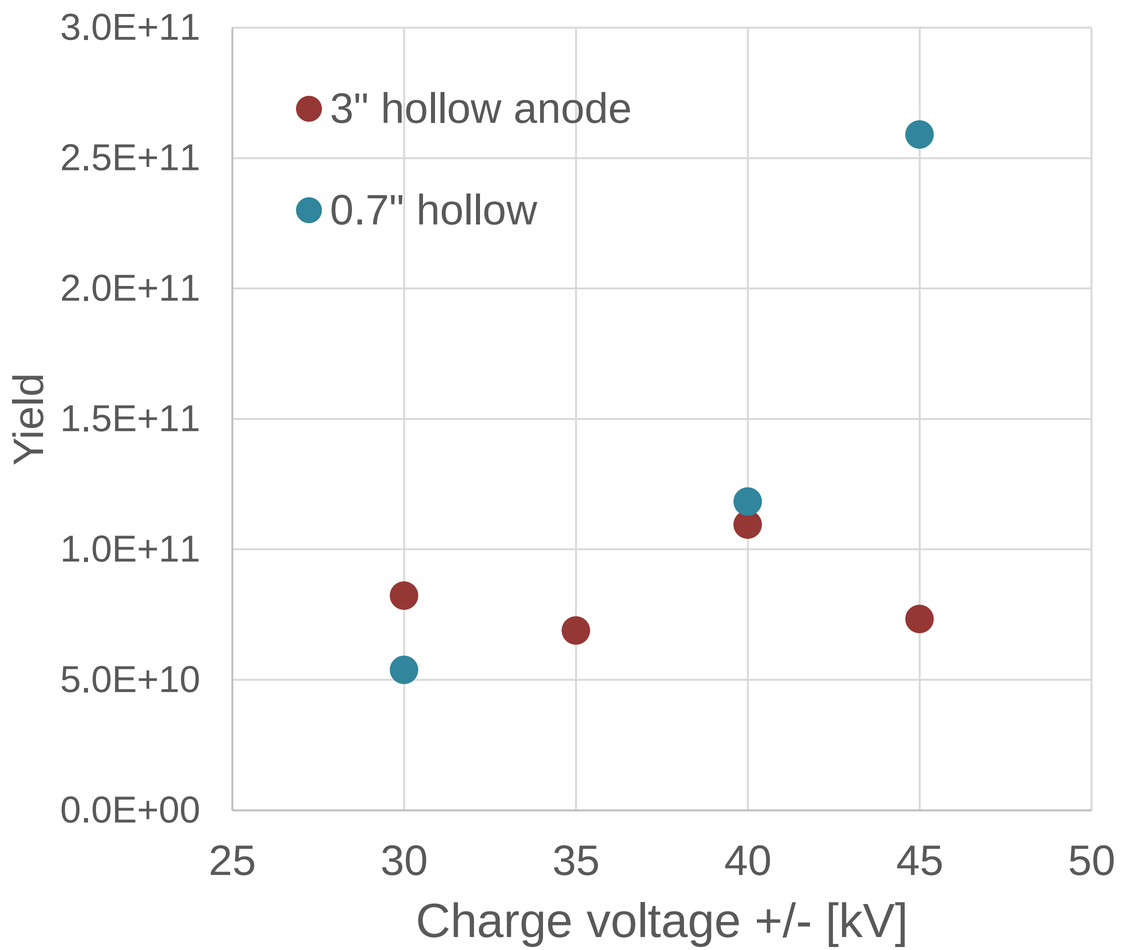
Smaller radius hollow

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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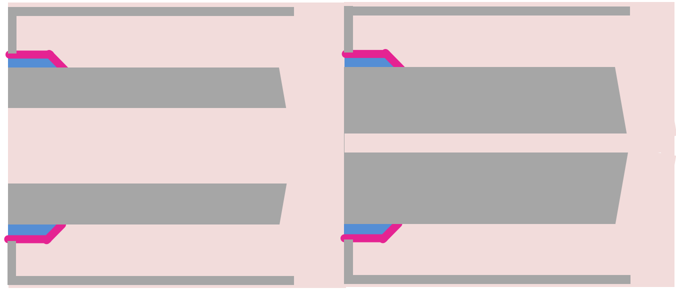

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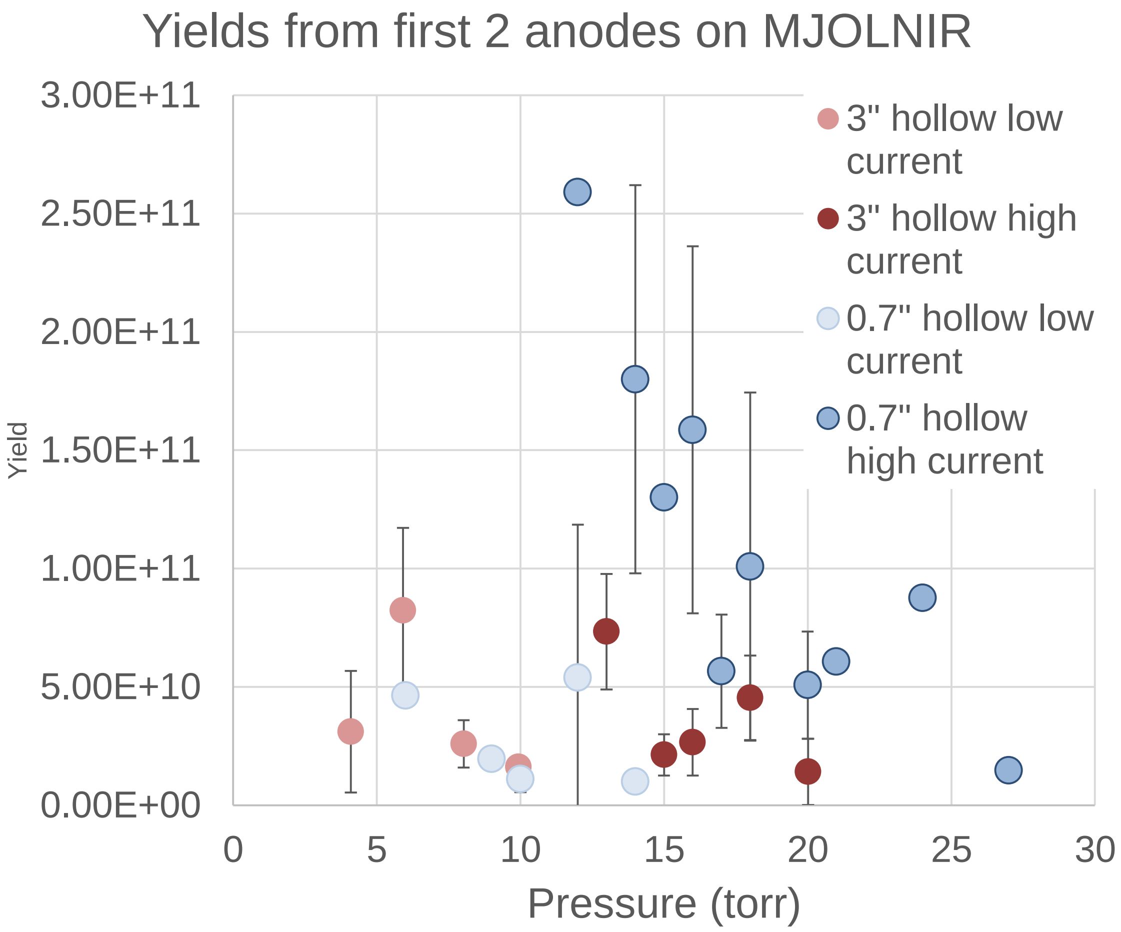

Key future questions

- 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?

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