SAND2011-3370C

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Compact Plasma Power Station

Quasi Spherical Direct Drive Capsule for Fusion Yield
Inverse Diode for Driver-Target Standoff
Magnetically Insulated Linear Transformer Drivers

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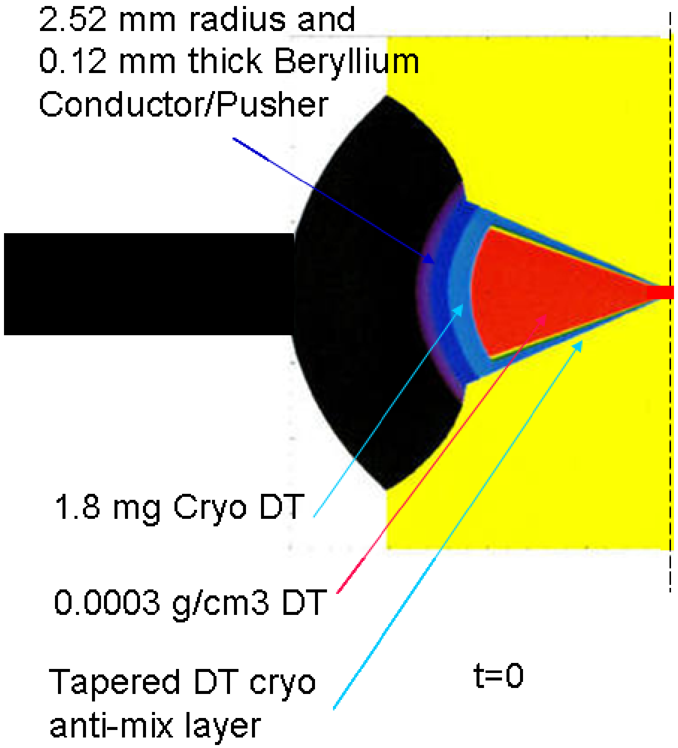
Architecture

Quasi Spherical Direct Drive capsule offers 500 MJ yields with 69 MJ energy store.



Many issues are mitigated with a higher dI/dt.

- **Uniform Initiation**
- **Less growth of Magnetic Rayleigh Taylor instability**
- **Lower driver energy**
- **Higher ηG**
- **Lower Cost of Electricity**

2D yield is currently limited by a wall instability.
Three possible solutions are being examined with LASNEX.

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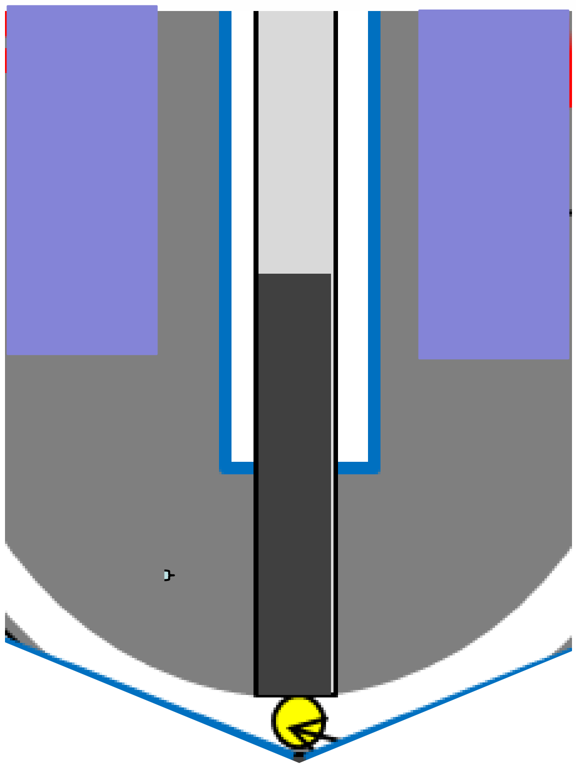
RTL drop tower leads to higher reprate and survivable center section from some radius.



- Recyclable Transmission Line (RTL)
- RTL with gun technology
- 3 Shots per second

- LiXY does every thing
  - $P<3x10^{-5}$ Torr at 600 deg K
  - 75%Sn and 25%Li w/o Sn122
  - GaLi, InGaLi with sealed surfaces

- 500 MJ yield
- 400 MJ of neutrons
  - Delta T ~600 deg C at 15 cm
- 100 MJ of Plasma
  - Energy/volume ~ 50 Kbarr at 15 cm
- Pressure relief from free expansion into vacuum chamber

Need 2D calculations of pressure versus radius.

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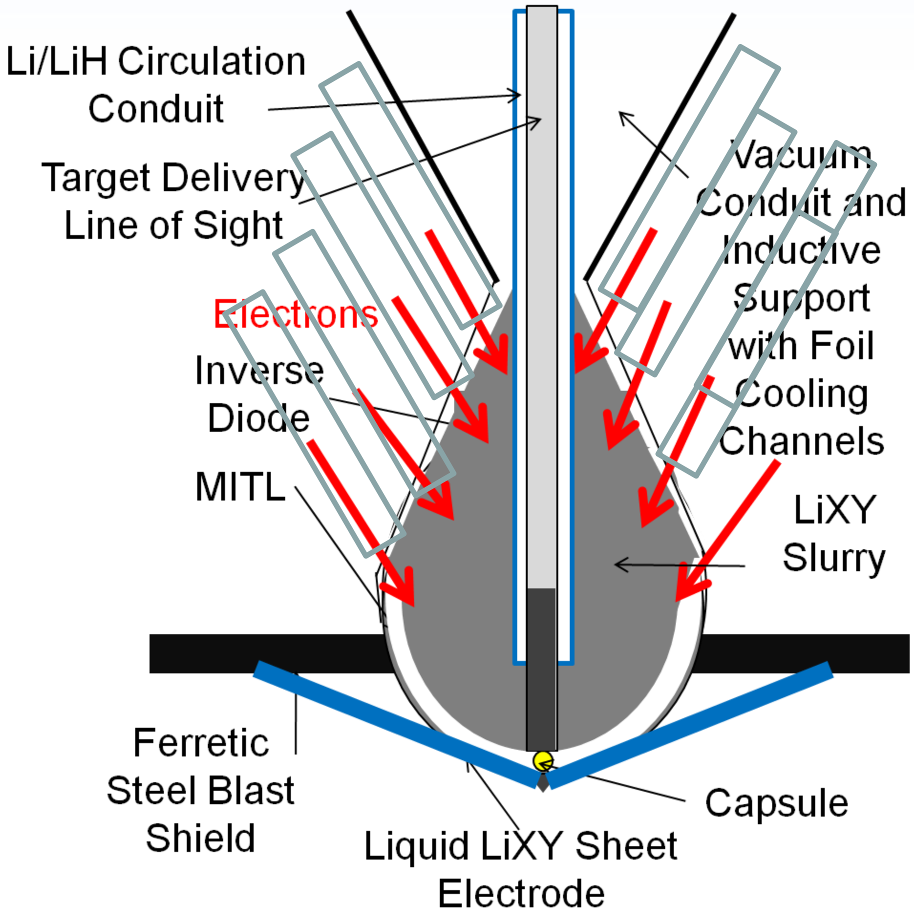
50 MA Inverse Diode connects the capsule to the driver.

- Converts multi-MITL electron current to single-MITL current
- Shields capsule from x-rays
- Powers the capsule
- Absorbs neutrons as part of heat exchanger fluid
- Interfaces with liquid metal anode.
- Minimize the complexity and mass of the RTL



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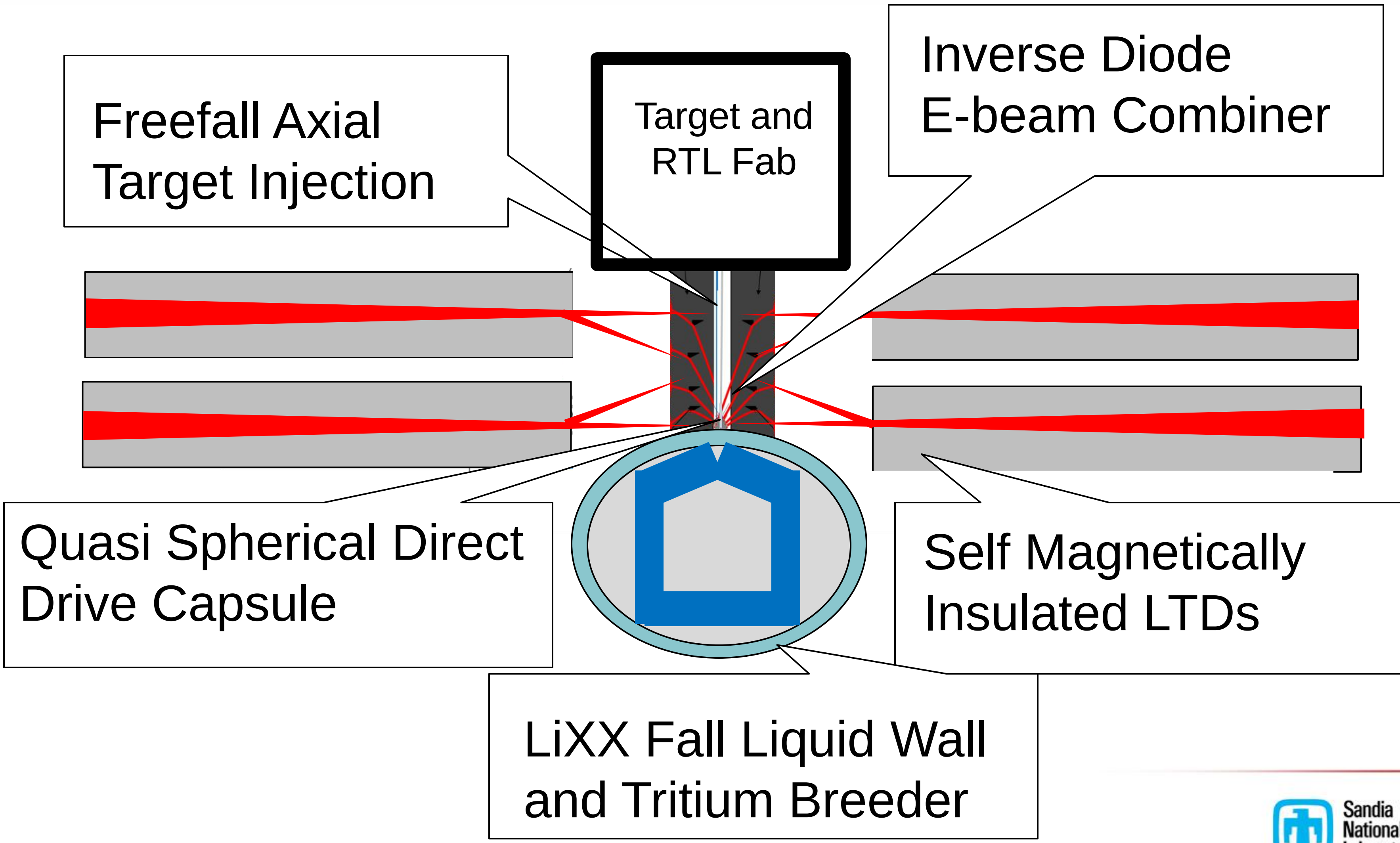
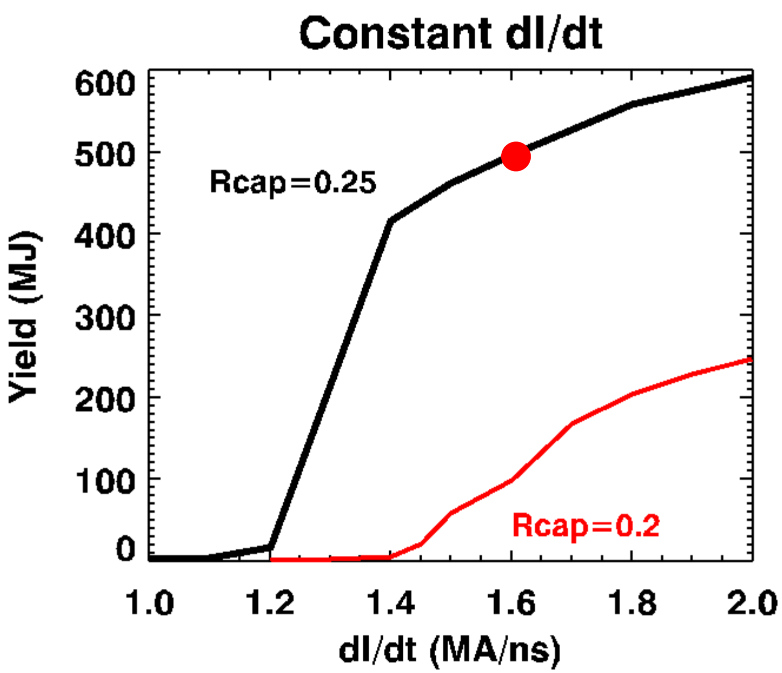
CPPS now targets 3 Hz operation to produce power at Meir-Mohr Model COE of 7.6 cents/kW-hr.

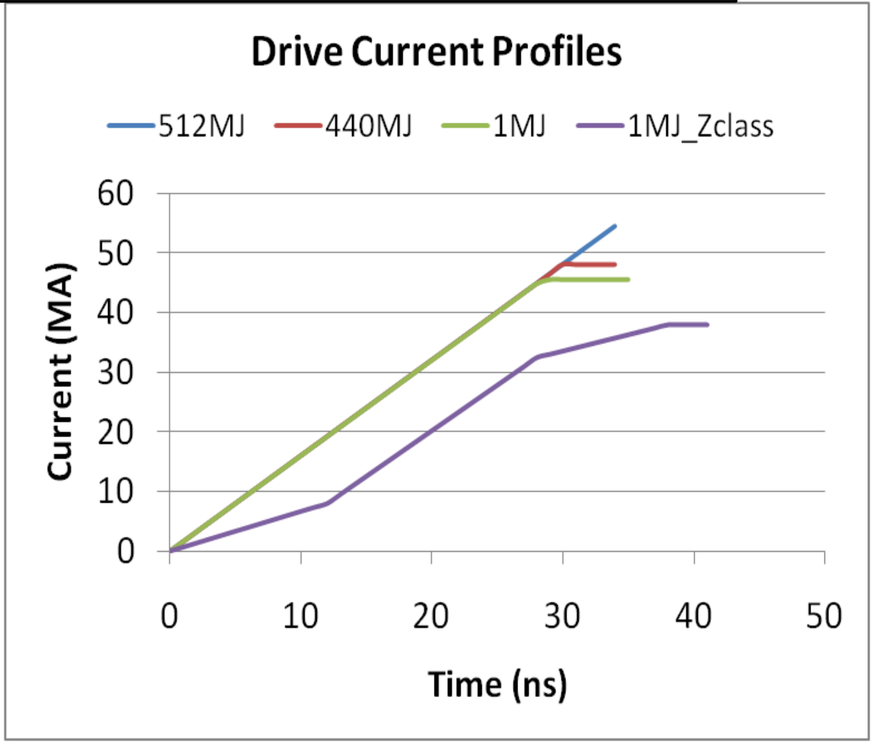


Target

Drive current is primary difference between high-gain on PPS and ignition on Z-class driver.

Magnetic Rayleigh-Taylor instability allows initial aspect ratio of $R_o / \delta = 21$.





A modification of Z could test the 512 MJ PPS capsule with a 1D clean yield of 2MJ.

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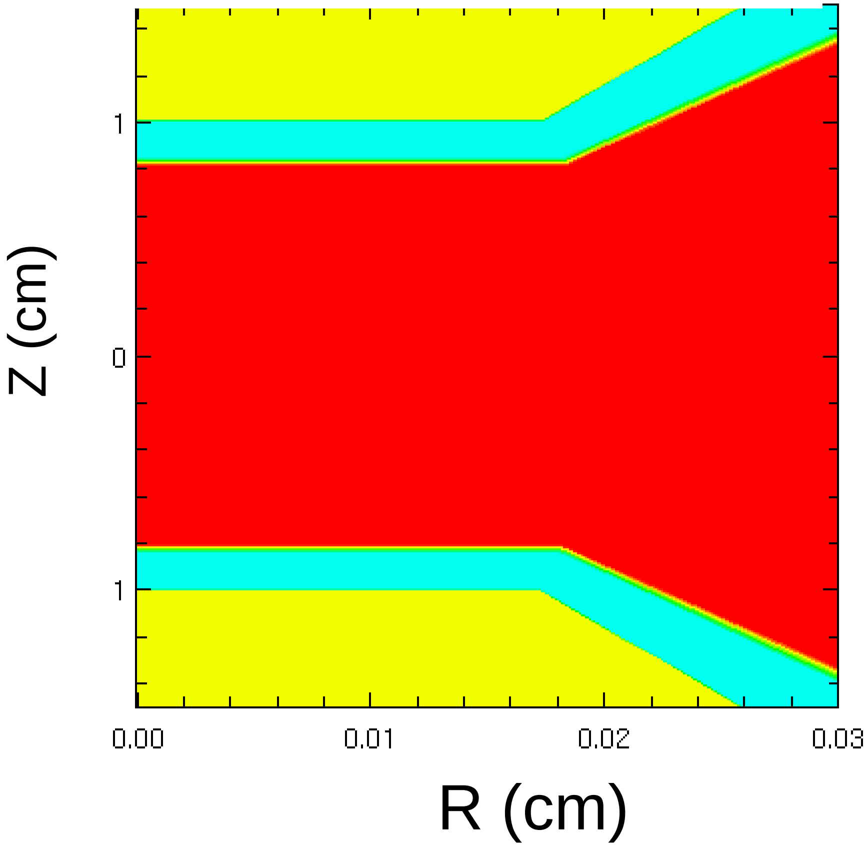
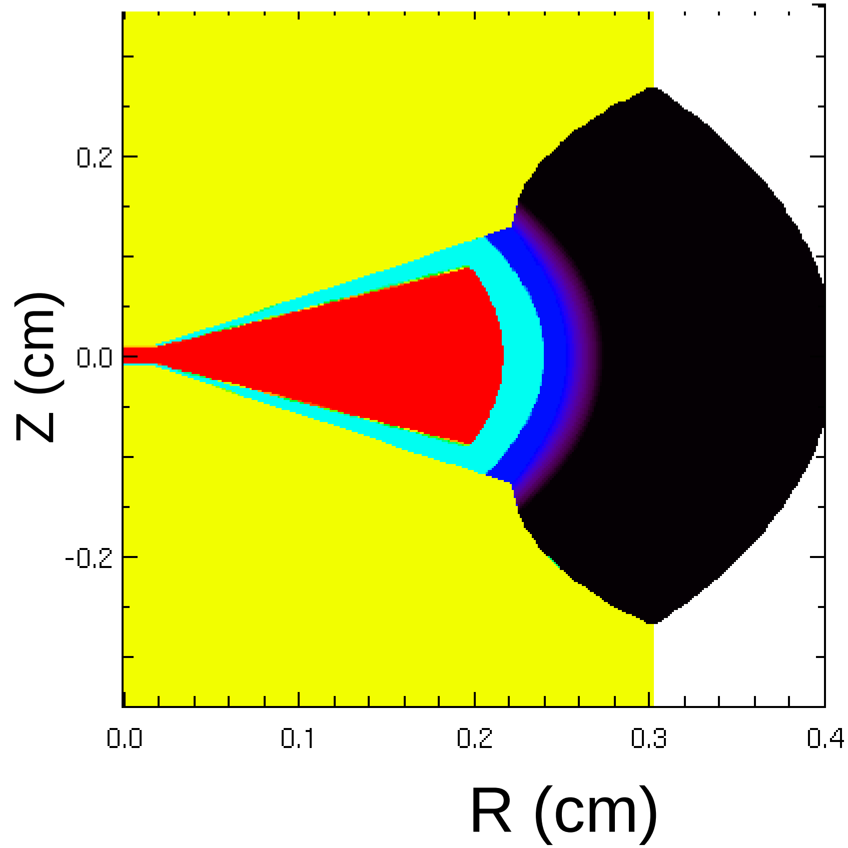
MRT OK for R_o/δ_o = 21 and QSDD capsule might ignite with a 40 ns version of Z.

Close-up of Central Cavity



Configuration at t=0.



R_{Be} = 0.252 cm, R_{cryo} = 0.240 cm

R_{gas} = 0.217 cm at t = 0.0 ns

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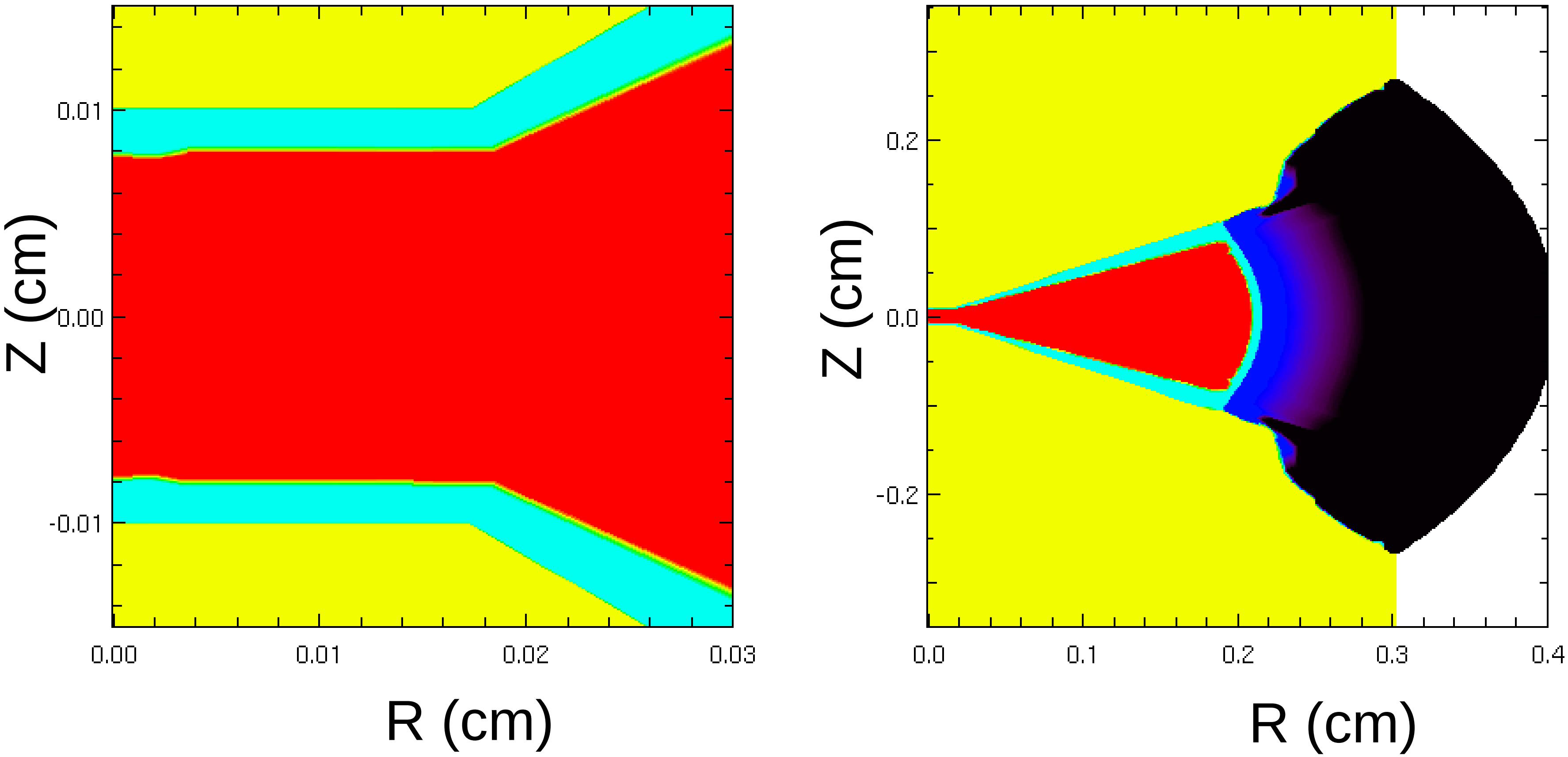
Beryllium has expanded and cryo compressed at 27.5 ns when shock enters gas.



200 micron Anode-Cathode gap is sufficient to prevent early electrical breakdown of DT in cavity and avoid preheating gas.

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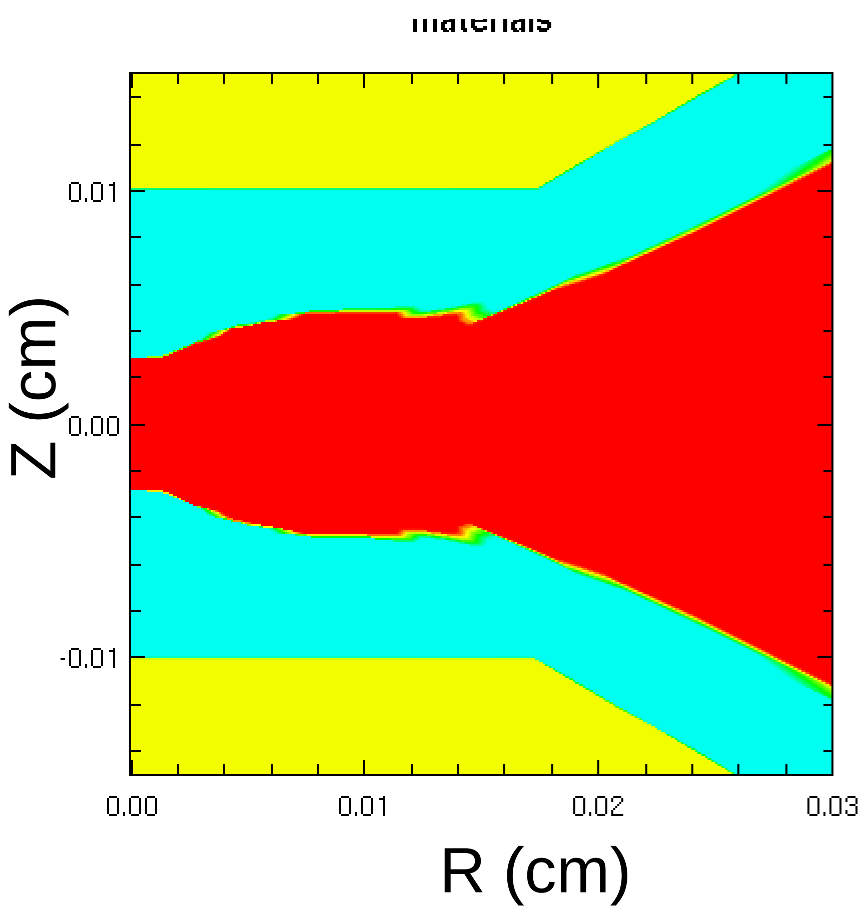
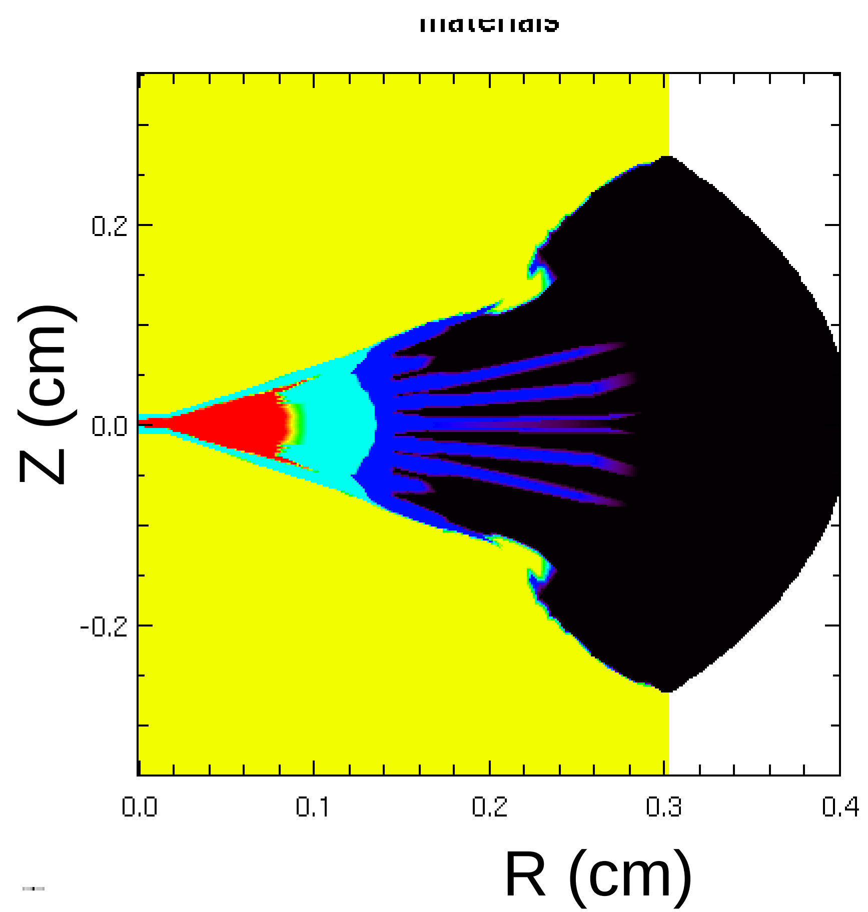
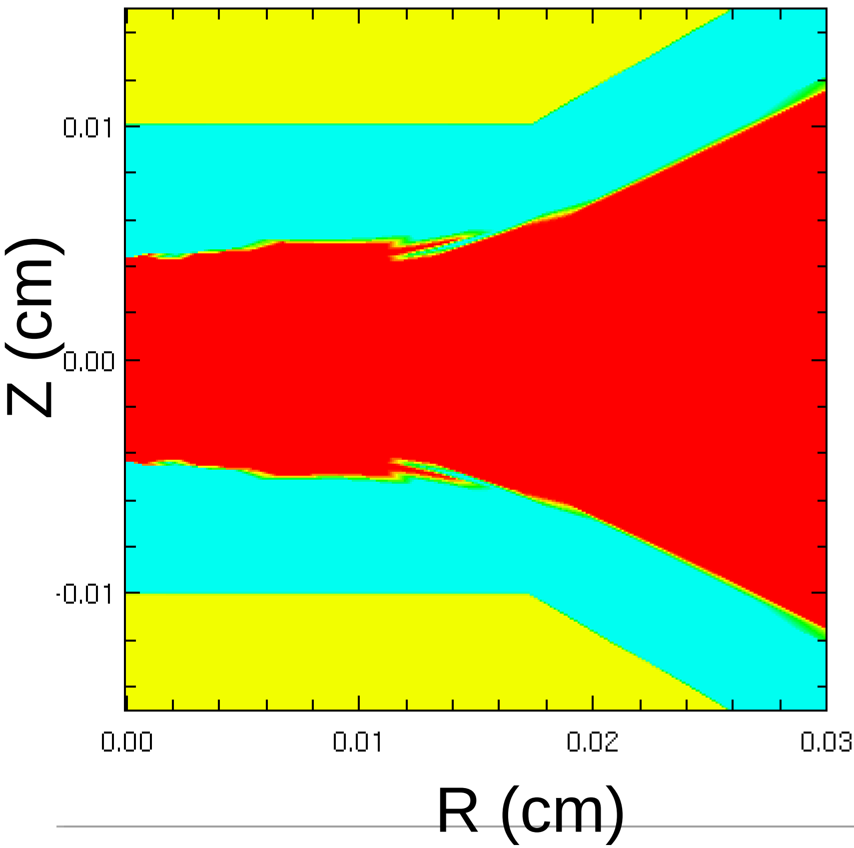
Magnetic Rayleigh Taylor is evident on the outer Be surface at 36.92 ns.

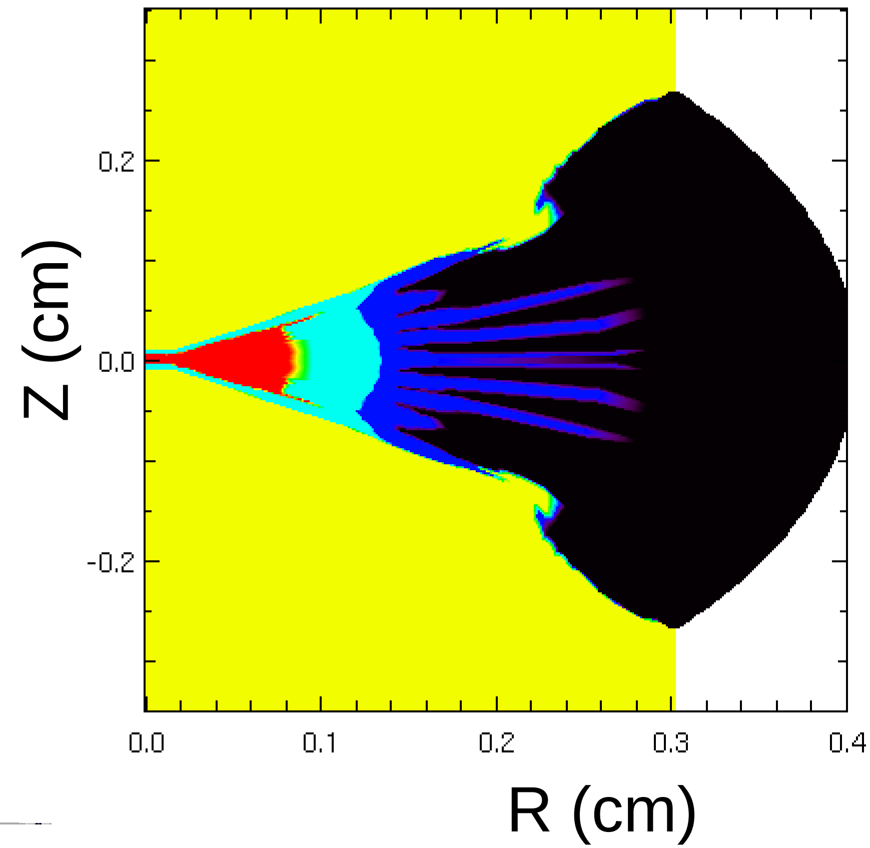




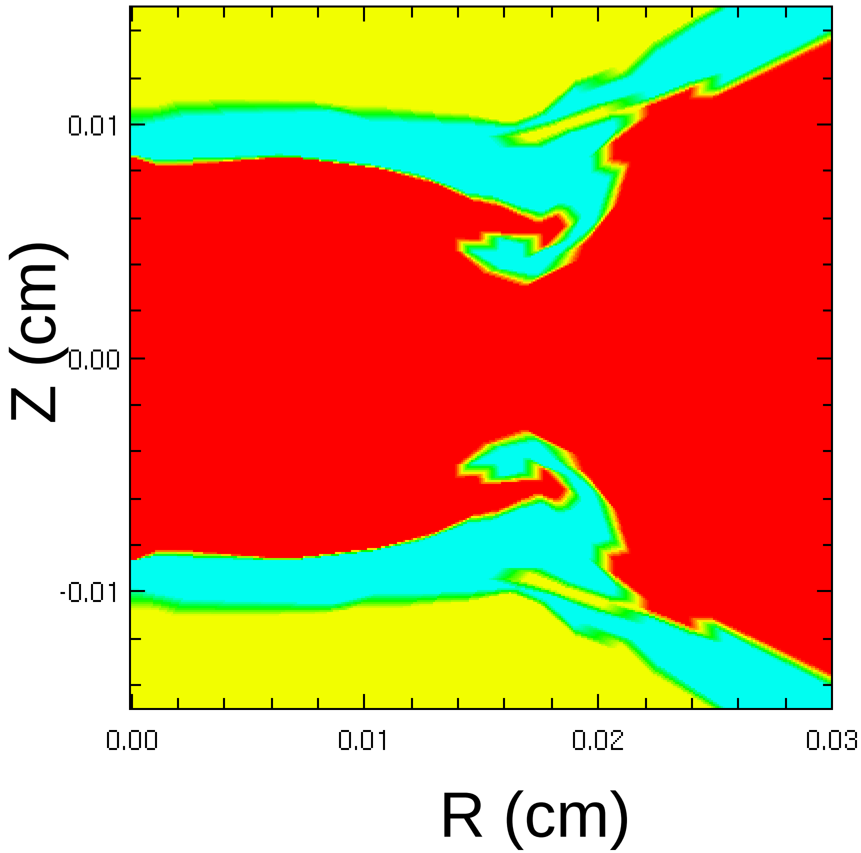
Anti-mix layer in the cavity thickens.

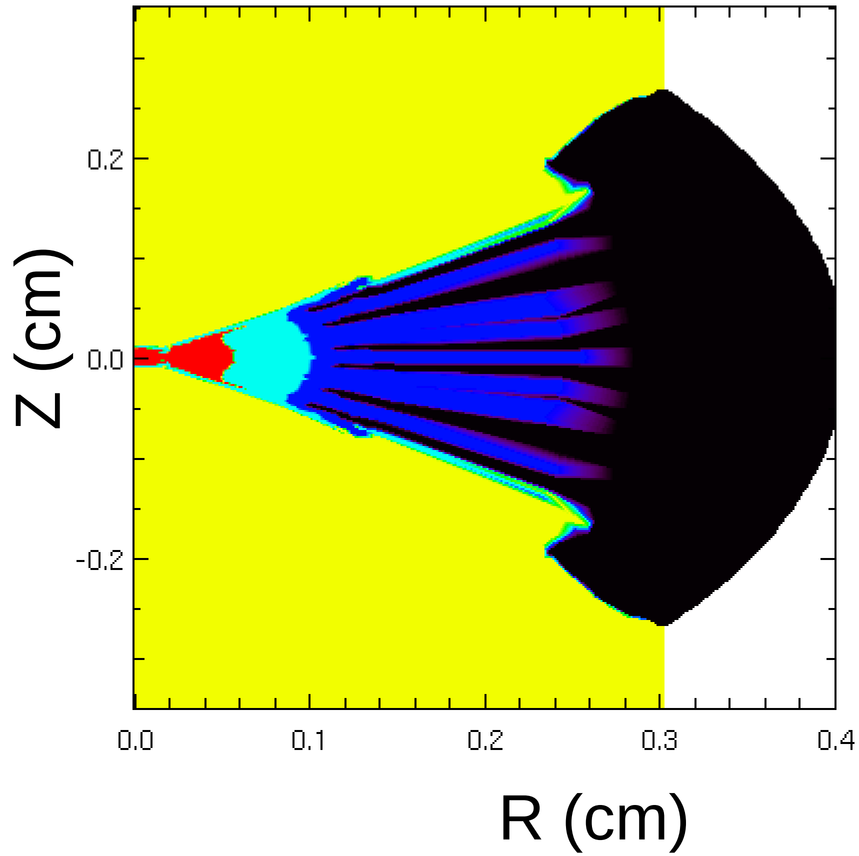
Anti-mix layer is mitigating the wall instability at 37 ns.





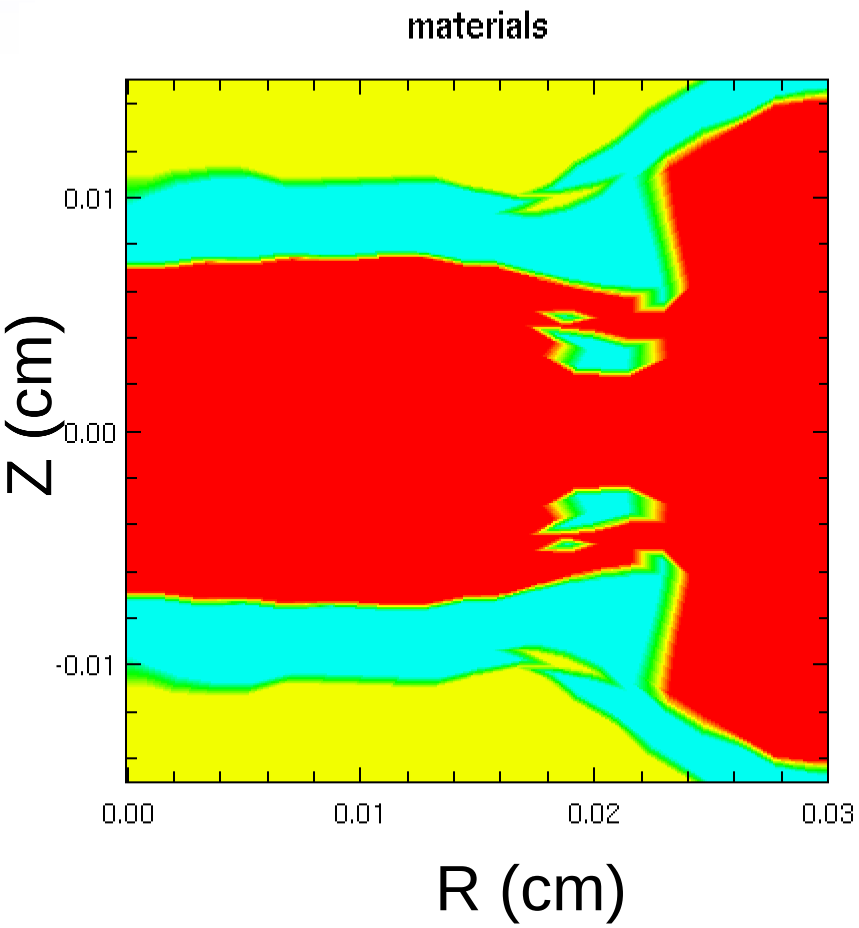
Implosion is spherical at 39.1 ns.

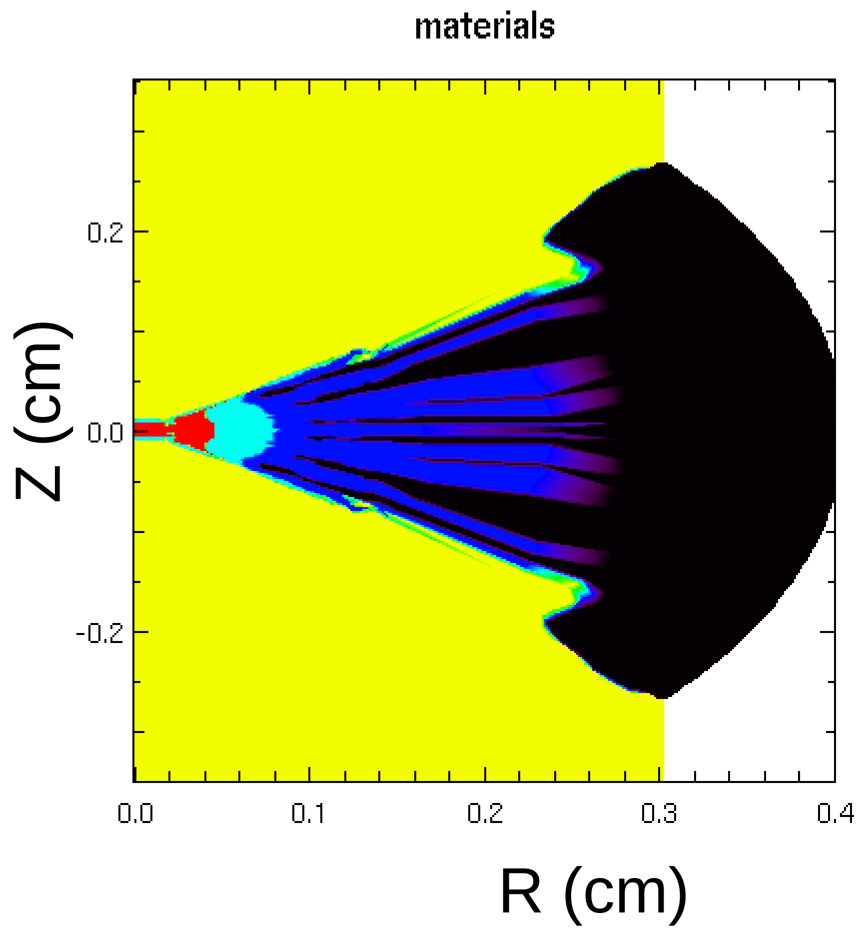




A discharge and associated disturbance appears in the cavity.

Implosion becomes pear shaped as wall instability grows at 40.3 ns.





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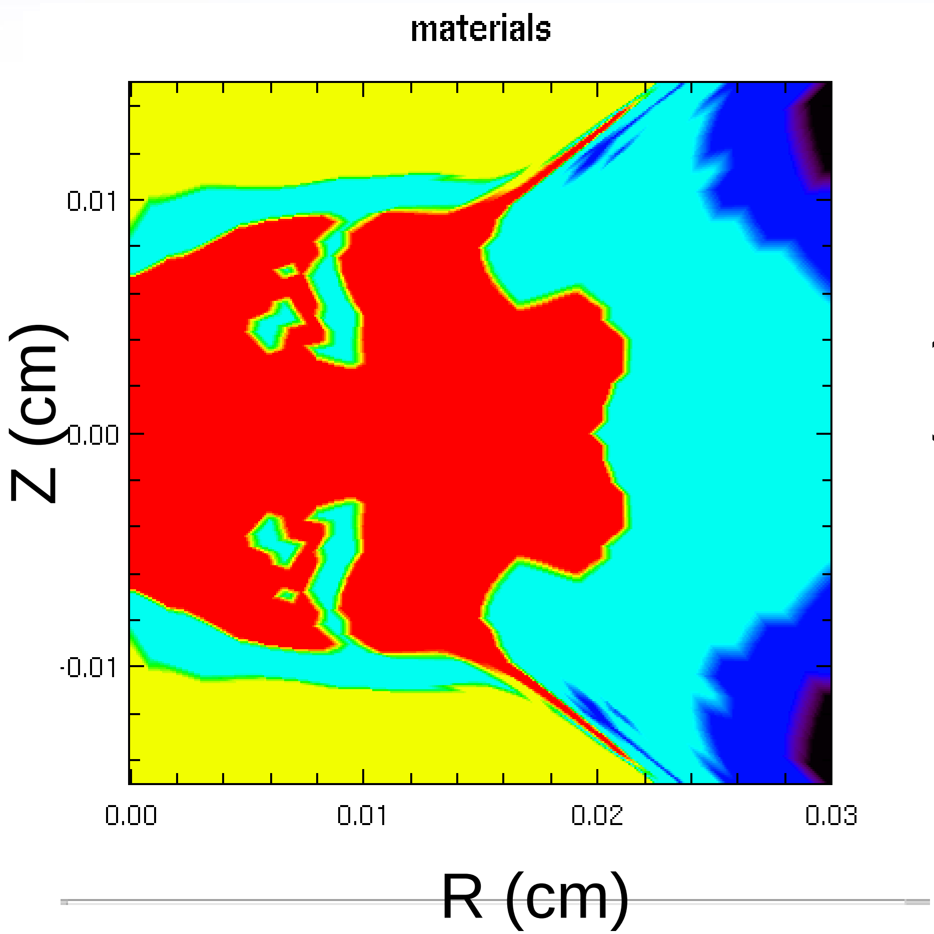
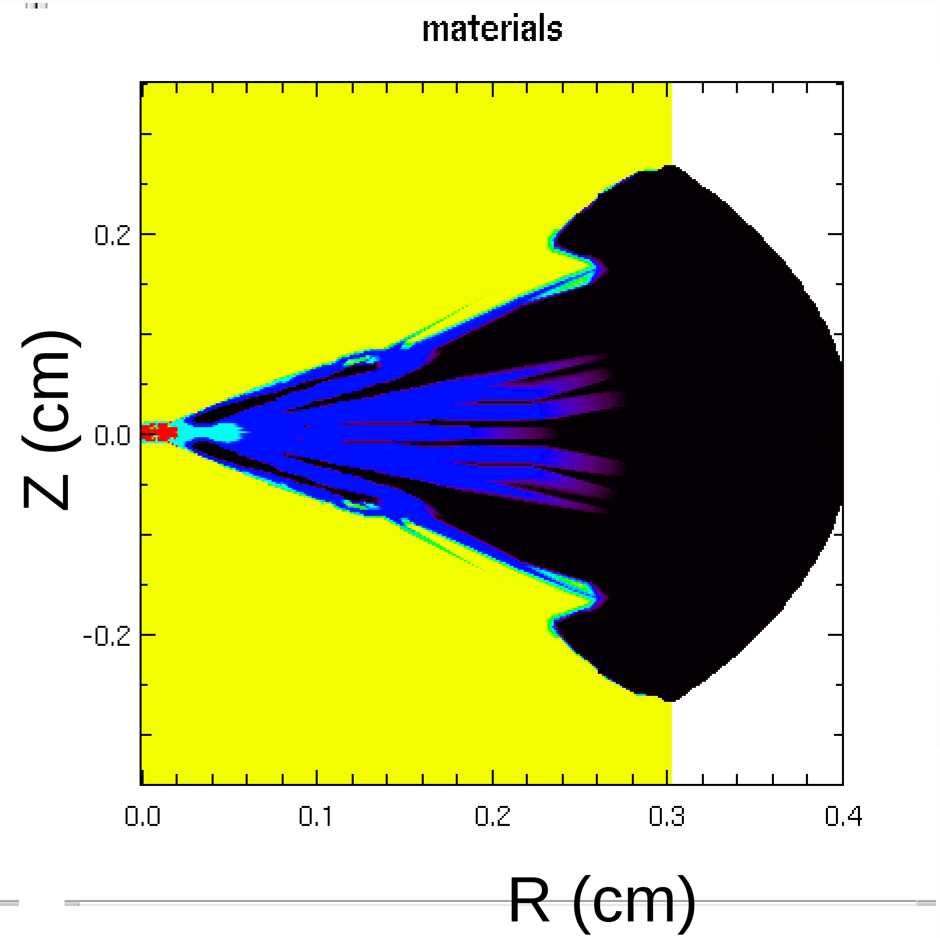
Wall instability dominates the Rayleigh-Taylor instability at 41.43 ns.





Hot spot is being pushed into the cavity with cold fuel close behind.

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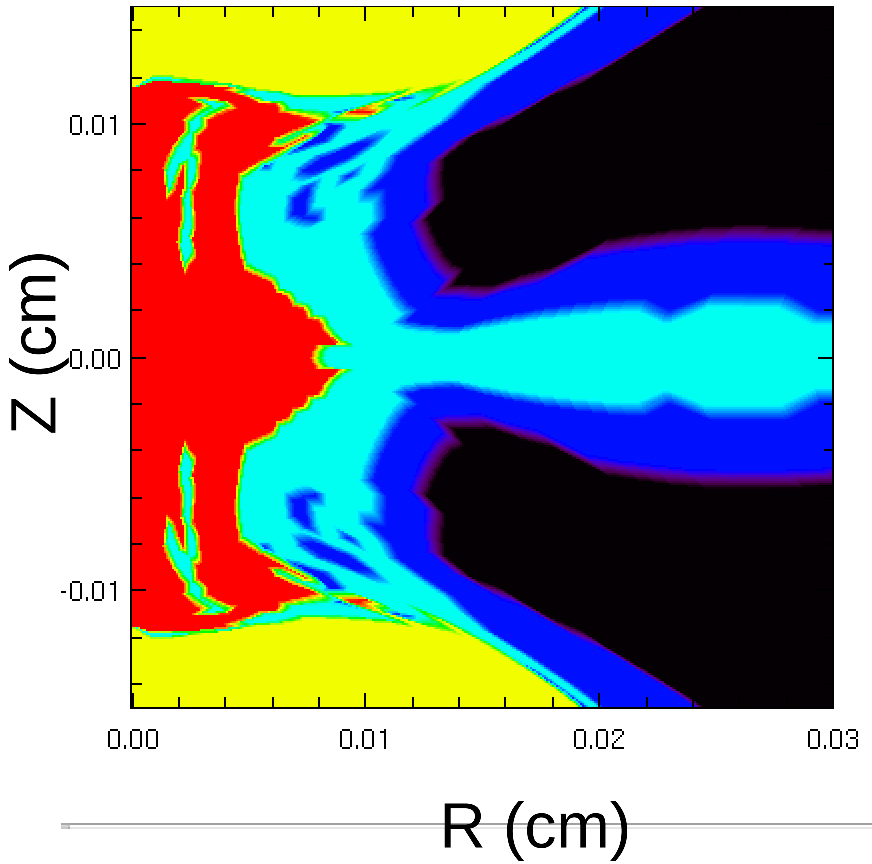
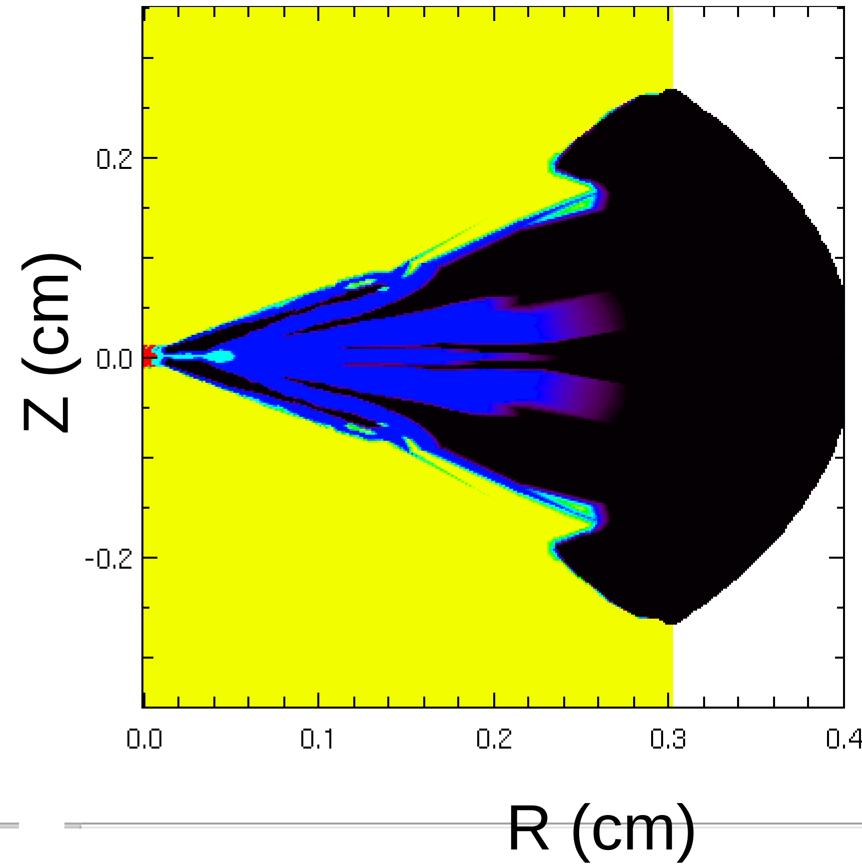
Most of the DT has become a pancake on the equator at 41.67 ns.





Temperature increases in the hot spot as adiabatic heating overcomes the losses to the wall before wall can expand.

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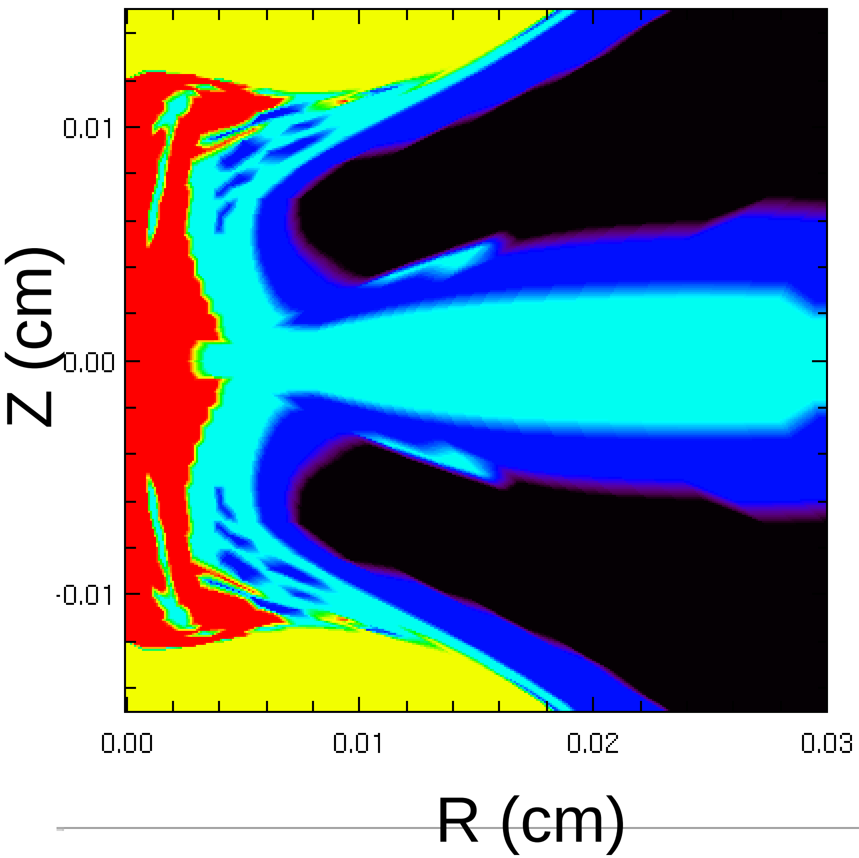
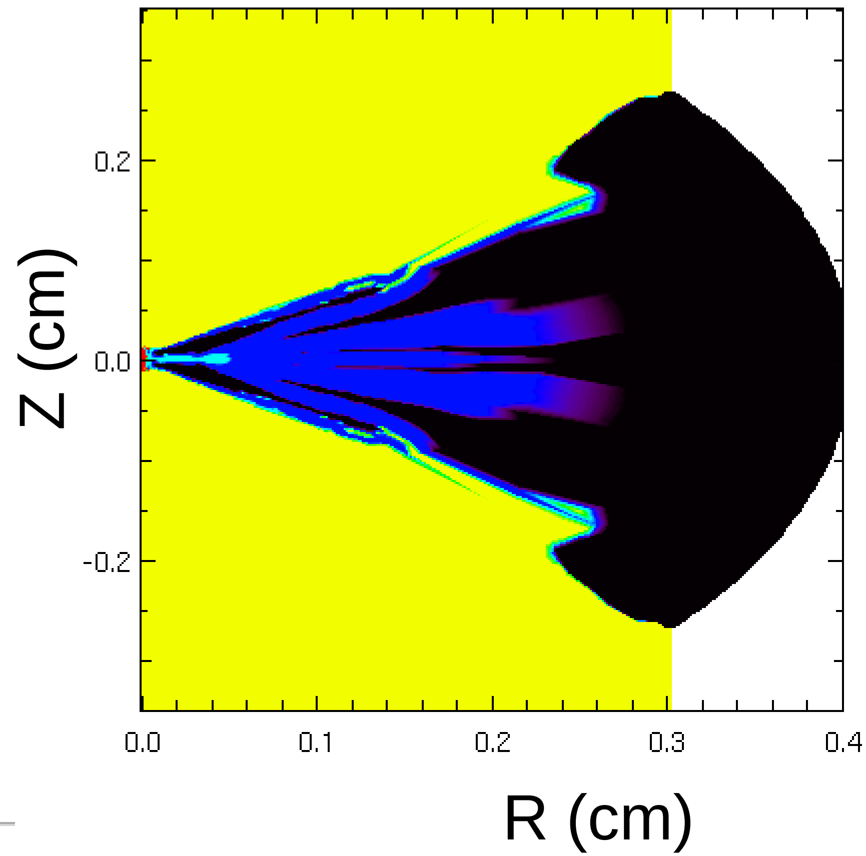
Burn begins at 41.72 ns.





Hot spot has a 40 micron radius for a convergence ratio of 60.

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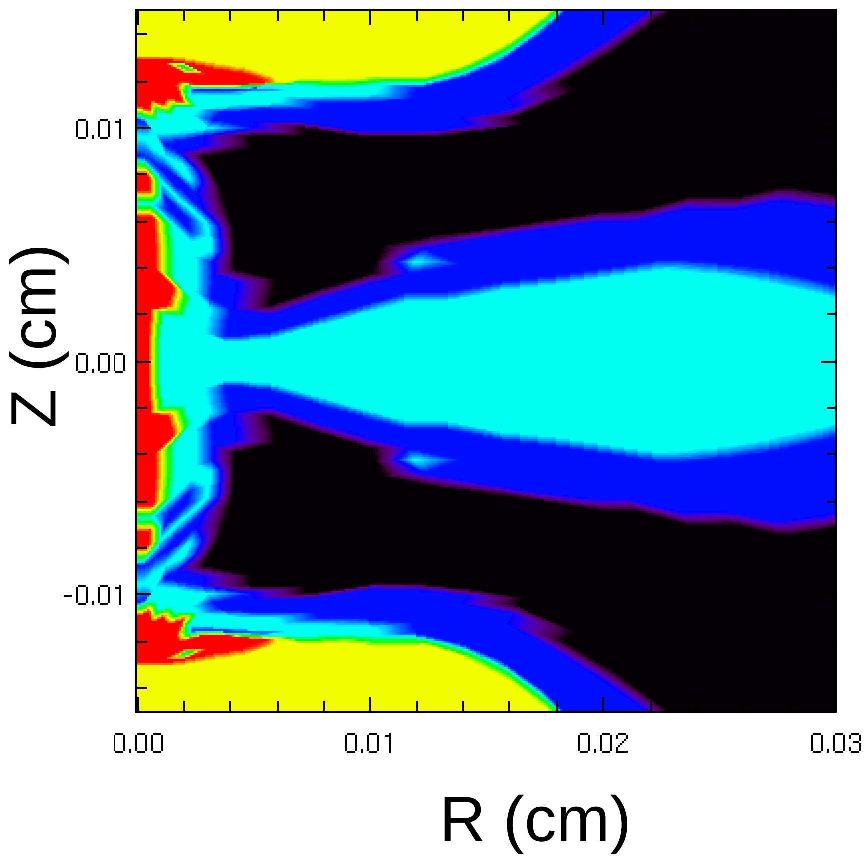
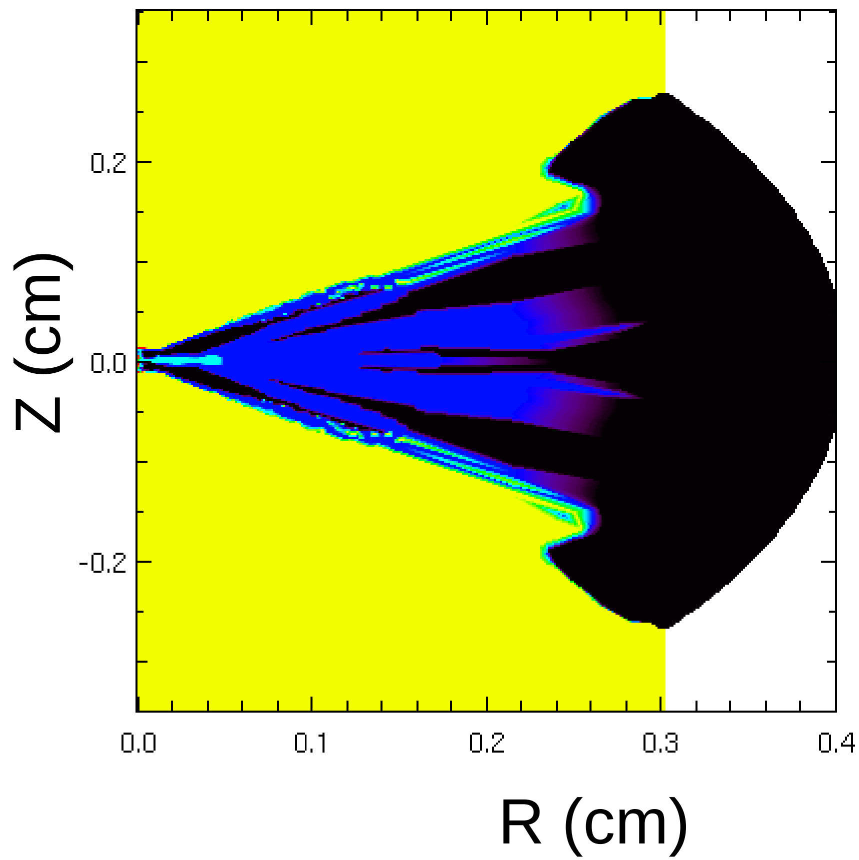
Yield is 800 KJ at 41.76 ns.





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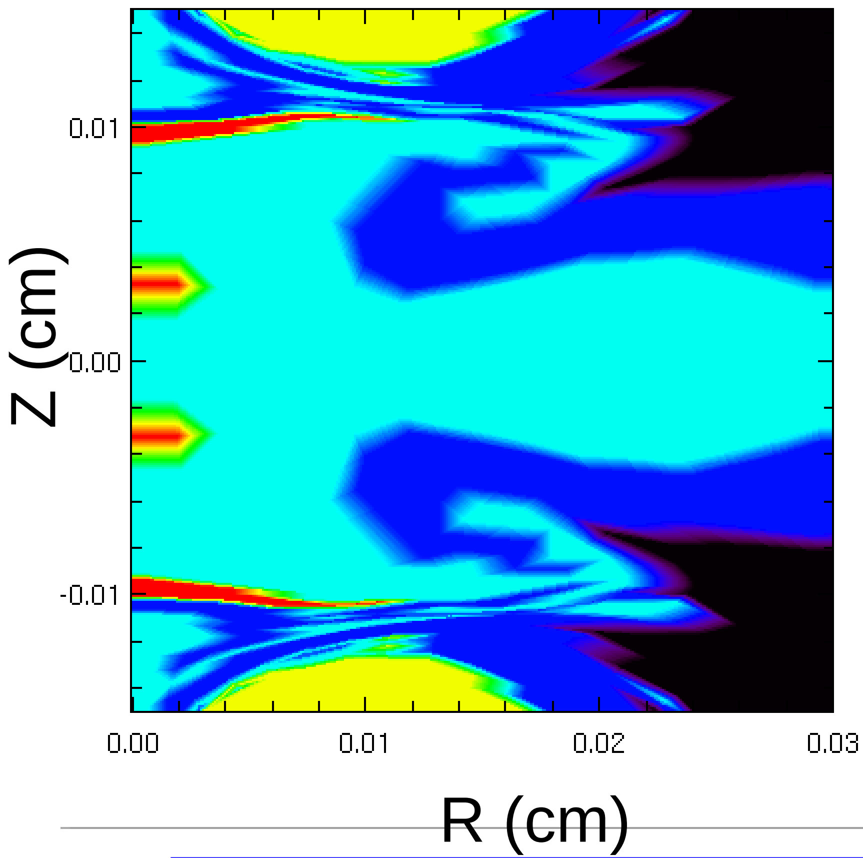
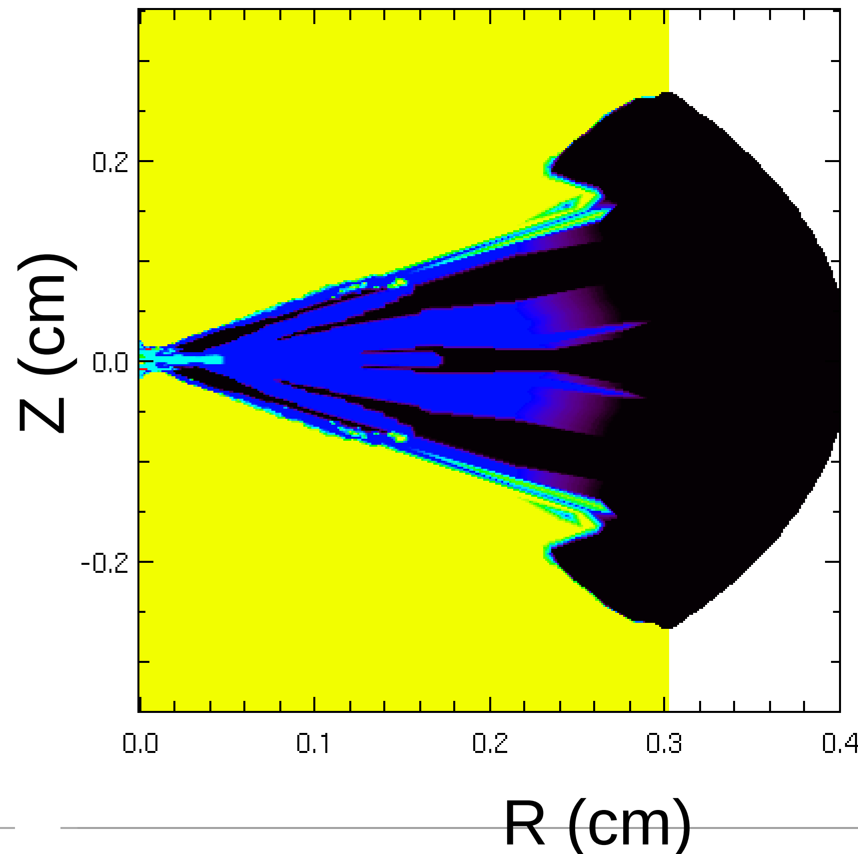
Hot spot disassembles at 41.86 ns.





Clean 2D yield is 1.3 MJ.

Clean 1D yield is 1.0 MJ.

Simulations reveal seven features that motivate QSDD.

1. Quantum Molecular Dynamics make design less uncertain than laser plasma interaction, wire initiation, and opacities make x-ray drive.
2. >6 times more energy in the fuel than x-ray drive.
3. Magnetic pressure >10 times ablation pressure of x-ray drive.
4. Internal pulse shaping automatically provides hot spot heating and adiabatic compression of main fuel.
5. Metal conductor tamps expansion during burn.
6. >4.5 MA current penetration into fuel gives alpha trapping and reduce $\rho r_{ignition}$ by a factor of 5 .
7. Possibility of MJ yields on some version of Z.

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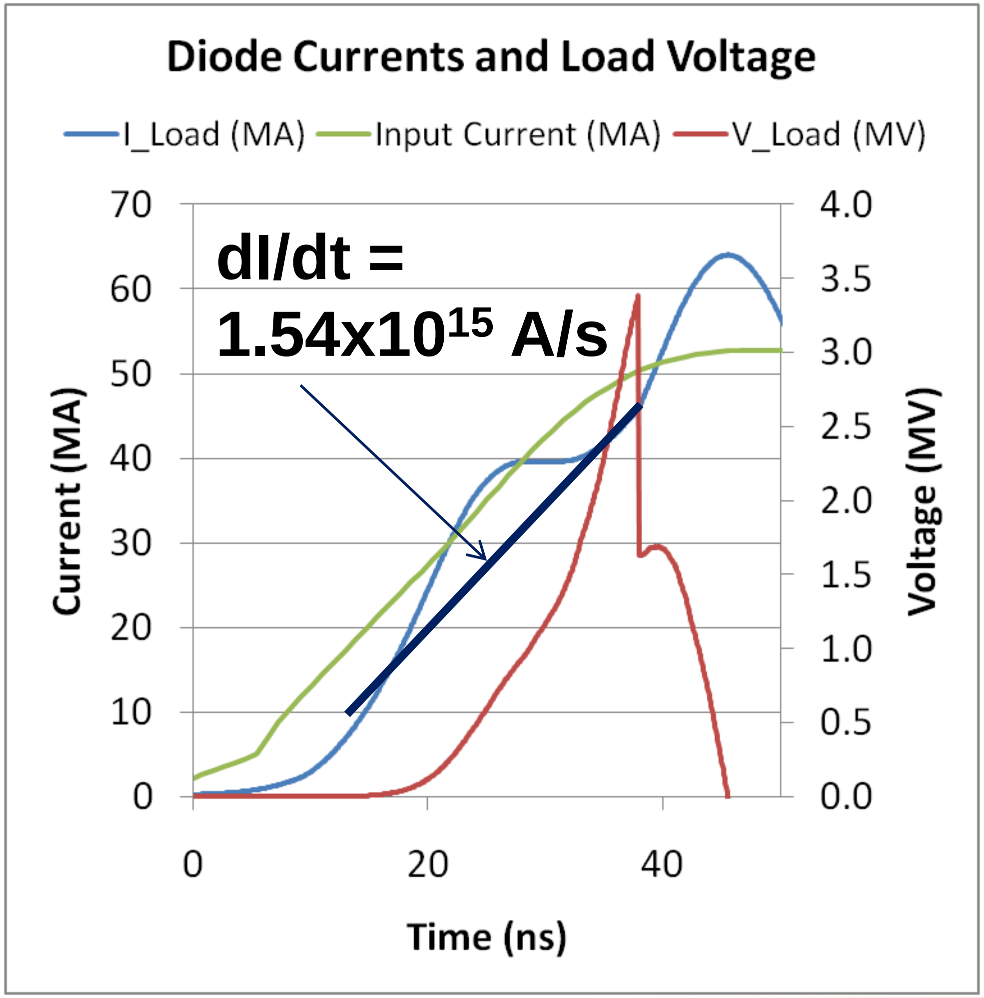
End-to-end simulation shows 45 MA 1.54x10^{15} A/s in QSDD capsule.

- Magnetically Insulated LTDs
  - 18 with 30 stages
  - 18 with 50 stages
  - 18 with 70 stages
  - 18 with 90 stages
- Direct Inverse Diode
  - 1 meter radius
  - 560 A/cm^2 injected electrons
  - 2 mm minimum AK gap
- MITL and Capsule
  - 2mm to 1 mm AK gap
  - 2.5 mm QSDD capsule



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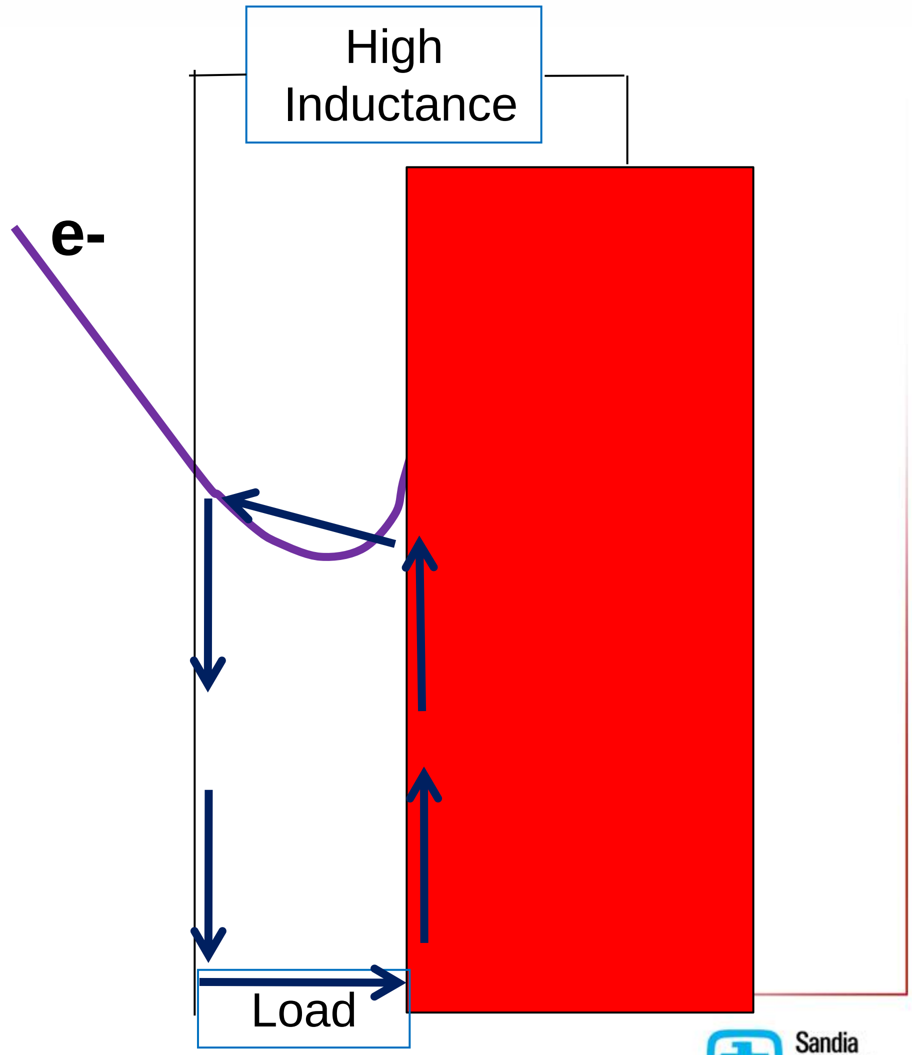
Coupling

Inverse diode couples multiple MITLs to single implosion.

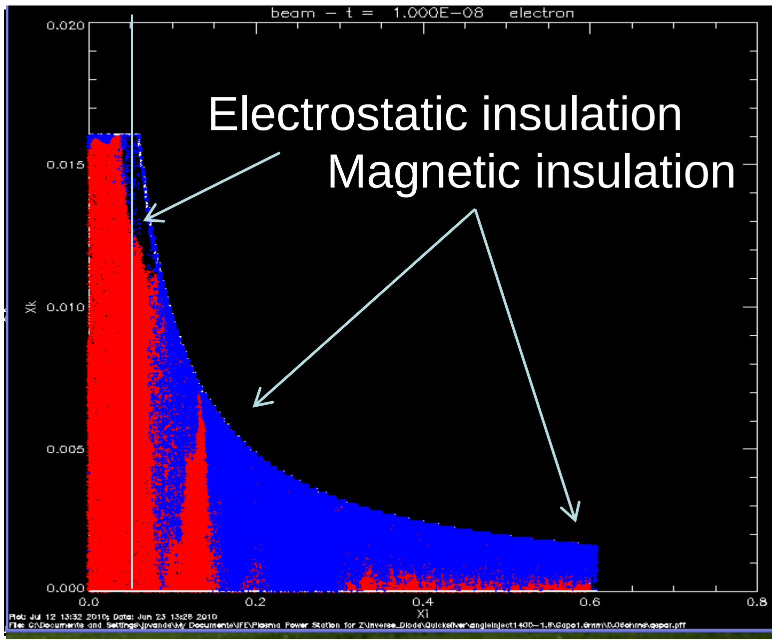
- **Electrons (purple line) injected through 1 to 3 mm thick Be anode foil (primary containment)**
- **>90% of electrons reach cathode**
- **MITL module voltages increase with proximity to capsule and net magnetic field to maximize energy efficiency**
- **So, the inverse diode is ~90% current efficient but only ~75% energy efficient.**

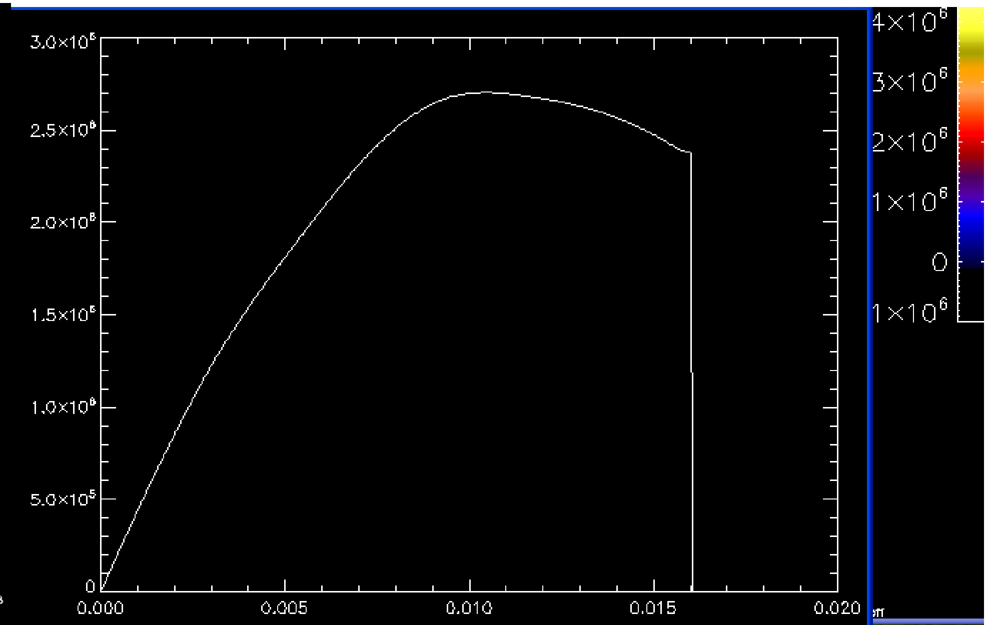


Space charge distribution prevents secondary electrons from neutralizing injected current.

Red: Injected electrons
Blue: Electrons emitted from cathode

Potential distribution across AK gap at r=0.05 m shows E-field reversal at cathode.





40 MA at 4 MeV injected and 33 MA at 2 MV at load without optimization

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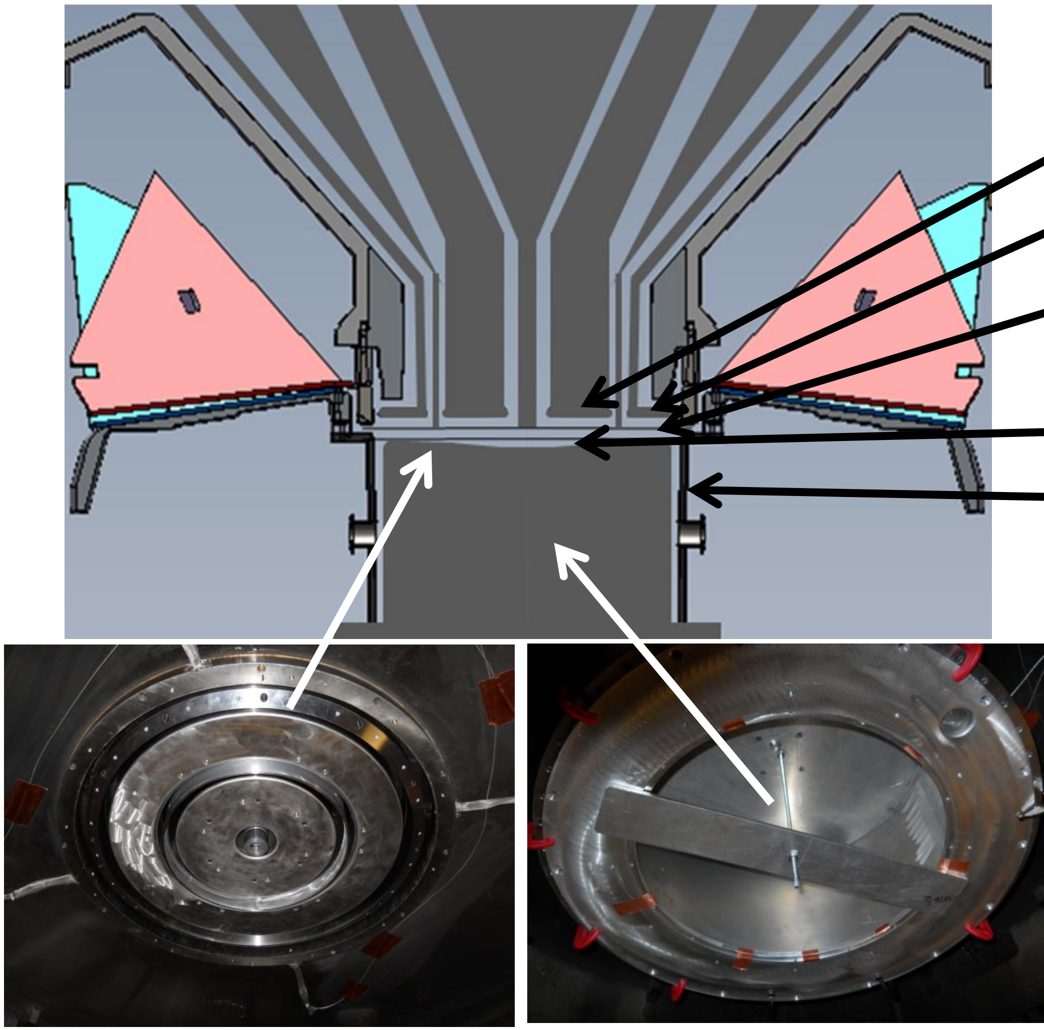
Inverse Diode experiment has 63% current efficiency without optimization.



- Inner MITL Cathode
- Outer MITL Cathode
- Post Accelerating Gap (PAG)
- Inverse Diode Gap
- Voltage Monitoring Inductor

Saturn	PPS
1,3 MV	3,5,7,9 MV
2 kA/cm^2	0.5 kA/cm^2
2.5 MA	50 MA

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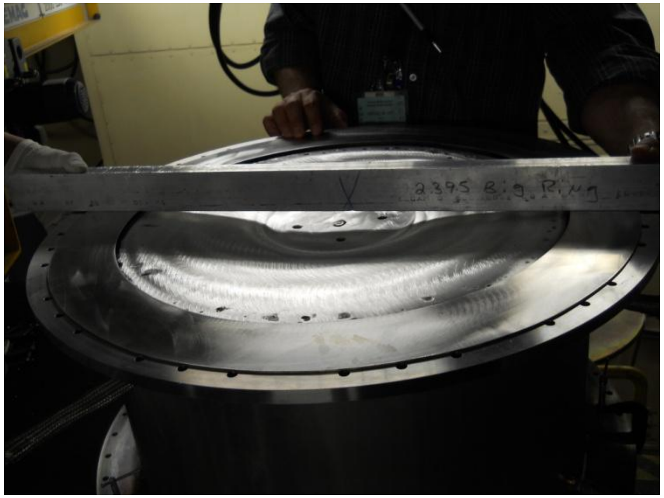
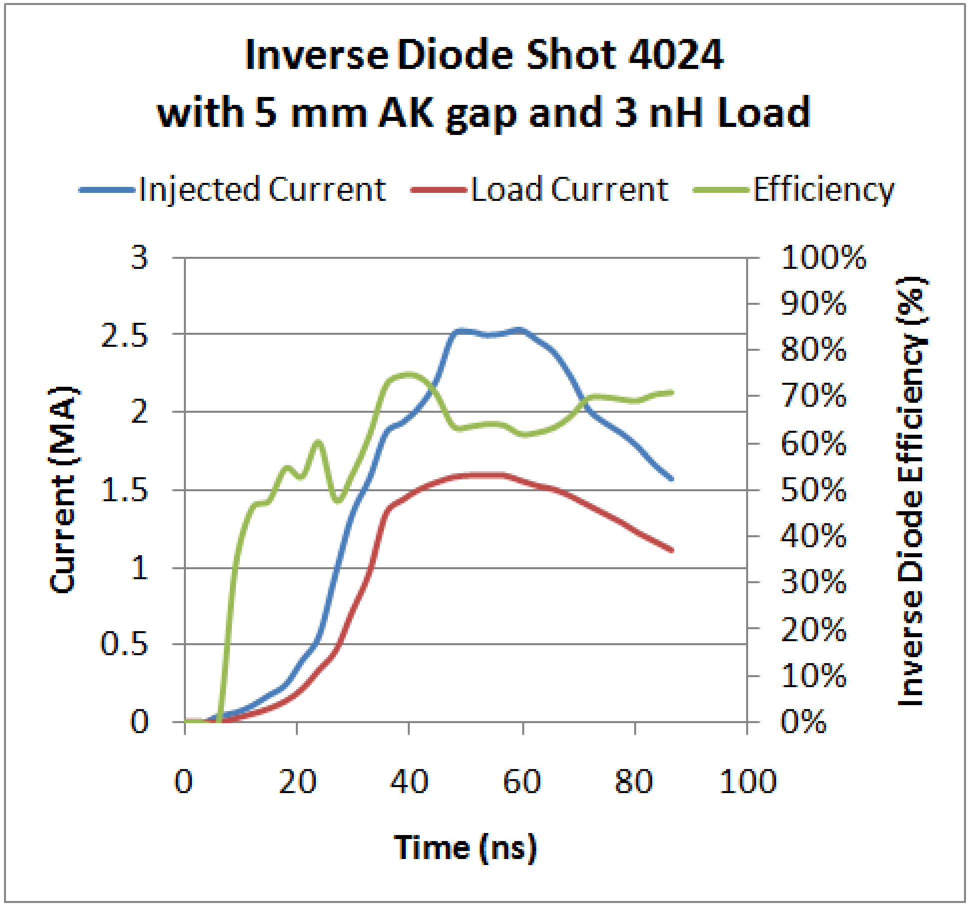
Unoptimized Inverse Diode had ~65% collection efficiency on Saturn.





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Driver/Economics

Long Self Magnetically Insulated Lines have been proven technology for 30 years.

Hermes III, 18 MV, 700 KA
in 1988

RHEPP II, 120 HZ,
in 1993

PBFA-I, 2 MV, 12 MA
in 1980

Magnetically Insulated LTDs protect the vacuum insulator and provide secondary containment

MYKONOS LTD Driver Test Bed

Prototype costs are:
$11/Joule
~10^{-4} cents/peak watt

- 1 MA, 0.2 TW, 25 kJ, two cavity tests planned in FY2011
  - Fire 40,000 shots (= *1,600,000 switch firings*) at 6 shots/minute with resistive load
  - Engineer and test a replaceable transmission line system
  - 1 MA, 1 TW, 125 kJ, 10 cavity test planned to follow
- ZR was built for 4$/J. This technology scales more favorably.
- Gen 3 LTD designs have 80% peak current with 50% cavity radius

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LLNL's Meier and Moir system model guides design choices with estimate of the COE.

First Units with 10% Cost of Capital and 1.85 MIT 2009 Study Factor to 2007$ gives 14.7 cents/kw-hr.

Input: Nc=number of chambers	1.00
Input: RR=rep rate in shots per chamber per second	3.00
Input: Discount or Hurdle Rate for attracting capital	10.00%
MIT Escalation Factor	1.85
Approximation to Pe (MW)	799
Input: E=Fuel Energy (MJ	0.235
Eta=thermal to electrical	0.44
Bank/Fuel efficiency	0.34%
$/Joule for Bank Energy	2.00
Energy Store (MJ)	69
ηG_bank	9
Net Electrical Power (MW)	626
Output: COE in $/KWH	0.147
Y(E)=yield per chamber (MJ)	592
M=Energy multiplication factor	1.15

Proven Units with 7.8% Cost of Capital and 1.0 MIT 2009 Study Factor to 2007$ gives 7.6 cents/kw-hr.

Input: Nc=number of chambers	1.00
Input: RR=rep rate in shots per chamber per second	3.00
Input: Discount or Hurdle Rate for attracting capital	7.80%
MIT Escalation Factor	1
Approximation to Pe (MW)	799
Input: E=Fuel Energy (MJ	0.235
Eta=thermal to electrical	0.44
Bank/Fuel efficiency	0.34%
$/Joule for Bank Energy	2.00
Energy Store (MJ)	69
ηG_bank	9
Net Electrical Power (MW)	626
Output: COE in $/KWH	0.076
Y(E)=yield per chamber (MJ)	592
M=Energy multiplication factor	1.15

QSDD Capsule, Cylindrical RTL, Survivable Inverse Diode, Magnetically Insulated LTD.

Version 0.5 Plasma Power Station needs key improvements.

- Better mitigation of wall instability
- Experimental demonstration of QSDD performance
- 2D high-resolution LASNEX or Hydra simulation at 500 MJ yield with dI/dt ~$1.6x10^{15}$ A/s
- Experimental demonstration of > 90% current efficiency with Direct Inverse Diode (DID)
- Survivable DID anode at 560 A/cm^2 electron injection
- Ignition on short pulse modification of Z
- 2D LASNEX simulations of blast and radius for survivability
- LiXX working fluid with <$3x10^{-5}$ Torr vapor pressure at 400 ^{o}C
- Liquid metal MITL anode
- Simulation of chamber recovery for 3 Hz operation

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Backups

Design starts with the Meyer-Moir Economic Model for Pulsed Power IFE.

- Meyer-Moir Economic Model
- Quasi Spherical Direct Drive Capsule
- Recyclable Transmission Line
- Inverse Diode Current Adder
- Magnetically Insulated Linear Transformer Driver (MI-LTD)

Compact Plasma Power Station with Quasi Spherical Direct Drive Capsule for Fusion Yield and Inverse Diode for Driver-Target Standoff

J. P. VanDevender, M. E. Cuneo, S. A. Slutz, M. Herrmann, R. A. Vesey, D. B. Sinars, D. B. Seidel, L. X. Schneider, K. A. Mikkelson, V. J. Harper-Slaboszewicz, B. P. Peyton, A. B. Sefkow, and M. K. Matzen

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The Meier-Moir economic model for Pulsed Power Driven Inertial Fusion Energy shows at least two approaches for fusion energy at 7 to 8 cents/kw-hr: one with large yield at 0.1 Hz and presented by M. E. Cuneo at this conference and one with small yield at 3 Hz presented in this paper. Both use the same very efficient and low cost Linear Transformer Drivers (LTDs) for the pulsed power. We report the system configuration for the latter option, which is called the Compact Plasma Power Station (CPPS), and report new results on the two, least mature, enabling technologies: a magnetically driven Quasi Spherical Direct Drive (QSDD) capsule for the fusion yield and an Inverse Diode for the standoff between the driver and the target.

The evolving CPPS system configuration currently consists of the following subsystems: Linear Transformer Driver (LTD), a magnetic pulse compressor, vacuum interface, electron beam diode, beam transport cell, inverse diode, self-magnetically insulated transmission line (MITL), and QSDD capsule.

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A liquid-metal, neutron-absorbing first wall protects the vacuum/reactor chamber and provides the heated working fluid for a conventional balance of plant. The overall efficiency η of the driver is ~13% and the gain G of the QSDD capsule is 160 for $\eta G=22$. The Meir-Moir model for the CPPS gives ~7.6 cents per kW-hr for the estimated cost of electricity.

A newly invented, very-high-current Inverse Diode converts the electron beam (providing standoff between the accelerator and the target) to MITL current for driving the capsule. Counter streaming electron flow is prevented by self-magnetic insulation in most of the Inverse Diode and by self-electrostatic insulation where the magnetic field is low. Two-D simulations show ~90% of the injected electron beam current is captured and fed into the MITL.

The MITL current is conducted through the quasi-spherical metal shell of the QSDD capsule. The main fuel is cryogenic DT that is frozen onto the inside of the metal shell and surrounds the DT gas that becomes the central hot spot for ignition. The magnetically driven pressure wave transforms into a passively pulse-shaped drive that keeps the main fuel on a low ($\alpha=1.5$) adiabat for efficient compression while the hot spot is shock heated and adiabatically compressed to ignition. A cryogenic DT layer deposited onto the conical metal walls provides an anti-mix layer to mitigate mixing fuel and wall materials. Two-D simulations show the wall instability limits the yield to a ~1 MJ on a Z-class facility. We will report on simulations to mitigate the wall instability and increase the yield to >100 MJ.

The inverse diode uses electrostatic insulation to prevent electron losses in low B-field regions.

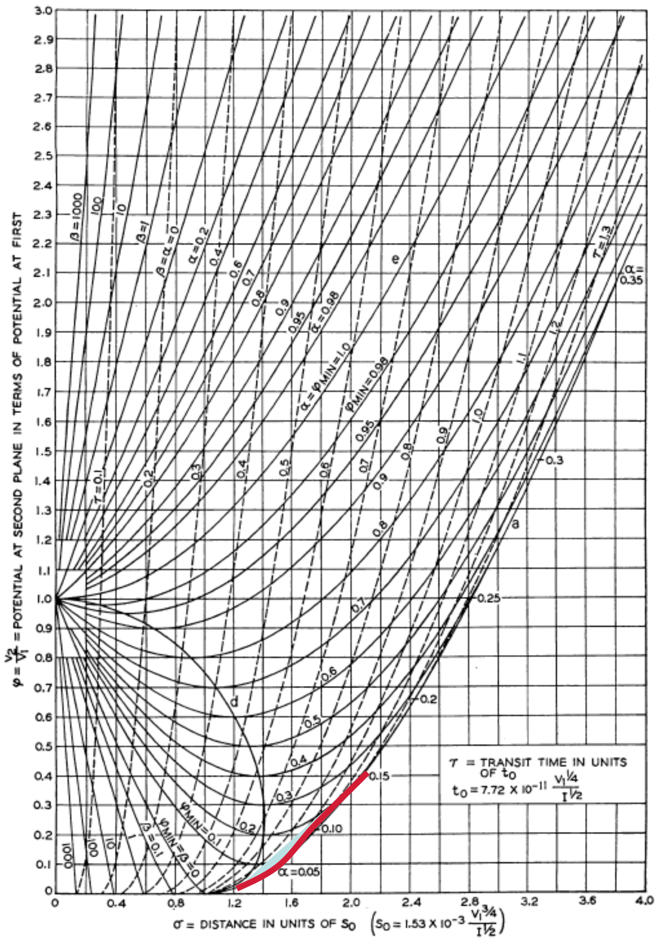

Fig. 3—Potential distributions of the C and D types. The solid lines are potential curves, the broken lines indicate the transit times.

On the Theory of Space Charge between Parallel Electrodes by C.E. Fay, A. LO. Samuel, and W. Shockley, Bell Systems Technical Journal, 17, Issue 1, pp 49-79 (1938)
Table 3

- Let d_scl = space_charge-limited gap and
  d_max= the maximum inverse diode gap
  (near the axis).

- For electrostatic insulation:
  1.2 d_scl < d_max < 2.1 d_scl

With relativistic correction:
$d\_scl = \text{sqrt}[(11.3/V^{0.187})*(2.32E\text{-}6*V^{1.5}/J)]$

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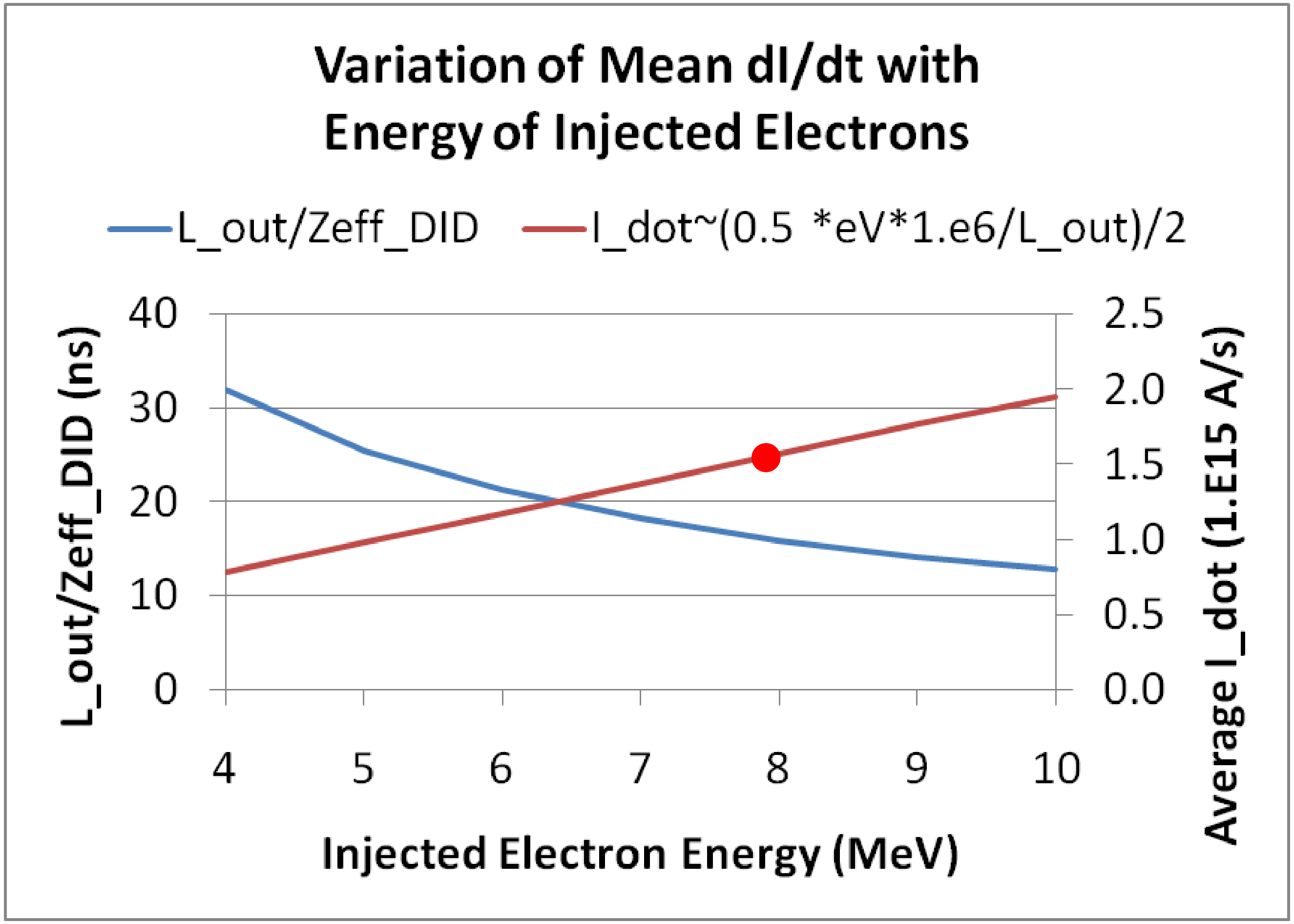
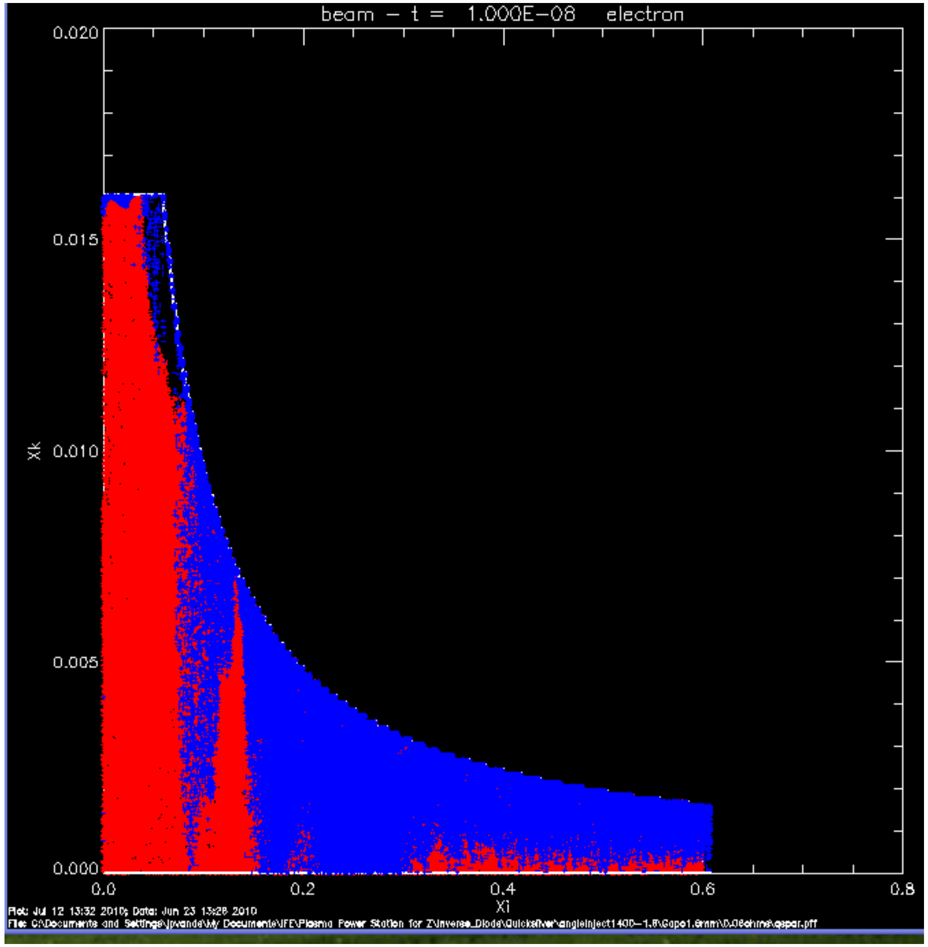
The driver must supply 50 MA of 8 MeV electrons into Inverse Diode to produce 1.6×10^{15} A/s in the capsule.



The minimum gap in the DID = 2 mm and equal to the Larmor radius.
Minimum gap in the MITL feed = 1mm.
DID Voltage = 0.5*eV_injected.

Quicksilver simulations show at least 80% current efficiency into load--without optimization.

- Red: Injected electrons
- Blue: Electrons emitted from cathode



- 40 MA at 4 MeV injected
- 33 MA at 2 MV at load without optimization

Cathode electrons are electrostatically insulated at small radius and magnetically insulated at large radius.