generalfusion

Progress in Acoustically-Driven Magnetized Target Fusion

Our Mission

Enable a transformation of the world's energy supply by developing the fastest, most practical, and lowest cost path to commercial fusion power.

World class team of 62, including 50 scientists and engineers

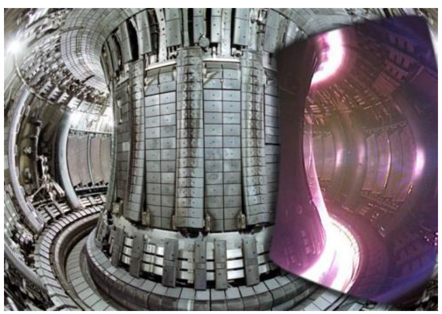
$78M in private capital from a global investor syndicate

Additional $23M from SR&ED, SDTC, NRC-IRAP, NSERC

Over 125 patents filed, granted, or in process

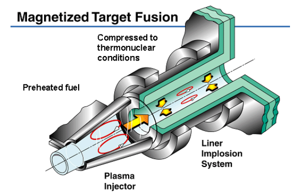
Approaches to Fusion

Magnetic Fusion



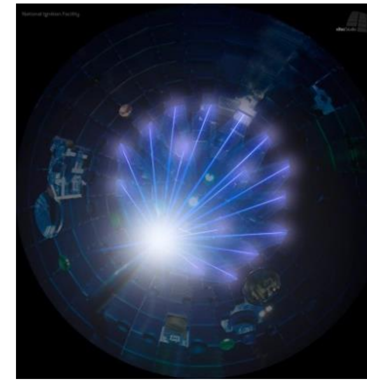
Very low density,
Continuous
(ITER)

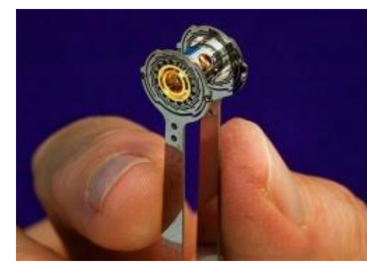
Magnetized Target Fusion



Medium density,
Pulsed

Laser Fusion



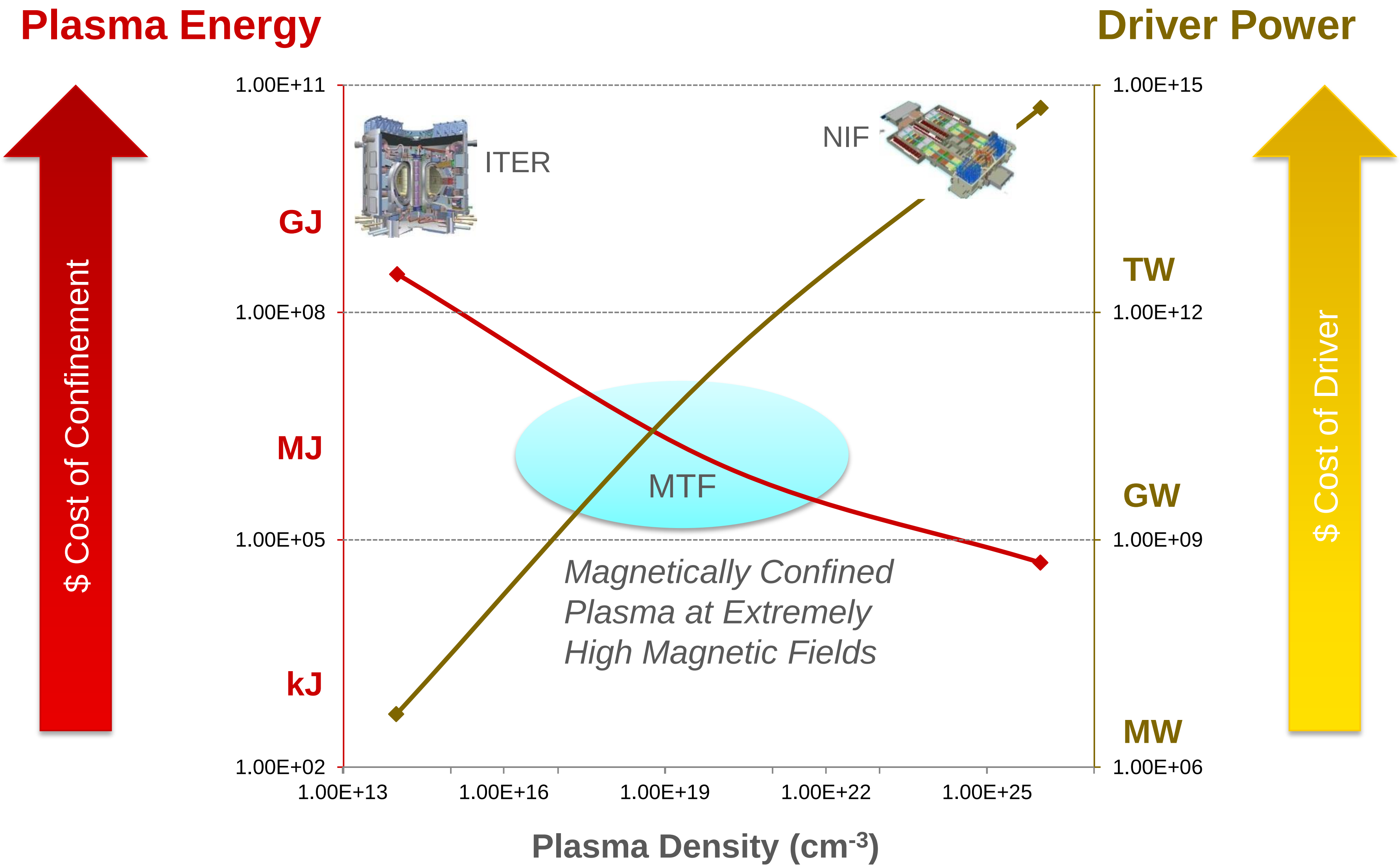


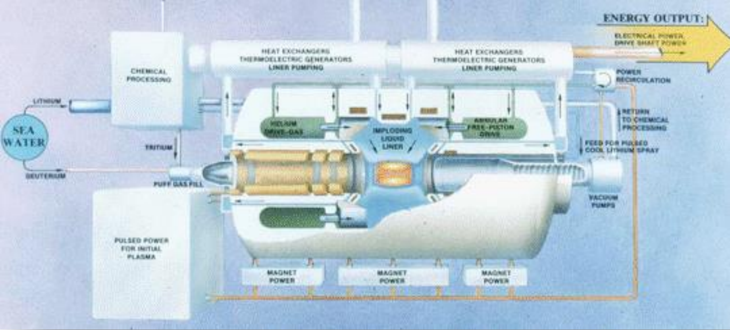
Extreme density,
Very short pulse
(NIF)

"The closest to a potential reactor is what General Fusion is proposing."

-Dr. R. Kirkpatrick, Los Alamos National Laboratory

Why this Middle Region is Attractive





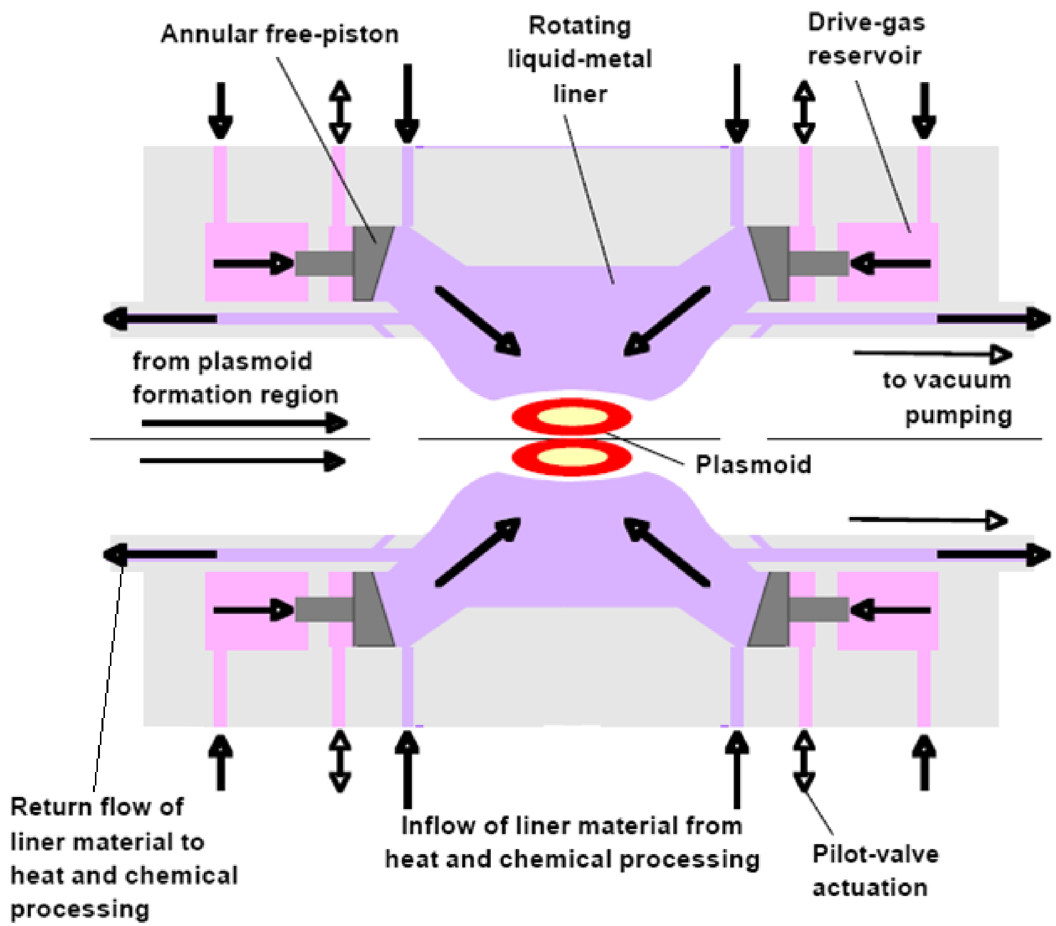
The MTF "Solution"

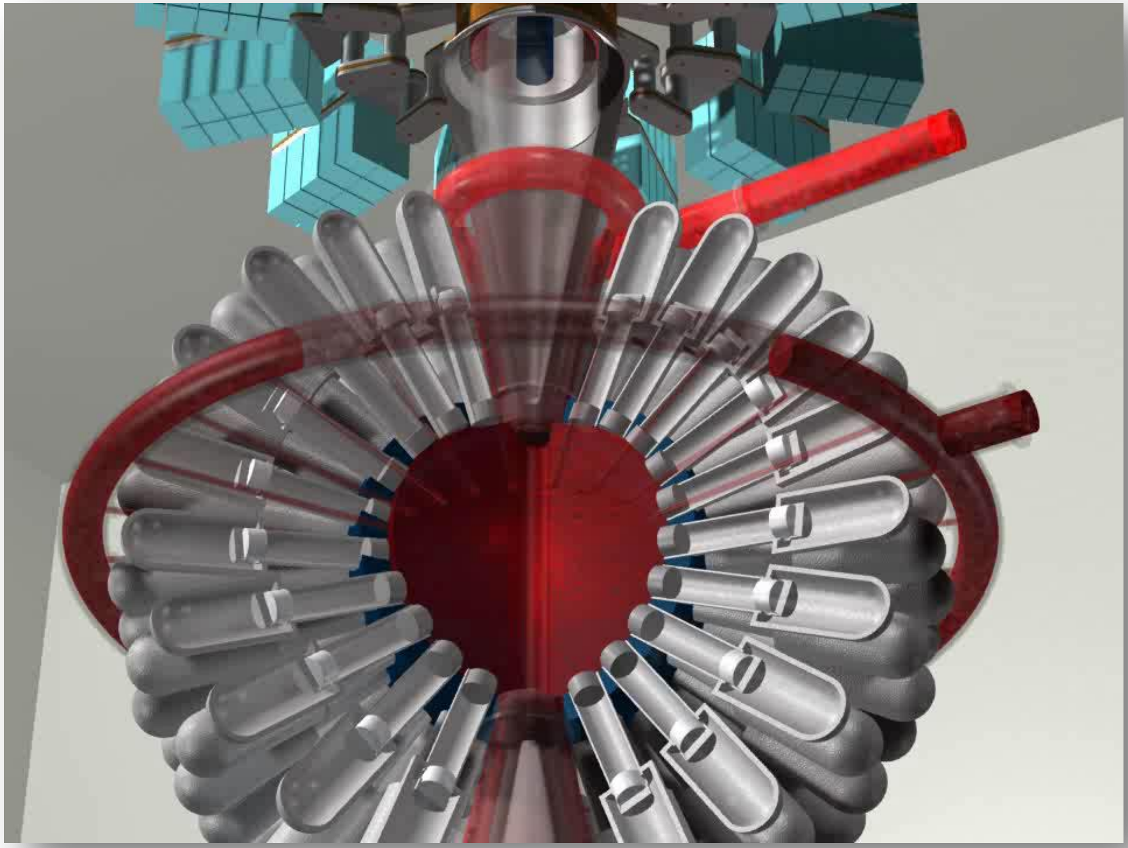
Recognized as:

- Low cost
- Practical

Fixed:

- First wall problem
- Stand off problem
- Cost/shot problem
- Fuel rebreeding





Example Parameters from Simulation

Initial Conditions

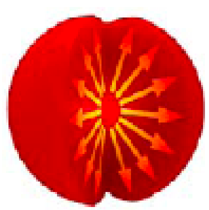
Pistons kinetic energy	120	MJ
Initial plasma density	1.25×10^{17}	cm^{-3}
Initial plasma temperature	100	eV
Initial magnetic field	7	Tesla
Initial plasma radius	20	cm

Compression

Radial compression	10	
Maximum fluid-plasma surface velocity	-2600	m/s
Energy transfer to plasma	14	MJ

Ignition

Peak plasma density	1.16×10^{20}	cm^{-3}
Peak plasma temperature	25	keV
Peak plasma pressure	5	Mbar
Peak magnetic field	670	Tesla
Confinement time (FWHM of plasma density):	7	μs



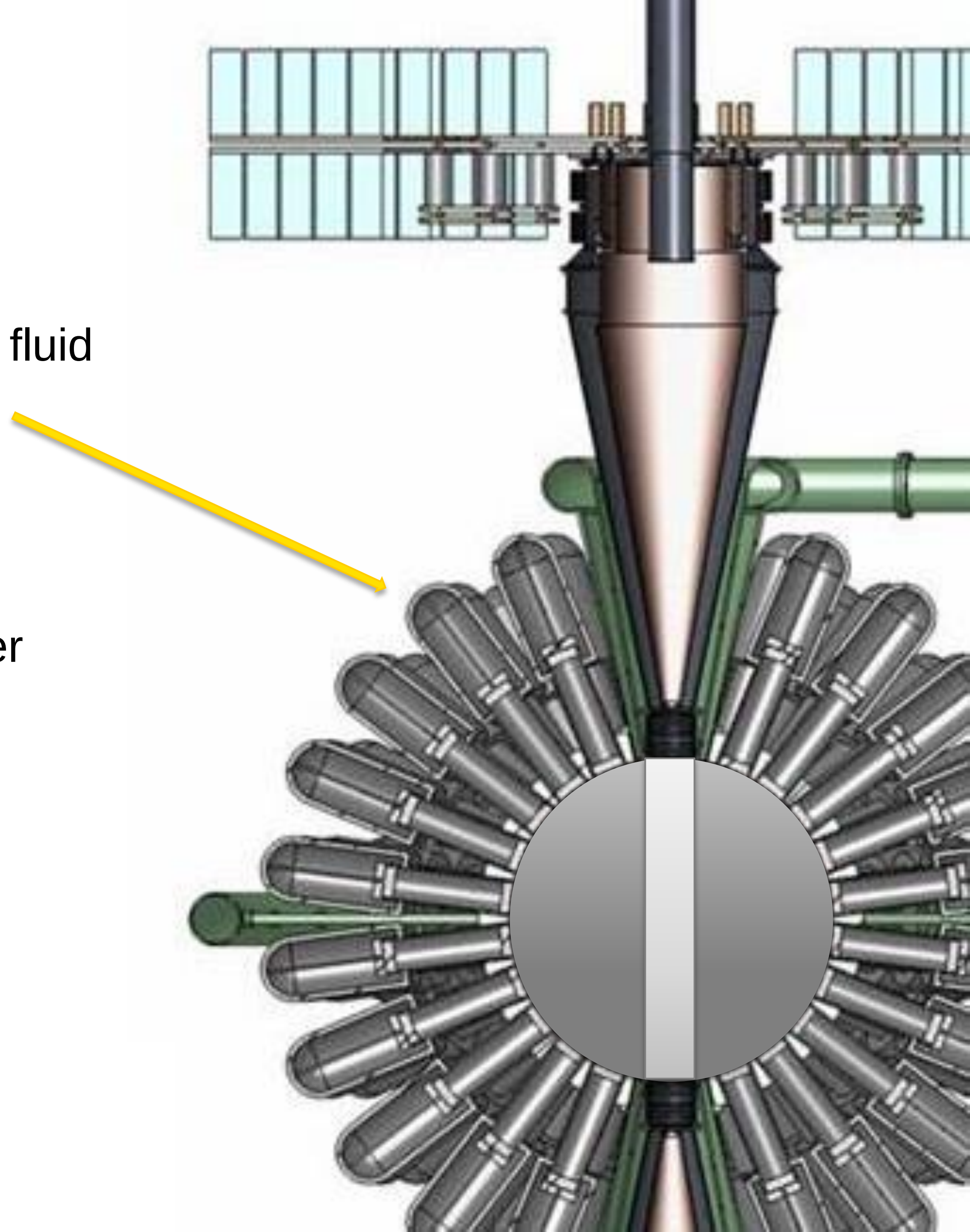
Energy Output

Fusion energy produced	700	MJ
Energy gain	6	

Practical

Compressed gas driver

- Uses power plant working fluid
- Baseline is steam (could be CO_2 or Helium)
- Low cost for high energy: <$0.2/Joule compared to >$2/Joule for pulsed power



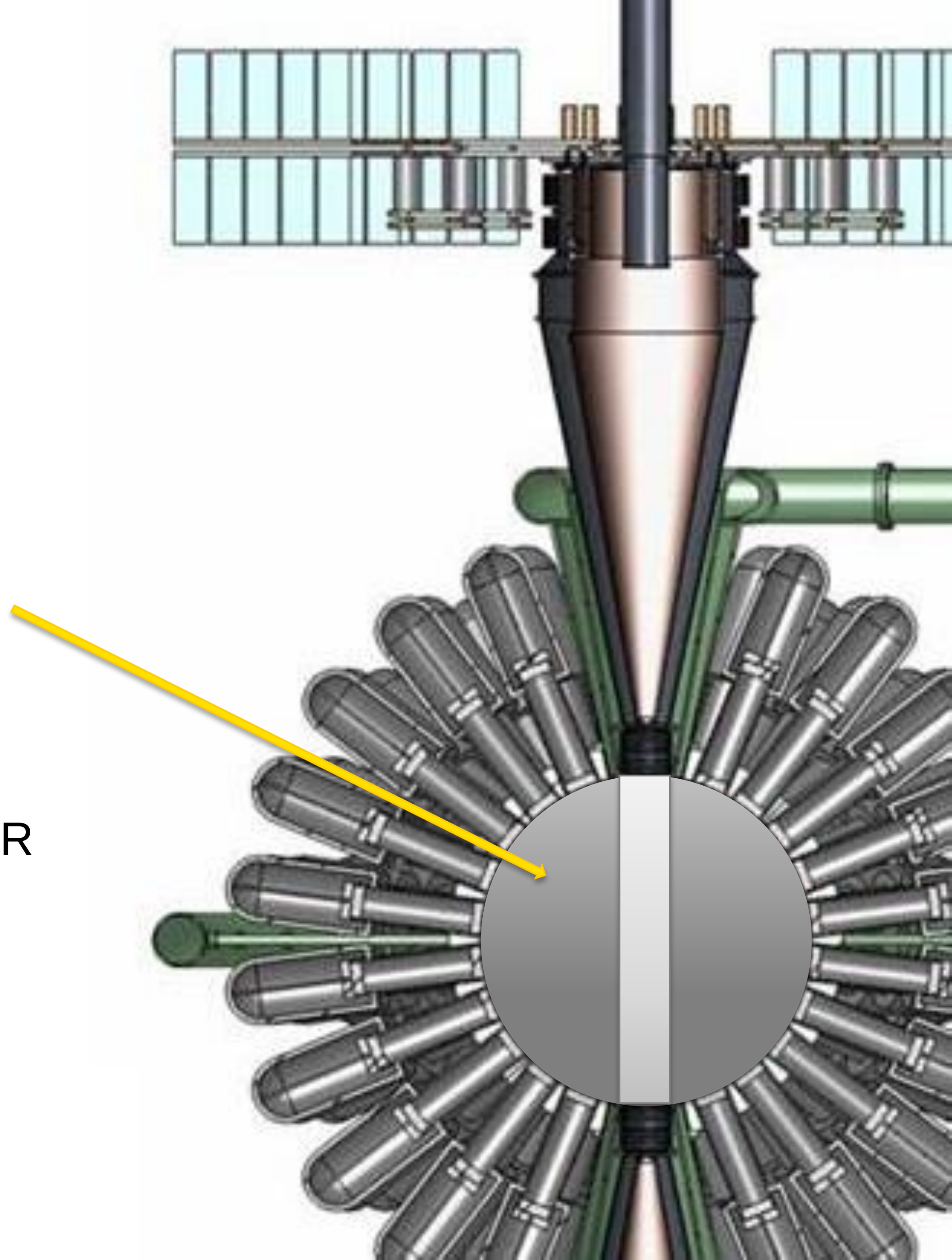
Practical

Thick Lead-Lithium blanket

- 300 °C inlet temperature
- 550 °C outlet temperature
- 2 m^3/s flow rate

- 2 MeV+ neutron flux to structure is **5 orders of magnitude** lower than ITER

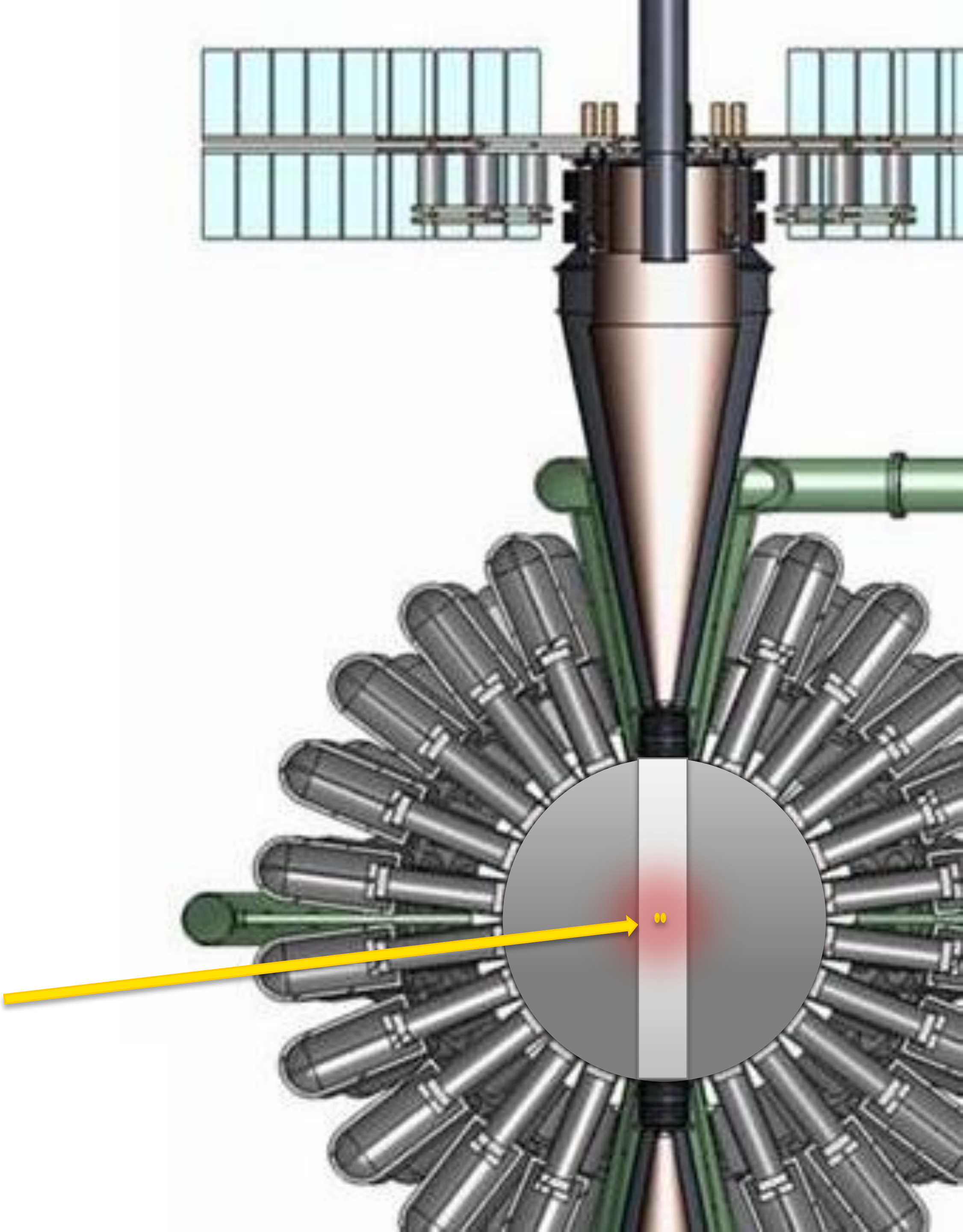
- 4π coverage, n,2n Pb reaction provides tritium breeding ratio of **1.5**

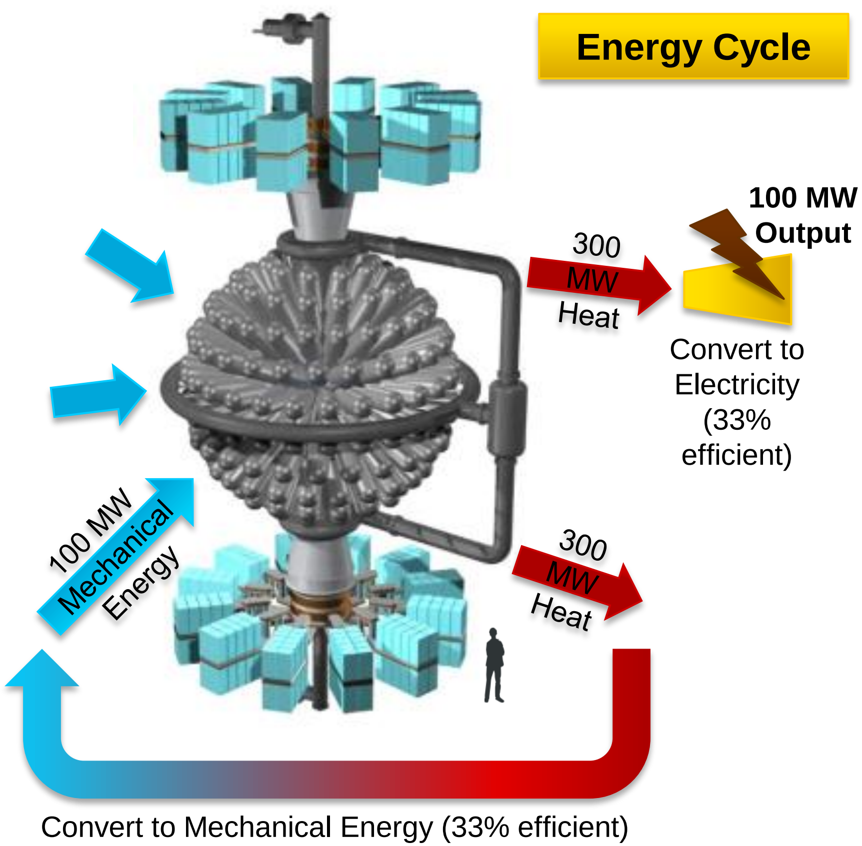


Practical

Plasma target

- Liquid wall cannot be destroyed
- Target is plasma only
- Provides a pulsed system with no consumables





- Modular 100 MWe power plant
- Heat converted to electricity with a straightforward steam turbine
- Capital cost of plant: ~$1,900/kW
  - + Fuel only $0.00001/kWh
  - + Limited fuel use each year: deuterium (18 kg/yr) & lithium (60 kg/yr)
- Levelized cost: ~$0.07/kWh
- Balance of plant similar to coal generation

Component Development

Plasma Injectors

✓ **Built largest injectors in the world**

Injectors built at scale

Temperatures >4 million degrees

Acoustic Driver

✓ **Full scale piston system completed**

50 m/s impact velocity

± 5 μs impact timing control

Symmetric Vortex Collapse

✓ **Constructed functioning piston/sphere prototype**

Liquid lead vortex and pumping system in operation

Reactor Physics Validation

Plasma Compression Tests

✓ **Advanced fusion yield tests underway**

Significant new data, working toward validating fusion yield

COMPRESSION SYSTEM

	Acoustic Driver	Complexity **Completed**	**Target**	50 m/s impact velocity ± 10 µs impact timing control (± 5 µs achieved)
	Symmetric Vortex Collapse	Complexity **Moderate**	**Target**	Smooth, symmetric collapse of molten Pb vortex

Acoustic Driver Milestones Met

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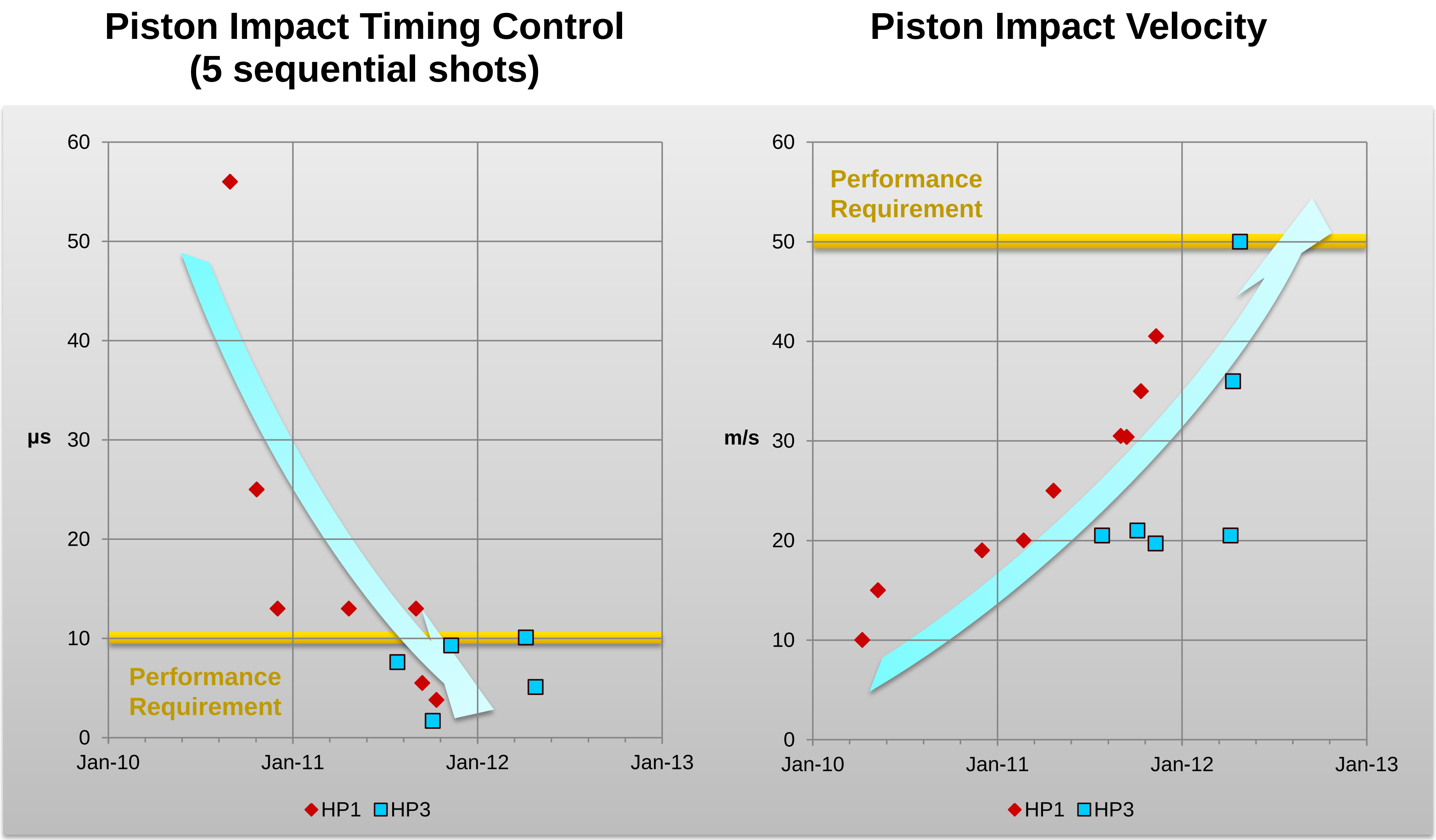


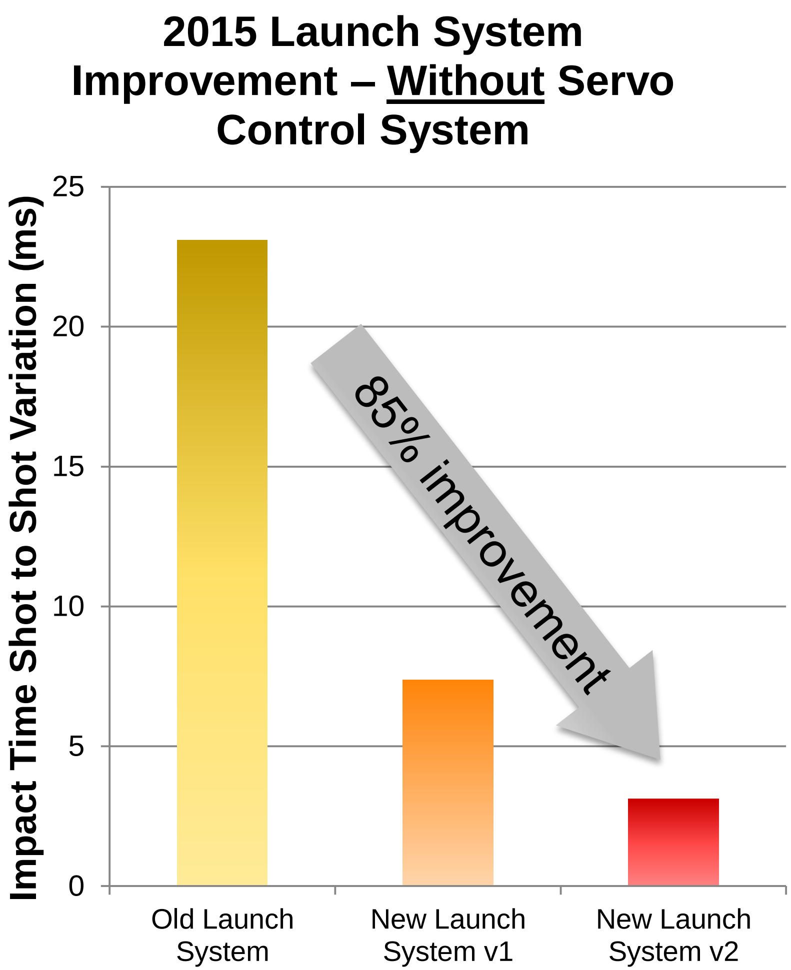
New Piston Design

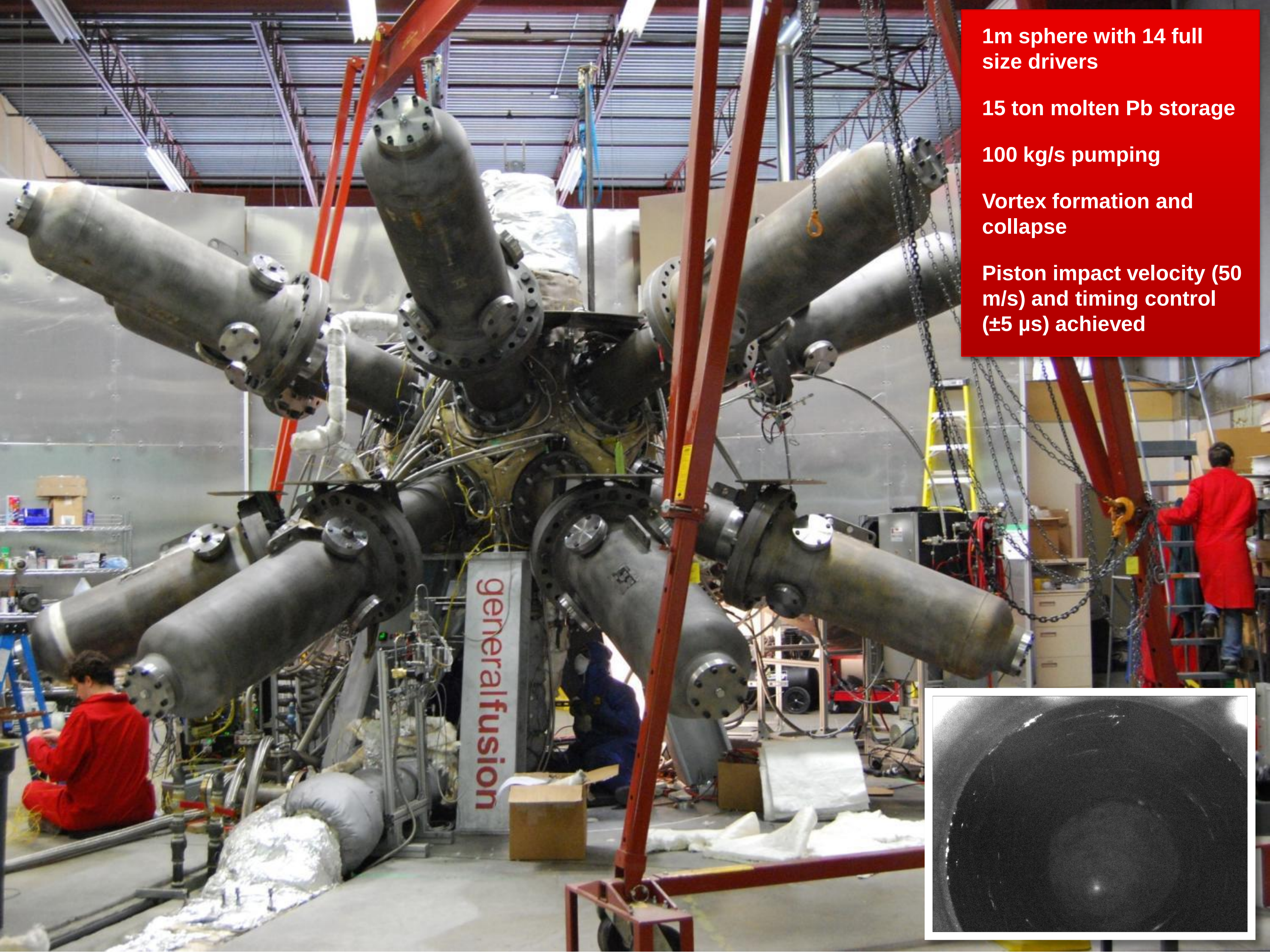
Goal: Higher impact speeds, and better impact timing control.

Incorporate power plant considerations

- Energy efficiency
- Piston reset
- Integration with balance of plant (steam systems)

New design to be complete by the end of 2015





- 1m sphere with 14 full size drivers
- 15 ton molten Pb storage
- 100 kg/s pumping
- Vortex formation and collapse
- Piston impact velocity (50 m/s) and timing control (±5 μs) achieved

Liquid Pb Vortex Collapse

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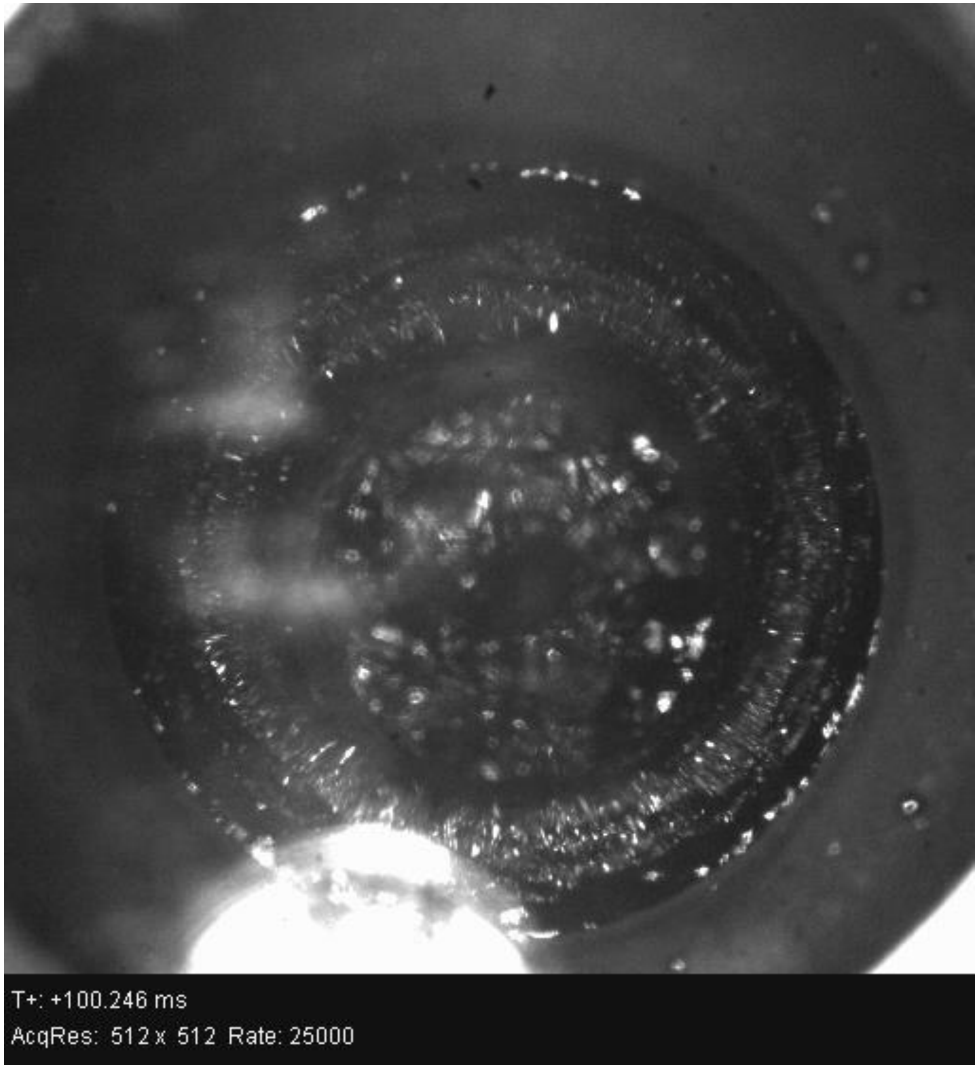

Simulation of Richmeyer-Meshkov Instability

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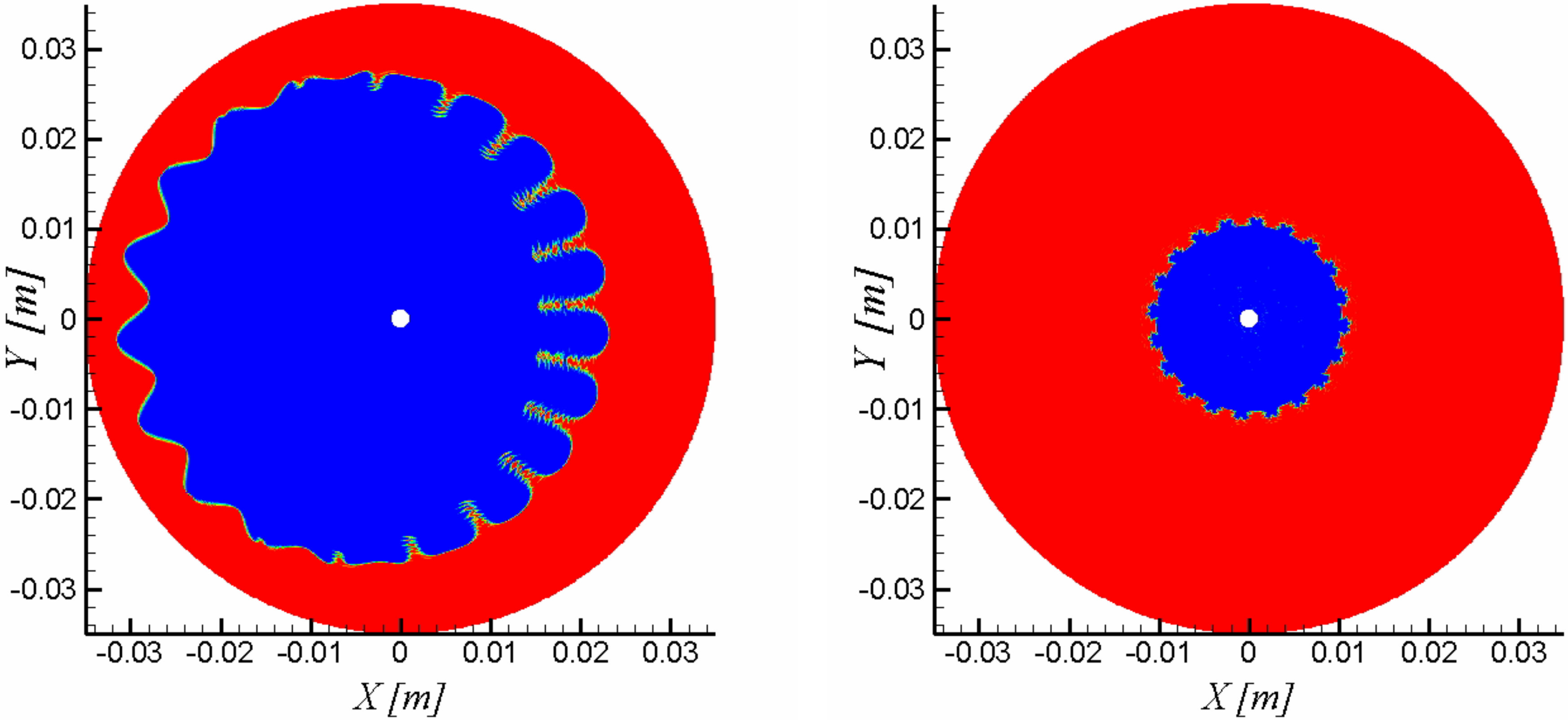

R-M Instabilities can be mitigated with a synchronized, convergent geometry

Vortex, Pistons & Sphere

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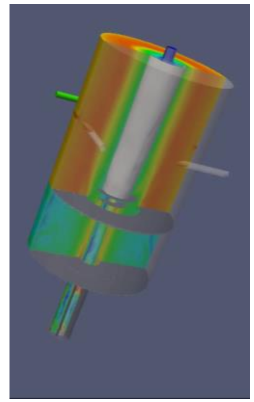
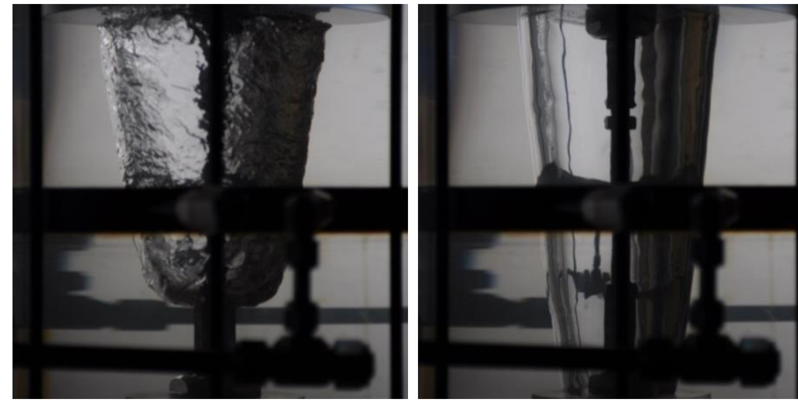
Internal Simulation and Experimental Work focused on Vortex Formation

- Experiment and simulation reconstructed mini-sphere behavior
- Developed pathway to smooth vortex
- Created reliable vortex simulation model

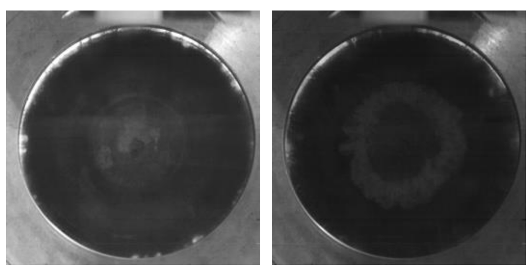




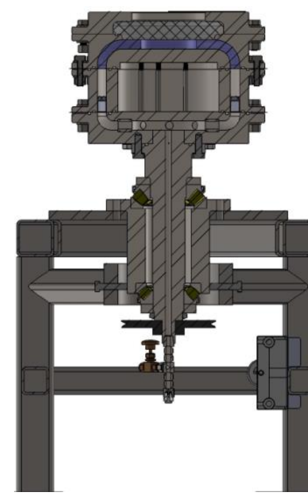
University Collaboration Simulation and Experimental Work on Vortex Collapse

McGill

- Experiments replicated R-M jetting
- Design support for new apparatus



2014 Molded Gelatin Experiments



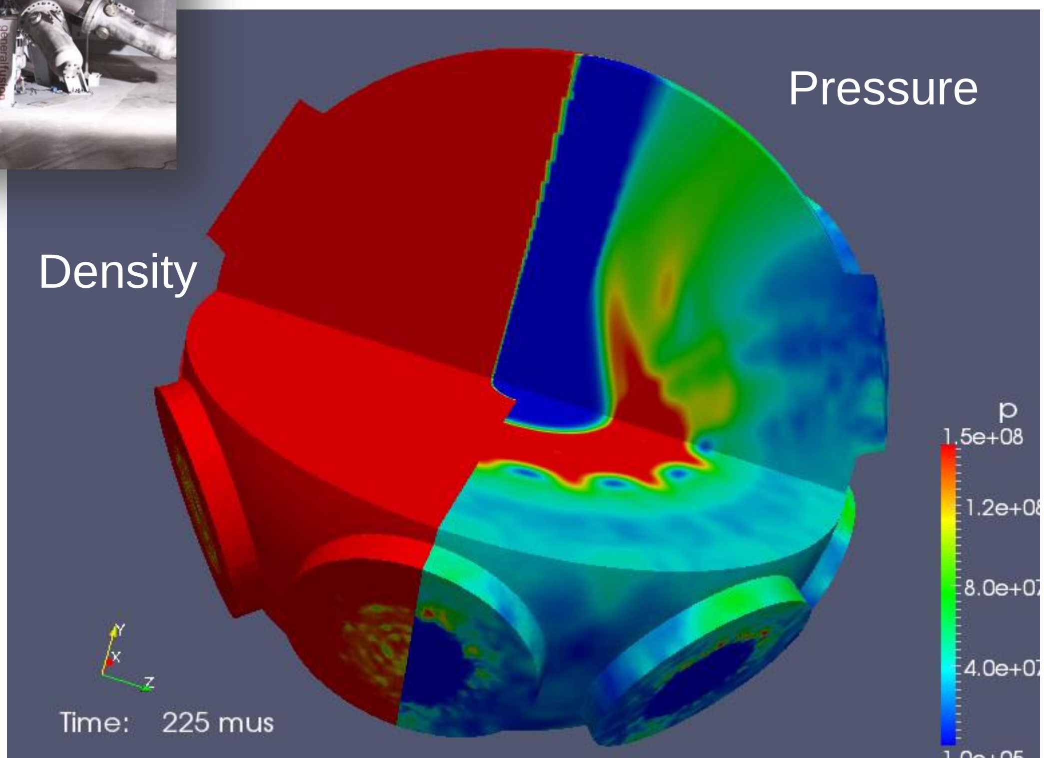
2015 Vortex Collapse Apparatus

2015

- McGill experiments to show shell formation in vortex collapse
- QMUL simulation effort starting now on anvil/fluid interface

Fluid and Vortex Behaviour – 3D Simulation

- 3D Fluid and Vortex Simulations have advanced significantly, now modeling many of the features seen in mini-sphere experimental data
- Shows that a smooth compression may be possible on mini-sphere if vortex smoothness can be improved



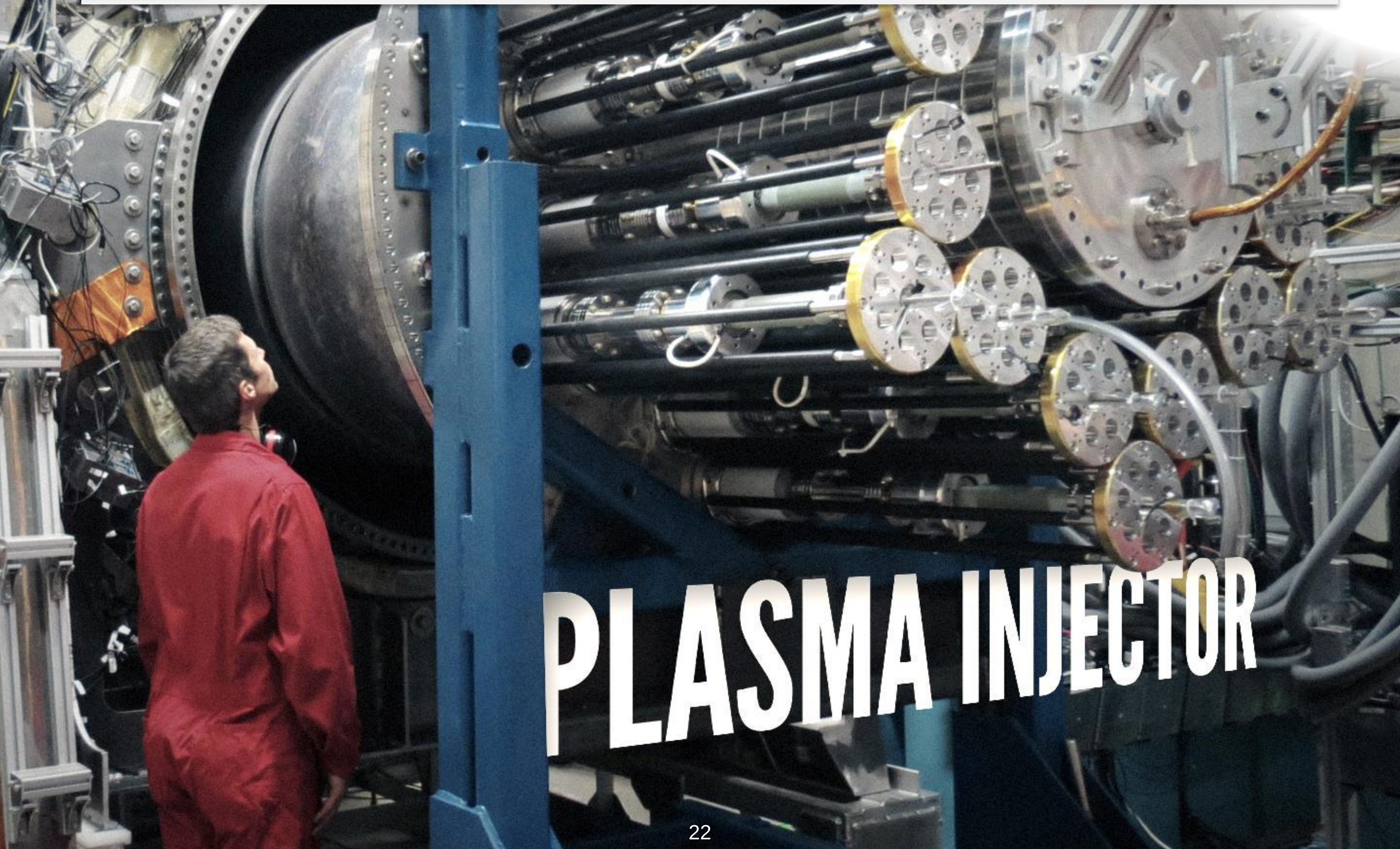
Plasma Injectors

Complexity
High

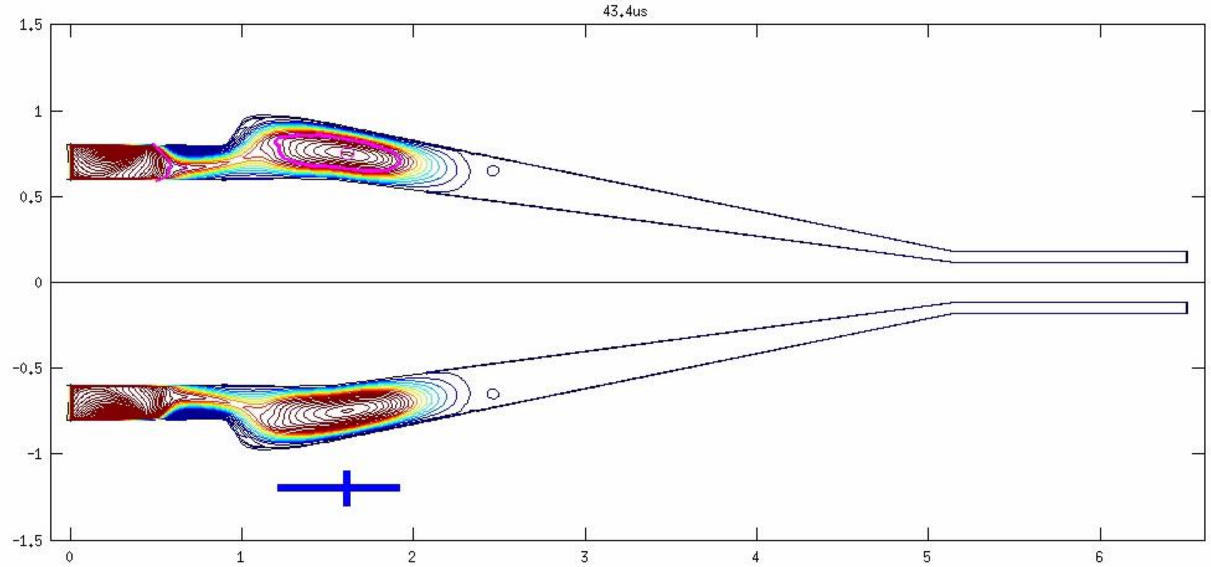
Target

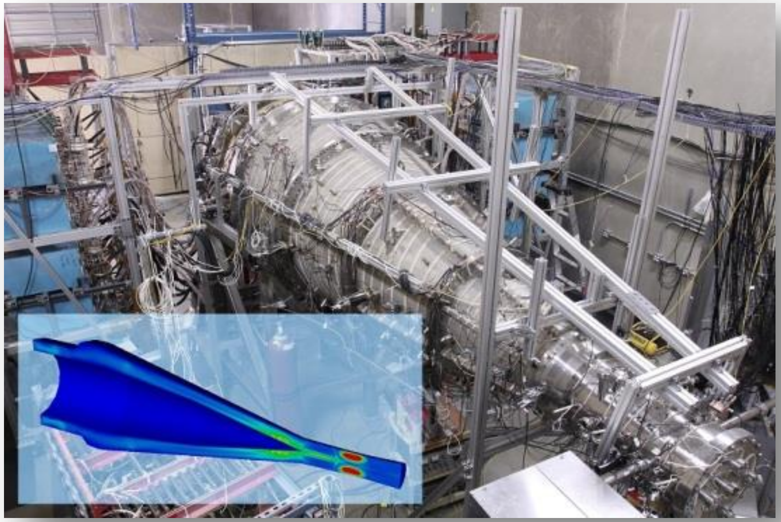
100 eV, 10^{16} cm^{-3}, 50 µs thermal life (for break-even)

100 eV, 10^{17} cm^{-3}, 50 µs thermal life (for power plant)



Large Plasma Injector





Plasma Acceleration: Summary of Results

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- 10^{14} cm^{-3}
- 40 eV
- 0.2 T

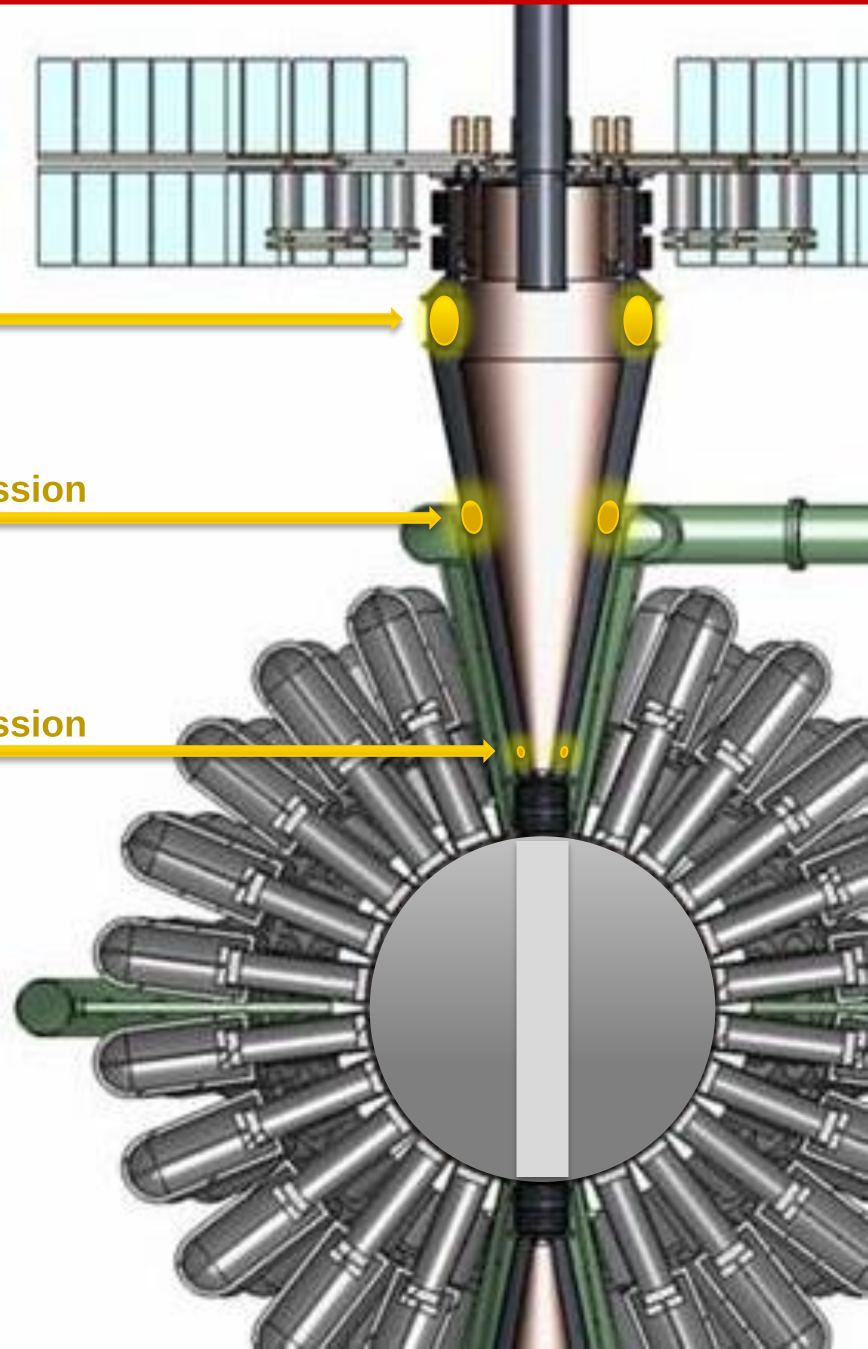
Formation

- 8×10^{14} cm^{-3}
- 160 eV
- 0.8 T
- **Adiabatic**

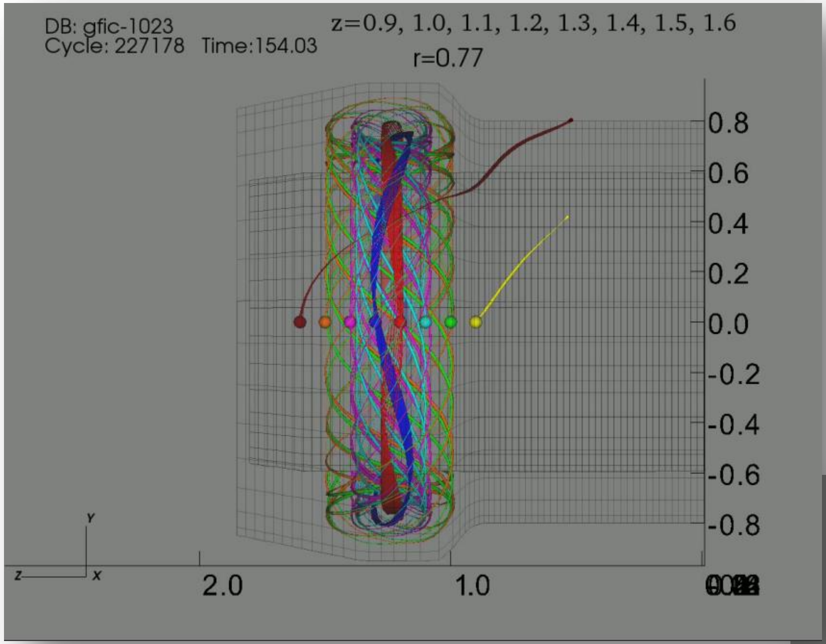
2X Radial Compression

- 6×10^{15} cm^{-3}
- 3.2 T
- 300 eV
- Expect >600 eV, not adiabatic

4X Radial Compression

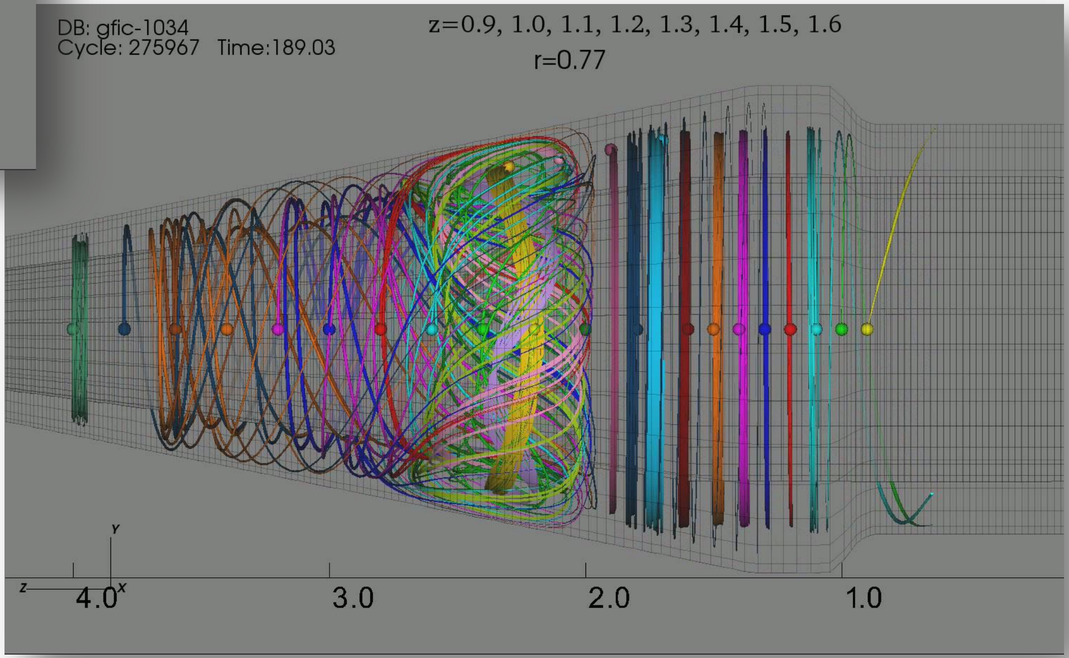


Plasma Injector: Confinement



Formation

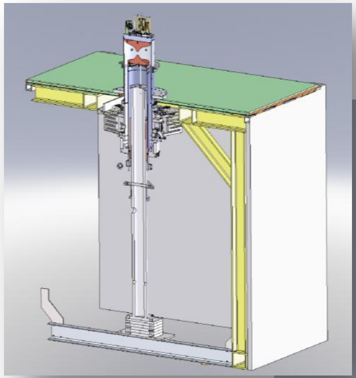
Simulation shows good plasma structure: formation confinement is good on large injectors

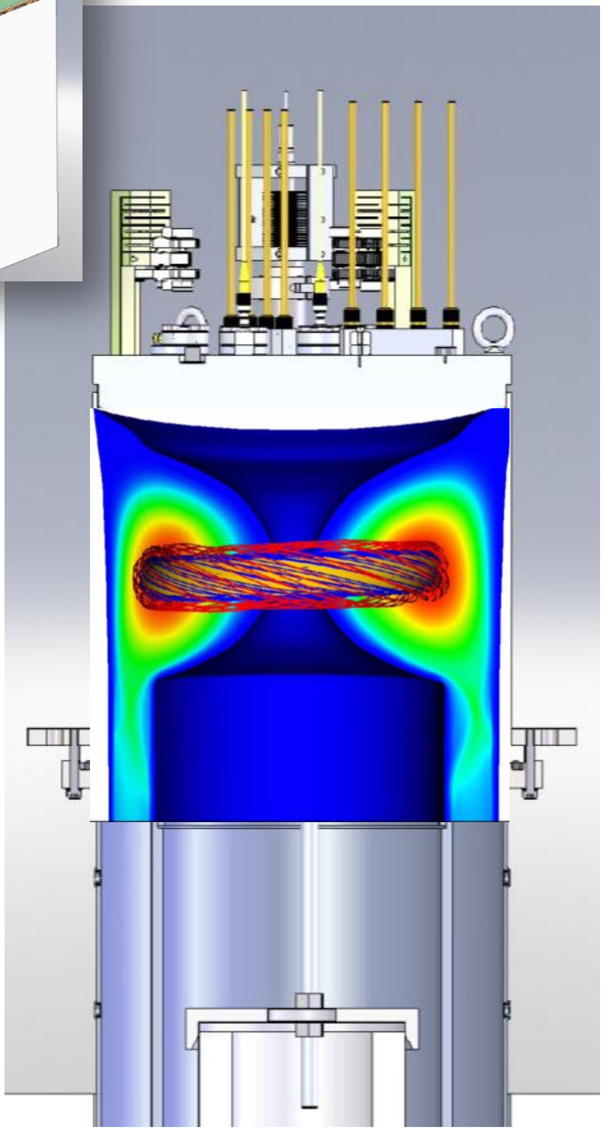


Acceleration

Simulation shows how the acceleration current can degrade the plasma structure and confinement

Small Plasma Injector





Direct formation: no acceleration stage.

Comparable to CTX and SSPX designs

Lower maximum plasma density than large injectors

Faster design iteration

Designed for use in plasma compression experiments

Plasma Lifetime Progress on Small Injector

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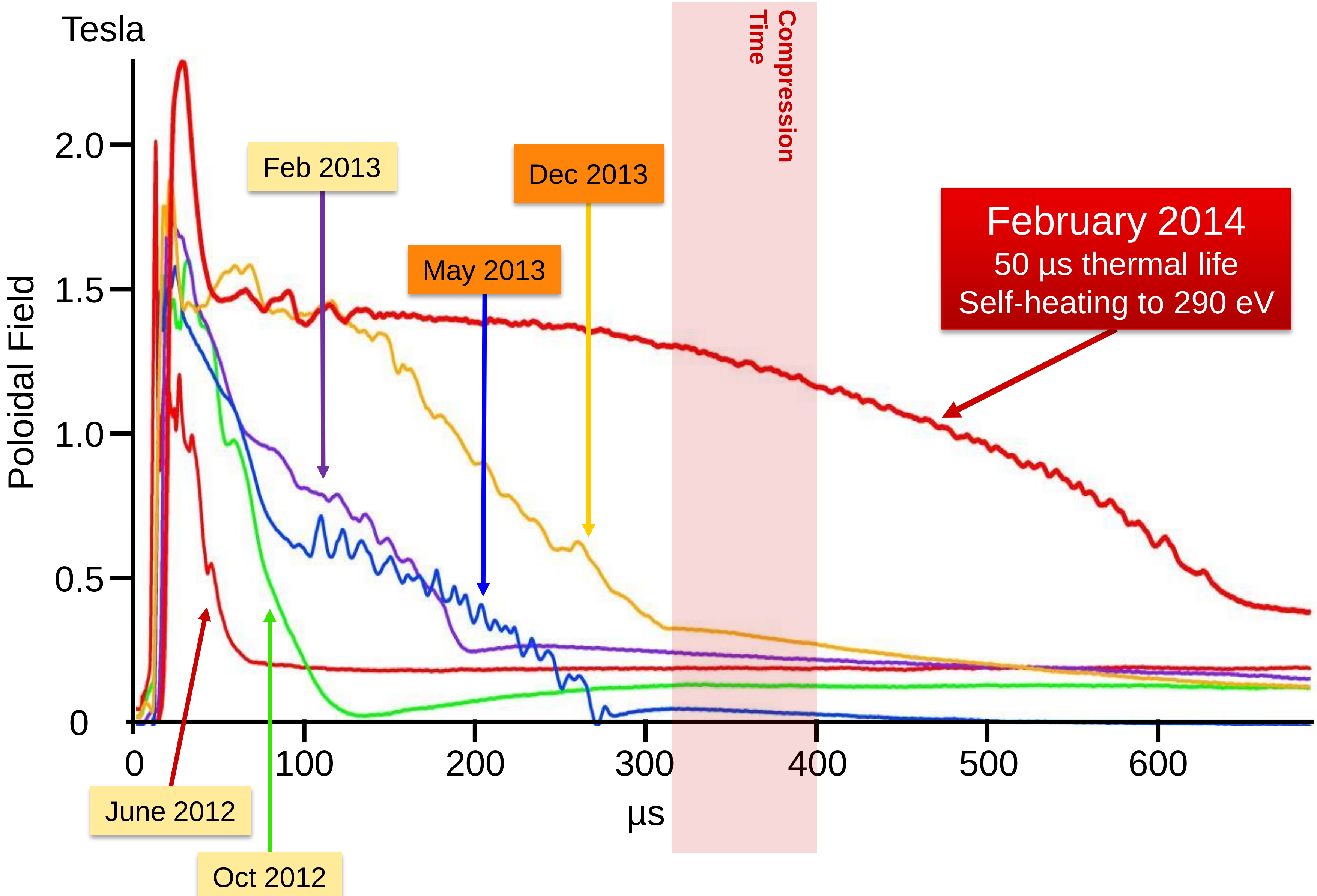


MHD Modulated by Sustain Current

Small gun current remaining after formation modifies MHD activity & lifetime

"Undersustained"

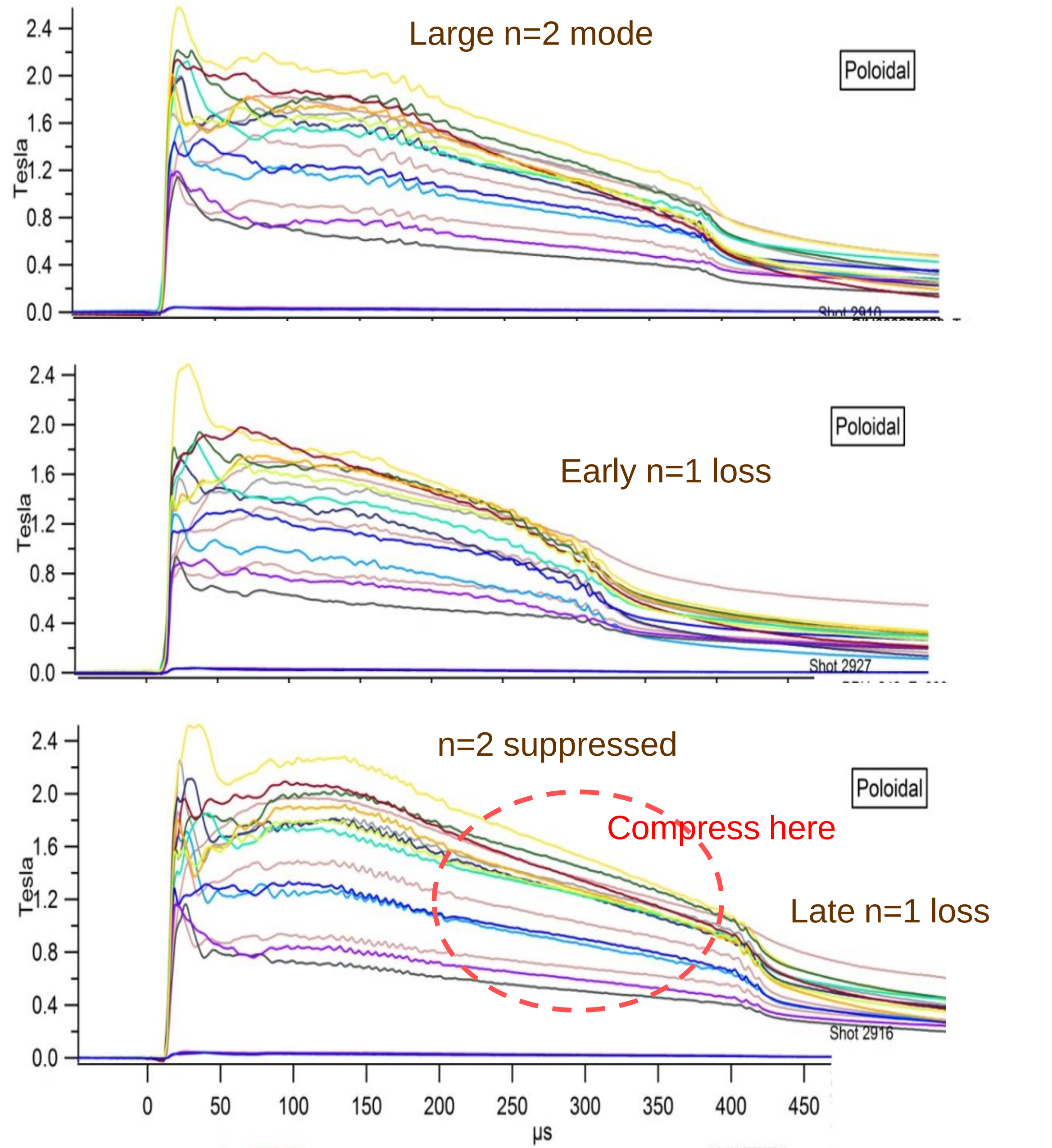
- 5.0kV
- q drops to 0.5 near core

"Oversustained"

- 5.5 kV
- q is driven → 1

Well sustained

- 5.2 kV
- q is held 0.5<q(r)<1 for longer period



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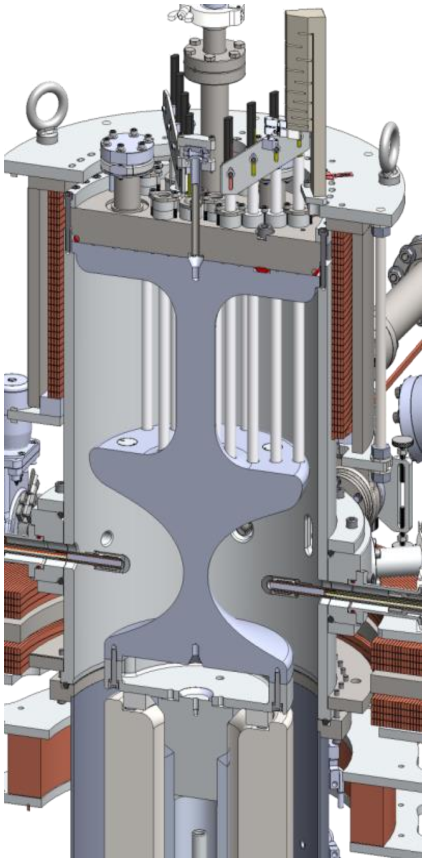
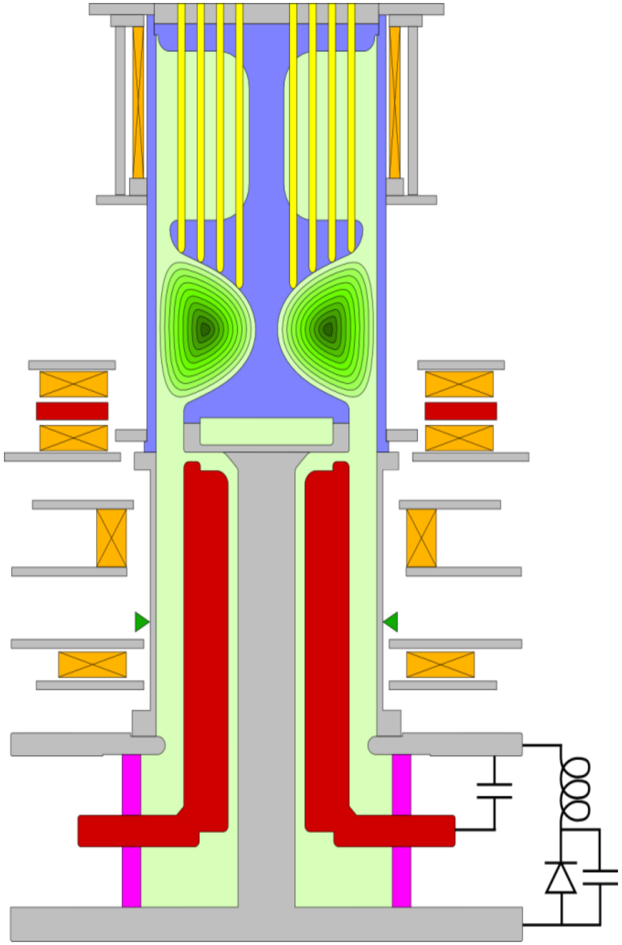


Built to allow more systematic/deliberate control of:

- 'Sustainment' current path:
- Overall safety factor: Stuffing Flux has Toroidal component



Can drive up to 800 kA through central shaft

Formation current of up to 1 MA

No gap below Center electrode

Reproduced sustained spheromak performance but with much better reliability

Scans of Shaft Current in PROSPECTOR

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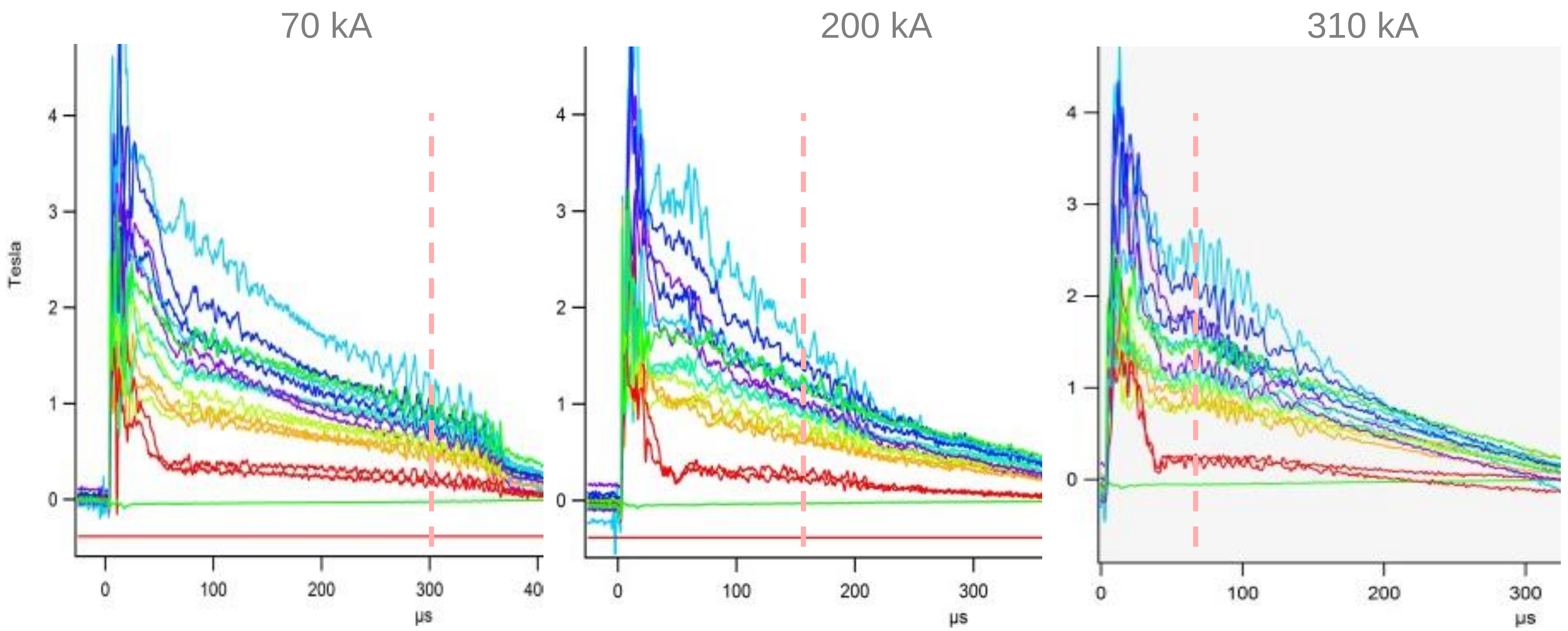
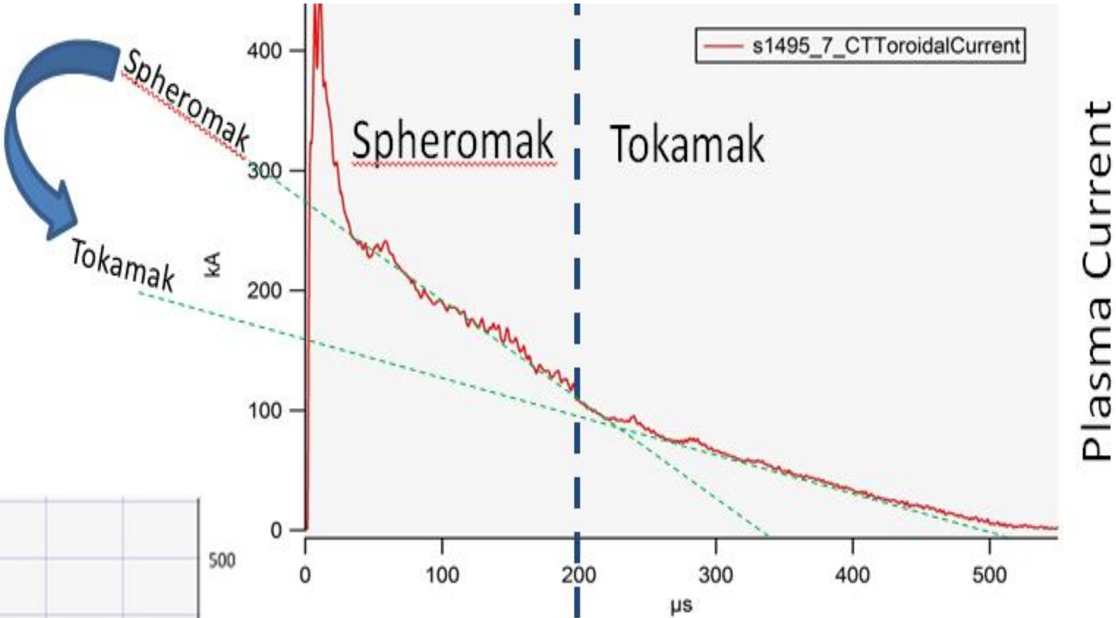
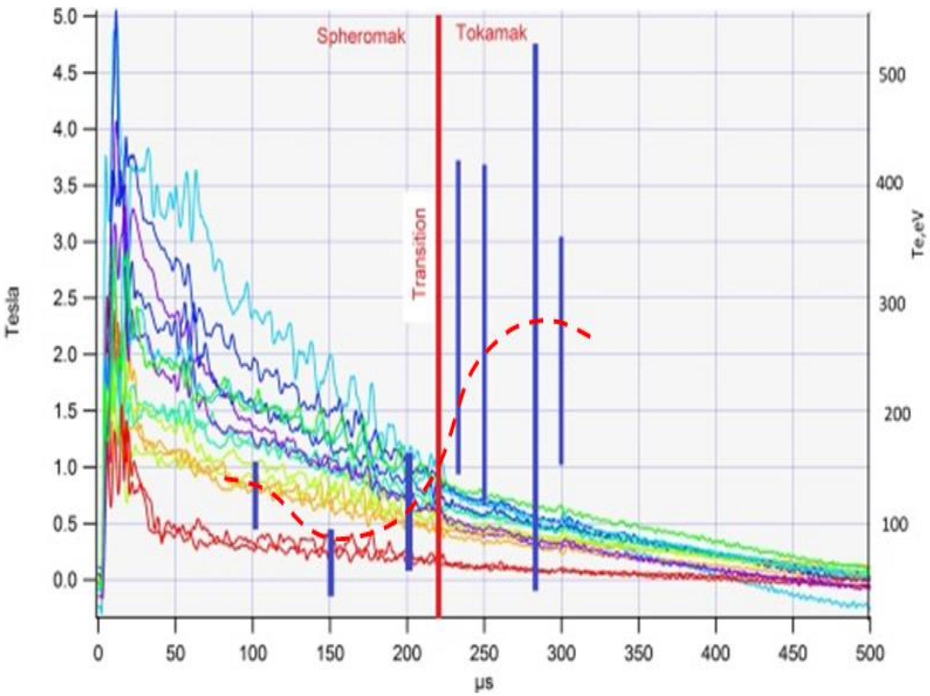


- Early scans of shaft current showed transition from familiar spheromak behavior to tokomak-like behavior (dashed line)
- Transition occurs earlier as shaft current (Toroidal field) increased
- ‘Tokamak’ discharge (q >1 everywhere) has reduced magnetic turbulence, visible radiation

Plasma Characteristics after Transition

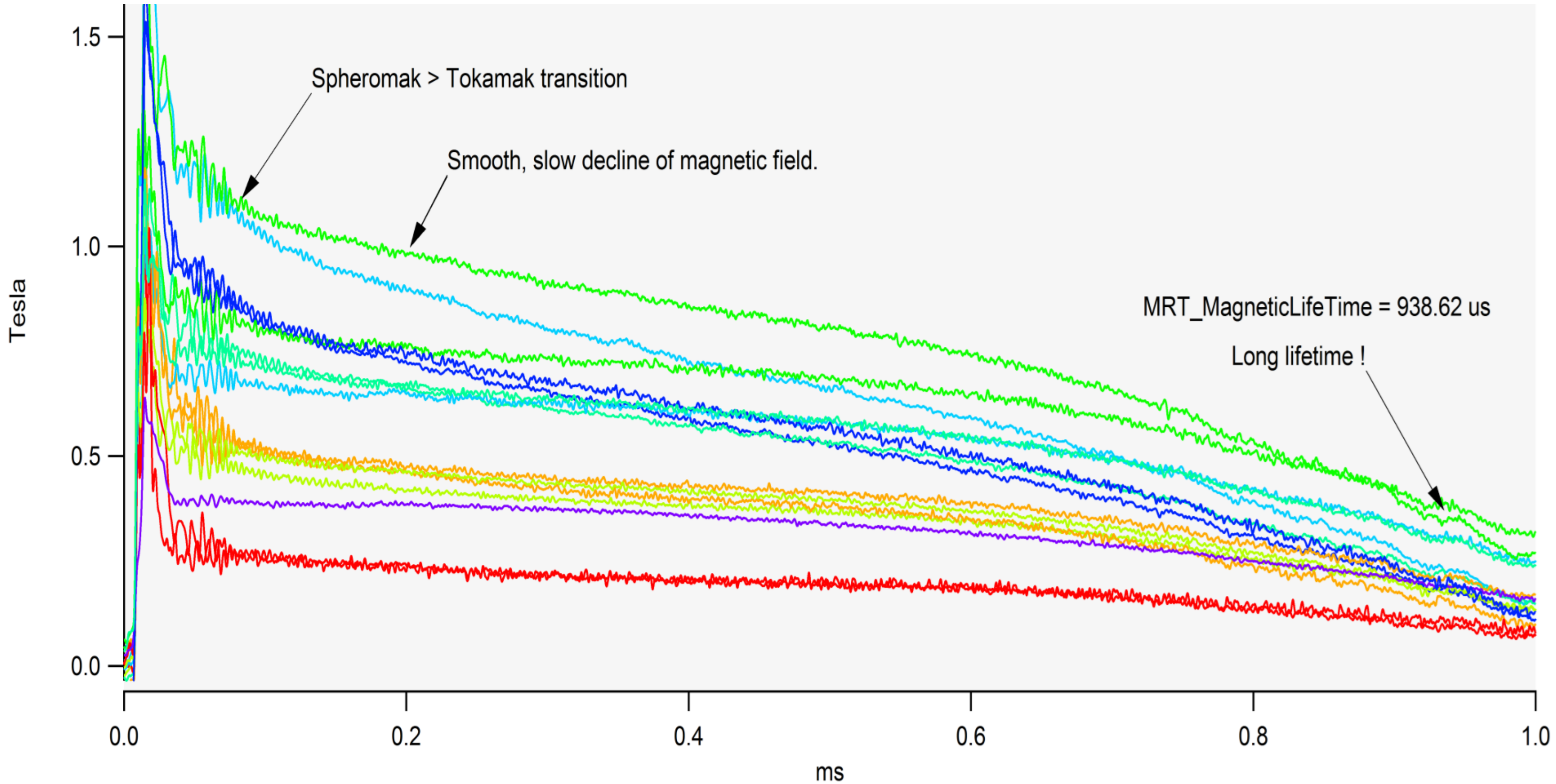
Improved Magnetic Lifetime





Increased Electron Temperature
(from Thomson Scattering)

Latest Data (October 2015)



Thermal lifetimes (τ) now exceeding 100 µs

Plasma Compression Testing

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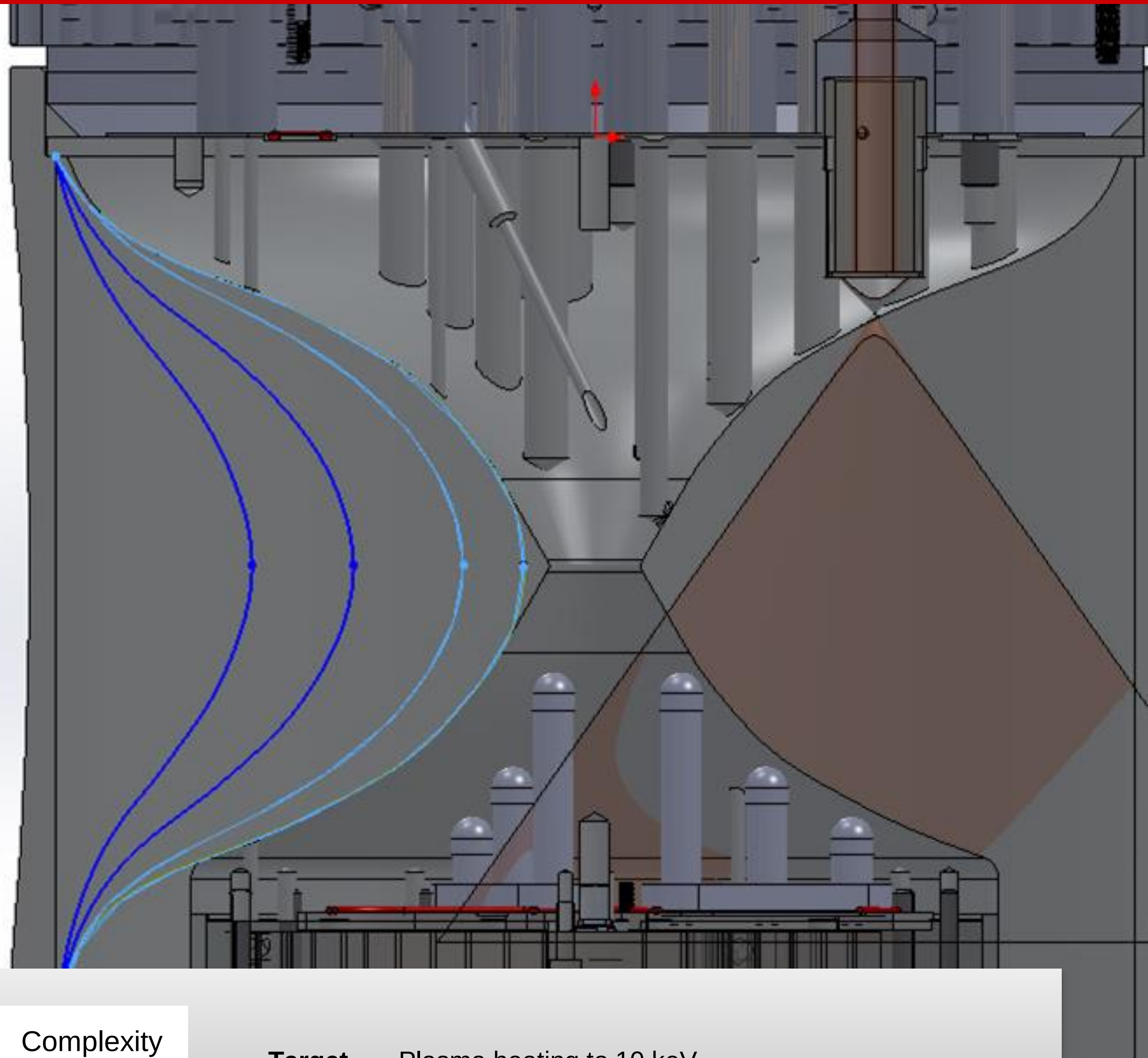

Reactor Physics Validation

Plasma Compression Tests	Complexity **High**	**Target**	Plasma heating to 10 keV

Example Magnetic Data – Test #2

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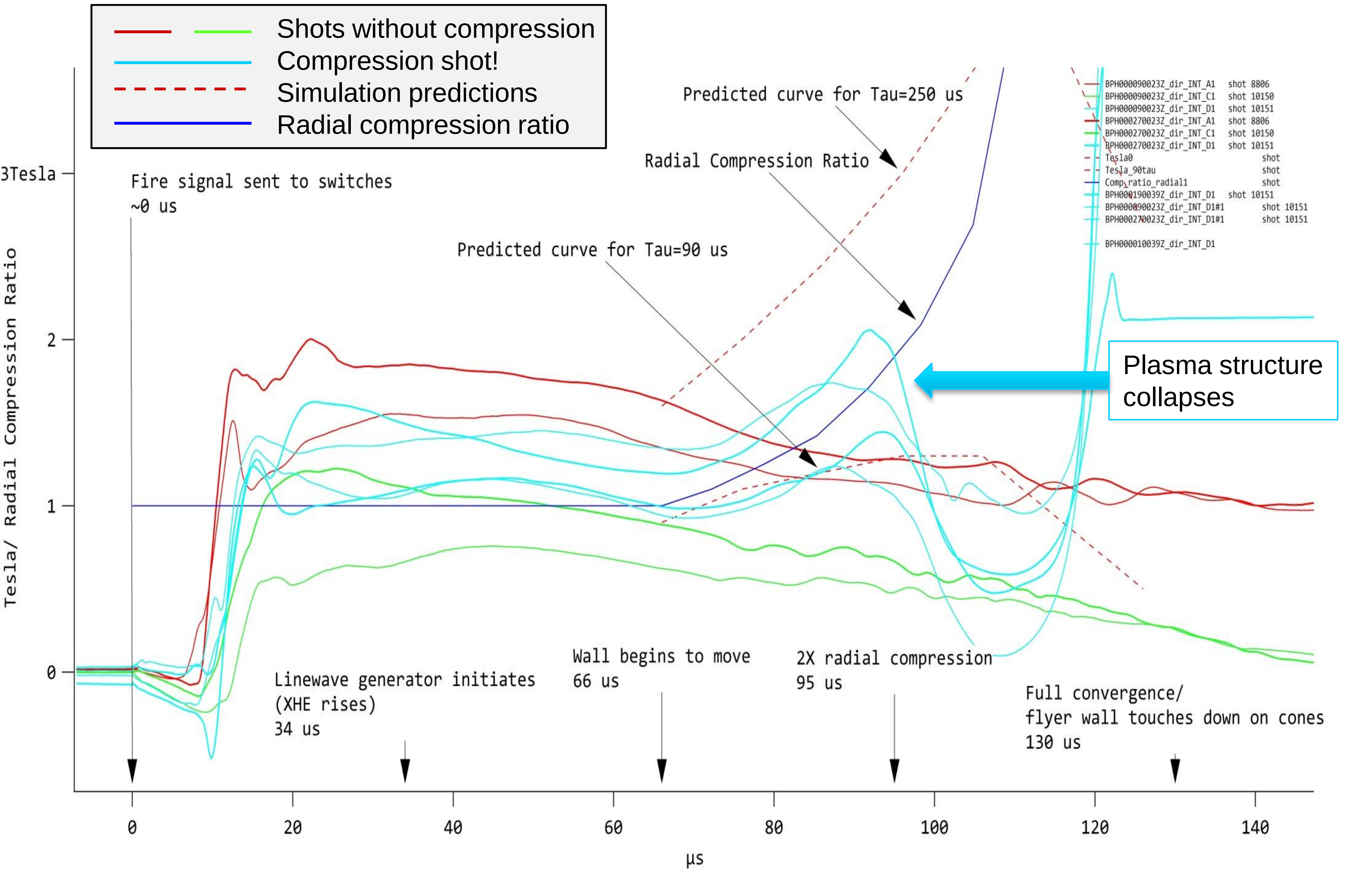

Effect of Lithium Walls - Test #7

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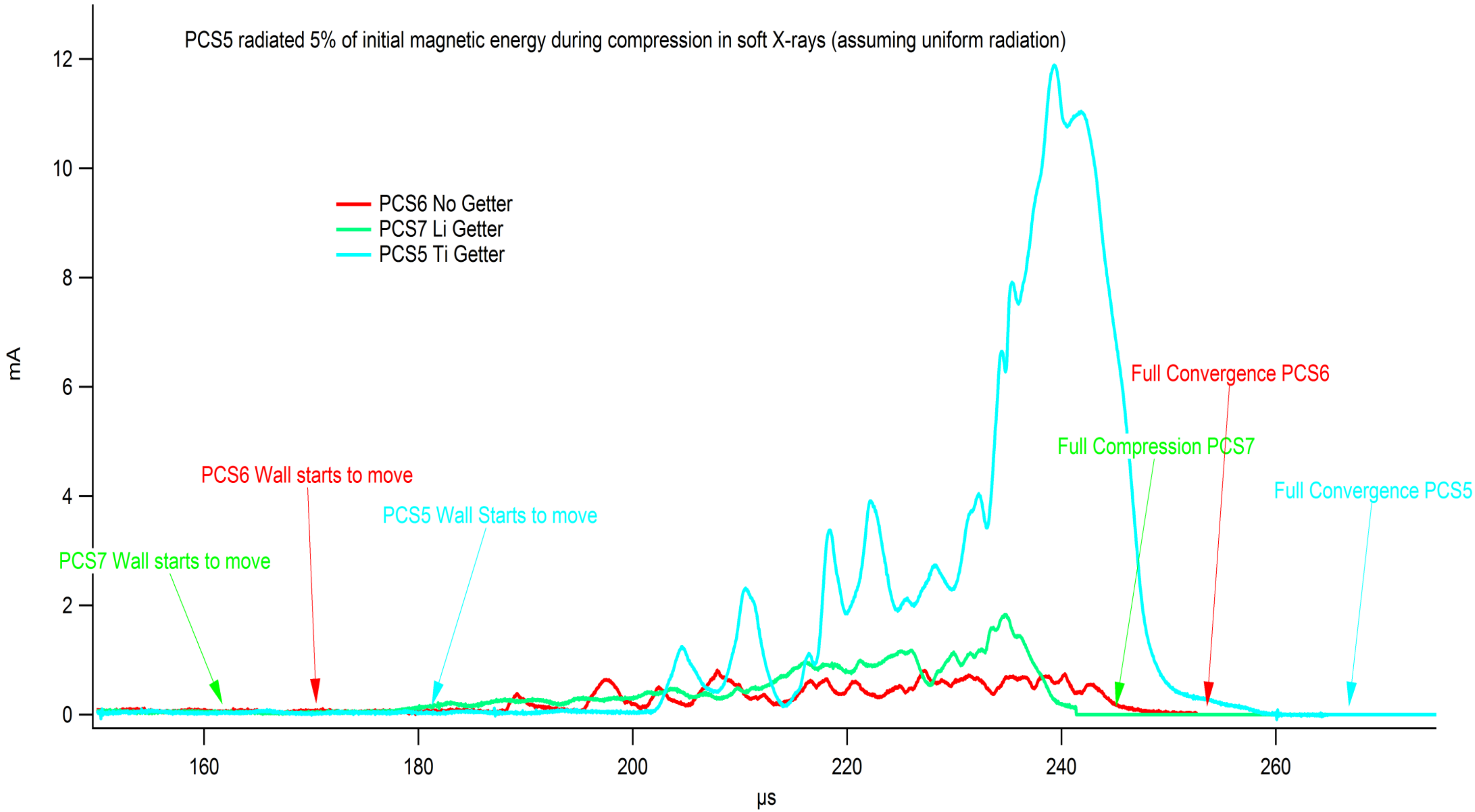
- Thin coating of Lithium on the walls on Test #7 allowed much more reliable plasma performance (much like Titanium). Known benefits of "Gettering"
- Unlike Titanium, Lithium does not appear to greatly increase radiation during the plasma compression



Magnetic Probe Results - Test #9

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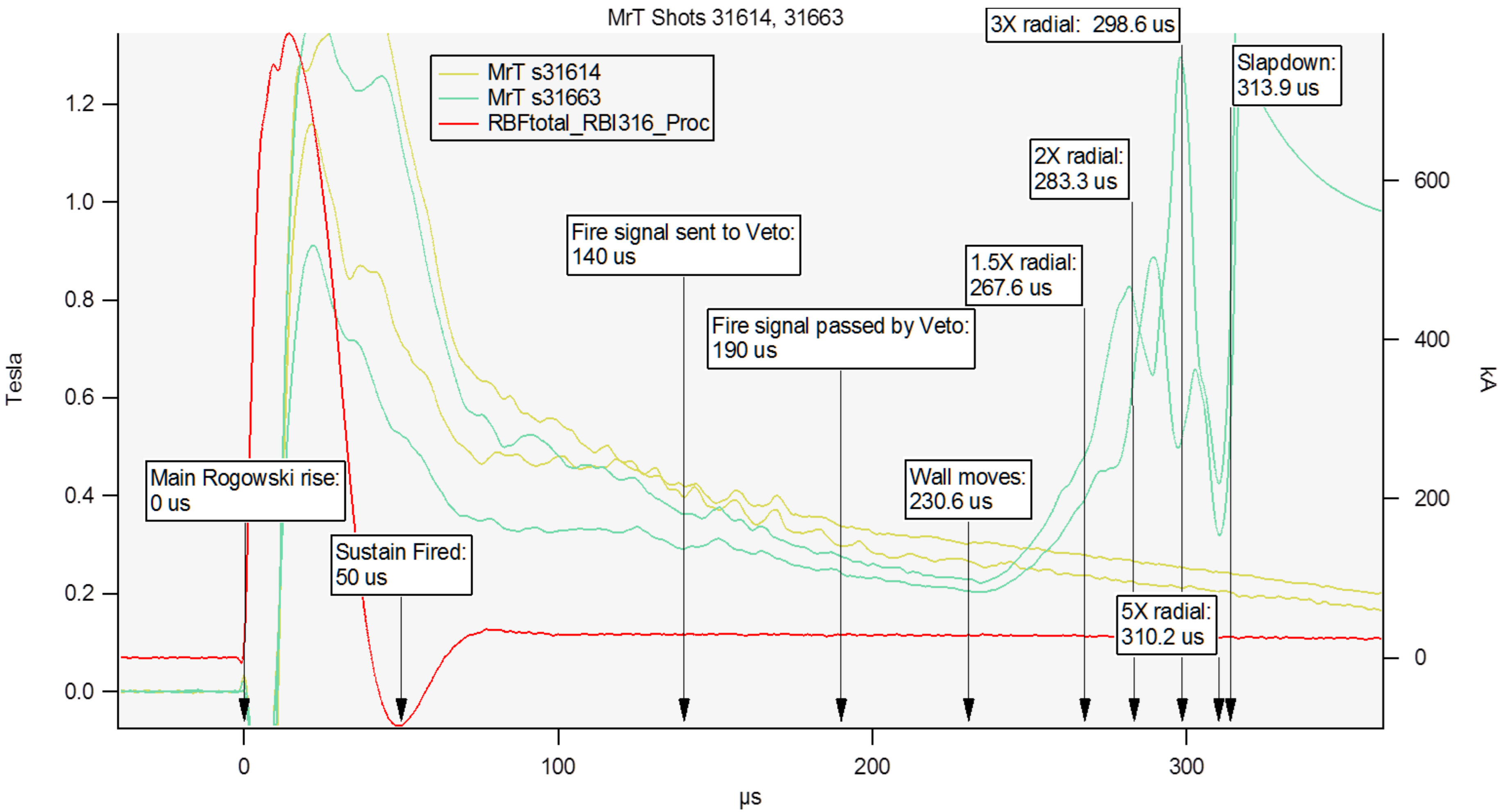
- First problem-free compression with Li gettering (B-lifetime = 250 μs).
- Magnetic compression ratio 4-5 followed by strong n=1 instability.



Increase in Magnetic Field: recent field tests

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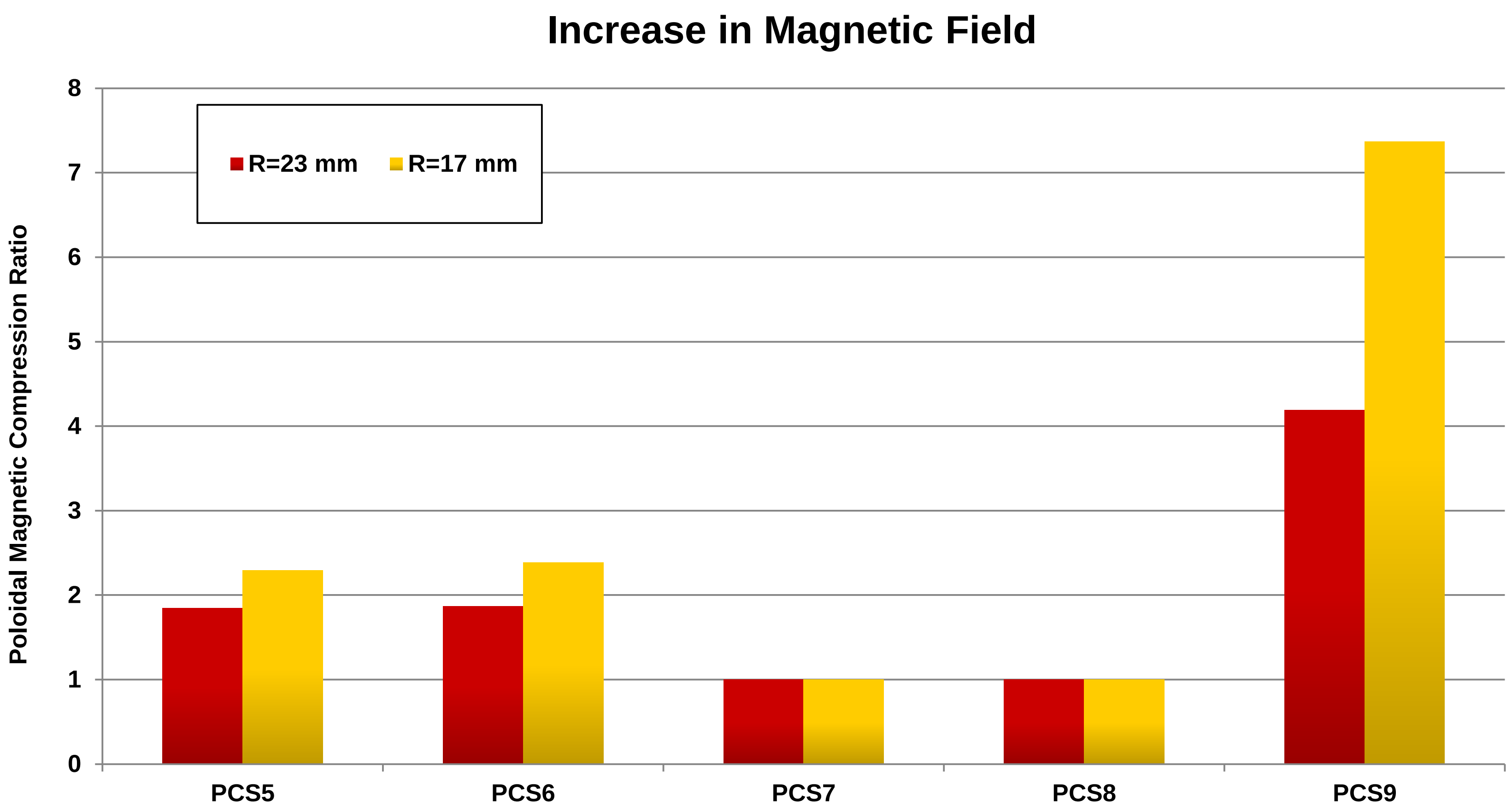
- *PCS#9*: ~4x to 5x increase in magnetic field.
- Magnetic instabilities continue to point to shape as a root cause



New Compression Shape for 2016

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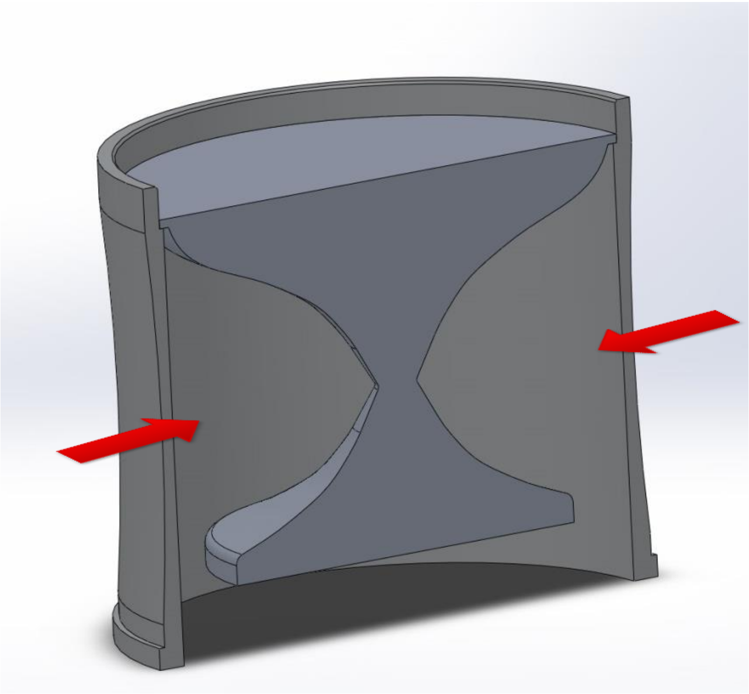
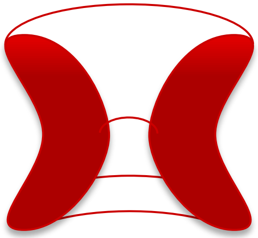
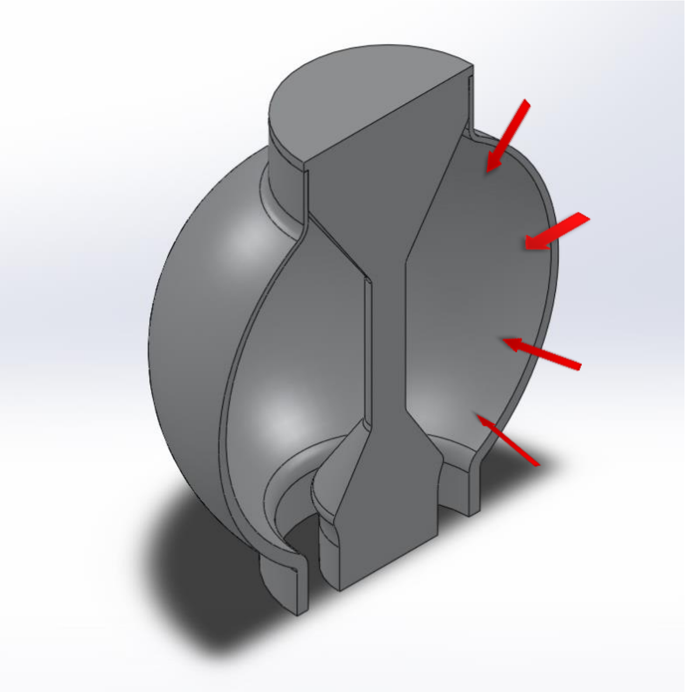
Current Geometry
Cylindrical Compression

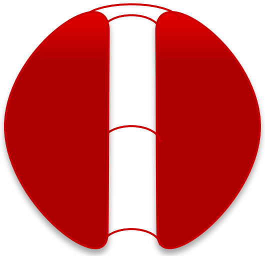




Compressed plasma shape is unstable; technique was easier to implement

New Geometry (SPECTOR)
Self-Similar Compression





Compressed plasma shape is stable and closer to actual reactor configuration

Plasma Compression Simulations

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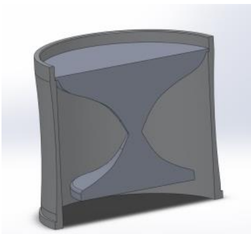
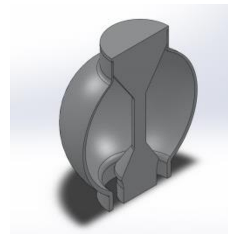
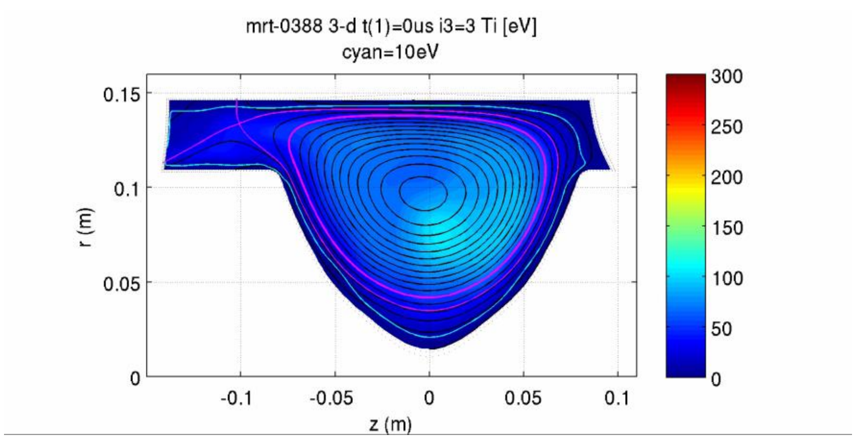
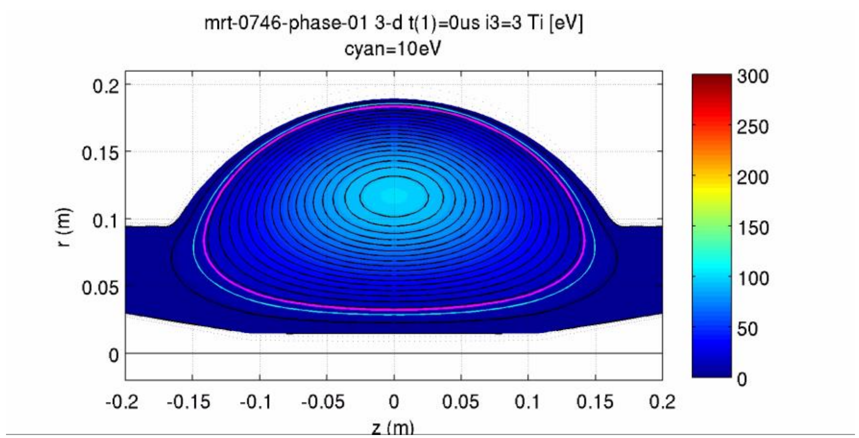


Cylindrical geometry causes MHD instabilities in compression



Self-similar geometry shows well nested flux surface and no instabilities





SPECTOR Injector (SPhErical Compact TORoid)

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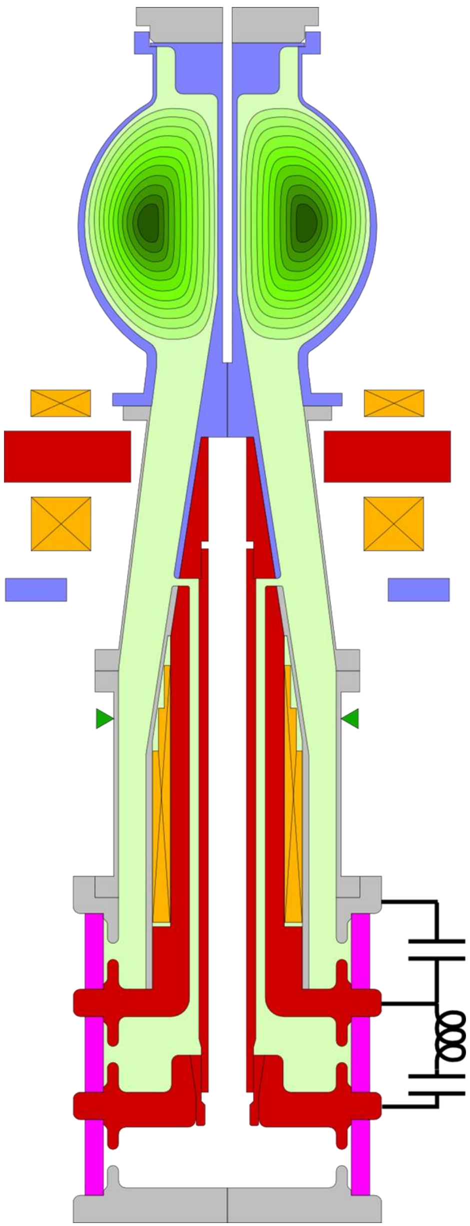

- Same circuit design as PROSPECTOR; 800kA formation current, 1MA preformation.
- Similar magnet design as MRT; Penning trap for gas breakdown.
- 36mWb of stuffing flux instead of 8mWb.
- New flux conserver geometry: compressing CT in a self-similar geometry is a challenge.
- Larger flux conserver, R=19cm
- Decreasing lambda along gun taper; gun radius much smaller than FC radius.
- Probe access from central shaft.
- D-shape FC has good stability, even during compression.
- No toroidal flux dump. Found unnecessary.
- Construction underway – first plasma end of 2015

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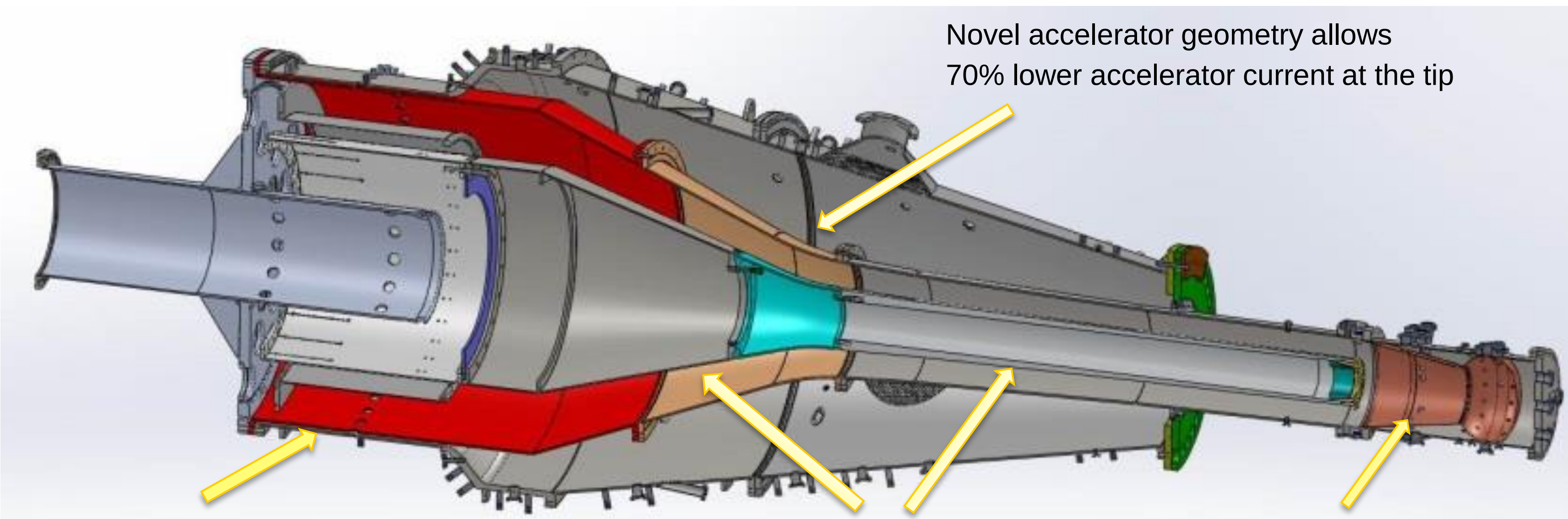
We are designing and building a new high-density injector, capable of breakeven (assuming 10x compression)

General Fusion is working with PPPL and Bick Hooper (LLNL)



Thank You

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