Development of a Compact Fusion Device based on the Flow Z-Pinch

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Harry S. McLean for the FUZE Team

Lawrence Livermore National Laboratory
UNIVERSITY of WASHINGTON

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Lawrence Livermore National Security, LLC

Outline

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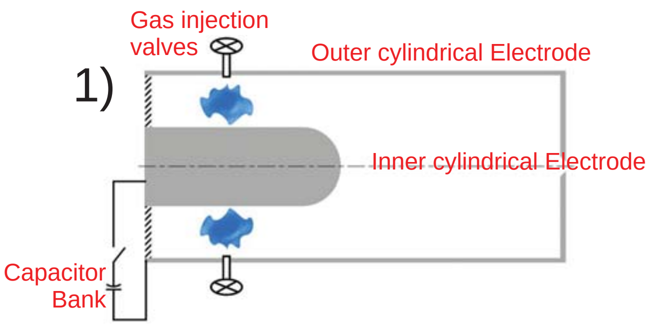
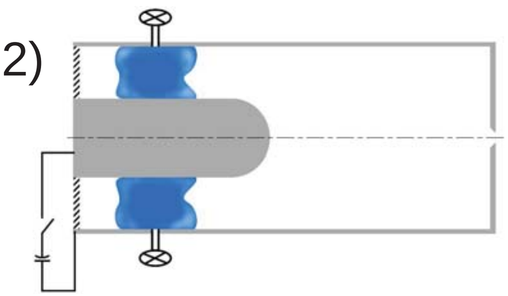
Shear-stabilized pinch concept

1)



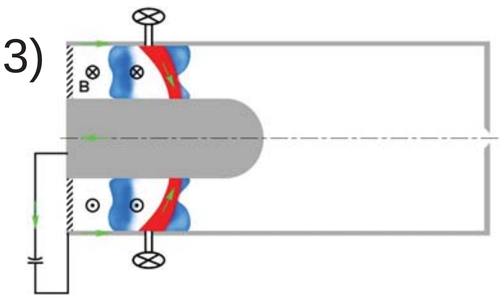
Neutral gas is injected through puff valves into the annulus of a coaxial plasma accelerator.

2)



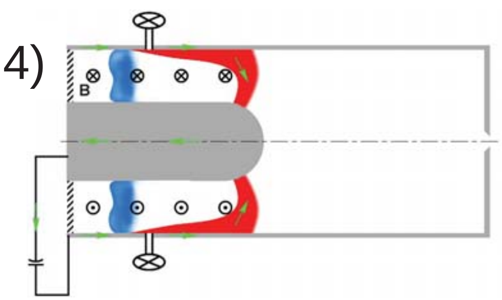
Neutral gas expands before a capacitor bank is discharged across the electrodes.

3)



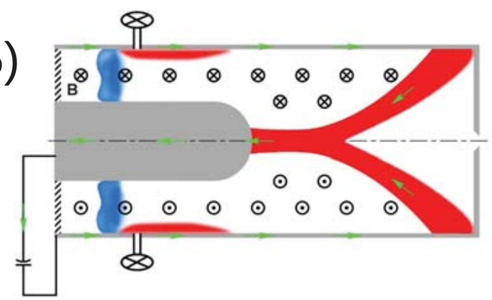
The plasma accelerates down the coaxial accelerator due to generated currents and magnetic fields.

4)



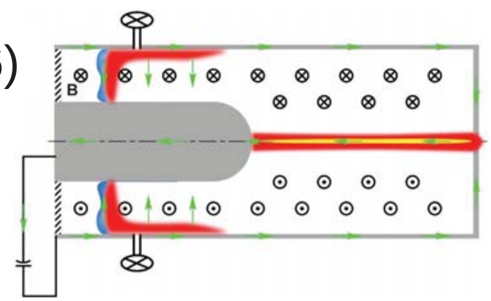
The plasma continues down the accelerator in a snow-plow manner.

5)



At the end of the accelerator the plasma assembles into a Z-pinch configuration.

6)



Inertia and gun currents maintain the plasma flow and supply until the accelerator plasma empties or the capacitor current vanishes.

Existing Device (ZAP) Results: Axial plasma flow with velocity shear in the radial direction has been shown to stabilize a 1 m long x 1 cm diameter 50 kA z-pinch column for 20-40 usec

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Equilibrium, flow shear and stability measurements in the Z-pinch

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Abstract
The stabilizing effect of a sheared axial flow is investigated in the ZaP flow Z-pinch experiment at the University of Washington. Long-lived, hydrogen Z-pinch plasmas are generated that are 1 m long with an approximately 10 mm radius and exhibit gross stability for many Alfvén transit times. Large magnetic fluctuations occur during pinch assembly, after which the amplitude and frequency of the fluctuations diminish. This stable behaviour continues for an extended quiescent period. At the end of the quiescent period, fluctuation levels increase in magnitude and frequency. Axial flow profiles are determined by measuring the Doppler shift of plasma impurity lines using a 20-chord spectrometer. Experimental measurements show a sheared flow that is coincident with low magnetic fluctuations during the quiescent period. The experimental flow shear exceeds the theoretical threshold during the quiescent period, and the flow shear is lower than the theoretical threshold at other times. The observed plasma behaviour and correlation between the sheared flow and stability persists as the amount of injected neutral gas and experimental geometry are varied. Computer simulations using experimentally observed plasma profiles show a consistent sheared flow stabilization effect. Plasma pinch parameters are measured independently to demonstrate an equilibrium consistent with radial force balance.

PACS numbers: 52.30.−q, 52.35.Py, 52.55.Dy, 52.58.Lq

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The Z-pinch provides a simple magnetic confinement configuration for plasma that has many advantages both as a possible fusion reactor and as a test bed to conduct basic plasma science research. The equilibrium is described by the radial force balance

$$\frac{B_\theta}{\mu_o r}\frac{d(rB_\theta)}{dr} = -\frac{dp}{dr}. \quad (1)$$

The pure Z-pinch is simply connected and has unity average beta. The only magnetic field present is the B_θ field generated by the plasma current. All magnetic field lines are closed, even though the plasma has open ends. However, the pure Z-pinch is classically unstable to the $m = 0$ sausage and $m = 1$ kink modes.

Conventional techniques to provide stability for the Z-pinch have drawbacks. The sausage mode can be stabilized if the pressure gradient is limited [1]. Controlling the pressure profile is difficult and the technique does not stabilize the kink mode. An axial magnetic field can be applied to provide stability. However, the plasma current and the pressure are limited by the strength of the axial magnetic field according to the Kruskal–Shafranov limit [2, 3]. Furthermore, an axial magnetic field opens all field lines and connects the electrodes to all regions of the plasma. A close-fitting, conducting wall can provide stability if the wall is located close to the plasma edge, $r_{wall}/a = 1.2$ [4], which is incompatible with a hot, fusion-grade plasma. The influence of an axial magnetic field and a conducting wall on the stability of a Z-pinch is also investigated in a classical work [5], which also reveals a stabilizing effect when the conducting wall approaches the plasma radius.

Flow shear can stabilize the MHD modes in a pure Z-pinch without the drawbacks of the conventional stabilization techniques. An axial flow does not alter the radial force balance that describes a Z-pinch equilibrium, see (1). Since the plasma geometry is simple, i.e. described by a one-dimensional force balance, the Z-pinch configuration is ideal for studying stability characteristics and isolating flow shear stabilization physics.

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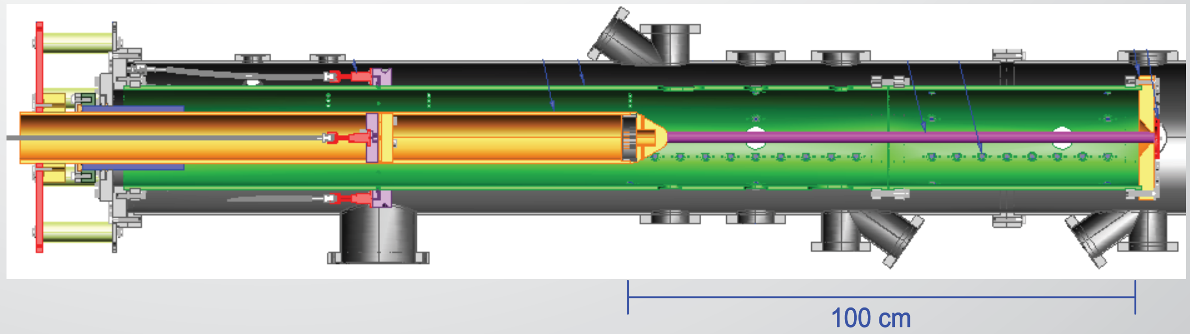


Nucl. Fusion **49** (2009) 075039 U. Shumlak *et al*

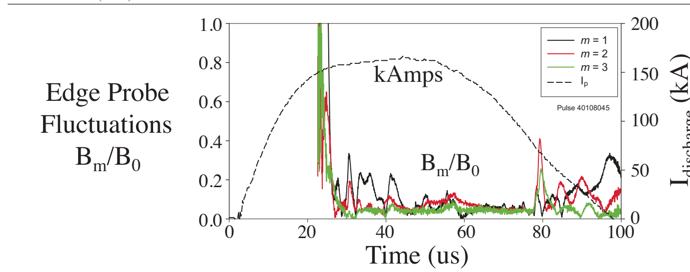
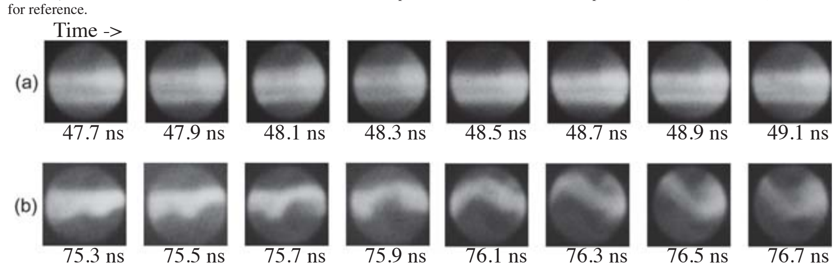


Figure 2. Time evolution of Fourier components of the normalized magnetic field fluctuation at $z = 0$ for the $m = 1, 2, 3$ modes for the original 0.1 m diameter inner electrode. The values are normalized to the average magnetic field value. A quiescent period is evident from 42 to 79 μs which defines the normalized time $\tau = 0$ to 1 for this pulse. The evolution of the total plasma current (dashed curve) is included for reference.

Stable for:
$T_{quiescent}$ ~ 40 us
I_{pinch} ~ 50 kA



Framing Camera Images

Figure 3. Fast framing camera images of visible light from the plasma viewed through a 5 cm hole at $z = 0$. Images are taken every 200 ns during a single plasma pulse. (a) Images obtained during 47.7–49.1 μs, the middle of the quiescent period. (b) Images obtained during 75.3–76.7 μs, near the end of the quiescent period.

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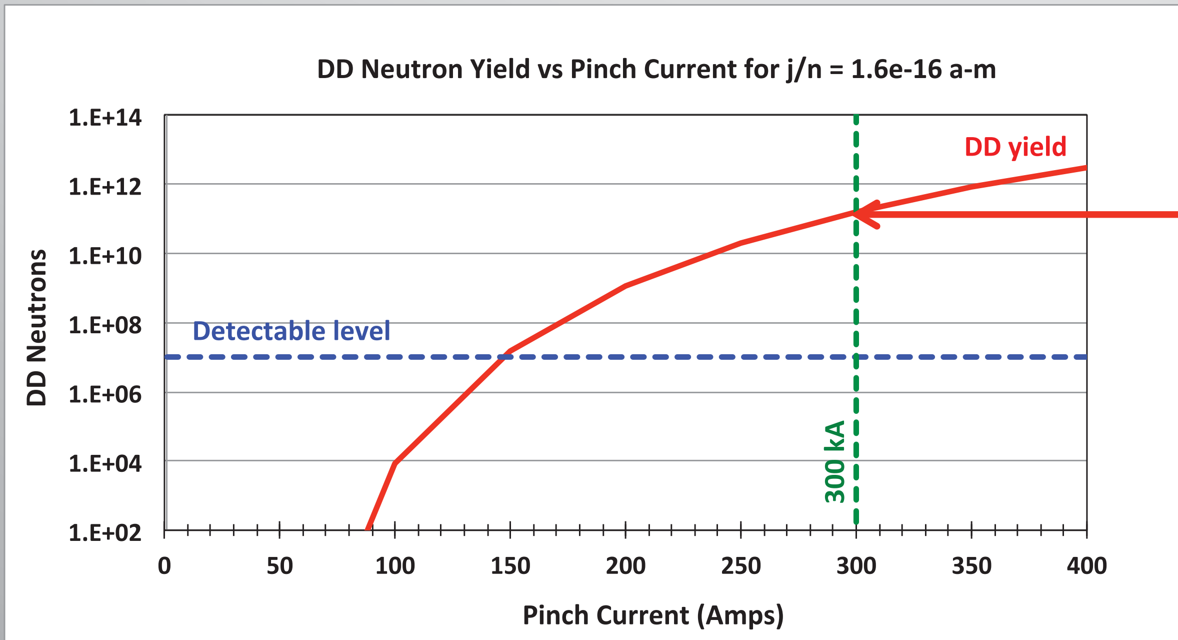
Power scaling projections show that reaching 300 kA with deuterium produces useful intensities of neutrons and x-rays, suitable for a variety of applications

Plasma Conditions	Existing (ZAP)	ALPHA (FUZE)	Reactor
Pinch current (kA)	50	300	1500
Total discharge (kA)	150	500	1700
Pinch radius (mm)	10	0.7	0.05
Ion Density (m^{-3})	1 E+22	2.5 E+24	3 E+27
Temperature	50-100 eV	2500-4000 eV	25-50 keV
Magnetic field (tesla)	1	90	6000
Lawson n-tau (m^{-3} sec)	1E+17	1E+19	1E+21
D-D Neutron Yield		1e11 - 4e11	
Radiation Power (MW)		10 MW	

Xray Source at 300 kA:
- Hot: 2 keV
- Intense: 10 MW
- Long pulse > 10 usec
- Energetic: 100 J/pulse



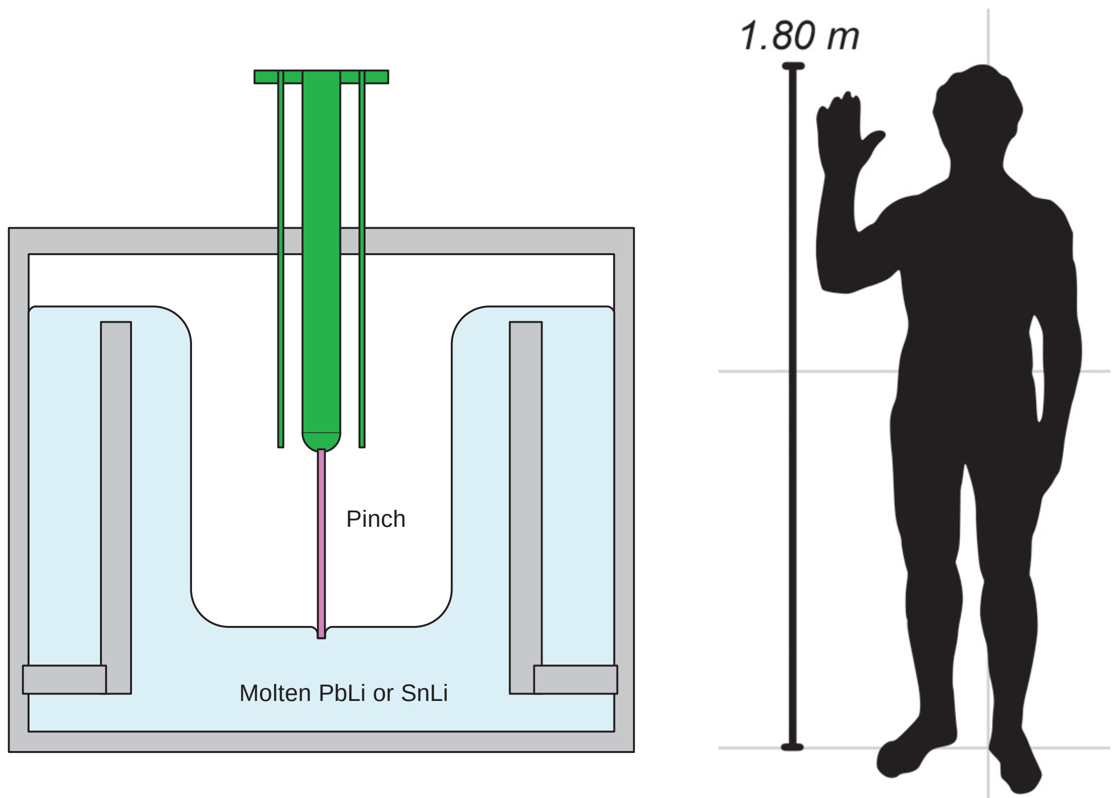
Neutron Source at 300 kA:
- 2.45 MeV neutrons
- 4e11 yield per pulse
- 0.160 J / pulse

Success at the ALPHA Goal would attract multiple customers and set stage for next steps

Shear-Flow Stabilized Z-Pinch Reactor Concept:
- Point a flow-stabilized z-pinch down into liquid metal
- Addresses critical material and technology issues that are unresolved for other concepts

Prototype reactor design point:

- Reactor Q ~ 5
- Discharge Current / Volts
  = 1.7 MA / 22 kV
- Rep-rate / Pulse Length
  = 10 Hz / 230 usec
- Fusion energy per pulse
  = 19 MJ
- Average Fusion power
  = 190 MW



Ignitron technology is a mature technology with commercially available units that can conduct reactor-scale relevant currents through liquid cathodes

NATIONAL

NL-9000
Ignitron

The NL-9000 is a size "E" dual bath cooled ignitron intended for use as a high energy switch in capacitor circuits. The following ratings are at this printing maximum and may be exceeded only with the end users full liability.

Anode Material- **NL9000** - "Graphite" **NL9000A** - "Stainless"

GENERAL:[1]
Mercury pool electronic tube, water cooled
Number of electrodes:

Main anode	1
Ignitors	2
Cathode "Body with Hg Pool"	1

IGNITORS:

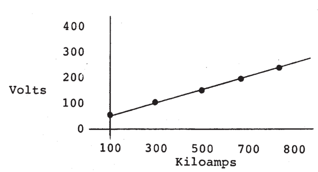
Forward Voltage "open circuit"	1000-3500 V
Inverse voltage	5 V
Current peak "short circuit"	200-500 A
Length of firing pulse	5-15 usec
Net weight, approximately	60 lbs

COOLING REQUIREMENTS:

Flow minimum at peak current	6 GPM
Temperature range[2]	
Cathode cup	15-25° C
Side Walls	15-45° C

MAXIMUM RATING: DAMPED DISCHARGE (NON-SIMULTANEOUS RATING)

Peak forward or inverse voltage	10 kV[5]
Peak anode current[3]	700 kA
Coulombs per pulse at max amps	250 C
Pulse repetition rate per minute	1



TUBE DROP AT PEAK CURRENT
DAMPED SINUSOID I peak 150us

NATIONAL ELECTRONICS
A Division of Richardson Electronics, Ltd.
LaFox, IL 60147 (630) 208-2300

700 kA rating

- Flow-stabilized pinch requires ~ 1-1.5 MA to reach reactor conditions.

Figure 19. Size E (9-in.) NL9000 close-spaced, hollow-anode tube.

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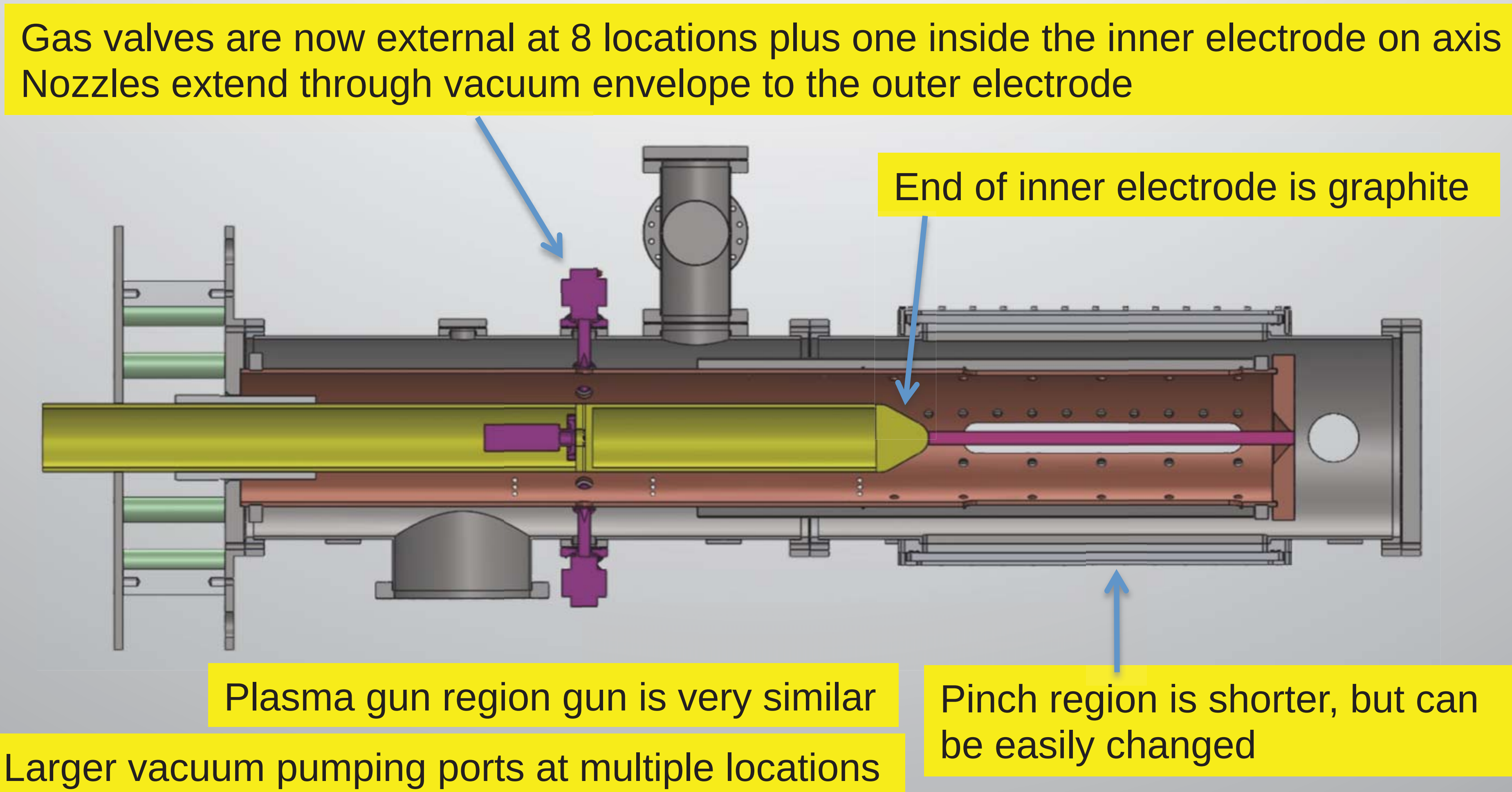
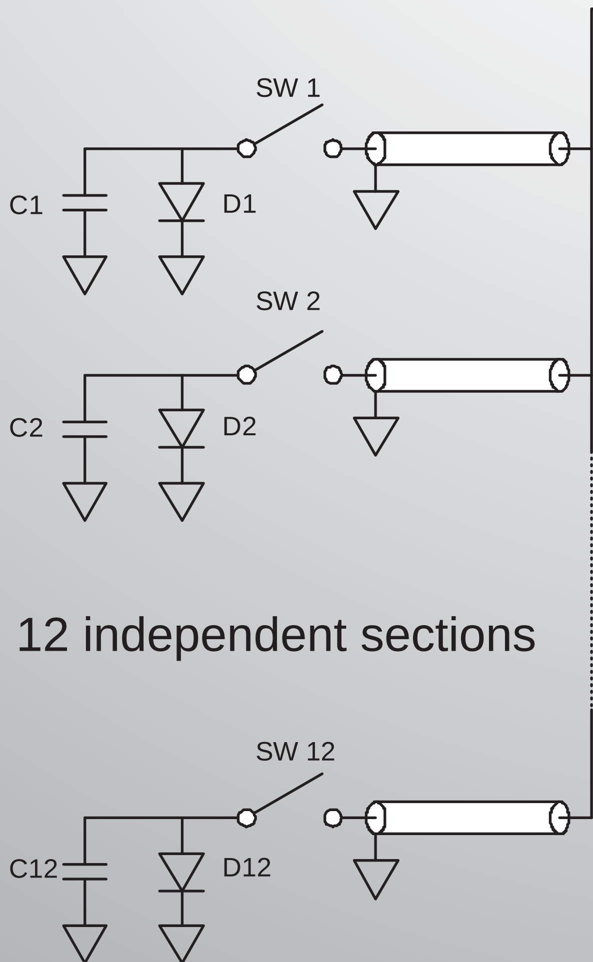
Why now?
What's new in our approach?

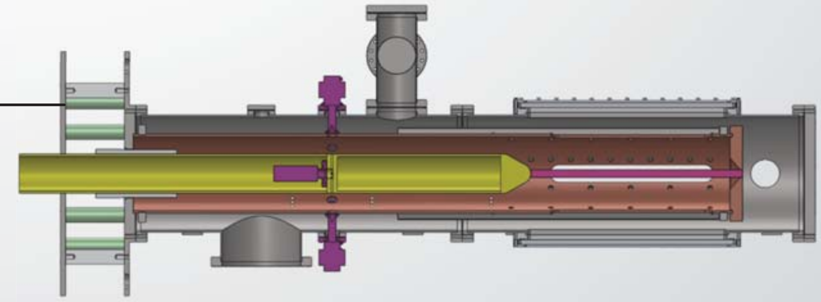
- We are building unprecedented capability and flexibility into a new device which accommodates the following:
  - Higher input energy, power, and gas loading.
  - A modular (12 independent section) 20 kV capacitor bank to allow a variable and flexible current pulse.
  - Multiple pulsed gas valves (9) to allow a variable and flexible injection of gas
- We are applying the most recent state-of-the-art computer simulations to resolve the microscopic (kinetic vs. fluid) nature of the experiment as well as the fluid nature and whole-device macroscopic behavior.

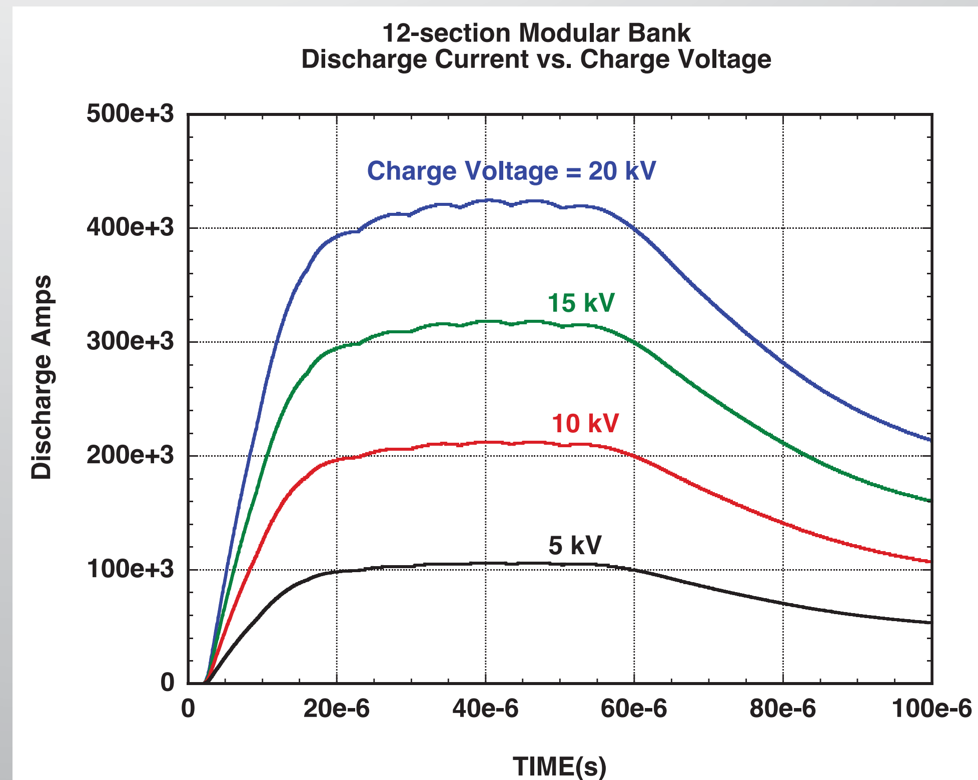
The new device (FUZE) is about the same dimensions but is designed to handle much higher discharge currents and higher heat loads. A flexible gas injection system employs a total of 9 fast-puff gas valves.



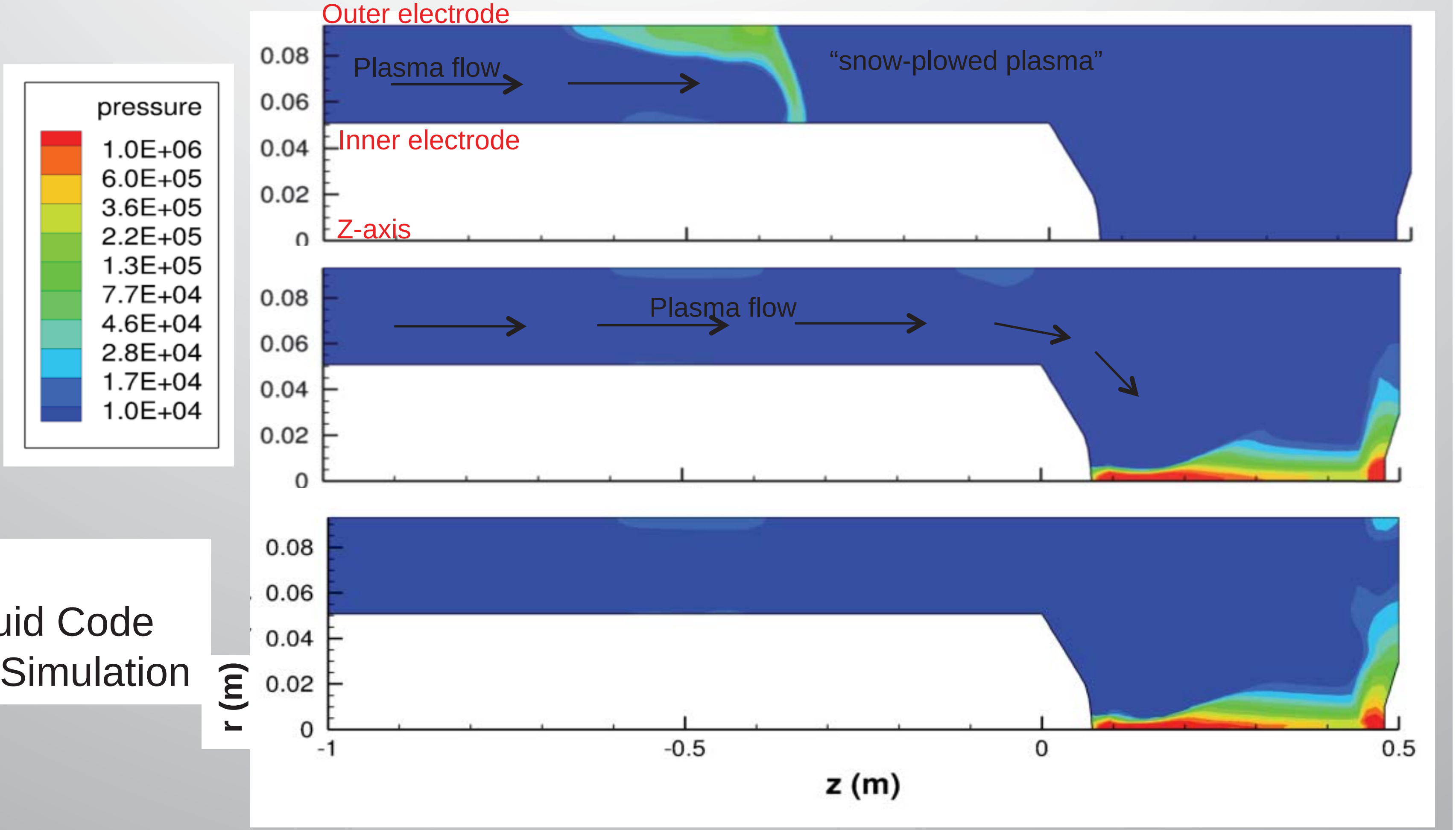
We will drive the new electrode set with a capacitor bank that has 12 independently triggerable sections-This provides excellent flexibility in current pulse shape.







To help understand the physics in detail, we are applying state-of-the-art MHD fluid and kinetic particle plasma computer simulation codes.

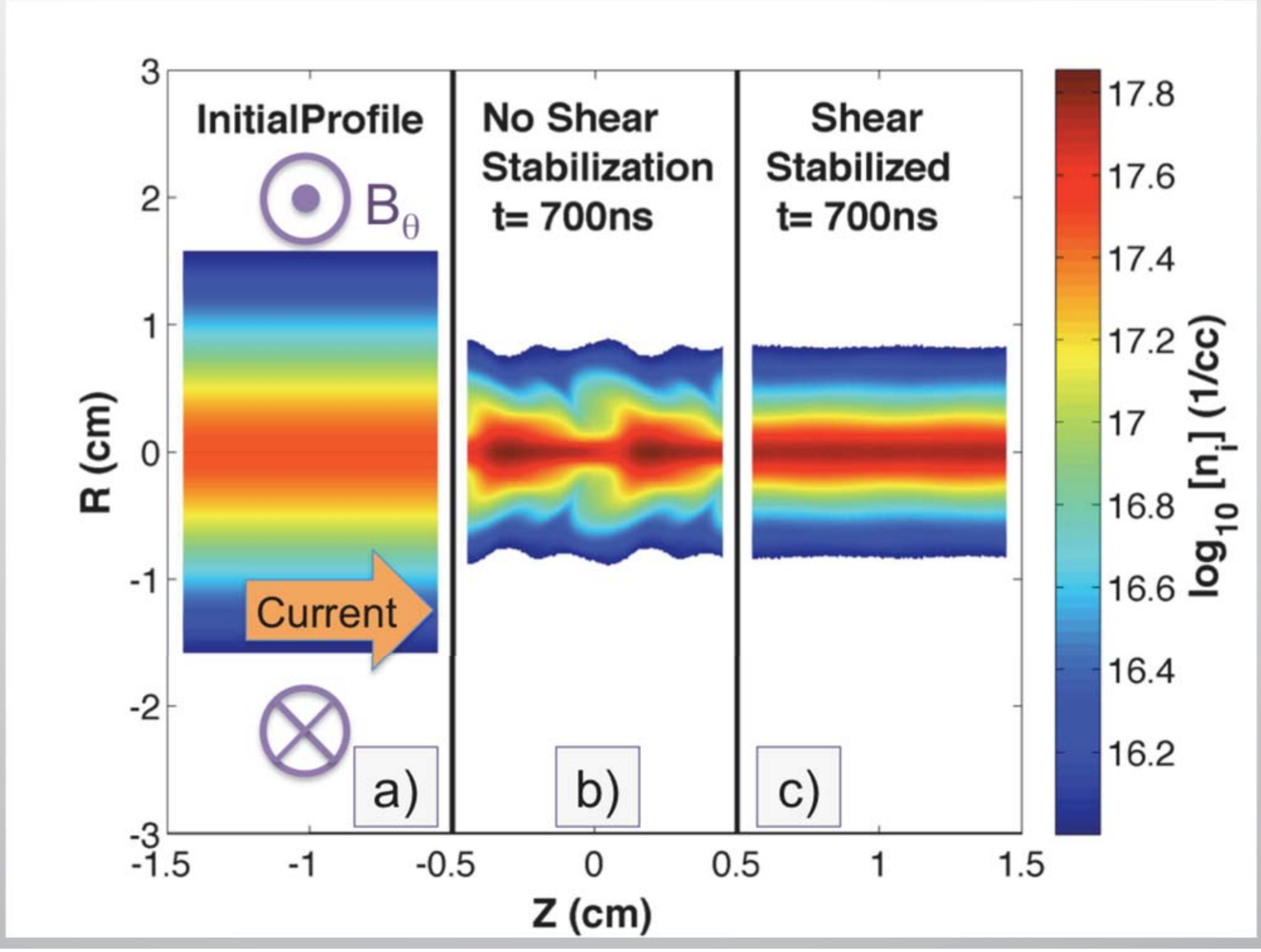


MACH2
MHD Fluid Code
Plasma Simulation

Whole device modeling for hardware design and experimental predictions

Particle-in-cell kinetic simulations can calculate critical details of anomalous plasma viscosity/resistivity or other transport phenomena

LSP PIC Code
Kinetic Simulation



Results of kinetic simulations feed back into whole-device MHD fluid modeling

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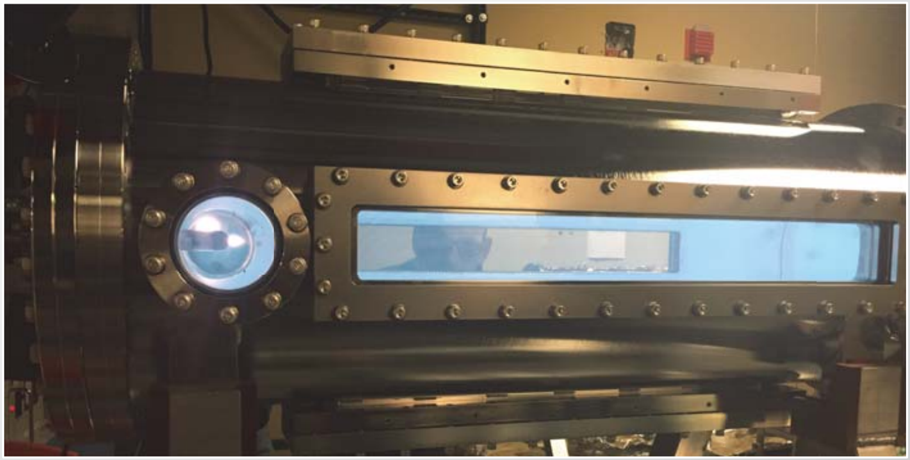
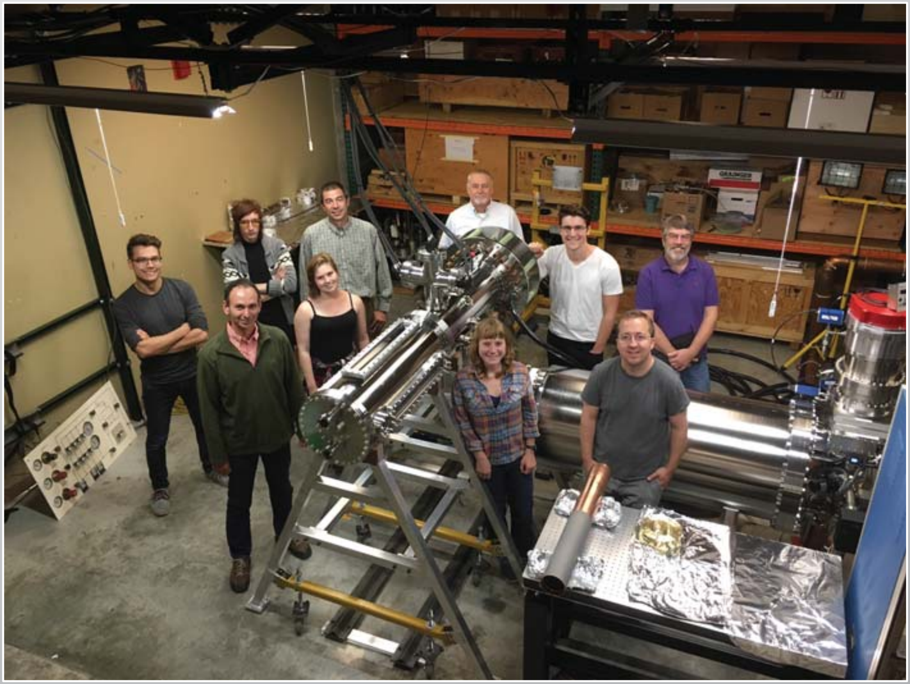
Status

- Vessel, pumping systems completed
  - First Plasma May 6, 2016
- Electrodes:
  - Inner and outer electrodes complete
- Diagnostics
  - Axial magnetic probes installed in outer electrode
  - In-situ calibrations performed using 10 kV / 50 kA bank
- Main bank
  - Capacitor HV testing complete
  - Most components on-site, construction in progress
- Gas valve bank-completed
- Data Acquisition-operational
- Controls-in progress
- Simulations: high value proven





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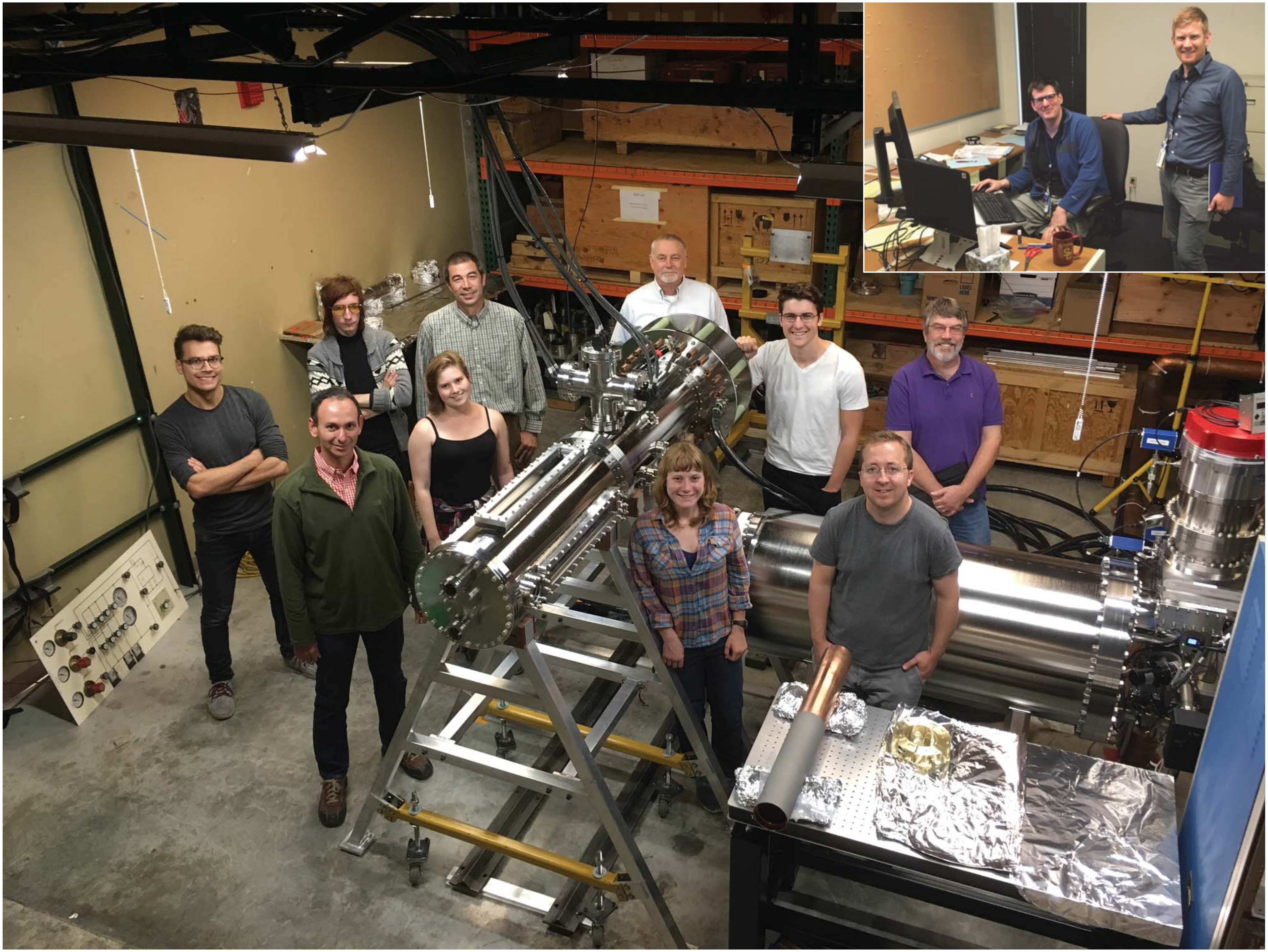
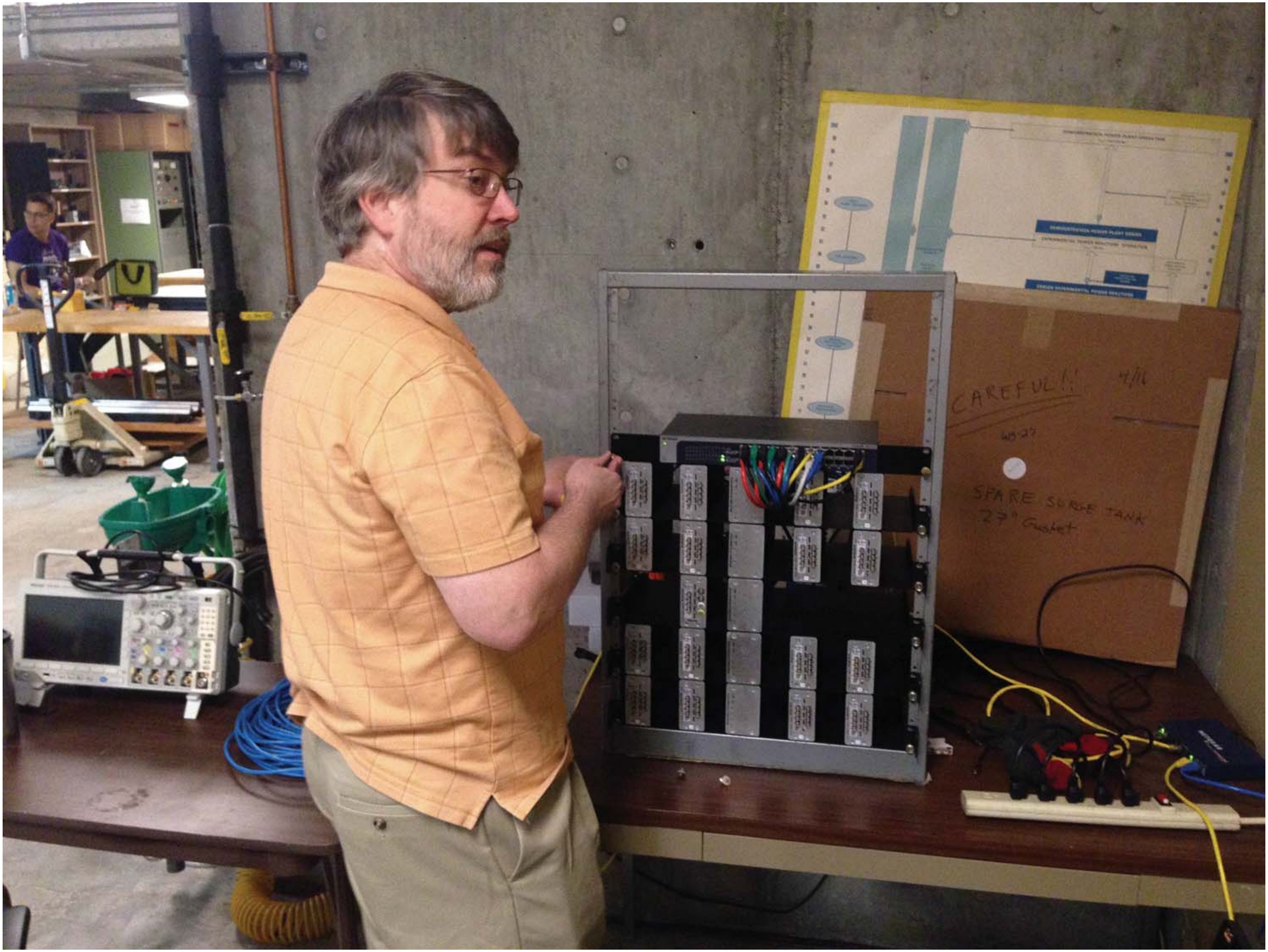
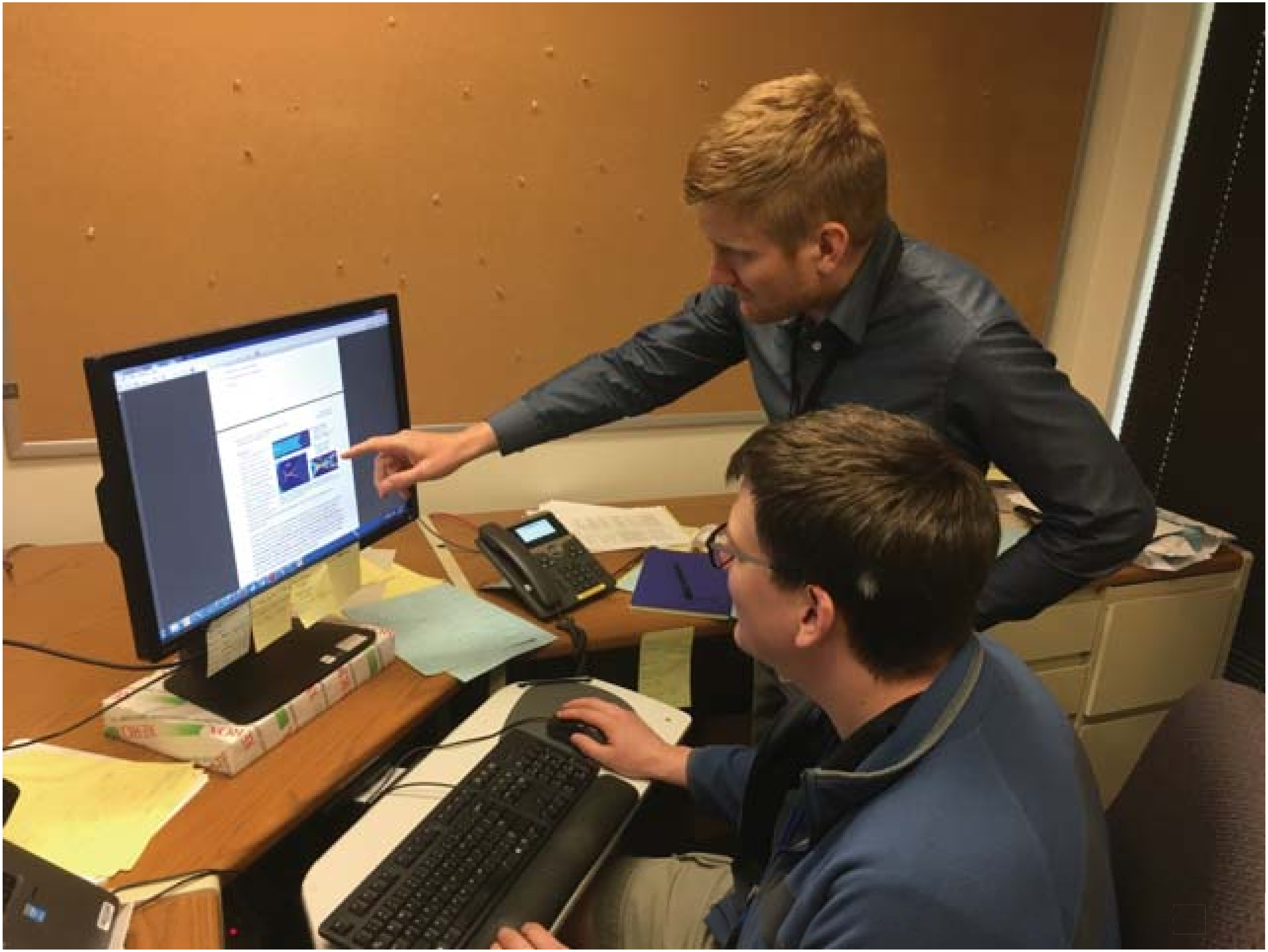
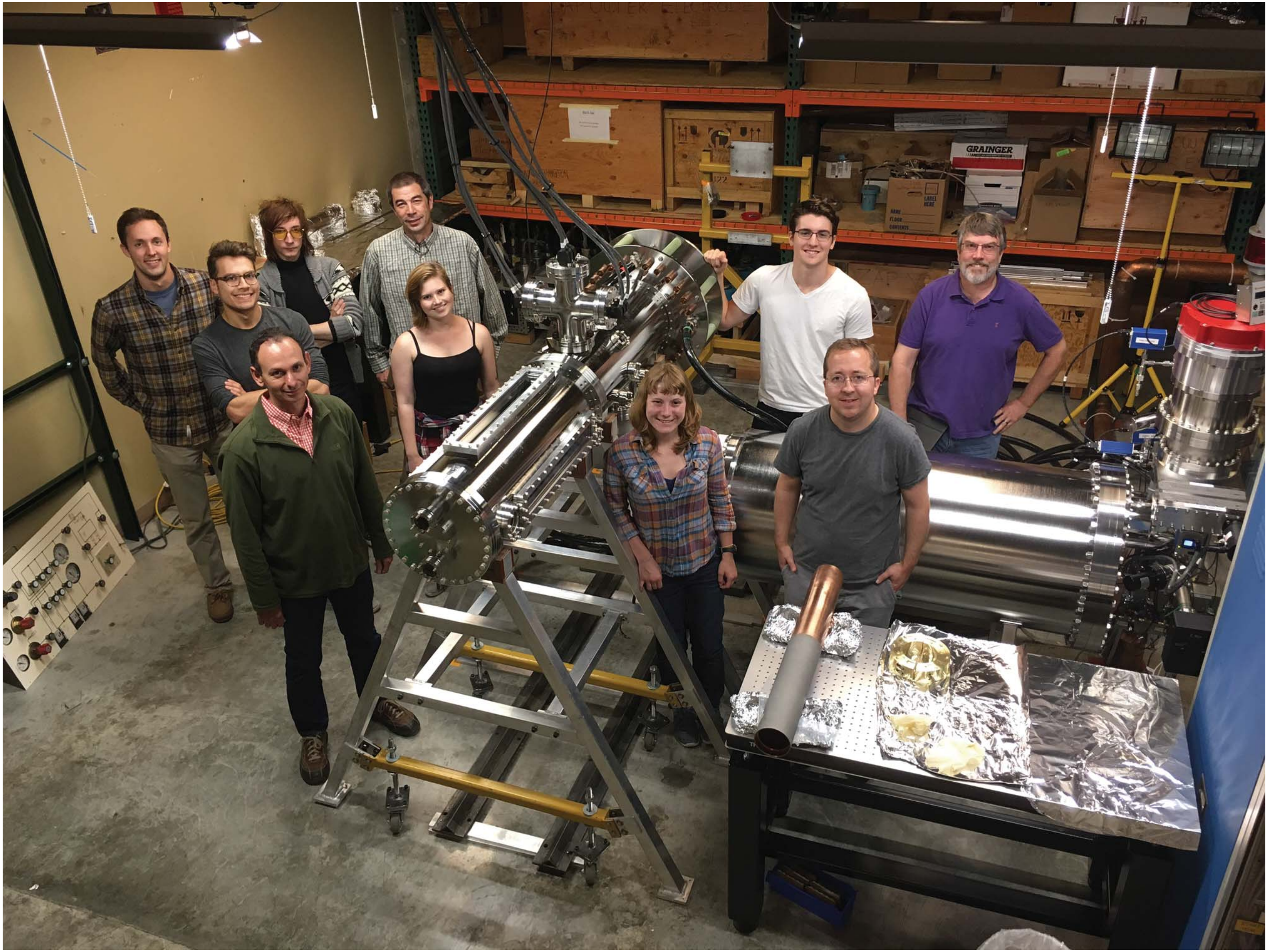



CAREFUL!!
SPARE SURGE TANK
27" Gusset




GRAINGER

To understand how the system scales with current we apply an equilibrium power balance ($P_{in} = P_{out}$) in the plasma:

- P_{in}
  - P_{ohmic}
  - $P_{compression}$
  - P_{flow}
  - $P_{alpha\_heating}$

=

- P_{out}
  - $P_{radiation}$
  - $P_{conduction}$
  - P_{flow}
  - $P_{thermal}$

- Assumptions:
  - Bennett pinch equilibrium $nk\left(T_e + ZT_i\right) = \frac{B^2}{2\mu_0}$; $B = \frac{\mu_0 I}{2\pi a}$; a = pinch radius
  - Flat current, density, temperature profiles across pinch
  - $V_{flow} = 0.1\ V_{alfvén}$
  - P_{rad} is bremsstrahlung only, $Z_{eff} = 2.0$
  - $P_{conduction}$ is ad-hoc, using D_{bohm} * multiplier to match experimentally-measured pinch radius at 50 kA. Conduction losses are not understood and usually ignored.
  - Spitzer Resistivity, look over a range in 0.8 e -14 amp-m < j/n < 1.6 e -14 amp-m
    - How j/n adjusts is also not well-understood. Density and current profiles adjust when $u_{e,drift}$ = j/en approaches ion sound speed → pinch needs to heat during current ramp or bad things will happen
  - $P_{thermal} = U_{thermal} / t_{flow}$ where $t_{flow} = Length_{pinch} / V_{flow}$
    - The entire thermal energy of the pinch is dumped on the end wall every flow time and is, by far, the largest power loss in the system at reactor conditions (exceeding ohmic and conduction losses during ramp-up)

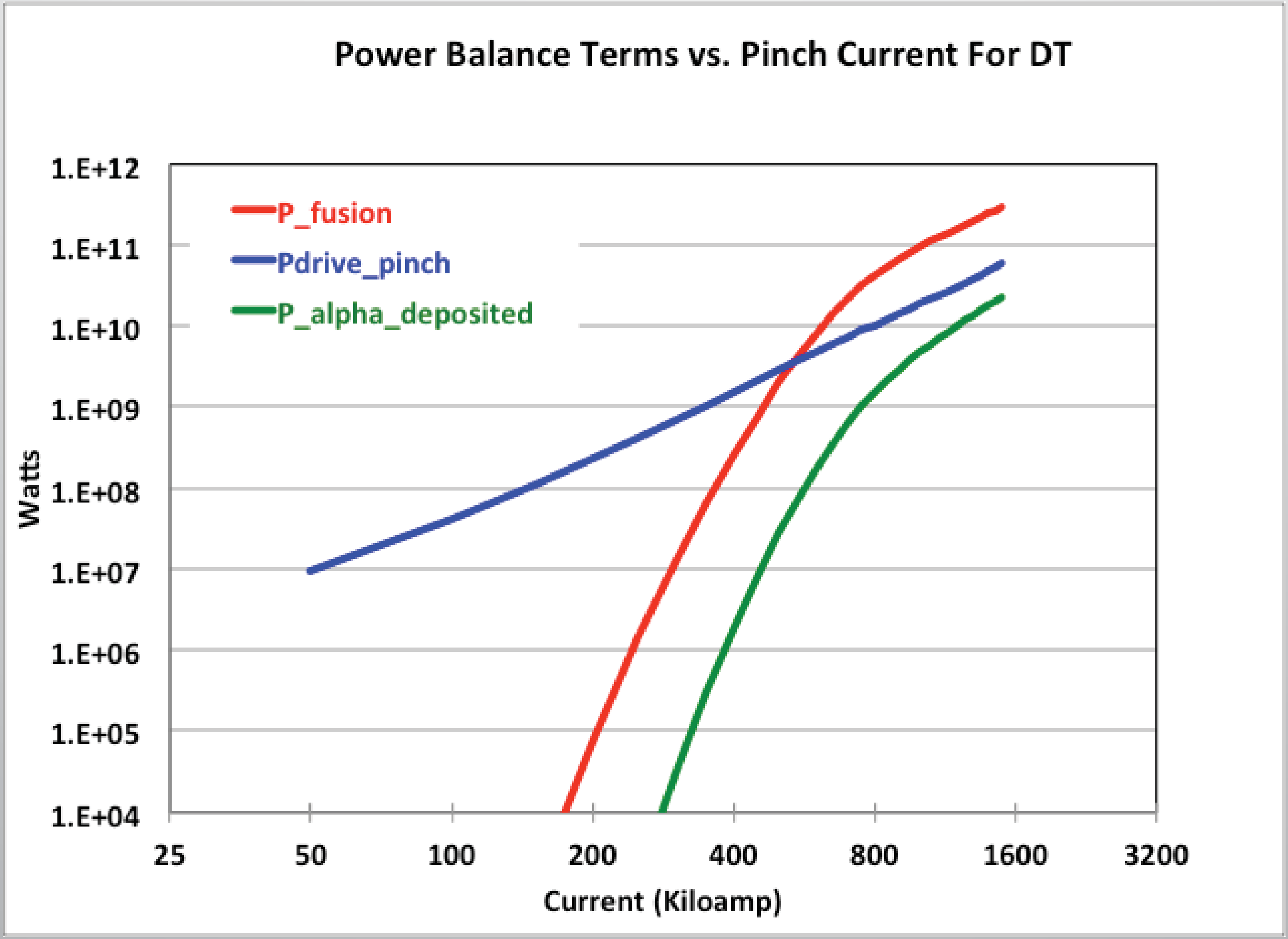
Reactor Development path requires ~30x increase in pinch current from existing capabilities

Development Path Platform -->			ZAP	2xZap	4xZap	FUZE = 6x ZaP	Scientific Breakeven	Engineering Breakeven	Prototype Reactor
Definition	Symbol	Unit	Existing Experiment	Alpha Mid-term	Alpha Mid-term	Alpha Goal	Pfusion > Pohmic	Ufusion > Ugun	Ufusion > 5 Ugun
Plasma									
Current	Ipinch	kA	50	100	200	300	700	1000	1500
Radius	a	mm	10.0	3.94	1.53	0.865	0.241	0.166	0.150
Length	H	m	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Volume	V	cm^3	157080	24340	3669	1176	91	43	35
Density	n	m^-3	3.18E+22	2.05E+23	1.36E+24	4.25E+24	5.48E+25	1.16E+26	1.41E+26
Temperature	T	keV	0.035	0.141	0.564	1.27	6.91	14.1	31.7
Magnetic field	B	Tesla	1.00	5.09	26	70	582	1210	2006
Energy Confinement Time	TauE	usec	2.60	3.10	3.43	3.41	2.55	1.97	1.44
Lawson Parameter	nTauE	sec/m^3	8.29E+16	6.37E+17	4.67E+18	1.45E+19	1.40E+20	2.29E+20	2.04E+20
Peak Power									
Fusion Power (if DT)	Pfusion	GW	0.000	0.000	0.000	0.000	7.35	96.0	349
Ohmic Power	Pohmic	GW	0.035	0.113	0.376	0.782	4.32	6.40	5.20
Power input to electrodes	Pgun	GW	0.101	0.296	0.999	2.18	13.5	29.9	36.9
Pulse Length	T_Pulse	uSec	0.0	32.3	69.9	93.6	145	168	228
Neutron Yield									
Fusion Yield (if DT)	Ydt		4.8E-06	2.9E+03	3.1E+09	1.4E+12	2.4E+16	3.9E+17	6.7E+18
Fusion Yield (if DD)	Ydd		2.2E-09	4.0E+01	8.6E+07	3.3E+10	3.1E+14	4.6E+15	1.1E+17
Energy Per Pulse									
Fusion energy per pulse (if DT)	Ufusion	kJ	0.00	0.000	0.000	0.004	66.8	1108	18887
Energy input to gun electrodes	Ugun	kJ	6.54	16.102	44.955	88.1	441	931	3397
Ohmic dissipation per pulse	Uohmic	kJ	2.27	5.923	16.878	32.5	149	280	605
Fractional Burnup per flow time	Fb	%	0.00%	0.00%	0.00%	0.00%	0.48%	4.39%	10.66%
Reactor Gain Ufus/Ugun	Q_pulse		0.00	0.00	0.00	0.00	0.15	1.19	5.56
Driver									
Current	Igun	kA	100	150	251	353	764	1078	1669
Voltage	Vgun	kV	2.0	3.0	5.0	7.3	19.3	27.7	22.1
Energy	Ugun	kJ	6.5	16.1	45.0	88.1	441.4	930.7	3396.8
Power	Pgun	GW	0.101	0.296	1.00	2.18	13.53	29.85	36.91
Efficiency = Ugun/Ubank	η		0.10	0.10	0.10	0.10	0.10	0.10	0.45
Cap Bank Stored Energy	Ucap	kJ	65	161	450	881	4414	9307	7549
Reactor Gain x Driver Efficiency	ηG		0.00	0.00	0.00	0.00	0.015	0.119	2.50
Rep-Rated Performance									
Physics Platforms-Single Shot	Rep-Rate	Shots/Day	50	50	50	50			
Engineering Test Platforms	Rep-Rate	Hz					1	1	10
Average Input Power	Pgun_avg	MW					0.441	0.931	34
Average Fusion Power	Pfusion_avg	MW					0.067	1.108	189

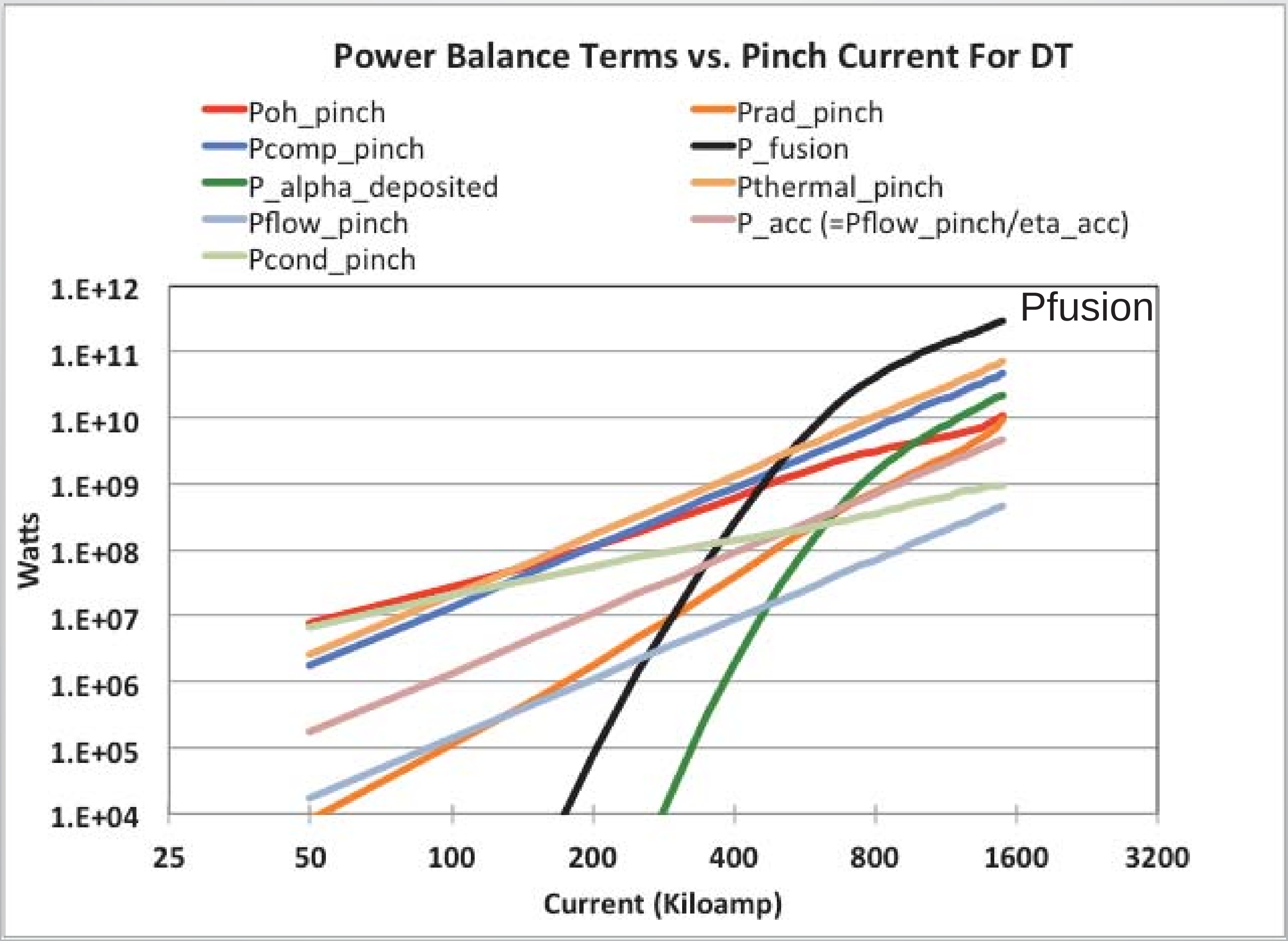
Prototype reactor:

- Discharge Current / Volts = 1.7 MA / 22 kV
- Rep-rate / Pulse Length = 10 Hz / 230 uS
- Fusion energy per pulse = 19 MJ
- Average Fusion power = 190 MW
- Reactor Q ~ 5

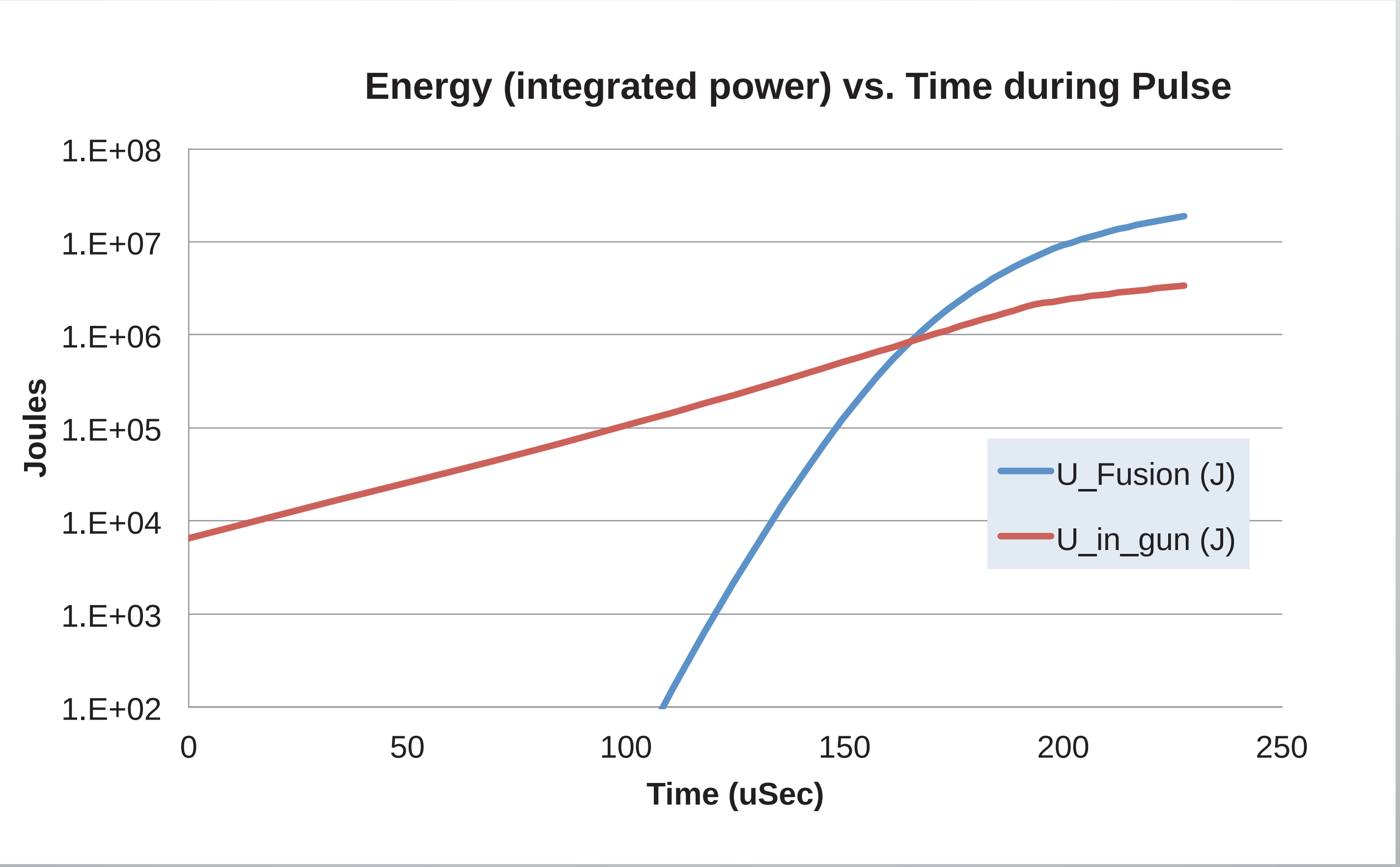
Power Balance projections show reaching 500-700 KA using 50-50 DT achieves "Scientific Breakthrough" as defined by Pfusion > Pinput



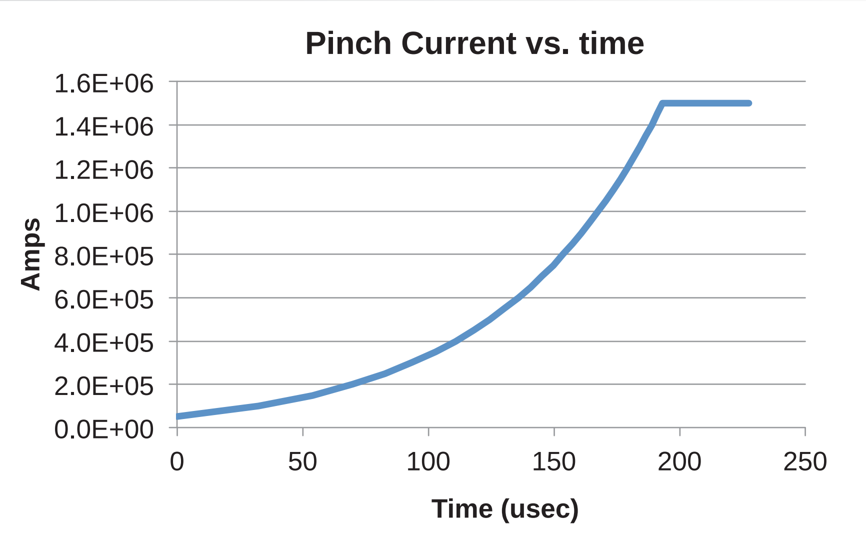
Power Balance projections show reaching 500-700 KA using 50-50 DT achieves "Scientific Breakthrough" as defined by Pfusion > Pinput

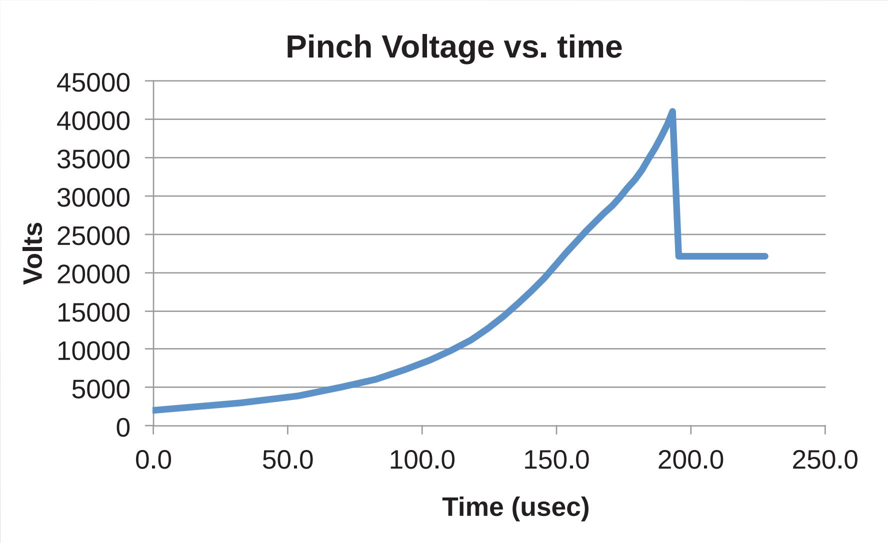


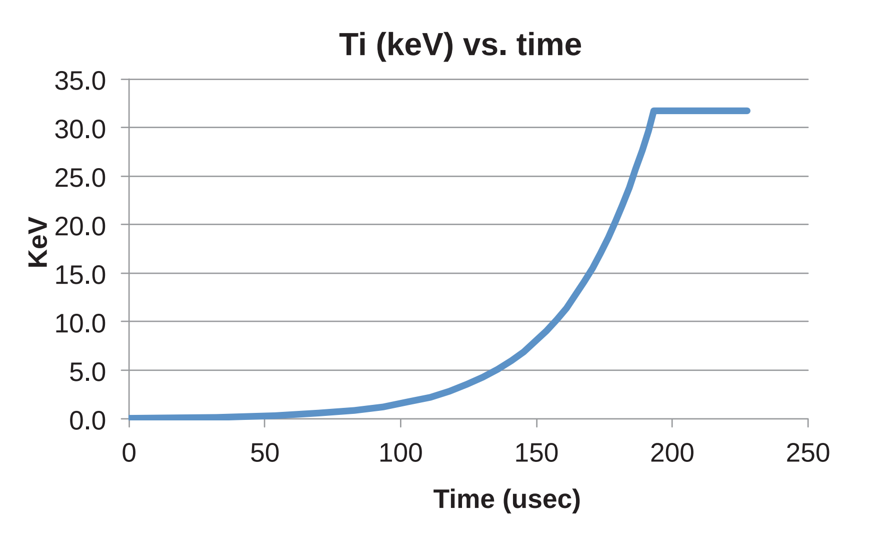
Integrating the Power vs. Time tells us how long we need to hold the pinch to achieve Q>1

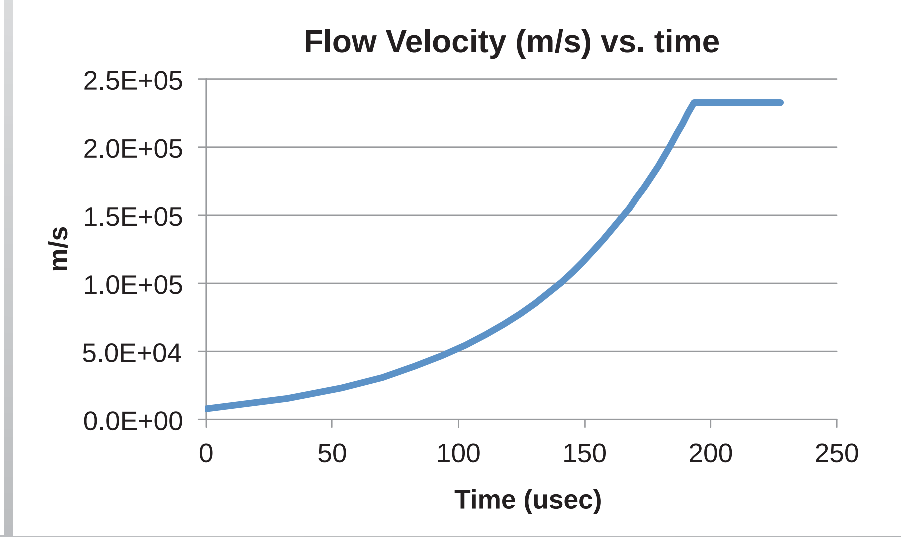


Discharge parameters









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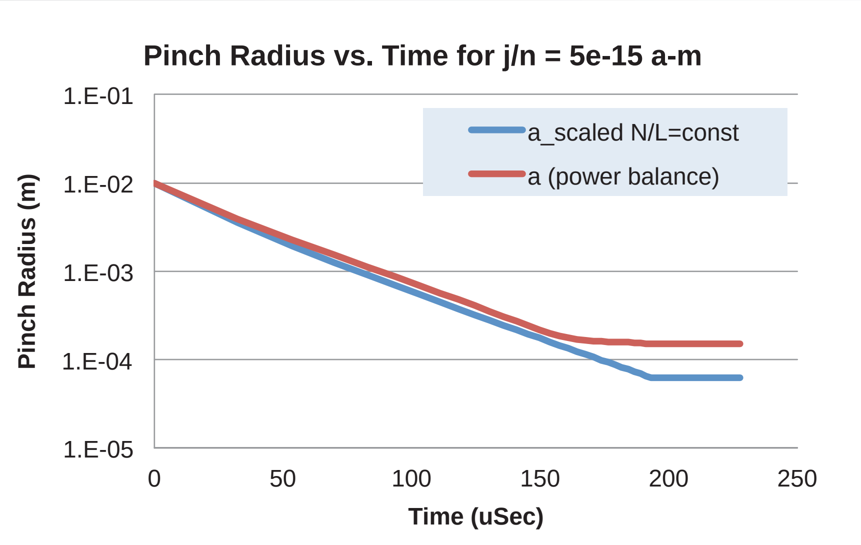

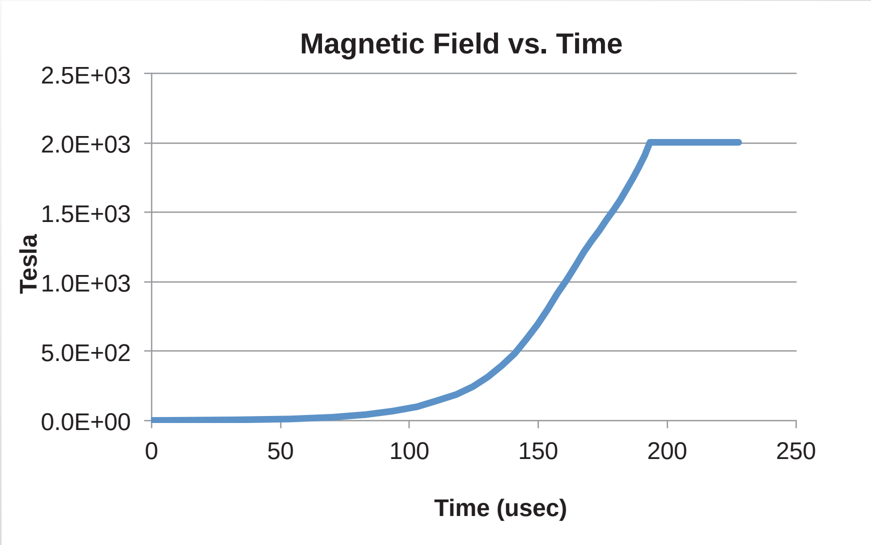

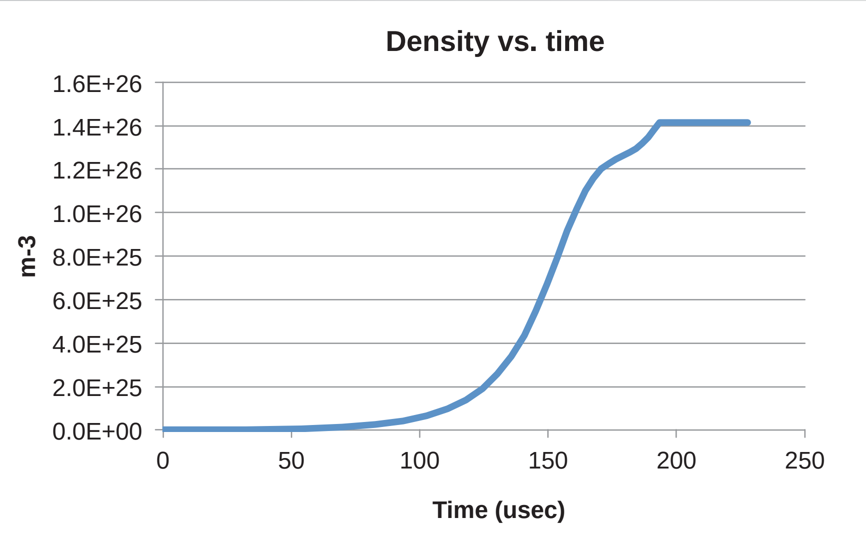

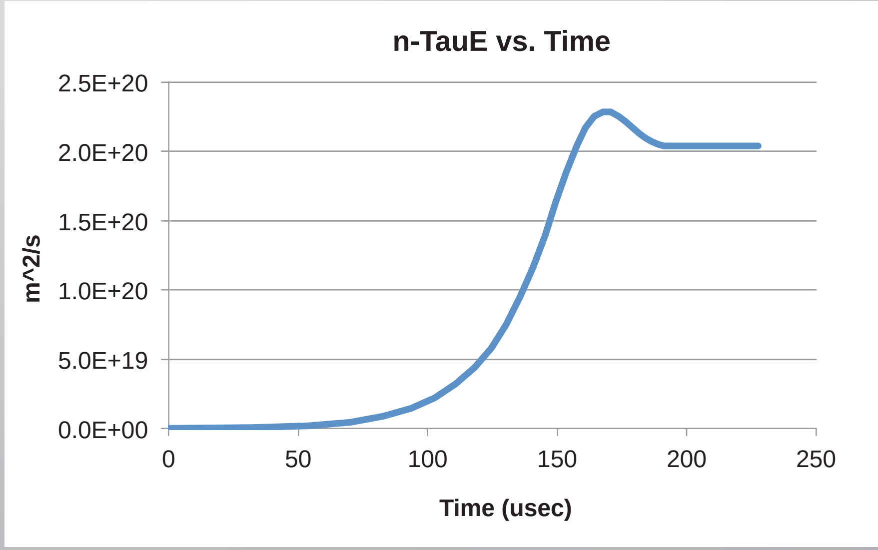

Heilmeier's Catechism

- What are you trying to do? Articulate your objectives using absolutely no jargon.
  - Scale the ZAP device from 50 kA pinch current to 300 kA pinch current (from ~150 kA discharge current to ~450 kA discharge current) while maintaining stability of the pinch for 10's of microseconds.
  - Scope out a reactor concept that has compelling technology advantages if the system scales to reactor conditions.

Plasma Conditions	Existing (ZAP)	ALPHA (FUZE)	Reactor
Pinch current (kA)	50	300	1500
Total discharge (kA)	150	500	1700
Pinch radius (mm)	10	0.7	0.05
Ion Density (m^{-3})	1E+22	2E+24	3E+26
Temperature (kev)	0.1	4	>25
Magnetic field (tesla)	1	90	6000
Lawson n-tau (m^{-3} sec)	1E+17	1E+19	4E+20

- How is it done today, and what are the limits of current practice?
  - The classic z-pinch, with current flowing axially in a stationary plasma between two electrodes, was the very first concept for confining and heating plasma [W.H. Bennett, Phys.Rev. 45 p890 (1934)].
  - The system suffers severe instabilities- a sharp pinch develops in a single location, which heats a very small volume to fusion conditions, but also terminates the plasma in tens of nanoseconds.
  - Much research in the intervening time has attempted to suppress the instabilities
    - including adding an external magnetic field in the direction of current flow (screw pinch)
    - wrapping the axial system into a toroidal shape and driving current inductively (toroidal pinch, tokamak)
    - adjusting the internal profiles of current, density, and flow velocity (c.f. M.G. Haines, Plasma Phys. Control. Fusion 53 (2011) 093001.
  - Plasma flowing in an axial direction with a flow velocity that is sheared in the radial direction has been shown to stabilize a 1 m long x 1 cm diameter 50 kA z-pinch column for 20-40 usec
  - This is an interesting result because it was predicted by most others that velocities near the Alfven speed would be needed to stabilize the pinch. Shumlak's calculation indicated that velocities of about 1/10 the Alfven speed would be enough to stabilize-- and this was born out in his experiments.

Heilmeier's Catechism

- What's new in your approach:
  - We are building unprecedented capability and flexibility into a new device which accommodates the following:
    - Higher input energy, power, and gas loading.
    - A modular (12 independent section) 20 kV capacitor bank to allow a variable and flexible current pulse.
    - Multiple pulsed gas valves (9) to allow a variable and flexible injection of gas
  - We are applying the most recent state-of-the-art computer simulations to resolve the microscopic (kinetic vs fluid) nature of the experiment as well as the fluid nature and whole-device macroscopic behavior.
- Why do you think it will be successful?
  - This type of scale-up has never been attempted before, but the existing experimental results, projected performance based on modest extrapolations, building in experimental flexibility, and application of world-class computer simulations provide a sound foundation for improving the the state of the art and success.
- If you're successful, what difference will it make?
  - Achieving goals of the project, while not approaching the conditions required for a fusion reactor, will nevertheless be suitable for several exciting applications:
    - Intense, neutron source, >1e11 neutrons per pulse
    - Ultra-intense (10 MW) thermal plasma light source operating at a plasma temperature of several kilo-electron volts.
- What are the risks and the payoffs?
  - Discussed briefly in other areas.
- How much will it cost?
  - $5M
- How long will it take?
  - 3 years
- What are the midterm and final "exams" to check for success?
  - Reproduce ZAP results with new hardware in year 1
  - Extend performance factor of 2 in year 2
  - Achieve 6X goal in year 3.