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

The Fusion Z-Pinch Experiment: FuZE

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Outline

• **What are you trying to do? (Project goal and plans to accomplish it.)**
  • Scale up an existing 50 kAmp z-pinch device to higher current and performance: [Goal = 300 kA of pinch current.]
  • This requires new electrodes, new capacitor bank, new gas injection/pumping
  • Understand in some detail the plasma physics important in the scale up to improve and inform projections of performance to reactor conditions

• **Why is this important? (Particularly for fusion power, but also science.)**
  • A stable pinch at 300 kA of pinch current has some exciting applications
  • If the concept works at >1 MA of current, a reactor is possible
    • Direct adoption of liquid walls solves critical materials issues
    • Fundamental questions about plasmas in these regimes are unresolved.

• **Why now? (What is new and different vs. previous work?)**
  • First attempt at scaling up by large factor. (6x in current)
  • First look at physics with recently developed kinetic modeling methods
  • First use of agile power drive and gas input (multiple cap bank modules and multiple gas valves)

• **Why it is hard? (What are the critical challenges you must overcome?)**
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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
The new device under construction (FUZE) is about the same dimensions but will handle much higher discharge current, higher heat loads, and will provide flexible gas injection capability with a total of 9 fast-puff gas valves.

Gas valves are now external at 8 locations plus one inside the inner electrode on axis. Nozzles extend through vacuum envelope to the outer electrode.

Pinch region is shorter, but can be easily changed.

End of inner electrode is graphite.

Plasma gun region gun is very similar.

Larger vacuum pumping ports at multiple locations.
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 will apply state of the art fluid and kinetic particle plasma simulation codes.

- The physics inside the pinch is complicated and a kinetic, or particle, approach is needed to properly simulate pinch conditions. Fluid approaches do not capture kinetic instabilities or kinetically-driven anomalous plasma viscosity/resistivity.

- Schmidt et al have modeled a similar device, the dense plasma focus (DPF) in the particle-in-cell code LSP [2] and demonstrated that a fully kinetic approach was needed to reproduce experimentally measured neutron yields, ion beam energies, and electromagnetic oscillations. In this project, we will extend the kinetic modeling to a flow pinch geometry.

Fully kinetic pinch model
A. Schmidt, V. Tang, D. Welch, PRL 2012
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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
  \[ nk(T_e + ZT_i) = \frac{B^2}{2\mu_0} \; ; \; B = \frac{\mu_0 I}{2\pi a} \; ; \; a = \text{pinch radius} \]

- Flat current, density, temperature profiles across pinch
- $V_{flow} = 0.1 \, V_{\text{alfvén}}$
- $P_{rad}$ is bremsstrahlung only, $Z_{eff} = 2.0$
- $P_{conduction}$ is ad-hoc, using $D_{\text{bohm}} \ast$ 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 $0.8 \times 10^{-14}$ amp-m < $j/n$ < $1.6 \times 10^{-14}$ amp-m
  - How $j/n$ adjusts is also not well-understood. Density and current profiles adjust when $u_{e,\text{drift}} = j/en$ approaches ion sound speed $\rightarrow$ pinch needs to heat during current ramp or bad things will happen

- $P_{thermal} = U_{\text{thermal}} / t_{flow}$ where $t_{flow} = \frac{\text{Length}_{pinch}}{V_{flow}}$
  - 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)
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

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<tr>
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<th>ALPHA (FUZE)</th>
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<td>50</td>
<td>300</td>
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<td>Total discharge (kA)</td>
<td>150</td>
<td>500</td>
<td>1700</td>
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<tr>
<td>Pinch radius (mm)</td>
<td>10</td>
<td>0.7</td>
<td>0.05</td>
</tr>
<tr>
<td>Ion Density (m⁻³)</td>
<td>1 E+22</td>
<td>2.5 E+24</td>
<td>3 E+27</td>
</tr>
<tr>
<td>Temperature</td>
<td>50-100 eV</td>
<td>2500-4000 eV</td>
<td>25-50 keV</td>
</tr>
<tr>
<td>Magnetic field (tesla)</td>
<td>1</td>
<td>90</td>
<td>6000</td>
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<td>Lawson n-τ (m⁻³ sec)</td>
<td>1E+17</td>
<td>1E+19</td>
<td>1E+21</td>
</tr>
<tr>
<td>D-D Neutron Yield</td>
<td>1e11 - 4e11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation Power (MW)</td>
<td>10 MW</td>
<td></td>
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**X-ray Source at 300 kA:**
- Hot: 2keV
- 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
Shear-Flow Stabilized Z-Pinch Reactor Concept:
- Point a flow-stabilized z-pinch down into liquid metal
- Addresses many technology issues that are unresolved for other concepts

Liquid metal performs multiple jobs:
- Protects the walls
- Act as one of the electrodes
- Heat transfer fluid
Ignitron technology is a mature technology with commercially available units that can conduct reactor-scale relevant currents through liquid cathodes.

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


Back-up slides
Reactor Development path requires ~30x increase in pinch current from existing capabilities

Prototype reactor:

- **Discharge Current / Volts**: 1.7 MA / 22 kV
- **Rep-rate / Pulse Length**: 10 Hz / 230 μS
- **Fusion energy per pulse**: 19 MJ
- **Average Fusion power**: 190 MJ
- **Reactor Q ~ 5**
Power Balance projections show reaching 500-700 KA using 50-50 DT achieves “Scientific Breakthrough” as defined by Pfusion > Pinput
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The pinch is short, ~10-50 cm long, so the reactor can be small and modular.
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.

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• 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)
  • 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 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.