STABILIZED LINER COMPRESSOR FOR LOW-COST CONTROLLED FUSION: PROGRESS AND ISSUES

Peter J. Turchi, Sherry D. Frese, Michael H. Frese
NumerEx
Santa Fe and Corrales, NM USA

ARPA-E ALPHA Review
29-31 August 2017
San Francisco, CA

Energy costs $\$_w$ decrease and power-density costs $\$_s$ increase with higher plasma density, offering a minimum total cost between the conventional magnetic- and inertial-confinement concepts.

<u>Challenges</u>:

Compression needs to be stable

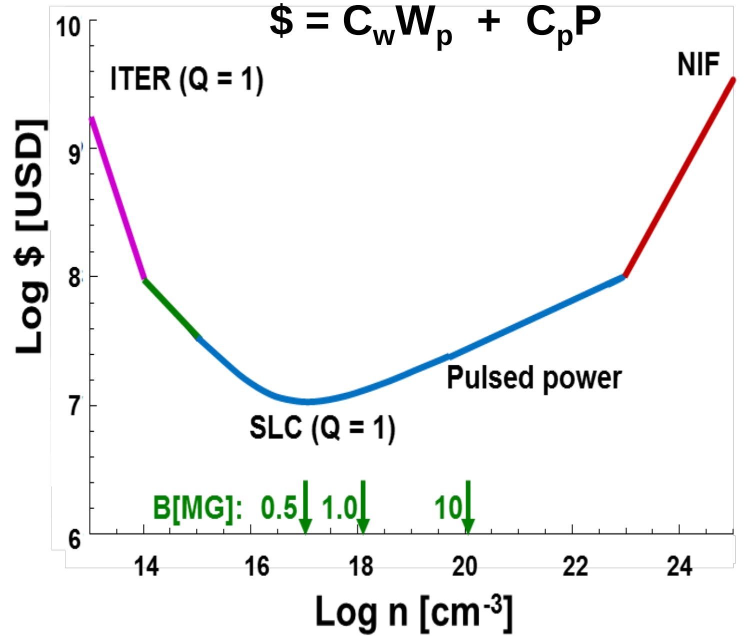
- **Avoid mixing of high-Z material with fuel**
- **Plasma target must survive compression**

"Kopek" problem

- **For economical, pulsed reactor, need to re-establish conditions each shot for price of coke bottle**
- **To enable development of low-cost fusion, need hundreds of plasma shots (several shots per day <u>vs</u> several weeks per shot)**

Ferocious fluence of high-energy neutrons

- **100 MW(e) means 10^{20} n/s <u>vs</u> 10^{15} n/cm^2 for insulator damage**

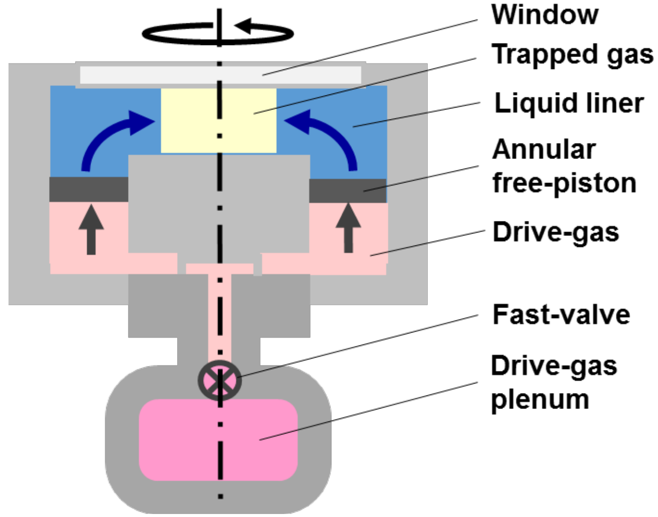


from P.J.Turchi, S.D.Frese, M.H.Frese, *IEEE Trans. on Plasma Sci., Special Issue* (Nov 2017). http://ieeexplore.ieee.org/document/7947151.

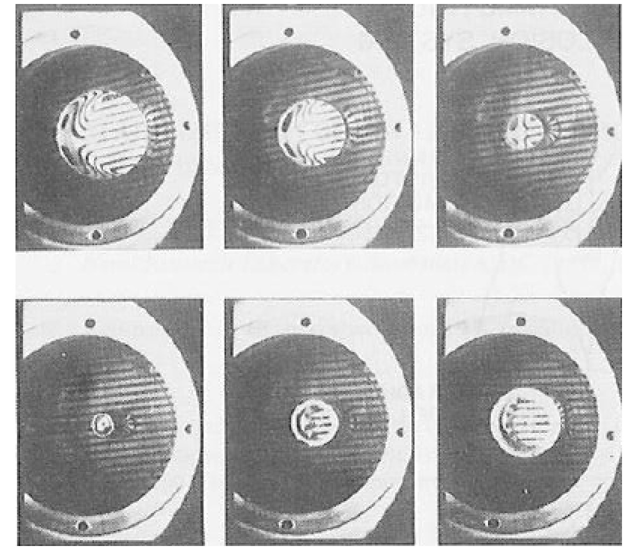
Megagauss fields can be readily obtained by imploding-liner flux compression, but need stabilized liner compression for economical operation.

The Stabilized Liner Compressor (SLC) derives from successful demonstrations at the Naval Research Laboratory of stable implosions.

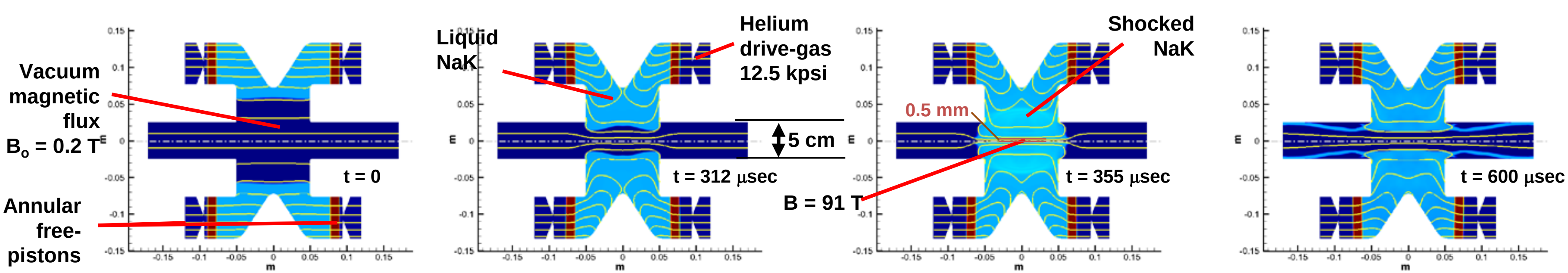
Basic arrangement for Stabilized Liner Compressor (used in NRL experiments)



Implosion/expansion of rotating liquid liner compressing trapped-gas payload (NRL, c.1978)



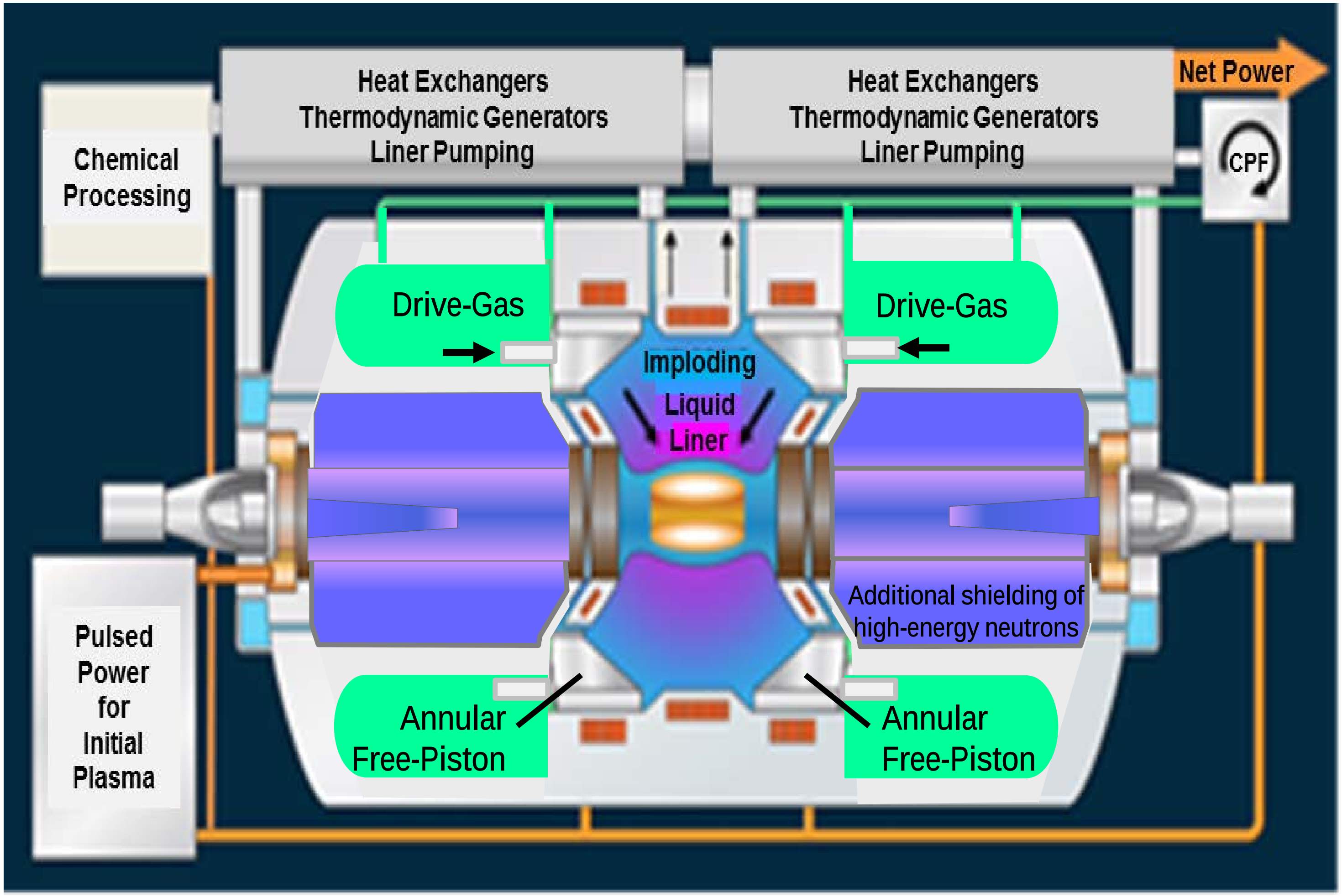
Sequence of frames of MACH2 simulation of liquid NaK liner compressing magnetic flux



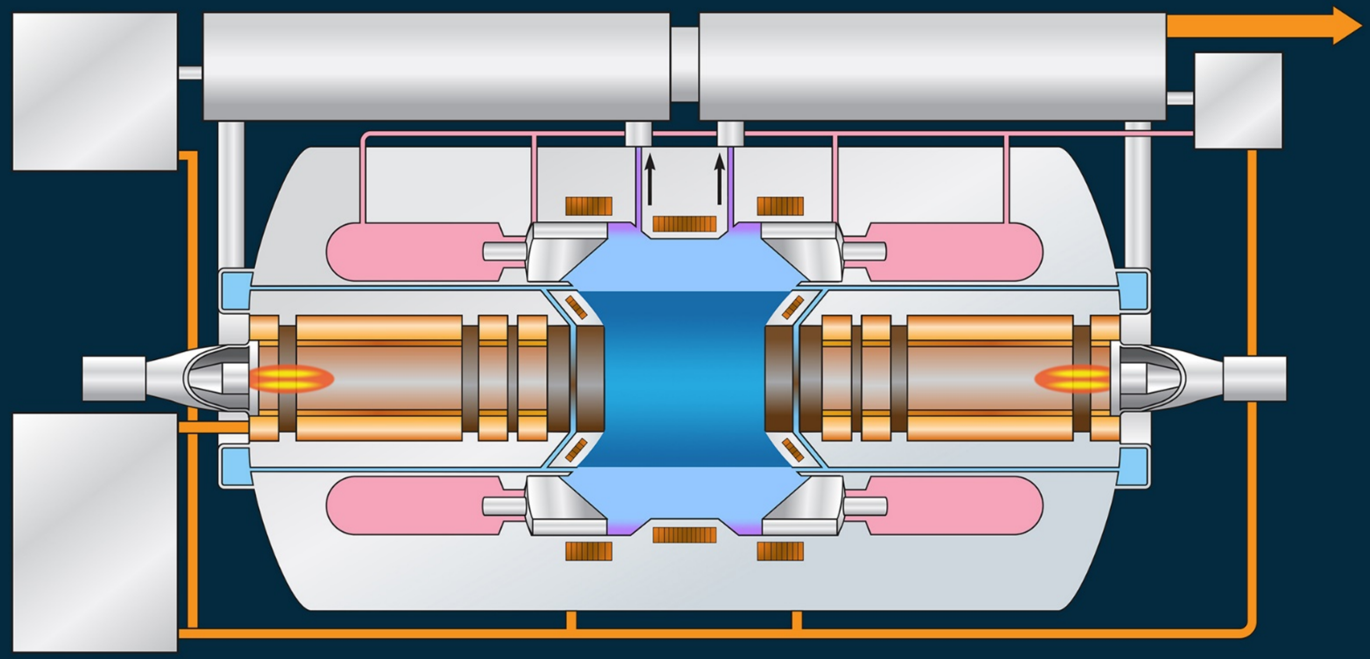
Path Ahead: MACH2 code is used to design SLC, compare with experiments and then predict performance of liner compression of plasma targets for near term experiments, breakeven demonstration and the power reactor.

NumerEx

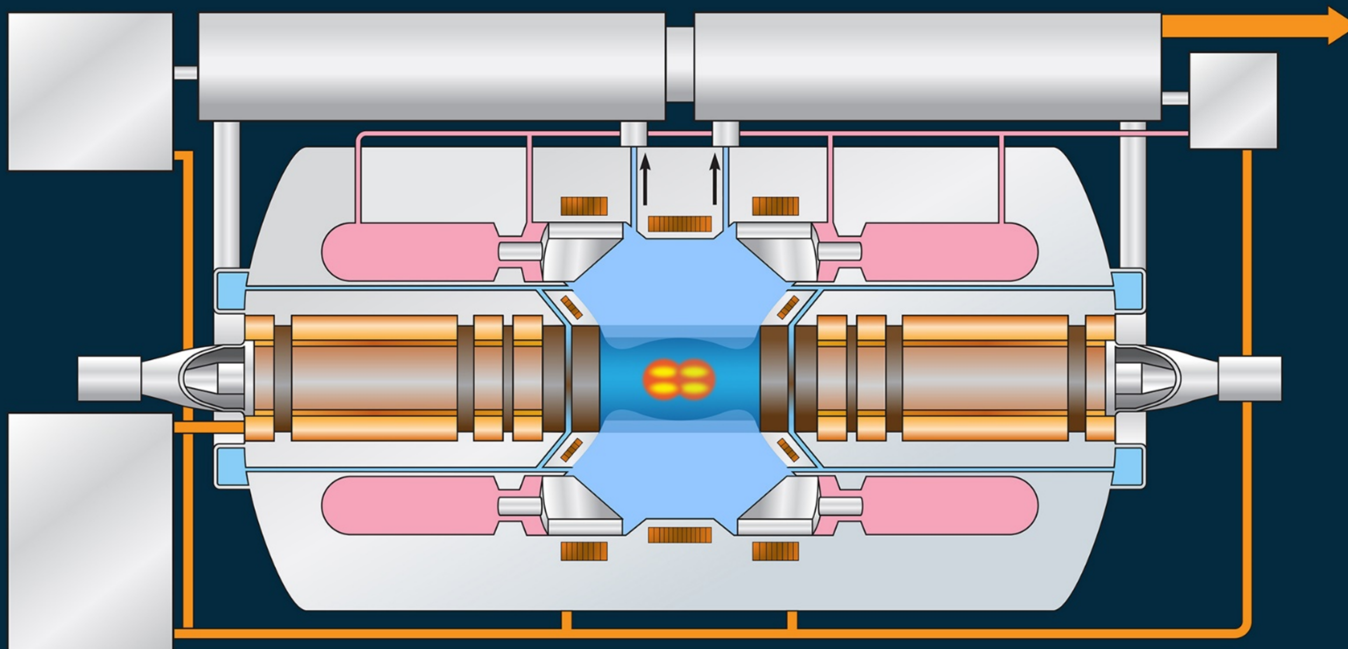
The Stabilized Liner Compressor (SLC) provides a compact fusion reactor based on two annular free-pistons driven by high-pressure gas to implode a rotating liquid metal cylinder onto a plasma target.



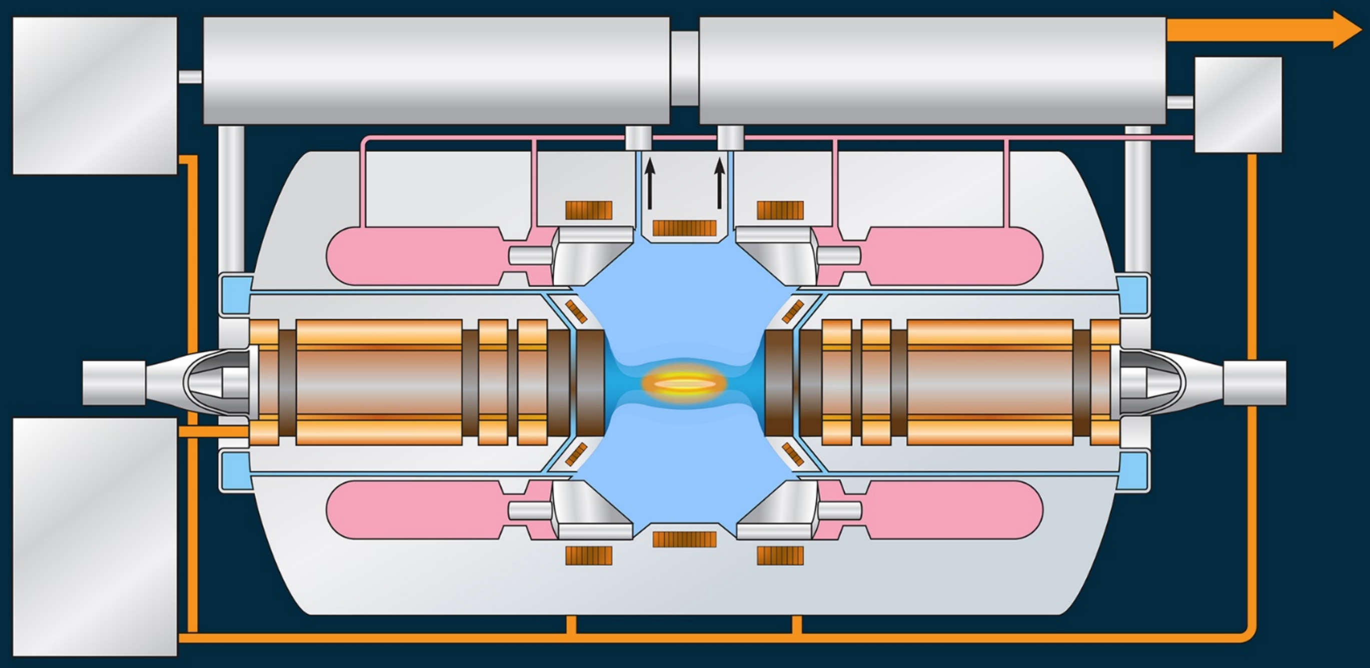
At peak compression, the liquid metal cylinder shields sensitive components from the high-energy neutron output of D-T fusion reactions (10^{20} n/sec at 500 MW).



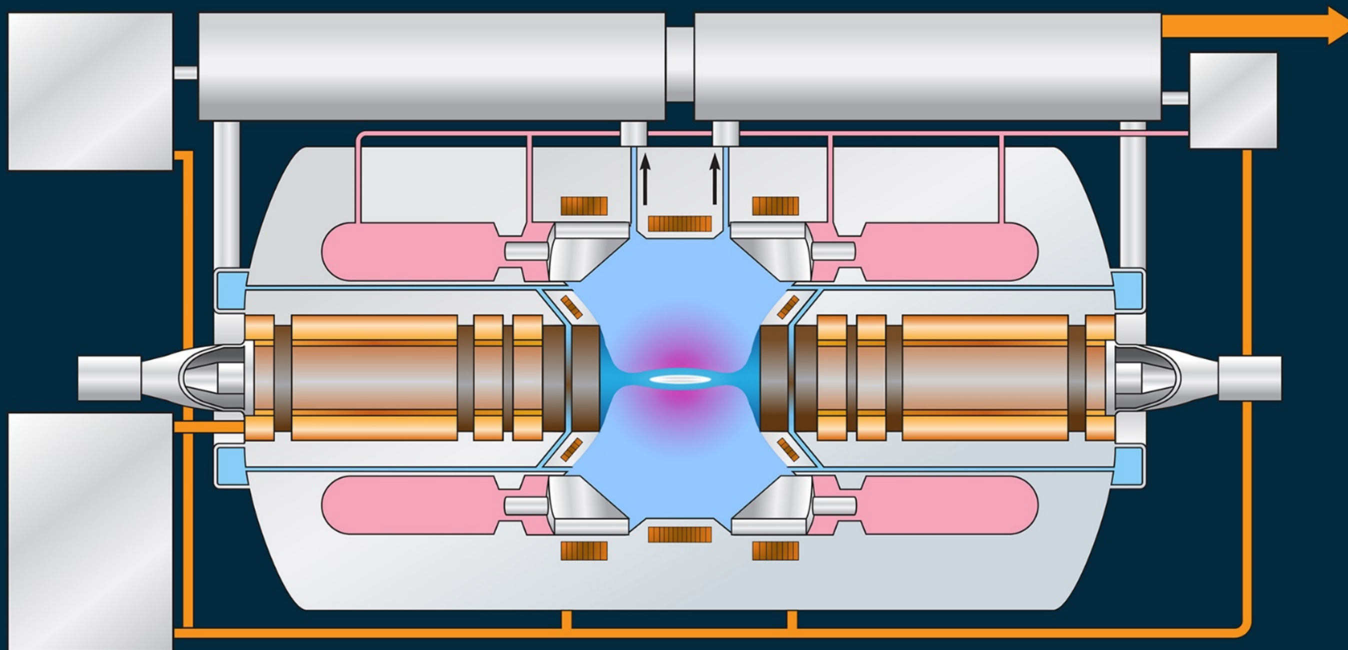
Injection of compact toroid magnetized-plasma



Compact toroids merge to form magnetized-plasma target.

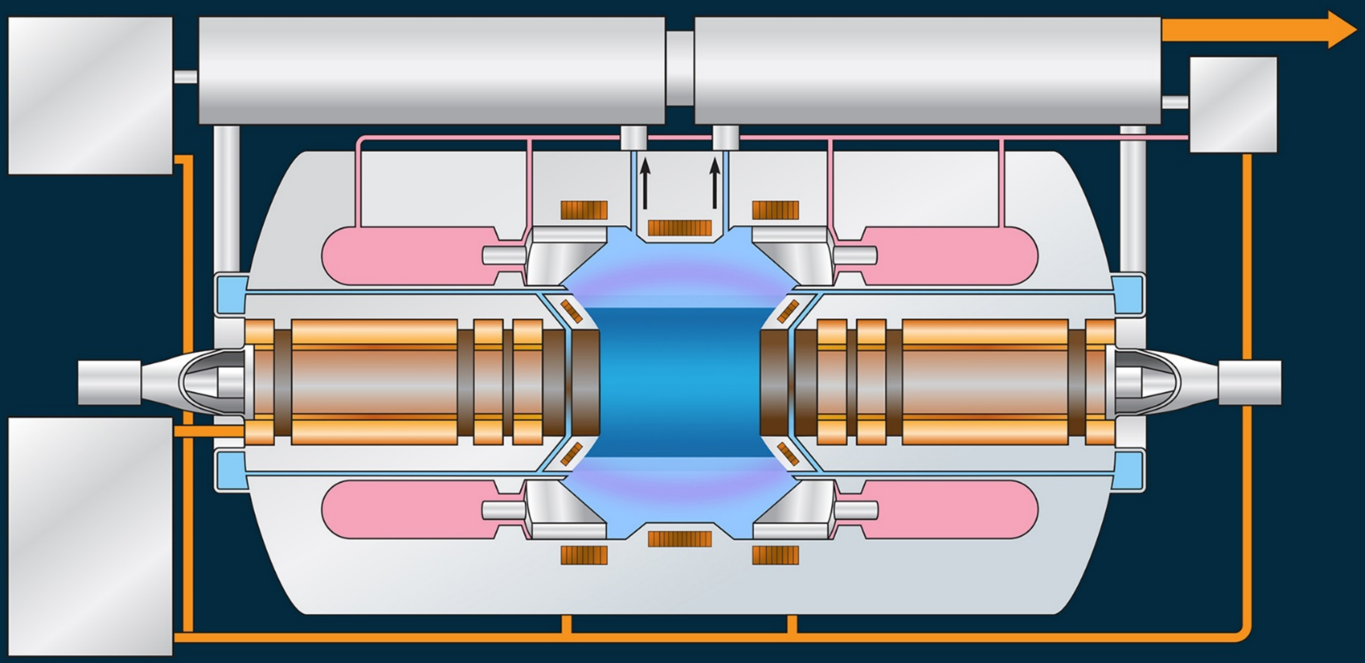


Strong adiabatic compression replaces costly beam- and RF-heating to achieve fusion temperatures.



Liner serves as reactor blanket to protect electrical components from neutron damage.

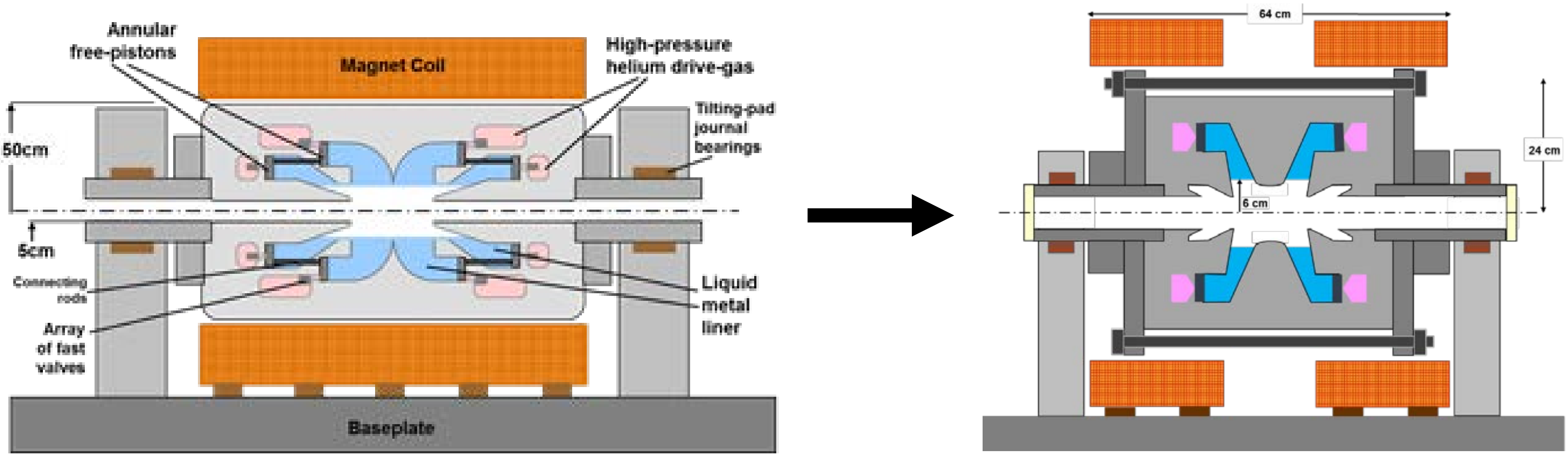
NumerEx

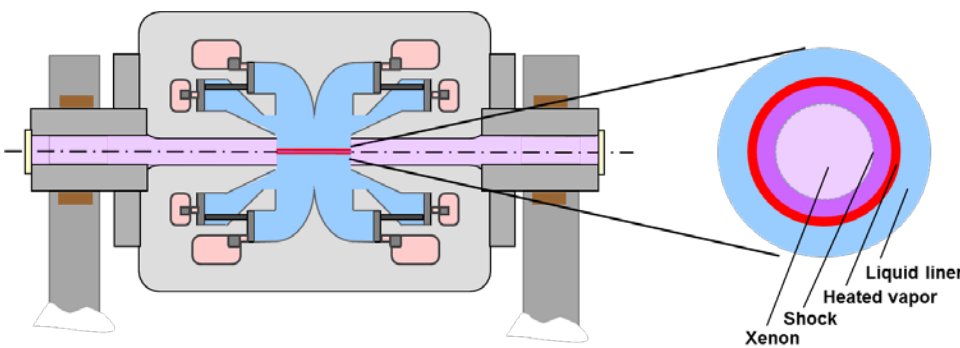


Liquid liner provides medium for heat transfer and tritium recovery.

We accomplished a successful Conceptual Design Review (CDR) for a panel of experts in MHD, alkali-metal handling and pulsed power programs. Their recommendation was to focus on high energy-density issues for SLC, rather than early plasma targets.

<u>Accordingly, we have reduced size of first SLC by factor of two</u>





Zeeman-splitting and laser-shadowgraphy will measure magnetic fields and liner implosion speeds.

$$\Delta\lambda = (M_2 g_2 - M_1 g_1)\lambda^2 \; 4.67 \times 10^{-13} \; B$$

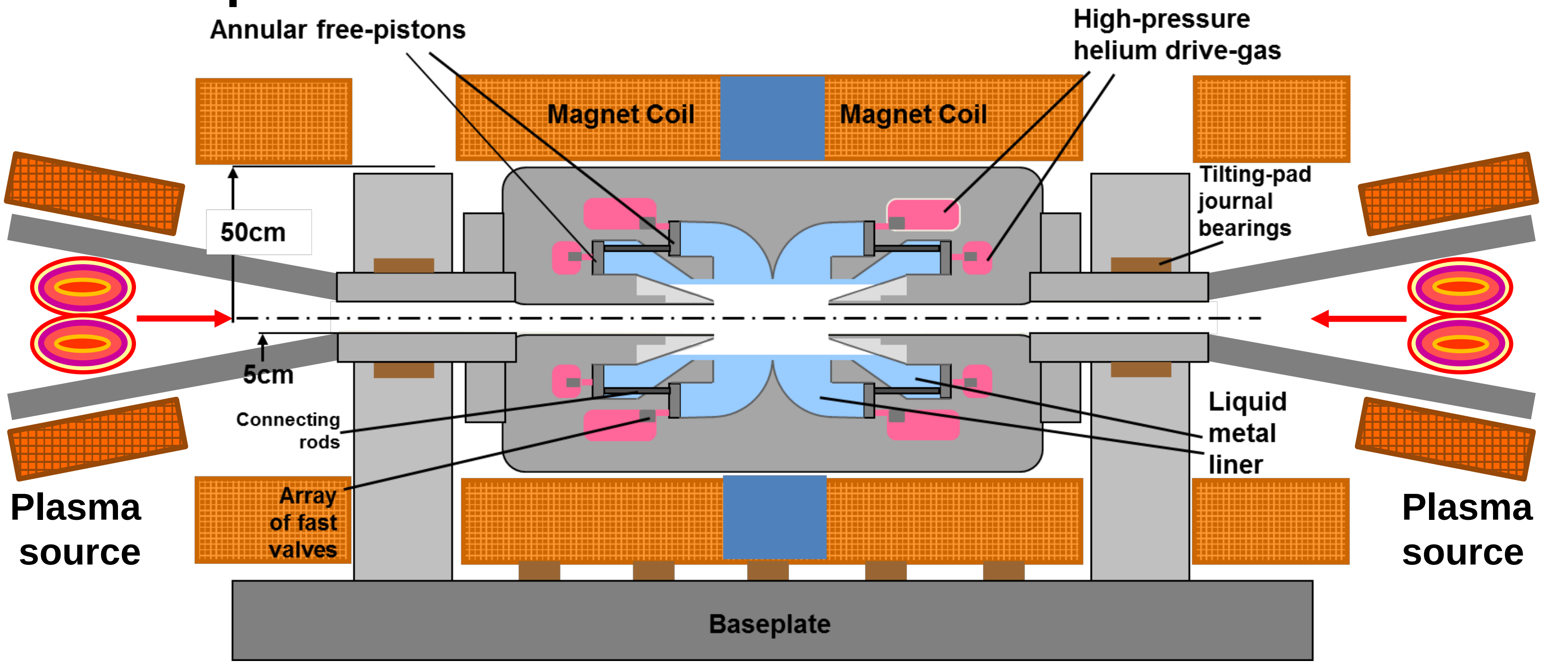
Sodium D at 100T, $\Delta\lambda \approx 4$ nm

Success with this first SLC will be used in design of the larger system to enable plasma target development.

NumerEx

We are planning with partner for the initial development of a plasma target to understand plasma lifetime better. This will inform MACH2 calculations to design and build the larger SLC.

The larger SLC, which may correspond to the earlier nominal design for CDR, would enable repeated liner compression of plasma for further development.

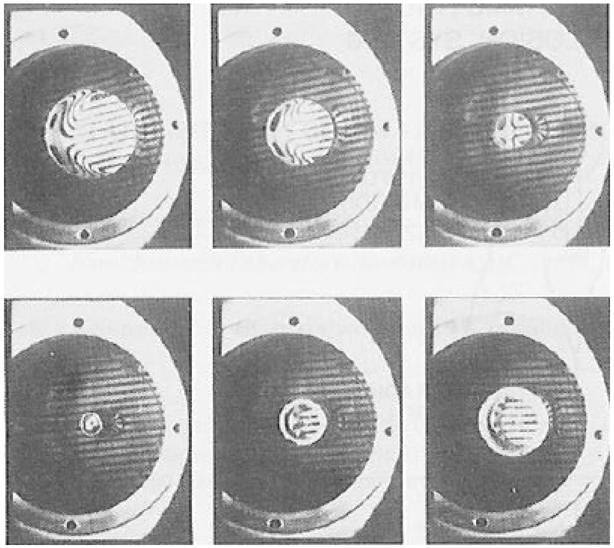


The initial plasma experiments will look at diffusion (e.g., Bohm <u>vs</u> classical) and stability. The repeated SLC experiments will examine compression. MACH2 will then extend these results to breakeven and the reactor.

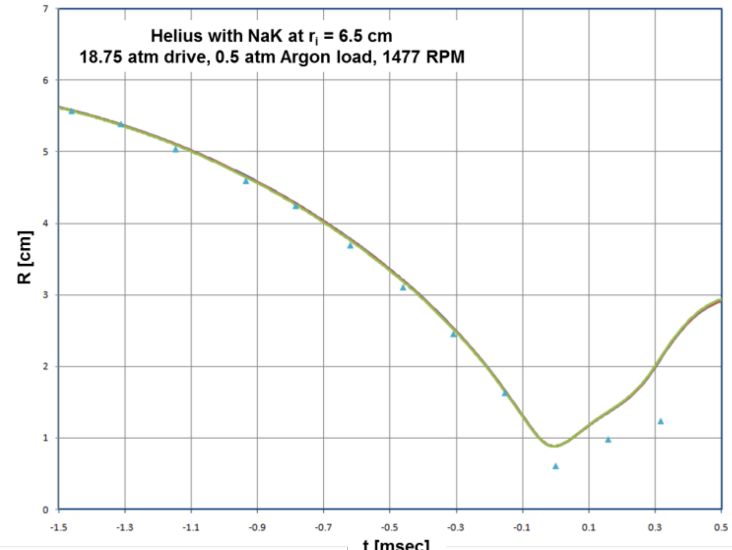
Backup Slides

We use the 2-1/2 dimensional MHD code MACH2 to simulate rotationally-stabilized, piston-driven liquid liner implosions.

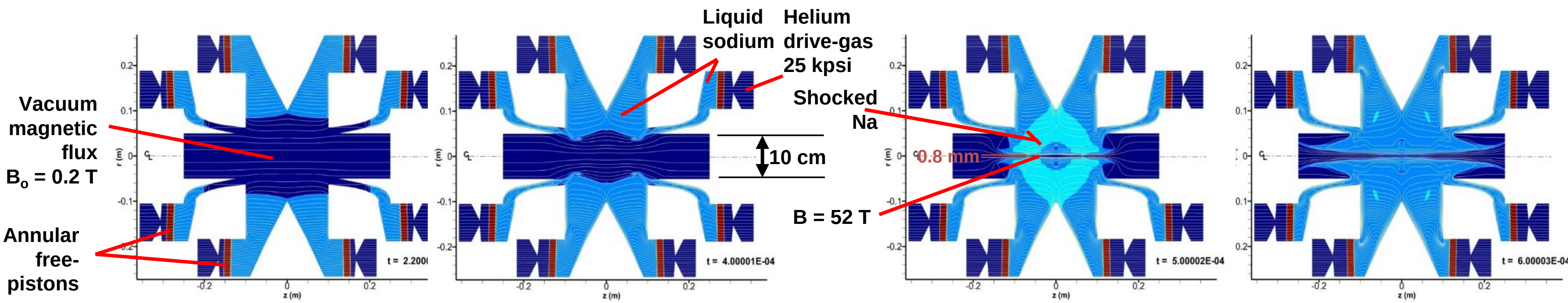
Implosion/expansion of rotating liquid liner compressing trapped-gas payload (NRL, c.1978)



Benchmarking of MACH2 code against NRL Helius experiment (c. 1979)



Sequence of frames of MACH2 simulation of liquid Na liner compressing magnetic flux



Path Ahead: MACH2 is used to design SLC, compare with experiments and then predict performance of liner compression of plasma targets for near term experiments, breakeven demonstration and the power reactor.

NumerEx

The opportunity for the stabilized implosion to exchange energy reversibly with the payload, lowers the required nuclear gain.

Fractional loss f_L of liner energy W_T is replaced by energy fraction f_α due to alpha-particle energy and by energy circulation fraction C:

$$f_L W_T = f_\alpha f_p f_F Q W_T + C [f_t(f_p f_F Q (1 - f_\alpha) + f_L)] W_T$$

with f_p = fraction delivered to payload, f_F = fraction of payload for fusion reactions, and f_t = thermal generator efficiency.

Thus, required gain relative to plasma energy is:

$$Q = f_L(1 - Cf_t)/f_p f_F[f_\alpha + Cf_t (1 - f_\alpha)]$$

For $f_L = 0.2$, $f_p = 0.4$, $f_F = 0.3$, $f_t = 0.33$, and $f_\alpha = 0.156$, a circulating power fraction of 25% needs Q = 6.8. If $f_L = 1.0$ and $f_\alpha = 0$, Q = 46.3 (w/ f_p =0.8).

Burn-time: based on diffusion - $W_p \sim Q^{3/2}$ <u>vs</u> based on inertia - $W_p \sim Q^3$

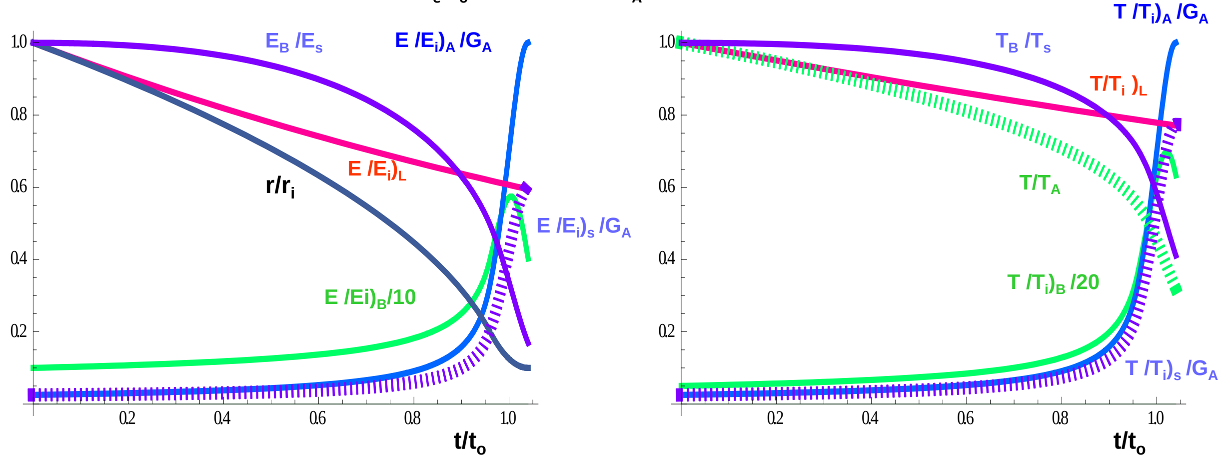
Ability to retain liner energy and use work performed by alpha-particles can reduce reactor size by orders of magnitude .

NumerEx

Previously, we estimated the importance of loss-time <u>vs</u> implosion time, t_e/t_o by prescribing a generic trajectory u(t)r(t) = constant until r(t) = $2r_f$, followed by uniform deceleration to minimum radius r_f.

<u>Bohm vs Classical Diffusion</u>

$t_e/t_o = 2.0$, $\alpha = 10$, $G_A = 39.8$



For loss time: $t_e = 16(\alpha r_f)^2 B/(kT/e)$ <u>vs</u> Implosion time: $t_o = (\alpha r_f)^2 / 4u_2 r_f$, with u_2 the speed at $2r_f$, we need $2u_2 r_f = (kT/e)/16B$

Stabilized Liner Compressor using lithium offers $2u_2 r_f = 15\ m^2/s$ <u>vs</u> $(kT/e)/16B = 14.1$, for initial FRC values of 475 eV and 2.1 T, (e.g., Slough, et al, *Nucl. Fusion* 51.5 (2011)).

Bohm Diffusion		"Classical" Diffusion*	
$E/E_i)_B$	$T/T_i)_B$	$E/E_i)_s$	$T/T_i)_s$
6.0	14	23	31

Q_{sci} (10 keV)	n_i [cc^{-1}]	B_i [T]	d_i [cm]	n_i [cc^{-1}]	B_i [T]	d_i [cm]	Q_{sci} (22 keV)
0.13	7.9×10^{15}	2.1	10	7.9×10^{15}	2.1	10	1.0
1.0	7.9×10^{15}	2.1	78	7.9×10^{15}	2.1	68	6.8

*For same t_e, "classical" transport would be multiplied by 100-200X to match initial Bohm diffusion.

from P.J.Turchi, S.D.Frese, M.H.Frese, *IEEE Trans. on Plasma Sci., Special Issue* (Nov 2017).

Estimate suggests possible increase of temperature toward 10 keV during multi-shot development with stabilized liner compression.

NumerEx

The Stabilized Liner Compressor represents a pulsed power system that differs from "conventional" techniques by using pneumatic and hydrodynamic vs capacitive and inductive energy storage and delivery.

Pneumatic energy storage:

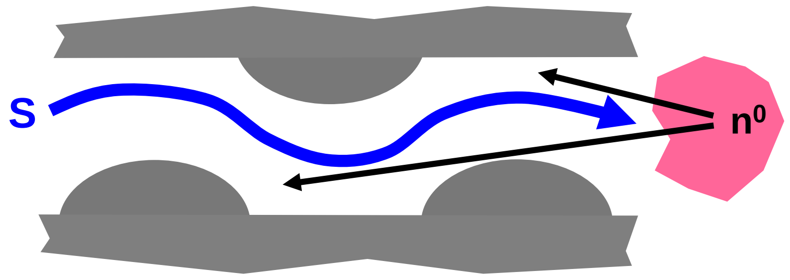
- At 25 kpsi, inert gases (e.g., helium) can store 255 MJ/m^3 vs 140 kJ/m^3 for capacitors
- Charge/hold time >> normal inductive storage

Hydrodynamic energy storage:

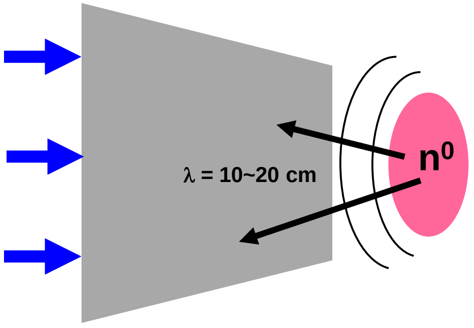
- At 1000 m/s, liquid metal (e.g., 1 g/cm^3) stores 500 MJ/m^3

Additional important difference is opportunity to deliver energy by work in flux-compression and thereby block high-energy neutrons:

Delivery of electromagnetic or plasmadynamic energy requires open channel (vacuum or insulator)



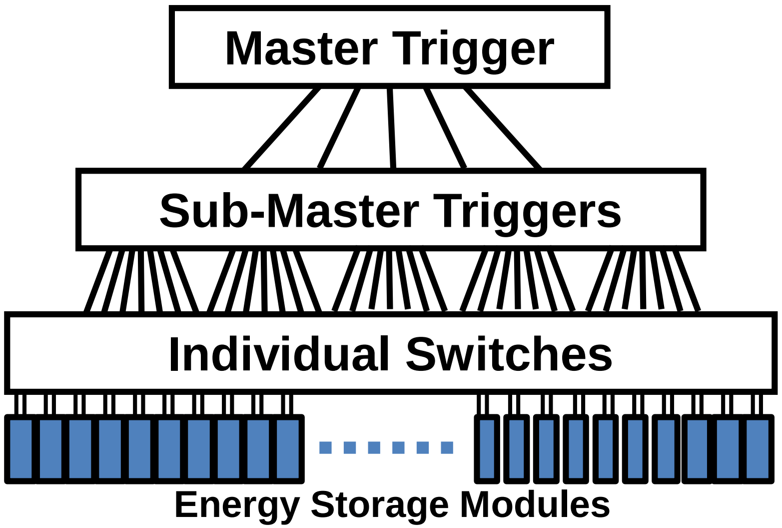
Hydrodynamic compression of flux allows thick liner to block neutrons



Efficient compression requires rotational stabilization.

For compact , low-cost fusion, we are creating a new type of pulsed power system, based on pneumatic energy storage and control.

For conventional pulsed power, based on capacitive and inductive energy storage, large systems typically use a large number of closing switches, fired by a lower number of “sub-master” switches that are fired by a single “master” switch.



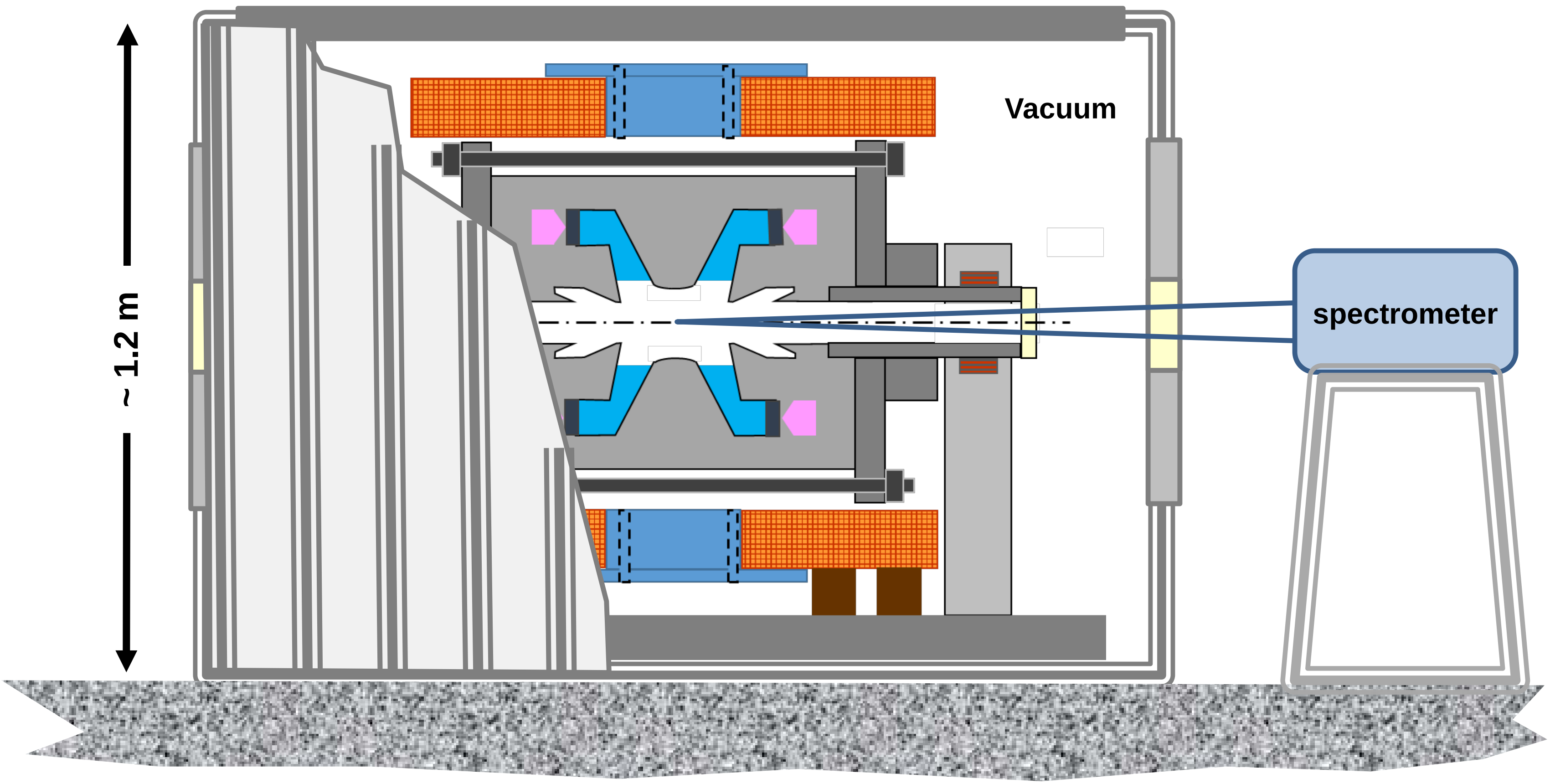
The Late Shiva Star Bank ~9 MJ stored

Our challenge: Duplicate the sequence of electrical switches using high-pressure gas valves controlling much higher energies.

Master Trigger Valve — **Sub-Master Trigger Valves** — **Fast-Valve Canisters** — **Drive-gas Plenum** **85 MJ/m^3**

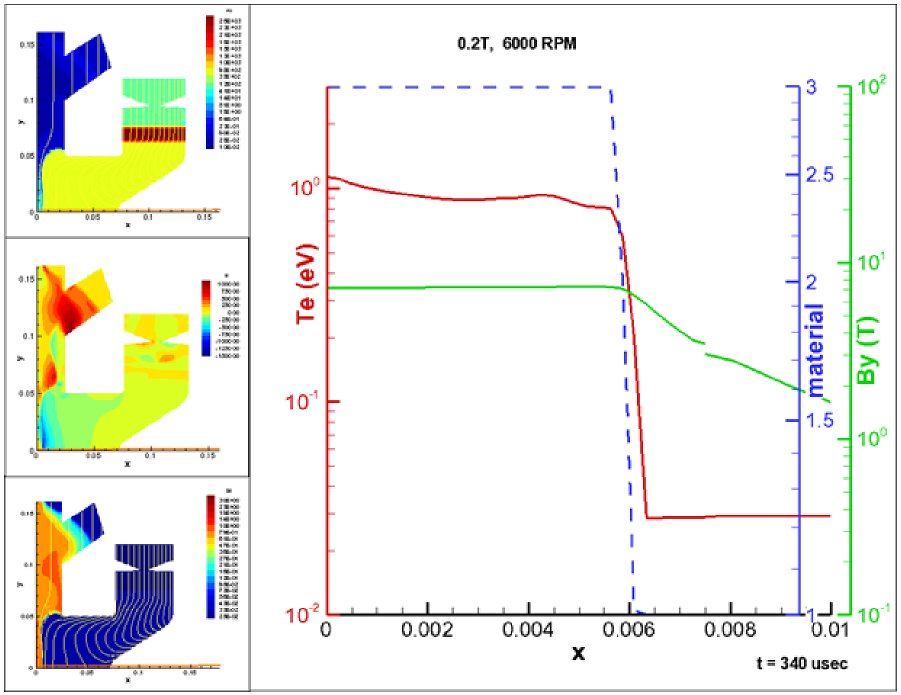
NumerEx

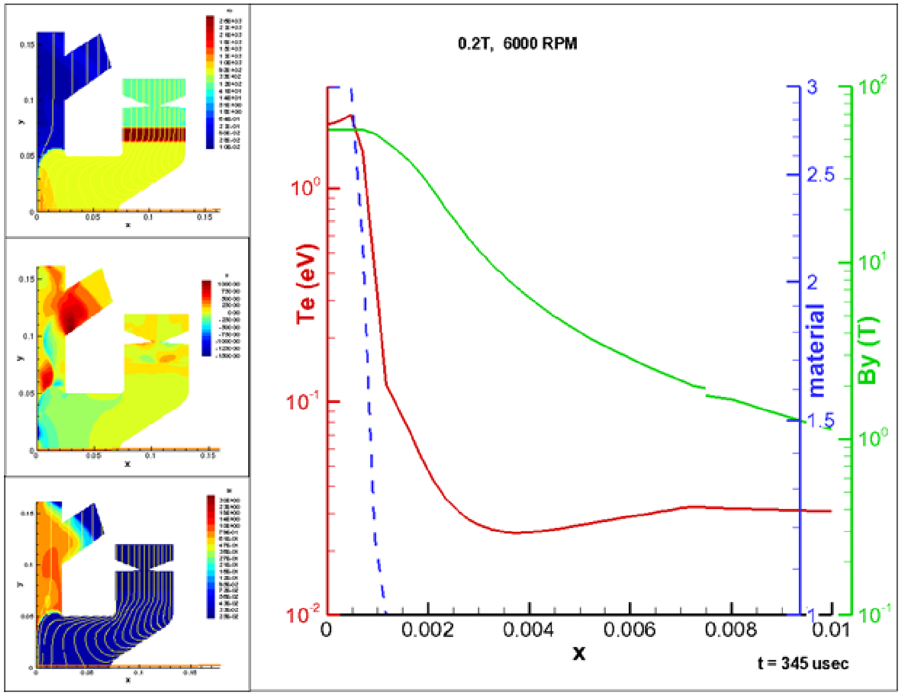
Based on further analyses after our Conceptual Design Review, we have lowered the drive-pressure to 12.5 kpsi, selected eutectic NaK for the liquid liner, and titanium as the primary structural material.



SLC is a multi-hazard experiment, including very high pressures, high-speed rotating machinery, and alkali-metal, so it will be operated within a safety enclosure.

MACH2 can provide conditions in the shocked and compressed xenon indicating luminosity and magnetic field distributions for Zeeman splitting measurement.





Complex situation requires MACH2 synthesis of data for comparison to experimental data. Our line-of-sight is through regions of varying magnetic field strength and luminosity. The effects of Doppler and Stark broadening will also differ.