SAND2010-4388 C
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Portable Current Source for 50 T and 200 T Magnetic Field Coils for Cluster Fusion Experiments

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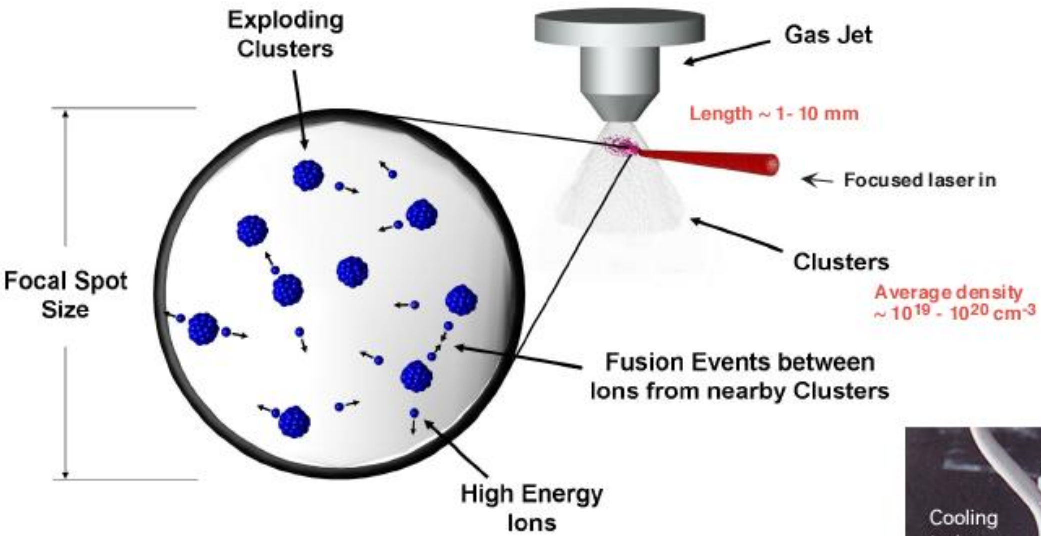
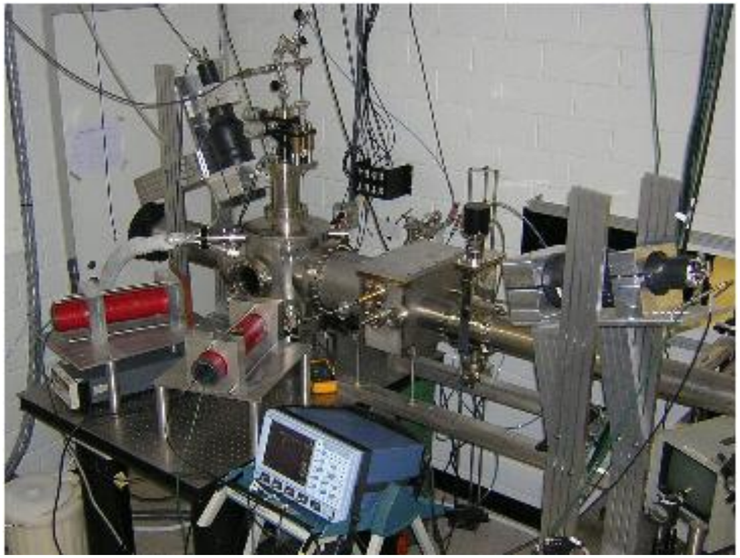
Suzhou, China, July 5 – 9, 2010

Sandia is developing a 2 MG driver for cluster fusion experiments at the Univ. of Texas at Austin

- Project Purpose and Approach
  - Enhance neutron production from high-temperature, ultra-fast, laser-produced cluster plasmas by embedding them in intense magnetic fields
- Significance of Results
  - Addition of strong magnetic fields to cluster plasmas may dramatically increase neutron yield.
  - Device also allows investigating laser-produced plasmas external to Z
- Key Accomplishments
  - 50 T prototype system completed
    - 2 cap system at 50 kV, 200 kA
    - Vacuum chamber with feed-through and coil
    - LABVIEW control system
  - Circuit code design of a 200 T system done
  - 50 T system to be delivered to UT by 7/1/10
  - UT progress with coils and cluster gas gun
  - Initial tests of coil indicate possible shorting
  - Optical diagnostics developed

Irradiating a gas of deuterium clusters creates a high temperature plasma

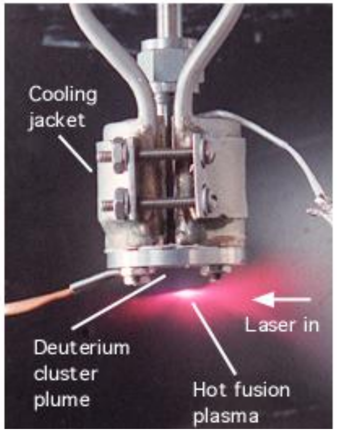




Relevant fusion reactions:

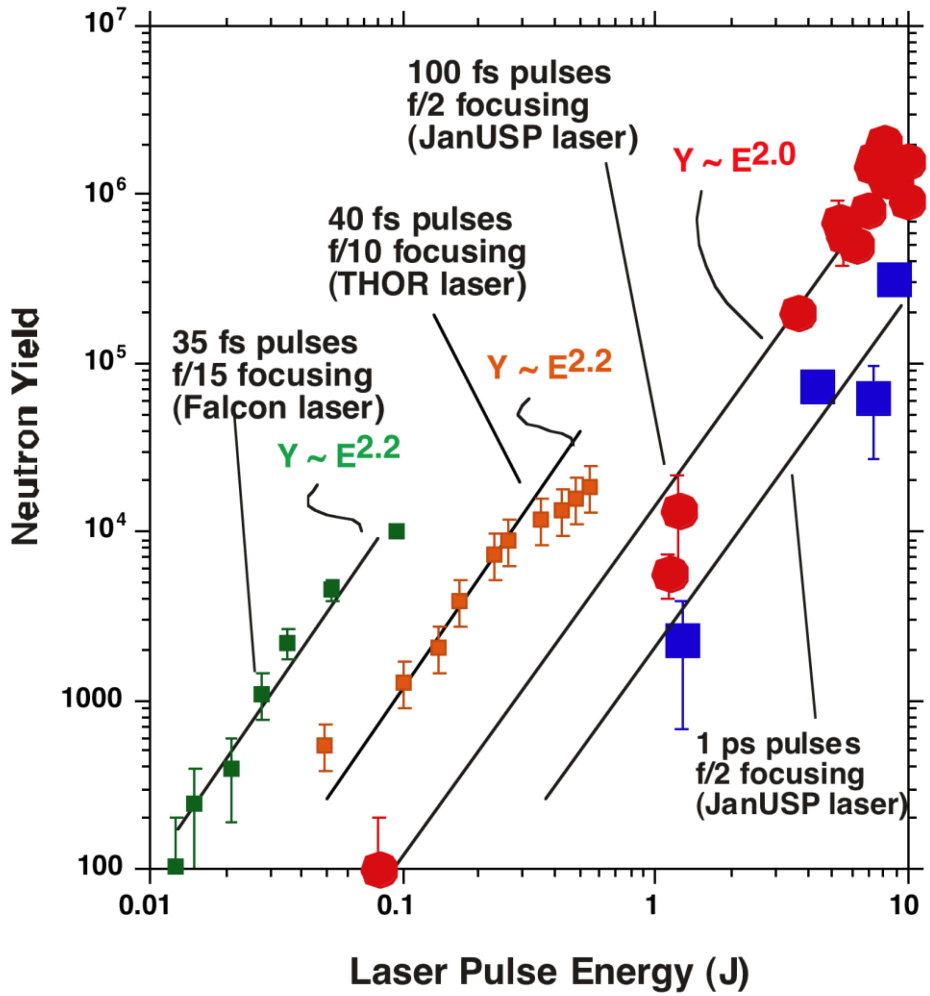
$D + D \rightarrow He^3$ (0.82 MeV) + n (2.45 MeV)

$D + T \rightarrow He^4$ (3.5 MeV) + n (14.1 MeV)



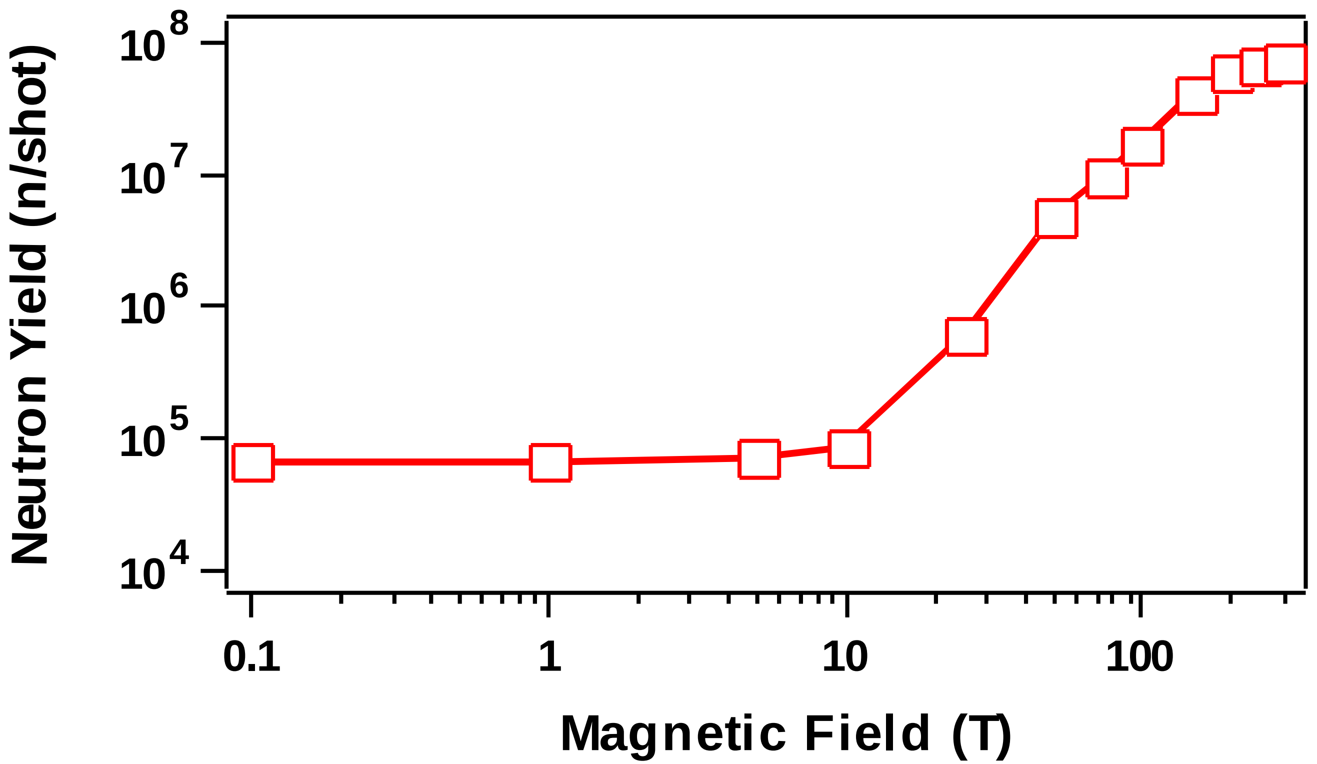
- **T. Ditmire *et al.* "Nuclear Fusion from Explosions of Femtosecond-Laser Heated Deuterium Cluster," *<u>Nature,</u>* 398, 492 (1999).**

The fusion yield with small scale lasers has been well characterized in experiments

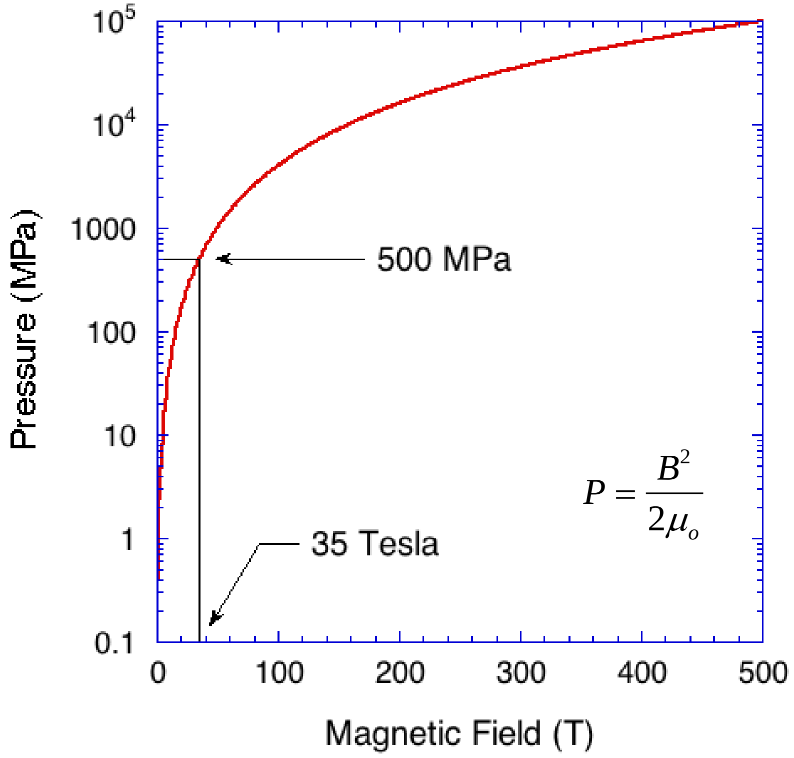


Data courtesy Roger Bengston, Univ. of Texas, Austin

Calculations suggest that neutron yields can be increased 2 to 3 orders of magnitude with an axial



Magnetic pressure can be severe with these fields



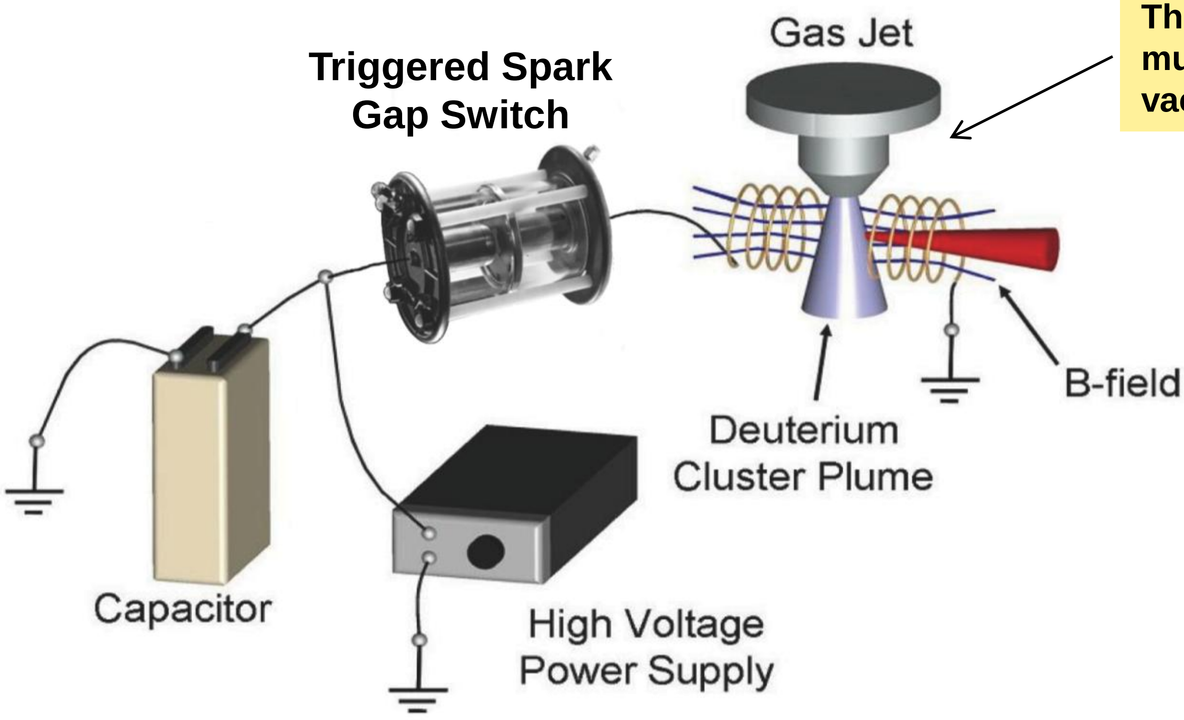
Materials normally used in the construction of high field magnets

Material	Yield Strength MPa	Ultimate Strength MPa
Plain carbon steel AISI-SAE 1020		450
Stainless steel type 304	240 - 300	550 - 650
High-strength alloy steel, ASTM A514	690	760
Copper 99.9%, annealed	70	220
Copper 99.9%, hard	300	340
Yellow brass	200	550
Zylon fiber		4500
Glass fiber		3400
Carbon fiber		5650

With fields above about 35 T (0.35 MG) magnetic pressure is high enough to destroy most materials. At 200 T (2 MG) nothing will survive.

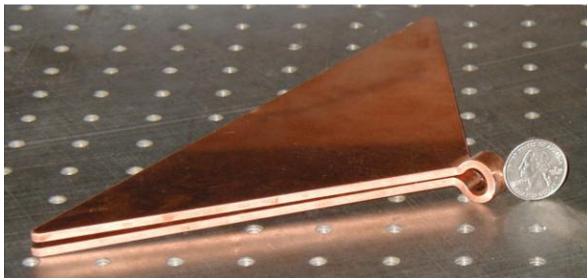
The approach is to discharge a bank of parallel capacitors through a small-diameter coil in vacuum

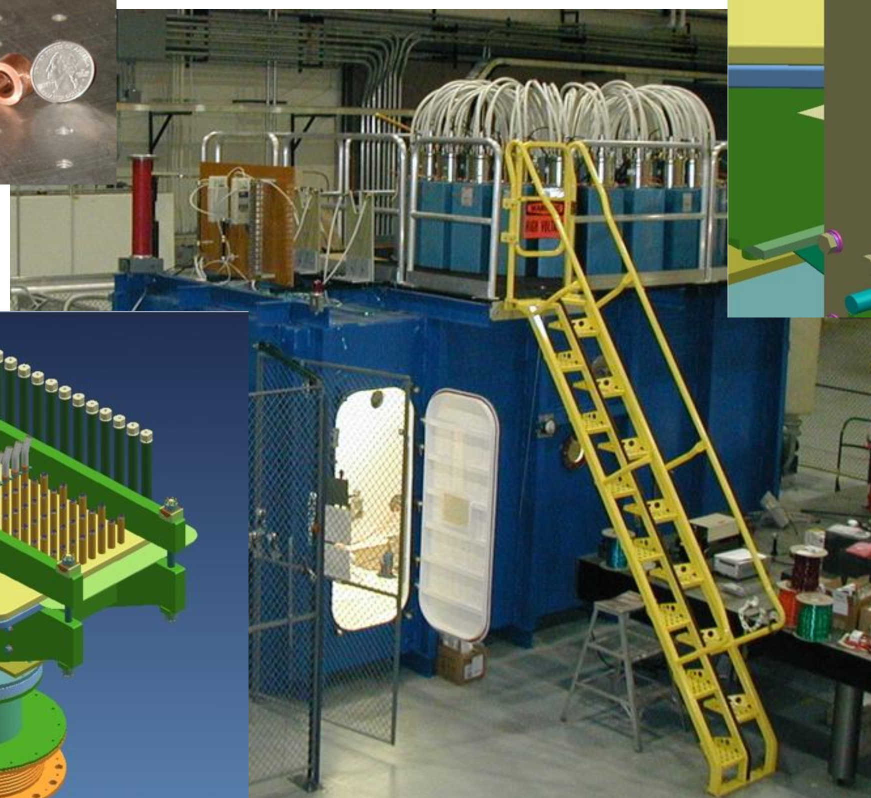
This experiment must be done in vacuum

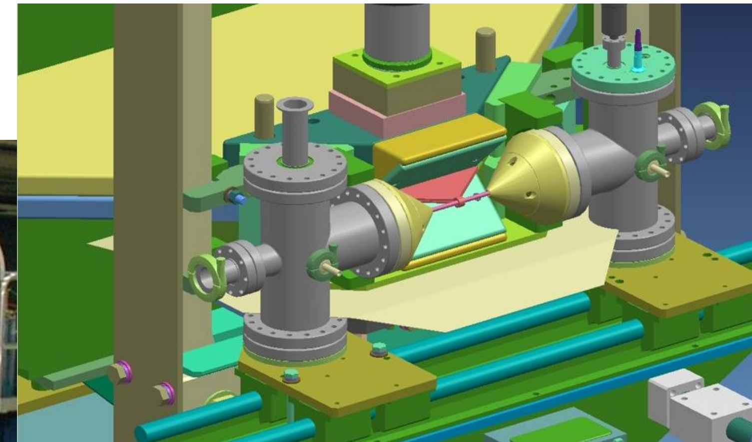


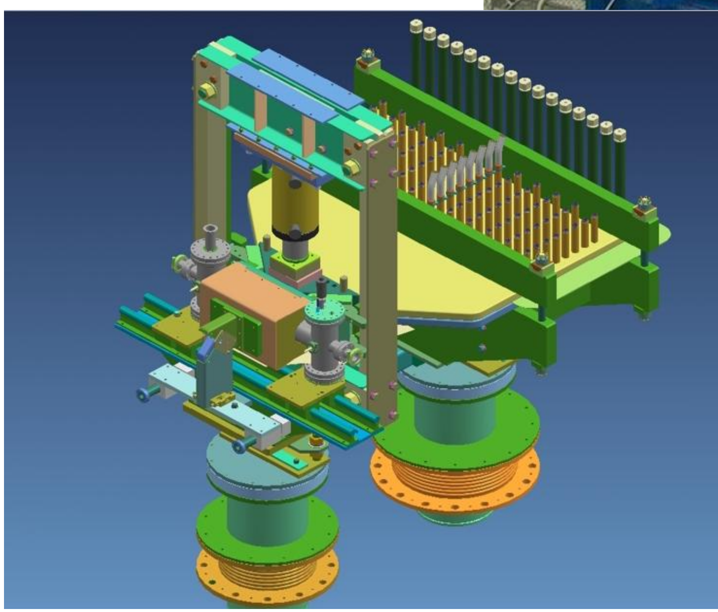
Sandia: Leverages pulsed power expertise
UT: Leverages expertise in cluster production and high field physics

Our driver design copies the Single-Turn Facility of the National High Magnetic Field Laboratory at LANL*





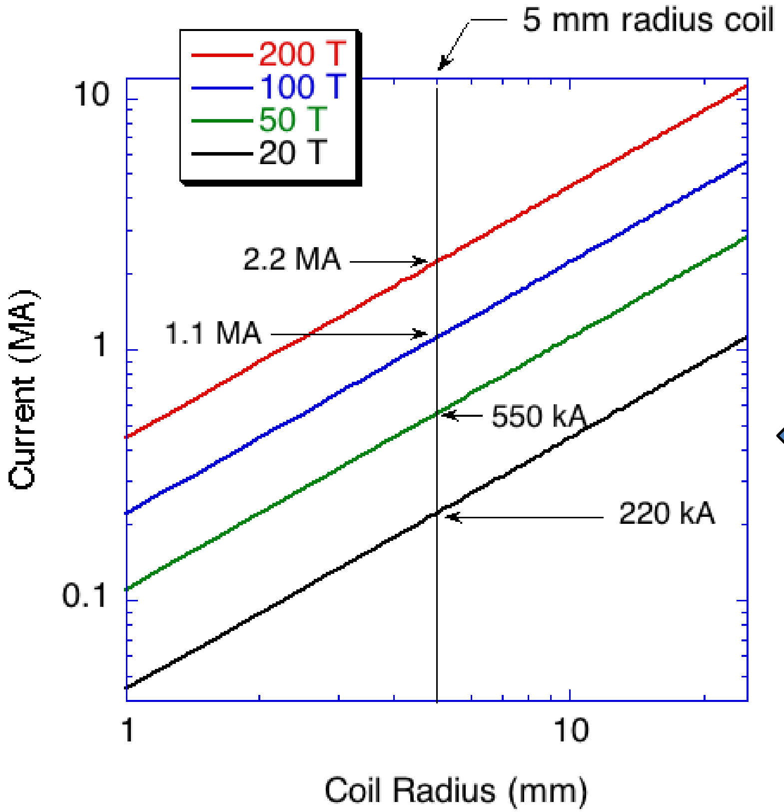




- Uses 24 6 µF / 60 kV caps
- One switch per cap
- Four cables per switch
- Bi-plate line to coil
- Extraordinary clamping
- Capable of 300 T
- System L ≈ 30 nH
- Coil in air

*Photos courtesy of Chuck Mielke

The coil radius determines the current needed to produce the desired field

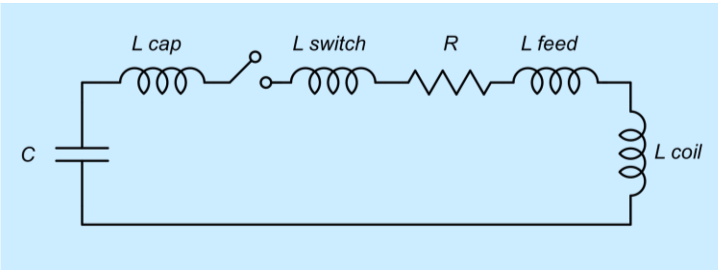


$$B_z(z<a) \cong \frac{4}{5^{3/2}}\frac{\mu_o I_d}{a}\left[1+\ldots+O(z/a)^4\right] \cong 0.358\mu_o\frac{I_d}{a}$$

Current vs. coil radius for a Helmholtz coil pair, each one turn.

Thus, for a 5 cm radius Helmholtz pair we need 2.2 MA for 200 T

Machine parameters are based on the lowest inductance that can be achieved

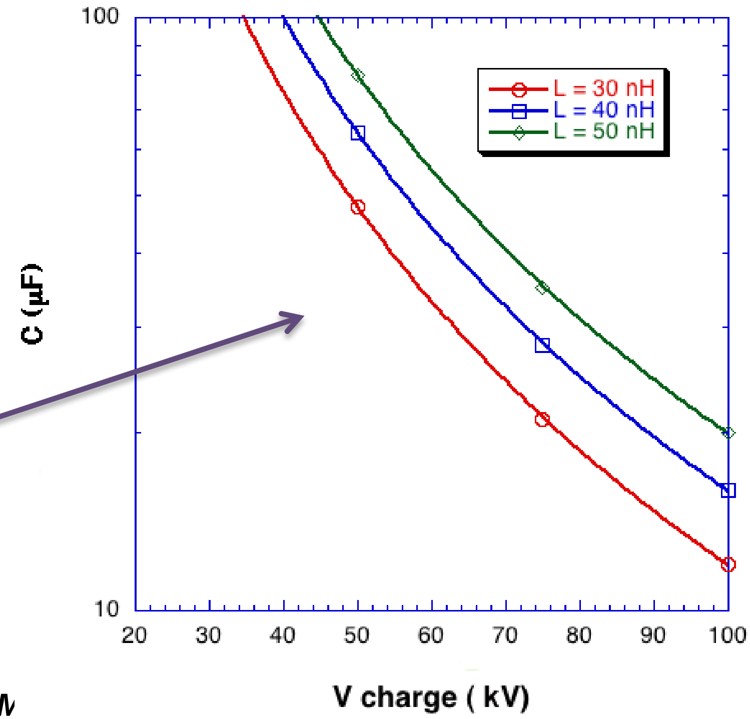


Radius a (mm)	I_{total} (MA) @ 100 T	I_{total} (MA) @ 200 T
3	0.67	1.33
5	1.11	2.22
10	2.22	4.44

Choose I = 2 MA

$$I_p \cong V_o\sqrt{\frac{C}{L}} \quad \text{and} \quad T_p \cong \frac{\pi}{2}\sqrt{LC}$$

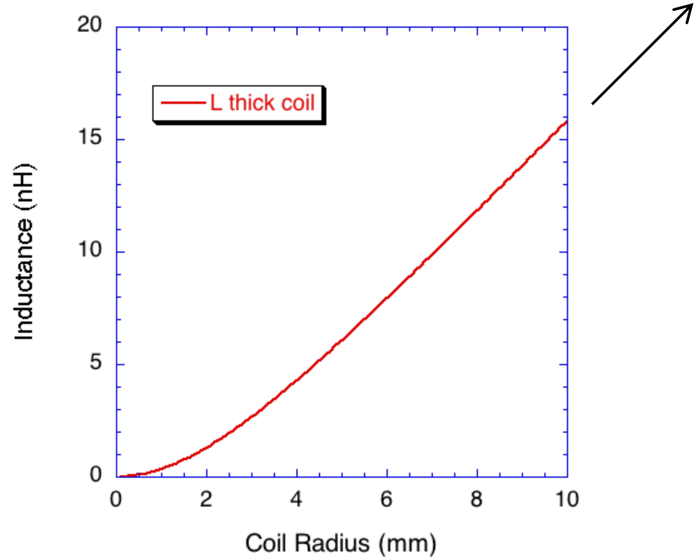
Required *C* for *I* = 2 MA



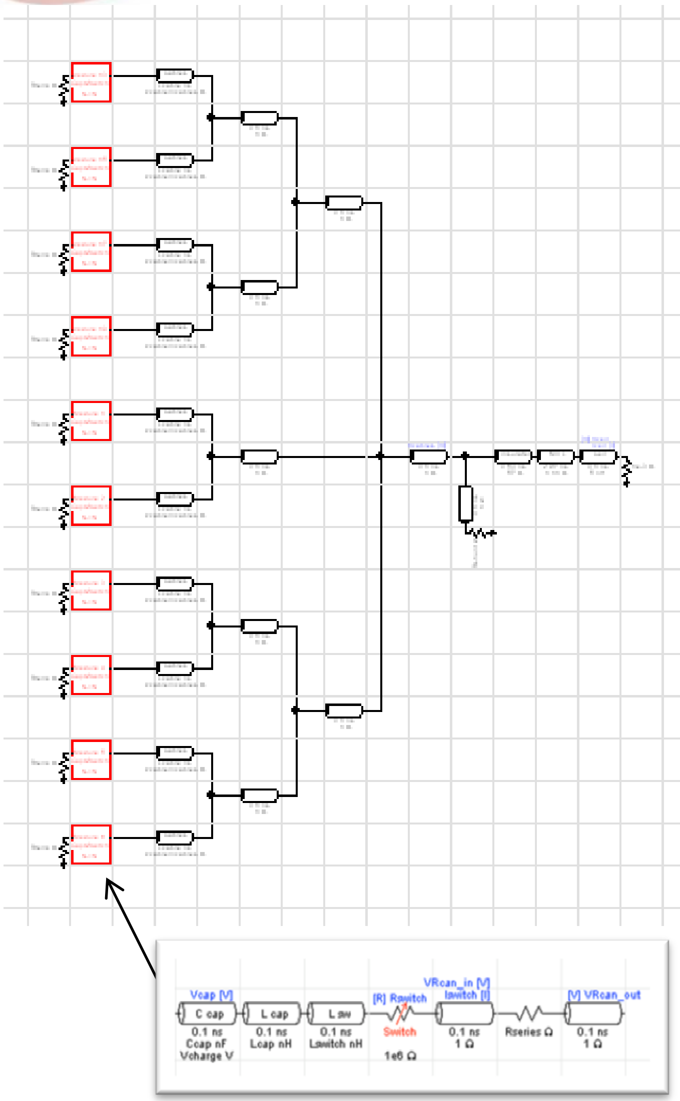
Choose C = 24 µF (= eight 3.1 µF / 100 kV caps)

System inductance estimates

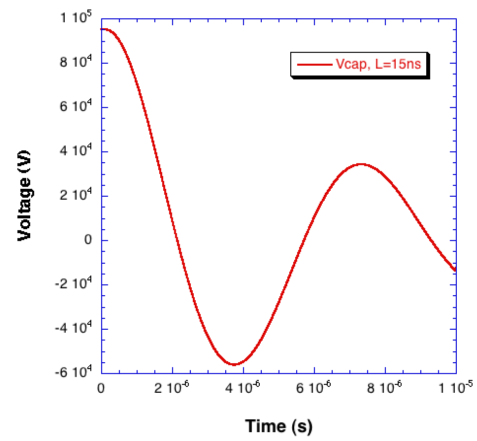
Number of capacitors and switches	*L capacitor* (40 nH per cap)	*L switch* (60 nH per switch)	*L cables* (six cables, 20 ns, 59 Ω)	*L insulator (2 cm gap)*	*L MITL (1 cm gap, 48" dia)*	*L coil* (10 mm dia)	*Total Inductance* with six cables per cap	*Total Inductance* with four cables per cap
8	5.0	7.5	24.6	0.3	3.2	5.0	45.6	57.9
10	4.0	6.0	19.7	0.3	3.2	5.0	38.2	48.1
12	3.3	5.0	16.4	0.3	3.2	5.0	33.2	41.4



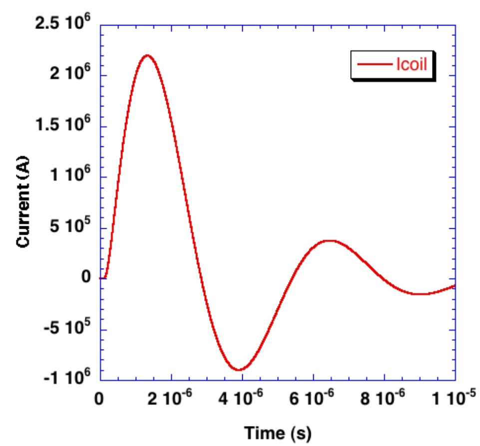
Circuit simulations show that we can achieve 2.2 MA with minimal capacitor voltage reversal using a ten-capacitor configuration with both series and shunt resistors



Voltage at the capacitor



Current at the coil



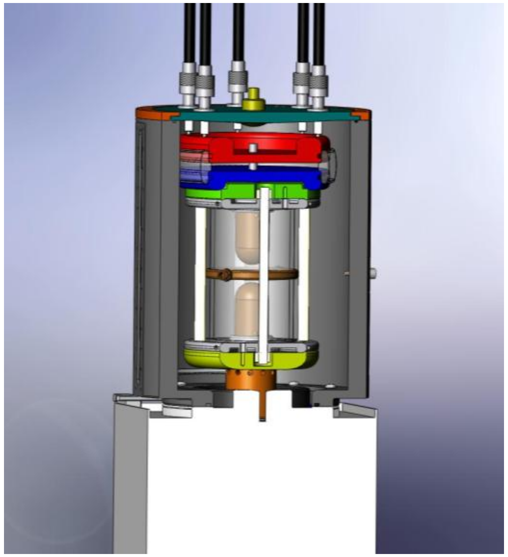
- Ten capacitors, 3.1 µF each
- Charge voltage 95 kV
- Ten switches, 60 nH each
- Six cables per switch, each 15 ns long, 59 Ω
- System L ≈ 38 nH
- Series resistance 0.10 Ω
- Shunt resistance 0.50 Ω
- Peak coil current 2.2 MA
- Peak cap ring-over 55 kV
- Peak switch current 220 kA
- Peak cable voltage 58 kV
- Peak voltage at insulator 23 kV

A key component is the switch. Two switches are being tested

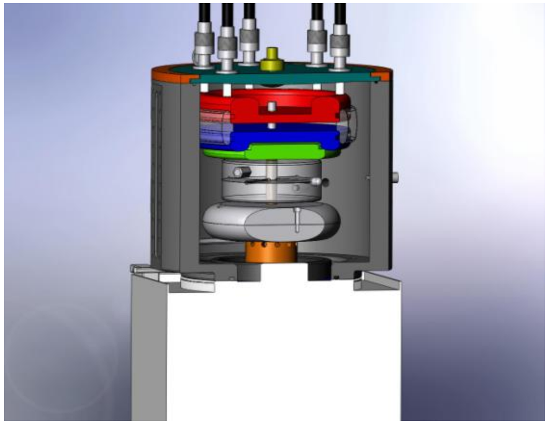
The switch must be able to hold off up to 100 kV, and conduct a peak current of 250 kA (0.5 C).

T-508
150 kA,
200 kV

PI T-508 switch
(Z Marx generator switch)



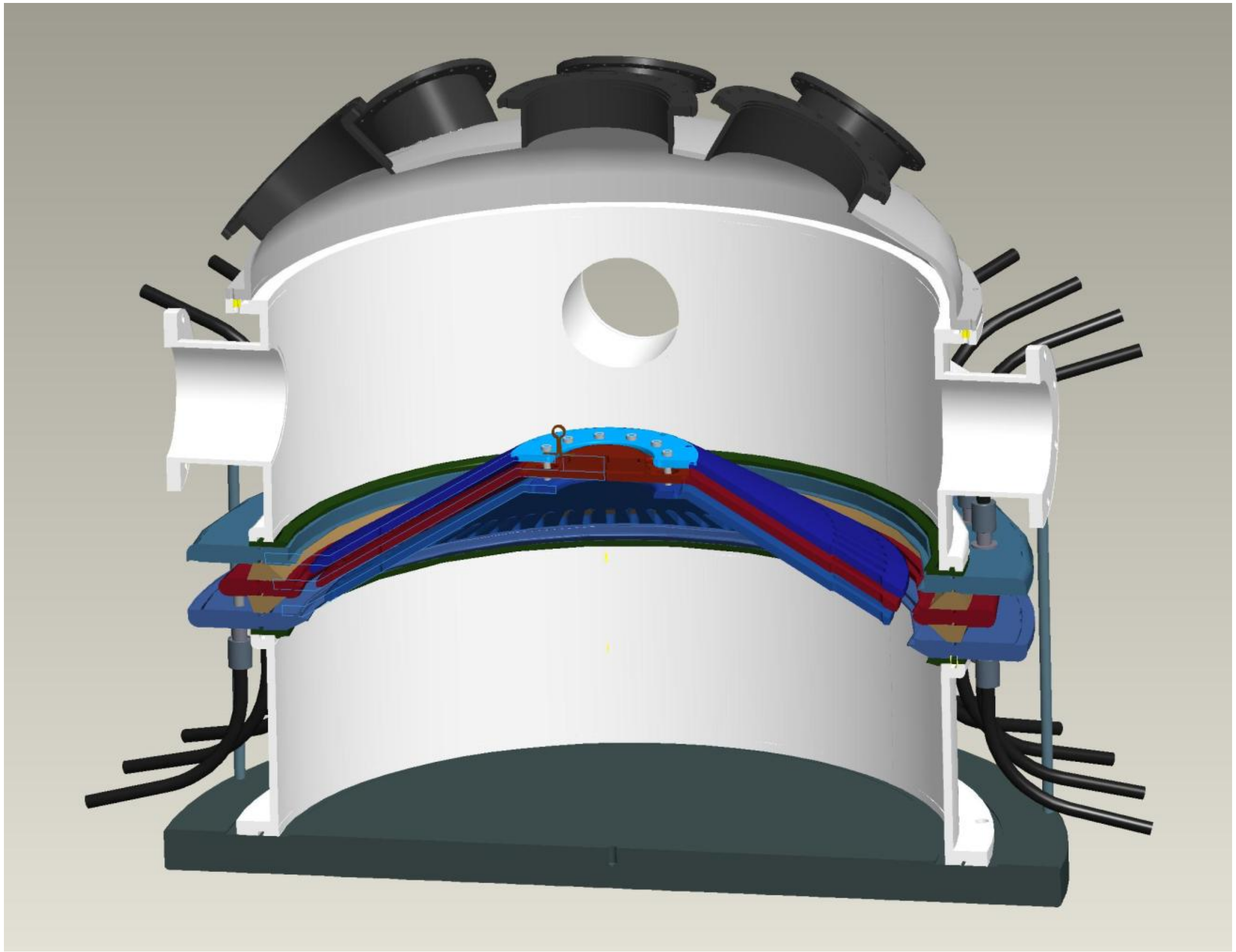
L3 Communications 40364
(Marx trigger generator switch)



L3 40364
100 kA,
100 kV

We think that both of these switches will handle the 250 kA peak current for several thousand shots without refurbishing.

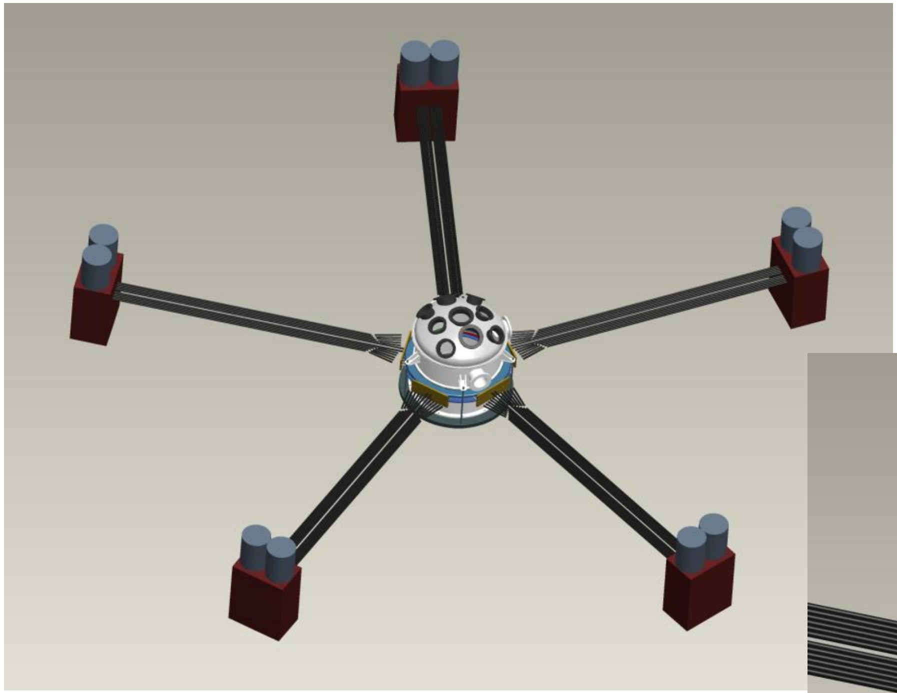
A sensible approach for the feed-through is to use a Z-like insulator and conical vacuum transmission lines*



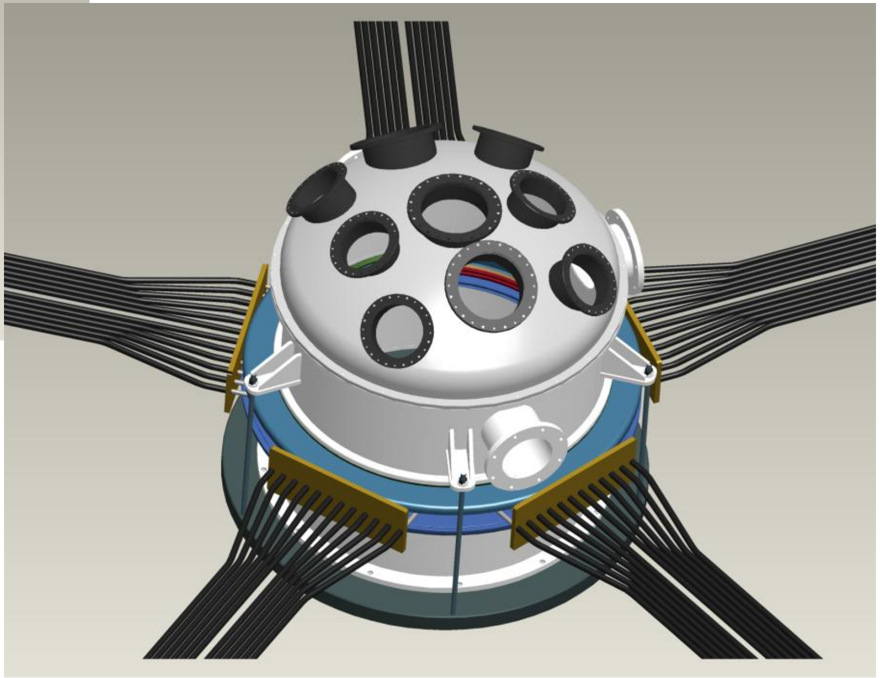
Coaxial cables connect to the outside of the vacuum insulator. The tank diameter (about 1 m) is determined by the number of cables.

*Proposed by Bill Stygar

With a 15 ns (10') cable length, we may need to distribute capacitors around the chamber

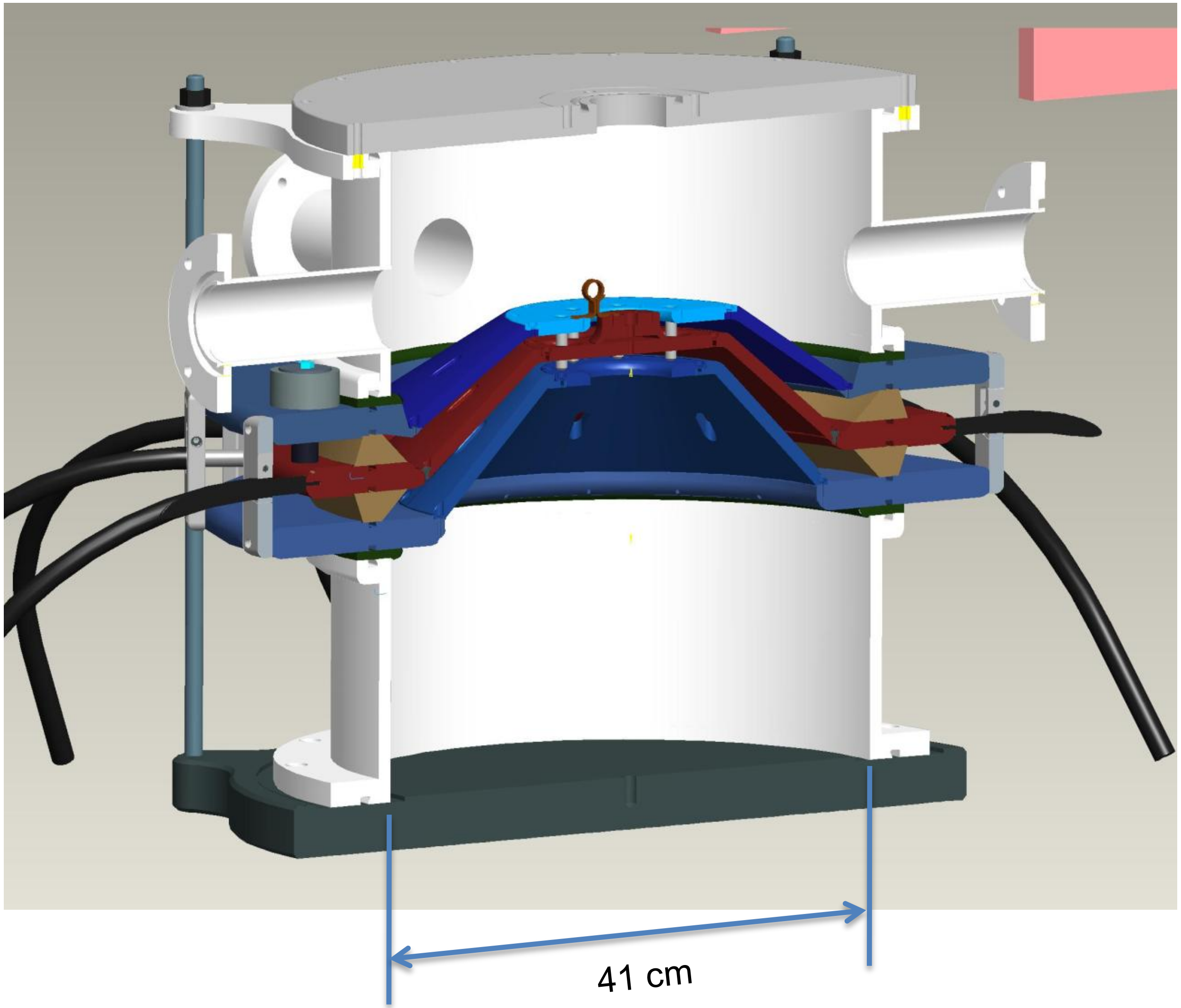


Modules can be placed where convenient

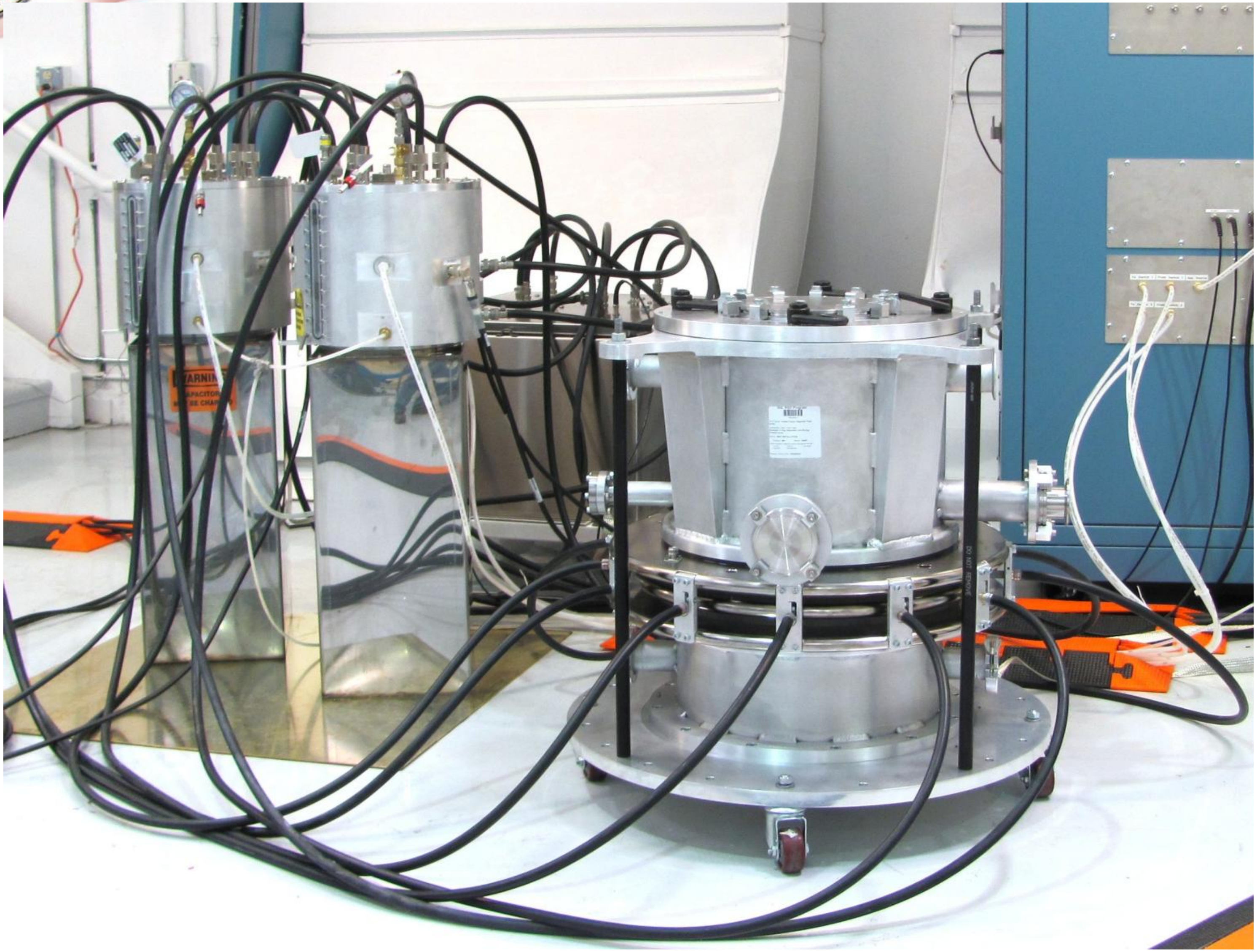


Alternatively, if longer cables can be used we could place all capacitors together

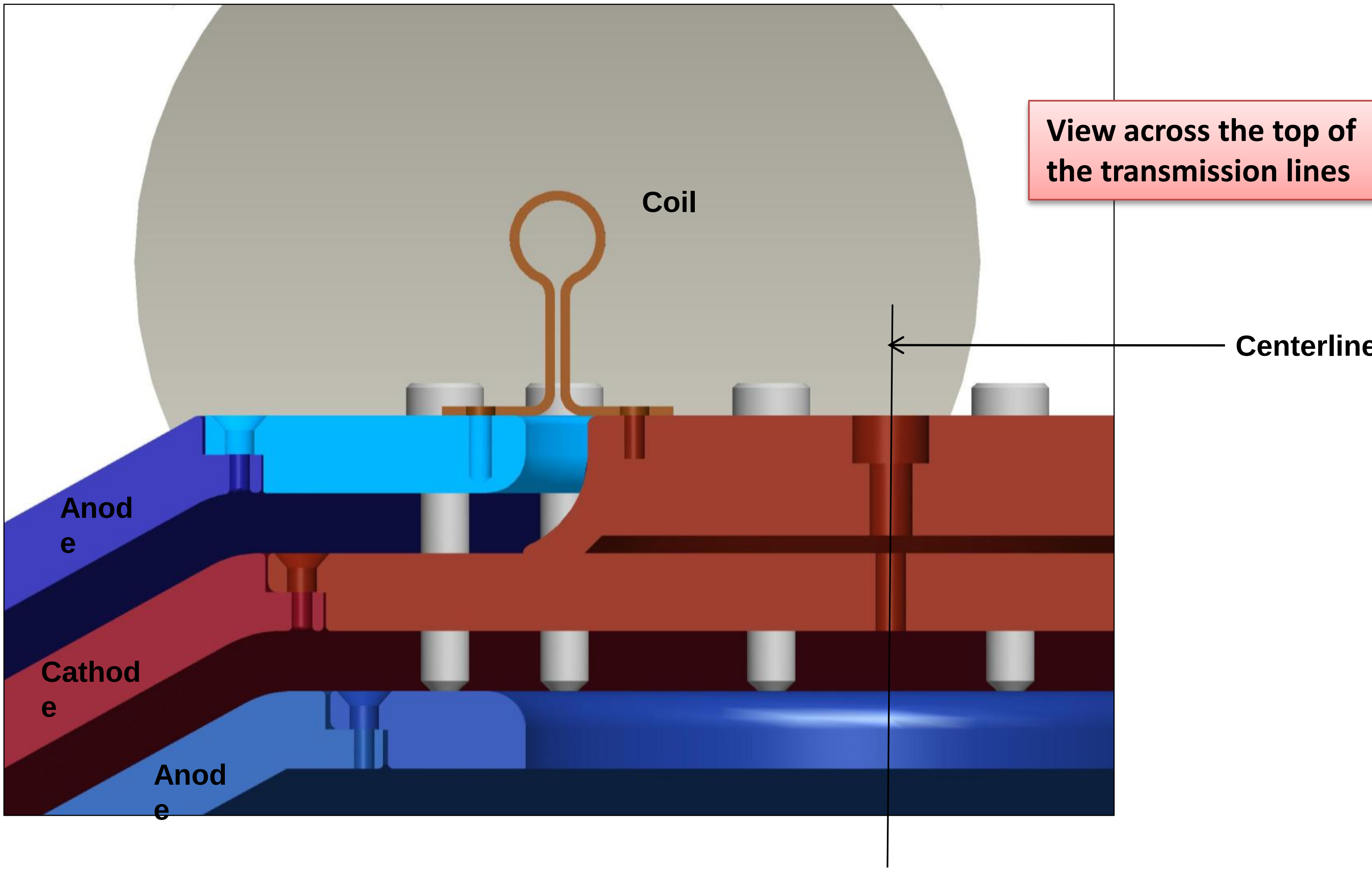
A small-diameter prototype version was built for a two capacitor and switch test at 50 T



Two-capacitor system

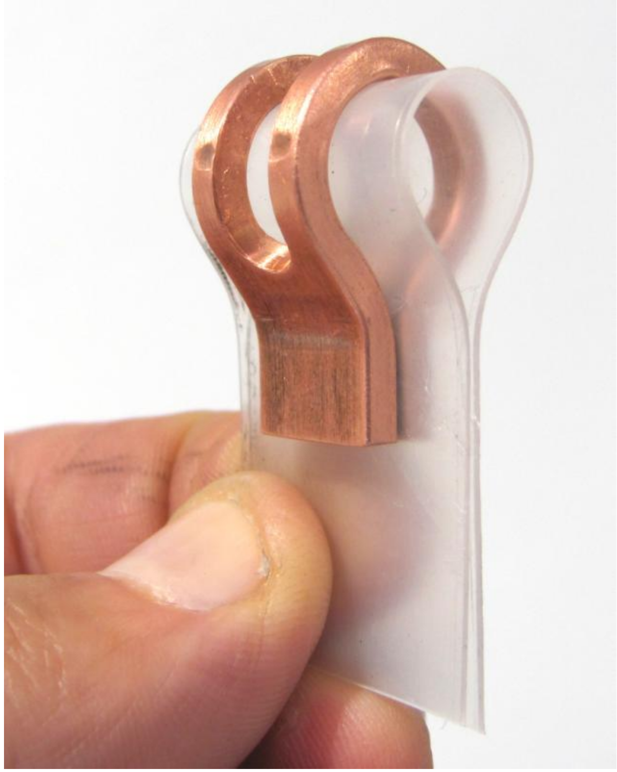


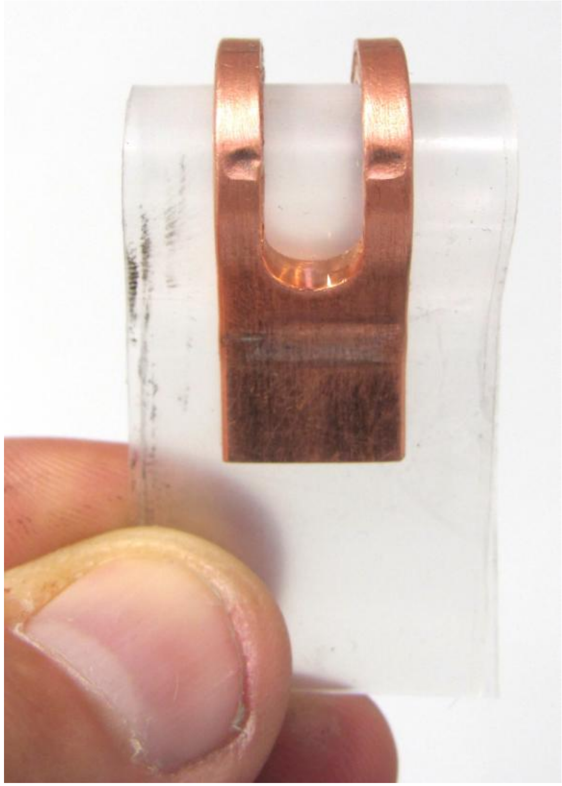
The magnetic coil is a 1 cm wide Cu strip formed into a 1 cm diameter loop and connected between anode and cathode



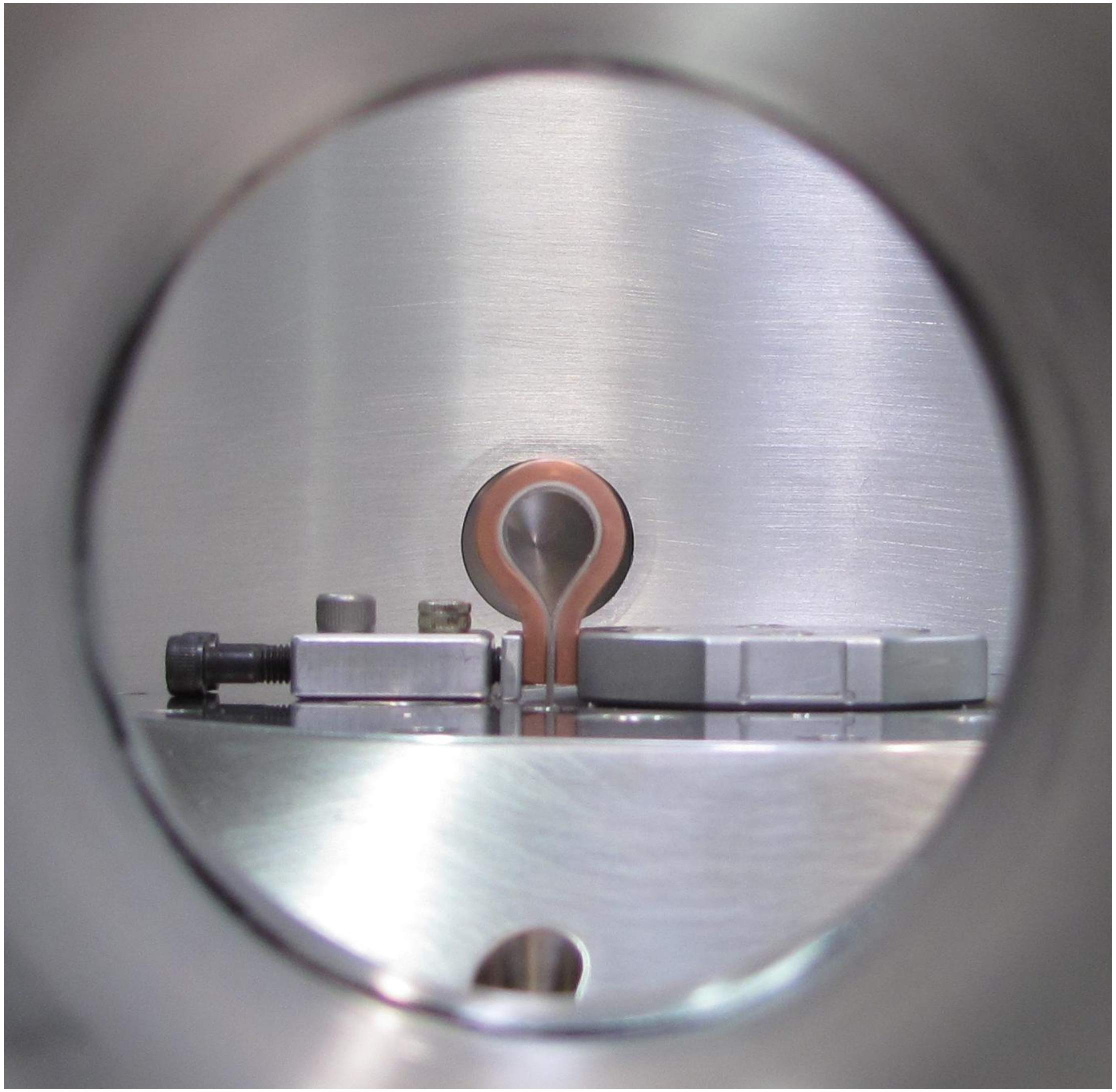
View across the top of the transmission lines

Initial coil designs

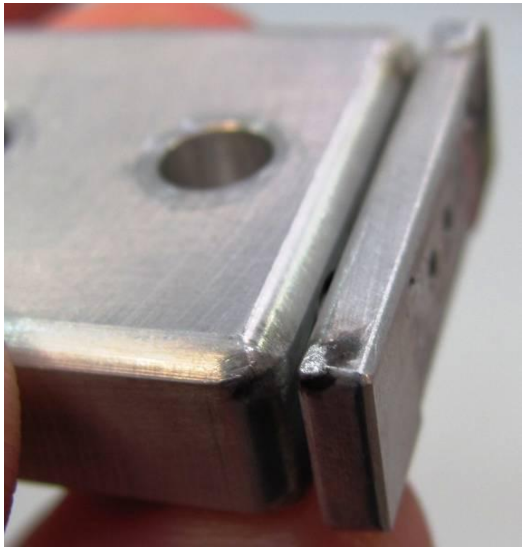




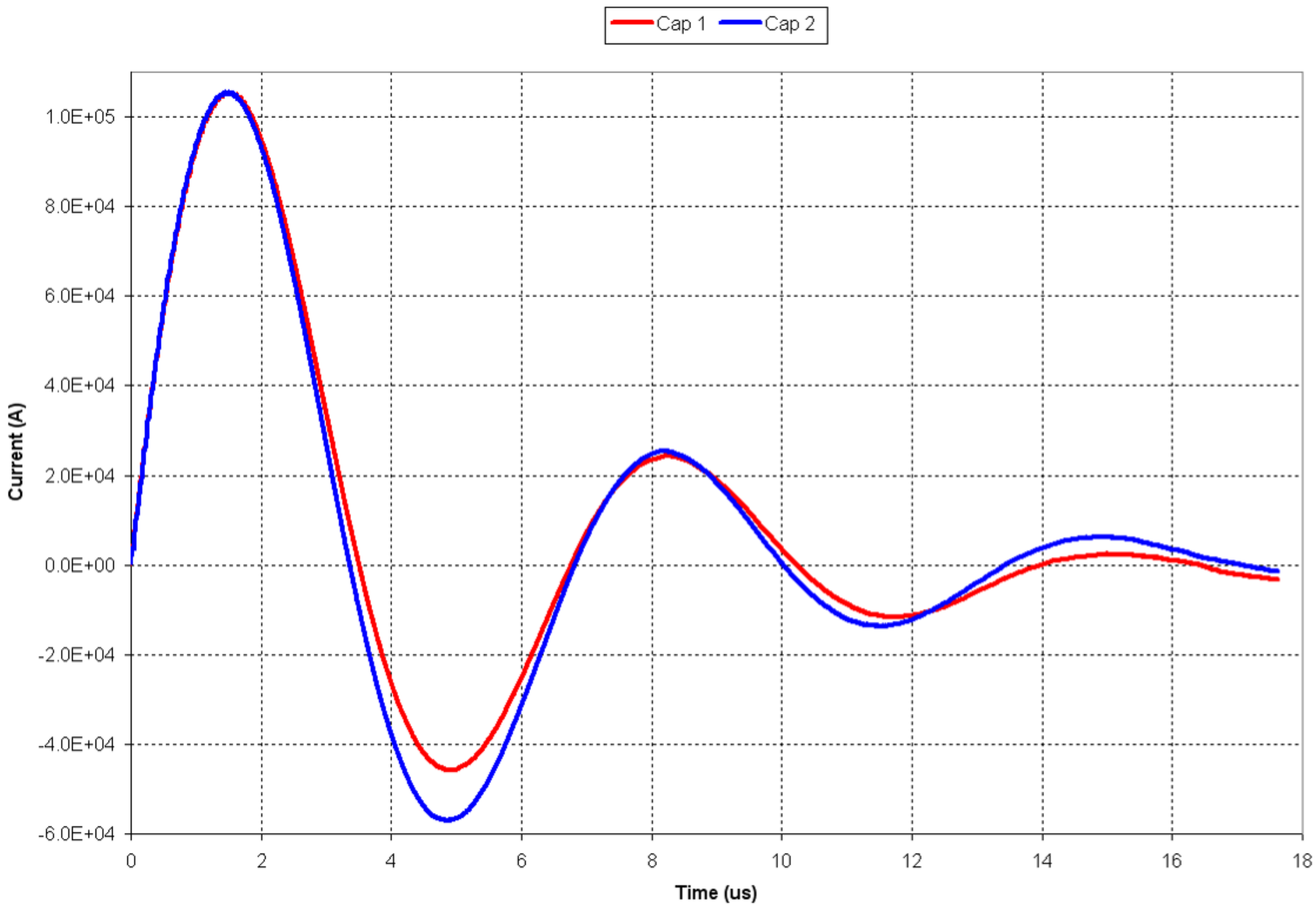
Coil mounted in vacuum chamber



Some electrode damage is seen at 200 kA. Much more is expected with higher currents

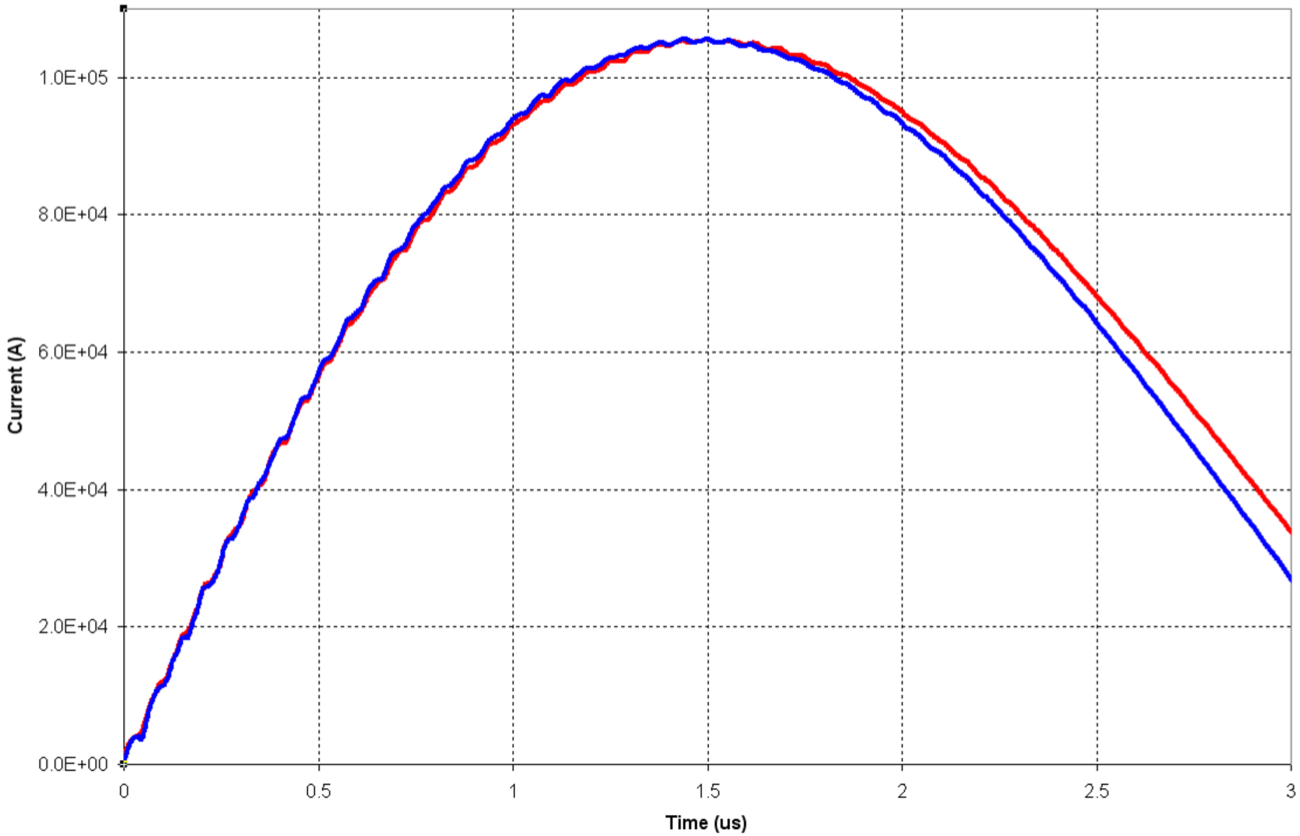


Capacitor current with a 50 kV charge voltage



Two capacitors, charged to 50kV, were pulsed into the chamber with a coil installed. The B-dots in the capacitor cans were calibrated, with an estimated 210 kA conducted through the coil (105 kA per can). The about 50% reduction in subsequent peaks is consistent with a 0.150 ohm series resistance.

The two-cap results indicate that a ten-cap system will have an inductance of 30 nH



$$T_{peak} \cong \frac{\pi}{2}\sqrt{LC}$$

Peak current is reached at about 1.5 µs into the pulse, which is consistent with 300 nH and 3.1 µF per line

Schedule/Goals

Goal (1): Demonstrate capability to produce 100 T or greater magnetic fields

- Produce 50 T fields in air with the prototype unit – May 2010
- Deliver prototype unit to UT – July 2010
- Do magnetic coil and cluster nozzle tests in vacuum with the prototype unit – August 2010
- Complete construction and test in air of the 200 T system. Deliver to UT March 2011
- Do cluster injection and diagnosis in the 200 T system with coil but without laser – April 2011
- Perform initial low-power laser test with clusters and magnetic field – May 2011

Goal (2): Measure the plasma conditions and neutron yield without magnetic fields

- UT develops the gas jet operation and gas flow through the magnetized mirror coils – June 2011
- Construct the optical time resolved interferometric and Schlieren probing – done January 2010
- Characterize the fusion plasma and neutron yield generated by the Texas Petawatt – July 2011

Goal (3): Demonstrate increased neutron yield with magnetic fields

- Synchronize the cluster plasma formation with the magnetic field pulse – December 2010
- Measure the fusion neutron yield and cross-field transport of the magnetized plasma – June 2011

How results may be used

- Enhanced cluster fusion with magnetic fields offers the opportunity to produce 10^8 to10^{10} neutrons per shot with a petawatt laser source
  - Study scaling with magnetic field and confinement
  - Diagnostics calibration
  - Fusion plasma research
- The portable driver provides capability for doing laser/plasma experiments with strong magnetic fields without use of a large accelerator
  - Plasma formation with intense magnetic fields
  - Support flux compression schemes
  - Driver for laser beam components
- Provides a means to collaborate with the Univ. of Texas in common areas of interest

Summary

- 50 T prototype system complete
  - 2 cap system at 50 kV, 200 kA
  - Vacuum chamber with feed through and coil
  - LABVIEW control system
- Circuit code design of 200 T system done
- 50 T system delivered to UT by early July 2010
- UT progress with coils and cluster gas gun
  - Initial tests of coil indicate possible shorting
  - Optical diagnostics developed