MagNIF Conceptual Design and Coil Testing

Meeting on Magnetic Fields in Laser Plasmas

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Outline

- MagNIF Lab Pulser
  - Requirements, main components, system diagram and basic electrical schematic
- Pulser Components
  - Energy storage, switch, transmission line and load
- Experimental Results
  - Numerical simulations, PSPICE, magnetic probes, high-speed imaging, two-color pyrometer and debris catcher
- Proposed Design
  - Conceptual CAD, Controls
- Pulse Power Future Plan

Gas pipe disassembly imaged with 10 MHz video camera

Pulser Specific Requirements

- **Electrical**
  - Max voltage 40 kV, short circuit current of 50 kA, pulse widths ~ μs
  - Max inductance ~ 750 nH
- **Vacuum Integrity**
  - Must pass NIF vacuum cleanliness standards
- **Volume**
  - Constrained to an airbox that must fit within TANDM payload adapter (or slightly modified)
- **Input power**
  - +28 VDC
- **Radiation resistance**
  - Needs to withstand NIF harsh radiation environment

MagNIF Lab Pulser[1]

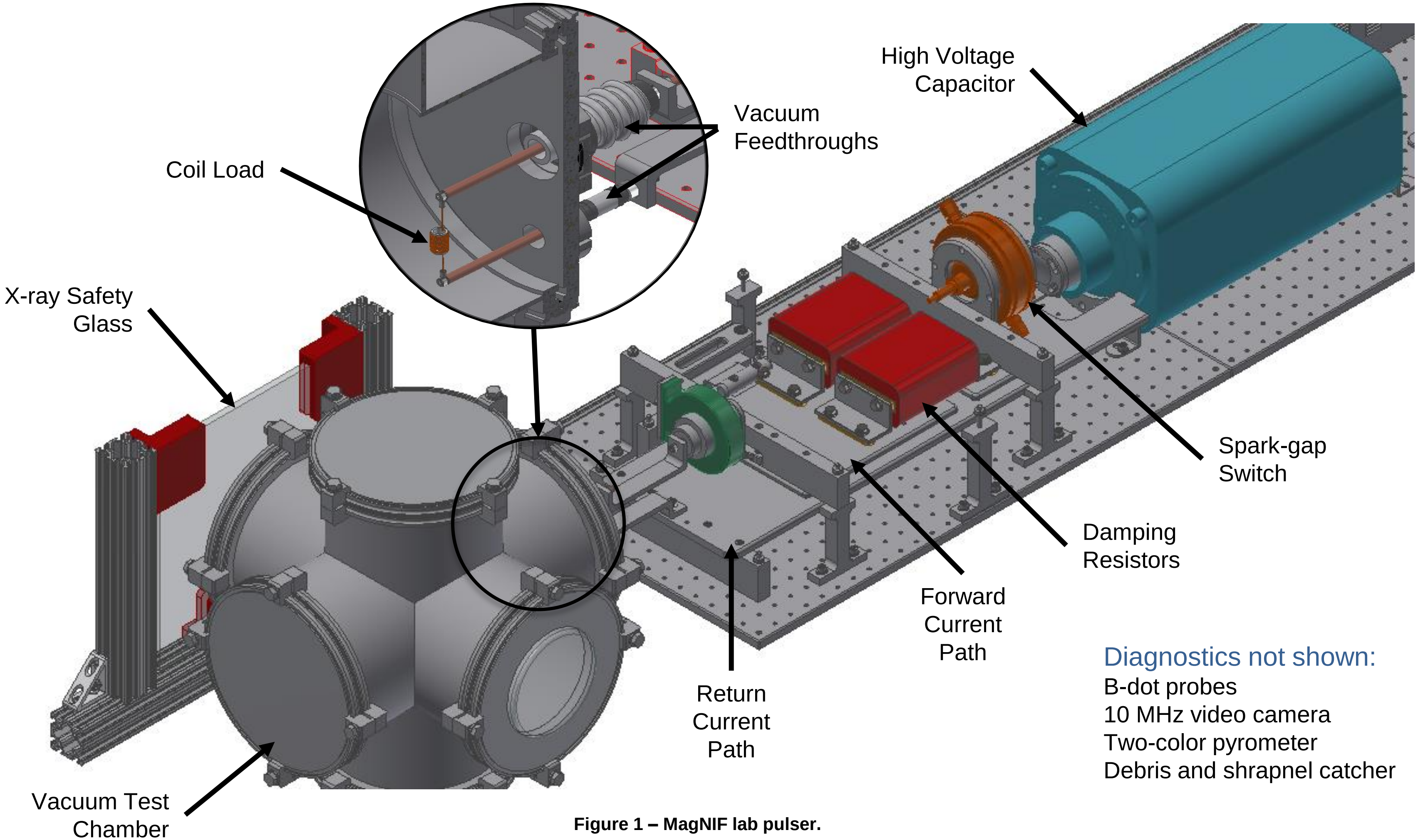


Figure 1 – MagNIF lab pulser.

Diagnostics not shown:
B-dot probes
10 MHz video camera
Two-color pyrometer
Debris and shrapnel catcher

[1]Original design by M. Rhodes, F. Allen and S. Hawkins

Offline lab pulser allows significant development and understanding of the dynamics of exploding solenoids.

Lab Pulser System Diagram

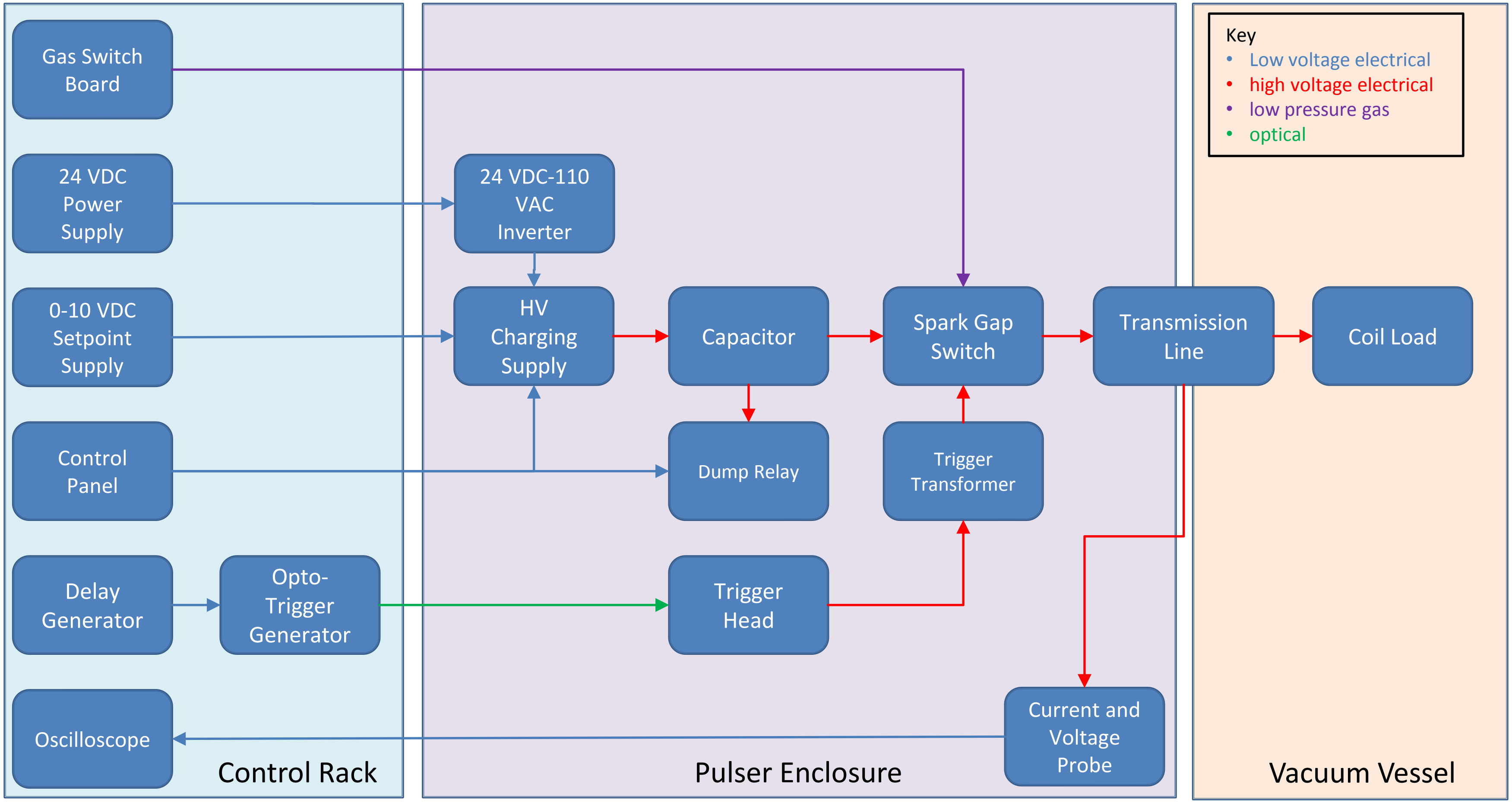


Figure 2 – System diagram of MagNIF lab pulser.

MagNIF lab pulser simplified electrical schematic

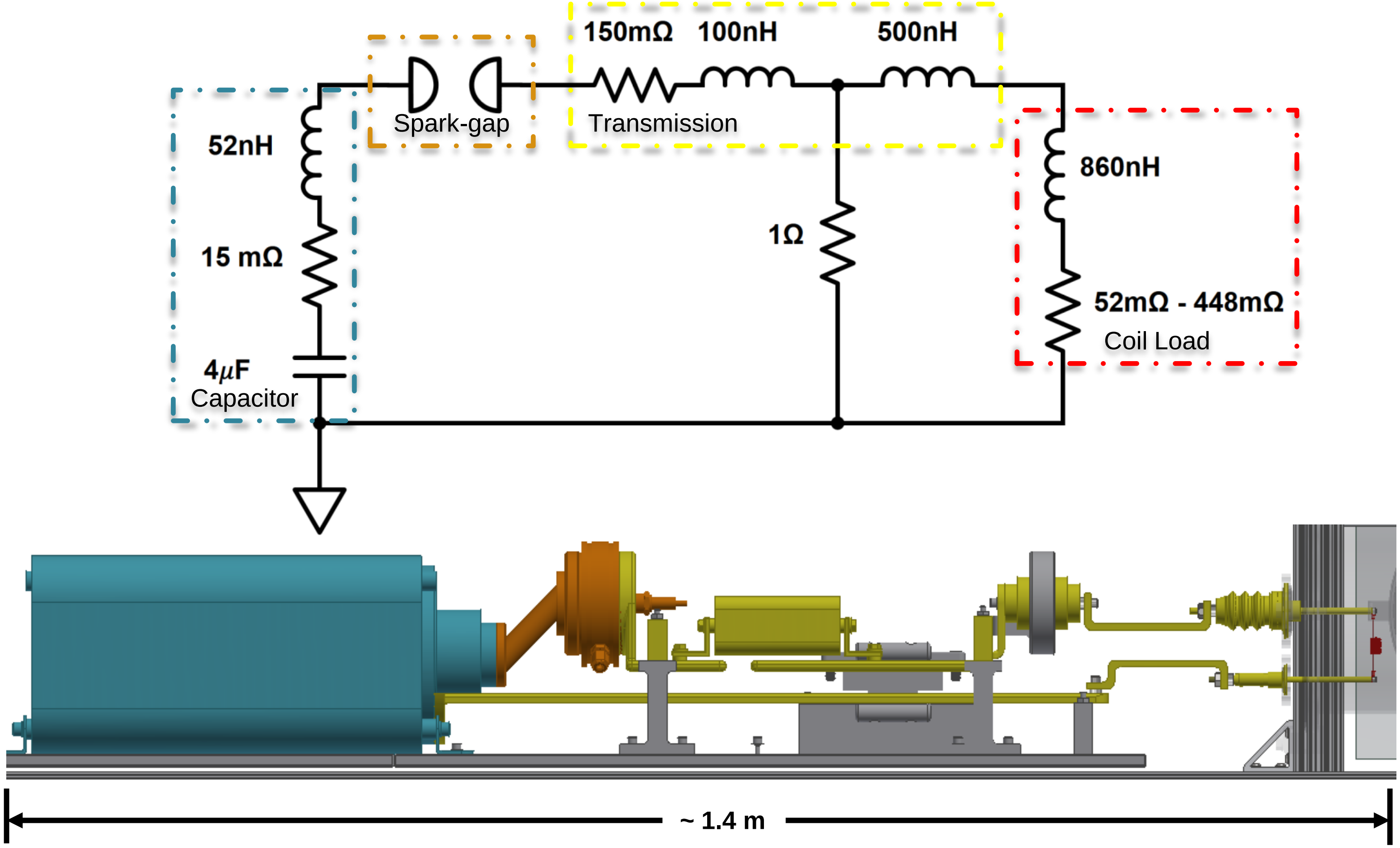


Figure 3 – Side view of MagNIF lab pulser with basic electrical schematic.

MagNIF lab pulser reduces to four main components: energy storage, switch, transmission line and load.

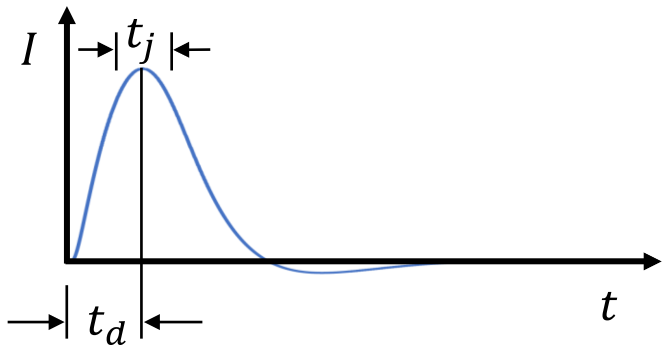
Energy Storage and Switch: MagNIF lab pulser uses a high voltage capacitor paired with a commercial spark gap for reliable and economical switching

- 4 μF self-healing metallized polypropylene oil filled capacitor
  - max voltage 40 kV
  - peak current 70 kA
  - max stored energy 3.2 kJ, stored charge 0.16 Coulomb
  - ESR < 15 mΩ, ESL 52 nH

- Trigatron spark gap
  - working voltage 20-50 kV (N_2)
  - peak pulsed current 100 kA
  - inductance < 35 nH
  - breakdown delay and jitter of < 0.5 μs and < 0.2 μs respectively ($V_g = 0.8V_{sb}$)
  - Max charge transfer 0.5 Coulomb

Pulser delay and jitter is dominated by spark-gap breakdown

- **Total delay t_d is measured from time to current peak and jitter t_j is estimated from spread in that measurement**



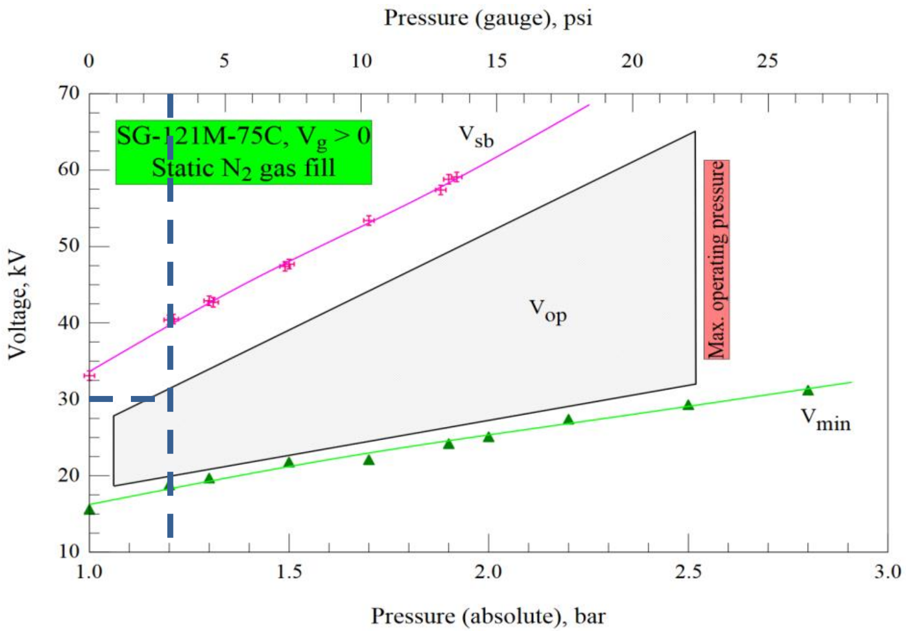


Figure 9 – Breakdown curves for SG-121 spark-gap.

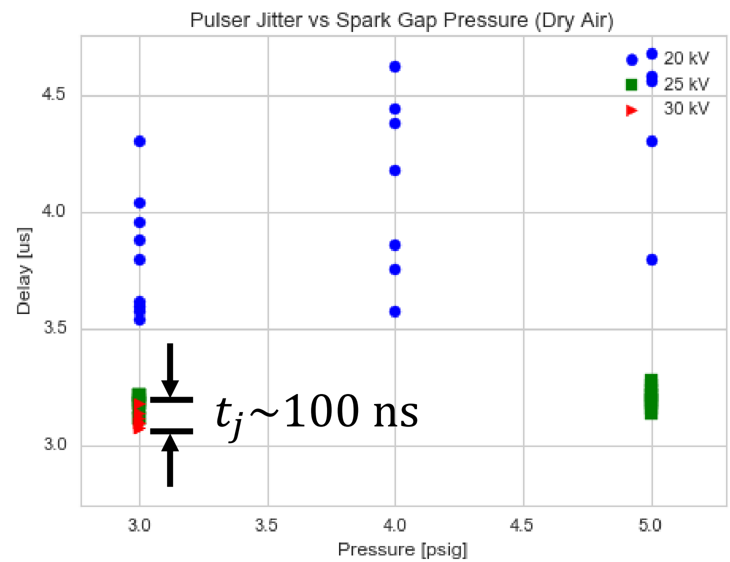


Figure 10 – Jitter is approximately +-50 ns for 30 kV, 3 psig (Nitrogen).

Note: operating at 6 psig (67% V_{sb}) t_j ~120 ns, however will drastically reduce chance of pre-fire.

Electrical triggering provides cost effective and reliable switching

- **Electrical trigger system block diagram**

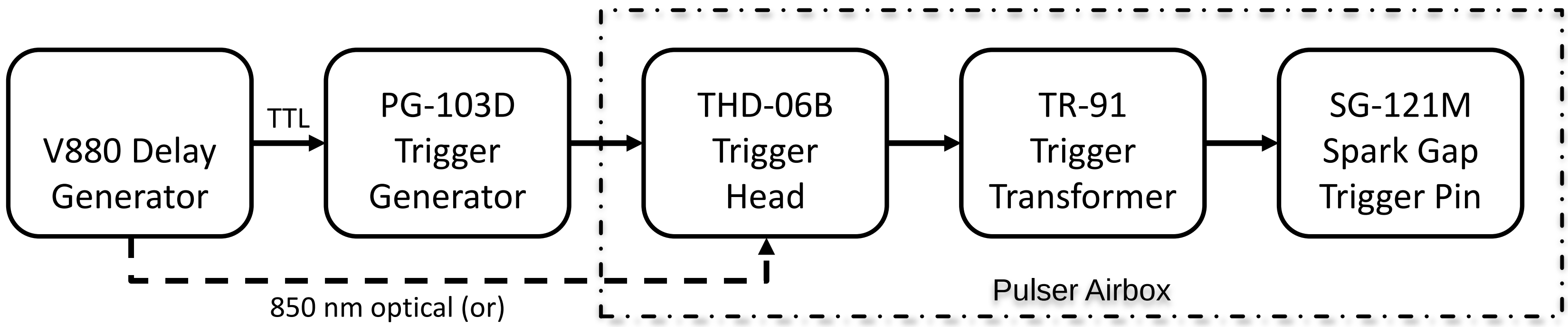


Figure 10 – Trigger system diagram.

- **Concerns**
  - **Neutron and X-ray radiation resistance of electronics**

- **Possible alternative**
  - **Laser triggered spark-gap**

Radiation Damage Component Testing

- **Largest concern is integrated electronics and discrete components at voltage such as capacitors, FETs and IGBTs.**
  - **Capacitors will most likely degrade over time.**
  - **IGBTs and FETs are susceptible to catastrophic failure from prompt dose.**

- **Plan 1: Test current hardware selection under normal operation in a similar radiation environment.**
  - **Turn off radiation susceptible components before the shot?**
  - **Relocate components within the airbox?**

- **Plan 2: Relocate high voltage power supply to rack. Laser triggered spark gap.**

Transmission line: Kapton strip-line provides very low inductance, high voltage standoff and vacuum compatibility.

- **Tested prototypes to 32 kA and 12 kV (drop over strip-line and load)**
- **Working on new prototype for 50 kA and 40 kV**
- **Passed NIF cleanliness testing**

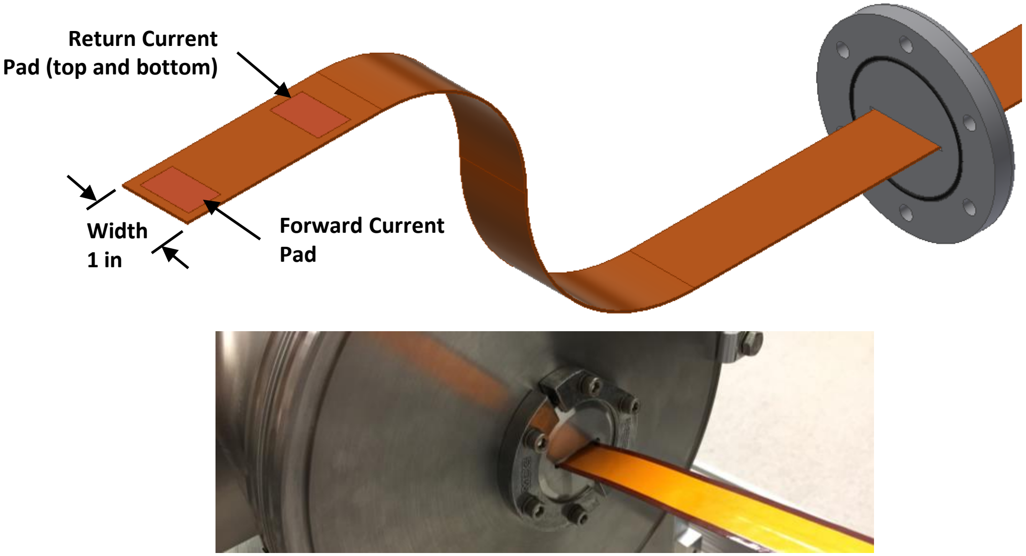


Figure 4 – CAD model and prototype strip-line potted in a vacuum flange.

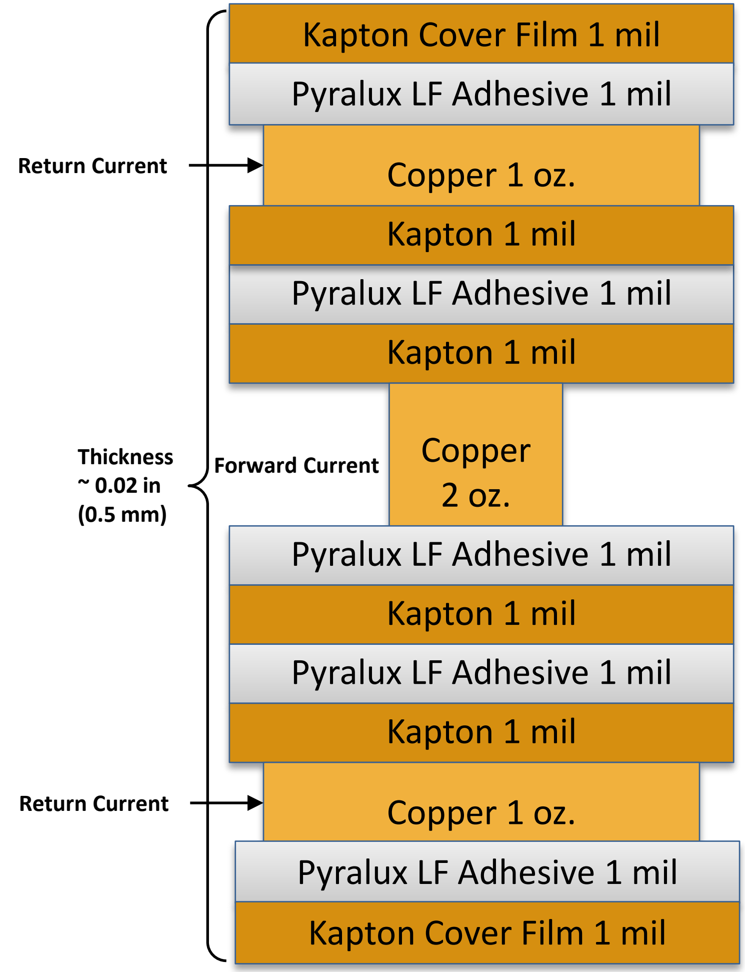


Figure 5 – Kapton strip-line layup.

Load: During testing, simple solenoids are wound on ABS and PEEK mandrels and terminated with ring lugs.

- Gas Pipe Coil
  - 14 turn
  - 1 mm pitch
  - 9 mm diameter
  - 26 AWG Kapton coated silver-plated solid-core copper wire
  - 52 mΩ (300 K) – 448 mΩ (1350 K)[1]
  - ~ 800-900 nH
- Warm Hohlraum Coil (less defined)
  - 5.5-6.5 turn
  - 0.7 mm pitch
  - 6 mm diameter
  - 24 AWG Kapton coated silver-plated solid-core copper wire
  - 14 mΩ (300 K) – 90 mΩ (1350 K)[1]
  - ~ 200 nH

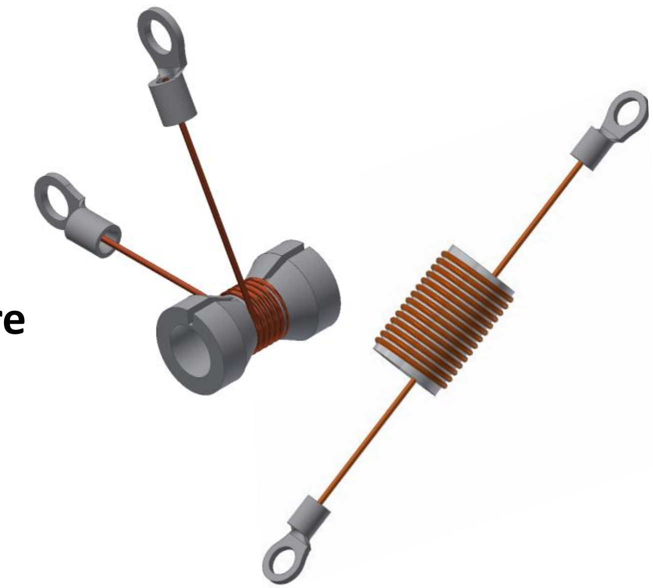


Figure 6 – CAD model of typical gas pipe and Hohlraum coils used for testing.

[1]Matula Ra, Journal of Physical and Chemical Reference Data 1979

PSPICE Model[1] and action dependent coil resistivity accurately predicts pulser performance

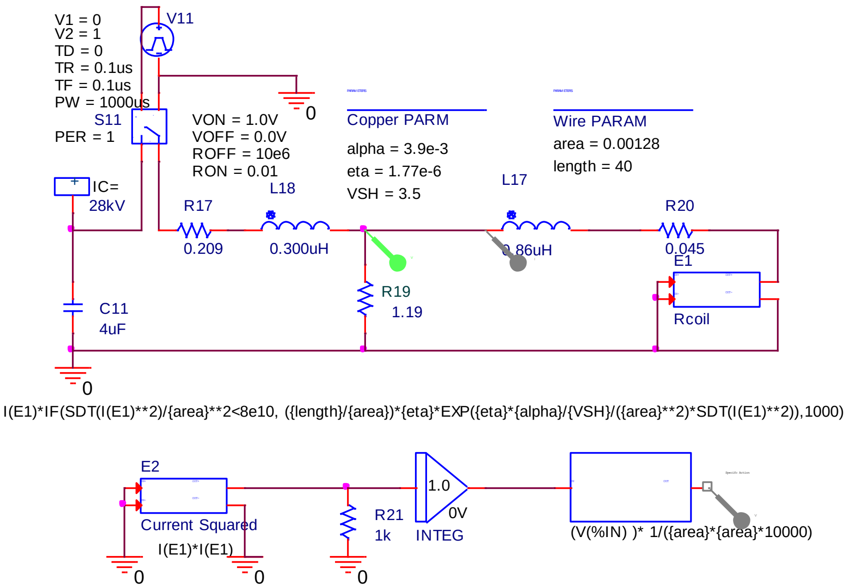


Figure 7 – PSPICE model of the MagNIF lab pulser.

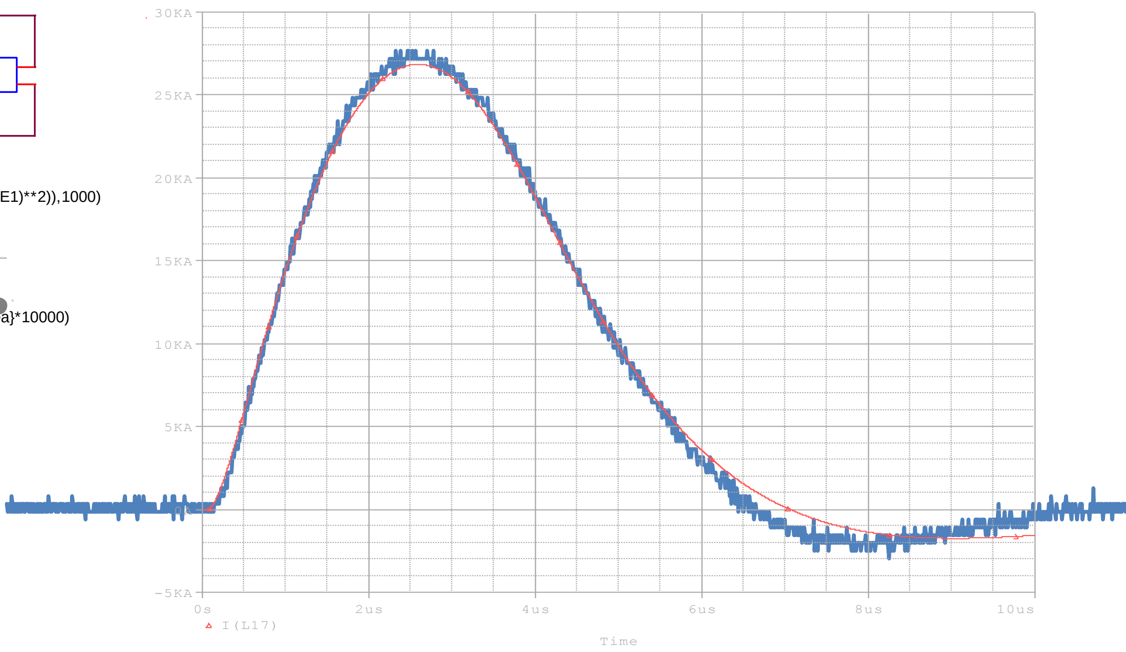


Figure 8 – Comparison of PSPICE model with experimental gas pipe 28 kV data.

[1]PSPICE simulation and plot courtesy of Glen James

Typical magnetic pick-up probe measurements for gas pipe and Hohlraum style coils

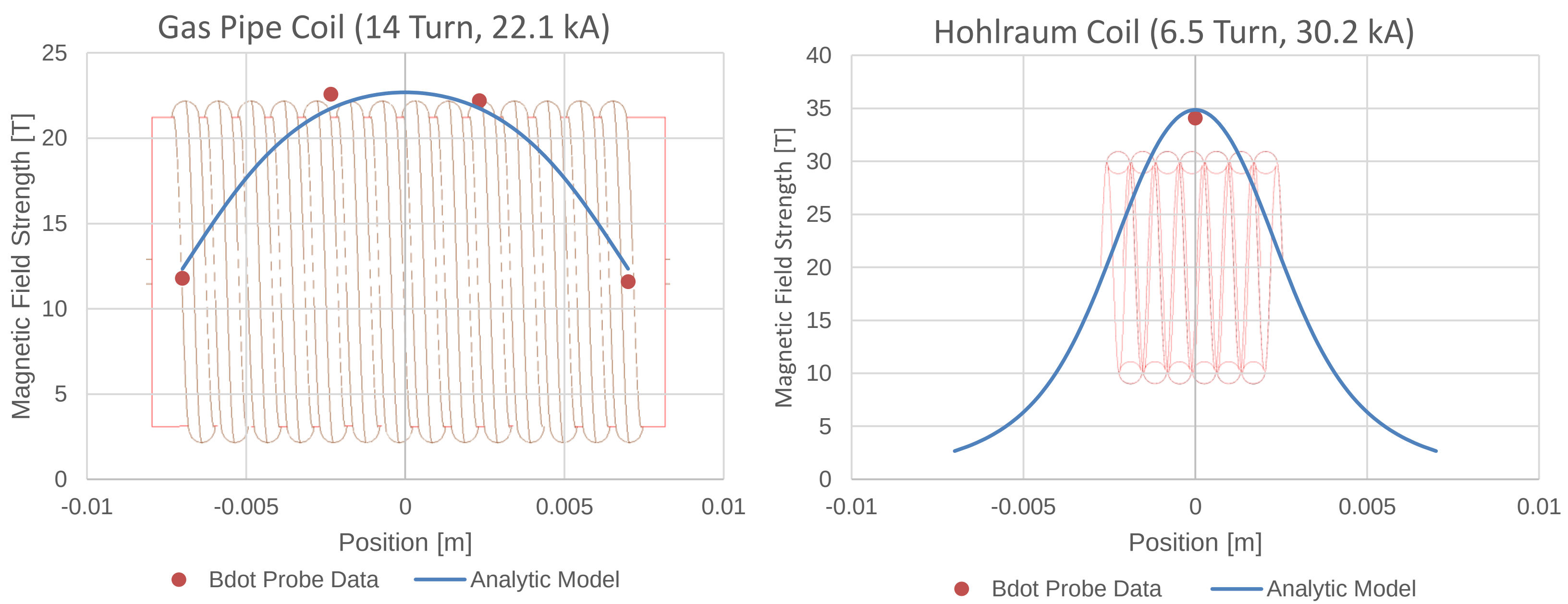


Figure 11 – Typical magnetic measurements of gas pipe and Hohlraum style coils.

$$B(t,z) = \frac{I(t)\mu_0 N}{2l}\left(\frac{z+\frac{l}{2}}{\sqrt{r^2+\left(z+\frac{l}{2}\right)^2}} - \frac{z-\frac{l}{2}}{\sqrt{r^2+\left(z-\frac{l}{2}\right)^2}}\right)$$

Numerical Studies[1] of 5.5 Turn Hohlraum Coil

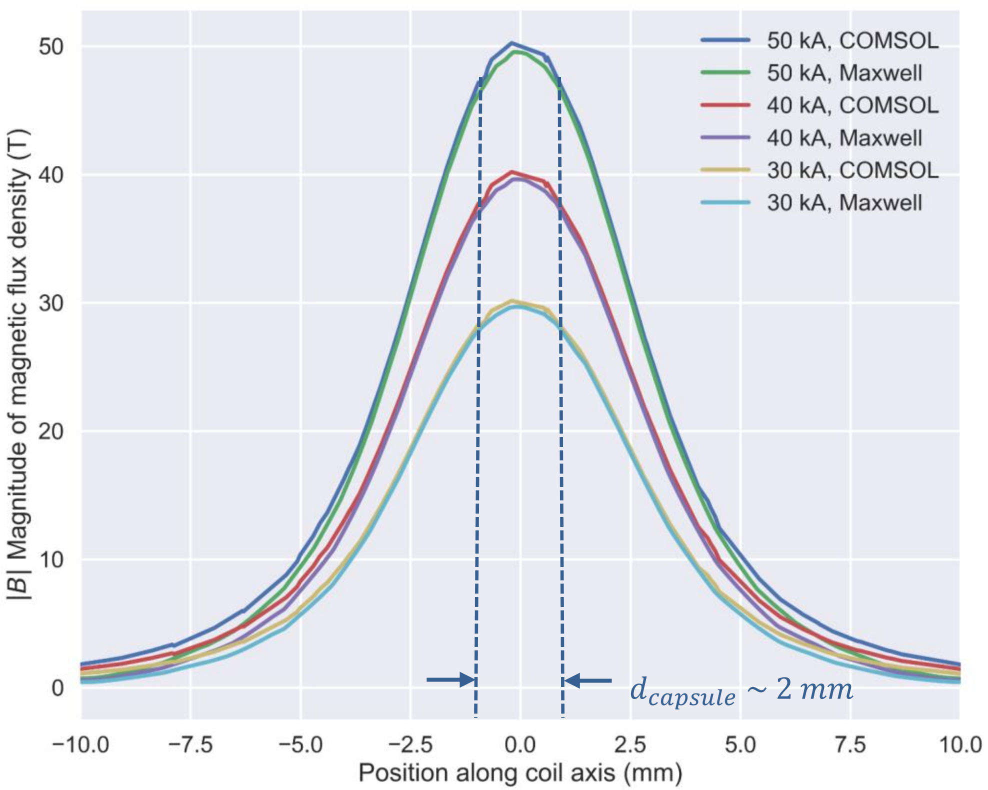


Figure 12 – On axis magnetic field strength of 5.5 turn Hohlraum coil with varying currents.

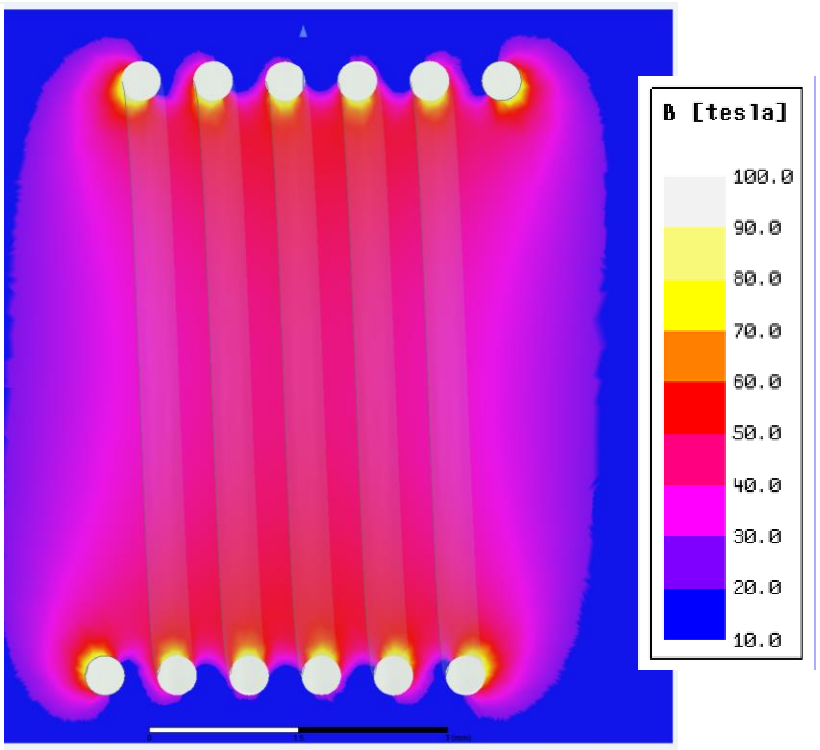


Figure 13 – Spatial profile of magnetic field for 5.5 turn Hohlraum coil at 40 kA.

[1]Simulation plots courtesy of Charles Brown

Electrostatic Simulations[1] of Pulser Hardware Allow for Optimization

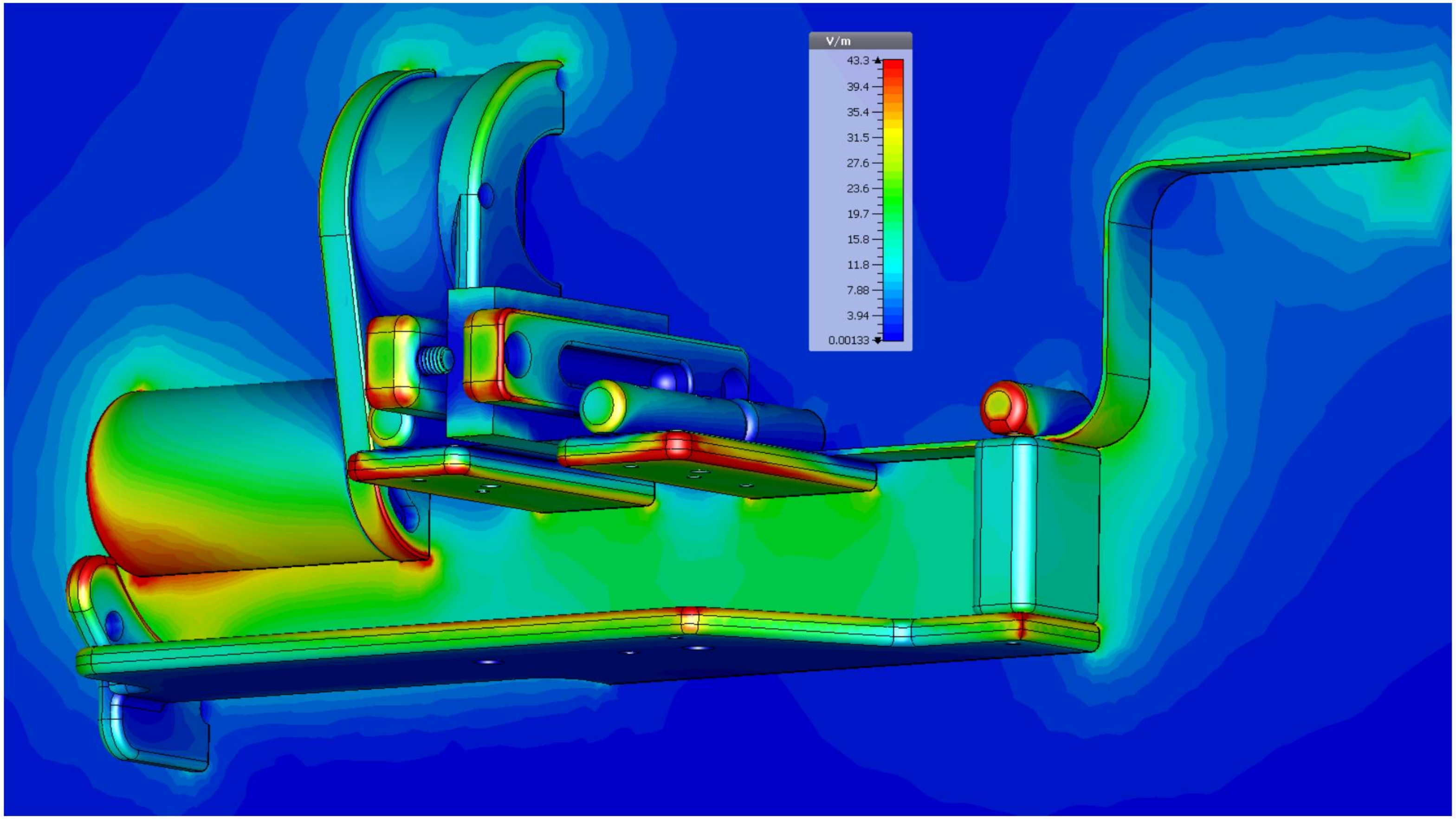


Figure 12 – Electrostatic field simulation of pulser hardware. Simulation voltage is 1 V, with a maximum electric field strength of 43.3 V/m, which corresponds to 1.7 MV/m when scaled to 40 kV. The dielectric strength of air at 1 atmosphere is 3 MV/m.

[1]Simulation plots courtesy of Charles Brown

Multi-channel magnetic probes have been developed using PCB inductor chips with spatial resolution of ~ 2 mm.

2.92 x 2.79 x 2.03 mm
(1.80 x 1.12 x 1.02 mm)

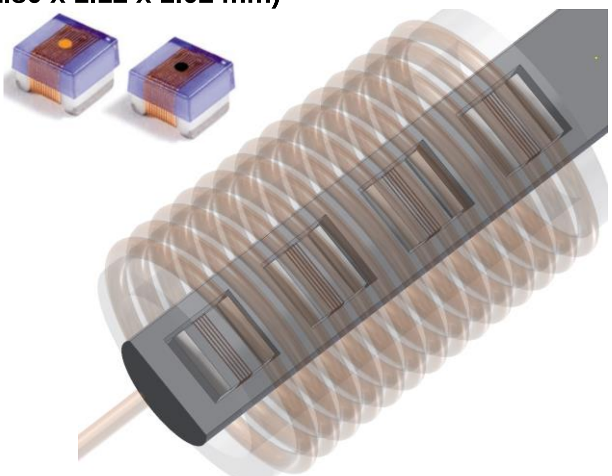


Figure 14 – CAD model of gas pipe coil and 4 channel B-dot probe.

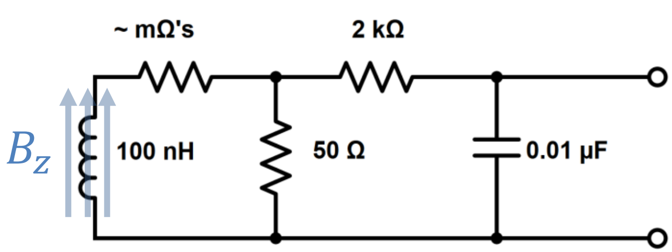


Figure 15 – simplified probe circuit with RC integrator.

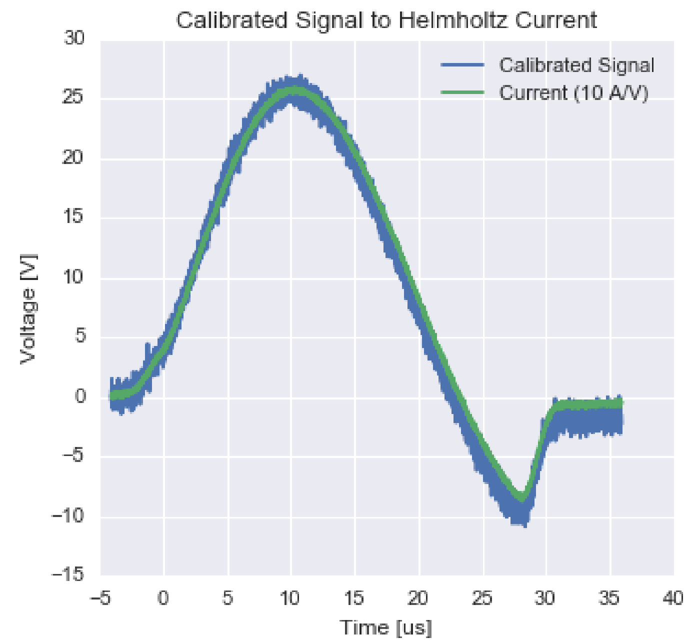


Figure 16 – Calibrated probe signal to Helmholtz current used for calibration.

$$V_{induced} = \frac{Nd\Phi}{dt}, \qquad V_2 = \frac{1}{RC}\int V_1(t)dt$$

$$\therefore V_{measured} = \frac{NAcos(\theta)}{RC}B$$

To help quantify coil melting, debris is captured in Aerogel pucks and analyzed under a microscope

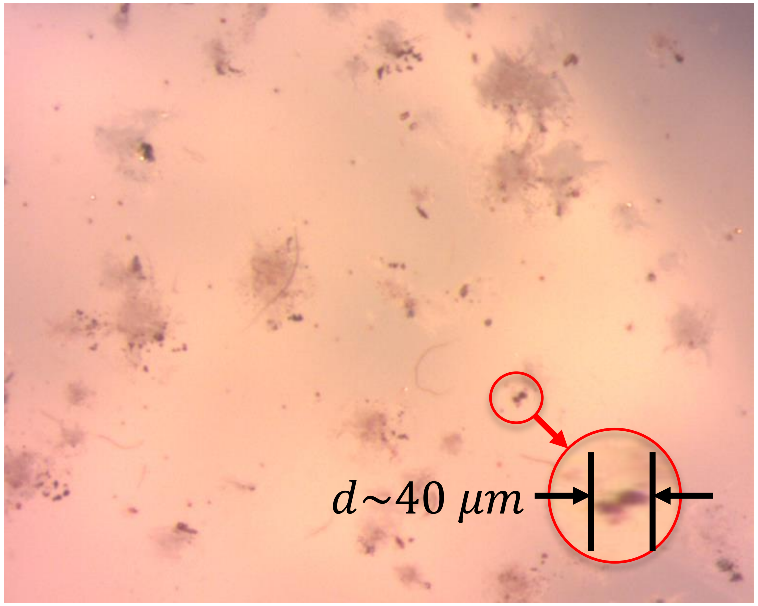


Figure 17 – Microscope image of debris captured in Aerogel puck.

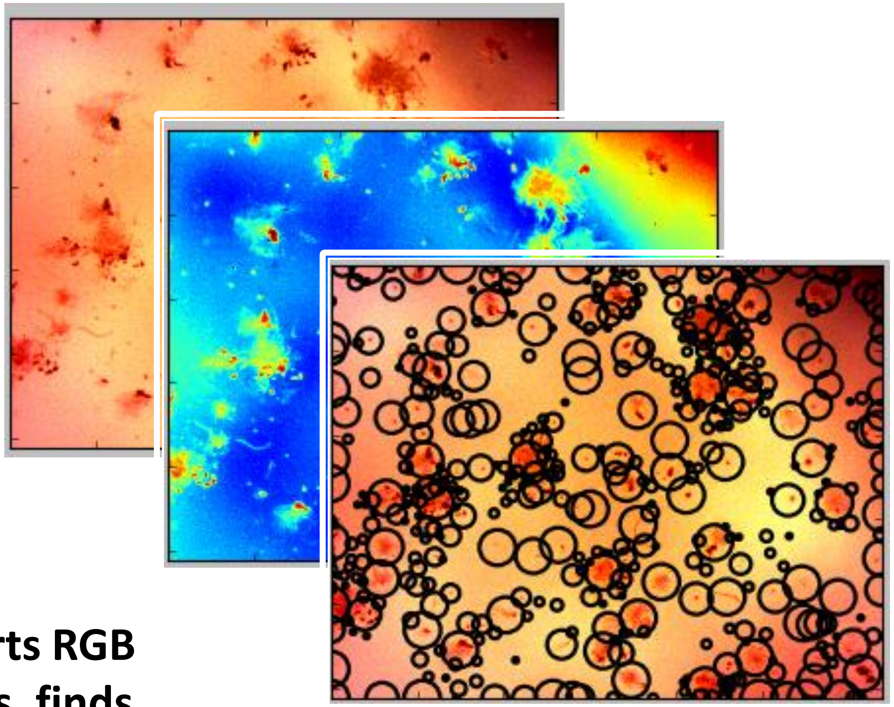


Figure 18 – Python script is used for further processing and tracking blobs.

- **Python script adjusts contrast, converts RGB information into scalar intensity maps, finds “blobs” and measures their relative size**

2D temperature maps are estimated using two-color pyrometry at 10 MHz

- **Two-color pyrometer is used to measure the temperature of the coils to ensure adequate melting just after the peak of the current pulse**

Figure 19 – Two-color pyrometer captures the same image at two wavelengths at 10 MHz.

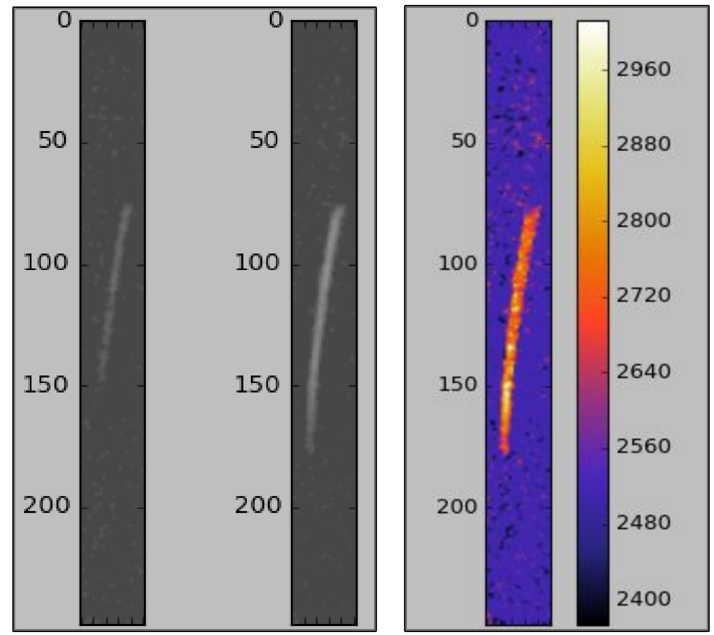
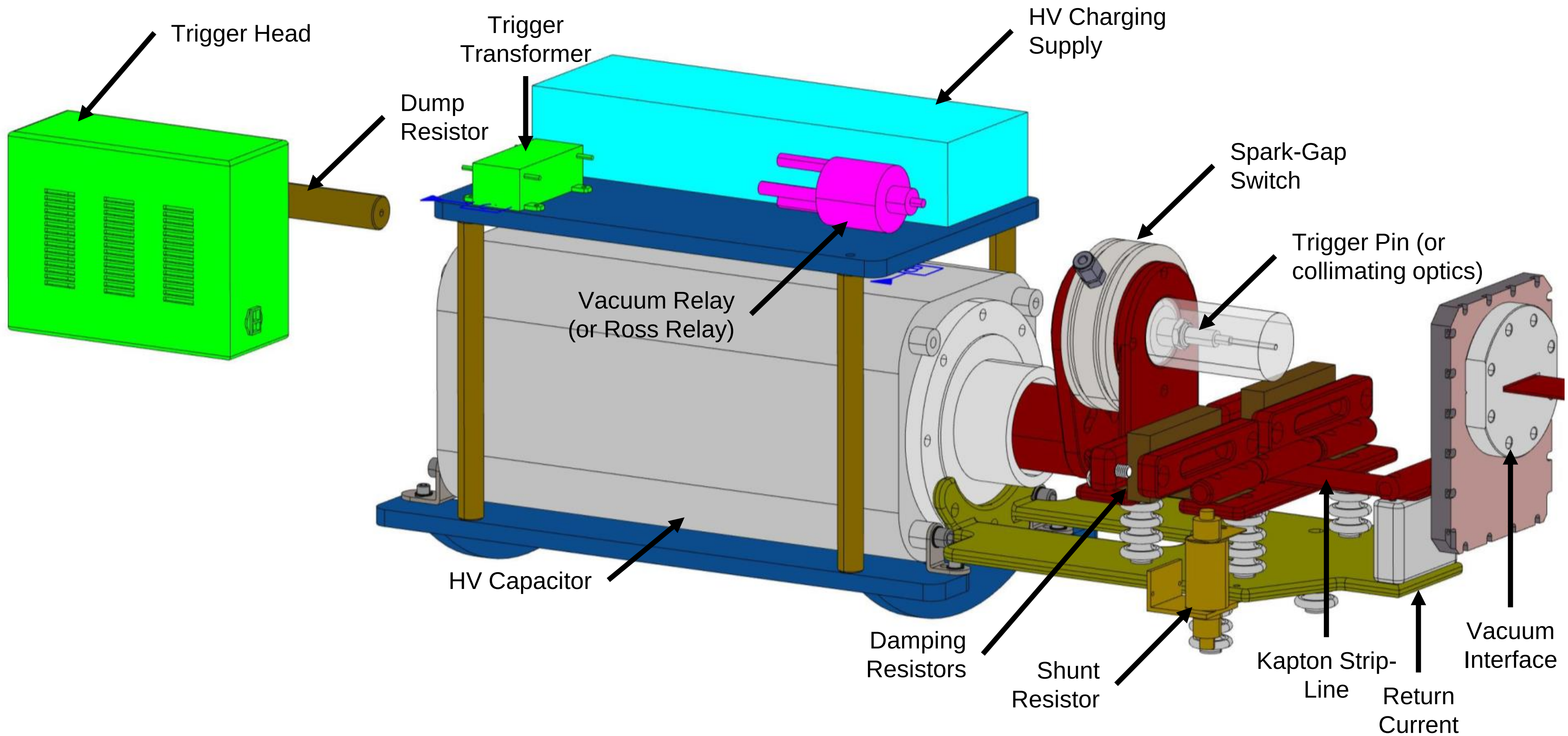
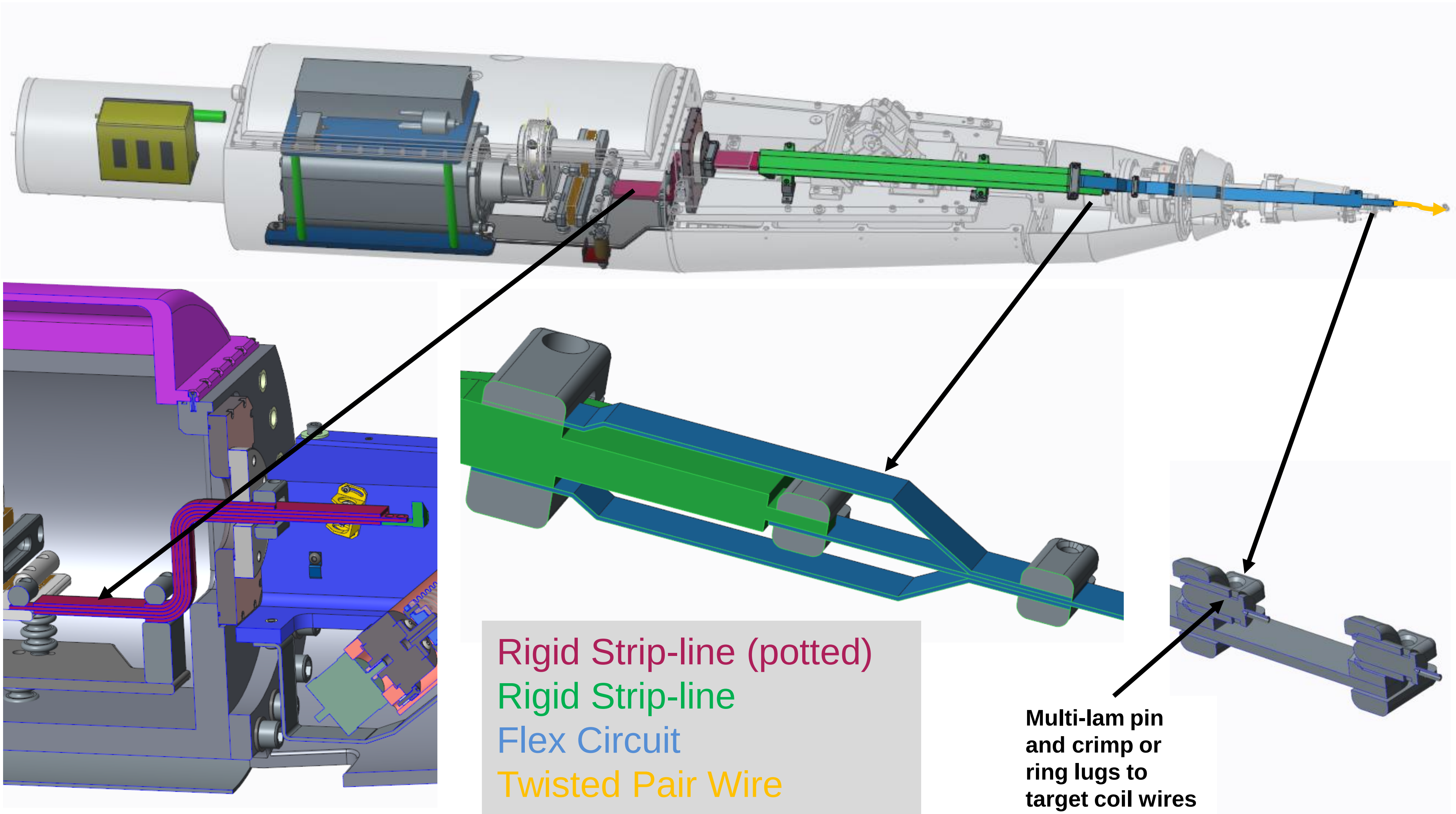


Figure 20 – Exploding wire short example. Temperature units not calibrated

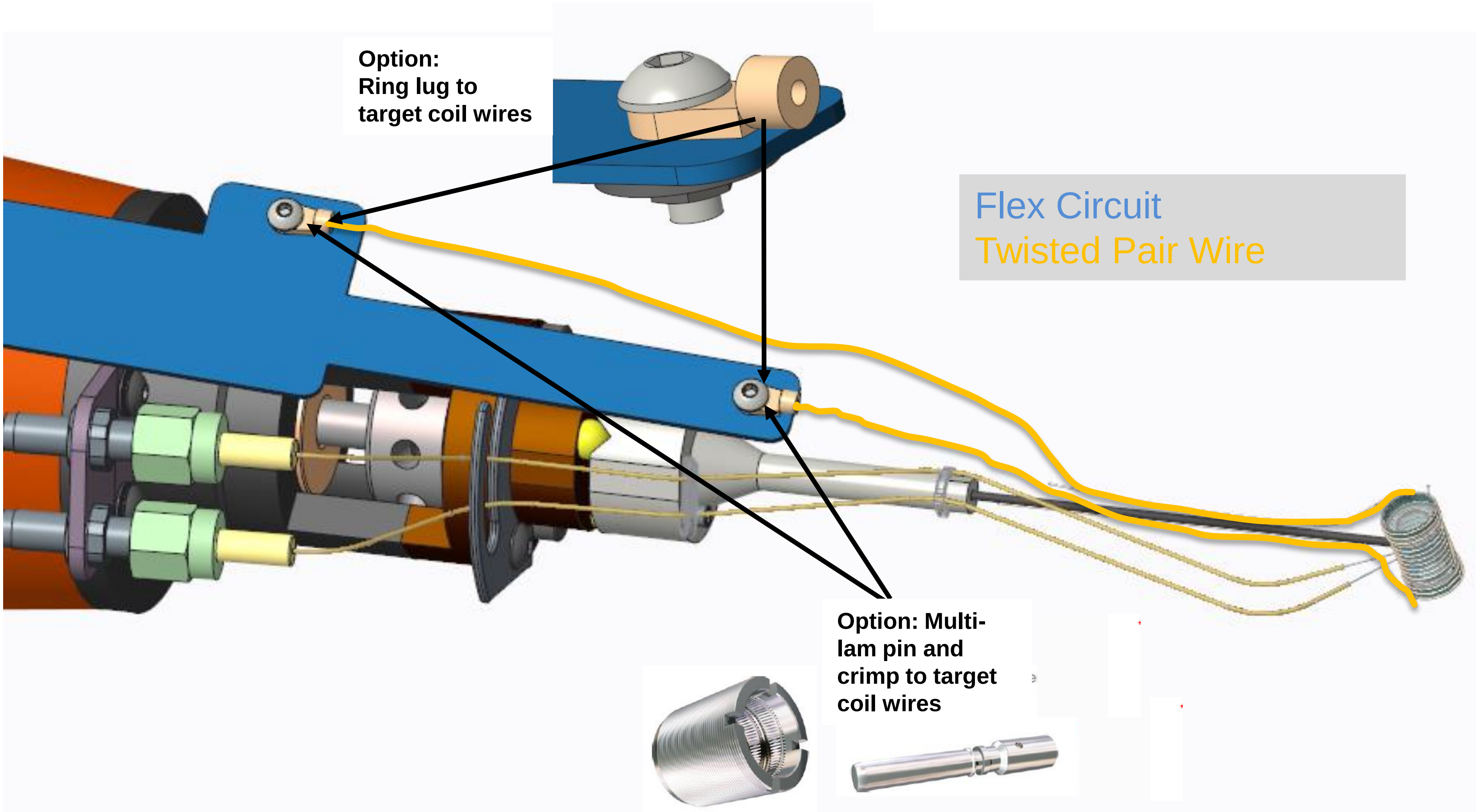
Conceptual Design



Three high-voltage vacuum connections are required to connect the pulser to the target



Strip-line to wire connection: ring lugs are a simple connection that have proven reliable in lab testing.



Experimental Summary

- **Achieved 30 Tesla in gas pipe coil targets**
- **Achieved 35 Tesla in Hohlraum coil targets**
  - **Limited by pulser voltage and inductance in lab**
- **Developed a full suite of diagnostics for continuing coil development**
- **Integrated pulser into DIM compatible volume**

Pulse Power Plan Forward

- Current Design Status
  - Conceptual design that fits inside of an airbox in TANDM with tested components that should be compatible with the NIF facility

- Current Experimental Status
  - 50 kA, 40 kV strip-lines in development
  - Need to test strip-line performance in vacuum
  - When new high-speed camera arrives, can finish pyrometer diagnostic and resume coil testing
  - Testing connection methods for rigid and flexible strip-lines to pulser and coil loads.

- Risks
  - Strip-line vacuum integrity
  - Radiation resistance for electronics
  - Connections from pulser to coil load
  - High voltage standoff in pulser airbox

Backup Slides

Sample Slide

- **Warm B-field requirements review on 12/18/17**
- **Warm B-field FMEA review on TBD**
- **Warm B-field pulsed power CDR on 2/14/18**
  - **Focused session on electrical design concept**
  - **Reviewed by SMEs from LLNL, LLE, SNL, Univ. of Michigan**

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Radiation Resistance of Kapton Film

Table 12. Effect of Gamma Radiation Exposure on Kapton® Polyimide Film (Cobalt 60 Source, Oak Ridge)

Property	Control 1 mil Film	10^4 Gy 1 h	10^5 Gy 10 h	10^6 Gy 4 d	10^7 Gy 42 d
Tensile Strength, MPa (psi $\times 10^3$)	207 (30)	207 (30)	214 (31)	214 (31)	152 (22)
Elongation, %	80	78	78	79	42
Tensile Modulus, MPa (psi $\times 10^3$)	3172 (460)	3275 (475)	3378 (490)	3275 (475)	2903 (421)
Volume Resistivity Ω·cm $\times 10^{13}$ at 2°C (392°F)	4.8	6.6	5.2	1.7	1.6
Dielectric Constant 1 kHz at 2°C (73°F)	3.46	3.54	3.63	3.71	3.50
Dissipation Factor 1 kHz at 23°C (73°F)	0.0020	0.0023	0.0024	0.0037	0.0029
Dielectric Strength V/µm (kV/mm)	256	223	218	221	254

Table 13. Effect of Electron Exposure on Kapton® Polyimide Film Mixed Neutron and Gamma

	5×10^7 Gy	10^8 Gy
5×10^{12} neutrons/cm/s Flux at 175°C (347°F)	Film Darkened	Film Darkened and Tough

Table 14. Effect of Ultraviolet Exposure on Kapton® Polyimide Film*

	1000 h Exposure
Tensile Strength, % of Initial Value Retained	100
Elongation, % of Initial Value Retained	74

*Vacuum environment, 2×10^{-6} mmHg at 50°C (122°F). UV intensity equal to space sunlight to 2500A.

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Inductance Calculations

- **Gas pipe solenoid (single layer coil approximation)[1]**

$$L = \frac{0.004\pi^2 a^2 N^2 K}{b} = 1.05\ \mu H$$

Where, a = mean radius, b = length, N = number of turns, K = tabulated end-effect correction factor

- **Hohlraum Solenoid**

$$L = \frac{0.004\pi^2 a^2 N^2 K}{b} = 0.191 \mu H$$

[1]Grover F., Inductance Calculations 1973

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Transmission Line Impedances[1]

Transmission Line Capacitance and Inductance per Length				
Constants				
μ_0	1.25664E-06	[H/m]		
μ_r	1	[H/m]		
ε_0	8.85419E-12	[F/m]		
ε_r	2	[F/m]		
π	3.141592654			
Coaxial Line				
a	0.01	[m]		
b	0.1	[m]		
C	4.83218E-11	[F]		
L	4.60517E-07	[H]		
Z_0	97.69041201	[Ω]		
2 Parallel Open Wire Line				
a	0.01	[m]		
b	0.1	[m]		
C	1.85706E-11	[F]		
L	1.19829E-06	[H]		
Z_0	254.1963126	[Ω]		
Parallel Plate Line				
w	0.1	[m]		
s	0.01	[m]		
C	1.77084E-10	[F]		
L	1.25664E-07	[H]		
Z_0	26.65792565	[Ω]		
Single Wire Above Conducting Plate				
a	0.01	[m]		
h	0.1	[m]		
C	3.01623E-11	[F]		
L	7.37776E-07	[H]		
Z_0	156.5059006	[Ω]		

[1]Smith F., Pulse Electronics

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