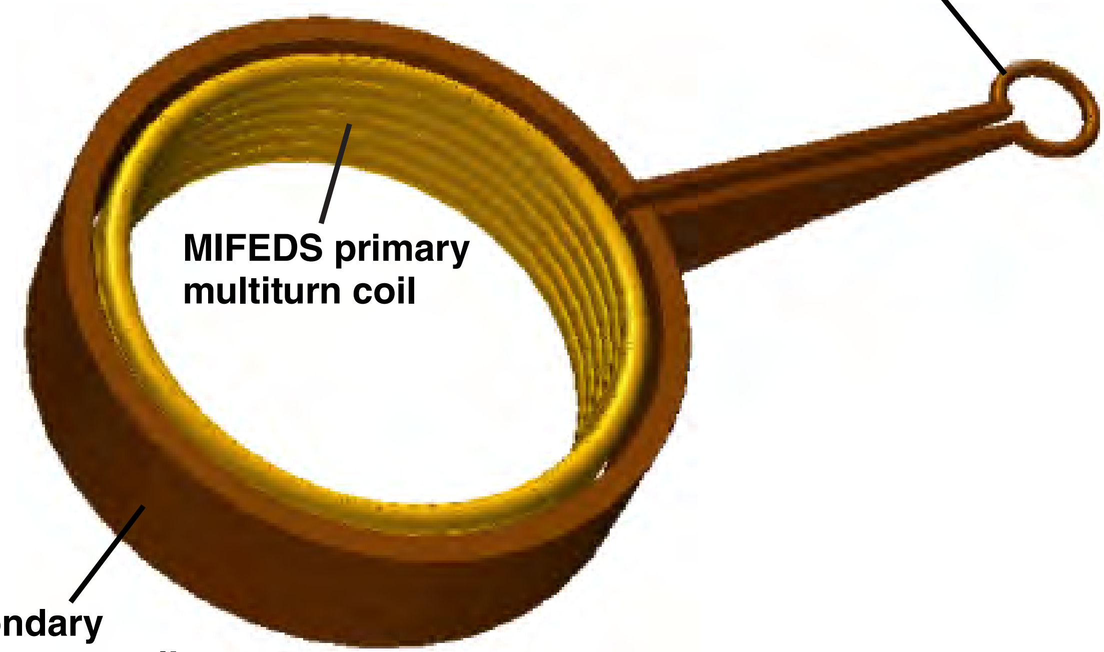
Increasing the Magnetic-Field Capability of MIFEDS Using an Inductively Coupled Coil



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55th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Denver, CO
11–15 November 2013

Summary

Inductively coupled coils provide strong magnetic fields for magnetized high-energy-density-physics (HEDP) experiments

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- Tests of a prototype verified the coupling model
- The coupling characteristics were measured to be in agreement with the coupling model
- A maximum magnetic-field strength of up to 60 T at the center of a 1-mm coil is predicted

Collaborators

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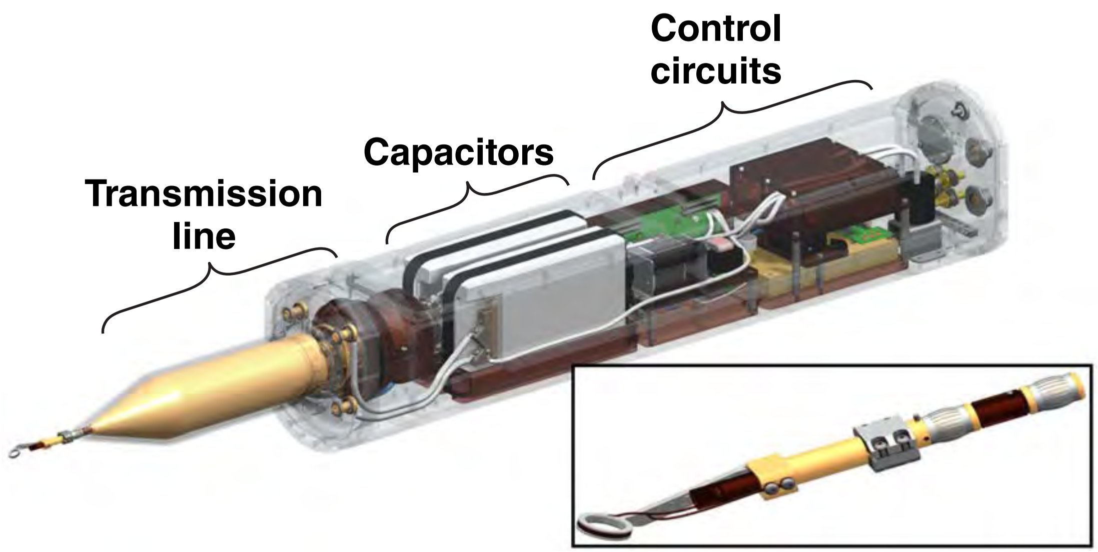
*also with Fusion Science Center for Extreme States of Matter

MIFEDS provides an experimental platform for magnetized HEDP

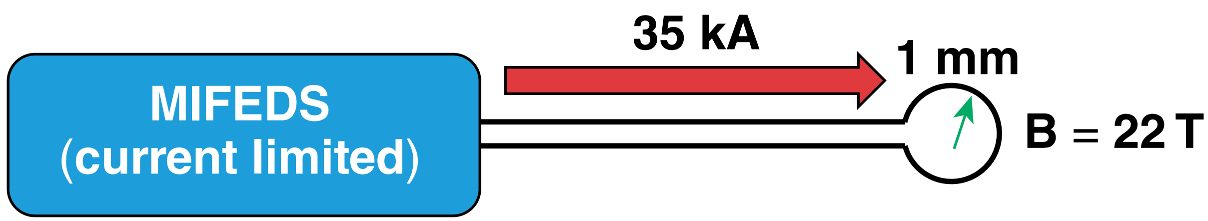
- **Magneto-inertial fusion electrical discharge system (MIFEDS)**
  - **generates tens of kiloamps**



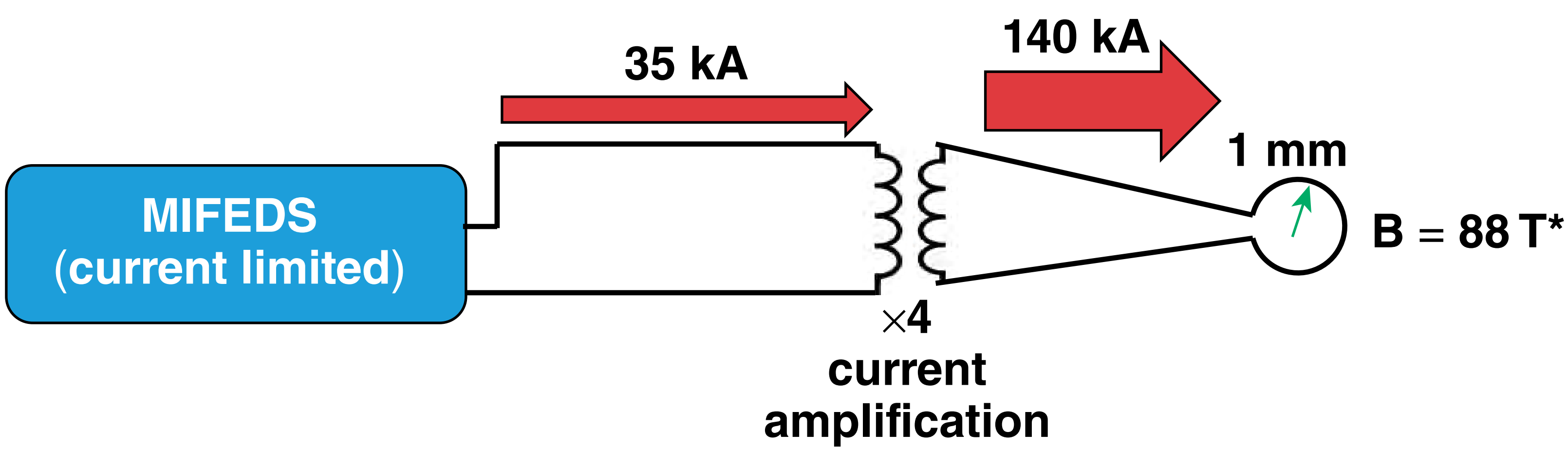
MIFEDS is continually being modified to increase the magnetic-field strength and to provide more possibilities for magnetized HEDP.

Inductively coupled coils increase the current in the coil, which increases the field strength

- MIFEDS is current limited by its internal impedance



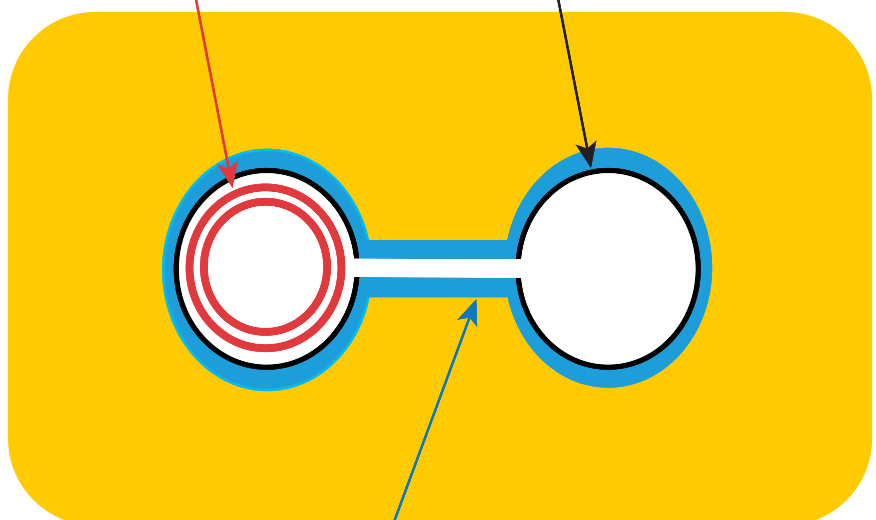
- An inductively coupled coil will produce a higher current in a small volume, which produces a higher field



*Example values neglecting losses

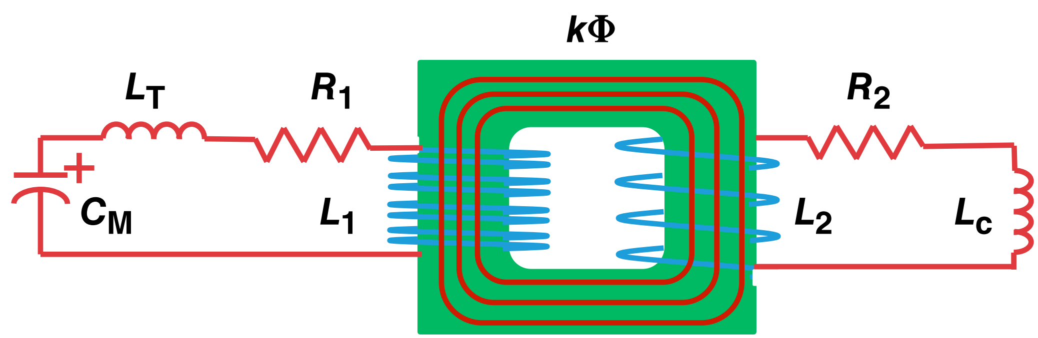
A prototype transformer coil was designed to test the coupling model

- **A multiturn coil is clamped between a figure-eight structure that serves as a coupling and a magnetic-field coil**
  - **calculated values used a skin-depth model of a current pathway**

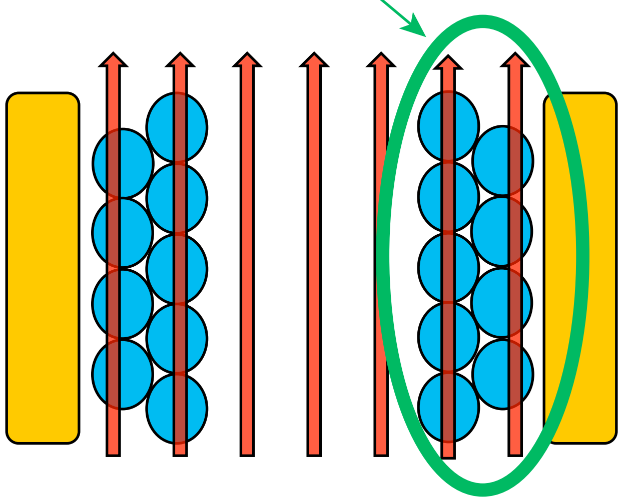


An equivalent circuit was used to model inductive coupling

- A simple transformer setup was modeled with circuit simulation software
- The current amplification predicted by the simulation with ideal coupling is 3.7



- Layered turns result in flux leakage
- Results in a coupling factor of $k = 80\%$
- Simulations predict a current amplification of 2.4 with this estimated coupling



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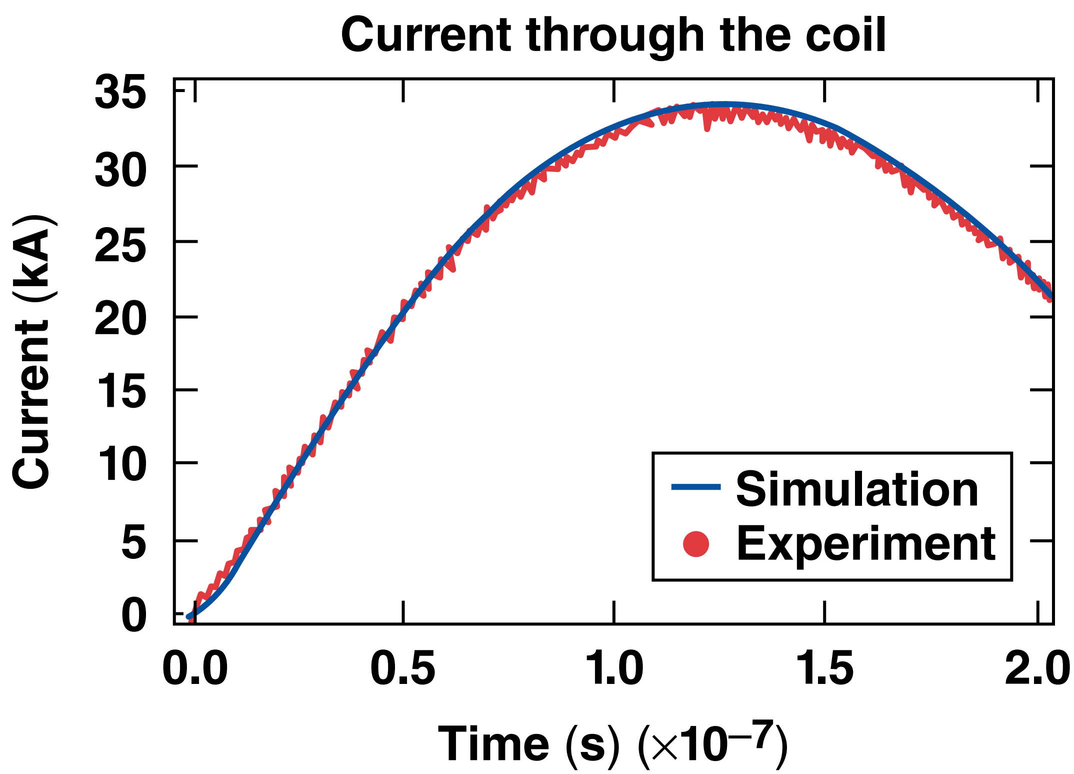
A current amplification of 2.4 was measured in agreement with simulations



Parameter	Prediction	Measured
L_1	1 mH	1 mH
L_2	17.7 nH	21 nH
L_c	17.7 nH	21 nH
R_2	6 mΩ	6 mΩ
Coupling	80%	79%

Inductively coupled coils are well understood and can be easily designed.

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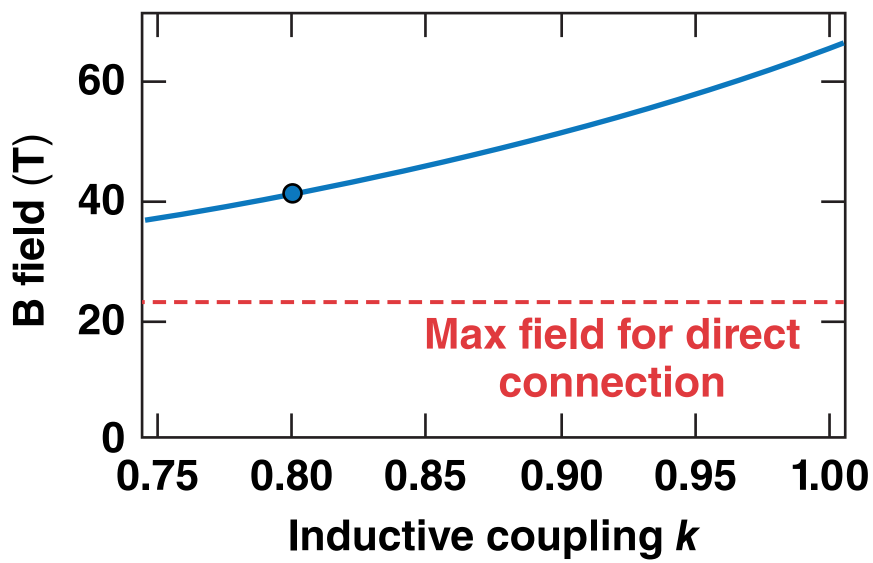
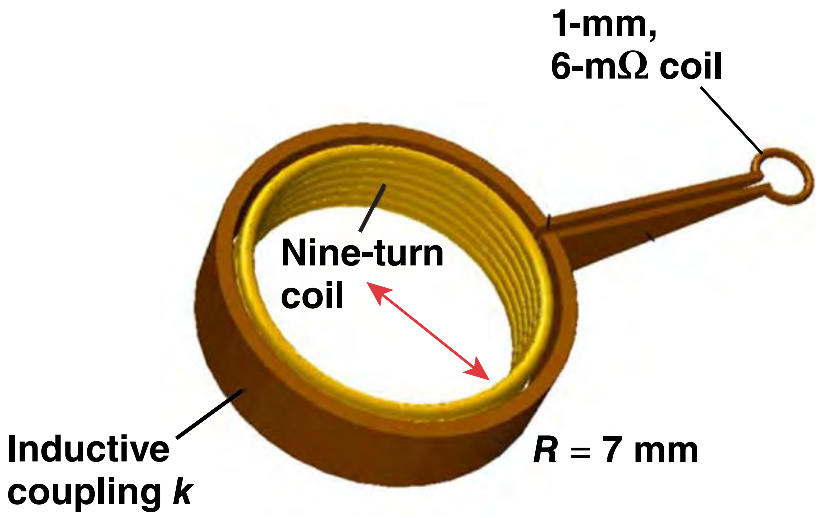
Magnetic fields of up to 60 T can be obtained with improved inductive coupling

Magnetic-field strength for 1-mm-radius coil





The magnetic field can be increased by more than a factor of 3 with sufficient coupling.

Summary/Conclusions

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Inductance and resistance calculations of a transformer coil prototype

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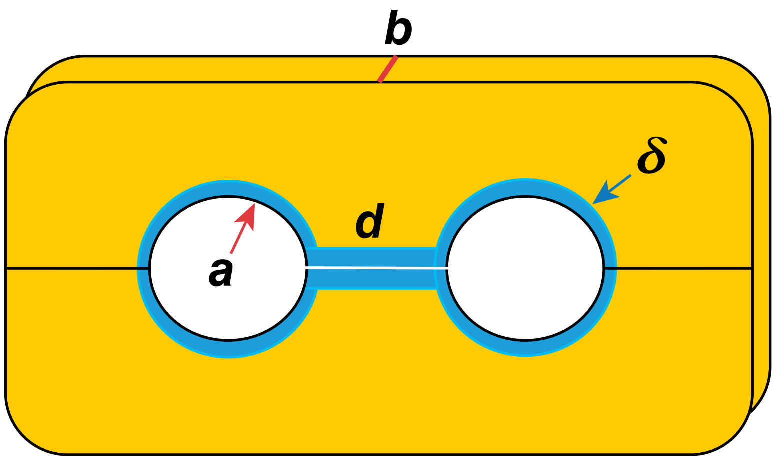

$a = 6.75$ mm

$b = 4.2$ mm

$d = 5.5$ mm

$\delta = 103\ \mu$m

$\rho_{Al} = 2.7 \times 10^{-8}\ \Omega \cdot$ m

K = 0.413

$$L = \frac{\mu_0 \pi a^2 N^2}{b} K = 17.7\ \text{nH}$$

$$R = \frac{\rho \ell}{A} = \frac{2\rho_{Al}\left[(2\pi a) + d\right]}{b\delta} = 6\ \text{m}\Omega$$

- The same formula can also be used for the primary coil

*F. W. Grover, Inductance Calculations: Working Formulas and Tables (D. Van Nostrand, New York, 1946), pp. 94–113 and 144.

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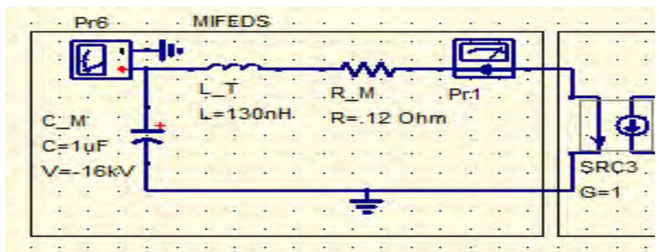
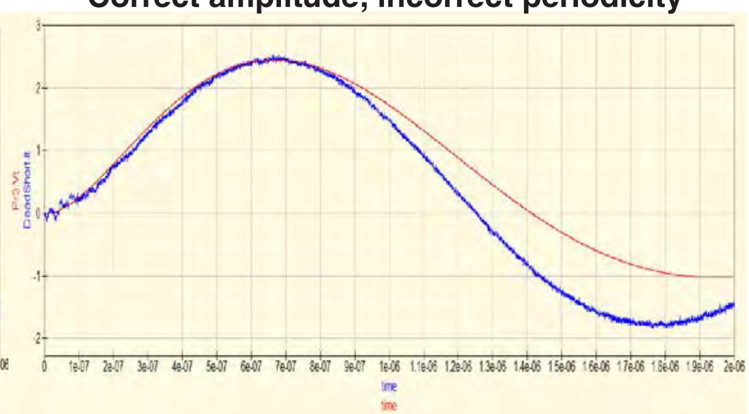
Why doesn't the MIFEDS trace in your simulation match the experiment?

- **MIFEDS may have a time-dependent resistance caused by a spark gap current switch, or a frequency-dependent capacitance caused by the inner dielectric (demonstrated by varying *L* and *R* in the model)**



Correct periodicity; incorrect amplitude

Correct amplitude; incorrect periodicity



Numerical equations

$$\frac{N_2}{N_1} L_1 \dot{I}_1 - L_2 \dot{I}_2 = L_c \dot{I}_2 + R_2 I_2$$

Substitute out the flux

$$\frac{Q}{C} = L_T \dot{I}_1 + R_1 I_1 + L_1 \dot{I}_1 - \frac{N_1}{N_2} L_2 \dot{I}_2$$

Make dimensionless substitutions

Using $I_1 = -\dot{Q}$ $\quad \frac{N_1}{N_2} = N$

$$Q = \tilde{Q} V_0 C$$

$$t = \tilde{t}\sqrt{(L_T + L_1)C}$$

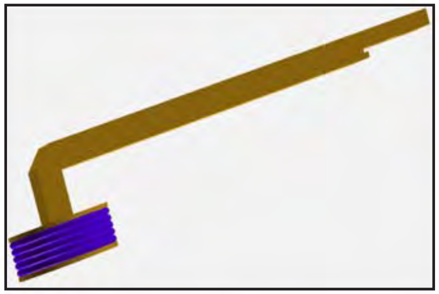
$$I_2 = \tilde{I}_2 \frac{V_0}{\sqrt{\frac{L}{C}}} = \tilde{I}_2 \frac{V_0}{Z}$$

$$\tilde{Q} = -\ddot{\tilde{Q}} - \frac{R_1}{Z}\dot{\tilde{Q}} - N\frac{L^2}{L}\dot{\tilde{I}}_2$$

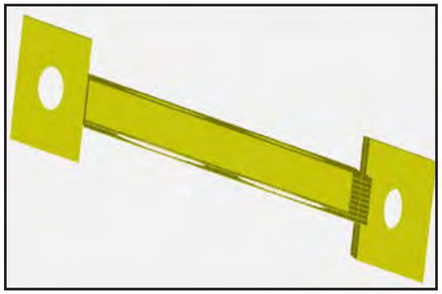
$$-\ddot{\tilde{Q}} = N\frac{L_2 + L_c}{L_1}\dot{\tilde{I}}_2 + \frac{NR_2}{Z}\frac{L}{L_1}\tilde{I}_2$$

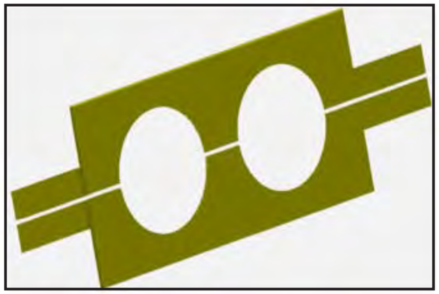
VisRad model of transformer coil prototype

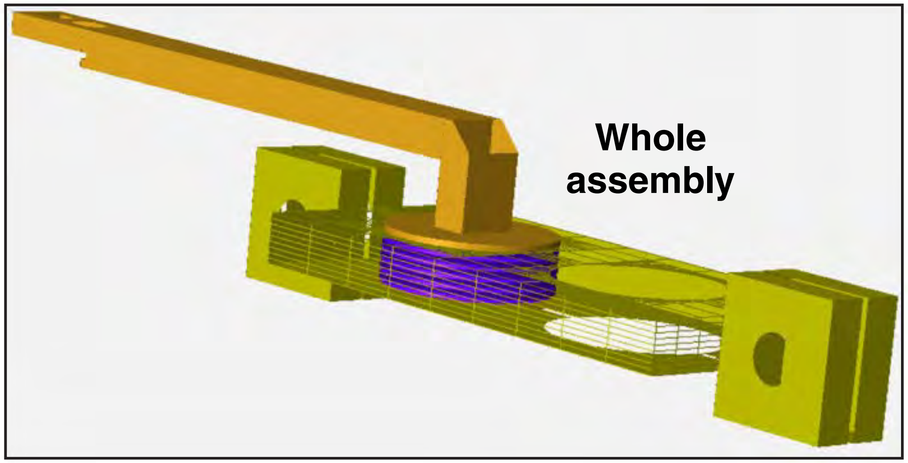
Primary coil



Secondary coil







Methods of increasing magnetic field delivered by MIFEDS

Method	Pros	Cons
• Decrease coil size	Easy to design and make	Limited by wire size; possible blocked beams
• Increase stored energy in MIFEDS	Does not change coil design; works for all applications	High voltages inside MIFEDS cause many issues; limited storage
• Increase number of turns in the coil	Easy to design and make; not limited by wire size	Coil too bulky and blocks laser beams; large inductance
• Decrease internal impedance of MIFEDS	Does not change coil design; works for all applications	Very hard to accomplish; requires redesign of all MIFEDS circuitry

- We need a high current in a small volume; this can be accomplished by using a small coil with low inductance