MIFEDS-10kJ project - results and status

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Summary

A field of 30 T was obtained with a custom-built 10kJ power supply intended for use outside of OMEGA TIMs

- A B-field of ~20 T was achieved using directly driven coils. However, they suffer from thermal and mechanical damage due to the high magnetic field and a long pulse duration.
- A B-field of ~30 T was achieved using inductively coupled coils. Their damage threshold is significantly higher and they are capable of generating a 30 T magnetic field.
- The inductive coil can be used in many applications including ICF direct and indirect drives, and MagLIF

Motivations and Goals

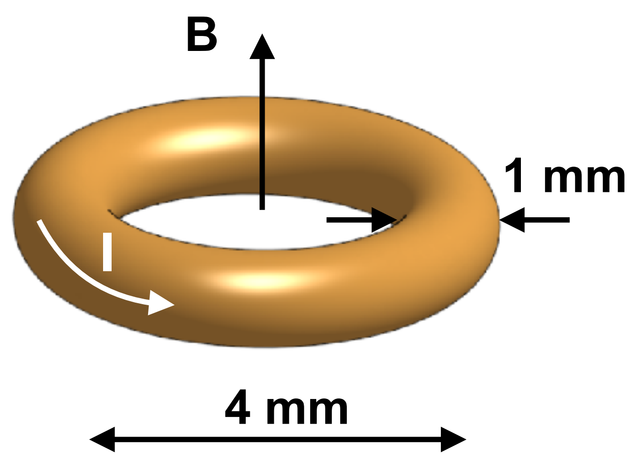
- **Motivations:**
  - **Use of a large stored energy requires the placement of the power supply outside of the TIM**
  - **Long connecting cable and a large capacitor result in a long current pulse imposing thermal and mechanical challenges**
- **Goals:**
  - **Build a power supply**
  - **Investigate various coil designs**
  - **Create and benchmark simulation models**

MIFEDS development path - increase in the stored energy brings new challenges

		Capacitor	Stored Energy	Time zero-to-peak (depends on the load inductance	TIM placement Inside/Outside
	MIFEDS Gen 1 2007	0.2 μF/ 30 kV	100 J	100 μs	Inside
	MIFEDS Gen 2 2012	1 μF/20kV	200 J	1 μs	Inside
	MIFEDS Gen 3 (Under development) 2017-18	5 μF/30 kV	2 kJ	2 μs	Inside
This talk	MIFEDS 10kJ (Under development) 2017-18	50 μF/ 20kV	10 kJ	10 μs	Outside

- There is a limit on how much energy can be stored inside a TIM
- Further increase requires the placement of the power supply outside of the TIM
- A large storage capacitor and increased inductance of the transmission increases the pulse duration from ~1 μs to ~10-20 μs
- This brings complications such as increase of the thermal and mechanical stresses

Resistive heating imposes a limit on achievable magnetic field



Case : current pulse through a wire loop

$$I = I_0 \sin\left(\frac{\pi}{2}\frac{t}{\tau}\right) \qquad B_{edge} = 70\ \mathrm{T} \quad \textbf{B at wire surface}$$

$$I_0 = 130\ \mathrm{kA} \qquad B_{axis} = 40\ \mathrm{T} \quad \textbf{B on axis}$$

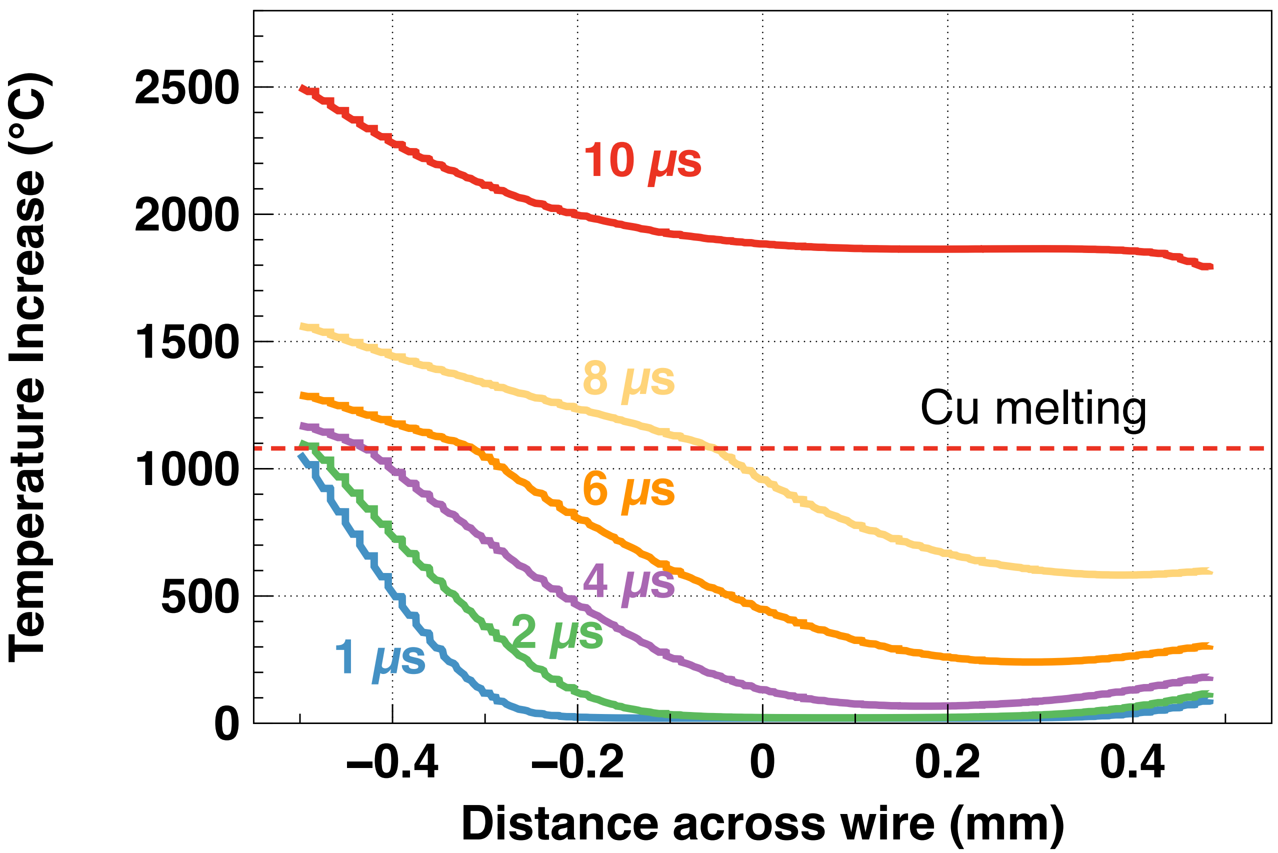
Simulations include current and heat transport, resistivity dependence on temperature, and melting phase transition

At a short pulse duration, the wire starts melting at B = 70 T at the inner edge (40 T on-axis) regardless of the pulse length

B=70T is an upper limit on the surface field above which Cu starts melting. Whether the melting is tolerable is a different matter.

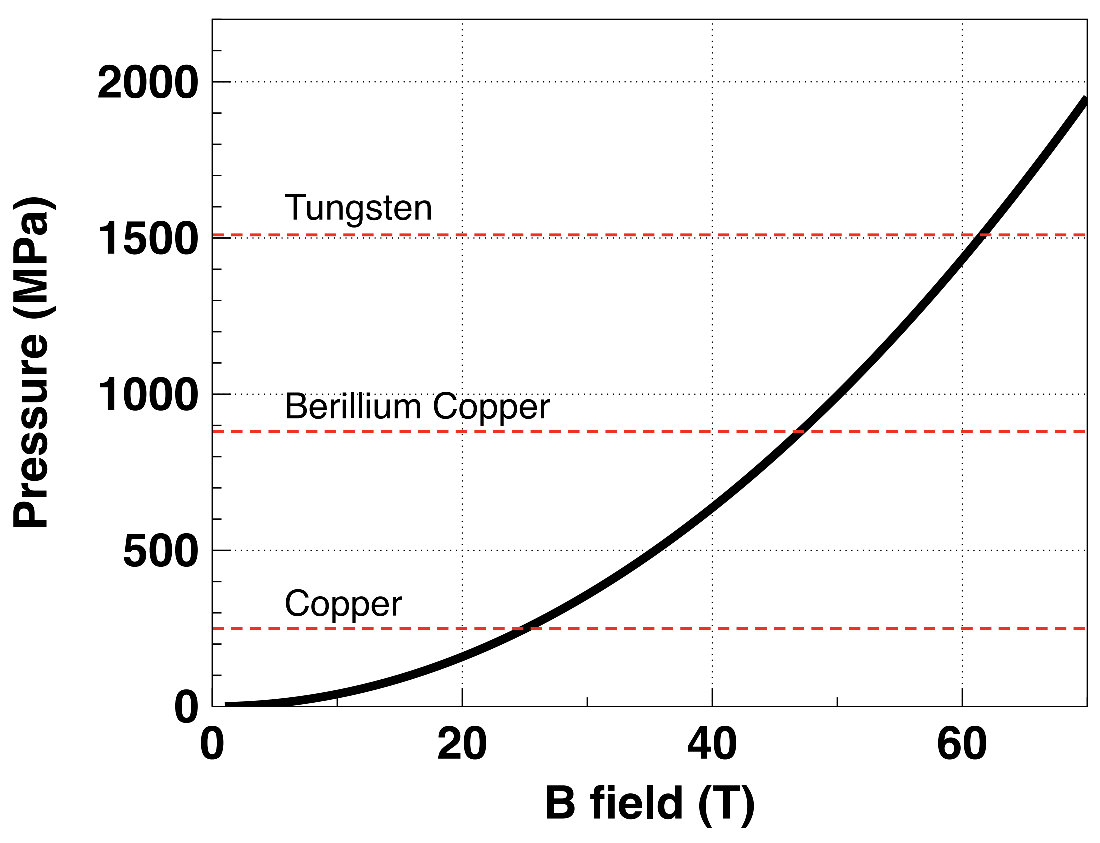
At longer pulses, the melting intensifies and propagates deeper into the material

Temperature profiles across the wire at different pulse durations

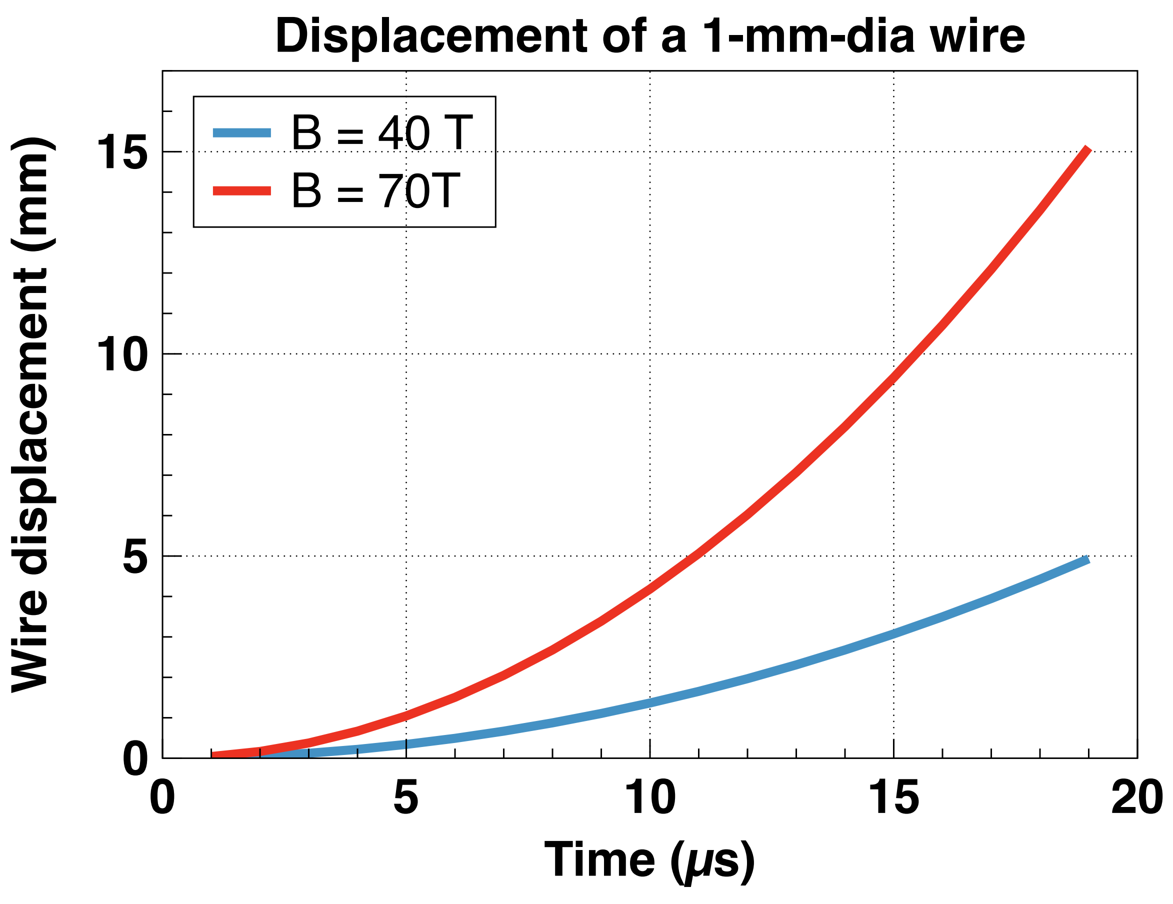


Enormous EM forces present another challenge

Magnetic pressure becomes larger than the material ultimate tensile strength

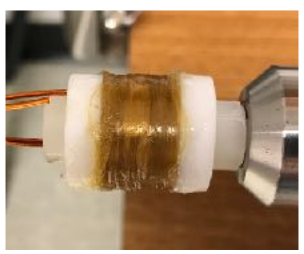


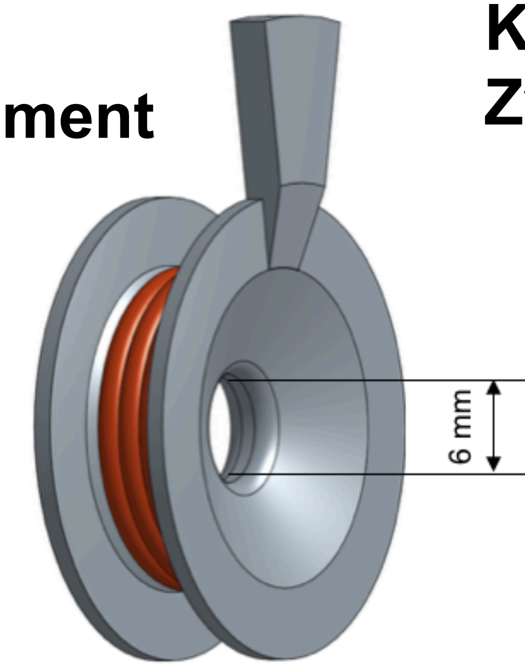
Coil displacement becomes very large destroying the structural integrity

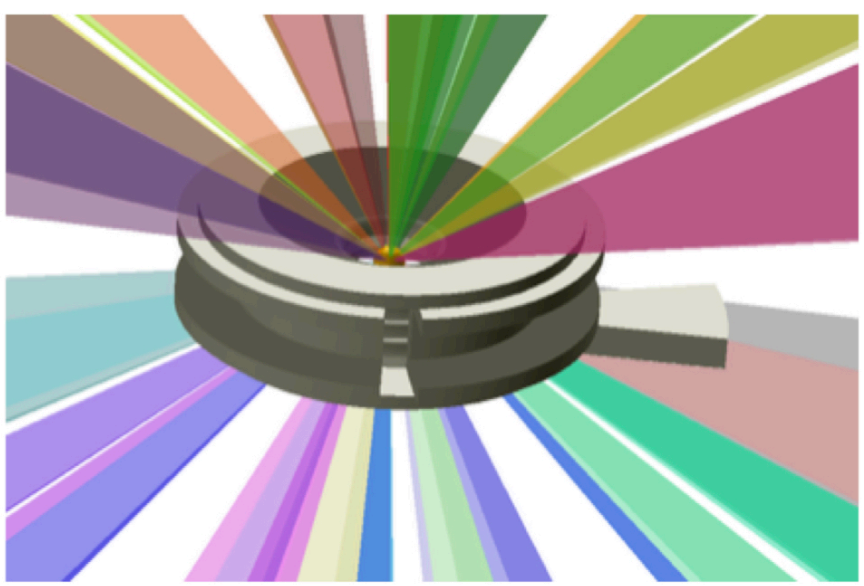


Several geometries of directly-driven coils with an opening of 6 mm and able to accommodate OMEGA-60 beams (all but the equatorial ring) have been tested

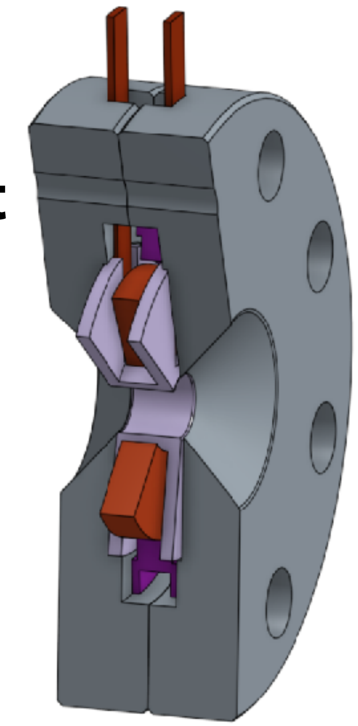
Round copper wire
Kapton insulation
Zylon fiber reinforcement

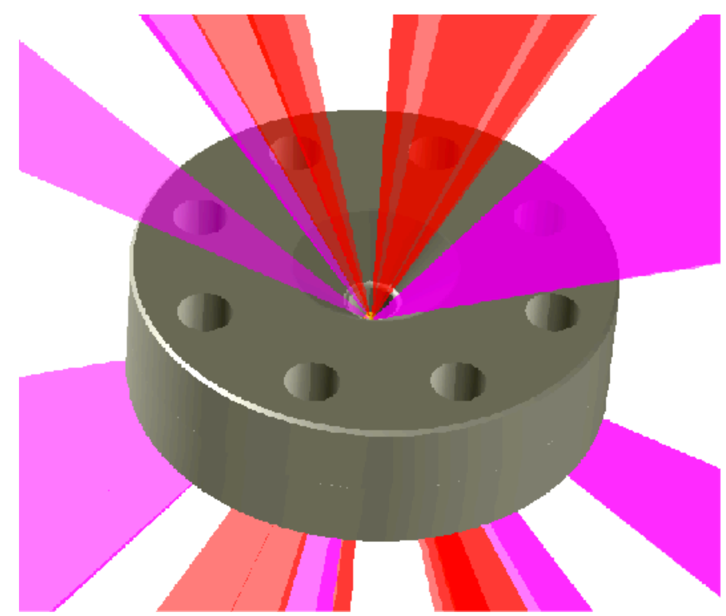






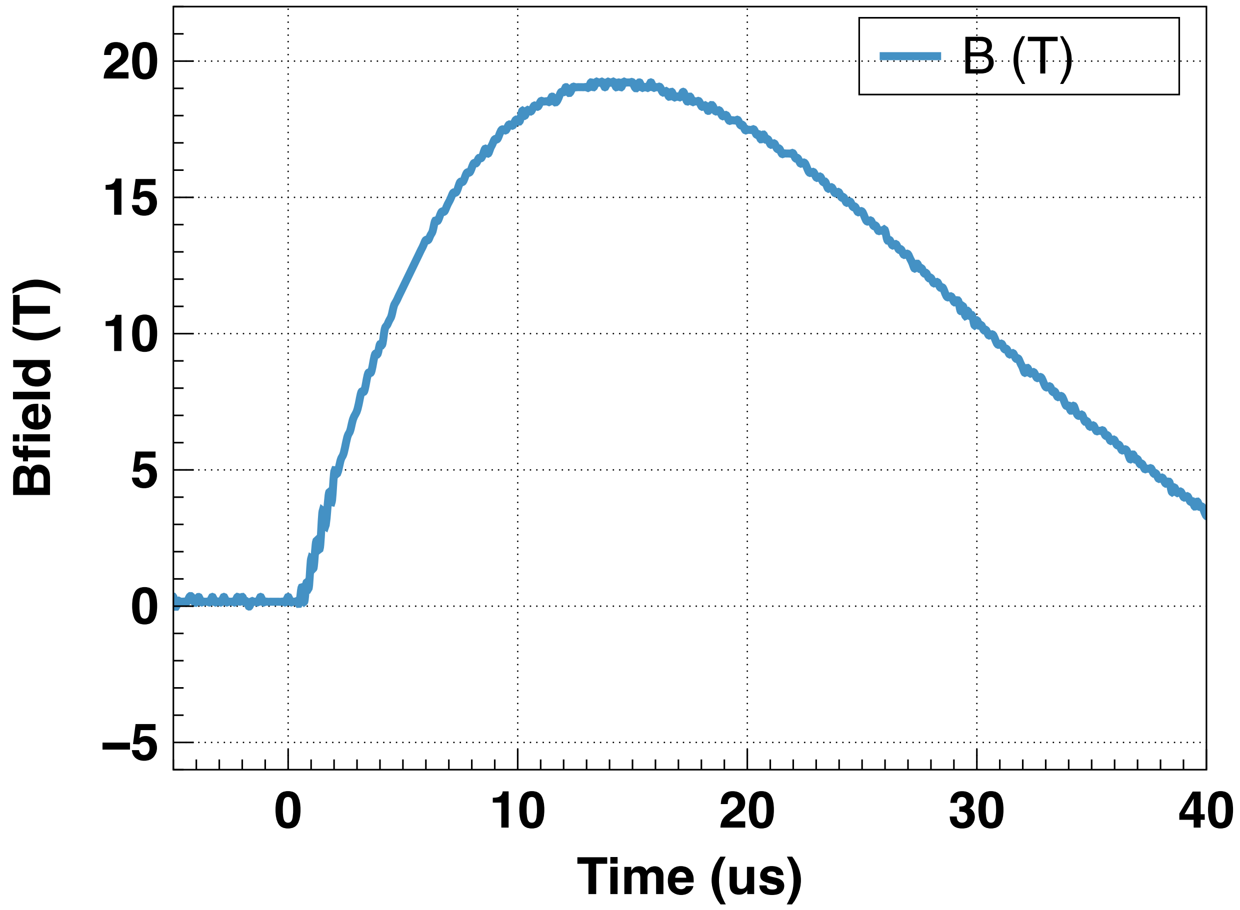
Flat copper wire
Kapton insulation
Zylon fiber reinforcement





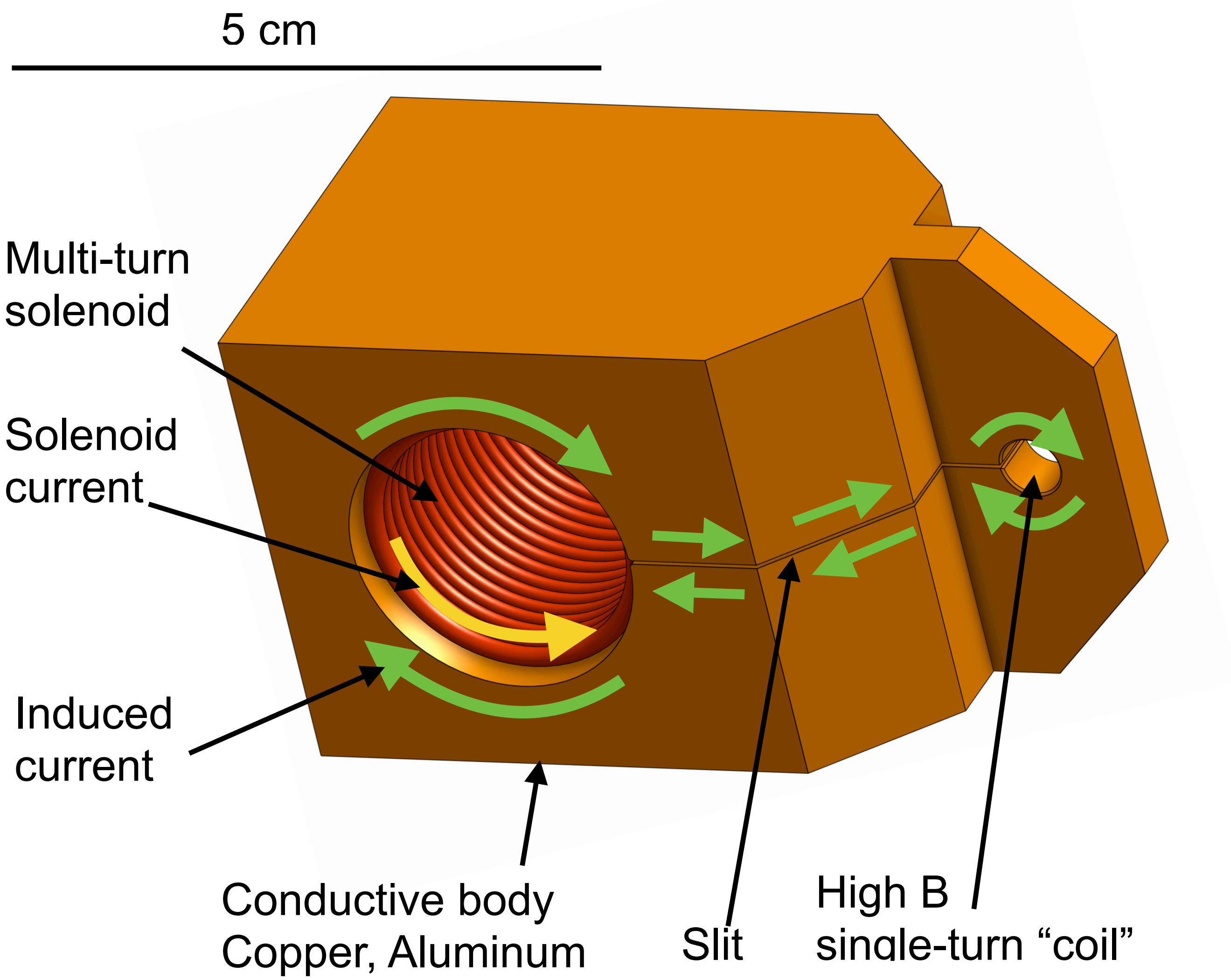
A typical field of about 20 T at a coil current of 20 kA was obtained with these coils. Increasing the current results in mechanical failure and destruction of the coil and the support structure.

The coils were tested using the UM-built power supply with a storage capacitor of C = 50 μF and a stored energy of 10 kJ at 20 kV



Using these coils would be unacceptable due to the large amount of debris

Inductively-coupled coil generates a high field while operating at a low input voltage and current. In addition, it eliminates debris.

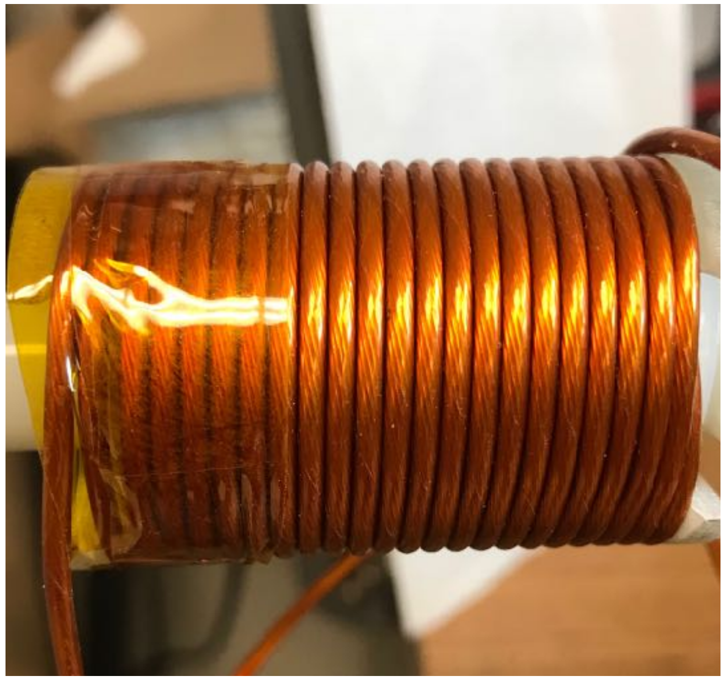


- **Essentially a current transformer. Primary - solenoid with N turns. Secondary - single-turn coil. Ideal-case current amplification ~ N:1.**
- **Current steps-up at TCC. The input feeds operate at low voltage and current.**
- **Provides good beam and diagnostic access**
- **Provides debris containment. The primary coil is completely enclosed in a thick metal shell and moved away from the target.**

D.H. Barnak, et. al, RSI, 89, 033501 (2018)

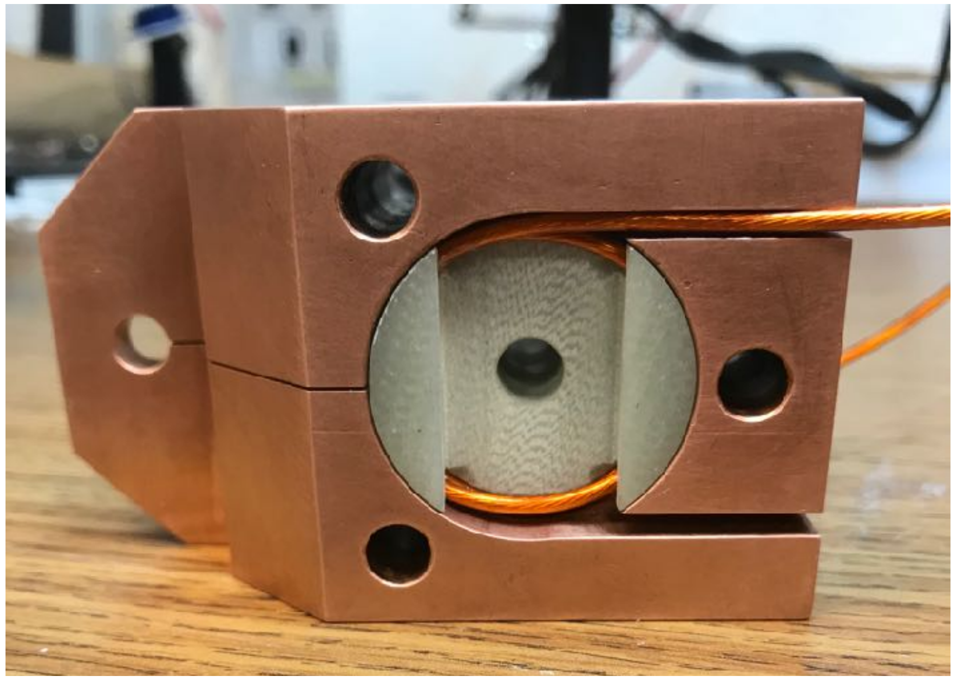
Components of the inductively-coupled coil

Solenoid
AWG 14 wire
Kapton insulation



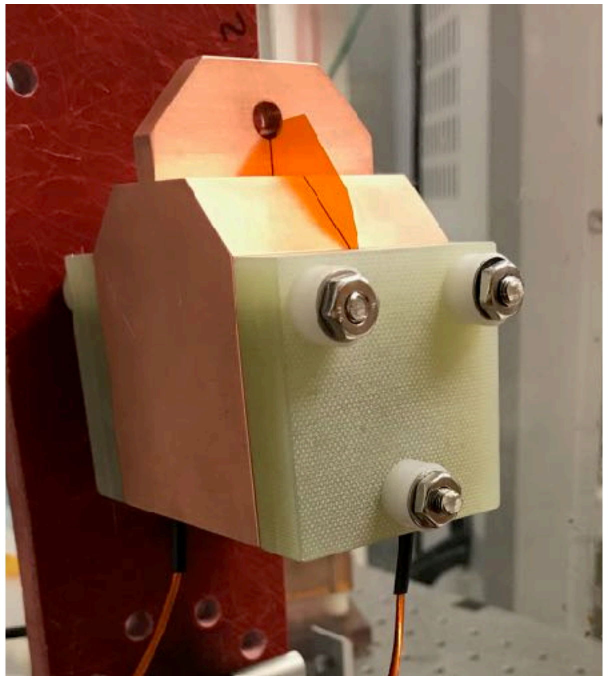
5 cm

Enclosure with
the solenoid inserted.
High B bore diameter 6.53 mm



5 cm

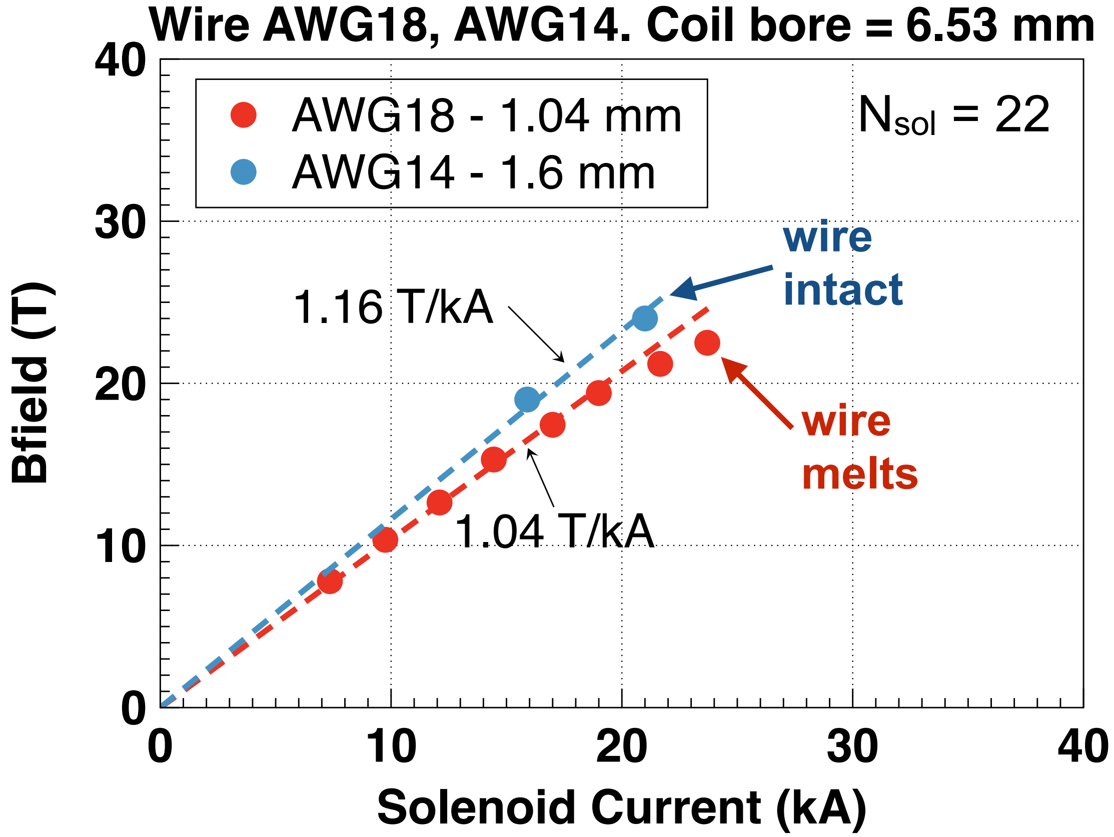
Assembled
for testing



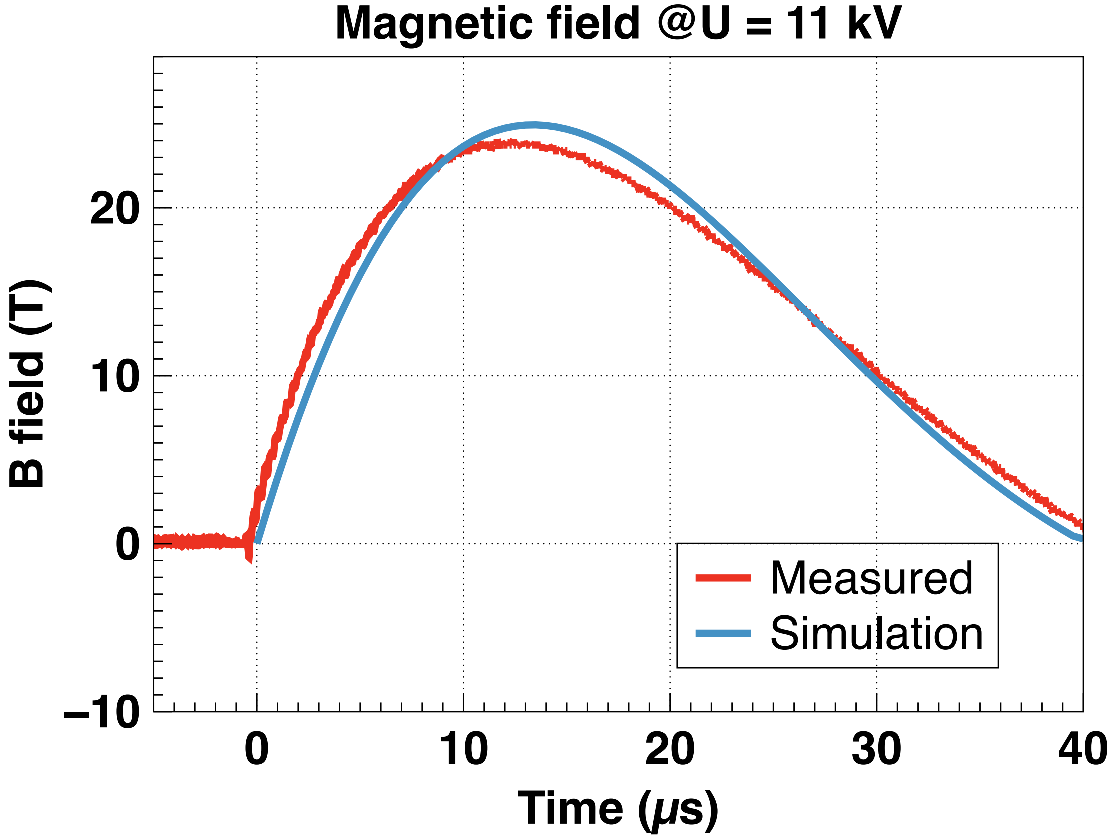
5 cm

At B below 20-23 T, the field is proportional to the solenoid current. Multiple repetitive shots are possible.

AWG 18 wire had a 23 kA limit
AWG 14 is capable of > 30 kA

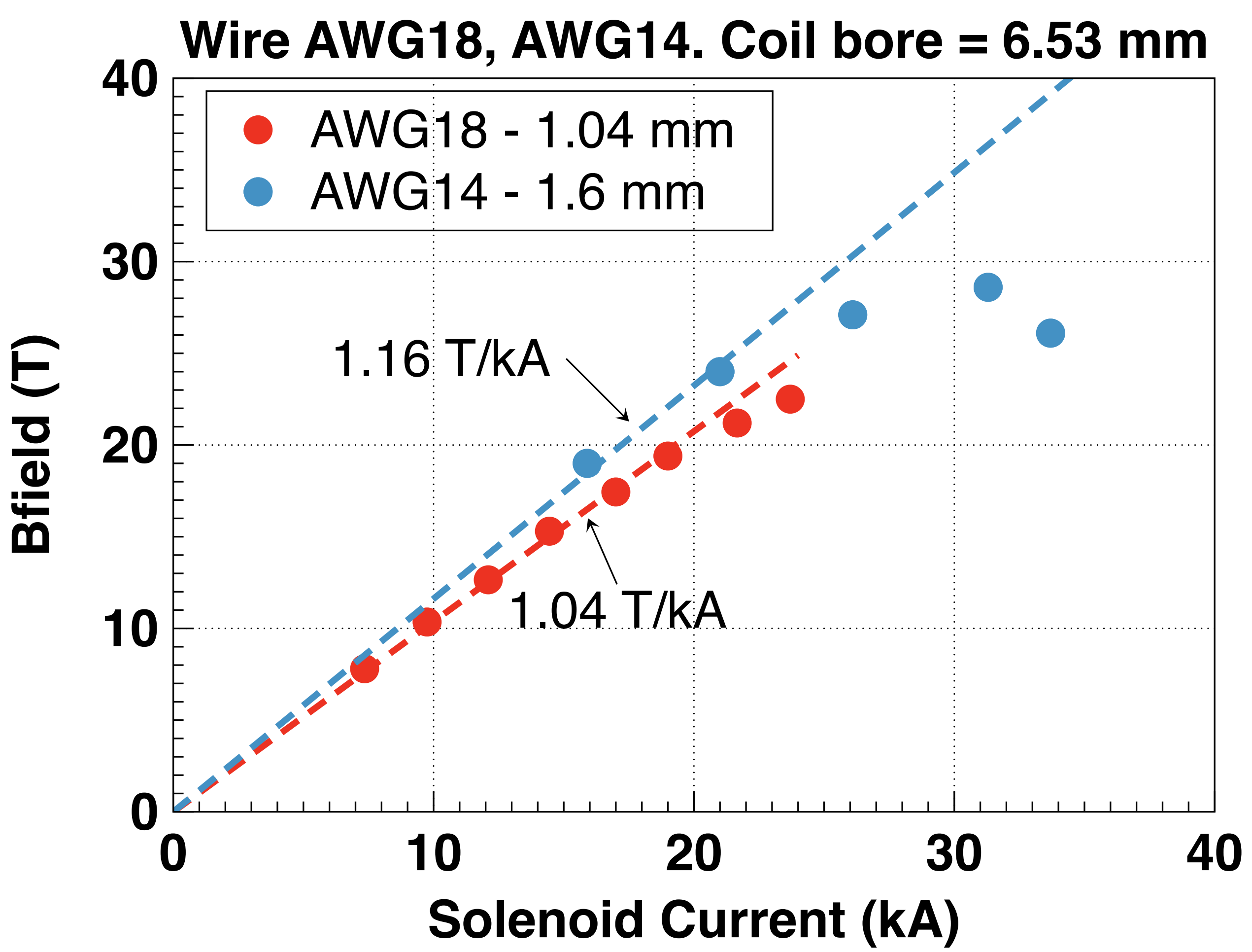


Excellent agreement with simulations (COMSOL)

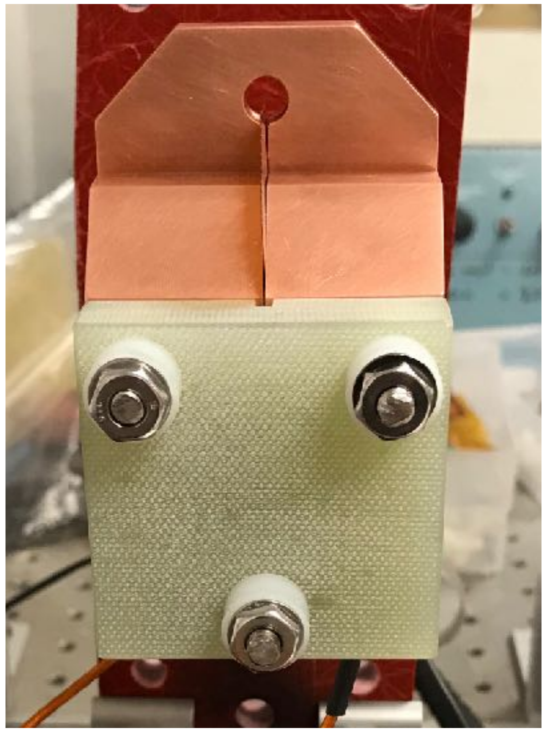


The B-field peaks at 12 μs (24 T)

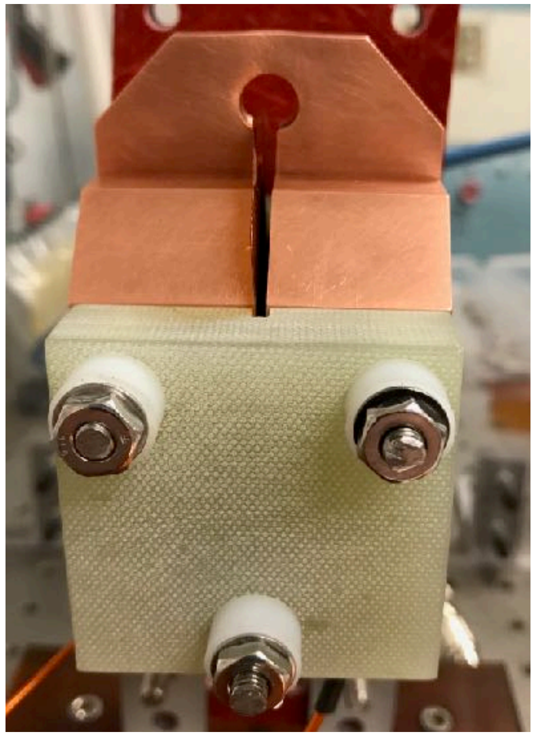
A B-field of 30 T was obtained at higher solenoid currents with AWG 14 wire. The deviation from linear growth is caused by the coil size increase due to the large EM forces

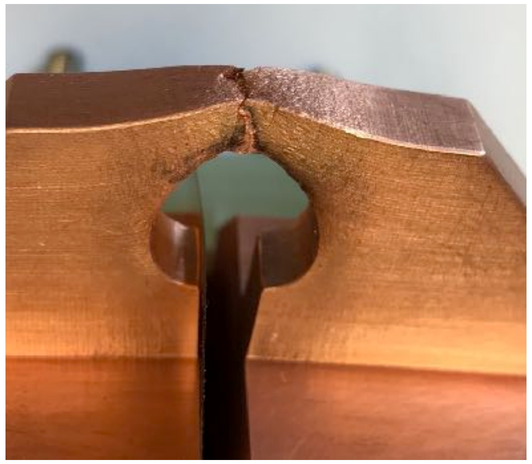


Before shot - 6.5 mm



After shot - 12.1 mm

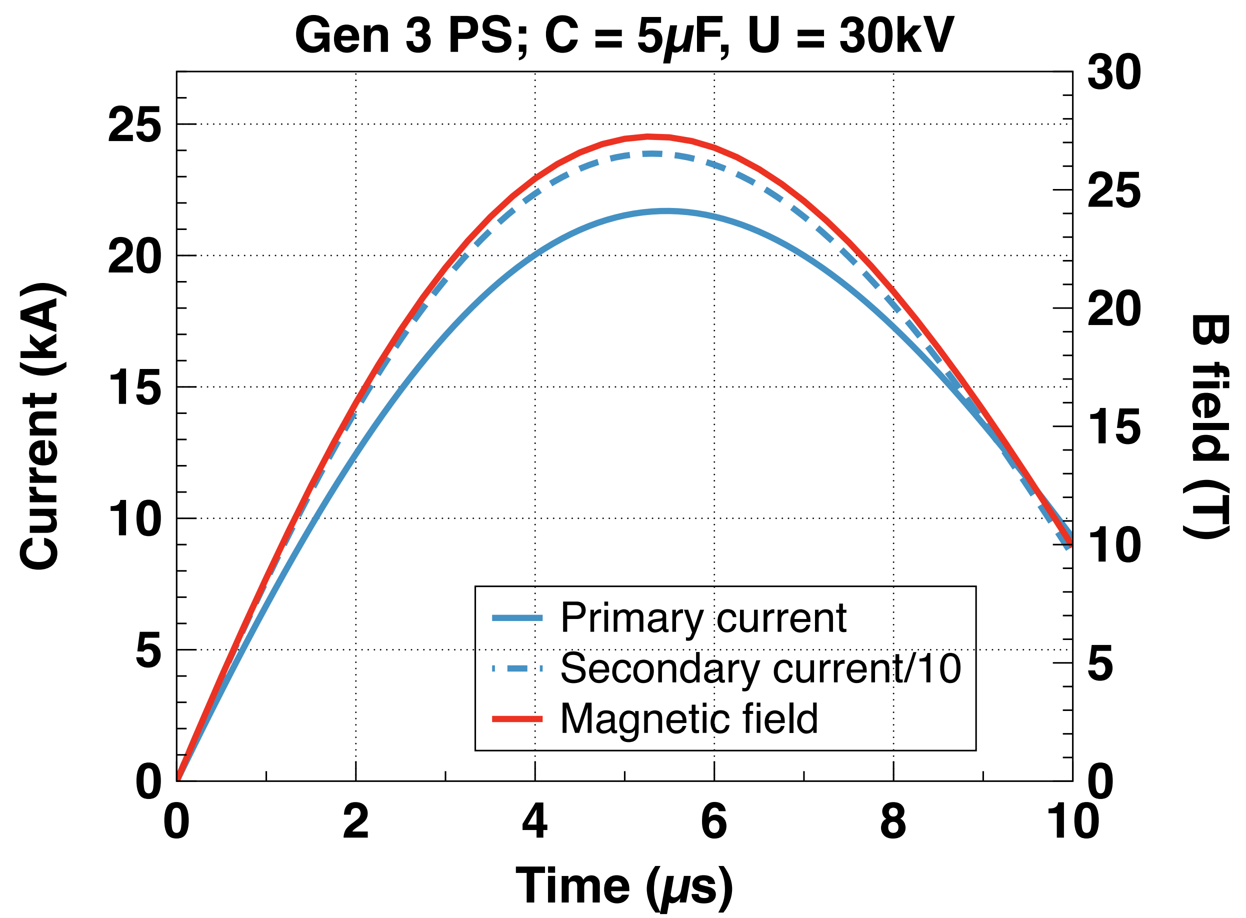




With a stronger material, a field as high as 40 T could have been possible. E.g. Beryllium Copper is x3 stronger while still low-resistive.

The inductive coil can be used with the MIFEDS Gen3 power supply

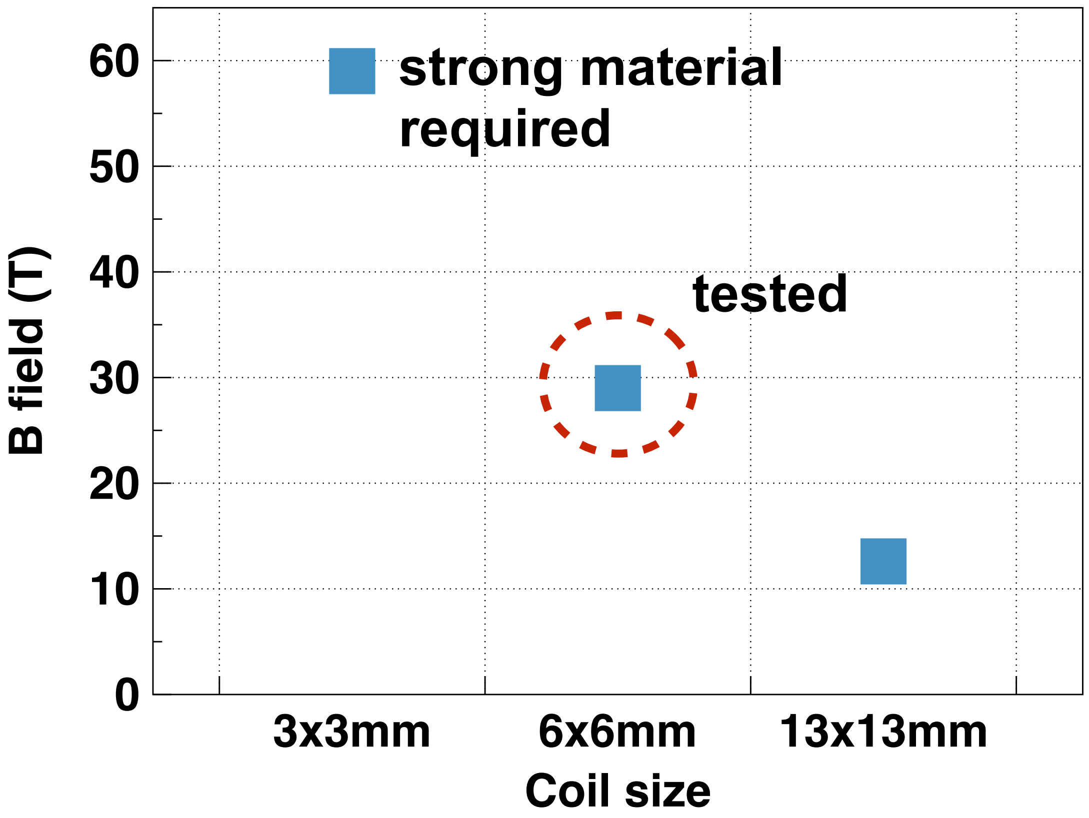
- **Connected to the Gen 3 power supply. C = 5 μF, U = 30 kV.**
- **Provides a 27 T B-field in a 6.5 mm sized coil with a zero-to-peak time of 5 μs**
- **The B-field pressure is the same as with a long-pulse power supply but the action is decreased by a factor of 6, which should significantly reduce the coil distortion**



The inductively-coupled coil approach can benefit applications such as ICF direct and indirect drives, and MagLIF

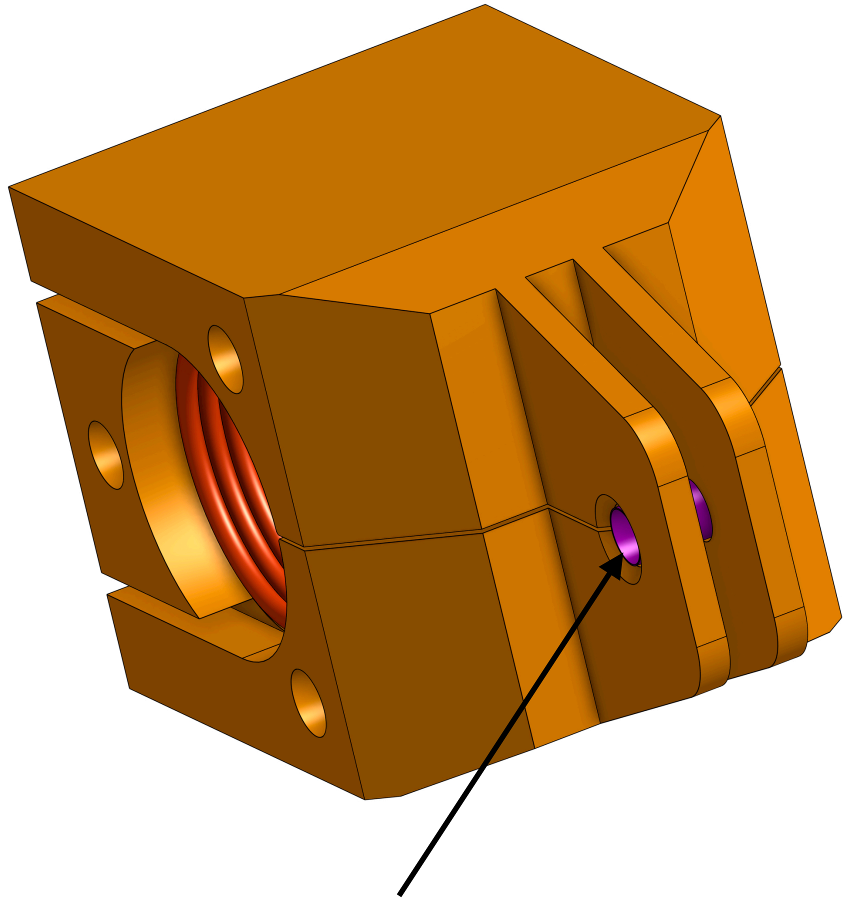
A combination of the tested field and size appears to be a good middle ground

One can go to a smaller size and a higher field or a larger size and a lower field



The coil provides good beam and diagnostic access along with the absence of debris

It make it suitable for applications such as ICF implosions, MagLIF, and NIF hohraums



A 5x10 mm hohlraum inside a Helmholtz configuration

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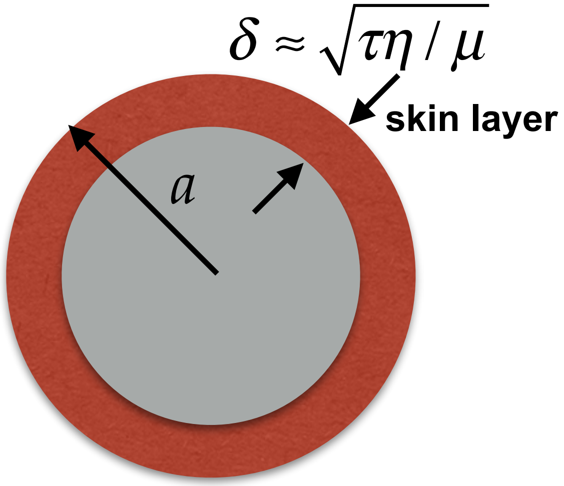
Backup slides

Resistive heating imposes a limit on achievable magnetic field



Case - short current pulse through a straight wire

If the pulse duration << skin time then the current is concentrated inside a thin skin-layer with a thickness $\delta \approx \sqrt{\tau\eta / \mu_0}$, where η is resistivity.

$$\Delta T = \frac{I^2 R\tau}{C_p \rho V} = \frac{\mu_0 I^2}{4\pi^2 a^2 C_p \rho} = \frac{B_a^2}{\mu_0 C_p \rho}$$

Wire resistive heating in the short-pulse limit does not depend on the wire size, resistivity, and pulse duration, only on the magnetic field at the wire surface!

$$\Delta T = 1080\ °\mathrm{C} \ \Rightarrow \ B = 70\ \mathrm{T}$$