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HTS Thin Films for Flux Pumping

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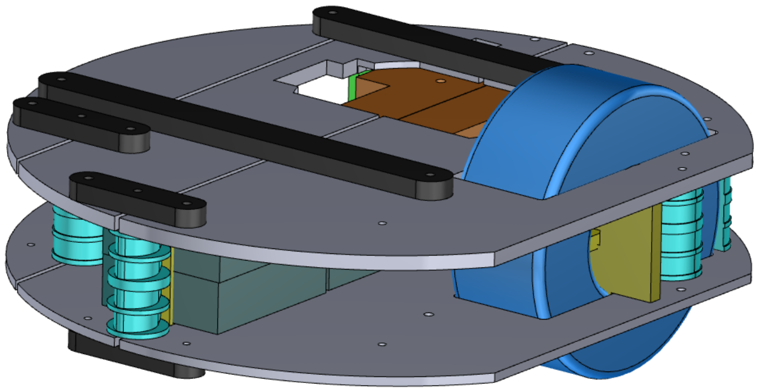
Contents

- Flux pump background
- SPICE simulations
- HTS thin film AC field switch
- Thin film flux pump initial results
- Proposed future designs

Flux Pumps – Superconducting Rectifiers

- **Wireless** (inductive) **power supply** for superconducting magnets
- Provides **thermal, mechanical, electrical isolation** of magnet
- **No** high-current **DC supply** or **current leads** required

University of Cambridge/NHMFL
Application: High Field Magnets



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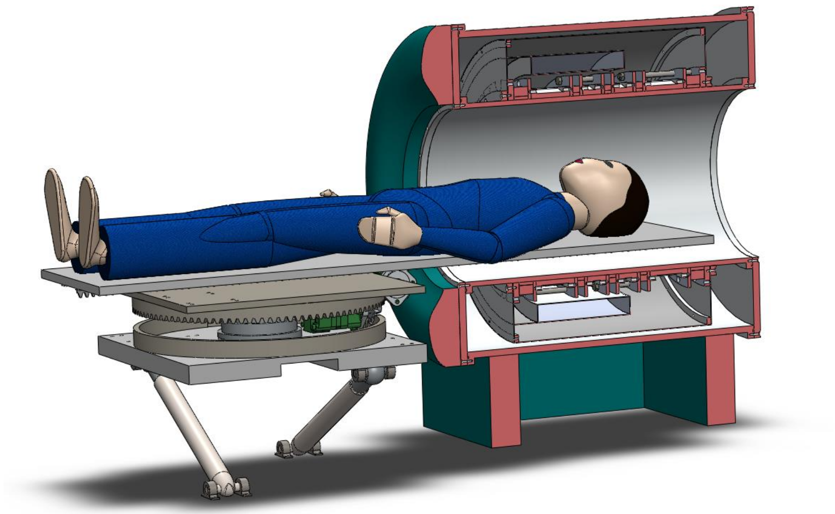
Application: Compact MRI



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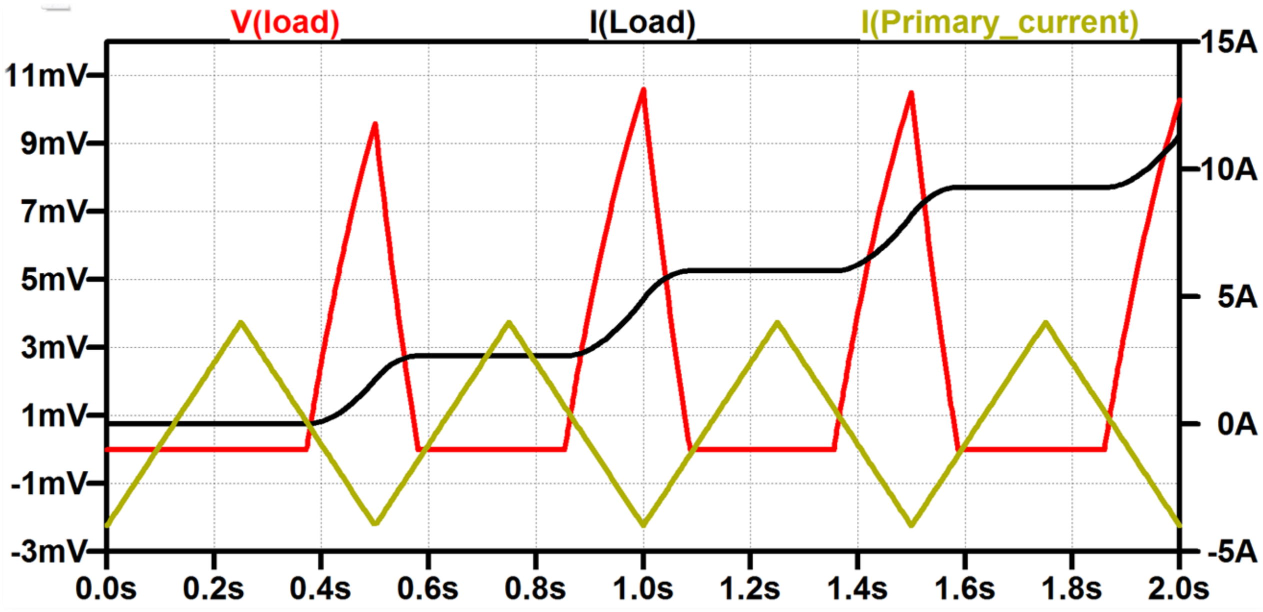
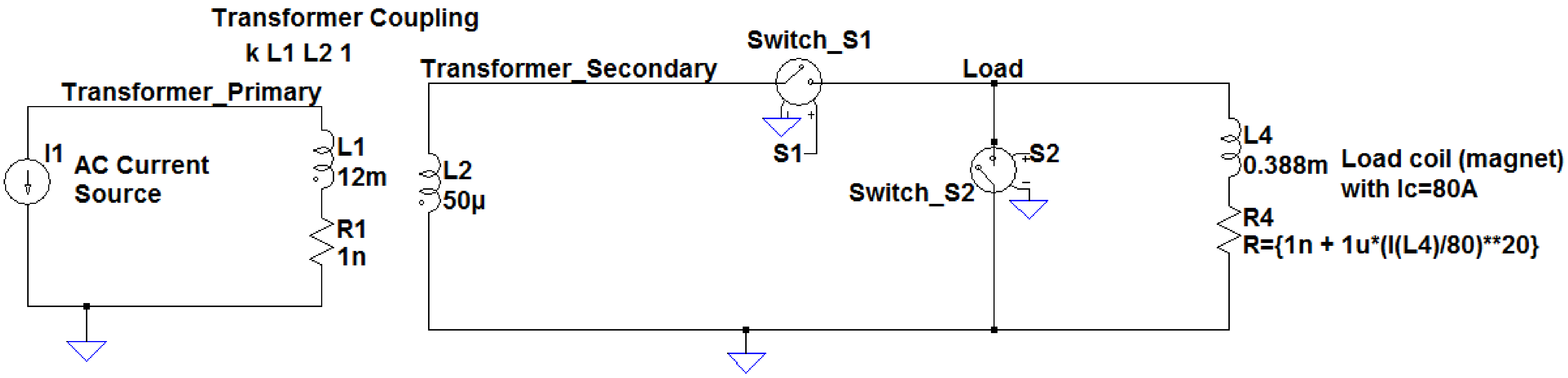
SPICE Simulation

- Standard for simulating SMPS
- Verified with prototypes
- Useful for design and analysis





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Key Findings from Simulation

- **Superconducting transformer**
  - **Power density** proportional to **operating frequency**
- **Superconducting switches**
  - Operation **frequency** is limited by on/off **switching time**
  - Majority of power **loss** depends on switch **off-state resistance**
  - Maximum **pump current** limited by **switch I_C**

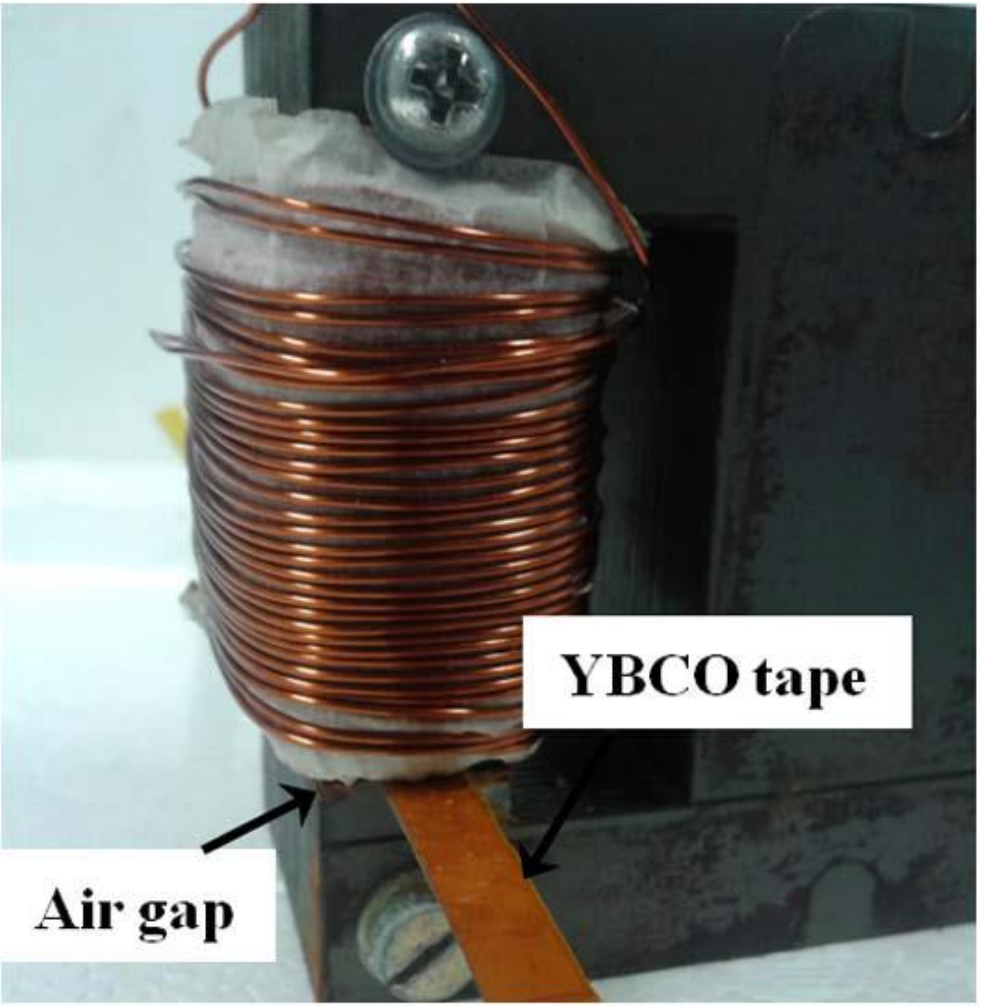
AC Field Switch

$$R_{d\perp} = \frac{4aLf}{I_{c0}}\left(B_{a,\perp} - B_{th,\perp}\right)$$

(for $B_{a,\perp} >> B_{th,\perp}$)

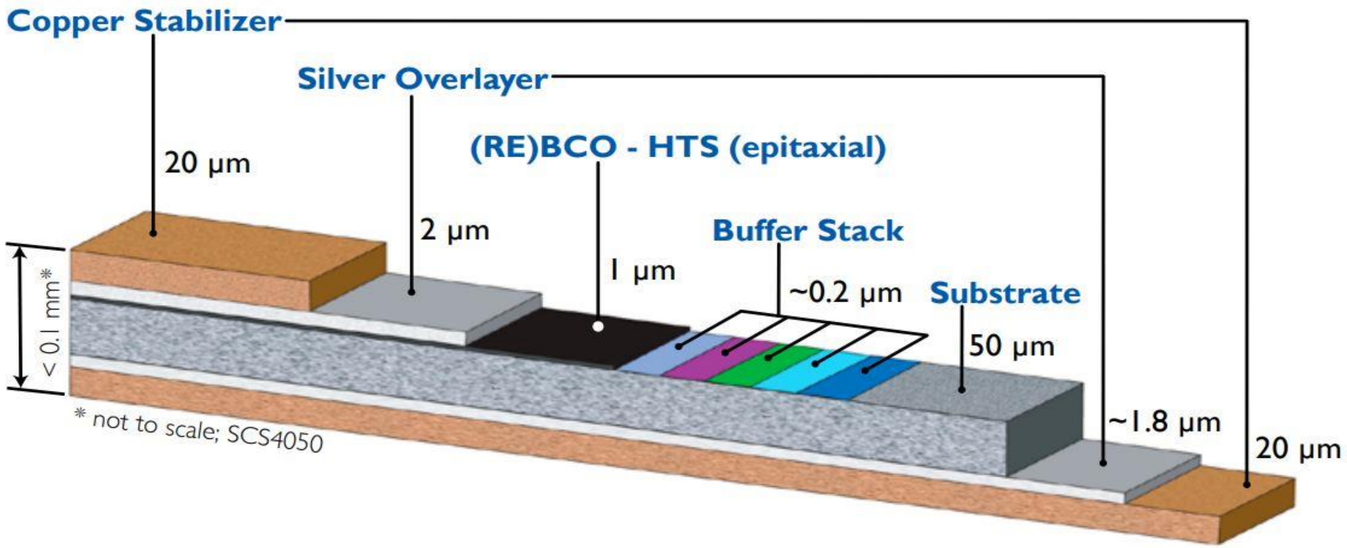
- Off-state resistance only ≈ 0.2mΩ
- Increase frequency and field
  - Better electromagnets
- Use **suitable superconductors**

AC Field Switch Developed by Geng [2]



[2] J. Geng *et al.*, “HTS Persistent Current Switch Controlled by AC Magnetic Field,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 1–4, Apr. 2016

Improved AC Field Switch – Conductor

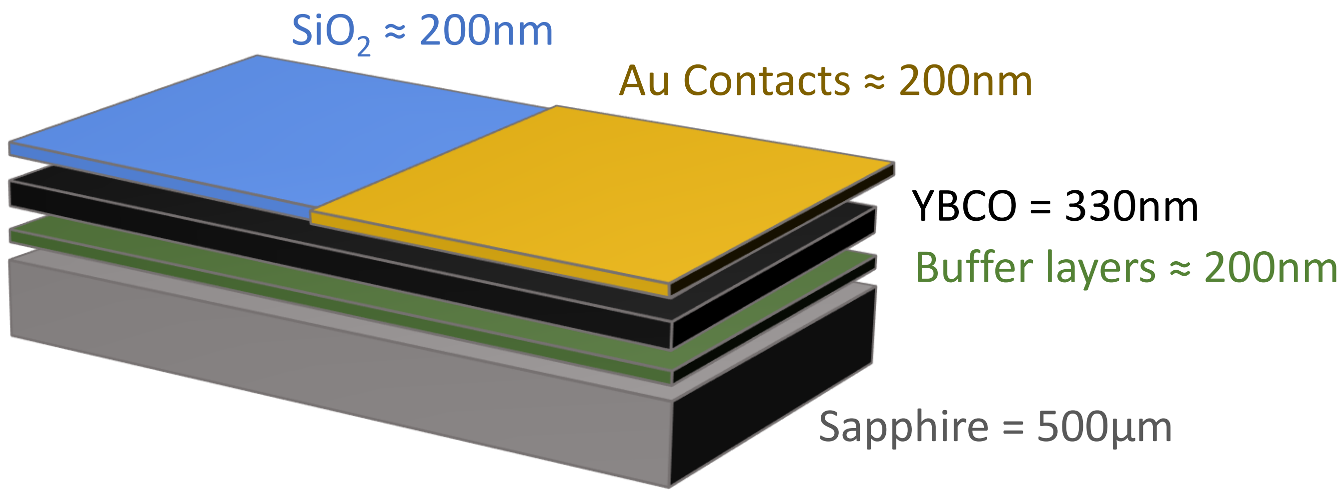


'2G HTS Wire'. http://www.superpower-inc.com/content/2g-hts-wire

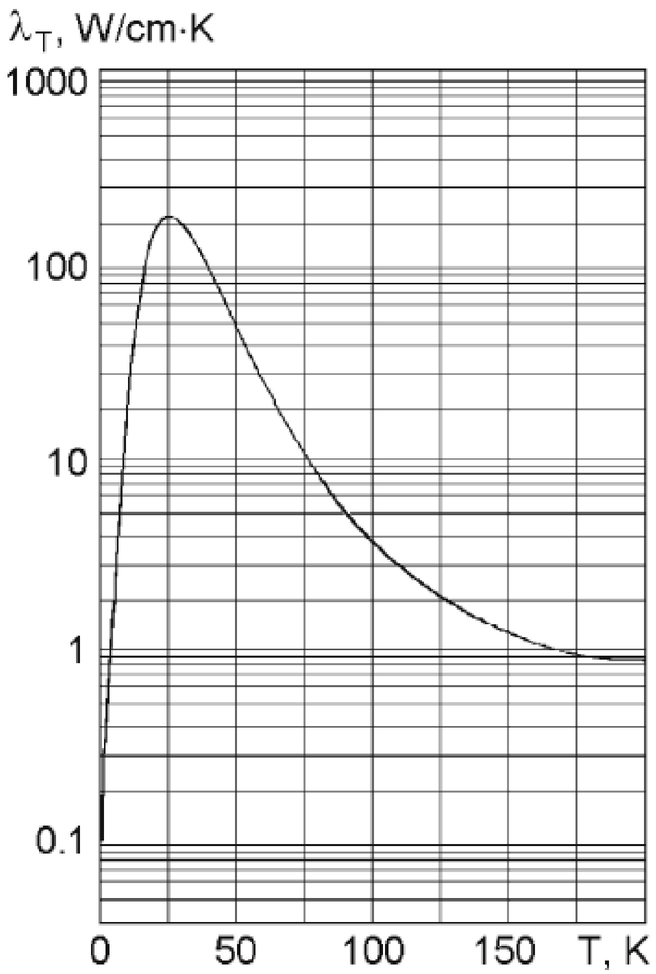
- Mechanically strong and high I_C
- Stabilizer and Ag provide parallel conduction
- Stabilizer and Ag shield applied field

Layer	Resistance per meter (Ω)
40µm Copper Stabilizer at 77 K	0.015
3.8 µm Ag layer at 77 K	0.3
50 µm Hastelloy at 77 K	7.5
Dynamic Resistance of YBCO layer at 100 mT, 1 kHz	1.5
Dynamic resistance of YBCO layer at 100 mT, 10 kHz	15
1 µm YBCO Thin Film at 100 K*	120

HTS Thin Films on Insulator



- No parallel conduction paths
- Excellent heat sinking to sapphire at 77K
- Brittle substrate
- More expensive than coated conductor



Thermal Conductivity of sapphire vs temperature

E. R. Dobrovinskaya, L. A. Lytvynov, and V. Pishchik, *Sapphire: Material, Manufacturing, Applications*. Springer US, 2009.

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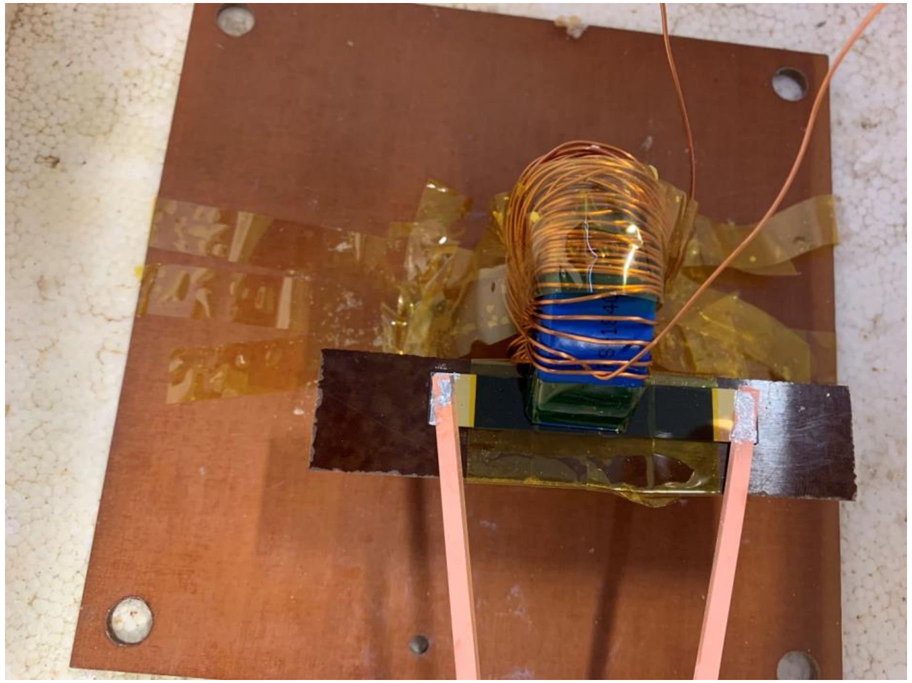
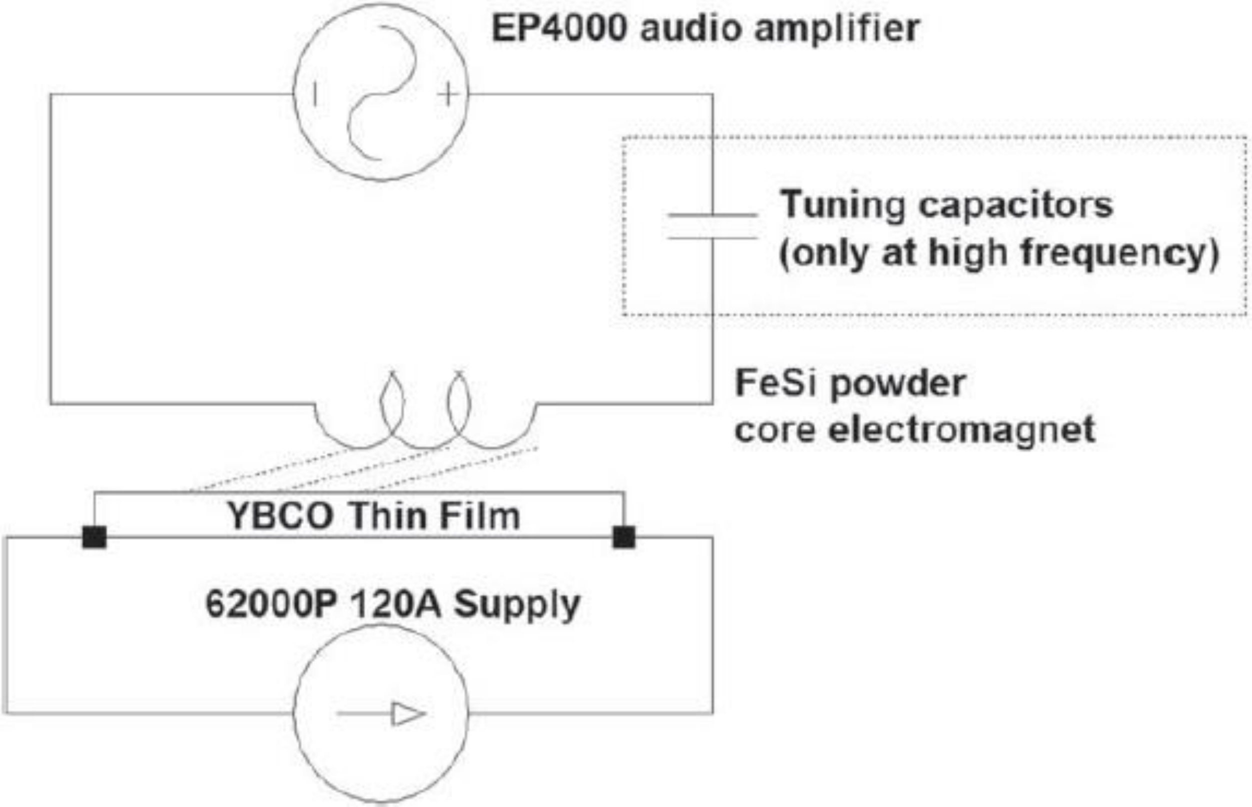
Thin Film Switch





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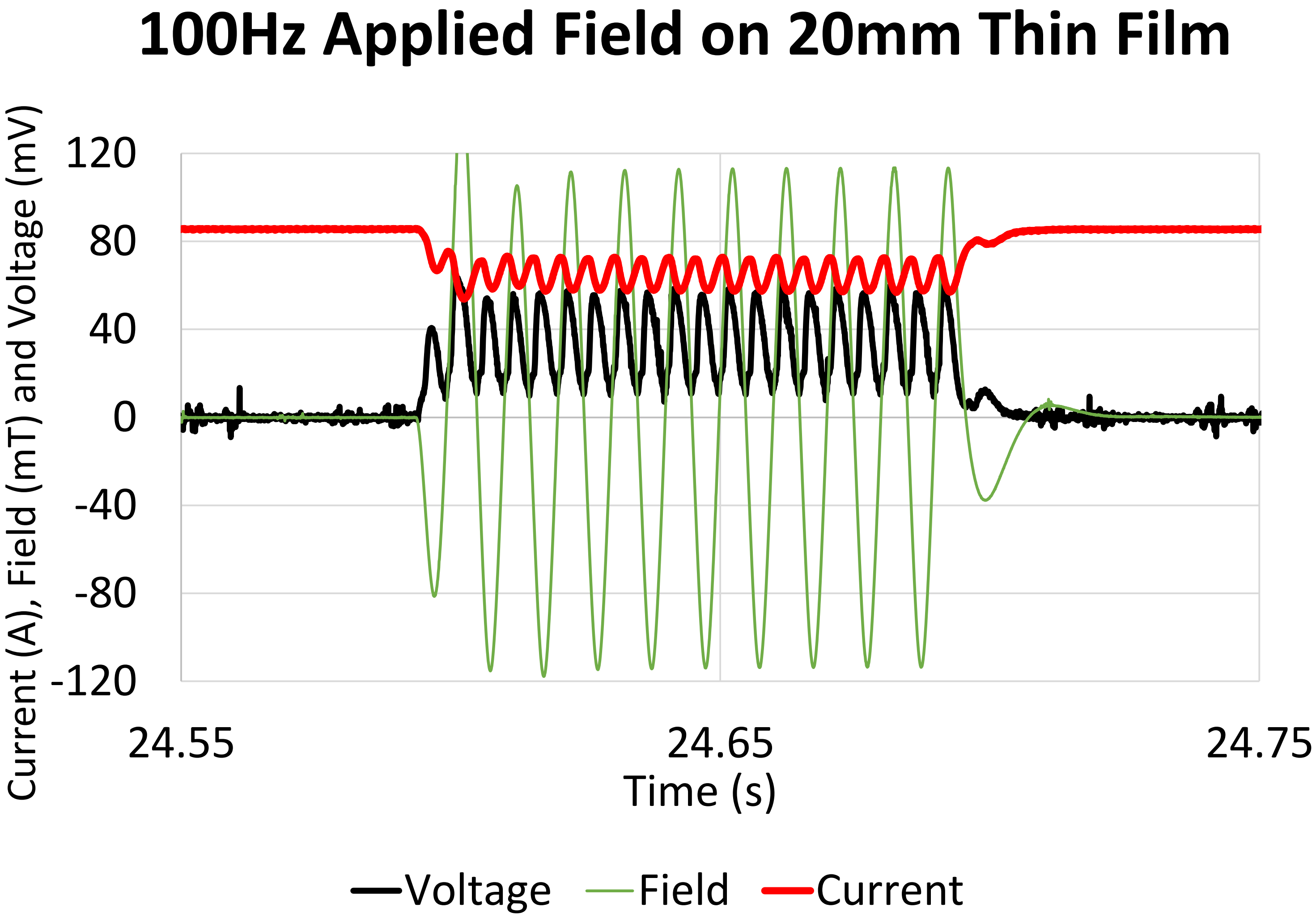
Thin Film Switch

- ≈0.5mΩ off-state
- Negligible switching delay
- Decent electric field (≈2Vm^{-1})



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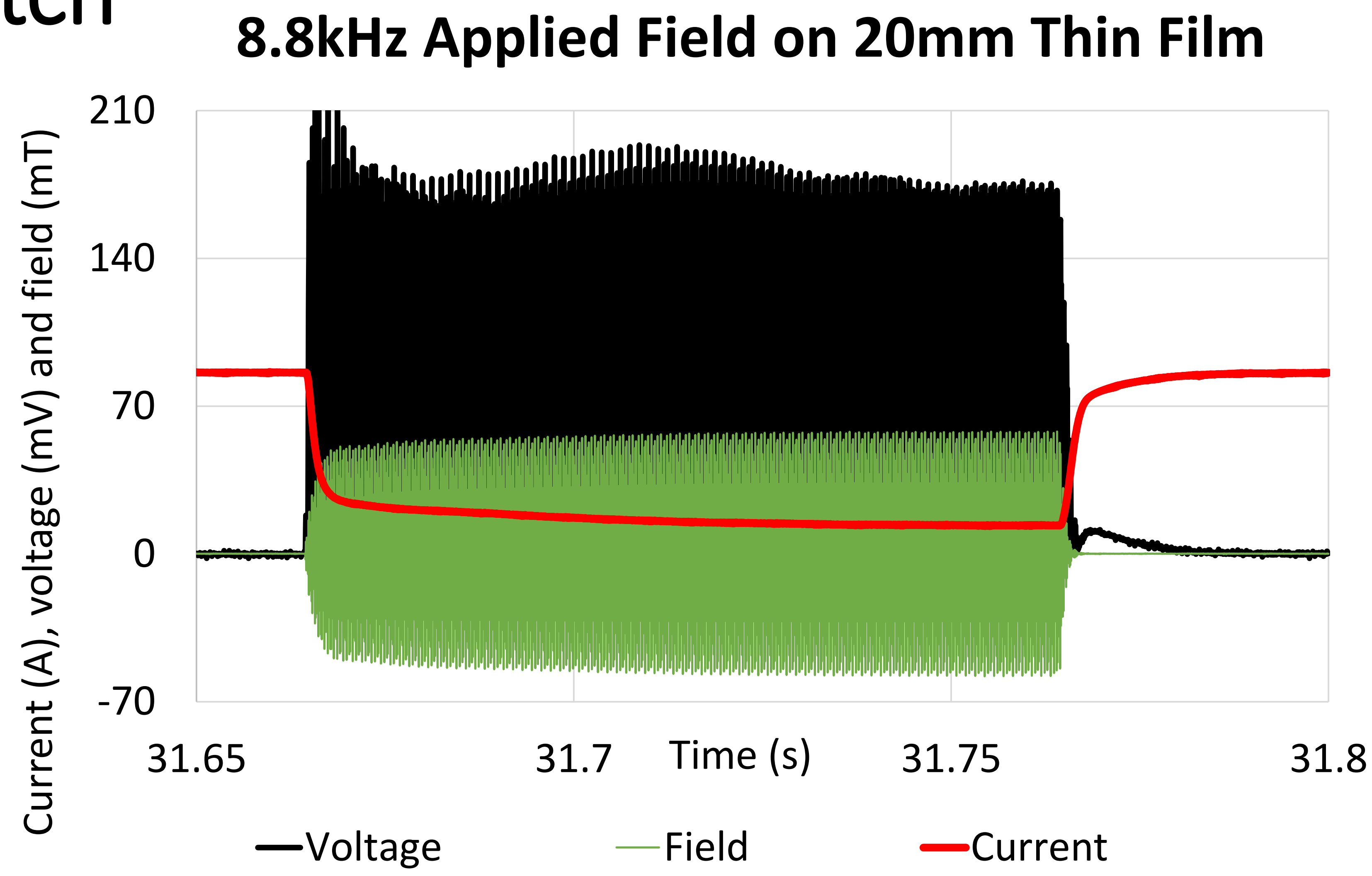
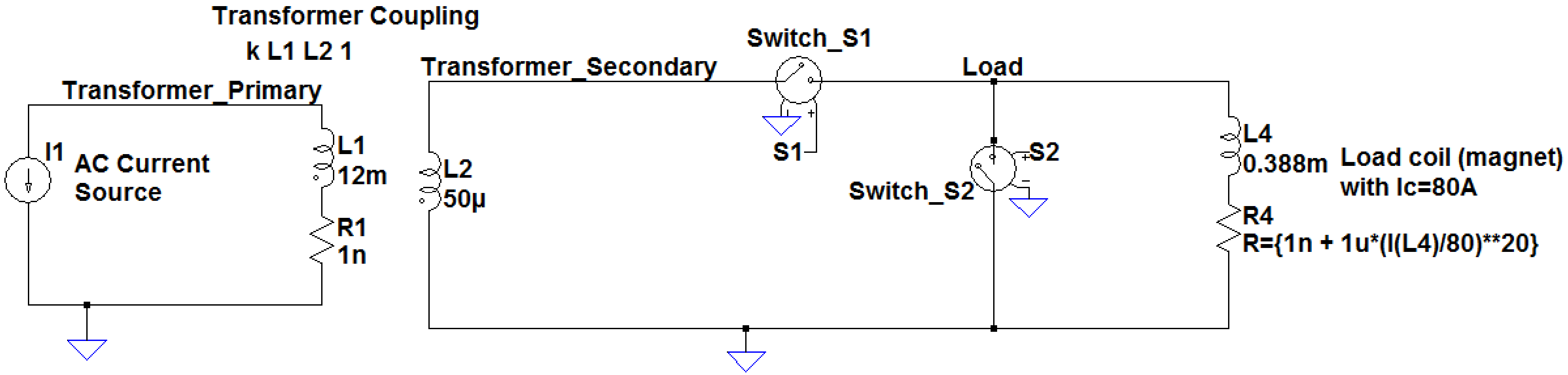
Thin Film Switch

- ≈9mΩ off-state
- Short switching time (<15ms)
- Good electric field (≈5Vm^{-1})
- Current limiting demonstrated

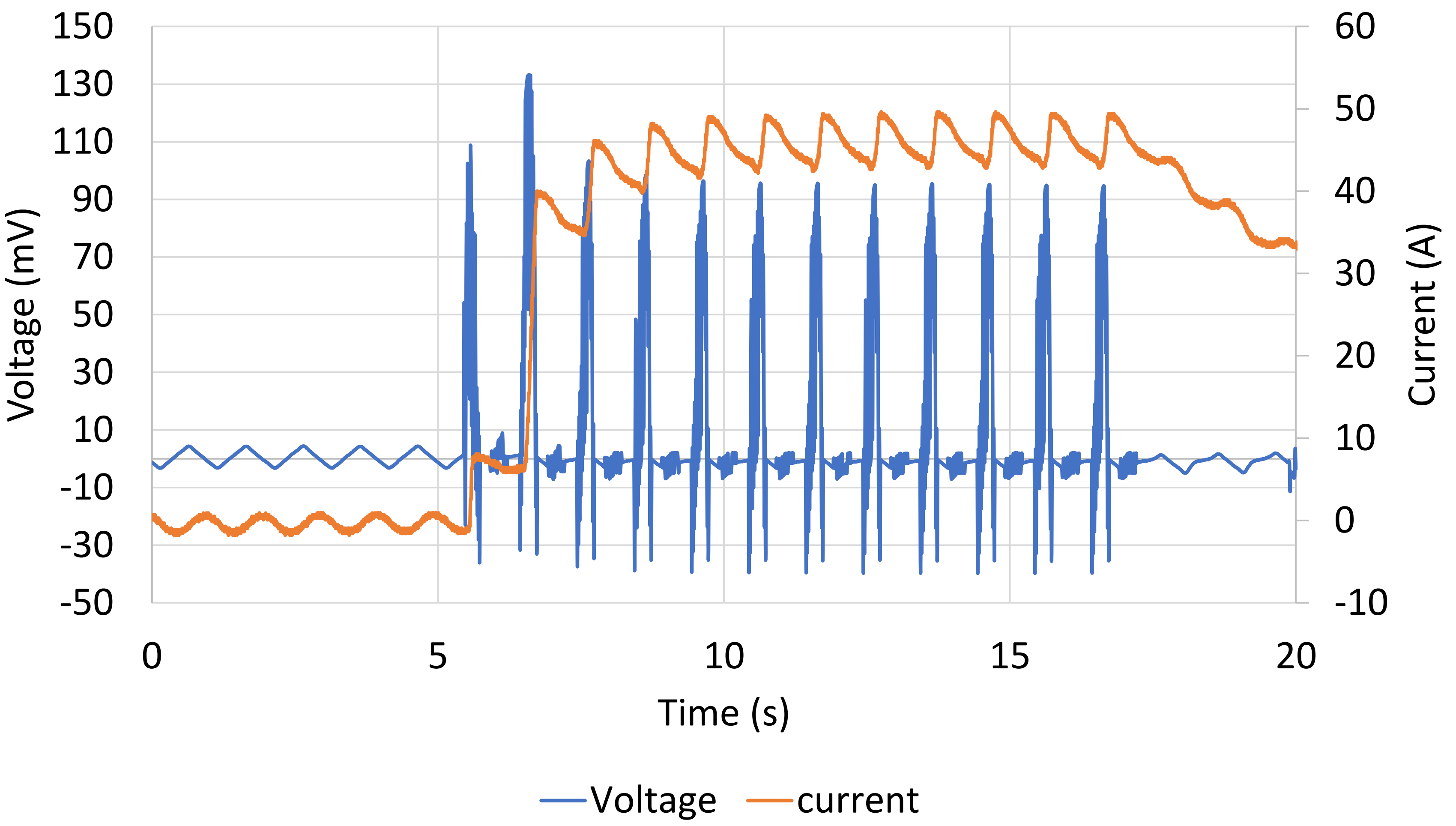


Thin Film Flux Pump

- Half-bridge configuration
- 1Hz operating frequency
- 25cm^2 iron-core transformer cross section

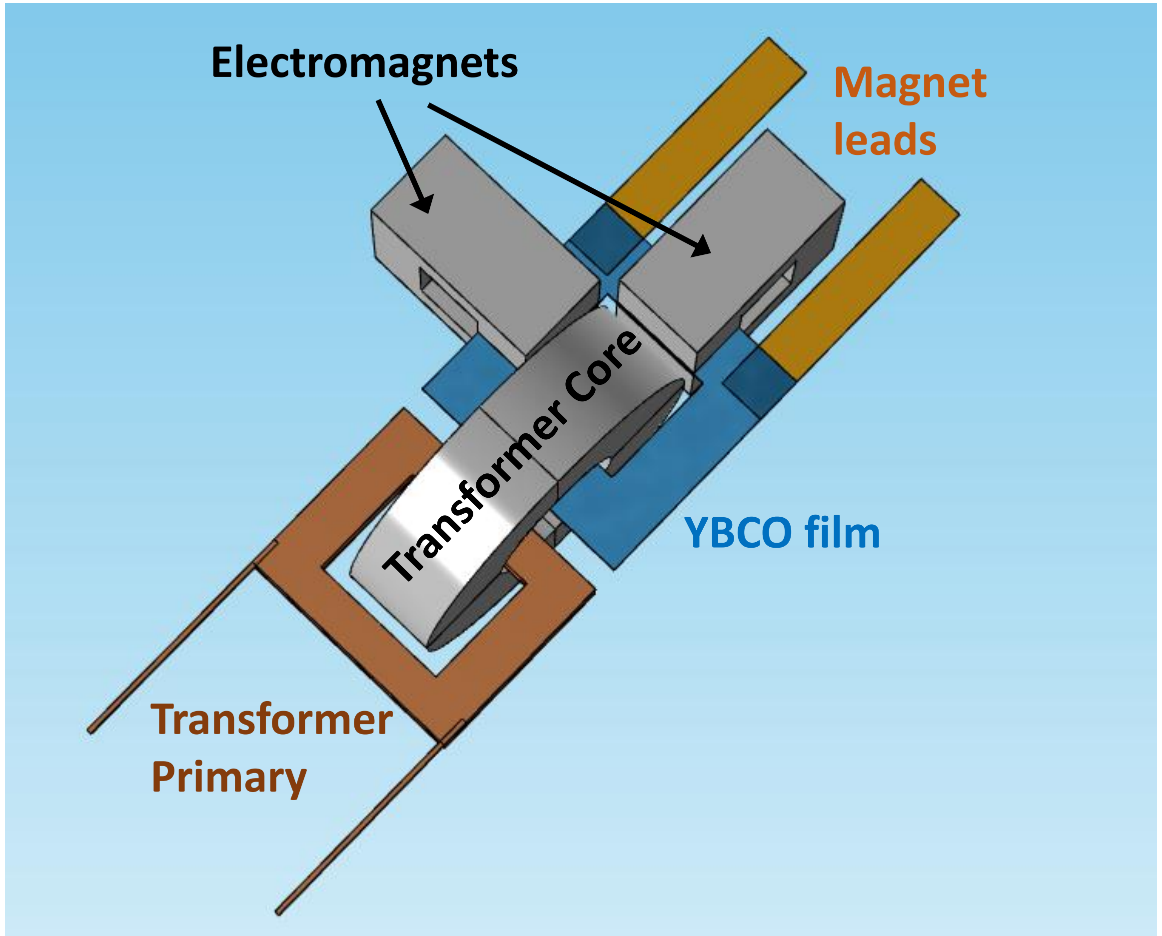


Thin Film Flux Pump Results



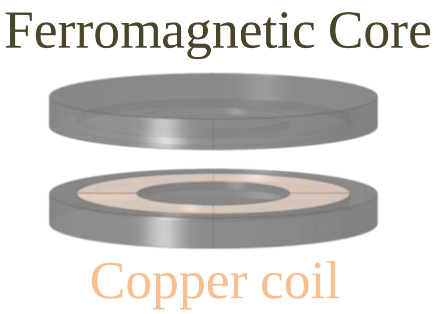
- Can provide >100mV to load
- Fast Recovery
- Performance limited by high joint resistance (10 joints)
- Development ongoing

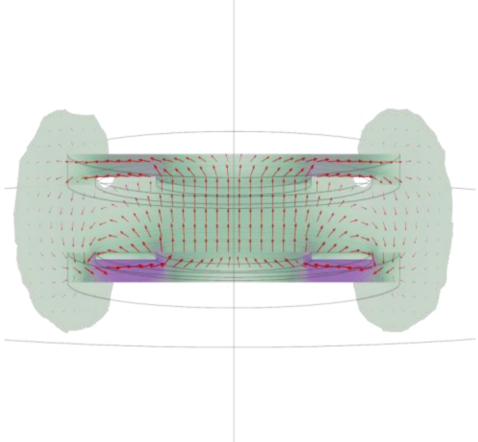
Single Film Flux Pump – Concept

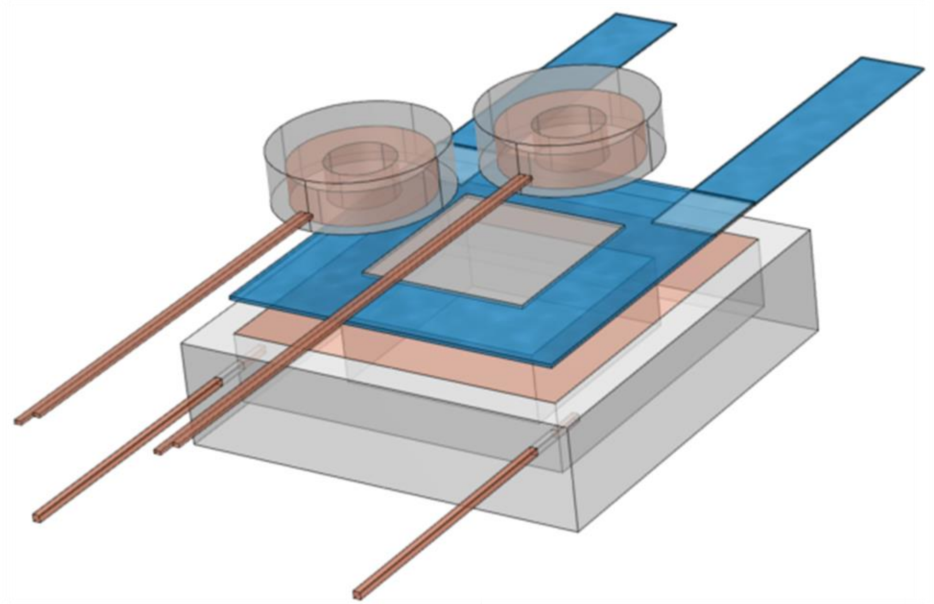


- Transformer and switches integrated on a single film
- Only 2 joints (down from 10!)
- Low stray switch inductance
- Bulky transformer and electromagnet cores
- Incomplete mechanical isolation due to transformer core

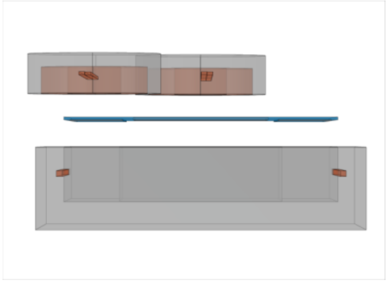
Wireless Power Coupler Flux Pump – Concept

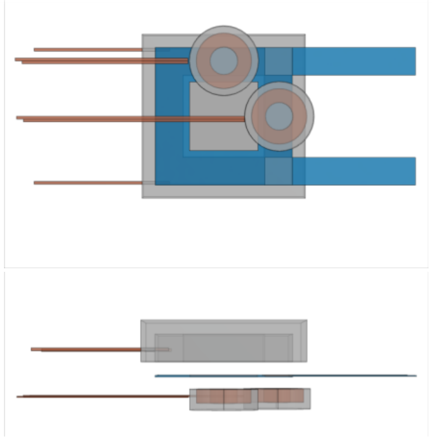






- Mechanically compact
- Full mechanical isolation
- Stray fields from transformer and switches may cause I_C reduction, power loss





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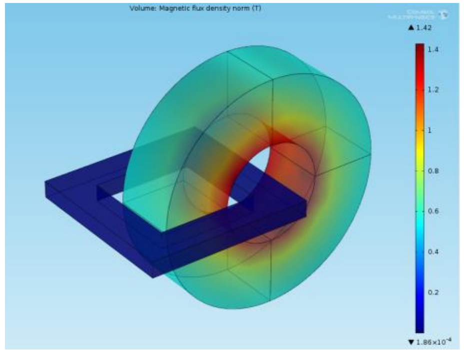
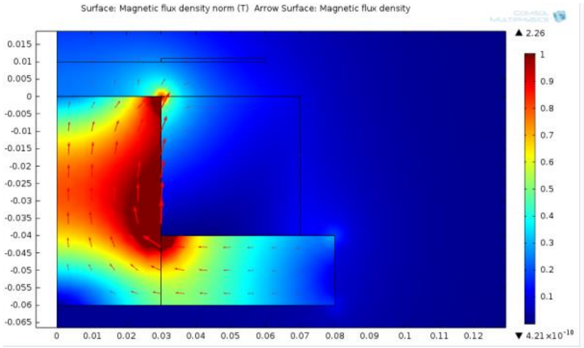
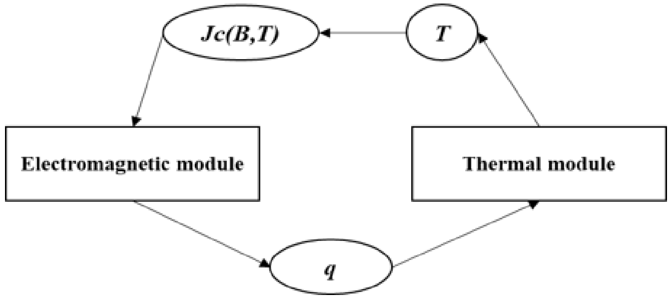
Design Workflow

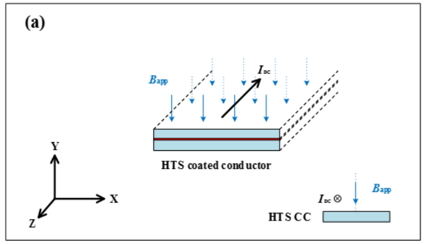
Magnetostatics 2D/3D FEM



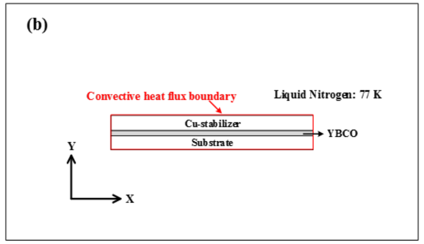


Thermal-Magnetic 2D Transient



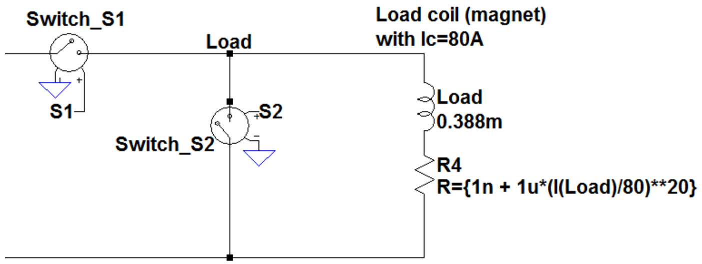


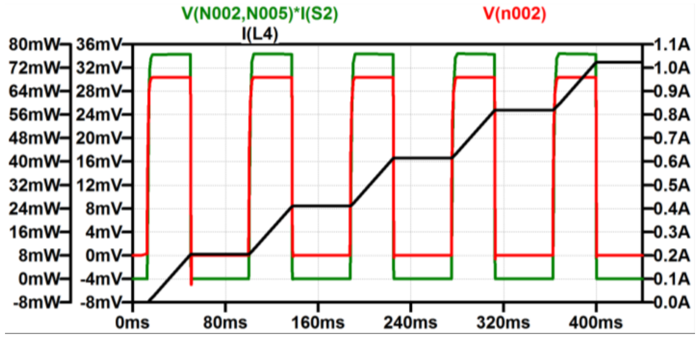
Electromagnetic module



Thermal module

Circuit Simulation Transient





Switch and Transformer Field Profiles → **Switch resistance, electric field, power loss and temperature** → **System behaviour, transformer and switch interaction, total power loss**

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Conclusion

- **Flux pumps** are a **promising alternative** to conventional superconducting magnet power supplies
- Better **switches** needed for better flux pumps
- Good **switches** can be made using **thin YBCO films** on insulator
- These switches have been used to build a **prototype**
- Flux pumps can be **fully simulated** from component to system level
- Many **avenues** exist for significantly **improving** flux pumps

Thanks for Listening!

Contact:
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YBCO Films supplied by:
Ceraco GmbH

Cambridge EPEC Superconductivity Group

Future Work

System

- Improve thin film flux pump joints
- Build integrated transformer secondary and switches on a single film

Switches

- Look at other candidate HTS materials and other switching mechanisms
- Outperform semiconductor technology in the low voltage/high current space

Transformer

- Wireless power transfer - primary outside cryostat
- Operate at higher frequency (HTS AC Conductor)

Control

- Lossless commutation
- Bi-directional power transfer
- High field stability