HTS Shim Coils Energized by a Flux Pump for MIT 1.3-GHz LTS/HTS NMR : Design, Construction, and Results of Proof-of-Concept Prototype

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Motivation

- For a high-resolution NMR the field must be uniform with an error field of 0.01ppm over a sample volume

  ➔ ***Field shimming*** is absolutely necessary!

- Conventional shims are made of NbTi, and NbTi shims are mostly located outside the magnet
  - Field limitations: <12 T even at 1.8 K
  - Radial build winding size: 15~30 mm

Motivation

- Two inherent disadvantages of NbTi shims for *MIT 1.3 GHz LTS/HTS high-resolution NMR magnet* (1.3G):

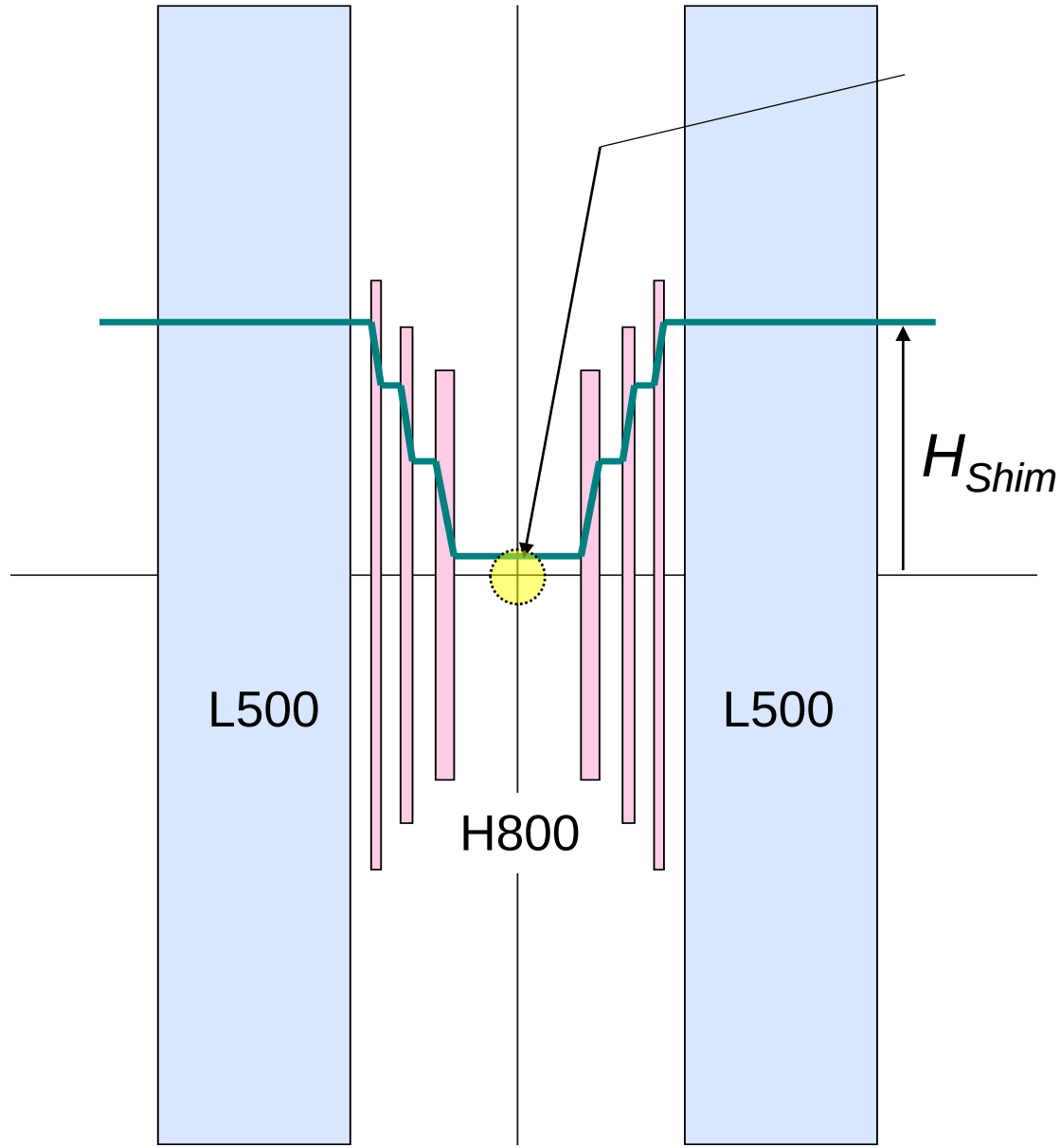
  1) Outside the magnet each coil must work harder to generate a required shim strength:
     A greater **ampere (current) - turns (coil size)**
  2) The shim fields are attenuated by **"Diamagnetic" walls** of the 3-nested-coil H800 as the shim fields reach the center

Inner-Bore HTS Shim Idea

- HTS shim coil is:
  - operable even in **>12-T**
  - slim (**1-mm radial build**)

➔ can be placed inside the magnet assembly

➔ can be designed for stronger shim field



Z1/Z2 HTS Shim for 1.3G

❑HTS conductor selection for the shim

- Radial space: as small as possible for 1.3G RT bore = Ø54 mm
  → Both Z1 and Z2 be wound on the same plane with <u>1-layer winding</u>
- Persistent mode operation at >100 A, 30.5 T, 4.2 K
  → **<u>Reinforced Bi-2212 wire</u>**

❑Design requirements

- Z4/Z6 Error % <0.1 @ 10 mm-DSV, e.g. when the shim coil produce 1000 ppm of Z2, <1 ppm of z4 and z6
- Mutual inductance with 1.3 GHz magnet must be minimized to protect the shim coils from magnet quench
- Shim Strength: **<u>>500 Hz/cm^n/A</u>** → as high as possible

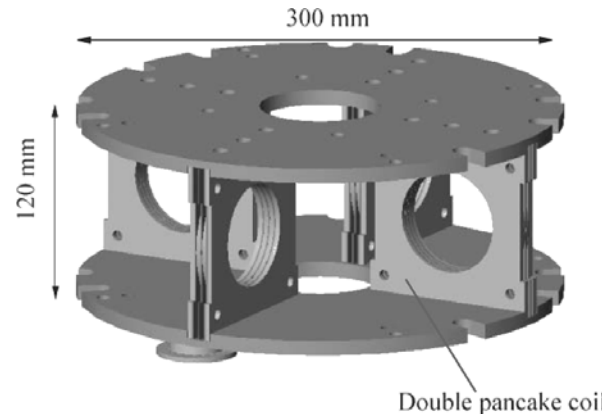
Z1/Z2 HTS Shim for 1.3G

Shim dimension	Z1 (Negative symmetry)	Z2 (Symmetry)		
		$Z2_1$	$Z2_2$	$Z2_3$
a1 [mm]	40	40	40	40
a2 [mm]	40.6	40.6	40.6	40.6
b1 [mm]	30	8	41	102.6
b2 [mm]	40	15.5	88.5	145.1
Turns	8	6	-38	34
Shim performance				
Z0 [Hz/A]	0.0	4.7		
Z1 / Z2 [Hz/cm^{1,2}/A]	1684.5	-892.9		
Z3 / Z4 [Hz/cm^{3,4}/A]	-2.2	-0.5		
Z5 / Z6 [Hz/cm^{5,6}/A]	-3.2	1.7		
Shim - 1.3G Inductance				
Self Inductance [μH]	17	338		
Self Inductance of 1.3G Magnet [H]	218.5			
Mutual Between Z2 and 1.3G [μH]	0	6		

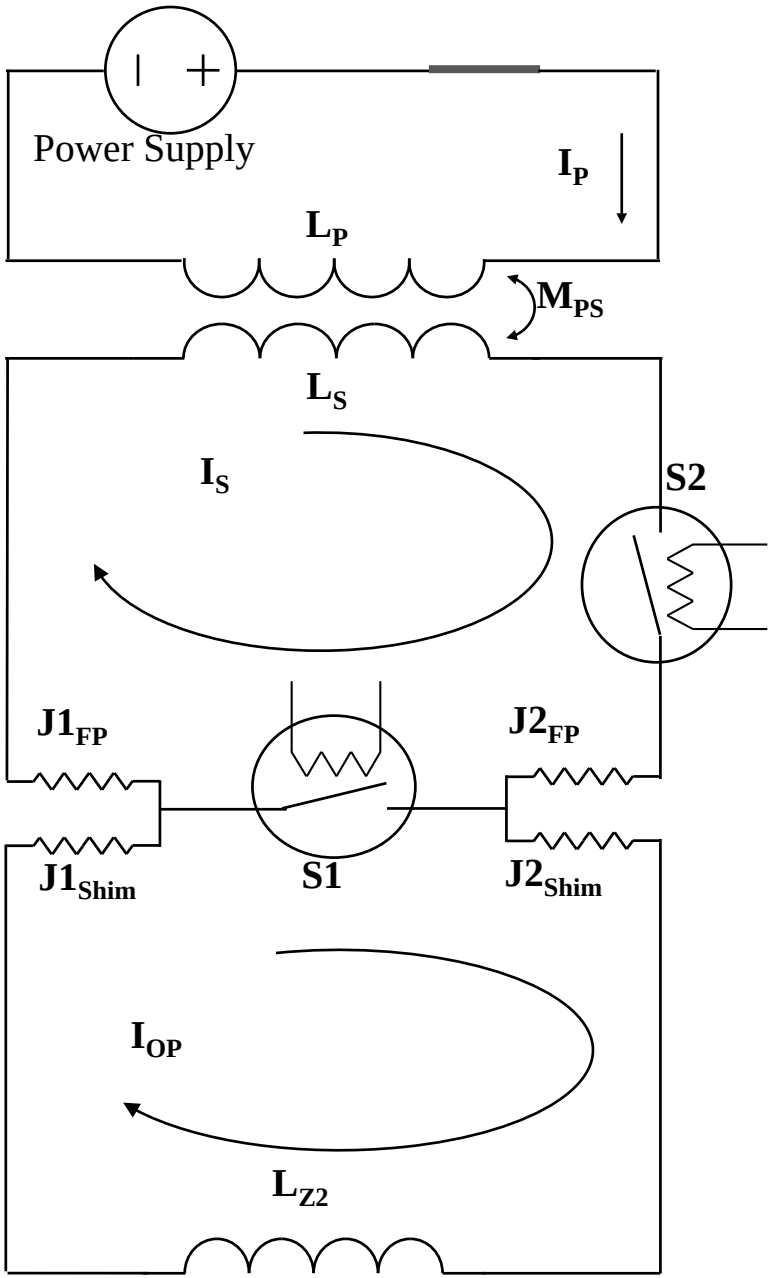
Energization with Flux Pump

Conditions and Requirements

- Making flux pump coils Toroidal so that the field at the magnet center must be ~0
- Placing the flux pump above the liquid level and conduction-cooled
- Opening time of each switch must be within a few seconds – the vapor environment will be helpful



A Proof-of-Concept Test at 77 K



Objectives

- ❑ Z2 shim coil design verification
- ❑ Build and test an HTS Flux pump
- ❑ Proof-of-Concept (POC) test in LN2

Superconductor

- ❑ Z2 shim coil, Flux pump coil (2nd)

  : 2-mm *wide* REBCO (SuperPower)

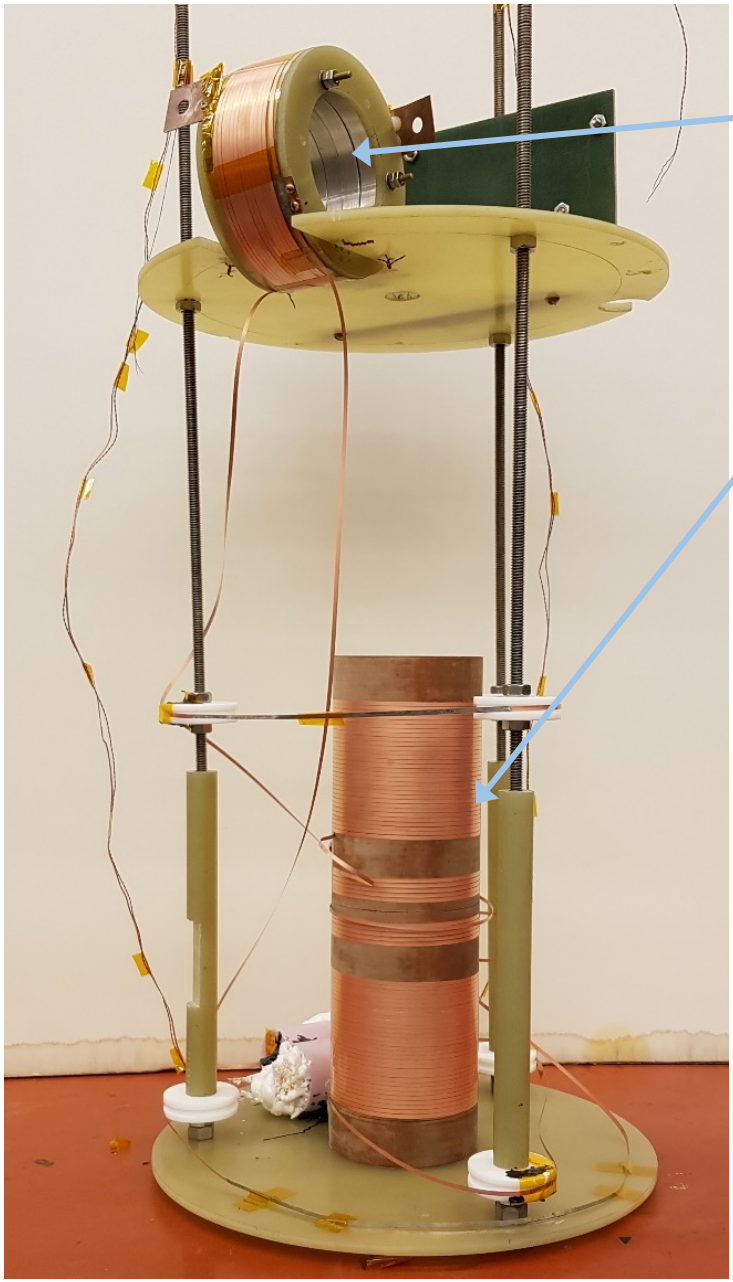
- ❑ Flux pump coil (Primary)

  : 4.5-mm *wide* Bi-2223 (SEI)

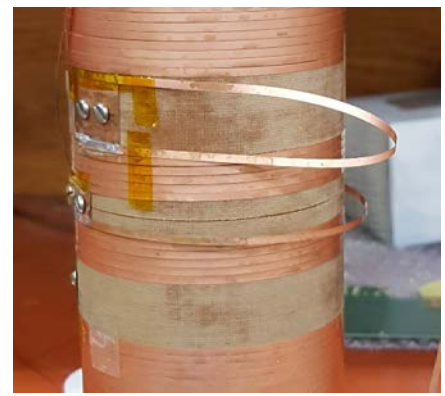
A Prototype Design

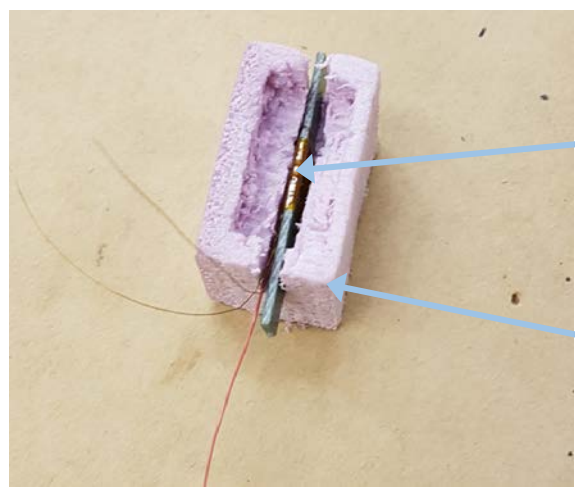
Z2 Shim Coil		**Z2-1**	**Z2-2**
Conductor, dimension	[mm]	REBCO, 2 x 0.065	
Winding ID (2a1) / OD (2a2)	[mm]	76 / 76.1	
Bottom / Top z positions (b1 / b2)	[mm]	6.2 / 16.7	36.9 / 102
# of Turns / (coil pair)		2 x -5	2 x 31
Self-inductance, L_{Z2}	[μH]	110.9	
0th, 2nd, 4th, and 6th Term	[Hz/cm^n/A]	-8 / **794** / 1 / 2	
Flux Pump Coils		**Primary**	**Secondary**
Conductor		Bi2223 tape	REBCO tape
Conductor dimension	[mm]	4.5 x 0.31	2 x 0.065
Winding ID (2a1) / OD (2a2)	[mm]	72.6 / 90	92.5 / 92.6
Winding height (2b)	[mm]	36.9	30
Total # of turns		224	14
Self-inductance, L_P & L_S	[H]	3913	23.3
Mutual inductance, M_{PS}	[H]	250.9	

Photos of the Prototype System



- Flux pump coils 2nd winding was wound on the 1st winding
- Z2 shim coil was wound continuously
  *each pair was wound oppositely

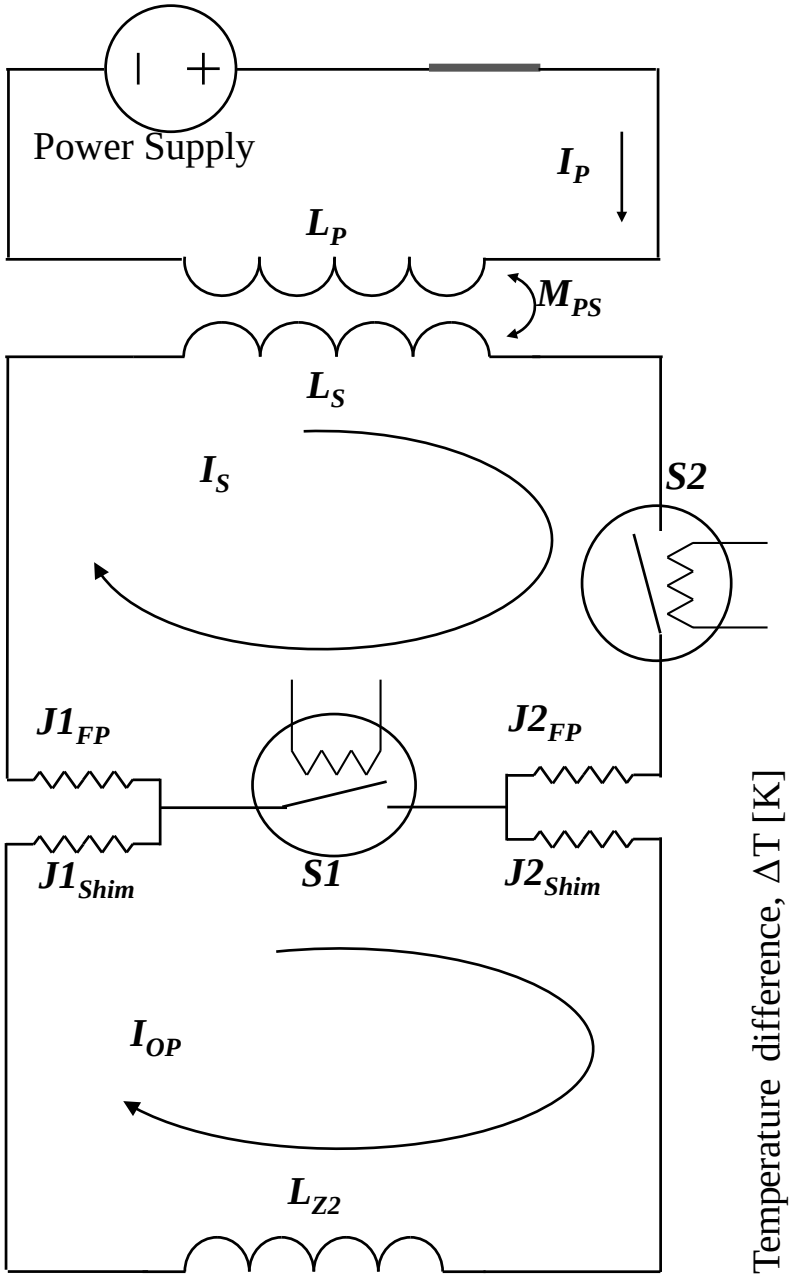




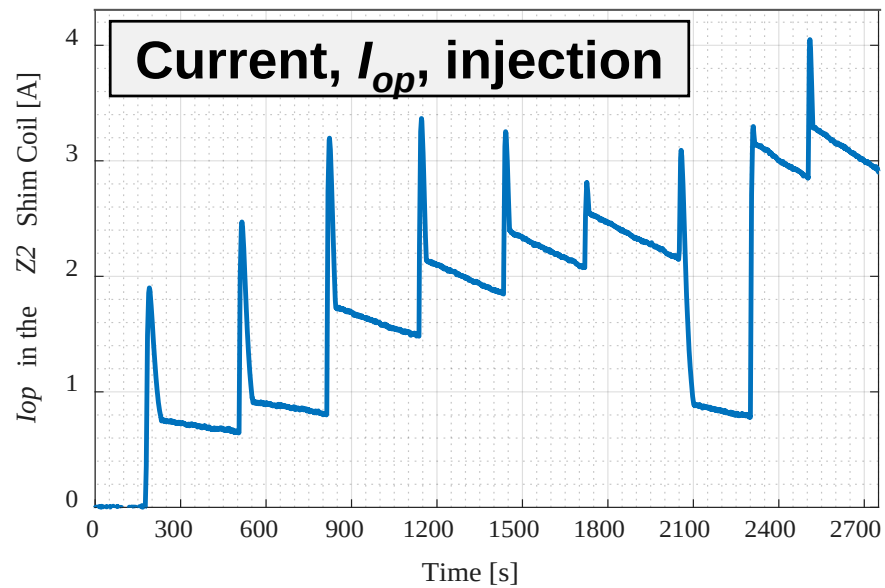
350-Ω heater (strain gauge)

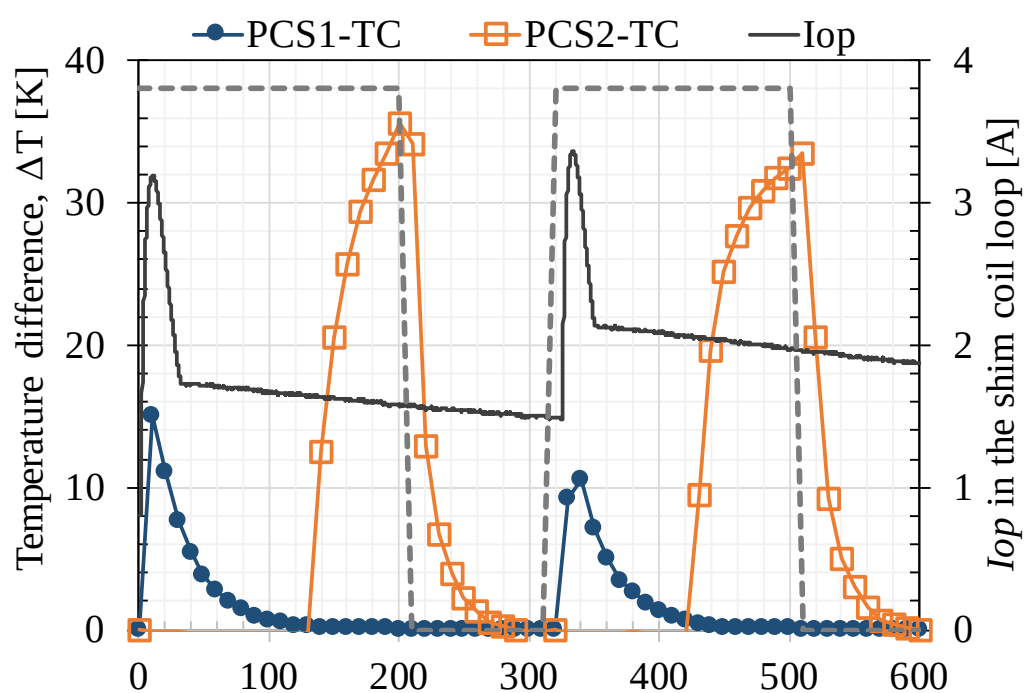
Styrofoam Insulation

Flux Pumping Result-1



Circuit Diagram





A plot of flux pump test

Flux pump Sequence

1) $I_p \uparrow$
2) S1 open
3) S1 close
→ Persistent Mode
4) S2 open
5) $I_p \downarrow$
6) S2 close

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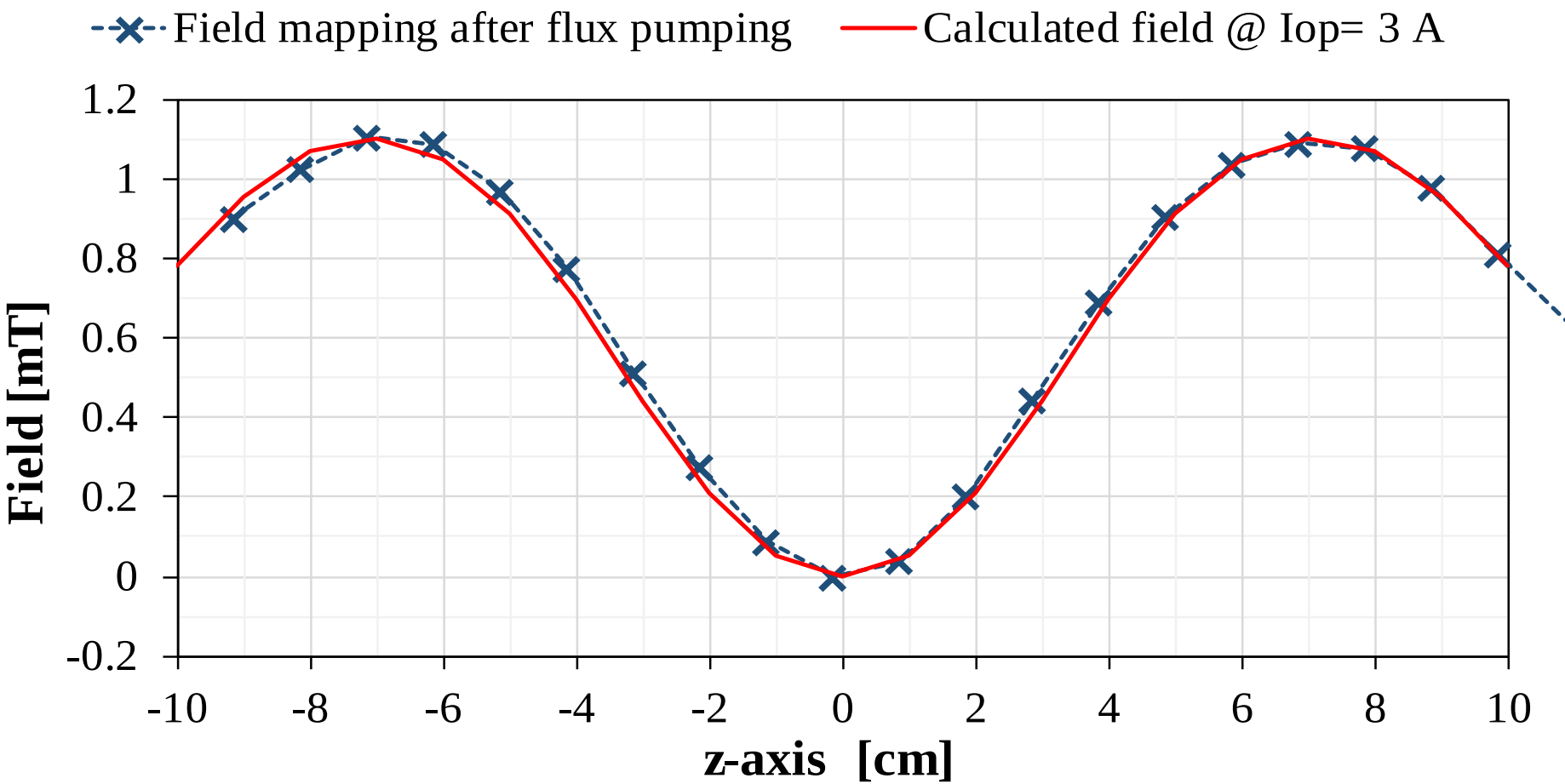
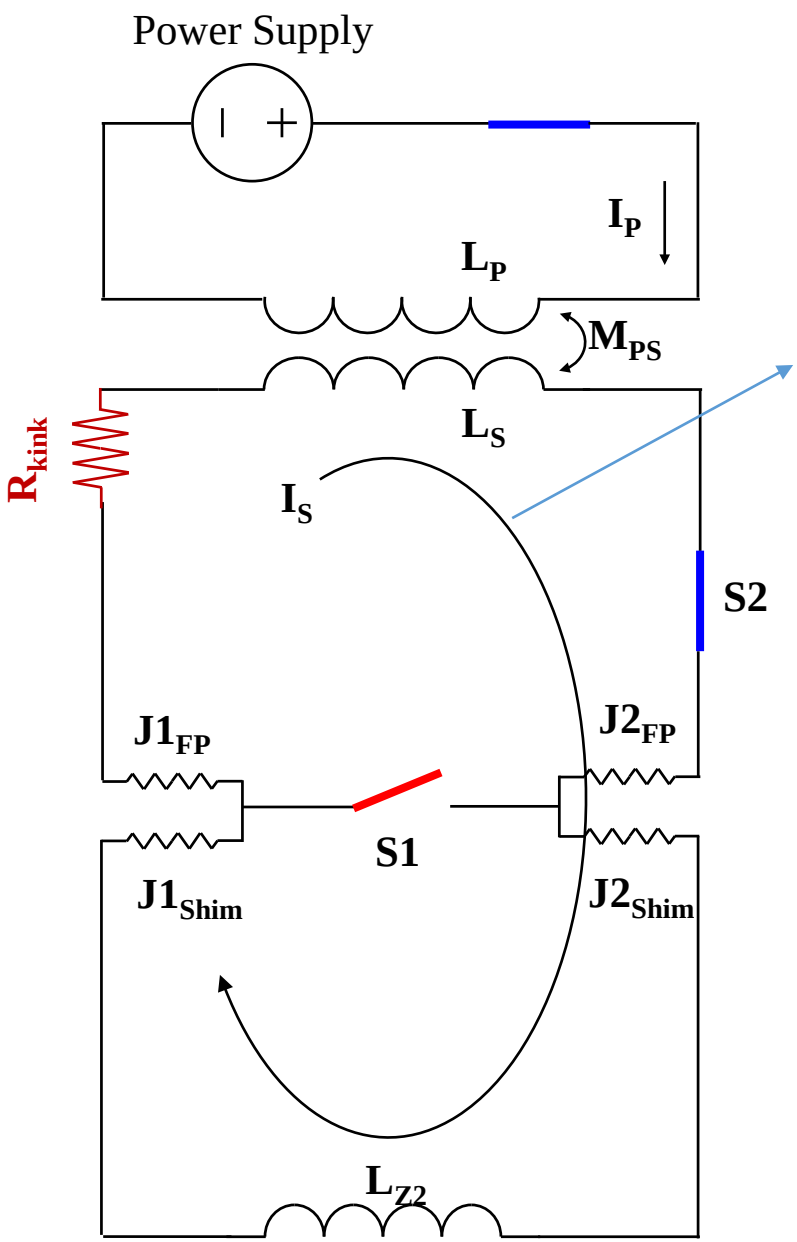
Result-2



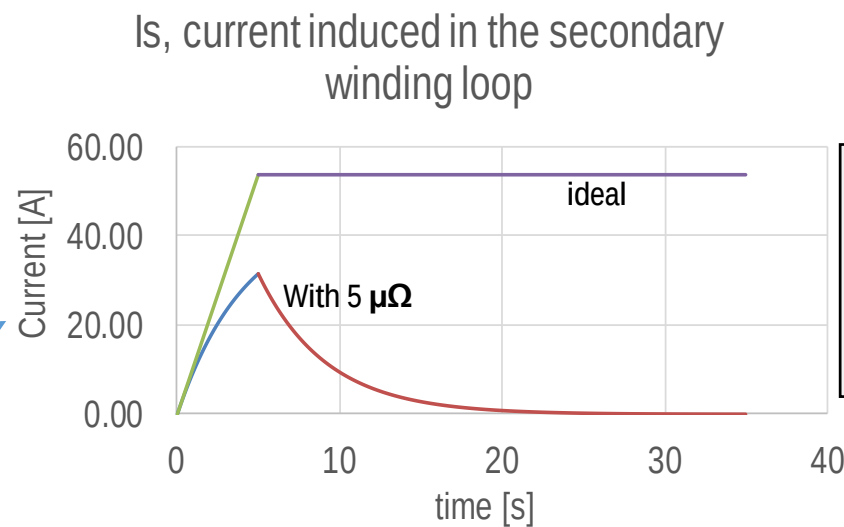
Field mapping results along the axis after 10 irregular iterations @ Iop = 3 A

	Calculation	Measured with flux pump
Z2 [Hz/cm^2/A]	794.1	880

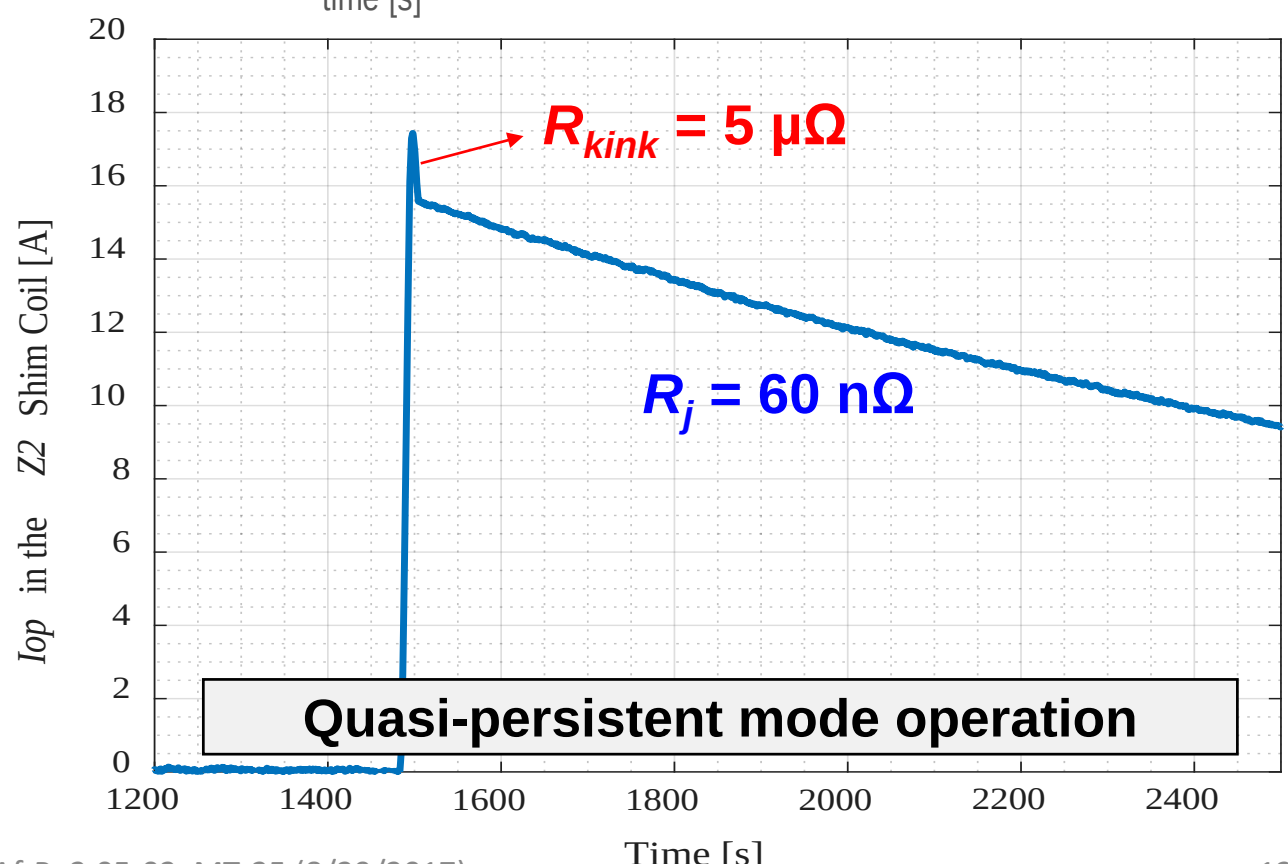
Result-3



Circuit for direct inducing current



:S1 should be closed as soon as I_p reach at the set current



Quasi-persistent mode operation

Summary

- We have designed a new set of HTS Z1 and Z2 shim coils placed within a 5-mm annular space in the cold bore of MIT 1.3G and also introduced an idea of powering the shim coils with a flux pump to possibly eliminate high-current leads and power supply.

- We demonstrated the prototype Z2 shim coil performance and validated a flux pump operating sequence and the persistent mode operation at 15 A, although we couldn't energize the Z2 shim coil efficiently because of "kink" resistance of 2-mm wide REBCO tape