Development status of a levitated dipole experiment for pair-plasma production

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Motivation and objectives

- We aim to create the first magnetically-confined electron positron pair plasma in a laboratory using a dipole magnetic field configuration.
- In a mechanically supported prototype dipole experiment with a permanent magnet, operated at the NEPOMUC facility, efficient injection and trapping of positrons have been demonstrated (P13.1 Singer, P13.3 Horn-Stanja).
- In order to simultaneously trap positrons and electrons as plasmas, we plan to develop a superconducting levitated dipole experiment as one of next steps of the pair-plasma project.

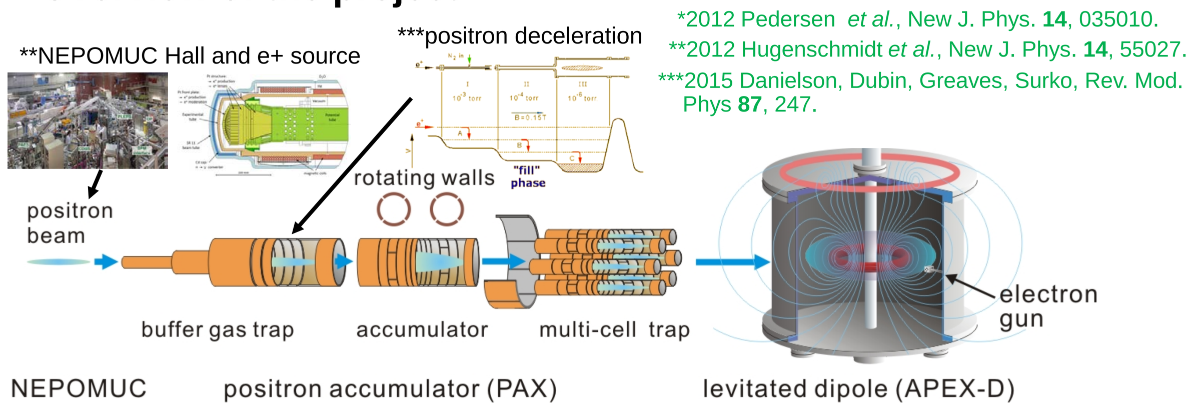
Main results

- Cooling and inductive excitation of persistent current were demonstrated with a high-temperature superconducting (HTS) coil.
- Basic design concept of the levitated dipole (namely, compact dipole trap with a thermal-contact cooled HTS coil) was decided.
- Feedback controlled levitation system was numerically investigated and compared with a small levitation experiment.
- A small HTS coil winding is ready for a forthcoming supported HTS coil experiments with positrons and electrons.

The pair-plasma project of IPP*

Overview of the project

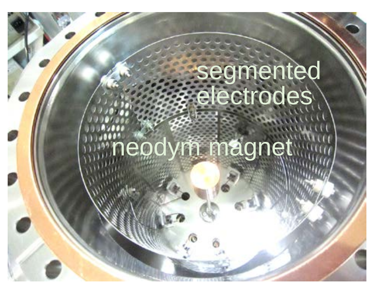
*2012 Pedersen *et al.*, New J. Phys. **14**, 035010.
2012 Hugenschmidt *et al.*, New J. Phys. **14, 55027.
***2015 Danielson, Dubin, Greaves, Surko, Rev. Mod. Phys **87**, 247.



The grand scheme of the electron-positron plasma experiment

Use of the NEPOMUC intense positron facility, buffer gas / multi-cell trap, and toroidal magnetic configuration(s) is the key issue.

Prototype dipole trap with a permanent magnet



Inside the prototype dipole

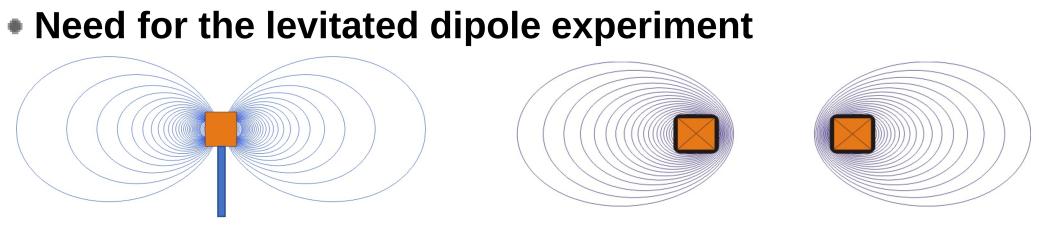
Experiments with positrons are conducted with a supported dipole device.

- efficient ExB drift injection (up to ~100%)
- trapping of positrons (~ 20 ms)
- interaction with rotating wall (RW) electric fields in a dipole field

P13.1 Singer, P13.3 Horn-Stanja

How can we create symmetric closed field lines?

Need for the levitated dipole experiment

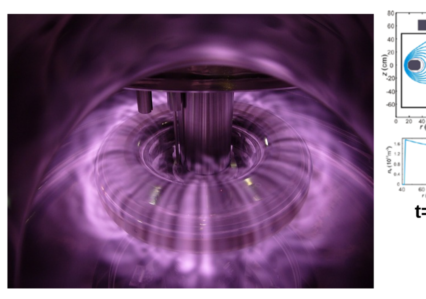


Permanent magnet dipole	Levitated SC dipole
• field lines intersect the magnet • confinement along field lines was done by electric fields and mirror trapping	• closed field lines • positrons and electrons fly on the field lines without any perturbation

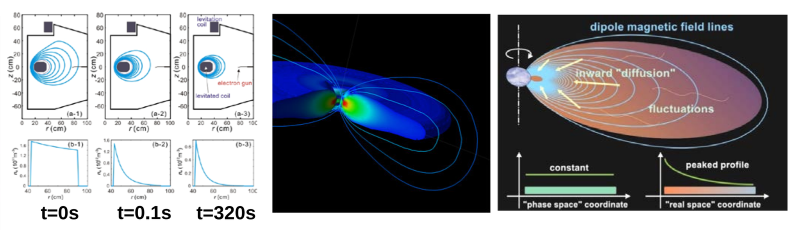
For simultaneous trapping of positrons and electrons as a plasma, we need closed field lines / magnetic surfaces, which are realized by a magnetically levitated superconducting coil (or stellarator).

Other levitated dipole experiments

2010 Yoshida *et al.*, Phys. Rev. Lett. **104**, 235004.



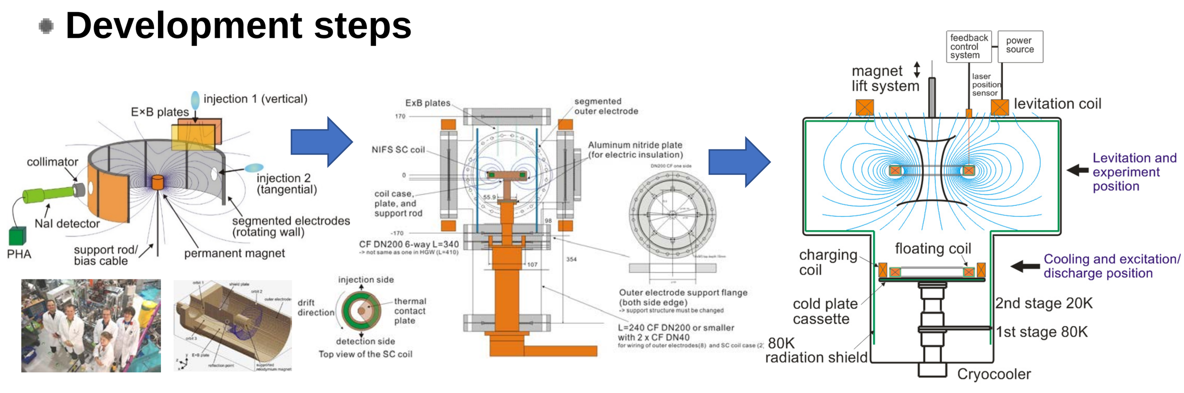
RT1, example of levitated dipole



Recent experiments at RT-1 and LDX showed fluctuation-induced inward diffusion and excellent confinement of plasmas.

Compact levitated dipole for pair plasmas

Development steps



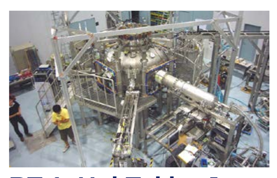
Permanent magnet trap — Supported SC trap (2017-) — Levitated SC trap (2018-)

Basic concept and tentative parameters

- compact thermal contact cooling system for high-temperature SC coil
- inductive excitation of SC coil with magnetically coupled another coil

	RT-1	LDX	APEX-D
SC tape	Bi-2223	Nb3Sn	Bi or ReBCO
Rcoil	250 mm	300 mm	75 mm
current	116 A	1820 A	100 A
turn	2160 turns	714 turns	300 turns
total current	250 kA	1400 kA	30 kA
operation temperature	20-30 K	4 K	20-50 K
coil weight	110 kg	580 kg	2 kg
cooling method	He gas	He	thermal contact
excitation method	direct (PCS)	induction	induction
thermal shield	coil	coil (He)	chamber

Parameters and comparison with other experiments



RT-1, Uni Tokio, Japan

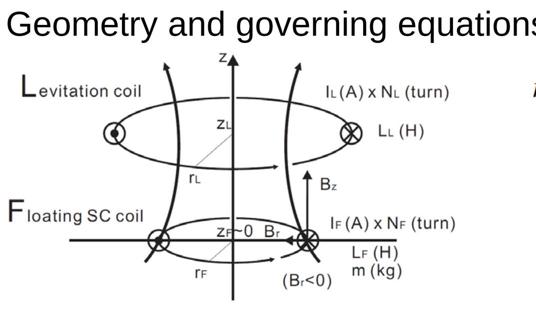
LDX, MIT/Columbia, USA
2010 Boxer *et al.*, Nature Phys. **6**, 207.

Levitation physics and engineering

Equilibrium of coil position

2010 Yano *et al.*, Fusion Eng. Design **85**, 641.

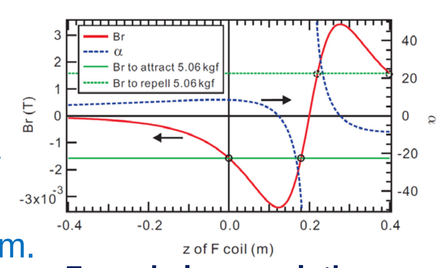
- Geometry and governing equations



$$m_F \frac{d^2 z_F}{dt^2} = -2\pi r_F N_F I_F B_r - m_F g$$

$$\frac{d}{dt}(L_F I_F + M I_L) = 0$$

A superconducting F coil is levitated by using L coil. Force balance and flux conservation lows decide the equilibrium.

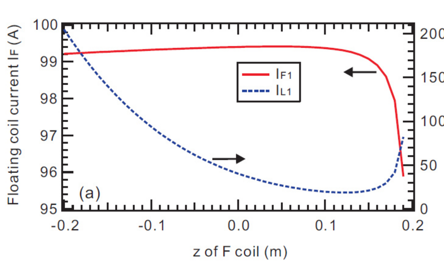


Force balance solutions

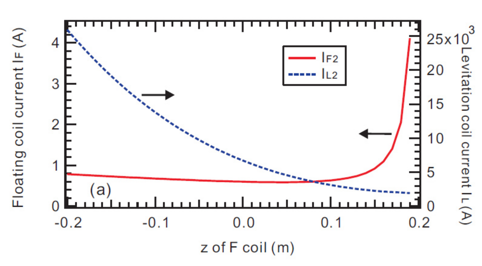
- Two equilibrium solutions

$$I_F^2 - I_{F0} I_F - \frac{m_F g M}{\pi r_F N_F h L_F} = 0$$

$$A = I_{F0}^2 + \frac{2 m_F g M}{\pi r_F N_F h L_F} \qquad I_F = \frac{I_{F0} \pm \sqrt{A}}{2} \ \text{and} \ I_L = \frac{L_F(I_{F0} \mp \sqrt{A})}{2M}$$



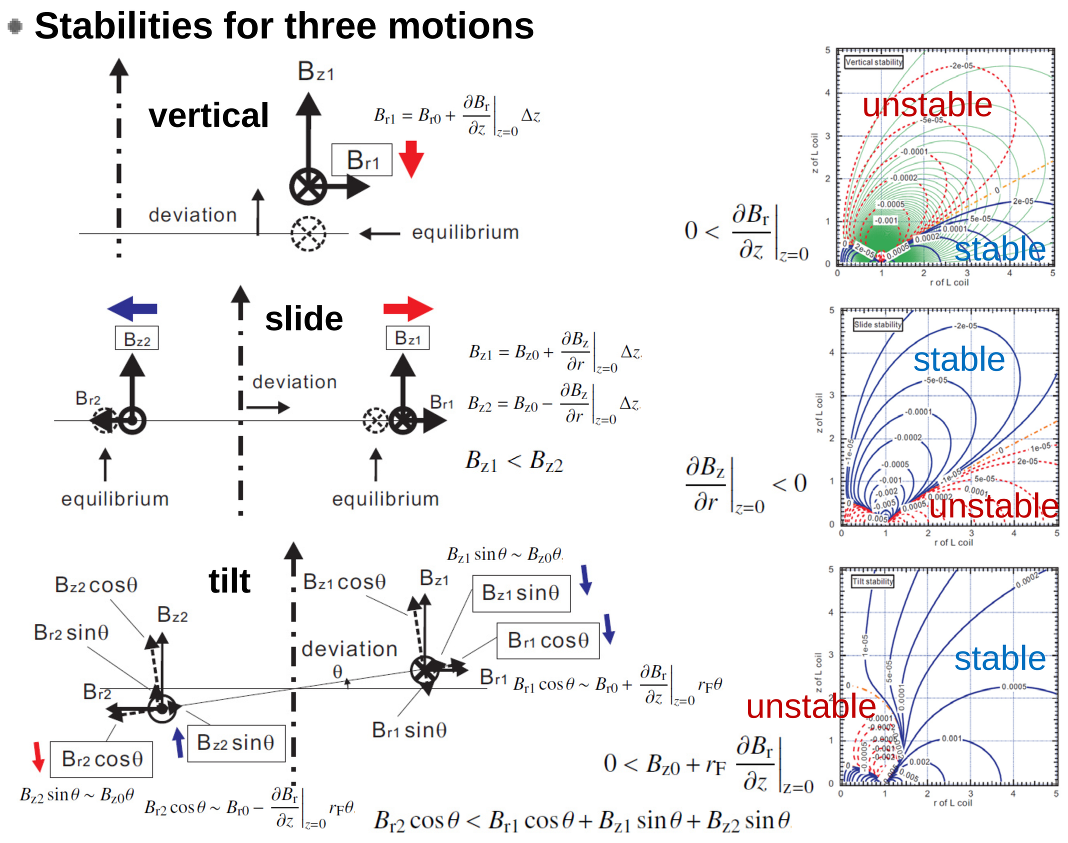
Solution 1 of SC dipole



Solution 2 of SC dipole

Including the flux conservation effects, two different current sets for the F and L coils are found for the levitation equilibrium. The former is suitable for plasma experiments.

Stabilities for three motions

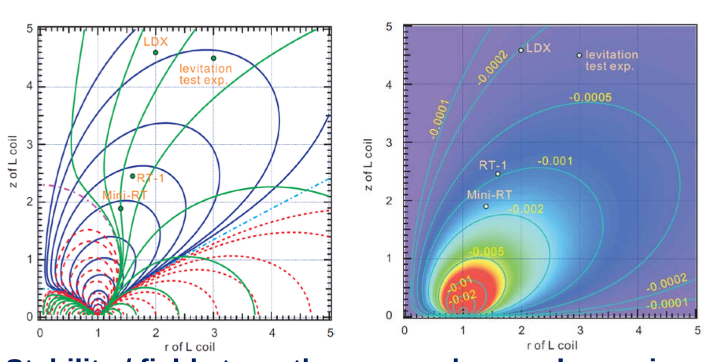


$$B_{r1} = B_{r0} + \left.\frac{\partial B_r}{\partial z}\right|_{z=0} \Delta z \qquad 0 < \left.\frac{\partial B_r}{\partial z}\right|_{z=0}$$

$$B_{z1} = B_{z0} + \left.\frac{\partial B_z}{\partial r}\right|_{z=0} \Delta z \quad B_{z2} = B_{z0} - \left.\frac{\partial B_z}{\partial r}\right|_{z=0} \Delta z \quad B_{z1} < B_{z2} \qquad \left.\frac{\partial B_z}{\partial r}\right|_{z=0} < 0$$

$$B_{z1}\sin\theta \sim B_{z0}\theta \quad B_{r1}\cos\theta \sim B_{r0} + \left.\frac{\partial B_r}{\partial z}\right|_{z=0} r_F\theta \quad B_{z2}\sin\theta \sim B_{z0}\theta \quad B_{r2}\cos\theta \sim B_{r0} - \left.\frac{\partial B_r}{\partial z}\right|_{z=0} r_F\theta$$

$$B_{r2}\cos\theta < B_{r1}\cos\theta + B_{z1}\sin\theta + B_{z2}\sin\theta \qquad 0 < B_{z0} + r_F \left.\frac{\partial B_r}{\partial z}\right|_{z=0}$$



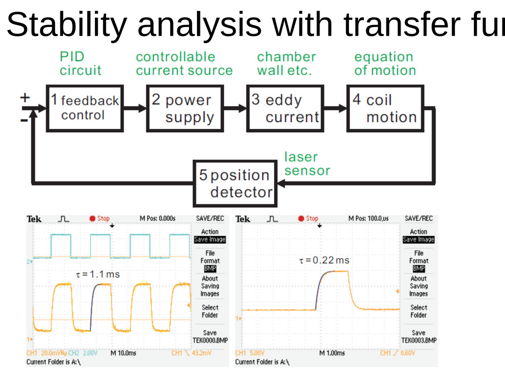
Stability / field strength maps and several experiments

Vertical, slide, and tilt motions can be unstable.

According to the relative positions of F and L coils, we can chose a condition so that only 1-d vertical motion is unstable.

Feedback stabilization of the vertical motion

- Stability analysis with transfer function



Model and measured response of the power supply and laser sensor

$$G_1 = P + Ds + I\frac{1}{s}$$ PID circuit shown below

$$G_2 = \frac{1}{1 + s/909} \ (\mathrm{A/V})$$ power supply, 1.1 ms delay

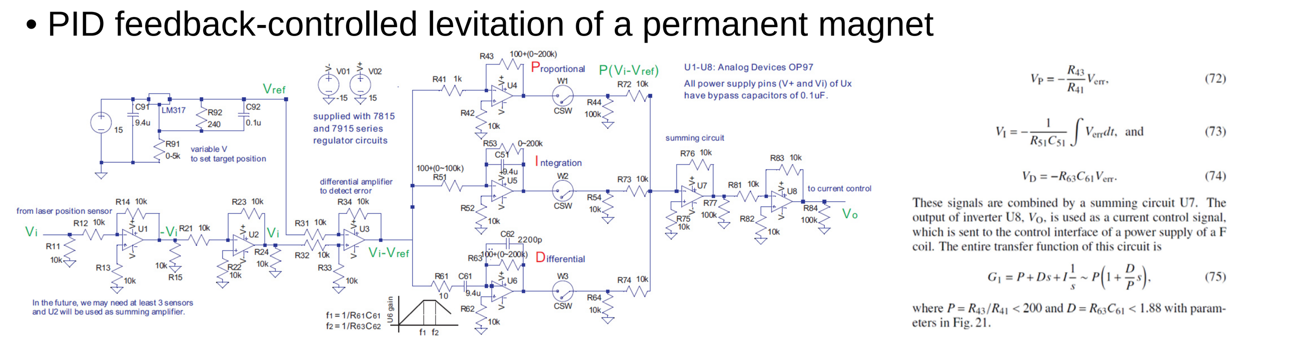
$$G_3 = 1$$ eddy current effects are negligible

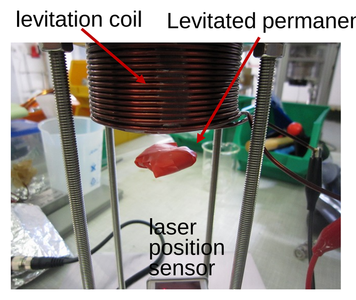
$$G_4 = \frac{1}{I_{L0}\alpha}\frac{1}{s^2/(g\alpha) - 1} = \frac{1}{379}\frac{1}{s^2/530 - 1} \ (\mathrm{V/m})$$ eq. motion

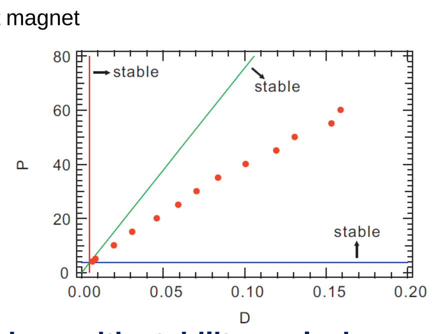
$$G_5 = 100\frac{1}{1 + s/4550} \ (\mathrm{V/m})$$ laser sensor, 0.22 ms delay

$$G_T = \frac{\frac{P}{379}\left(1 + \frac{D}{P}s\right)\left(1 + \frac{s}{4550}\right)}{\left(1 + \frac{s}{909}\right)\left(\frac{s^2}{530} - 1\right)\left(1 + \frac{s}{4550}\right) + \frac{100}{379}P\left(1 + \frac{D}{P}s\right)}$$

- PID feedback-controlled levitation of a permanent magnet





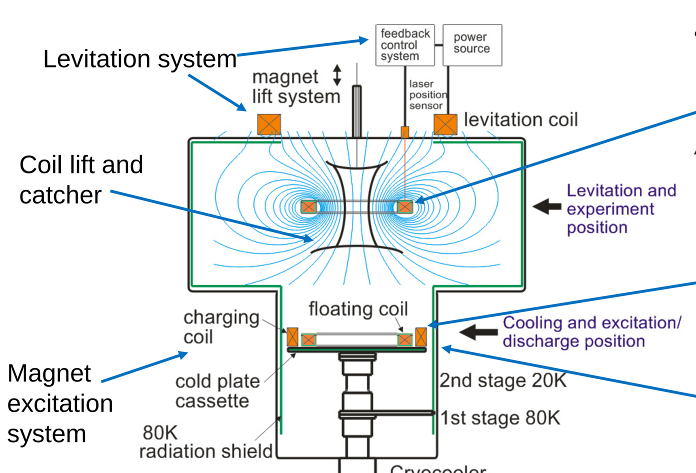


Levitation test and comparison with stability analysis

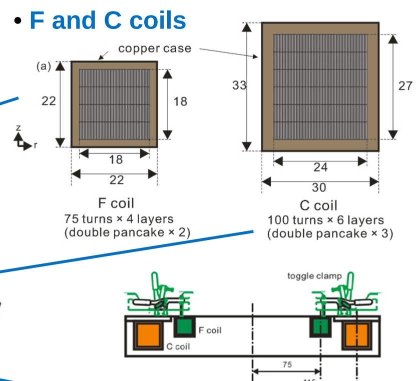
Stability conditions are calculated with standard transfer function method.

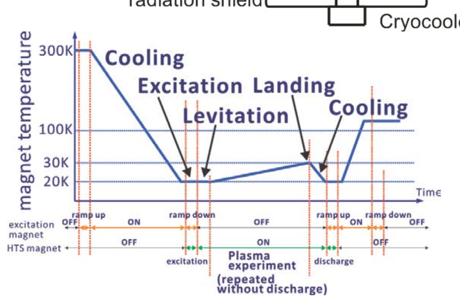
Levitation control circuit was developed and stable levitation of a permanent magnet for hours were demonstrated.

Components of the levitated SC experiment



• F and C coils

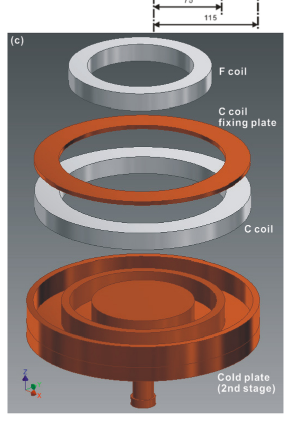


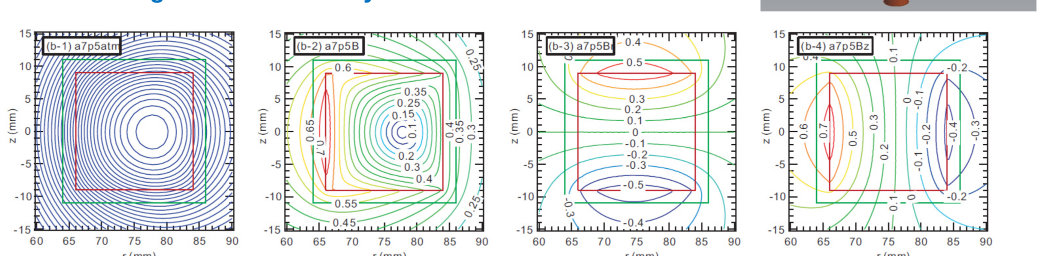


• coil cooling and excitation cycle

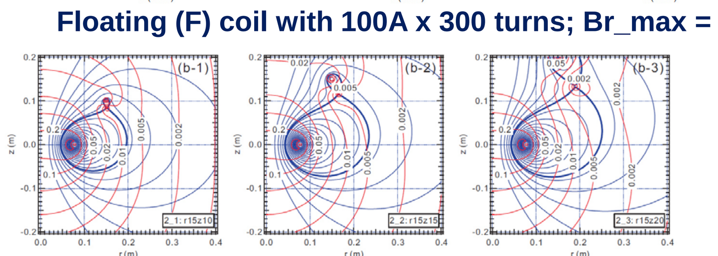
• cooling station for the F and C coils

thermal contact of the F coil is realized with toggle clamps

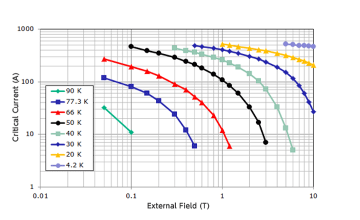




Floating (F) coil with 100A x 300 turns; Br_max = 0.54 T, Bz_max=0.73 T



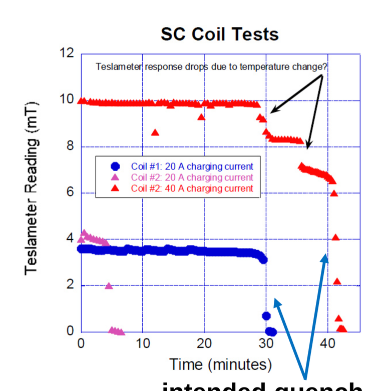
Trapping geometry generated by F and L coils



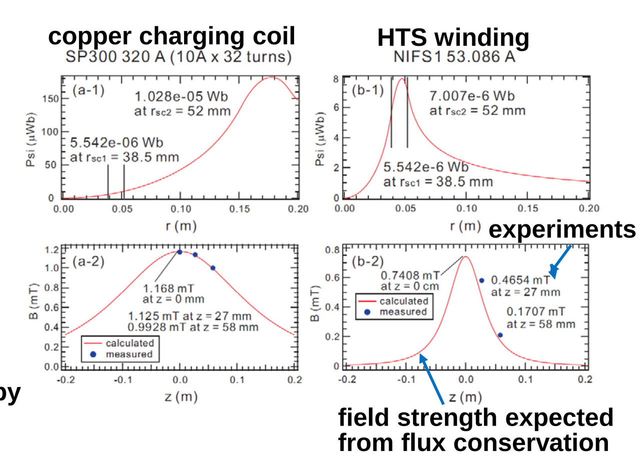
Sumitomo DI-BSCCO data

Cooling and excitation tests with Bi-2223 HTS tape windings

Liquid nitrogen cooling and inductive excitation



intended quench by temperature rise

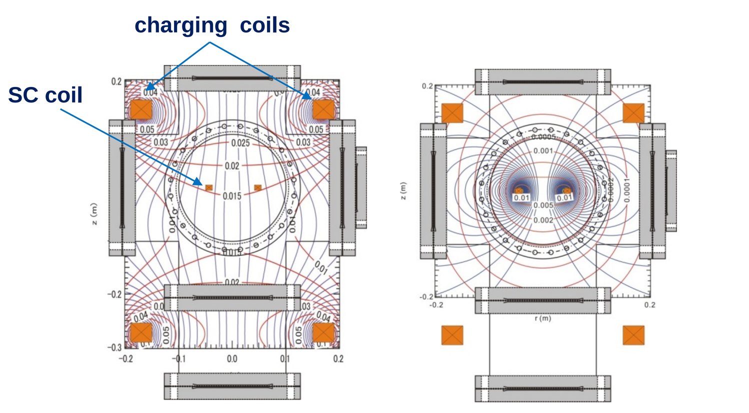


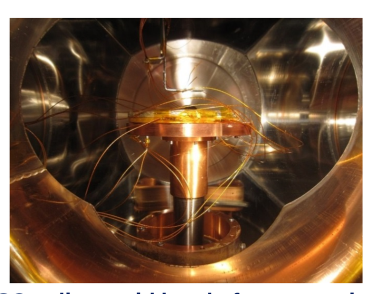
field strength expected from flux conservation

Inductive excitation with a copper charging coil was demonstrated.

Generated persistent current values showed good agreement with values predicted from the conservation of magnetic flux inside the SC loop.

Cooling using cold head of a cryocooler



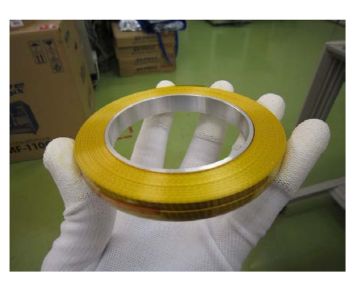


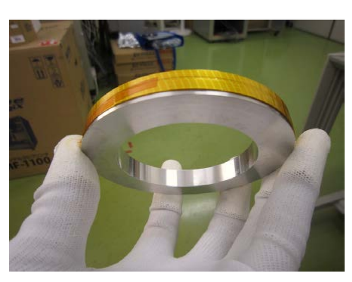
SC coil on cold head of a cryocooler

Cooling below Tc and transition to the SC state was realized only by applying enough contact pressure between the coil winding and the cold head.

New coil winding for supported SC coil experiment

- Coil winding made at NIFS, Japan

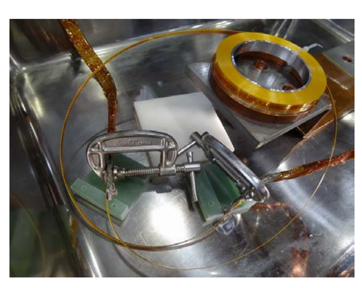


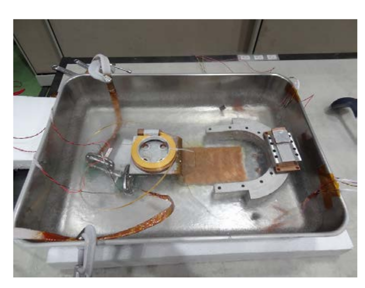


DI-BSCCO 4mm tape

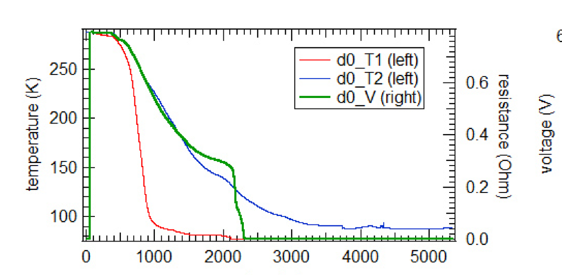
A new spindle with large flange in order to enhance thermal contact.

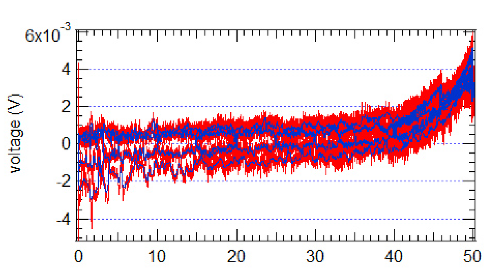
- Cooling and excitation test with cooled copper plate (in air)





The winding was connected to an external power supply, and SC transition and excitation tests were conducted.





SC transition and excitation to I=50A was demonstrated with 77K plate.