Max-Planck-Institut für Plasmaphysik

Technical design of a compact, levitated dipole for confinement of a low-temperature, long-lived, electron-positron plasma

A. Card[1*], M. R. Stoneking[1,2], J. Horn-Stanja[1], T. Sunn Pedersen[1,3], and the APEX Collaboration[1,2,3,4,5,6]
1 Max Planck Institute for Plasma Physics, Garching & Greifswald, Germany — 2 Lawrence University, Appleton, WI, U.S.A. — 3 University of Greifswald, Greifswald, Germany — 4 Technische Universität München, Garching, Germany — 5 University of California San Diego, La Jolla, CA, U.S.A. — 6 The University of Tokyo, Kashiwa, Japan

Motivation

THE GOAL of the APEX collaboration is to create the world's first magnetically confined electron-positron plasma and test theoretical predictions for pair plasma regarding wave behavior, stability and confinement.

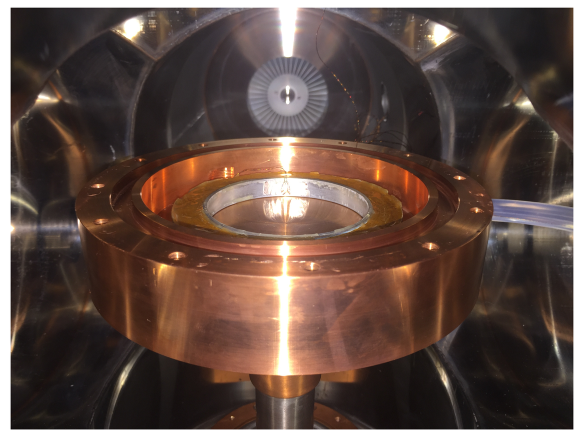
THE APPROACH is to use a levitated dipole which can confine low density plasma at any degree of neutrality. EPOS, a stellarator trap is being developed in parallel, but on a longer timeline.

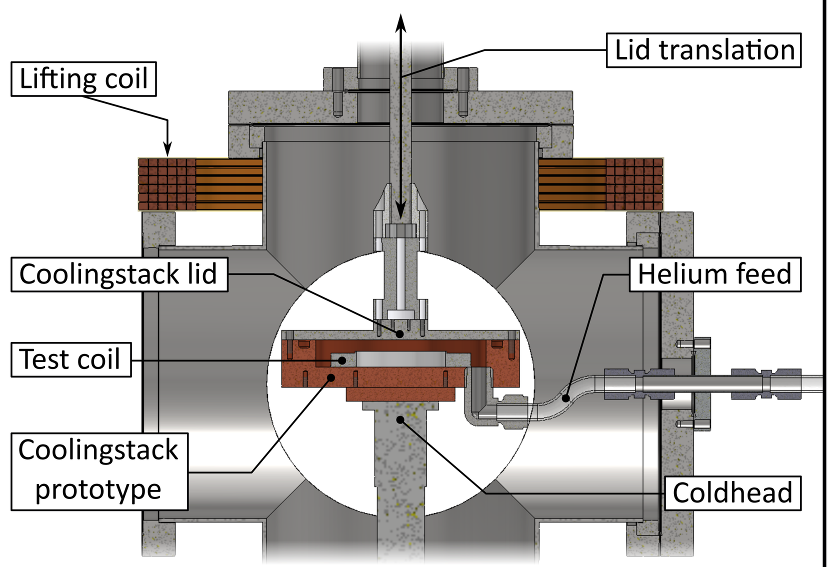
Technical Challenges

- To cool the floating HTSC coil, which experiences only transient contact with cryogenic surfaces
- To inductively charge the closed floating coil using a second SC charging coil
- To position the floating coil and stably levitate it for times on the order of one hour

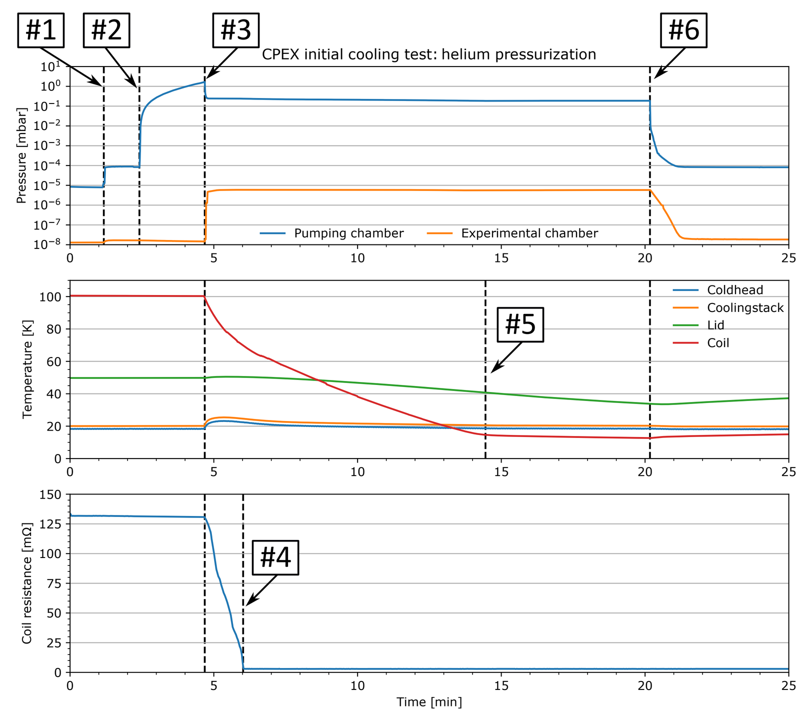
Coolingstack Prototype EXperiment (CPEX)

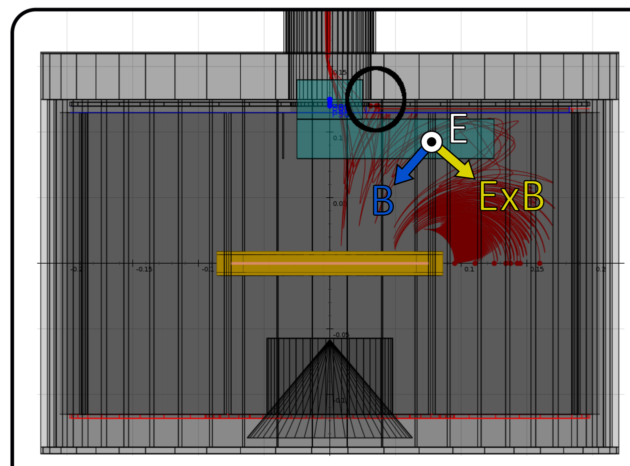
We built a prototype magnet cooling experiment to test the methods of cooling the floating coil. The design employs a dynamically sealable internal chamber (the "coolingstack") into which helium gas is introduced to provide thermal contact between the floating coil and the coldhead without raising the pressure in the main chamber to an unacceptable level. A metal-on-metal seal - using linear force with a stepper-motor translator - maintained adequate pressure differential (4-5 orders of magnitude) for cooling. An open lead, superconducting test magnet was cooled via the process explained below.





(1) Close off the pumping chamber turbopump
(2) Open leakvalve to calibrated position
(3) Flow helium through the coolingstack
(4) Coil resistance measurement indicates transion into SC state
(5) Coil temperature reaches base value
(6) Simultaneously cut off helium flow, and re-open turbopump





Positron Injection

A static potential between two plates creates an ExB drift that moves incoming particles onto field lines in the trapping region. Lossless positron injection was achieved using this technique in the Proto-APEX supported dipole experiment [1]. Recent simulations indicate that an injection efficiency up to 90% is possible for the levitated dipole.

Diagnostics

The primary tool used to dianose an electron positron plasma is gamma ray detection. Pictured here are 48 gamma ray detectors (1" BGO crystals) arranged in a way such that coincident detection of annihilation events is maximised.

Floating Coil | ∅15 [cm]
Charging Coil | ∅24 [cm]

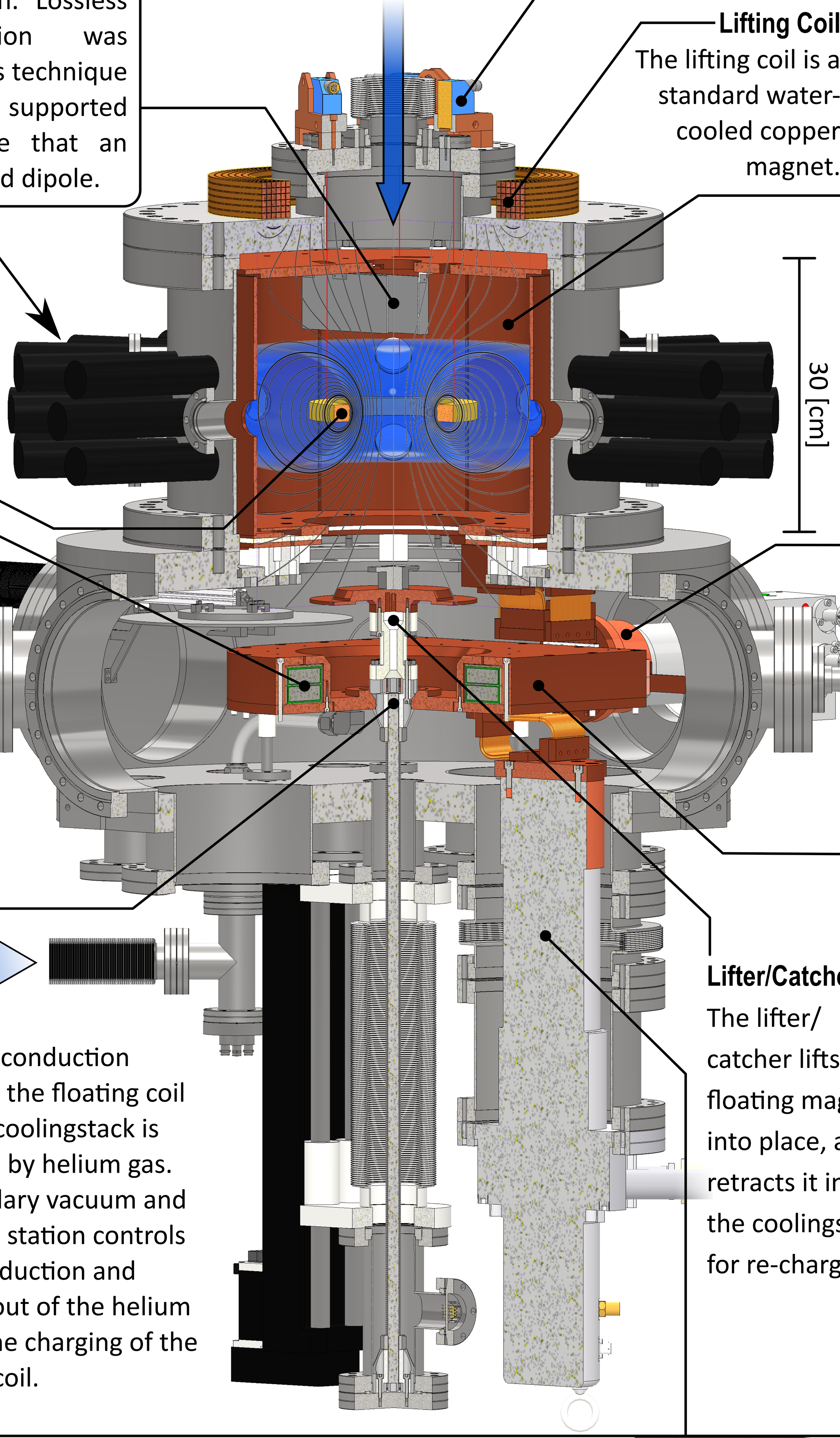
Both coils are wound using high-temperature REBCO superconducting tape. The floating coil will be electroplated with gold to lower its emissivity.

Positron Source

Positrons from the NEPOMUC source (5×10^{7} [s^{-1}] at 20 [eV]) at the FRM II neutron source are trapped, cooled, and accumulated - ultimately up to 10^{11} positrons (see A. Deller and M. Singer posters) - and delivered in pulses to the levitated dipole.

Lifting Coil

The lifting coil is a standard water-cooled copper magnet.

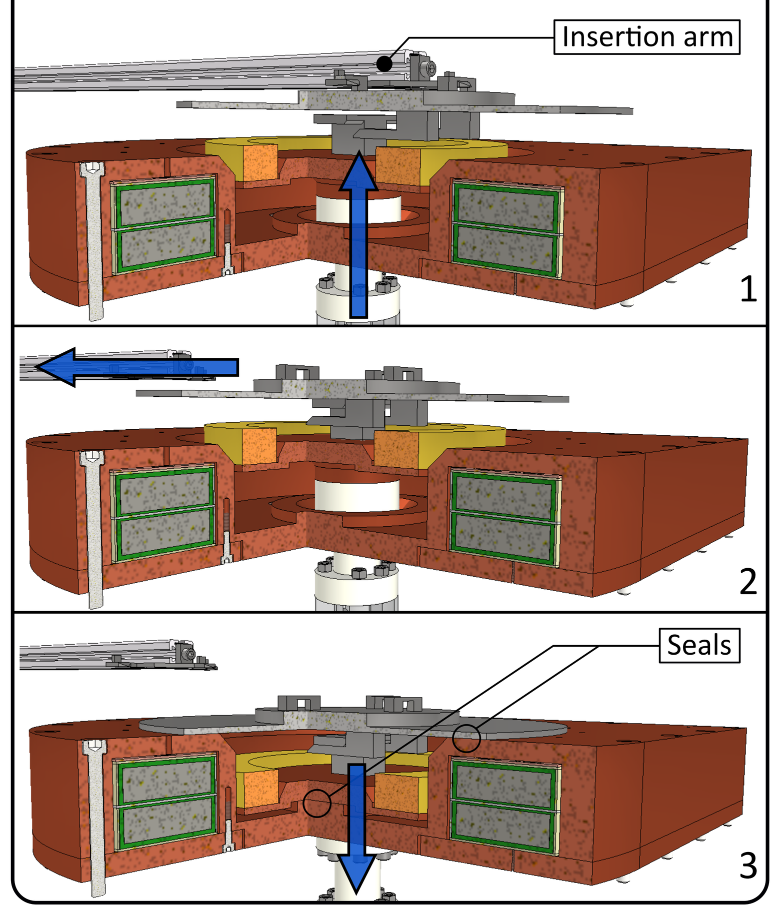


Lifter/Catcher

The lifter/catcher lifts the floating magnet into place, and retracts it into the coolingstack for re-charging.

Sealing the coolingstack

The coolingstack is sealed with a removable lid. The lid is handed off from an insertion arm to the lifter/catcher using a hook and latch approach. A hook on the bottom of the lid engages with a latch attached to the lifter/catcher. Thicknesses are chosen such that slight flexion in the material ensures the two seals mate.

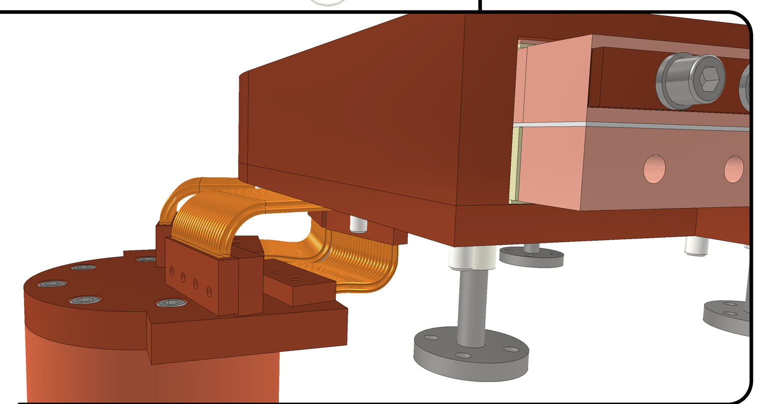


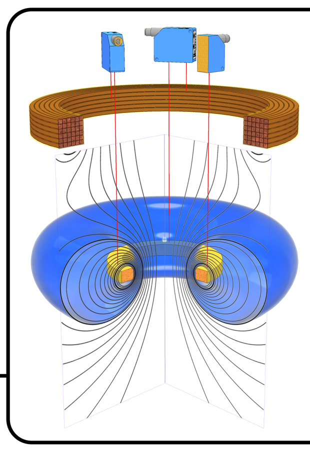
Helium

Thermal conduction between the floating coil and the coolingstack is provided by helium gas. A secondary vacuum and pumping station controls the introduction and venting out of the helium during the charging of the floating coil.

20K Cryocooler

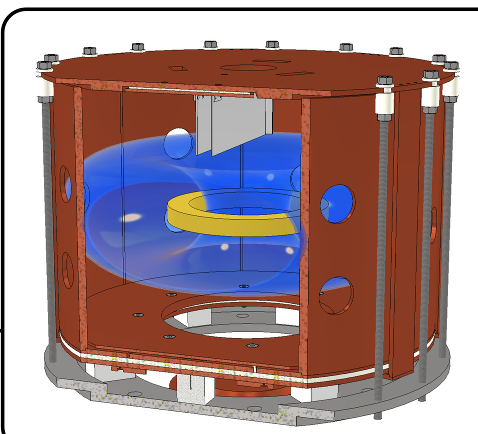
A single-stage cryocooler with a rated power of 100W @ 20K cools the primary components. These include the charging coil, the floating coil, as well as the lifter/catcher. Thermal straps, which primarily provide thermal conduction, also serve to isolate the cryocooler vibrations.





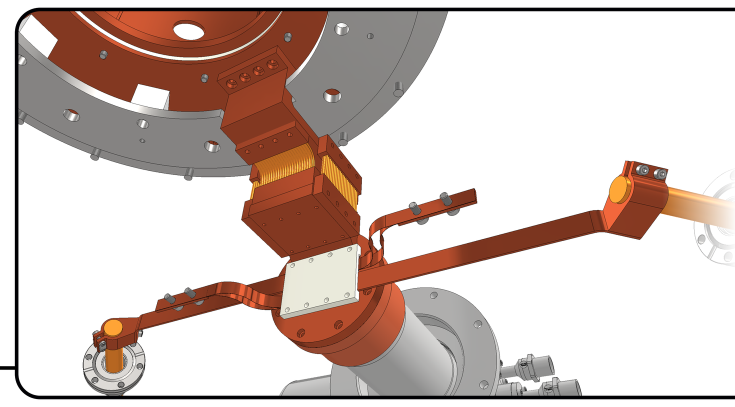
Magnetic levitation

Once current has been induced in the floating coil (see *Inductively charging the floating coil*), it is lifted into place at which point magnetic levitation is engaged [2,3]. The placement of the lifting and floating coils is chosen to be stable to slide and tilt perturbation. Vertical instability is mitigated by a PID feedback circuit, which controls the floating coil height by varying the lifting coil current in response to deviations in the averaged signal from three laser rangefinders [4]. Levitation time is estimated to be on the order of an hour, and is limited by ambient warming (see *Thermal radiation shield*).



Thermal radiation shield

The floating coil lacks thermal insulation in order to increase cooling rates, thus thermal radiation is the primary source of warming. To mitigate, polished surfaces (reduced emissivity), and an actively-cooled thermal shield will be utilized. The walls (8), floor (2), and ceiling (2) are segmented into a total of 12 electrodes which can be biased to assist in injection/steering/compressing the plasma.

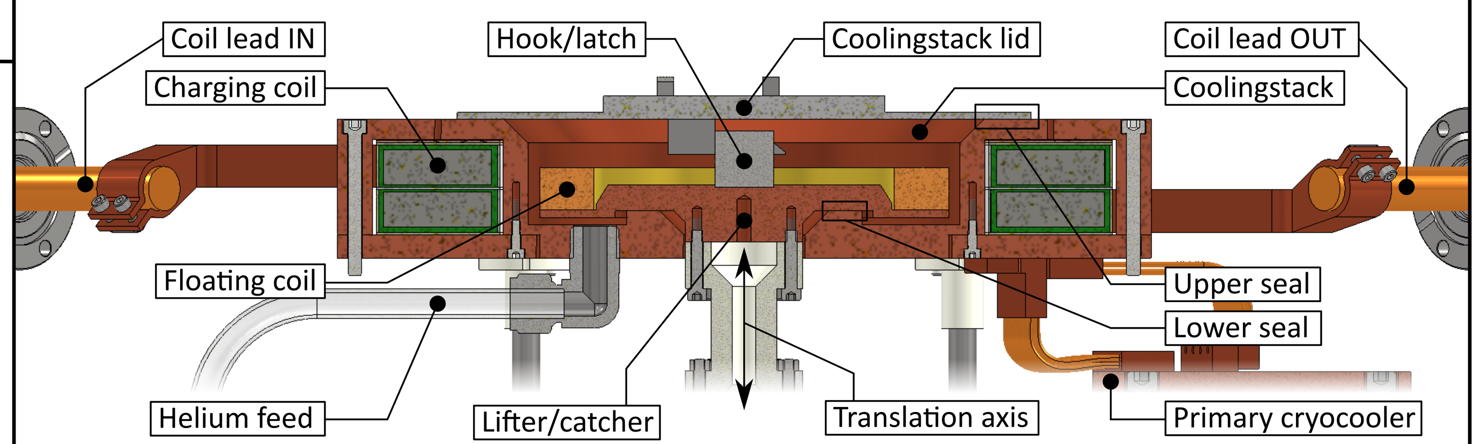


80K Cryocooler

A cryocooler with a power of 175W @ 80K cools peripheral components. These include the radiation shield, and the charging coil current leads. Thermal straps are utilized to isolate the radiation shield thermal busbar from vibrations.

Inductively charging the floating coil

The coolingstack is designed to maximize the inductive coupling between the charging and floating coils. Some portion of the charging coil magnetic flux is trapped in the floating coil when it becomes superconducting. The algorithm below describes the charging process.



(1) Lifter/catcher & floating coil are retracted into the coolingstack | **(2)** Coolingstack is sealed (see *Sealing the coolingstack*) | **(3)** Charging coil is energized to 144 [kA-turns] (max 0.8 [T]) | **(4)** Helium is introduced, which cools the floating coil through the SC transition, ultimately to 20 [K] | **(5)** Charging coil current is ramped down, inducing up to 54 [kA-turns] (max 0.5 [T]) in the floating coil | **(6)** Helium is vented | **(7)** Lid is extracted | **(8)** Floating coil is lifted into place | **(9)** Lifting coil is energized, which begins magnetic levitation (see *Magnetic levitation*)

Timeline

Many subsystems - specifically the helium pumping chamber, core diagnostics (pressure, thermal sensors, linear translator control), and software control - were completed during the CPEX phase. Q1 to Q2 2021 will see main system assembly, levitation, and first experiments with electron trapping. Following this, the system will be moved to the FRM-II reactor for experiments with positrons.

Acknowledgments: *The APEX collaboration receives/has received support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme; the Deutsche Forschungsgemeinschaft (DFG); the Helmholtz Association; the UC San Diego Foundation; the Japan Society for the Promotion of Science (JSPS); the National Institute for Fusion Science (NIFS); and the U.S. Department of Energy (DOE).*

*Corresponding Author: alexander.card@ipp.mpg.de
MLZ User Meeting & German Neutron Scattering Conference 2020

References

[1] Stenson et al., Physical Rev. Letters 121, 235005 (2018)
[2] Boxer et al., Nature Physics 6, 207-212 (2010)
[3] Yoshida et al., Fusion Science & Tech. 51, 2007 (2017)
[4] Saitoh et al., Rev. of Scientific Inst. 91, 043507 (2020)