Developments in Superconducting Insertion Devices

E.R. Moog & Y. Ivanyushenkov

PAC 2011, March 28 – April 1, 2011, New York

Introduction

Superconducting IDs are the new frontier for IDs but they also have quite a history.

In the mid-to-late 1970's, superconducting insertion devices were being built and used at several places worldwide:

- Stanford University, to demonstrate an FEL
- ACO, France: on a storage ring instead of single-pass
- Novosibirsk: "Siberian snake" installed on VEPP-3
- Novosibirsk, 1986: superconducting undulator on VEPP-2M to measure polarization of electron / positron beams

Introduction, cont.

Then there was a lull in interest in superconducting IDs. Rare earth magnets were available.

- Strong magnets
- No cryogenic baggage

Much development work was done to increase the capabilities of permanent magnet IDs.

Permanent magnet IDs met users' demands for awhile, but users kept asking for more – specifically, higher photon energy and more photons. This prompted a resurgence of interest in superconducting IDs.

Wavelength shifters

Development began on wavelength shifters (3-pole wigglers)

The strong center pole gives a high critical energy to the photon spectrum.

Weaker side poles make the overall electron trajectory straight.

A number were built:

- 4-Tesla device at ESRF in 1994
  - Used for about 5 years; replaced with 3-T PM wiggler
- 6.4-Tesla device built and installed at MAX-Lab, in the late 1990's
- Taiwan Light Source built and installed a 6-T, warm-bore, cryogen-free device in 2002. It serves 3 beamlines.

Wavelength shifters, cont.

Budker Institute also began making wavelength shifters

Intended light source	Max and Operating field, Tesla	Year
Siberia-1 (Moscow)	5.8 / 4.5	1985
PLS (Korea)	7.68 / 7.5	1995
LSU-CAMD (USA)	7.55 / 7.0	1998
Spring-8 (Japan)	10.3 / 10.0	2000
BESSY-II (Germany)	7.5 / 7.0	2000
BESSY-II (Germany)	7.5 / 7.0	2001

The technology advanced during this time. The first three used only liquid cryogens to cool; the last three added cryocoolers, reducing liquid He use from ~2.5 to ~0.5 liter/hr.

Superbends

Superconducting devices that enhance photon output don't have to be restricted to straight sections.
A standard bending magnet can be replaced with a (shorter) high-field superconducting magnet.

At the ALS in Berkeley, three of the original bending magnets (out of a total of 36) were replaced in 2001.

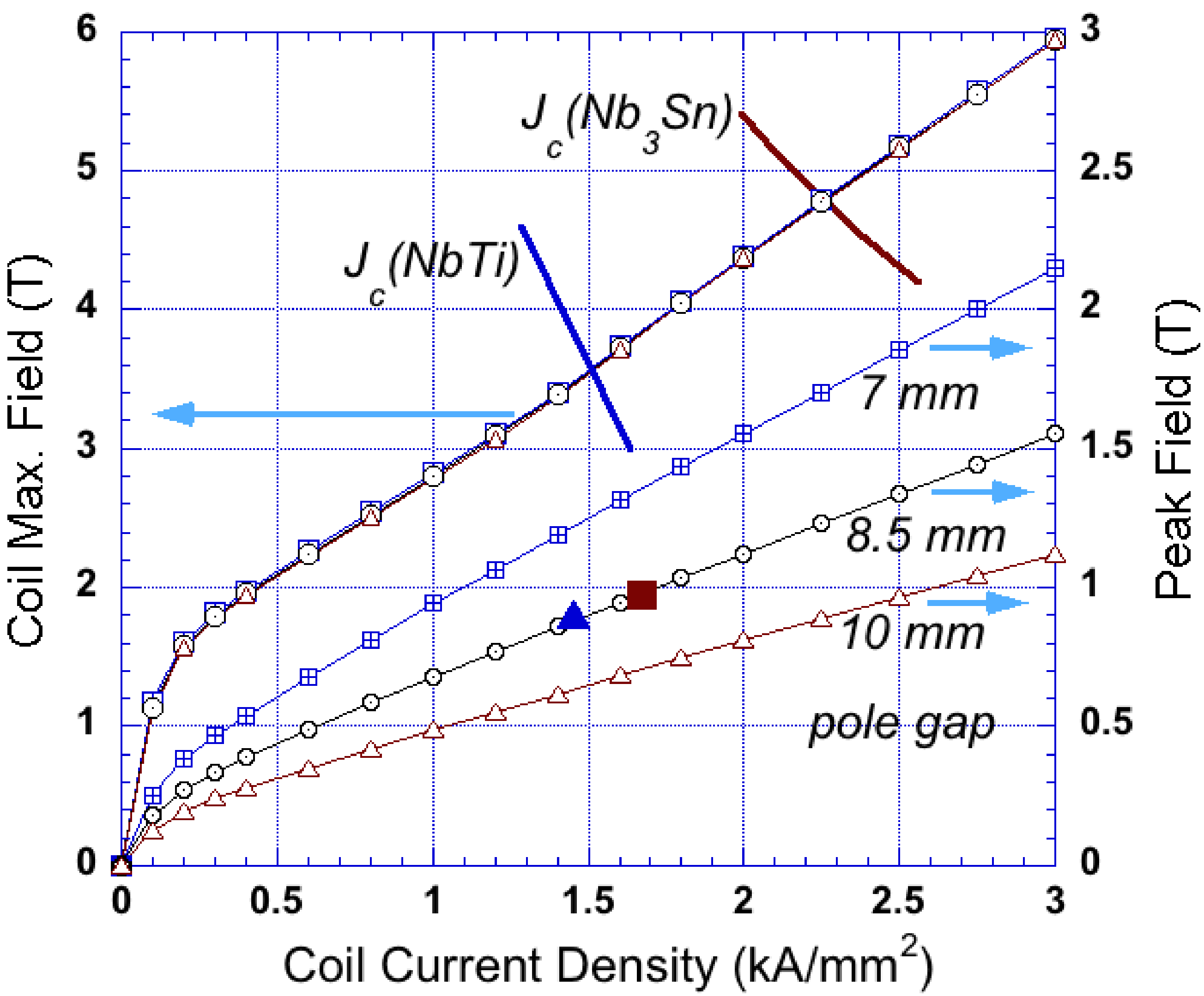
- Original magnets: 1.3 T, 10° bend, 3.1 keV critical energy
- Replacements: 5 T, still 10° bend, 12 keV critical energy

Budker Institute built a 9-Tesla superbend that was installed on BESSY-2 in 2004. The magnet has four superconducting coil sections, two Nb_3Sn-based and two NbTi-based (one is for correction).

NbTi vs. Nb_3Sn superconductor

- NbTi and Nb_3Sn are well-known and long-used superconductors.
- More NbTi has been used because it is easier.
- Nb_3Sn must be wound in its ‘raw’ state, then reacted (typically a week at 700° C) to become a superconductor. It is then extremely brittle.
- If you can deal with the extra challenge, though, Nb_3Sn has a significantly higher critical current.

NbTi vs Nb_3Sn: critical current and undulator field



Calculated peak on-axis field (*right*) and max field in the coil (*left*) as a function of average current density in the coil for pole gaps of 7, 8.5, and 10 mm.

Superconducting undulator period is 14.5 mm.

Critical current densities for NbTi and Nb_3Sn conductor at 4.2 K are also shown.

The filled triangle on the 8.5 mm curve was achieved with a NbTi test winding. The filled rectangle was achieved with a Nb_3Sn winding.

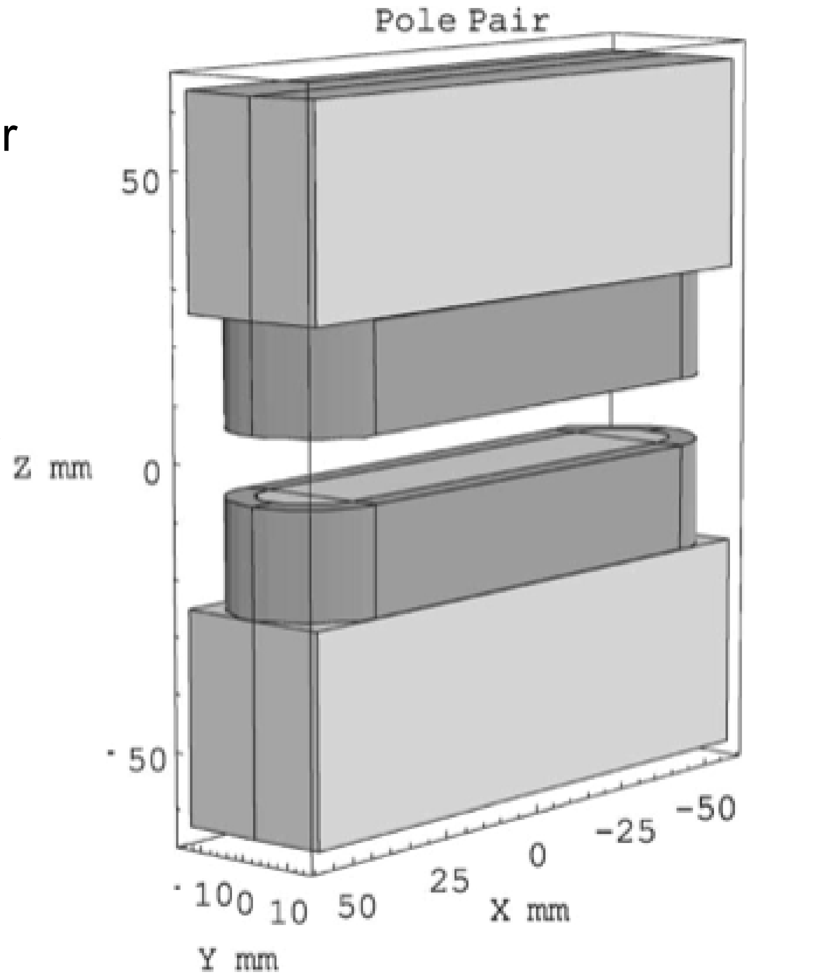
Superconducting wigglers

After the MAX-Lab wavelength shifter, time for a full wiggler

MAX-Wiggler has coils wound around the top and bottom poles.

NbTi superconductor; coils are immersed in a liquid He bath.
Cold-bore vacuum pipe.

Wiggler period	61 mm
Vertical beam stay-clear	10.2 mm
Magnetic aperture	12 mm
Magnetic length	1512 mm
Cryostat length, flange to flange	2500 mm
Number of poles	49
Peak field	3.54 T
K	21.2



E. Wallén, et al., Nucl. Instrum. Meth. A 467 (2001) 118. Figure courtesy of E. Wallén.

Two MAX-Wigglers have been operating successfully for nearly a decade.

Superconducting wigglers, cont.

The Taiwan Light Source built and installed several wigglers:

- 3.2-T, 6.0-cm period, 32 poles installed in 2004 to serve 3 beamlines.
- Three devices: 3.2-T, 6.0-cm period, 16 poles, wider beam chamber.

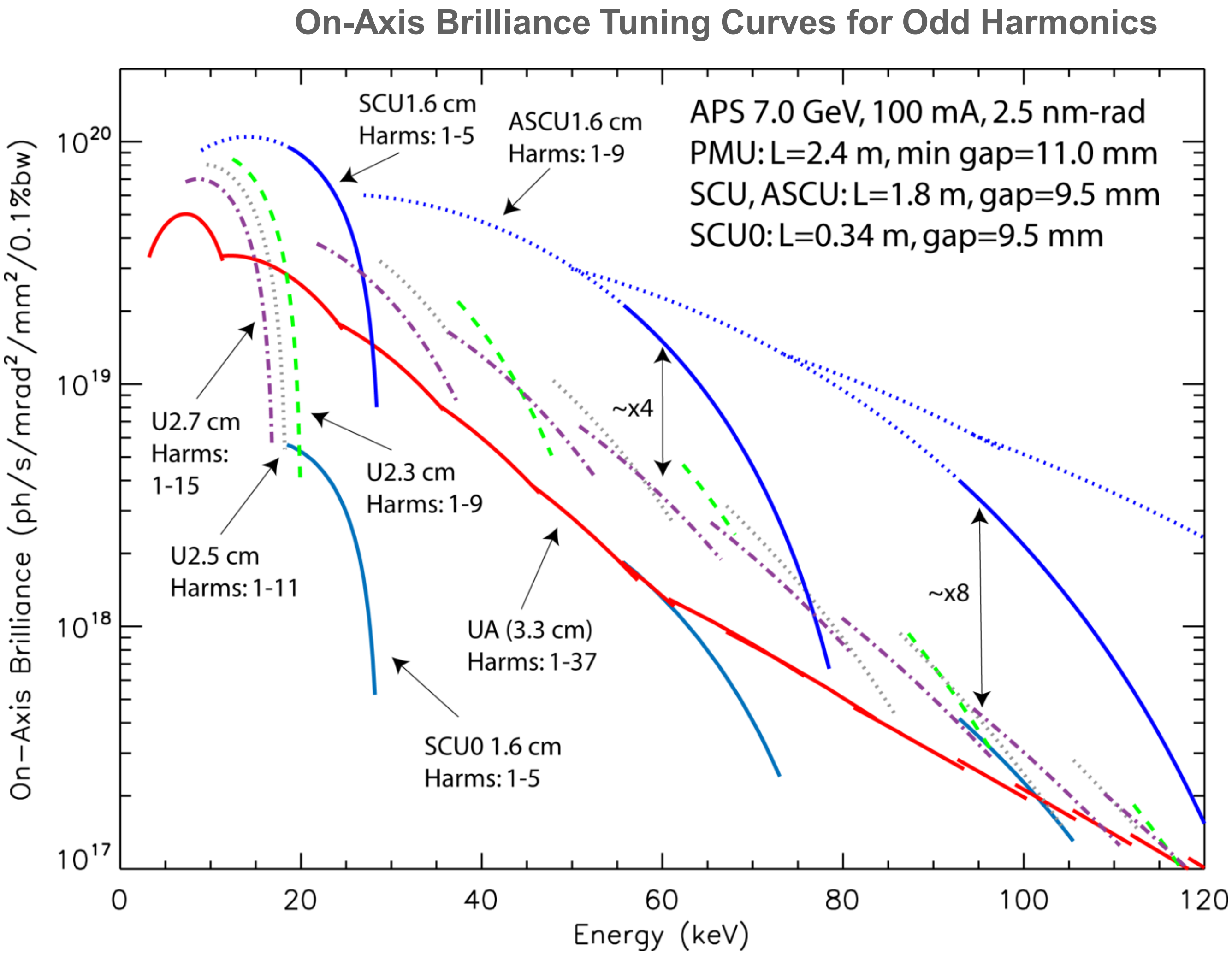
And the Budker Institute folks were busy:

Light source	Field (T)	Period (mm)	# of poles	Pole gap	Year
BESSY-II	7	148	17	19	2002
ELETTRA	3.5	64	49	16.5	2002
CLS	2.1	34	63	13.5	2005
DLS	3.5	60	49	16.5	2006
Siberia-2	7.5	164	21	19	2007
CLS	4.2	48	27	14.5	2007
DLS	4.2	48	49	13.8	2009
LNLS	4.1	60	35	18.4	2009
ALBA	2.1	30	119	12.6	2010

Superconducting undulators (SCUs)

- The photons produced by wigglers cover a broad range of energies all at once. It is up to the users' monochromator to pick out the desired energy.
- It's a lot of power. Way too much, for a high-energy storage ring like APS.
- Undulators produce photons in narrow bands at the fundamental and its harmonics, giving lots more photons at the desired energy for much less power.
- But – the magnetic field quality requirements are greater for an undulator.
- Many labs had or have projects, but a fully-functioning SCU that meets its specs and that is suitable for a light source that demands >97% reliability for users is still a work in progress.

What can you gain from a superconducting ID?



Shorter periods & higher field. That translates to more photons at higher energy!

- Reductions due to magnetic field errors were applied the same to all undulators (estimated from a measured undulator).
- The tuning range for the "Advanced SCU" (ASCU) assumes a factor of two enhancement in the magnetic field compared to today's value – 9.0 keV can be reached in the first harmonic instead of 18.6 keV.

Superconducting undulators at Brookhaven

- At Brookhaven in 1996, an SCU was desired as part of an FEL at the Accelerator Test Facility.

It was to be built in 3 segments that would be butted end-to-end to make the total undulator length. Although the field quality was good within a segment, the junctions were a problem.

- Later, a vertical test facility was built and instrumented for testing and measuring SCU magnetic structures.

There were discussions about it becoming part of a possible collaboration between DOE-funded light sources.

Not just any Hall probe can measure at cryogenic temps. Some change calibration with every temp cycle.

SCUs at ANKA and Karlsruhe Institute of Technology (KIT)

- A jointly-built device was tested on the Mainz Microtron MAMI in ~1999.
  It had superconducting wires in grooves cut into a core. Liquid He flowed through the top and bottom cores. The gap between the cores could be adjusted. Current was limited to 400 A by the feedthroughs (1400 A to quench). Results were promising.

- ACCEL was brought in as an industrial partner.

- Proof of principle demonstration at ANKA in 2005. An SCU with 14-mm period, 100 periods, NbTi conductor was installed.
  Gap adjustable to 16, 12, or 8 mm, or opened to 25 mm during injection and energy ramping of beam.

SCUs at ANKA and KIT, cont.

- A thin foil separates the beam vacuum from SCU insulating vacuum.
- The device worked in beam tests at ANKA, but the beam heat loading is much higher than expected, even at 12 mm gap. Temperature rise of 1K was seen.
  The heating limits the performance of the undulator.
- Possible causes of heating:
  - Synchrotron radiation from upstream magnets
  - Resistive heating from image currents
  - Ion bombardment
  - RF effects
  - Electron multipacting

SCUs at ANKA and KIT, cont.

- Experiments have been done, looking at beam current, vacuum pressure, gas loading in the vacuum chamber, bunch lengths and patterns, and coil temperature.
- Electrons striking and depositing energy can heat the superconductor. They can also cause a pressure increase by causing desorption of gas from the walls. But the models don't match the data.
- The most likely cause is electron multipacting: electrons hit the wall and create secondary electrons. The secondaries are accelerated by the unfortunate arrival time of the next bunch, hit the wall and create more secondaries in a cascading process.

COLDDIAG

Under construction: a diagnostic cold vacuum chamber **measure the beam heat load** on a cold bore in a storage ring. The beam heat load is needed to specify the cooling power for the cryodesign of superconducting insertion devices.

ANKA and KIT, in collaboration with
CERN: V. Baglin
LNF: R. Cimino, M. Commisso, B. Spataro
University of Rome ‚La sapienza': A. Mostacci
DIAMOND: M. Cox, J. Schouten
MAXLAB :Erik Wallèn
Max-Planck Institute for Metal Research: R. Weigel,
STFC/DL/ASTeC:J. Clarke, D. Scott
STFC/RAL: T. Bradshaw
University of Manchester: I. Shinton, R. Jones

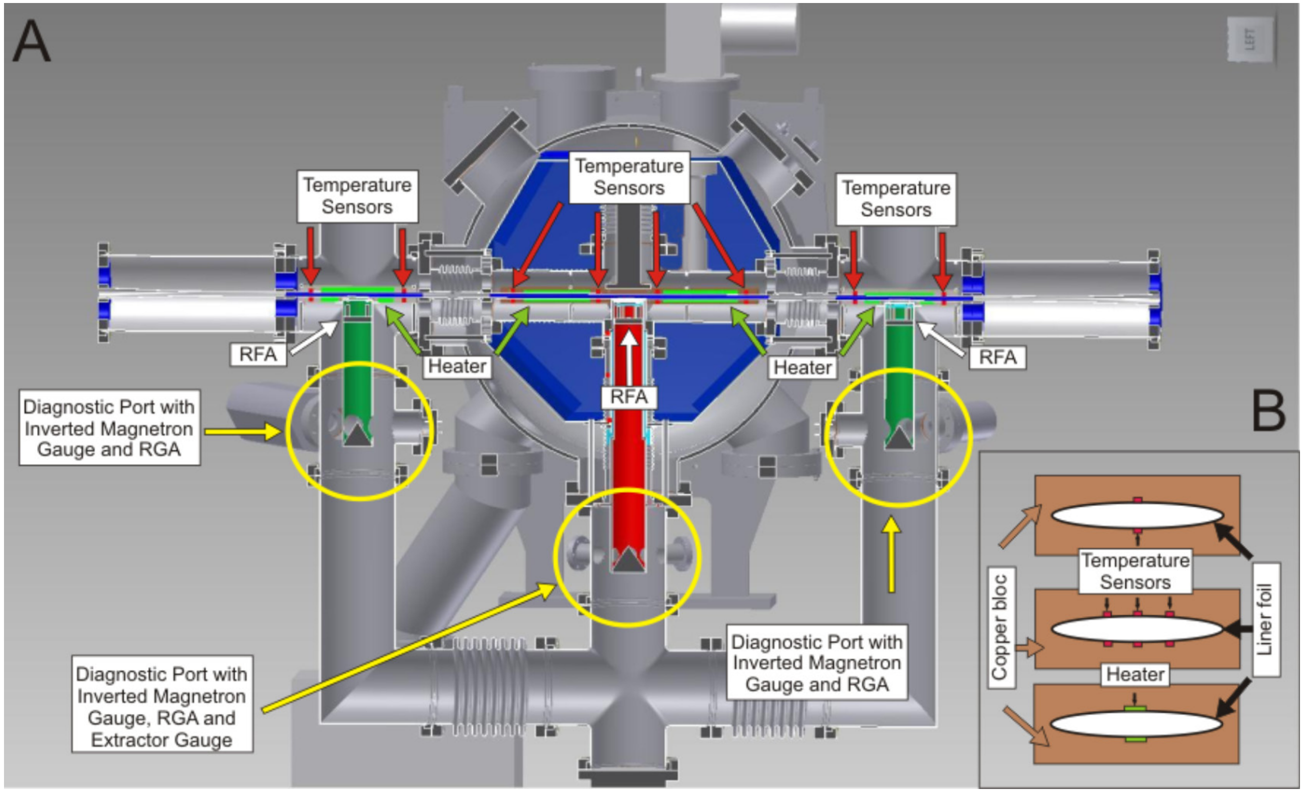
A first installation at the synchrotron light source DIAMOND is foreseen in June 2011.

slide courtesy of S. Casalbuoni

S. Gerstl et al., IPAC10

COLDDIAG: diagnostics

Possible Beam Heat Load Sources: 1)Synchrotron radiation from upstream bending magnet, 2) Resistive wall heating, 3) RF effects, 4) Electron and/ or ion bombardment

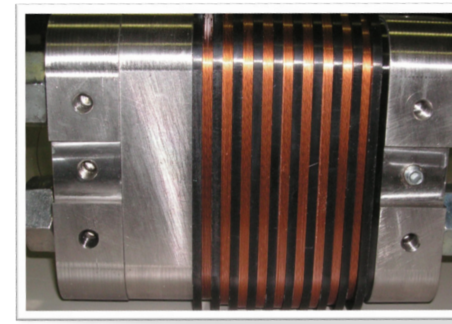


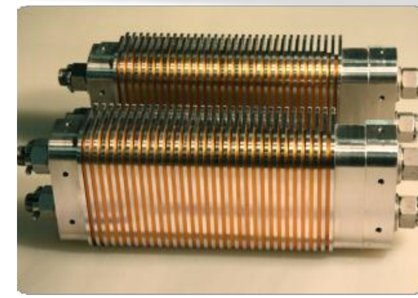
The diagnostics will include measurements of the **heat load**, the **pressure**, the **gas composition**, and the **electron flux of the electrons bombarding the wall**.

slide courtesy of S. Casalbuoni

S. Gerstl et al., IPAC10

ANKA / KIT SCUs, cont.





A new industrial partner: Babcock-Noell GmbH.

Building a new SCU, with 15 mm period, 100.5 periods long, NbTi conductor. Cryogen free.

Beam liner thermally isolated from superconducting coils and separately cooled.

Measurements of the coil found some curvature in the yoke, but it can be mechanically shimmed. After the mechanical shimming, phase errors of 3.5 deg are anticipated (compared to 7.4 deg initially).

photos courtesy of S. Casalbuoni

SCUs at Taiwan Light Source

- Careful and systematic development work on winding procedures and evaluation of prototype magnet structures
- Shimming techniques using trim coils or iron pieces as shims were investigated. Good agreement was found between simulation and measurement. It was noted that shimming without coils was less expensive in heat loss through current leads and in power supplies.
- Vertical dewar measurement system is used, but there are challenges in knowing the position of the Hall probe sensitive area because of thermal contraction.
- Shimming will be needed at the ends of SCUs. We don’t know yet how much will be needed in the middle.

SCUs for the ILC -- the HeLiCal collaboration

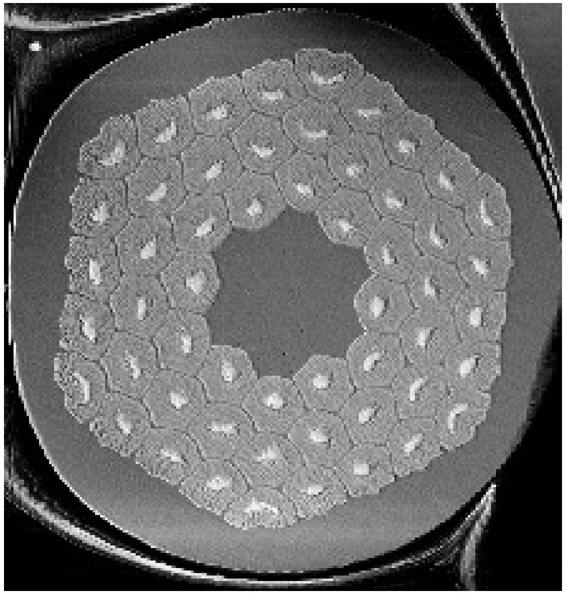
- The International Linear Collider seeks to use a helical SCU as part of the positron production system.
- A number of short prototypes were successfully built and tested at the STFC Rutherford Appleton Laboratory.
- A full-scale 4-m-long superconducting helical undulator was built.
- Work is underway on a planar SCU for Diamond and possibly a Nb_3Sn design.

SCUs at the Argonne Advanced Photon Source (APS)

- Some users at the APS are asking for more photons at higher energy, so a development program has been underway for some time.
- Initial tests with NbTi conductor were successful.
- Testing was also done with Nb_3Sn. On the first test, despite flux jumping that limited the current (the superconducting filaments were too big), the current reached was still encouragingly higher than for NbTi.
- Collaborations were established with LBNL and National High Magnetic Field Lab in Tallahassee to pursue Nb_3Sn.
- Each lab independently succeeded in reaching expected critical current, showing that Nb_3Sn conductor is feasible.

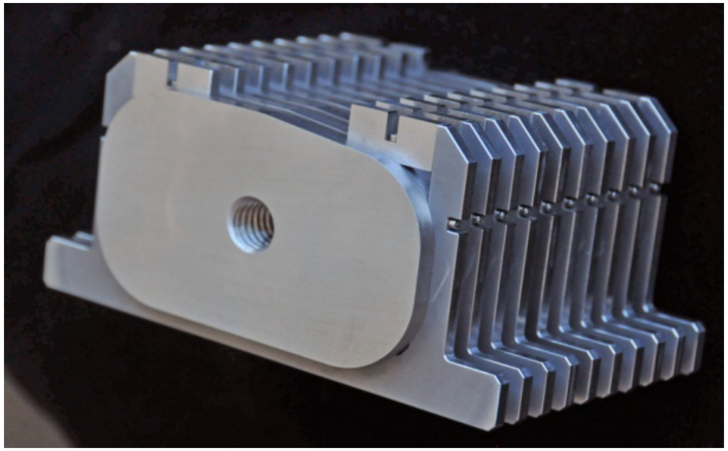
Flux Jumping

- If there is a change in the magnetic field outside of the superconductor, it can cause heating.
- This heating can cause the superconductor to quench (become normal-conducting) at currents well below the critical current.
- The way around it is to use superconducting wire with smaller filaments. ~50 μm or less is good.
- Appropriate Nb_3Sn conductor is now readily available.



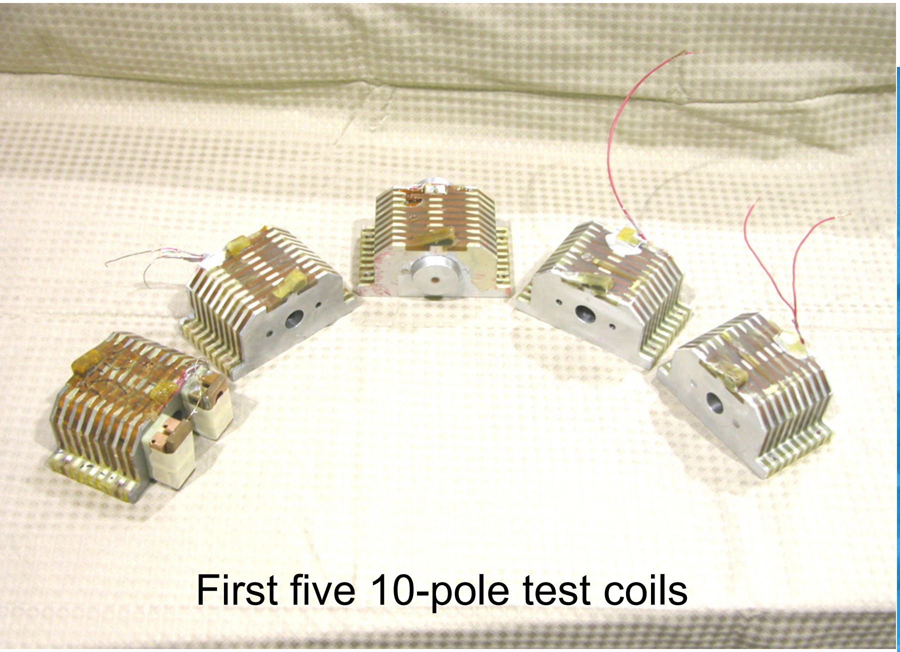
SCUs at APS, cont.

- However, Nb_3Sn is trickier to work with and more prone to minor oversights that cause it to not work.
- The decision was made to use NbTi first. There are many details to resolve to make an SCU that is compatible with a ring that expects >97% reliability.
- An assembled design was chosen for the core. Period length is 16 mm.
- Poles are polished separately.
- Core is smoothed.
- Poles fit into notches in the core.
- All surfaces that touch the superconductor are smooth, to avoid shorts.



SCUs at APS, cont.

- Winding is done at APS
- Epoxy impregnation assistance at the beginning came from Sasha Makarov & coworkers at FNAL; now it is done at APS.
- Many coils have been wound.



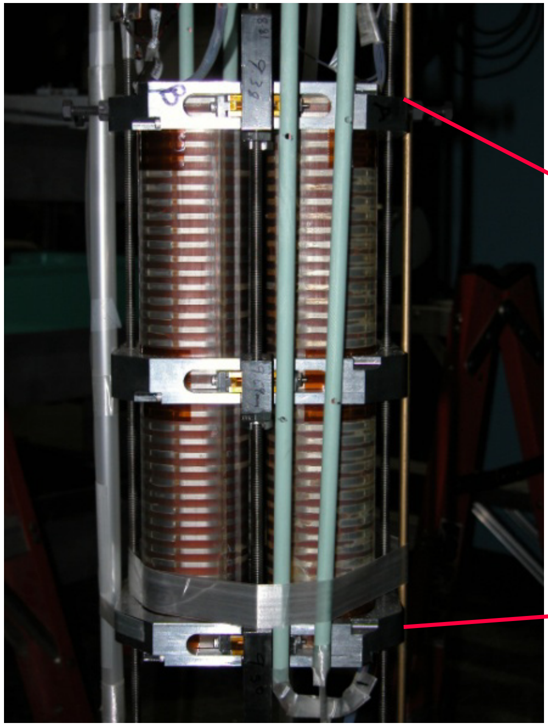
First five 10-pole test coils

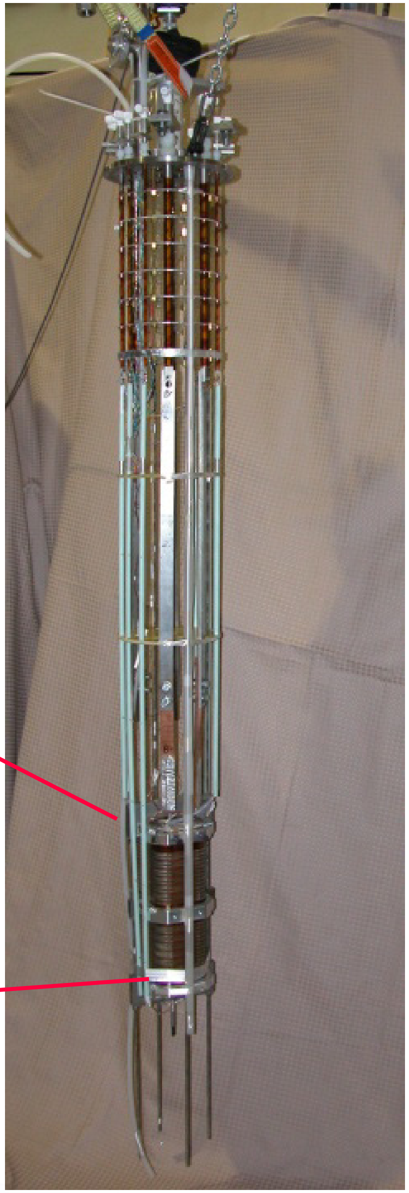
Additional windings at the ends can serve as correction coils.

First wound 42-pole test coil

Measurements of latest coil pair

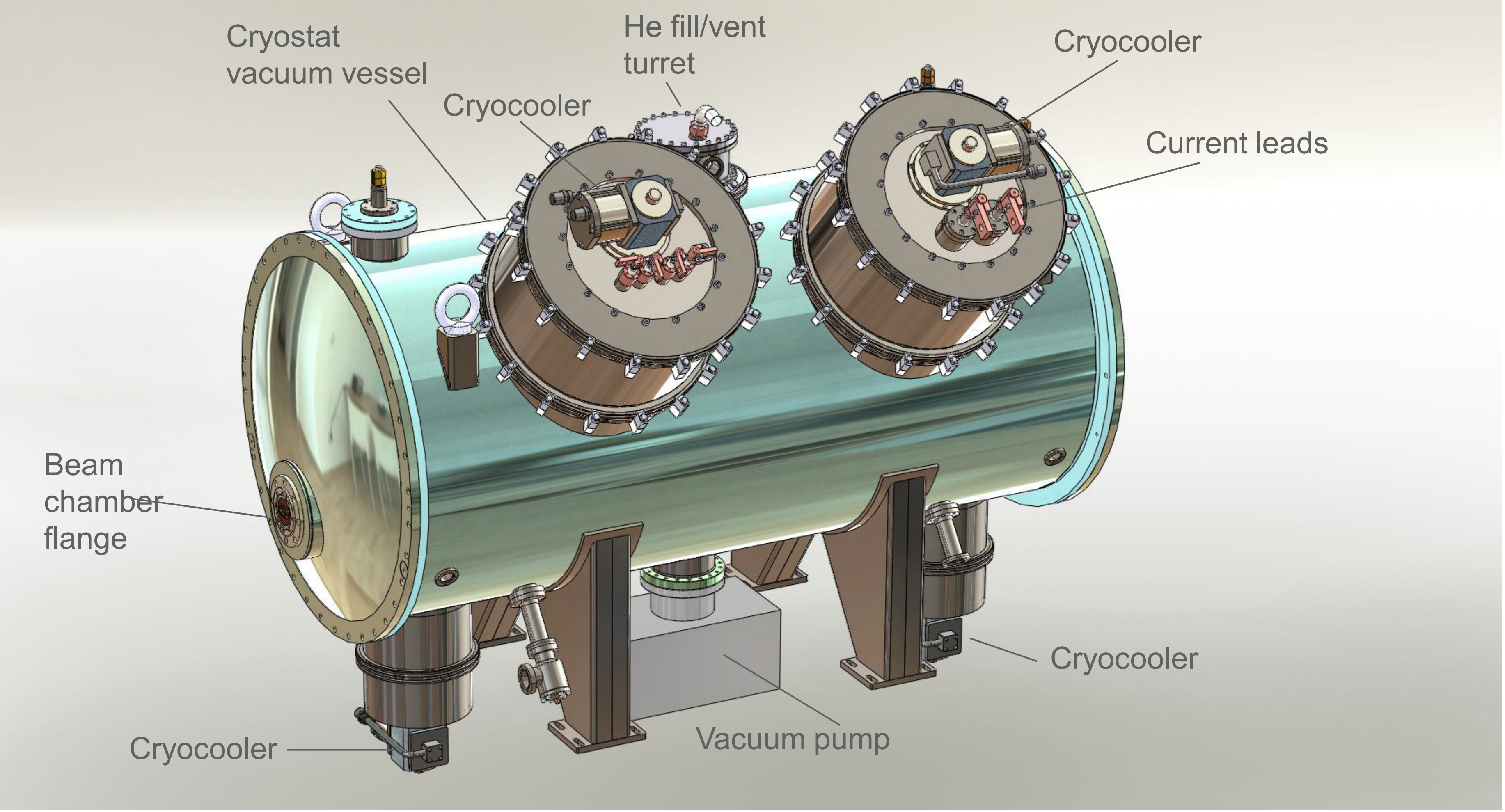
- Magnetic measurements on the latest coil pair found an rms phase error of <2° .





Cryostat

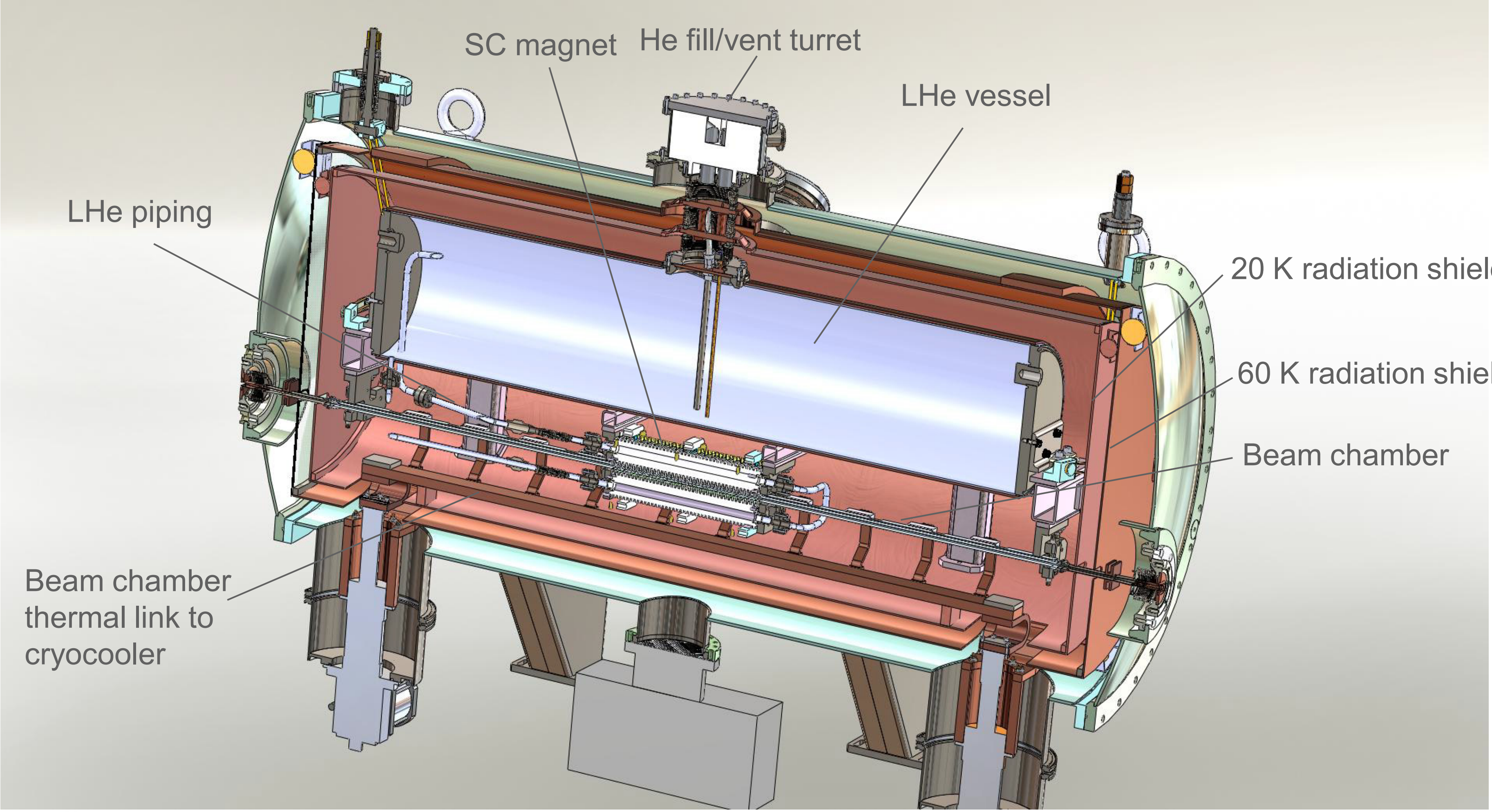
Conceptual design done by N. Mezentsev & V. Syrovatin. Details done at APS.



Cryostat is 2.06 m long, so will fit in half of the straight section

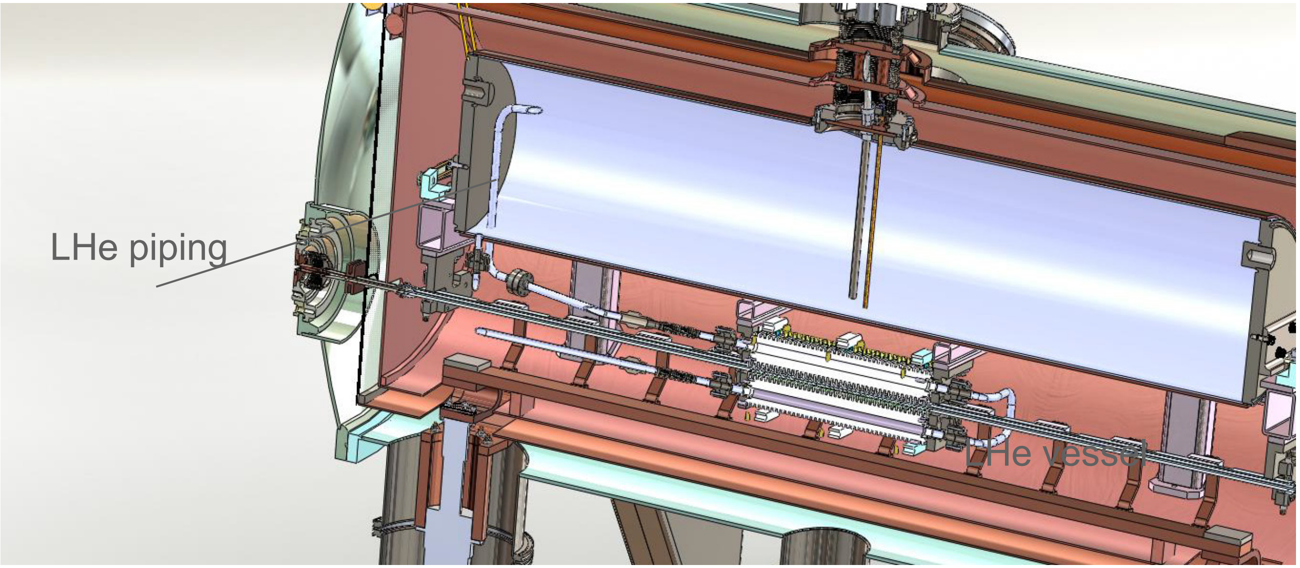
Cryostat structure

Cryostat contains cold mass with support structure, radiation shields, cryocoolers, and current lead assemblies. Liquid He circulates through the magnet cores via a thermosiphon. A recondenser (not shown) reliquefies the He.



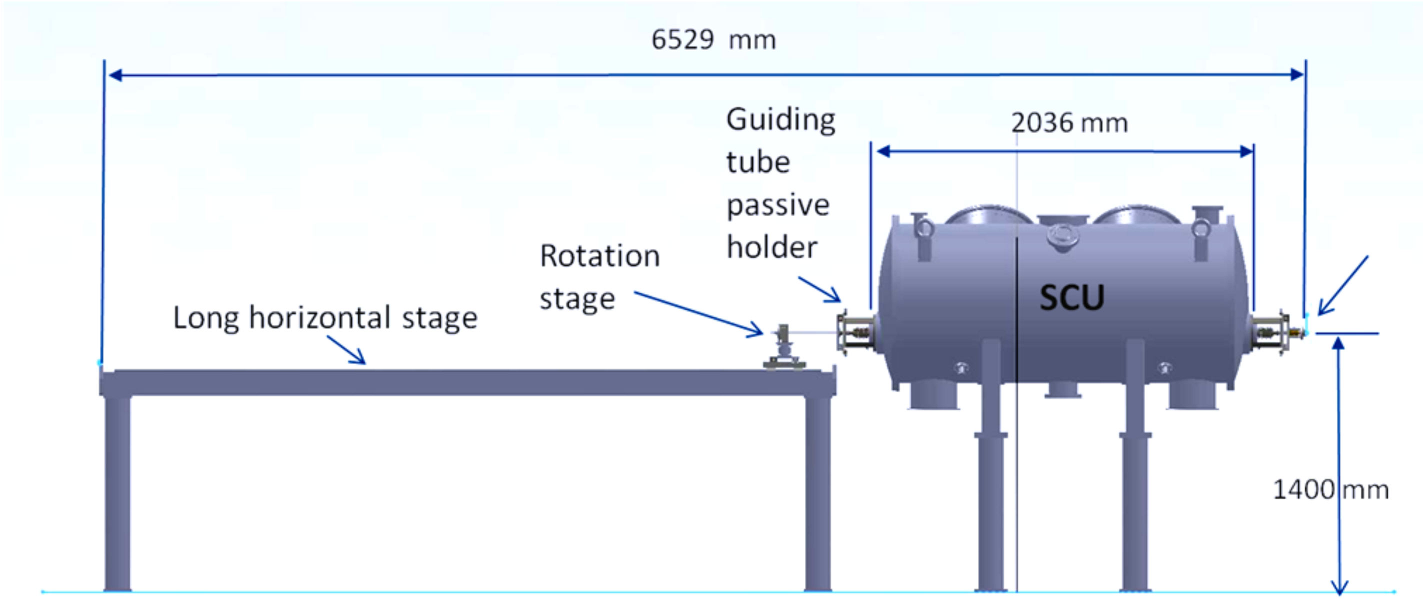
Thermosiphon

- Liquid He (LHe) moves from the tank into the pipe that leads through the core.
- It cools the magnetic cores, and some of the liquid vaporizes.
- In the vertical return pipe, the mixture of gas and liquid has less weight, so there is a pressure differential between the supply and return legs that drives the circulation.
- If additional driving power is needed, a heater can be added to the vertical return leg.



SCU Magnetic Measurement System – Warm Bore

- Conceptual design is completed, with the help of V. Tsukanov and V. Lev.
- Detailed design is underway, being fleshed out by APS.
- System capabilities will include Hall probe, long rotating coil and twisted coil
- Tests of new rotating coil prototypes are being done.
- Behavior & calibration of Hall sensors vs. temperature is being studied.



For the future: High-temperature superconductor (HTS) possibilities

- High-temperature superconductors' advantage is that the critical current is very high. Challenges in using it:
  - Packaging. Most of the tape conductor is not superconductor, but support and non-superconducting layers. However, engineering current densities are approaching being competitive with NbTi.
  - Highest critical current depends on the angle of the ambient B field. (Parallel to tape plane is better.)
- At the usual cold (~4.5K) temperatures, the high-temp capability of the HTS provides thermal margin. But, high thermal margin means slow quench propagation and a greater risk of developing hot spots that burn out the coil.

The End