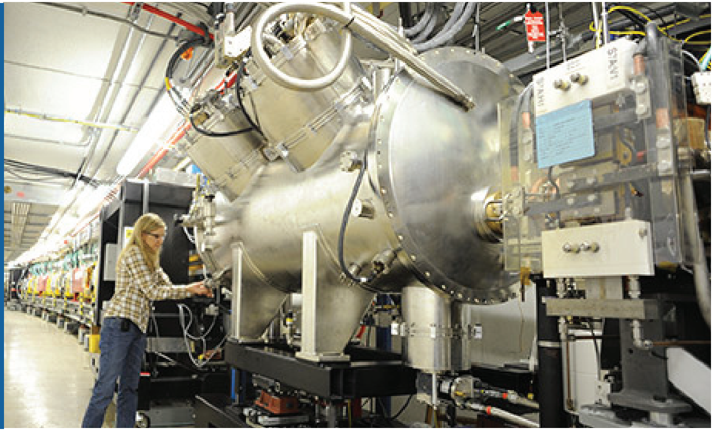
OPERATIONAL EXPERIENCE WITH SUPERCONDUCTING UNDULATORS AT APS



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OUTLINE

- Introduction
- Operational history
- Integration into APS storage ring
  - Planar SCUs
  - Beam abort system
  - Helical SCU
- Summary

This work is the result of the combined effort of many groups at APS: Magnetic Devices, Accelerator Physics, Mechanical, Vacuum, Controls, Survey and Alignment, Diagnostics, Power Supplies.

Special thanks to M. Kasa, C. Doose, Y. Ivanyushenkov, and S. Casalbuoni.

INTRODUCTION

- Advanced Photon Source (APS) has been developing superconducting undulators (SCUs) for over a decade.
- SCUs provide higher peak field on axis for a given gap and period length.
- Two planar and one helical SCU are in operation in the APS storage ring.
- All SCUs are highly reliable and minimally impact APS operations.
- Technical details of the SCUs have been published elsewhere [1-3].
- Operational experience with, and integration of, SCUs into the APS storage ring will be described.

[1] Y. Ivanyushenkov et al., *PRST-AB* **18**, 040703 (2015).
[2] Y. Ivanyushenkov et al., *PRAB* **20**, 100701 (2017).
[3] M. Kasa et al., *IPAC'18*, 1263.

WORLDWIDE LANDSCAPE

SCUs are in operation only at APS and Karlsruhe (KIT) [1]

Facility	Operation period	λ (mm)	# periods	Vacuum aperture (mm)	Gap loss (mm)	B(T)	Cooling
APS	2013-2016	16	20.5	7.2	2.3	0.8	*
APS (2)	2015-pres. 2016-pres.	18	59.5	7.2	2.3	0.97	*
APS Helical	2018-pres.	31.5	38.5	26	5	0.41	*
KIT/Noell	2014-2015	15	100.5	7, 16 (open)	1	0.73	**
KIT/Noell	2017-pres.	20	74.5	7, 15 (open)	1	1.18	**

* 4 cryocoolers, LHe closed circuit
** 4 cryocoolers

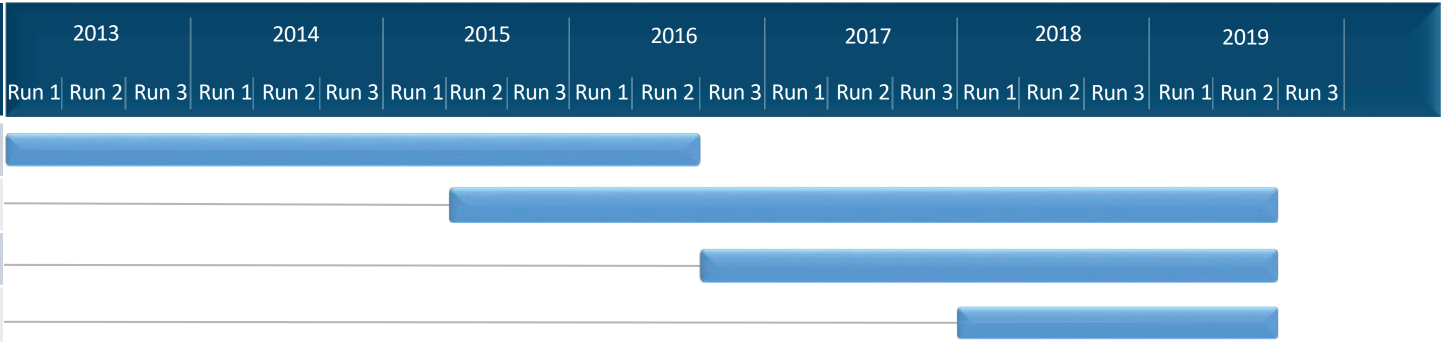
[1] J. Bahrdt, E. Gluskin, *NIM-A*, 2018.

OPERATIONAL HISTORY AT APS

SCUs IN OPERATION AT THE APS

Combined operating years > 11

Device name	λ (mm)	# of periods	B (T)
SCU0	**16**	**20.5**	**0.8**
SCU1[1]	**18**	**59.5**	**0.97**
SCU6[2]	**18**	**59.5**	**0.97**
HSCU	**31.5**	**38.5**	**0.41**



[1] Also known as SCU18-1
[2] Also known as SCU18-2

Table: M. Kasa

- Extensive commissioning plan was executed for SCU0 (5 days equivalent) [1].
- SCU1, SCU6, HSCU commissioning executed in fraction of time (1-2 days equivalent).
- All devices were turned over for beamline operations immediately after commissioning.

[1] K. Harkay, *NA-PAC'13*, 703.

SCU AVAILABILITY IS > 99%

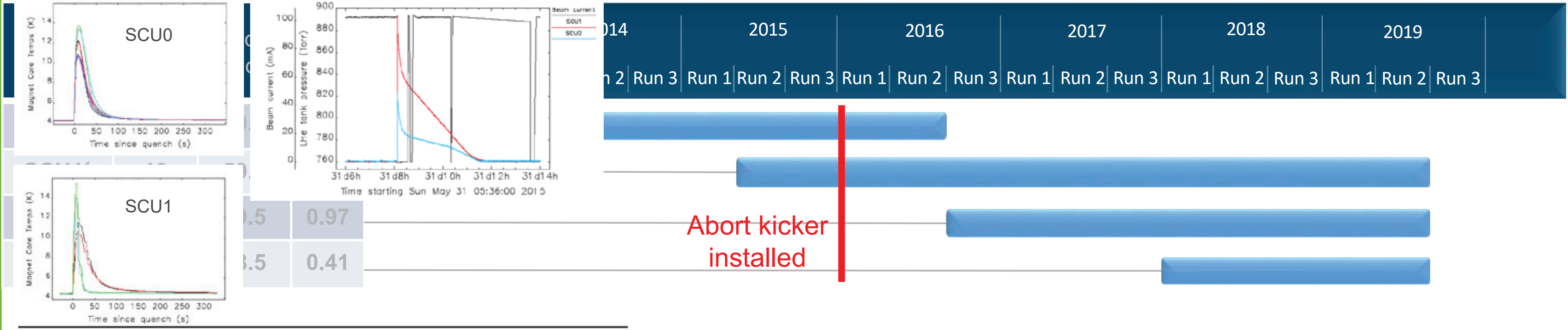
We maintain detailed operational statistics – I. Kesgin TUPLH01

Device name	Availability %	Operation %
SCU0	98.9%	92.3%
SCU1	99.992%	96.6%
SCU6	99.89%	84.9%
HSCU	100%	14%

- Availability = ratio hours $\frac{\text{device powered}}{(\text{powered+down})}$
- Operation = ratio hours $\frac{\text{device powered}}{(\text{APS delivered beam})}$
- Sector 6 beamline down since Jan 2019 (unrelated to SCU6).
- HSCU demand relatively low so far.

QUENCHES ARE TRANSPARENT

Most quenches occur during beam dumps; timely recovery [1]



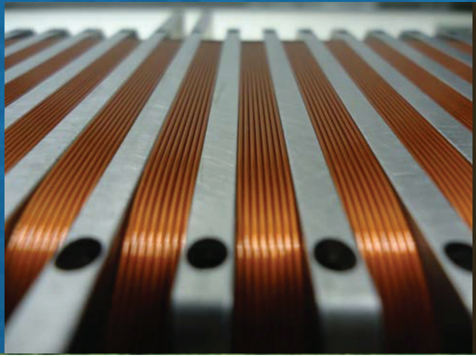
Device name	# Quenches, beam dump	# Self-quenches
SCU0	98	6
SCU1	40	5
SCU6	32	3
HSCU	0	0

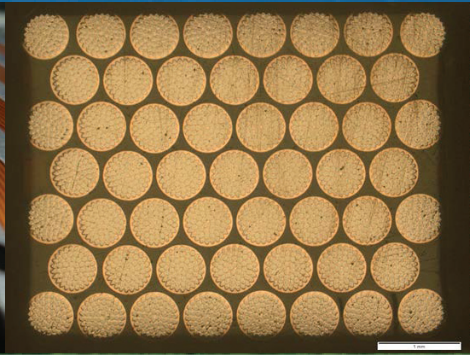
- Abort kicker significantly reduced rate of beam-dump-induced quenches.
- Self-quenches occur ~once a year per device
  - Perturbation of the storage ring beam orbit is minimal.
  - No self-quench has ever caused the beam to be lost.

[1] Y. Ivanyushenkov et al., *PRAB* **20**, 100701.

INTEGRATION OF PLANAR SCUs

Figs: C. Doose





ID EFFECTS ON THE BEAM

IDs should not degrade SR operation below acceptable level

Insertion devices (IDs) can affect the storage ring (SR) beam through magnetic fields errors and by introducing small physical apertures.

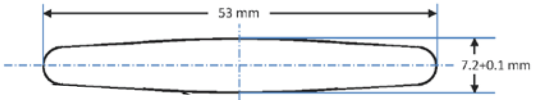
Storage ring operation means

- Being able to inject with high efficiency (small injection losses).
- Having long enough lifetime of the electron beam.
- Being able to accumulate high charge in a single bunch.
- Keeping SR operating parameters stable.
  - Orbit
  - Tunes
  - Beta functions
  - Beam sizes

Physical aperture and nonlinear fields

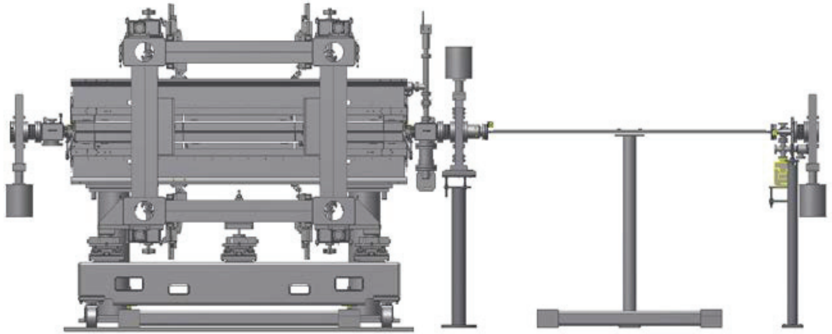
1st and 2nd field integrals and field linearity

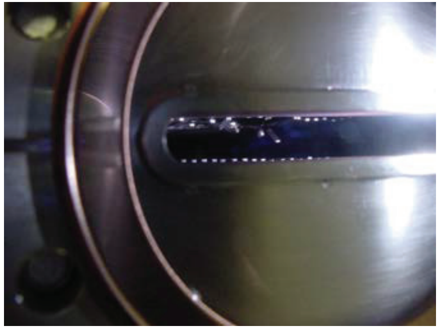
TEST CHAMBER MITIGATES RISK



Lessons learned with SCU0 test chamber

- Test chamber was pre-installed with same aperture, and in the same location, as SCU0 (May 2012).
- Standard 4.8-m-long ID chamber replaced with half-length ID chamber and SCU0 test chamber; similar vertical apertures. Special transition in between used small-aperture gate valve and bellows.
- Due to oversight, there was no rigorous reviews of the special transition.
- Heat load from beam image currents melted the rf liner of the bellows.

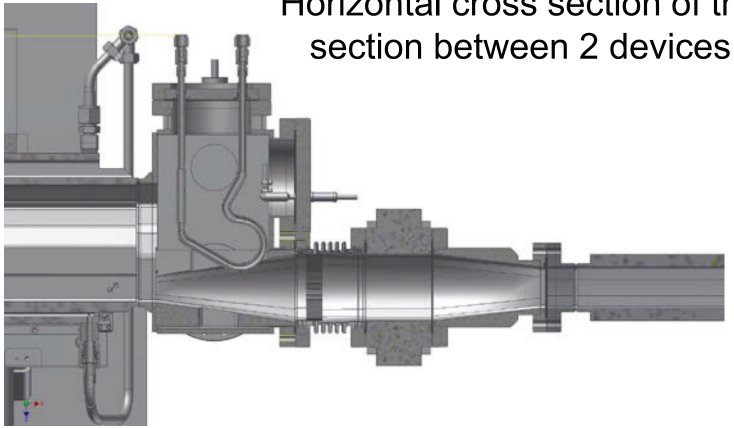




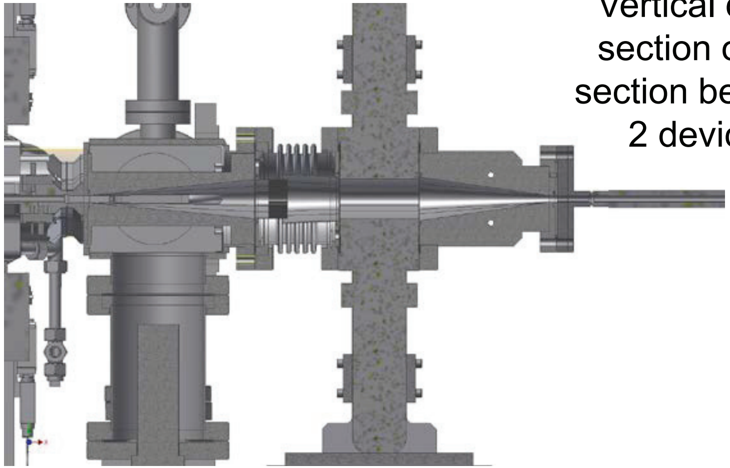
VACUUM TRANSITION WAS CHANGED FOR SCU0

All SCU designs avoid gate valves or bellows at small apertures

- Two transitions were added and a standard-aperture gate valve and bellows are used between the upstream permanent-magnet ID and the SCU.
- No further vacuum issues when first device, SCU0, was successfully installed Jan 2013.



Horizontal cross section of the section between 2 devices

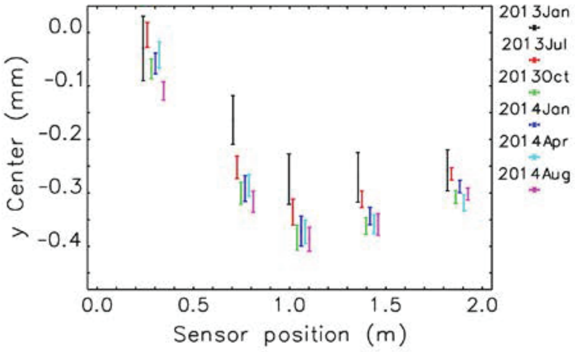


Vertical cross section of the section between 2 devices

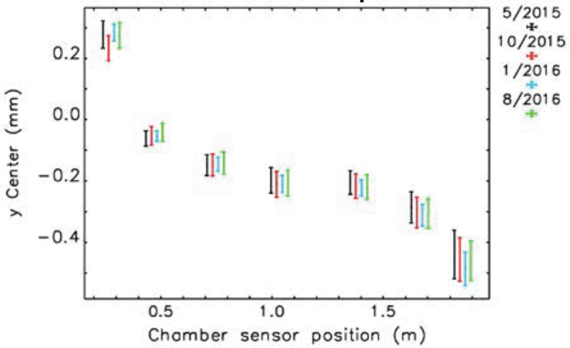
CHAMBER LONG-TERM DRIFT MINIMIZED

- Cold mass is suspended using Kevlar strings, and vacuum chamber is attached to the cold mass. Chamber height could change with time.
- Electron beam was used to measure the position of vacuum chamber [1].
  - Chamber temperature is sensitive to the beam position, which allows to measure the relative position of the beam and chamber with high accuracy.
- SCU0 showed small position change; design modification was implemented in next device to reduce it [2].

SCU0 chamber position



SCU1 chamber position

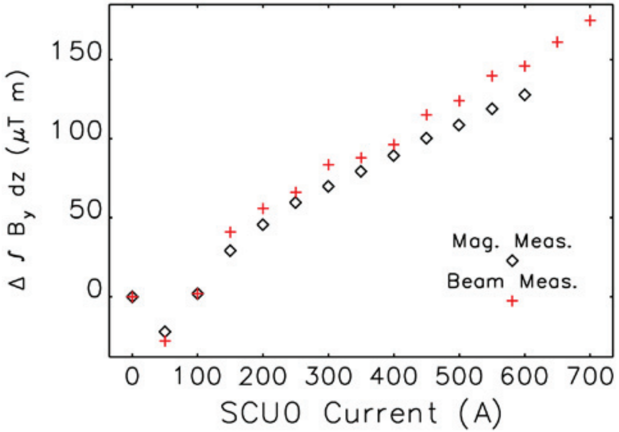


[1] K. Harkay, *NA-PAC'13*, 1058.
[2] Y. Ivanyushenkov et al., *PRAB* **20**, 100701.

MAGNETIC PERFORMANCE VERIFIED

SCUs transparent for user operation after applying corrections

- Strongest effect expected from IDs is on the beam orbit through changing field integrals when an ID gap (or current) changes.
- We give requirements on field integral errors to limit the effect.
- Feedforward (FF) tables combined with orbit feedback ensure that the devices do not perturb beam orbit.
- SCU0 FF table required skew quadrupole correction due to effect on coupling; SCU1, SCU6, and HSCU did not.
- Field integrals measured in the lab and with beam agreed well [1].



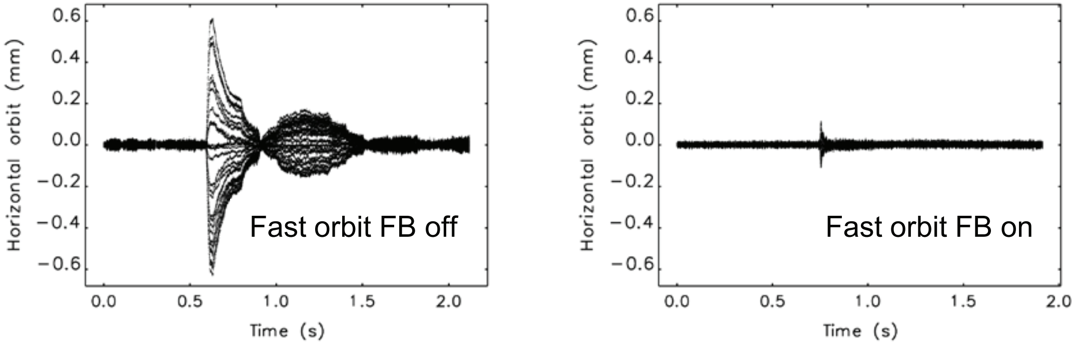
Change in first field integral with current;
100 μT m = 4.2 μrad.

[1] Y. Ivanyushenkov et al., *PRST-AB* **18**, 040703.

ORBIT PERTURBATION DUE TO QUENCH IS SMALL

- In case of a quench, the SCU field integrals can change suddenly and quickly
  - This could lead to beam dump if the resulting orbit excursion exceeded the protection limits (±2 mm in X and ±1 mm in Y).
- All devices satisfy requirement on maximum allowable field integral change during a quench, main effect is in horizontal plane.
- During the total 14 self-quenches, beam was never lost.

Measured orbit at different ID locations, induced SCU1 quench [1]

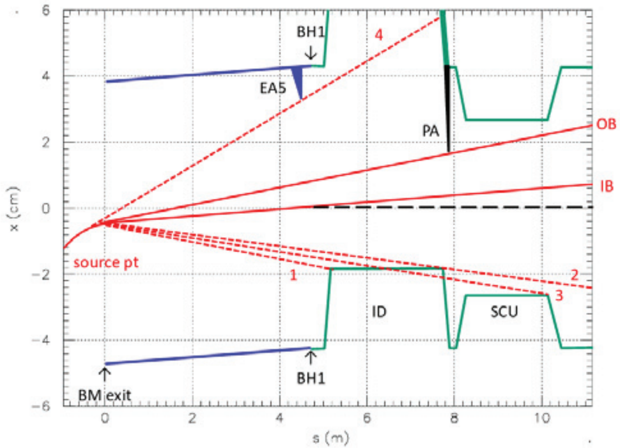


[1] Y. Ivanyushenkov, *et. al.*, *PRAB* **20**, 100701.

BEAM EFFECTS ON THE SCU

Beam-induced heating a unique challenge for SCUs

- Electron beam generates a heat load on the SCU vacuum chamber.
  - Synchrotron radiation from the upstream dipole (6.6 kW is generated in the dipole).
  - Beam image-current heating.
  - Higher-order mode heating in transitions.
- Heating needs to be accurately predicted to design adequate cooling.
- Vacuum chamber for planar SCU is designed to let most of the radiation pass through; image-current heating dominates.



Ray tracing used to calculate synchrotron radiation power for nominal and missteered beam (1,2,3).
Detailed photon tracking confirmed analytical estimates [L. Boon, PhD Thesis, 2014].

CHAMBER HEATING BY THE BEAM AGREED WELL WITH CALCULATIONS

- Image-current heating was calculated, including anomalous skin effect [1].
- Power derived by comparing temperatures with calibrated chamber heaters.

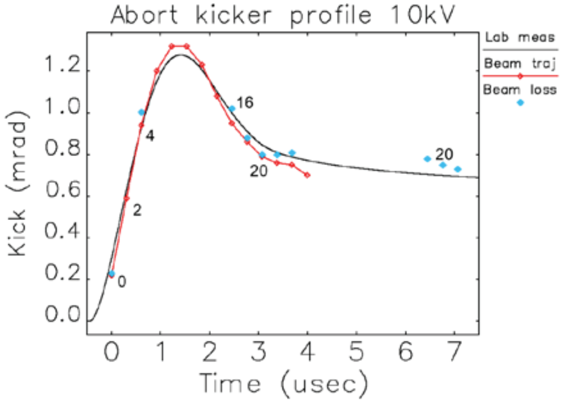
Beam current (mA)	No. bunches	Calculated power (W)	Power from measured T (W)	Predicted T (K)	Measured T (K)
100	24	3.8	3.3	13.6	12.8
100	1+56	2.7	2.7	11.8	11.9
100	324	0.5	0.6	7.9	8.2
150	324	1.2	1.3	9.3	9.5

[1] K.C. Harkay et al., NAPAC'13, 1055.

SCUs OFTEN QUENCHED DURING BEAM DUMPS

New beam abort system implemented to mitigate quenches [1]

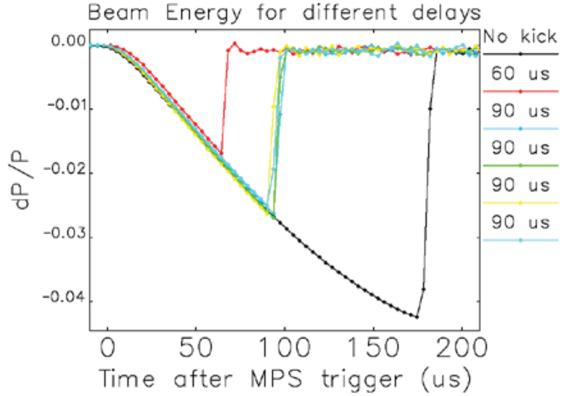
- Original beam dump process: the rf drive is removed and the beam loses energy until most of it is lost on the smallest inboard aperture, which is ID4.
- There is enough energy carried by scattered electrons through the vacuum chamber at SCUs to heat up the magnet coils.
  - Estimates show that 0.1-1 nC (0.03%-0.3% of the total beam charge) reaching coils is enough to cause a quench.
- A horizontal kicker was modified to serve as a beam abort kicker. Pulse was stretched to last for several turns.



[1] K. Harkay *et al*., *IPAC'15*, 1787; *NAPAC'16*, 890; W.A. Wurtz *et al*., *IPAC'14*, 1992.

ABORT KICKER REDUCED FREQUENCY OF QUENCHES

- Simulations were used to design the beam abort process.
- Most of the beam is now lost on the injection septum, the second smallest horizontal aperture after ID4.
- To improve the localization of losses, the kicker is fired with some delay after the rf drive is taken away.
- SCU0 quench rate decreased from 80% to 14% of beam dumps.

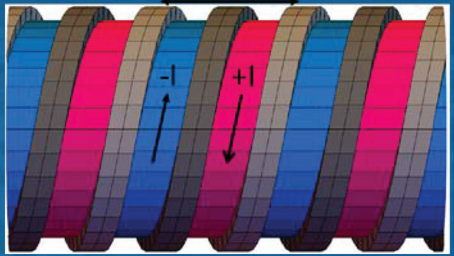


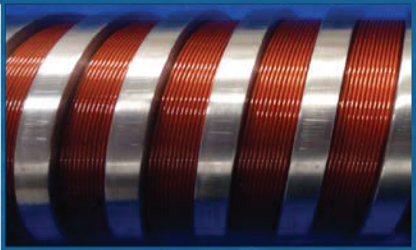
Beam loss monitor calibrated loss charge, Q, vs. abort kick and delay (100-mA beam) [1].

Conditions	ID1 Q (nC)	ID6 Q (nC)
0 kV, 0 delay	11.5	0.29
10 kV, 60 μs	0.33	0.060
10 kV, 90 μs *	0.044	0.0028
8 kV, 90 μs	0.56	0.54

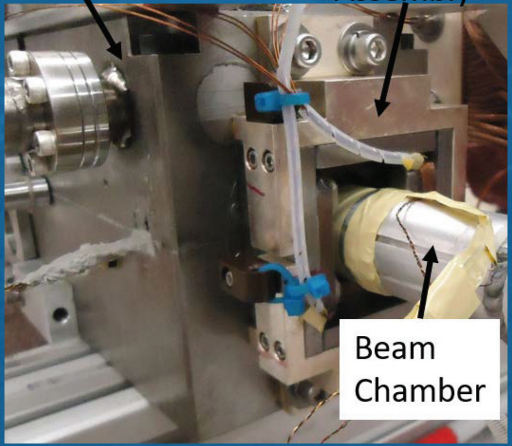
* SCUs energized; no quench detected.

[1] K. Harkay et al., NAPAC’16, 892.





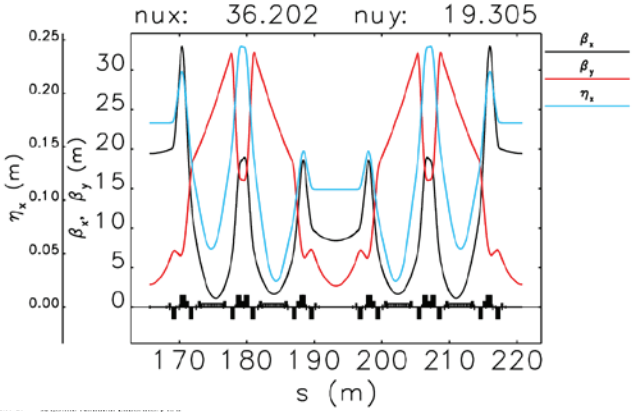
INTEGRATION OF HELICAL SCU



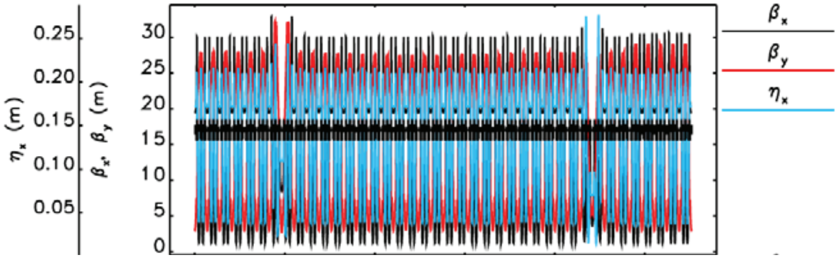
Figs: M. Kasa *et al*., *IPAC'18*, 1263.

HELICAL SCU REQUIRED LATTICE CHANGE

- HSCU vacuum chamber is the smallest horizontal aperture: ±13 mm.
- To make its acceptance larger than the two smallest acceptances in the ring, the horizontal beta function has to be changed from 20 m to 9 m.
- Multi-objective genetic optimization was used to design lattice without impact on lifetime or injection efficiency.
- The lattice was first tested before any hardware modifications.



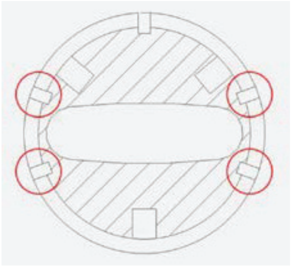
Lattice functions of entire ring; two reduced betas.



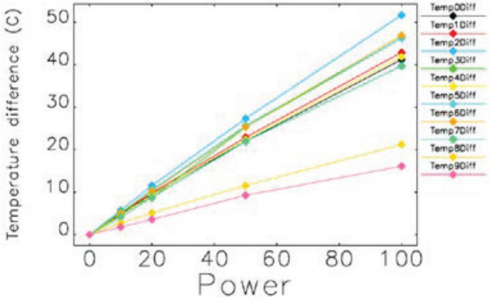
TEST CHAMBER TO VERIFY HIGHER HEAD LOAD

- Unlike planar devices, HSCU chamber cannot be fully protected from the synchrotron radiation heating. Heat load needs to be carefully calculated.
- Prior to HSCU installation, a test chamber was installed.
- Heating of the chamber was measured and the heat load from the beam was found to be in reasonable agreement with predictions.
  - Total predicted heat load was 45 W, measurements showed 30-40 W.

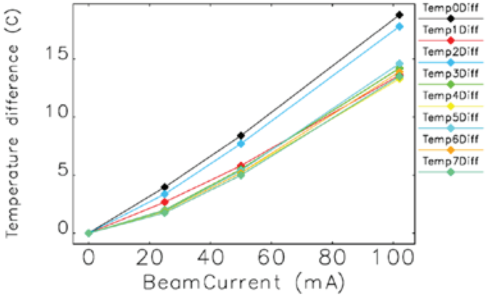
Chamber profile (13x4mm half) and heater wire locations



Temperature as a function of heater power

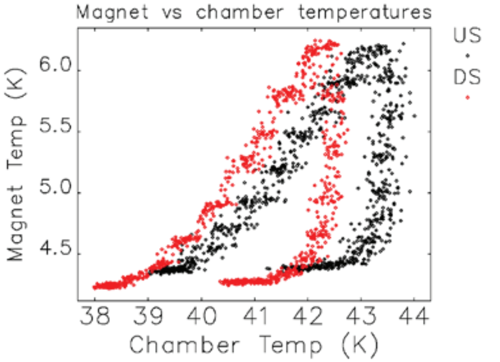


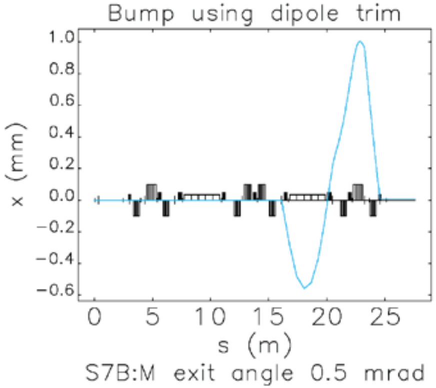
Temperature as a function of beam current

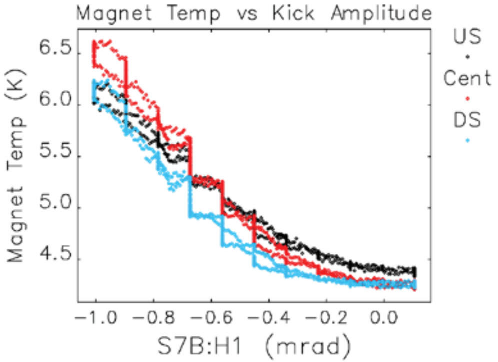


UNEXPECTED HEATING OF MAGNET OBSERVED

- After HSCU installation, unexpected heating of magnet coils was observed, but the vacuum chamber temperature consistent with 30-40 W incident power.
  - Magnet coils exceeded 6 K at 80 mA (operational current is 100 mA).
  - Magnet temperatures did not depend on the chamber temperature.
- Heating did not depend on bunch pattern, pointing to synchrotron radiation as the source.
- An orbit bump was used to reduce the heat load.

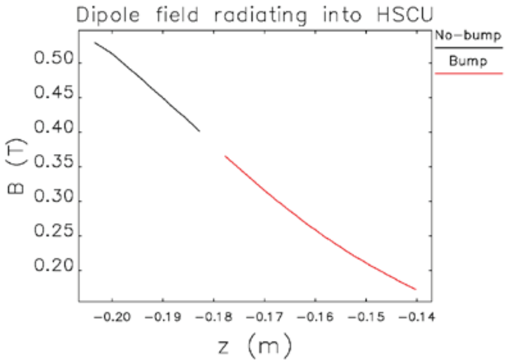


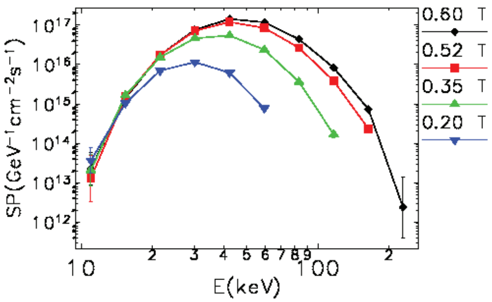




COMPTON SCATTERING THROUGH CHAMBER

- Literature shows that Compton scattering is the dominant effect in photon interaction with aluminum at 100 keV and above.
- Compton scattering in this energy range can result in high-angle events that significantly reduce the path length of scattered photons through the vacuum chamber.
- MARS simulations were carried out that showed that scattered photons could transfer 2-3 W to the coils [1].
- Orbit bump moved the radiation that reaches the chamber into softer range.
- HSCU presently in operation without any issues (with the orbit bump).





[1] J..C. *Dooling et al.*, *IPAC'19*, 4328.

SUMMARY

- SUPERCONDUCTING UNDULATORS SUCCESSFULLY OPERATE AT APS FOR MANY YEARS.
- SCUs DO NOT DEGRADE APS OPERATION.
- ORBIT EFFECT OF SCUs IS CONTROLLED USING FEED FORWARD (LIKE ANY OTHER ID)
- HEAT LOAD ON PLANAR DEVICES MATCHED PREDICTIONS WELL.
- HSCU INSTALLATION REQUIRED LATTICE MODIFICATION DUE TO SMALL HORIZONTAL APERTURE.
- HSCU SHOWED UNEXPECTED HEATING OF COILS ATTRIBUTED TO COMPTON SCATTERING; IT WAS MITIGATED USING AN ORBIT BUMP IN THE UPSTREAM DIPOLE.

FOR MORE INFO, VISIT: I. KESGIN, TUPLH01