Correction Schemes for Superconducting Undulators

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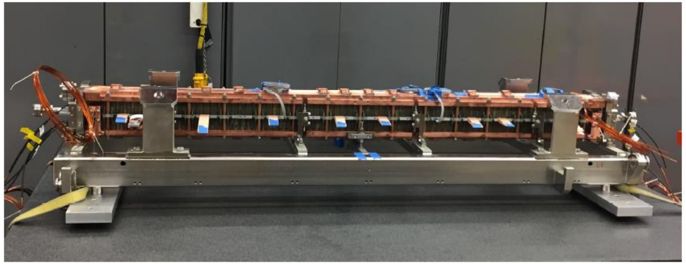
Introduction

- Planar superconducting undulators commonly require global and local field correction
  - Global field can be present in undulators with iron yoke
  - Local corrections are usually required at the ends
- Local (periodic) errors can be well controlled by precise machining / fabrication of parts but some methods exist for local correction if specifications are difficult to meet
- Overall control of the mechanical structure (undulator gap) is also critical to obtaining low phase error

LBNL 1.5 m Nb_3Sn Undulator from LCLS-II R&D Program

Several examples are shown from LBNL Nb_3Sn SCU Design and testing for 19 mm period undulator with 8.0 mm gap



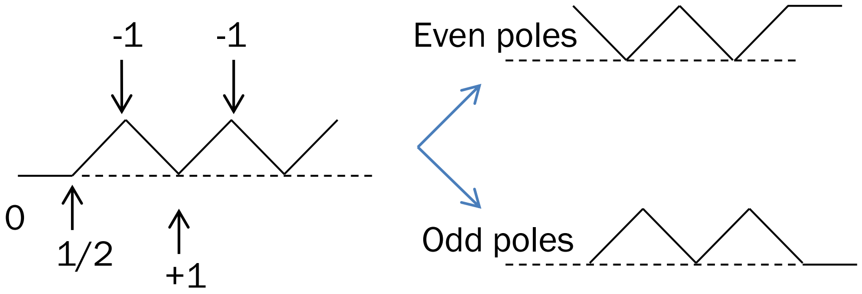
D. Arbelaez, et al., International Committee for Future Accelerators, Beam Dynamics Newsletter No. 78. 2019

Outline

- Basic end design considerations for planar SCUs
    - Saturation effects
    - Local vs. global effects
- End correction schemes
- Local (periodic) correction schemes
- Gap corrections
- Conclusions

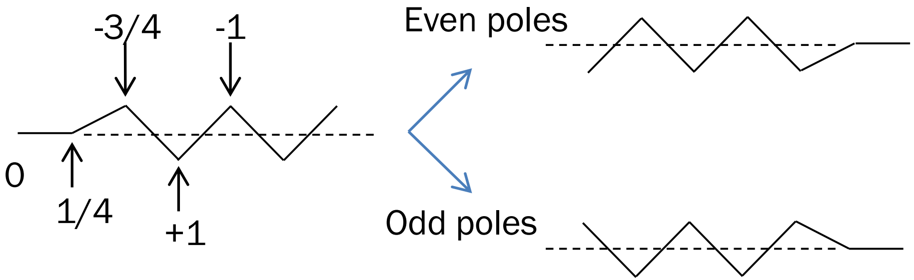
Basic End Design Kicks (ideal)

Potentials at Poles: 0, ½, -1, +1, ...



# of coil turns:
1/4, 3/4, 1 ...

Potentials at Poles: 0, ¼, -3/4, +1, -1, ...

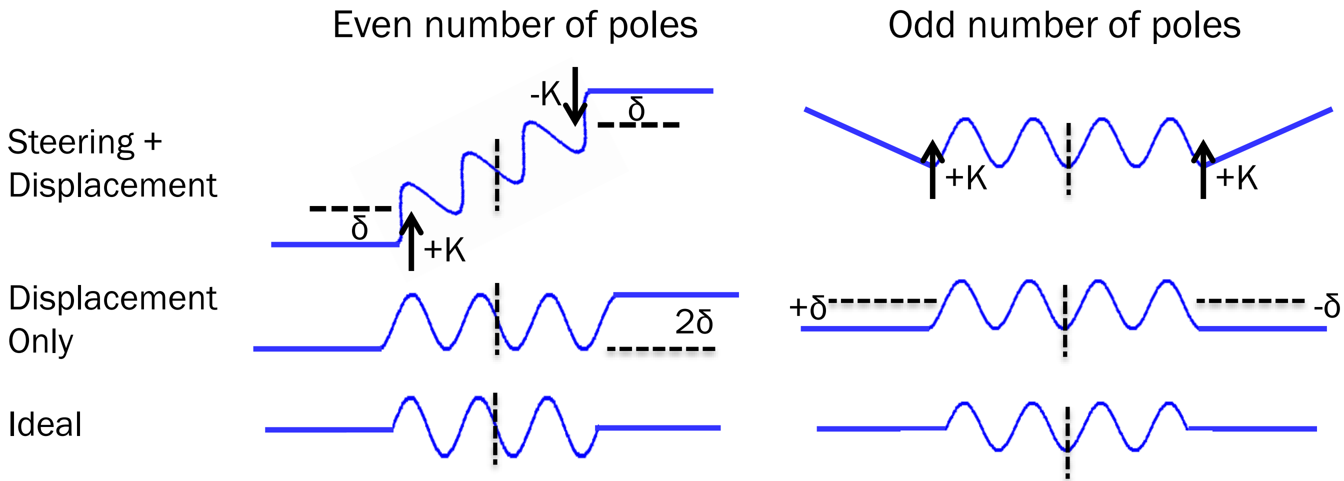


# of coil turns:
1/8, 1/2, 7/8, 1 ...

# of coil turns is given by the difference in neighboring pole potentials

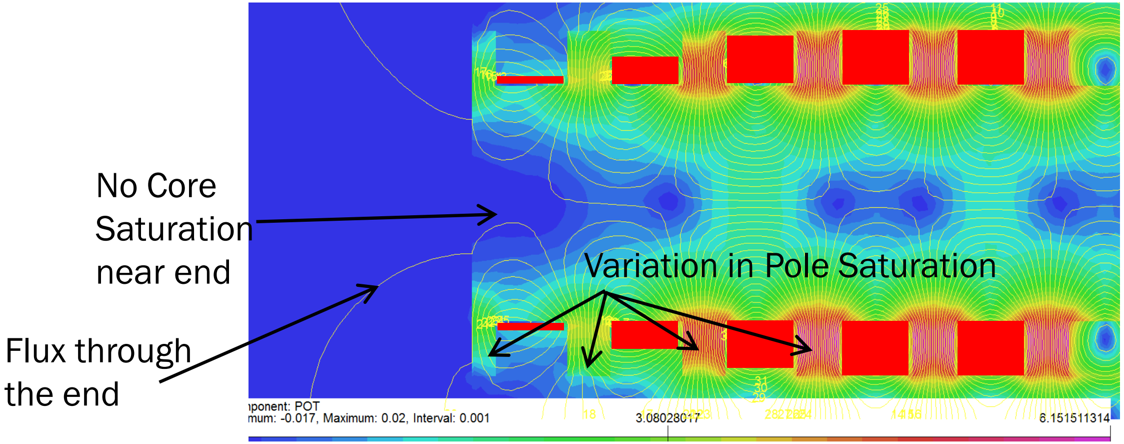
End Design Including Local End Errors

- Kick and displacement errors at the ends due to non-ideal effects
- Even or Odd number of poles
  - Even – zero net steering, non-zero net displacement
  - Odd – zero net displacement, non-zero net steering



Undulator Pole/Core Saturation

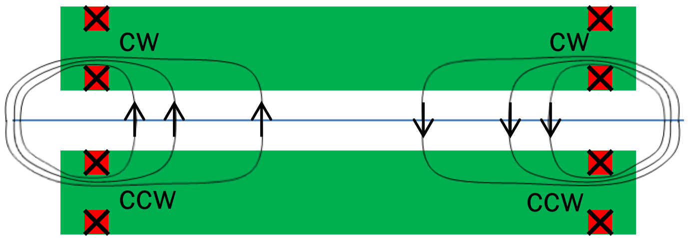
- Saturation of the undulator core and poles leads to non-ideal effects
  - Pole saturation changes the local kick strength
  - Pole and core saturation leads to non-ideal global effects



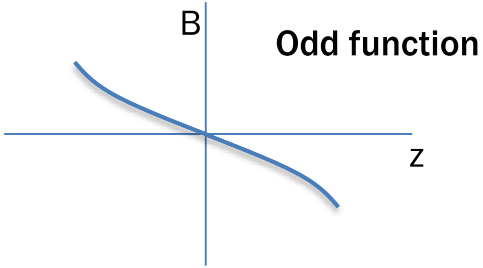
❖ 2D calculations are shown to demonstrate the principles
❖ For accurate results 3D calculation must be used

Global Field Effects

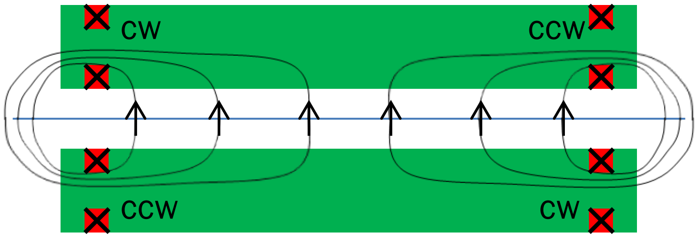
Even # of poles, Odd # of coils



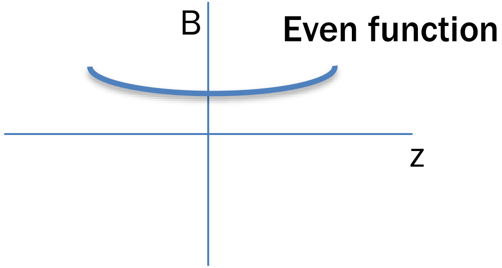
On-Axis Field Profile



Odd # of poles, Even # of coils



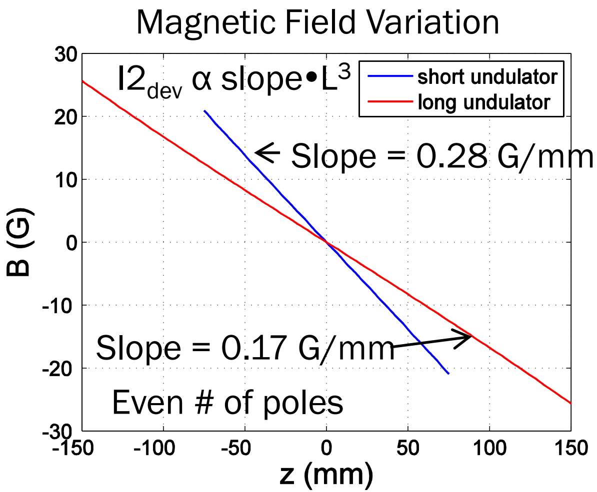
On-Axis Field Profile

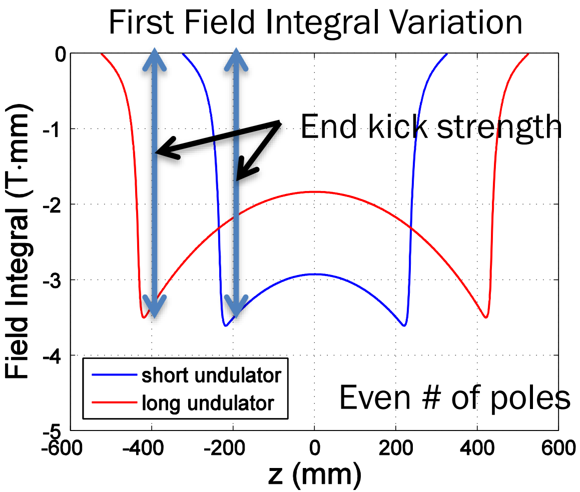


- Number of turns are chosen to cancel these effects in an ideal case
- Global field effects are present due to saturation

Global Field Effects Can Scale Unfavorably With Undulator Length

- Magnetic field was calculated with two different length undulators (second one is twice as long) with odd symmetry
- The effect of the end coil corrector is shown
- Slope of the distributed field scales approximately with 1/L
- Second field integral scales with slope*$L^3 \approx L^2$

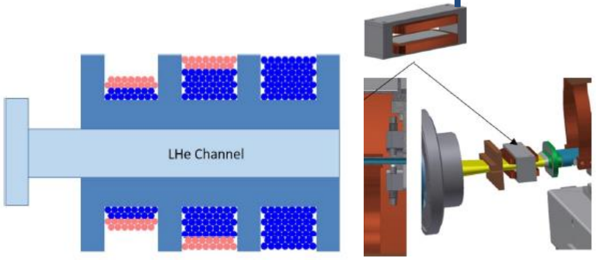




End Correction Schemes

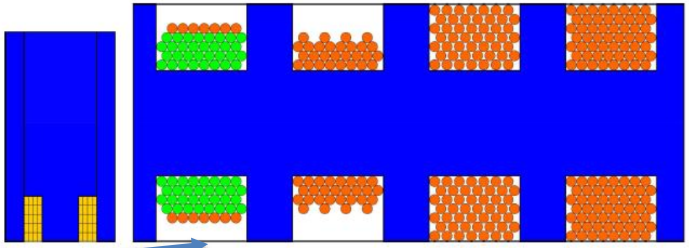
- Less turns in the pockets at the ends of the undulator
- Corrector coils can be wound in the main coil pockets at the ends
- External dipole kick corrector is usually required since local and global errors may be coupled for co-wound correctors

ANL SCU1 Example



Y. Ivanyushenkov et al., Phys. Rev. AB. ***20****, 100701 (2017)*

LBNL Nb_3Sn Undulator Example



# of coil turns:
1/8, 1/2, 7/8, 1 …

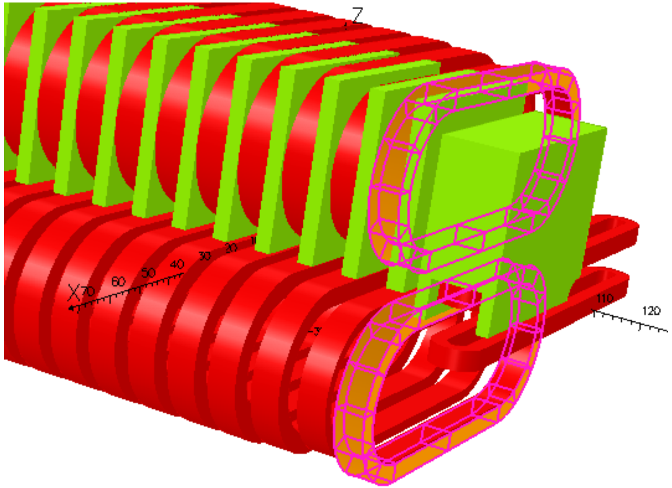
Example of End Design Approach for LBNL Nb_3Sn Undulator

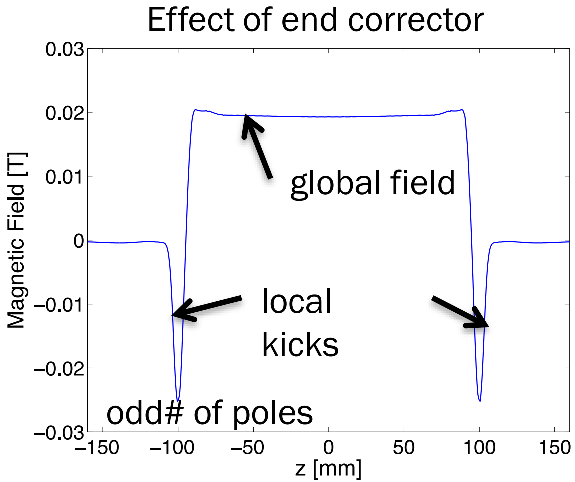
2 Independent Correctors

- Correction of global field effects
  - 1 corrector (coil at each end wired in series) is used for correction of the global field effect
  - corrector produces both a local kick and a global field
- Correction of local end kick
  - 1 corrector at each end wired independently for entrance and exit kick correction
  - This correction is decoupled from the main core and produces no global fields
  - Field clamps are included for this corrector in order to avoid interference with nearby magnetic components

Global Field Correction

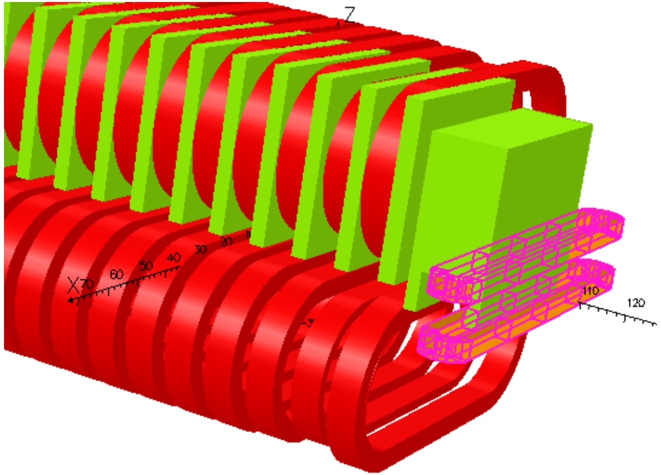
- Coils are wound in first and last pocket of each core
- Produces a global correction + local kick
- Strength is chosen to cancel only global field error

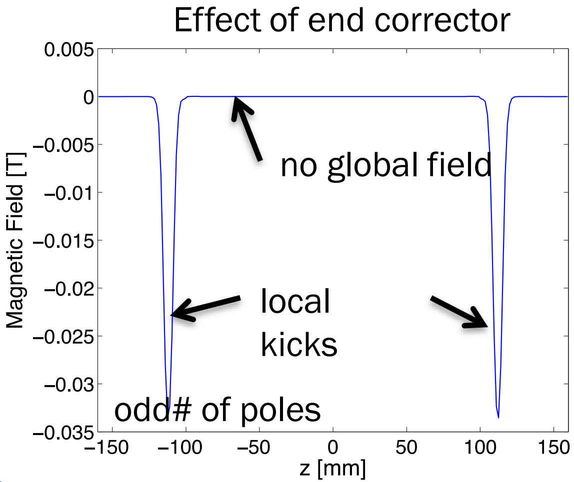




Local End Kick Correction

- Magnetically decoupled from main undulator core
- Produces only local kicks
- Field clamps are used to minimize stray field
- Compact design (fits under splice joint in Nb_3Sn device)

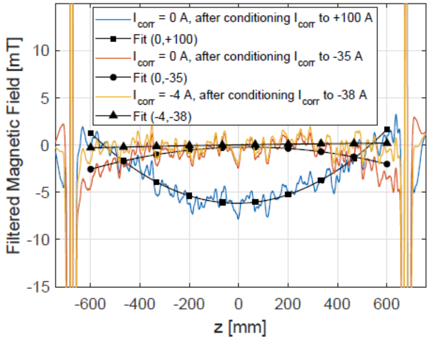




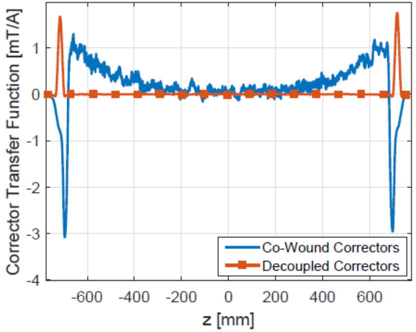
Measurement Results for End Correctors for LBNL Nb_3Sn Undulator

- **Co-wound corrector produces global field when powered**
  - Field decreases towards the center of the undulator due to high reluctance path
  - Hysteresis is present and pre-cycle has to be performed to avoid strong second field integral errors
- **Kick corrector produces local response and is well decoupled from the undulator**

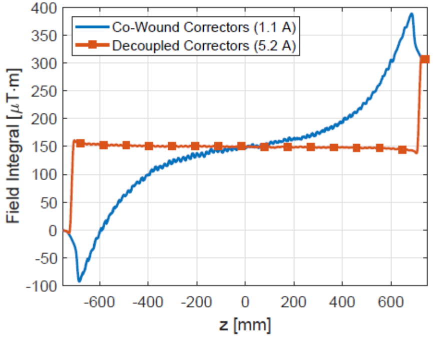
Magnetic Hysteresis



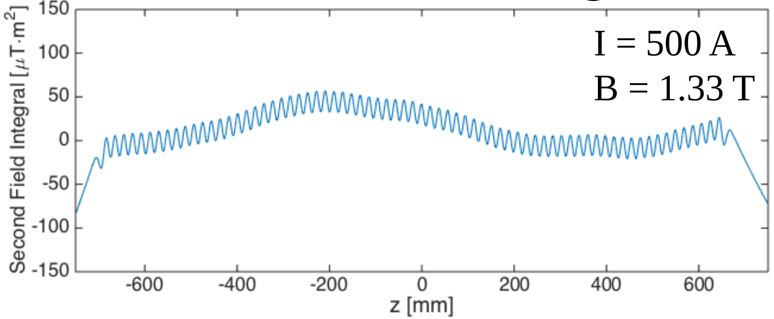
End Corrector Response



End Corrector Field Integral



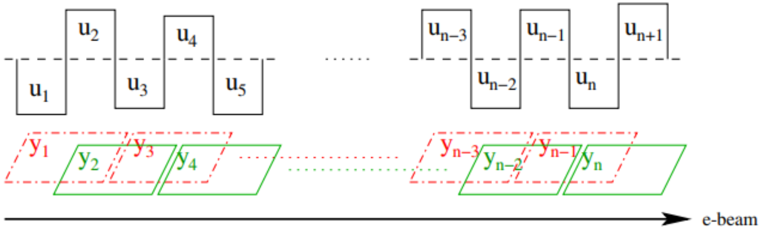
Second Field Integral



Local Correction Schemes

- Induction shimming (demonstrated on short undulator)
- Addition of iron pieces in core pockets
- Small coil loops around poles
- Current loops on vacuum chamber

Induction Shimming Concept

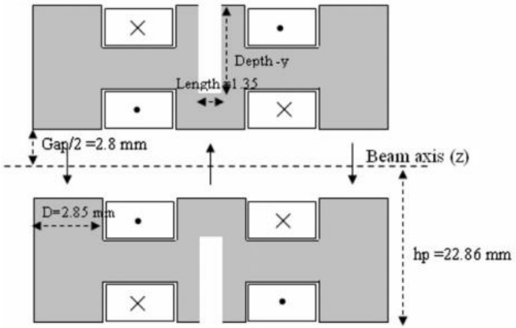


D. Wollman et al., Phys. Rev. AB. ***12****, 040702 (2009)*

Wire Loops Around the Poles

S. Prestemon et al., IEEE TRANS. APPL. SUPERCOND., VOL. 15, NO. 2, JUNE 2005

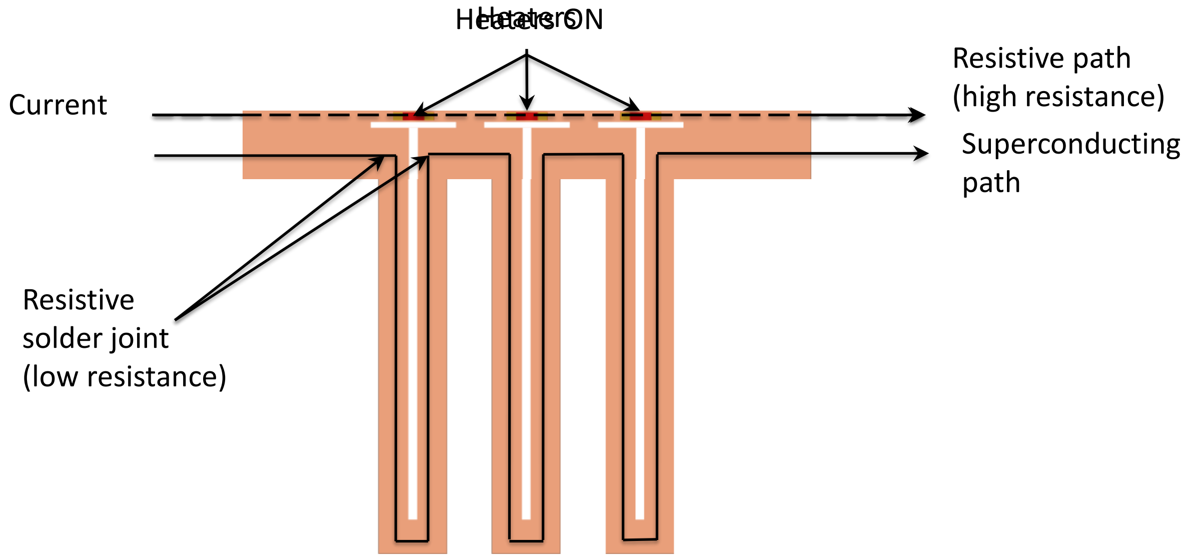
Additional Iron Pieces Concept



S Chunjarean et al., Supercond. Sci. Technol. 24 (2011) 055013

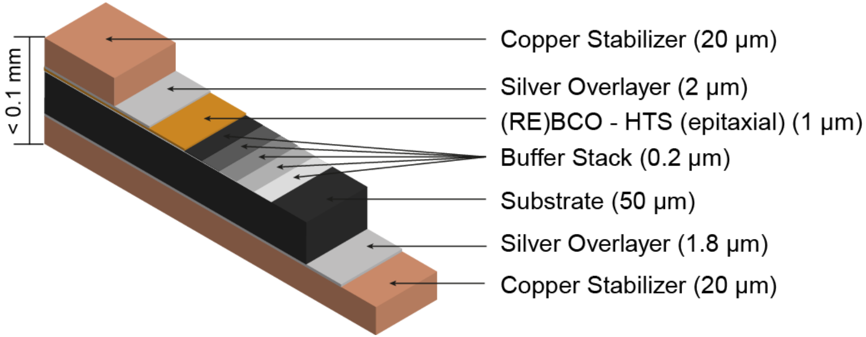
Switch-Based Tuning Concept

- **One superconducting path - with heater**
- **One resistive path (low resistance)**
- **When heater is on the superconducting path becomes resistive (high resistance)**

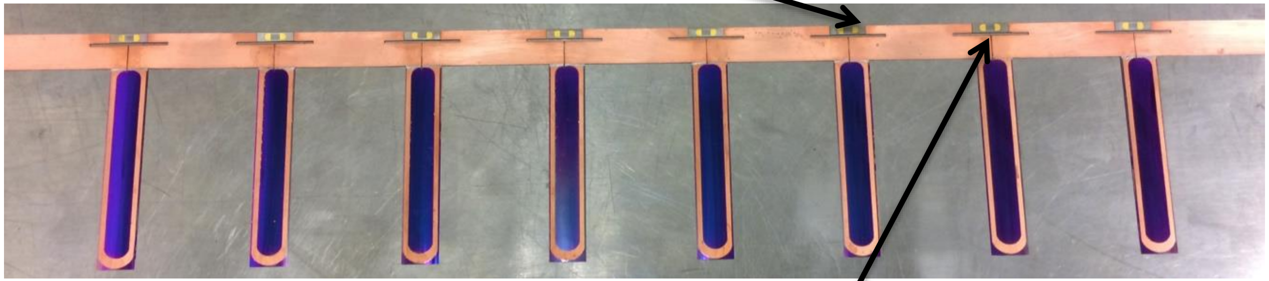


Current path via lithography on YBCO Tapes

- Commercial tape from SuperPower Inc.
- Masks designed for photolithography process
- Chemical etching used to remove Copper, Silver, and YBCO layers where desired
- Solderable thin film heaters were developed for efficient and reliable fabrication
- Laser cutting is used to separate joint section



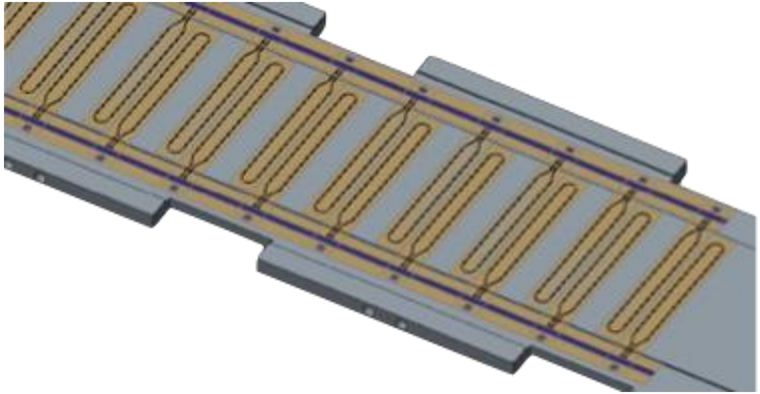
Heater

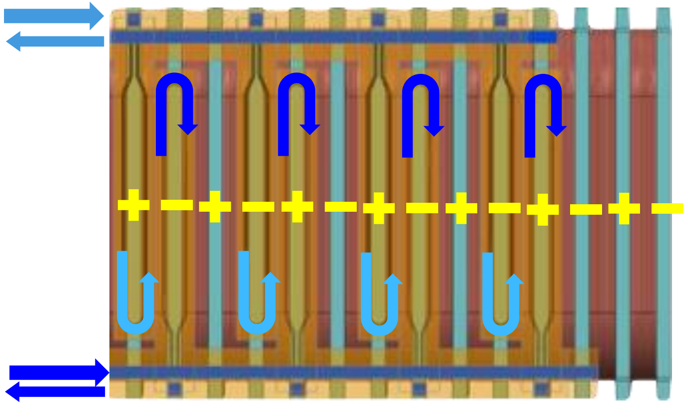


Laser cut path

Full Length Layout Concept

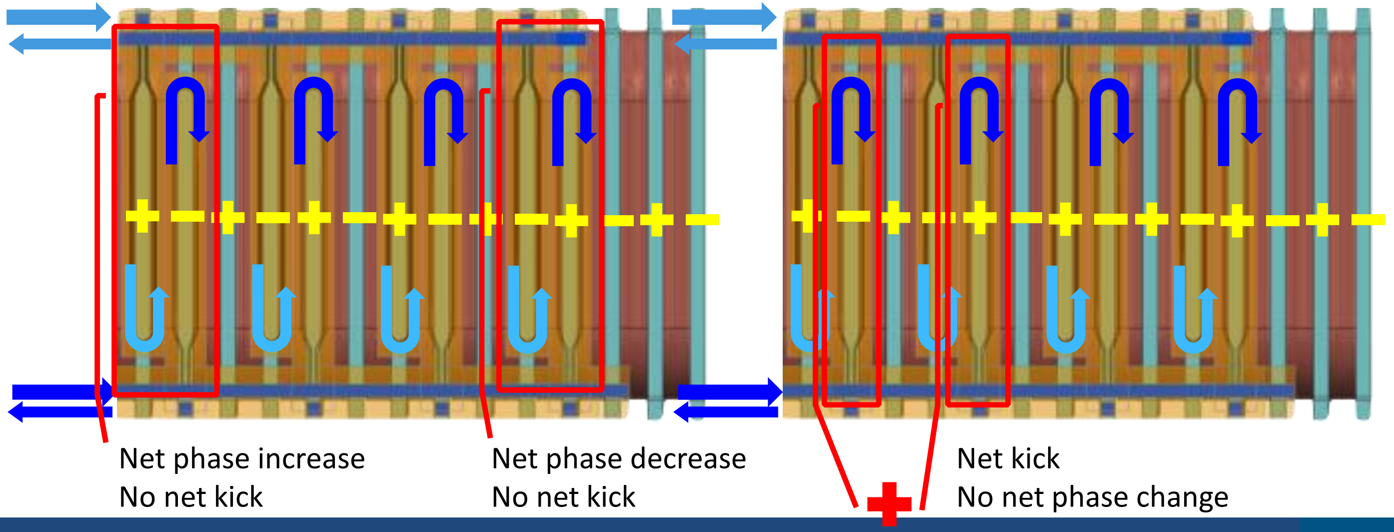
- Correctors are placed on both sides of the vacuum chamber
- Top and bottom correctors are used together
- Drive current on each side of the vacuum chamber
  - Allows for loops with positive and negative orientation
  - Return current line is directly below the drive current





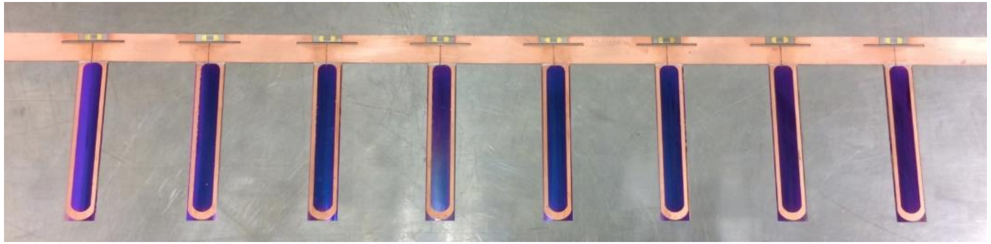
Full Length Layout Concept

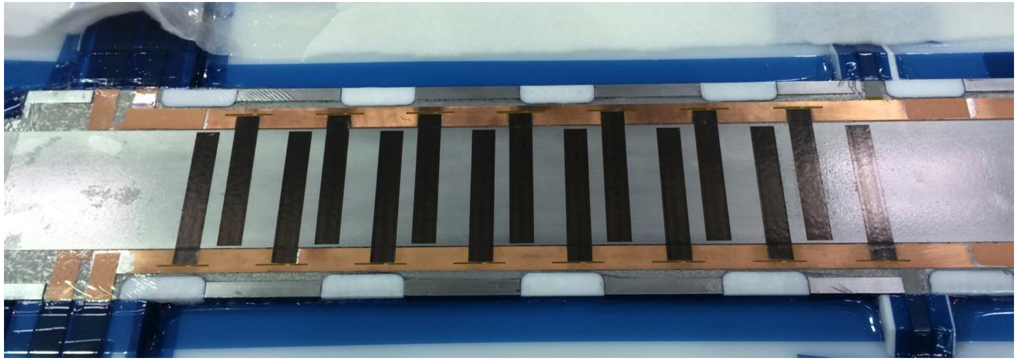
- Various configurations allow for:
  - Increase and decrease in the phase error without introducing a net kick
  - Positive and negative net kicks without net changes in the phase
  - Individual correctors give both a kick and phase change

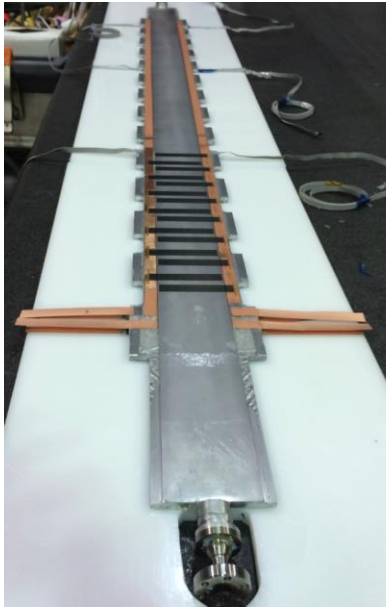


Corrector Fabrication

- Process to adhere correctors to the vacuum chamber was developed using vacuum bag process
- Correctors and glue take up 0.2 mm of excess thickness

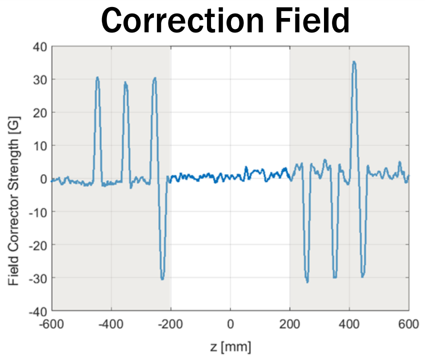


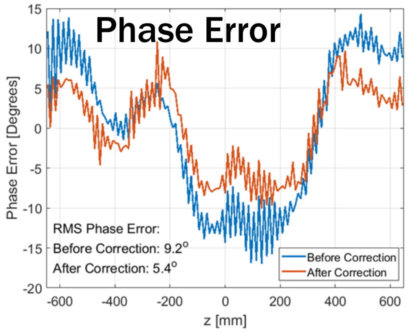




Correction Method Demonstration

- Local (periodic) correction method using HTS loops was successfully demonstrated
- Independent correction of net phase and trajectory errors was demonstrated
- Correction strength was still sufficient to reduce phase error from 9.2^{o} to 5.4^{o}
  - Due to fabrication issues correctors were only placed on one side of the vacuum chamber (1/2 strength)
- Local increase in vacuum chamber temperature did not affect the undulator





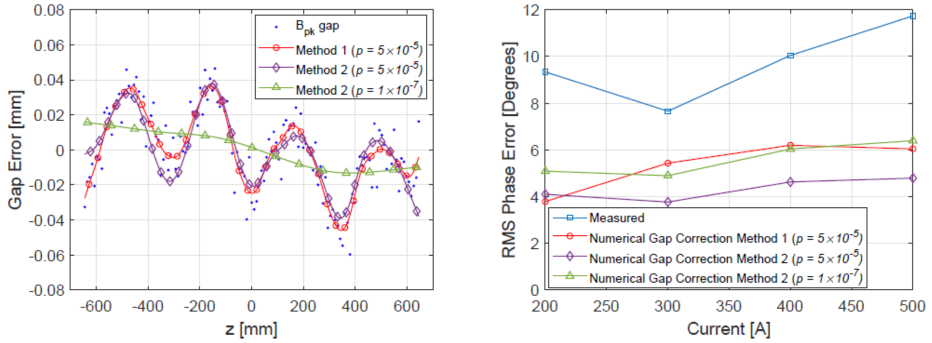
D. Arbelaez et al., Synchrotron Radiation News ***31****(3), 9–13 (2018)*

Phase Error Correction by Gap Adjustment

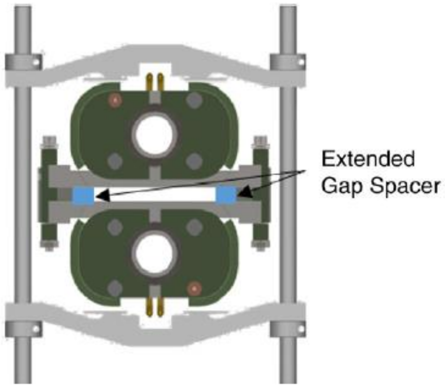
- Phase errors can be reduced by mechanical adjustment of the undulator gap
- Method was developed and successfully implemented at APS

$$\Delta P(z_p) = 360^\circ \frac{K^2}{\lambda_u\,(1+K^2/2)} \frac{1}{B_0} \frac{dB}{dg} \int_{z0}^{z_p} \delta g(z) dz.$$

Simulated Effect of Gap Correction for LBNL Nb_3Sn Undulator



Gap Adjustment Mechanism for APS Undulator



J. Bahrdt, E. Gluskin, Nuclear Inst. and Methods in Physics Research, A 907 (2018) 149–168

Conclusions

- Analysis shows the need for local and global correction
- End corrections can be performed using co-wound and independent kick correctors
- Local (periodic) correction scheme has been developed using HTS loop coils and heater switches
- Precise fabrication and assembly process is essential to obtaining low magnetic field errors

Acknowledgements

- LBNL
  - S. Prestemon, R. Schlueter, D. Dietderich, H. Pan, S. Myers, M. Morsch, T. Seyler, T. Lipton, J. Swanson, R. Oort
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  - ANL: E. Gluskin, Y. Ivanyushenkov, I. Kesgin, M. Kasa, C. Doose, J. Fuerst, Q. Hasse
  - SLAC: P. Emma