National Synchrotron Light Source II

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Magnetic Measurement Activities by the ID Group at the National Synchrotron Light Source-II

IMMW23

Toshi Tanabe (NSLS-II Insertion Devices Group Leader)

6-11 October, 2024

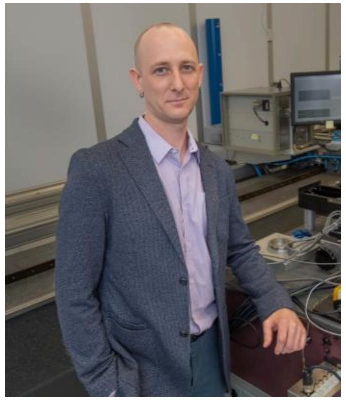
NSLS-II:ID Group Staff

- Sr. Physicist (Group Leader)
  - Toshi Tanabe Ph.D.

- Sr. Physicist (Deputy)

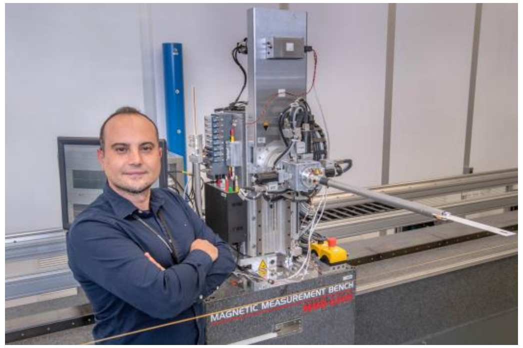
  Dean Hidas Ph.D.

  (Spectral calc., Controls)



- Physicist

  Marco Musardo (Mag. Meas)



- Lead Mechanical Engineer

  James Rank (Ring WCC, LOTO, Maintenance)

- Electrical Engineer

  Brian Eipper

- Mechanical Engineer

  Thomas Brookbank

- Electro-mechanical Technician

  Dan Migliorino

- Electro-mechanical Technician

  Bryan Holland

Outline

- National Synchrotron Light Source-II (NSLS-II) Current Status
  - Storage Ring Status & Beamlines
  - Installed Insertion Devices and Other Magnetic Devices
- Magnetic Measurement Facility
  - Flip Coil bench upgrade
  - Pulsed wire bench upgrade
- HEX-Superconducting Wiggler
  - Device, Operation and Maintenance Issues
  - Measurement system
- SC-Adaptive Gap Undulator
  - Concept & Development Plan
  - Magnetic Measurement Plan
- Other Development for Future Upgrade
  - Complex Bend Lattice for Upgrade
  - New Flip Coil, Rotating Coil and In-Vacuum Pulsed Wire bench
- Summary

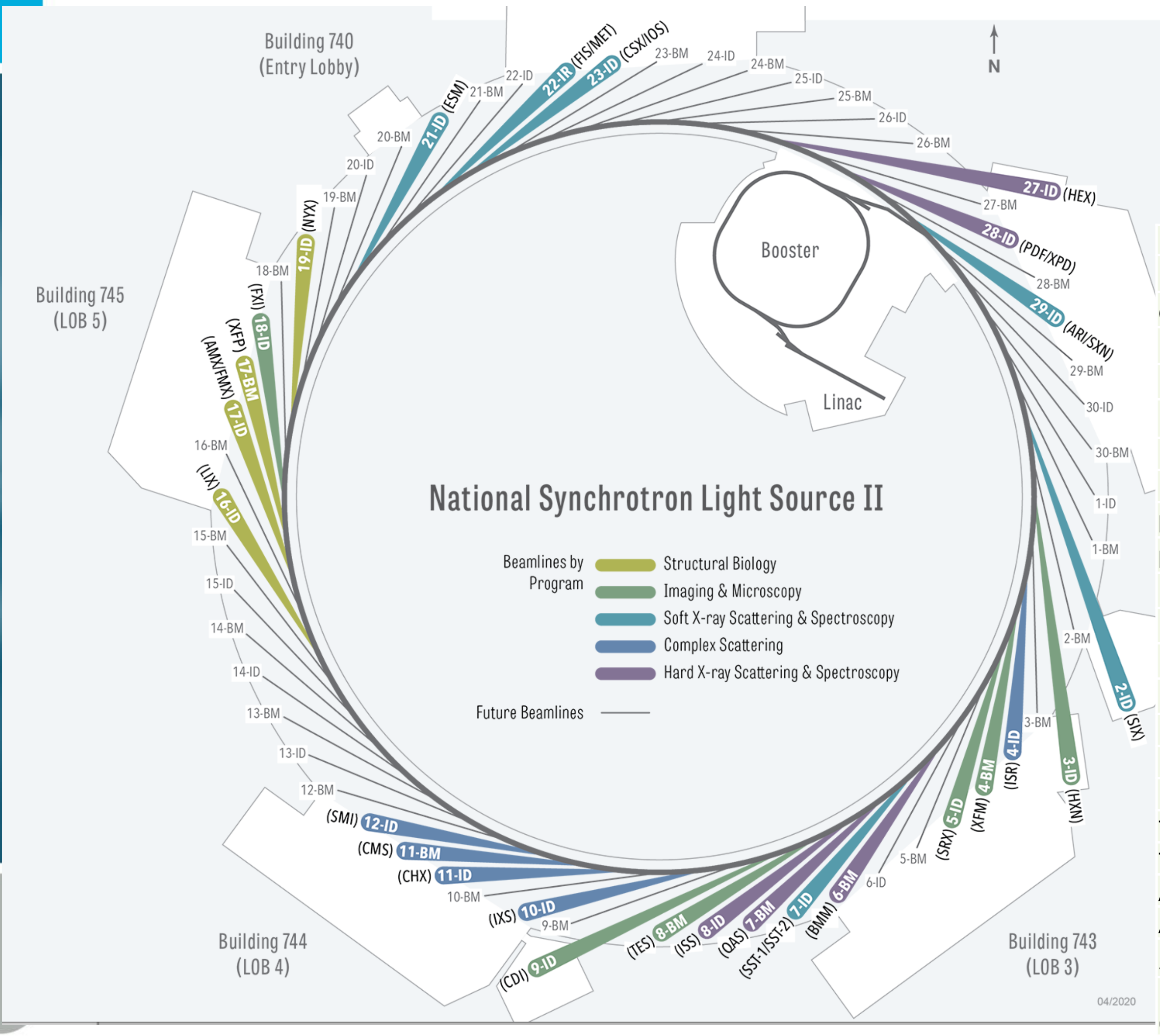
NSLS-II Current Status

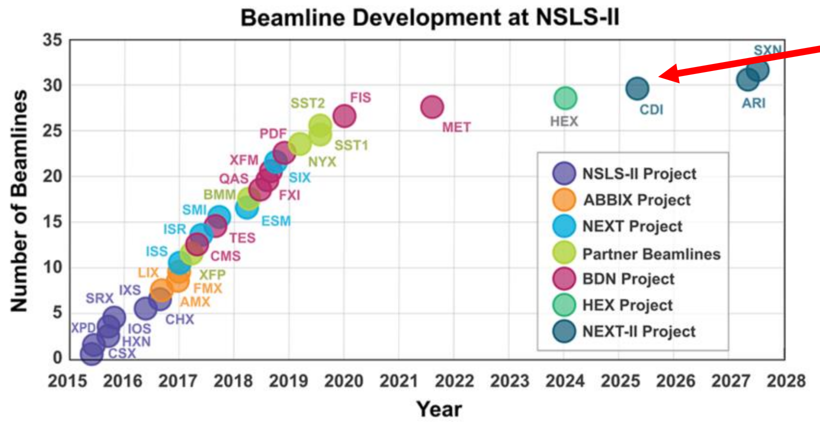
Storage Ring Status & Beamlines

Installed Insertion Devices and Other Magnetic Devices

NSLS-II Storage Ring &Beamlines

https://www.bnl.gov/nsls2/





3IDs for NEXT-II

~5-7 IDs for NEXT-III

NSLS-II Ring Parameters (as of Aug. 24)

	Bare Lattice	3DW Lattice	All-ID w.o SCW	All-ID with SCW
Energy (GeV)	3			
Circumference (m)	791.958			
Emittance e_x (pm-rad)	2086	957	747	657
Energy Spread s_d (%)	0.0514	0.0818	0.0799	0.093
Energy Loss per Turn U_0 (keV)	286.4	649.1	831.8	958
Length of Long Straight (m)	9.3			
Length of Short Straight (m)	6.6			
b_x, b_y at Long Straight Center (m)	20.1, 3.4			
b_x, b_y at Short Straight Center (m)	1.8, 1.1			
Betatron Tunes n_x, n_y	33.2, 16.26			
Natural Chromaticisty x_x, x_y	-98.5, -40.2	-98.4, -39.8	-98.4, -39.9	-98.2, -40.1
Momentaum Compaction a_c	0.000363			
Radiation Damping Time t_x, t_y, t_s (ms)	55, 55, 28	24, 24, 12	19, 19, 9.5	16.6, 16.6, 8.3
RF Frequency (MHz)	499.681			
Number of RF Buckets	1320			
Number of Bunches	1056			
Time between Bunches (ns)	2			
Total Beam Current (mA)	400 (500)			
Average bunch current (mA)	0.47			
Average bunch charge (nC)	1.25			
Synchrotron Tune @ V_{RF} = 3 MV	0.00871	0.00862	0.00856	0.0085
RMS Bunch Length @ VRF = 3 MV (mm)	2.7	4.34	4.27	5.02

NSLS-II Insertion Devices Current Installation

LS: Long Straight

- 2 x 3.0m-In Vacuum Undulators (IVU20)
- 1 x 3.0m-IVU22 (LS)
- 3 x 1.5m-IVU21s (two for canted configuration)
- 2 x 2.8m-IVU23s (canted : LS)
- 1 x 2.8m-IVU23 (LS)
- 1 x 1.0m-IVU18 (canted)
- 7 x 1.13T-3PW
- 6 x 3.4m-Damping Wigglers W100s (LS)
- 2 x 2.0m-Elliptically Polarizing Undulators (EPU49)
- 1 x 2.8m-Quasi-period EPU105 and 1 x 1.4m-EPU57 (in-line configuration)
- 1 x 3.5m-EPU57 (LS)
- 1x1.6m-U42 and 1x 1.0m-EPU60 (canted)
- 1 x 3.5m-U68 (LS)
- 1 x 1.2m-Superconducting Wiggler (SCW70)

3m-IVU20 for HXN beamline

3.4m Damping Wigglers in tandem configuration

15 Different types of Insertion Devices to maintain.

ID Magnetic Measurement Facility (ID-MMF)

Current Measurement Systems

Upgrade of Flip Coil Bench

Upgrade of Pulsed Wire Bench

Hall Probe Bench

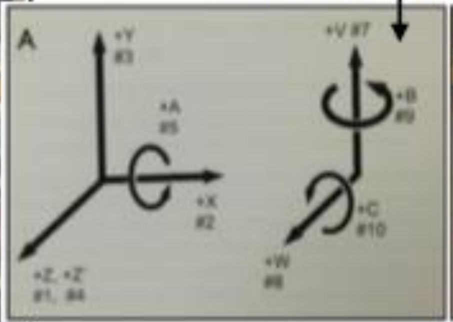
3D Hall probe-mapping bench MMB-6500 built by Kugler, GmbH

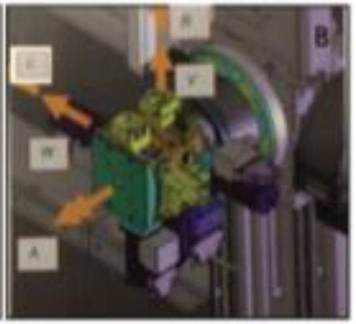
Total Z-axis travel is 6.5 m.

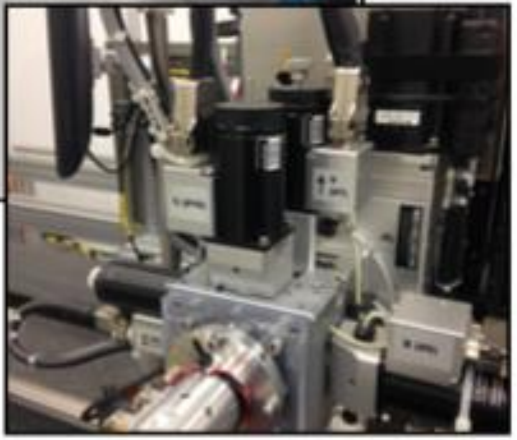
A Heidenhain linear encoder provides position feedback for Z-axis closed loop control.

A Renishaw laser linear encoder is used as a trigger for the on-the-fly measurements.

- Granite guide-beam length: 7.7 m
- Flatness deviation < ± 7 μm
- Positioning accuracy is ± 1 μm.
- **9 Motion Controlled Axes.**







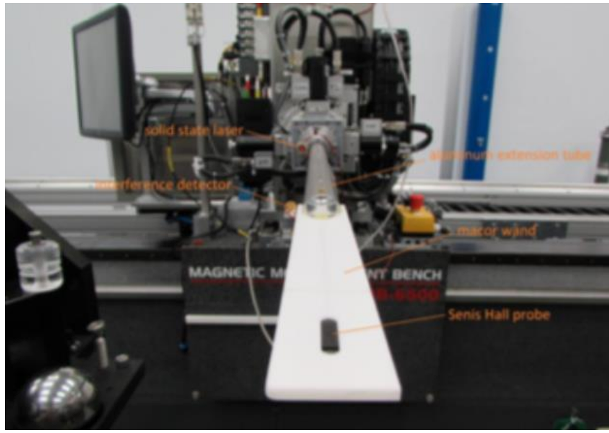
4 Primary Axes

- **Z** master axis and **Z'** follower axis
- **Y** axis and **X** axis

5 Secondary Axes

- **A** rotary axis
- **V** linear axis
- **W** linear axis
- **B** goniometer axis and the **C**

A and **C** secondary axes are particularly useful for fine angular positioning of the By Hall sensor



Senis 3D Hall Probe

NI CompactRIO

Current Flip Coil Bench

Achieve 1st Integral Repeatability: ~ 2 G.cm for 4 m long ID

Delta Tau GeoBrick PMAC-2

Motion Controller

- *Eight servomotors*
- *master-slave configuration*
- *Closed loop mode*
- *Limit/home switches*

Linear X, Y and Z stages:

Encoder resolution: 0.1 μm
Absolute accuracy: ±1 μm
Pitch and yaw angles: ± 50 μrad

Rotary stage:

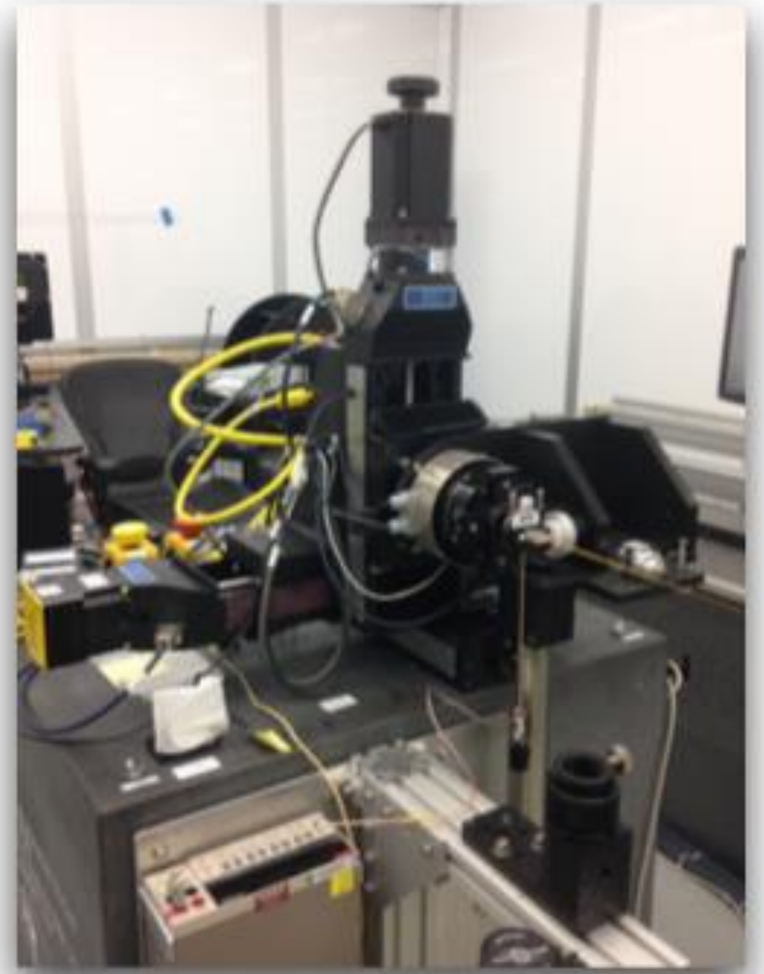
Full 360° capacity
Encoder resolution: 0.005 deg
Angular accuracy: ≤ 40 arc sec
Angular repeatability: ≤ 2 arc sec

Keithley DMM 2701

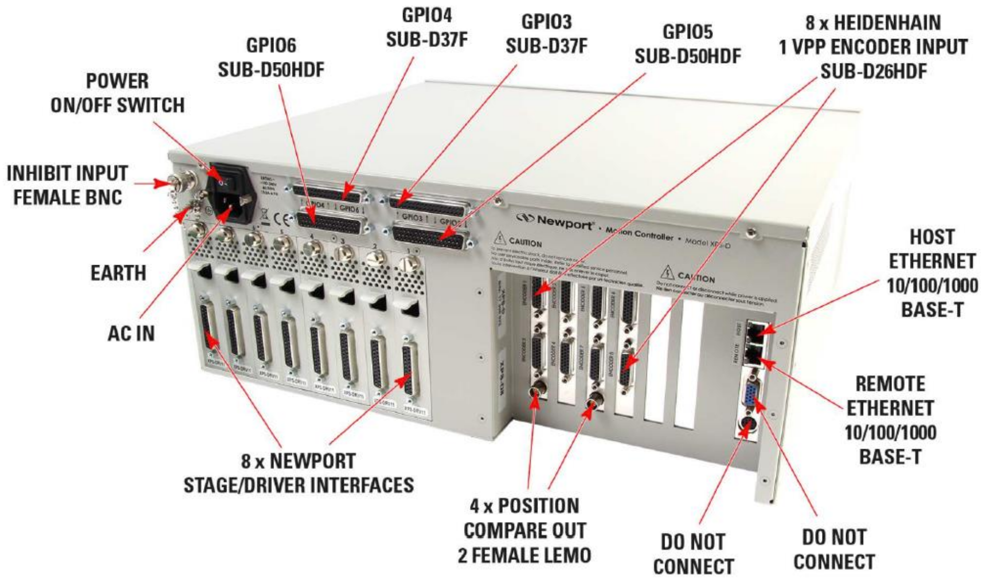
Digital Multimeter

- 6½-digit (22-bit) resolution
- Serial communication RS-232
- Integration time 16.67 ms (1 PLCs)
- Repeating average digital filter

ADC Linear Stages and Yasukawa rotary drive

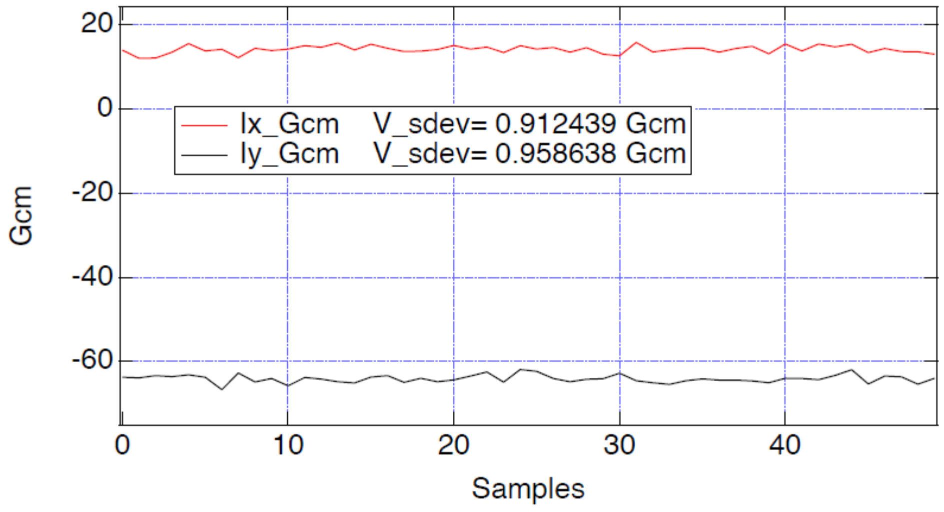


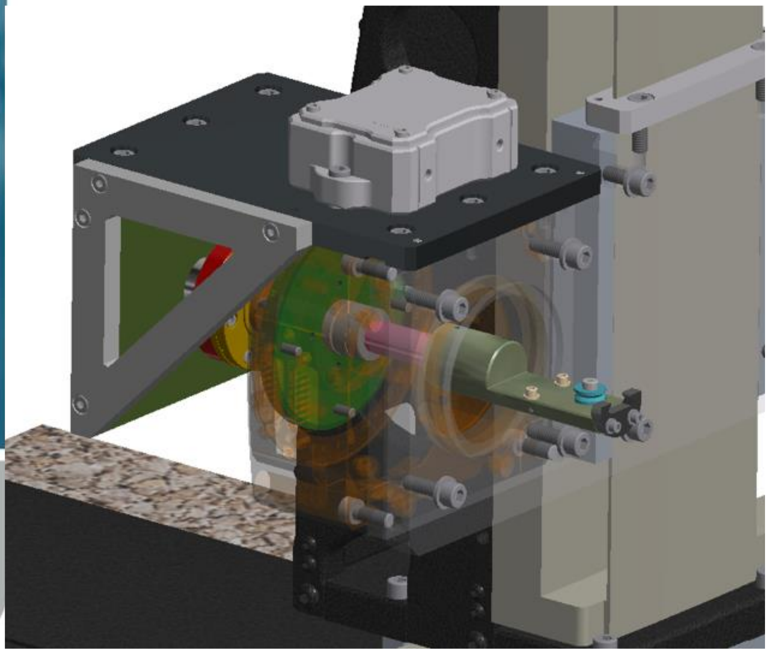
New Flip Coil Bench

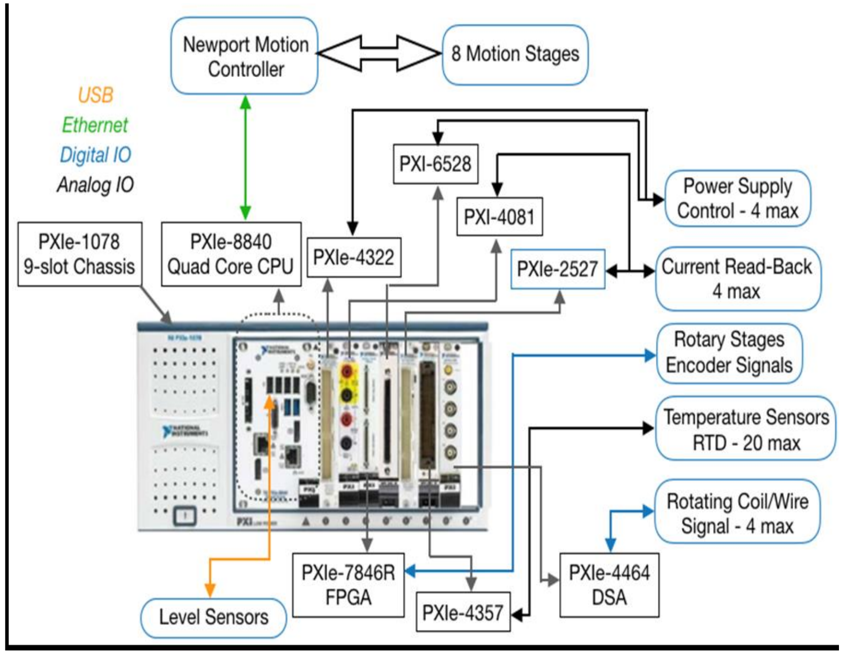


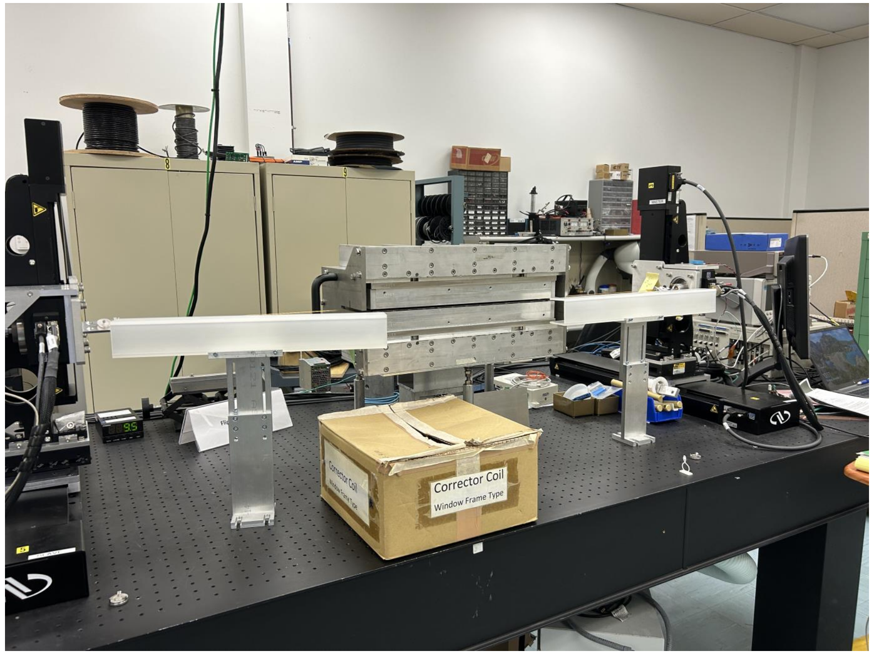
Newport XPS-D Controller

50-scans









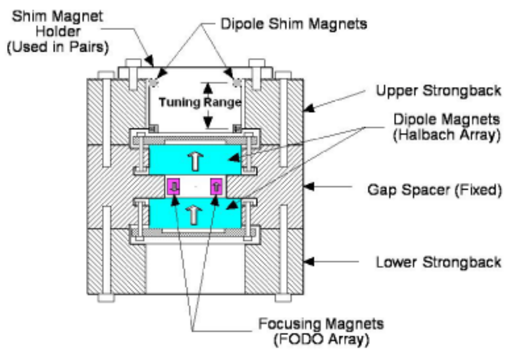
New Pulsed Wire Bench

Old bench at NSLS

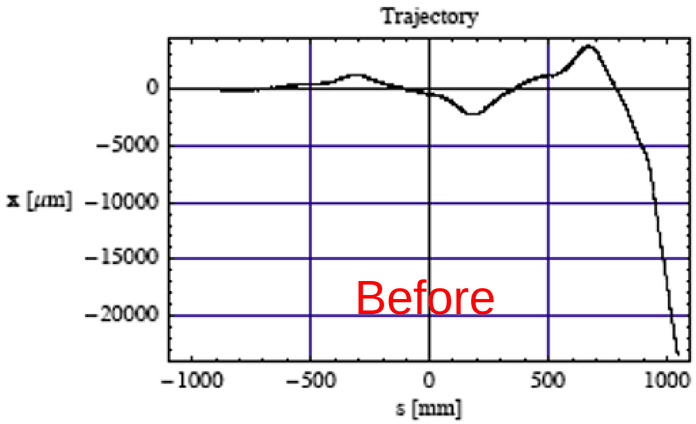
New bench

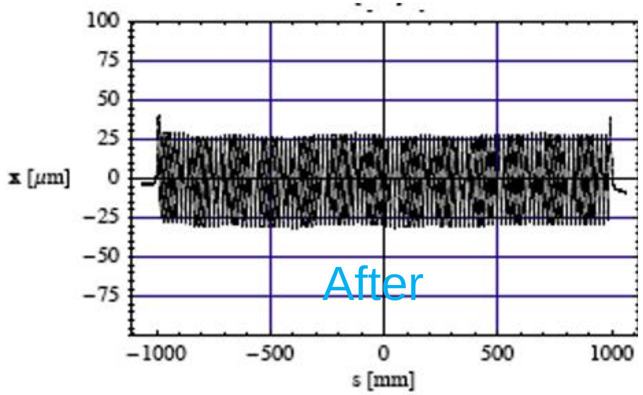
Old Pulsed Wire Bench at the NSLS

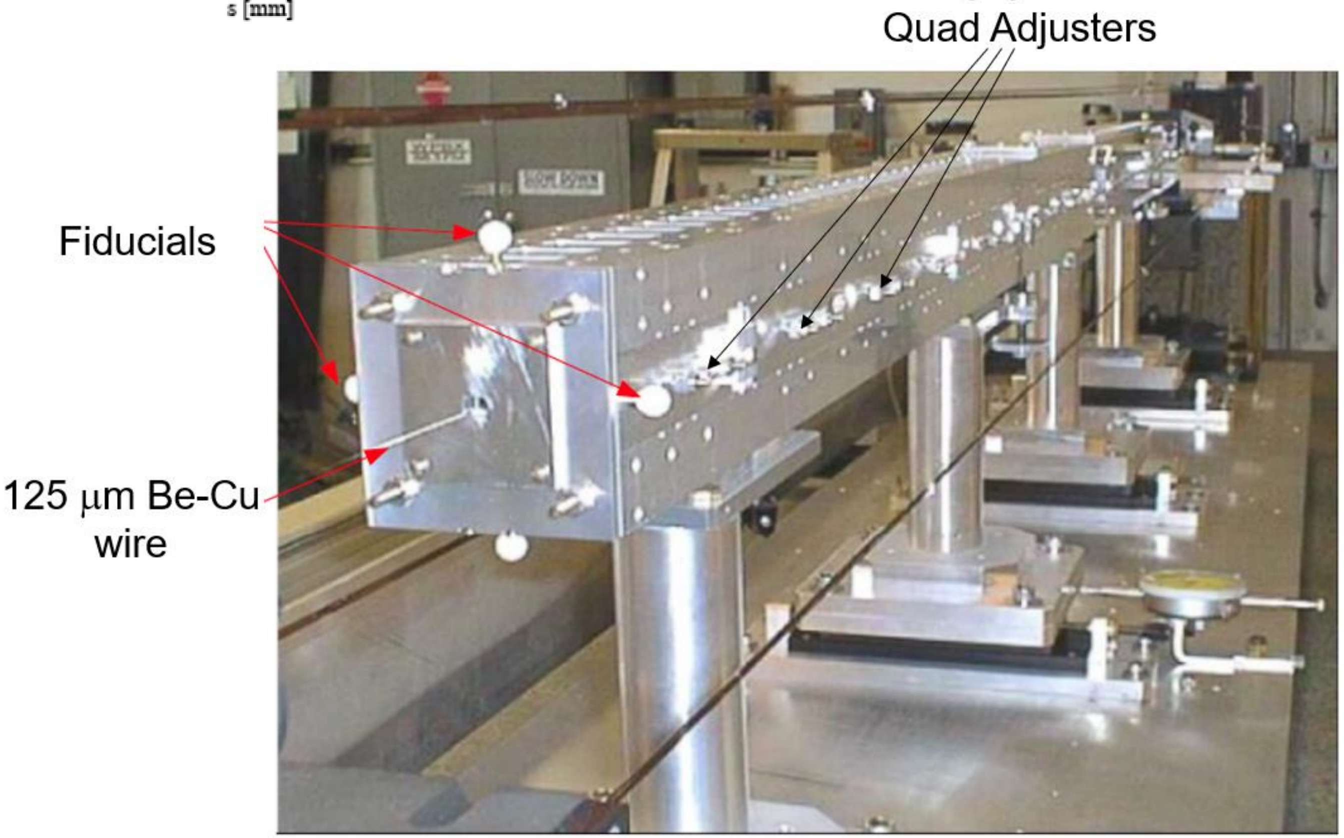
VISA Undulator



Trajectory at 64 MeV

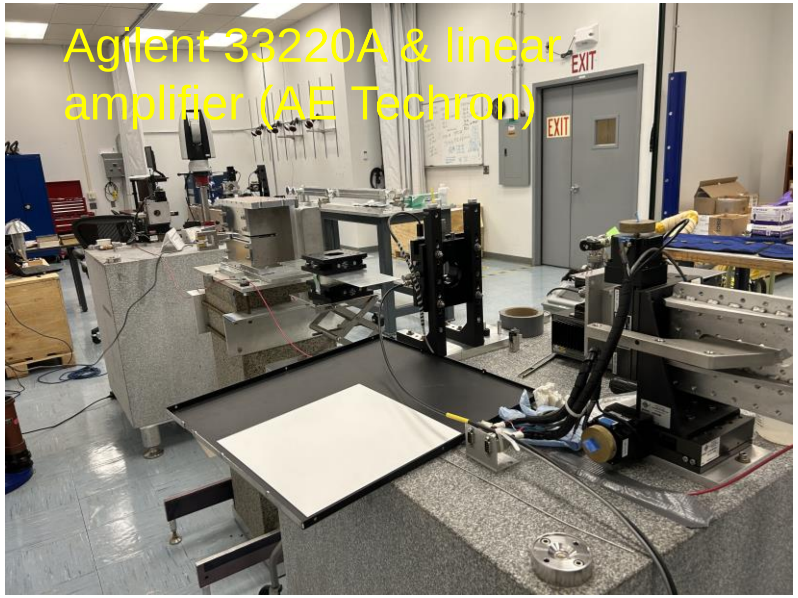


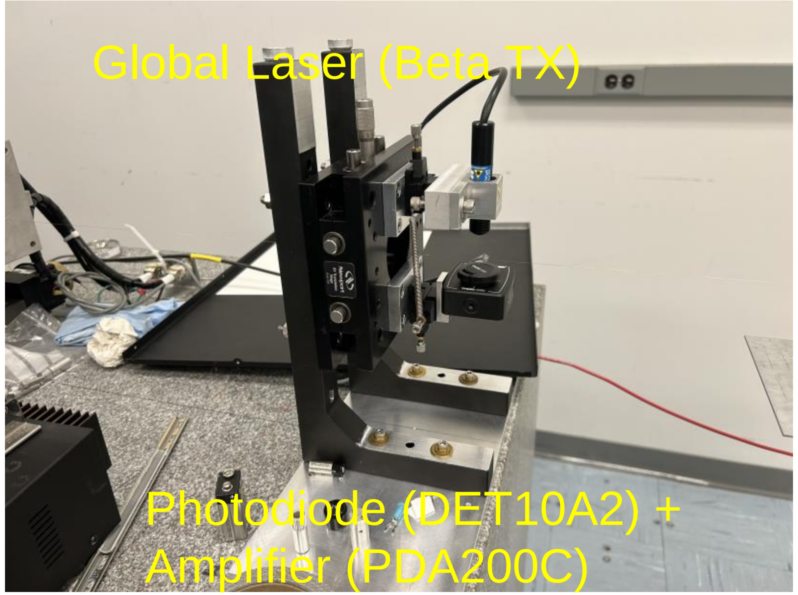




New Pulsed Wire Bench

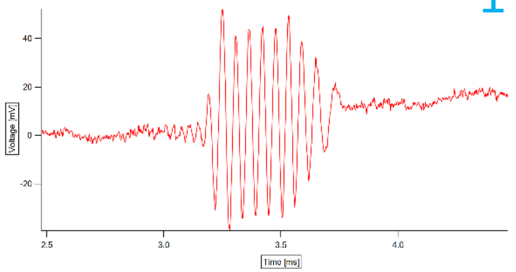
N'gotta, P., Ebbeni, M., Thiel, A., & Tarawneh, H. (2019, June 1). *First Results of a Pulse Wire Measurement System for ID Characterization at MAX IV* .

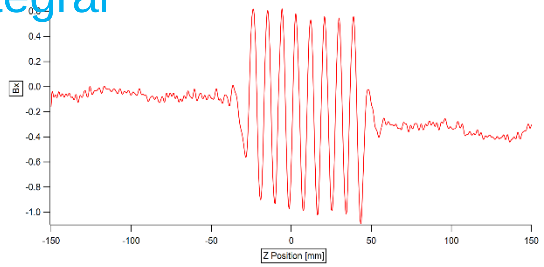


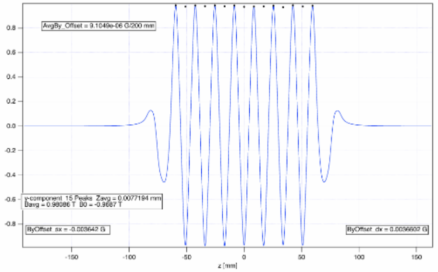


Courtesy of A. Khan and P. N'gotta

1st Integral





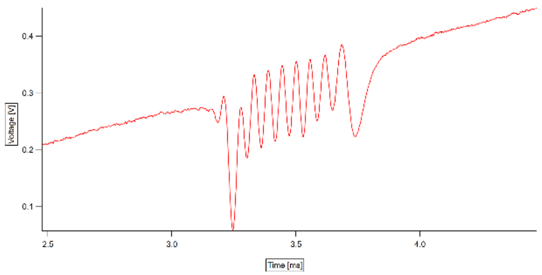


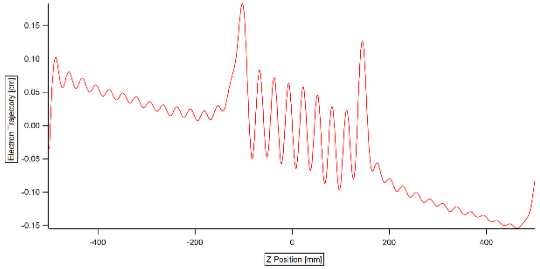
Raw Data

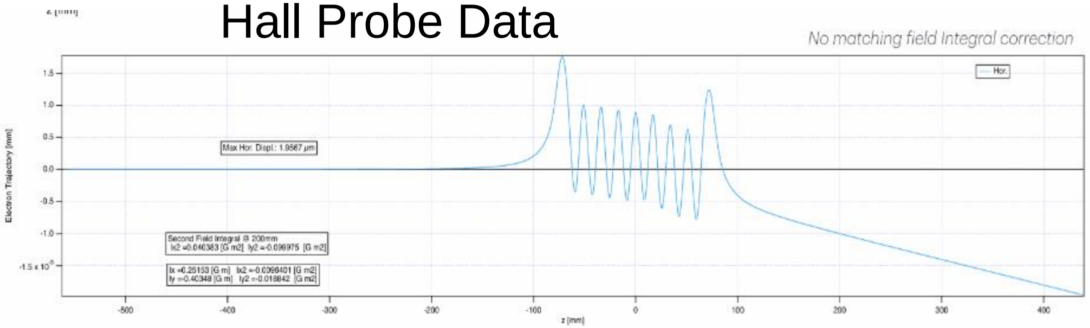
2nd Integral

After Processing

Hall Probe Data







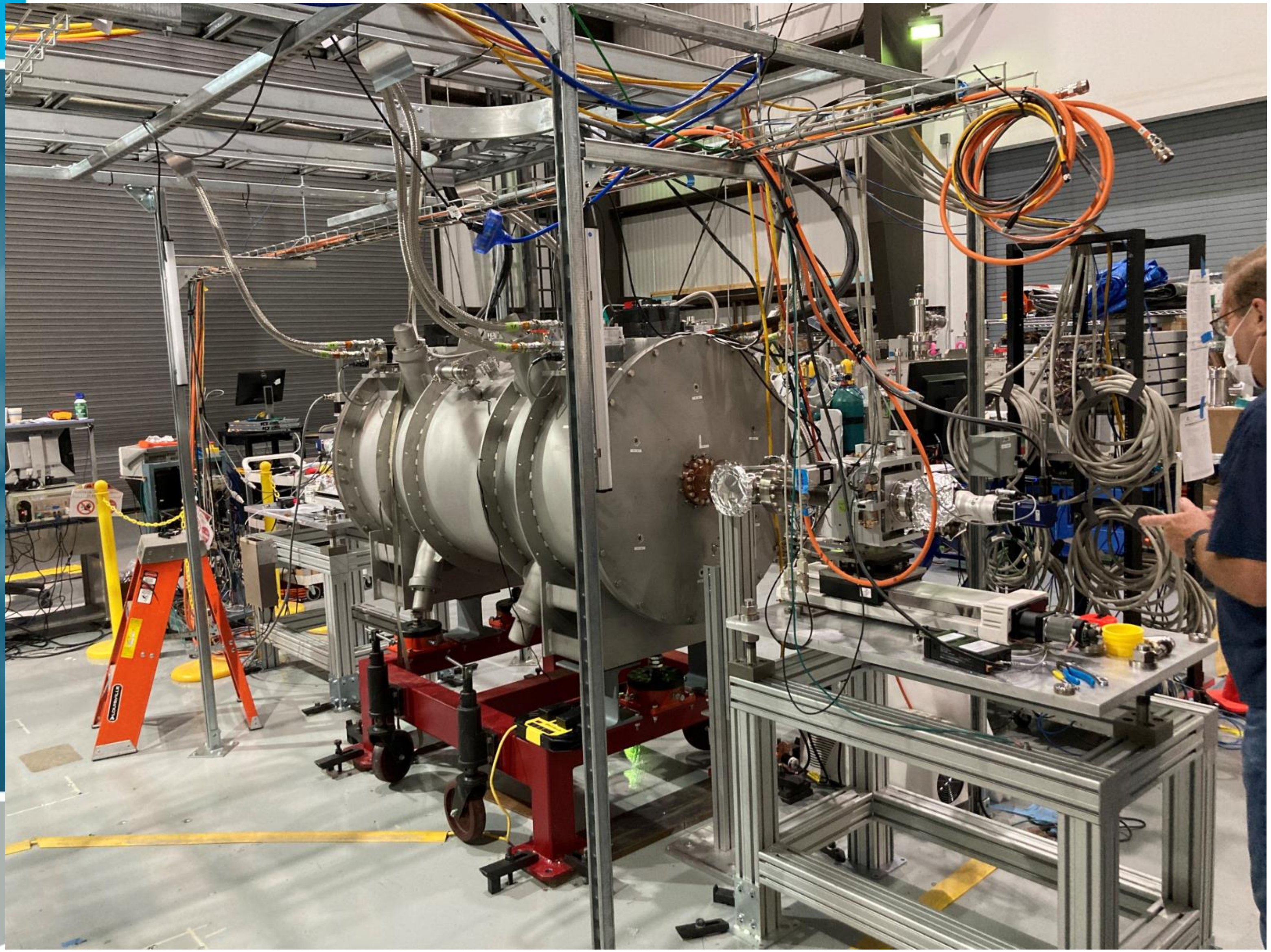
HEX Superconducting Wiggler

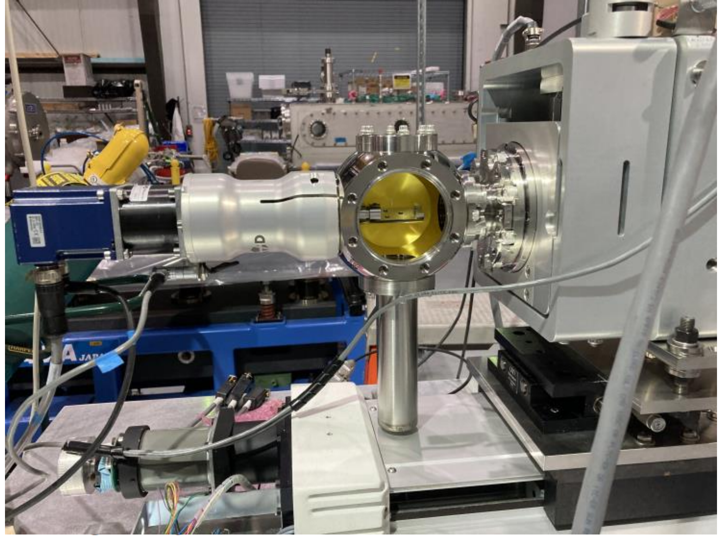
In-Vacuum Flip Coil Measurement for Integrated Multipoles & SCW Specs

In-Vacuum Hall probe bench

HEX-SCW Mag. Meas. by In-Vacuum Flip Coil

Using COTS in-vacuum XY stages (Kurt J. Lester, XY31-31065-001) and rotary feed-throughs (UHV Design, MD40-31065-001)





Item		Parameter
Magnet Array length		≤1200 mm
Period Length		70.0 mm
Operating field (By) on axis		4.3T
Number of pole pairs @ full field		29
Number of pole pairs @ ¾ field		2
Number of pole pairs @ ¼ field		2
Electron beam chamber full vertical aperture		10mm
Electron beam chamber full horizontal aperture		76mm
Field stability ΔBy / By over two weeks		$< 10^{-4}$
Max. Stray field on axis at each end of the cryostat		10 G
Ramping time, 0 to 4.3 T up or down		≤ 30 minutes
Liquid Helium consumption per quench		<10 liter
Maximum temperature of magnet coil during quench		< 75 K
$\int_{-\infty}^{\infty} By(x,y,z)dz$	Requirement for the **Absolute Value** of 1st and 2nd Field Integral Error (|x|<10mm, y=0mm), (from 0 to 4.3T) (**with** correction coils)	≤50 G.cm
$\int_{-\infty}^{\infty} Bx(x,y,z)dz$		≤30 G.cm
$\int_{-\infty}^{\infty}\int_{-\infty}^{z} By(x,y,z')dz'dz$		≤10,000 G.cm.cm
$\int_{-\infty}^{\infty}\int_{-\infty}^{z} Bx(x,y,z')dz'dz$		≤5,000 G.cm.cm
Requirement for the **Absolute Value** of On-axis Electron Trajectory for E=3GeV at any longitudinal position		|x|<60 μm, |y|<5 μm and |y'|<10 μrad
Requirement for the **Absolute Value** of Integrated Multipole (|x|<10 mm, y = 0 mm), (from 0 to 4.3T)		Definition of Multipole Expansion about ($x = x_0$, $y = 0$)* $\int_{-\infty}^{\infty} dz(B_y+iB_x) \equiv \sum_{n=0}^{\infty}(b_n(x_0)+ia_n(x_0))(x-x_0+iy)^n$
Normal quadrupole (b1(x0))		50 G
Skew quadrupole (a1(x0))		50 G
Normal sextupole (b2(x0))		50 G/cm
Skew sextupole (a2(x0))		50 G/cm

*The reference points (x_0, 0) shall be chosen less than 5.0 mm apart, for example; x_0=-6.0mm, -3.0 mm, 0 mm, 3.0mm, 6.0 mm

HEX-SCW Mag. Meas. by In-Vacuum Hall Probe Bench

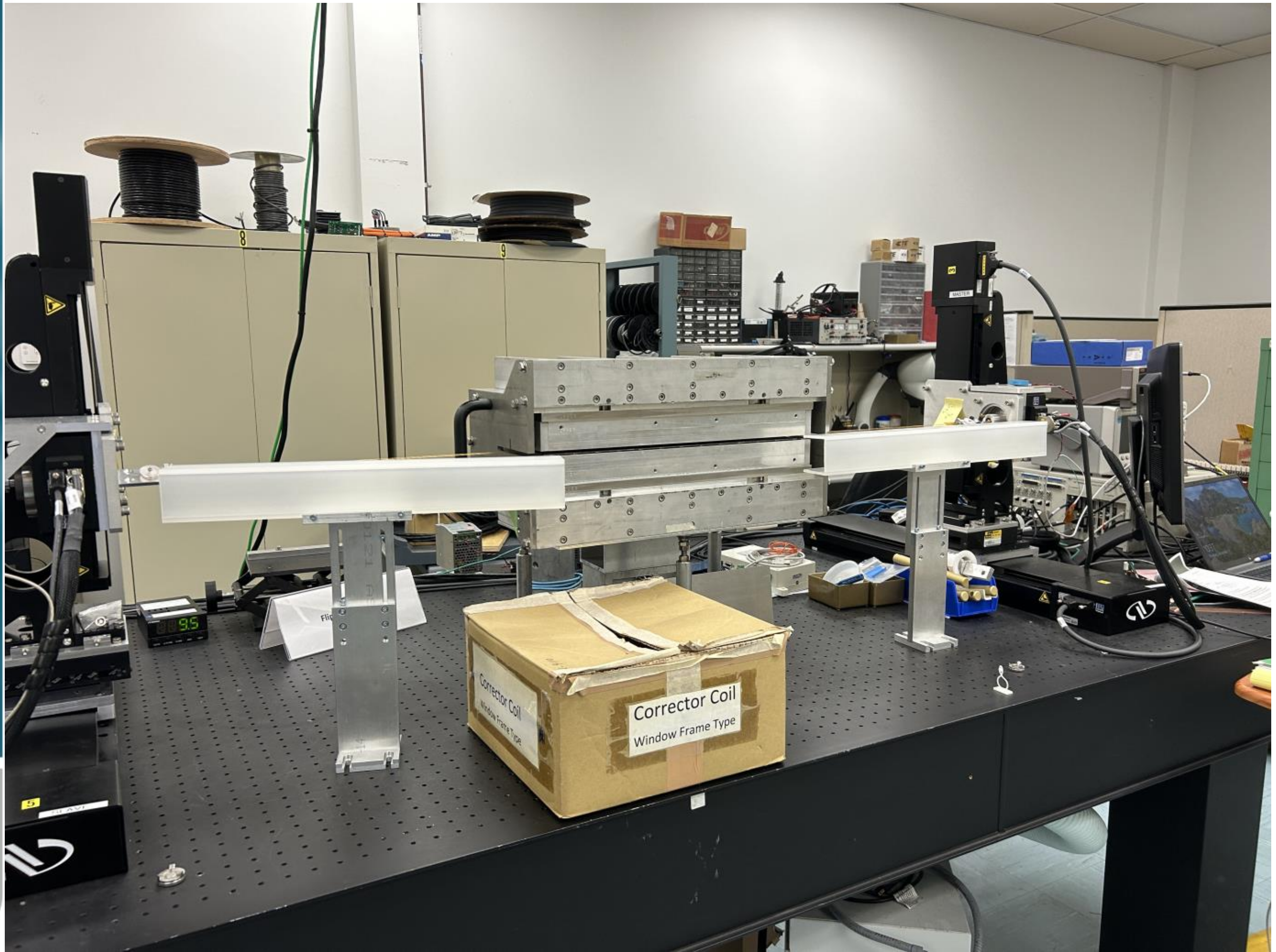
T. Tanabe, *et. al*.,"Development of the high energy engineering X-ray (HEX) superconducting wiggler, magnetic measurement, installation, and commissioning", Review of Scientific Instruments 94, (2023): https://doi.org/10.1063/5.0146964

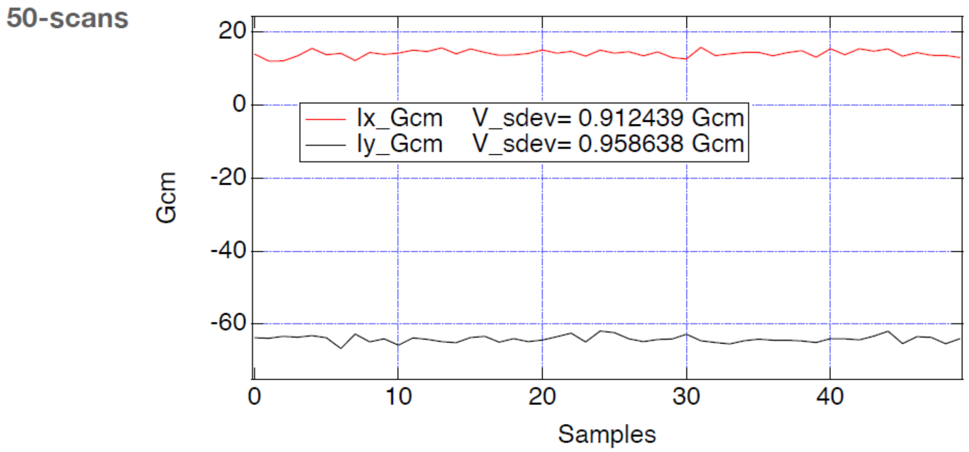
New Flip Coil Bench

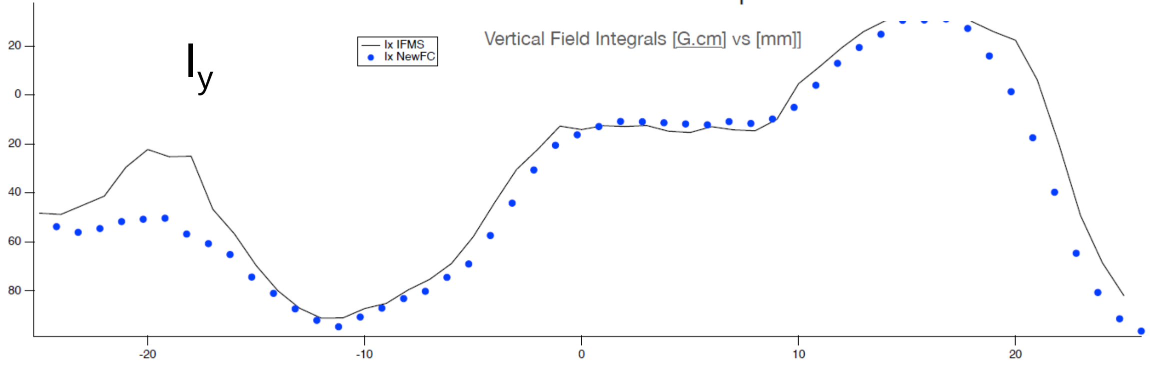
Newport based design with continuous rotation

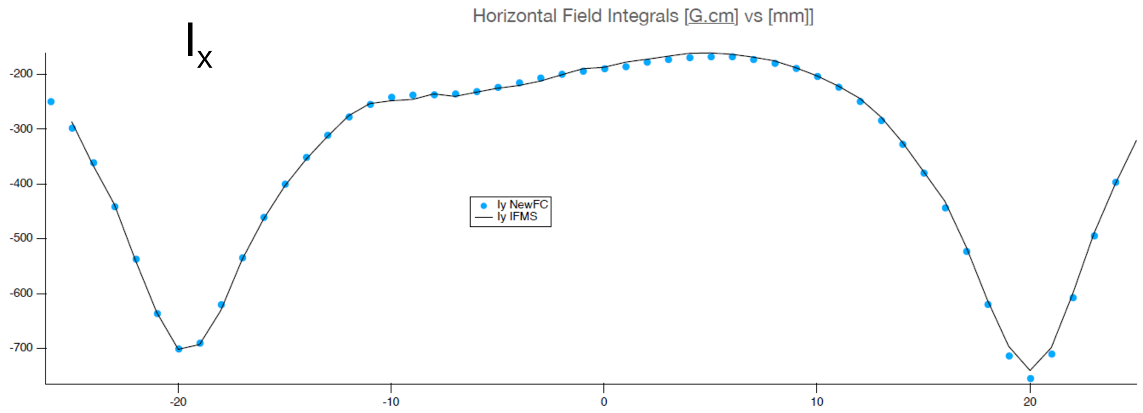
New Flip Coil Bench

Integration with Newport Stages
DAQ with Ni CompactRIO with FPGA
Continuous rotation possible for the use of a lock-in amplifier







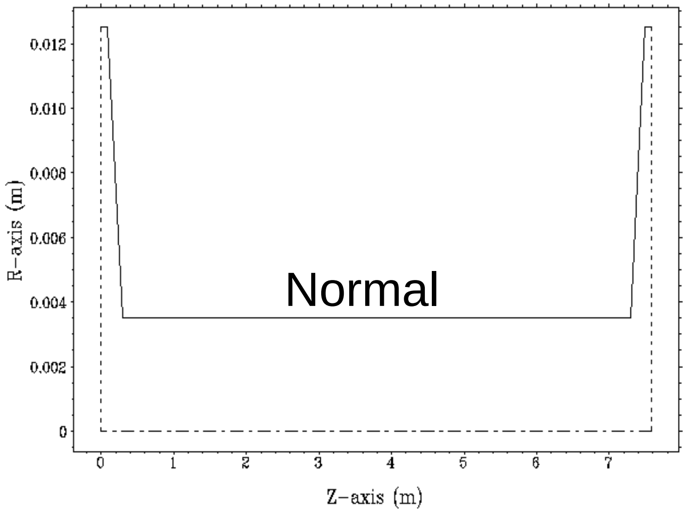


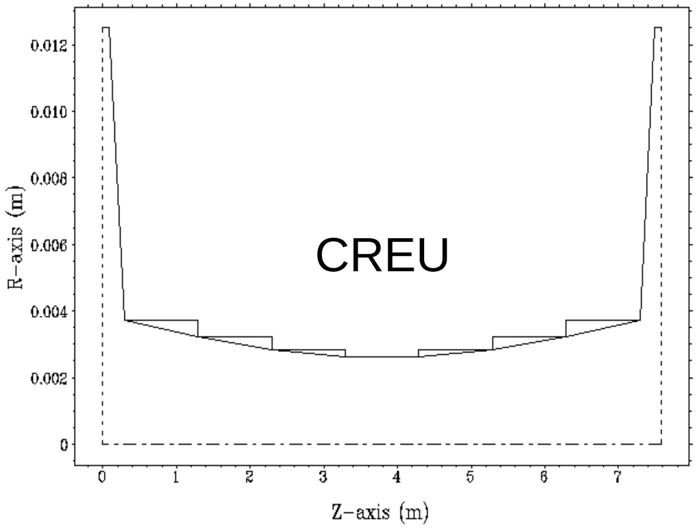
SC Adaptive Gap Undulator

Concept &Magnetic Design

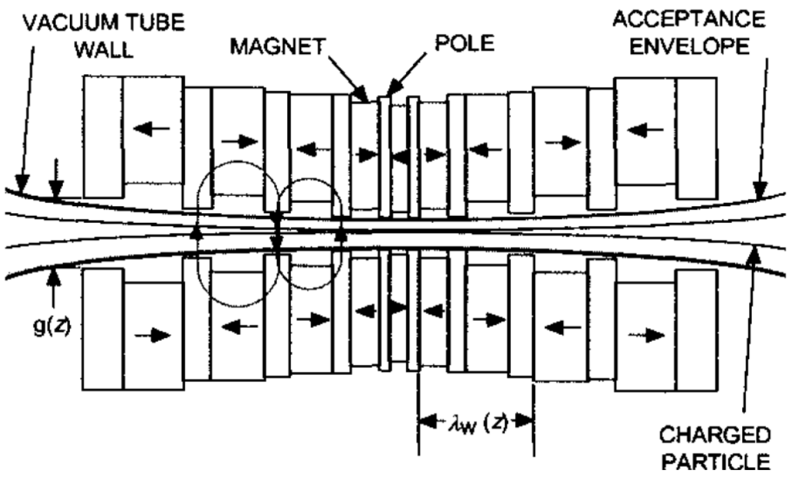
Measurement Plan

Segmented Adaptive Gap Undulator (SAGU)

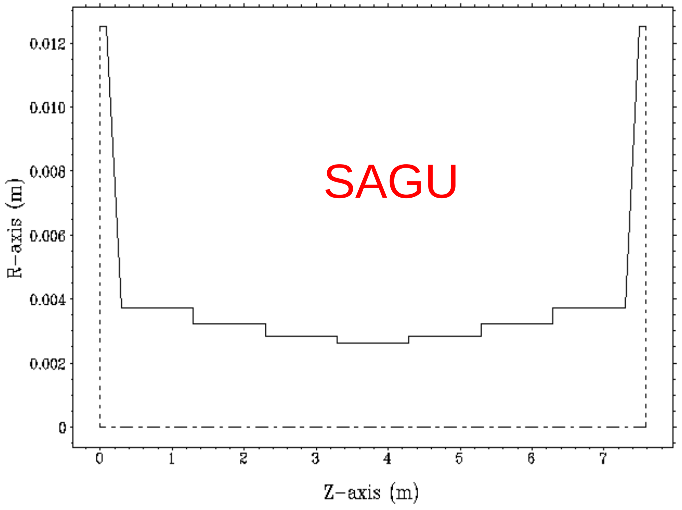


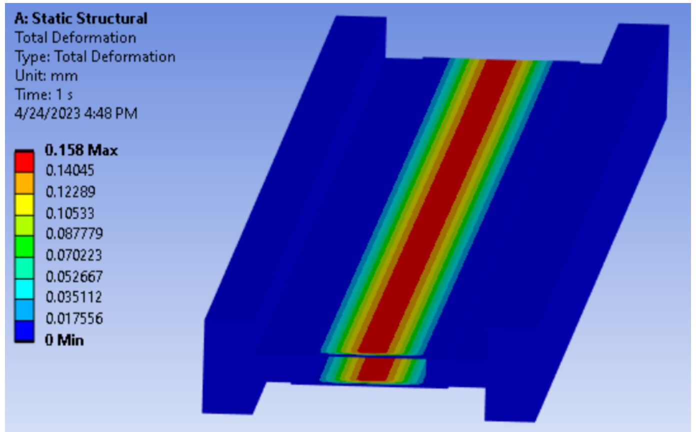


Assembled PM-SAGU segment by Insertion Devices group at BNL



Constant Resonant Energy Undulator (S. Gottschalk, 2000)



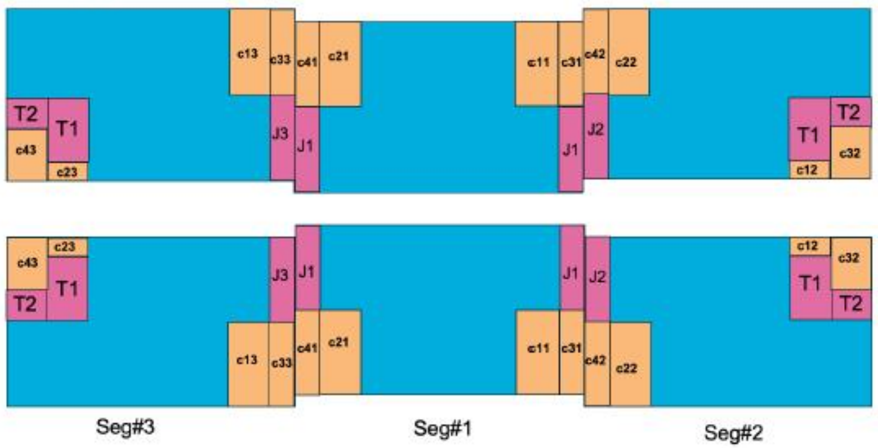


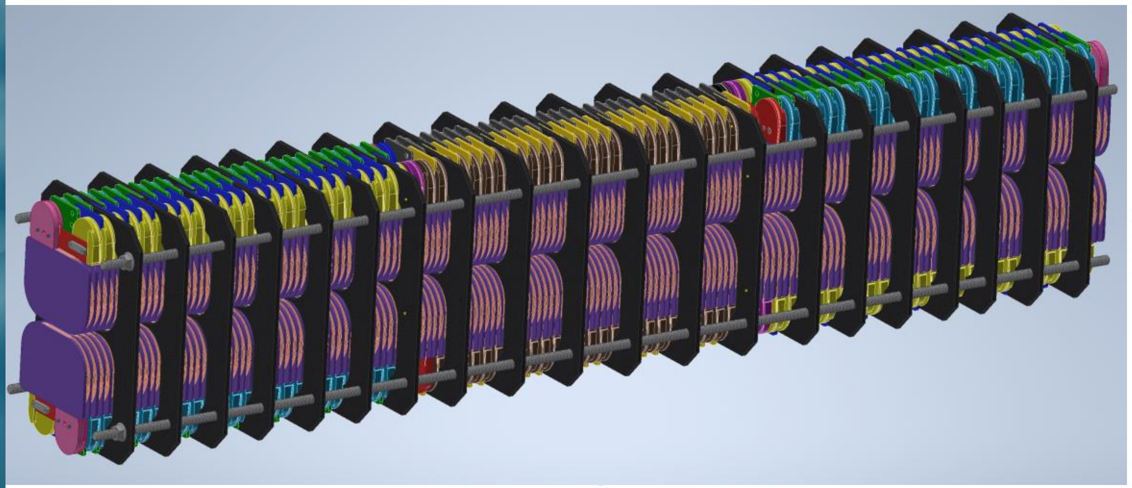
SC-SAGU vacuum chamber analysis

SC-AGU Magnetic Design

Correction Coils Configuration

Seg#3=Seg#2
J1=J2=J3





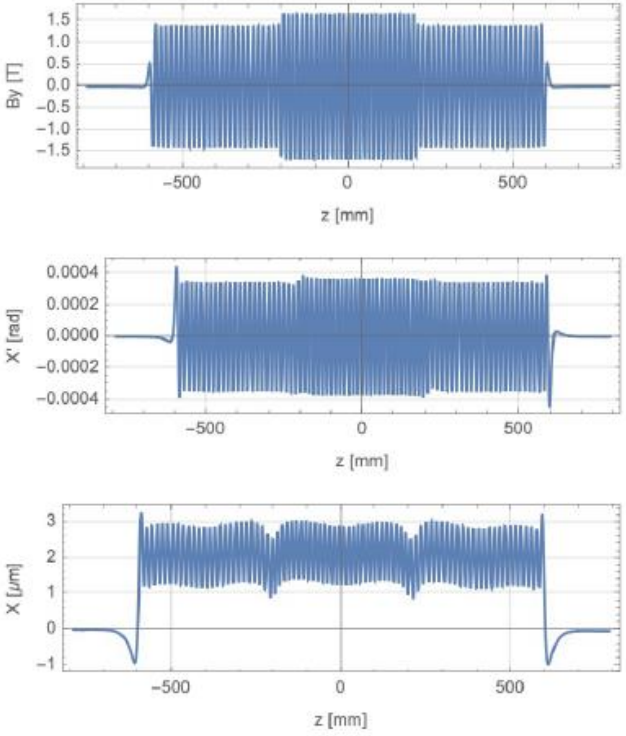
```
Icc1 = {jc11, jc21, jc31, jc41}
Icc2 = {jc12, jc22, jc32, jc42}
Icc3 = {jc13, jc23, jc33, jc43}
```

Magnetic field and e-trajectory with CC=0

```
Segment #1: Bpeak= 1.68247 T   K= 2.2
Segment #2: Bpeak= -1.41604 T   K= 2.05
Segment #3 :Bpeak= -1.41604 T   K= 2.05

Number of wires in the half-layer junction S1: 3
Number of wires in the half-layer junction S2: 3

Number of layers in the termination  coil S2_T1: 8
Number of layers in the termination coil S2_T2: 3
```



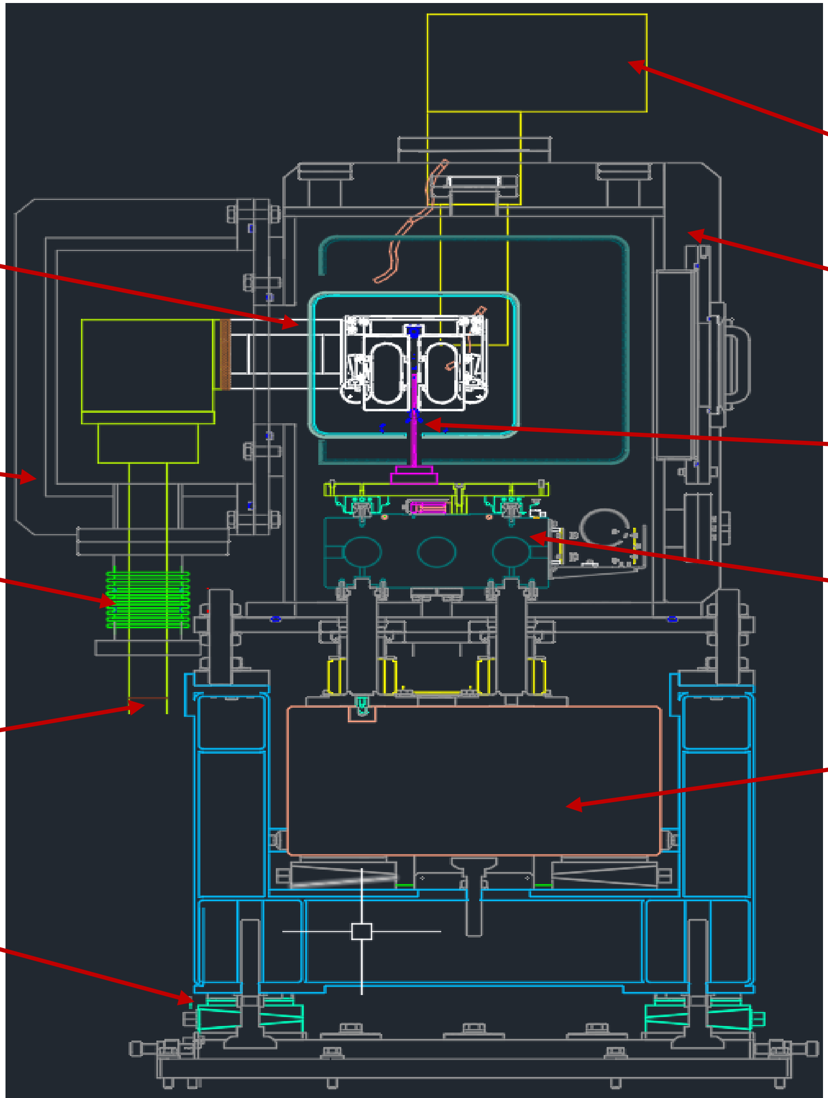

```
Output angle: -0.133267 μrad
Field Integral: -0.0133267 G.m
```

	Segment 1	Segment 2&3
Period length (mm)	14.0	15.5
Number of periods	30	26
Coil crosssection (mm²)	38.4	38.4
Engineering current densiy (A/mm²)	~1700	~1700
Pole width in Z (mm)	2.2	2.95
Pole height (mm)	8.0	8.0
Length of SC wire (m)	~1940	~1675
Max effective K	2.2	2.05

Brookhaven National Laboratory

SC-AGU : Magnetic Measurement Option

- ✓ Plan A: Use vertical measurement system with Liquid Helium
  - New small Hall probe (Senis ???) is planned to be used.
- ✓ Plan B: Develop conduction cooled measurement bench using In-Vacuum Magnetic Measurement System (IVMMS).



22

NSLS-II Upgrade R&D

Complex Bends Lattice

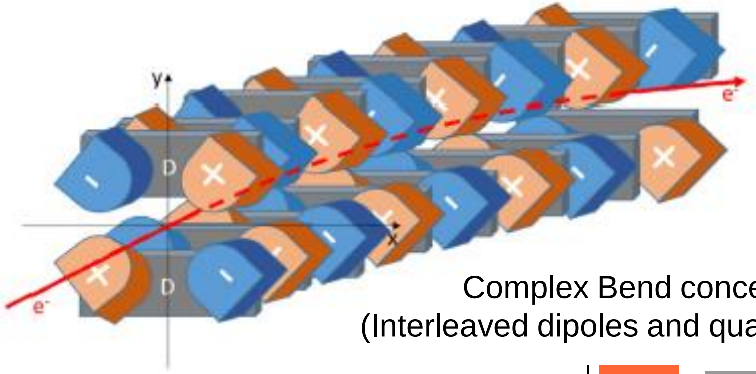
Small Aperture Rotating Coil Bench

Gradient Permanent Magnet Quadrupole

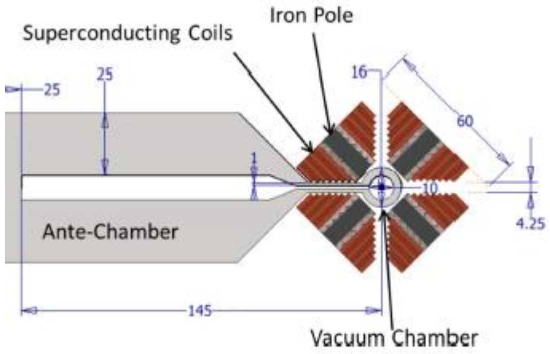
NSLS-IIU Complex Bend Lattice

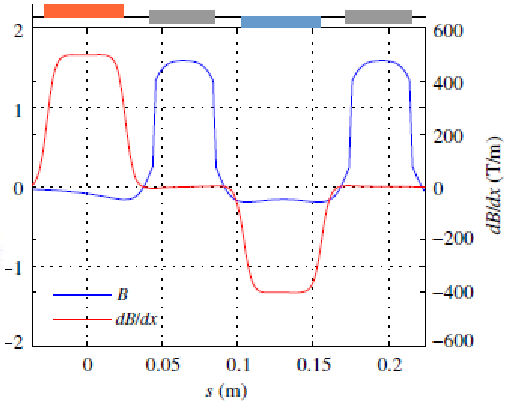
History of Complex Bend development

T. Shaftan et al., Complex Bend II, BNL-211223-2019-TECH, Oct 2018
T. Shaftan, Methodology for designing Complex Bend lattice, BNL-223858-2023-TECH, Jan 2022



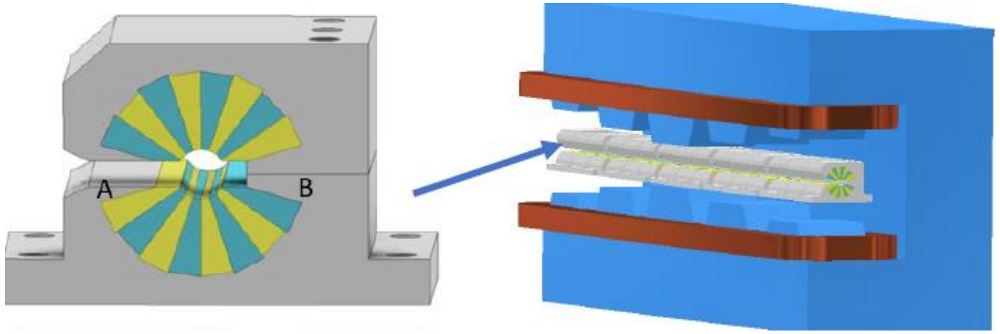
Complex Bend concept
(Interleaved dipoles and quadrupoles)





Superconducting magnet design (B=1.05T, G=500T/m)

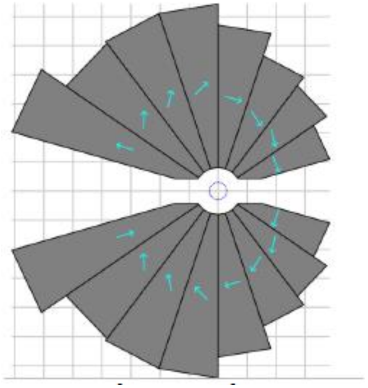
G. Wang et al., PRAB 21,(2018)



Decoupled Dipole-Quadrupole magnets (B=0.25-0.5 T, G=±250T/m)

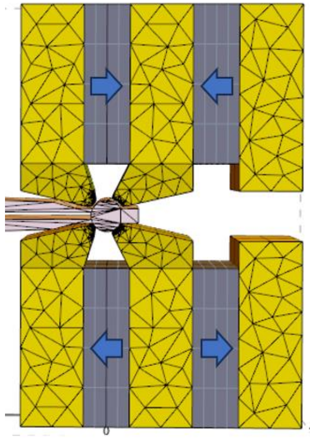
G. Wang et al., PRAB 22,(2019)

Combined Function Dipole-Quadrupole PMQs (B=0.25-0.5T, G=±130T/m)



Halbach type

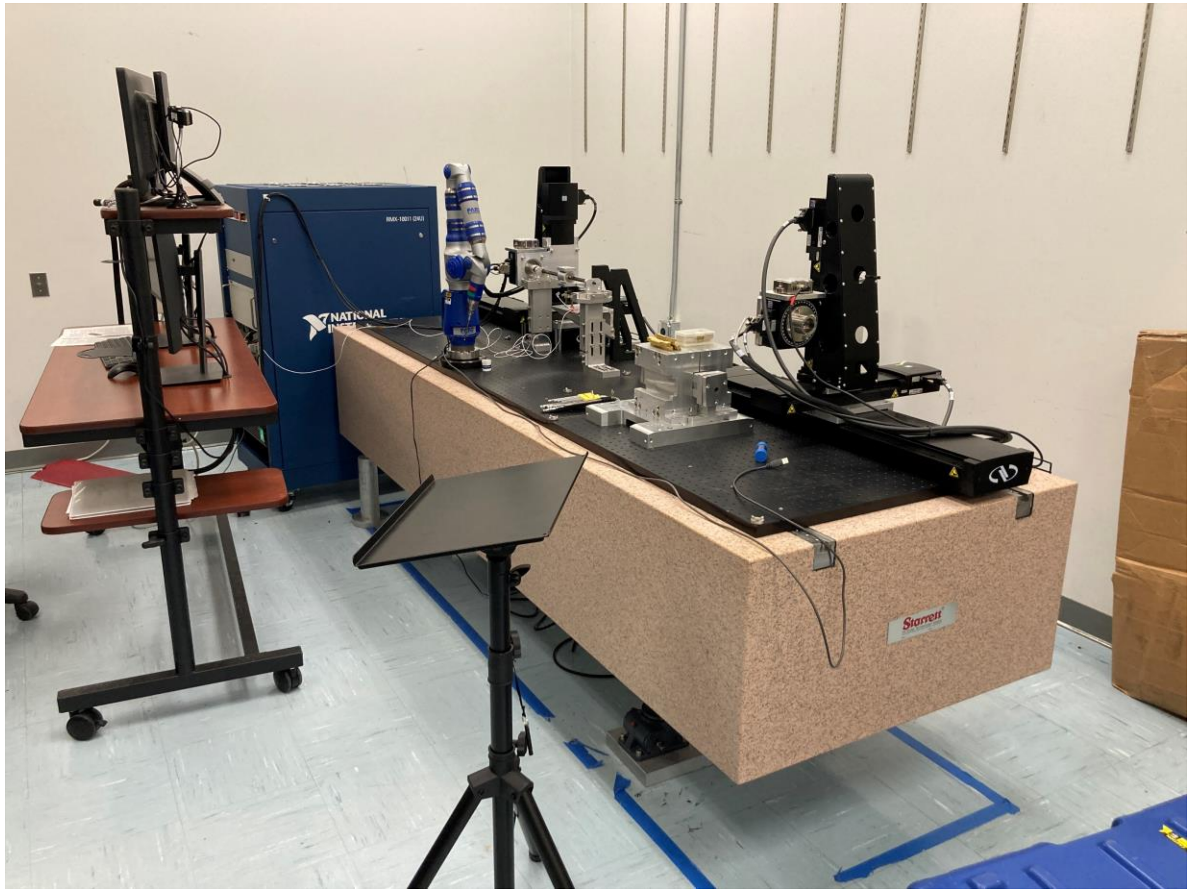
S. Brooks et al., PRAB,(2020)



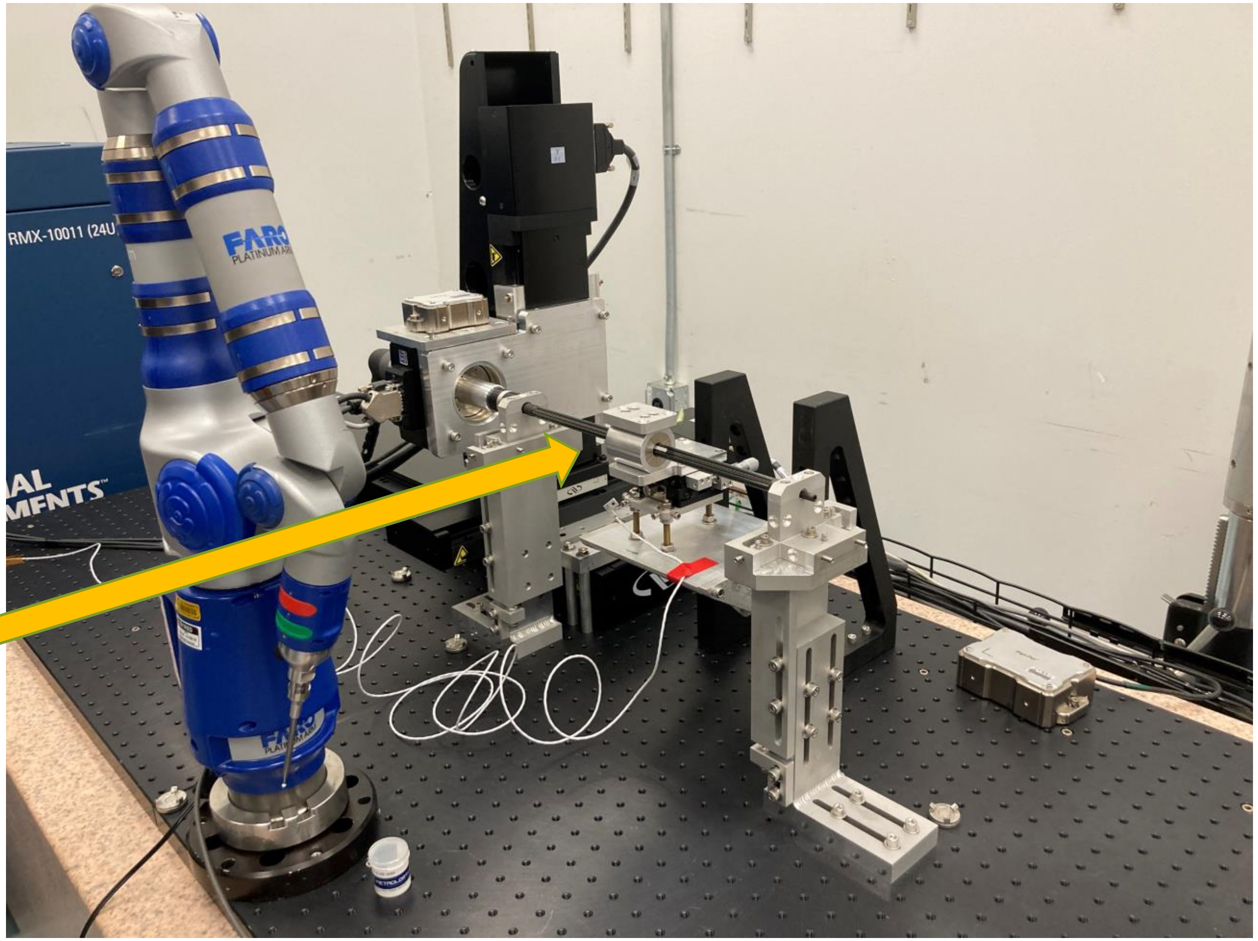
Hybrid type

P. N'Gotta et al., PRAB,(2016)

Rotating Coil Bench



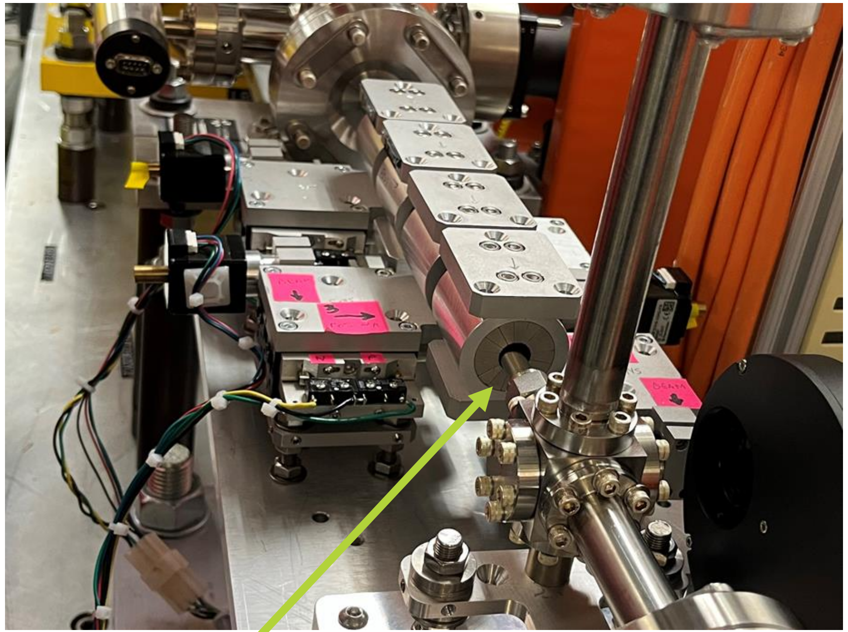
12 mm diameter rotating coil with 1.8 mm thick printed circuit board, wiring, and ceramic bearings.



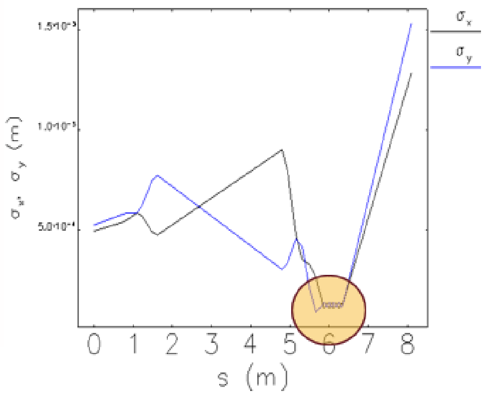
Small Permanent Magnet Quadrupole for complex bend

Halbach Magnet Development- Prototypes, Test

CB concept successfully tested at NSLS-II linac diagnostic beamline 100-200 MeV electron beam energy

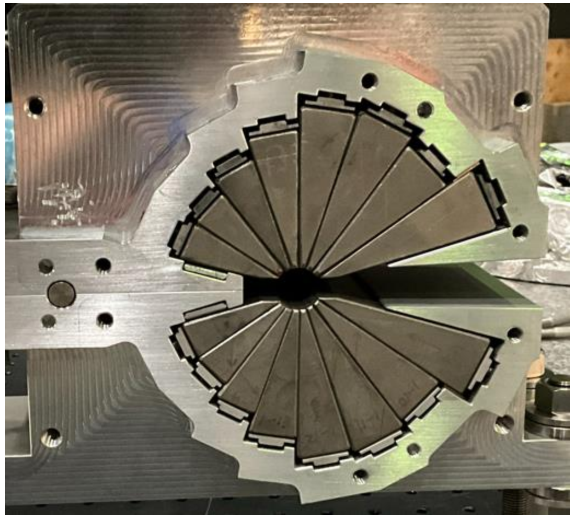


CB beamline beam size



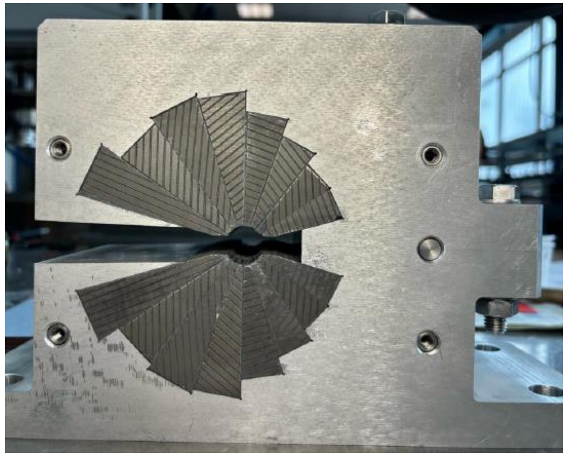
S. Sharma et al.

In-house magnet prototype



- 1 defocusing magnet assembly successful
- 1 focusing assembly foreseen

Vacuumscmelze magnet prototype



- 9 defocusing magnets assembly procured
- 6 focusing magnets assembly procured

In-house PMQ prototype measurement

Normalized

	bn	an
1	-12828.2	-0.6673
2	-10000	0
3	-181.326	29.79
4	-27.7127	4.2156
5	-3.5331	0.777
6	3.2568	-1.5846
7	-3.1613	-0.7419
8	-0.7607	-0.3551
9	0.172	0.0874
10	-0.2507	0.0437
11	-0.0523	0.0169
12	-0.01	0.0081
13	0.0109	0.0026
14	0.0061	0.0012
15	0.0011	0.0001
	RSS= 186 units	

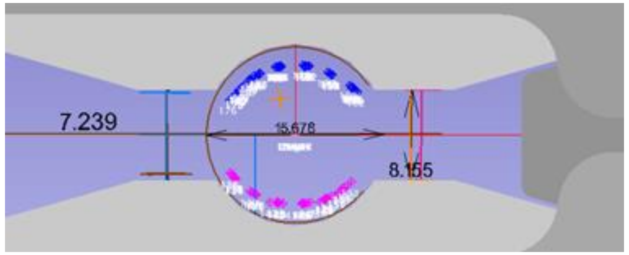
Absolute

	bn	an
1	-4.94E-02	-2.57E-06
2	-3.85E-02	1.24E-17
3	-6.99E-04	1.15E-04
4	-1.07E-04	1.62E-05
5	-1.36E-05	2.99E-06
6	1.25E-05	-6.10E-06
7	-1.22E-05	-2.86E-06
8	-2.93E-06	-1.37E-06
9	6.63E-07	3.37E-07
10	-9.66E-07	1.68E-07
11	-2.01E-07	6.50E-08
12	-3.86E-08	3.13E-08
13	4.18E-08	1.00E-08
14	2.34E-08	4.72E-09
15	4.23E-09	4.62E-10

B=-0.494 T

G=-128.33 T/m

- High sextupole component (b3)
- Assembly error (800 um error for vgap)
- Modification of the aperture spacer



Summary

- The NSLS-II ring currently has 29 beamlines and running with 660 pm.rad emittance. Plan to construct 8-12 new beamlines over the next decade.
- Magnetic measurement systems for SCWs (with less than 2 m) have been developed.
- SC-AGU prototype is under construction. The minimum gap at the center is 3 mm.
- A new flip coil bench with continuous rotation capability has been developed.
- The measurement system for a 4.4 m long CPMU is planned.
- Research and developments for complex bend lattices for future NSLS-II ring upgrade are in progress.