

REPM 2025



Applications of Permanent Magnets at the National Synchrotron Light Source-II

Toshi Tanabe (NSLS-II Insertion Device Group Leader)

Not Export Controlled

July 31st , 2025

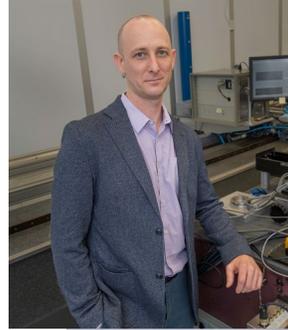


ID Group Staff

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- Electro-mechanical
Technician
Bryan Holland



Patrick N'Gotta

Outline

Synchrotron Light Source

- Principle of Synchrotron Radiation
- NSLS-II and World Wide Examples
- Wigglers and Undulators
- Various Insertion Devices

PM Applications for SR sources

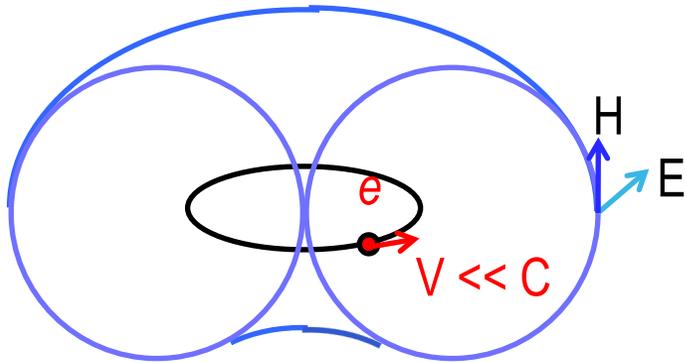
- In-Vacuum Undulator (IVU) and Cryogenic Permanent Magnet Undulator (CPMU)
- PM based Lattice Magnets
- Higher performance PM than $\text{Pr}_2\text{Fe}_{14}\text{B}$?

Principle of SR

SR is electromagnetic radiation produced by a relativistic electron when its path is deflected by a magnetic field **B**.

Non-relativistic ($v \ll c$)

$$E_e \sim E_{\text{REST}} = 0.511 \text{ MeV}$$

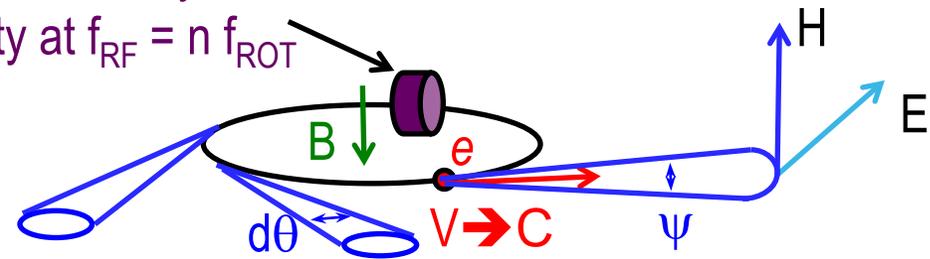


- EM radiation at $f = f_{\text{ROTATION}}$
- Radiation pattern like a dipole antenna
- Horizontally polarized in mid-plane
- Elliptically polarized above/below orbit

Relativistic ($v \rightarrow c$)

$$E_e = \gamma E_{\text{REST}} \text{ (0.38 to 8 GeV typ.)}$$

Electrons are accelerated by RF cavity at $f_{\text{RF}} = n f_{\text{ROT}}$



- Radiation is emitted tangential to orbit
- Observer sees Doppler-shifted frequencies
- Spectrum extends from RF to X-rays,
- Pattern is compressed vertically into angle $\psi = 1/\gamma$
- Total Radiated Power:

$$\propto B^4$$

$$P = \frac{\beta^4 \gamma^4}{4\pi\epsilon_0} \frac{2e^2 c}{3\rho^2}$$

Synchrotron Light Sources (lightsources.org)



Home About Lightsources.org For Users Careers **Light sources of the world**

Light sources of the world

There are more than 50 light sources in the world (operational, or under construction). This page lists all the members of the lightsources.org collaboration.



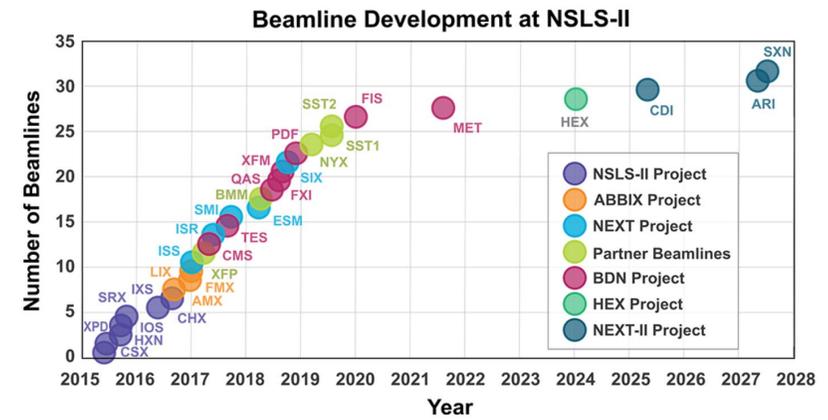
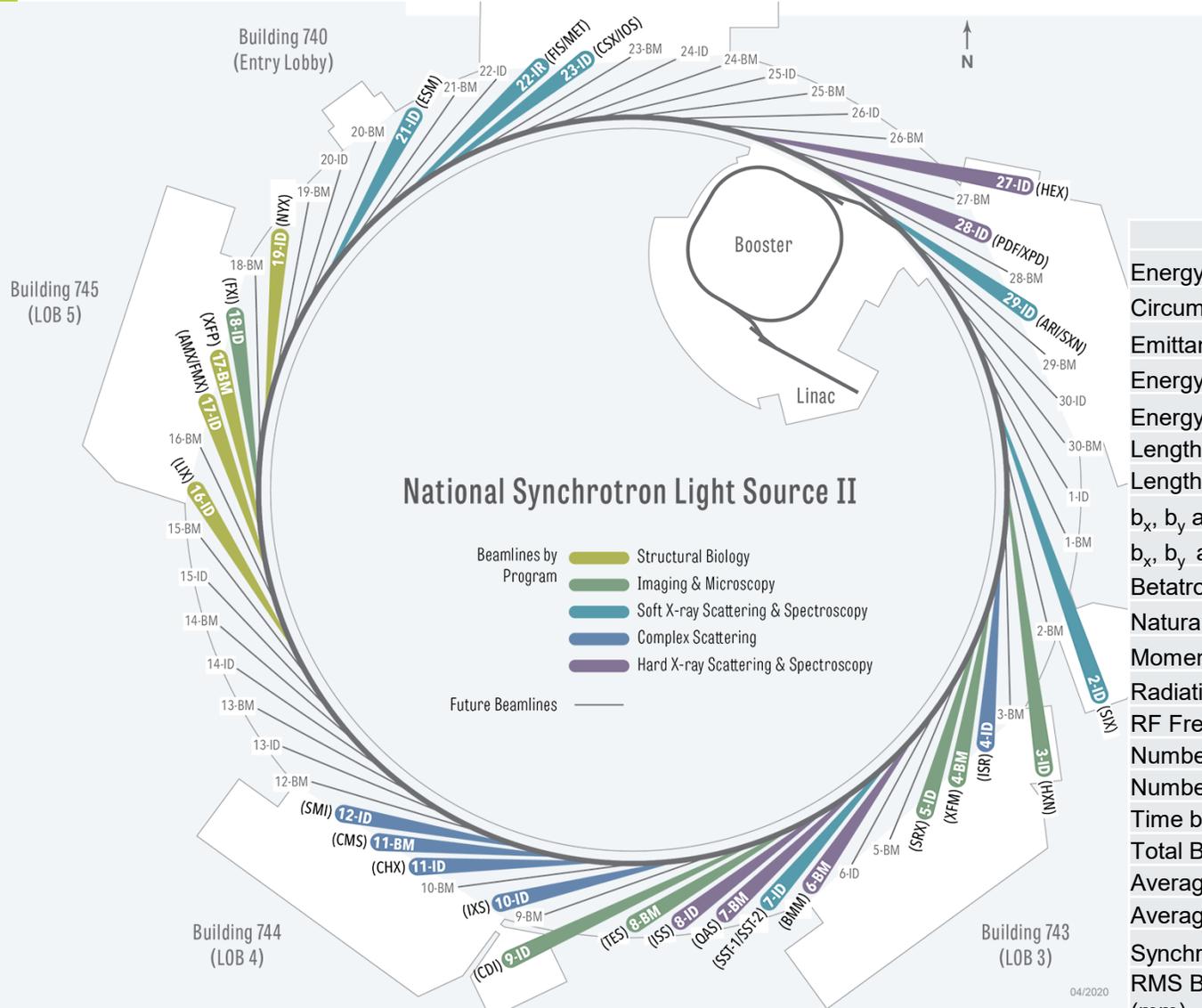
 Orange pins on the map represent members of the lightsources.org collaboration. If your facility is not listed below and you wish to join our collaboration, please contact our [project manager](#).

Synchrotron facilities

 <p>African Light Source Project (Honorary Member)</p>	 <p>ALBA</p>	 <p>ALS ADVANCED LIGHT SOURCE</p>	 <p>Argonne NATIONAL LABORATORY APS at Argonne National Laboratory</p>
 <p>Australian Synchrotron</p>	 <p>HZB</p>	 <p>Canadian Light Source Centre canadien de rayonnement synchrotron</p>	 <p>CHESS CORNELL HIGH ENERGY SYNCHROTRON SOURCE</p>
			

NSLS-II Storage Ring & Beamlines

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



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

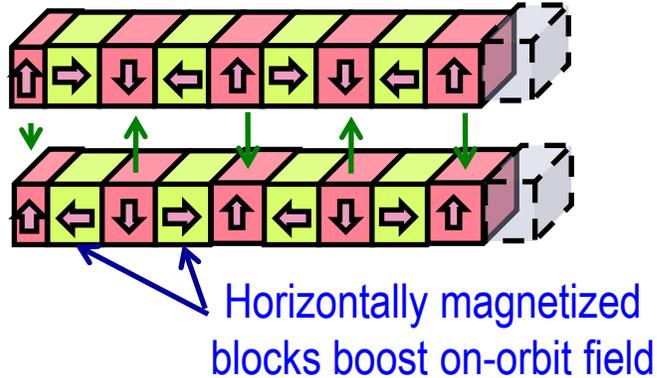
	Bare Lattice	3DW Lattice	All-ID w.o SCW	All-ID with SCW
Energy (GeV)	3			
Circumference (m)	791.958			
Emittance e_x (pm-rad)	2086	957	747	657
Energy Spread s_d (%)	0.0514	0.0818	0.0799	0.093
Energy Loss per Turn U_0 (keV)	286.4	649.1	831.8	958
Length of Long Straight (m)	9.3			
Length of Short Straight (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 Chromaticity x_x, x_y	-98.5, -40.2	-98.4, -39.8	-98.4, -39.9	-98.2, -40.1
Momentum 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 @ $V_{RF} = 3$ MV (mm)	2.7	4.34	4.27	5.02

Wigglers and Undulators

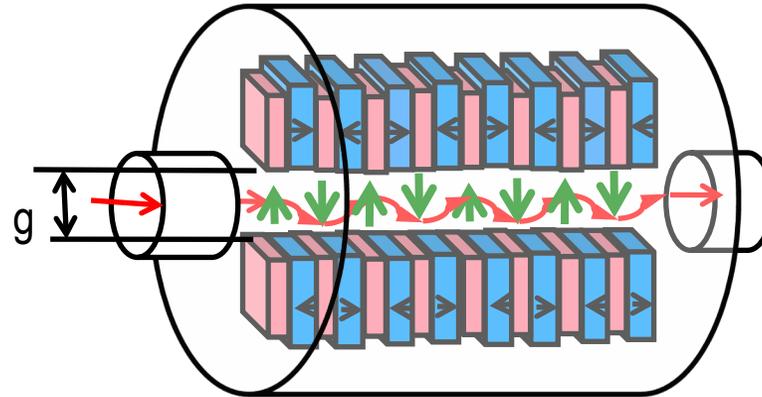
$$K \equiv \frac{eB_0\lambda_u}{2\pi mc}$$

where λ_u is period length

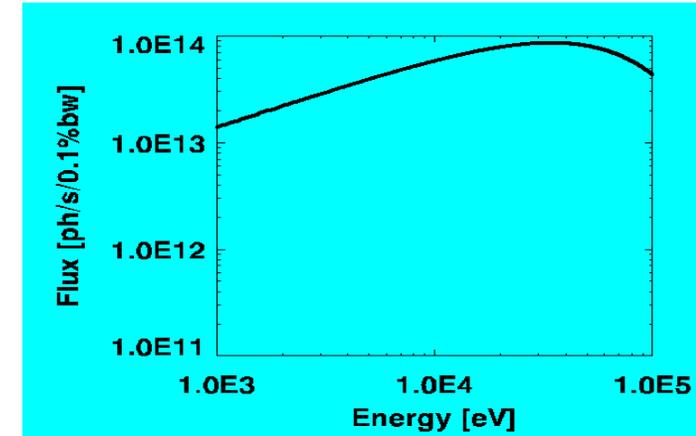
Halbach Pure-PM Undulator



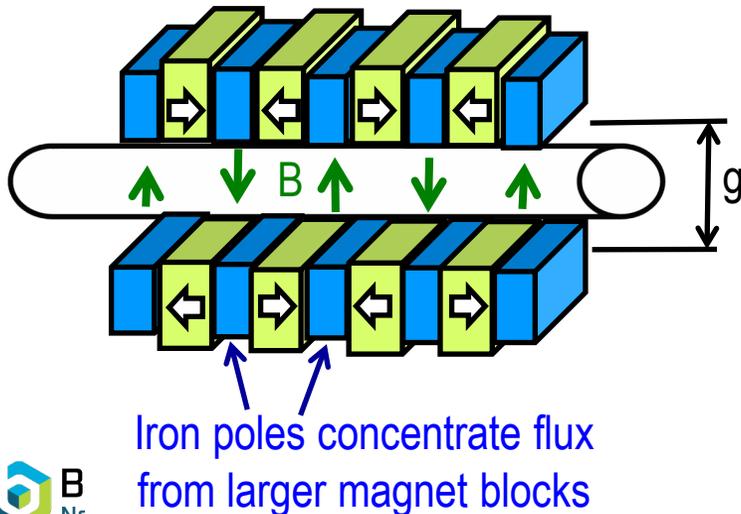
In-Vacuum Undulator (For hard x-rays)



Wiggler Spectrum $K \gg 1$

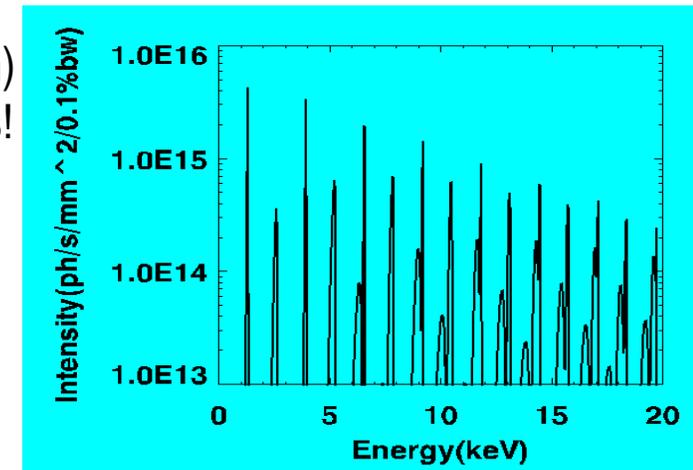


Halbach PM-hybrid Undulator

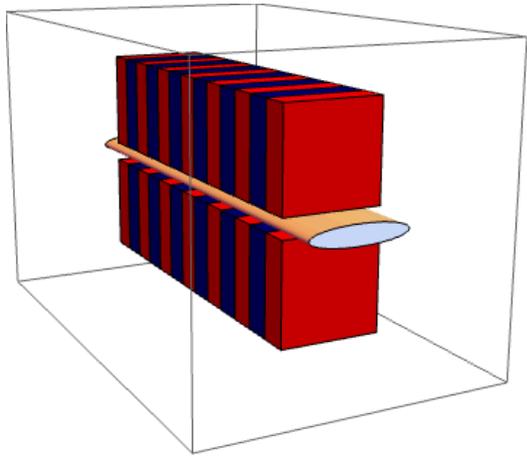


- Put magnet arrays *inside* vacuum chamber
- Minimum gap can be reduced to stay-clear required by electron and photon beams (a few mm)
- Reduce period \rightarrow more periods \rightarrow more photons!
- Shorter period \rightarrow higher photon energies
- Must be UHV-compatible \rightarrow Ni- or Ti-N-coated
- PM must withstand baking to $>100^\circ$ C without demagnetizing \rightarrow Use Hybrid car motor grades of PM

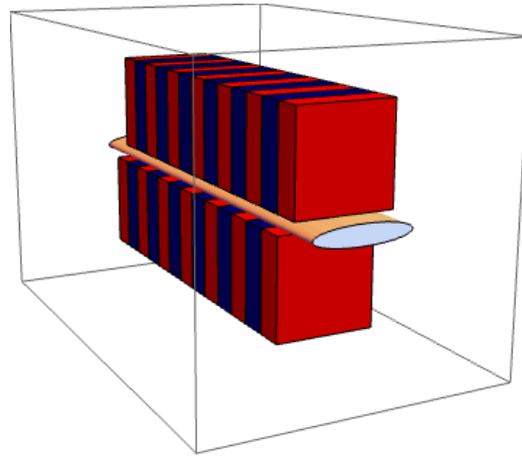
Undulator Spectrum $K \sim 2$



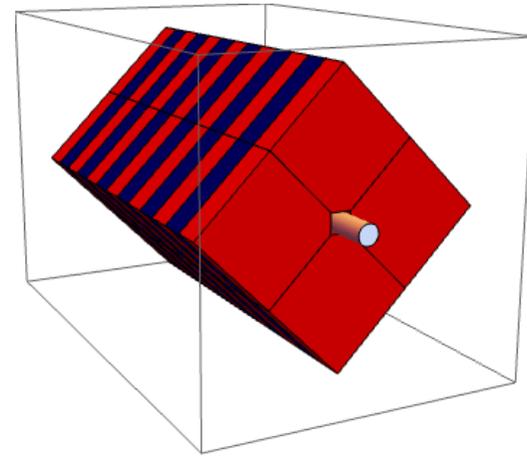
Permanent Magnet Undulators



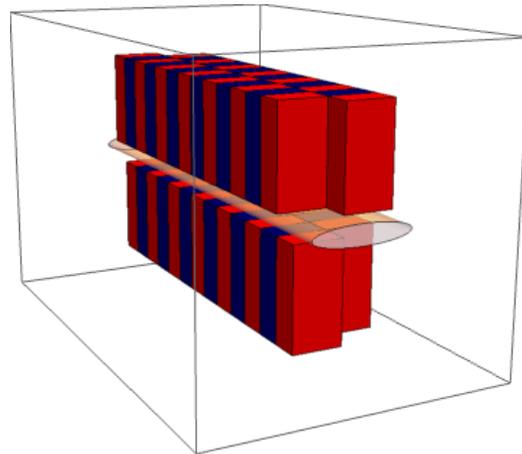
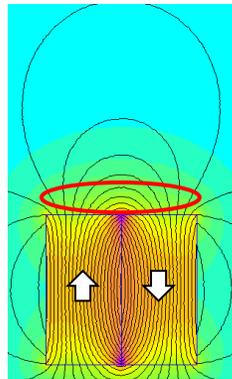
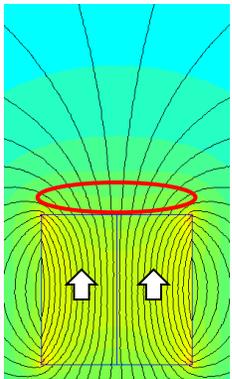
Variable gap



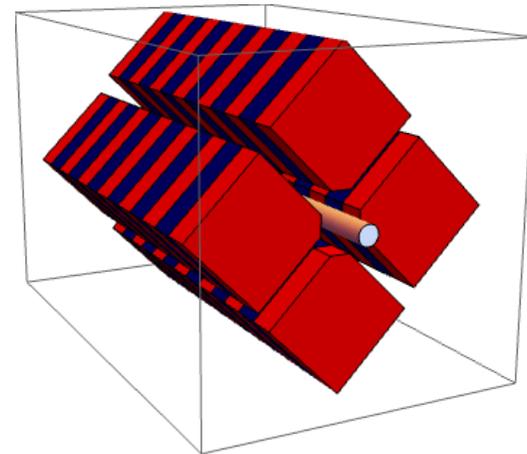
Adjustable phase



DELTA



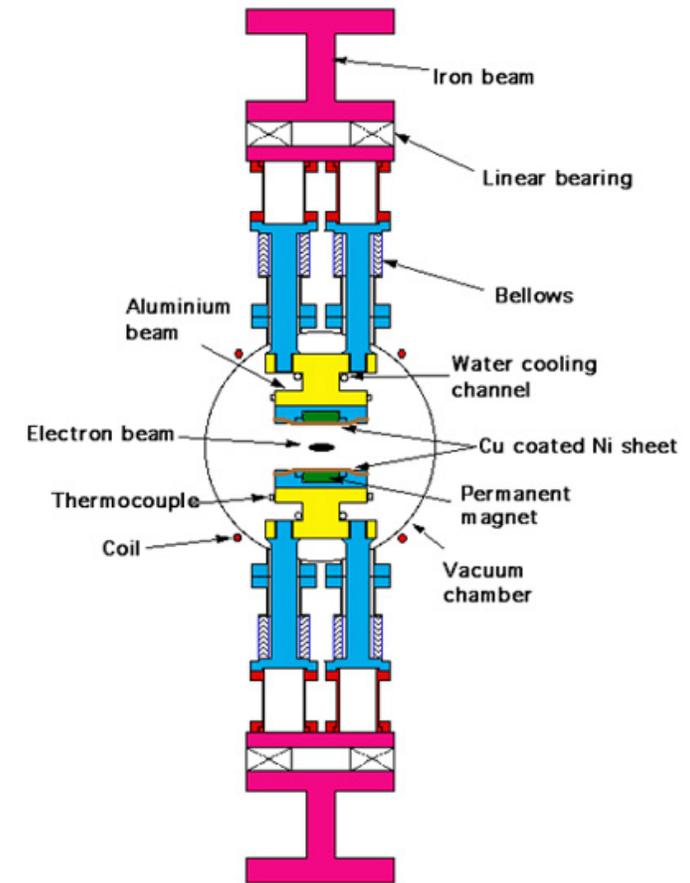
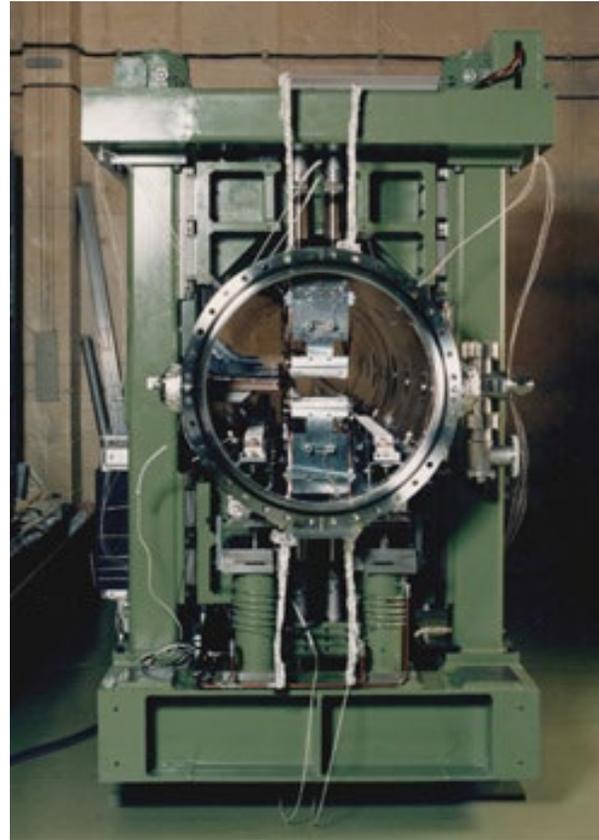
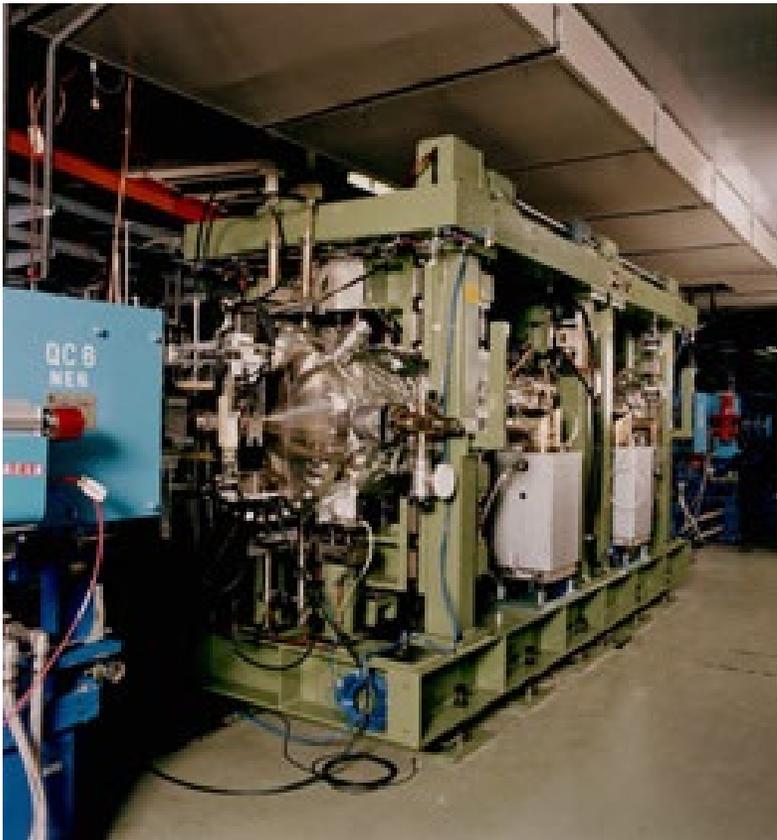
APPLE-II



APPLE-X

In-Vacuum Undulator (IVU)

- PM must be coated with TiN, Ni or Al to be used in the ultra-high vacuum (UHV) environment
- PM must have high enough coercivity to withstand baking $>100\text{ C}^\circ$



SPring-8 In-Vacuum Undulator

Temperature characteristic of Remanence of Permanent Magnets for CPMU

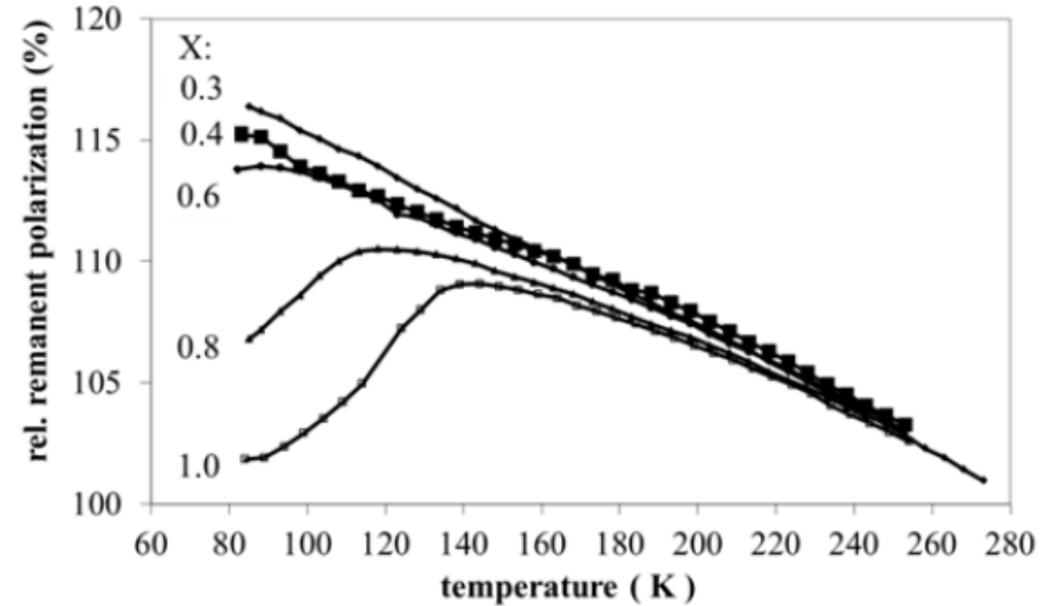
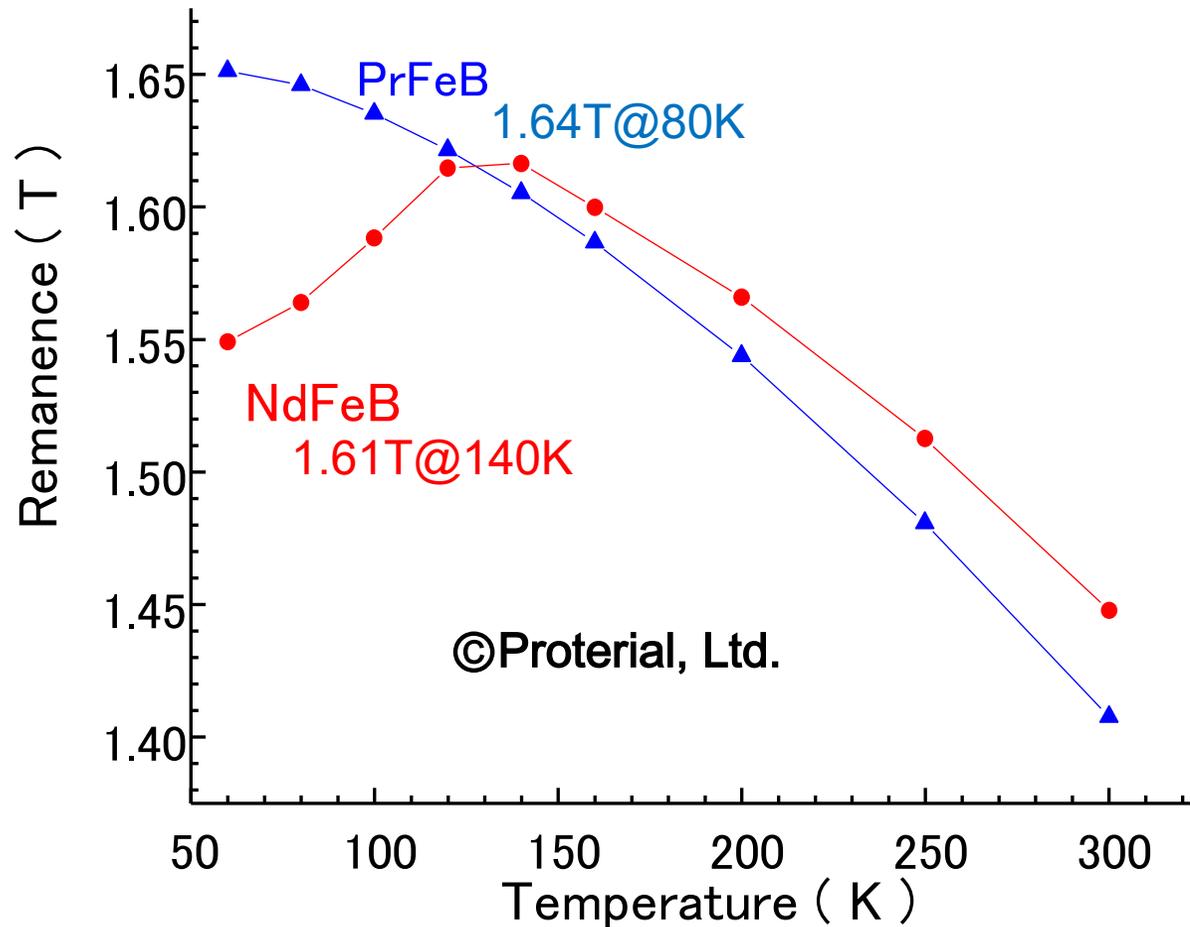
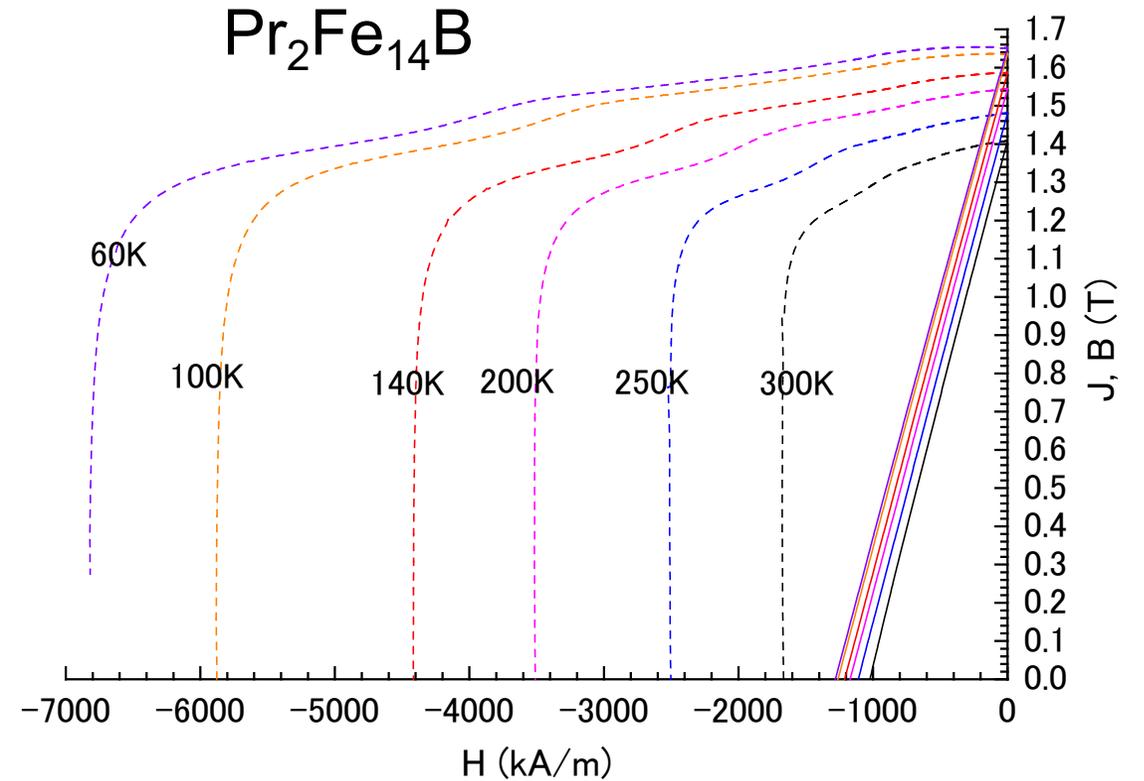
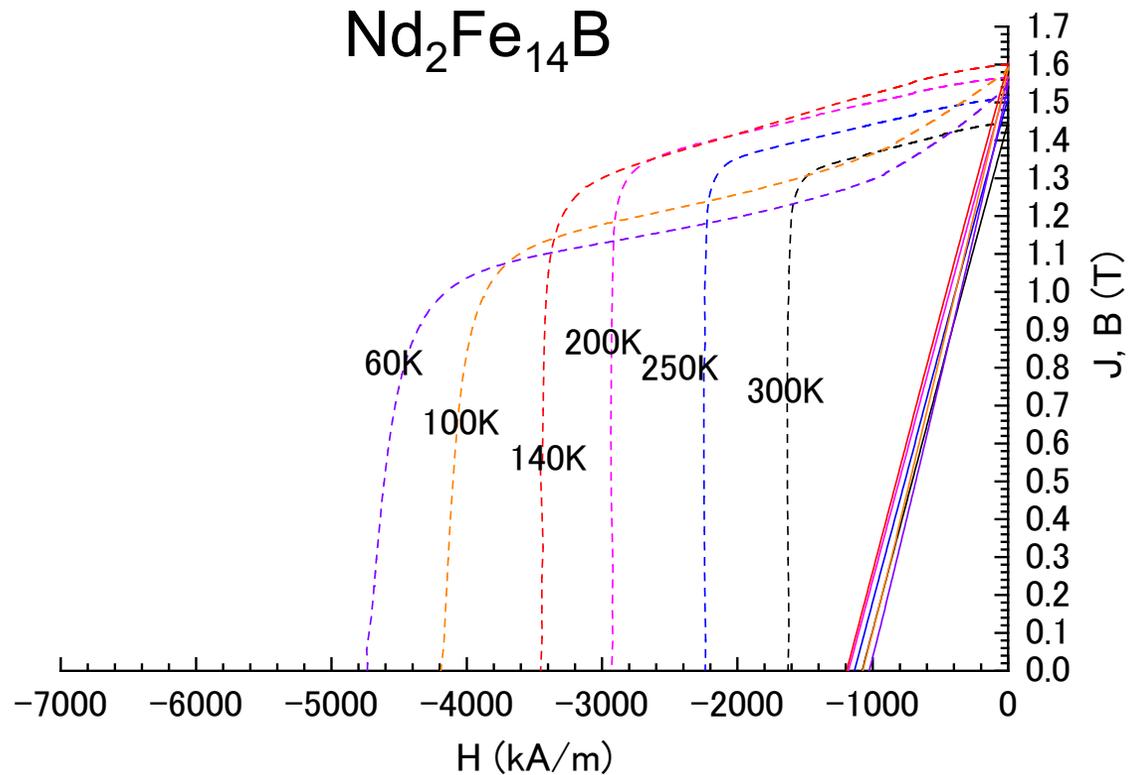


Figure 1: relative change of polarization with temperature for $(\text{Nd}_x\text{Pr}_{1-x})_2\text{Fe}_{14}\text{B}$ -magnets [1].

F.J. Bögermann, et. al., Proc. of IPAC2014 pp1238

Demagnetization Curves



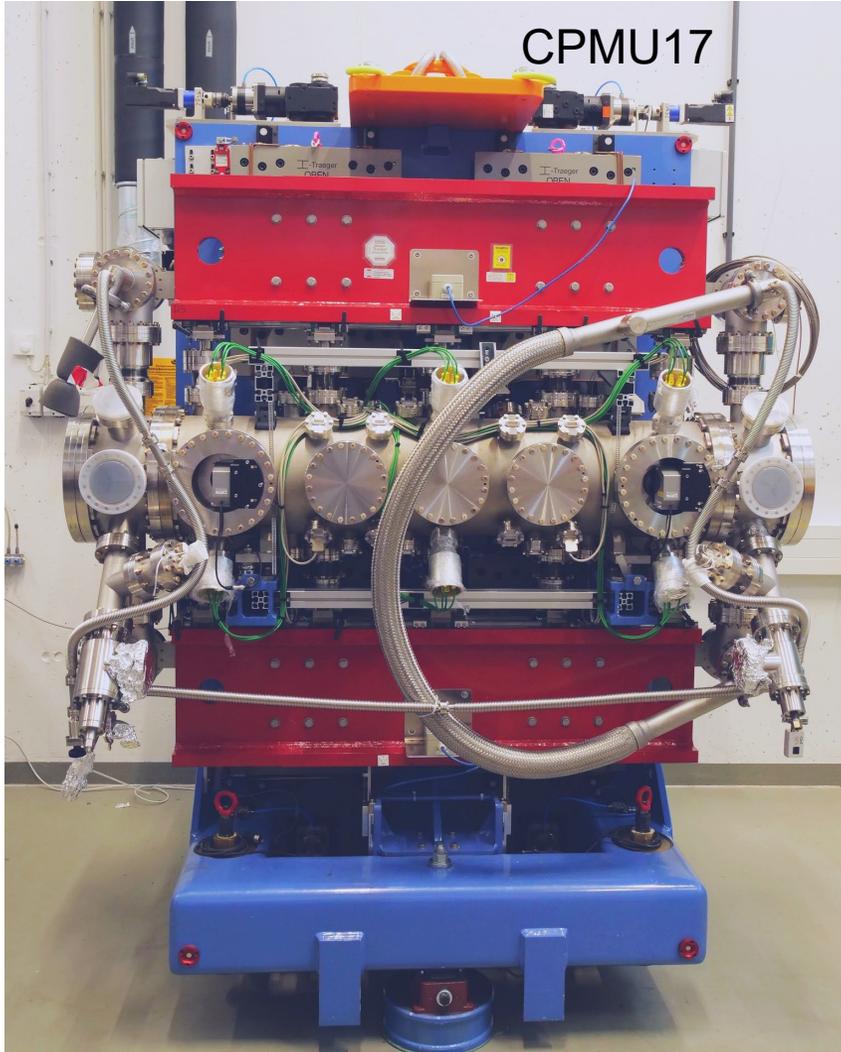
Proterial, Ltd.



©Proterial, Ltd.

Cryogenic PM Undulator (CPMU) at Bessy-II and at TPS

- No need to bake the PMs as cryo-pumping is expected
- Higher coercivity due to lower temperature for better radiation hardness

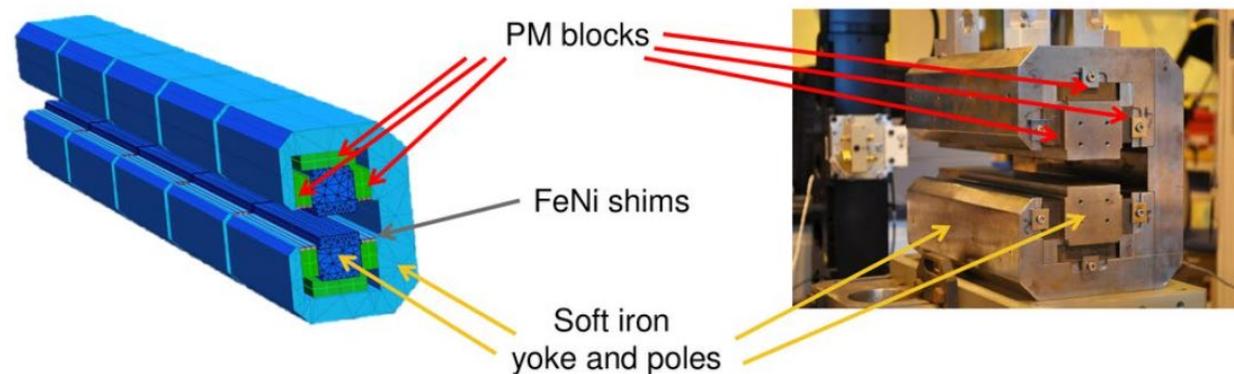


PM use for other accelerator magnets

PM dipole magnets for ESRF-EBS
(Extremely Brilliant Source)

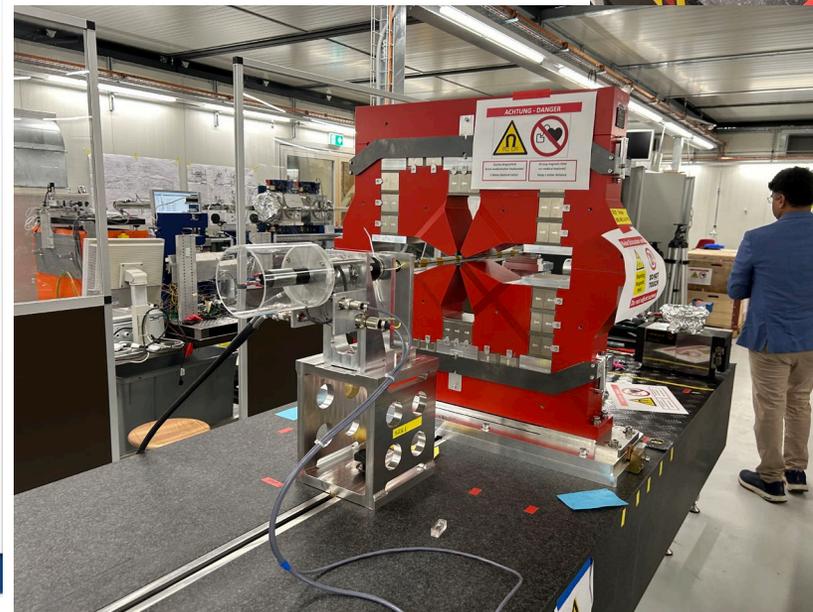
PM quadrupole magnets for the
Swiss Light Source –II

ESRF **Dipoles** A Light for Science



PM dipoles with longitudinal gradient (DL)

- $\text{Sm}_2\text{Co}_{17}$ PM material (proven resistance to radiation damage)
- Possible use of strontium ferrite for low field modules
- 25 kg of $\text{Sm}_2\text{Co}_{17}$ and 25 kg of strontium ferrite per dipole
- “Thermoflux” FeNi shims for temperature compensation

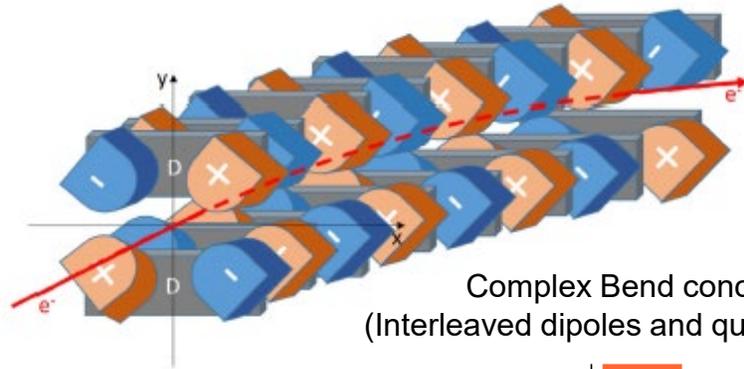


NSLS-IIU Complex Bend Lattice

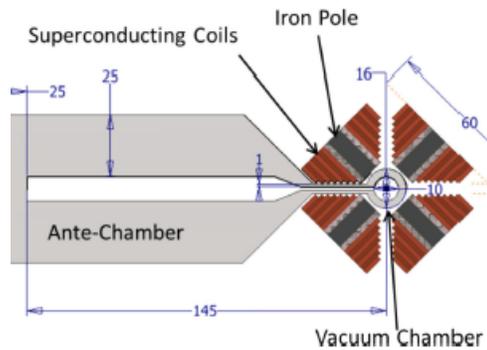
History of Complex Bend development

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

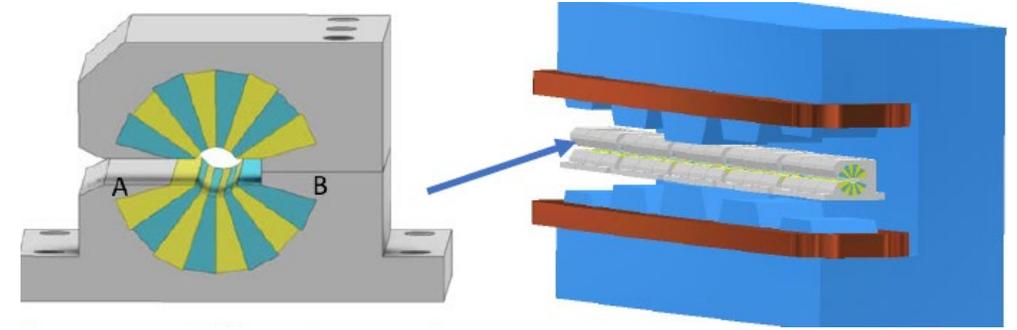
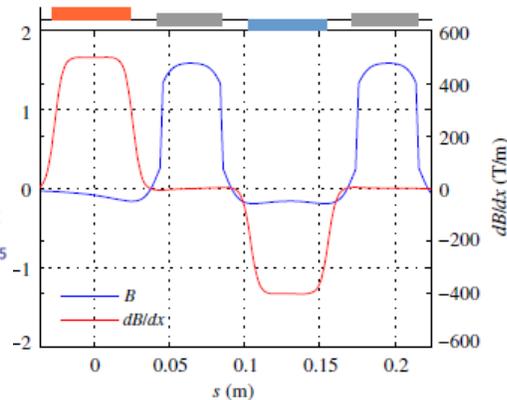


Complex Bend concept
(Interleaved dipoles and quadrupoles)



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

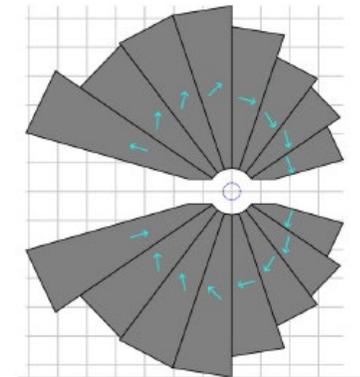
G. Wang et al., PRAB 21,(2018)



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

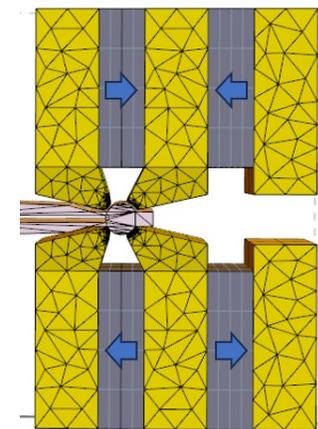
G. Wang et al., PRAB 22,(2019)

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



Halbach type

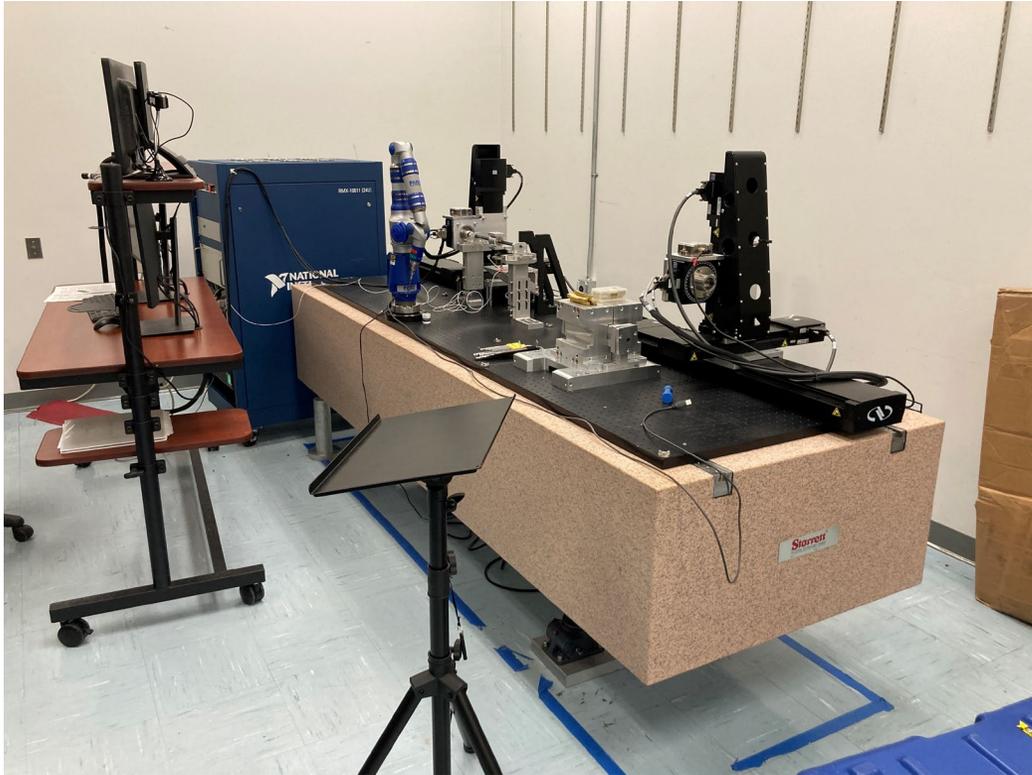
S. Brooks et al., PRAB,(2020)



Hybrid type

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

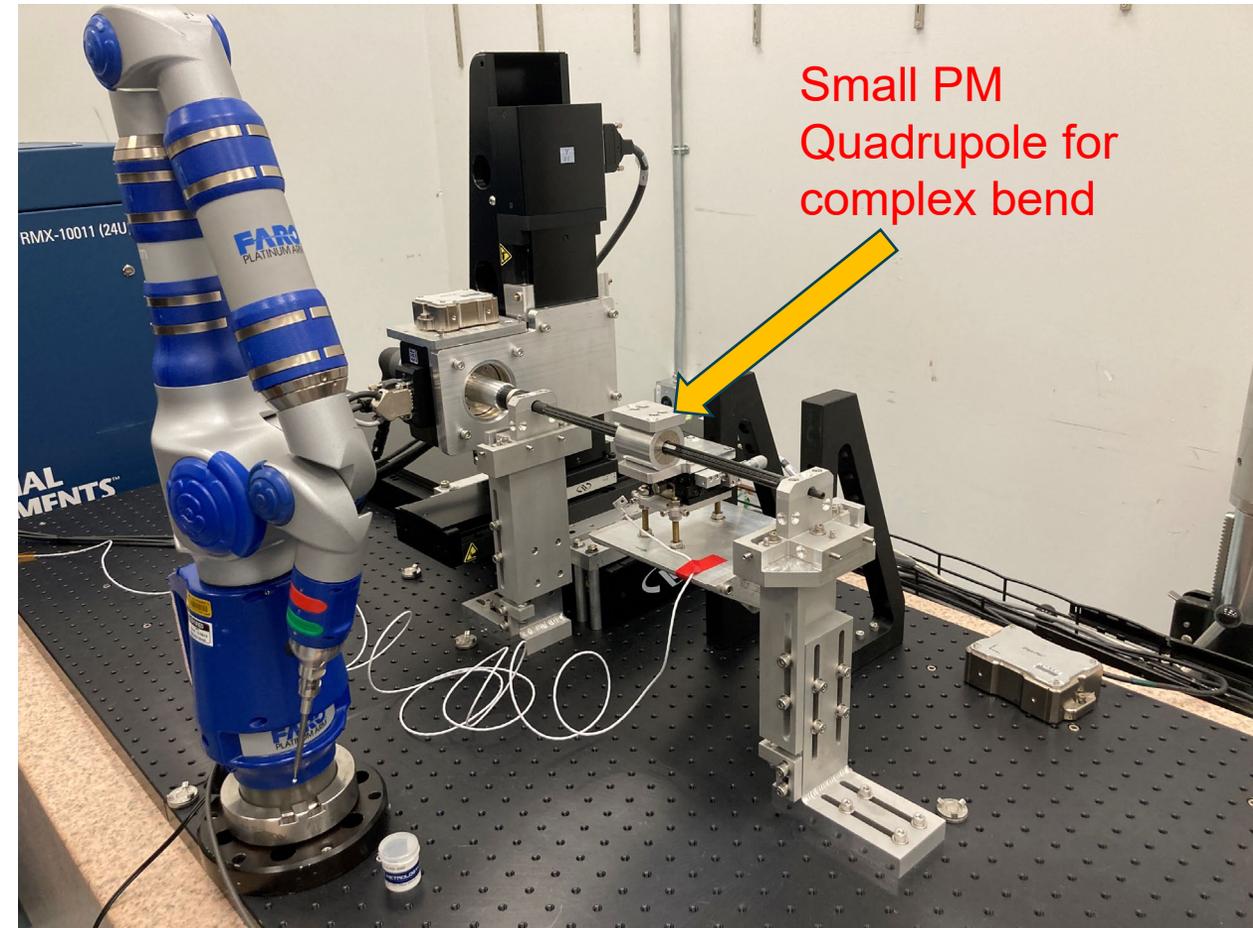
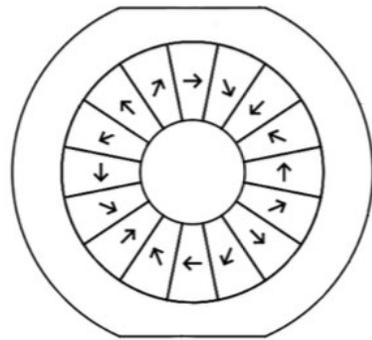
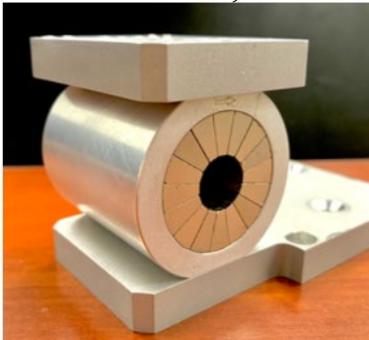
NSLS-II Rotating Coil Bench for PM Quads



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

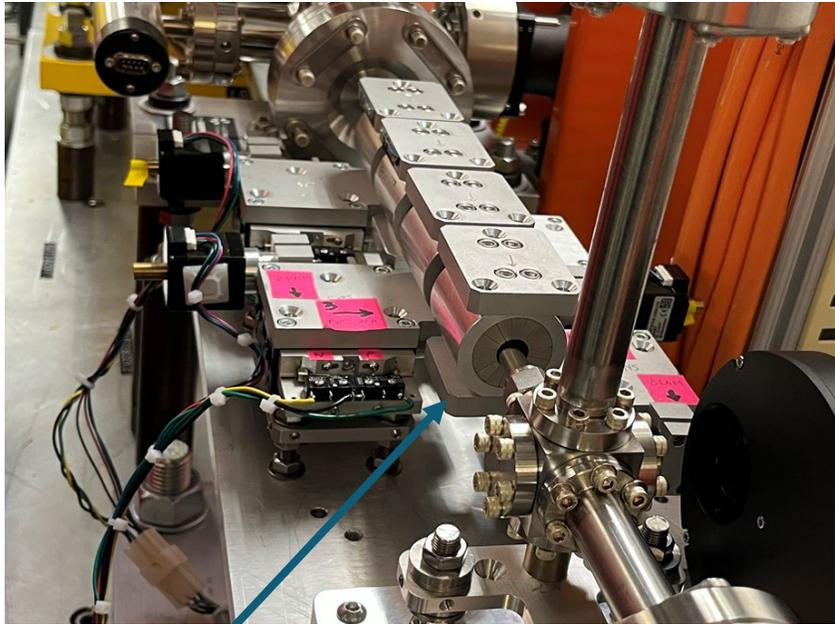


16 wedges (SmCo) in a Halbach configuration housed in an aluminum keeper $L = 46.7$ mm, $G = 146.6$ T/m, $ir = 6.35$ mm, $or = 15.875$ mm; 12.7 mm bore diameter.

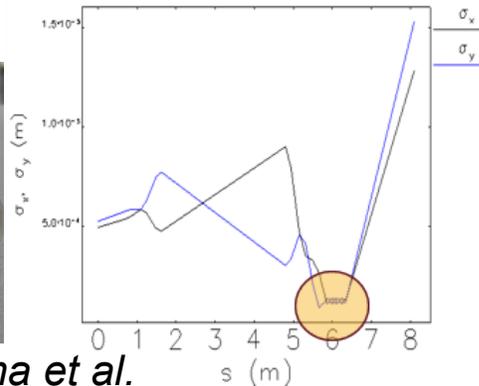


Halbach Magnet Development- Prototypes, Test

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

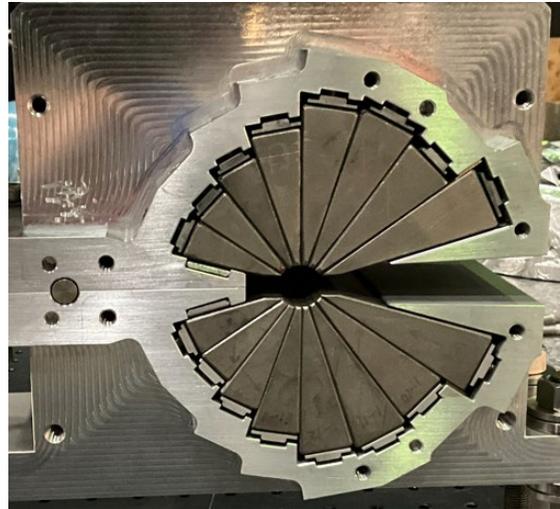


CB beamline beam size



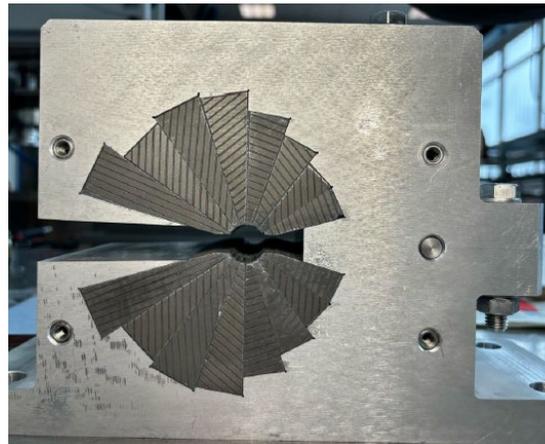
S. Sharma et al.

In-house magnet prototype



- 1 defocusing magnet assembly successful
- 1 focusing assembly foreseen

Vacuumschmelze magnet prototype



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

In-house PMQ prototype measurement

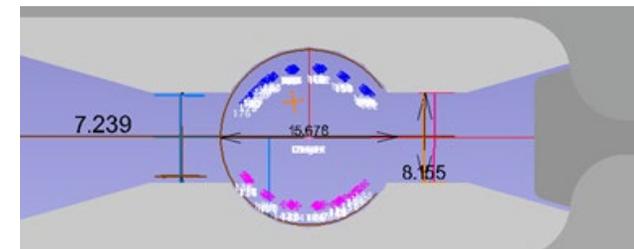
Normalized			Absolute		
	bn	an		bn	an
1	-12828.2	-0.6673	1	-4.94E-02	-2.57E-06
2	-10000	0	2	-3.85E-02	1.24E-17
3	-181.326	29.79	3	-6.99E-04	1.15E-04
4	-27.7127	4.2156	4	-1.07E-04	1.62E-05
5	-3.5331	0.777	5	-1.36E-05	2.99E-06
6	3.2568	-1.5846	6	1.25E-05	-6.10E-06
7	-3.1613	-0.7419	7	-1.22E-05	-2.86E-06
8	-0.7607	-0.3551	8	-2.93E-06	-1.37E-06
9	0.172	0.0874	9	6.63E-07	3.37E-07
10	-0.2507	0.0437	10	-9.66E-07	1.68E-07
11	-0.0523	0.0169	11	-2.01E-07	6.50E-08
12	-0.01	0.0081	12	-3.86E-08	3.13E-08
13	0.0109	0.0026	13	4.18E-08	1.00E-08
14	0.0061	0.0012	14	2.34E-08	4.72E-09
15	0.0011	0.0001	15	4.23E-09	4.62E-10

RSS= 186 units

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



Future Prospect

Q: Is there any magnet which can theoretically outperform Nd₂Fe₁₄B Magnet?

Theoretical BH_{max} varies among different articles....

Rank	Material system	Status	BHmax (MGOe)	Comment
1	α"-Fe ₁₆ N ₂ (iron nitride)	late-stage R&D (Niron, academic)	135 (theoretical)	Rare-earth-free, record-high M _s ; synthesis & stability hurdles.
2	Nd ₂ Fe ₁₄ B (Nd-Fe-B, sintered; N48–N56)	widely commercialized	52–56	Current industrial benchmark; Dy/Tb diffusion boosts coercivity.
3	Sm ₂ Fe ₁₇ N ₃ (Sm-Fe-N)	pilot-scale R&D	≤62 (theoretical)	Heavy-rare-earth-free; experimental values still <20 MGOe.
4	(Nd,Ce) ₂ Fe ₁₄ B (Ce-rich Nd-Fe-B)	pre-production	≈43	Lower-cost Ce replaces part of Nd; slight strength drop.
5	L1 ₀ -FeNi (tetrataenite)	lab synthesis	42~110? (theoretical)	Abundant Fe, Ni; ordering kinetics & scaling under study.
6	Sm ₂ Co ₁₇ ("2-17" Sm-Co)	commercial	29–33	Excellent stability to 350 °C; Co cost.
7	SmCo ₅ ("1-5" Sm-Co)	commercial	15–25	Great temp stability; lower energy density than 2-17.

Summary

- Insertion devices for modern accelerators require state-of-the-art permanent magnets to achieve the highest magnetic performance necessary for generating ultra-bright X-ray beams.
- A higher Br is desirable; however, moderate to high coercivity is also essential to withstand demagnetization during assembly and the baking requirement of IVU.
- Nd₂Fe₁₄B magnets exhibit a spin reorientation transition at low temperatures.
- Pr₂Fe₁₄B or (Nd_xPr_{1-x})₂Fe₁₄B magnet is used for CPMU.
- More potent magnet (α'' -Fe₁₆N₂ or L1₀FeNi?) is highly anticipated.
- Permanent magnets are increasingly replacing conventional lattice magnets in modern accelerators, driven by the need for high magnetic field gradients and energy-efficient operation.
- For next-generation storage rings, Sm₂Co₁₇ magnets are the preferred choice for lattice applications owing to their low temperature coefficient and enhanced resistance to radiation-induced degradation.