National Synchrotron Light Source II

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Magnetic designs and tests of the Complex Bend approach at NSLS-II

Timur Shaftan for the NSLS-II upgrade team

NSLS-II

February 13th, 2024

Outline

- Criteria for light source lattice design
- DBA → MBA → Complex Bend (CB)
- Challenges of compact strong-focusing magnets
- Integration of CB poles into single element
- Vacuum system
- Tests at NSLS-II
- Summary

Criteria for light source lattice design

- Low emittance
  - High photon brightness and flux
- Large real estate for machine components
  - Long ID straights
  - Sufficient room for vacuum, correctors, diagnostics
- Reduced power consumption
  - Saving MWh in operations for 5000 hrs/year
- Robust design with high injection efficiency and reasonable lifetime
  - ➢Demonstrating feasibility of key technologies

Low emittance

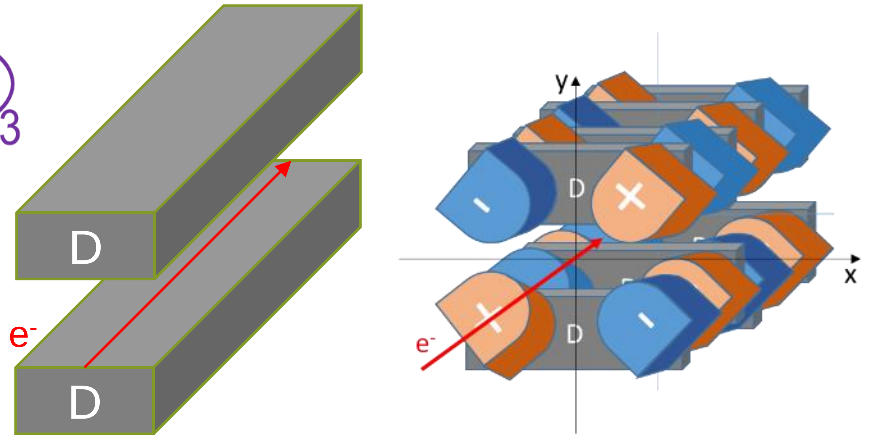
$$\varepsilon_x = C_q \gamma^2 \frac{I_5}{j_x I_2} \qquad I_5 = \oint \frac{\mathcal{H}_x}{|\rho^3|} ds \qquad I_2 = \oint \frac{1}{\rho^2} ds$$

$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2$$

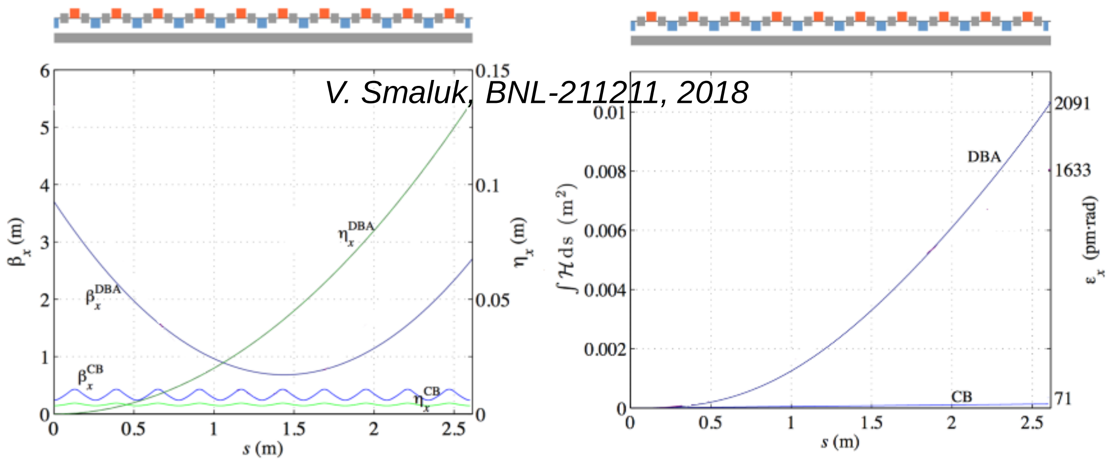
- Searching for low-emittance lattice solution
  - Multiple dipoles
  - LGB
  - Reverse bends

$$\varepsilon_x = \underset{2}{\boxed{F(\text{lattice})}} \frac{E^2}{\underset{1}{\boxed{J_x}} \underset{3}{\boxed{N_d^3}}} \rightarrow F(\text{lattice}) \frac{E^2}{J_x \underset{3}{\boxed{[N_d N_p]^3}}}$$

- Complex Bend concept (NSLS-II, 2018)
- Transition from individual dipoles to multiple dipole poles
  - APS DBA: 40x2=80 dipoles
  - APS-U MBA: 40x7=280 dipoles
  - NSLS-IIU via CBs: 30cells x 4 dipoles x ~10 poles =1200 poles
- Reducing β_x , η_x,… in the regions where $\rho \neq \infty$
- ✓ Reducing H_x and therefore ε_x
- Side notes
  - Can realize lattice solutions such as LGB
  - “Stackable” design



DBA dipole versus Complex Bend

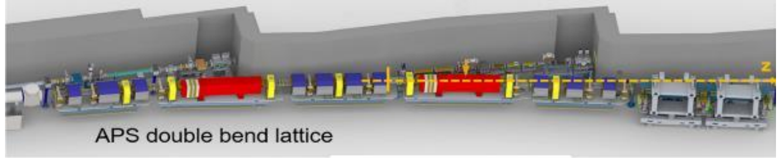


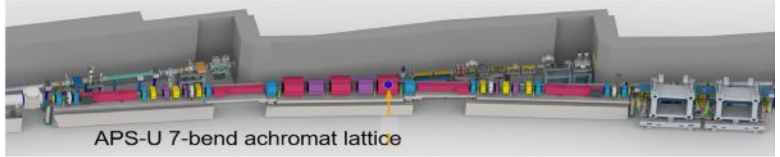
V. Smaluk, BNL-211211, 2018

Large real estate for machine components

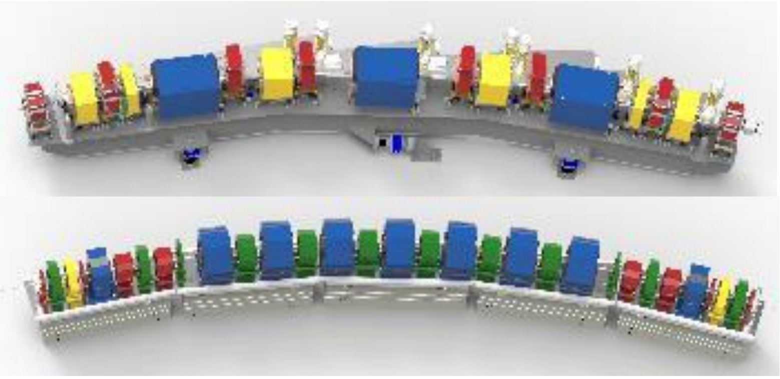
- MBA lattices feature much tighter arrangement of elements as compared with DBAs
  - Large number of magnets
  - Small diameter of vacuum chambers constrains conductivity and calls for distributed pumps and NEG
  - Strong focusing calls for large suite of diagnostics and correctors
- The essential requirement of the high-brightness light sources is long straight sections with optimal beta-functions for long Insertion Devices
- These considerations motivate the need to look for more compact solutions

APS/APS-U
E=7→6 GeV
C=1104 m
ε_x=3100→36 pm

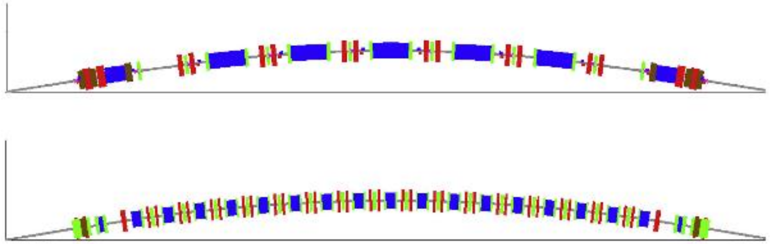




ALS/ALS-U
E=1.9→2 GeV
C=197 m
ε_x=2000→70 pm

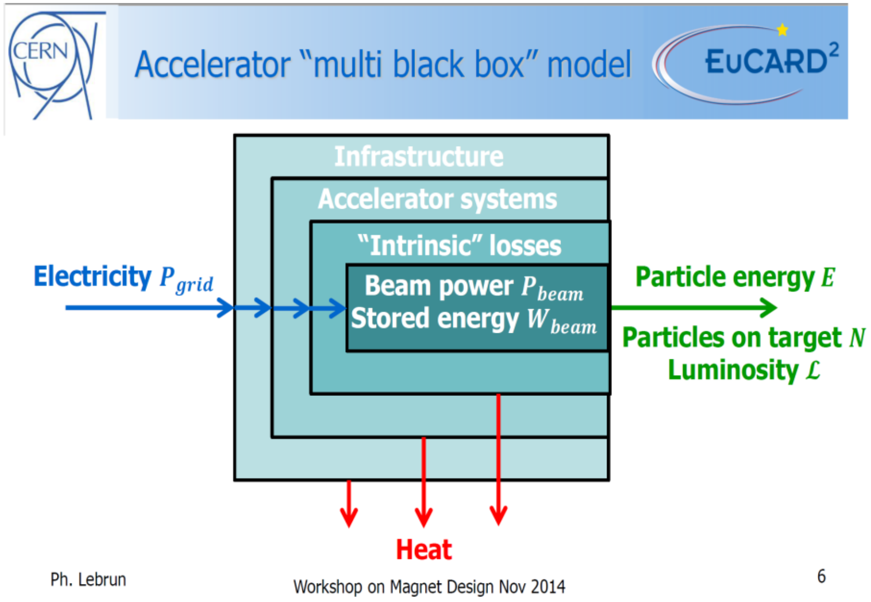


MAX-4
E=3 GeV
C=528 m
ε_x=250→10 pm



Low power consumption

- NSLS-II power systems
  - Magnets 60 dipoles, 300 quadrupoles, 270 sextupoles, 180 slow and 90 fast x/y correctors
  - PS ~900 power supplies, ~600 sealed PS/electronics enclosures, ~2 km of cable trays, cabling
  - RF system with 3 single cell 500MHz S.C. cavities, three 300kW RF transmitters + Cryogenic Plant 700W @4K
- NSLS-IIU power systems
  - 120 Complex Bends with 15 types PMQBs
  - 90 quads, ~90 sextupoles, ~90 octupoles, slow and fast correctors with their PS
  - Choice of SC RF system
- NSLS-IIU magnets at 3 GeV (4 GeV) will consume 17% (30%) of power relative to that for NSLS-II magnets


Accelerator "multi black box" model

Ph. Lebrun

Workshop on Magnet Design Nov 2014

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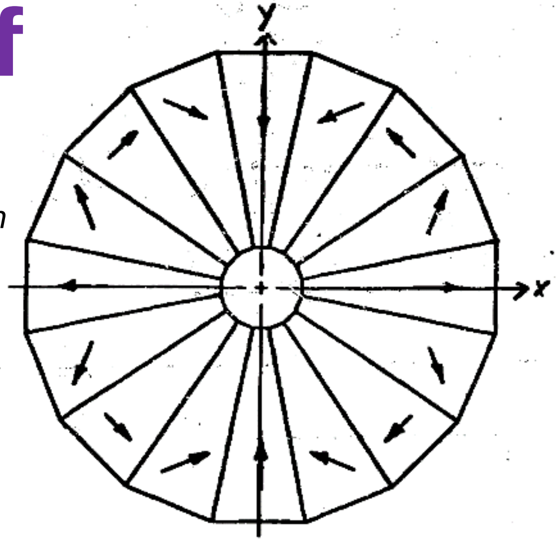
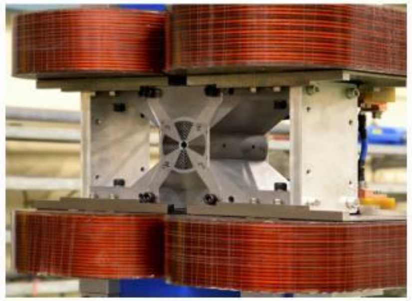
NSLS-II racks along 800 m long mezzanine

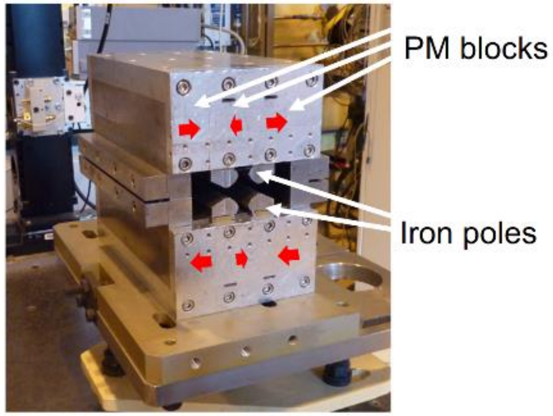
Historical perspective for development of PM for light sources



Design of permanent multipole magnets with oriented rate earth cobalt material
K. Halbach, LBL-9604, 1979

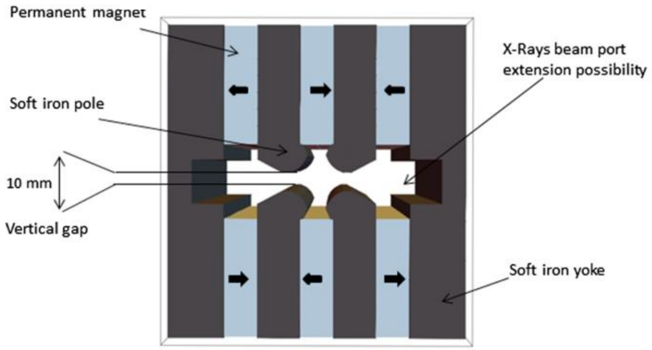


M. Modena et al., IPAC-2012, USA

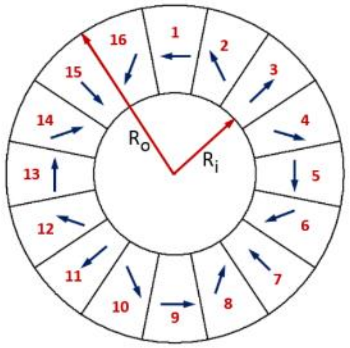


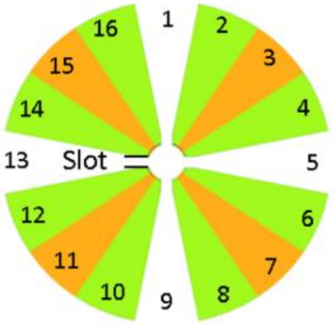
Courtesy P. N'gotta, G. Le Bec

E. Karantzoulis, B. Diviacco, 2015



P. N'gotta et. al., PRAB19, 122401 (2016)





High gradient quadrupoles for low emittance synchrotrons
S. Sharma et. al., in Proceedings of IPAC2019, Australia

Some Uses of REPMMs for SRs and Colliders, J. Spencer, SP 3647, 1985

Complex Bends for Low-Emittance Ring Design

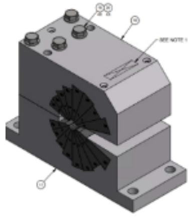
- Putting Complex Bend concept to use

- Gains
  - Reaching diffraction-limited emittances at 10 keV of ph. energy
  - Compact arrangement of ring elements, gaining length for IDs

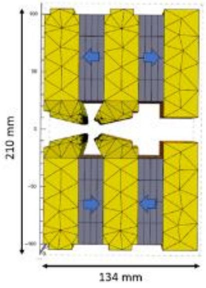
- Engineering challenges being addressed
  - Gradients of ~150 T/m are required (Permanent Magnet Bend/Quad)
  - Small apertures / Heat load from Synchrotron Radiation

- We are building full-scale CB element prototype (S. Sharma, IPAC-2022)

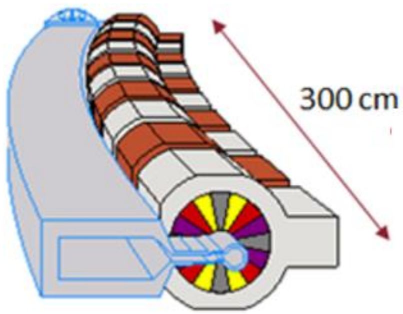
- Pursuing this as an option for NSLS-II upgrade
  - NSLS-II has developed Triple Complex Bend Achromat (**TCBA**) lattice
  - 30 cell 792 m lattices at 3 GeV with emittance of ~20 pm·rad

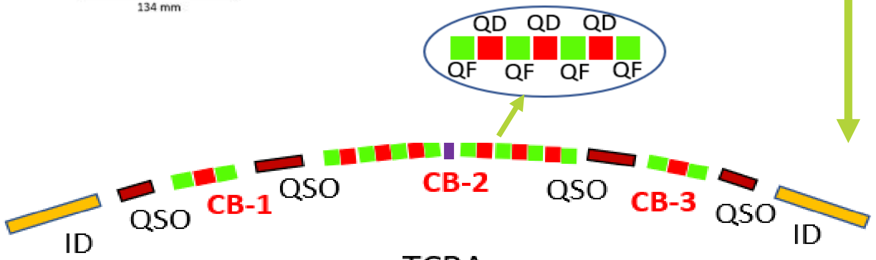


Halbach PMQ



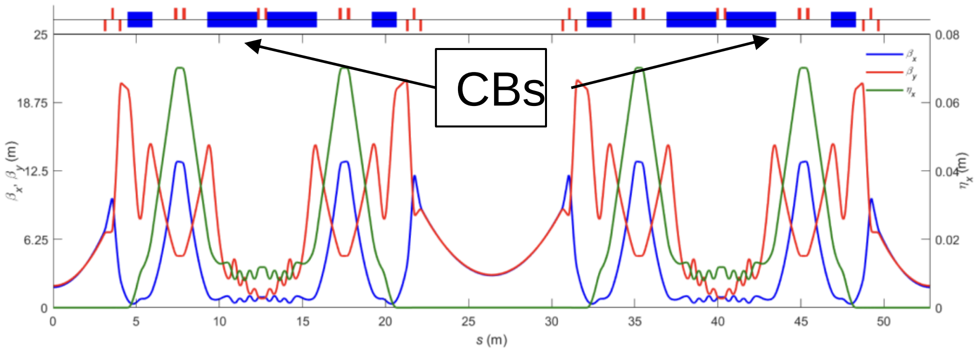
Hybrid PMQ





TCBA

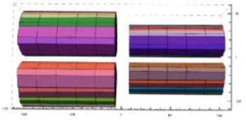
M. Song, Y. Li, et al.

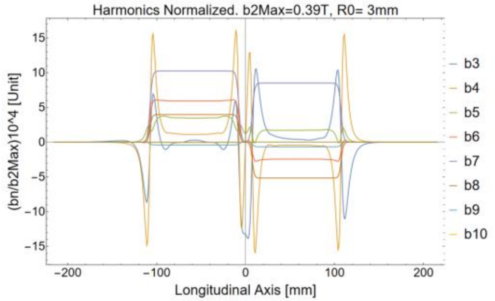


Challenges

- Field quality
  - With +/-130 T/m harmonic spectrum between PMQs is quite rich
  - We developed methods of global and local corrections
  - Our decades long experience in compensating IDs at NSLS-I / II
- Extraction of Synchrotron Radiation fan
  - Crude estimate of radiating 3 kW per Complex Bend element
  - Choice of the extraction slot is defined by the SR fan
- Irradiation of Permanent Magnets in the ring
  - Wealth of knowledge on irradiation of PMs in accelerator community
  - Upcoming studies on resilience of PMQs under irradiation at NSLS-II IFE beamline
  - Experience with running ~20 IDs with 5 mm gap at NSLS-II
- Robust assembly and alignment methods of PMQ cells
  - We developed methods and fixtures for 1.5 m long CB prototype

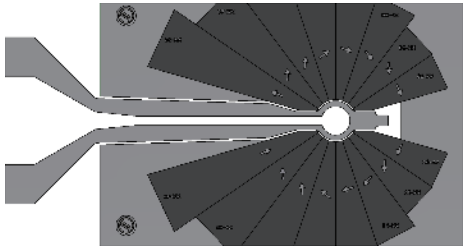
RADIA analysis of 2 PMQs with +/-130 T/m and 0.5/0.25 T field



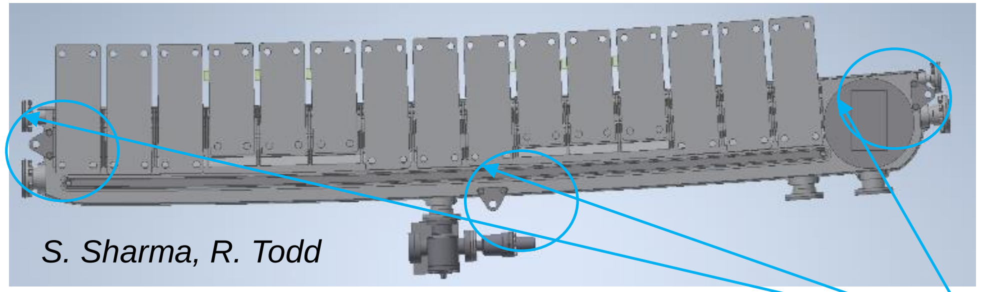


P. N'gotta

Slot in the vacuum chamber for extraction of SR fan



S. Sharma,
S. Brooks,
R. Todd et al

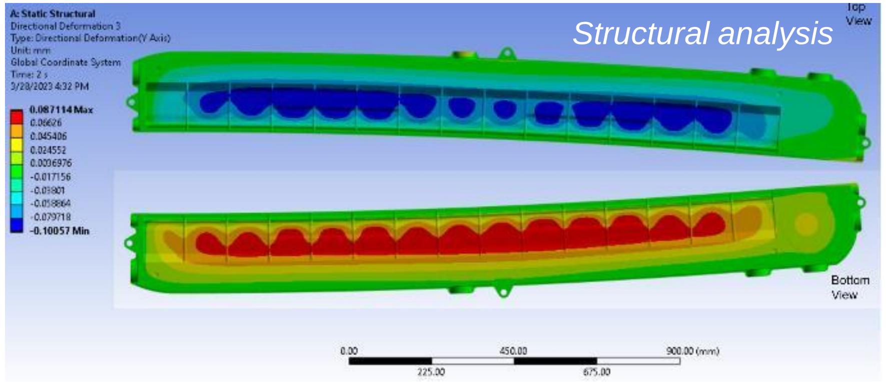


S. Sharma, R. Todd

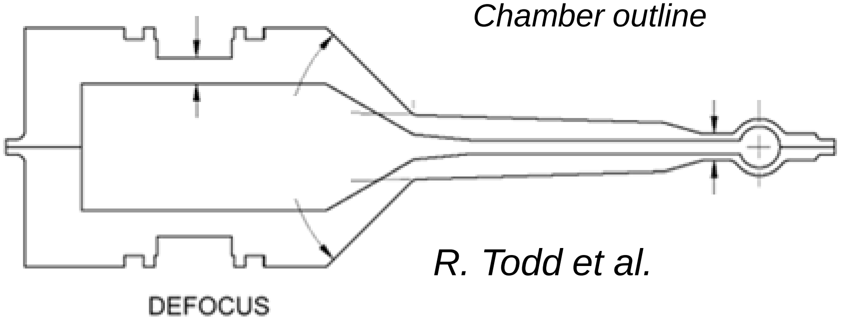
3-point mounting scheme independent of PMQ assemblies

Vacuum chamber design

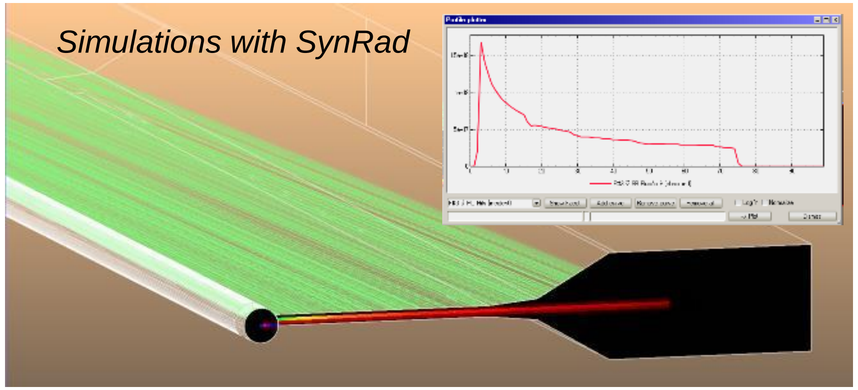
- 2 m long prototype vacuum chamber
  - G1/001 – simple straight extrusion of chamber
- Impedance
  - Resistive wall heating is acceptably low, 13 W/m (assuming 3mm bunch length)
  - Power loss from geometric impedance is negligible (<1 W/m) resonance peaks occur at > 15 GHz
- Simulations of synchrotron radiation with SynRad
  - After applying relevant feature information, power and flux from beam can be charted/plotted. Relevant for desorption and power mapping.
  - This information can be exported to MolFlow for use in vacuum simulations.
- Structural analysis demonstrated robustness against deformations

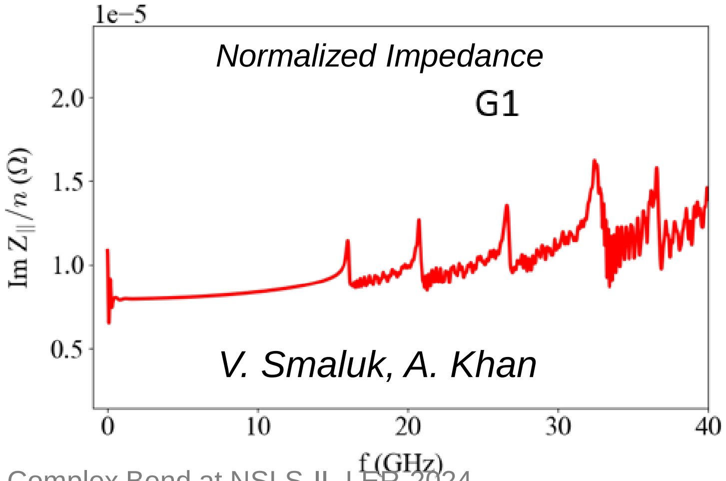

Structural analysis

Chamber outline



R. Todd et al.

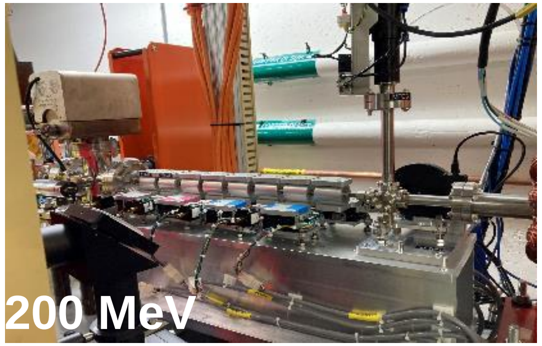

Simulations with SynRad


Normalized Impedance

V. Smaluk, A. Khan

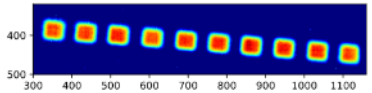
Tests of the concept at NSLS-II

- We have organized tests in three steps
- Low-energy beam studies
  - 8 compact PMQs with +/-100 T/m have been installed on the 200 MeV NSLS-II linac
  - Last year we commissioned the string of 8 PMQs and demonstrated high quality of the magnetic field in the Complex Bend set-up
  - We achieved focused beam size (X/Y) of 60/120 *u*m at 168 MeV and 50/110 *u*m at 200 MeV
- We are building a 1.5 m long CB element with 5 PMQs at +/-130 T/m with the total angle of 6°
  - The magnets, supports and vacuum chambers are arriving in March-June
  - High precision magnetic measurement and alignment set-up has been developed
- If funded, we will build two CB elements
  - Install them into NSLS-II tunnel replacing two DBA dipoles
  - Will run the ring with CBs in regular operations

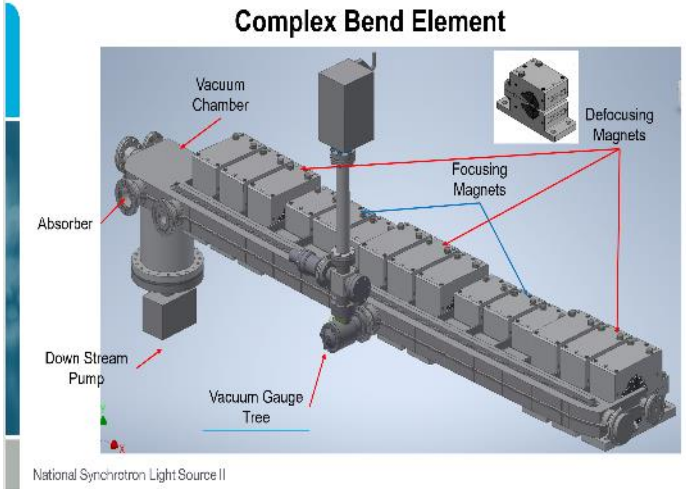


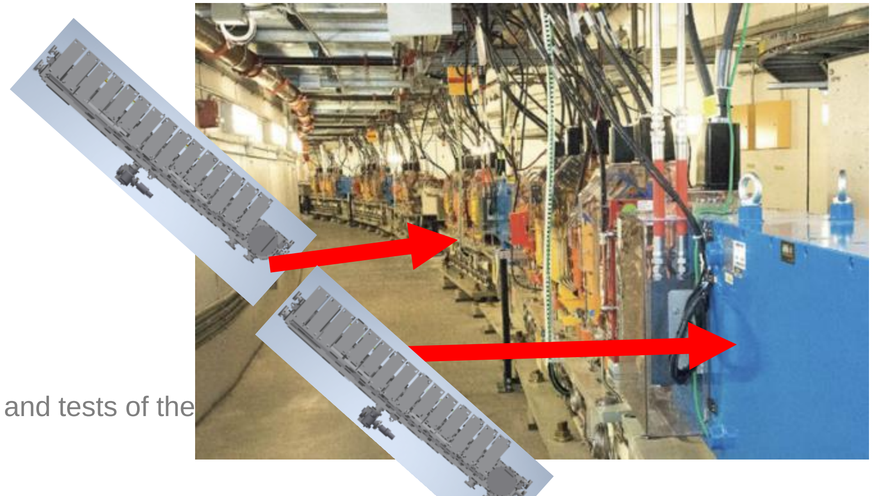
Four periods of CB in the linac tunnel

Collated beam images after passing through CB element



G. Wang et al.





Conclusions: advances presented by the Complex Bend approach

Design goals for the upgrade lattice

A. High brightness (low emittance)

B. Long straight sections (long undulators + tandem undulators)

C. Low power consumption (low operating cost)

Solution

- Replace long dipole electro-magnets with permanent magnet combined-function elements combined into a single curved strong-focusing assembly = Complex Bend

Using 120 Complex Bends in NSLS-IIU leads to the following benefits:

A. Ultra-low emittance of 23 pm rad at 3 GeV (best in class)

B. Straight sections of 8.8 m (longest among other light sources)

C. Power consumption for the ring magnets 17% of that for today’s NSLS-II lattice

NSLS-II colleagues and collaborators

V. Smaluk, Y. Li, G. Wang, M. Song, F. Plassard, A. Khan, Y. Hidaka, X. Yang, G. Bassi, D. Hidas, J. Choi,

S. Sharma, S. Brooks (CAD), P. N’gotta, L. Doom, O. Chubar, B. Parker (ATRO),

R. Todd, M. Seegitz, B. Kosciuk, P. Palecek, M. Ferreira (ESS)