Source Properties of a Potential MBA Lattice at the APS

Glenn Decker for the APS Upgrade Team*

October 21, 2013

Advance Photon Source
Argonne National Laboratory

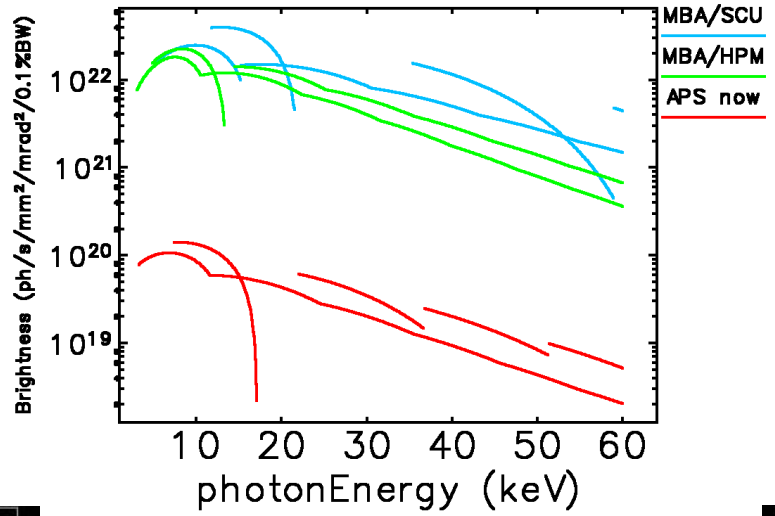
*Special thanks to Michael Borland, ASD

Outline

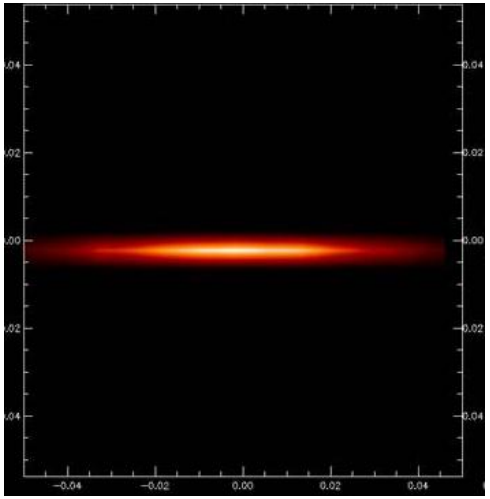
- Goal of multi-bend achromat (MBA) upgrade
- Background
- APS upgrade to a 4th-generation source
  - Parameters
  - Performance
  - Conceptual implementation
- Summary

Primary Goal

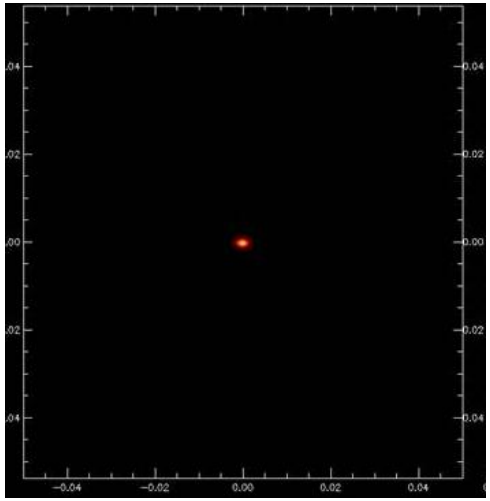
Dramatically enhance the performance of the APS as a hard x-ray source



APS Now



MBA



Particle Beam Profiles

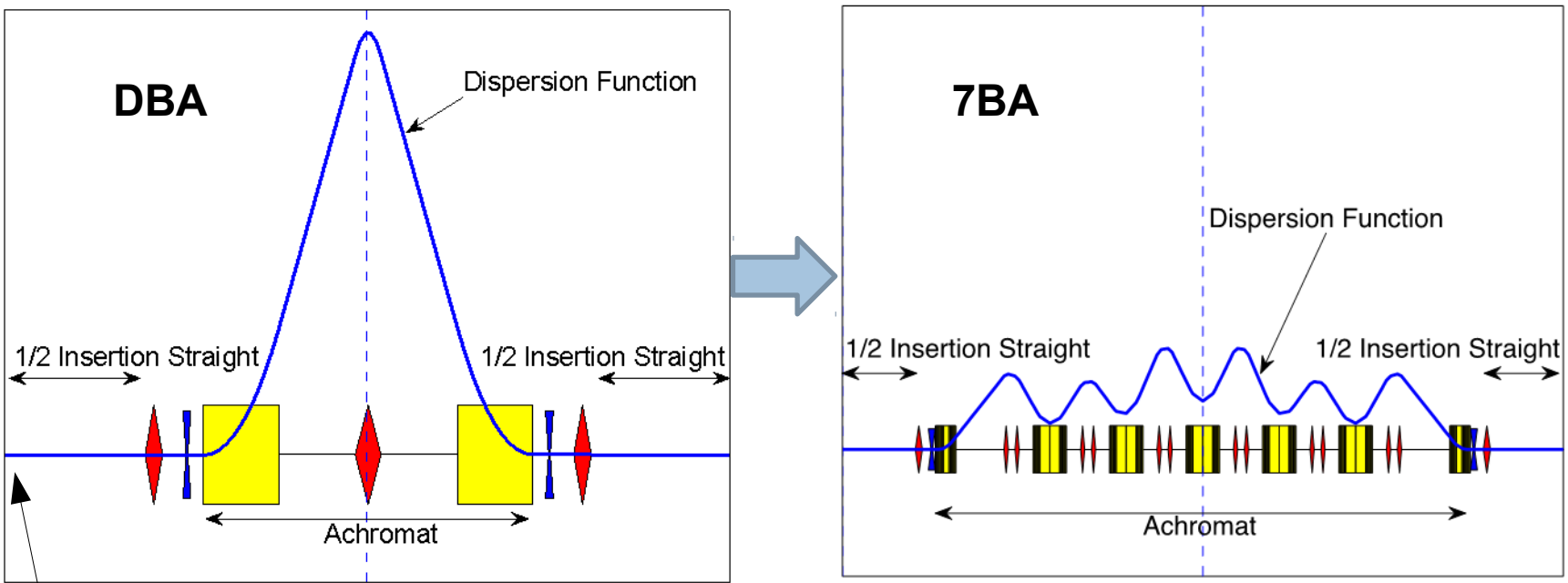
*Courtesy Lahsen Assoufid, APS-XSD

1 mm

Background

- Significant advances in accelerator modeling over the past 5 years have generated considerable interest in Ultimate Storage Rings.
  - APS has played a significant role in this process, in particular as the home of the ELEGANT suite of simulation tools.
- A number of workshops have focused on this exciting prospect:
  - The ICFA future light source workshop series http://www.aps.anl.gov/asd/ICFA/ICFA-FLS.html
  - USR2012, http://usr2012.ihep.ac.cn
- Implementation of this concept is under way at other labs:
  - MAX-IV (Sweden)
  - Sirius (Brazil)
  - ESRF, SPring-8 have initiatives

Lattice design evolution from double-bend achromats (DBA) to multi-bend achromats



D. Einfeld *et al.*, Proc. PAC 95, Dallas TX

ID Source Point

$$\varepsilon_x = C_L \frac{E^2}{N_D^3}, \quad \varepsilon_x \underbrace{\propto}_{\text{Fixed E}} \frac{1}{C^3}$$

C_L = lattice constant

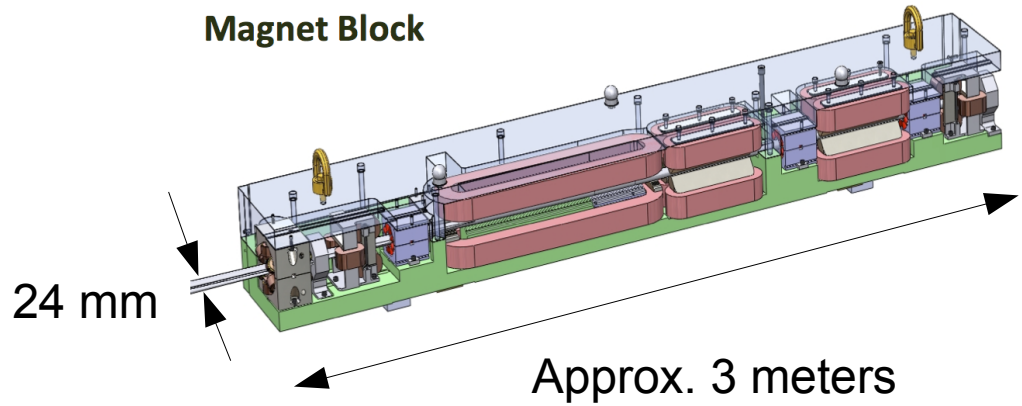
N_D = # dipoles

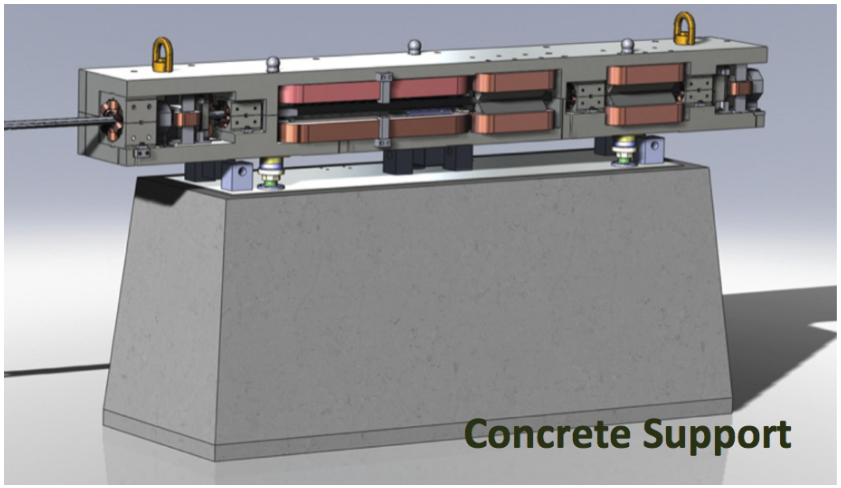
C = Circumference

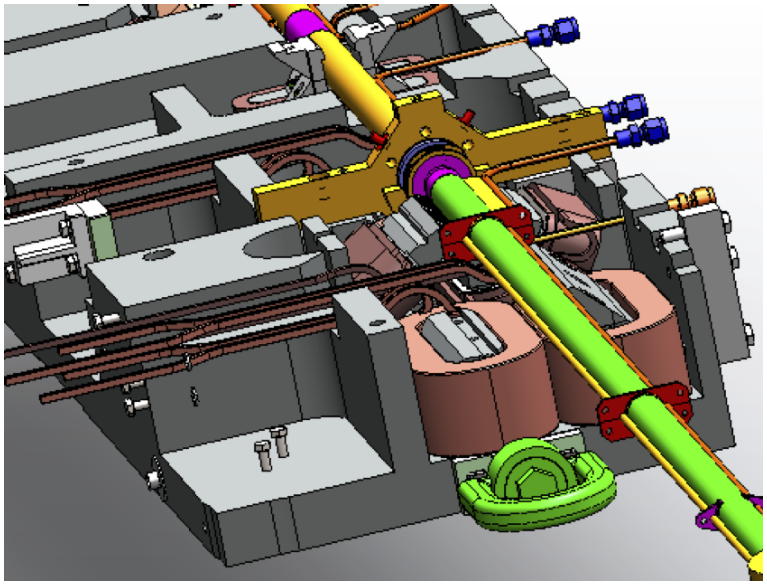
Factor of > 40 improvement in emittance from cubic scaling

MAX-IV (Sweden) 7BA Magnet / Vacuum Design

- 3 GeV, 528-m circumference, ε_0=330 pm
- Innovative, cost-effective construction of multiple magnets with a shared iron yoke
- 26-mm magnet bore diameter allows strong fields in magnets
- NEG-pumped round chamber in arcs allows small magnet bores
- Commissioning in early 2015

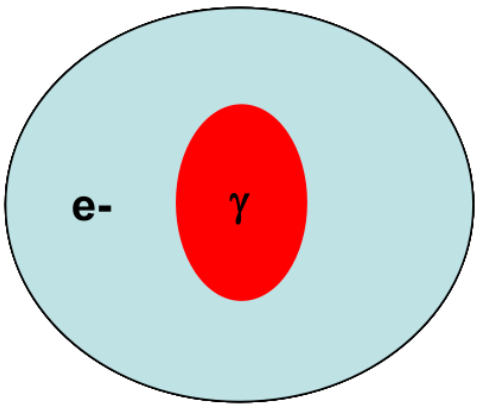




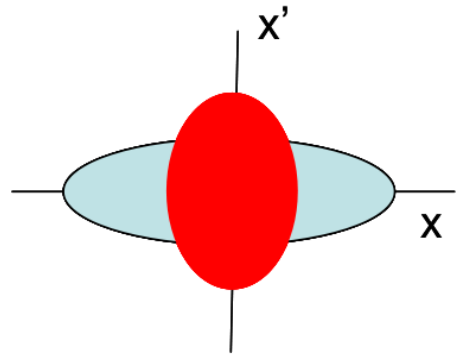


Figures courtesy S. Leemann, MAX-Lab.

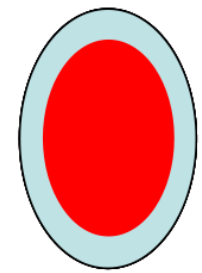
Electron-photon phase space matching:



high electron emittance

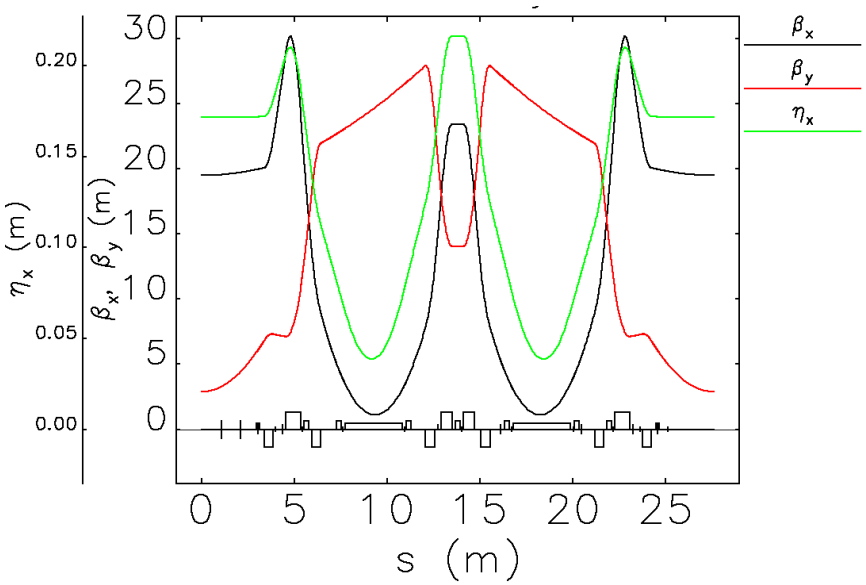


low electron emittance, mismatched

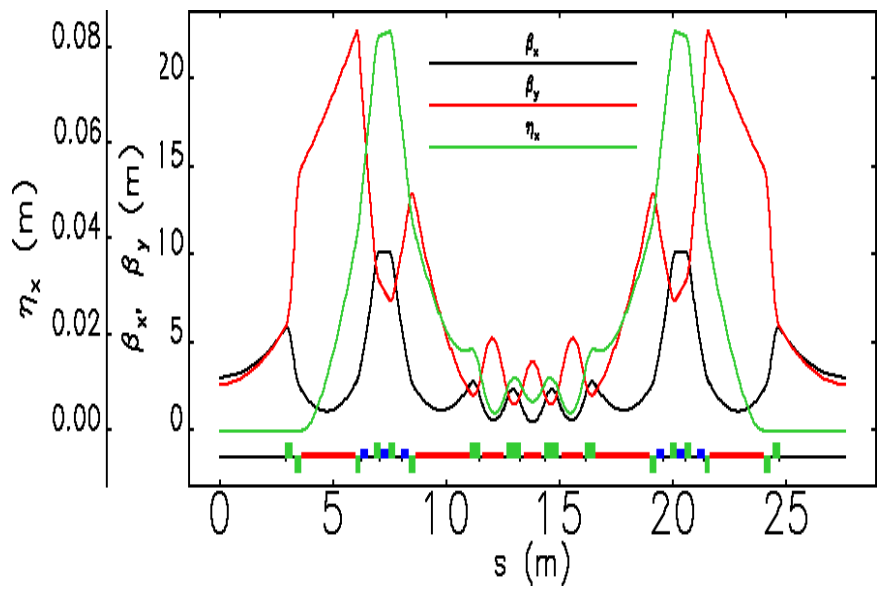


low electron emittance, matched *

APS Now



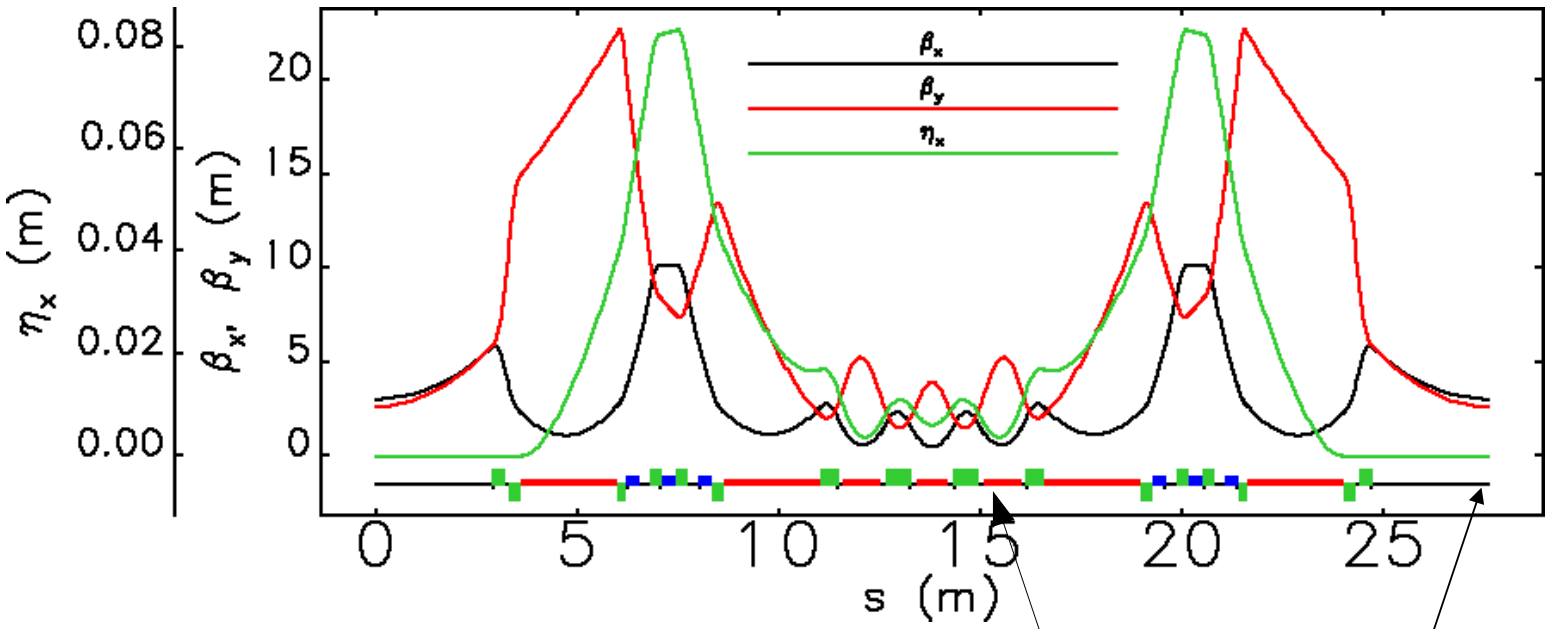
MBA



*Courtesy R. Hettel, SSRL

Hybrid 7-Bend Achromat APS Lattice Concept

Emittance ε of 60 - 80 pm at 6 GeV



Electron beam size $\sigma^2 = \beta\,\varepsilon$

Angular Divergence $\sigma'^2 = \varepsilon / \beta$

Insertion Device Source Point

Bending Magnet Source Point

Original lattice concept from ESRF.
L. Farvacque *et al.*, Proc. IPAC13, 79 (2013).

Preliminary APS MBA Parameters

- Preliminary parameters for a possible APS MBA lattice

Quantity	Symbol	APS	MBA	MBA	Units
Beam energy	E	7	6	6	GeV
Effective emittance	ϵ_0	3100	60	60	pm
Number of Bunches	N_b	24	48	324	
Emittance ratio	$\kappa = \epsilon_y/\epsilon_x$	0.016	1.0	0.1	
Horizontal emittance	ϵ_x	2500	30	60	pm
Vertical emittance	ϵ_y	40	30	6	pm
Rms energy spread	σ_δ	0.1	0.1	0.1	%

Note that intrabeam scattering has been ignored

Preliminary APS MBA Fill Patterns

- Total beam current is expected to be 200 mA
- Fill patterns with 48 to 324 bunches will be possible
- Various timing patterns should be possible with up to 4.2 mA/bunch

Total current	I	200	200	mA
Number of bunches	N_b	48	324	
Bunch current	I_b	4.2	0.6	mA
Bunch rate	f_b	13	88	MHz
Rms bunch duration	σ_t	70	18	ps

Preliminary APS MBA ID Source Parameters

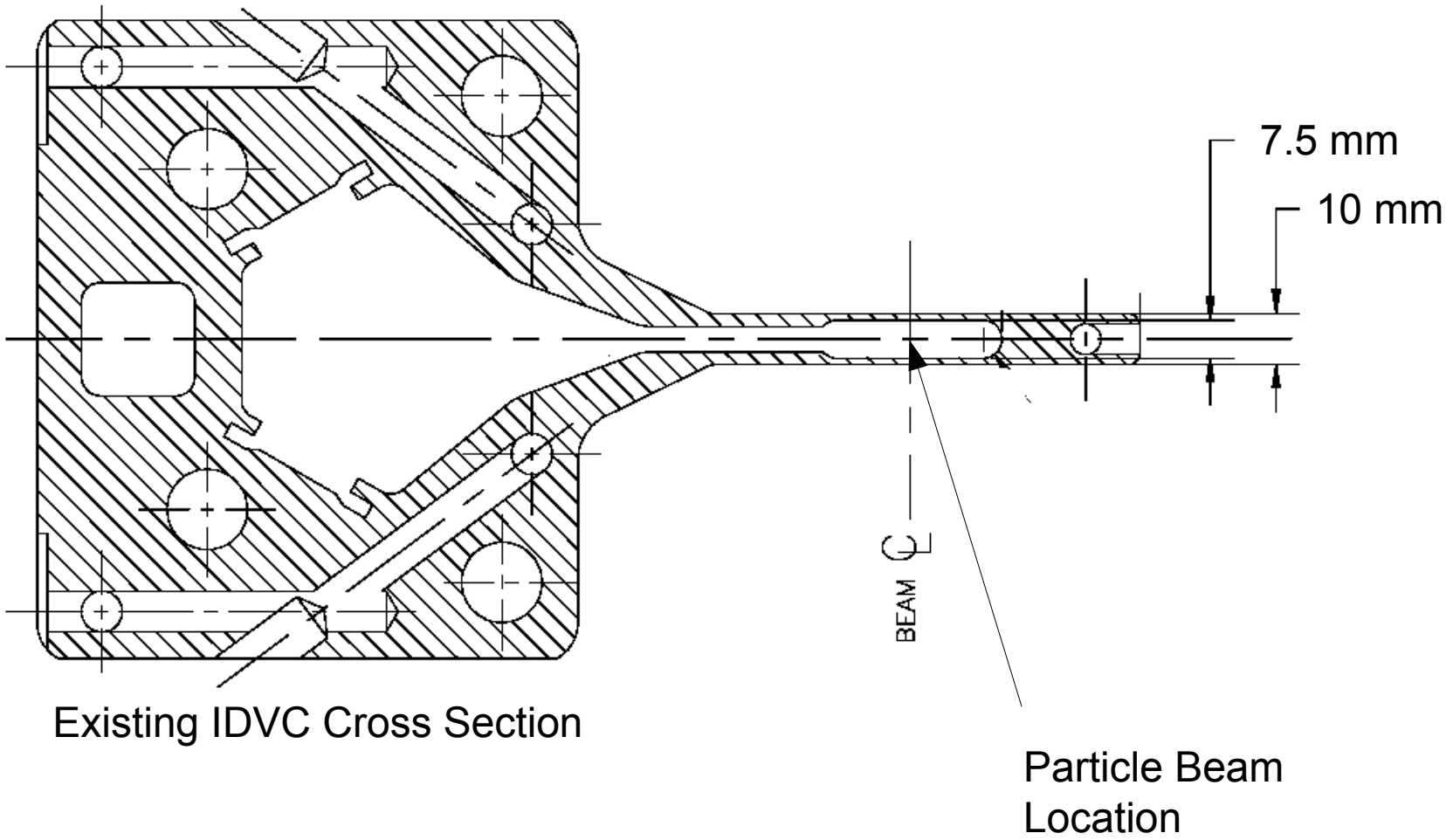
- Beam sizes and divergences will be small in both planes

Quantity	Symbol	MBA Range	Present-day	Units
Horizontal beta function	β_x	1-4	19.5	m
Horizontal dispersion function	η_x	< 3	170	mm
Horizontal beam size	σ_x	5 - 19	275	μm
Horizontal beam divergence	$\sigma_{x'}$	3 - 10	11	μrad
Horizontal size-divergence product	$\sigma_x \sigma_{x'}$	30 - 91	3100	pm
Vertical beta function	β_y	1-4	2.9	m
Vertical dispersion function	η_y	0	0	mm
Vertical beam size	σ_y	2 - 13	10	μm
Vertical beam divergence	$\sigma_{y'}$	1 - 6	3.5	μrad
Vertical size-divergence product	$\sigma_y \sigma_{y'}$	5 - 40	35	pm

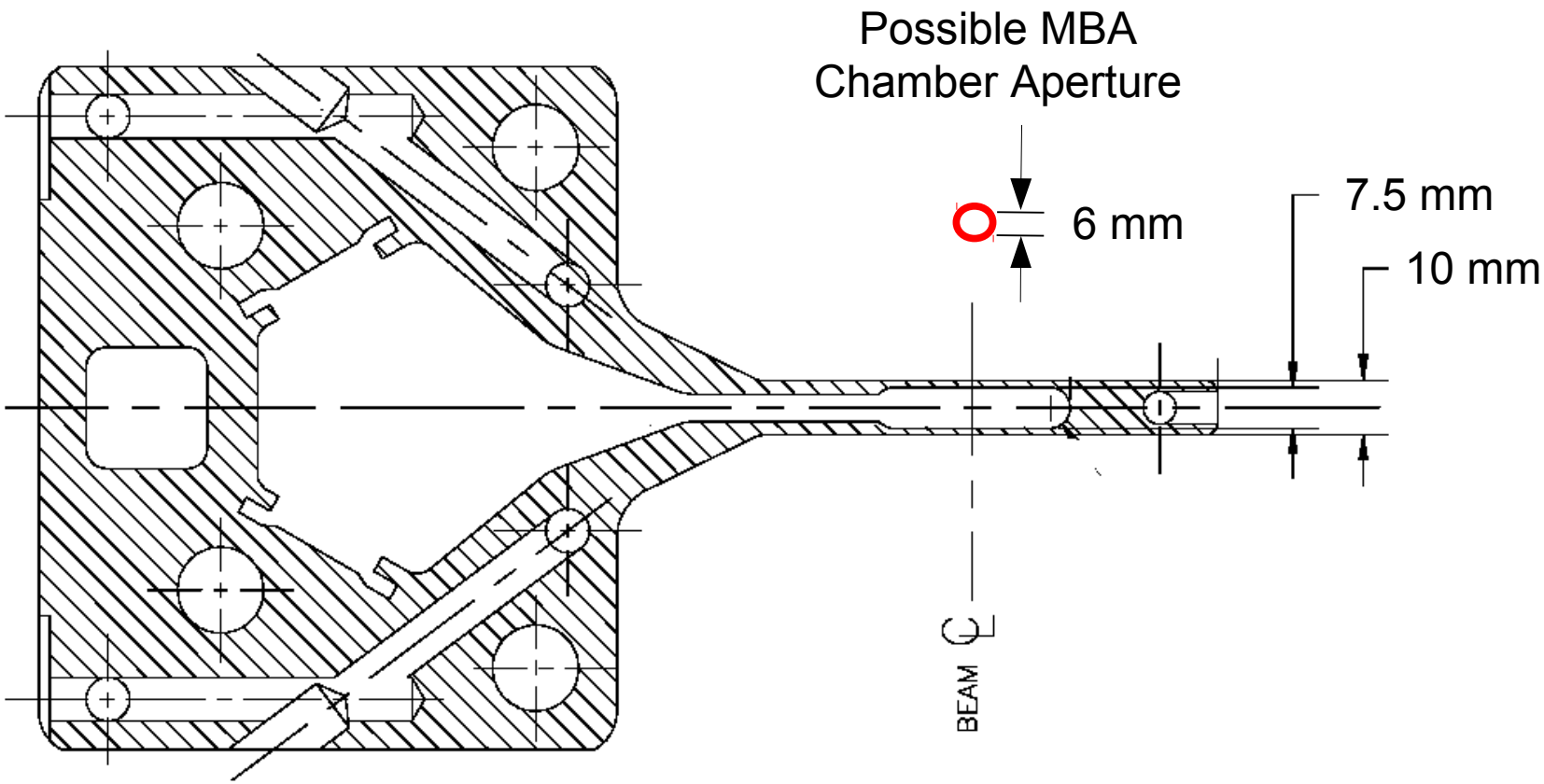
Preliminary APS MBA ID Parameters

- MBA will permit
  - Vertically polarized undulators (small horizontal gap)
  - Helical devices at a few locations
- ID gaps can be significantly smaller than in the present machine
  - More than compensates for decrease of beam energy
  - Note that ID field increases exponentially with gap
  - Undulator length up to 4.8 meters, same as present APS

Insertion Device Vacuum Chambers



Insertion Device Vacuum Chambers

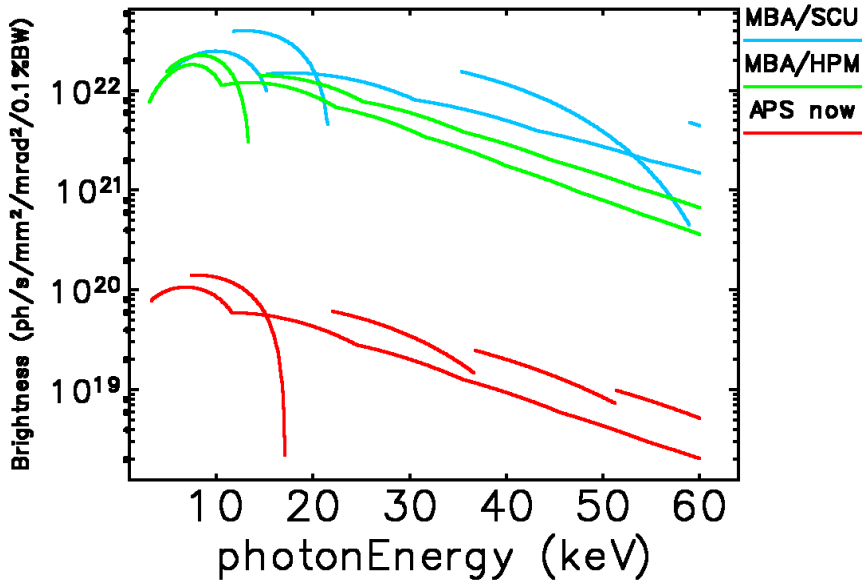


Existing IDVC Cross Section

Performance

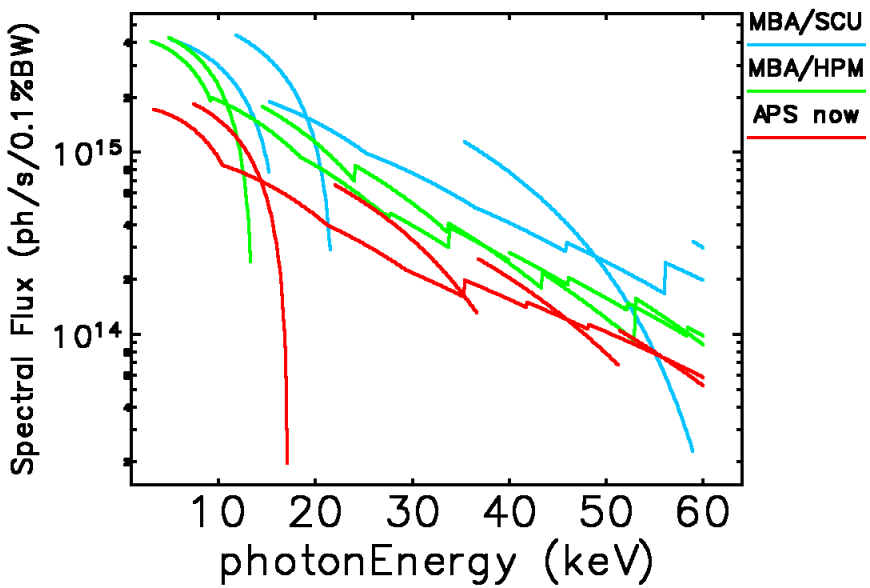
- Measures of performance
  - Average brightness
  - Average flux
  - Brightness per pulse
  - Flux per pulse
- Opportunity exists with new lattice designs to provide
  - Much higher brightness
  - Higher flux
  - Significantly improved timing characteristics

Examples of Preliminary Expected Performance



Brightness increases of 100x or more compared to the brightest devices in APS today

Biggest increases for hard x-rays

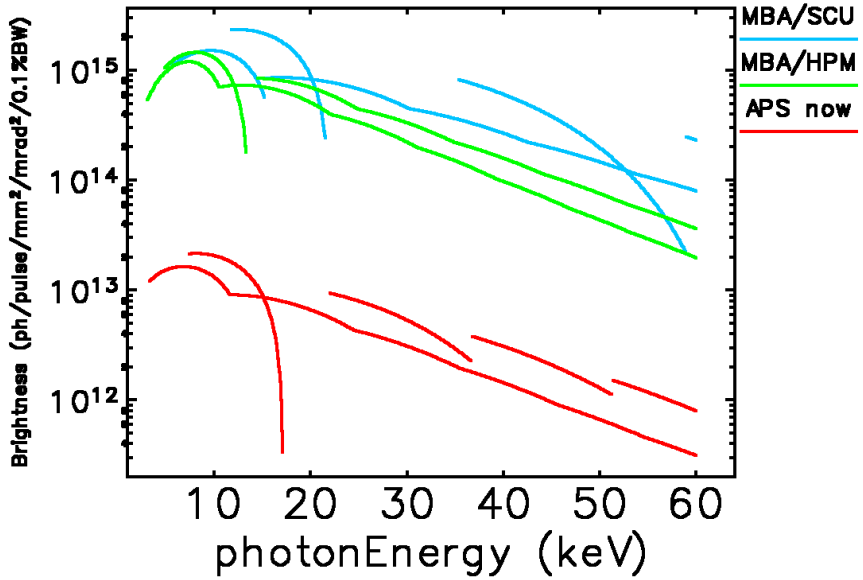


Flux increases of about a factor of two or more

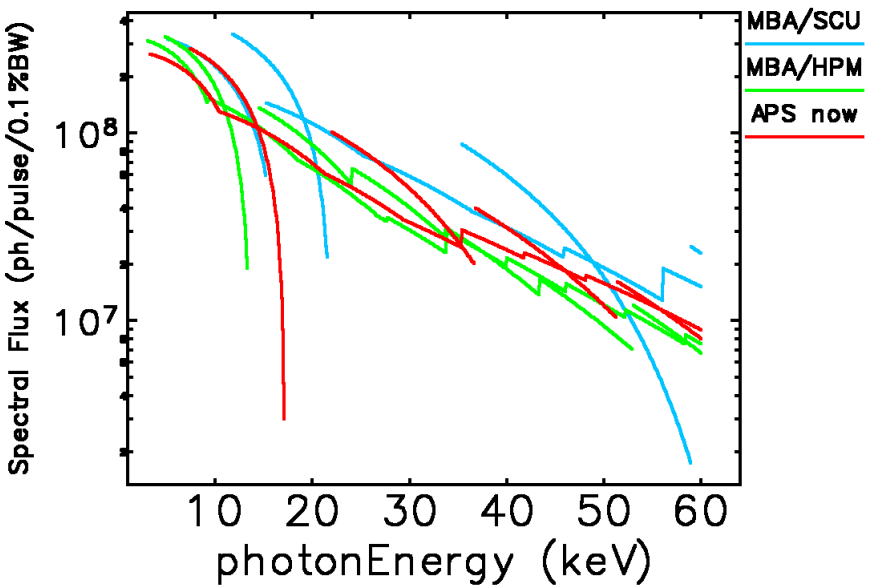
APS now: existing 4.8-m U27 and U33 at 100 mA
MBA curves based on latest 60-pm lattice, 200 mA
MBA/HPM: 8.5-mm-gap,4.8-m-long HPMs.
MBA/SCU: 8.5-mm-gap, 3.7-m-long NbTi SCUs.

Plots courtesy of M. Borland, V. Sajaev

Examples of Preliminary Expected Timing Performance



Brightness per pulse increases by 100x or more, with larger gains for harder x-rays



Flux per pulse comparable to or better than present-day APS

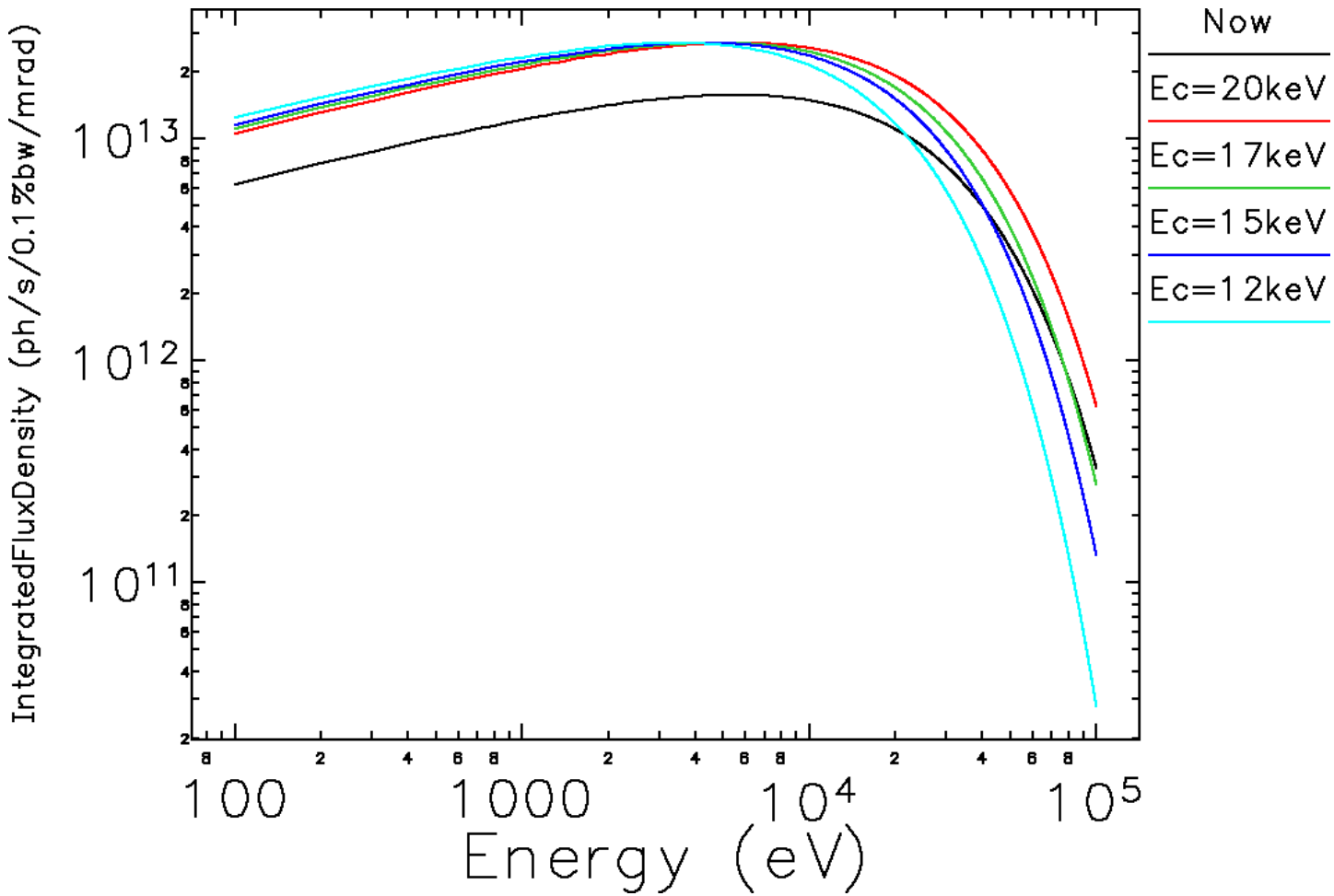
APS now: existing 4.8-m U27 and U33 at 100 mA
MBA curves based on latest 60-pm lattice, 200 mA
MBA/HPM: 8.5-mm-gap,4.8-m-long HPMs.
MBA/SCU: 8.5-mm-gap, 3.7-m-long NbTi SCUs.

Preliminary APS MBA Dipole Source Parameters

- Initial emphasis has been on high brightness for ID beamlines
- Goal is to retain all dipole beamlines with comparable performance to present day: 15 – 20 keV critical energy, 5 mrad fan.
- Source dimensions are approximately as follows:

	Symbol	APS Now	MBA 10% Coupling	MBA Full Coupling	Units
Number of Bunches	N_b	24	324	48	
Horizontal Emittance	ϵ_x	2500	60	30	pm
Vertical Emittance	ϵ_y	40	6	30	pm
Horizontal Beam Size	σ_x	85	12	10	μm
Horizontal Divergence	σ'_x	56	21	18	μrad
Vertical Beam Size	σ_x	34	4.5	10	μm
Vertical Divergence	σ'_x	1.5	4.5	10	μrad

Bending Magnet Performance

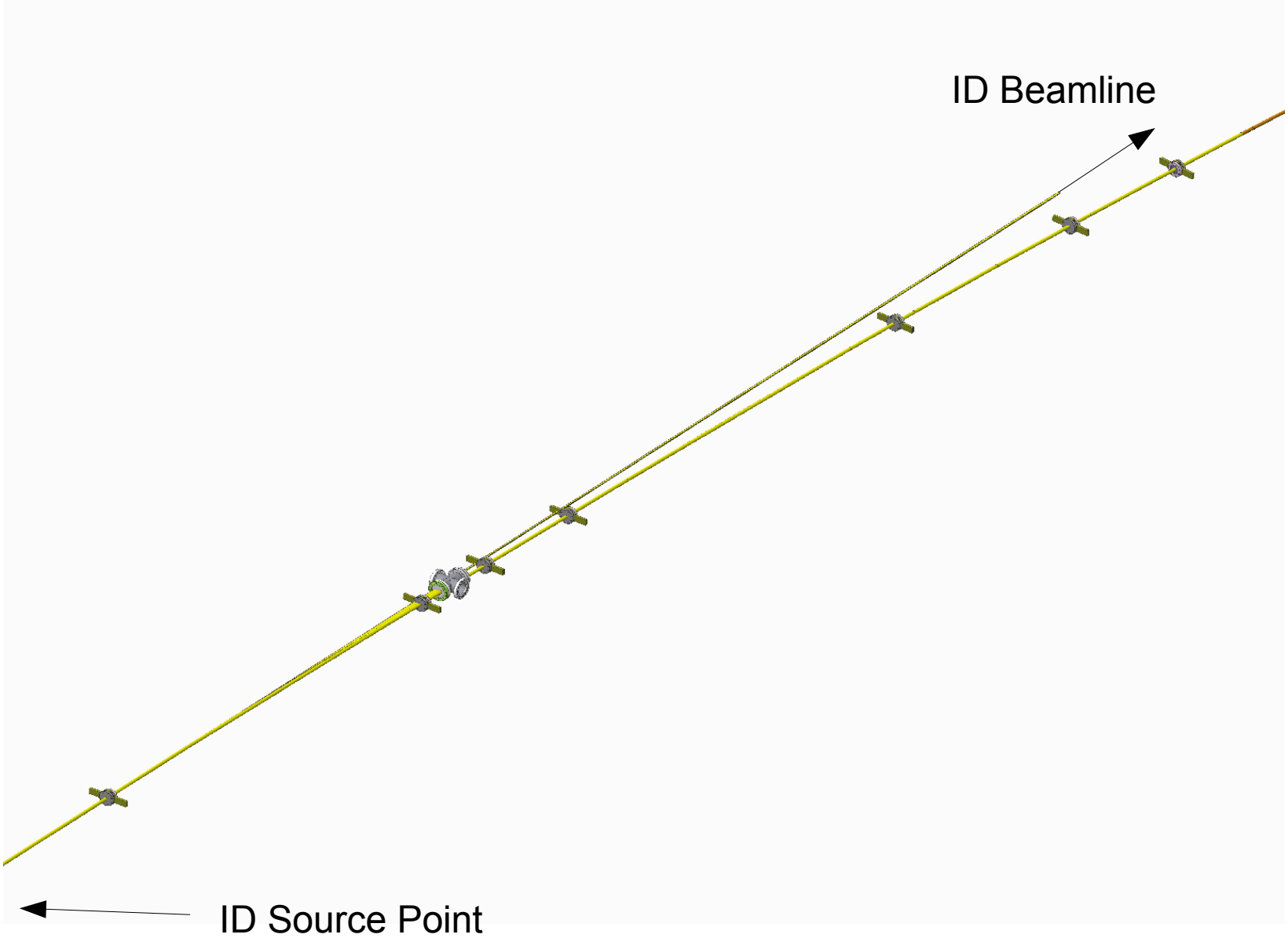


A critical energy of 17 keV matches or beats present performance over a wide range of photon energies

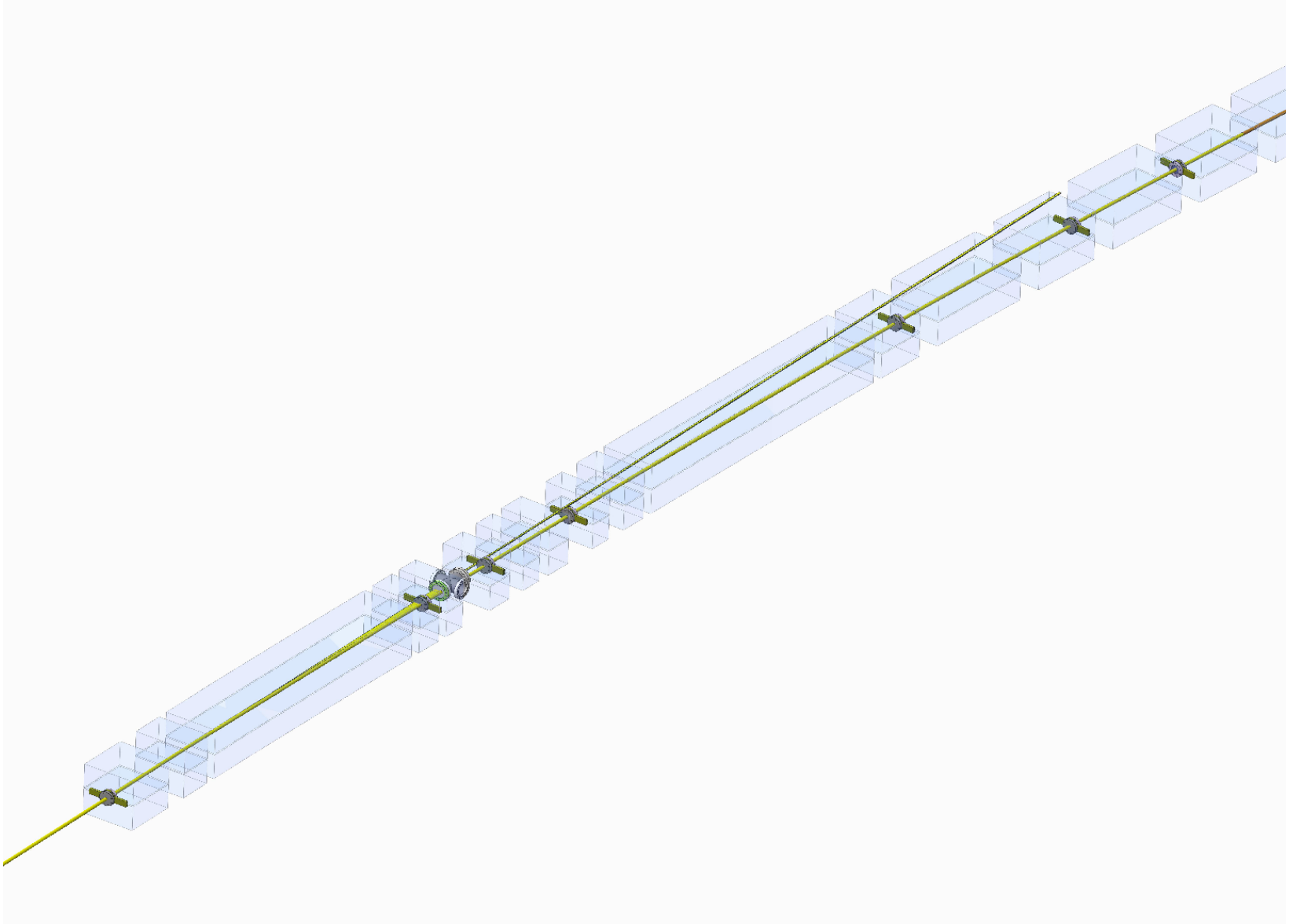
Accelerator Implementation

- High-Level specifications have been captured in a working assumptions document (50 pages and growing).
- Magnet, vacuum, and support structure system design is picking up speed in a closely-integrated fashion.
- Working groups have been established in the areas of magnets, vacuum, support structures, power supplies, fast injection kickers, controls, and diagnostics, meeting on a weekly basis.
- In addition, system engineering, mechanical systems integration, electrical systems integration, decommissioning, installation, supply chain management, and infrastructure are also addressed at a high level on a weekly basis.

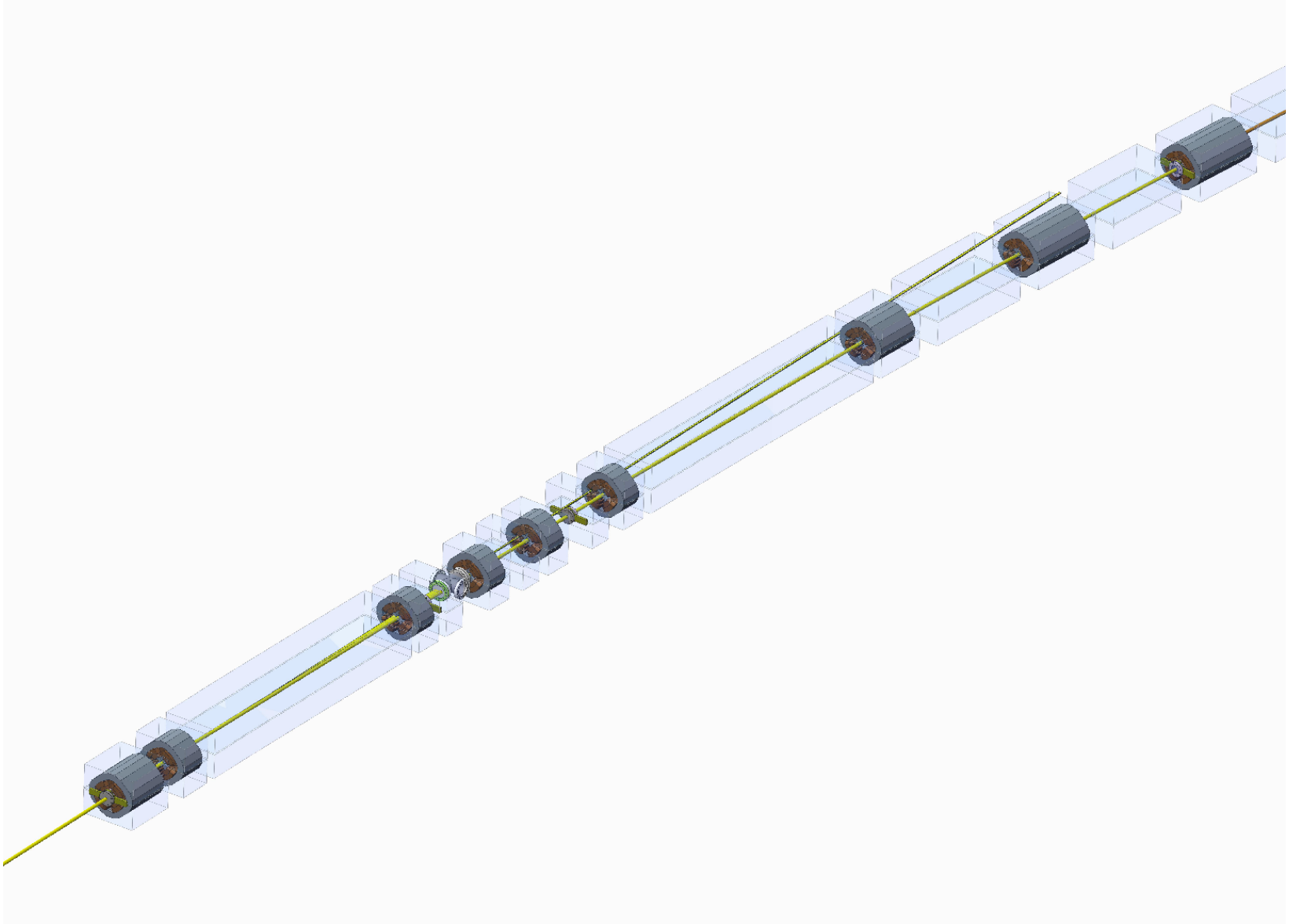
APS MBA Design Development



APS MBA Design Development

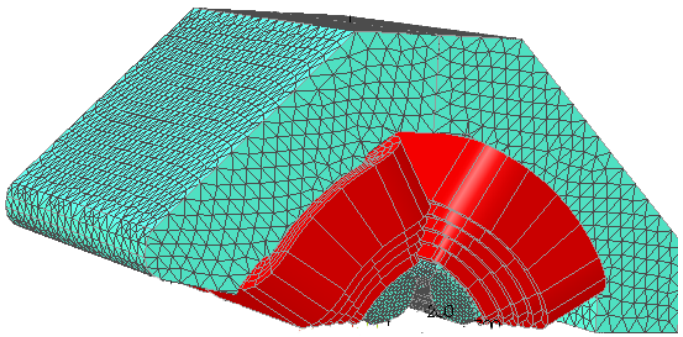


APS MBA Design Development

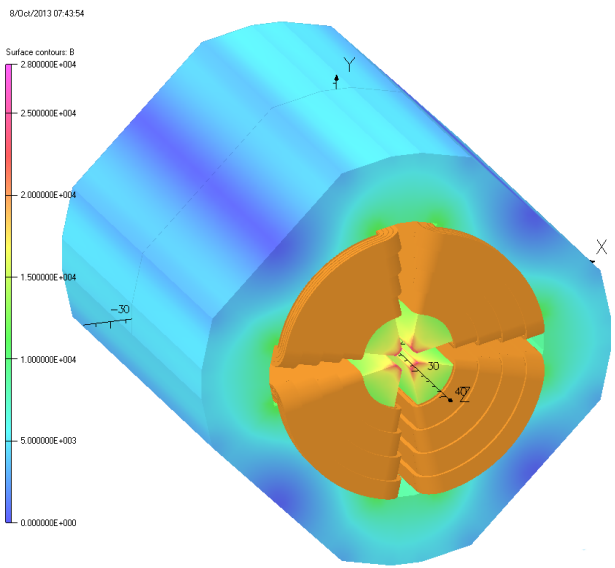


APS-U Magnet Counts and Concepts

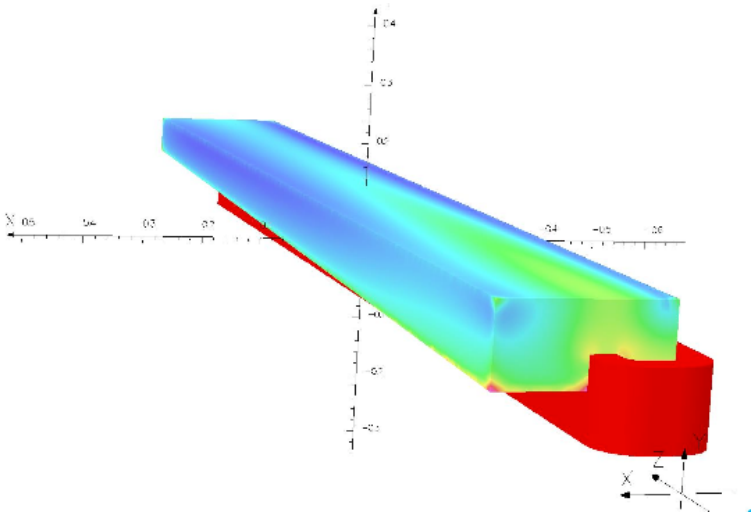
- Magnets
  - Long. Grad. dipoles 160
  - Trans. Grad. dipoles 120
  - Quadrupoles 640
  - Sextupoles
  - Fast correctors 160



Transverse-gradient dipole



Quadrupole



Longitudinal-gradient dipole

Proposed R&D Activities

- Development activities will focus on the following areas:
  - Magnet prototyping of longitudinal-gradient dipole and integrated straight multiplets (quadrupoles + sextupoles).
  - Mechanical alignment and vibration studies of integrated magnet / girder assemblies
  - Advanced power supply regulation and control
    - 3 ppm stability initial target
  - Investigation of advanced vacuum methodologies
    - NEG coatings for distributed pumping
    - Low-impedance vacuum joints and bellows
    - Achieving mechanical stability (especially for BPMs) under changing thermal loads
  - Diagnostics and Controls
    - Beam stability
    - Synchronization and timing
    - Data acquisition

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https://apsshare.aps.anl.gov/apsu/MBAWorkingGroup/Pages/Home.aspx

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Site Actions

Decker, Glenn

Argonne NATIONAL LABORATORY

Advanced Photon Source Upgrade Project

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I Like It Tags & Notes

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This Site: MBA Working G

- Home
- Libraries
  - Shared Documents
- Lists
  - Links
  - Tasks
- Pictures

General References

- Working » Main Assumptions Document | Lattice File
- MBA Beam Physics » NGSR Wiki | Beam Physics Tolerances
- MBA Contacts and Meetings
- Assumptions Meetings
- Cost Basis (restricted)
- Other Similar Storage Rings
- APS References and Photos

Decommissioning | Chuck Prokuski

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Magnets | Mark Jaski

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Magnet Power Supply | Ju Wang

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Diagnostics | Bob Lill

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Beamline Related

- Insertion Devices
- Front Ends
- Beamlines

System Integration and Engineering

- Tom Fornek (mechanical) | John Carwardine (electrical) | Nancy Grossman
- Interface Control Documents
- Recent Presentations and Meeting Notes
- Internal Documents (restricted)
- Infrastructure » Space Planning | Utilities
- Supply Chain | Mechanical Support

Installation | Tom Fornek

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Vacuum | Herman Cease

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Controls | Richard Farnsworth

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Fast Injection Kickers | Frank Lenkszus

- Specifications
- Recent Presentations and Meeting Notes
- References » Documents | Links

Injector

Links (local)

- USR Workshop on Accelerator R&D for Ultimate Storage Rings Oct 2012
- MBA Working Group SharePoint Page Full Set of Folders
- COMPARATIVE STUDY OF VIBRATION STABILITY AT OPERATING LIGHT SOURCE FACILITIES AND LESSONS LEARNED IN ACHIEVING NSLS II STABILITY GOALS
- Workshop on new science opportunities provided by a multi-bend achromat lattice at the APS Oct 21-22
- SharePoint Tips for Posting, Updating, Alerts, etc.
- NSLS II Workshop on Lessons Learned

Add new link

What's New (last 7 days)

- 10/17/2013 MBA_SECTOR_1_LAYOUTS_AND_RAYTRACES_131017.pdf
- 10/16/2013 MBA_TolerancesWG_10Oct2013.docx
- 10/16/2013 Magnet_Meeting_Notes.docx
- 10/16/2013 Monday 10-14-2013.pdf
- 10/15/2013 ElectricalSystemsIntegration_15Oct2013.pptx
- 10/15/2013 Electrical Integration meeting notes.docx
- 10/14/2013 APS MBA Storage Ring Working Assumptions and Parameter List.pdf
- 10/14/2013 MBA_SECTOR_1_LAYOUTS_131014.pdf
- 10/11/2013 Panofsky cartoon.pdf
- 10/11/2013 Magnet Electrical Vacuum Meeting Notes.docx
- 10/11/2013 MBA Magnets_review_20131011.pptx
- 10/11/2013 Update on transv grad dipole magnet 10-11-13.ppt
- 10/11/2013 Borland - 2013-08-26-MagnetMeeting.pdf
- 10/11/2013 BID Dipole Magnet_Kashikhin_092013a.pdf
- 10/11/2013 MBA_SECTOR_1_LAYOUT_131011.pdf
- 10/11/2013 mba_vc_section1_131003.jpg
- 10/11/2013 APS 1kHz Dipole Magnet_101113a.pdf
- 10/10/2013 Previous APSU PDR Preparation E-mail References PDR Instructions Files.pdf
- 10/10/2013 Previous APSU CDR AuthorInstructions.pdf
- 10/10/2013 Previous APSU PDR-TOC.pdf
- 10/10/2013 Previous APSU PDR AuthorInstructions.pdf
- 10/10/2013 Previous APSU PDR_Outline_Accelerator-V3.xls
- 10/10/2013 injector-study-summary-2013-10-09.pdf

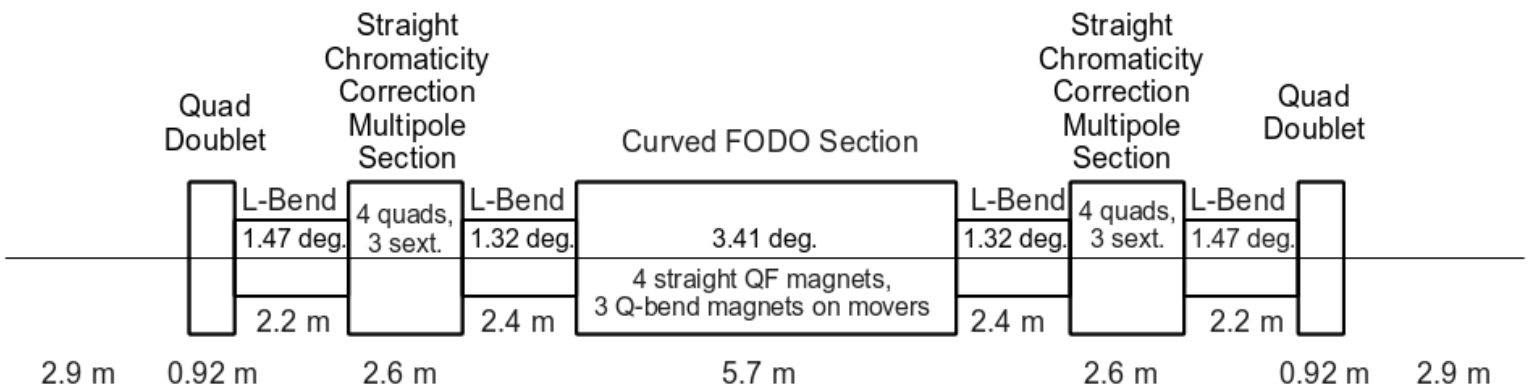
Summary

- Two orders of magnitude brightness increase appears feasible.
  - Will preserve 4 mA / bunch capability
  - Will support all existing beamlines including BM and canted ID.
- An aggressive effort is underway to develop a design optimized for use at the APS
  - A significant design effort for magnets, vacuum, power supplies, beam stability and several other areas is underway.
  - The accelerator design teams are in place, have already made great progress, and are highly motivated by this new opportunity.
- MBA@APS is the next generation for storage-ring-based synchrotron light sources, and we are ready to build it.

Backup Material

APS MBA Lattice Implementation Concept

H7BA-TwoSector-60pm-nux105-nuy34 - M. Borland



	APS Now	APS-MBA
Dipoles	80	280
Quadrupoles	400	640
Sextupoles	280	240
Fast Correctors	80 H + 80 V	160 H + 160 V
Skew Quad Correctors	20	240
Slow Correctors	240 H + 240 V	760 H + 760 V
Total	1420	3240

X-ray Brightness

- An important quality of a beam is expressed by the brightness

$$B \propto \frac{N_\gamma}{(\Delta\lambda/\lambda)\Delta t \underbrace{\Sigma_x \Sigma_{x'}}_{\text{Horizontal size*divergence}} \underbrace{\Sigma_y \Sigma_{y'}}_{\text{Vertical size*divergence}}} \qquad \text{(simplification)}$$

- Maximizing brightness entails minimizing the denominator, i.e., minimizing the photon beam sizes and divergences
- Ideally, for the electron beam we want “diffraction-limited” emittances and matched beta functions

$$\epsilon_{x,y} \leq \frac{\lambda}{4\pi} \qquad \beta_{x,y} \approx \frac{L_u}{\pi}$$

How Close are We Now to the Diffraction Limit?

- For an undulator filling a typical 5-m-long straight, ideal beta function is

$$\beta_r = 1.6\mathrm{m}$$

  which is feasible, though not always easy.
- Emittance is another matter

$$\begin{array}{lcl} \epsilon_q[pm] & \lesssim & \frac{100}{E_p[keV]} \\ \epsilon_q[pm] & \lesssim & 8\lambda[\mathring{A}] \end{array} \Rightarrow \begin{array}{lcl} 1\ \mathrm{keV} & \rightarrow & \epsilon_q \lesssim 100\ \mathrm{pm} \\ 10\ \mathrm{keV} & \rightarrow & \epsilon_q \lesssim 10\ \mathrm{pm} \end{array}$$

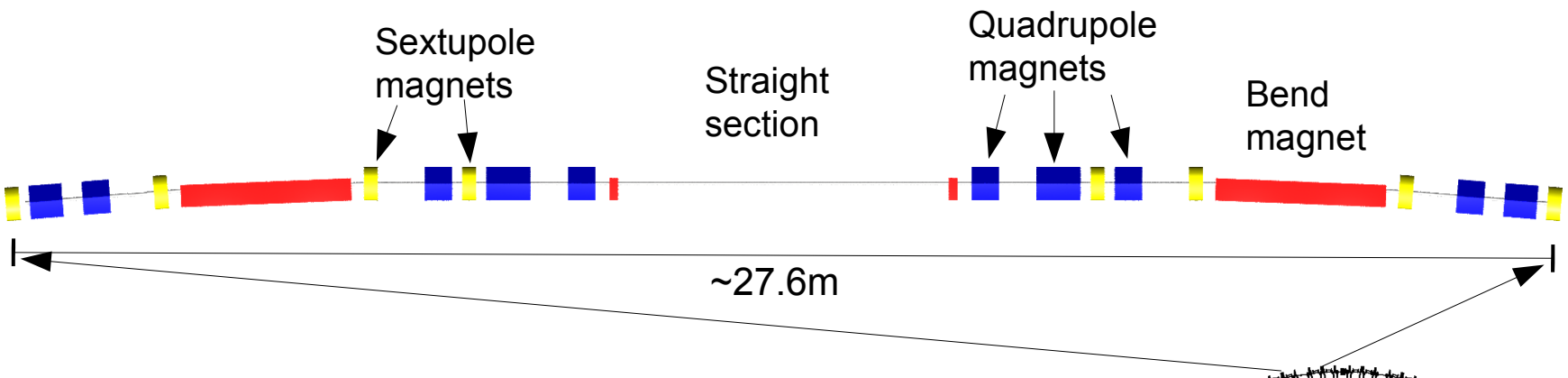
- For typical 3rd-generation rings

$$\epsilon_x : [1, 5]\mathrm{nm} \qquad \epsilon_y : [1, 40]\mathrm{pm}$$

- <u>Next-generation rings should bring horizontal emittance below ~100 pm</u>

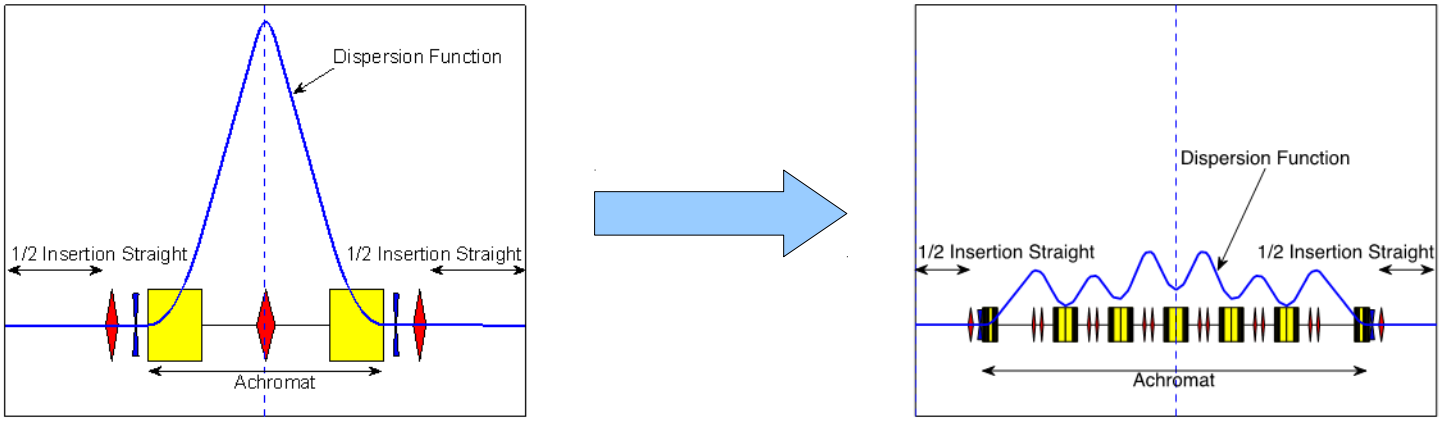
Contemporary Storage Ring Light Sources

- Conventional storage rings (e.g., APS) typically have double-bend configuration



- Bends: force the beam into a closed path
- Quadrupoles: provide focusing
- Sextupoles: correct focusing aberrations
- Straight sections all-important
  - Typically 20-50, each 5-10 m long
  - Undulators/wigglers in most
  - Rf cavities, injection pulsed magnets

From Double- to Multi-Bend Achromats



All figures courtesy C. Steier, LBNL.

- Rings today have N_d=2 or (more rarely) 3
- Emittance scales like[1]

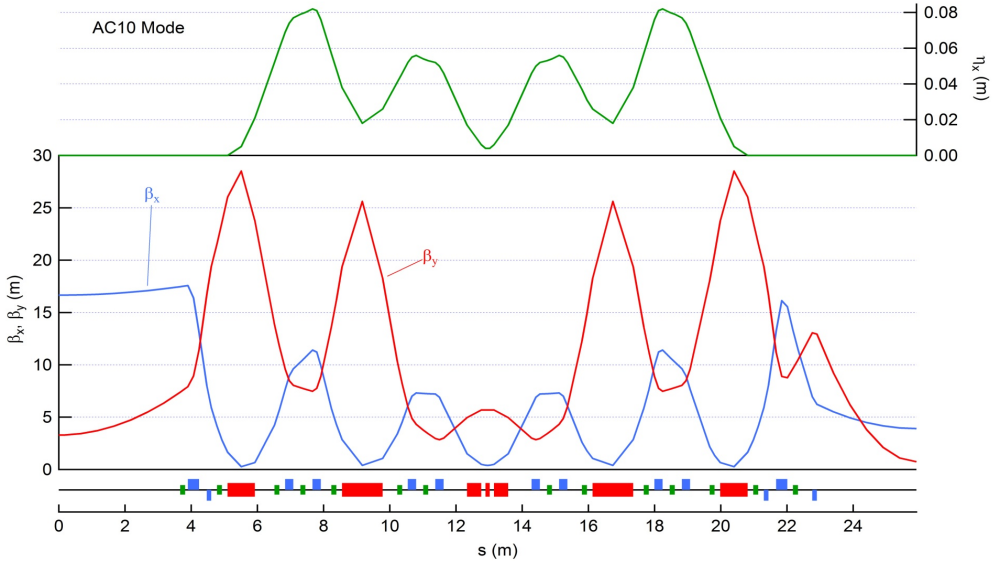
$$\epsilon_0 \sim \frac{E^2}{(N_d N_s)^3}$$

- Several groups proposed N_d>3 lattices in 1990s[2]
  - 7BA should have ~40x lower emittance than today's 2B(A) lattices
  - Promises much higher brightness and coherence over entire spectrum

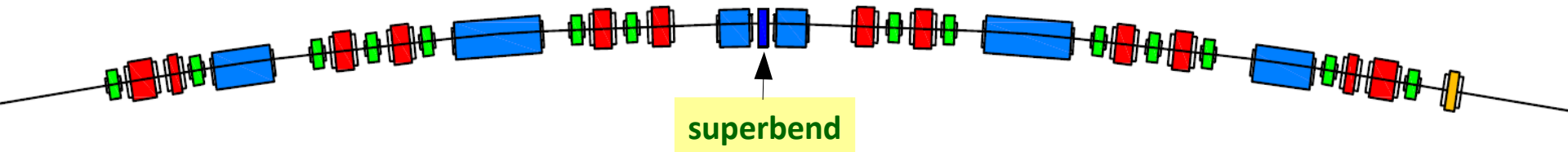
1: J. Murphy, Synchrotron Light Source Data Book, BNL 42333, 1989.
2: Einfeld *et al.*, NIM A 335, 1993; Joho *et al.*, EPAC 94; Einfeld *et al.*, PAC95; Kaltchev *et al.*, PAC95.

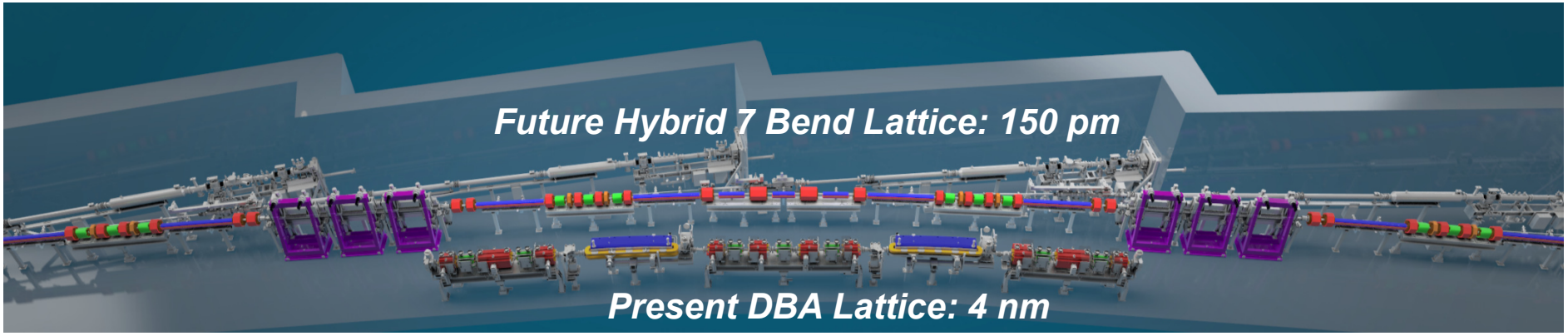
5BA SIRIUS Project (Brazil) Underway

- 3 GeV, 518-m circumference, ε_0=280 pm
- Ten 6-m and ten 7-m straights
- Alternating high/low beta functions
- 2-T superbend for 12-keV critical energy



All figures courtesy L. Liu, LNLS.





Thanks to the large expertise gained during ESRF UP phase 1 and the worldwide efforts to develop an Ultimate Storage Ring

ESRF Upgrade Phase II will be an excellent opportunity to:

- Drastically increase the brightness of our Light Source to maintain world-wide excellence for the next 1-2 decades
- Improve and expand the science reach of the SR-based light sources
- Enable new technologies
- Provide important know-how to continue the push for higher performances of the SR-based Light Sources