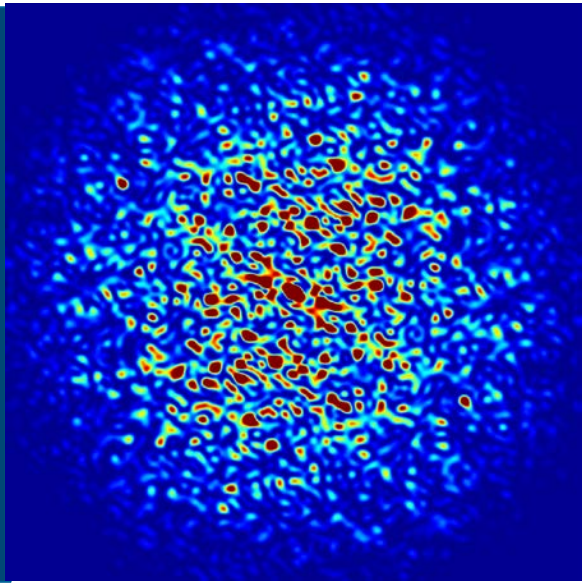
Status of the APS Upgrade Project



Robert Hettel
Director, APS Upgrade Project
Argonne National Laboratory

APS Users Organization/Partner User Council/All Hands Meeting

May 1, 2019

APS-U Project Scope

All existing beamlines incorporated in plans to come back online at conclusion of APS-U

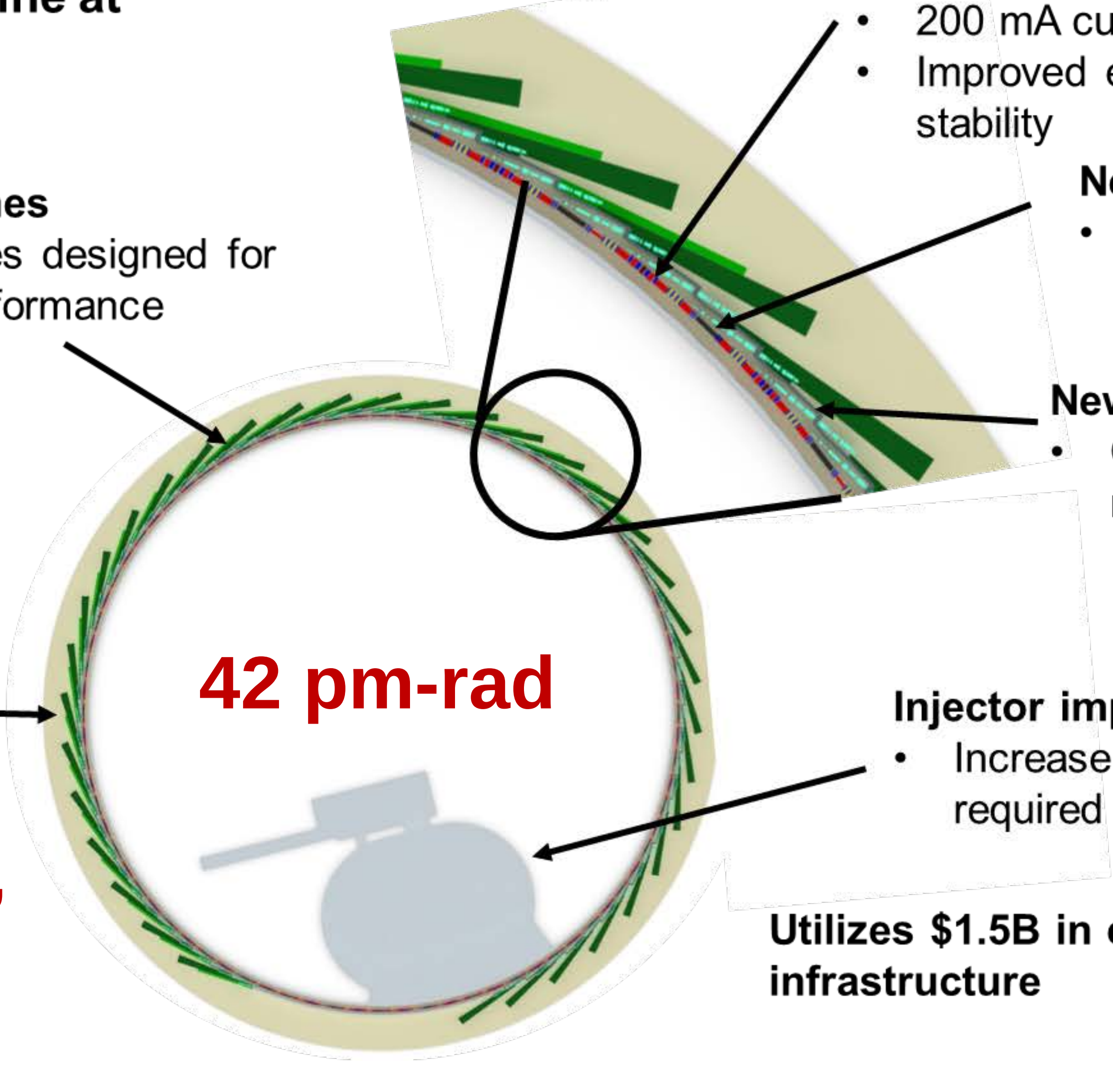
New Storage Ring
- 6 GeV MBA lattice
- 200 mA current
- Improved electron/photon stability

Feature beamlines
Suite of beamlines designed for best-in-class performance

New Insertion Devices
- Incorporate SCUs on selected beamlines

New/upgraded Front-ends
- Common design for maximum flexibility

Beamline Enhancements: improvements to make beamlines "Upgrade Ready"



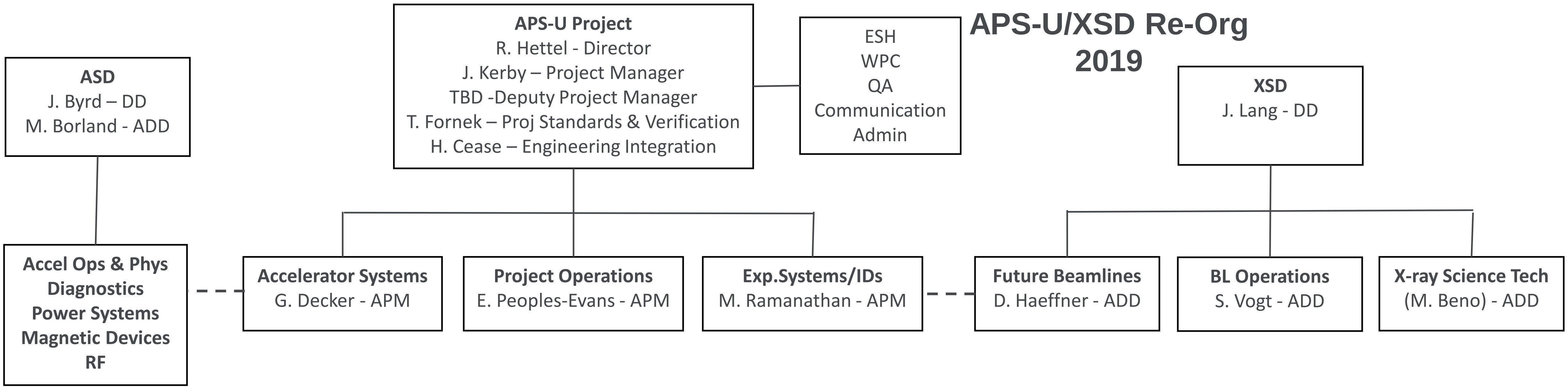
42 pm-rad

Injector improvements
- Increase performance as required to meet APS-U needs

On-axis "swap-out" injection

Utilizes \$1.5B in existing infrastructure

APS-U organization 2019

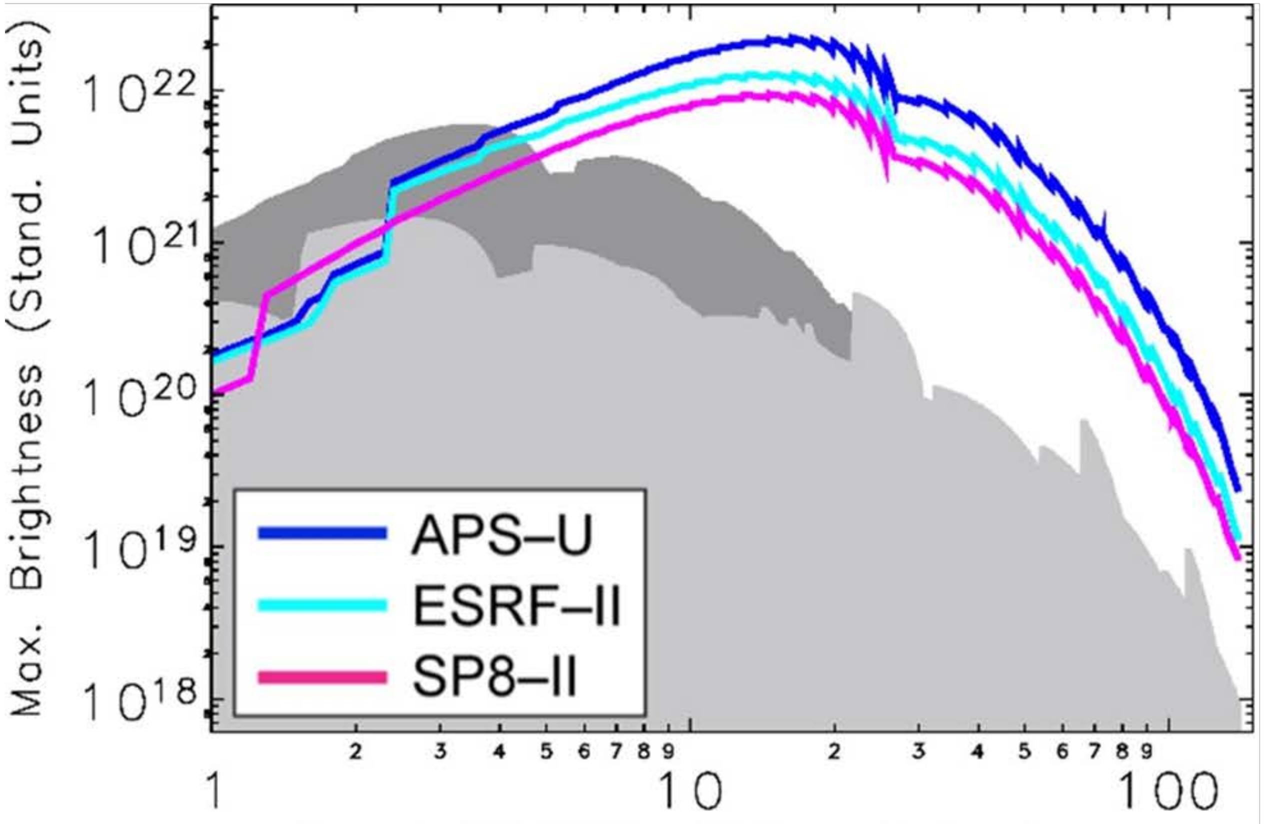


APS-U Parameters

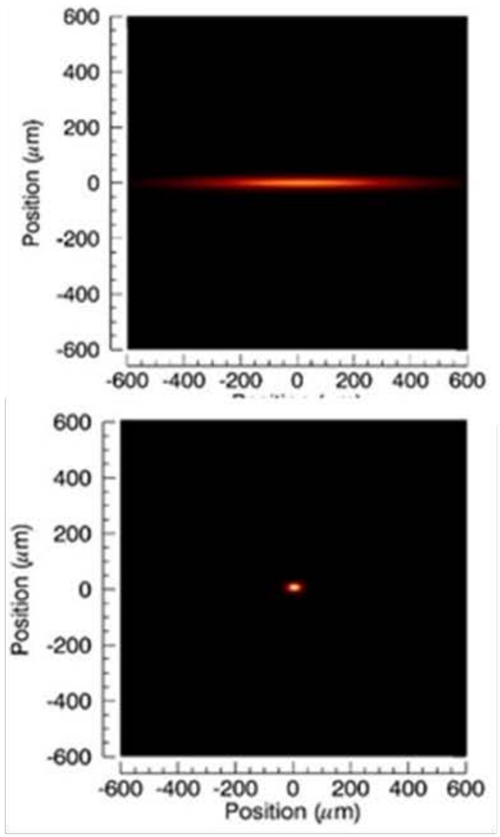
Quantity	APS Now	APS MBA Timing Mode	APS MBA Brightness Mode	Units
Beam Energy	7	6	6	GeV
Beam Current	100	200	200	mA
Number of Bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Emittance Ratio	0.013	1	0.1	
Horizontal Emittance	3100	31.9	41.7	pm-rad
Horizontal Beam Size (rms)	275	12.6	14.5	μm
Horizontal Divergence (rms)	11	2.5	2.9	μrad
Vertical Emittance	40	31.7	4.2	pm-rad
Vertical Beam Size (rms)	10	7.7	2.8	μm
Vertical Divergence (rms)	3.5	4.1	1.5	μrad

APS-U Preliminary Design Report, September 2017

APS-U ensures that the US maintains leadership position in high energy X-ray sources



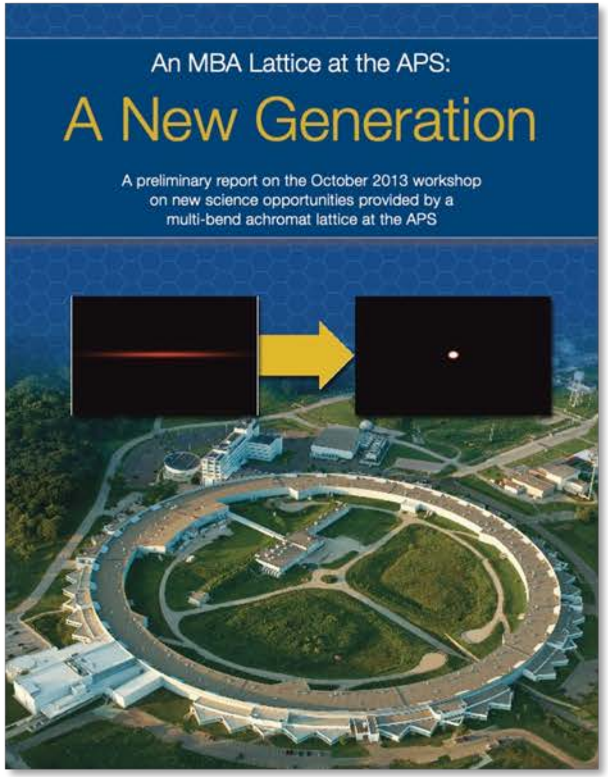
Curves for APS, ESRF, and SP8 upgrades based on present designs, assuming identical undulators

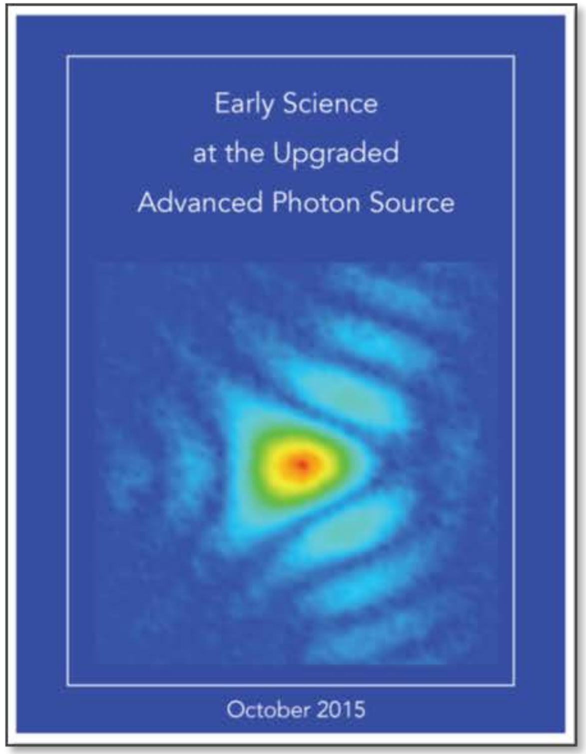


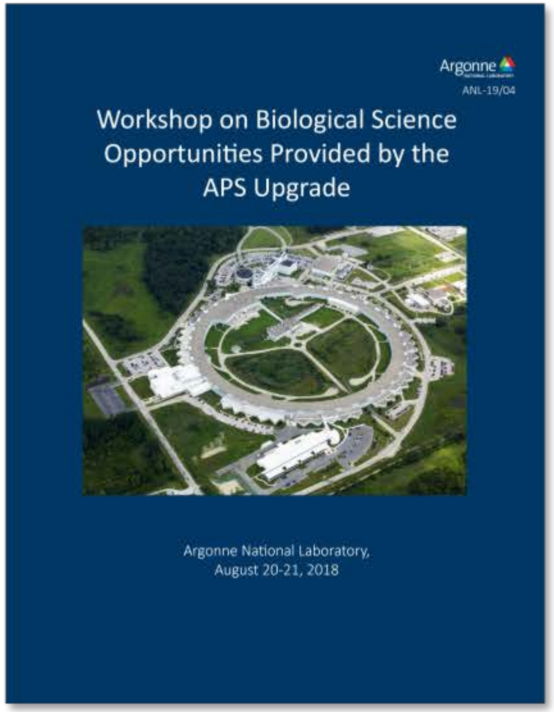
HEPS/Beijing may exceed APS-U brightness by a small amount due to larger circumference (1.3 km vs 1.1 km), as could SP8-II (1.44 km)

PETRA-IV could exceed APS-U brightness by a larger amount due to even bigger circumference

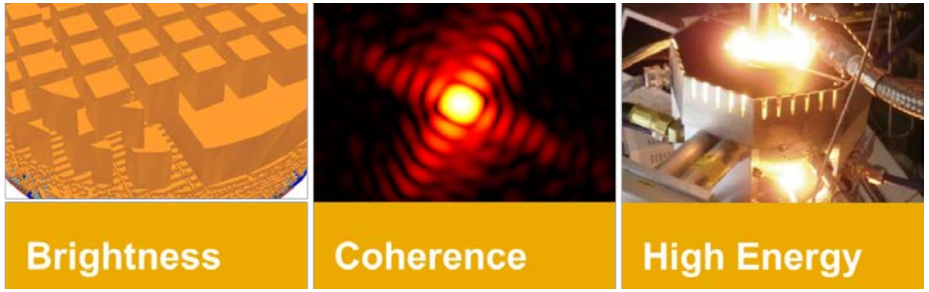
APS-U science workshops





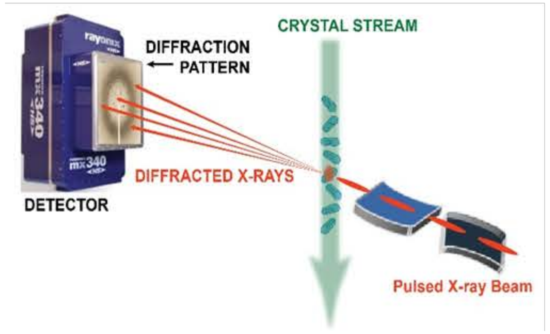


APS-U enables pivotal research across disciplines



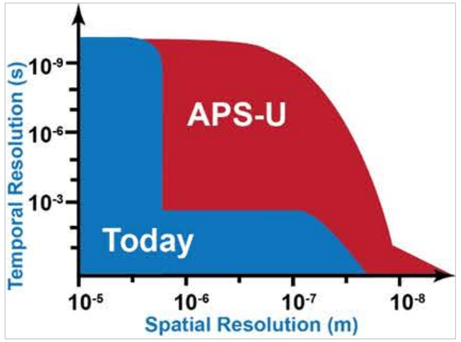
Small-Beam Scattering & Spectroscopy

- Nanometer imaging with chemical and structural contrast; few-atom sensitivity
- Room-temperature, serial, single-pulse pink beam macromolecular crystallography



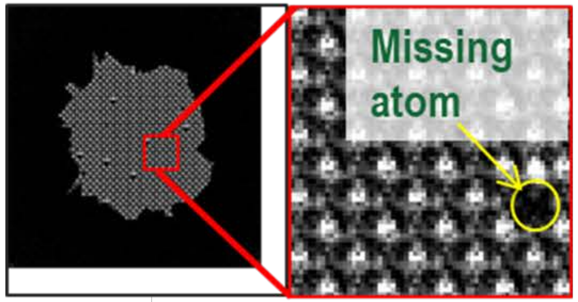
Resolution with Speed

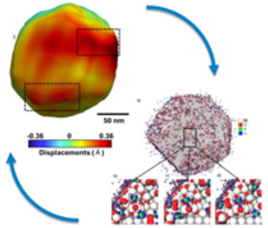
- Mapping all of the critical atoms in a cubic millimeter
- Detecting and following rare events
- Multiscale imaging: enormous fields of view with high resolution



Coherent Scattering & Imaging

- Highest possible spatial resolution: 3D visualization; imaging of defects, disordered heterogeneous materials
- XPCS to probe continuous processes from nsec onward, opening up 5 orders of magnitude in time inaccessible today,

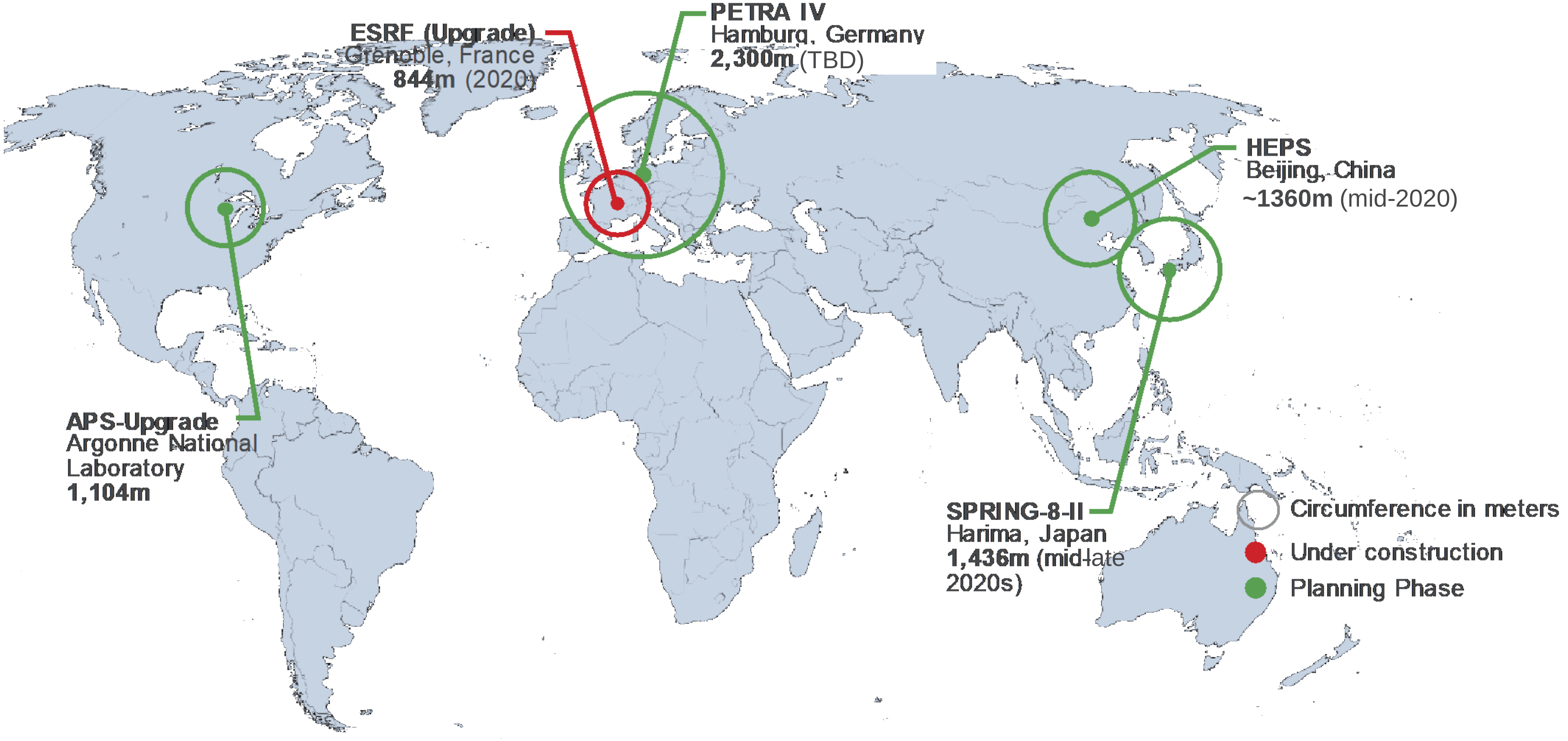




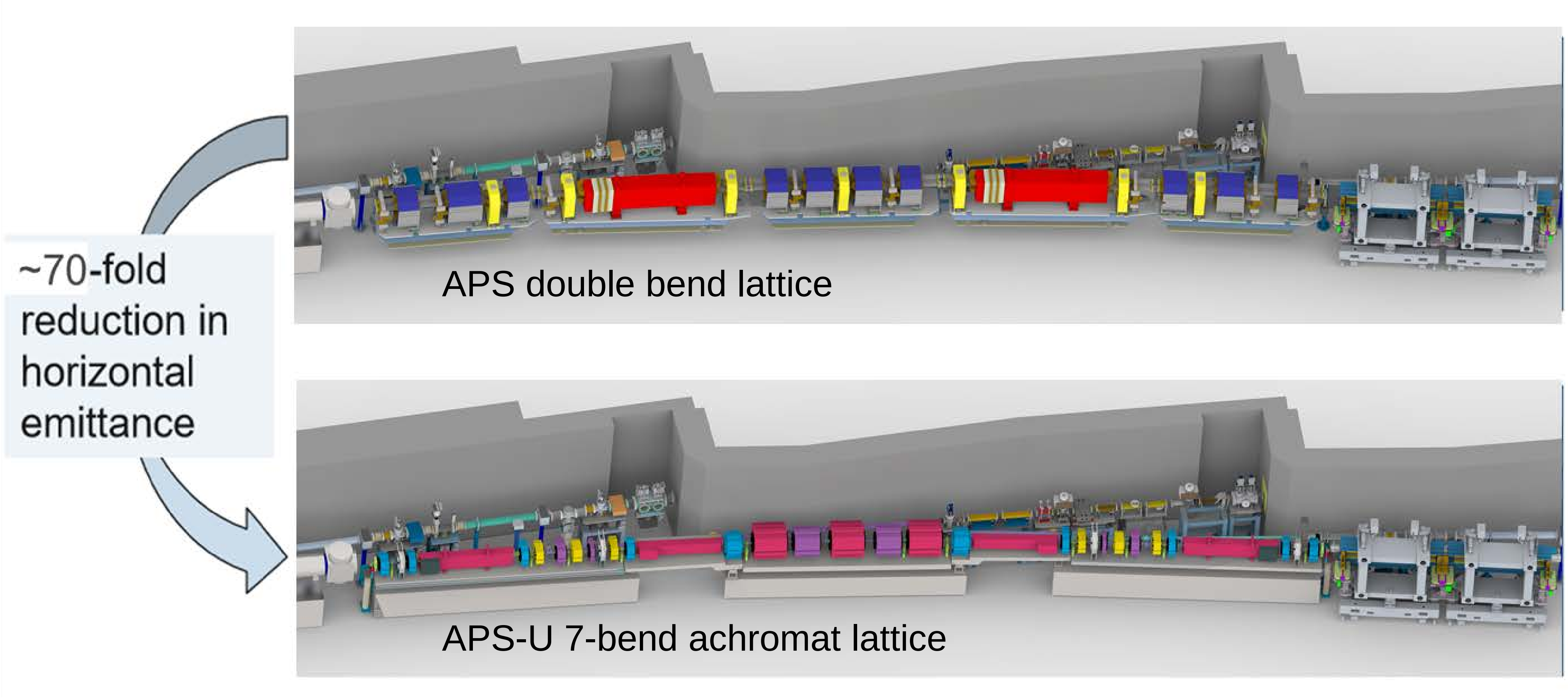
Exploit high performance computing, artificial intelligence

Automatic control of experiments, high volume data acquisition, analysis and reconstruction

International high energy X-ray 4GSR landscape



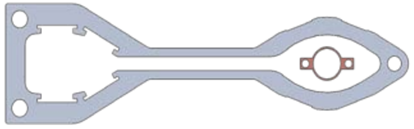
APS-U – High brightness storage ring lattice



Hybrid 7BA lattice with longitudinal gradient, transverse gradient and reverse bend dipoles

$$\varepsilon \propto \frac{E^2}{(N_D N_S)^3}$$

N_D = # dipoles/sector
N_S = # sectors



APS and APS-U chambers

Feature beamline workshops in 2018

- Workshops for each APS-U beamline
  - Further develop science cases
  - Feedback from user community on preliminary design
  - Reported out at the User Meeting

Date	Workshop
April 14	3DNano (3D Micro & Nano Diffraction)
April 24	CHEX (Coherent High-Energy X-ray Sector for In Situ Science)
April 25	Polar (Polarization modulation spectroscopy)
April 26, 27	ISN/Ptycho (PtychoProbe/In-Situ Nanoprobe)
April 28	HEXM (A High-Energy X-ray Microscope)
May 1	ATOMIC (Extremely high resolution coherent imaging of atomistic structures)
May 2	XPCS (combination of WAXPCS and SAXPCS)
May 3	CSSI (Coherent Surface Scattering Imaging)

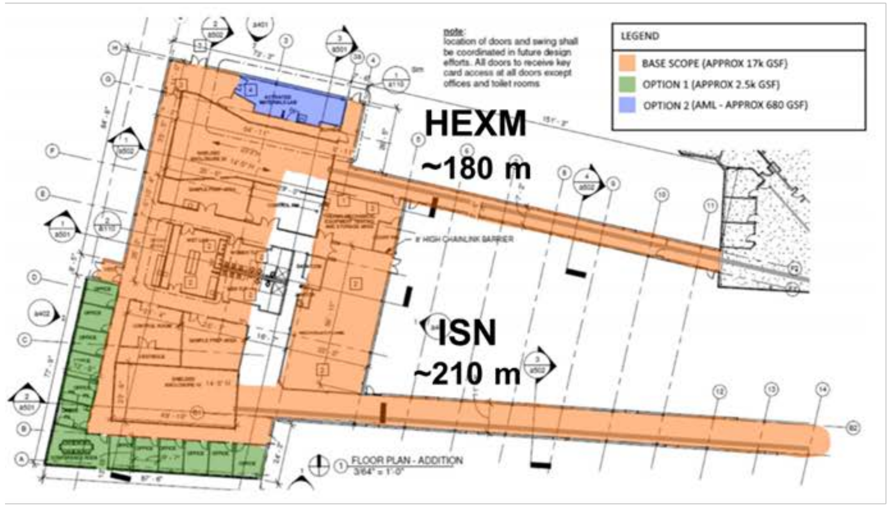
- Sessions well attended, discussion lively, constructive
- Feedback being used to revise FReDs, PDR
- Science case material incorporated into PDR science chapter
- Follow ons:
  - Coordination of capabilities and possible gap identification
  - Follow on cross-cut technique workshops
  - Common technical challenges will benefit from joint efforts
  - Working groups and focused technical workshops organized by APS-U

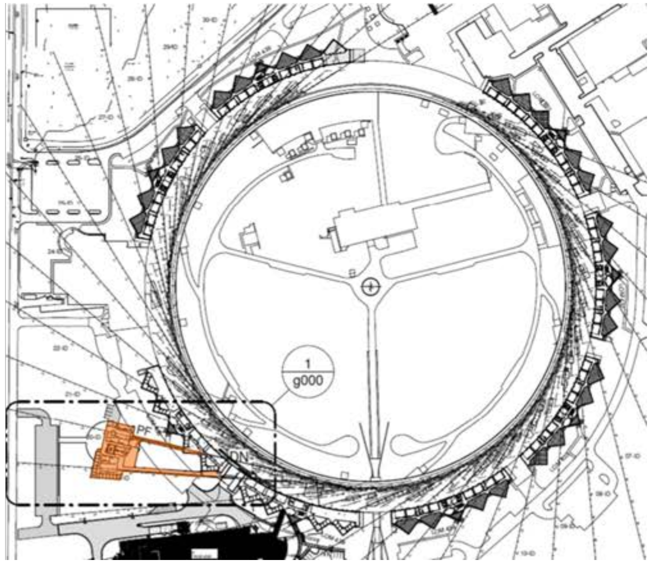
APS-U feature beamlines and capabilities

Loc.	Name	Title	Technique	Key Science Example
8-ID	XPCS	Small-Angle XPCS Beamline for Studying Dynamics in Soft Matter Wide-Angle XPCS and Time-Resolved Coherent X-Ray Scattering	Small angle XPCS Wide angle XPCS	Understanding soft matter assembly and dynamics, Glass hierarchical dynamics for superstrong materials, Fluid/solid interfaces, …
28-ID	CHEX	Coherent High-Energy X-ray Sector for In Situ Science	In situ, high energy coherent scattering	Real-time imaging of film-growth for higher performance energy-to-light conversion, power transmission, and novel materials
33-ID	Ptycho	PtychoProbe	Sub-5 nm imaging with chemical contrast, extended further w/ lensless imaging to 1 nm and potentially below	Nanoarchitectured electrochemical structures & Defect engineering for devices, improved materials for infrastructure, buildings, …
4-ID	Polar	Polarization modulation spectroscopy – Electronic Matter: Inhomogeneity, tunability, and discovery at extreme conditions	Magnetic Spectroscopy, combining nanofocusing w/ x-ray polarization,high pressure/low T/high field	Probe mesoscale electronic/magnetic ordering and excitations with resonant diffraction and inelastic scattering
34-ID	ATOMIC 3DMN	Extremely high resolution coherent imaging of atomistic structures 3D Micro & Nano Diffraction	Bragg coherent diffractive imaging, combining high spatial, temporal and strain resolutions. 3D nano-diffraction with significantly improved sensitivity	Image active catalytic materials approaching atomic resolution Mapping single defects in nanocrystalline materials to improve thermoelectric devices, structural integrity of mechanical components…

New beamlines and capabilities – cont.

Loc.	Name	Title	Technique	Key Science Example
9-ID	CSSI	Coherent Surface Scattering Imaging for Unraveling Mesoscopic Spatial-Temporal Correlations	Coherent GISAXS, XPCS	Visualizing nano-structured metamaterials in 3D for development of novel photonic materials and improved control of light-matter interaction
20-ID	HEXM	A High-Energy X-ray Microscope	High energy, high resolution diffraction microscopy and high energy CDI	Mesoscale grain dynamics under real conditions to develop new, more durable materials
19-ID	ISN	In Situ Nanoprobe	In-situ trace element, chemical state and structural imaging at 20 nm spatial resolution	Operando studies of element dependence of transport phenomena in new energy harvesting materials, catalytic processes, …





Provision for future SC arbitrary polarizing emitter (SCAPE)

Insertion Device Scope

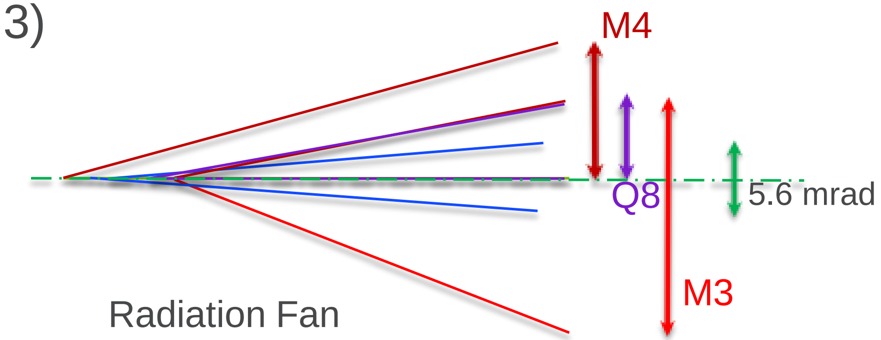
Device		Comments
Planar Hybrid Permanent Magnet Undulator (HPMU)	23 + (19)	New 2.8 cm period. Additional new periods are 2.5 cm, 2.1 cm and 1.35 cm. Will reuse all/some of 3.3 cm, 3.0 cm, 2.7 cm and 2.3 cm period undulators
Revolver HPMU	8 + (1)	Two headed revolvers. Will reuse one existing revolver mechanism. For high brightness at select energies or for continuous energy coverage.
Super Conducting Undulator (SCU)	8 + (1)	Two undulators (1.8 m each) in long cryostat (2 locations) Two undulators (1.3-1.5 m each) with canting magnets in long cryostat (2 locations) One existing undulator located co-linear with planar HPMU. Planned periods are 1.85 cm and 1.65 cm for high energy x-rays.
Electromagnetic Variably Polarizing Undulator(EMVPU)	(1)	Reuse IEX (Intermediate Energy X-ray) for low energy x-rays.

Device count in parenthesis () indicates existing undulators which may need minor modifications.
Nominal length of HPMU devices: ~2.3 m (2.1 m in canted configurations).
Nominal length of SCU devices: ~1.8 m (1.2 – 1.5 m in canted configurations).
Both planar and revolver undulators will reuse the existing gap separation mechanisms (“harvested”).

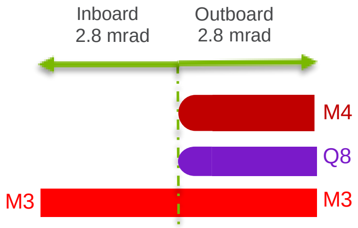
Bending Magnet Beamline Source

- The APS-U BM beamline source is complex due to the MBA lattice and the reverse bend makes it even more complex
- Angle between center of BM fan and the ID centerline has been kept the same from APS to APS-U
- APS-U BM beamline centerline will be displaced laterally inboard by 42.3 mm while keeping the angle the same (M3 magnet source point)
- The reverse bend lattice overlays the two dipole sources (M4 and M3) and the Q8 (weak dipole) on top of each other
- Beamlines will see a combination of three sources (M4+Q8+M3) on the outboard half and a clean M3 source on the inboard

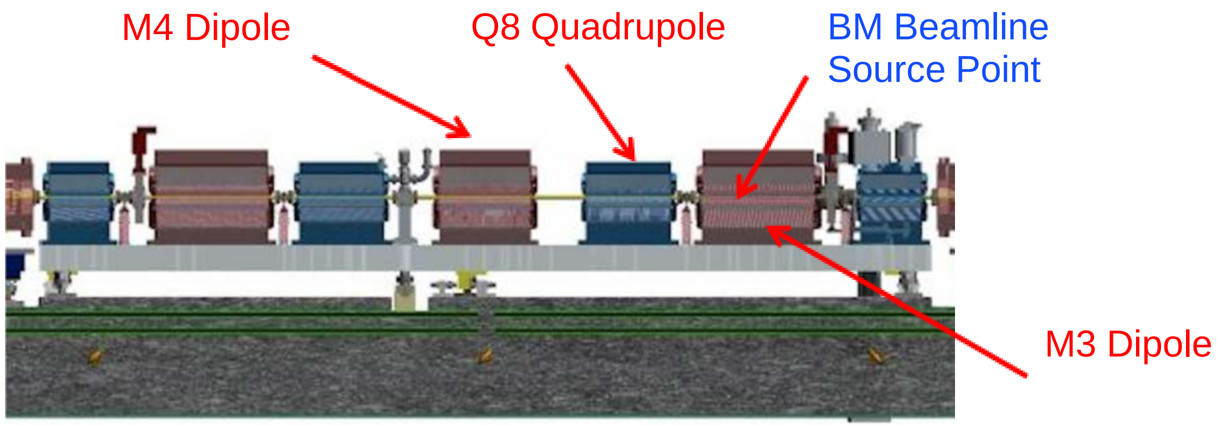
Schematic of radiation sources



Radiation Fan



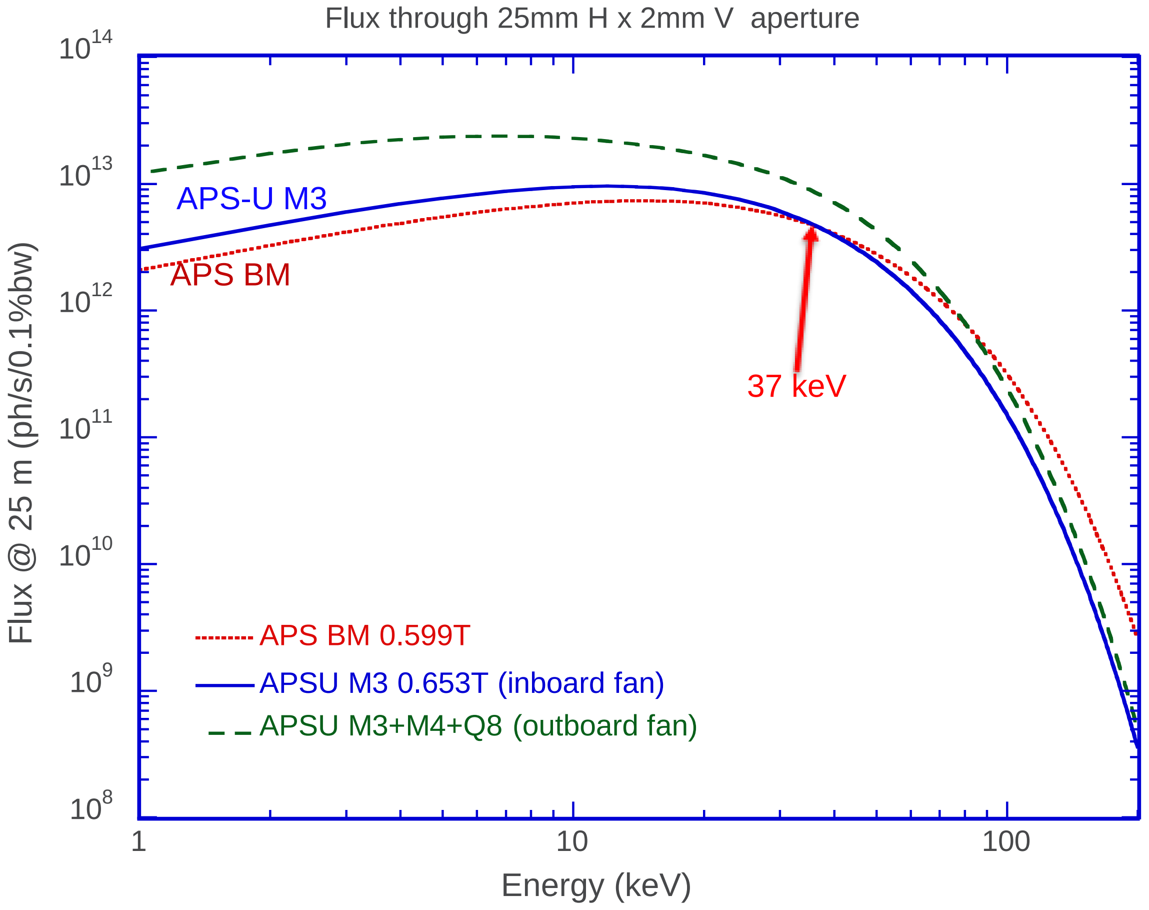
View from beamline



FODO Section

Bending Magnet Beamline Source

- The radiation fan for the new BM source will be different between the inboard and outboard fans (outboard has multiple magnet sources)
- M3 and M4 serve as two individual sources. The longitudinal distance between the two sources are about 1.24 m
- The inboard fan is a clean source from M3
- The outboard fan may cause problems for some experiments, but when focused, the beams can be separated specifically between M3 and the other magnets
- Most BM beamlines can be aligned to use the clean M3 radiation (inboard 2.8 mrad fan)



Flux on BM beamlines is higher than existing BM source for all energies up to 37 keV with very little increase in power and power density

Photon transport simulation tools

Levels of simulation: accuracy vs efficiency

Analytical method

- Mathematica/Excel
- Gaussian beam profile
- Optics acceptance
- Focusing condition using geometric magnification and diffraction formula
- Fast optimization of the beamline layout with reasonable accuracy

Numerical method

- *SHADOW*, Ray, McXtrace, xrt
- ***HYBRID*** (add diffraction)
- SRW, Phase
- More accurate source profile
- Effects of non-ideal optics
- Effects of optics vibration and misalignment
- Beam intensity, spot size, divergence, and energy spectra
- Optics specification and mechanical requirements

Mutual coherence

- **The Mutual Optical Intensity (MOI) model**
- Multi-electron SRW
- Coherent mode decomposition method
- Comsyl
- Partially coherent source and propagation through optics
- Local coherence and wavefront

Coherent wavefront preservation

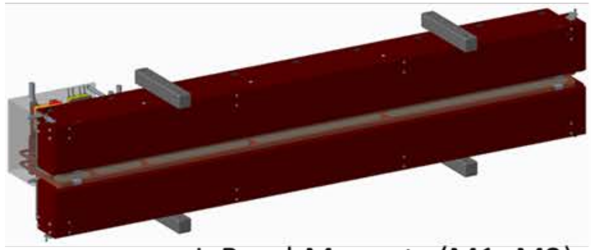
CD-3B long lead procurements

Control Account / CD-3B Package	FY17	FY18	FY19	Grand Total
U.U2.03.03.01 - Magnets	**$3,058K**	**$13,892K**	**$3,512K**	**$20,462K**
Q1/Q2 Quadrupole Magnets	$3,058K			$3,058K
8-pole Corrector Magnets		$2,691K		$2,691K
Q3, Q6 Quadrupole Magnets		$2,548K		$2,548K
Q4, Q5 Quadrupole Magnets		$3,317K		$3,317K
Sextupole Magnets		$5,337K		$5,337K
M1 Dipole Magnet			$1,722K	$1,722K
M3 Dipole Magnet			$1,790K	$1,790K
U.U2.03.03.02 - Support Structures and Alignment Systems		**$0K**	**$4,437K**	**$4,437K**
DLM A Plinth and associated			$4,437K	$4,437K
U.U2.03.03.03 - Magnet Power Supply Systems		**$8,189K**	**$6,831K**	**$15,021K**
Unipolar Power Supply Components		$8,189K		**$8,189K**
Bipolar Power Supply Components			$5,196K	$5,196K
Fast Corrector Power Supply Components			$1,636K	$1,636K
U.U2.03.03.04 - Vacuum System			**$7,471K**	**$7,471K**
Multiplet/Doublet vacuum chambers			$1,776K	$1,776K
FODO section chambers			$3,671K	$3,671K
L-bend chamber components			$936K	$936K
Fast Corrector chambers			$1,088K	$1,088K
U.U2.03.03.05.02 - Bunch Lengthening System	**$251K**	**$348K**	**$1,632K**	**$2,231K**
Bunch Lengthening Cavity and Cryomodule	$251K	$348K	$278K	$877K
Bunch Lengthening System Cryoplant			$1,354K	$1,354K

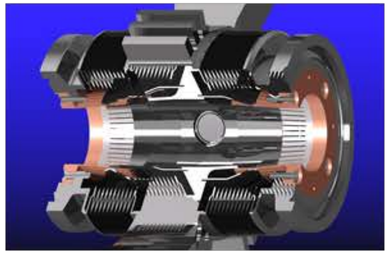
Control Account / CD-3B Package	FY17	FY18	FY19	Grand Total
U.U2.03.03.06 - Injection / Extraction Systems			**$1,414K**	**$1,414K**
High Voltage Pulsers			$1,414K	$1,414K
U.U2.03.03.07 - Diagnostics		**$178K**	**$1,149K**	**$1,327K**
RF BPM Components (Relay Racks)		$178K		$178K
RF BPM Libera boxes (20%)			$1,149K	$1,149K
U.U2.03.04 - Injector			**$130K**	**$130K**
PAR 12th Harmonic Amplifier			$130K	$130
U.U2.04.02 - Global Beamline Support	**$355K**	**$719K**	**$887K**	**$1,961K**
Optics, Stability Components	$355K	$719K	$887K	$1,961K
U.U2.04.04 - Beamlines		**$3,886K**	**$2,790K**	**$6,676K**
ASL Hutch Procurement		$2,339K		$2,339K
ASL Beamline Critical Components		$1,547K	$2,790K	$4,336K
U.U2.05.02 - Front Ends		**$3,443K**	**$1,244K**	**$4,687K**
High heat load front end components (all FE GlidCop)		$1,086K	$382K	$1,468K
Canted front end components (all FE GlidCop)		$684K	$160K	$844K
X-ray Beam Position Monitor Components (GlidCop)		$816K		$816K
FE Equipment Protection Systems & Pneumatics		$617K		$617K
ASL CUFE		$240K	$702K	$943K
U.U2.05.03 - Insertion Devices		**$1,847K**	**$5,259K**	**$7,106K**
Magnetic Structures		$1,581K	$3,226K	$4,807K
Insertion Device Vacuum Chamber Components		$266K	$2,033K	$2,299K
Grand Total	**$3,664K**	**$32,502K**	**$36,757K**	**$72,923K**
Contingency @10% existing contracts, 35% on estimates	$366K	$3,250K	$12,865K	$16,481K
Grant Total Including Contingency	**$4,031K**	**$35,752K**	**$49,621K**	**$89,405K**

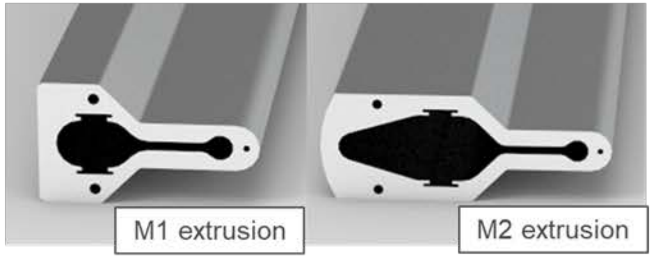
89.5 M$ spending authority

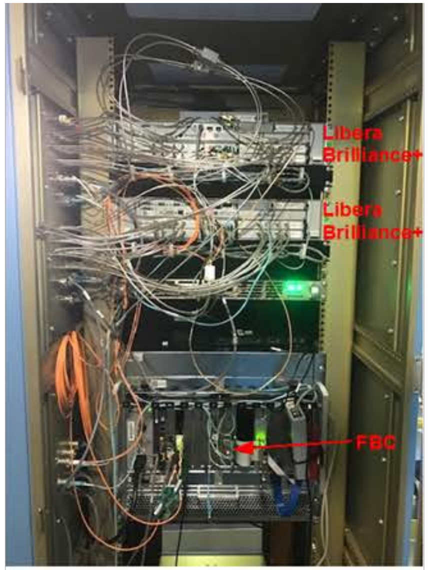
APS-U accelerator technology



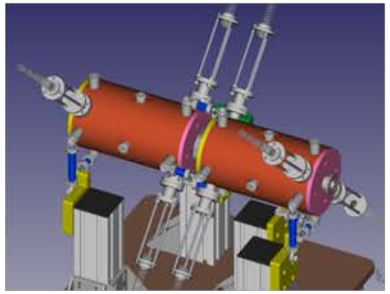
L-Bend Magnets (M1, M2)

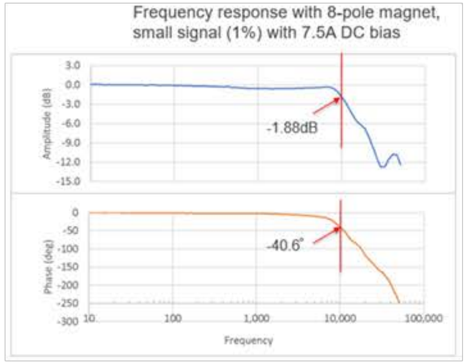




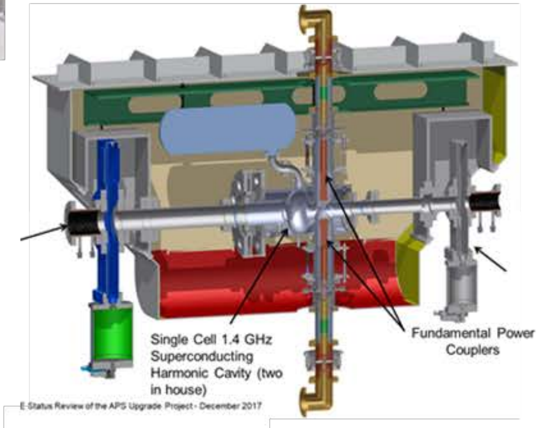


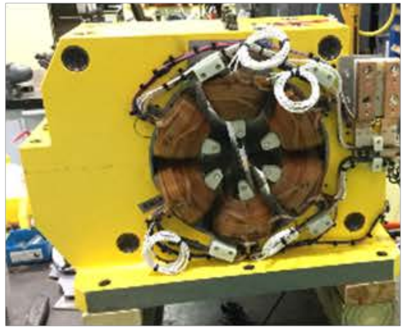
Libera Brilliance+ and FBC uTCA Crate

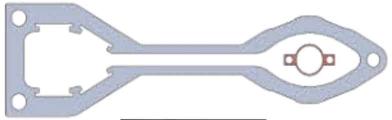




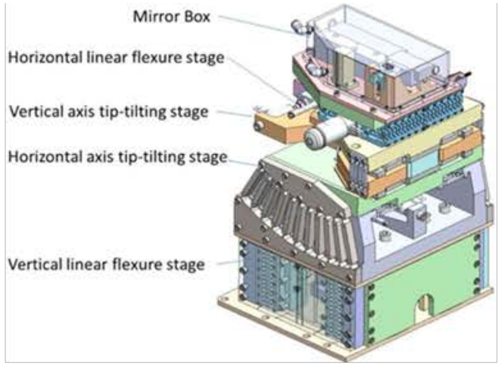
SC bunch lengthening

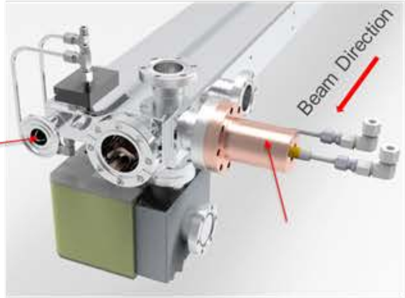




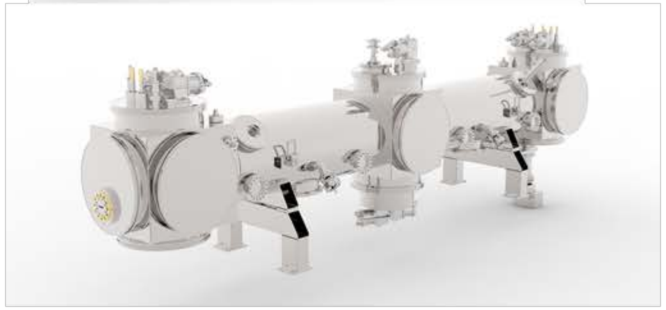


APS-U Beamline and ID Technology

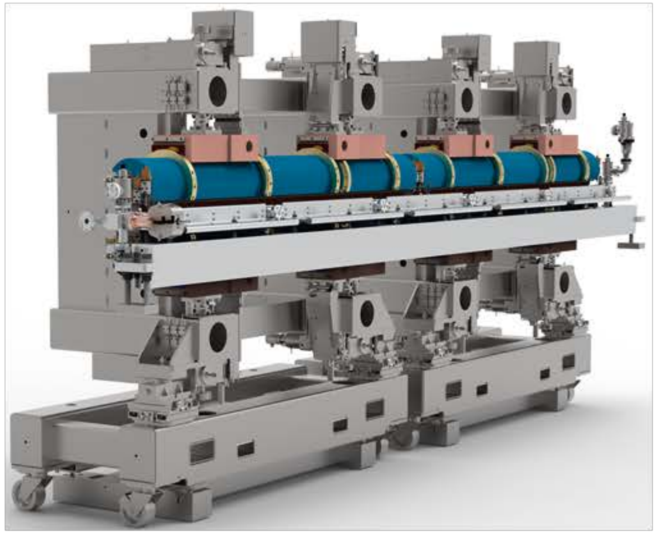




superconducting ID

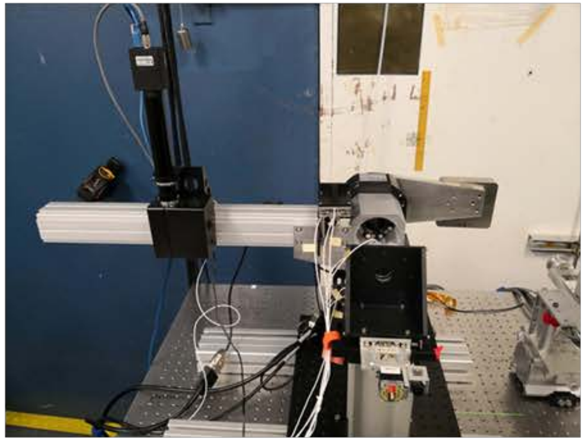


Velociprobe: fast scanning nano-probe



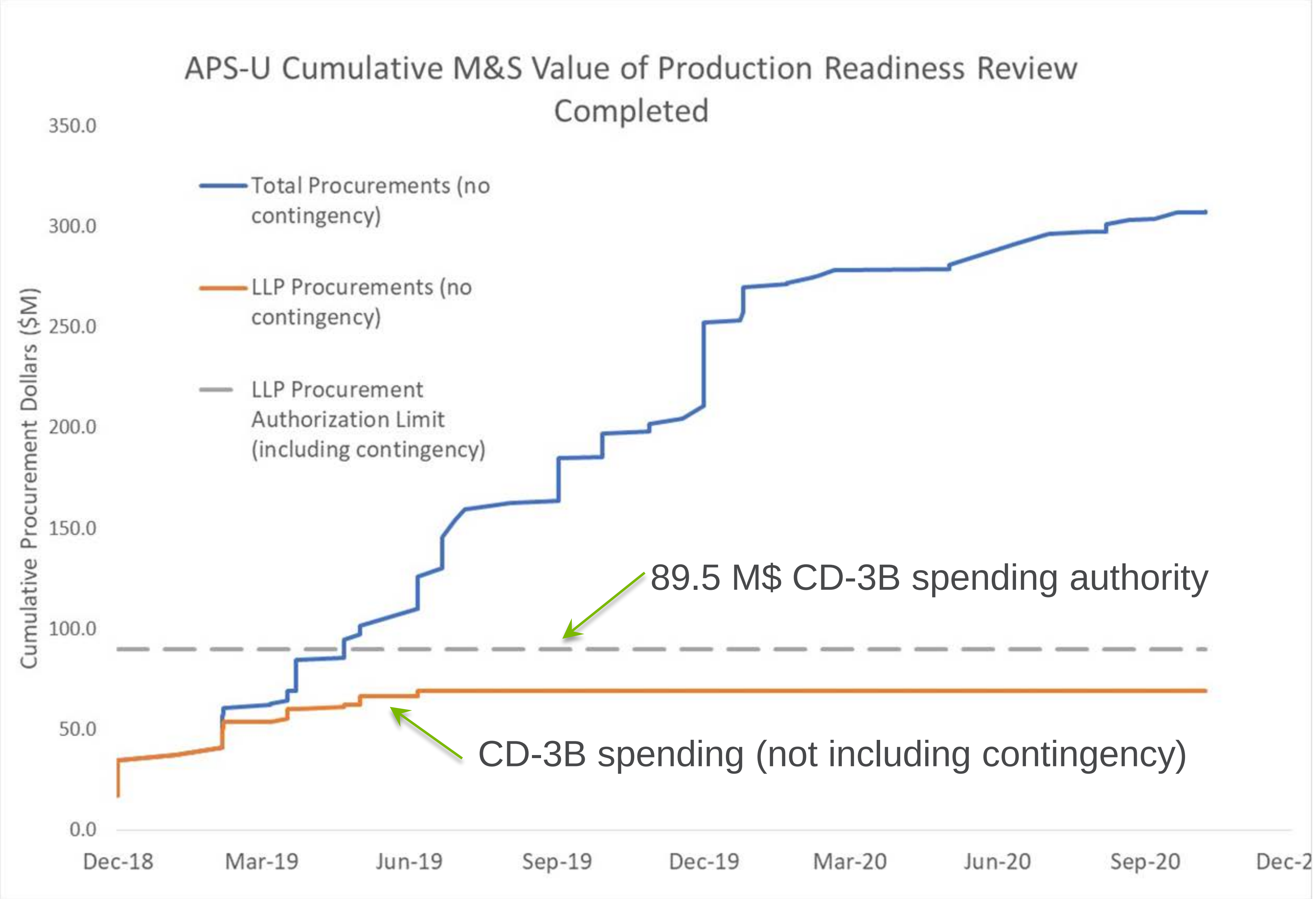
revolver IDs

high heat load front end

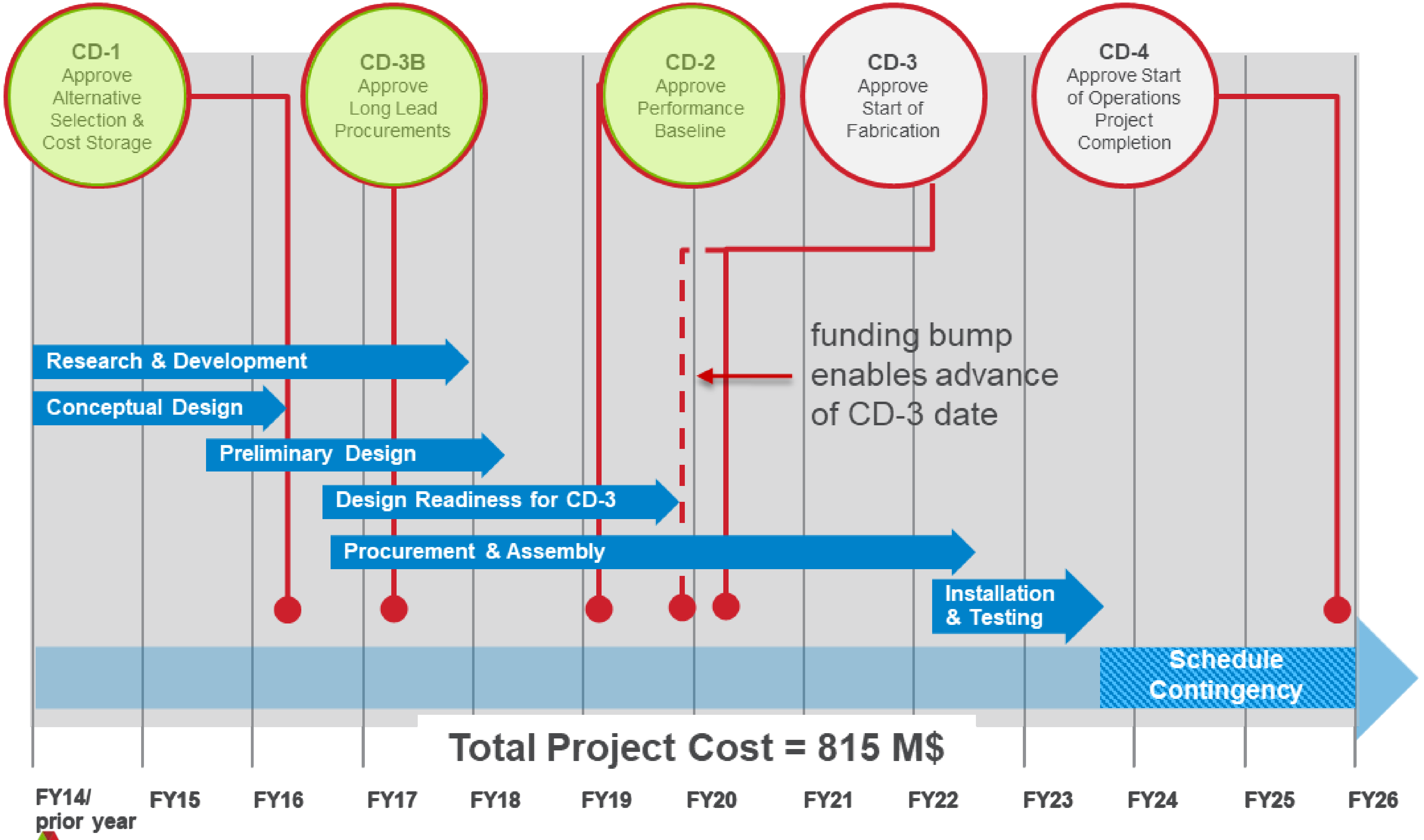


prototype compact wavefront sensor

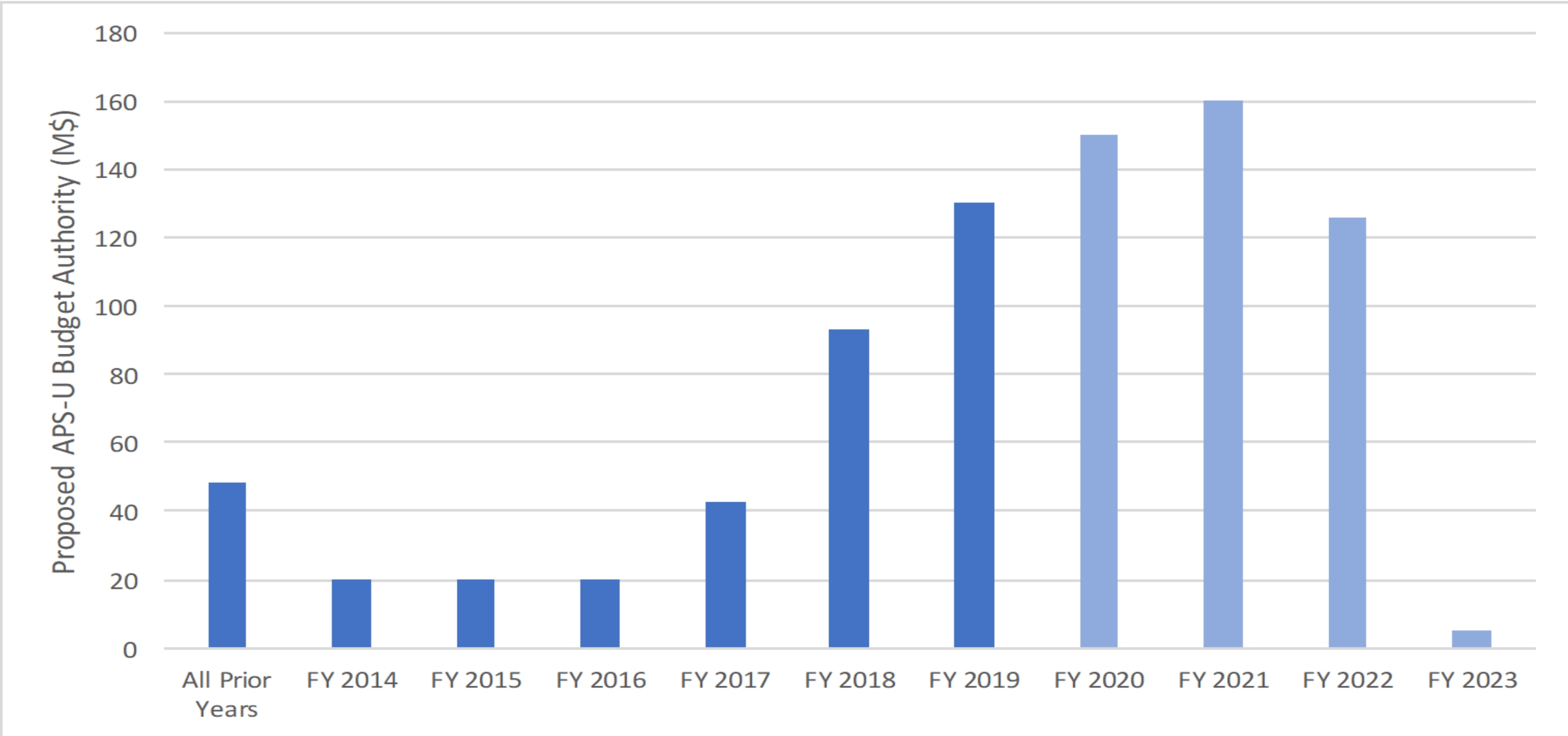
Need CD-3 spending authority soon



APS-U project is on schedule



APS-U proposed funding profile



Funding (BA) in Millions of Dollars (Then-year Dollars)

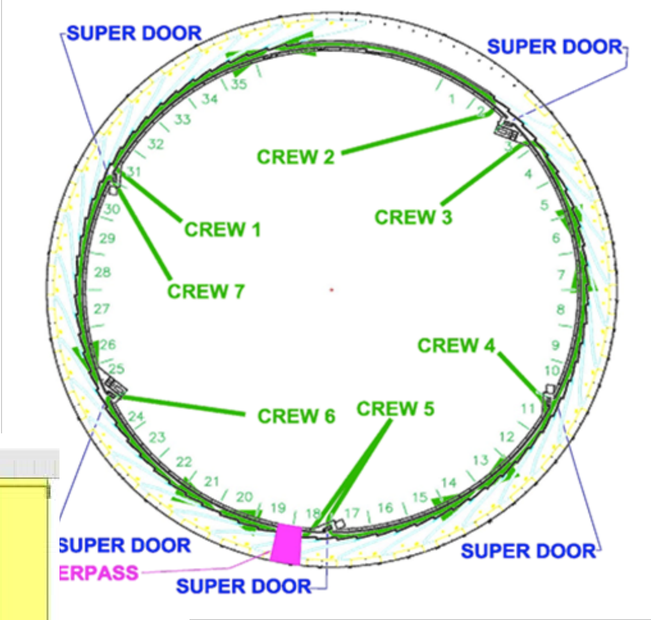
	All Prior Years	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	FY 2022	FY 2023	Total
OPC	8.5									5.0	5.0	18.5
TEC	40.0	20.0	20.0	20.0	42.5	93.0	130.0	150.0	159.8	121.2		796.5
Total	48.5	20.0	20.0	20.0	42.5	93.0	130.0	150.0	159.8	126.2	5.0	815.0

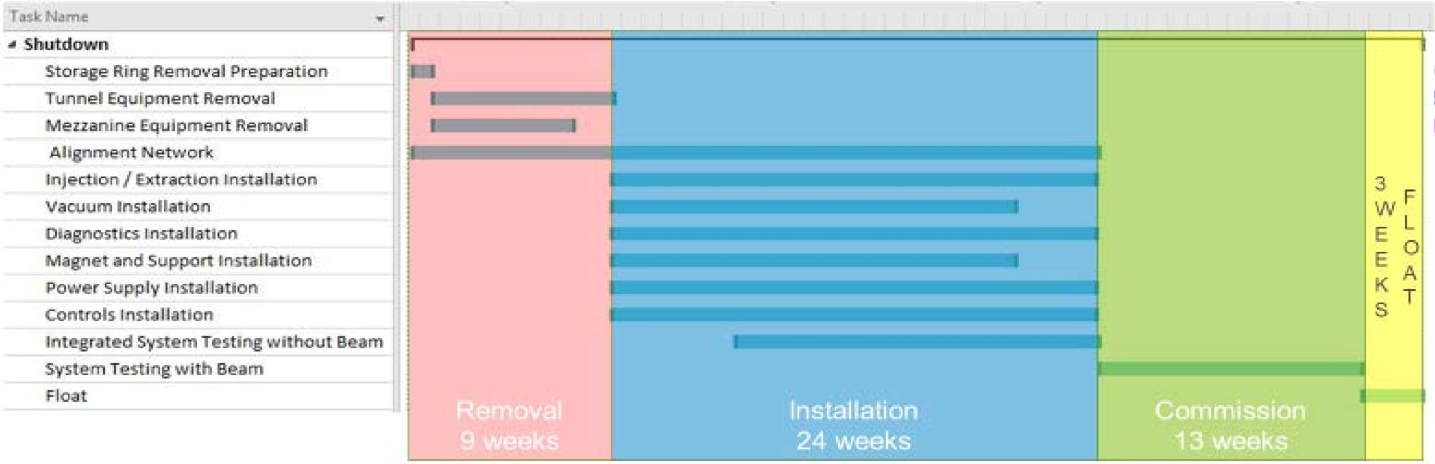
- FY17 – FY19 Funding very favorable; APS-U taking full advantage.
- Project executing production procurements within CD-3B Long Lead Procurement (LLP) authorization.
- Will exhaust LLP funds by ~June 2019 with present spending plan.
- Project proposing to advance CD-3 Review to spring 2019 to gain full authorization and enable procurements on schedule beyond LLPs.
- FY20 and beyond funding critical to keep momentum going.

APS-U removal/installation/restart plan

The Project has developed and has independently reviewed a bottom-up 12-month plan for removal, installation, and testing-with-beam for the facility

- Resource planning/timelines consistent with previous world-wide experience
- Plan has substantial detail for this stage of the Project (resources, shifts, materials handling estimates)
  – Risk mitigation includes additional shifts, additional workdays





61 enhanced beamlines operational 13 months after APS shutdown

Remaining 8 new/rebuilt/upgraded beamlines operational 18 months after APS shutdown

- Overtime
- Number of shifts
- Arrangement of shifts
- Holidays/lab shutdowns
- Access points to mezzanine
- Contract flexibility

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DOE/SC CD-2 Review of the APS-U Project - October 10-12, 2018 16

Key Performance Parameters

Key Performance Parameter	Thresholds (Performance Deliverable)	Objectives
Storage Ring Energy	> 5.7 GeV, with systems installed for 6 GeV operation	6 GeV
Beam Current	$\geq$ 25 mA in top-up injection mode with systems installed for 200 mA operation	200 mA in top-up injection mode
Horizontal Emittance	< 130 pm-rad at 25mA	$\leq$ 42 pm-rad at 200mA
Brightness @ 20 keV[1]	$> 1 \times 10^{20}$	$> 1 \times 10^{22}$
Brightness @ 60 keV[1]	$> 1 \times 10^{19}$	$> 1 \times 10^{21}$
New APS-U Beamlines Transitioned to Operations	7	$\geq$ 9

[1]photons/sec/mm^2/mrad^2/0.1%BW

A Transition to Operations Plan is being developed; and advanced draft will be ready for the CD-3 review.

Beamline Transition to Operations Parameters

- Brightness measurement required for each new beamline.
- For completion of beamline transfer to operations: Threshold TTOP must be met or exceeded; key equipment is verified to be in place and working

Beamline	TTOP Thresholds (Performance Deliverable)	Energy Range (keV)	Description
Polar	Brightness @ 9 keV > 4.9 x 10^{19}	2.75 – 27	Magnetic spectroscopy beamline designed to take advantage of novel undulators developed for the APS-U storage ring. Nanofocused, polarized beams will be used to study materials in extreme conditions.
XPCS	Brightness[1] @ 20 keV > 4.2 x 10^{19}	8 – 25	X-ray photon correlation spectroscopy beamline with instruments for small- and wide-angle scattering, designed for maximum coherent flux.
CSSI	Brightness[1] @ 20 keV > 4.2 x 10^{19}	6 – 30	Coherent surface scattering imaging beamline to explore the structure and dynamics of low dimensional, mesoscale, heterogeneous systems.
ISN	Brightness[1] @ 20 keV > 4.2 x 10^{19} Focused beam < 50 nm (FWHM)	4.8 – 30	A scanning nanoprobe optimized for large working distances and in situ experiments
HEXM	Brightness[1] @ 60 keV > 5.1x10^{18}	35 – 120	High-energy x-ray microscope for experiments on in situ environments for materials science and engineering applications.
CHEX	Brightness[1] @ 20 keV > 3.9 x 10^{19}	5 – 60	One tunable and three fixed-energy beamlines designed for coherent, high-energy x-ray in-situ diffraction studies of materials synthesis and chemical transformations.
Ptycho	Brightness[1] @ 10 keV > 1.3 x 10^{20}	5 – 30	Ultimate spatial resolution, ultra-fast scanning nanoprobe with ptychography for extremely high-resolution structural measurements.
ATOMIC	Brightness[1] @ 20 keV > 3.8 x 10^{19}	5 – 30	Bragg coherent diffraction imaging to study materials with spatial resolution of one nm or better. Zoom optics allow variable spot sizes so that the x-ray probe can be matched to the needs of individual experiments.
3DMN	Brightness[1] @ 20 keV > 2.5 x 10^{19}	5.3 – 30	3D diffraction nanoscope using both pink and monochromatic x-rays to study materials structure and mechanical behavior.

[1] Brightness = photons/sec/0.1% BW/mm^2/mrad^2 @ > 5.7 GeV, $\geq$25 mA, <130 H/65 V pm-rad, 20% high β_x (6.24 m) and β_y (2.88 m) with 8-mm η_x and 4-mm η_y leakage at source ; brightness measurements inferred by measurements of central cone spectral flux, β_x , β_y, η_x , η_y at source point.

Preparation for APS-U CD-3

- Machine Advisory Committee meeting - March 12-14, 2019
- ESAC Beamline Technical Review – May 20, 2019
- CD-3 Director’s Review – May 21-22, 2019
- Complete “Final Design Report”, draft of “Transition to Operations Plan”
- Advance as many designs as possible
- DOE CD-3 Review – June 18-20, 2019
- DOE CD-3 approval (Binkley) – hopefully by August 2019