

Argonne NATIONAL LABORATORY

Some Thoughts on Storage Ring RF System for the Advanced Photon Source Upgrade (APS-U)

A. Nassiri

Accelerator Systems Division
Advanced Photon Source

Contributions:
D. Horan, T. Berenc, G. Waldschmidt,
M. Borland, Y. Sun, M. Kelly(PHY),and
S-H. Kim(PHY)

22 June 2016

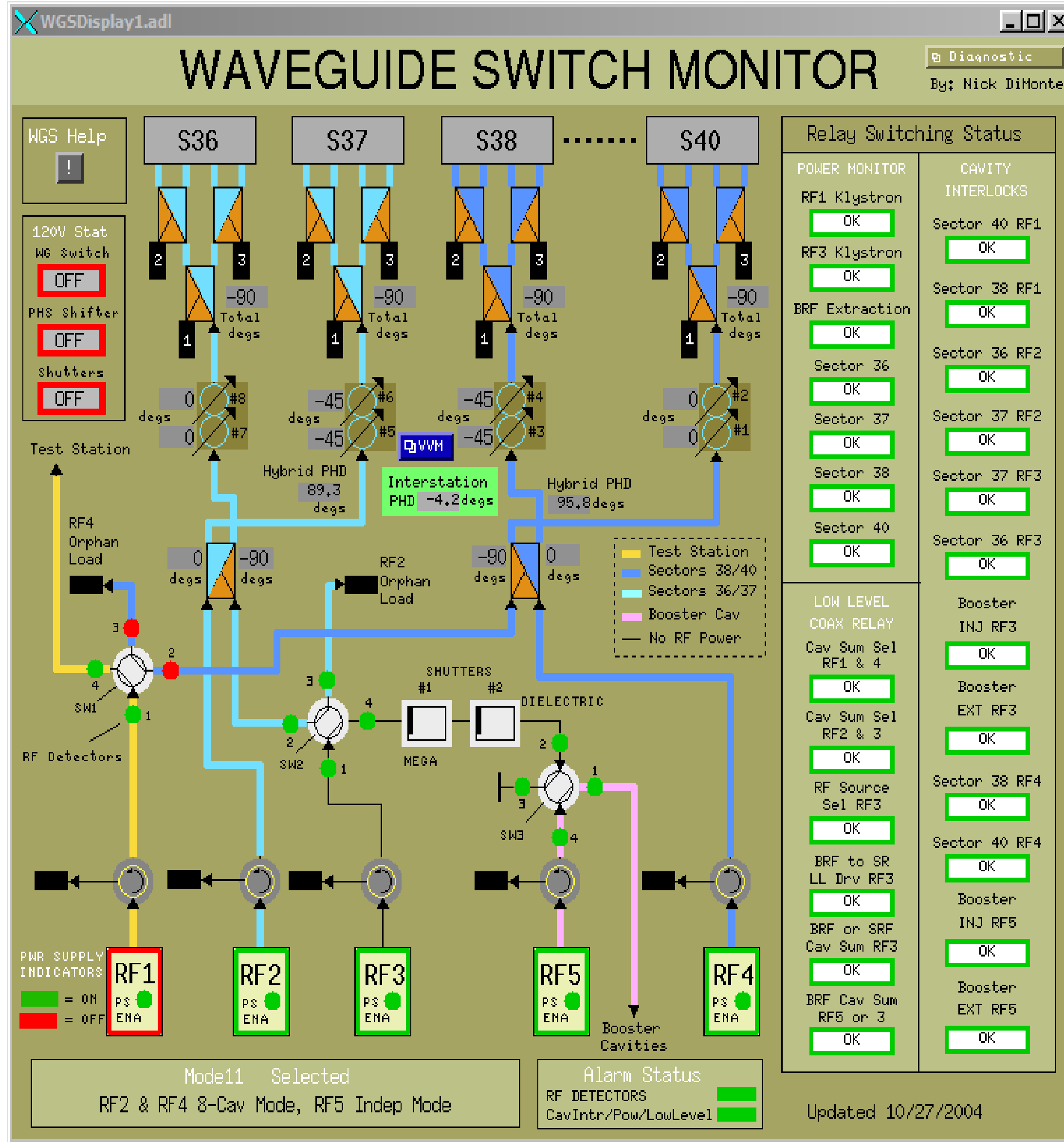
9th CW and High Average Power RF Workshop
21 June – 24 June, 2016
Grenoble, France

Outline

- Present APS Storage Ring RF Configuration and Performance
- Toward 4^{th}-Gen sources
- Motivation for APS-U
- APS-U RF systems considerations
- Low Frequency RF System Alternative
- Summary

Present configuration and performance - HLRF

- Five klystron-based 1.1MW cw rf systems
- Four for Storage Ring, one for Booster
- Waveguide Switching System provides rf system redundancy
- Present Storage Ring operation at 100mA requires two rf systems operating at ≈ 650kW each
- Parallel-klystron mode available for stored beam greater than 150mA



Present configuration and performance - Klystrons

- In operation

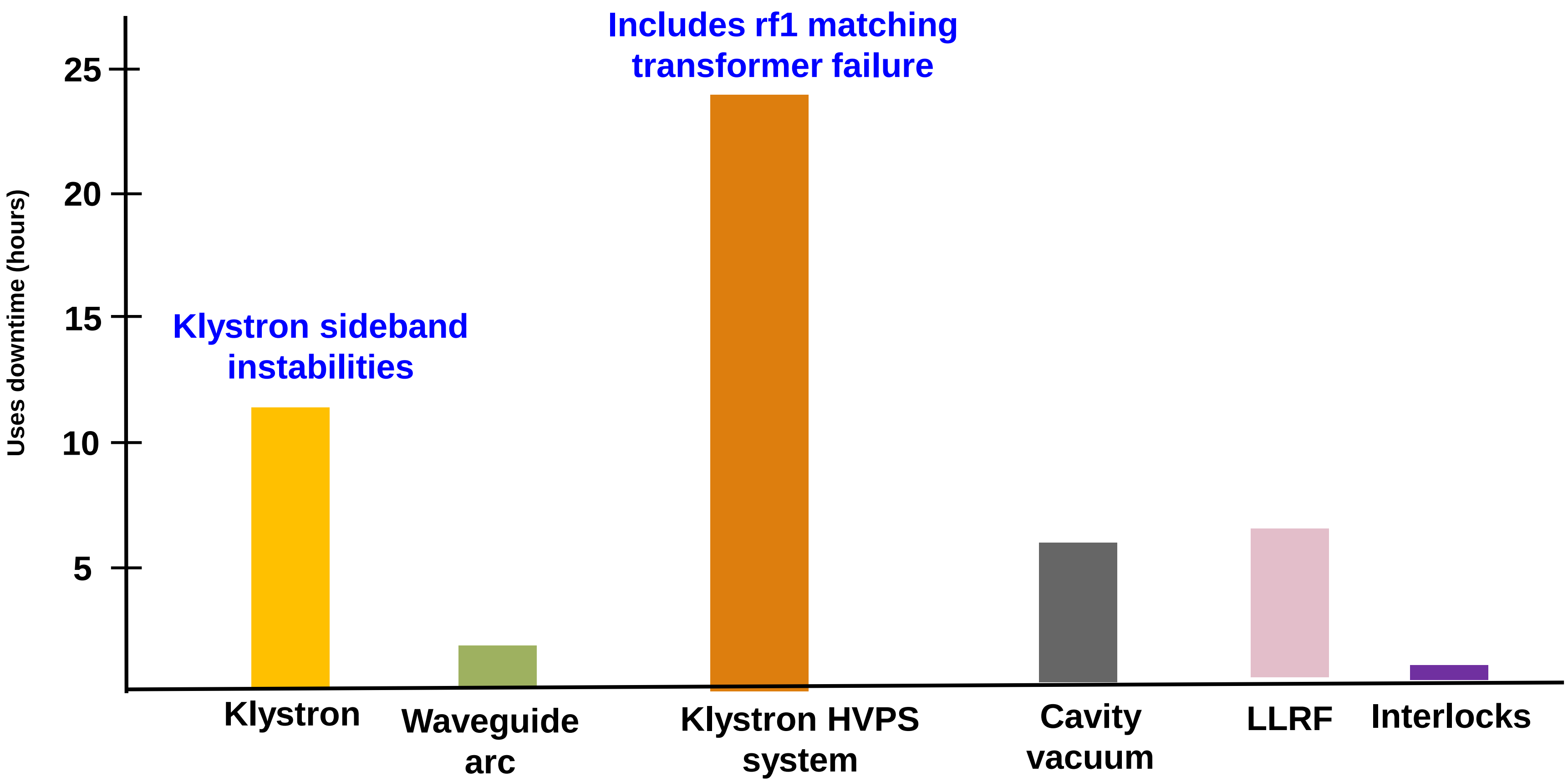
System	S/N	Filament Hours
RF1	TH089043	**38,217**
RF2	TH089033(rebuilt)	189 (new install)
RF3	TH089048	13,569
RF4	TH089030	**71,276**
RF5 (booster)	TH089029 (rebuilt)	11,030

- Spares

Type	Quantity	Filament Hours
Thales (new)	2	200
Thales (rebuilt)	1	200
E2V	2	LANL

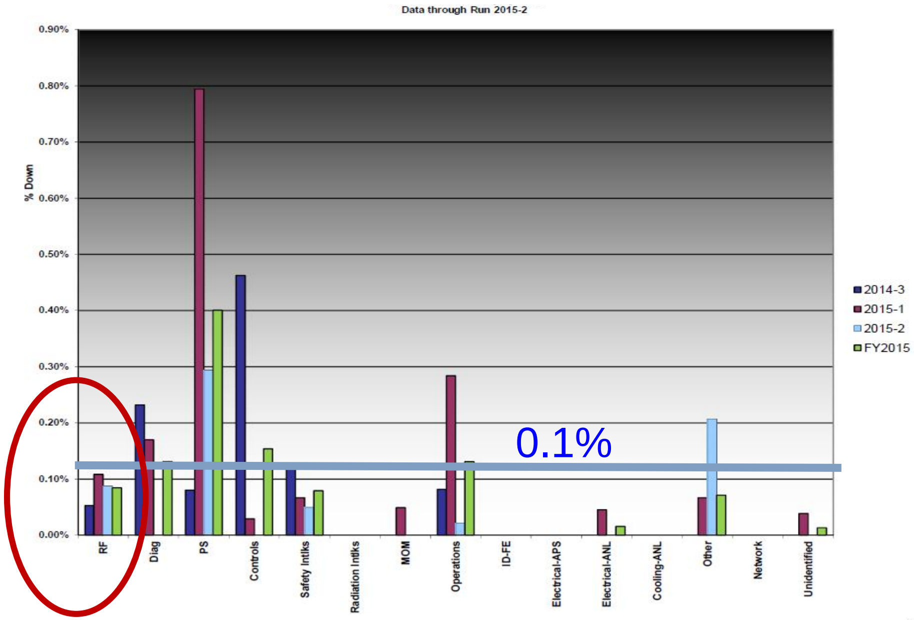
Present configuration and performance - Statistics

- SR RF Sub-System Faults (FY2013-present)

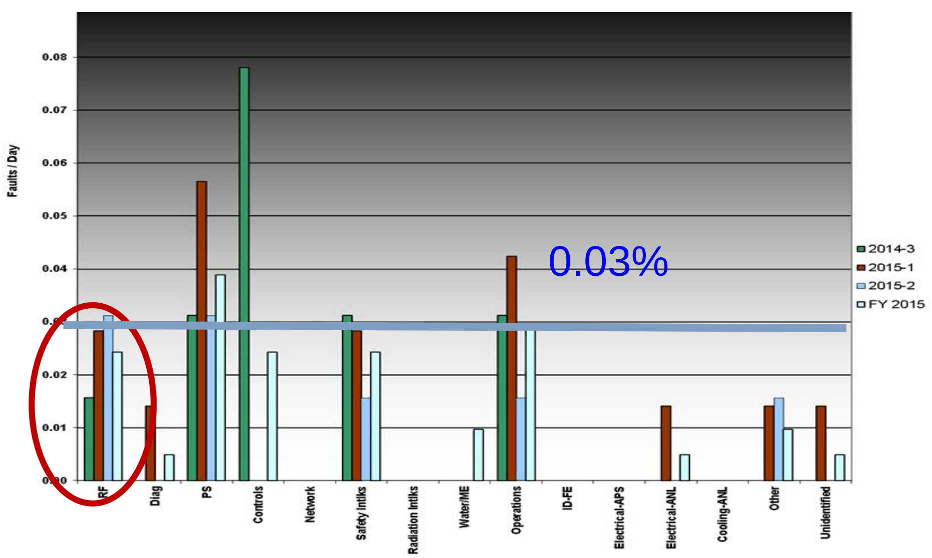


Run Statistics

FY2015 DT by System through run 2015-2

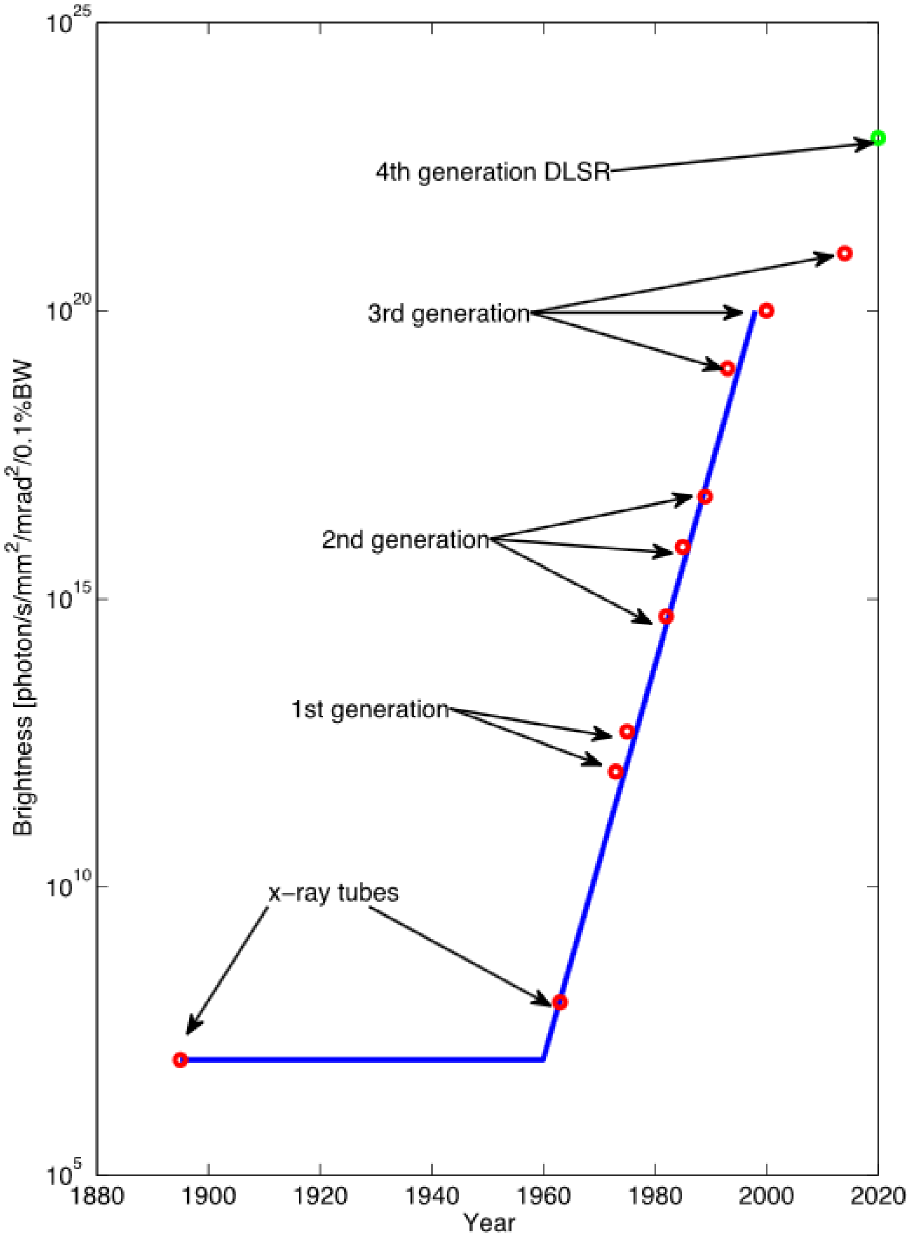


FY2015 faults by System through run 2015-2



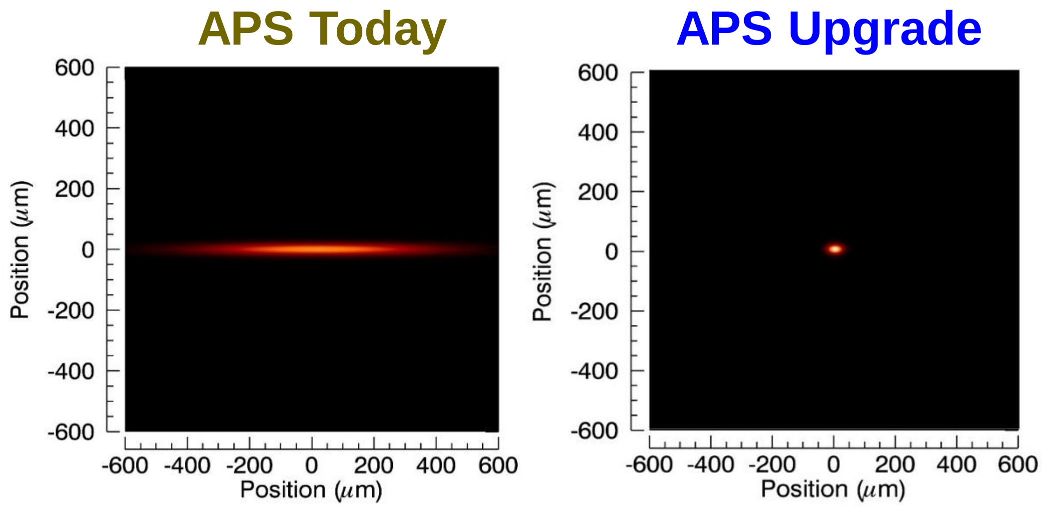
Toward DLSR

- Revolutionary increase in storage ring brightness by a factor of 1000 has been proposed and is now being proposed, planned, or under construction at facilities around the world
- Lower-energy SR
  - Ground-breaking 3 GeV MAX-IV utilizing MBA (7BA) 500 mA, 230 pm x 8 pm
  - SIRIUS (Brazil) 3GeV 5BA with super-bend, 500 mA, 280 pm x 8 pm
- High-energy SR
  - ESRF-EBS (1st MBA ring upgrade)
    - 6 GeV 7BA-EBS
    - 200 mA, ε_x= 135 pm ε_y= 3 pm
  - APS-U
    - 6 GeV 7BA
    - 200 mA, ε_x= 67 pm, ε_x= 41 pm ε_y= 8 pm
  - SPring-8-II
    - 6 GeV 5 BA
    - 100 mA, ε_x= 149 pm



Motivation for APS-U

- Build the world's leading high-brightness hard x-ray synchrotron facility
- The APS Upgrade is a **next-generation facility:**
  - Optimized for hard x-rays
  - Incorporating advanced beamlines, optics and detectors
  - 'Round' source ideal for imaging
- APS-U exceeds the capabilities of today's storage rings by **2 to 3 orders of magnitude** in
  - Brightness, coherent flux, nano-focused flux

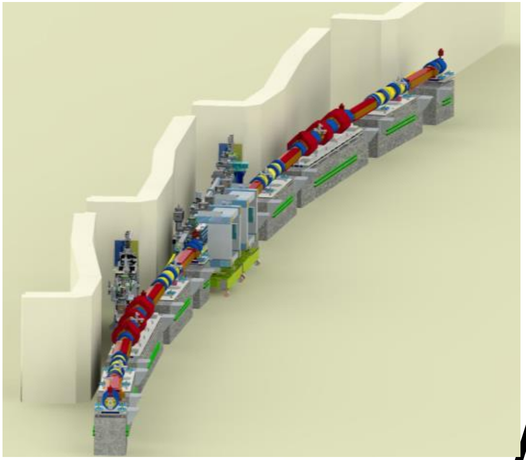


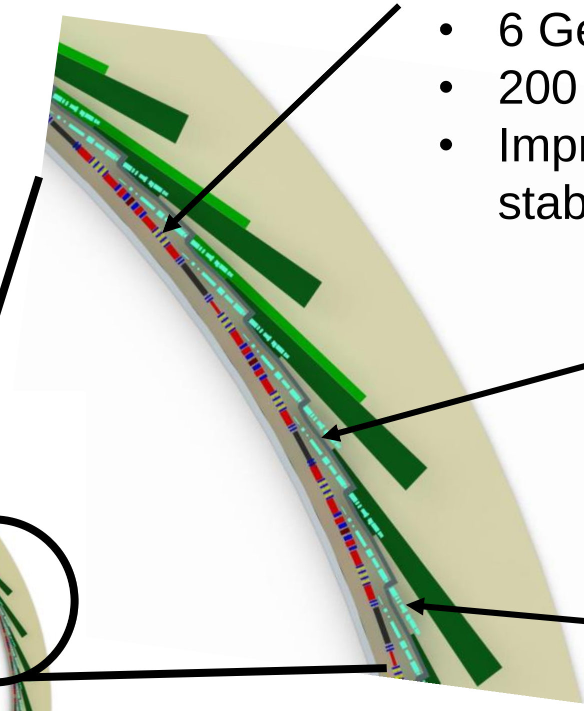
Technical Features

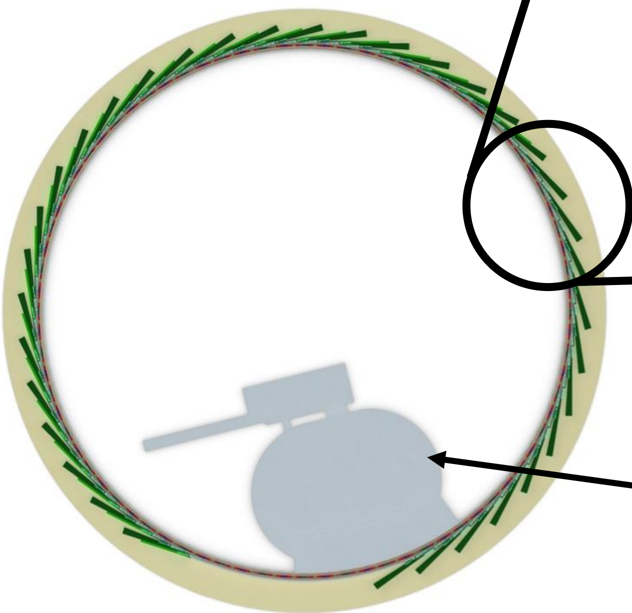
- 6 GeV storage ring, 200 mA, swap-out injection
- Circumference 1100 m
- Multi-bend achromat (7 bend) lattice
- High-brightness, ultra-low emittance: ε_x < 75 pm goal
- Diffraction limited vertical emittance to 15 keV, horizontal emittance to 2 keV
- 35 ID straight sections with >60 operating beamlines
- Flexible operation: High-brightness and timing modes, round and flat beams

APS-U Scope

- SR, IDs, FEs







New Storage Ring

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

New Insertion Devices

- Incorporate SCUs on selected beamlines

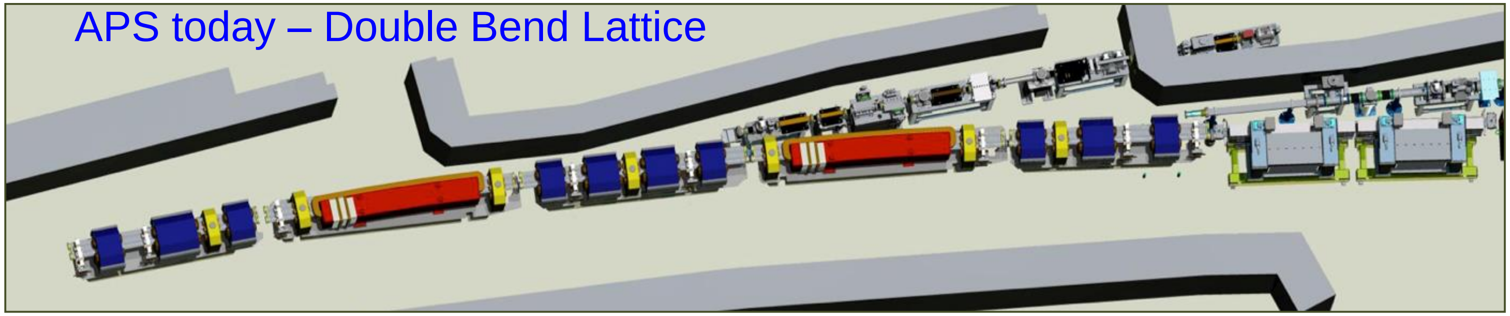
New/upgraded Front-ends

- Common design for maximum flexibility

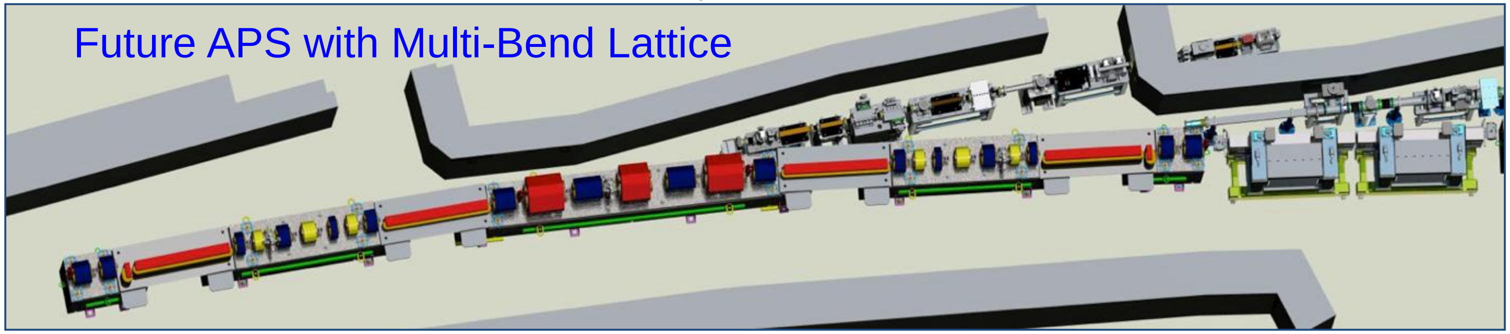
Injector improvements

- Increase performance beyond present capability

Multi-Bend Achromat Lattice



~50-fold reduction in horizontal emittance

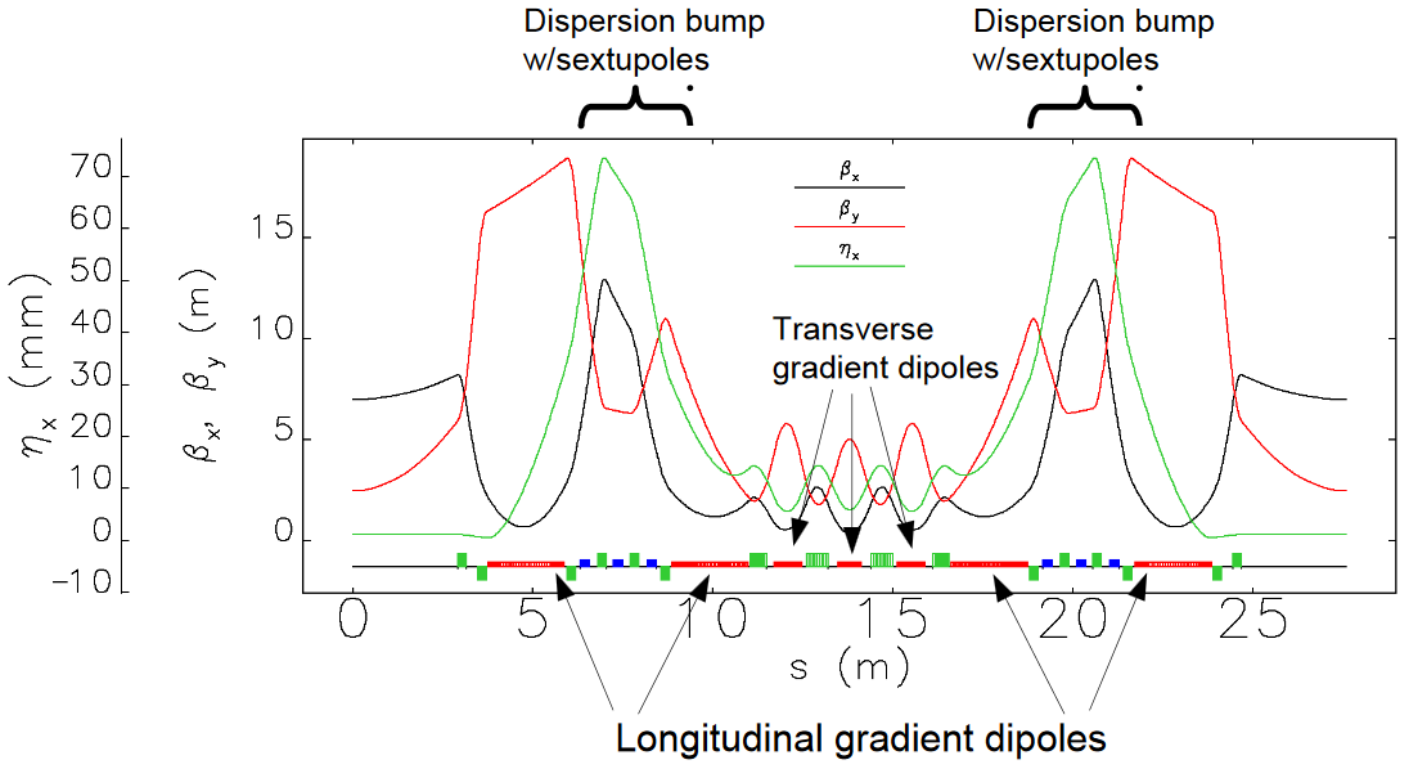


$$\varepsilon_x = C_L \frac{E^2}{N_D^3}$$

E = Beam energy (E = 6 GeV for APS MBA)

N_d = Number of dipoles per sector (N_d = 7 for APS MBA)

67-pm Hybrid 7BA Lattice Concept

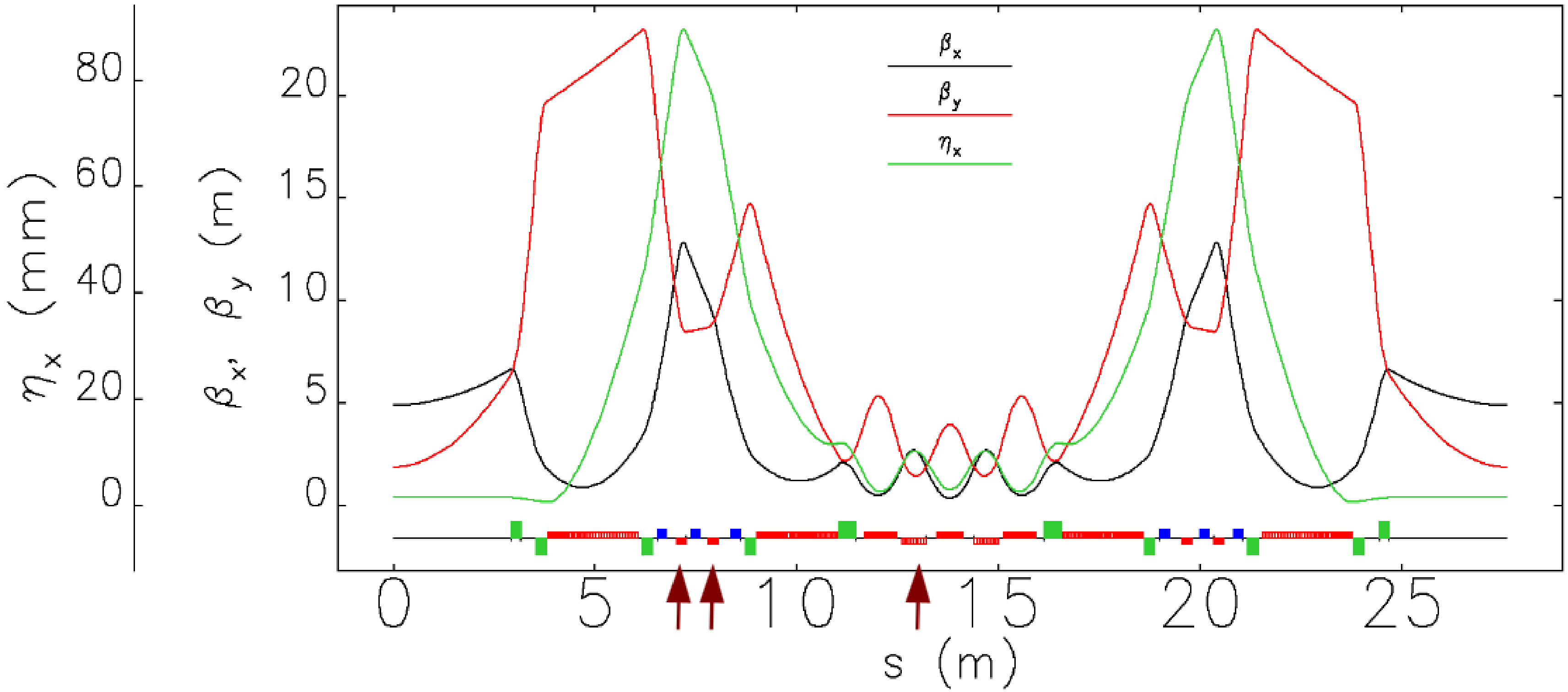


- Inspired by ESRF-EBS design*
- Phase advance of $\Delta\varphi_x = 3\pi$ and $\Delta\varphi_y = \pi$ between corresponding sextupoles chosen to cancel geometrical sextupole kicks
- Thick, interleaved sextupoles:
  - Imperfect cancellation

M. Borland/Y. Sun , APS/ANL

*L. Farvacque et al., IPAC13

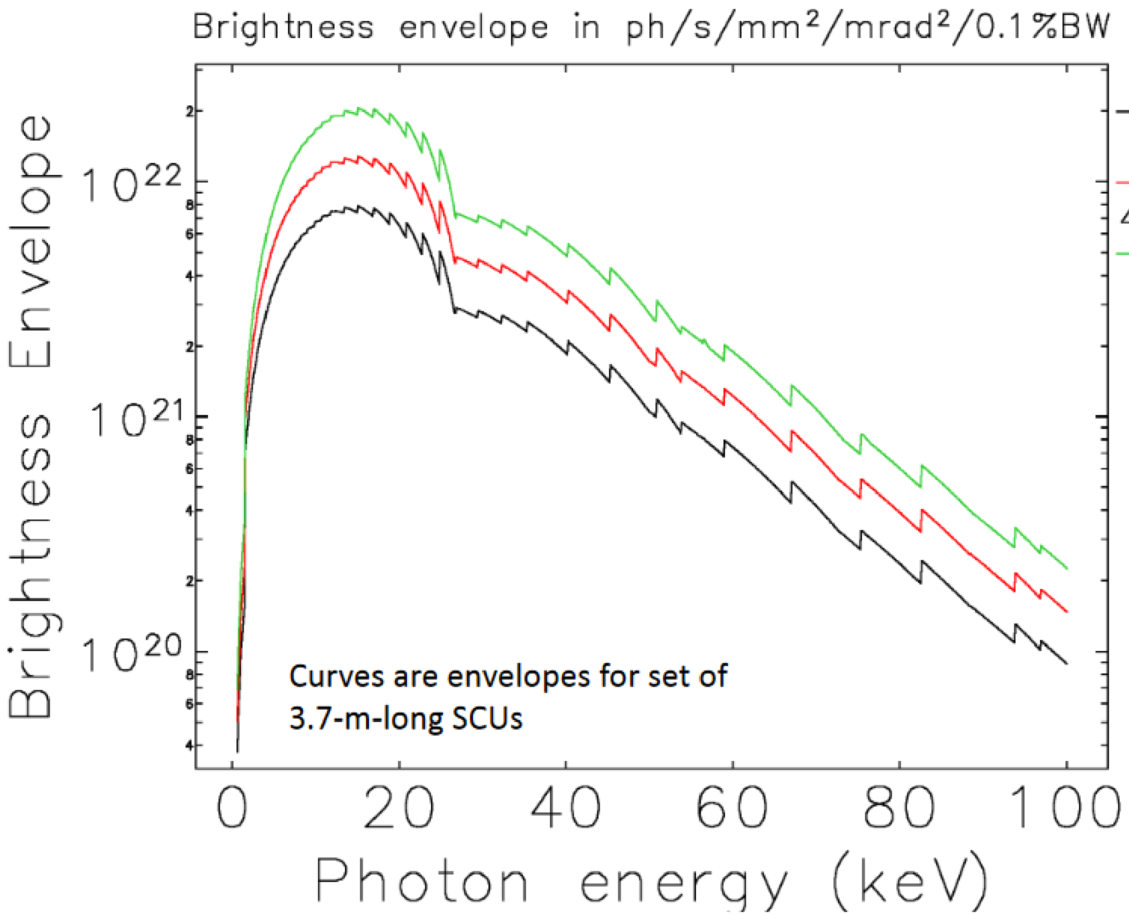
41-pm lattice with reverse bends

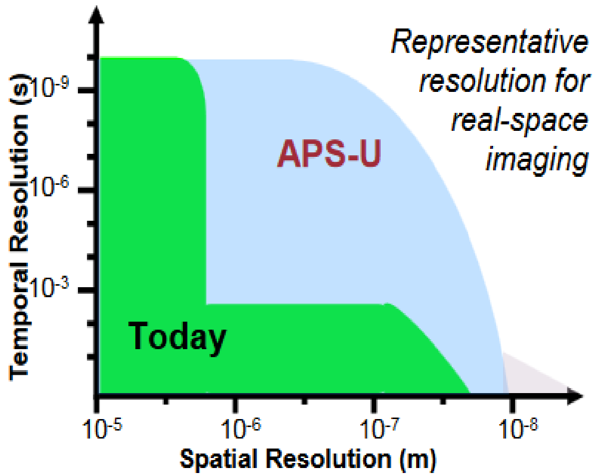


- Reverse bends in Q4,Q5, and Q8
- Emittance reduced from 67 pm to 41 pm
- Max η_x from 74 mm to 90 mm
- Weaker sextupole magnets

M. Borland/Y. Sun , APS/ANL

Brightness comparison for 324 bunch mode





- Additional improvement (about 2-fold) possible with flat beam (κ=0.1)
- 90-pm is no longer an option due to lower brightness

M. Borland/Y. Sun , APS/ANL

APS-U Technical Performance Summary

- For 67 pm lattice

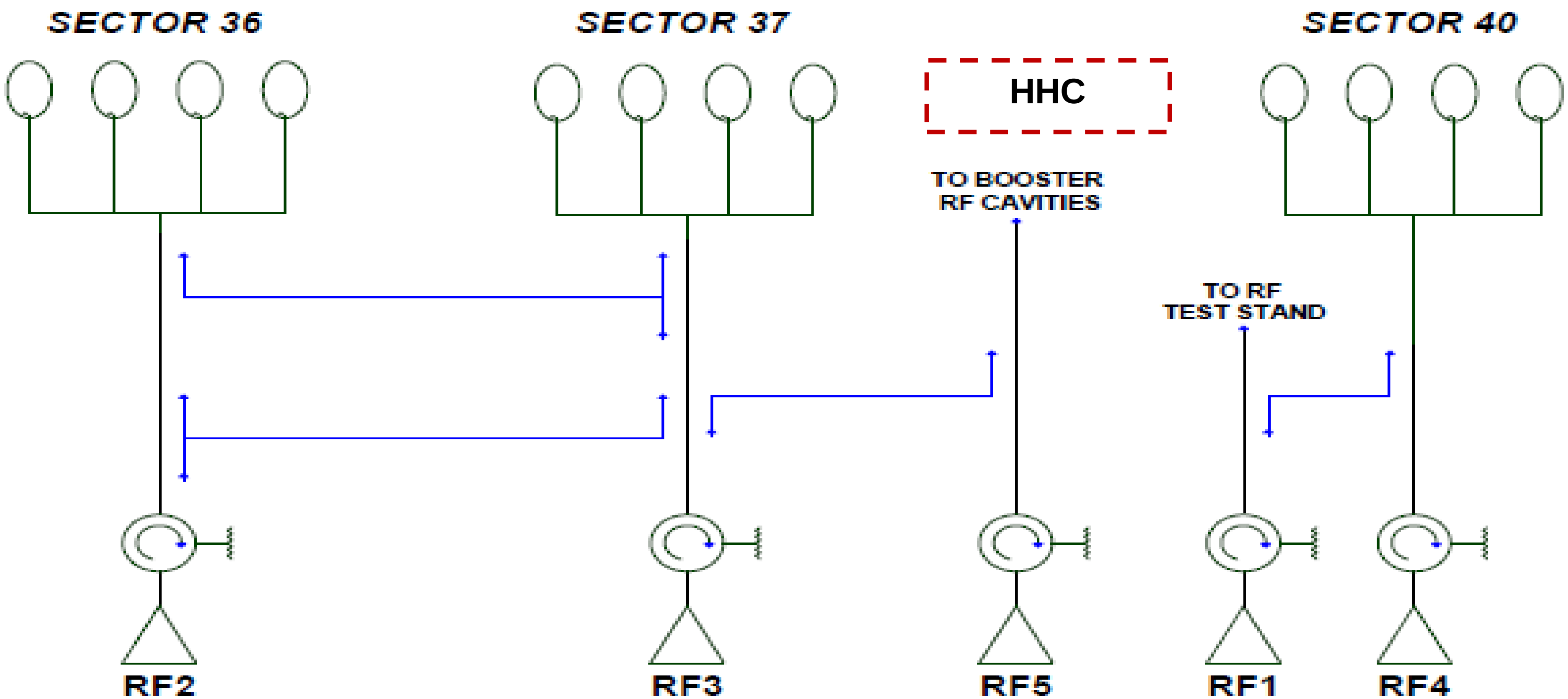
	APS-U Timing Mode	APS-U Brightness Mode	APS Now	Units
Beam Energy	6	6	7	GeV
Beam Current	200	200	100	mA
Number of Bunches	48	324	24	
Effective Emittance	47	68	3100	pm-rad
Emittance Ratio	1	0.1	0.13	
Horizontal Beam Size (rms)	18.2	21.8	274	µm
Horizontal Divergence (rms)	2.6	3.1	11.3	µrad
Vertical Beam Size (rms)	10.8	4.1	10.8	µm
Vertical Divergence (rms)	4.4	1.7	3.7	µrad
Brightness - 20 keV	90	203	0.6	(*)
Pinhole Flux - 20 keV	185	211	20.1	(#)
Coherent Flux - 20 keV	87	195	0.6	10^{11} photons/sec
Single-Bunch brightness - 20 keV	188	63	2.6	(&)

(*) 10^{20} photons/sec/0.1%BW/mm^2/mrad^2

(#) 10^{13} photons/sec in 0.5x0.5 mm^2 pinhole at 30 m

(&) 10^{18} photons/sec/0.1%BW/mm^2/mrad^2

APS-U RF System Considerations



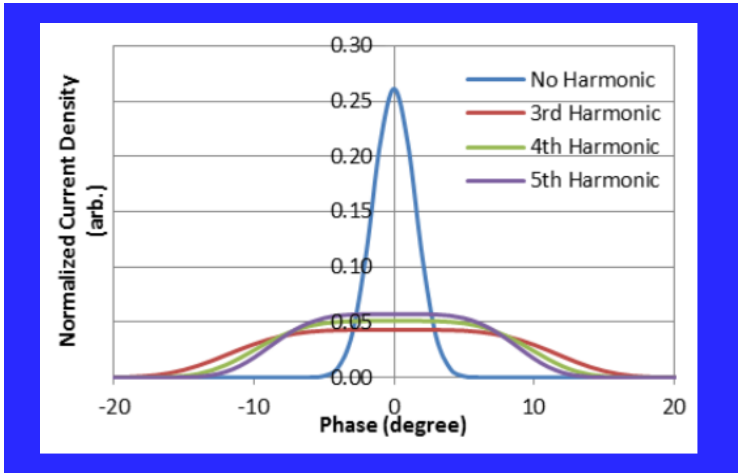
- Sector 38 rf cavities removed -- nominal operation with twelve cavities at ≈ 90kW/cavity to support 200mA stored beam
- Operation on eight cavities possible at higher cavity power
- “Hot-standby” rf stations preserved
- RF3 switchable to power booster

APS-U RF System Considerations- Performance Parameters

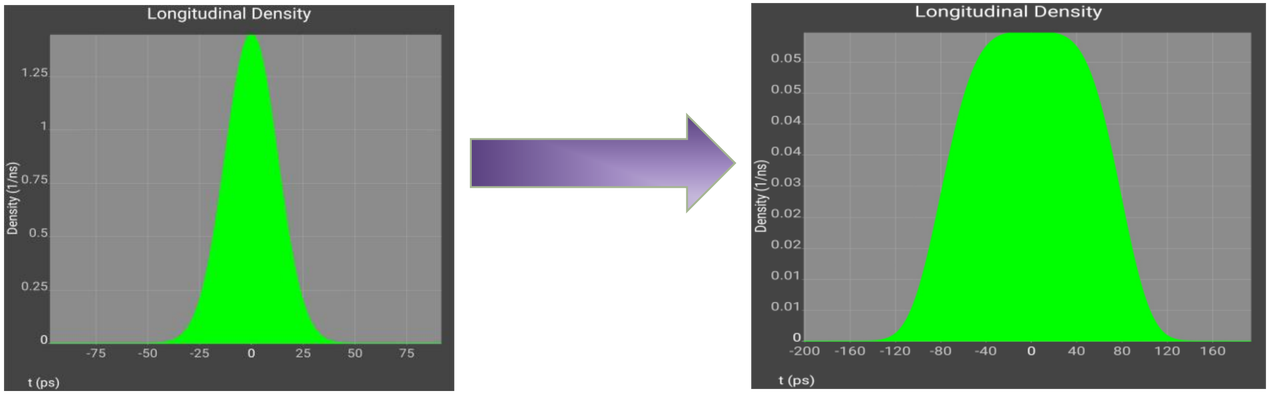
Parameter	Unit	352 MHz RF System
Beam Energy	GeV	6
Beam current	mA	200
Momentum compaction		5.66×10^{-5}
$\Delta f_{rf} / f_{rf}$		$- 3.55 \times 10^{-5}$
Synchrotron frequency	kHz	0.7
Accelerating voltage (±4% BHH with HHC)	MV	5.53
Energy loss per turn with IDs (67 pm)	MeV	3.57
rf bucket half-height	%	4
Cavity quality factor unloaded		48,000
Q_{ext}		11.3×10^3
Q_L		9.1×10^3
3dB ½-BW	KHz	10.3
R/Q	Ω	226.7
R_s	MΩ	10.88
E_p @1MV	MV/m	9.7
Cavity nominal accelerating voltage	MV	0.461
Number of cavities		12
Harmonic number		1296
Beam power/cavity (includes losses to HHC)	kW	63.2
Wall power/cavity	kW	19.5
Gen. power/cavity	kW	82.7
Total required power (15% overhead, 10% loss)	kW	1240

Motivation for Higher Harmonic Cavity*

- A number of collective effects foreseen to present challenges to APS-U
  - Intra-beam scattering
  - Touschek scattering
  - Single-bunch collective instabilities
  - Multi-bunch collective instabilities



- SB effects can be mitigated by lengthening the bunch
  - Reduces electron density
  - Reduces peak current
  - Narrows frequency spectrum
- Harmonic cavity allows effective bunch-lengthening
  - Bunch-lengthening using a higher harmonic cavity (HHC) can help
  - Optimized 4th harmonic HHC increases rms bunch duration from 12.3 to 50 ps
  - Naively expect ~4-fold reduction in IBS and Touschek rates



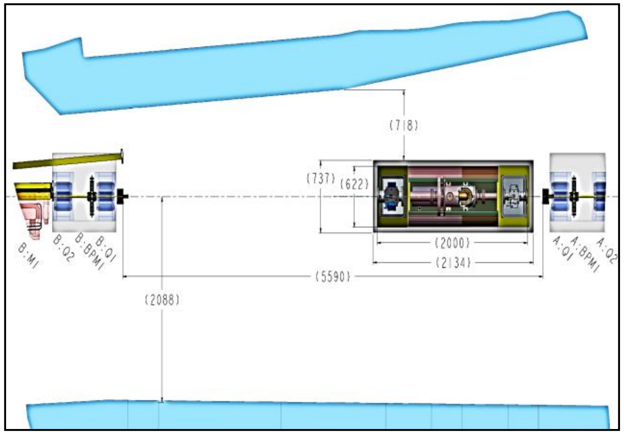
*M. Borland, ANL/APS

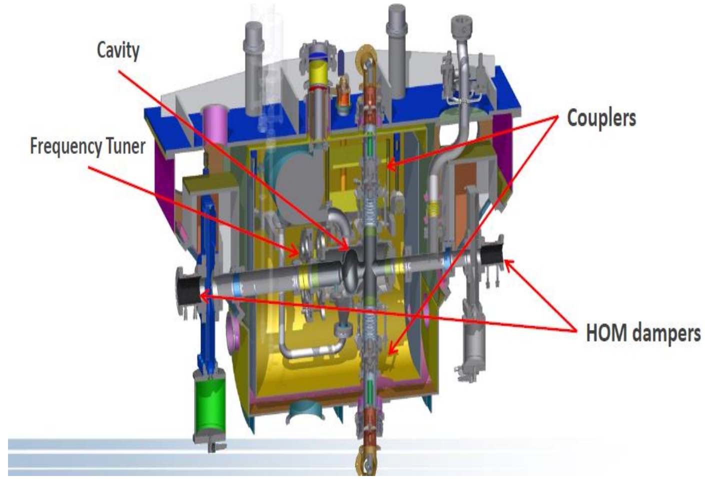
HHC Parameters*

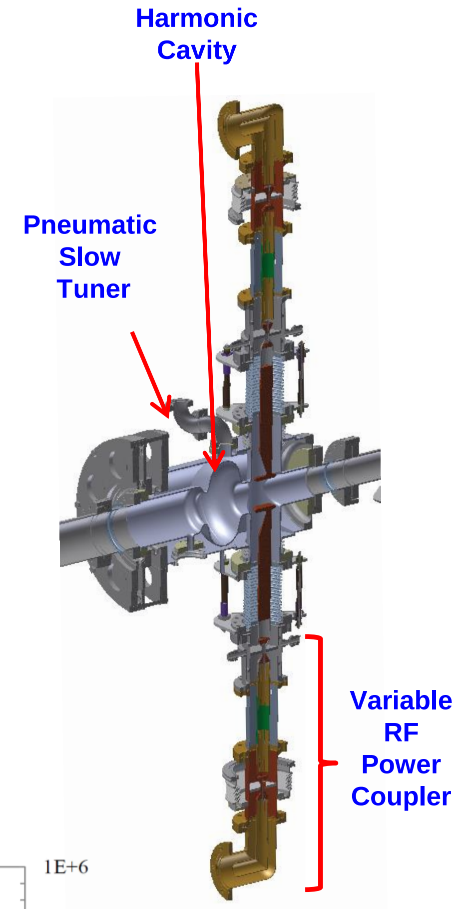
	Parameter	Symbol	Unit	Value
	Operating Temperature	T	K	2.1 or 4.3
	R/Q	r/Q	Ohm	104
	Cavity Quality Factor (2.1 K, 4.3K)	Q_0		$1x10^{10}$, $2x10^8$
	External Q range	Q_{ext}		$2x10^5$-$2x10^7$
	Detuning Frequency	Δf_r	kHz	13.5
	Q_L nominal	Q_L		$6x10^5$
	Cavity Resonant Frequency	f_r	MHz	1407.8
	Beam-Induced Voltage	V_b	MV	1.1
	Detuning angle	ψ_h	degrees	85.0
	Cavity Loaded Bandwidth	Δf_{BW}	kHz	2.35
	Beam Loss Power (nominal Q_L=$6x10^5$)	P_b	kW	12.8
	Cavity Wall Loss Power (2.1 K, 4.3K)	P_{wall}	W	1, 58
	Peak Surface Electric Field	E_{peak}	MV/m	21
	Peak Surface Magnetic Field	B_{peak}	mT	43

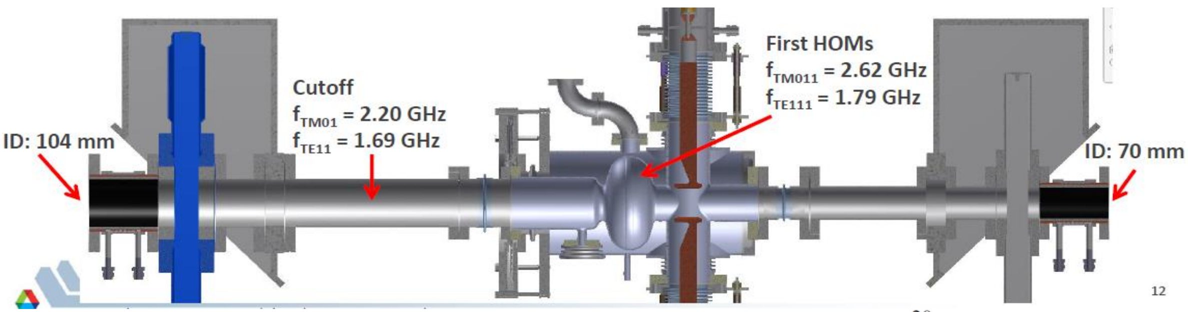
Courtesy of M. Kelly PHY/ANL

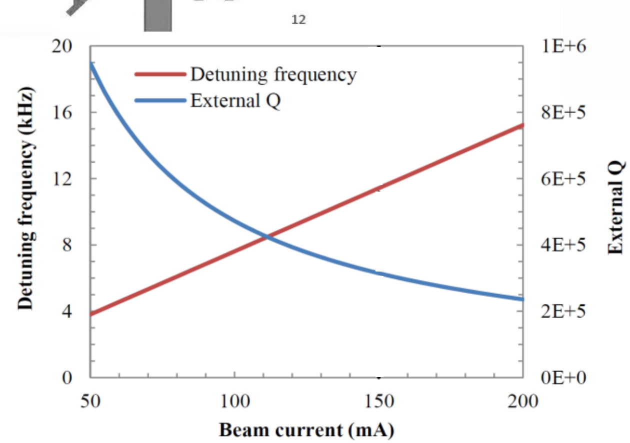
HHC Cryomodule







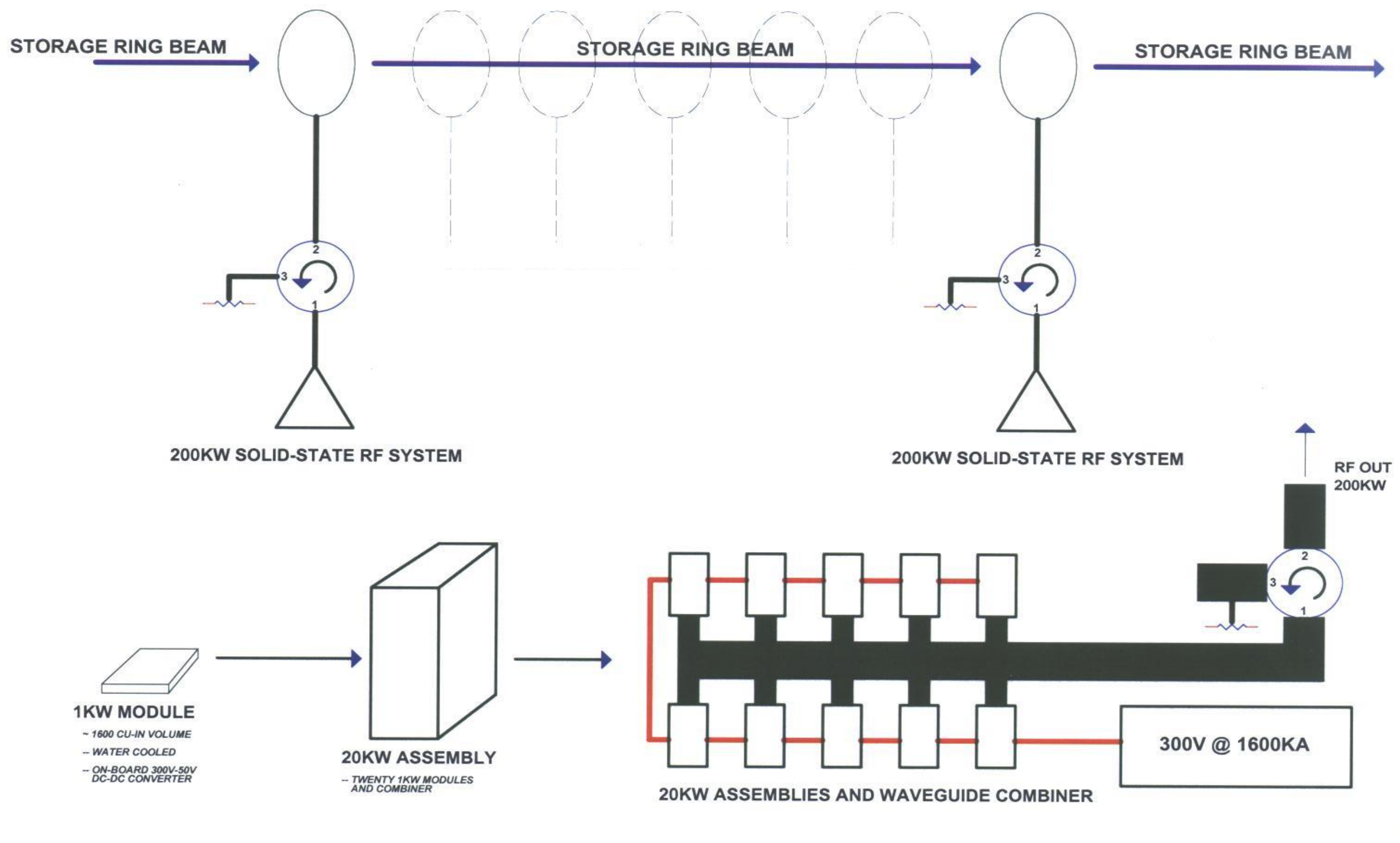




Courtesy of M. Kelly PHY/ANL

Long-Term APS RF System option

- Replace present klystrons with modern solid-state rf amplifier systems
  - Eliminates reliance on klystrons and HVPS upgrades



Long-Term APS RF System option, cont.

- Implement a flexible digital LLRF system
  – Substantial changes in the design are possible by changing program routines without affecting the hardware
  – With digital LLRF, amplitude and phase stabilities better that 0.1% and 0.1°areacheivable.
- From operation perspectives, we will pursue that digital LLRF in lieu of upgrading our analog electronics
  – Address obsolescence issues
  – Reduces maintenance cost and repair/maintenance effort
  – It is more cost effective
  – Would provide more RF control flexibility, better detection, and diagnostics capabilities
  – We are evaluating next generation chassis platforms with COTS products
    - Flexibility in product choices and expansion over 20+ year lifetime after APS-U
    - Flexibility in reconfiguring the system while driving the car (e.g., transitioning from klystron to solid-state)
    - Would like to standardize across all our RF systems

Lower Frequency RF System Alternative

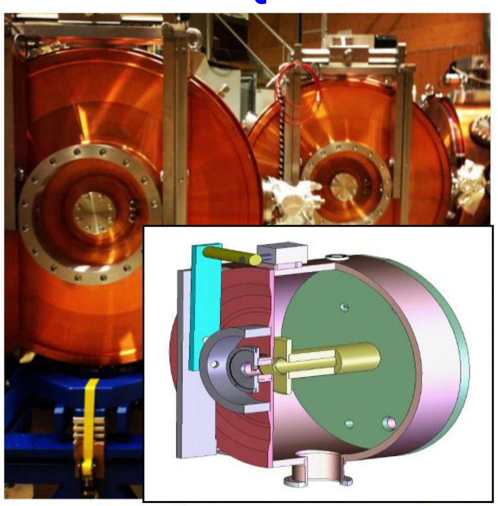
- Explored both 88- and 117-MHz RF systems

	90pm	67pm	68pm-HB	41pm-RB
Lattice Parameters				
Energy loss per turn w/IDs [MeV]	3.19	2.77	2.78	3.30
Bucket Half-Height [%]	4.0	4.0	4.0	4.5
117 MHz (Fundamental)				
Voltage [MV_{pk}]	4.114	3.752	3.762	4.307
P_{beam} @200mA [kW]	715	621	623	739
352 MHz (Harmonic)				
Voltage [MV_{pk}]	0.780	0.778	0.779	0.837
P_{beam} @200mA [kW]	-77	-67	-67	-79
Bunch Length (I=0)				
rms [psec]	137	148	148	154
FWHM [psec]	430	464	463	481

Cavity Options

- We reviewed various options [1],[2] :
  - **MAX-IV QWR** [quarter-wave resonator, normal conducting]
    - Voltage limited, but offers an operational design to leverage from
  - **Symmetric reentrant cavity** [normal conducting]
    - Improved shunt impedance and peak fields over QWR, but longer cavity
    - conceptual design, would require extensive R&D thus is a higher risk
  - **Superconducting QWR**
    - Beam power is 620 kW (67pm) to 740 kW (41pm-RB) therefore reduction in number of cavities is limited to input coupler design
    - SRF technology increases complexity and risk
    - Also only at conceptual design

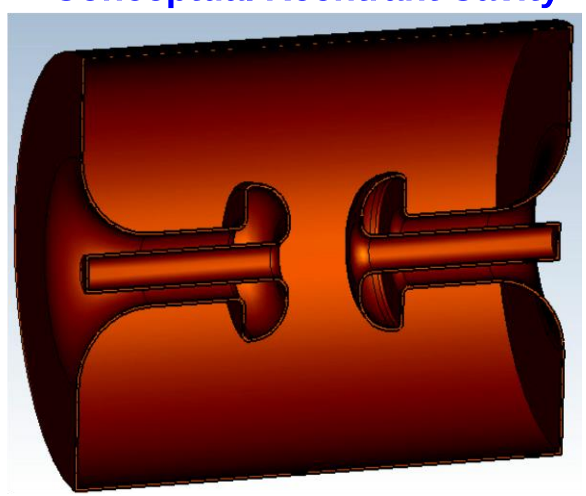
MAX-IV QWR



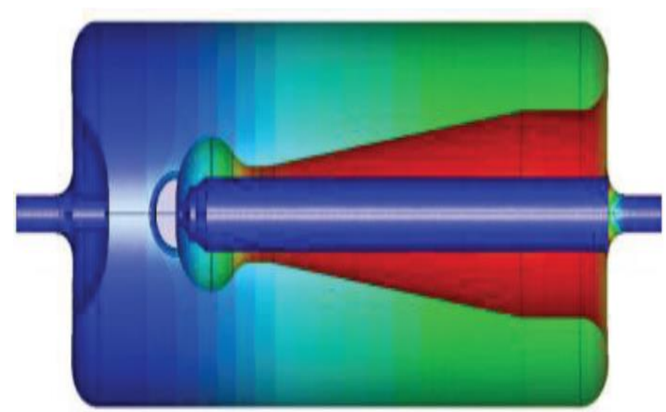
The RF cavities will soon be installed at MAX IV.

Courtesy of P. Tavares, MAX-IV

Conceptual Reentrant Cavity



Conceptual SRF QWR



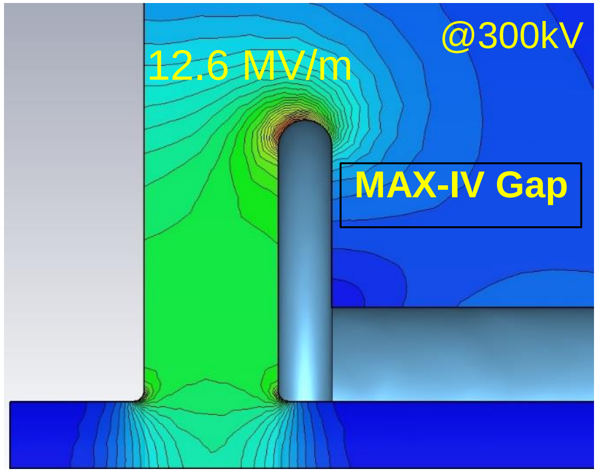
[1] AOP-TN-2017-038, Nov. 2015
[2] RF-TN-2016-001, Jan. 2016

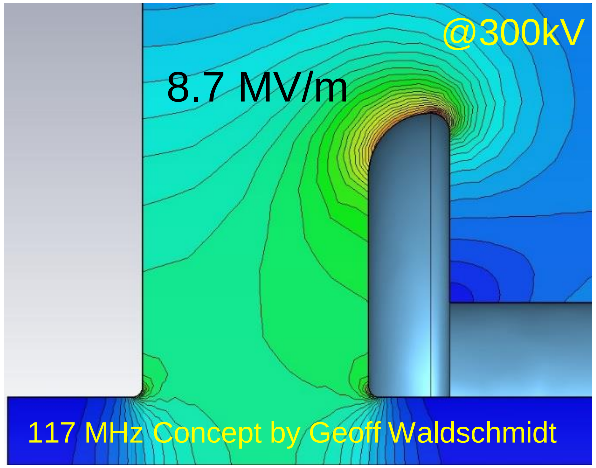
Cavity Options

- The wise choice is to leverage off of the MAX-IV design
- But need to modify for higher voltage to keep # of cavities reasonable
  - Modified electrode shape and gap length

	MAX-IV	117 MHz Mod.	88 MHz Mod
$(R/Q)_a$ [Ω]	168.3	187.8	139.2
Q_o	~20,200	~20,000	~17,150
R_a [MΩ]	~3.4	~3.8	~2.4
E_{peak}/V_{cav} [1/m]	42	29	25.3
V_{cav} limit [kV_{pk}] *	288	413	425
Length Estimate [m]	0.54	0.65	0.65

* Kilpatrick limit of ~12 MV/m @117MHz and ~10.8 MV/m @88MHz





- MAX-IV uses 6 cavities
  - each at ~300kV, ~27kW wall loss

117MHz Power Requirements

67pm

67pm	117 MHz Fundamental			352 MHz Harmonic
Voltage	3.752 MV			0.778 MV
# of Cavities	10	11	12	2
V_{cav} [kV]	375	341	313	389
P_{cav} [kW]	37	31	26	14
P_{beam}/cav [kW]	62	56	52	-33
P_{rev}/cav [kW]	0	0	0	20
P_{gen}/cav [kW]	100	87	78	0
Total Installed RF [kW]	995	961	933	0

41pm-RB

41pm-RB	117 MHz Fundamental			352 MHz Harmonic
Voltage	5.251 MV			0.981 MV
# of Cavities	10	11	12	2
V_{cav} [kV]	525	477	438	491
$Q_{ext} \times 10^3$	8.9	8.4	8.0	38.6
$Q_L \times 10^3$	6.2	5.9	5.7	21.4
3dB $\frac{1}{2}$ BW [kHz]	9.5	9.9	10.3	8.2
Δf [kHz]	-2.0	-2.2	-2.4	13.1
P_{cav} [kW]	73.4	60.7	51.0	22.0
P_{beam}/cav [kW]	91.9	83.5	76.6	-49.3
P_{rev}/cav [kW]	0	0	0	27
P_{gen}/cav [kW]	165.3	144.2	127.5	0.0
Total Installed RF [kW]	1652.8	1586.0	1530.4	0.0

88 MHz Power Requirements

67pm

	88 MHz Fundamental			352 MHz Harmonic
Voltage	3.465 MV			0.489 MV
# of Cavities	10	11	12	2
V_{cav} [kV]	346	315	289	244
P_{cav} [kW]	50	42	35	5
P_{beam}/cav [kW]	59	54	49	-18
P_{rev}/cav [kW]	0	0	0	12
P_{gen}/cav [kW]	109	95	84	0
Total Installed RF [kW]	1092	1046	1008	0

41pm-RB

	88 MHz Fundamental			352 MHz Harmonic
Voltage	3.988 MV			0.518 MV
# of Cavities	10	11	12	2
V_{cav} [kV]	399	363	332	259
P_{cav} [kW]	67	55	46	6
P_{beam}/cav [kW]	70	64	58	-21
P_{rev}/cav [kW]	0	0	0	15
P_{gen}/cav [kW]	137	119	105	0
Total Installed RF [kW]	1368	1307	1257	0

Summary

- We continue to have excellent operation statistics
  - Record operation reliability statistics
    - 0.08% downtime and 988.0 hours mean-time-to-beam-loss
    - Only four beam losses caused by rf over the entire year
  - Two 352MHz klystrons reached 66k and 77k hours lifetime
    - Nearly double the average expected lifetime
  - Proactive maintenance
  - Obsolescence issues are addressed
  - Hardware improvements and upgrades when possible
- For APS-U, 67-pm lattice design delivers ~100-fold increase in brightness for hard x-ray
  - 6 GeV close to optimal for hard x-ray performance
- Passive bunch-lengthening cavity works will for 48- and 324-bunch modes
- Several effects show benefit from bunch lengthening
  - Intrabeam scattering effects significantly suppressed
  - Detailed Touschek lifetime calculations confirm the beneficial effort
  - Increase single-bunch instability thresholds
  - Reduced energy spread and fluctuations
- Long-term goal is to replace klystrons with SSAs