Advanced Photon Source Upgrade Plans

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Seminar at BESSY

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U.S. Department of Energy

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Outline

- Introduction
- Near-term facility upgrades (5-10 yrs)
  – Evolutionary
- Far-term upgrade options (>10 yrs)
  – Revolutionary
  – R&D
- Summary

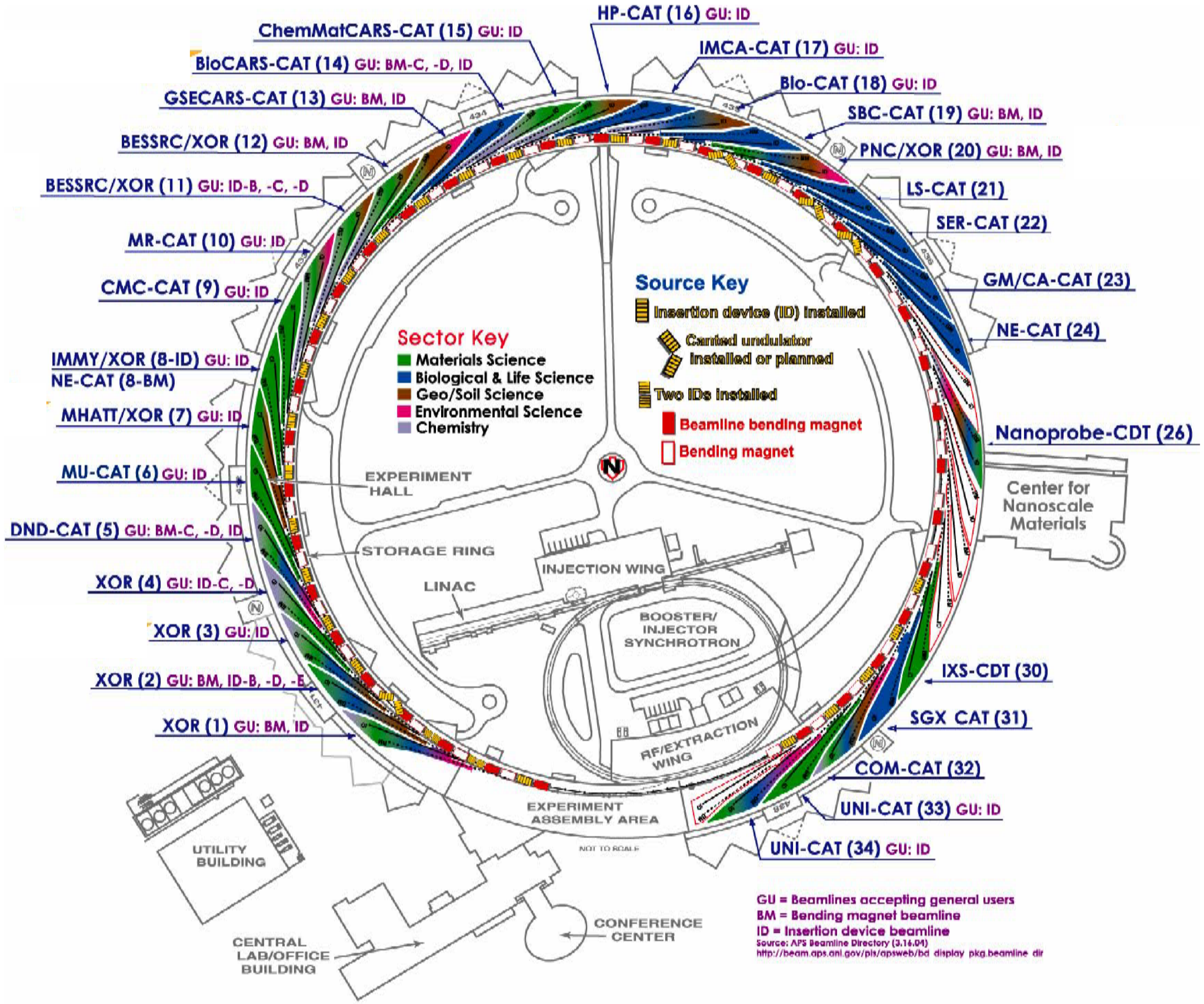
Introduction

- APS is a mature third-generation light source
  - In operation for over a decade
  - Performance and stability incrementally improved
    - Top-up operation
    - Emittance pushed down to 3.1 nm; close to the practical minimum with existing hardware
- Meanwhile,
  - Large, on-going investment in beamlines and facilities
  - Next-generation sources are on the horizon (LCLS, NSLS II, etc)
- Upgrades are required to keep APS relevant
  - Near-term evolutionary
  - Far-term “revolutionary” in line with U.S. Department of Energy Office of Science 20-year plan

Short introduction to APS

- 7 GeV, 100-mA x-ray synchrotron operating since 1995
- 31 insertion device (ID) beamlines and 24 bending magnet beamlines
- >3,000 users per year
- 98.6% availability, 101 h MTBF (2007)
- 3.1 nm eff. emittance, 1% coupling
- Flexible bunch patterns and lattice

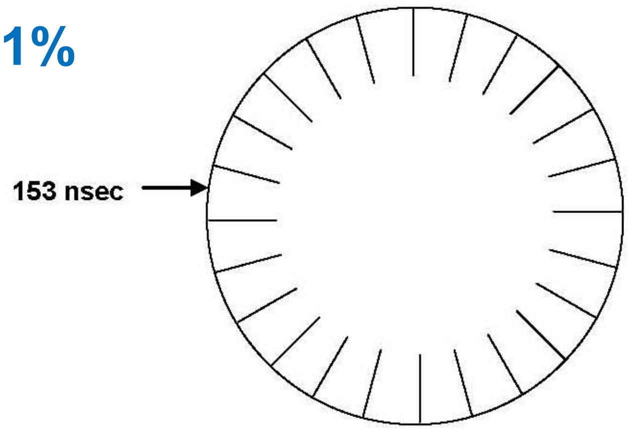
APS injectors and beamlines



APS operating modes, 100 mA

Singlet 24

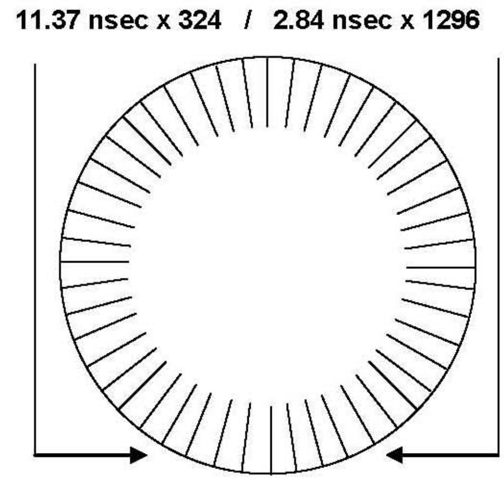
61%



← **Topup**

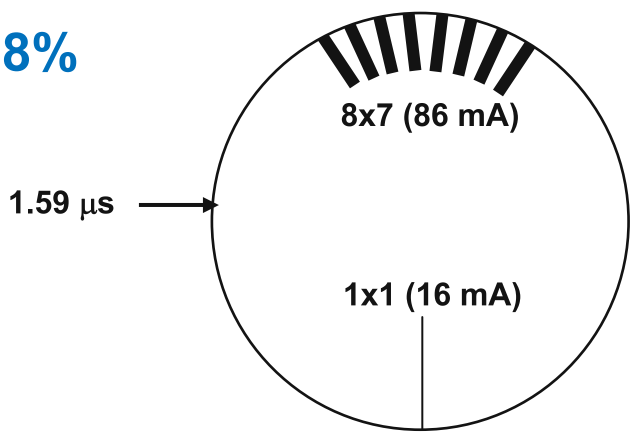
Multi bunch 324 / 1296

21%



Hybrid with singlet 1 + 8*7

18%



Non-topup→

Near-term upgrade options (5-10 yrs)

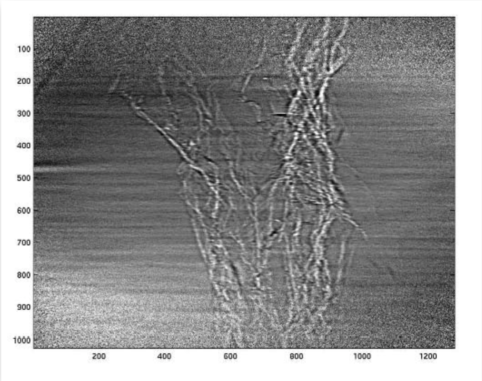
- APS Renewal plan in preparation, expected completion Oct 2008
- Proposals collected March 2008 for accelerator systems and beamlines
- Beamlines include detectors, optics, and undulator requirements
- Accelerator systems includes
  - Spares/obsolescence
  - Customized undulators (including superconducting)
  - Customized lattices made possible by individually powered power supplies on all quad & sext magnets
  - Short-pulse capability (~ 1 ps)

Customized lattices: Reduced Horizontal Beta (RHB)

- First evaluated 2004[1,2], operational since 2007 (13% total time)
- Horizontal size reduced from 286 µm to 120 µm at expense of <10% increase in horizontal emittance
  - Improved in-line phase contrast imaging
  - Virtually transparent to other beamlines

Table 2. Parameters at RHB sectors vs. standard sectors.

Type	Horiz. Beta (m)	Horiz. Eta (m).	Horiz. Size (µm)	Horiz. Diverg. (µrad)	Vert. Beta (m)	Vert. Size (µm)	Vert. Diverg. (µrad)
Normal	19.5	0.170	286	12.0	2.9	9.0	3.1
RHB	3.2	0.078	120	29.6	5.4	12.3	2.3



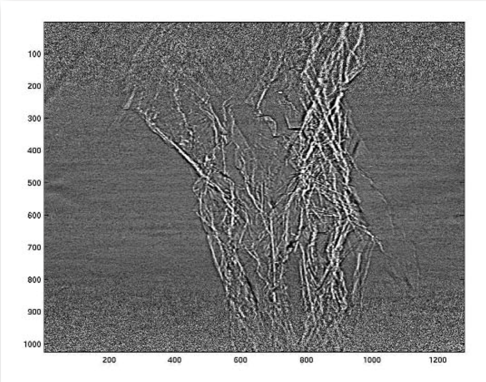


Fig. 2. Phase contrast images of an aluminum stress-crack sample, ~3 mm thick, taken with nominal beta (left) and low beta (right) (30-keV photons). Both figures show the same grey scale. (Images courtesy of Wah-Keat Lee, XSD.)

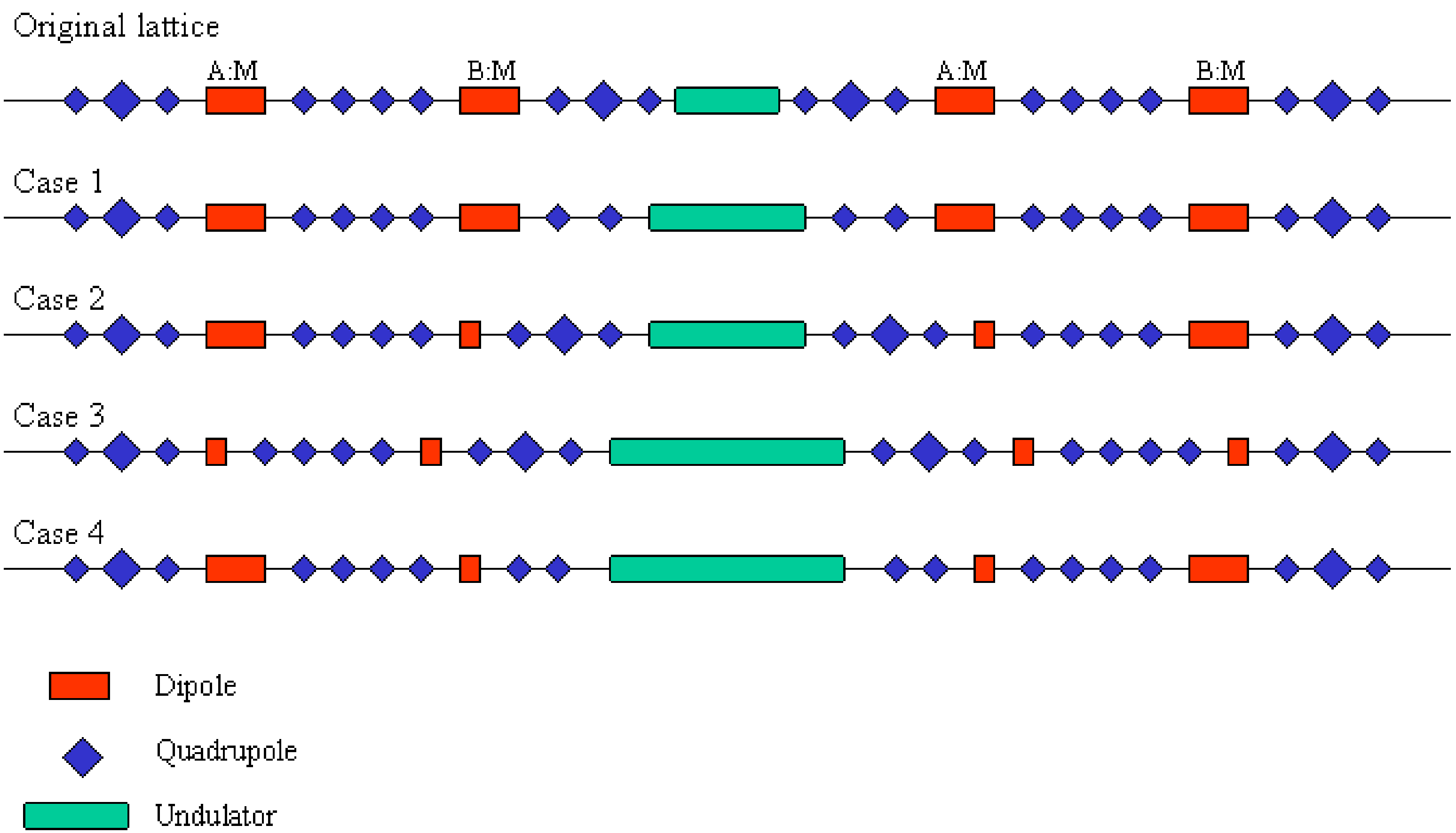
[1] V. Sajaev, P. Illinski, M. Borland, ASD/APG/2004-01 (Apr 12, 2004)
[2] M. Borland, OAG-TN-2004-056 (Dec 1, 2004)

Customized lattices: Long straights

- Benefits
  - Longer or additional, specialized undulators
  - Short pulse x-ray project
- Machine studies 2001
- Engineering study 2003-2005
- Revisited 2008 for APS Renewal
  - Challenges: commissioning during normal maintenance period
  - Tools for lattice design, linear/nonlinear modeling; calculations [1,2]
  - Tools for calculating impedance [3]

[1] M. Borland, V. Sajaev, Y.-C. Chae, L. Emery, K. Harkay , "Lattice options for and impact on storage ring of long ID (IXS)," May 8, 2003 (memo).
[2] M. Borland, OAG-TN-2008-022.
[3] Y.-C. Chae, ICFA Beam Dynamics Newsletter 45, April 2008.

Long straight options (two sectors shown)



Flange-to-flange:

5.6 m

8.5 m

8.8 m

10.8 m

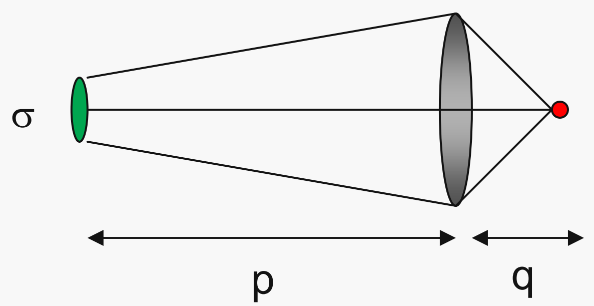
11.9 m

Case 1 most straightforward to implement (ESRF approach), but Case 3 preserves tuning flexibility and extends length albeit at increased emittance.

Customized lattices: Nanofocusing beamline

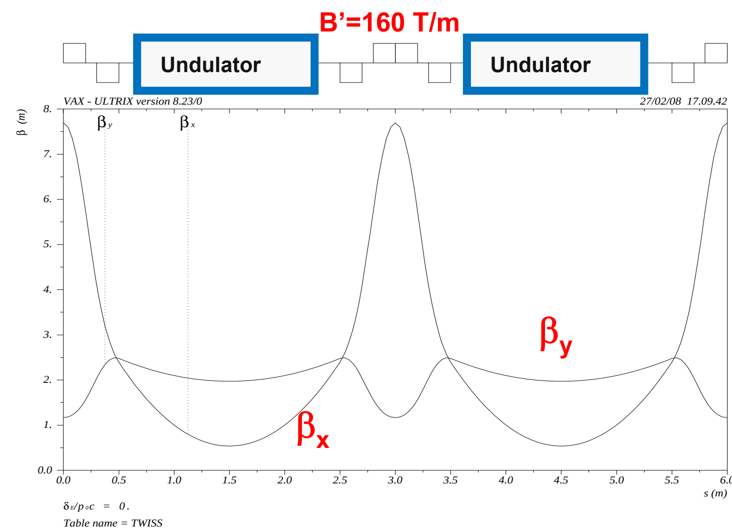
Yong-Chul Chae, Shigemi Sasaki [Y.-C. Chae, ASD/APG/2008-1 (Mar 6, 2008)]

- Motivation
  - Nano-science needs a nano-scale resolution at the sample
- Make small spot
  - Long beam line p ~ 120 m (ESRF Upgrade)
  - Small beam $\langle\sigma(s)\rangle$ ~ 40-70 μm vs. current APS's 280 μm (a proposal for the APS Renewal Plan)

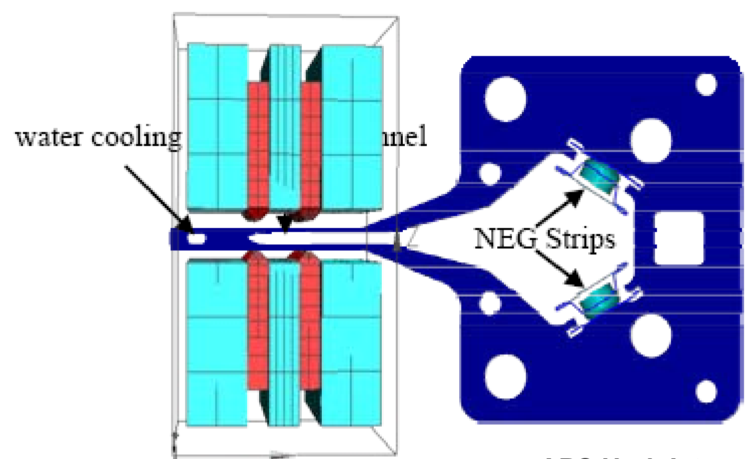


- Electron beam size along ID, $\sigma(s)$, is varying.
  - ID is a 2.4-m long extended source.
  - $\sigma(s)^2=\varepsilon\,\beta(s)$, where ε is emittance and $\beta(s)$ is lattice function in ID.
  - Effective source size to optimize in ID is not σ_{min} (ESRF approach) but $\langle\sigma(s)\rangle$.
- Spot size at sample is $\Sigma = \langle\sigma(s)\rangle \times (q/p)$.

Triplet Insertion



R&D on PM Quadrupole and Installation

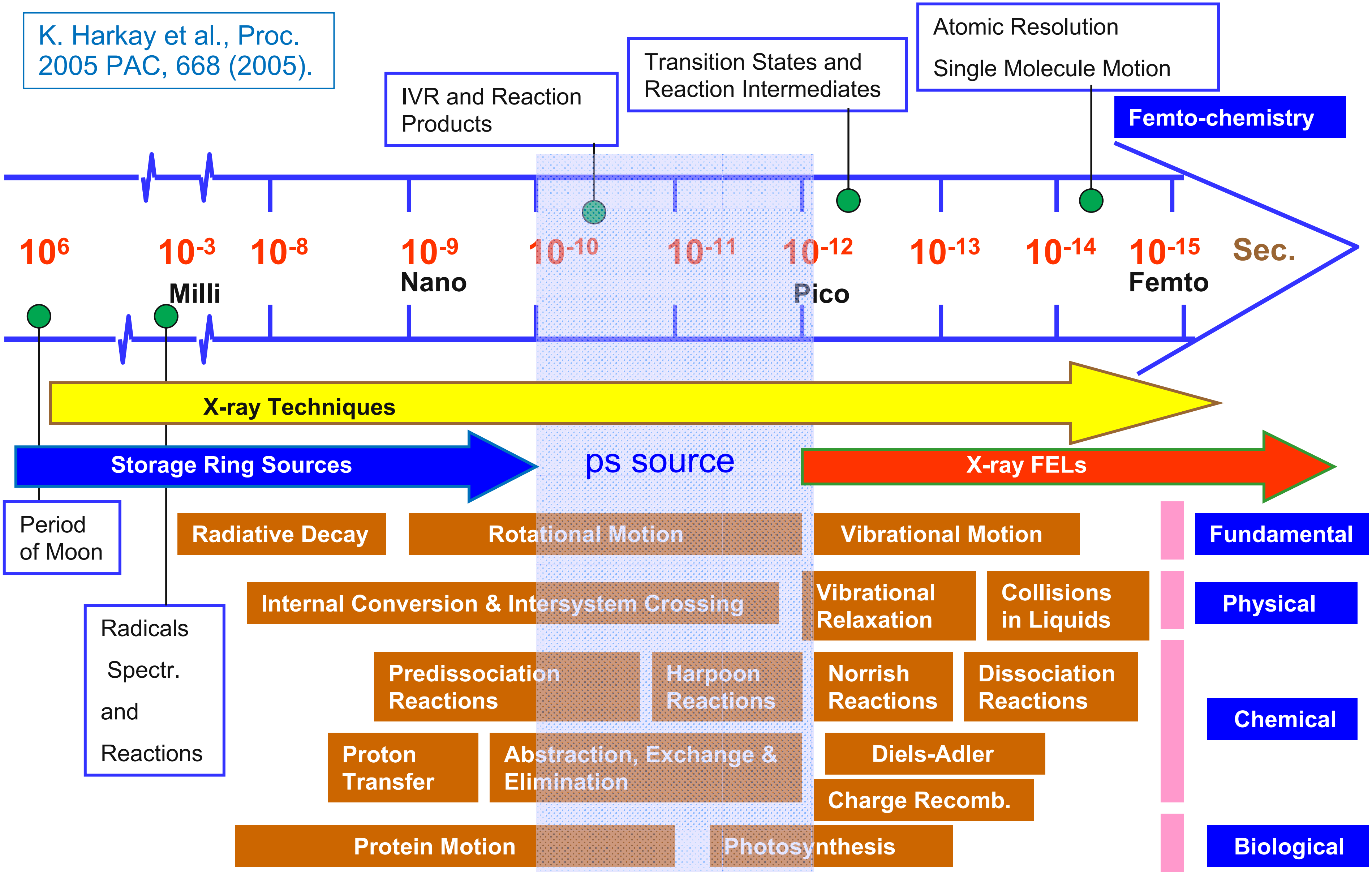


160 T/m Permanent Magnet Quadrupole designed by S. Sasaki

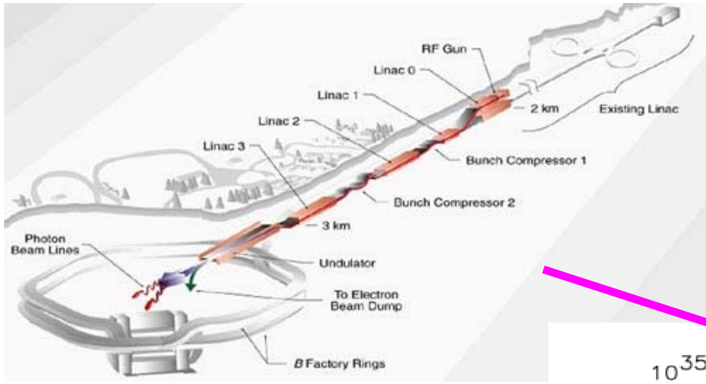
APS Undulator Chamber

Short-pulse x-rays (SPX) at APS (2004 Workshop)

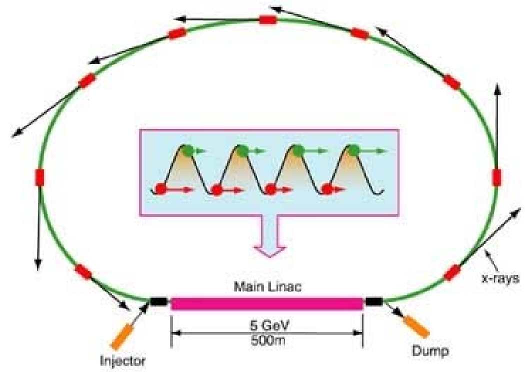
K. Harkay et al., Proc. 2005 PAC, 668 (2005).

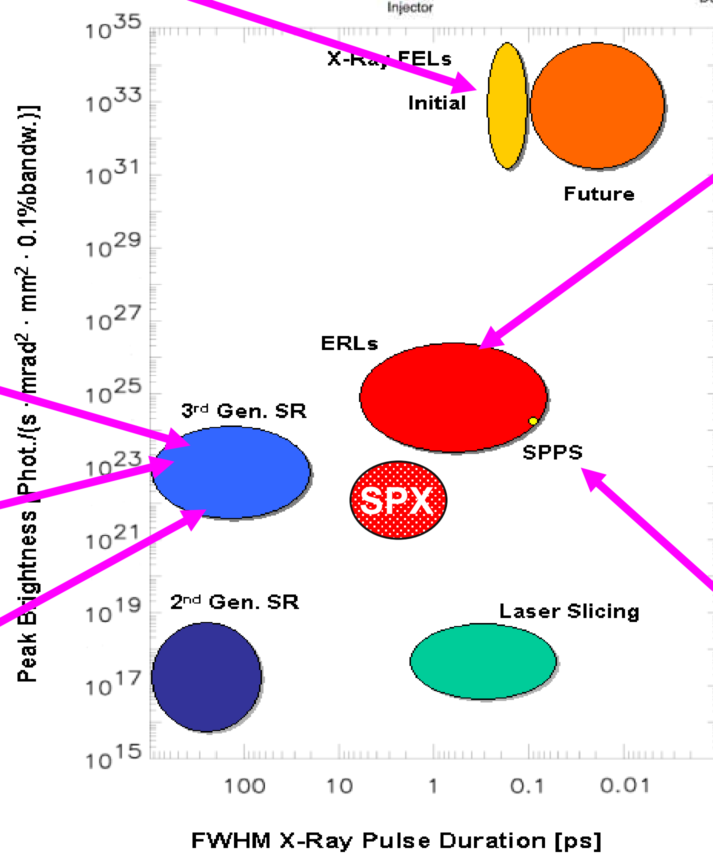


A New Era of Ultrafast X-ray Sources

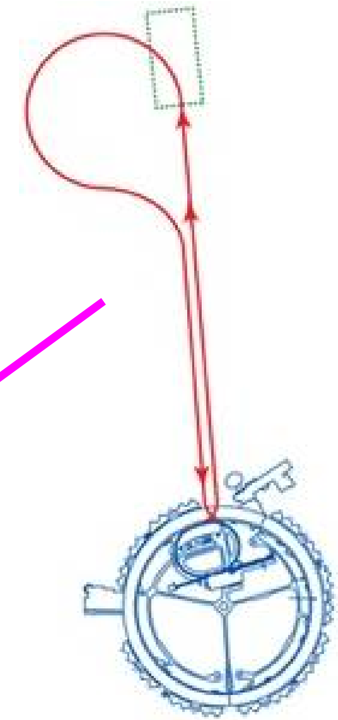


LCLS: 120Hz





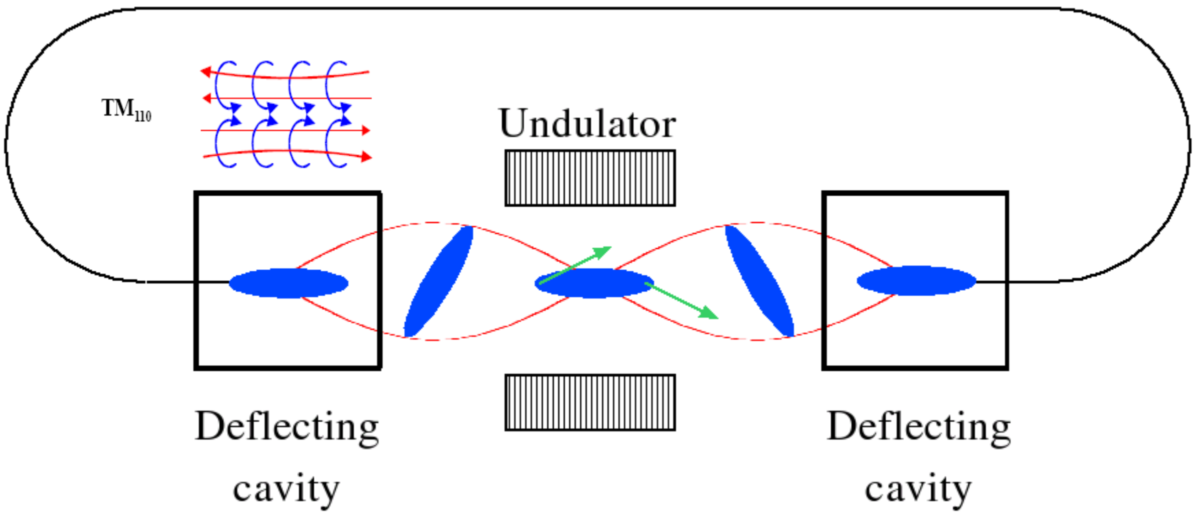
APS ERL Concept



SPPS 10Hz

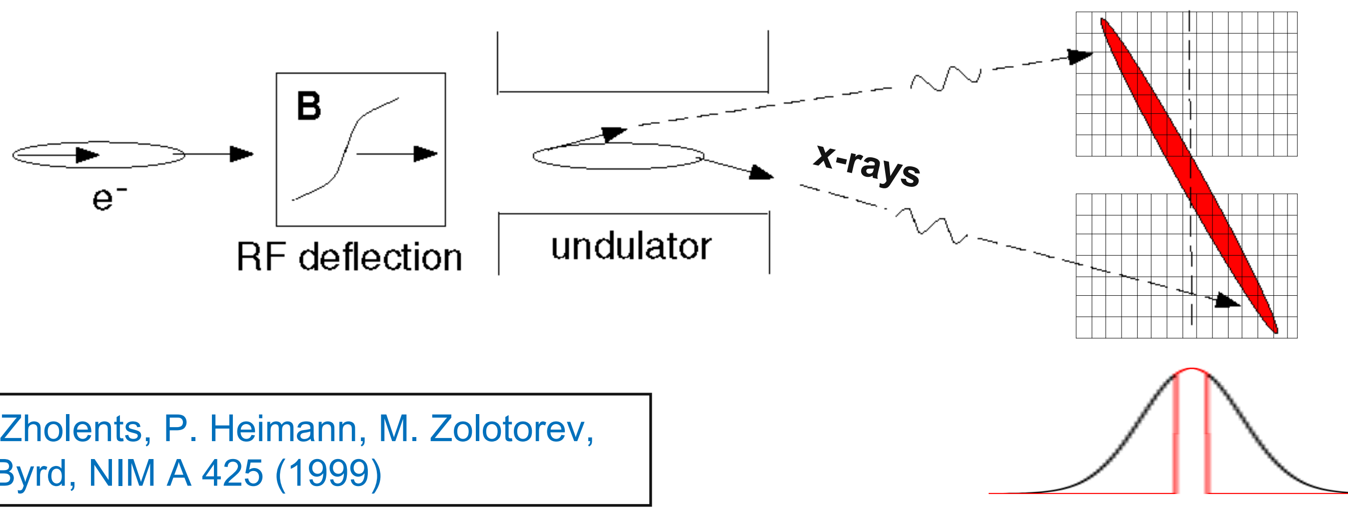
Photo courtesy: D. Reis, UM

Short-pulse generation with rf deflection†



Deflecting cavity introduces angle-time correlation, "chirping" the beam

Second cavity at nπ phase cancels "chirp"; rest of the storage ring unaffected

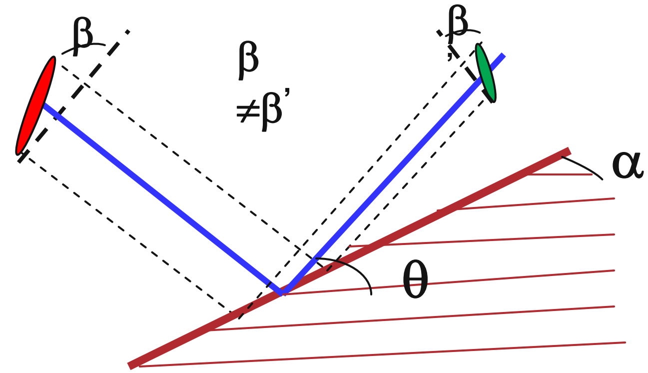


Slits can be used to clip out a short pulse.

Can also use asymmetric cut crystal to compress the pulse.

† A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425 (1999)

Estimating X-ray Pulse Duration



- **X-ray pulse length can be estimated assuming Gaussian distributions[1]**

Electron beam energy

$$\sigma_{t,xray} \approx \frac{E}{Vh\omega_a}\sqrt{\frac{\beta_{id}}{\beta_{rf}}}\sqrt{\sigma^2_{y',e}+\sigma^2_{y',rad}}$$

→ For 4 MV, 2800 MHz (h=8) deflecting system, get ~0.6 ps

Deflecting rf voltage & frequency

Unchirped e-beam divergence (typ. 2-3 μrad)

Divergence due to undulator (typ. ~5 μrad)

- **Emittance growth matters because it increases the minimum achievable pulse duration.**

[1] M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2005).

Emittance Growth [1,2]

[1] M. Borland, private communication, 2004.
[2] M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2005).

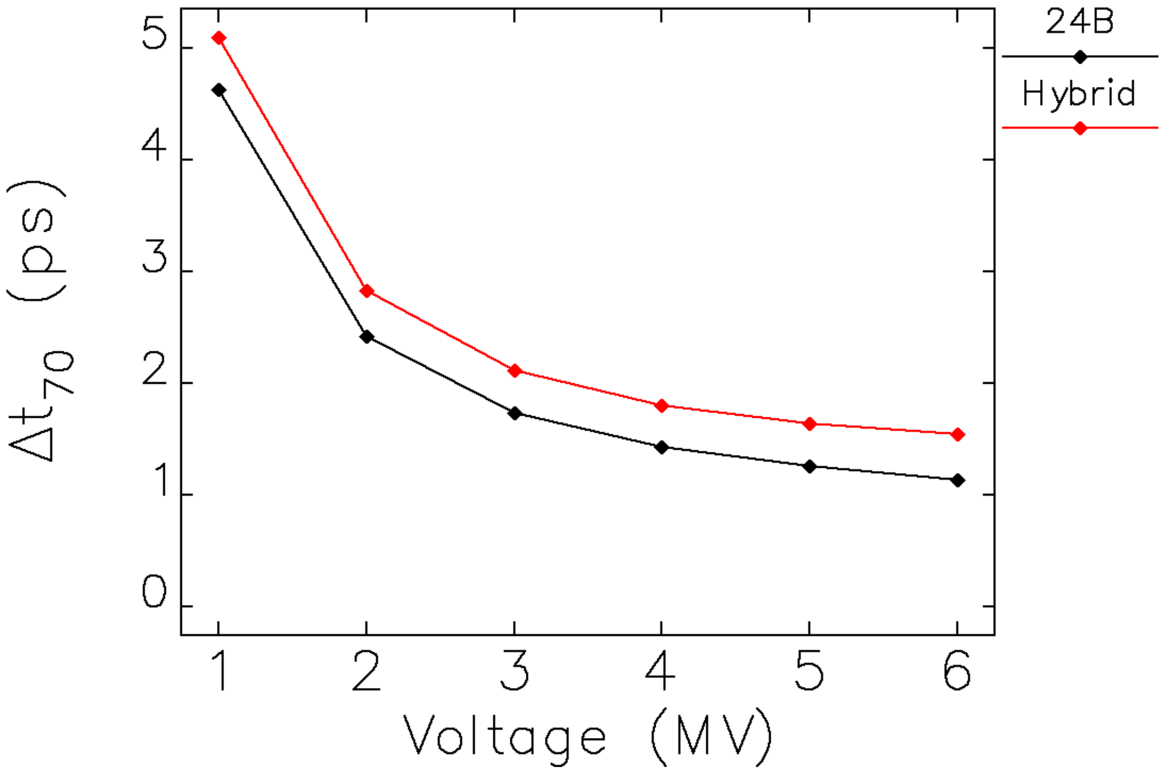
- **In the idealized concept, a second set of cavities exactly cancels the effect of the first set**
  - In reality, it doesn't work exactly and we have emittance growth
- **Sources of growth in an ideal machine**:
  - Time-of-flight dispersion between cavities due to beam energy spread
  - Uncorrected chromaticity, if present (normally it is)
  - Coupling of vertical motion into horizontal plane by sextupoles
  - Quantum randomization of particle energy over many turns
- **Additional sources of growth in a real machine**
  - Errors in magnet strengths between the cavities
  - Roll of magnetic elements about beam axis
  - Roll of cavities about beam axis
  - Orbit error in sextupoles
  - Errors in rf phase and voltage
- **Emittance growth is not just a worry for brightness**
  - It also limits how short an x-ray pulse can be achieved

Reducing Emittance Growth[1,2,3,4]

- There are several methods of reducing emittance growth:
  - Don't power cavities past point of diminishing returns
  - Manipulate sextupoles between cavities
    - *Turning them off is not the best approach*
    - *Minimize emittance directly using particle tracking simulation*
    - *Tune sextupoles for zero chromaticity between cavities*
  - Choose vertical oscillation frequency ("tune") to facilitate multi-turn cancellation of effects
  - Increase separation of horizontal and vertical tunes

[1] M. Borland, private communication,2004.
[2] M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2005).
[3] V. Sajaev, private communication, 2005.
[4] M. Borland and V. Sajaev, Proc. PAC 2005, 3886-3888 (2005).

Results for Constant 1% Transmission (2.4-m U33, 10keV)



- Assume two slits at 26.5 m; Vertical slit is varied from ±100 mm to ±0.010 mm and fixed horizontal slit of ±0.25 mm (E. Dufrense)
- 24-bunch mode has a slight edge due to smaller emittance
- Effect of emittance increase is clear in comparison of 2 MV and 4 MV results
- No compelling reason to go above 4 MV

Summary of Tolerances[1]

Quantity	Driving Requirement	24-bunch	Hybrid
Common-mode voltage	Keep intensity and bunch length variation under 1%	±1%	±1%
Differential voltage	Keep emittance variation under 10% of nominal	±0.44%	±0.43%
Common-mode phase relative to bunch arrival	Constrain intensity variation to 1%	±10 deg	±10 deg
Differential phase	Keep centroid motion under 10% of beam size	±0.07 deg	±0.09 deg
Rotational alignment	Emittance control	~1 mrad	~1 mrad

- Tolerance on timing signal from crab cavity to users: ±0.9 deg

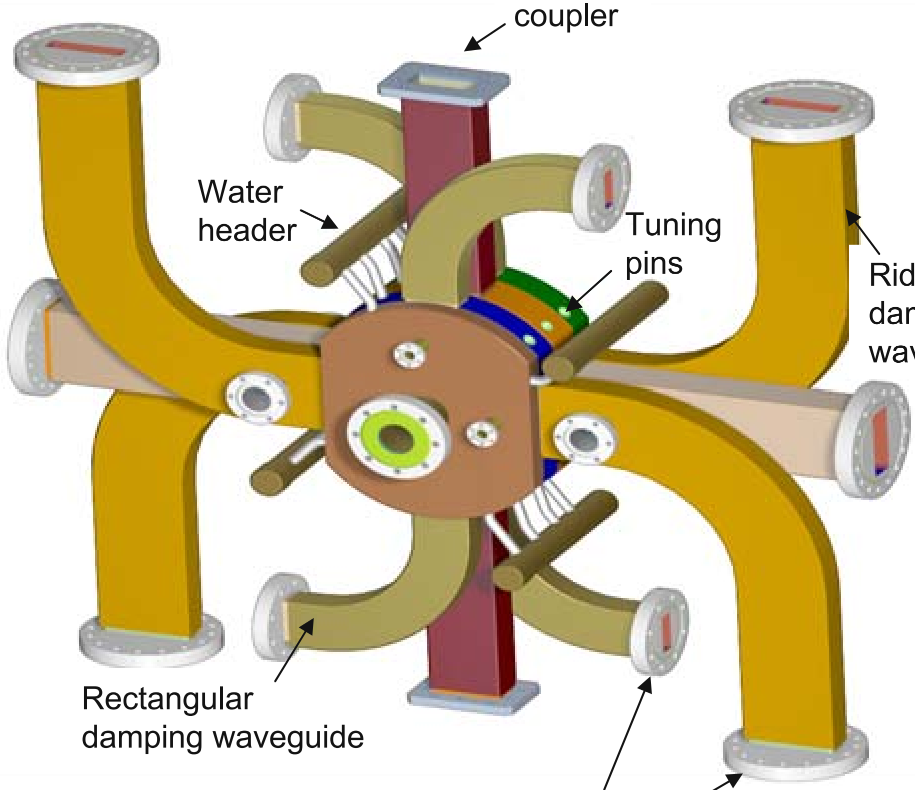
[1] M. Borland, "Long-Term Tracking, X-ray Predictions, and Tolerances," SPX Cavity Review, 8/23/07.

APS Short-Pulse X-Ray Normal-Conducting Cavity Design[1]

Limitations: rep rate ≤1 kHz; can only operate in hybrid operating mode; cost

Frequency	2.815 GHz
Deflecting Voltage	2 MV
Peak Power	2.8 MW
Working Mode Q_o	12000
R_t / Q	117
Iris Radius	22 mm
Phase Advance	π
Structure Length w/o beam pipes	11.17 cm
Duty Factor	0.147%
Pulse Rate	1.0 kHz
Kick / (Power) $^{1/2}$	1.19 MV/MW$^{1/2}$
Beam Current	100 mA

Normal-conducting 3-cell cavity with damping waveguide and dual input couplers

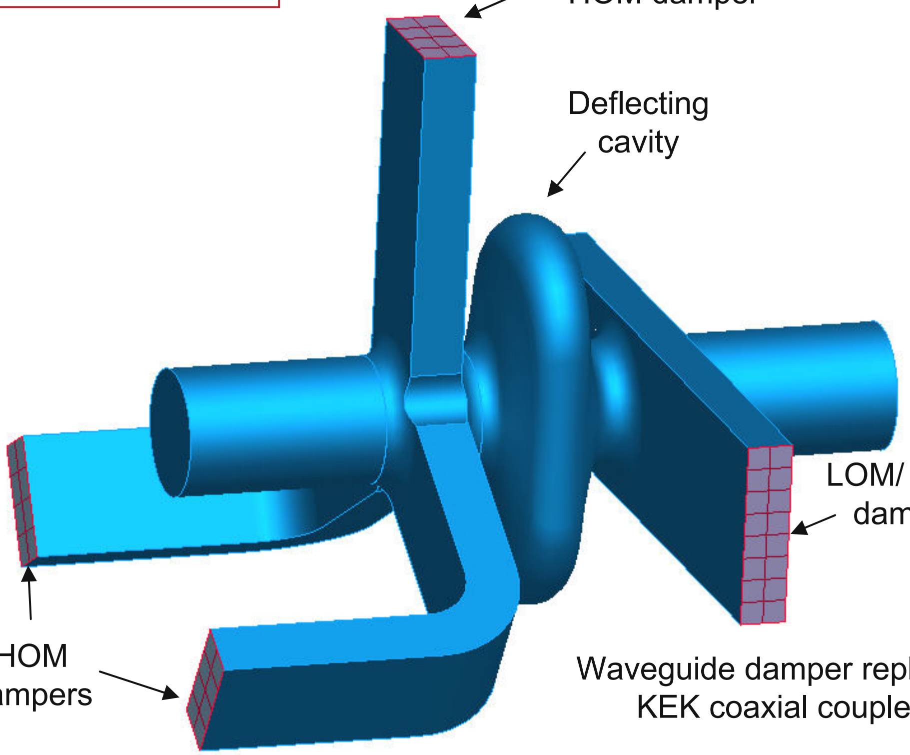


[1] In collaboration with V. Dolgashev (SLAC)

APS 2.8 GHz Superconducting Single-Cell Deflecting Cavity[1]

Compatible with all operating modes (cw); HOM damping favors 1-2 cells; compact design required

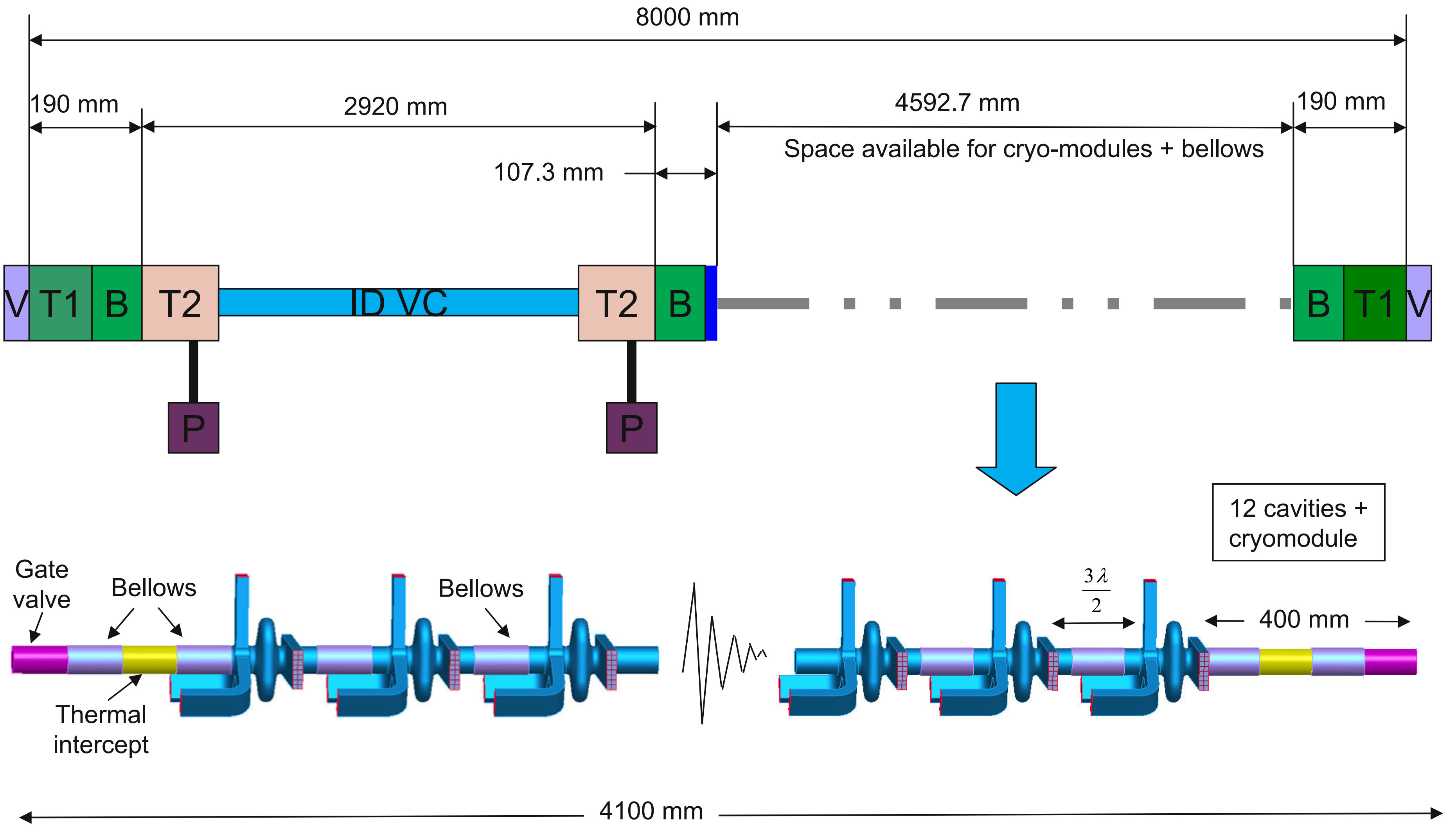
Frequency (GHz)	2.815
Deflecting Voltage	4 MV * 2
Qo (2K)	$3.8 * 10^9$
G	235
R_T / Q (Ω/m)	37.2
Beam Radius	2.5 cm
No. Cavities	12 * 2
Operation	CW
Beam Current (mA)	100
E_{sp}/V_{defl} (1/m)	83.5
B_{sp}/V_{defl} (mT/MV)	244.1



Compact single-cell cavity / damper assembly

[1] In collaboration with JLab and LBL

Deflecting Cavity Layout - Schematic



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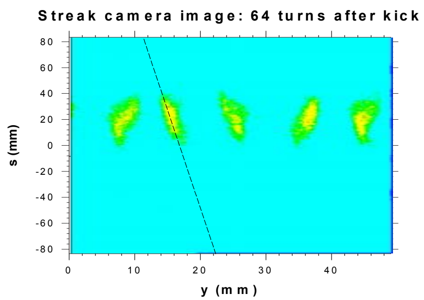
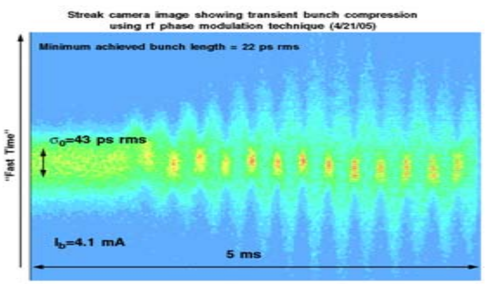
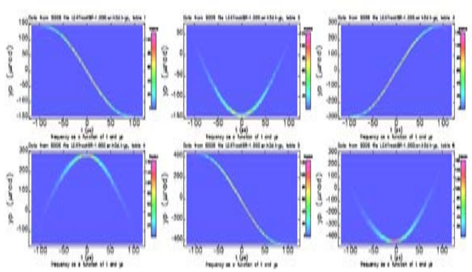
Rev: 00

Transient short pulse generation via beam manipulation

		Pulse compression achieved	Repetition rate limit	Pro	Con
Synchro-betatron **W. Guo et al., Phys. Rev. ST Accel. Beams 10, 020701 (2007)**		3x (avg) 6.5x (w/o jitter)	~40 Hz (1 kHz possible with fast kickers)	Available hardware	Bunch current limited to few mA; sensitive to tune jitter & wakefields
Rf phase modulation **G. Decker et al., Phys. Rev. ST Accel. Beams 9, 120702 (2006)**		2x	~40 Hz	Available hardware, should allow ~50 mA	Limited pulse compression
Quarter-integer resonance **W. Guo and M. Borland, (2005)**		TBD (simul. 50x)	~20 Hz	Same as RT deflecting cavity	Needs hardware

Figs. courtesy B. Yang, G. Decker, M. Borland

Far-term upgrade options: timeline

- **2006 activities**
  - *Mar/Apr*: Encouraged by DOE to explore options for a major APS accelerator upgrade in the next decade
  - Upgrade options
    - *Remove and replace the existing ring*
    - *Create a linac-based source that incorporates the existing ring*[1]
  - *Jun-Aug*: Science planning workshops (14); Cornell ERL Science Workshop (Cornell, ORNL, BNL, SLS); Summary APS upgrade workshop
  - *Nov*: External Machine Advisory Committee review: ERL the most promising potential upgrade path for revolutionary science
- **2007 activities**
  - *Feb*: APS ERL R&D Whitepaper submitted to DOE
  - *Apr*: ERL Optics Workshop (APS, Cornell)
  - *Sep*: ERL Accelerator R&D proposal submitted to DOE
- **No final decision on far-term upgrade option (focus on near-term)**
- **ERL R&D pursued since Oct 2006 under internal lab-directed R&D**

[1] Y. Cho, M. White, Proc. 2003 SRF Workshop (2003).

Options for Replacing the APS Ring

- We investigated possible storage ring replacement options
  - "XPS": eXtreme Photon Source, 80pm emittance[1]
    - *10 m straight sections*
    - *Magnets are beyond what is feasible*
  - "APS1nm": 1 nm effective emittance[2]
    - *10 m straight sections*
    - *200 mA beam current*
  - "APSx3": 1.7 nm effective emittance[3]
    - *10 m straight sections*
    - *200 mA beam current*
    - *Two extra short straight sections per sector*
- Practical brightness gain is ~40-fold (APS1nm)
  - Mostly results from longer undulators, higher current
  - Increase in coherent fraction is only factor ~3
- ~1 year "dark time" to replace.[4]

[1]M. Borland, NIM A 557 (2006) 230-235.
[2]A. Xiao and M. Borland, MAC Review, 11/15/06.
[3]V. Sajaev and M. Borland, MAC Review, 11/15/06.
[4]J. Noonan, private communication.

Other Ring Options

- Damping wigglers can decrease emittance
  - Damping wigglers are planned for NSLS II, PETRA III
  - This was investigated for APS[1,2]
    - *Requires users to give up six straight sections*
    - *Improvement in emittance is less than two-fold*
- Emittance scales like E^2, so lower energy promises higher brightness and coherence
  - Even at 3.5 GeV, only a factor of 4 reduction
    - *Intrabeam scattering increases obtainable emittance*
  - Perhaps a four-fold improvement could be realized[3].
- New facility, "Ultimate Storage Ring" design[4,5]
  - Must be very large (~3 km) to approach ERL performance
  - Magnet technology need not be exotic
  - APS has an on-going effort to explore this.

[1] S. Milton, private communication, 8/7/06.
[2] M. Borland and L. Emery, OAG-TN-2006-033, 8/22/06.
[3] A. Xiao, private communication.
[4] A. Ropert, Proc. EPAC 2000, (2000) 83-85.
[5] K. Tsumaki et al., NIM A 565 (2006) 394-404.

Cornell ERL Parameters[1] Scaled to 7 GeV

[1]G. Hoffstaetter, FLS 2006 Workshop, DESY

	APS	ERL		
	now	High flux	High coherence	Ultrashort pulse
Average current (mA)	100	100	25	1
Repetition rate (MHz)	0.3~352	1300	1300	1
Bunch charge (nC)	0.3~60	0.077	0.019	1
Emittance (nm)	3.1 x 0.025	0.022 x 0.022	0.006 x 0.006	0.37 x 0.37
Rms bunch length (ps)	20 ~ 70	2	2	0.1
Rms momentum spread (%)	0.1	0.02	0.02	0.3
Energy spread	**0.096%**		**140 keV (10MeV)**	
Norm. trans. emittance (μm)	**42 x 0.3**	**0.3**	**0.1**	**5.1**
Norm. long. emittance (μm)	**82**	**1.6**	**1.6**	**1.2**

- Promise of very high brightness and transverse coherence
  - Very low emittance in both planes, low energy spread
  - Picosecond pulses
- Electron beam 10x brighter than SOA must be generated & preserved to realize performance

Physics Favors a Linac-Based Hard X-Ray Source

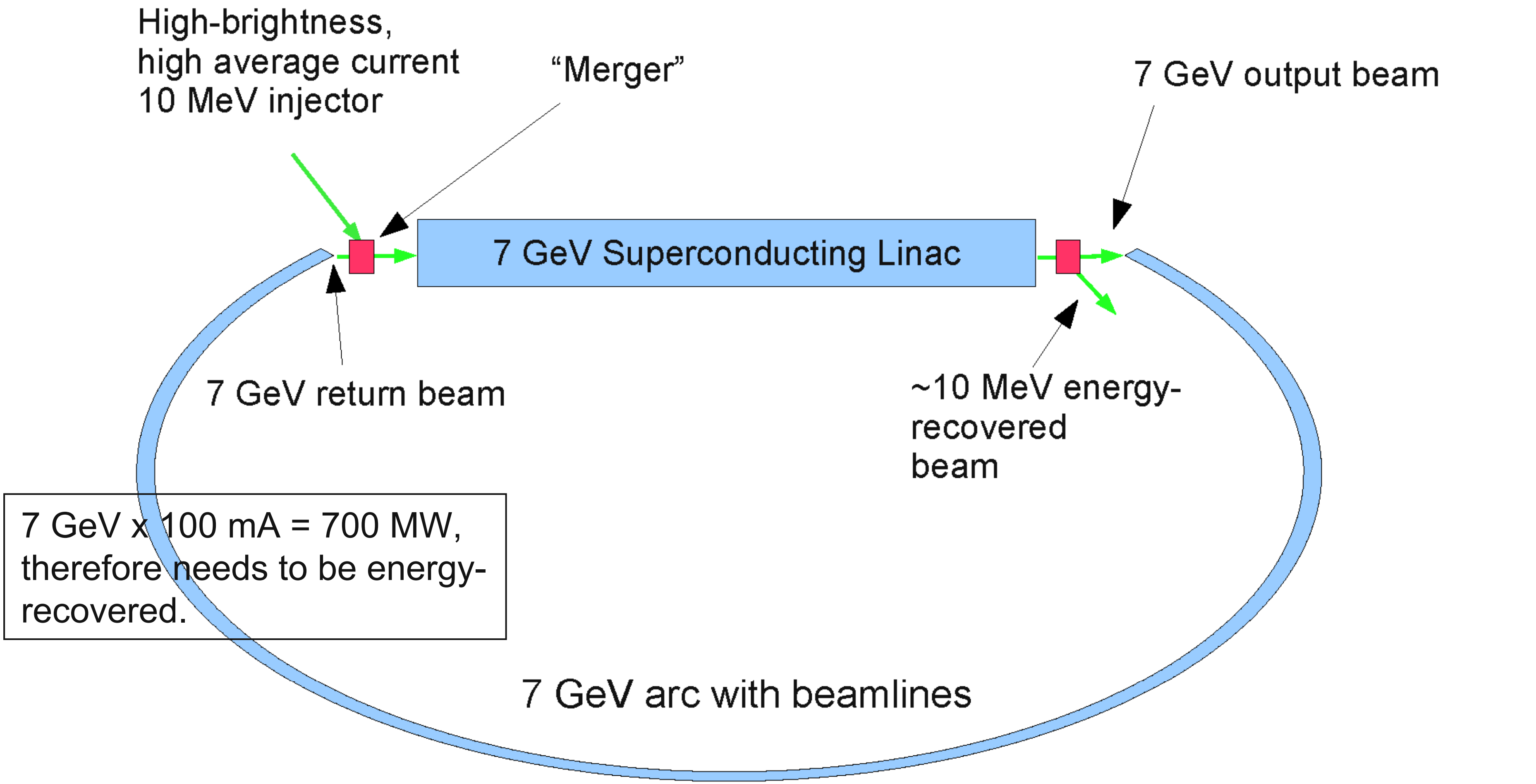
- Emittance scaling favors linac ($\varepsilon \propto 1/E$) over rings ($\varepsilon \propto E^2$)
- Undulator photon brightness[1] $B \propto I/\sigma_T \sigma'_T \delta\omega$, where I is the average beam current and $V = \sigma_T \sigma'_T$ is the total phase space volume, $\sigma_T = \sigma_{Tx}\sigma_{Ty}$ (similarly for σ'_T), and $\delta\omega = \sqrt{4\sigma_\delta^2 + \left(0.4/nN\right)^2}$ is the spectral line width[2], where *N* is the number of undulator poles and *n* is radiation harmonic number. For undulator: $\sigma_{Tu} = \sqrt{\beta_u \varepsilon_u + \left(\eta_u \delta\right)^2 + \sigma_r^2}$ and $\sigma'_{Tu} = \sqrt{\varepsilon_u/\beta_u + \sigma_r'^2}$
- Volume *V* should be minimized. Optimum condition occurs when beam and photon phase space volumes are matched and

$$\beta_u = \sigma_r/\sigma'_r = \left(\sqrt{2\lambda L}/4\pi\right)/\left(\sqrt{\lambda/2L}\right) = L/2\pi$$

- Use APS as example: L=2.4 m, β_u = 0.38 m. ERL beam poorly matched with present $\left(\beta_x, \beta_y\right)$= (20,3) m.
- However, with (1,1) m, and high-coherence emittance ε_n = 0.1 µm, the ERL with only 150 µA has brightness equal to APS at 100 mA and λ = 1Å (12.4 keV); at 25 mA, it is 200x brighter. Even more dramatic at smaller λ: 500x brighter at 40 keV.

[1] K.-J. Kim, AIP Conf. Proc. 184 (1989).
[2] M. Borland, OAG-TN-2008-014 (Apr. 10, 2008).

Energy Recovery Linac[1] Concept



Energy recovery addresses the primary advantage of rings: high current.

See also: D. Douglas, "Incoherent Thoughts about Coherent Light Sources," JLAB-TN-98-040, Oct 13, 1998.

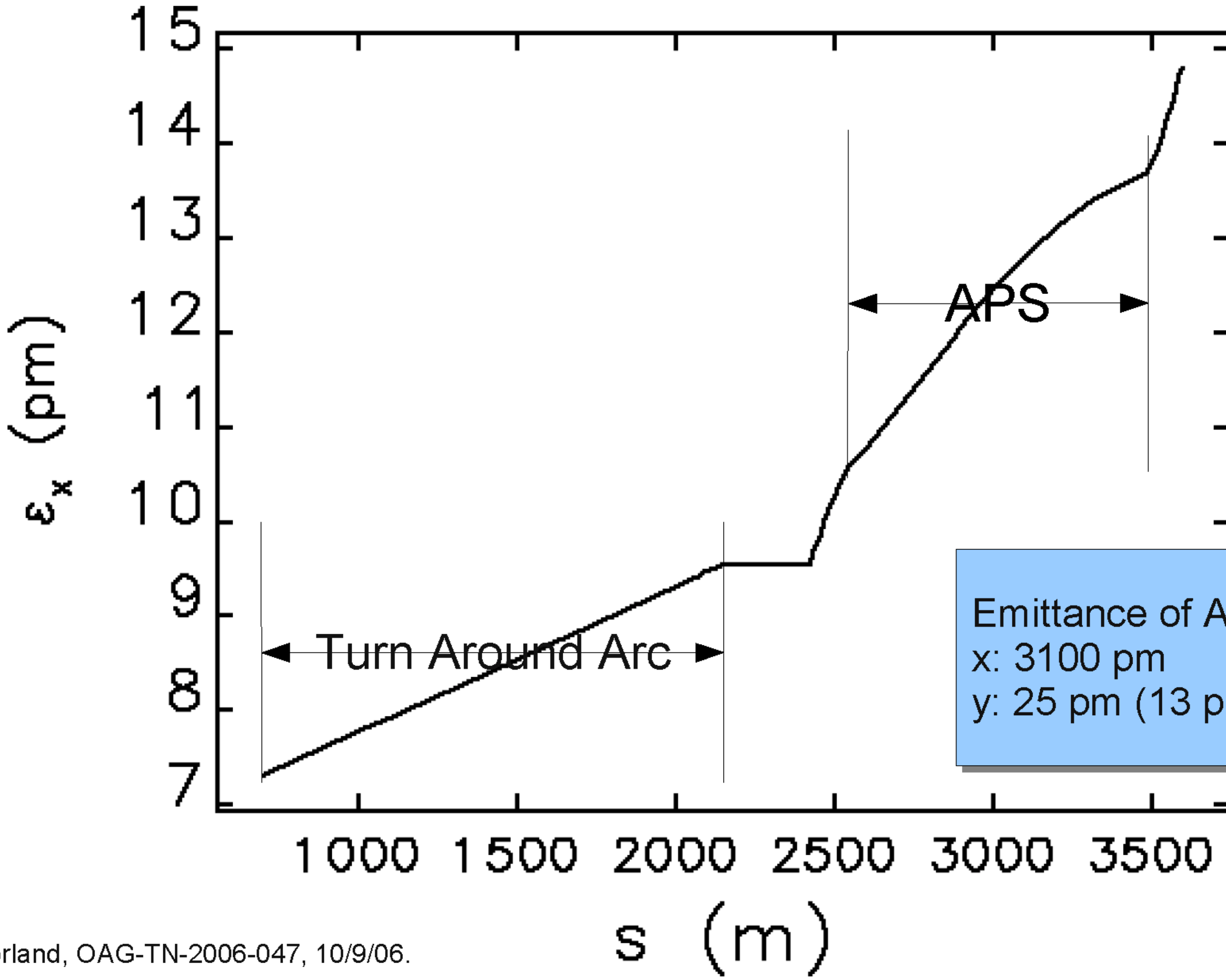
[1] M. Tigner, *Nuovo Cimento* **37**, 1965.

Ultimate APS ERL Upgrade Concept[1]

- Single-pass 7 GeV linac points away from APS to permit straight-ahead hard x-ray short-pulse facility[2,3]
- Beam goes first into new, emittance-preserving turn-around/user arc[4]
  - Second-stage upgrade would add many new beamlines
- ERL can benefit from very long undulators[5]
  - Higher flux and brightness
  - Could add these using somewhat different geometry
- Ability to store beam unchanged[1]
- Existing injector complex unchanged.

[1]G. Decker,OAG-TN-2006-058, 9/30/06.
[2]M. Borland, "ERL Upgrade Options and Possible Performance," 9/18/06.
[3]M. Borland, "Can APS Compete with the Next Generation?", May 2002.
[4]M. Borland, OAG-TN-2006-031, 8/16/06.
[5]S. Gruner et al., "Synchrotron Radiation Sources for the Future," 11/30/200.

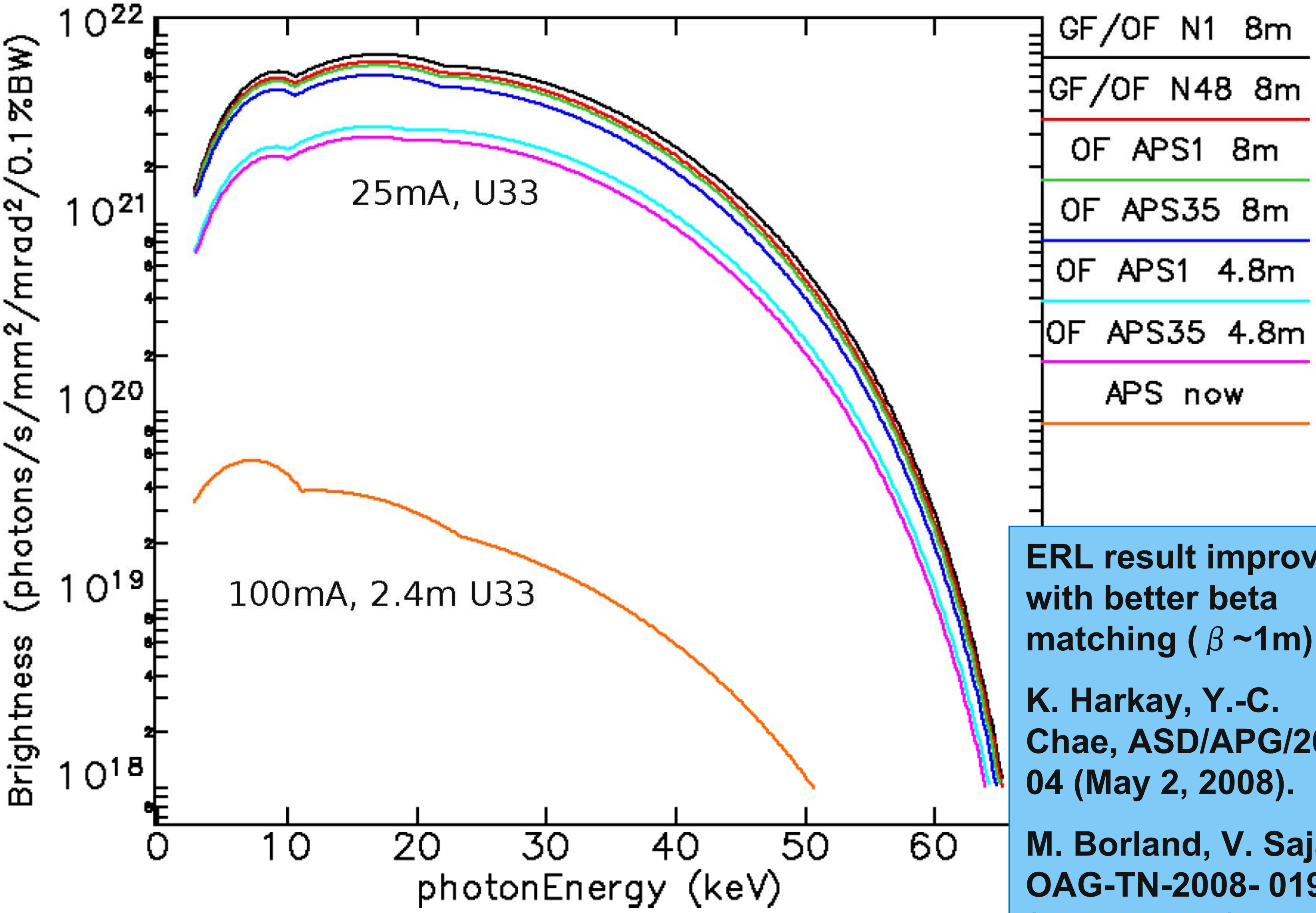
ERL@APS Modeling Results (7 GeV Portion Shown)[1]



Emittance of APS now:
x: 3100 pm
y: 25 pm (13 pm min.)

[1]M. Borland, OAG-TN-2006-047, 10/9/06.

Brightness Comparison for High Coherence Mode



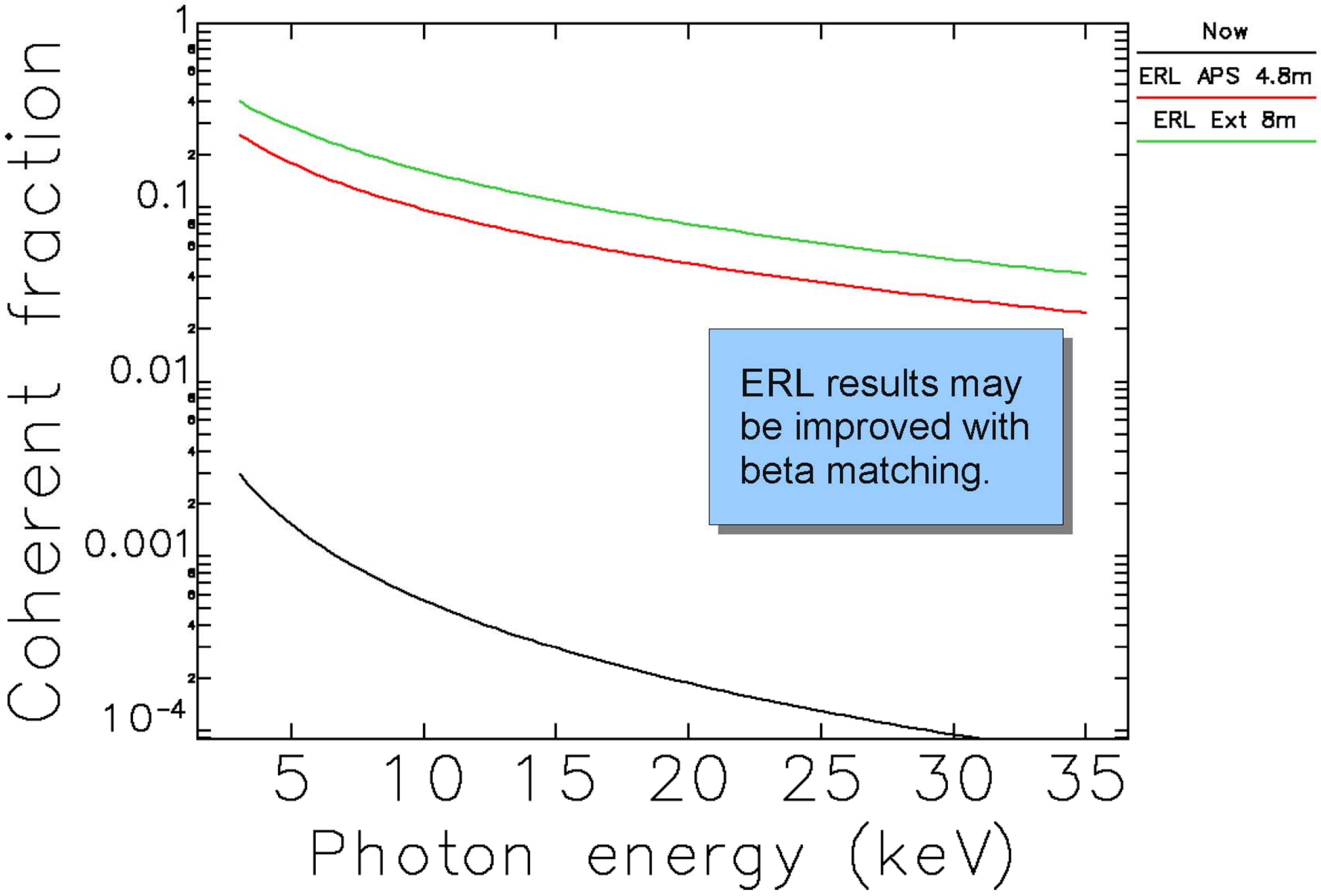
Computed with sddsbrightness (H. Shang, R. Dejus).

ERL result improve with better beta matching (β ~1m):

K. Harkay, Y.-C. Chae, ASD/APG/2008-04 (May 2, 2008).

M. Borland, V. Sajaev, OAG-TN-2008- 019 (May 1, 2008).

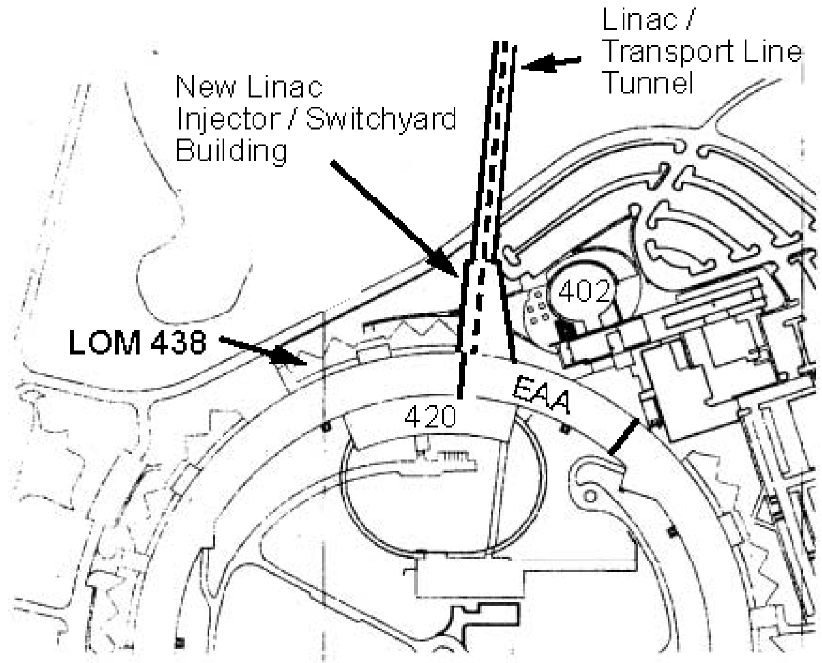
Transverse Coherent Fraction Increases Dramatically

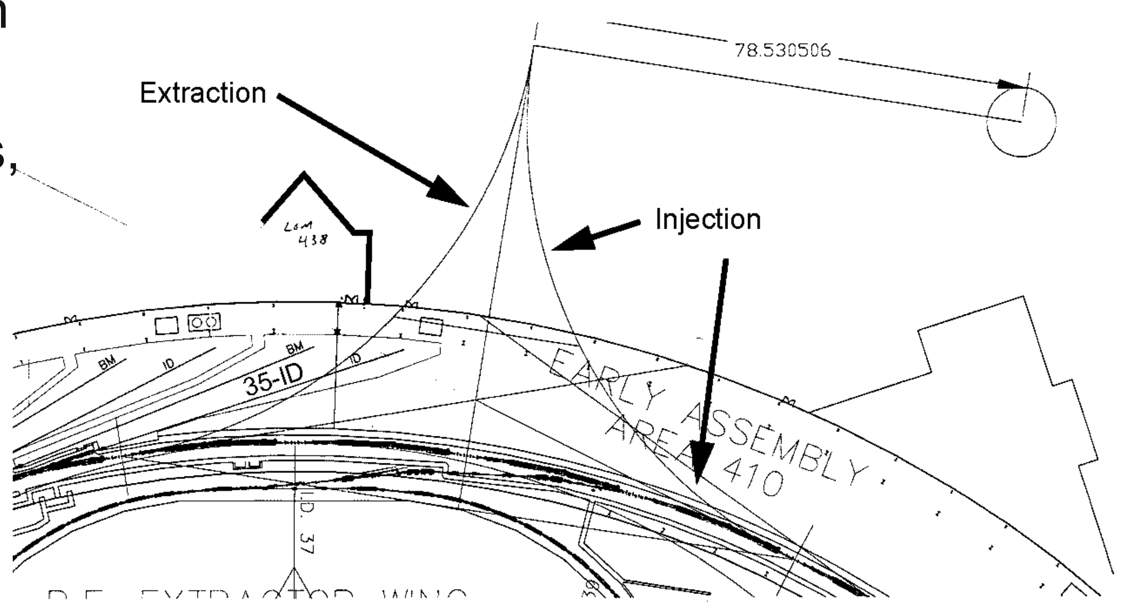


ERL results may be improved with beta matching.

ERL integration with APS

- Construct ERL test prototype[1] prior to final design, else stage ERL[2]
- Optimize APS lattice to match ERL beam
- Move rf cavities to allow storage ring ops but exclude ERL
- Schedule ERL construction to minimize downtime
- Commission ERL in stages, continue injector R&D as needed





[1] M. Borland, A. Nassiri
[2] K. Harkay, Y.-C. Chae ASD/APG/2008-04 (May 2, 2008).
[3] G. Decker, OAG-TN-2006-058, Sep 2006.

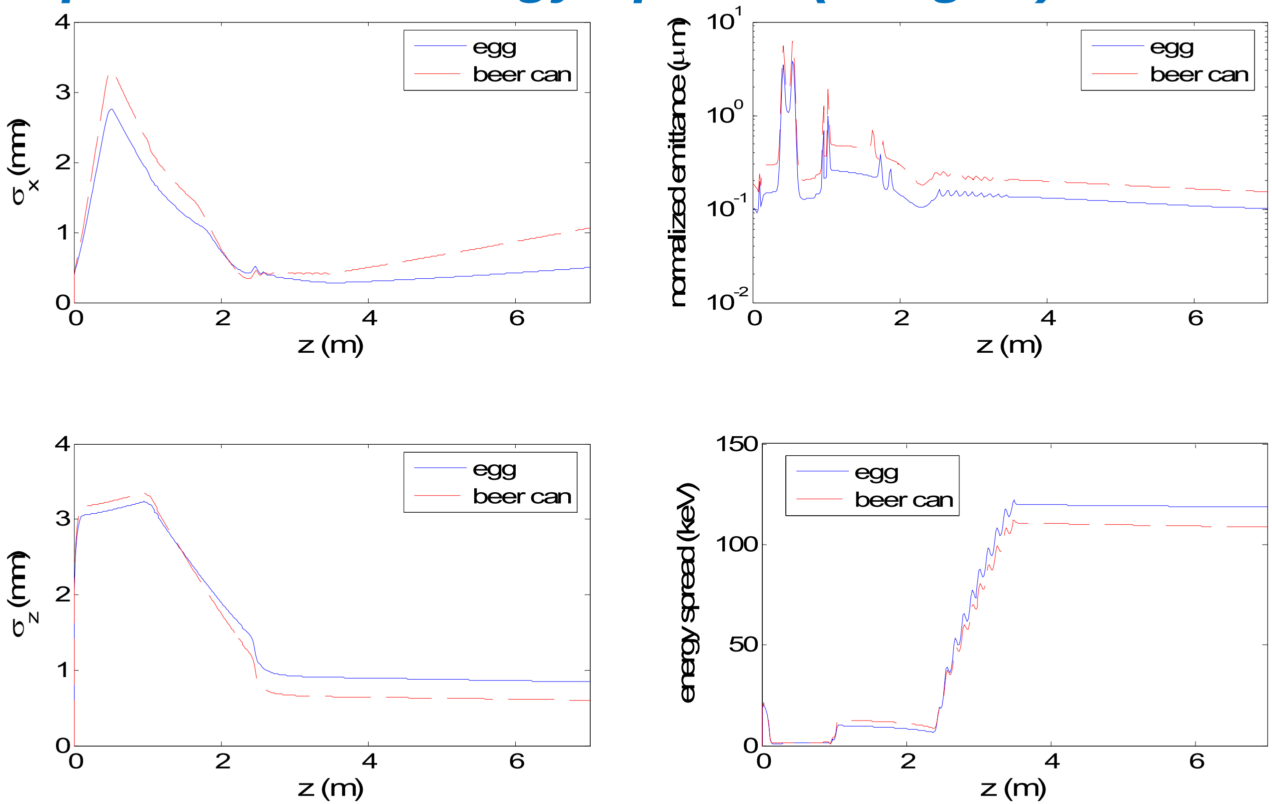
Far-term upgrade R&D

- Beam dynamics
- Superconducting RF
- Injector and cathodes

ERL beam dynamics

- Beam emittance production and preservation
- Merger optics (injector beam and high-energy beam)
- Beam halo modeling
- Control of beam losses
- Beam instability modeling and control (including ion effects)
- Wakefield computation for ps bunches
- Lattice design options for large ERLs
- Operational issues
- ….

Prelim. injector optimization with ASTRA: Rms beam properties and energy spread (DC gun)



Following: I. Bazarov, C. Sinclair, Phys Rev ST-Accel Beams 8, 034202 (2005).

Laser pulse shaping to linear space charge:
Y. Li, J. W. Lewellen, Phys. Rev. Lett. **100**, 074801 (2008).
Y. Li, S. Chemerisov, Opt. Lett. (submitted).

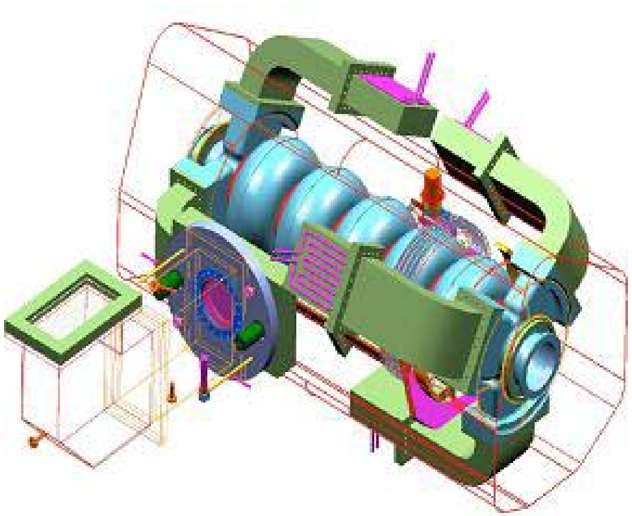
	"egg"	"beer can"
normalized emittance (μm)	0.10	0.15
rms bunch length (ps)	2.8	2.0
rms momentum spread	1.0%	0.9%
beam energy (MeV)	12.1	12.5

Improving SC RF Cavity Quality Factor Q_0

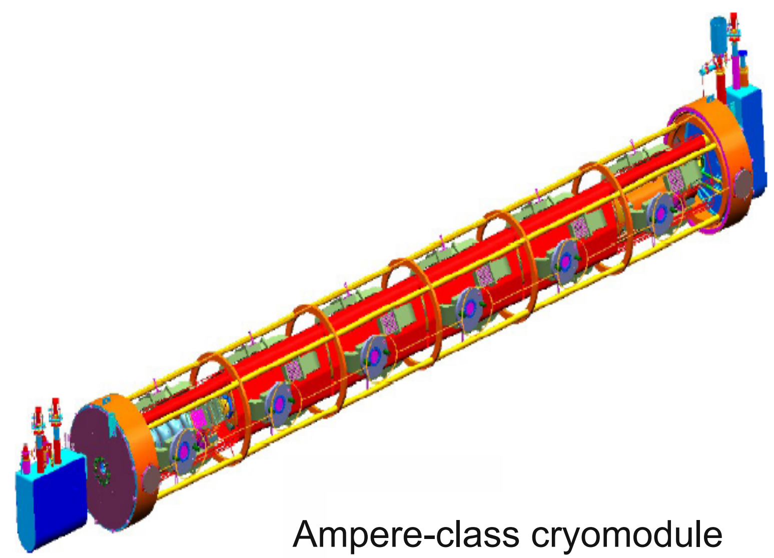
- Light source ERLs require continuous wave (CW) rf power.
- Wall-plug power for high beam current ERL-based light sources with $Q_0 \sim 1\times10^{10}$ is on the order of tens of megawatts
- Improving niobium cavity quality factor, Q_0, by at least a factor of two, will substantially reduce the overall wall-plug power consumption
- Reducing the size of the cryoplant will improve operational reliability and improve machine uptime
- Goal is to conduct R&D to improve cavity quality factor to $Q_0 \sim 5\times10^{10}$.
  - Investigation of seamless cavities
  - Large or single grain niobium cavity (JLab)
  - Exploring niobium cavity surface coating using atomic layer deposition (ALD)
    - *Precision synthesis of ultra-thin films on complex surfaces*
    - *Films are adherent and pinhole free even at 1-2 nm film thickness*
    - *Alumina by ALD forms an extremely effective diffusion barrier to H, O, N*
    - *TiN ALD reduces secondary electron surface yield and is a diffusion barrier*
  - Investigating other materials (e.g., Nb_3Sn)

Multi-cell Cavity and Cryomodule Design for CW Operation

- Optimize multi-cell cavity shape to achieve good accelerating gradient with high rf efficiency
- Optimize a multi-cell cavity to reduce trapped higher-order-modes (HOMs) inside the cavity and to efficiently extract and absorb HOM power
- Design cost-effective HOM power absorbers
- Investigate the design of an optimized and magnetically-shielded cw cryomodule to reduce the effect of microphonics and to maintain the cavities' high Q values



Concept of a 5-cell SRF cavity optimized for high-current and good rf efficiency for CW operation



Ampere-class cryomodule concept

High-brightness ERL Injector R&D

- ERL requirements ***very*** demanding on electron gun
- Grand challenges:
  - Extremely low emittance AND
  - Relatively high average current (low bunch charge)
- Physics and engineering of high brightness guns have long been pursued – performance achieved but at low duty factors
- Interest in high-average-power FELs and ERLs is driving a vigorous beam source R&D effort world-wide.
- Characterization of high-brightness beams subject of CHBB Workshop this week at DESY Zeuthen.

Key Physics

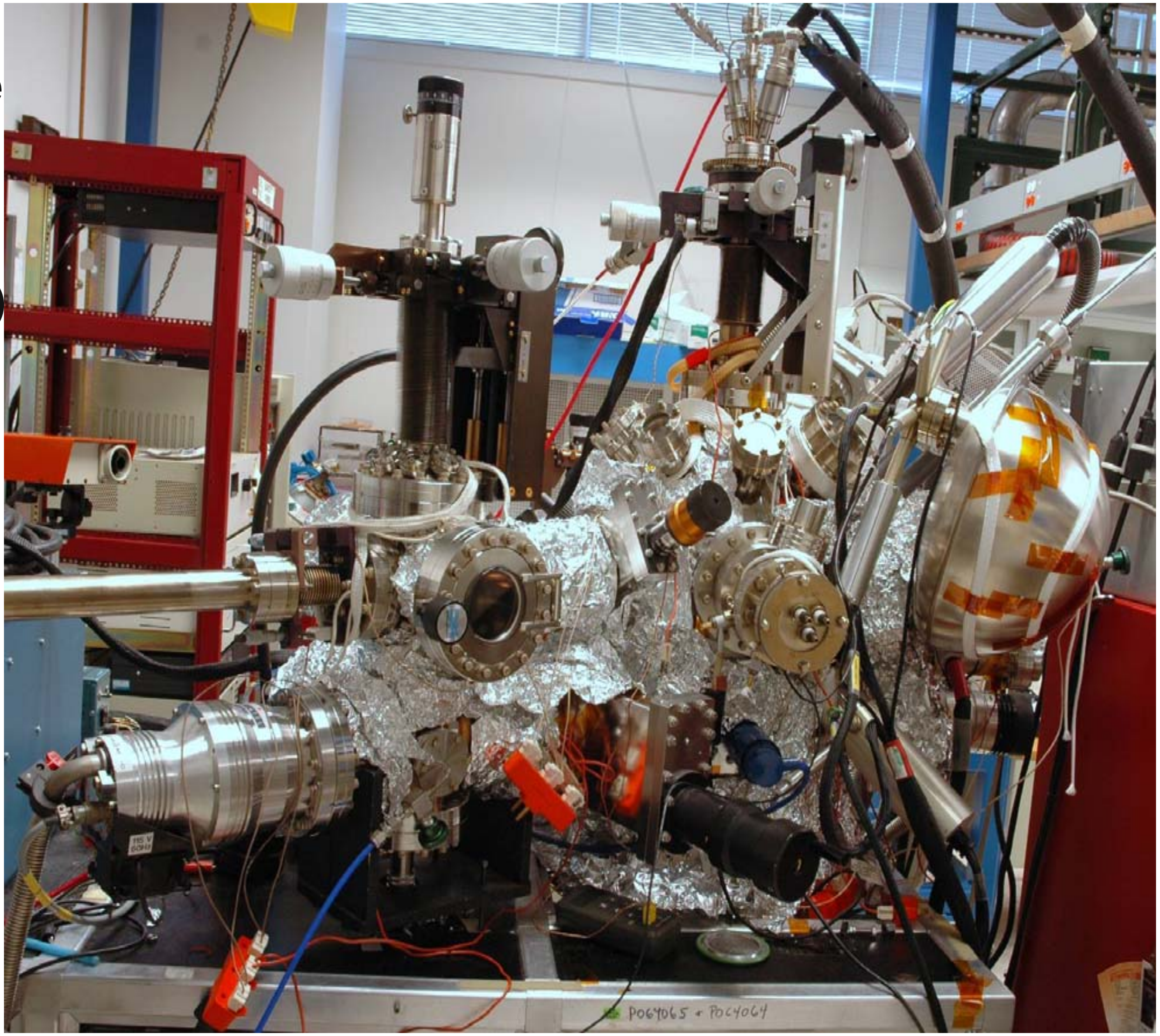
- **Physics optimization**
  - Perform optimization study of laser-photocathode system, including laser pulse shaping, to set boundaries on minimum QE and maximum intrinsic emittance
- **Characterize intrinsic emittance in the lab**
  - Systematically characterize the intrinsic emittance for a variety of cathodes using advanced surface analysis to measure the emission momentum distribution (ARPES) and spatially-resolved cathode composition and surface geometry (e.g., SEM, scanning Auger)
- **Improved emission models** for use in cathode injector design
  - Evaluate and/or design novel cathodes with optimized characteristics
  - Benchmark improved physics models based on these data in a test injector
- **Cathode lifetime**
  - Study lifetime improvement and develop load-lock system to allow quick cathode exchange
- **Injector design**
  - Carry out design study for cw operation, high-coherence mode (technology not yet decided: dc vs RT rf vs. SC rf)

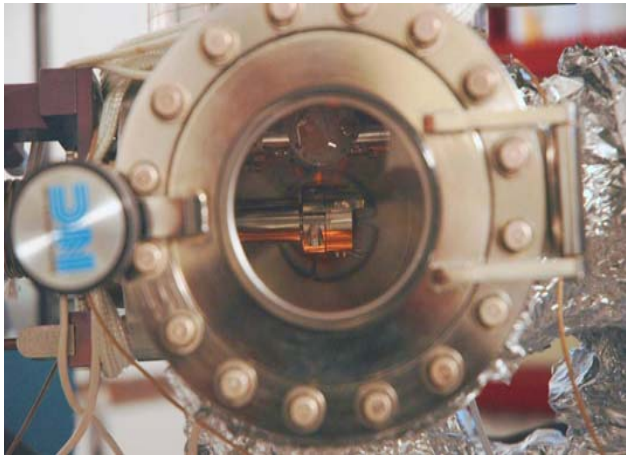
Home of proposed Cathode Test Stand (CATS)

Surface analysis laboratory, courtesy R. Rosenberg (APS)

Present capabilities: XPS, scanning Auger, SEM, heat/cool sample, ion sputtering

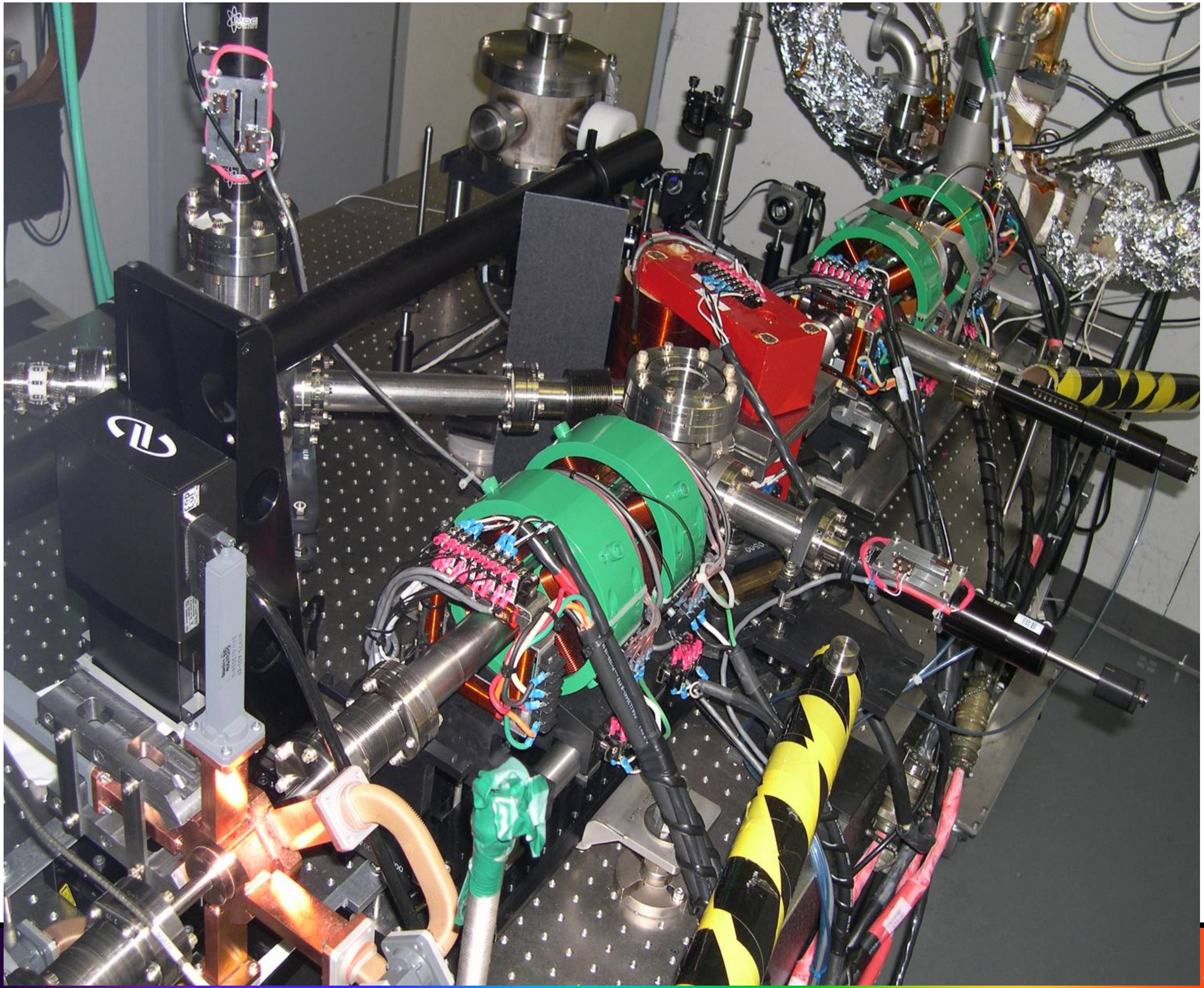
New hardware required for ARPES





photos: M. White

Injector Test Stand, showing one beamline. Second beamline is proposed for ERL cathode development. (photo: Y.-e Sun)



Summary: Near-term upgrade plan (APS Renewal)

- APS upgrade options are being actively investigated
- Evolutionary upgrade path
  - Driven by near-term science goals
  - Primary focus on beamlines; accelerator systems spares, undulators, customized beamlines
- Short-pulse X-ray (SPX) project
  - Studied single-particle beam dynamics; extensive tracking
  - Advantage of cw system: flexibility and performance (rep rate)
  - Baseline uses S-band SC rf deflecting cavity at 4 MV deflecting voltage; acceptable emittance growth
  - SPX can deliver < 2 ps FWHM with ~1% of nominal intensity

Summary: Far-term upgrade options

- In far-term, ring replacements seem not to offer enough
  - Only ~40-fold in brightness, ~3-fold in coherent fraction
  - Relatively long disruption of operations
- An ERL upgrade would revolutionize x-ray science at APS
  - Brightness and coherence fraction many orders of magnitude enhanced, especially at high energy
  - Disruptions to APS operations greatly reduced
  - Endorsed by external, international Machine Advisory Committee
- R&D required on many topics before ERL can deliver on promise
  - Ongoing at APS with steady progress; many interesting and important beam dynamics R&D topics could not be covered in talk
  - Complementary to ongoing efforts being pursued world-wide (ERL R&D and projects; X-FELs (seeded and SASE))
  - Good reasons to be optimistic; interested in collaborations

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Accelerator Systems: M. Borland, T. B. Brajuskovic, D. Bromberek, J. Carwardine, Y.-C. Chae, A. Cours, G. Decker, R. Dejus, L. Emery, R. Flood, R. Gerig, E. Gluskin, A. Grelick, K. Harkay, D. Horan, S. Krishnagopal, Y. Li, R. Lill, E. Moog, L. Morrison, A. Nassiri, V. Sajaev, S. Sazaki, N. Sereno, H. Shang, R. Soliday, T. Smith, X. Sun, Y. Sun, N. Vinokurov, G. Waldschmidt, C.-X. Wang, Y. Wang, M. White, A. Xiao, B. Yang, C.-Y. Yao

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