Short pulse plans for SPEAR3 and PEP-X

BESSY VSR - Workshop

- **Short photon pulses from storage rings**
- **SPEAR3 low alpha operations**
- **SPEAR3 superconducting RF plans**
- **PEP-X short pulse/FEL plans**

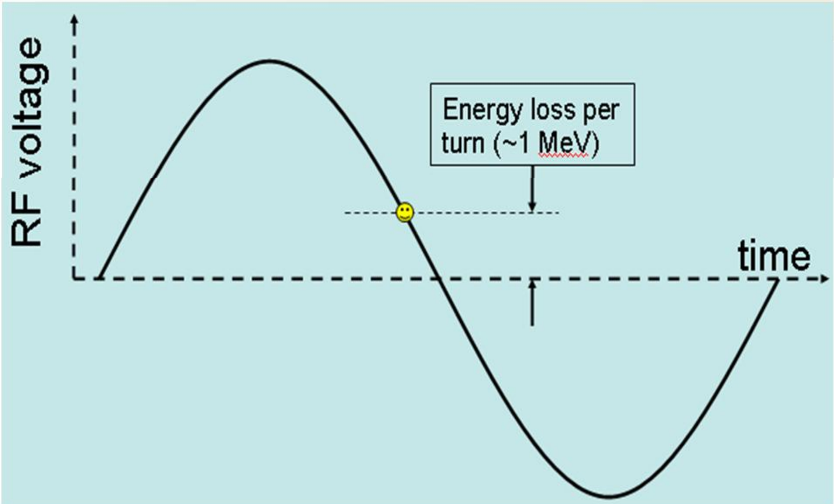
James Safranek for the SSRL accelerator group

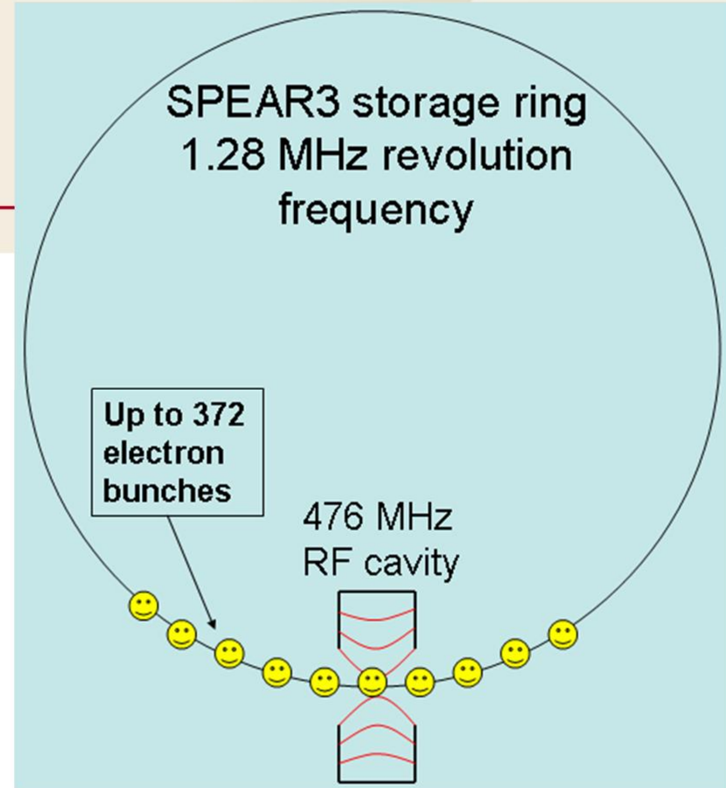
10/15/2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

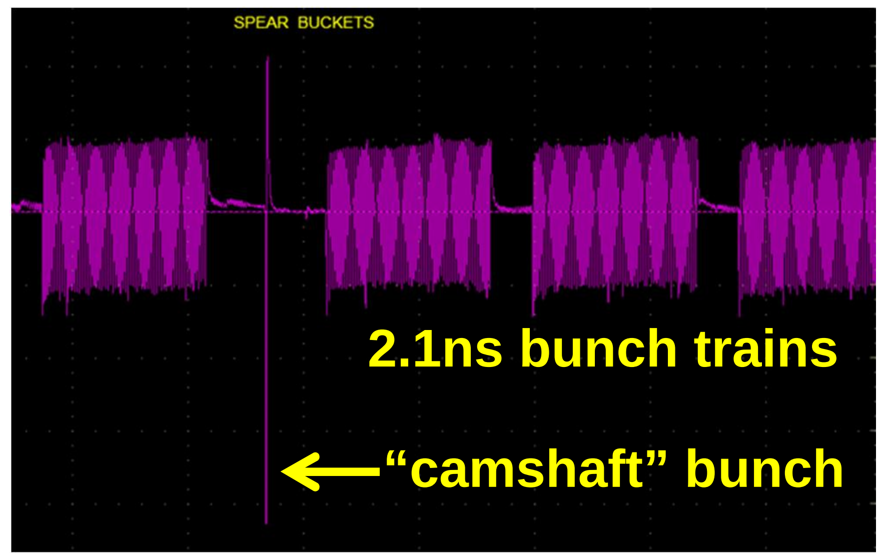
Timing experiments in SPEAR3



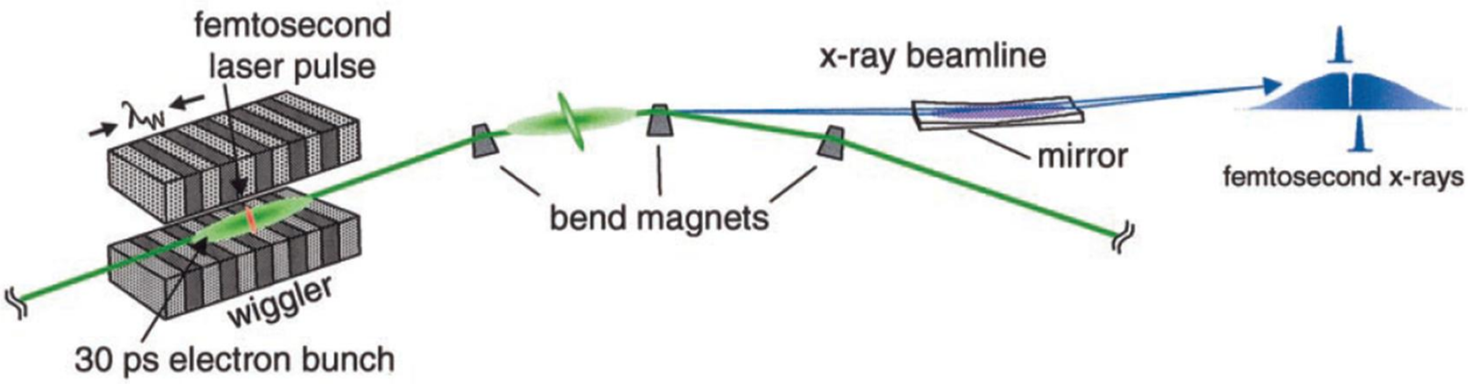


Nominal operations configuration:

- 500mA, 5 minute top-up
- 4 to 6 bunch trains
- ion clearing gaps
- 1-4 5mA bunches in 50ns gaps
- 1.28 MHz revolution frequency
- 10nm-rad horizontal emittance
- 50ps fwhm bunch lengths



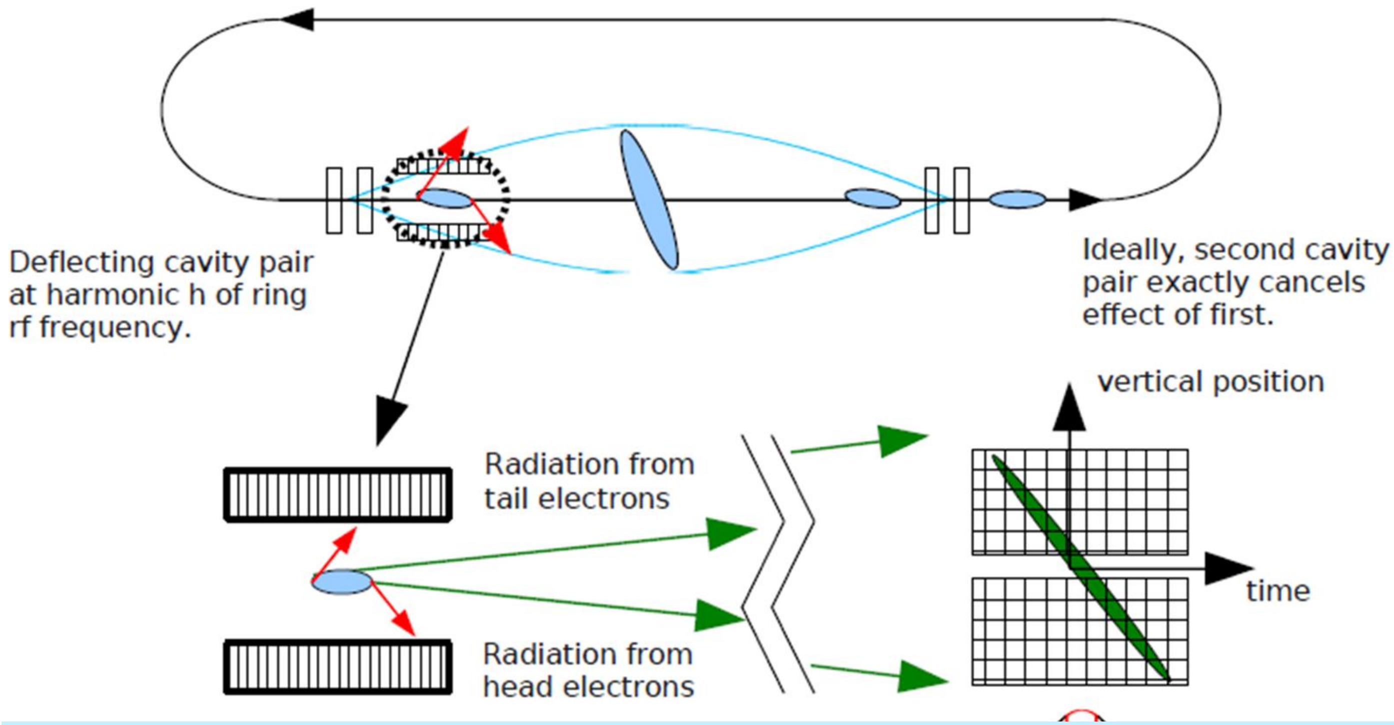
Method 1: Laser slicing



Ultra-short pulse length, 100~300 fs (FWHM)
Low repetition rate, <20 kHz
Low flux, ~1000 photons/pulse/0.1%BW (2 keV)
Available only at a couple beamlines

A. A. Zholents and M.S. Zolotorev, Phys. Rev. Lett., 76, 912 (1996);
R. W. Schoenlein, et al, Science 287, 2237 (2000).

Method 2: Crab cavity



Short pulse length,	~1.3 ps (FWHM), (APS SPX parameters)
High repetition rate,	6.5 MHz
High flux,	~10^6 photons/pulse/0.1%BW (8 keV)
Available only at a few beamlines	

A. A. Zholents, et al, Nucl. Instrum. Methods, A 425, 385 (1999); Conceptual Design Report, APS Upgrade Project, May 2011, APSU-1.1-PLN-002-02.1

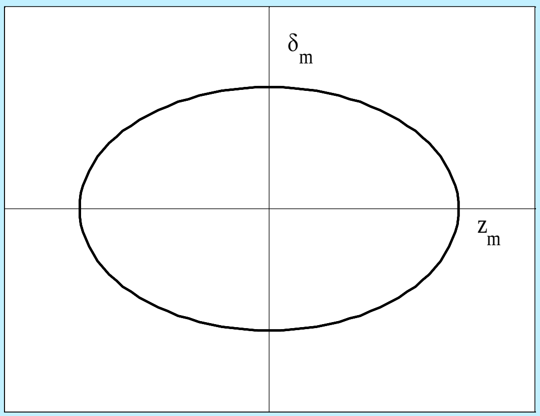
Bunch length in an electron storage ring

The longitudinal motion (to first order) is a harmonic motion

mass $m \rightarrow \frac{1}{\alpha c},$

spring constant $k \rightarrow -\frac{1}{ET_0}\frac{\partial V}{\partial z}$

α is momentum compaction factor (alpha)
$\partial V/\partial z$ is rf focusing gradient



$$z_m = \left(\frac{c\alpha ET_0}{\left|\frac{\partial V}{\partial z}\right|}\right)^{1/2} \delta_m$$

Bunch length is related to energy spread.

The equilibrium energy distribution

$$\sigma_\delta \approx 0.62\times10^{-6}\frac{\gamma}{\sqrt{2\rho}}$$

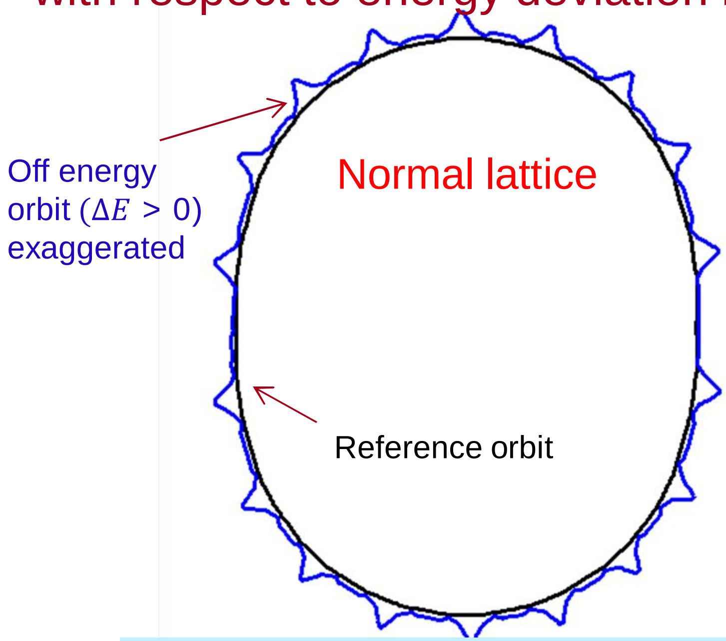
(for separate-function dipole ring)

Options for shortening bunch length:
(1) Reducing alpha.
(2) Increasing rf voltage slope.

$$\sigma_z = \left(\frac{c\alpha ET_0}{\left|\frac{\partial V}{\partial z}\right|}\right)^{1/2} \sigma_\delta$$

Method 3: Low alpha

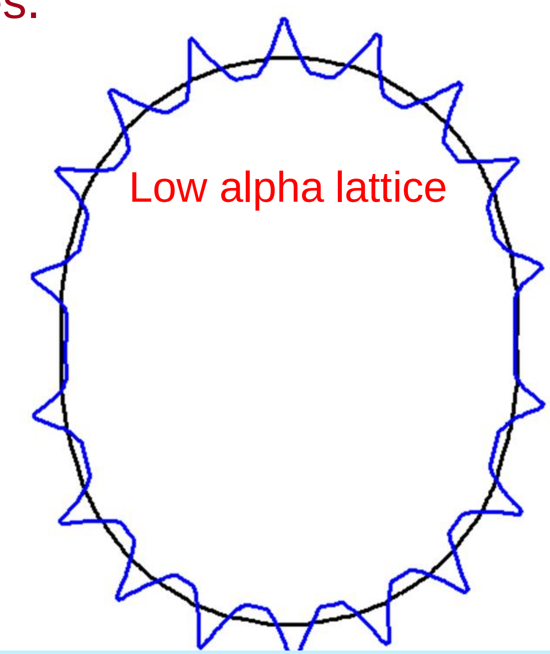
Momentum compaction factor (alpha): differential relative path length change with respect to energy deviation for off-energy particles.



$$\alpha = \frac{\Delta C/C}{\Delta E/E}$$

Bunch length

$$\sigma_t \propto \sqrt{\alpha}$$



Easy to implement (no extra cost)
High repetition rate, up to ~500 MHz
Available to all beamlines
Low flux for short pulse length, ~2×10^4 photons/pulse/0.1%BW (5.2 ps, 8 keV)
Not compatible with normal user operation.

J. Feikes, et al, EPAC'04, Luzern, Switzerland (2004);
X. Huang, et al, PAC'07, Albuquerque, NM (2007).

SPEAR3 well suited for low α

We measured α reduction of >1000 on second shift.

For small α, longitudinal dynamics depends on higher-order terms

$$\frac{\Delta L}{L} = \underbrace{\alpha_1}_{\text{quadrupoles;}} \frac{\Delta p}{p} + \underbrace{\alpha_2}_{\text{sextupoles}} \left(\frac{\Delta p}{p}\right)^2 + \alpha_3 \left(\frac{\Delta p}{p}\right)^3$$

For stability, require:

$$3\alpha_1\alpha_3 - \alpha_2^2 > 0$$

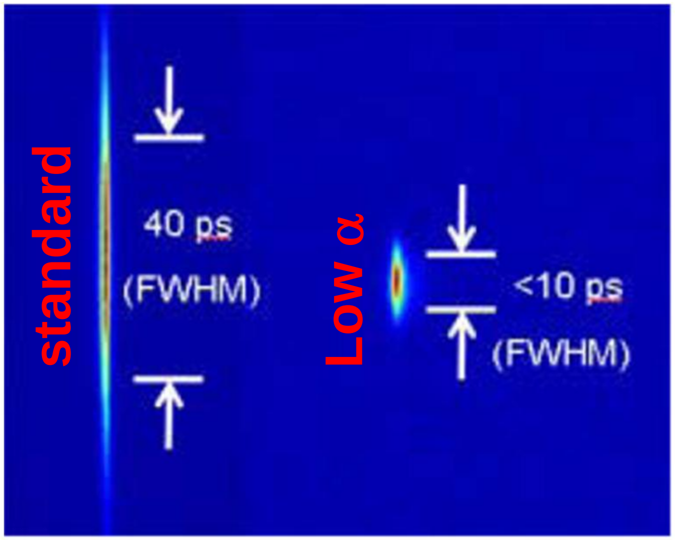
($\alpha(\Delta p/p) > 0$ for all $\Delta p/p$)

Need small α_2, which requires setting SF for ξ_x=-2.

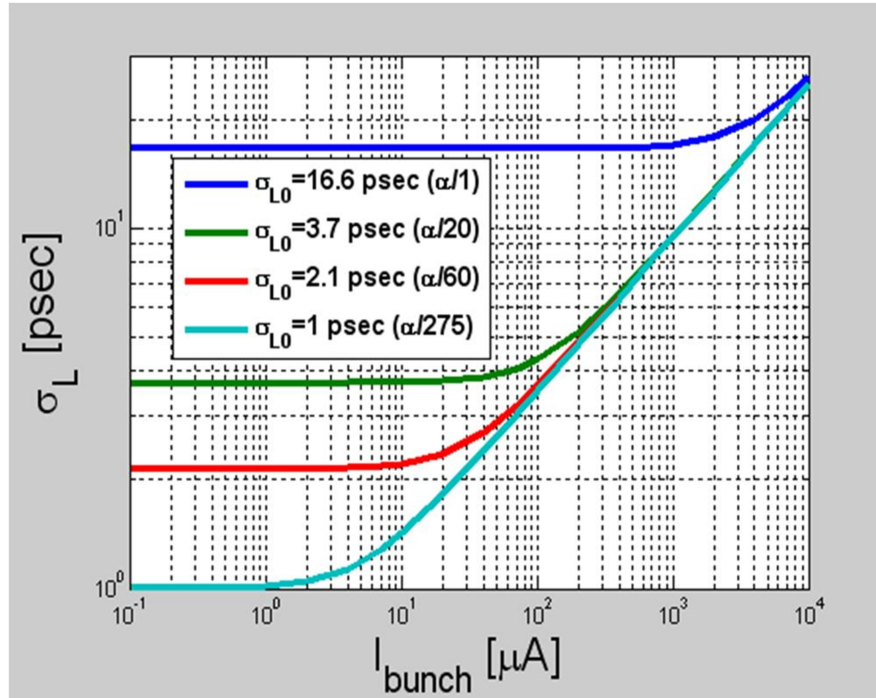
Prefer $|\alpha_3|$ large, and α_3>0.

- BESSYII: α_3=-0.01; SPEAR3: α_3=+0.05
- SPEAR3 lifetime insensitive to α_2, τ=30 hours
- SPEAR3 low alpha lattice first commissioned in 2006

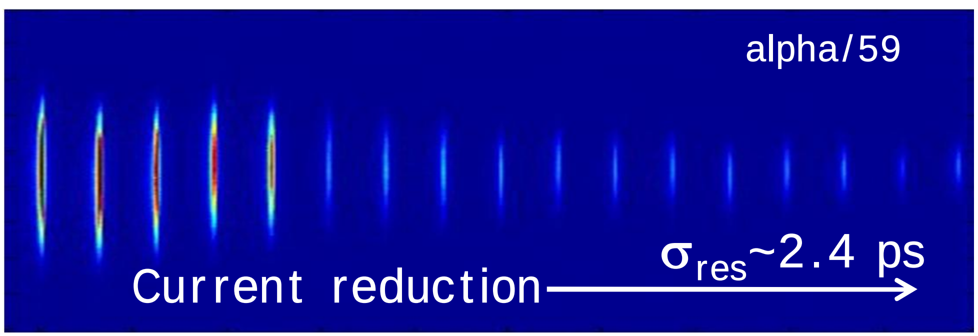
Low α (short pulses)



$$I[\mathrm{mA}] = 0.005\sigma[\mathrm{ps}]^{2.354}$$



Streak camera measurements, J. Corbett et al.



$$\left(\frac{\sigma}{\sigma_1}\right)^4 = \left(\frac{f_s}{f_{s,o}}\right)^4 + \left(\frac{I}{I_1}\right)^{1.7}$$

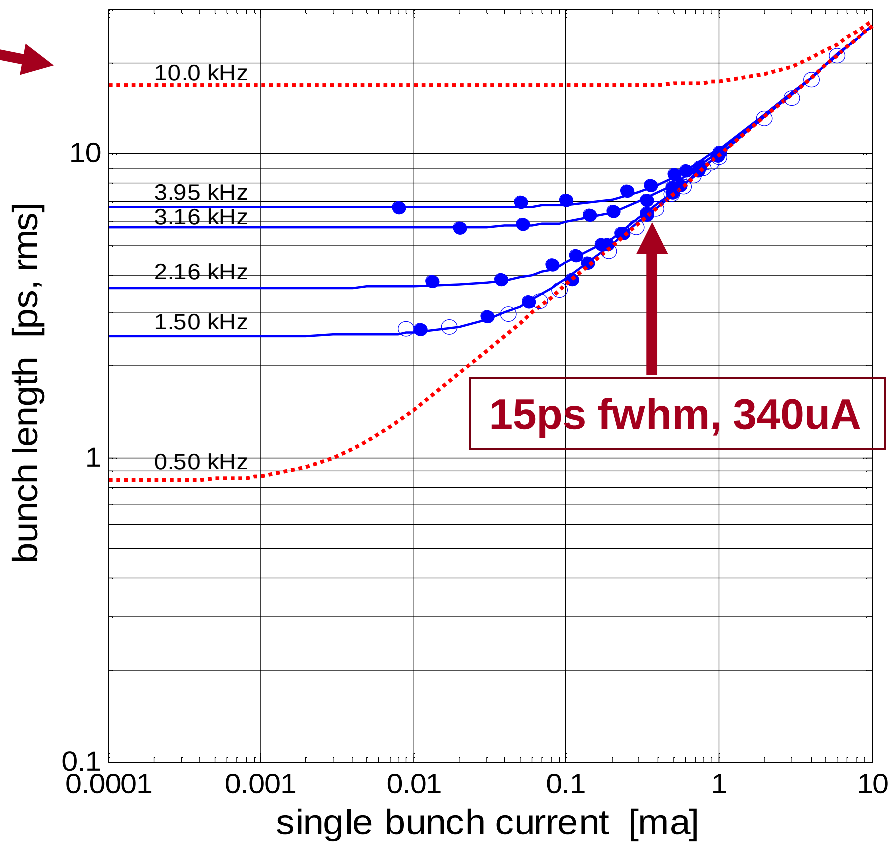
I_1 =3.8mA, σ_1 = 16.8ps, f_{s0}=10.8 kHz

Low-α 'hybrid' mode

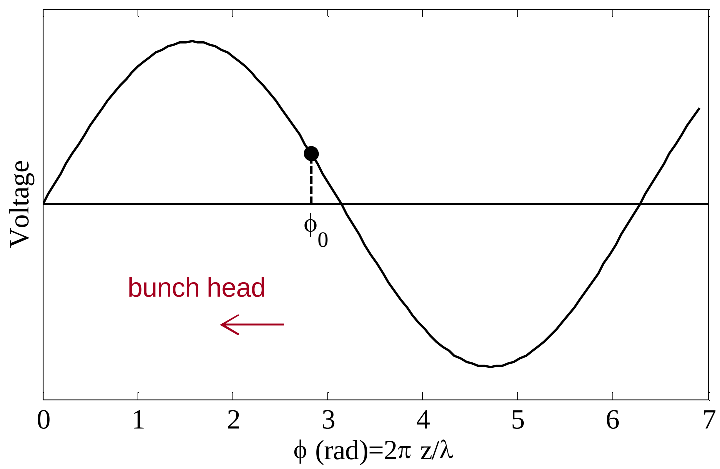
- Optics modification increases beam size
- To maintain beam stability, shorter bunches require lower current
- Hybrid mode running

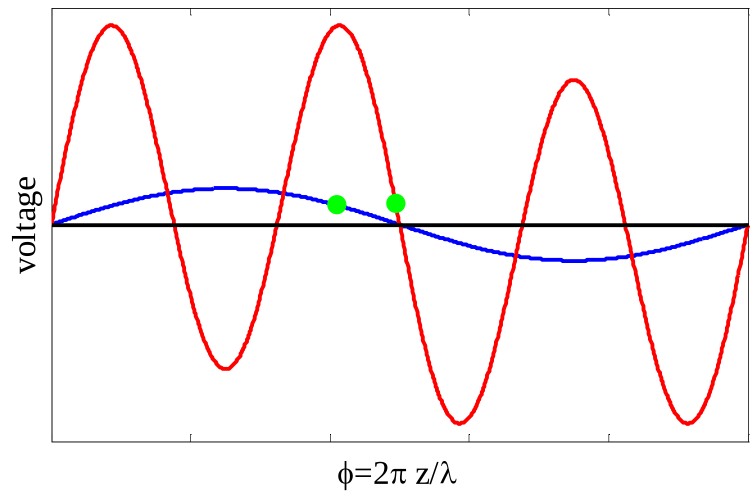
- Three 2-day runs in FY2012
- Four 3-day runs in FY2013
- Time available during AccPhys
- 100 mA total stored current
- 15 psec FWHM bunches
- 0.34 mA/bunch

Lattice	ε_x (nm)	σ_x ID (μm)
nominal	10	310
low-α	35	750



Method 4: Increasing RF focusing gradient





rf focusing $\dot{\delta} = \frac{1}{ET_0}\frac{\partial V}{\partial z} z$

Higher frequency (harmonic)
Higher voltage

High rf gradient can be provided with harmonic cavities.

High repetition rate, up to ~500 MHz
Available to all beamlines
High flux for short pulse length, ~1×10^6 photons/pulse/0.1%BW (5.2 ps, 8 keV)

Simultaneous long and short bunches

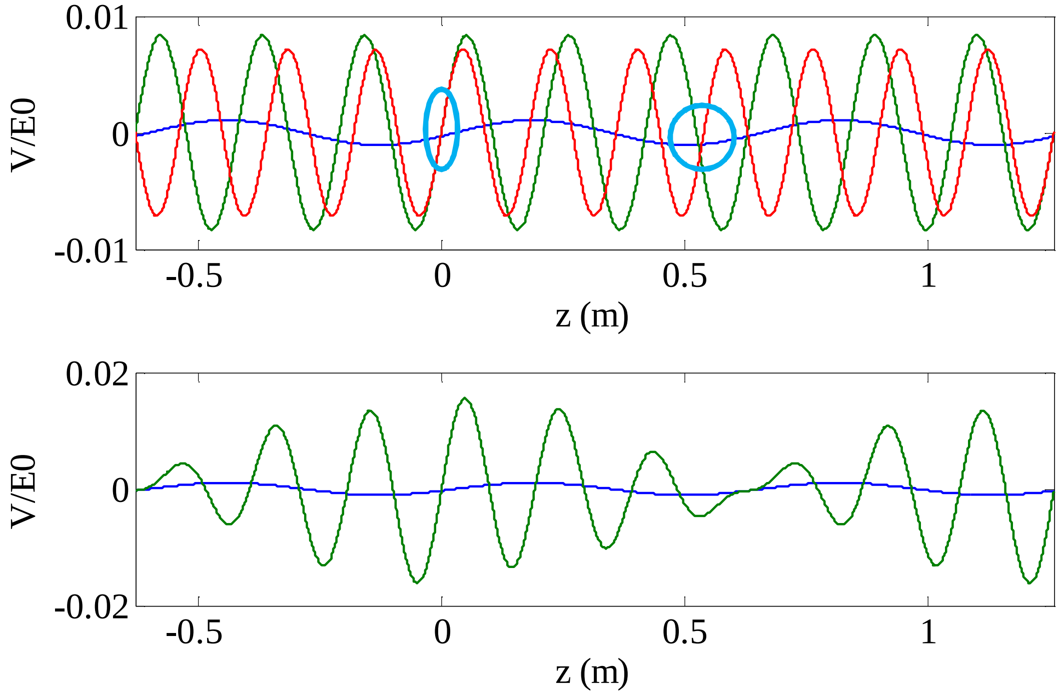
But we don't want all bunches to be short …

Sample for time-resolved experiments needs relaxation time.

Total stored current of short bunches is limited by vacuum chamber heating.

Add two harmonic cavity systems (harmonic n, and $n + 1/2$)

(G. Wüstefeld, et al, BESSY, IPAC2011).



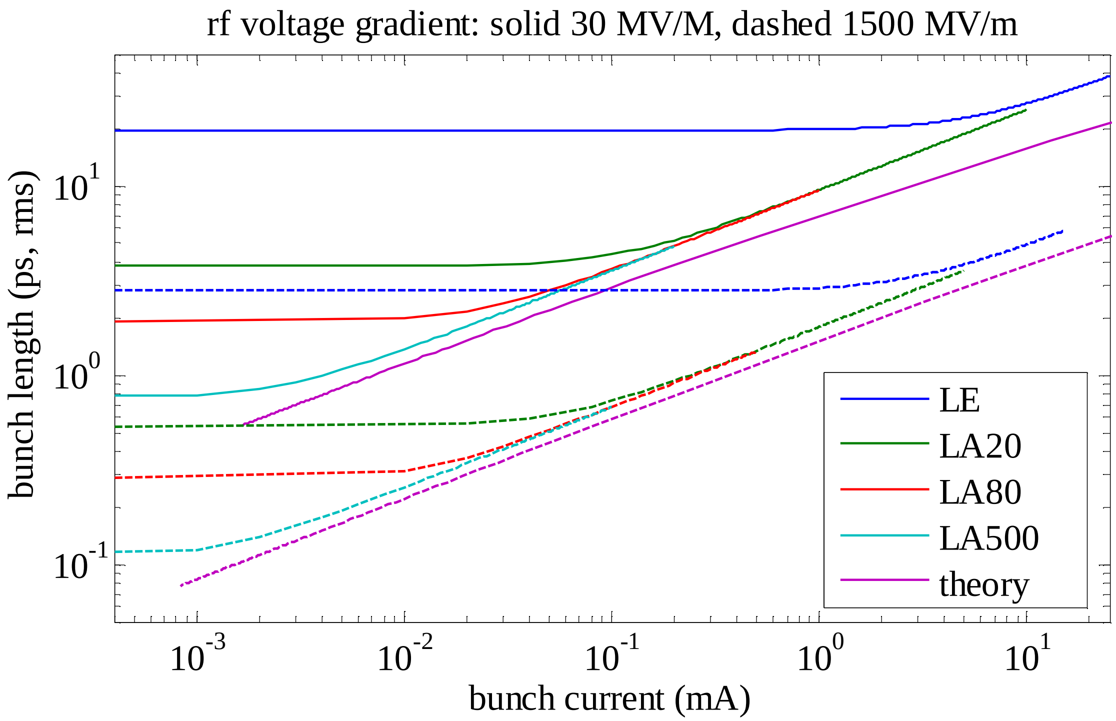
Half of the original buckets see increased voltage gradient, the other half remain the same.

Benefit of increased rf focusing gradient

Longitudinal microwave instability threshold (which limits single bunch current)

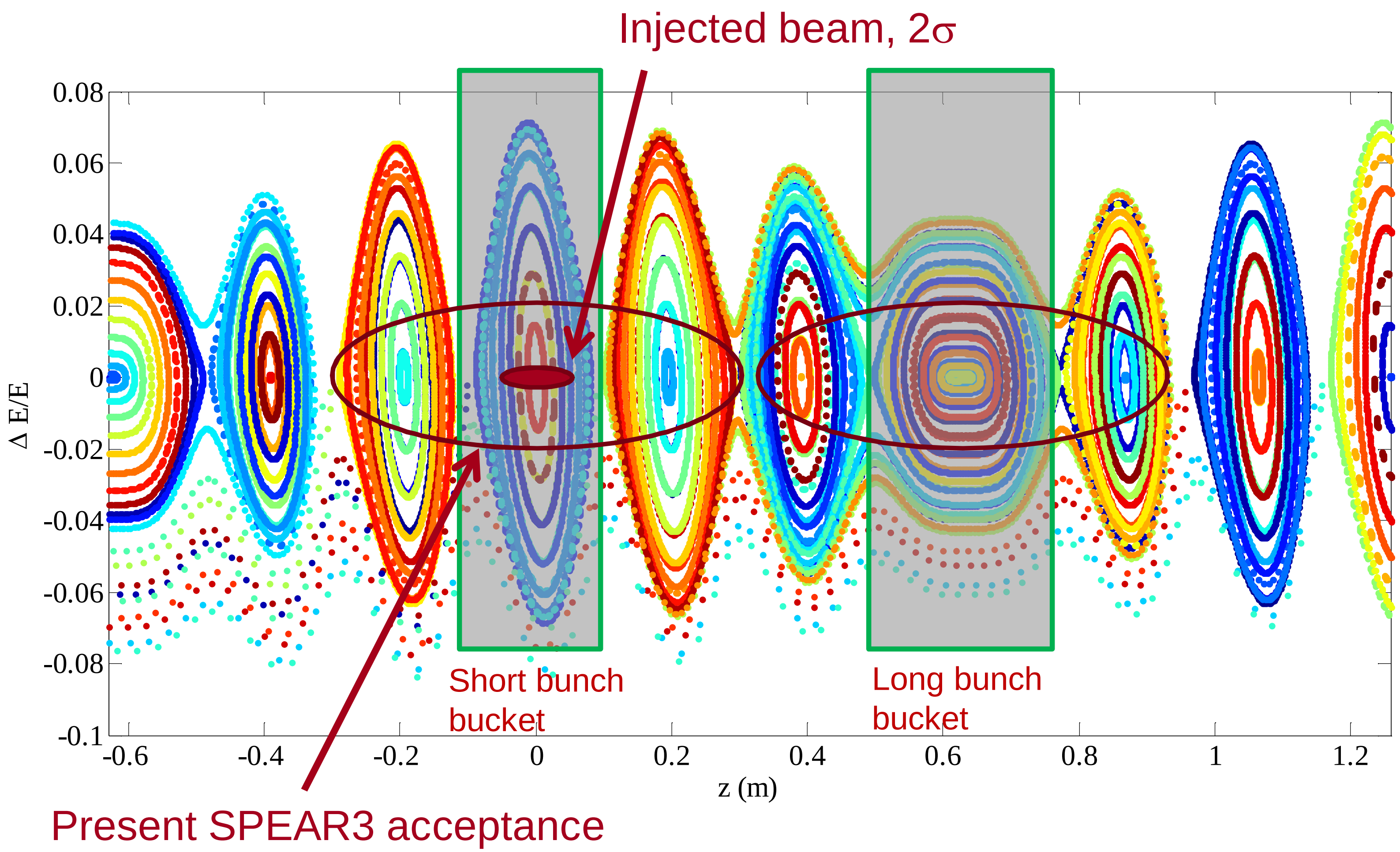
Peak current threshold $$\hat{I}_{\text{th}} \propto \alpha \frac{E\sigma_\delta^2}{|Z_{long}/\omega|}$$

To reduce bunch length to 1/7,
Option (1): decrease alpha by x1/50
Option (2); increase voltage gradient by x50
The threshold of option (2) is 50 times of option (1).



Possible parameters for SPEAR3 harmonic SRF

With 25 MV for 3rd harmonic, 21.4 MV for 3.5 harmonic, RF voltage gradient increases by a factor of 50, to 1500 MV/m..



Calculated performance

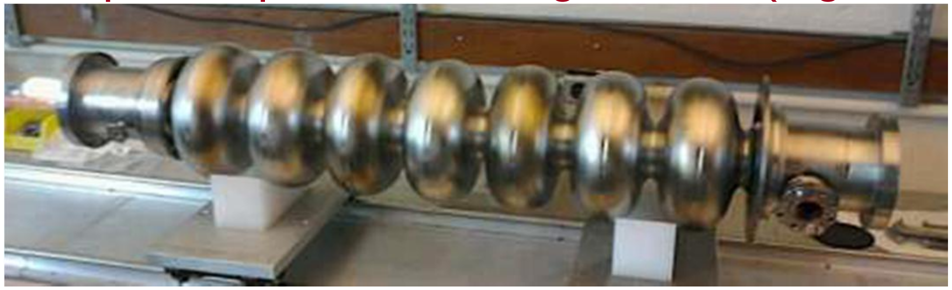
machine & mode	pulse length (ps, fwhm)	camshaft bunch charge (nC)	repitition rate (MHz)	1keV photons/pulse (ph/0.1% BW)	8keV photons/pulse (ph/0.1% BW)	eff. current (mA)	camshaft 1keV ave. flux (ph/s 0.1%BW)	camshaft 8keV ave. flux (ph/s 0.1%BW)
SPEAR3*/low alpha α/34, 100mA (present capability)	10	0.106	5.1	*8.3E+04*	*8.3E+04*	0.54	*4.2E+11*	*4.3E+11*
SPEAR3*/low alpha α/79, 40mA (present capability)	6.6	0.04	5.1	*3.1E+04*	*3.1E+04*	0.20	*1.6E+11*	*1.6E+11*
SPEAR3/standard lattice w/ SCRF upgrade, 500mA**	6.6	2.34	6.4	*2.3E+07*	*5.0E+06*	15.0	*1.50E+14*	*3.21E+13*
SPEAR3/low alpha α/41 w/ SCRF upgrade, 100mA**	1.3	0.044	6.4	*4.4E+05*	*9.4E+04*	0.28	*2.81E+12*	*6.03E+11*
SPEAR3/low alpha α/550 w/ SCRF upgrade, 2mA**	0.35	0.0020	6.4	*2.0E+04*	*4.3E+03*	0.0128	*1.28E+11*	*2.74E+10*
ALS*** femto-sec slicing	0.20	0.0012	0.02	*1.9E+03*	*153*	0.000023	*3.84E+07*	*3.06E+06*
APS - SPX**** (crab cavity)	1.3	0.23	6.5	*1.6E+04*	*1.1E+06*	1.50	*1.0E+11*	*7.4E+12*
SPEAR3*/standard lattice, camshaft 5 mA	54	3.9	5.1	*3.0E+06*	*3.1E+06*	20	*1.6E+13*	*1.6E+13*
APS timing mode 4.2 mA×24=100mA	80	15.4	6.5	*1.1E+06*	*7.6E+07*	100	*7.0E+12*	*5.0E+14*

* 65mm λ, 26 periods, 4.25 k_{max} (BL13 @ 1keV); 22mm λ, 67 periods, 2.17 k_{max} (BL12-2 @ 8keV)
** 22mm λ, 154 periods, 2.336 k_{max} (IVU in 10s)
*** 30mm λ, 50 periods, 4.26 k_{max}
**** 0.6T bend w/ 1hmrad and 1% vert. acceptance (1keV); 27mm λ, 89 periods, 1.78 kmax (7-ID revolver @ 8keV)

Flux calculated by Tom Rabedeau

Cavity options

Require multi-cell cavities (high voltage, limited space in the ring).
Require super-conducting cavities (high voltage, CW operation).



Cornell 7-cell 1.3 GHz cavity (for ERL)

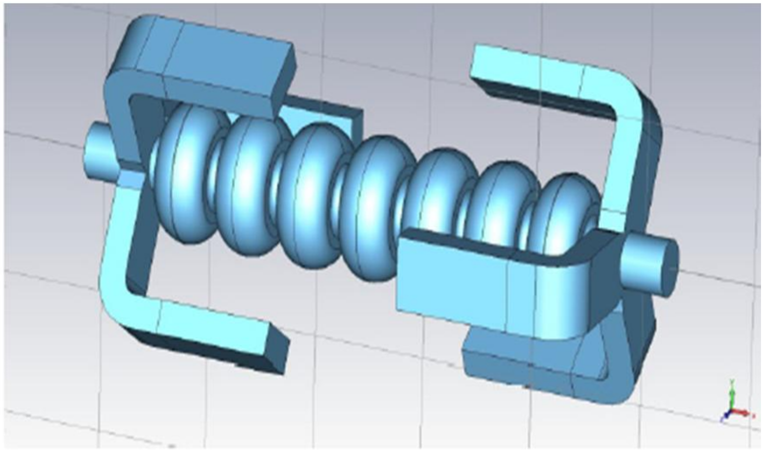
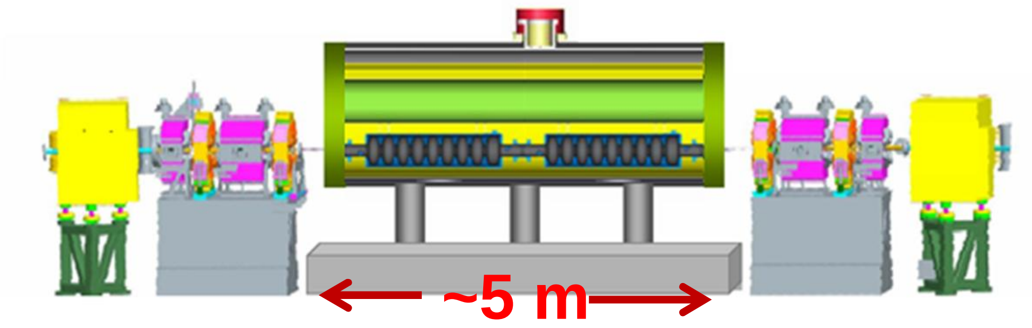


Figure 4: First outline of a 7-cell cavity with waveguide HOM dampers (courtesy B. Riemann)

7-cell cavity 1.5 GHz considered at BESSY



BESSY, 9-cell, (courtesy G. Wüstefeld).

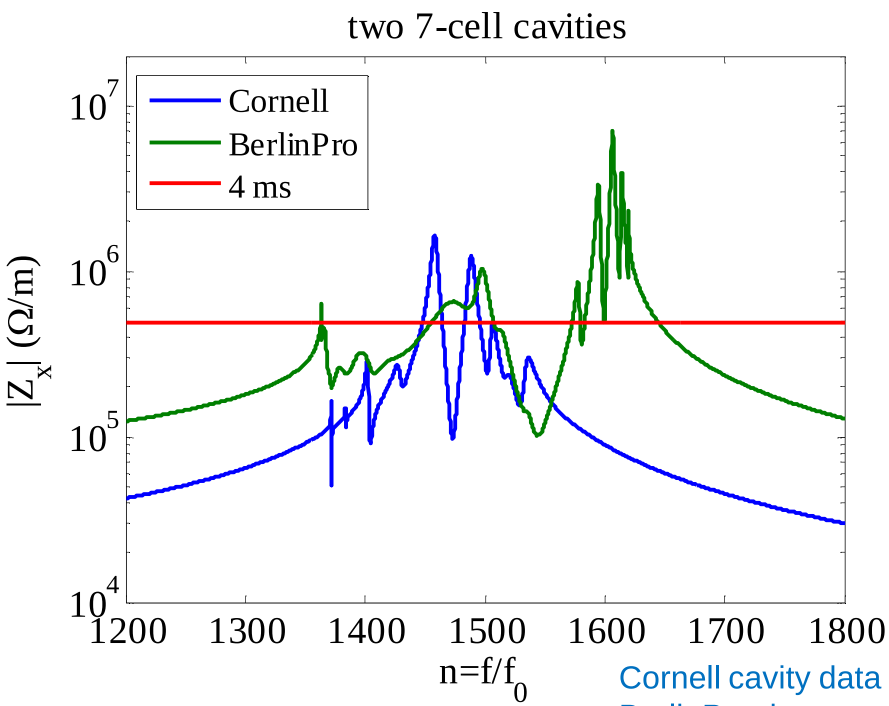
Challenges with multi-cell SRF cavities

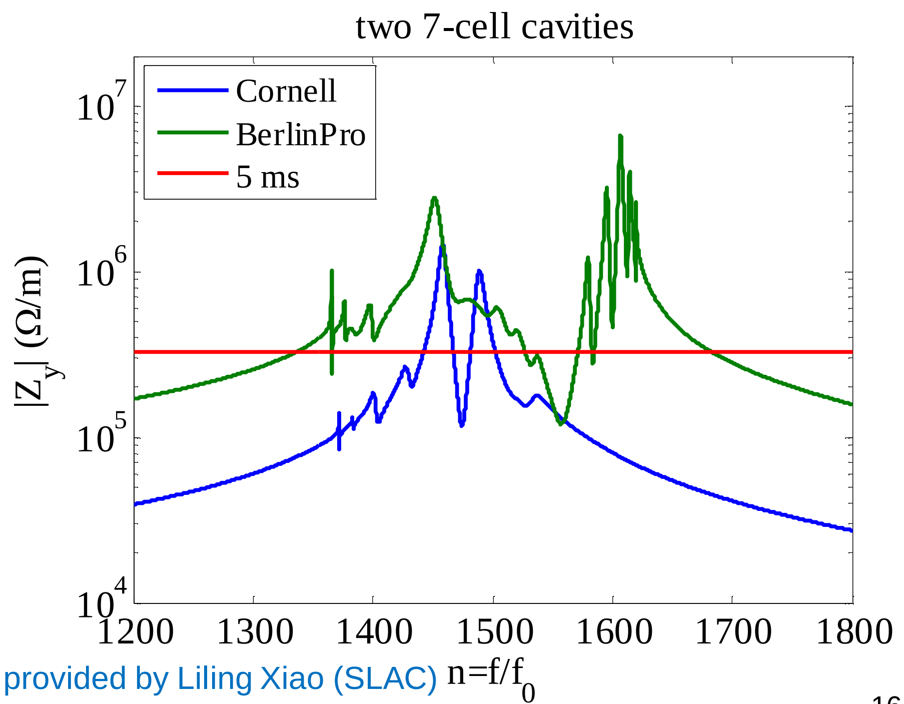
In multi-cell cavities beam excites LOM and HOM modes, causing

- heating in the cavity and
- coupled-bunched instabilities.

Design of mode-damped multi-cell cavity is key to the success of the idea.

- Damping of LOM modes is especially difficult since their frequencies are close to the fundamental mode.
- Reducing the number of cells helps the LOM and HOM modes, but also reduces the achievable voltage.
- LOM/HOM frequency control.





Cornell cavity data provided by Liling Xiao (SLAC)
BerlinPro data provided by Bernard Riemann (Dortmund University)

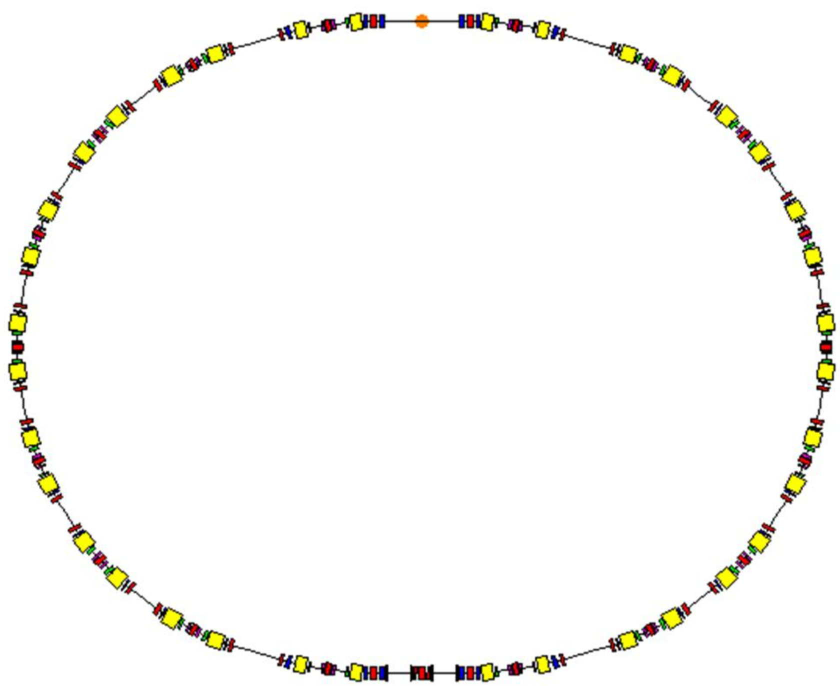
Other issues

- Injection of long bunches into short-bunch buckets.
  - Injecting beam bunch length is ~100 ps (rms), much longer than the short bunch in the ring. Low injection efficiency, leakage to adjacent buckets.
  - May need bunch cleaning system to improve bunch purity.
- Stability of short bunches.
  - RF noise.
  - Transient beam loading effects.
  - Stabilization of very small alpha for ultra-short pulses.
  - Synchro-betatron coupling.
- Beam dynamics issues with short bunches.
  - Coherent synchrotron radiation.
  - Ring impedance at high frequency.
- Other possibilities
  - Multiple, closely-spaced, 3-cell cavities in a single cryostat
  - Pulsed RF from ring resonator that interacts only with the camshaft bunch
  - Higher harmonic RF

Space in SPEAR3 for SRF cavities

Options:

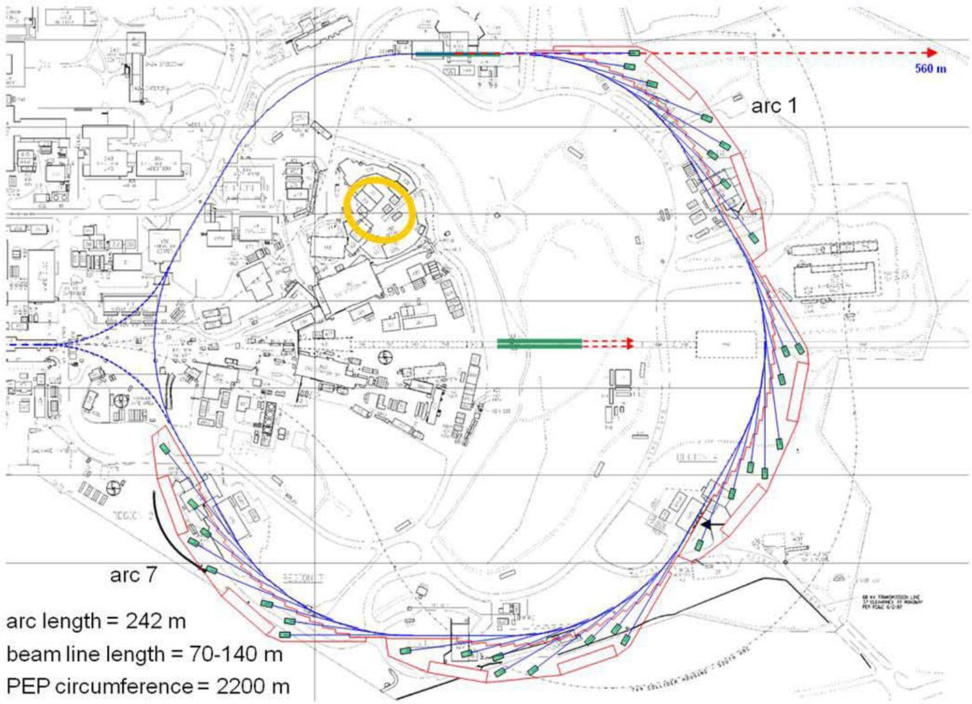
- Swap out all four existing 476 MHz cavities to free up the 7-m long straight section. This requires high power (>550 kW) ~1.5 GHz power source.
- Keep two 476 MHz cavities in the long straight. A second straight section is needed for SCRF cavities.
- Move two 476 MHz cavities to a matching straight. Use the long straight for SRF cavities.



Summary, SPEAR3 superconducting RF

- The two-frequency superconducting RF harmonic cavity approach is an attractive approach to generate <1~10ps X-ray pulses with storage rings.
  - High intensity.
  - Compatible with normal, high current operation.
  - Can be combined with low-alpha to reach very short pulses.
- Significant R&D effort is required before it becomes feasible.
  - SRF cavity design with LOM/HOM damped.
  - RF control and beam dynamics studies.
- Encouragement from DOE to Xiaobiao Huang to apply for an Early Career Award on SPEAR3 superconducting RF
- SLAC lab moving toward superconducting RF

PEP-X DLSR ("PEP-Hex")



- Diffraction limited ring for 1.5 Å ($\varepsilon = \lambda / 4\pi$ = 12 pm)
- Good beam lifetime 3 hours
- Good injection with 10 mm acceptance
- Achievable machine tolerances 20 microns
- Off-axis injection

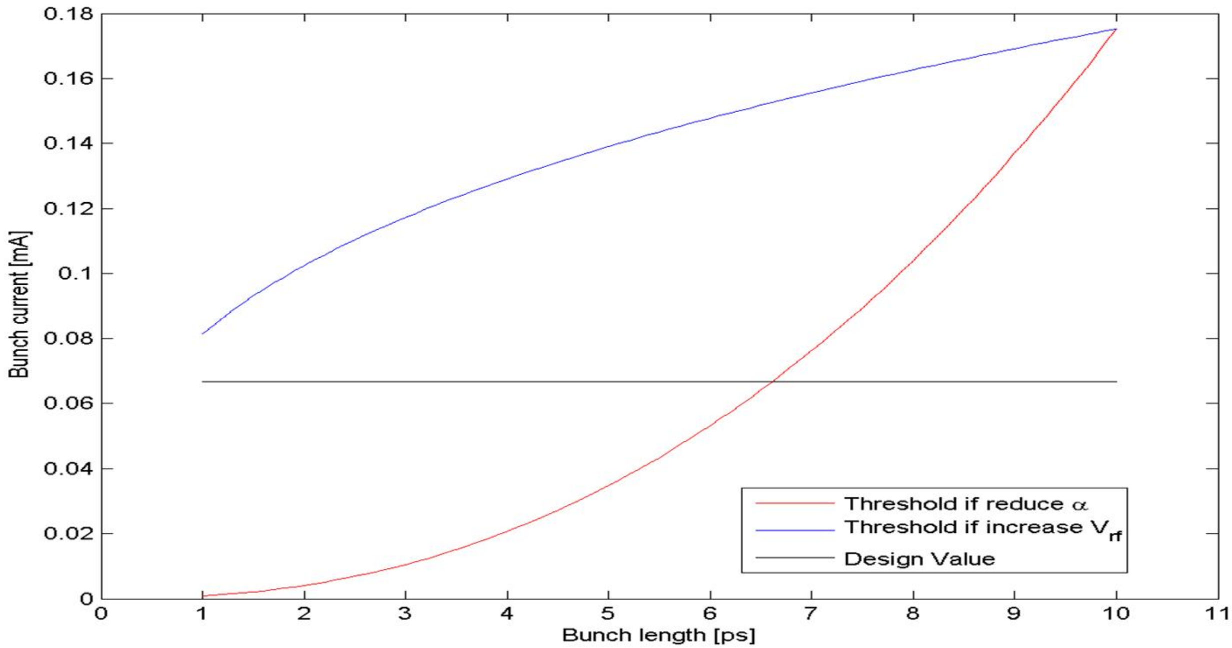
E = 4.5 GeV   I = 200 mA $\varepsilon_{x,y}$ = 12/12 pm-rad

54 7BA cells   off-axis injection

Y. Cai, K. Bane, R. Hettel, Y. Nosochkov, M-H. Wang, M. Borland, Phys. Rev. ST Accel. Beams 15, 054002 (2012)

Reduce bunch length from 10 ps to 1 ps without reducing bunch current

Calculation of CSR microwave instability threshold



An illustration using 4.5-GeV PEP-X nominal parameters: f_{rf} = 476 MHz, V_{rf}=8.3 MV, f_{rev} = 136.312 kHz, σ_z=3 mm, I_b=0.067 mA.

Parameter	PEP-X (USR)	PEP-X (FEL)
Beam energy [GeV]	4.5	
Circumference [m]	2200	
Current [mA]	200	10*
Betatron tune (H/V)	113.23/65.14	
Momentum compaction	4.96×10^{-5}	
Emittance [pm-rad] (H/V)	12/12	160/1.6
Bunch length [mm]	3	0.3
Energy spread	1.55×10^{-3}	
Energy loss per turn [MeV]	2.95	
RF voltage [MV]	8.3	282.0
RF frequency [MHz]	476	1428**
Damping time [ms]	18	
Length of ID straight [m]	5	Use also long straights (> 100 meter)
Beta at ID center (H/V) [m]	4.9/0.8	

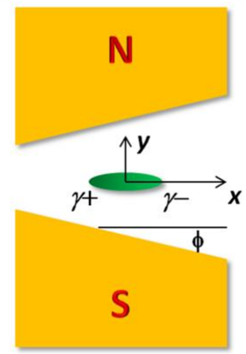
* Limited by SRF HOMs

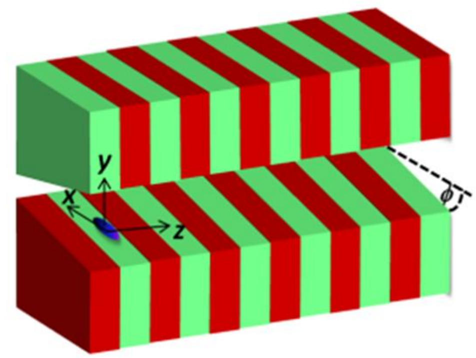
** 2- or 3-frequency RF to provide long and short bunches is possible

Transverse Gradient Undulator (TGU)

Generate a linear x-dependence of the undulator fields:

$$\frac{\Delta K}{K_0} = \alpha x \,.$$



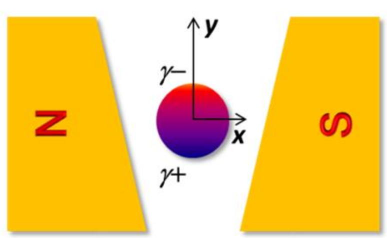


For a large energy-spread beam, disperse the beam according to its en$x = \eta\Delta\gamma/\gamma_0.$

Choose dispersion and transverse gradient:$\eta = \dfrac{2+K_0^2}{\alpha K_0^2}$

Betatron beam size << dispersed beam size

$\Rightarrow$ rotate TGU to take advantage of very small vertically coupled emittance in DLSR



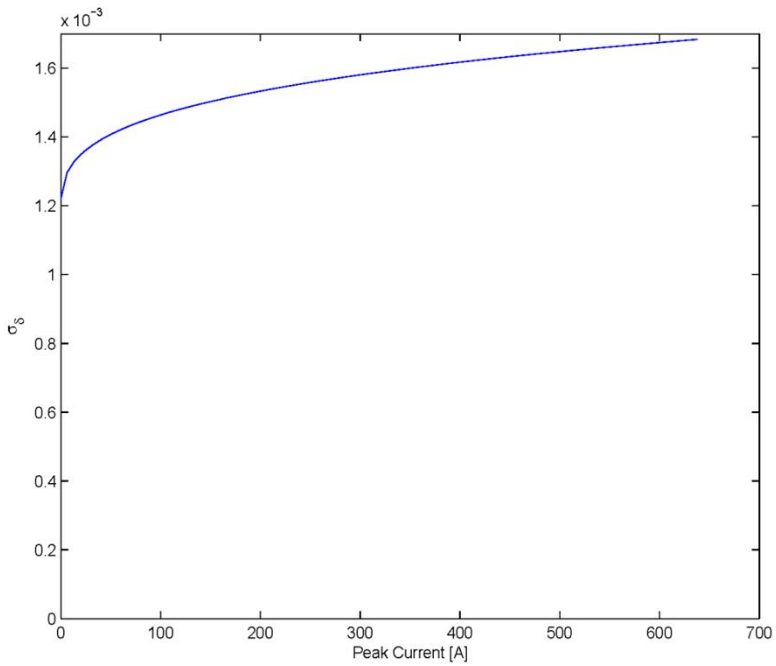
low gain FEL: T. Smith et. al., J. Appl. Phys. 50, 4580 (1979).

N. Kroll et. al., IEEE Journal of Quan. Electro. QE-17, 1496 (1981).

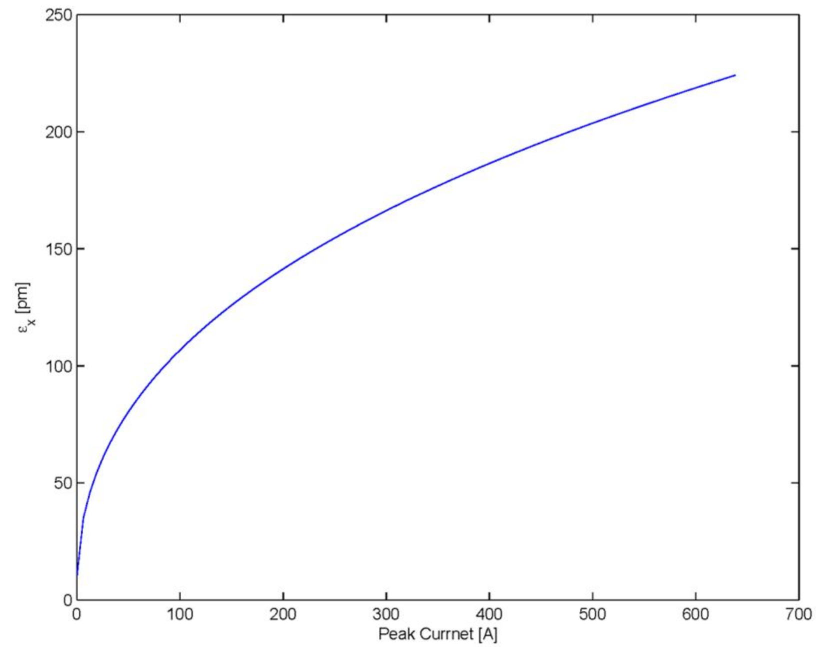
high gain FEL applying to laser-plasma driven accelerator: Z. Huang, Y. Ding and C. Schroeder, Phys. Rev. Lett. 109, 204801 (2012).

IBS growth for 1ps bunch

Energy Spread

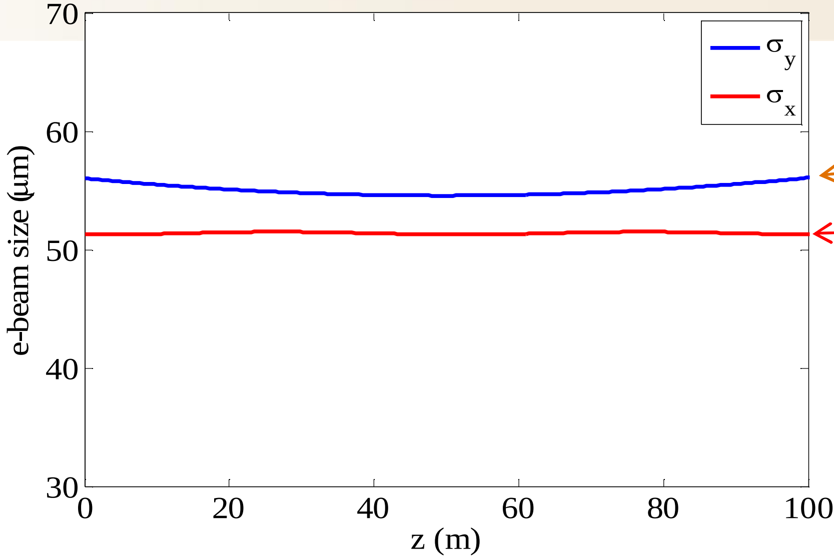


Horizontal Emittance



Flat beam option. Vertical emittance is 1% of the horizontal one.

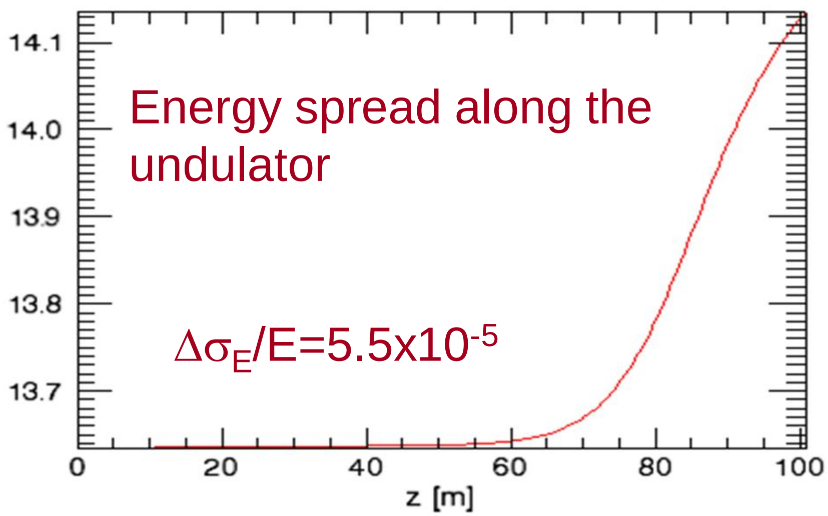
Electron beam and radiation size



Almost round beam

Dispersion dominated size

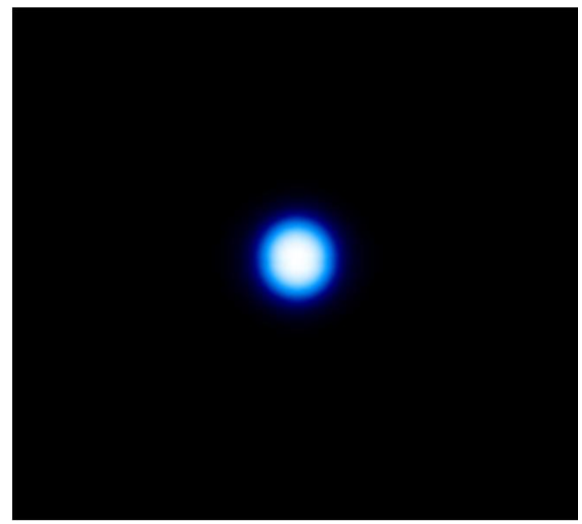
Emittance size



$\sigma_E/0.511$ [MeV]

Energy spread along the undulator

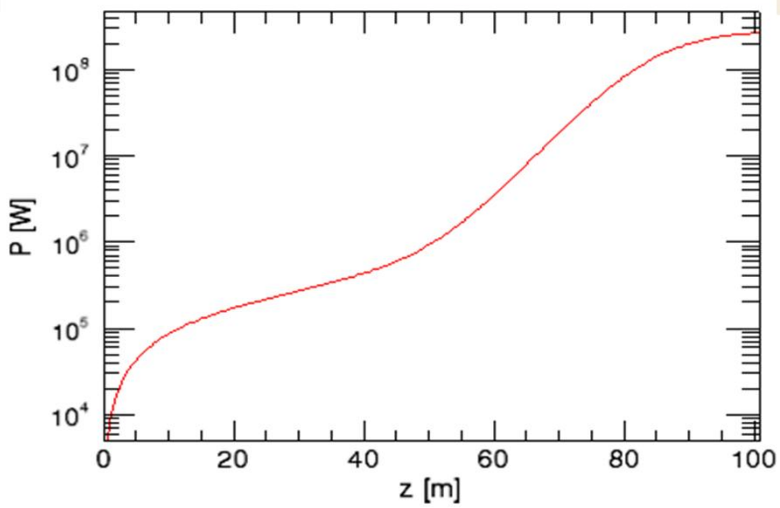
$\Delta\sigma_E/E=5.5\text{x}10^{-5}$

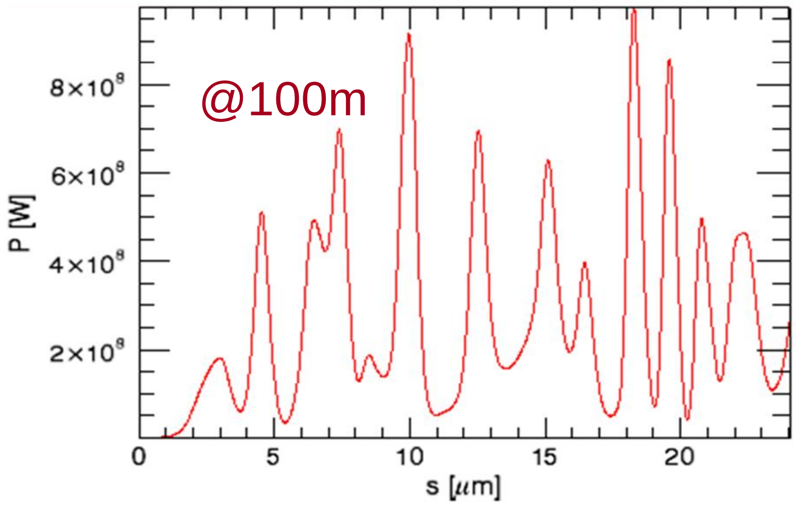


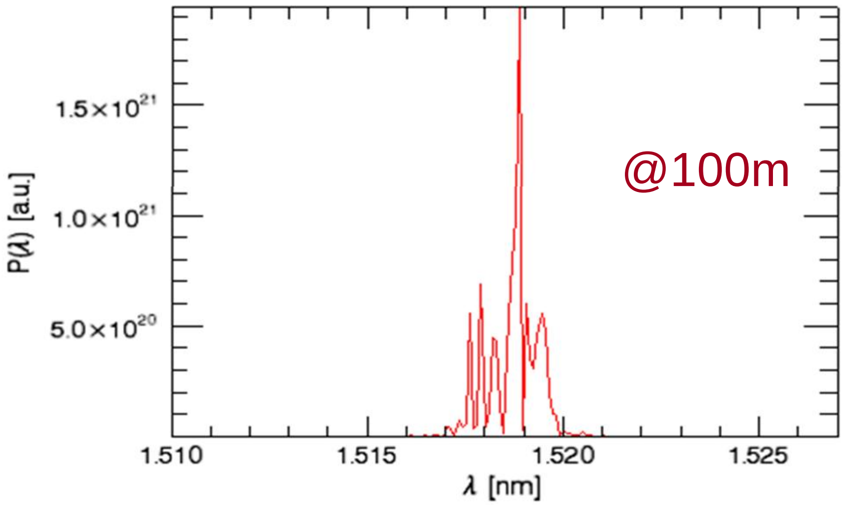
FEL radiation far-field pattern, (Full transverse coherence!)

Simulation using a modified Genesis

Radiation power and spectrum







Saturation is reached with > 200 MW FEL power

For a bunch with σ_z=1ps, FEL pulse energy is estimated about 0.2 mJ (~2×10^{12} ph/pulse)

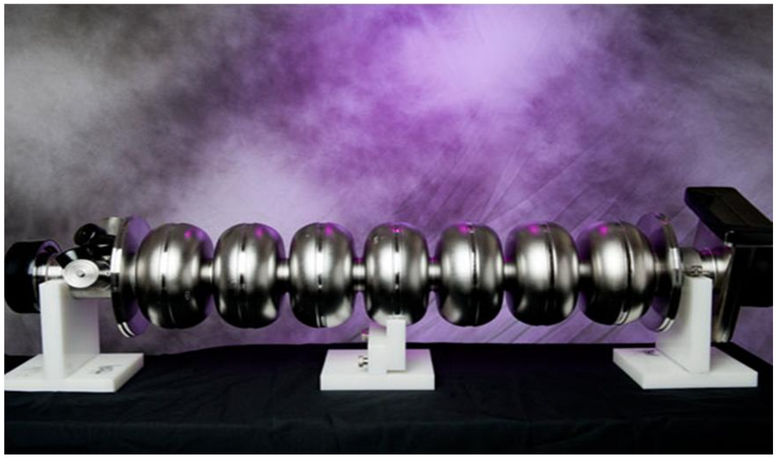
PEP-X(FEL) at 1.5nm

Parameter	PEP-X(FEL)	LCLS (150pC case)
Undulator	λ_u = 3cm, K=3.7 (TGU)	λ_u = 3cm, K=3.5
Radiation wavelength	1.5 nm	1.5 nm
Pulse energy	0.2 mJ (1.6×10^{12} photons)	2 mJ (1.6×10^{13} photons)
Peak power	200 MW	20 GW
Pulse length	1 ps	50-150 fs
Saturation length	90 m	40 m
Repetition rate	n_b x 100 Hz	120 Hz
Electron norm. emittance	1.45(x)/0.0145 (y) mm mrad	0.5 mm mrad
Electron peak current	300 A	1000-3000 A
Electron energy	4.5 GeV	4.3 GeV
Electron energy spread	1.55×10^{-3}	3.1×10^{-4}

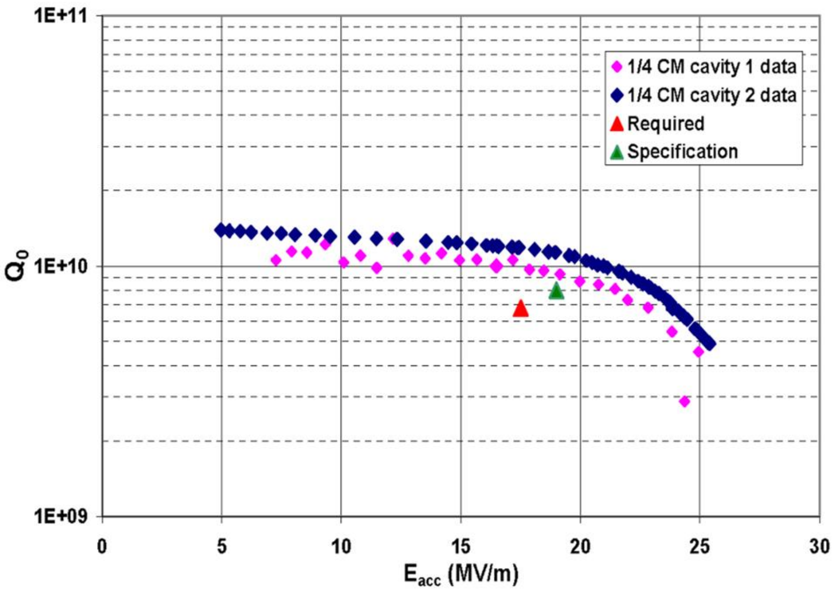
Note that n_b is number of bunches. Bunches are recycled after three damping times in PEP-X.

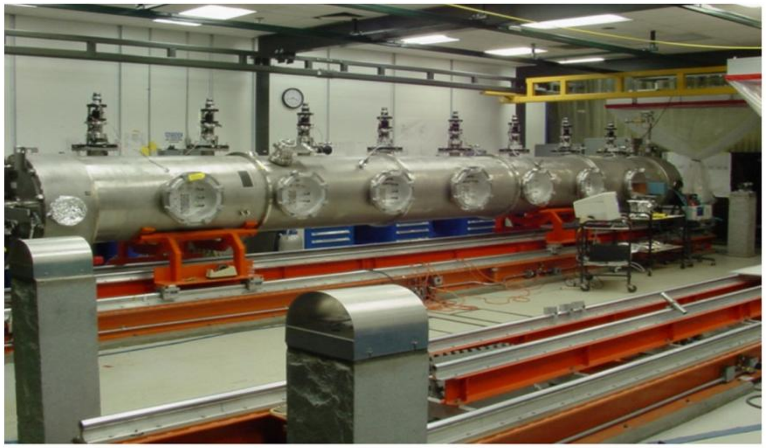
SCRF in 12 GeV CEBAF Upgrade

7-cell SCRF



Performance of SCRF (1497 MHz at 2 K)

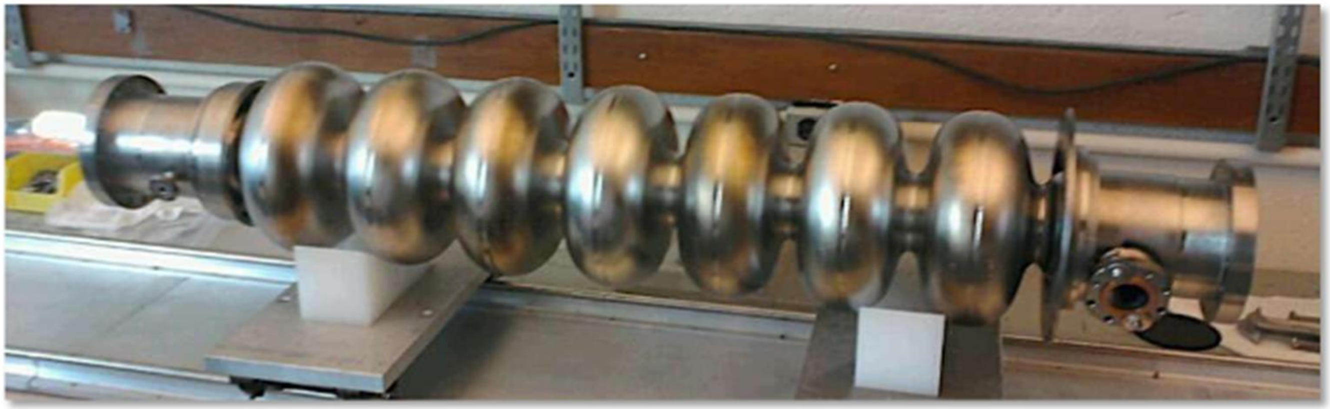




8 cavities in a cryomodule produce 108 MV

We assume 20 MV/m for accelerating gradient. Three modules are necessary to reach 1ps bunch length.

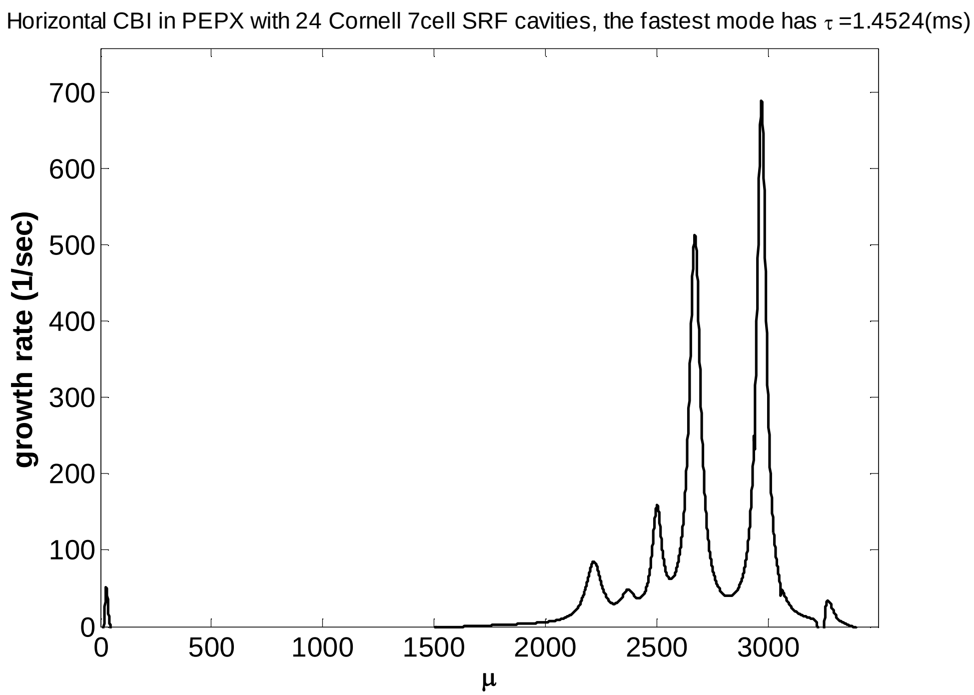
Cornell ERL's Main Linac Cavities

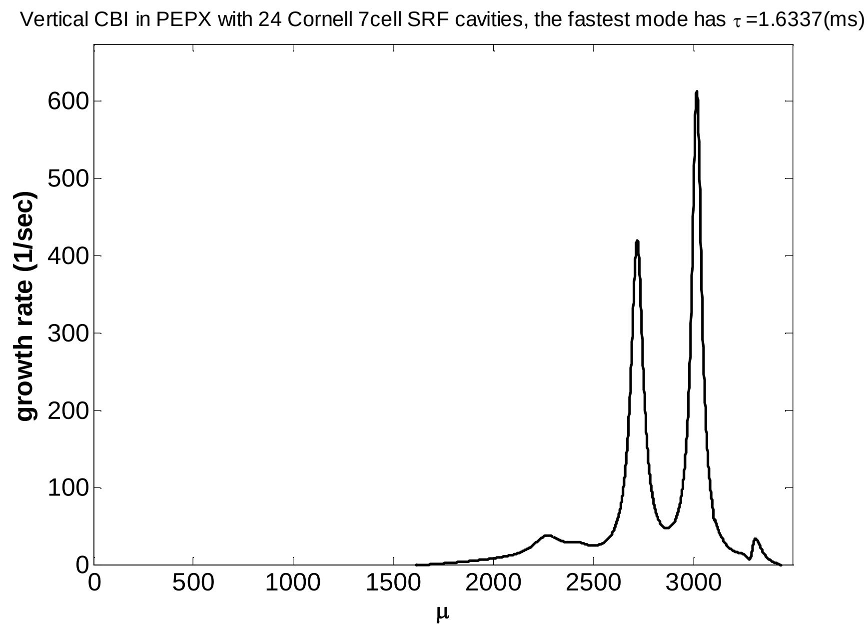


- Assume 24 such cavities in PEP-X
- Total 282 MV for 1 psec bunches

The unstable modes

- *With scaling of frequency (from 1.3GHz to 1.5GHz)*
- Fastest growth time is 1.45ms and 1.63ms for horizontal and vertical modes





L. Wang

Conclusion (PEP-X FEL)

DLSRs are capable to drive SASE FEL in soft x-ray region to saturation within 100 meter using 1ps bunch in transverse gradient undulators.

Based on the CEBAF upgrade, three cryomodules with 300 MV accelerating gradient are sufficient to reduce bunch length to 1ps and retain stability of 200 bunches with 20 mA beam current.

TGU can be applied to accommodate large energy spread in storage rings. It is necessary to rotate the undulator 90^0, taking advantage of a very small vertical emittance in the ring.

A feasible SASE FEL at radiation wavelength of 1.5 nm

- Achieves full transverse coherence
- Provides 0.2-mJ energy or $2\text{x}10^{12}$ photons per pulse
- Has pulse length of 1 ps
- Reaches a repetition rate of 10 kHz

DLSR-based hard X-ray XFELOs might be possible (under study)

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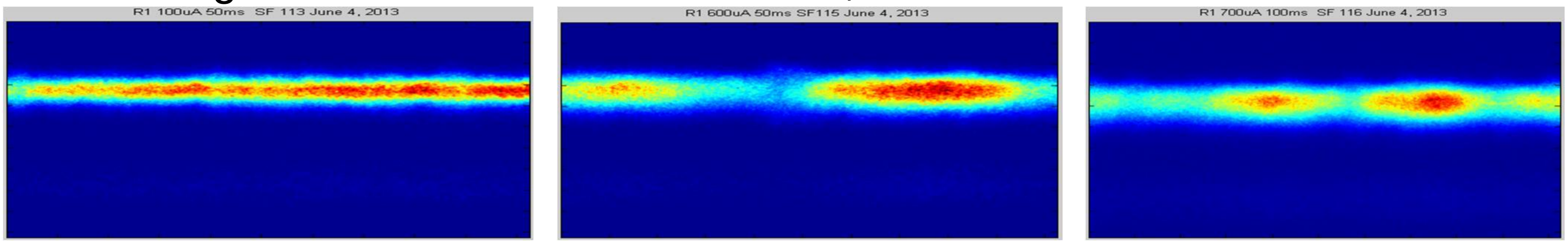
EXTRA SLIDES BEYOND HERE

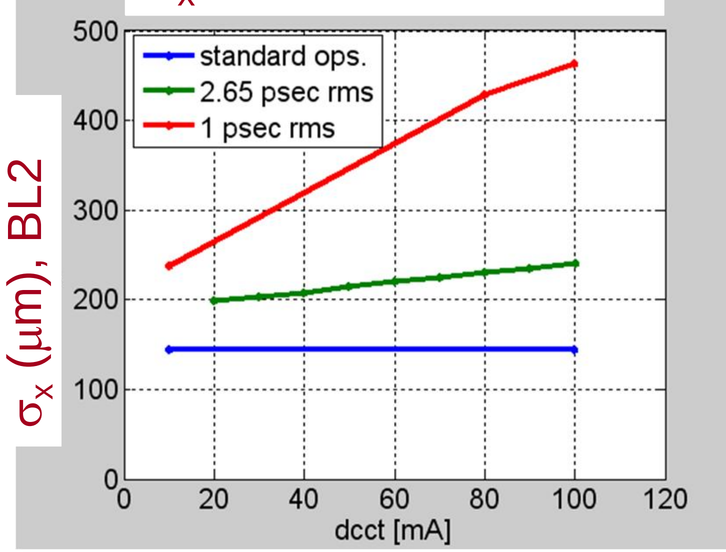
Threshold of μwave instability

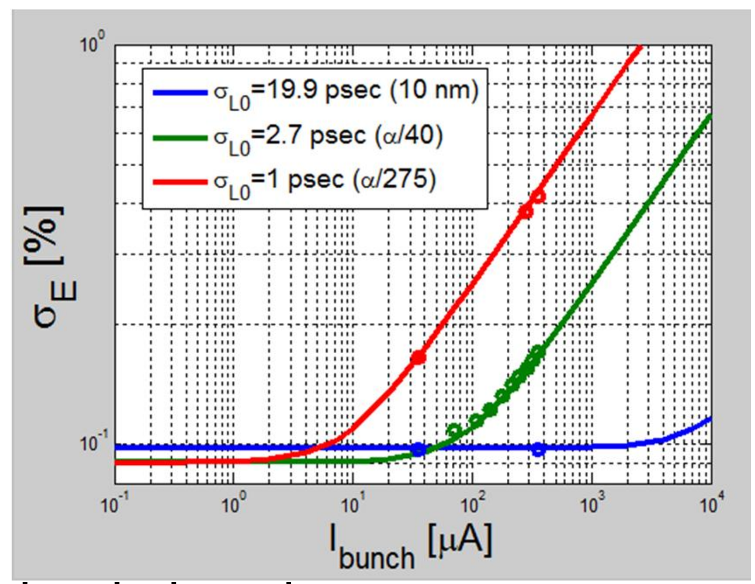
- No THz beamline at SSRL for bursting measurements
- Bursting measured with streak camera; difficult to determine threshold



- Can measure energy spread vs. bunch current:

σ_x vs. stored current:





- Indicates energy spread threshold 1.3x higher in bunch current.

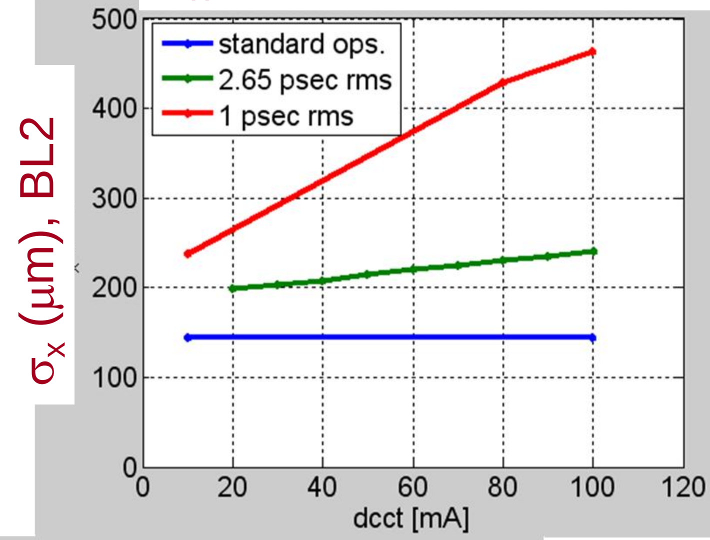
Energy spread vs. bunch current

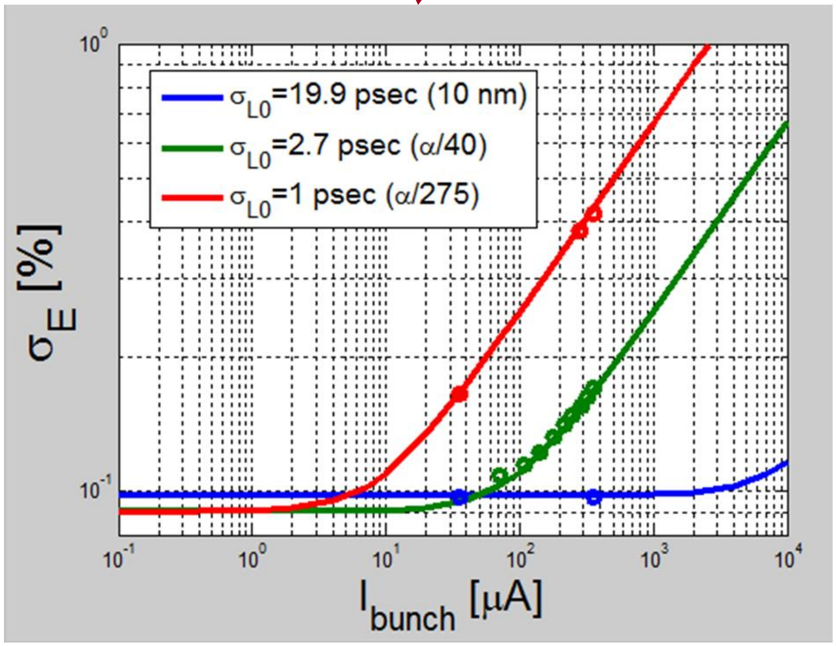
Measure σ_x vs. I_b … σ_E

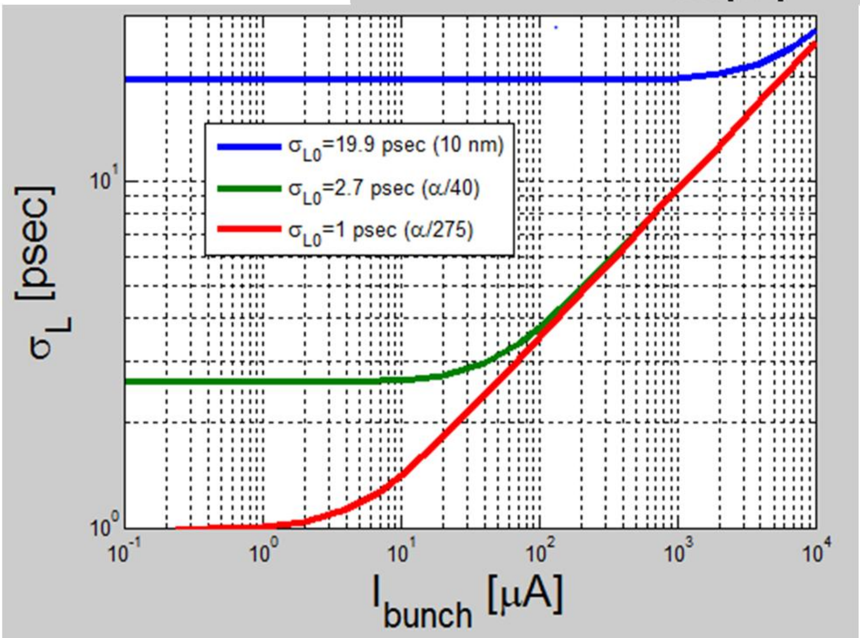
$1.8*I_{b0}$ for σ_E increase

$$\sigma_E = \sigma_{E0}\left(1+\left(\frac{\alpha_A}{\alpha}\right)^2\left(\frac{I_b}{1.8 I_{bo}}\right)^n\right)^{1/4}$$

σ_x vs. stored current:

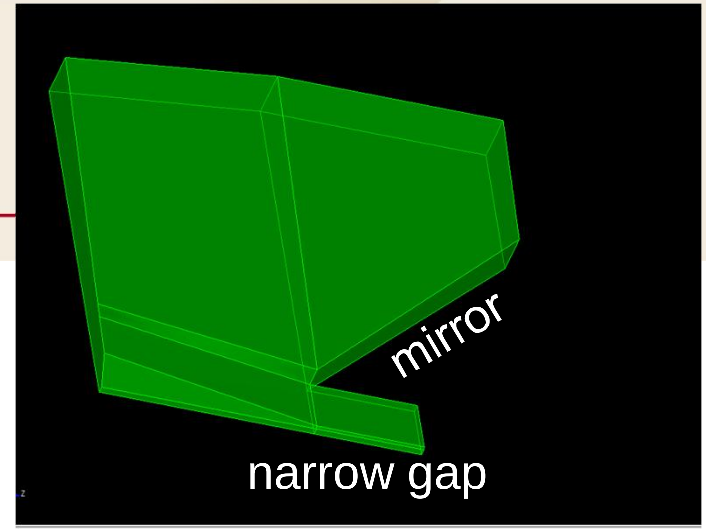


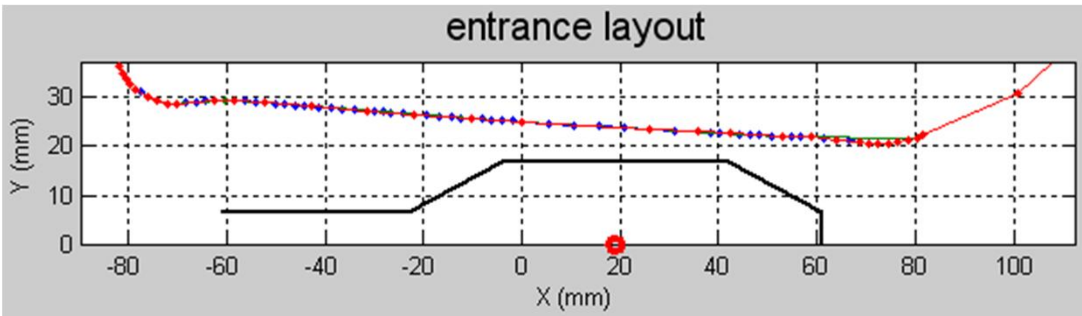


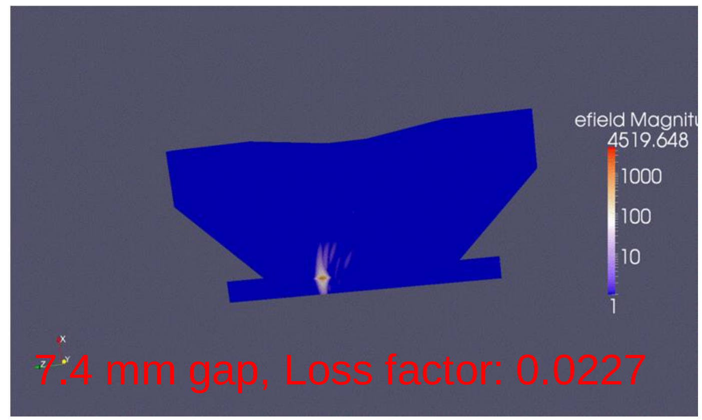


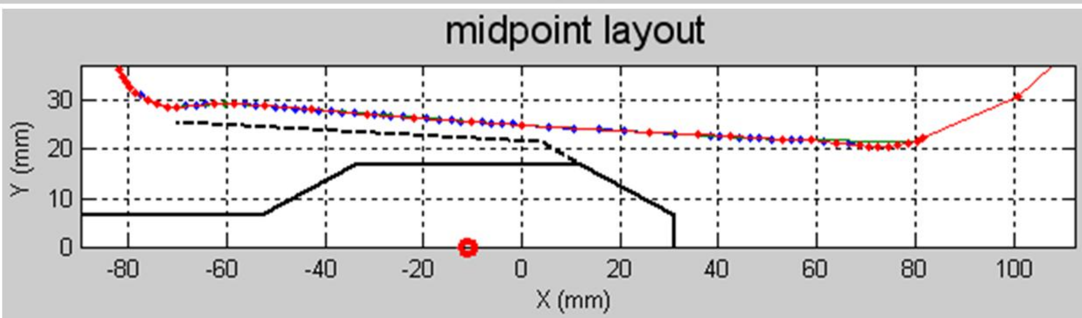
THz beamline proposal

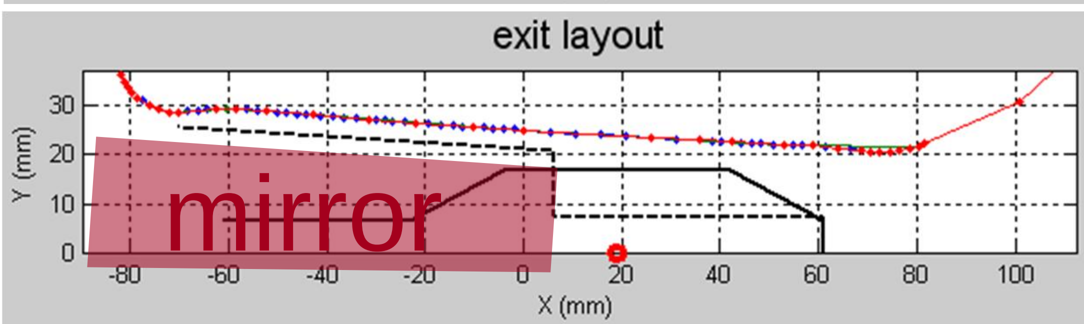
- Requires new dipole chamber
- Expanded exit slot for THz
- SCRF would increase THz power

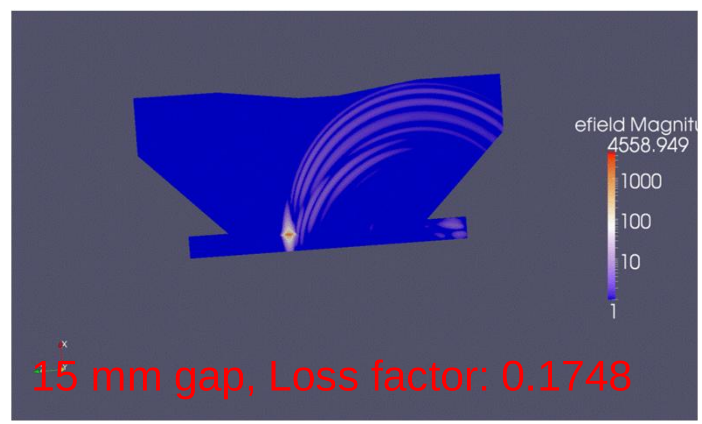




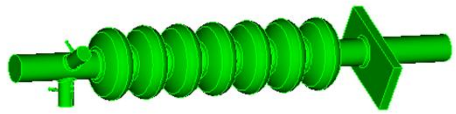


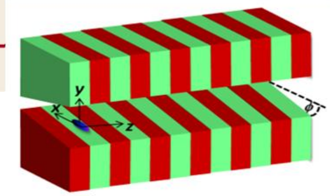






R&D plan





1ps bunch

- Improve design of a 1.5 GHz SCRF cavity similar to those built for CEBAF upgrade
- Build a prototype to demonstrate its performance in terms of accelerating gradient and sufficient damping of HOM
- Install the prototype in SPEAR3 to further quantify its performance with electron beam

Study how to drive an x-oscillator

- TGU in low-gain region with 20A peak current
- 10,000 bunches to reach 1MHz repetition rate
- Increase beam energy to 6 GeV (PEP-Xtra) and further reduce emitttance (5/5 pm) or use harmonic lasing