

# Short pulse for SPEAR with crab cavities

Presented at the LER2016 Workshop

Xiaobiao Huang for the SPEAR3 crab cavity study group

10/27/2016

## Contributors:

K. Bane, G. Bowden, Y. Cai, V. Dolgashev, K. Gaffney,  
**R. Hettel, X. Huang**, Z. Li, T. Rabedeau, J. Safranek, J.  
Schmerge, J. Sebek, S. Tantawi, K. Tian (SLAC),  
A. Zholents, Z. Conway (ANL),  
B. A. Lunin (FNAL)

# “Crabbing” the beam for short pulses in storage rings

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A. Zholents et al, NIMA 425, 385 (1999)

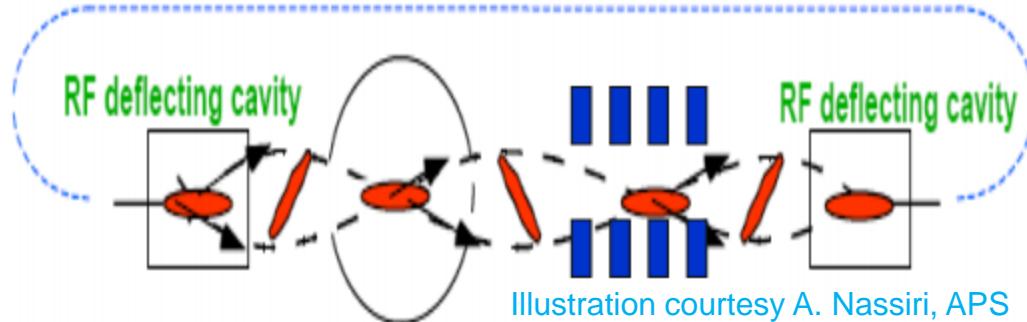
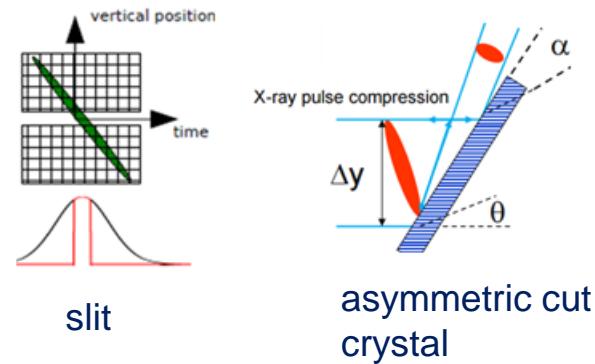


Illustration courtesy A. Nassiri, APS

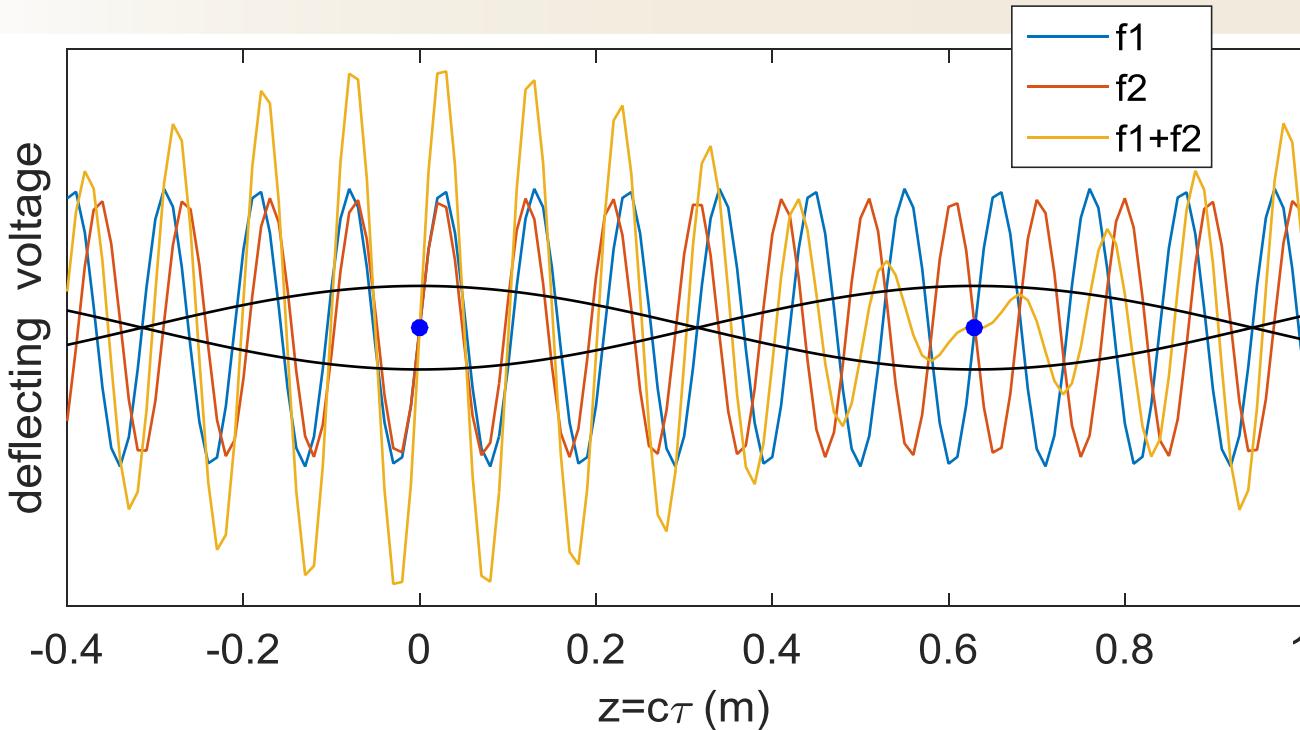
The tilt-and-cancel scheme

Deflecting cavity causes  $y' - z$  and  $y - z$  correlation at radiation source points.  
Photon beam is tilted in  $y - z$  at a downstream tilt.



# The two-frequency crab cavity scheme

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Two frequencies:

$$f_1 = n f_0,$$

$$f_2 = \left(n + \frac{1}{2}\right) f_0$$

Half of the buckets  
are tilted, the other  
half are un-affected.

Advantages of the new scheme:

- (1) Short pulses are available all around the ring.
- (2) No strict phase advance requirement for lattices.
- (3) Crab cavities occupy only one straight section (and only one cryostat for SRF)
- (4) Both cavities contribute to tilting (less total deflecting voltage required)
- (5) Beamlines can easily switch between short pulse mode and regular mode.

# Complete cancellation of crabbing kicks for regular beam

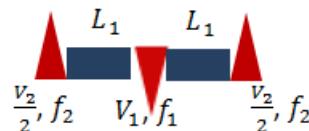
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- For complete cancellation, both the first and second integrals of the crabbing kicks need to be zeros.

$$\int_0^L g(s')ds' = 0, \text{ and } \int_0^L ds \int_s^L (L-s)g(s')ds' = 0$$

where  $g = \frac{dy'}{dt} \propto V_d f$ .

A symmetric configuration of the two frequencies in one drift can meet the requirements if the first integral is zero.



# Two frequency crab cavity configuration

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Crab cavities

Parameters		
$E_0$	3	GeV
$f_1$	2857.8	MHz 6 <sup>th</sup> harmonic
$f_2$	3096.0	MHz 6.5 <sup>th</sup> harmonic
$V_1$	1	MV
$V_2$	0.93	MV
$C$	234.1	m
$\sigma_\tau$	20	ps
$\beta_2$	2.8	m
$\beta_1$	4.9	m

Crab cavities of 6<sup>th</sup> and 6.5<sup>th</sup> harmonics of the main RF are located in a 4.5-m long straight section.

Buckets are alternately regular (flat) or tilted (in the y-z plane). Fill 480 mA to 140 regular buckets, and 20 mA to one camshaft bunch in the middle of a gap.

Fill pattern



# Beam dynamics challenges

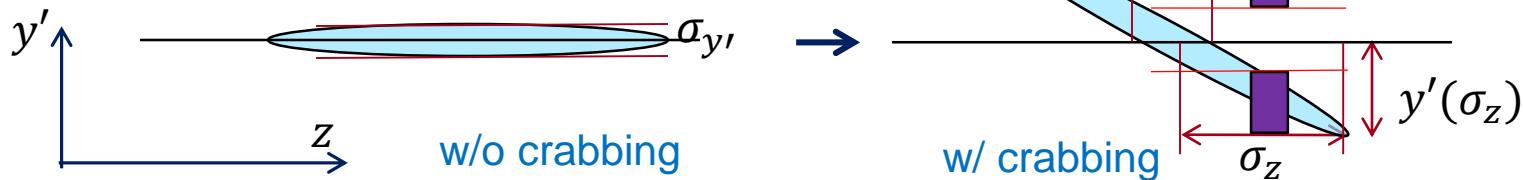
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- Achieve good short pulse performance with the tilted bunch.
  - Understand the factors that affect the short pulse performance
  - Optimize the system design for best performance.
    - Lattice
    - Crab cavity parameter choices
    - Location of crab cavities
    - Injection into tilted bunch
    - Single bunch current limit and bunch lengthening
    - Performance prediction
- Maintain good performance for the regular, long pulse users
  - Brightness, stability, beam lifetime, etc
  - Potential threats
    - Effect of RF noise
    - Effect of transit beam loading
    - Heat load due to doubled single bunch current
- Requirements and impact of the crab cavities
  - HOM specifications, impact of broad-band impedance

# Prediction of performance – tilt and vertical emittance

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Projection on  $y' - z$  plane



Minimum X-ray pulse length (for a pure  $y' - z$  tilt at the source point.).

$$\sigma_{ph} = \sigma_z \sqrt{\frac{\sigma_{y'}^2 + \sigma_\theta^2}{y'(\sigma_z)}}$$

A. Zholents, NIMA 798, 111 (2015)

Tilt of the beam:  $y'(\sigma_z) = \frac{\sigma_{y'z}}{\sigma_z^2}$

Vertical slice emittance (eigen-emittance)  $\epsilon_{y0}$ :  $\sigma'_y = \sqrt{\epsilon_{y0}/\beta_y}$

Need to find the equilibrium beam distribution for the prediction of short pulse performance.

# Tilt of the beam by crab cavity

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E-M fields in a (vertical) crab cavity, with  $k = \omega/c$

$$E_z = \mathcal{E}_0 k y \cos \omega t, \quad cB_x = \mathcal{E}_0 \sin \omega t,$$

Kicks by a crab cavity

$$\Delta y' = \frac{eV}{E} kz, \quad \Delta\delta = \frac{eV}{E} ky,$$

Transfer matrix for a crab cavity

$$\mathbf{T}_c = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \epsilon & 0 \\ 0 & 0 & 1 & 0 \\ \epsilon & 0 & 0 & 1 \end{pmatrix}$$

for  $(y, y', z, \delta)$ , with parameter  $\epsilon = \frac{eVk}{E}$

Tilt of the beam is given by the off-diagonal blocks of the 2<sup>nd</sup> order moment matrix. Projection of distribution onto subspace  $(y, y') \times (z, \delta)$

$$\Sigma_{yz} = \begin{pmatrix} \sigma_{yz} & \sigma_{y\delta} \\ \sigma_{y'z} & \sigma_{y'\delta} \end{pmatrix} \approx \mathbf{C}\Sigma_{z0} = \begin{pmatrix} C_{11}\sigma_z^2 & C_{12}\sigma_\delta^2 \\ C_{21}\sigma_z^2 & C_{22}\sigma_\delta^2 \end{pmatrix}$$

$\mathbf{C}$  the decoupling matrix of the one-turn transfer matrix.

Slope in  $y$ - $z$ :  $\frac{dy}{dz} = C_{11}$

$$C_{11} = \epsilon \frac{\sqrt{\beta_1 \beta_2}}{2 \sin \pi \nu_y} \cos(\pi \nu_y - \Psi_{12})$$

Slope in  $y'$ - $z$ :  $\frac{dy'}{dz} = C_{21}$

$$C_{21} = \epsilon \frac{\sqrt{\beta_2 / \beta_1}}{2 \sin \pi \nu_y} [\sin(\pi \nu_y - \Psi_{12}) - \alpha_1 \cos(\pi \nu_y - \Psi_{12})]$$

# Vertical eigen-emittance

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It was found that because of the tilted equilibrium distribution on  $y - \delta$  and  $y' - \delta$  planes, the vertical eigen-emittance grows with the crab cavity strength

$$\epsilon_y = C_q \frac{\gamma^2 \langle \mathcal{H}_c \rangle}{J_y \rho}, \quad \mathcal{H}_c = \frac{1}{\beta_y} (C_{12}^2 + (\alpha_y C_{12} + \beta_y C_{22})^2).$$

$$\langle \mathcal{H}_c \rangle = \frac{\epsilon^2 \bar{\eta}^2 \beta_2}{12} \frac{2 + \cos 2\pi\nu_y}{(\cos 2\pi\nu_s - \cos 2\pi\nu_y)^2}, \quad \text{where } \bar{\eta} = -\alpha_c C$$

X. Huang, PRAB 19, 024001 (2016)

The vertical eigen-emittance  $\epsilon \propto \epsilon^2 \alpha_c^2$  and depends on vertical tune.

Vertical emittance of this origin may dominate (for example, for SPEAR3 with nominal parameters and the  $\nu_y = 6.177$  lattice):

Vertical emittance (in an earlier example)

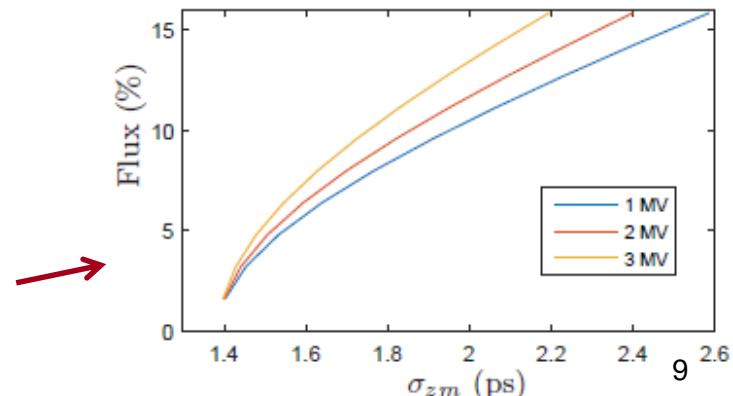
from tilted distribution:  $\epsilon_y = 680$  pm.

from photon beam (equivalent to e-beam)  $\epsilon_y = 130$  pm

(for BL15 at 12.5 keV),

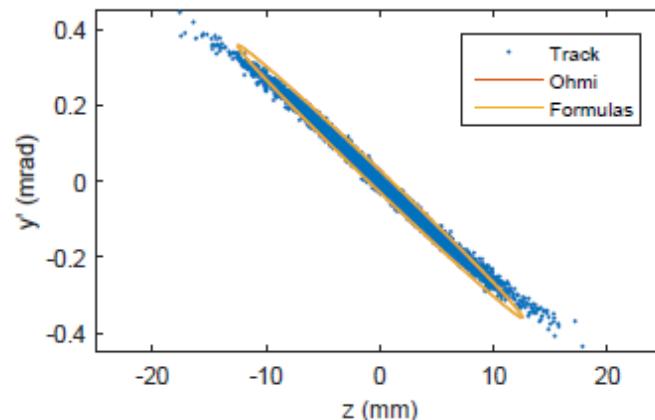
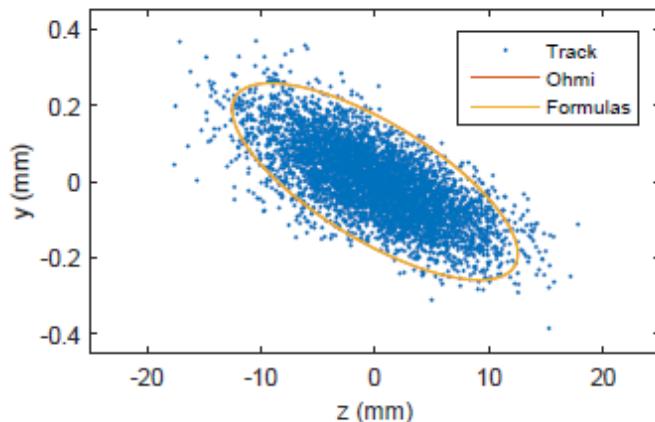
from  $x - y$  coupling  $\epsilon_y = 10$  pm

If not considering photon beam divergence and  $x - y$  coupling, the minimum pulse length would be independent of crab parameter strength.

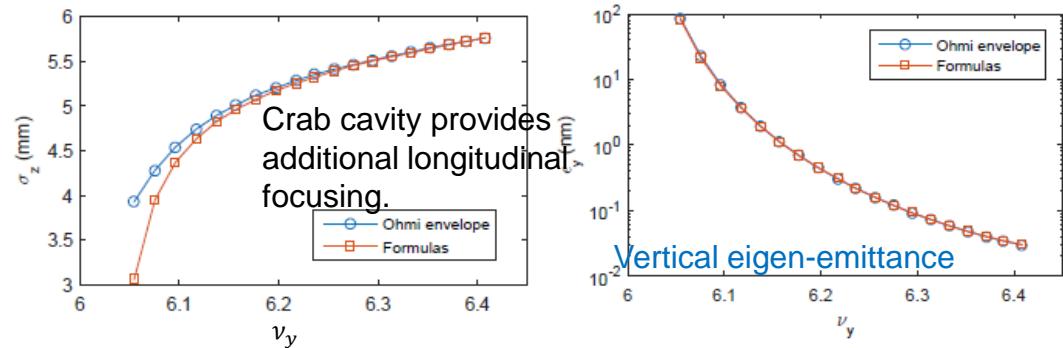


# Theory vs. simulation

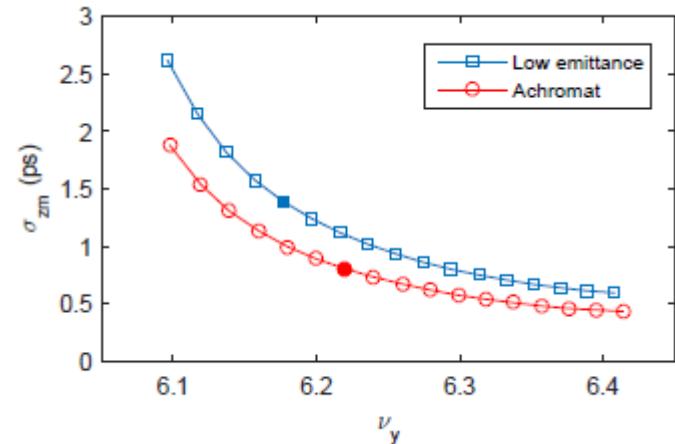
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Equilibrium distribution from tracking vs. calculated ellipses for an example ( $6\sigma$ ) for the lattice with  $\nu_y = 6.177$ .



Formulas agree with numeric calculation. With  $\nu_y$  increased from 6.177 to 6.32, vertical eigen-emittance drops by a factor of 10.



Higher  $\nu_y$ , lower  $\alpha_c \rightarrow$  shorter pulse

# Short pulse performance calculation

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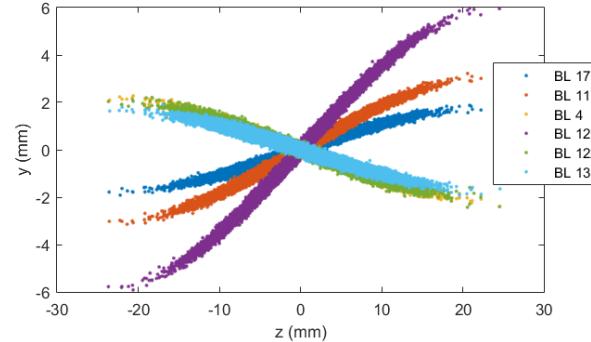
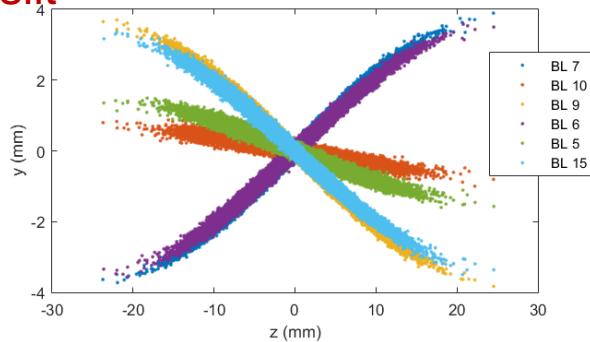
Vertical tune is raised from 6.13 to 6.32. A 7-nm upgrade lattice with tunes [15.13, 6.32] was tested on the machine. Vertical eigen-emittance is **83 pm**. The  $\nu_y = 6.32$  tune is not compatible with the 6-nm lattice (w/  $\nu_x = 15.32$ ).

Equilibrium distribution for electron beam is found by tracking for 30,000 turns (>4 damping time).

Options in photon optics:

1. Drift to a slit – simple, but performance is impacted by photon divergence.
2. Image the source point onto a slit – better performance, but more complicated, and performance may be limited by space and mirror.

Drift to a slit

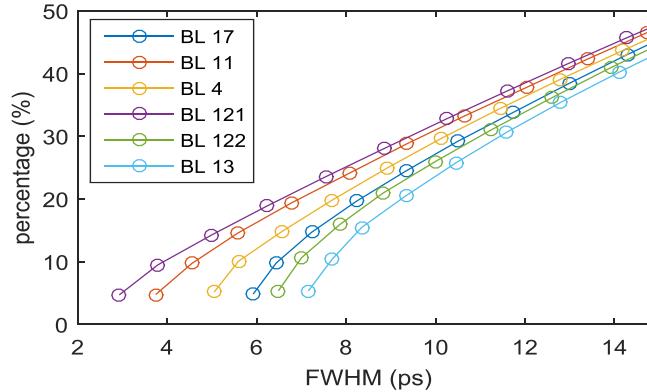
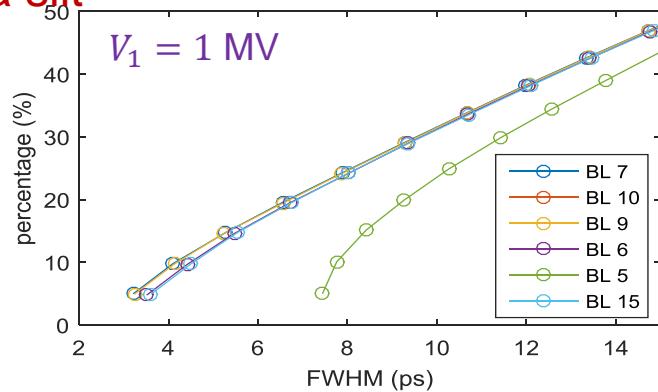


Deflecting voltage  $V_1 = 1$  MV. Photon beam at 13.5 m downstream of source point.  
Including photon beam divergence ( $\sigma_\theta = 5 \mu\text{rad}$ );

# Short pulse flux vs duration from tracking simulation

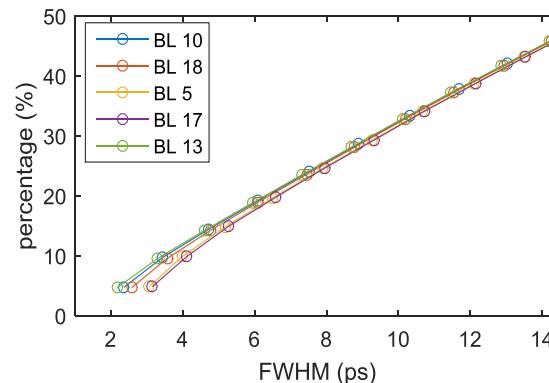
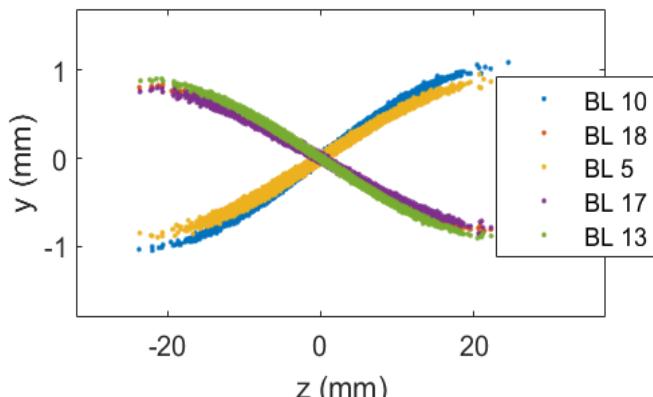
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Drift to a slit



Including radiation divergence ( $\sigma_\theta = 5 \mu\text{rad}$ ); Not including bunch lengthening.

1:1 imaging of source point



No contribution from radiation divergence; Not including bunch lengthening.

# Short pulse performance

Drift to a slit

Numbers in parentheses include bunch lengthening for a 20-mA bunch.

beam line	6% (3.8%) flux		10% (6.3%) flux		15% (9.4%) flux		20% (12.6%) flux	
	V1=1 MV	1.5 MV	V1=1 MV	1.5 MV	V1=1 MV	1.5 MV	V1=1 MV	1.5 MV
7	<b>3.4</b>	<b>2.9</b>	<b>4.2</b>	<b>3.7</b>	<b>5.3</b>	<b>4.9</b>	<b>6.7</b>	<b>6.2</b>
10	16.2	13.0	16.4	13.4	16.6	13.9	17.1	14.3
9	<b>3.4</b>	<b>3.0</b>	<b>4.2</b>	<b>3.8</b>	<b>5.3</b>	<b>4.9</b>	<b>6.7</b>	<b>6.2</b>
6	<b>3.7</b>	<b>3.2</b>	<b>4.5</b>	<b>3.9</b>	<b>5.6</b>	<b>5.1</b>	<b>6.9</b>	<b>6.3</b>
5	7.5	5.9	7.8	6.3	8.4	7.0	9.3	7.9
15	<b>3.8</b>	<b>3.2</b>	<b>4.6</b>	<b>3.9</b>	<b>5.6</b>	<b>5.0</b>	<b>6.9</b>	<b>6.3</b>
17	6.0	4.8	6.5	5.3	7.3	6.2	8.3	7.2
11	<b>3.9</b>	<b>3.3</b>	<b>4.6</b>	<b>3.9</b>	<b>5.7</b>	<b>5.1</b>	<b>7.0</b>	<b>6.4</b>
4	5.1	4.2	5.6	4.7	6.6	5.7	7.7	6.8
12-1	<b>3.2</b>	<b>2.9</b>	<b>3.9</b>	<b>3.7</b>	<b>5.2</b>	<b>4.9</b>	<b>6.5</b>	<b>6.2</b>
12-2	6.5	5.6	6.9	6.0	7.7	6.8	8.6	7.8
13	7.2	6.1	7.6	6.5	8.3	7.3	9.2	8.2

1:1 imaging of source point

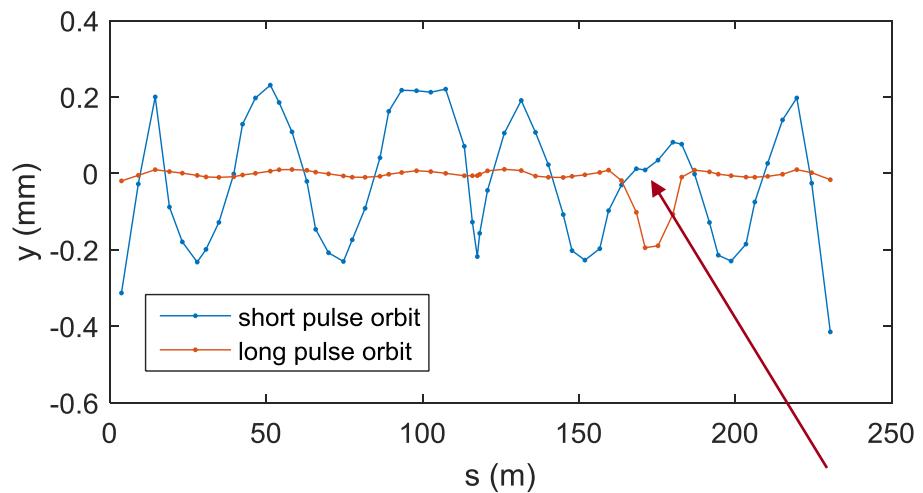
beamline	6% (3.8%) flux		10% (6.3%) flux		15% (9.4%) flux		20% (12.6%) flux	
	V1=1 MV	1.5 MV	V1=1 MV	1.5 MV	V1=1 MV	1.5 MV	V1=1 MV	1.5 MV
10	2.6	2.5	3.5	3.4	4.9	4.7	6.3	6.0
18	2.8	2.8	3.7	3.5	5.0	4.8	6.4	6.1
5	3.3	3.1	4.0	3.9	5.2	5.0	6.6	6.3
17	3.4	3.3	4.1	3.9	5.3	5.1	6.7	6.4
13	2.5	2.4	3.4	3.3	4.8	4.6	6.3	6.0

# Short pulse picking (separation from background)

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Crab cavities provide an easy way to separate the camshaft bunch from the regular beam – give them a phase shift, they apply a vertical kick to the camshaft bunch.

Short pulse beam orbit when a  $\Delta\phi = 0.2$  rad phase shift is applied.



A local orbit bump at BL15 source point is used to shift the short pulse toward the center.

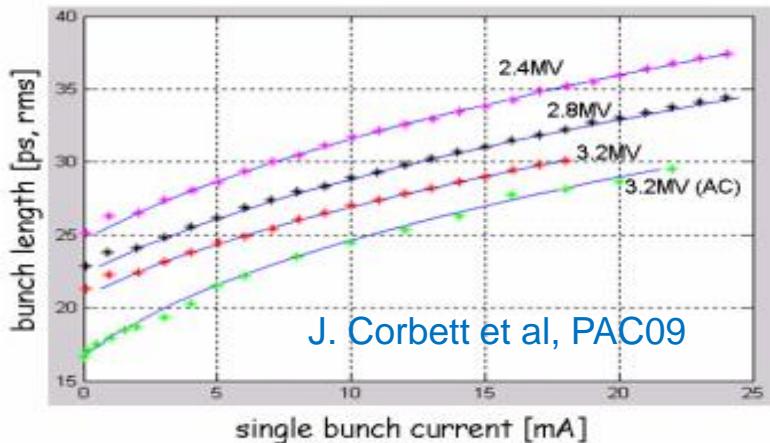
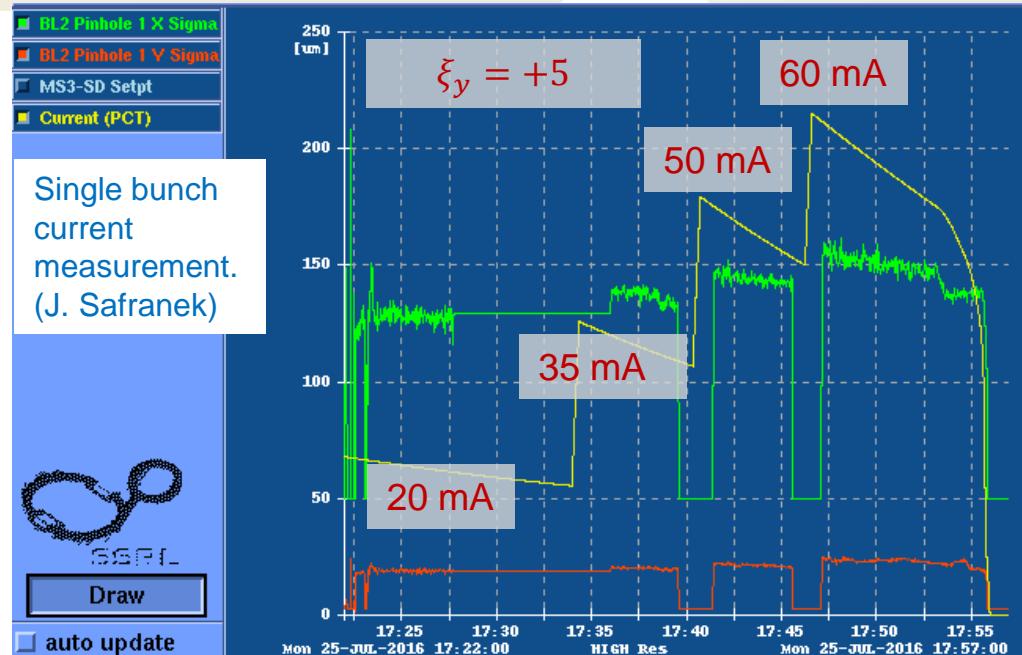
# Single bunch current limit

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Single bunch current is limited by TMCI in SPEAR3.

At 20 mA/bunch, no increase of momentum spread.

500 mA in half buckets (140 bunches) was also tested. No excessive vacuum chamber heating.



Bunch lengthening was measured up to >20 mA/bunch.  
For the 7-nm lattice, bunch lengths by 60% at  $I_b = 20$  mA.

# RF amplitude and phase noise

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Amplitude and phase noise in crab cavities causes imperfect cancellation and in turn an increase of vertical emittance for regular bunches.

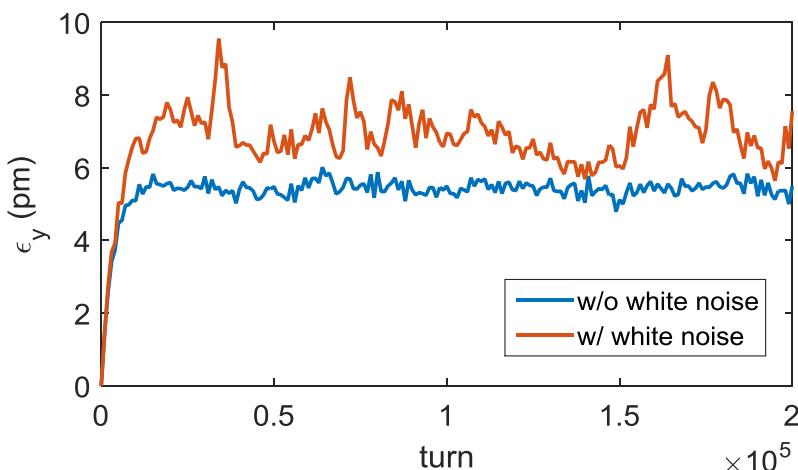
For high frequency noise, using

A. Zholents, NIMA 798, 111 (2015)

$$\Delta\epsilon_y^{(1)} \approx 2 \left( \frac{eU_1}{E_b} \right)^2 \frac{\tau_d L_u}{T} e^{-a_1^2} \left( \sinh(a_1^2) \sigma_U^2 + \cosh(a_1^2) \sigma_\phi^2 \right)$$

to keep  $\Delta\epsilon_y^{(1)} < 5$  pm, we'd need

$$\sigma_\phi < 0.005^\circ \text{, and } \sigma_u < 5.0 \times 10^{-5}.$$



Tracking for the  $v_y = 6.32$  7-nm lattice w/ 0.06% coupling.  $V_1 = 1$  MV,  $V_2 = 0.93$  MV, for regular bunches.

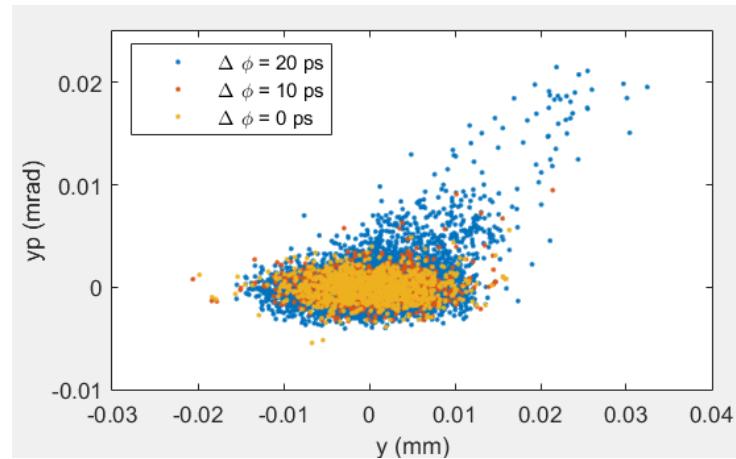
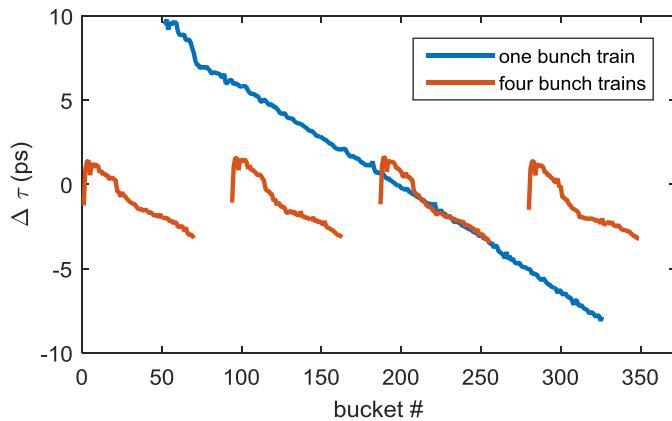
High frequency (white noise) as specified, plus a low-freq modulation at 1.24 kHz, with modulation amplitude of  $\phi_m = 0.01^\circ$  and  $u_m = 1 \times 10^{-4}$ .

Low frequency noise (~kHz) may be controlled (partially) with feedback. More study is needed.

# Phase shift due to bunch train gap-induced transients

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Measured bunch train phase shift due to gap-induced transient beam loading in SPEAR3 at 500 mA (Tian, Sebek, 2016 )



Measurements show that phase shift due to gap transients is below 20 ps for a long bunch train (worst case). Simulation indicates this is acceptable.

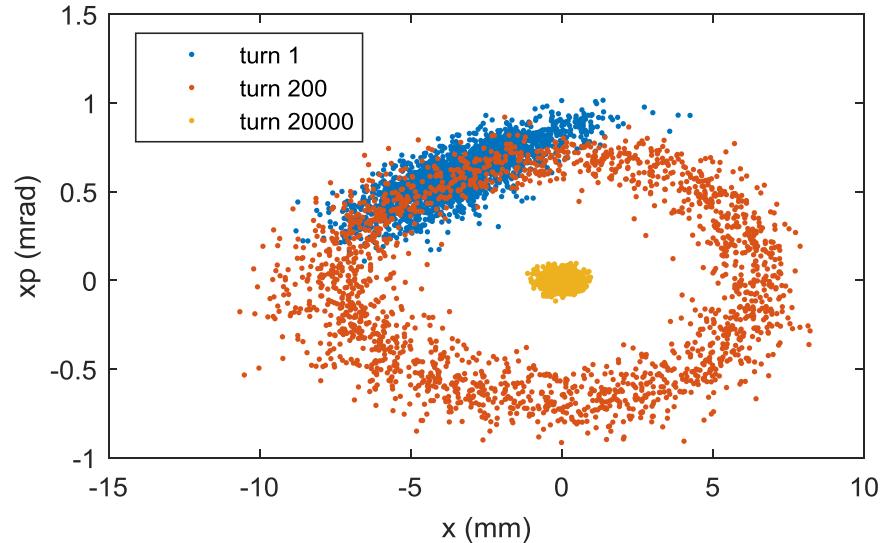
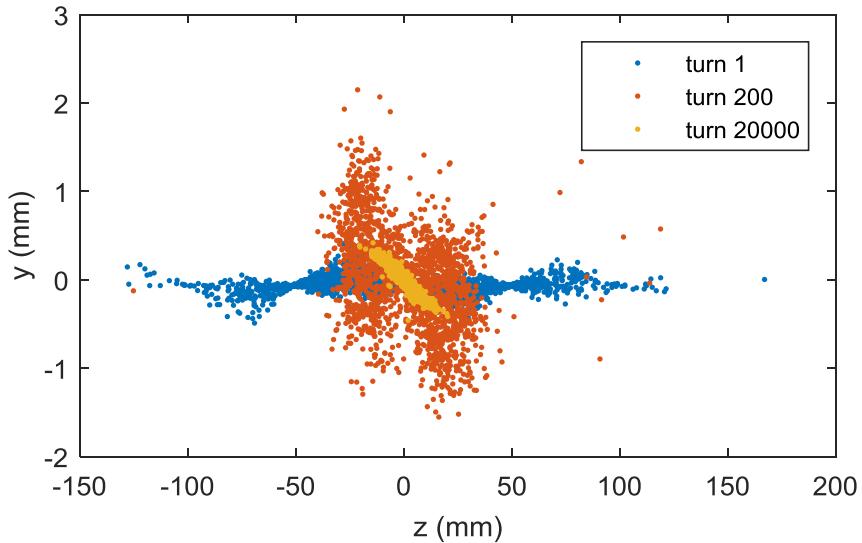
$\Delta\phi$ (ps)	Vert. eigen Emittance (pm)	Projected vert. emitt (pm)
0	5.3	6.5
10	6.0	7.3
20	6.7	9.4

Vertical emittances for regular beam ( $V_1 = 1$  MV)

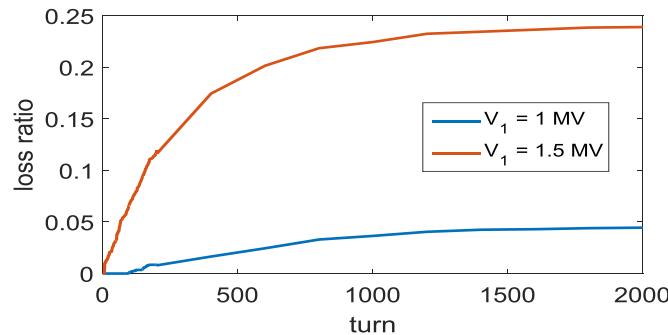
# Injection into tilted buckets

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The long injected beam will be tilted by the crab cavities. Beam with large vertical deviation may lose to the apertures.

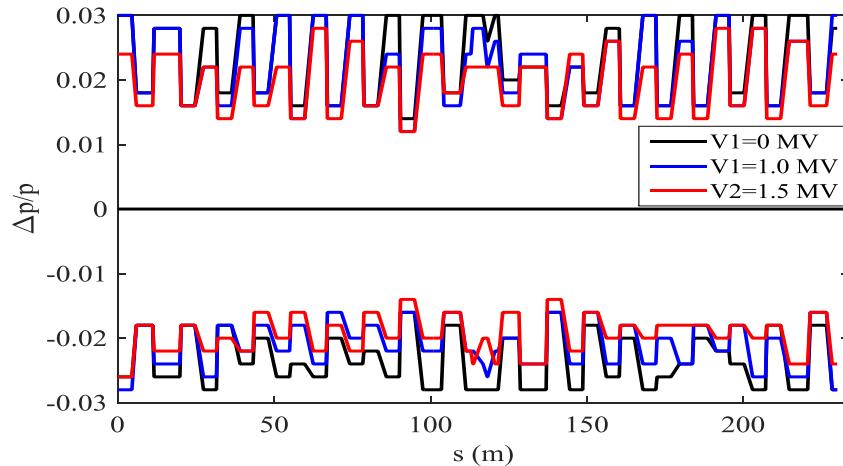


Tracking for the (DA optimized) 7-nm lattice with  $\nu_y = 6.32$  shows that the loss is below 5% for  $V_1 = 1$  MV.



# Touschek lifetime

Local momentum aperture for the tilted bunch w/ crab cavities



While the tilted bunch has reduced LMA and will be filled to higher current, its vertical emittance is increased. Overall the Touschek lifetime is lower, but acceptable.

$V_1 \text{ (MV)}$	$\epsilon_y \text{ (pm)}$	$\tau_T \text{ (hr) at } I_b = 20 \text{ mA}$
1.0	76	1.2
1.5	166	1.5

The 20-mA camshaft bunch loses 1.4 mA ( $V_1 = 1 \text{ MV}$  case) in 5 minutes between top-off fills.

# Coupled bunch Instabilities

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- Coupled bunch instability threshold

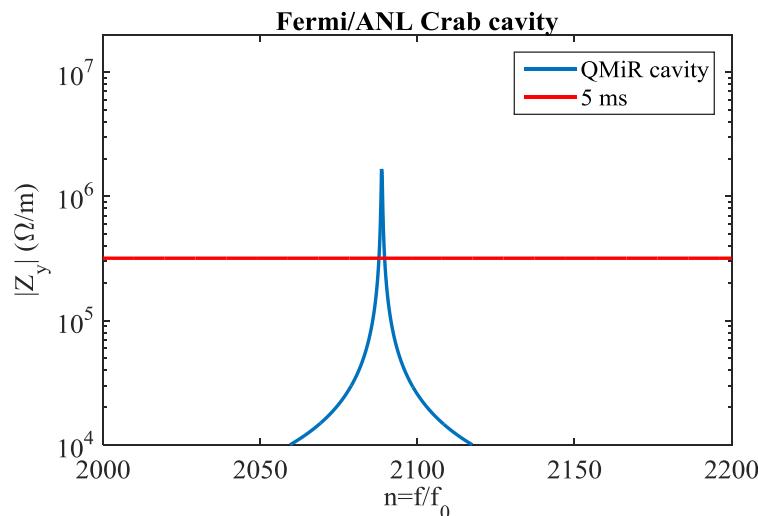
SPEAR3 (500 mA) impedance budget (w/ radiation damping only) for transverse CBI

Horizontal ( $\tau_x = 4$  ms),  $\text{Re}(Z_{\perp x}) < 0.89 M\Omega/\text{m}$ .

Vertical ( $\tau_y = 5$  ms),  $\text{Re}(Z_{\perp y}) < 0.31 M\Omega/\text{m}$ .

These thresholds can be raised with BxB feedback (designed to have damping time of 0.2 ms).

Frequency [MHz]	$(R/Q)_x$	$(R/Q)_y$	$(R/Q)_z$	Modal $K_{\text{loss}}$ [V/pC]	$Q_{\text{ext}}$
2476	0.001	0.034	-	-	2400
2675	1.7e-4	4.95	-	-	6800
2815	1e-5	521	-	-	5.1E5
4170	1.4e-4	7.3	-	-	32



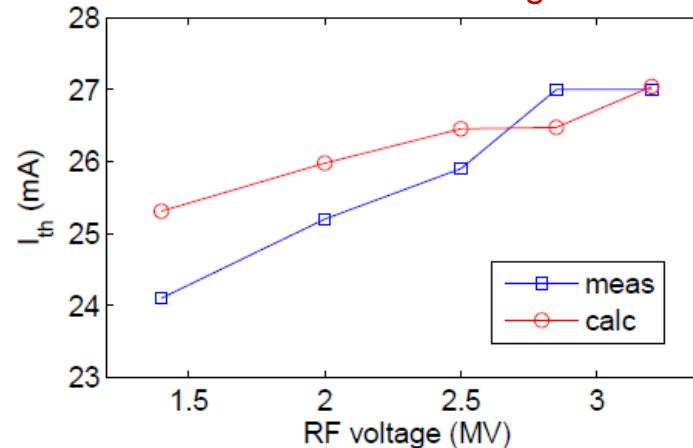
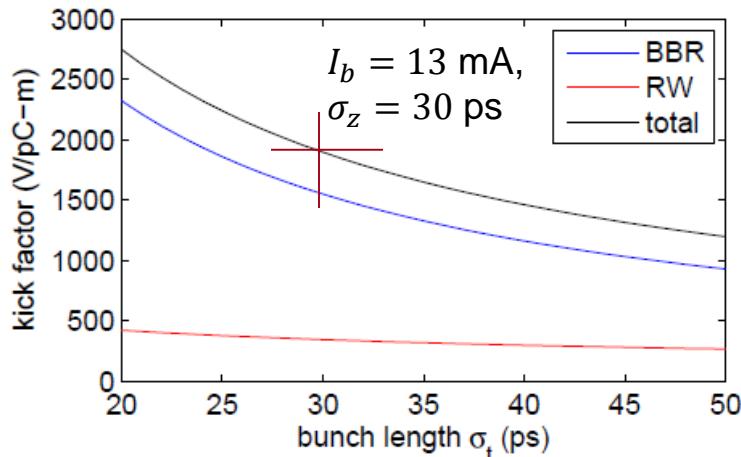
For the QMiR cavity, only one mode contribute significantly to CBI. The worst-case CBI rise time is  $\tau = 0.8$  ms.

A single mode may be dodged with some detuning (if necessary).

# Single bunch current limit

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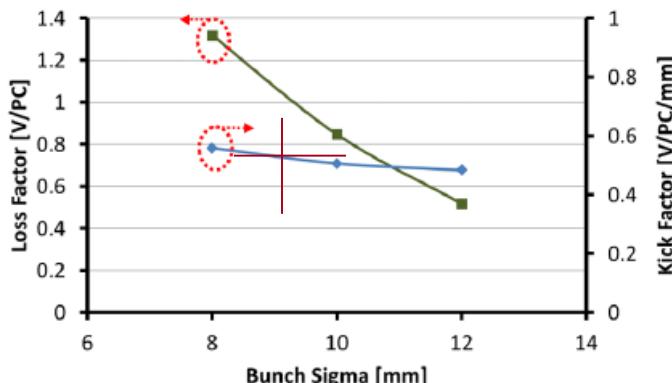
Impedance and single bunch current limit for SPEAR today



X. Huang and J. Sebek, IPAC 2015

- (1) BBR model is derived from tune shift vs. bunch current measurement.
- (2) Single bunch current is limited by TMCI instability.

## QMIR cavity kick factor



M. Awida, et al, IPAC 2015

At  $\sigma_z = 9$  mm (for SPEAR3 camshaft bunch), the vertical kick factor by one cavity is slightly over **500** V/pC/m.

Two QMiR cavities would contribute 50% of present ring impedance.

# S-band Crab cavities

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- APS-SPX SRF Crab cavities



Jefferson Lab

Courtesy of Haipeng Wang (JLab)

Mark-I crab cavity by Jlab:  
0.5 MV per cavity (0.5 m)  
Dense spectrum HOMs, big and  
expensive cryomodule.



Fermilab



Argonne  
NATIONAL  
LABORATORY

Lunin, et al., LINAC2014  
Conway, et al, IPAC 2014

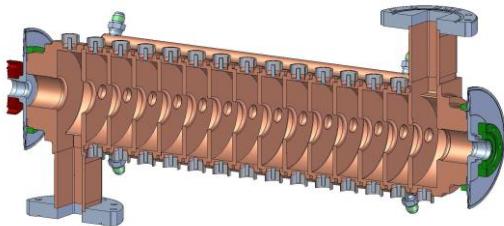
QMiR crab cavity by Fermilab/ANL:  
Up to 2 MV per cavity (0.5 m)  
Few HOMs, simpler cryomodule,  
Large impedance (smaller V-aperture).

- Potential warm cavity design

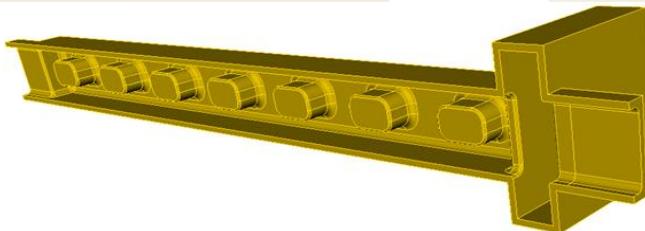
For S-band CW crab cavity w/ 1-MV deflecting voltage the RF power is ~50 kW,  
manageable with water cooling. (Zenghai Li, Sami Tantawi)

# Normal Conducting RF Deflector

SLAC



15-cell S-Band traveling wave deflector for LCLS



7-cell NC crab cavity for SPEAR3

Zenghai Li, SLAC

- Normal conducting RF deflectors are generally used for pulsed operations.
- Major challenge of using NC RF in a CW machine are the CW RF power and cooling requirements for high gradient operation.
- The SPEAR3 application requires 1-1.5 MV of deflecting voltage, it is relatively a low gradient for a 1-meter long structure. CW power and the cooling requirements become manageable.

# Comparison of performance for several short pulse schemes for SPEAR3

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Short pulse mode	Pulse length (ps, fwhm)	Camshaft bunch charge (nC)	Repetition rate (MHz)	Camshaft 8 keV average flux <sup>1</sup> (10 <sup>11</sup> photons/s/0.1%BW)
<b>Standard lattice, camshaft 13 mA</b>	70	10	1.28	100
<b>Low-<math>\alpha</math>, <math>\alpha/20</math></b>	15	0.27	1.28	2.7
<b>Standard lattice, w/ SRF</b>	7.4	1.6	1.28	16
<b>Ten-turn circulation<sup>2</sup></b>	5.2	0.20	1.28	2
<b>One-turn circulation</b>	1	0.30	0.085	0.2
<b>Crab cavity, large slice<sup>3</sup></b>	6.3	2.0	1.28	20
<b>Crab cavity, small slice</b>	2.5	0.6	1.28	6

<sup>1</sup> SPEAR3 BL12-2 is assumed for flux calculation ( $\lambda=22\text{mm}$ , 67 periods,  $k_{\max}=2.17$ ).

<sup>2</sup> Assuming beam power of 76.8 kW from LCLS-II.

<sup>3</sup> Charge given for slice from a 15.6 nC bunch with source imaging optics and slitting. 1 MV deflecting voltage per cavity system is assumed.

# Summary

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- The new two-frequency crab cavity scheme looks like a promising solution to produce short pulses at SPEAR.
  - Short pulse performance is competitive compared to other approaches.
  - Crab cavity parameters are not demanding.
- A comprehensive beam dynamics study has not found any show-stopper.
- Cavity design study is needed to proceed to the next phase.