Injection to tilted bunches for 2-frequency crab cavity and Injection with full coupling

Xiaobiao Huang

August 29, 2017

Presented to:
TWIIS 2017, BESSY, Berlin

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

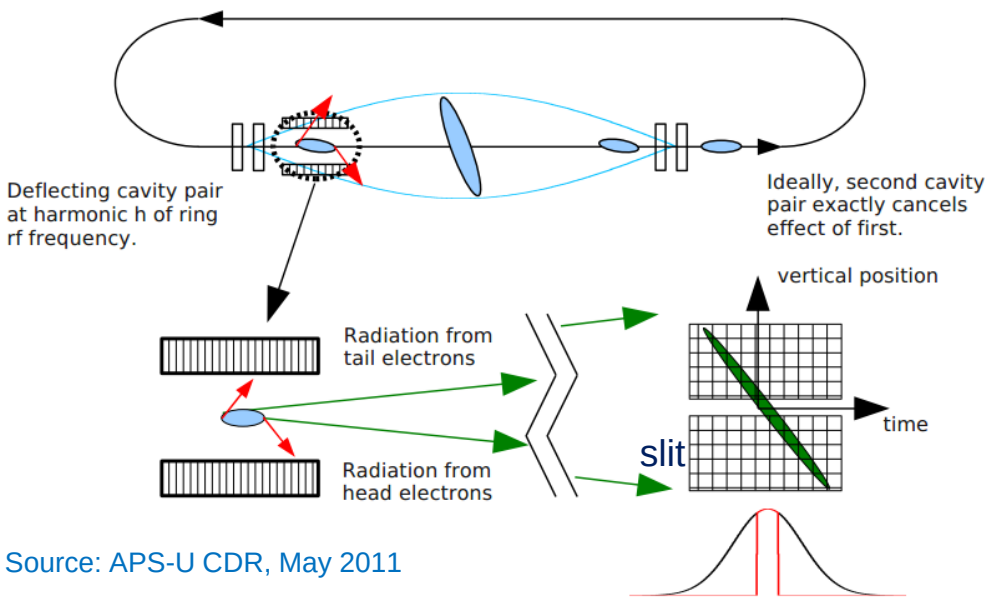
Outline

- Two-frequency crab cavity for short pulses
  - Basic concept
  - Components, system layout, and parameters
  - Short pulse performance
- Injection into tilted bunch
- A separate topic: Off-axis injection to storage ring with full coupling – an experimental study at SPEAR3

“Crabbing” the beam for short pulses in storage rings

The tilt-and-cancel scheme

A. Zholents, P. Heimann, M. Zolotorev, and J. Byrd, NIM A 425, 385 (1999).



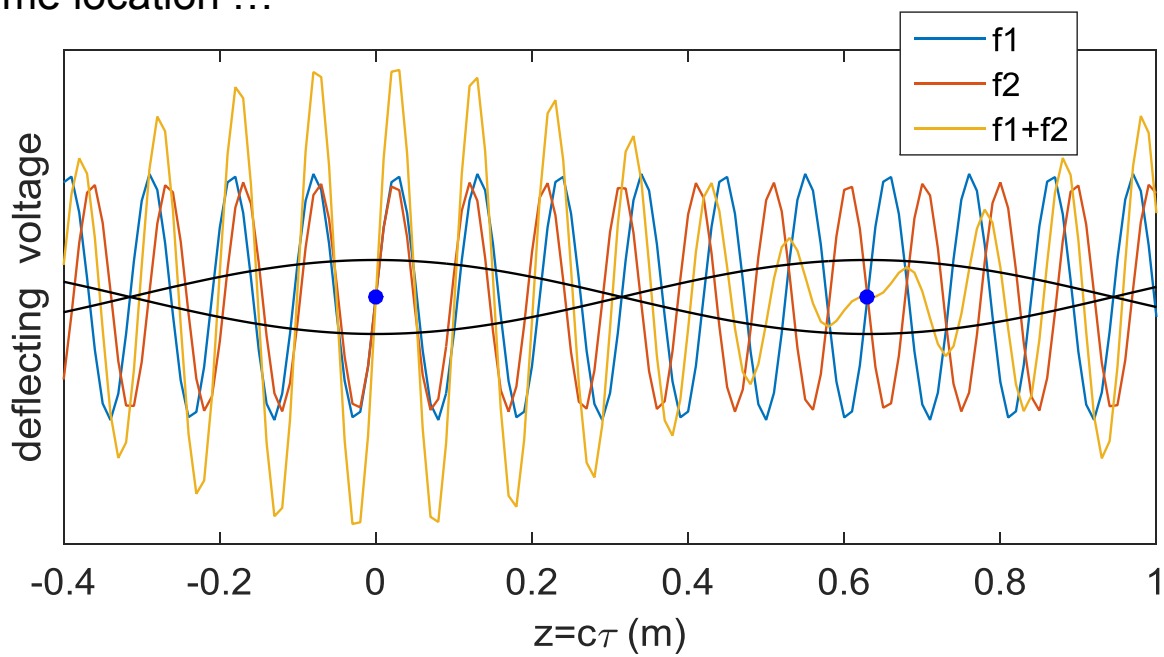
Source: APS-U CDR, May 2011

- The ID is $180° \times n_1$ downstream from crab cavity in vertical phase advance; radiation will have a maximum $y' - z$ correlation, which translates to $y - z$ correlation at a downstream slit.
- A second crab cavity is $180° \times n_2$ downstream from the first crab cavity to cancel the tilt.

A. Zholents, NIMA 798, 111 (2015)

The two-frequency crab cavity (2FCC) scheme

If crab cavities of two frequencies are located at the same location …



Two frequencies:

$$f_1 = nf_0,$$

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

Half of the buckets are tilted in $y - z$ plane, the other half are un-affected.

To store regular, un-tilted beam, cancellation of crabbing kicks is needed. For the 2FCC scheme, cancellation occurs in time, not in space as the tilt-and-cancel scheme does.

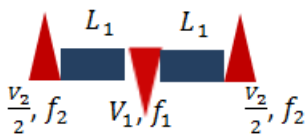
Cavity configuration for cancellation

- In reality cavities cannot overlap in space. To avoid complication from lattice, they are put in one straight section.
- For complete cancellation, both the first and second integrals of the crabbing kicks need to vanish.

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

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

This can be achieved with a symmetric configuration of the two frequencies whose deflecting slope (first integral) add up to zero.



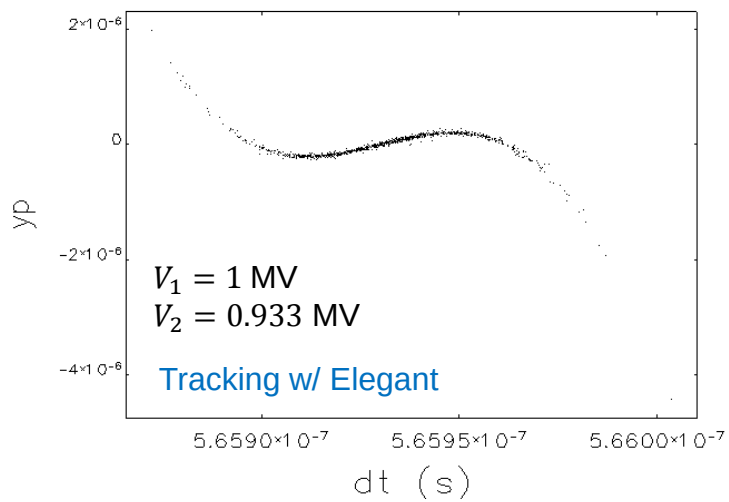
Deflecting voltage for optimal cancellation

- For the regular beam, to cancel the slope at the bunch center, needs $n_1 V_1 = n_2 V_2$.
- It is more desirable to cancel deflection over the entire bunch in an rms sense, which requires

A. Zholents, NIMA 798, 111 (2015)

$$V_2 = V_1(1+u) \qquad u \approx \frac{e^{-\frac{1}{2}(a_1+a_2)^2}\left(e^{2a_1a_2}-1\right)}{1-e^{-2a_2^2}} - 1$$

For SPEAR3, we need $V_2 = 0.933 V_1$ instead of $\frac{6}{6.5} = 0.923$.



The deflecting voltage is limited by injection requirements, to be discussed soon.

The nominal value is $V_1 = 1$ MV, can be up to $V_1 = 1.25$ MV

Advantages of the new scheme

- Short pulses are available all around the ring.
- No strict phase advance requirement for lattices.
- Crab cavities occupy only one straight section (and only one cryostat for SRF)
- Both cavities contribute to tilting and hence less total deflecting voltage is required.
- Beamlines can easily switch between short pulse mode and regular mode.
- Crab cavity can be used to separate short pulses from regular pulses.

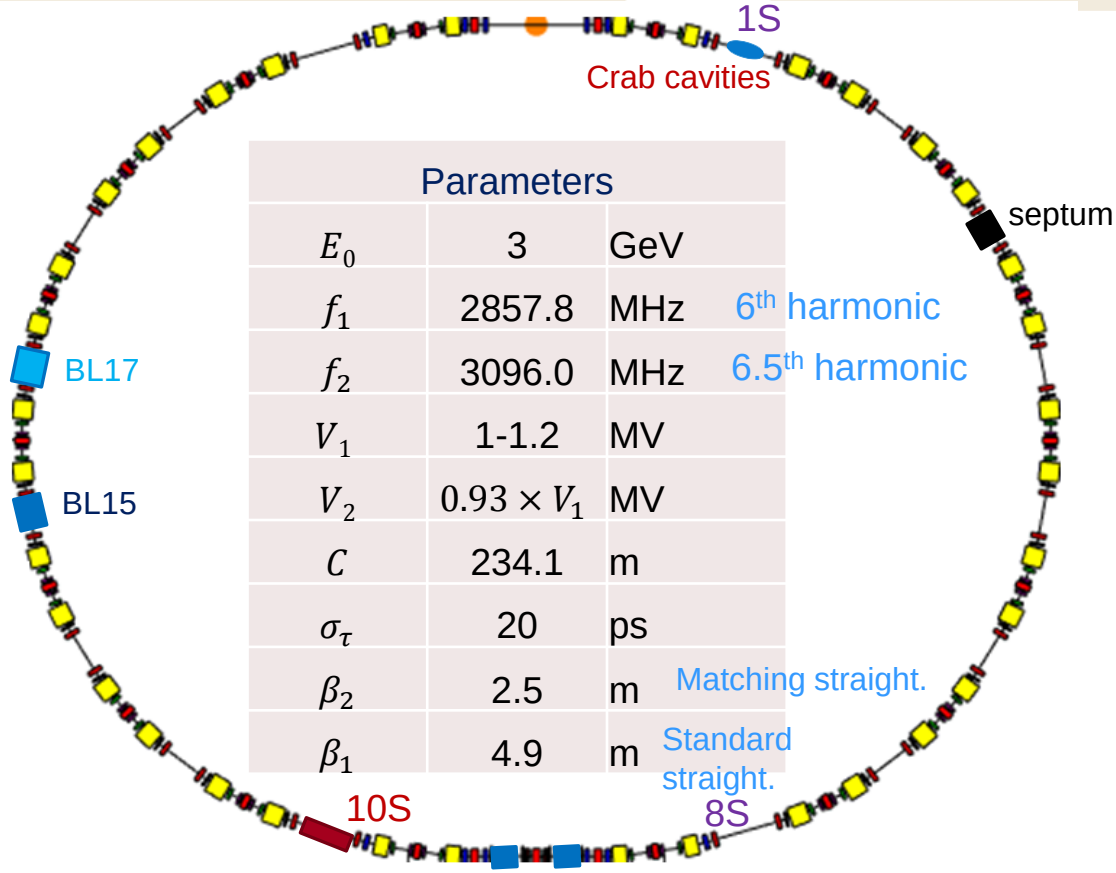
Disadvantages:

- Crab cavities (and power source) of a second frequency are needed, adding cost.
- Crab cavities add additional contribution to vertical emittance of the tilted bunch (to be discussed later), degrading performance.

An example: application of 2FCC to SPEAR3

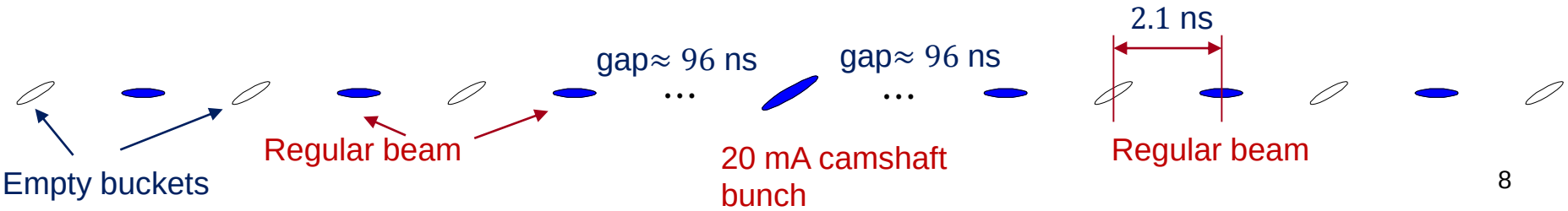
Crab cavity frequencies: 6th and 6.5^{th} harmonics of 476.3 MHz.

Harmonic number is 372,
Revolution frequency 1.28 MHz.
Can have 1, 2, 4 camshaft bunches.

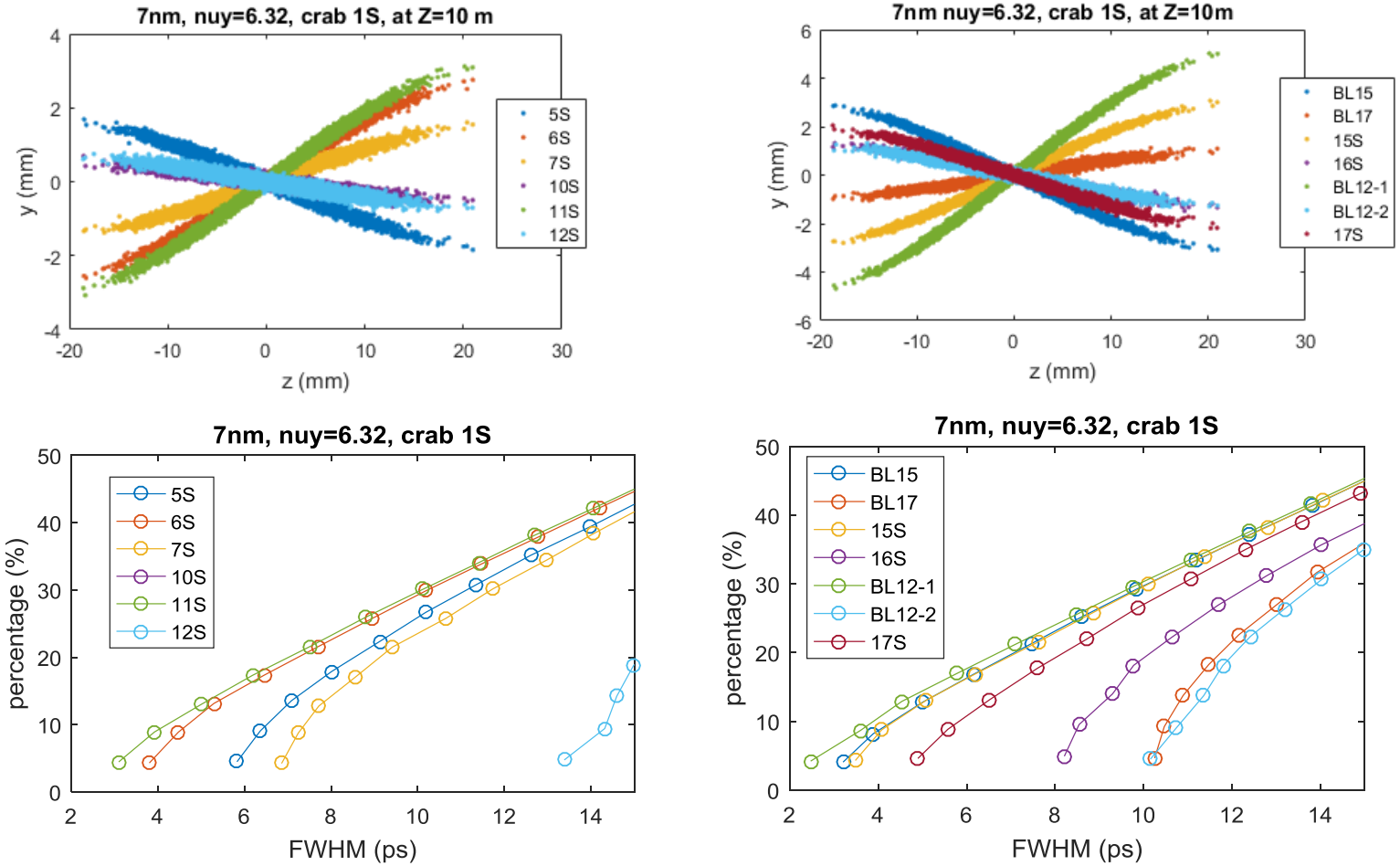


Parameters			
E_0	3	GeV	
f_1	2857.8	MHz	6th harmonic
f_2	3096.0	MHz	6.5^{th} harmonic
V_1	1-1.2	MV	
V_2	$0.93 \times V_1$	MV	
C	234.1	m	
σ_τ	20	ps	
β_2	2.5	m	Matching straight.
β_1	4.9	m	Standard straight.

Fill Pattern:
480 mA in 140 regular buckets, and 20 mA to one camshaft bunch in the middle of a gap.



Short pulse performance for SPEAR3 (w/ drift optics)



Photon divergence is added to the distribution at source points.

Beam dynamics effects of crab cavities

E-M fields in a (vertical, assuming TM110) crab cavity (with $k = \frac{\omega}{c}$)

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

Crab cavity operates at zero crossing ($t = 0$), for small amplitude motion in y, z, beam receives kicks (linearized) according to

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

with deflecting voltage $V = \int_{-\frac{g}{2c}}^{\frac{g}{2c}} dt\, c\mathcal{E}_0 \cos\omega t$

It is a coupling device with transfer matrix ,

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

for $\mathbf{X} = (y, y', z, \delta)^T$

with parameter $\epsilon \equiv \frac{eVk}{E}$

But for particles with large z-amplitude, the vertical kick takes the full sinusoidal form

$$\Delta y' = \frac{eV}{E} \sin kz$$

A long injected beam will see the maximum kick of $\Delta y' = \frac{eV}{E}$.

Maximum deflecting voltage by minimum aperture

- The peak vertical kicks by crab cavities will deflect portions of the injected beam to the vacuum chamber.
  - The affected portion of the injected beam oscillates about the new closed orbit defined by the peak kick. So maximum offset is twice the kick

$$\frac{\sqrt{\beta_1\beta_2}}{2\sin\pi\nu_y}\frac{eV_d}{E}\times 2 = y_m$$

$y_m = 3.5$ mm the half aperture at $\beta_1 = 5$ m.

With $\beta_2 = 2.5$ m, $\nu_y = 6.32$, we found $V_d = 2.5$ MV (total deflecting voltage). Therefore, the maximum deflecting voltage for frequency 1 is $V_1 = \mathbf{1.25}$ MV.

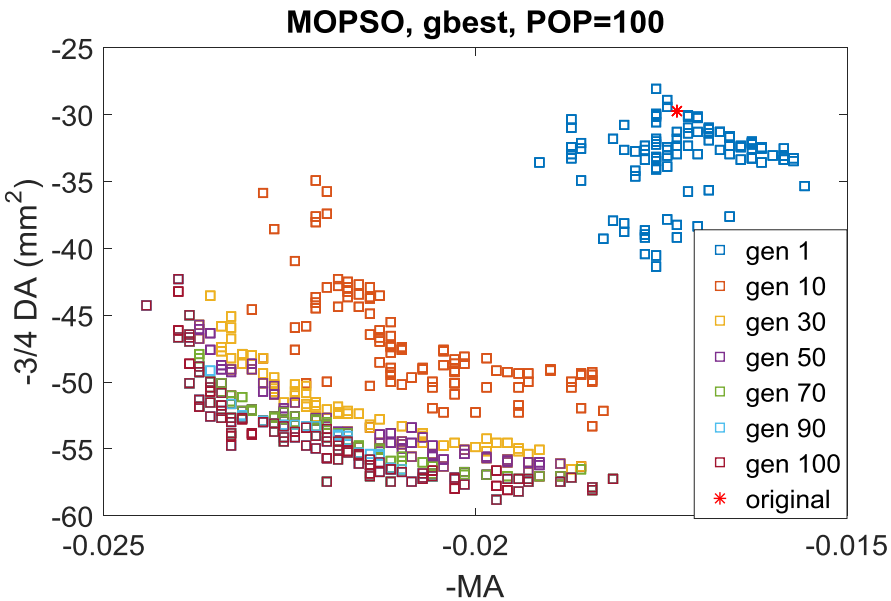
This is the limit by physical aperture and linear optics. Nonlinear motion may make things worse.

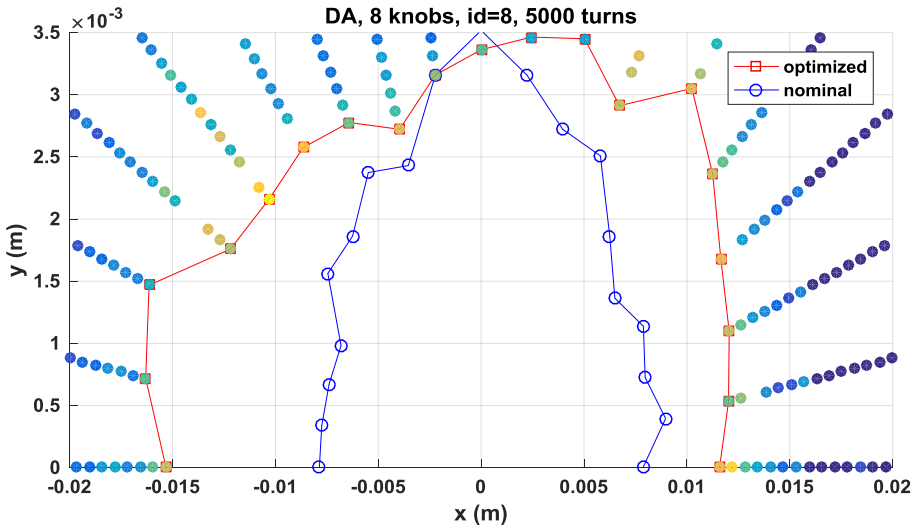
Injection into the tilted bunch

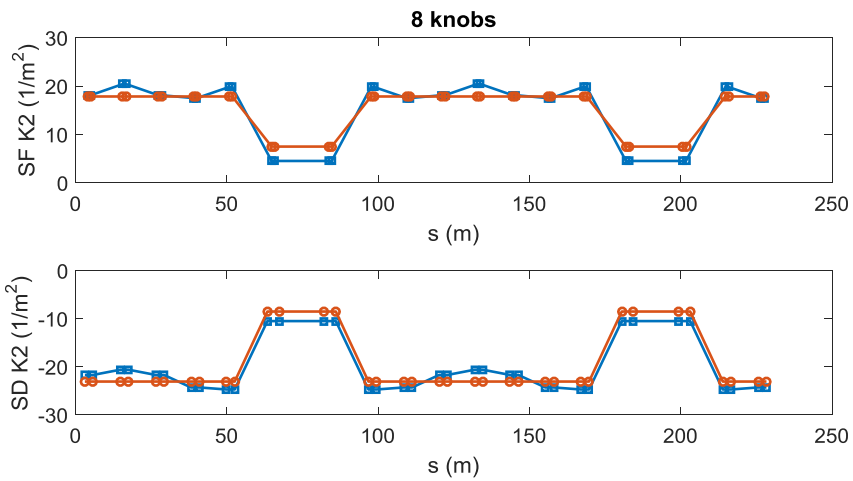
- SPEAR3 will implement a 7-nm lattice soon, when the septum upgrade is complete. The lattice is more challenging in dynamic aperture (DA) than the present 10-nm lattice.
  - The 7-nm with high ν_y lattice has been implemented on SPEAR3 and had reached injection efficiency of 75% w/ mismatched kicker bump, local obit bump at septum, and BTS end steering.
- For injection efficiency study, the lattice is first optimized with sextupole knobs.

- Injected beam is long ($\sigma_t = 140$ ps). Full injected beam is twice the S-band wavelength.

Sextupole optimization for the 7-nm, 6.32 lattice model





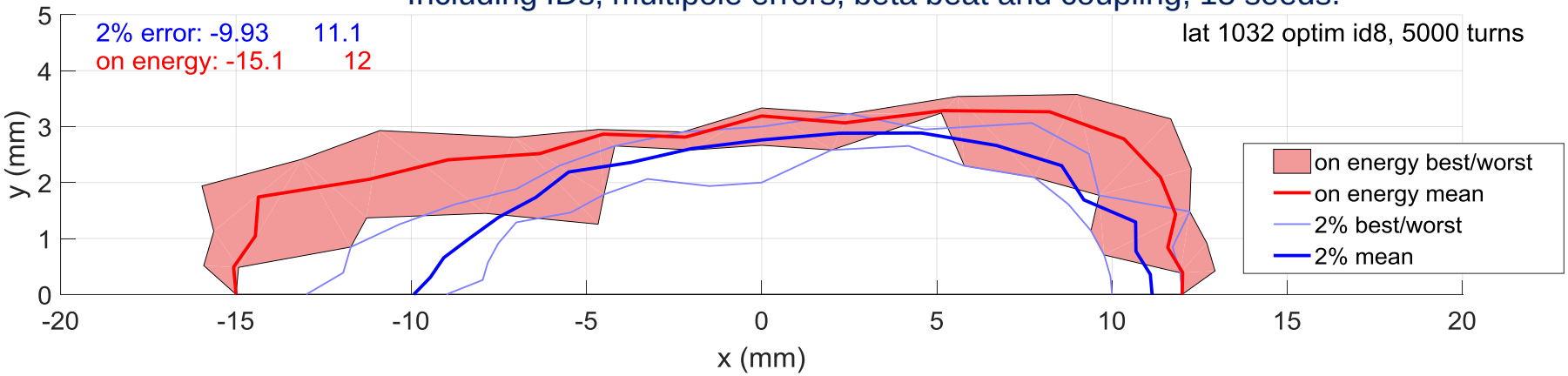


Optimize 8 sextupole knobs with MOPSO to increase momentum aperture and dynamic aperture.

Crab cavity is not in the model.

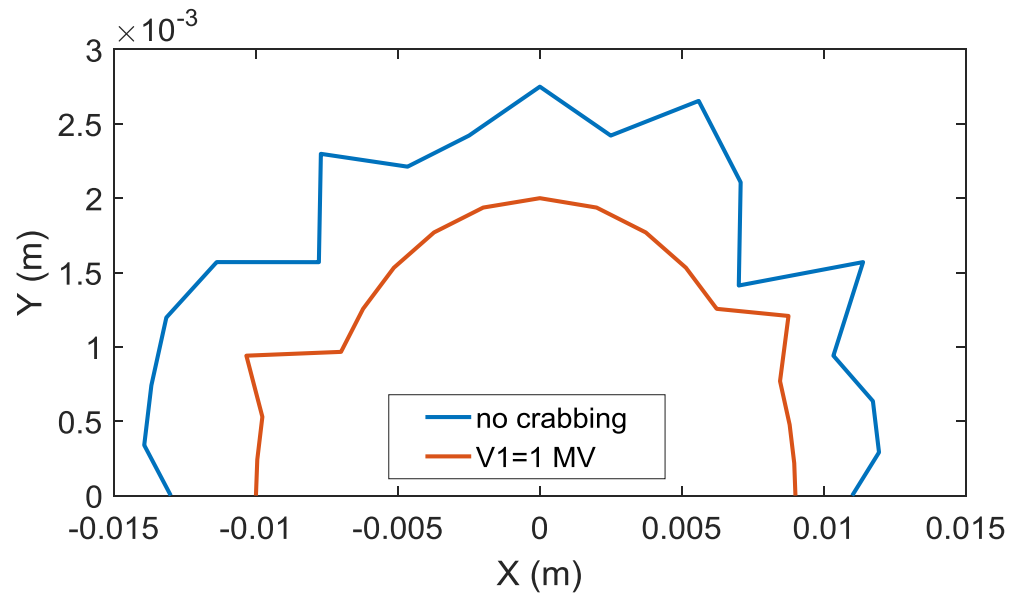
DA check w/ multi-seeds

Including IDs, multipole errors, beta beat and coupling, 15 seeds.



- Crab cavities reduce dynamic aperture.
- The evolution of (long) injected beam is not the same as how we track DA.
- Tracking injected beam directly is more realistic.

We should optimize DA using sextupole knobs with crab cavity in the model.



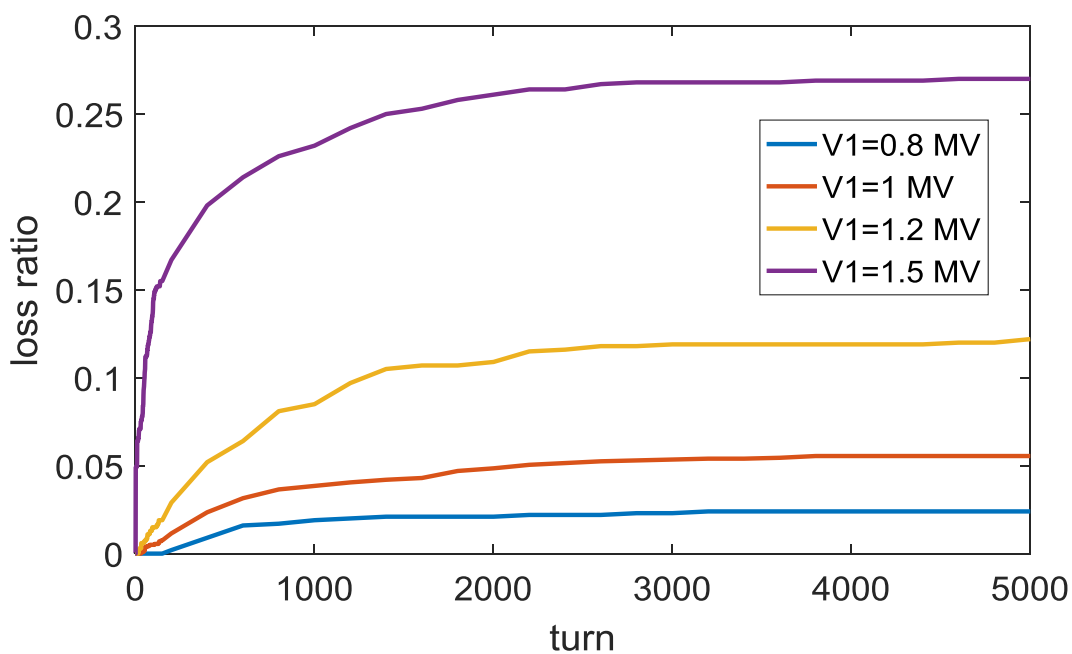
Injection simulation

- Launch 10,000 particles, spanned over 6 dimensions.
- Track for 20,000 turns.

Injected beam initial parameters

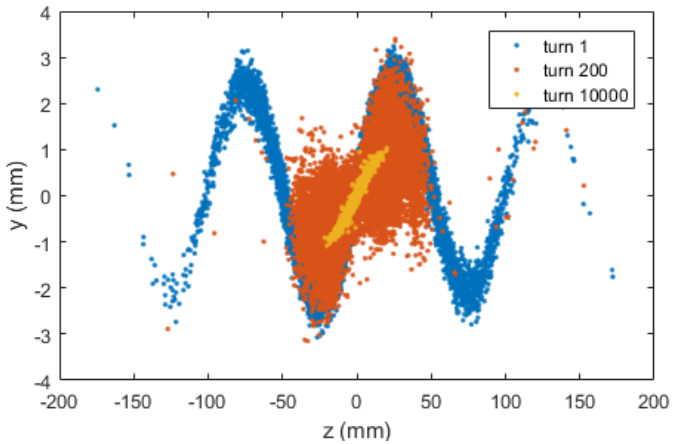
ϵ_x (nm)	ϵ_y (nm)	σ_t (ps)	σ_δ	β_x (m)	β_y (m)	$D_{x,y}$	$D'_{x,y}$	Initial x offset (mm)*
170	17	140	0.001	5	5	0	0	-7.5

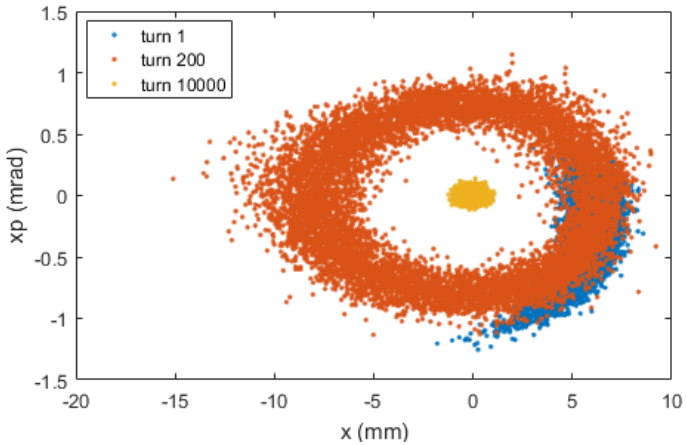
*$6 \times \sqrt{7.5nm \times 10m} + 3 \times \sqrt{170nm \times 5m} + 2.5 = 6.9$mm



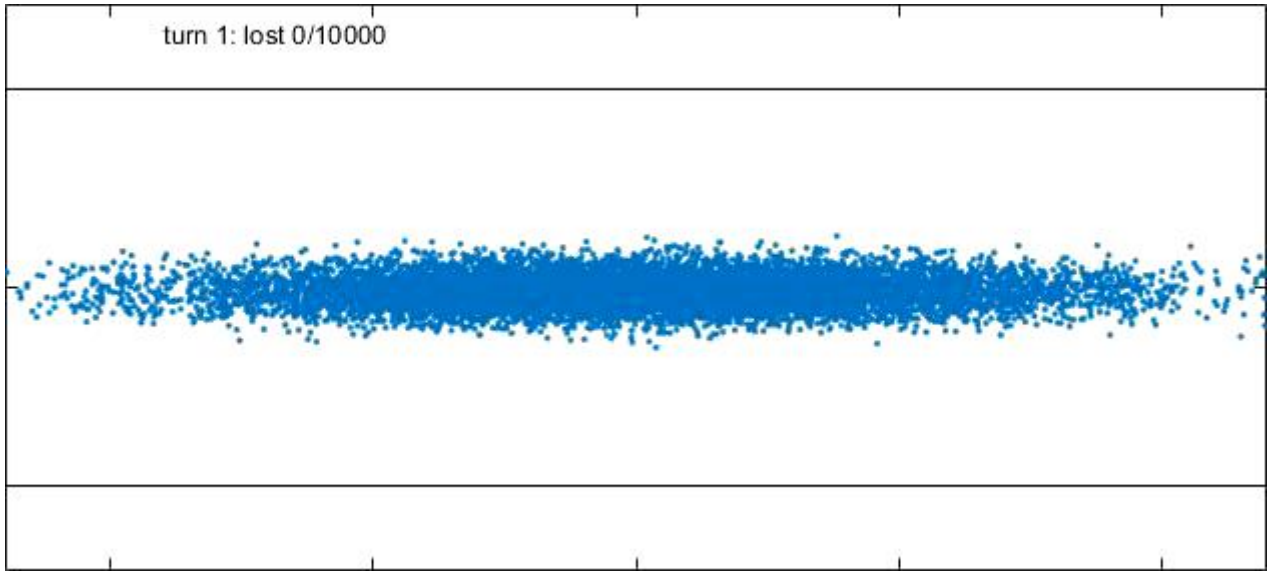
For the V_1 =1MV case, the loss ratio is 6%.

Injected beam in phase space



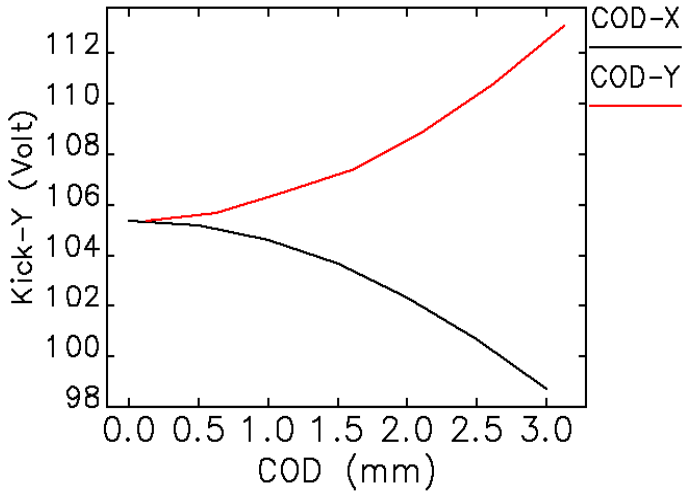


Observe at 13S (BL15) w/ z sign reversed.



Effect of transverse field variation in crab cavities

- The transversely non-uniform RF fields in crab cavities can be modeled as RF multipoles of the same frequency as the deflecting mode.



Vertical kick from APS SPX prototype crab cavity.
The kick varies by 7% at 3 mm.

The nonlinear fields of this APS-SPX crab cavity exceed the SPEAR3 insertion device field integral spec

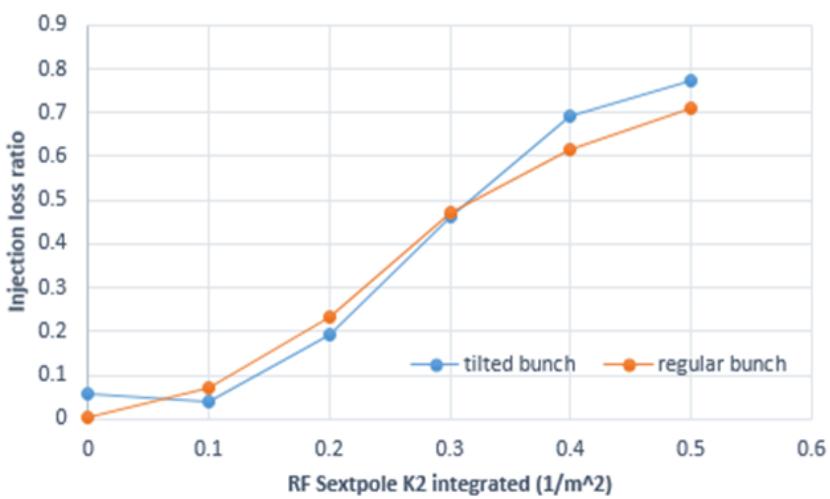
$$y' < 4 + 2.5\, x[\mathrm{cm}] \text{ mrad},$$

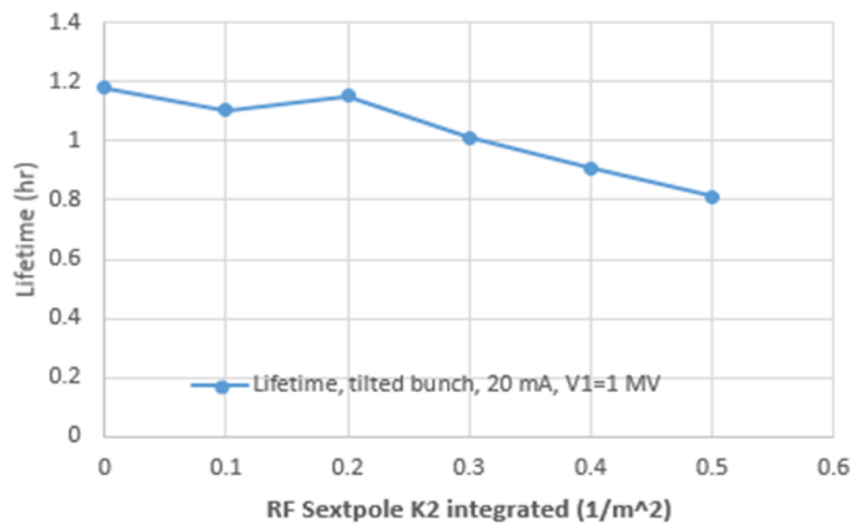
for $|x| < 1.7$ cm.

Tracking study w/ RF sextupole component

- Tracking simulation showed that RF multipole can have large impact to injection, and a smaller impact to Touschek lifetime.

However, the systematic RF multipoles of the two frequencies (located in one straight section) should mostly cancel.





And, the NC circular iris crab cavity design has very good field uniformity ($< 0.1\ \mathrm{m}^{-2}$) (Zenghai Li).
But, for QMiR type crab cavity, we will need more realistic simulation (w/ cancellation)

A separate topic …

Injection with full coupling – experimental study on SPEAR3

X. Huang, T. Zhang, J. Tang

Motivation

- Future Diffraction Limited Storage Rings (DLSR) may operate with full coupling to produce round beam for reduced IBS and long Touschek lifetime.
- Although on-axis, swap-out injection[1,2] may be used for DLSR, it is also possible that some future machines will prefer the accumulation mode with off-axis injection.
- Question: Is full coupling compatible with off-axis injection?
  - The initial (horizontal) offset of injected beam will be coupled to the other plane (vertical), which may have very small aperture.

1. M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
2. L. Emery, M. Borland, ”Possible Long-term Improvements to the APS,” Proc. PAC 2003, 256-258 (2003)

Previous measurements of injection efficiency at high coupling at SPEAR3

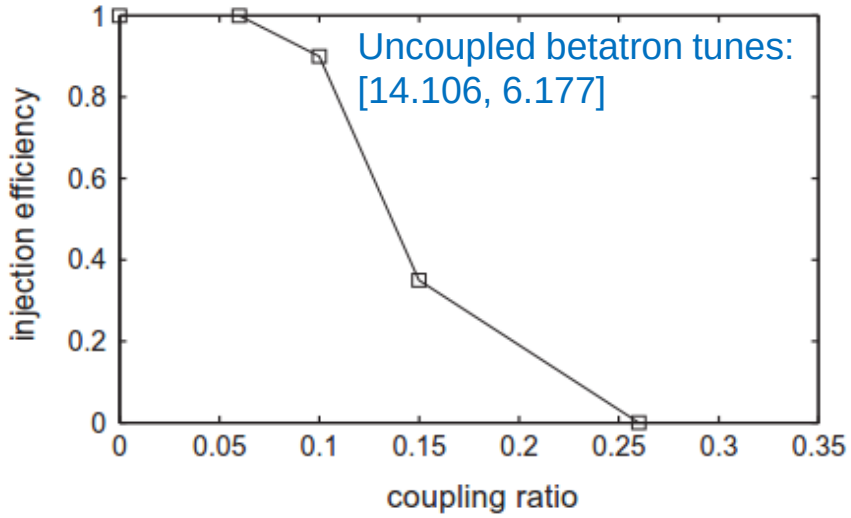


Fig. 1. Injection efficiency vs. coupling ratio at SPEAR3.

SPEAR3 experiment:
Kept uncoupled tunes fixed, increasing coupling by increasing skew quadrupole currents.

X. Huang, NIMA, 777 (2015) 118

Injection vs. coupling measurements at APS

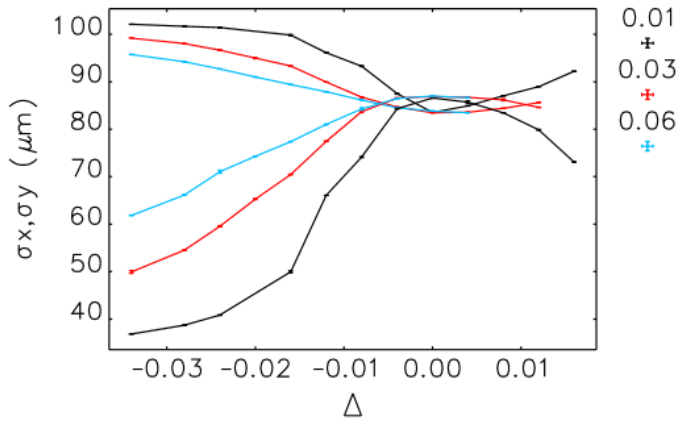


Figure 5: Measured beam size (raw data) and coupling vs. tune separation Δ at different κ (legend).

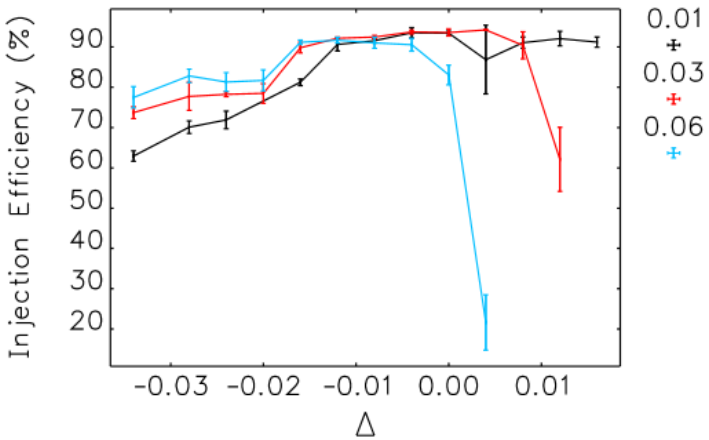


Figure 8: Measured topup injection efficiency vs. tune separation Δ at different κ (legend).

κ is initial emittance ratio with uncoupled tunes [0.17, 0.23].

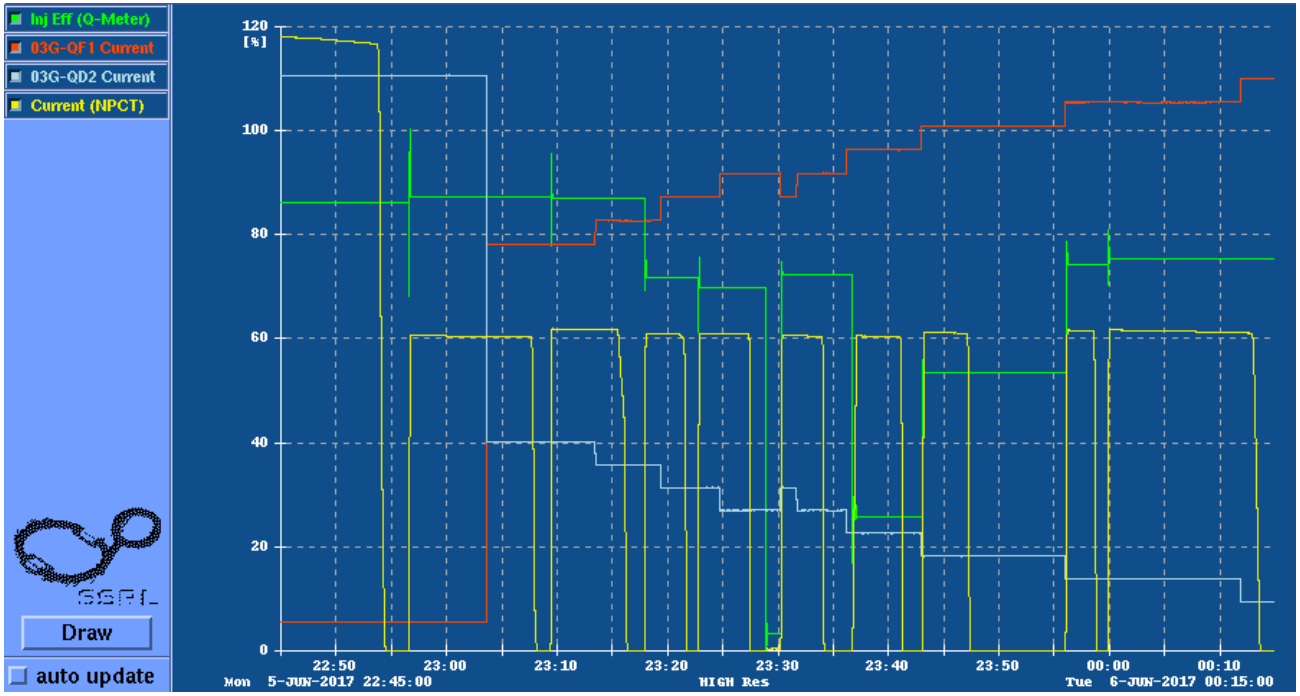
APS experiment:
Kept skew quadrupoles at several levels, adjust uncoupled tune separation.
Conclusion: With small coupling strength, injection loss at high coupling can be avoided.

A. Xiao, et al, IPAC 2015, MOPMA013

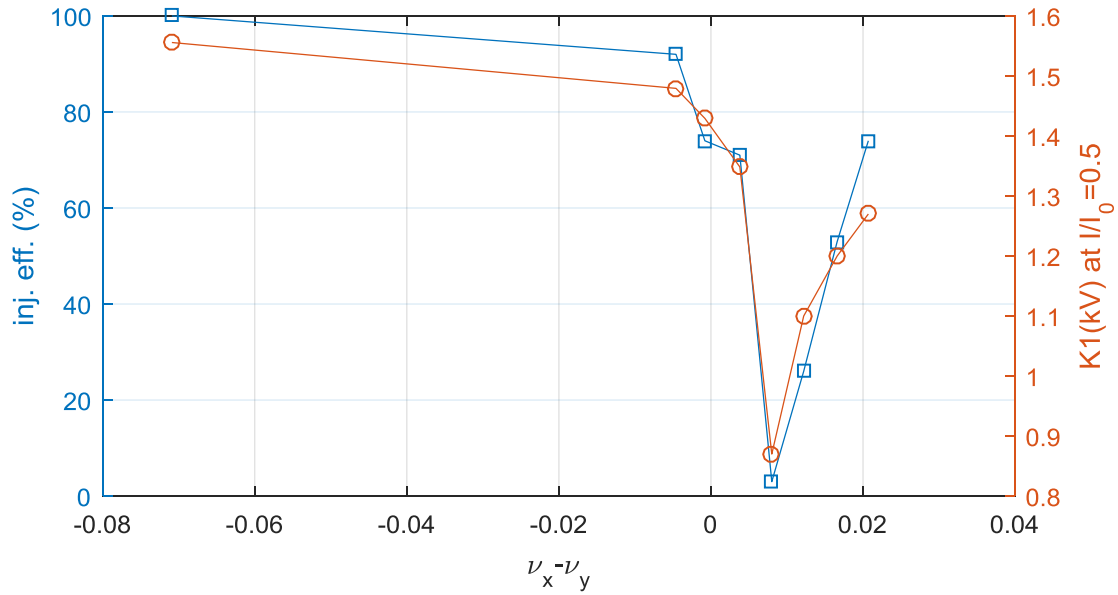
We wanted to test the APS study's conclusion at SPEAR3.

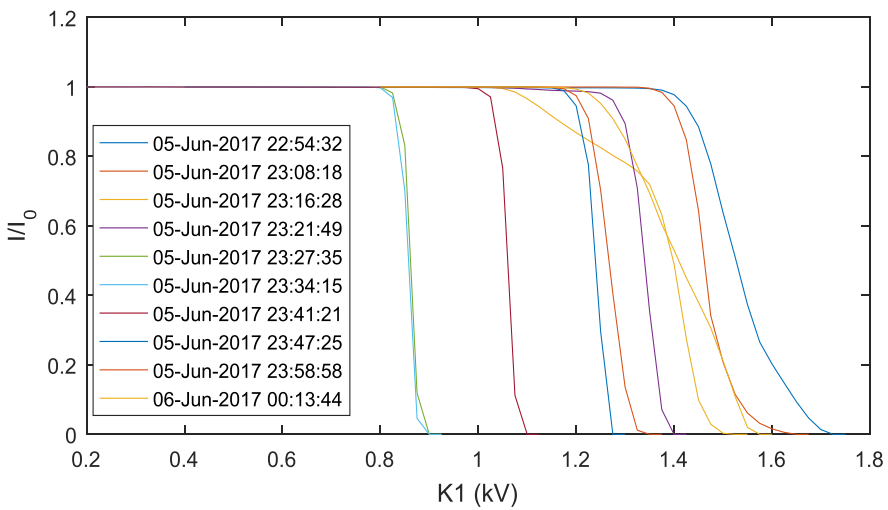
Experiments

1. With nominal tunes [14.106, 6.177], coupling was corrected (w/ LOCO) to $\frac{\epsilon_y}{\epsilon_x} = 0.07\%$
2. Measure injection efficiency as we step tunes across the difference resonance in steps.
3. At each step, also measure dynamic aperture by kicking beam out with increasing kicker K1 voltage.



Measured injection efficiency and DA vs. tune separation





Injection efficiency still drops to near zero, but it happens after the difference resonance is crossed!

And, at the minimum separation (w/ $\Delta = -0.0008$), injection efficiency was not so bad.

DA measurements agree with injection efficiency measurements.

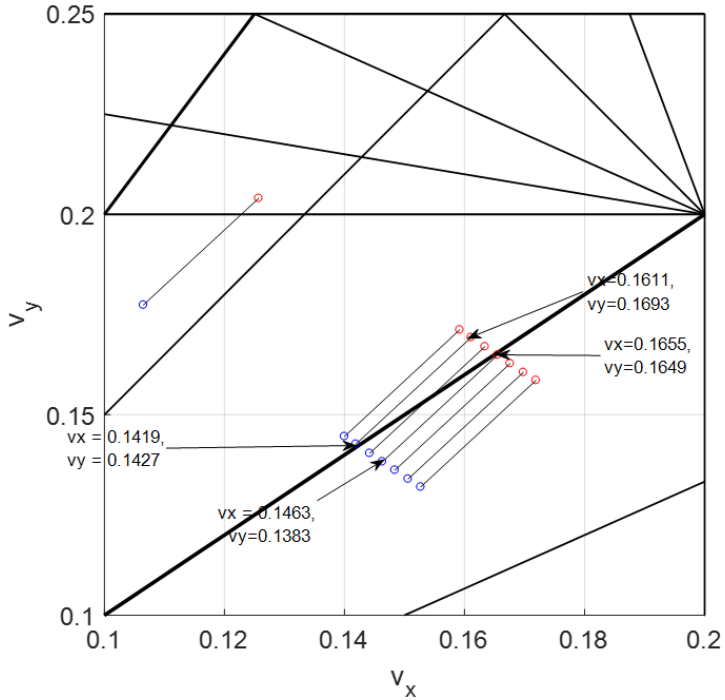
An explanation

Measured amplitude detuning coefficients for SPEAR3.

Table 1: Tune Shifts with Amplitude

	Measured	Model
$d\nu_x/d\varepsilon_x$ [1/m]	1590	1803
$d\nu_x/d\varepsilon_y$ [1/m]	2460	2145
$d\nu_y/d\varepsilon_x$ [1/m]	2200	2058
$d\nu_y/d\varepsilon_y$ [1/m]	2740	2131

J. Safranek, X. Huang, PAC 2009



The injected beam is centered at $x = -11$ mm ($\beta_x = 10$ m). The horizontal offset gives rise to tune shifts $\Delta\nu_x = 0.0192$, $\Delta\nu_y = 0.0266$, with

$$\Delta\nu_x - \Delta\nu_y = -0.0074$$

While the linear tunes are on the resonance line, the actual large amplitude tunes are not. When the large amplitude tunes are on resonance, dynamic aperture is reduced.

Summary

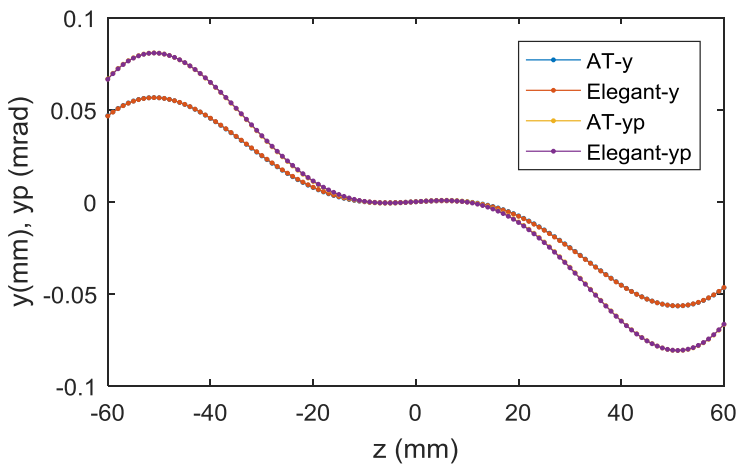
- The two-frequency crab cavity approach for short pulse generation in storage rings is a promising scheme for SPEAR3.
- Injection into the tilted bunch is challenging because
  - The injected beam is long compared to the S-band crab cavity period and hence get kicked vertically toward small aperture.
  - Crab cavities couples longitudinal motion and vertical motion and reduces dynamic aperture.
  - The RF multipole components in crab cavities can further reduce dynamic aperture.
- Off-axis injection into a high coupling lattice benefits from a large difference in nonlinear detuning coefficients $\frac{d\nu_x}{d\epsilon_x}$ and $\frac{d\nu_y}{d\epsilon_x}$.
  - Small linear tune separation for high coupling.
  - But tunes of injected beam are not on linear difference resonance.

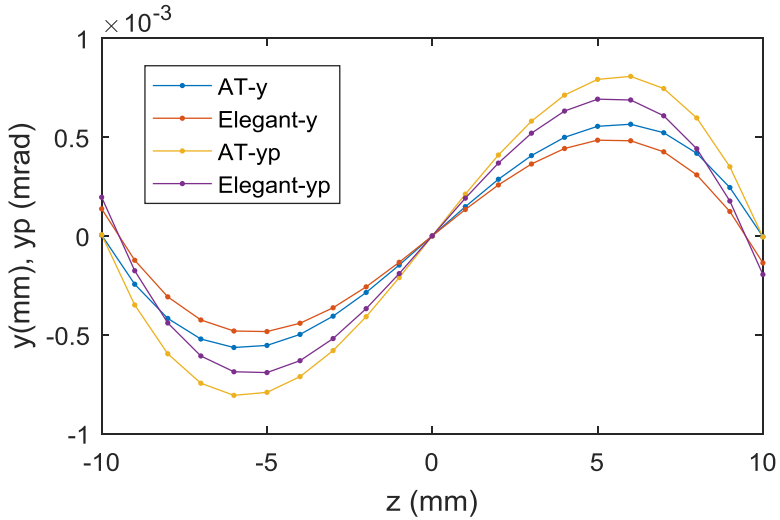
Acknowledgement (for the crab cavity study)

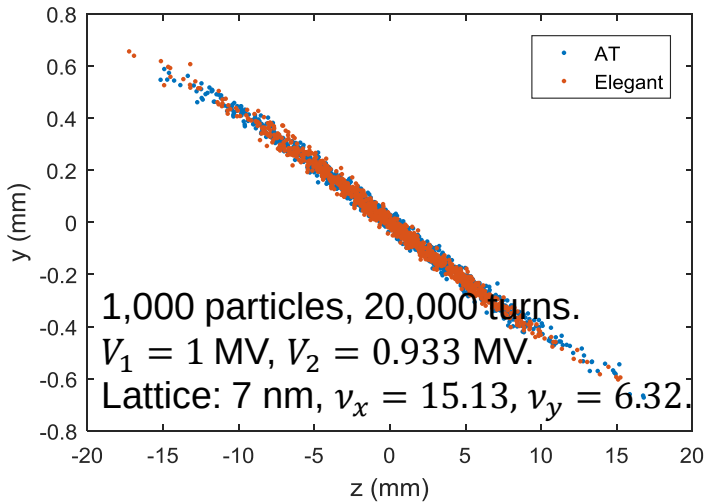
- Thanks to A. Zholents for many helpful discussions.
- Many input from SPEAR3 2FCC study team
  - Valery Dolgashev, Kelly Gaffney, Bob Hettel, Zenghai Li, Tom Rabedeau, James Safranek, Jim Sebek, Kai Tian.

Backup slide: AT and Elegant comparison

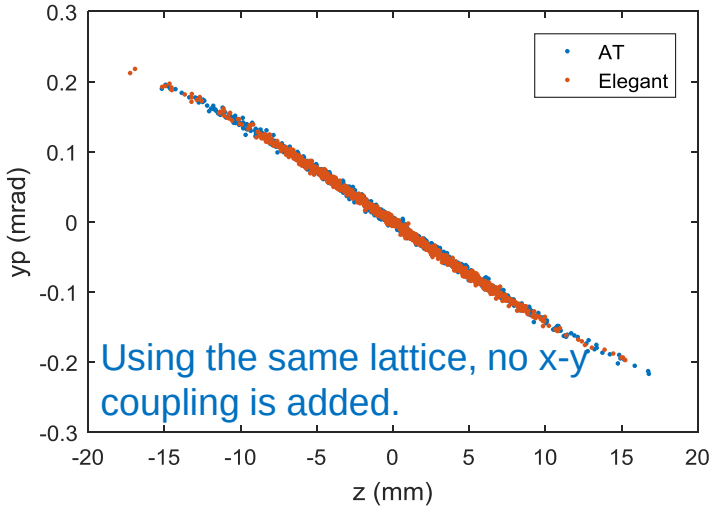
A test case: particles with initial z-offset, other coordinates are zeros.
For the regular bunch with cancellation.







1,000 particles, 20,000 turns.
$V_1 = 1$ MV, $V_2 = 0.933$ MV.
Lattice: 7 nm, $\nu_x = 15.13$, $\nu_y = 6.32$.



Using the same lattice, no x-y coupling is added.

Short pulse performance for SPEAR3 case

- Although tilted beam can be generated at many locations, only BL 15, 17, and a potential future 10S beamline could actually benefit.
  - Most other ID beamlines use wigglers.
  - BL 12-1 and 12-2 are for protein crystallography.

Drift to slit

Flux 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	1.2 MV	V1=1 MV	1.2 MV	V1=1 MV	1.2 MV	V1=1 MV	1.2 MV
BL15 (13S)	**3.5**	**3.1**	**4.3**	**3.6**	**5.6**	**4.8**	**7.1**	**6.1**
BL17 (14S)	10.3	8.9	10.5	9.1	11.1	9.6	11.8	10.3

- Charge for a 20 mA bunch is 15.6 nC.

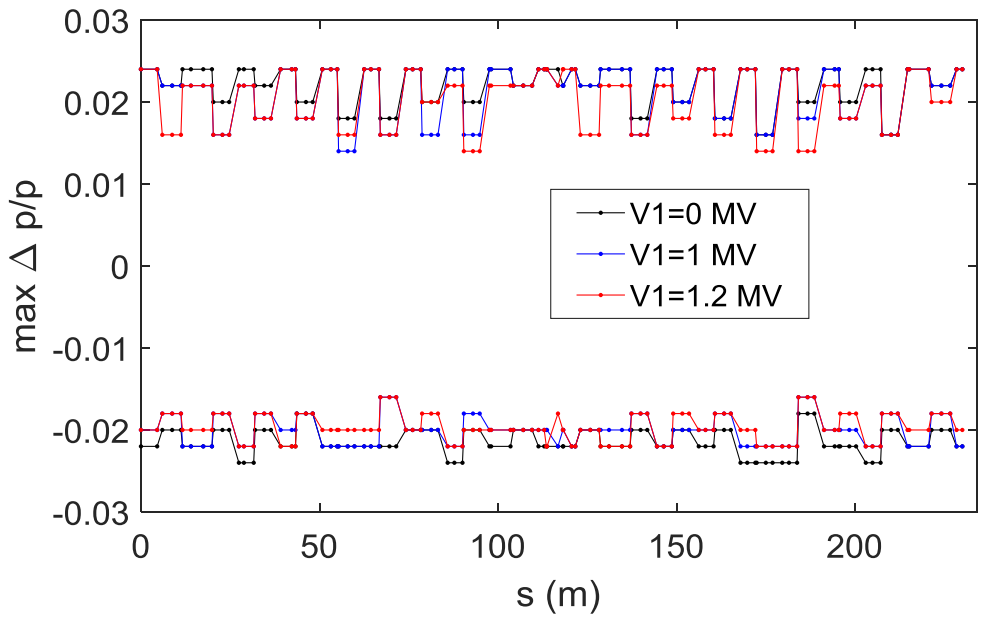
Imaging source point

beam line	6% (3.8%) flux		10% (6.3%) flux		15% (9.4%) flux		20% (12.6%) flux	
	V1=1 MV	1.2 MV	V1=1 MV	1.2 MV	V1=1 MV	1.2 MV	V1=1 MV	1.2 MV
Future 10S-BL	**2.3**	**2.3**	**3.3**	**3.3**	**4.7**	**4.6**	**6.2**	**6.0**
BL15 (13S)	**3.4**	**3.5**	**4.2**	**4.2**	**5.4**	**5.4**	**6.7**	**6.6**
BL17 (14S)	**2.6**	**2.6**	**3.5**	**3.5**	**4.8**	**4.8**	**6.3**	**6.1**

- Imaging optics needs to consider degradation from realistic mirror optics (not included).
- Could use less deflecting voltage for imaging optics.

Touschek lifetime

- The crab cavities give large vertical kicks to Touschek particles when they acquire large z-offset, which can lead to beam loss and poorer Touschek lifetime.
- Momentum aperture is calculated for the tilted bucket with crab cavities turned on, track for 2000 turns.



V_1 (MV)	Eigen ϵ_y (pm)	τ_T (hr) @ 20 mA*	5-min ΔI_b (mA)
0.8	54	1.73	0.94
1	80	2.03	0.80
1.2	120	2.30	0.71

*Touschek lifetime includes bunch lengthening by 60% at 20 mA.