Obtaining picosecond x-ray pulses on fourth generation synchrotron light sources

FLS'23 Workshop, Ring working group

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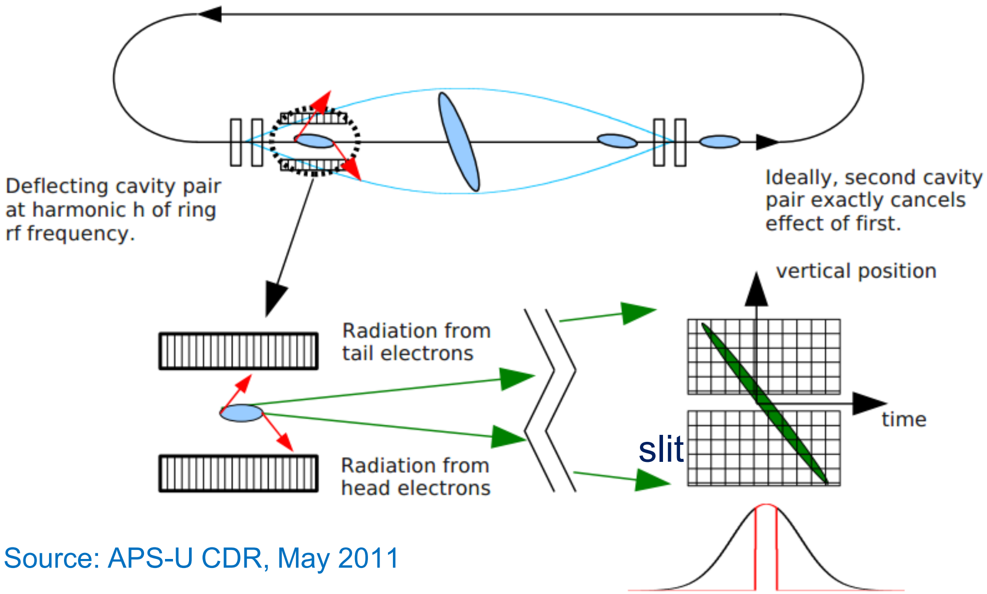
Outline

- The 2-frequency crab cavity (2FCC) scheme – a brief review
- 2FCC for fourth generation synchrotron light sources
  - Emittance growth, momentum compaction, vertical tune and deflecting voltage
  - Emittance growth for tilted, elongated bunches
  - Half-integer fractional harmonic cavity for simultaneous lengthening and shortening
- Application to APS-U
  - Configuration and parameters
  - Short-pulse performance
  - Injection and lifetime
- Summary

"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.

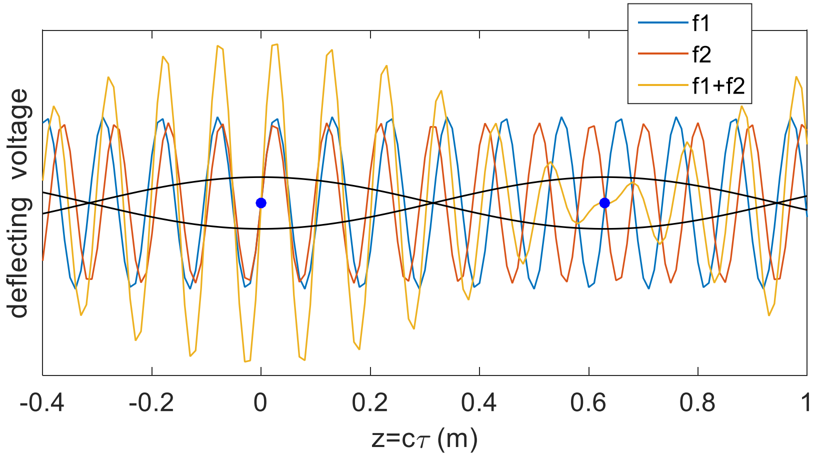
The two-frequency crab cavity (2FCC) scheme

Use crab cavities of two frequencies*, A. Zholents, NIMA 798, 111 (2015)

$$f_1 = hf_{RF}$$
$$f_2 = \frac{hm \pm 1}{m} f_{RF}.$$

The deflecting kicks cancel for some bunches

$$\delta y'(\hat{z}) = \frac{\mathrm{e}U_1}{\mathrm{E}_b} \sin(2\pi f_1 \sigma_\tau \hat{z}) - \frac{\mathrm{e}U_2}{\mathrm{E}_b} \sin(2\pi f_2 \sigma_\tau \hat{z}),$$



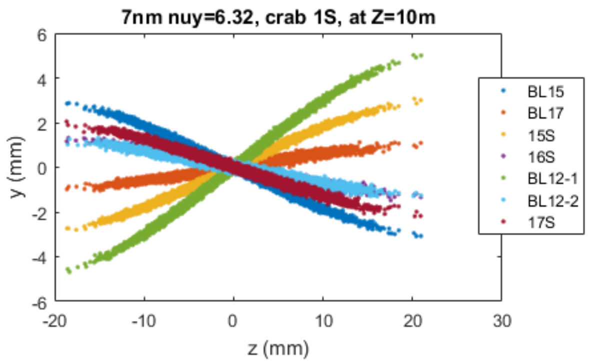
For example, w/ $m = 2$, half of the buckets are tilted in $y - z$ plane, the other half are un-affected.

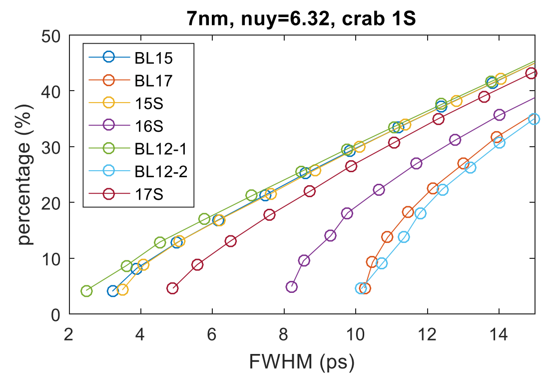
*Similar to the BESSY-VSR scheme (G. Wüstefeld, A. Jankowiak, J. Knobloch, M. Ries, IPAC'11)

A 2FCC study for SPEAR3

- Application of the 2FCC scheme has been seriously studied for SPEAR3

Parameters		
E_0	3	GeV
f_1	2857.8	MHz
f_2	3096.0	MHz
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
β_1	4.9	m





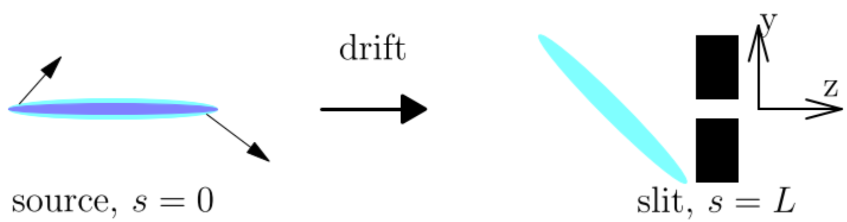
Beam line	Optics type	Short pulse duration (fwhm, ps) 6% (3.6%)	10% (6.3%)	15% (9.4%)	20% (12.6%)
BL15	Drift	3.5	4.3	5.6	7.1
BL12-1	Drift	2.9	3.9	5.2	6.7
Future 10S-BL	Imaging	2.3	3.3	4.7	6.2

Fill pattern

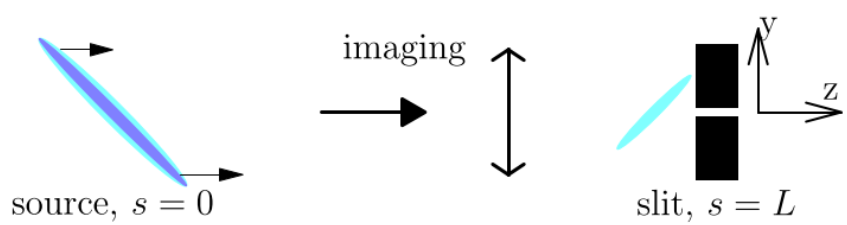
X. Huang, et al, PRAB 22, 090703 (2019)

Short pulse performance estimate

- Two types of optics to take advantage of tilted distribution to produce short pulses
  - Potentially hybrid optics
- Theoretical prediction of minimum pulse duration*



(a) drift optics



(b) imaging optics

Drift optics – good for large y'-z slope

$$\sigma_{z,\min} = \frac{2\sin\pi\nu_y}{\epsilon\sqrt{1+\beta_y^2/L^2}}\sqrt{\frac{\epsilon_y}{\beta_2}+\frac{\beta_y}{\beta_2}\sigma_\theta^2}$$

Imaging optics – good for large y-z slope

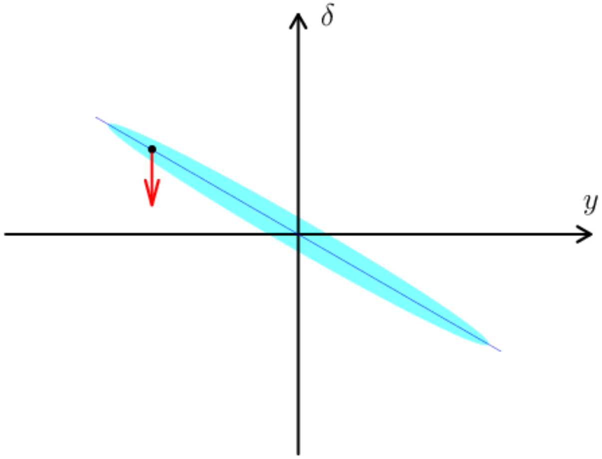
$$\sigma_{z,\min} = \frac{2\sin\pi\nu_y}{\epsilon}\sqrt{\frac{\epsilon_y}{\beta_2}+\frac{\sigma_r^2}{\beta_2\beta_y}}$$

Crab cavity coupling coefficient $\epsilon = \frac{e(k_1V_1+k_2V_2)}{E_0}$

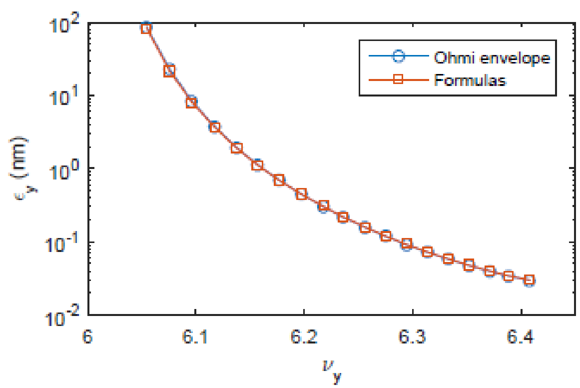
*X. Huang, et al, PRAB 22, 090703 (2019)

Emittance growth from tilted distribution

- An unexpected discovery was that the tilted beam distribution in dipoles cause a vertical emittance growth
  - Significantly impact tune choice for 3rd generation rings



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



For SPEAR3, we need to increase ν_y from 6.16 to 6.32

$$\Delta\epsilon_y = C_q \gamma^2 \frac{\chi^2 C^2 \alpha_c^2 \beta_2}{12 J_y \rho} \frac{2 + \cos 2\pi\nu_y}{(\cos 2\pi\nu_s - \cos 2\pi\nu_y)^2}$$

$$\chi = \frac{e(k_1 V_1 + k_2 V_2)}{E_0}$$

$$\bar{\eta} = -\alpha_c C$$

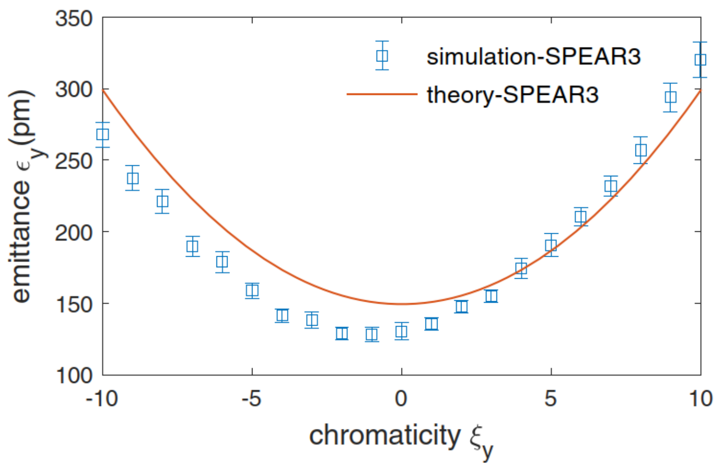
X. Huang, PRAB 19, 024001 (2016)

Nonlinear dependence of emittance on chromaticity!

- Additionally, the vertical emittance depends on the chromaticity
  - The nonlinear coupling of y-z motion through chromaticity cause additional excitation when electrons emit photons.
  - The nonlinear coupling is analytically studied and the emittance growth is predictable.

$$H = \mu_y J_y(y, p_y) + \mu_z J_z(z, \delta) + \chi \delta_D(\theta - \theta_0) yz + 2\pi \xi_y J_y(y, p_y)\delta,$$

$$\langle \mathcal{H}_c \rangle = \frac{\beta_y \chi^2 \bar{\eta}^2}{48} \csc^4 \pi\nu_y (2 + \cos 2\pi\nu_y) + \xi_y^2 \frac{\beta_y \chi^2 \pi^2 \sigma_\delta^2}{360} (120\beta_z^2 - 299\bar{\eta}^2 + 15\bar{\eta}^2 \csc^2 \pi\nu_y (7 + 30\csc^2 \pi\nu_y)) \csc^2 \pi\nu_y$$



(See our poster on Wednesday **WE4P25**)

J. Tang, X. Huang, PRAB 25, 074002 (2022)

2FCC for 4th generation synchrotron light sources

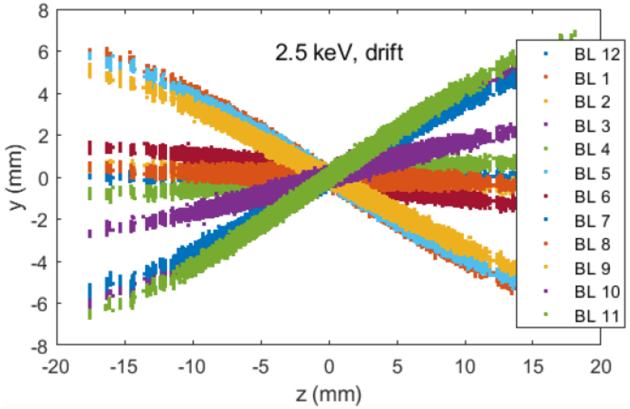
SLAC

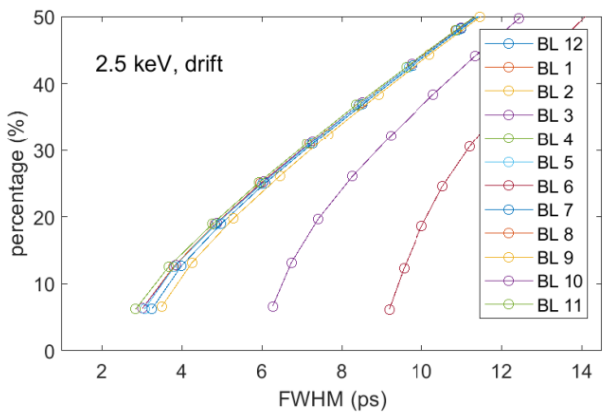
- How does the 2FCC apply to MBA-based low emittance rings?
  - Study for Elettra-2 showed that it is quite feasible

TABLE X The FWHM pulse duration for the drift optics case, assuming a photon energy of 2.5 keV.

Beamline	fwhm/5%	fwhm/10%	fwhm/15%	fwhm/20%
Sector	(ps)	(ps)	(ps)	(ps)
12	29.16	29.13	29.07	28.90
1	2.89	3.44	4.18	5.02
2	21.01	21.02	21.17	21.21
3	2.92	3.45	4.18	5.04
4	15.41	15.51	15.62	15.81
5	2.96	3.49	4.20	5.05
6	9.12	9.43	9.74	10.13
7	3.16	3.65	4.33	5.16
8	25.52	25.26	25.37	25.44
9	3.38	3.84	4.52	5.32
10	6.23	6.48	6.90	7.44
11	2.75	3.29	4.08	4.96

With deflecting voltage $V_1 = 0.8$ MV





X. Huang, A. Zholents, "Feasibility study for a production of picosecond x-ray pulses at Elettra-2", unpublished report (2019)

An advantage of 4G rings for 2FCC

- The low momentum compaction that comes along with low emittance reduces the crab cavity-induced emittance growth
  - A dominant effect in 3G rings goes away by itself.
    - Example: APS-U has $C\alpha_c = 0.0446$ m, while SPEAR3 has $C\alpha_c = 0.380$ m
  - This frees up the choice of vertical tune, and has an additional benefit: lower vertical tune corresponds to larger tilting slopes.

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

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

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

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

As we choose lower fraction tune for the vertical plane, the required deflecting voltage is smaller. This helps crab cavity design and operation.

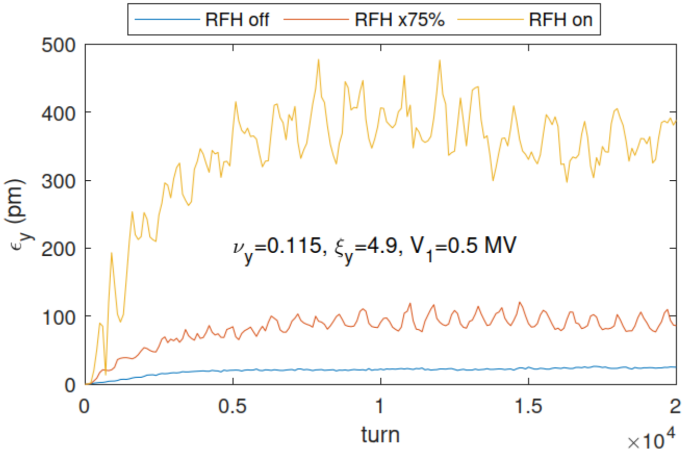
*X. Huang, PRAB 19, 024001 (2016)

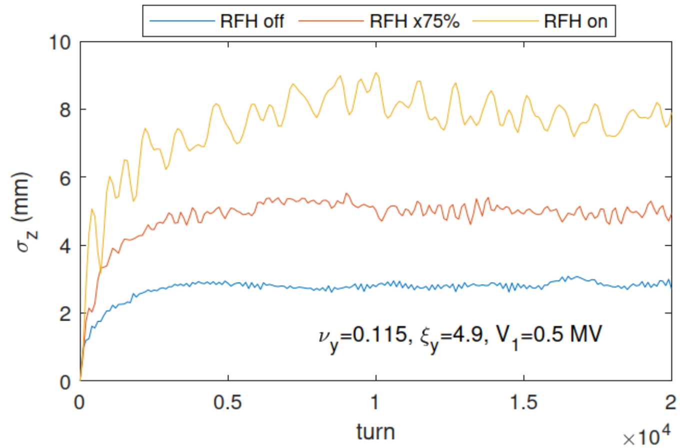
An issue of 4G rings for 2FCC

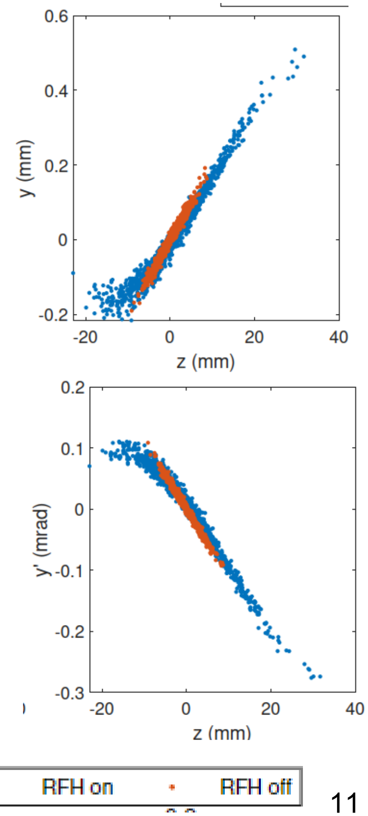
- The tilted bunch gets a substantially larger emittance increase when it is lengthened by harmonic cavity
  - An unexpected discovery as we apply 2FCC for APS-U (41pm lattice*)

*M. Borland et al, NAPAC'16

APS-U harmonic cavity (RFH): 4th harmonic, voltage $V_h = 0.866$ MV to cancel focusing slope





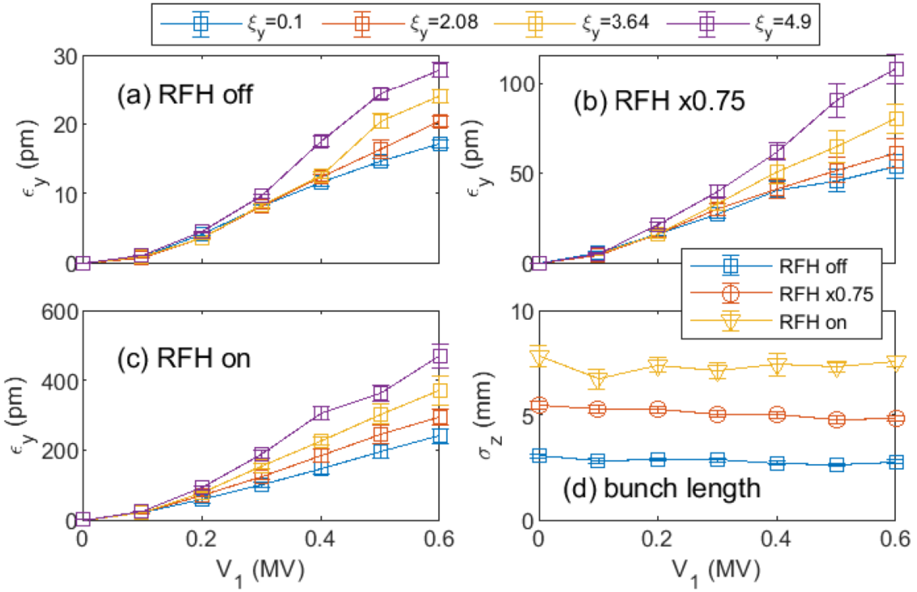


With deflecting voltage of V_1 =0.5 MV for $f_1 = 8f_{rf}$

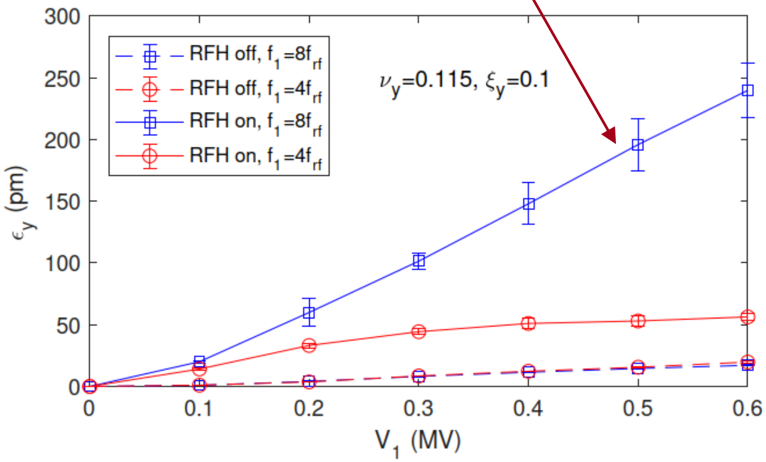
The huge increase of vertical emittance means poor short pulse performance.

What are causing the extra emittance growth?

- Is it the chromaticity effect?
  - Only partially. It has an effect, but doesn't explain all.
- The crab cavity waveform curvature seems to be the main culprit – changing crabbing frequency makes a big difference.



Emittance vs. V_1 for 3 RFH settings w/ 4 levels of vertical chromaticity



Emittance vs. V1 (8th harmonic) for $f_1 = 8f_{rf}$ and $f_1 = 4f_{rf}$ (w/ double V1 for equal deflecting slope)

Solution – using a half harmonic cavity

- A half harmonic cavity, with frequency $f = \left(n + \frac{1}{2}\right) f_{rf}$, can cancel the focusing slope for half of buckets, while doubling the slope for the other half
  - Similar to BESSY-VSR and 2FCC itself
  - Doubling the focusing slope helps increasing the charge density, good for short pulse performance
  - Only one frequency is needed, just trade the usual integer harmonic for one with half-integer frequency
  - It may benefit timing users even without using crab cavities – bunches that are much shorter can co-exist with regular beams

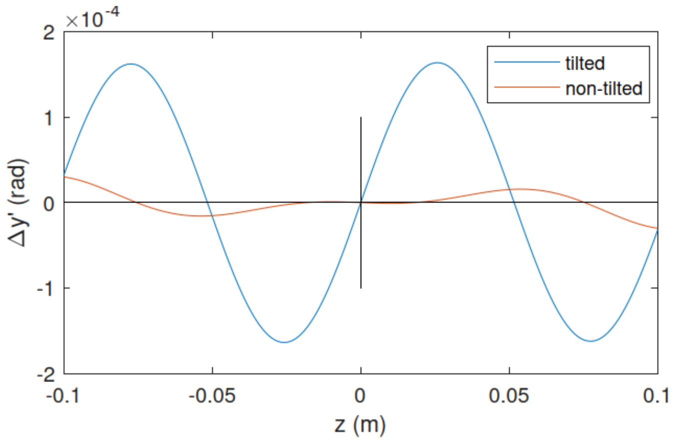
APS-U already has a 4th harmonic bunch lengthening cavity (M. Kelly et al, IPAC'15).
We assume a cavity with $f = 4.5 f_{rf}$ for APS-U for illustration purpose.

Application to APS-U: system layout

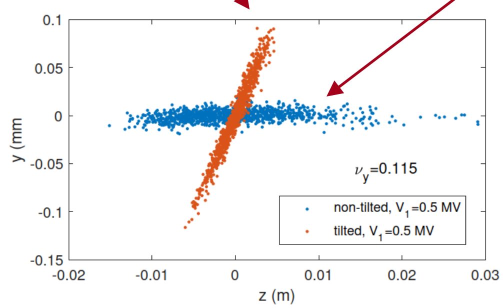
- Crab cavities: $f_1 = 8f_{rf}$, $f_2 = 8.5f_{rf}$, $V_2 = 0.967V_1$
  - Arranged in one straight section symmetrically as required to cancel position kick

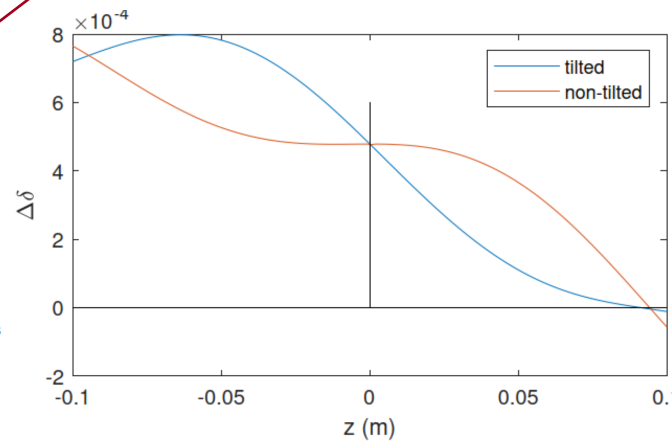
X. Huang, et al, PRAB 22, 090703 (2019)

- RFH: $f_{rfh} = 4.5f_{rf}$, $V_{rfh} = 0.770$ MV (w/ $V_{rf} = 4.5$ MV)
- Two types of buckets: (tilted, shortened) and (non-tilted, lengthened)



Vertical kick vs. z position by the crab cavities



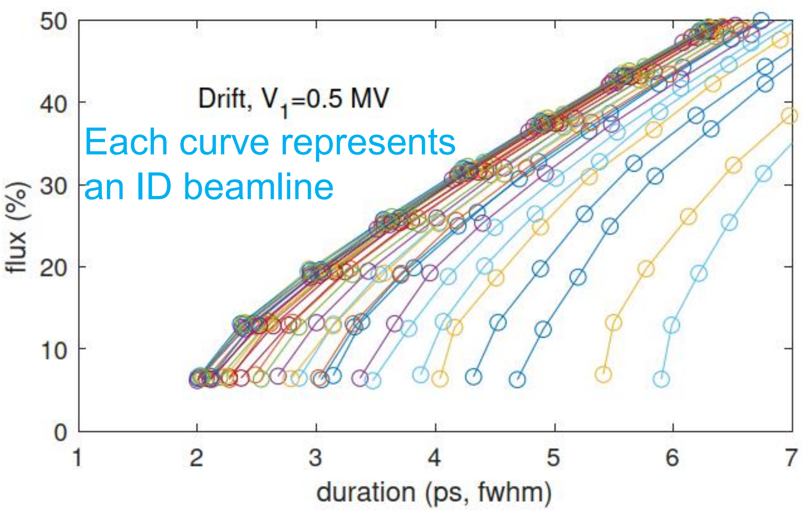


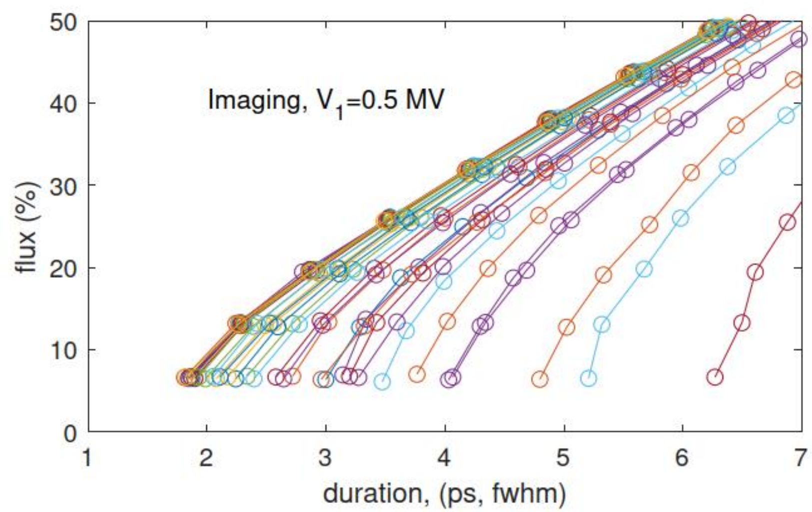
Energy kick vs. z position by main RF and RFH

Short pulse performance

- Simulation is performed to predict the short pulse performance

Including a 20% linear coupling (needed for non-tilted beam)





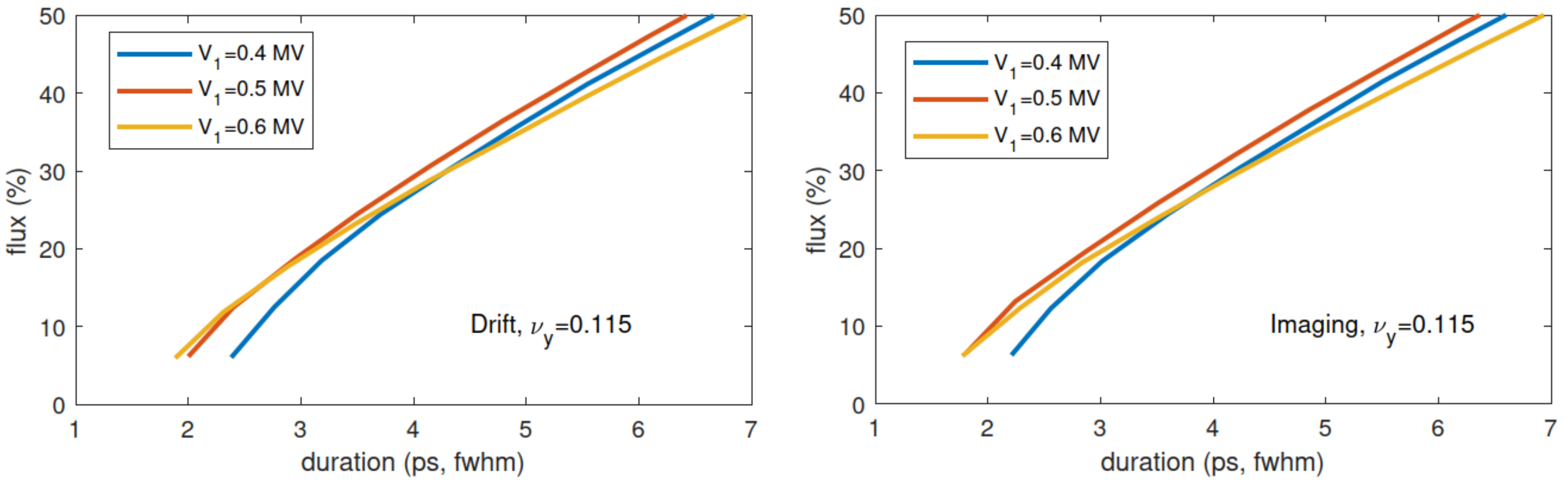
Minimum pulse duration in good agreement with analytic prediction

- Drift optics: 2.0 ps (FWHM) for 6% flux, minimum predicted to be 1.89 ps
- Imaging optics: 1.8 ps (FWHM) for 6% flux, minimum predicted to be 1.73 ps

Dipole beamline can only use imaging optics (dominated by single photon divergence), which produce similar performance as ID beamlines.

Optimal deflecting voltage

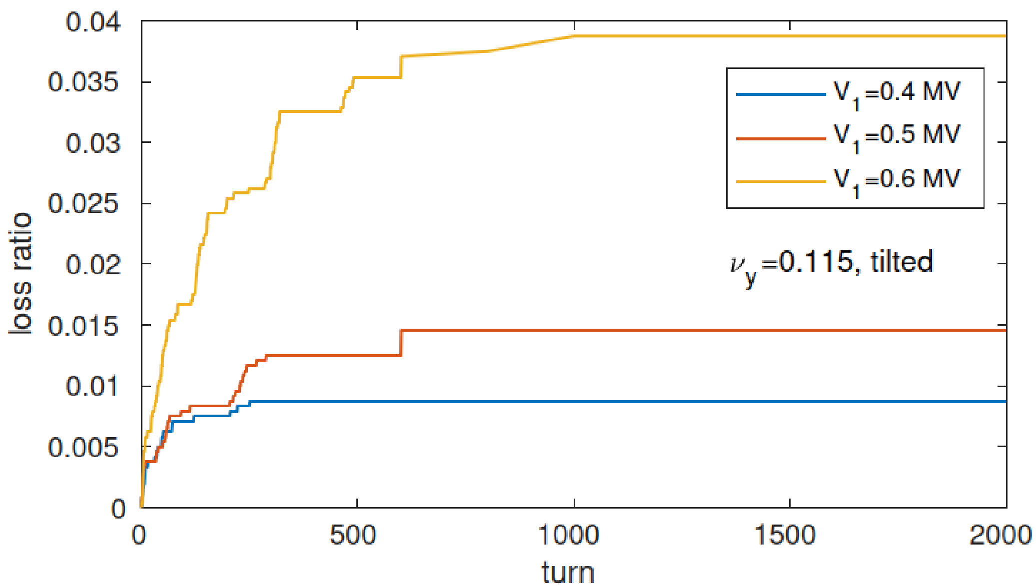
- As large deflecting voltage increases emittance, it is not always helpful for it to go larger
  - If crab cavity induced emittance is the only source, the minimum duration would be independent deflecting voltage   X. Huang, PRAB 19, 024001 (2016)



$V_1 = 0.5$ MV seems to be an optimal deflecting voltage for the APS-U case (w/ given vertical tune). This would change if the tune, photon property, or linear coupling change.

Injection into tilted bunches

- The crab cavities can affect injection performance as injected bunch is usually long
  - Some particles will see the peak of deflecting waveforms

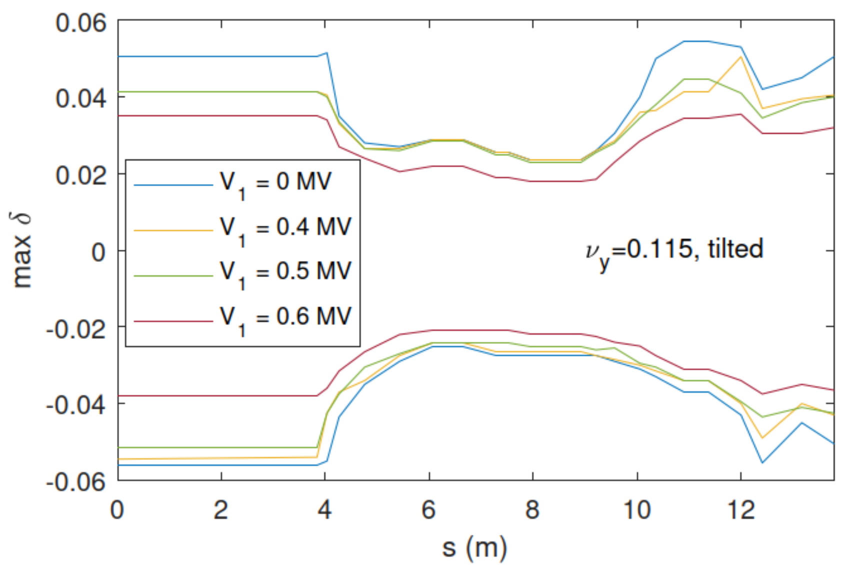


Assuming injected beam has
$\epsilon_x = 90$ nm
$\epsilon_y = 3$ nm
$\sigma_t = 74$ ps
$\sigma_\delta = 1.17 \times 10^{-3}$.

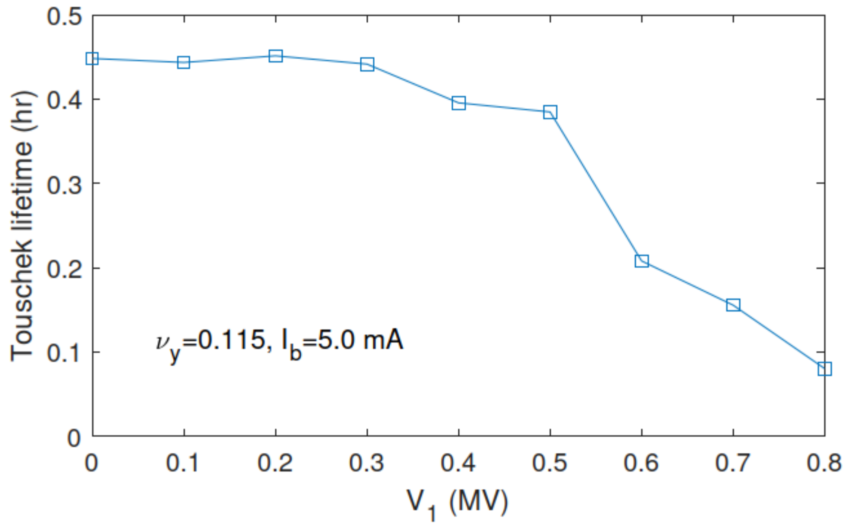
Simulation shows that the injection loss is acceptable

Touschek lifetime

- Similarly Touschek lifetime could suffer
  - Touschek particles will drift to large z-position and see vertical kicks
- Simulation can reveal the impact to local momentum aperture.



Impact to LMA

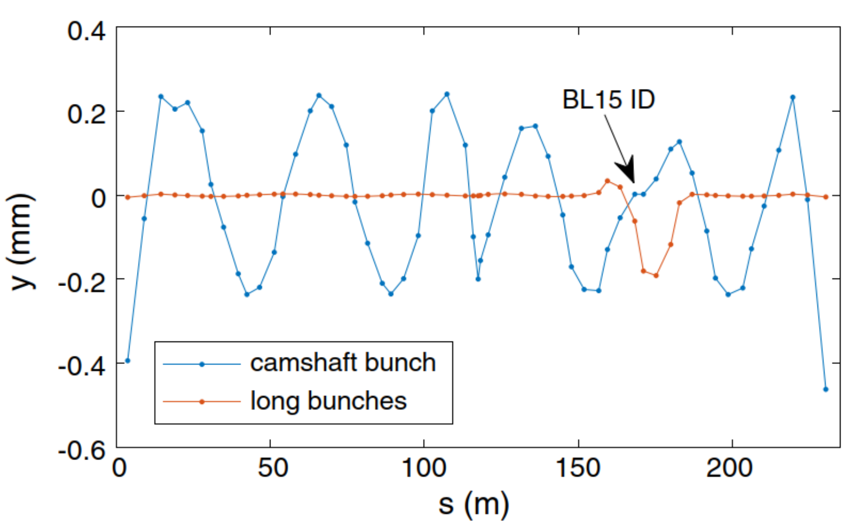


Touschek lifetime vs deflecting voltage

Emittance growth w/ V1 helps Touschek lifetime

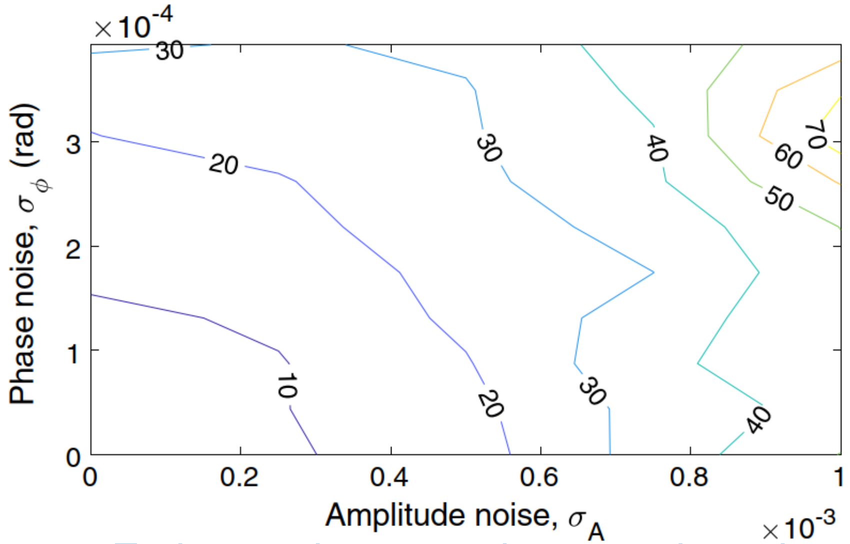
Some other operational aspects

- Separation of long and short pulses
  - By shifting crab cavity phases to produce two closed-orbits



SPEAR3 case w/ a 0.2 rad phase shift

X. Huang, et al, PRAB 22, 090703 (2019)



Emittance increase due to crab cavity rf noise (SPEAR3 case) – effect would be much weaker for APS-U due to low χ

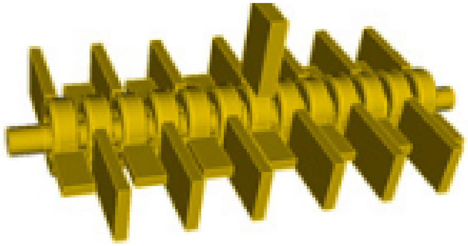
- Effects of rf noise to regular beam
  - Amplitude and phase noise of crab cavities can excite vertical emittance of non-tilted beam

These and other operational issues have not been studied for the APS-U case.

A design of normal-conducting crab cavity design

- During the SPEAR3 2FCC study, a normal-conducting design was completed
  - Meeting the space and deflecting voltage requirements (2 MV total in one 4-m straight section)
  - Meeting other requirements (heat load, impedance, et al)

Frequencies: 2858 GHz and 3096 GHz
Deflecting voltages: 1 MV and 0.93 MV



A 13-cell structure w/ HOM and FPC couplers

Table 2: NC Crab Cavity Parameters

Parameter	Value	Unit
Beam aperture	20	mm
Number of cell per structure	13	
Structure length	0.65	m
Number of structures	4	
Total length	2.65	m
Shunt impedance	21	MΩ/m
Sextupole field K_2L	0.05	1/m^2
Kick factor k_d (for σ_z= 5 mm)	1300	V/pC/m
RF power required	<40	kW/frequency

The APS-U 2FCC scheme only needs half of the deflecting voltage.

Z. Li, et al, IPAC'17 (2017)

Summary

- The 2FCC scheme is promising for producing short pulses in storage rings
- It has advantages and challenges when applied to MBA-based low emittance rings
- The half-integer fractional harmonic cavity approach turns a challenge into a benefit
- A case study with APS-U shows that good short pulse performance can be achieved with a weak deflecting voltage
  - Minimum pulse duration of 2 ps (FWHM), 50% flux for less than 7 ps (FWHM)
- Impact to injection and Touschek lifetime is acceptable