Injection schemes For HEPS

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on behalf of Accelerator Physics Group

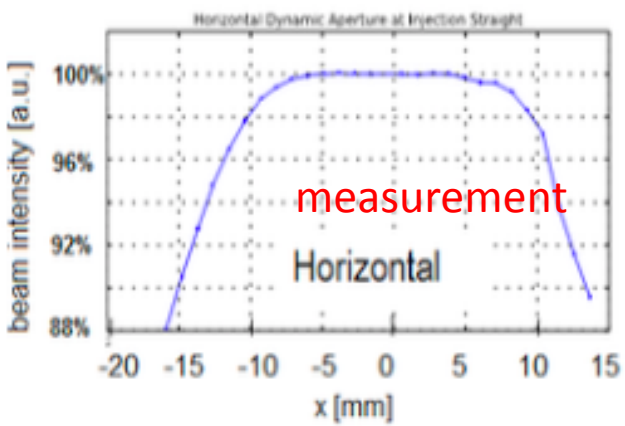
Presented at TWIIS 2017, Berlin, Germany

Outline

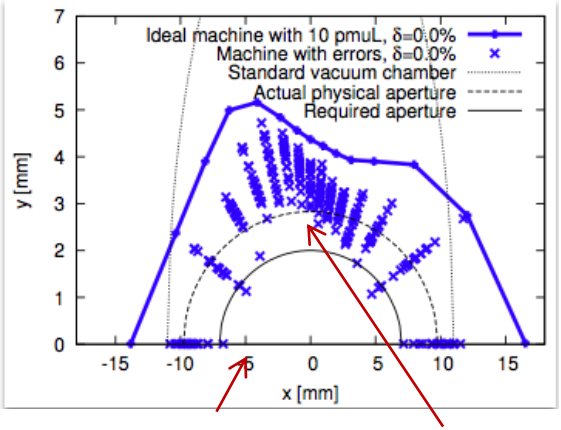
Motivation

Dynamic apertures of some recent built & proposed low-emittance light sources (or upgrades)

NSLS-II, 3 GeV, DBA 900 pm

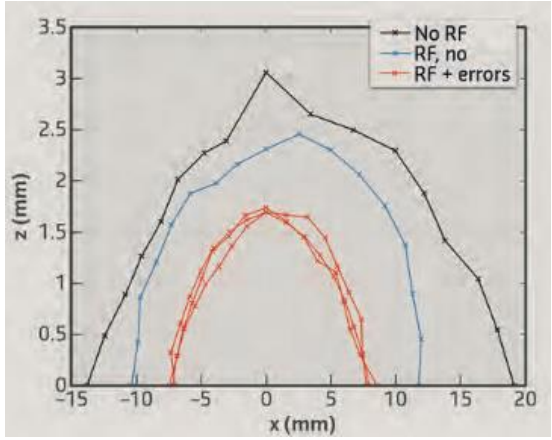


MAX-IV, 3 GeV, 7BA, 328 pm

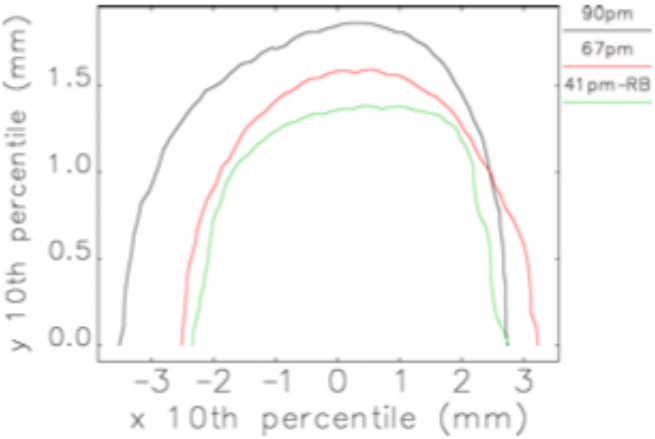


Meas: H (4.8 mm) / V (2.1 mm)

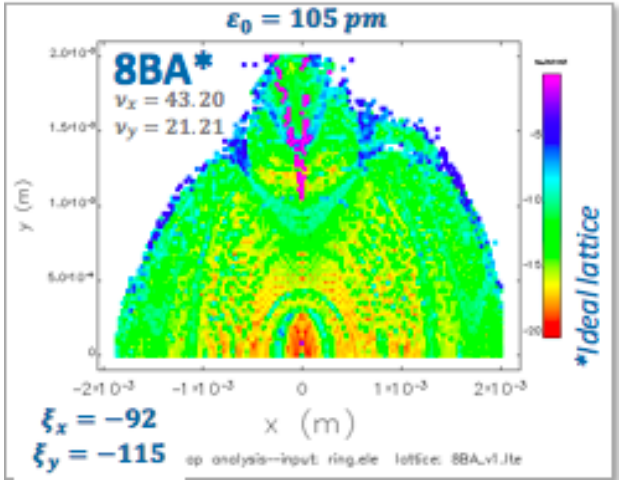
ESRF-EBS, 6 GeV, 7BA, 147 pm



APS-U, 6 GeV, 7BA, 41/67/90 pm



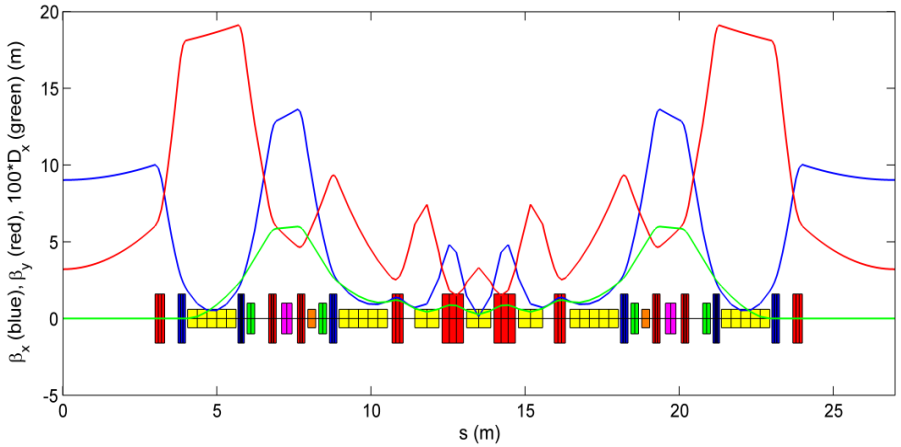
ALS-U, 2 GeV, 8BA, 105 pm



References:

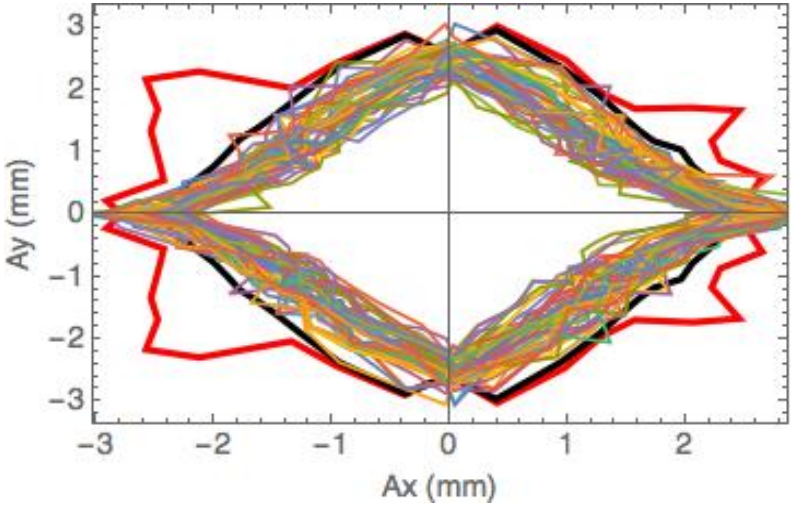
[1] F. Wileke, talk on IPAC'15
[2] S. Leemann, talk on LER2016
[3] ESRF-EBS TDR, the "orange" book
[4] M. Borland, IHEP seminar, 2016
[5] M. Venturini, talk on LER2016

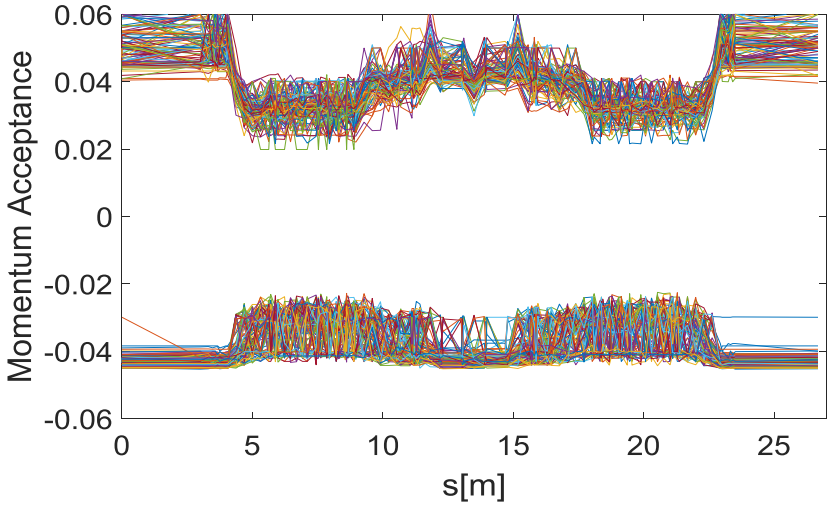
The baseline lattice design of HEPS-TF[1]



Parameters	Value
circumference	1295.616 m
Periodicity	48
natural emittance	59.4 pm
U0 (w/o IDs)	1.995 MeV
momentum compaction	3.7e-5
rms energy spread	8e-4
damping time(H/V/S)	19/26/16 ms

100 error seeds after comprehensive correction[2,3,4]

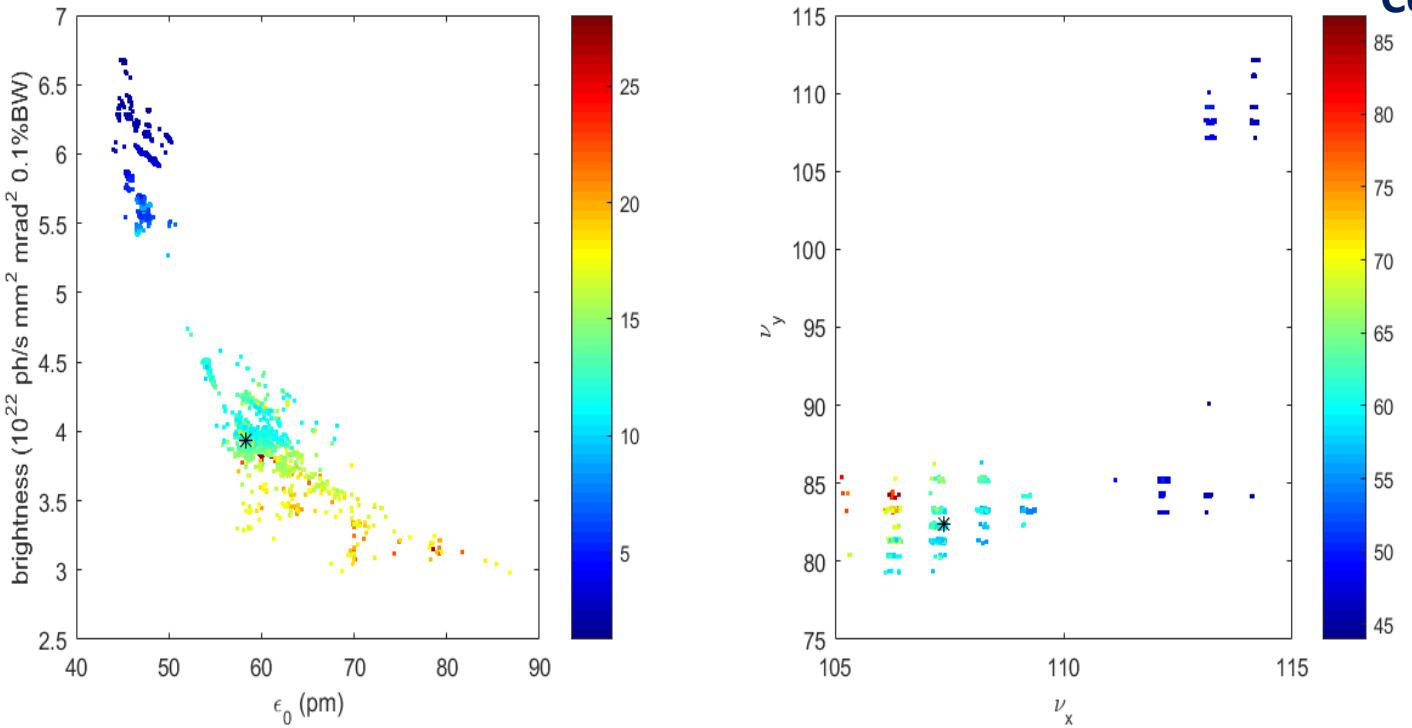




[1] Y. Jiao, *Chin. Phys. C*, 40 (7): 077002. [2]D. H. Ji, IPAC 2016, p3260. [3]Y. Jiao and Z. Duan, NIM A 841, (2017)97-103 [4]S. K. Tian, et al, IPAC 2017, TUPAB067

Trade-off between emittance & DA for HEPS hybrid 7BA lattice design

Courtesy of Yi Jiao



Different color represents different dynamic aperture area [mm^2]

- Pushing towards lower emittance & higher brightness likely leads to smaller dynamic aperture.
- Question: How to inject into the very small dynamic aperture??

Injection considerations for HEPS

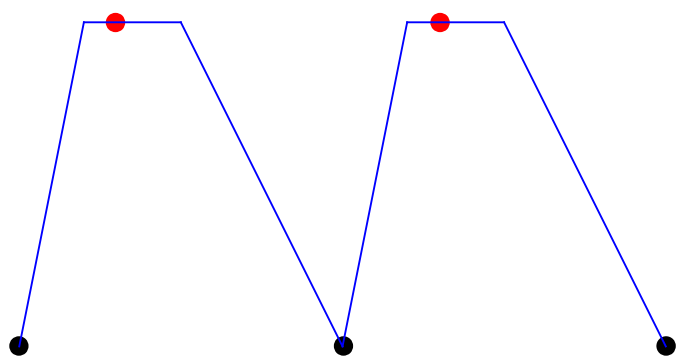
- Top-up injection aims at 0.2% beam current stability
- Filling patterns:
  - 648-bunch filling pattern, ~ 1.3 nC bunch charge
  - 60-bunch filling pattern, ~ 15 nC bunch charge
- Currently focus on on-axis injection schemes, in line with the continuous efforts on lattice optimization towards lower emittance & higher brightness.
- Strategy: swap-out injection as the baseline, compatible with possible upgrade of longitudinal injection schemes in the future.

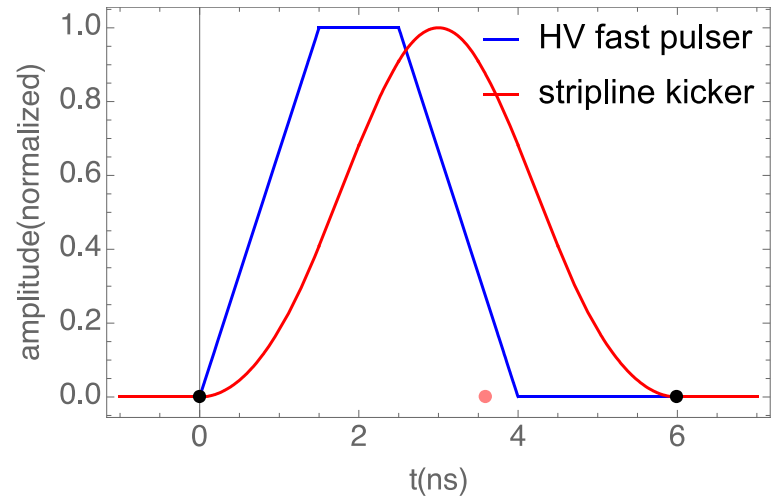
Longitudinal injection

- Golf club (proposed by M. Aiba)
- Double-RF manipulation
- Triple RF static (will be presented by Gang Xu on Tuesday morning)

Common technical challenges

longitudinal injection





- full pulse width < bunch spacing
- pulse rise/fall time < temporal separation between injected bunch and stored bunch
- Generally speaking, rise time << fall time technically-wise.
- Shorter rise/fall time -> shorter and more pieces of stripline kicker & power supply

The kicker fall time is approximately

$$t_f = t_{f,\mathrm{pulser}} + L_{\mathrm{kicker}}/c$$

HEPS RF: 166 MHz + 500 MHz
-> kicker full pulse width < 6 ns
Seek solutions allowing

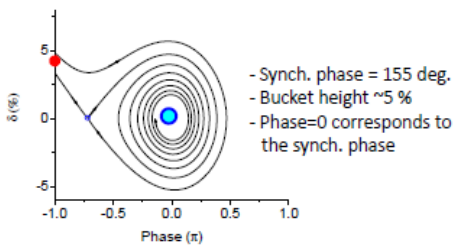
- rise time > 2 ns
- fall time > 2.5 ns

Longitudinal injection into the "golf club"

Longitudinal Acceptance (2)

- "Golf-club" acceptance
  - Well known for the cases with acceleration*
  - Because of energy dependent radiation loss in electron storage rings

Long. acceptance plot with synchrotron radiation loss



It allows an injection between two circulating bunches at the expense of slightly higher injection energy!
(Need to match the injection orbit to the off-momentum closed-orbit)

* e.g., P. M. Lapostolle, Los Alamos National Laboratory, LA-11601-MS (1989)

IPAC'14, Dresden, Germany, 18.06.2014 Masamitsu Aiba, PSI

When applied to the case of HEPS

- Much smaller αc leads to more stringent requirements on MA.
- Or more stringent requirements on kicker pulse fall time

Challenging!

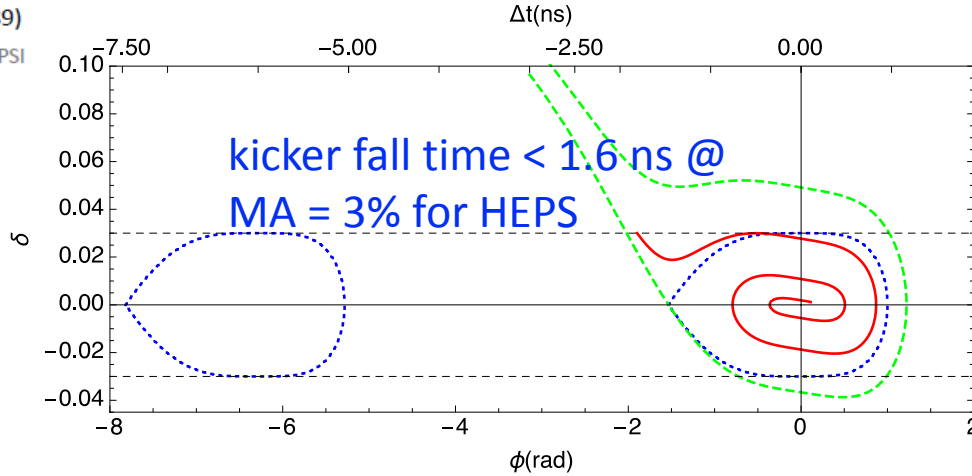
Aiba,et al, PRSTAB, 18, 020701, 2015.

Pros:

✓ No extra hardware complexities.

Cons:

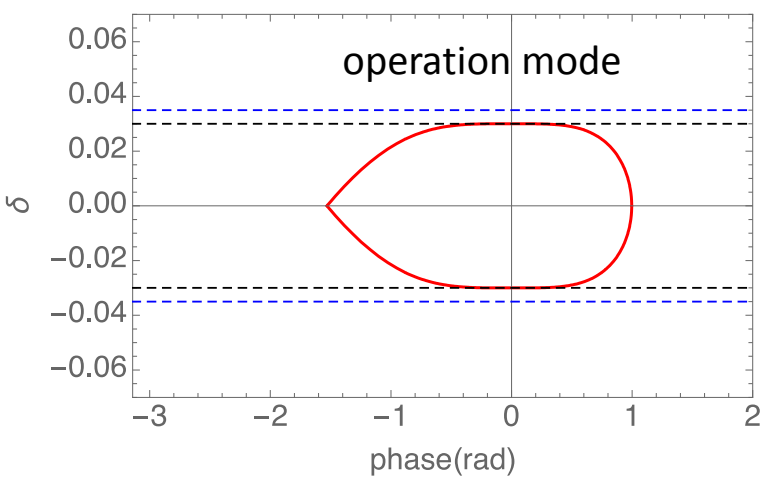
✓ Stringent energy/phase tolerance

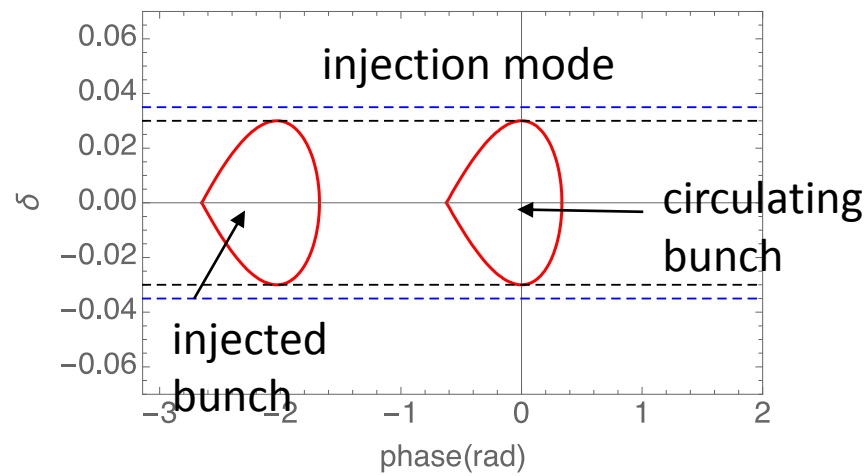


Longitudinal dynamics of an active double-RF system

$$H(\phi,\delta;t)=\frac{h_f\omega_0\eta}{2}\delta^2+\frac{\omega_0}{2\pi E_b}\left[eV_f\cos(\phi+\phi_f)+\frac{h_h}{h_f}eV_h\cos(\frac{h_h}{h_f}\phi+\phi_h)+\phi U_0\right]$$ [1]

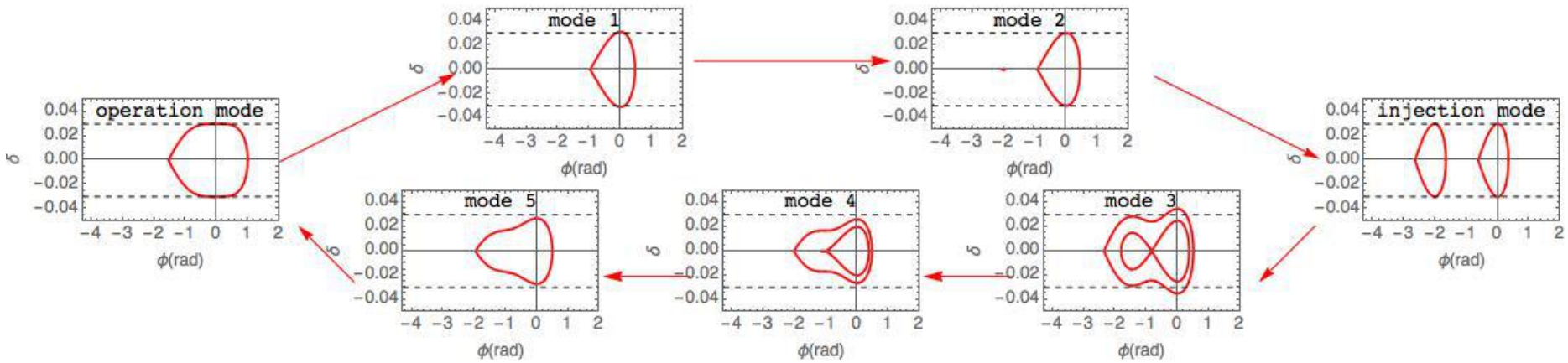
- Four free knobs $(V_f,\ V_h,\ \phi_f,\ \phi_h)$
- Shift between operation and injection modes can be realized with RF gymnastics.
- one constraint $eV_f\sin\phi_f+\frac{h_h}{h_f}eV_h\sin\phi_h=U_0$

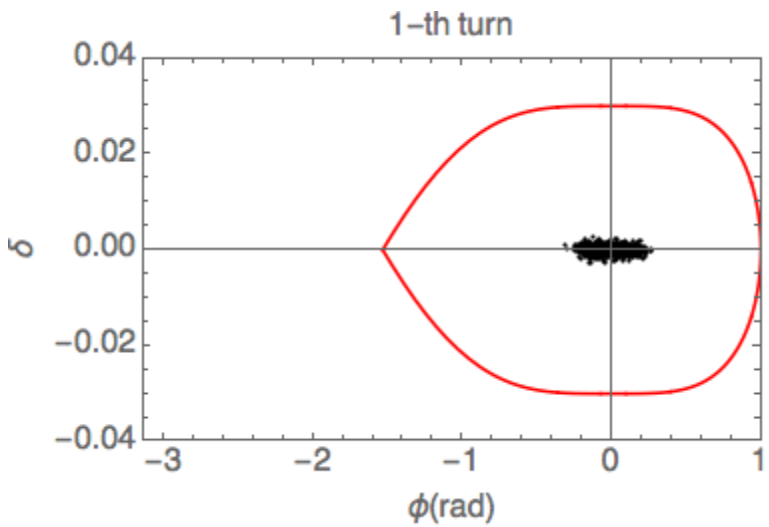




[1] S. Y. Lee, Accelerator Physics (2nd Edition), World Scientific, 2004

A complete injection cycle (~ 200 ms)

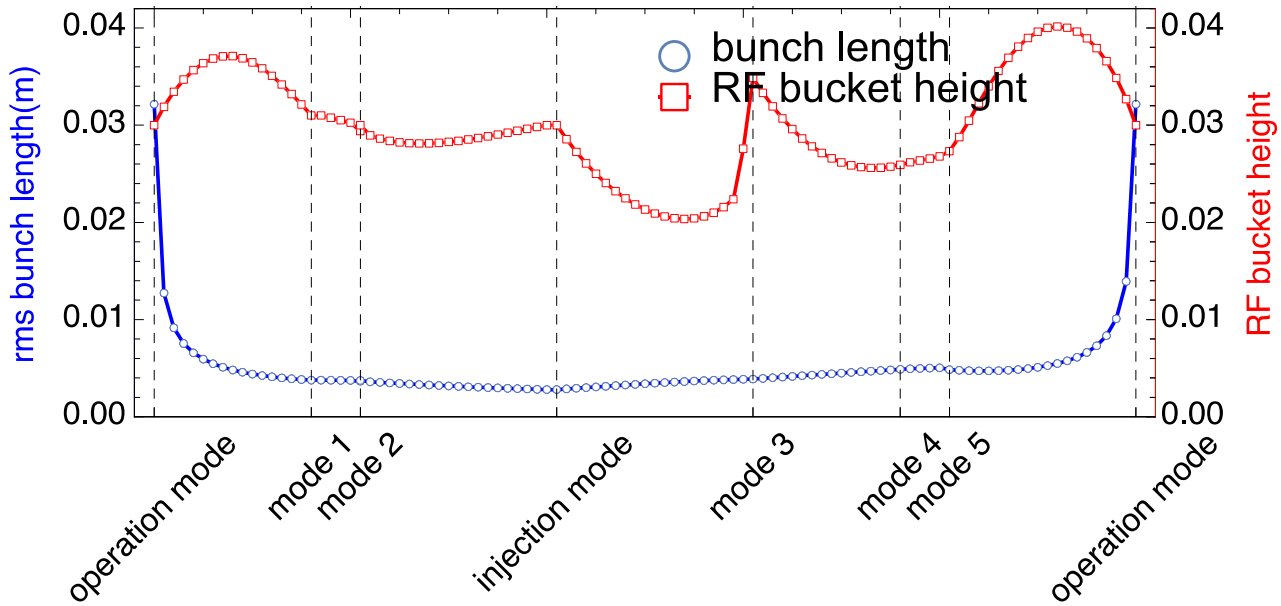




Elegant simulation

- Design the RF buckets according to the ring acceptance and U_0.
- Circulating bunches experience no large amplitude synchrotron oscillation.
- **Each step takes 0.5 ms, injection mode costs 100 ms to inject up to 30 bunches. A complete injection cycle takes about 200 ms.**

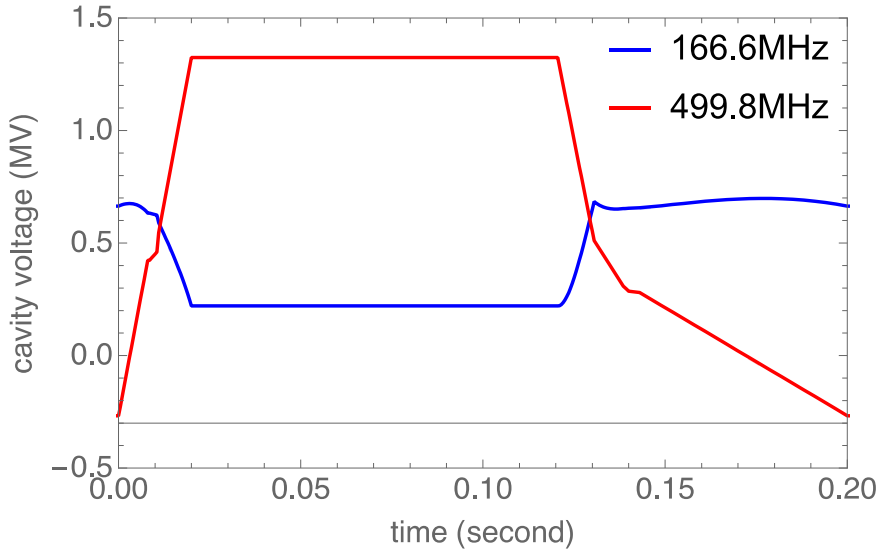
Evolution of beam parameters



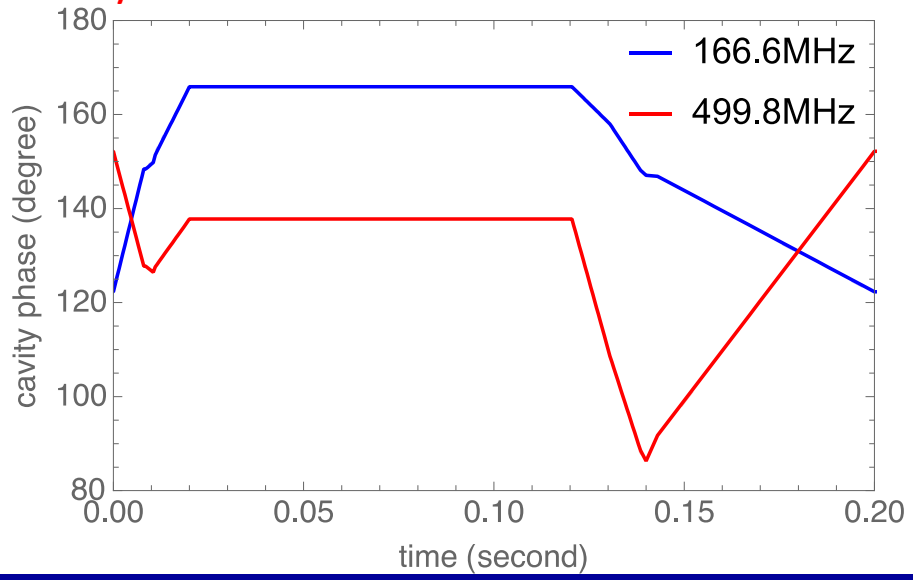
- rms bunch length (zero-current) decreases from 32 mm to 2.8 mm.
  - Collective instability leads to unstable beam during injection?
  - Beam sizes increase due to impedance & IBS effect, effects to the users? (Gate signal can be sent to users anyway).

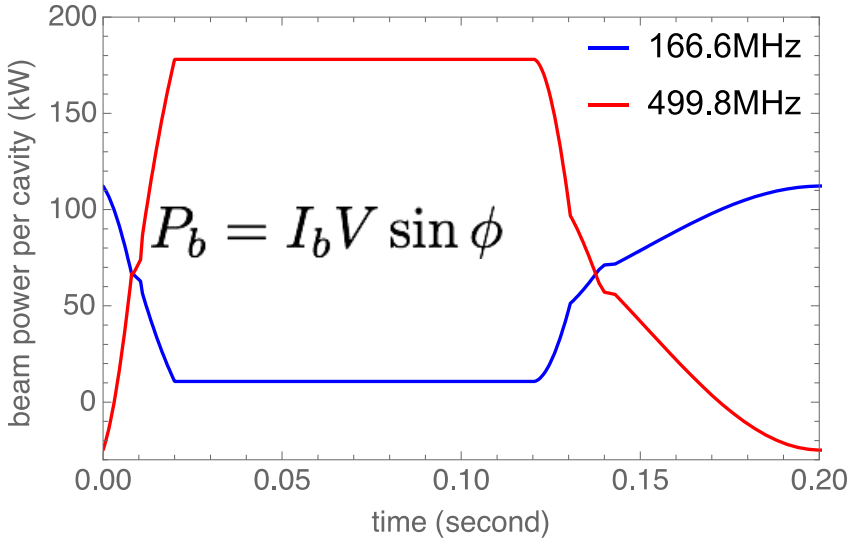
RF parameters in a complete injection period

- Four **166.6** MHz fundamental cavities and two **499.8** MHz 3rd harmonic cavities for HEPS nominal design.
- Assume cavities of the same frequency share the same voltage and phase settings.



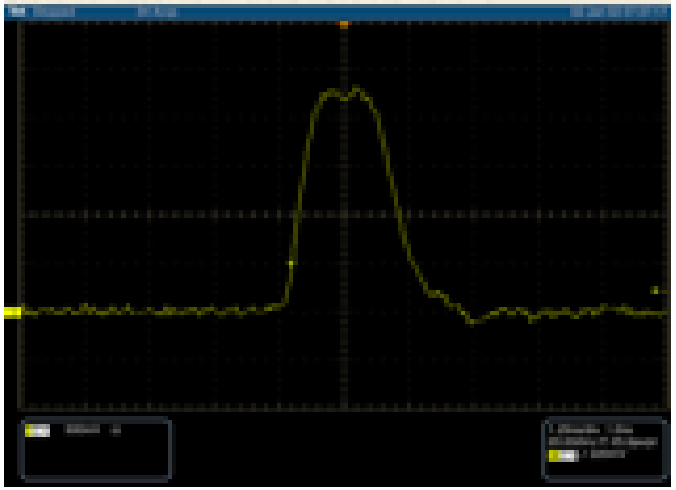
Can we ramp these RF parameters very fast?





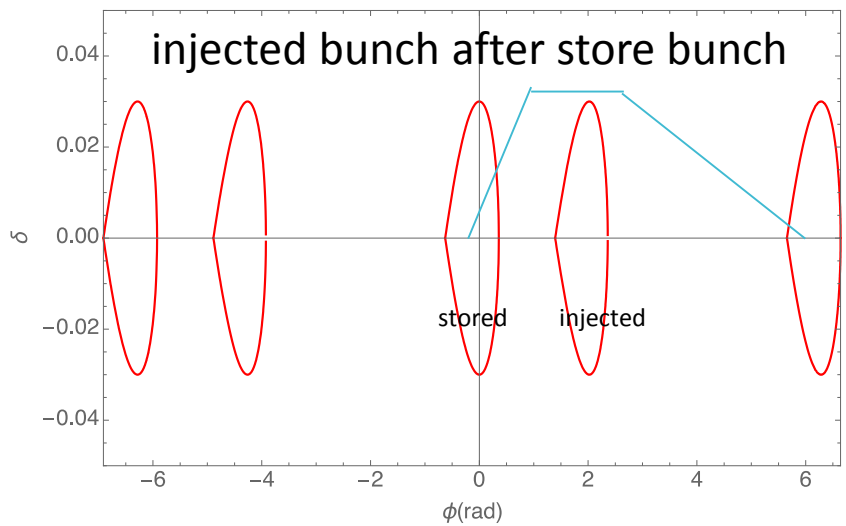
Inject after adjacent stored bunch

FID fast pulser measurement, V=20 kV

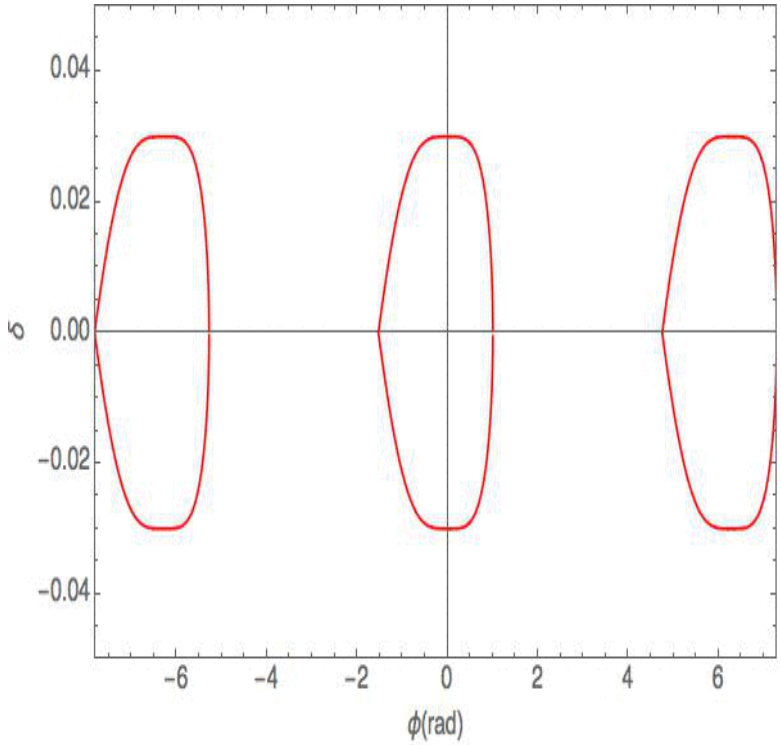


- rise time 5% - 95% : ~ 1ns
- fall time 95% - 5% : ~ 1.5 ns

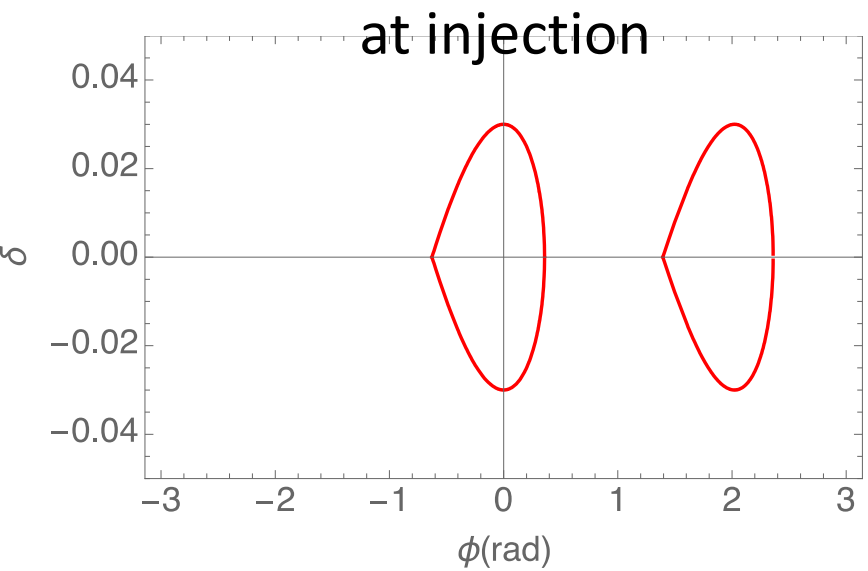
✓ It's better to inject after stored bunch

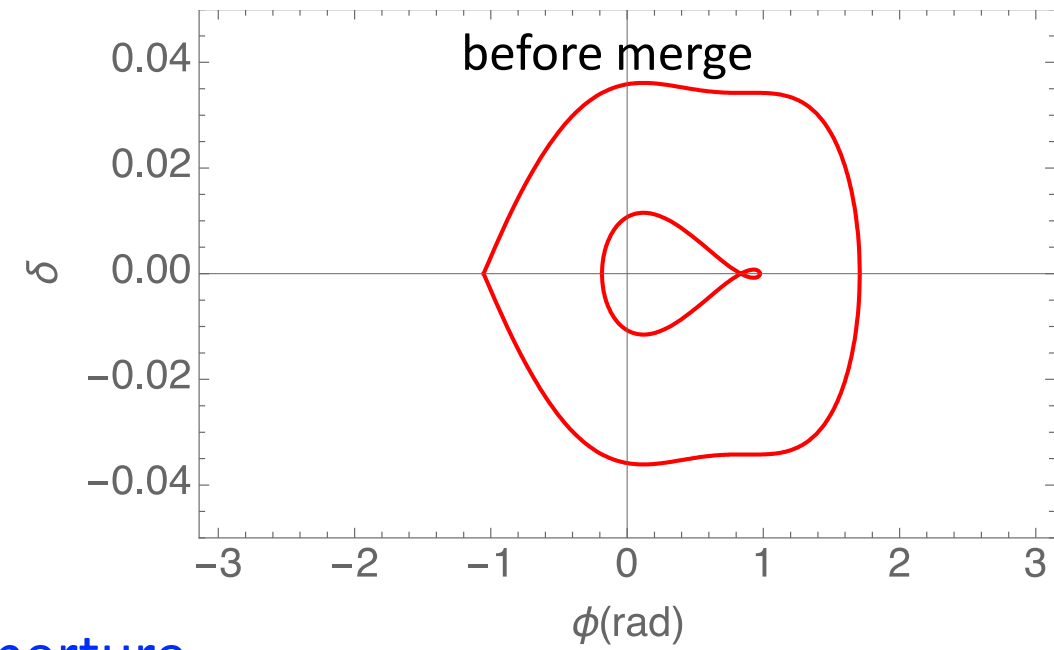


A complete injection cycle



Beam physics issues





Requirements on dynamic aperture

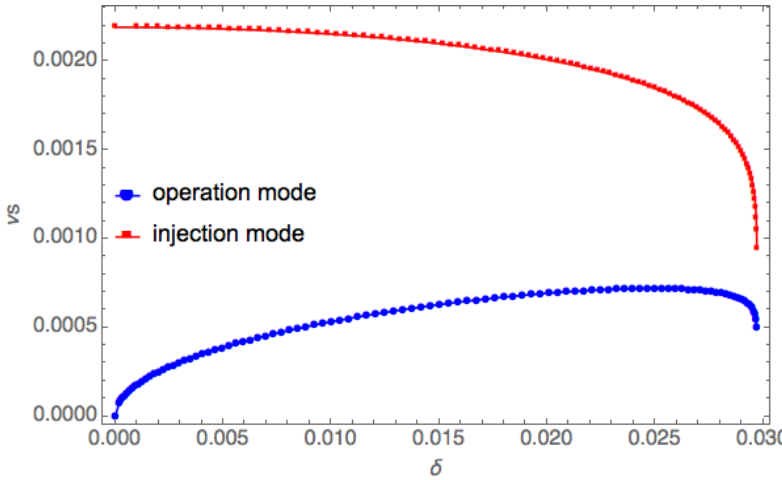
- ~ 2 mm on-momentum dynamic aperture at injection
- ~ 1 mm off-momentum (δ ~ 1%) dynamic aperture before merge

Collective instability for 60-bunch high charge filling pattern

- Simulation shows 15 nC can be kept stable from TMCI w/ chromaticities = 5, for bunch length = 30 mm & 3 mm
- Yet to evaluate the merging process
- Coupled to beam-cavity interation?

Physics and technical challenges

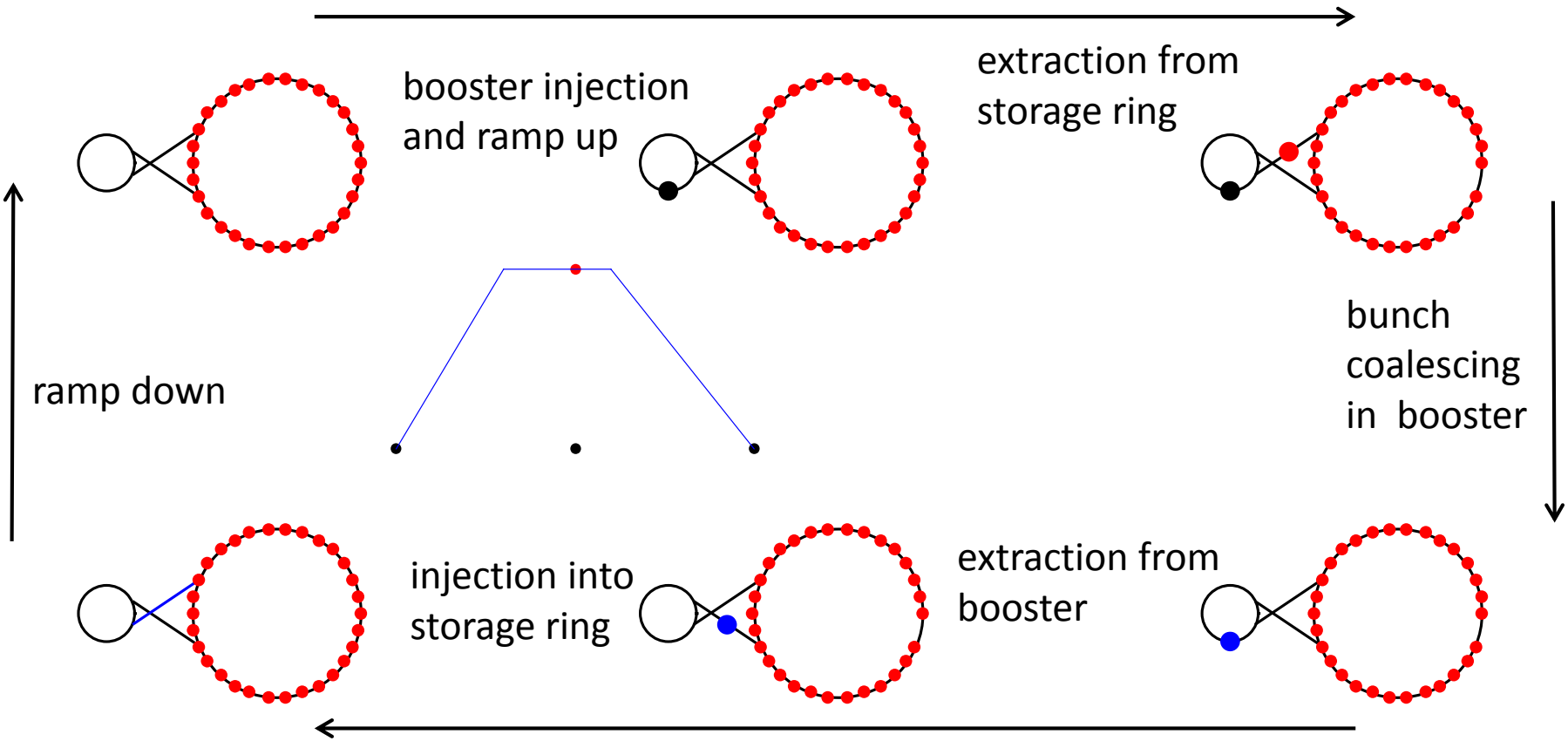
- RF fast & frequent ramping
  - Complexity in beam-cavity interation?
  - Complexity in LLRF design?
  - Robustness in operation?
- Adaptation to ID gap & U0 change
- Bunch-by-bunch feedback
  - Varying synchrtron tune
  - injected bunch with phase offset



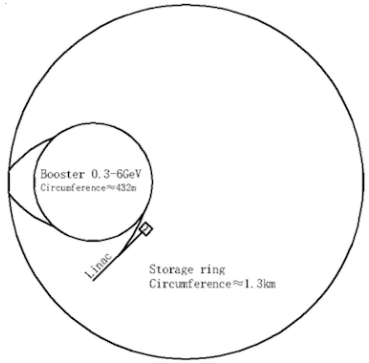
Swap-out injection

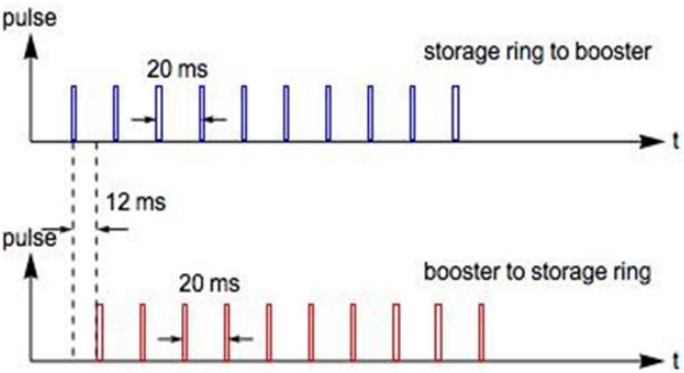
Swap-out scheme for HEPS

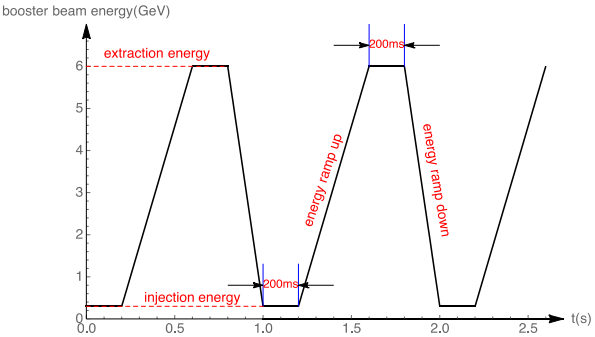
booster in effect is used also as an accumulator @ 6 GeV



Multiple bunches in booster







mode		A	B
	booster bunch number	2	10
	single bunch charge@300MeV	2nC	0.5nC
	beam total current/charge @300MeV	2.6mA / 4nC	3.3mA / 5nC
	beam maximum total current/charge@6GeV	12mA / 18nC	13mA / 20nC
	storage ring injection time 0 - 200 mA (680bunches)*	340s	272s
	storage ring injection time 0 - 200mA(63 bunches)*	315s	246s
储存环Top-up注入 (680bunches)	booster cycles	7	2
	required time	7s	2s
储存环Top-up注入 (63bunches)	booster cycles	1	1
	required time	~ 100ms	~ 100ms

- Single bunch charge ~ 2 nC @ 300 MeV
- Beam current ~ 15 mA, single bunch charge ~ 15 nC @ 6 GeV

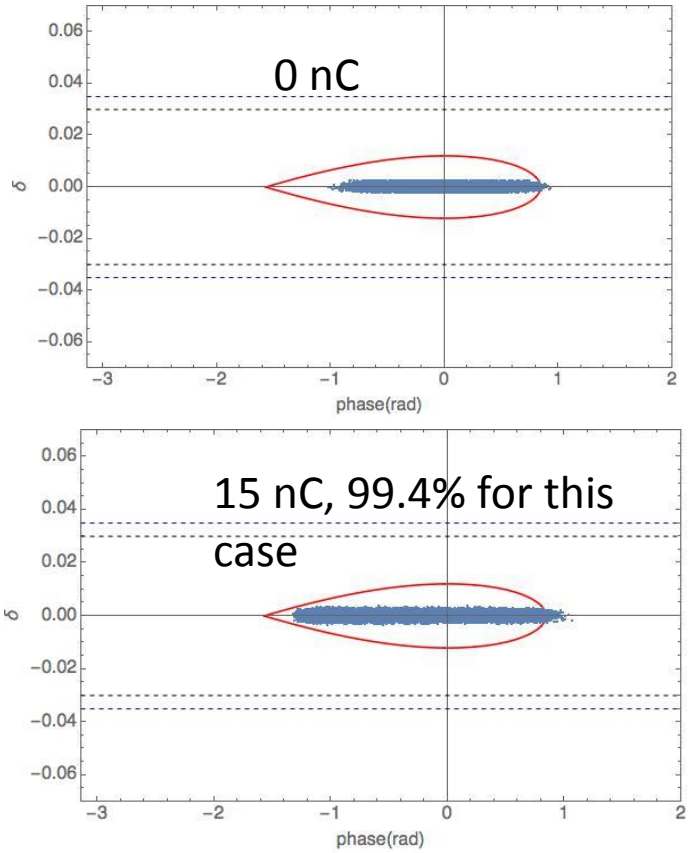
Well within instability threshold with current impedance budget.

Pros, extra hardware & concerns

- Pros
  - Relax the bunch charge requirement in the linac & booster accelerator, 2 nC rather than 15 nC
  - No need for extra accumulator ring
- Extra hardware
  - ring-to-booster transport line
  - injection system in booster @ 6 GeV
- Concerns
  - Overall injection efficiency? Three injection/extraction systems.
  - Beam current-related issues in high single charge operation?
  - Injection transient: ~1.5% beam current drop for ~ 15 ms in 60-bunch mode

Longitudinal phase space mismatch

parameter	booster (new)	storage ring (old)
RF system	500 MHz RF 6.5 MV	166 MHz + 500 MHz
harmonic number	756	756/2268
U0	4.594 MeV/turn	2 MeV/turn
rms energy spread	1.35 e-3	7.97e-4
rms bunch length @ 6 GeV	0.01 m	0.032 m
momentum compaction factor	9.5e-4	3.7e-5
bucket height	1.2%	3%



- Better capture favors lower U0 and higher Vrf.
- Uncerntainty lies in the turbulent behavoir of the 15 nC bunch in longitudinal phase space, might leads to injection efficiency jitter in the injection to booster.
- Injection simulation w/ impedance into the ring is under way, following APS-U experiences

Summary

Summary

- Extensive studies of longitudinal injection w/ RF manipulation, physics and technical challenges have been identified.
- Swap-out scheme with booster as a high energy accumulator looks promising, detailed studies are under way.
- Recently, XU Gang has proposed a novel triple RF longitudinal injection scheme, to be presented on Tuesday.
- At the moment, HEPS seeks a compatible design for swap-out & longitudinal injection, extensive R&D on both directions
  - extra ring-to-booster transfer line + injection system in booster @ 6 GeV
  - vertical injection & extraction in storage ring, stripline kicker + Lambertson
  - injection kicker system: 6 ns kicker pulse full width, 10 300 mm-long stripline kicker
  - extraction kicker system: 12 ns kicker pulse full width, 4 750 mm-long stripline kicker

Thank you for your attention!

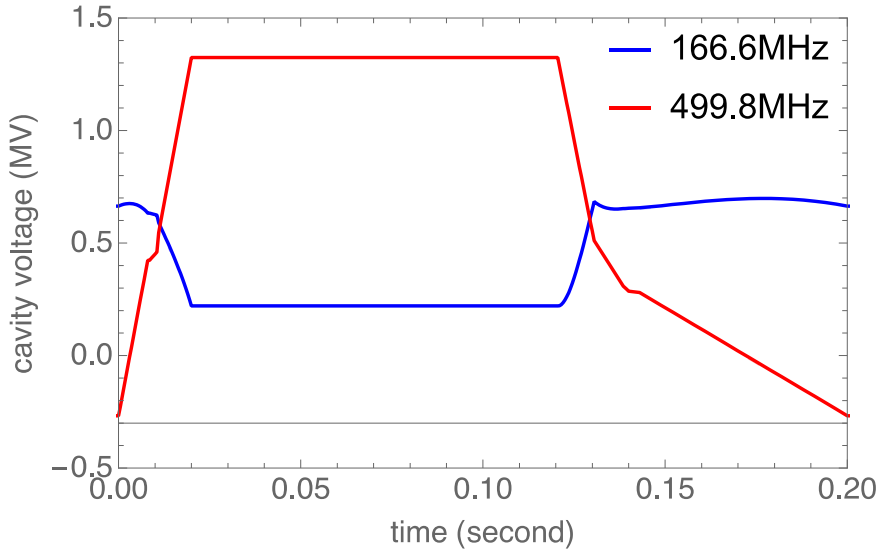
Backup

Injection efficiency?

- Booster dynamic aperture large enough to accommodate off-axis injection & extraction @ 6 GeV.
- Swap-out a 15 nC bunch in top-up mode @ 0.2% beam current stability,

RF parameters in a complete injection period

- Four **166.6** MHz fundamental cavities and two **499.8** MHz 3rd harmonic cavities for HEPS nominal design.
- Assume cavities of the same frequency share the same voltage and phase settings.



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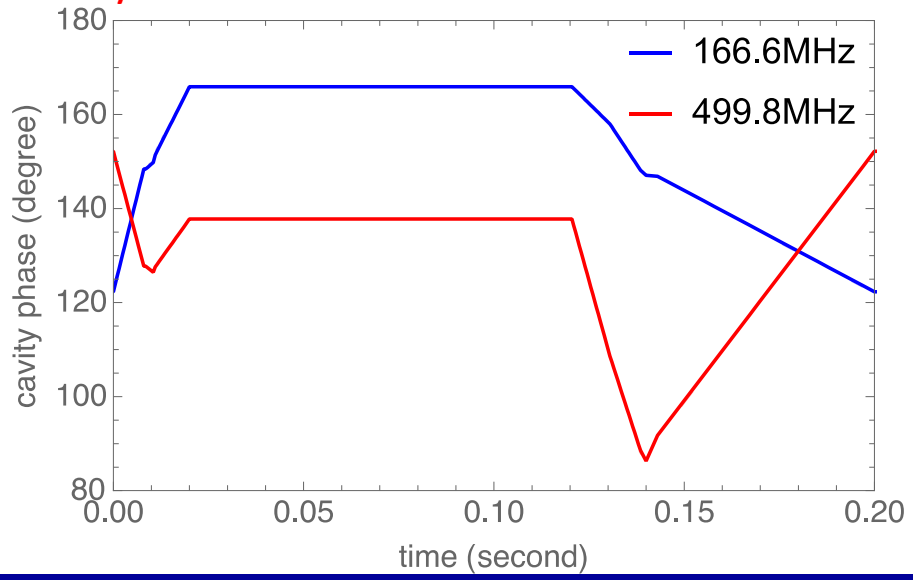
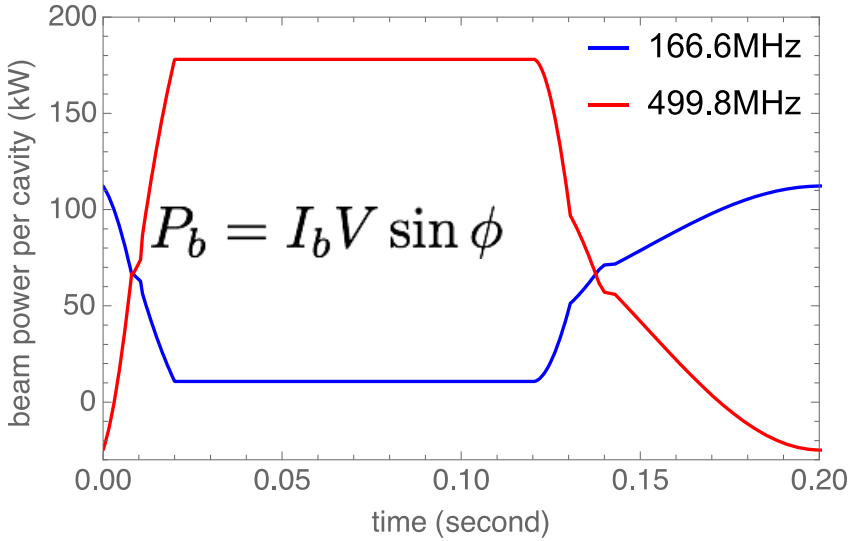
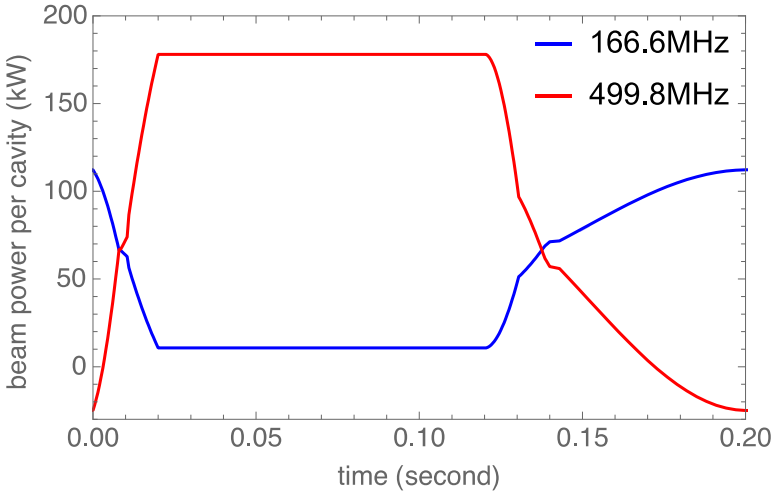




Choice of optimal cavity parameters

Parameter	Fundamental RF Cavity (4 cavities)	3rd Harmonic RF Cavity (2 cavities)
frequency(MHz)	166.6	499.8
Q0	5e8	1e9
R/Q	135.8	93.5
Max beam power per cavity P_{beam}(kW)	112.2	178.0
β	17293.4	9490.9
QL	28912.8	105364.
cavity filling time(μs)	55	67
optimal tuning angle ψ (degree)	-32.29	-47.77



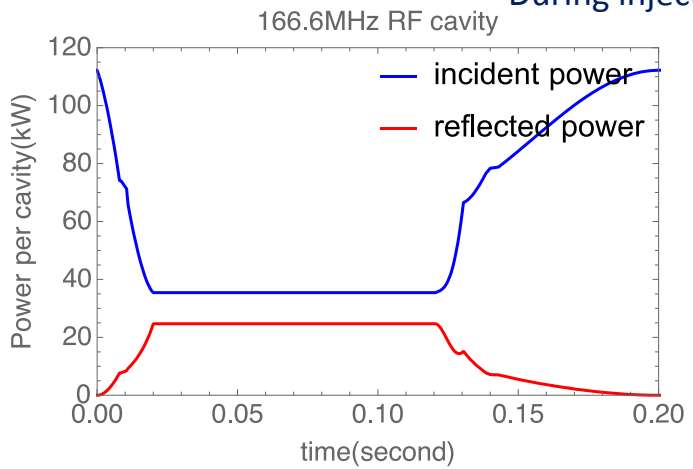
β, Q_L and tuning angle ψ are set so that no power reflection when maximum beam power is required for each cavity.

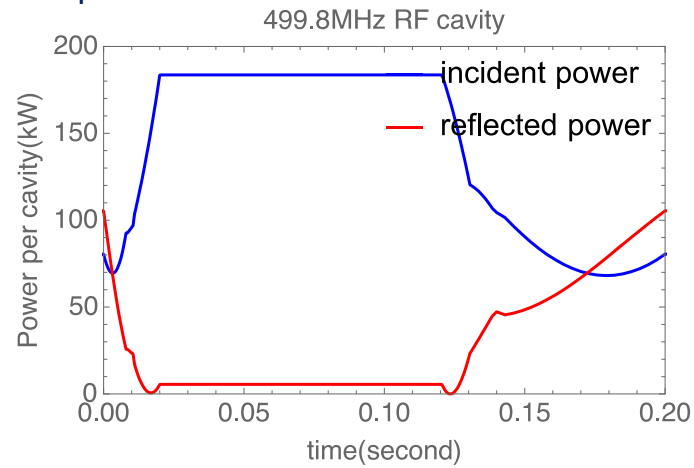
$$P_c = \frac{V^2}{2R_s}$$

$$\beta = \frac{P_{\text{beam}}}{P_c}$$

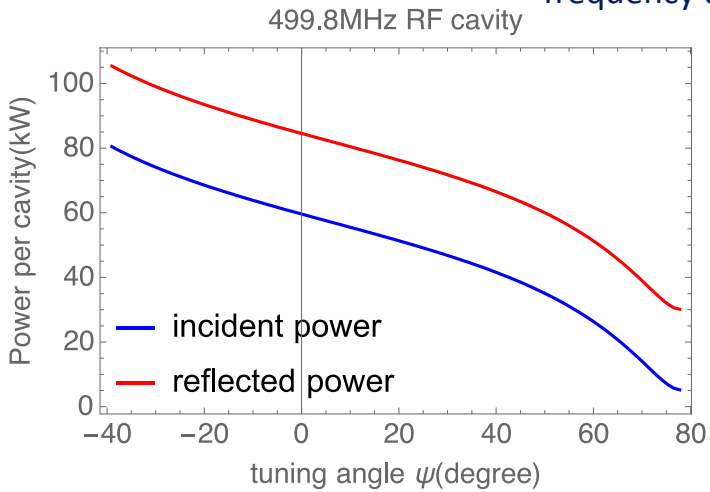
Strategy of RF parameter manipulation

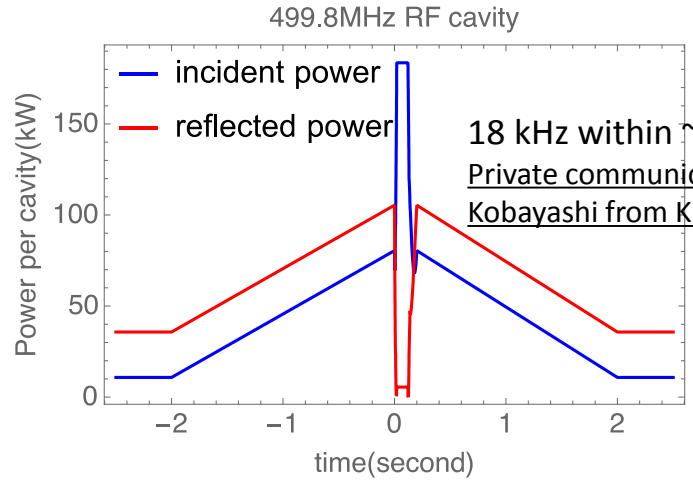
During injection, frequency is kept fixed.





frequency adjustment before and after injection.





18 kHz within ~ 2 seconds,
Private communication with T. Kobayashi from KEK.

Conclusion: this strategy satisfies the required fast RF parameter ramping.