HEPS Top-up injection schemes

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On behalf of HEPS accelerator physics group

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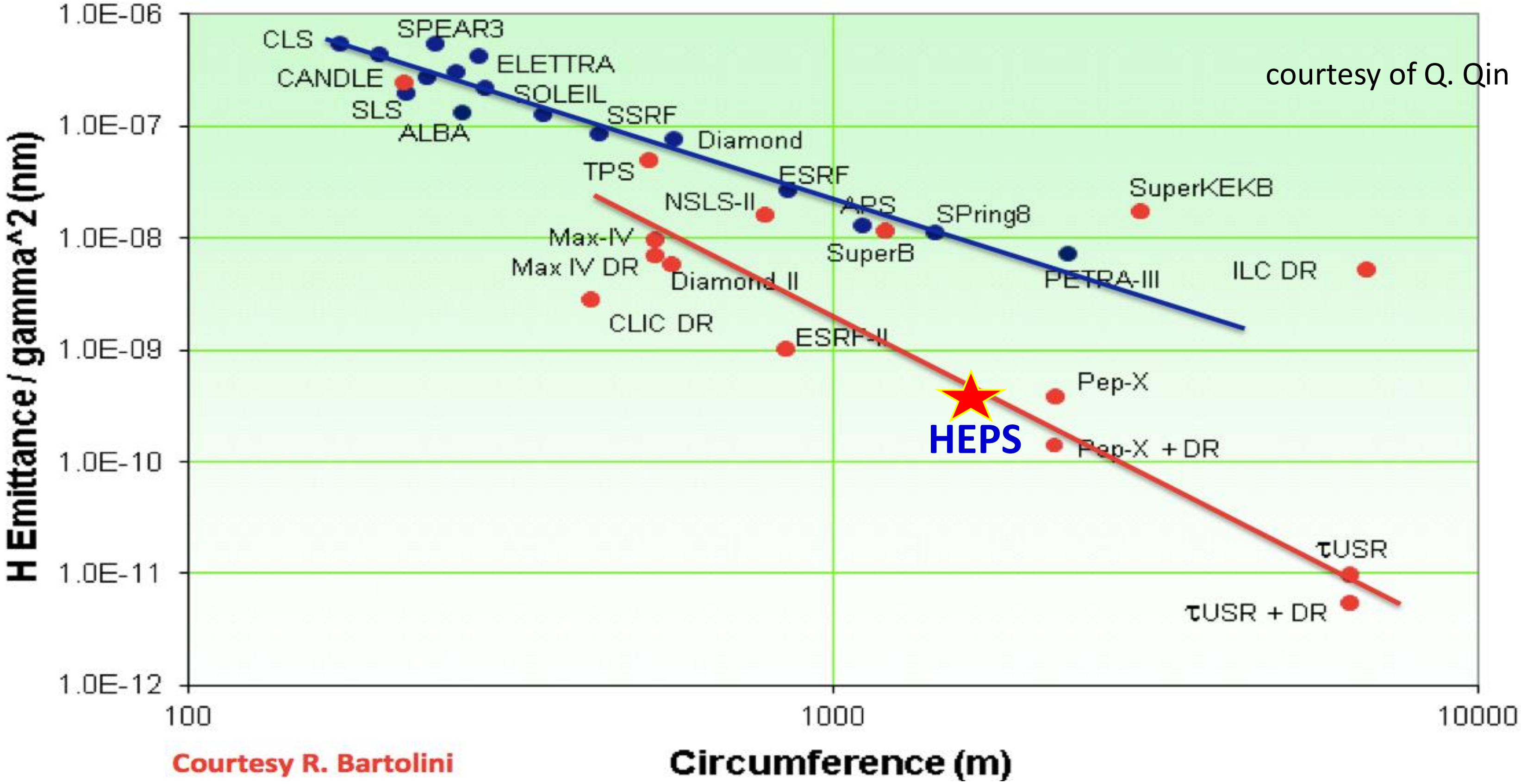
SSRF: B. C. Jiang, S. Q. Tian, and Z. T. Zhao
SLAC: A. W. Chao
Jlab: R. Rimmer
KEK: T. Kobayashi
BNL: M. Blaskiewicz

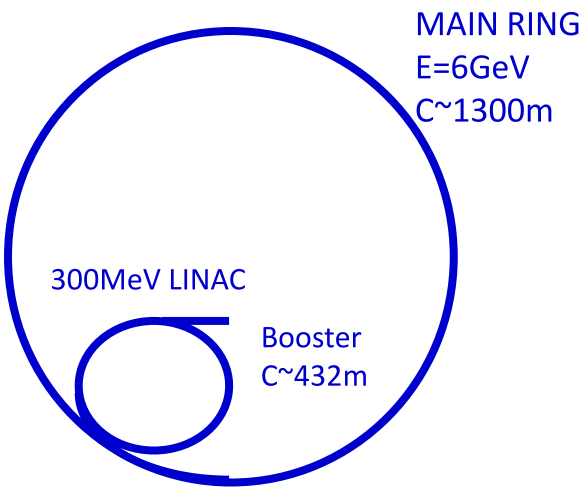
The High Energy Photon Source (HEPS)

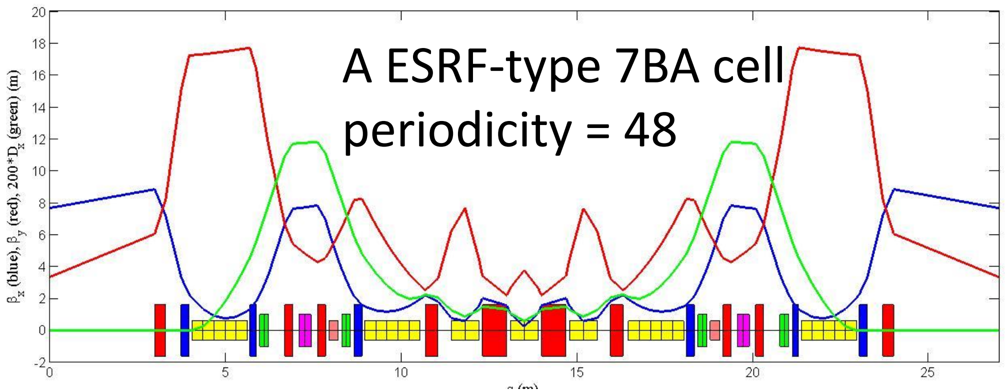


Design goal:

6 GeV, 1300 m, 200 mA beam current, 50 ~ 100 pm natural emittance

HEPS nominal design & parameters





References:
G. Xu, et al., Proc. IPAC 2016, pp. 2886–2888.
Y. Jiao, Chin. Phys. C, 40 (7): 077002.
Y. Jiao and G. Xu, arXiv:1605.05021.

U0 = 2.5 MeV, w/ insertion devices in the first phase.

Table 1: HEPS lattice parameters

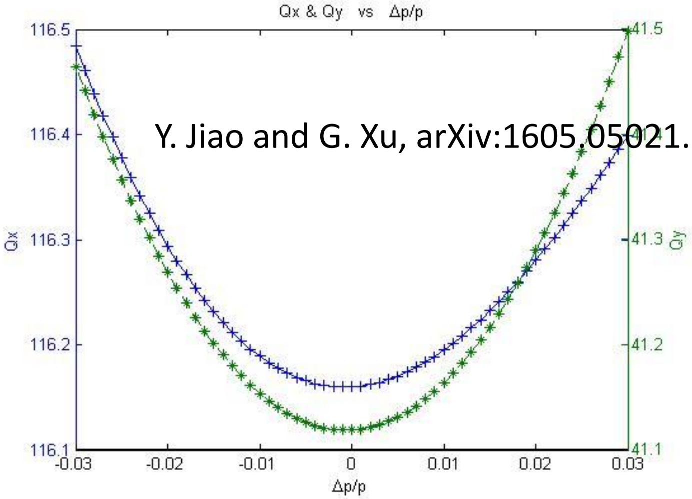
Parameters	Values
Energy E_0	6 GeV
Beam current I_0	200 mA
Circumference	1295.6 m
Natural emittance ε_{x0}	59.4 pm.rad
Working point υ_x/υ_y	116.16/41.12
Natural chromaticities (H/V)	-214/-133
No. of superperiods	48
ID section length L_{ID}	6 m
Beta functions at ID sect. (H/V)	9/3.2 m
Energy loss per turn	1.995 MeV
Rms energy spread	7.97×10^{-4}
Momentum compaction	3.74×10^{-5}

Ring acceptance & injection schemes

Linear & nonlinear aspects are optimized via MOGA & MOPSO algorithms, the achieved dynamic aperture is insufficient for off-axis injection, but should be fine for on-axis injection schemes:

- Swap-out   L. Emery and M. Borland, in Proc. PAC'03, pp. 256-258.
- Longitudinal injection M. Aiba, *et al.*, PRSTAB, 18, p. 020701, 2016.
- Double RF voltage adjustment B. C. Jiang, *et al.*, NIM A 814, 1, 2016.

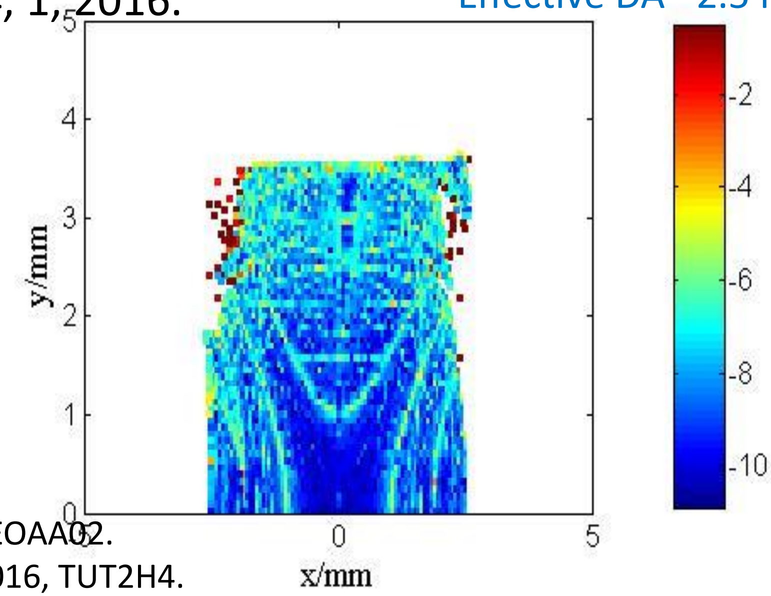
half integer resonance reached at δ = ±3%.

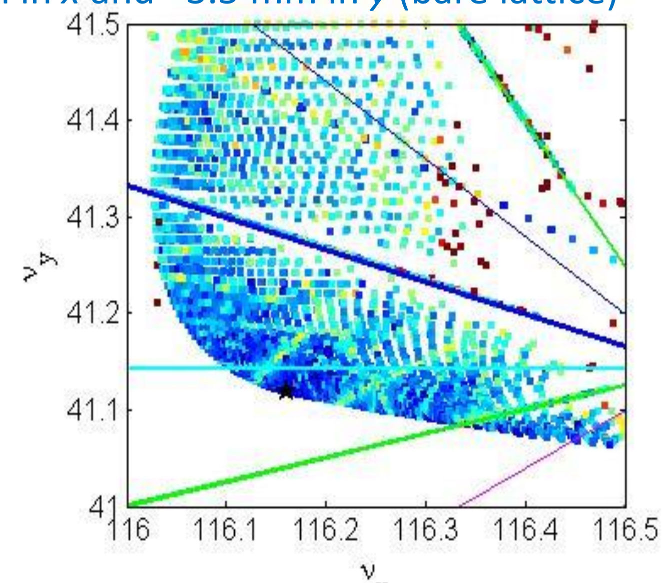


Y. Jiao and G. Xu, arXiv:1605.05021.

Effective DA ~2.5 mm in *x* and ~3.5 mm in *y* (bare lattice)

We proposed an alternative on-axis injection scheme based on a double-RF system





G. Xu el al., IPAC'16, WEOAA02.

Z. Duan el al., eeFACT2016, TUT2H4.

Longitudinal dynamics of a double-RF system

$$H(\phi,\delta;t)=\frac{h_f\omega_0\eta}{2}\delta^2+\frac{e\omega_0}{\pi E_b\beta^2}\left[\sum_{i=1}^{N_f}V_f^i\cos(\phi+\phi_f^i)+\frac{h_f}{h_h}\sum_{j=1}^{N_h}V_h^j\cos(\frac{h_h}{h_f}*\phi+\phi_h^j)+\phi\frac{U_0}{e}\right]$$

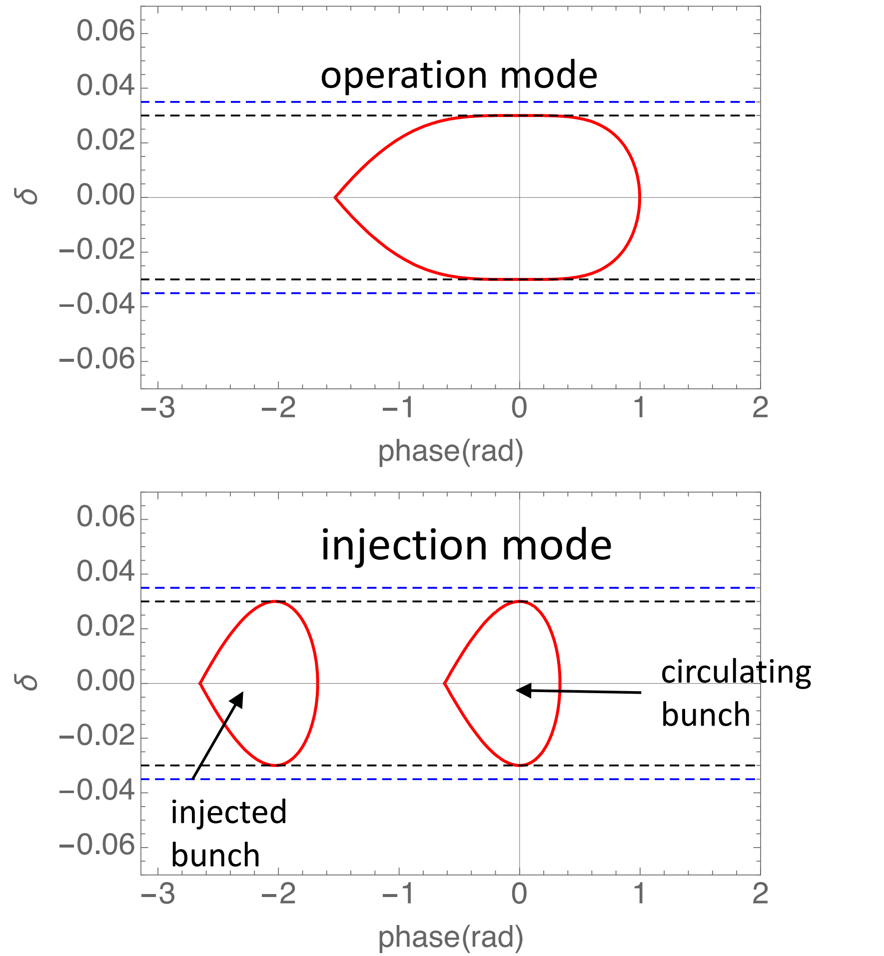
- Fundamental RF system: 166.6MHz, Nf=4
- 3rd harmonic RF system: 499.8MHz, Nh=2
- Same settings for cavities with the same frequency

$$V_f=4V_f^i,\phi_f=\phi_f^i,V_h=2V_h^i,\phi_h=\phi_h^i$$

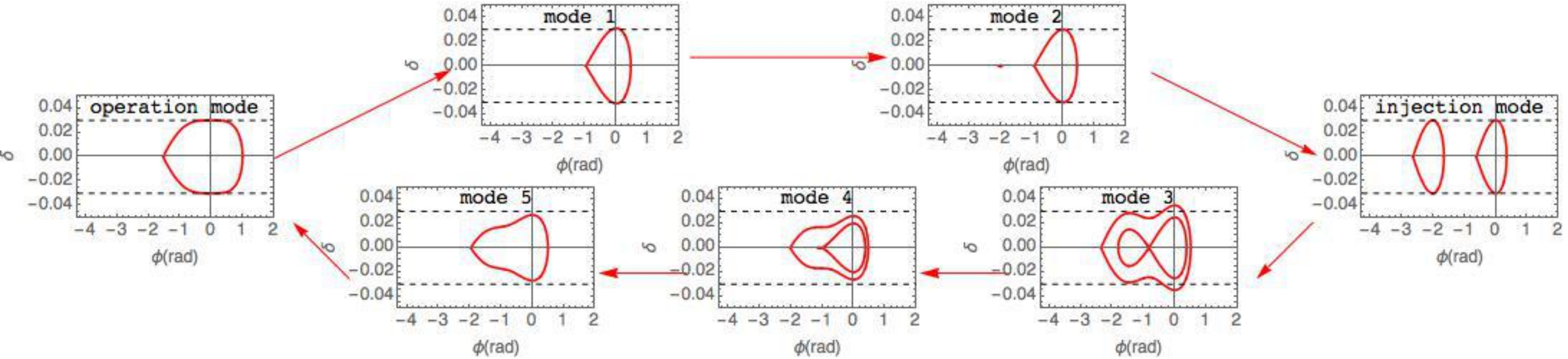
- 4 free variables (V_f, φ_f, V_h, φ_h)
- One constraint to fix longitudinal phase of circulating beam relative to the cavities

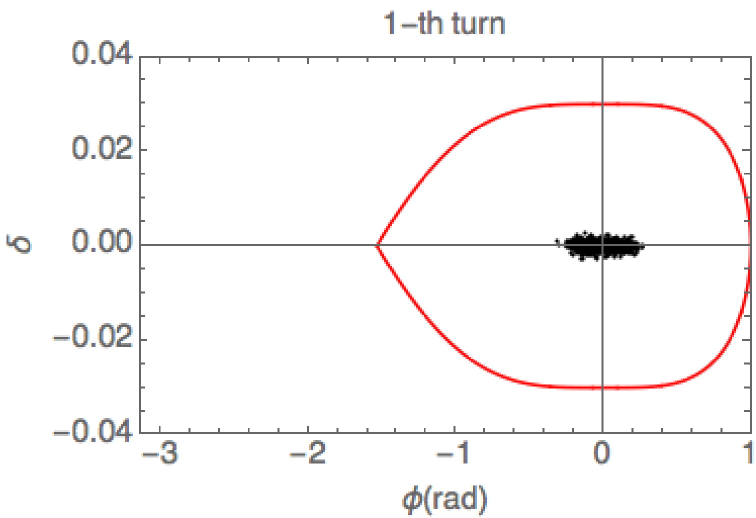
$$V_f\sin\phi_f+V_h\sin\phi_h=U0$$

- Longitudinal dynamics can be solved to achieve required RF acceptance, in particular, evolution between operation and injection modes.



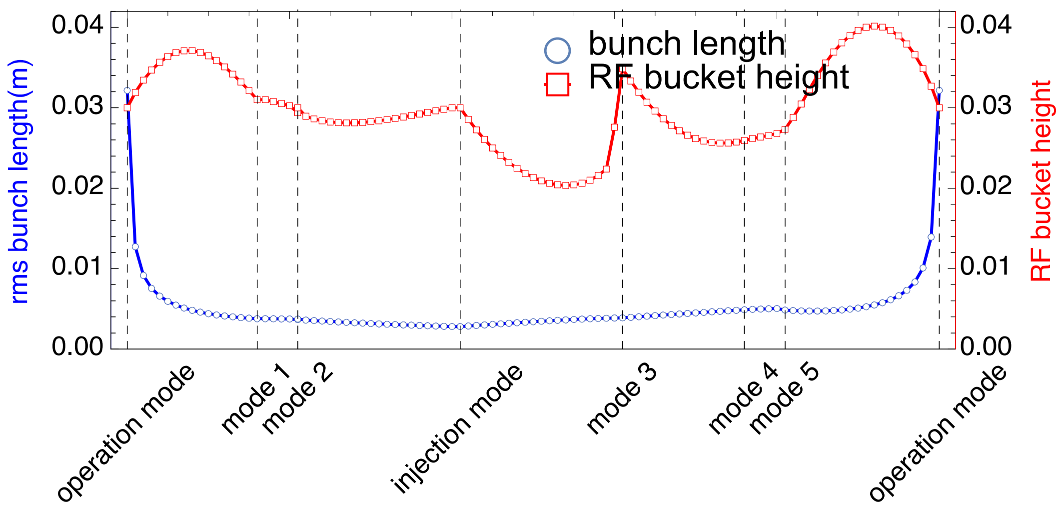
A complete injection period





- An injection period takes about 200ms
  - Operation to injection: 20ms ~ 1 damping time
  - Injection Process: 100ms
  - Injection to mode 5: 20ms ~ 1 damping time
  - mode5 to operation mode : 60 ms ~ 3 damping time
- Injection process could be longer allowing multi-turn injection
- 20ms is only a tentative choice, could be shorter if RF system permits.

Evolution of beam parameters



200 mA, 648 bunches, IBS effect via SAD

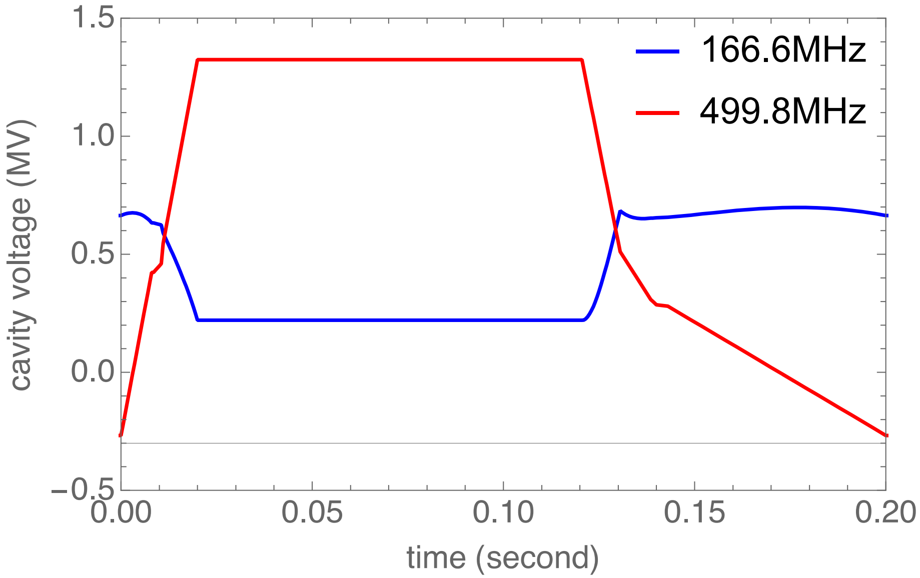
- Since an injection period takes ~ 200ms, beam lifetime reduction is not a big issue.
- Bunch length is as low as 2.8mm at injection mode w/o IBS.
- IBS induced beam parameter change might be an issue.
- Collective instability might be an issue too (under study).

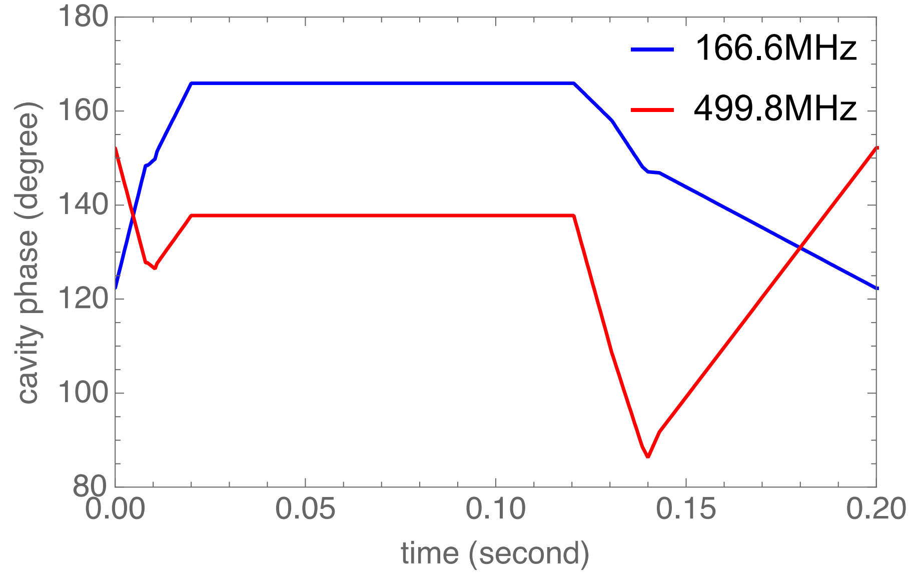
Cases	w/o IBS	injection mode	operation mode
ex (pm)	59.32	70.18	60.47
ey (pm)	5.96	6.91	6.06
ey / ex (%)	10.04	9.85	10.02
bunch length(mm)	2.8 / 32.0	3.01	33.03
energy spread (1e-4)	7.96	8.57	8.03

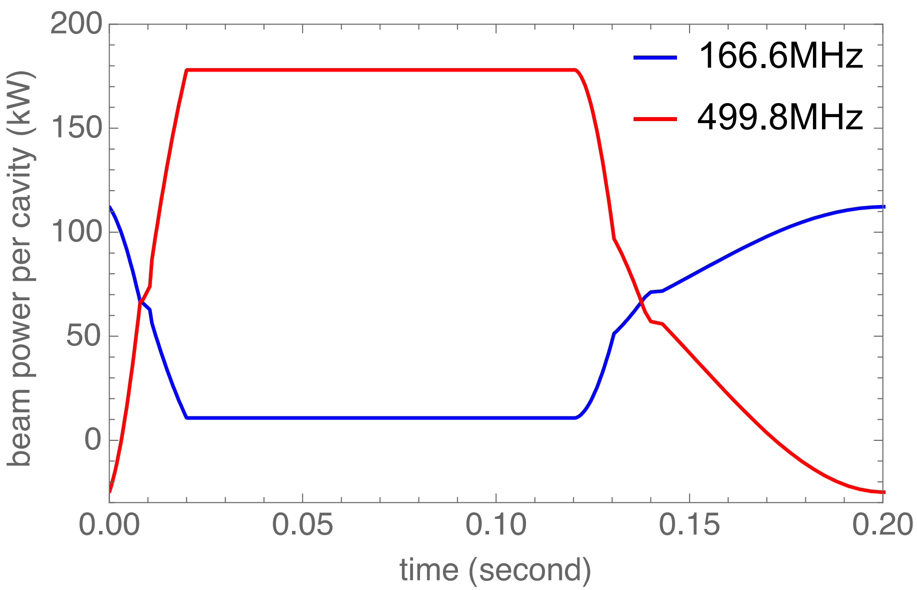
+ 8% σx
+ 6% σy
+

Impact to user experiments is being evaluated. Gate signal can be sent to users during injection.

RF parameters in a complete injection period







- The cavity phase adopts phasor convention

$$V_c \sin \phi_s = V_c \cos \phi$$

- Beam power per cavity is calculated via:

$$P_b = I_b V_c \cos \phi \quad I_b = 200\text{mA}$$

- What about beam loading effects?

Beam loading effects

- $(V_f, \varphi_f, V_h, \varphi_h)$ are combination of generator voltages and phases, with beam-induced voltages and phases.
- Cavity coupling β and tuning angle should be optimized to reduce power reflection and thus required generator power.

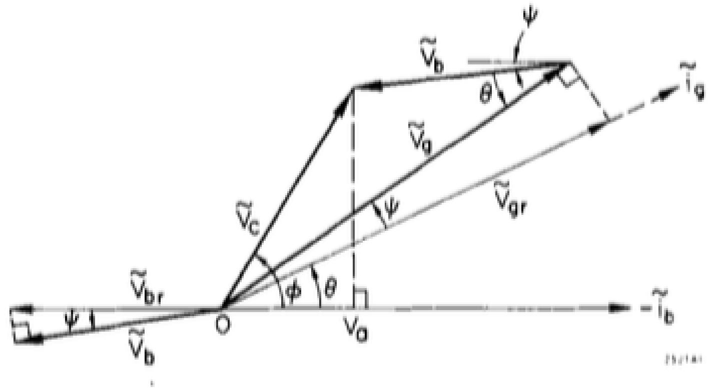
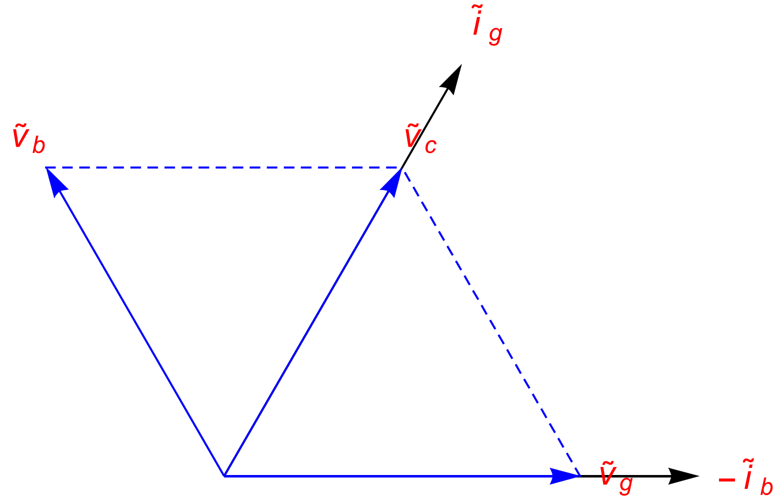
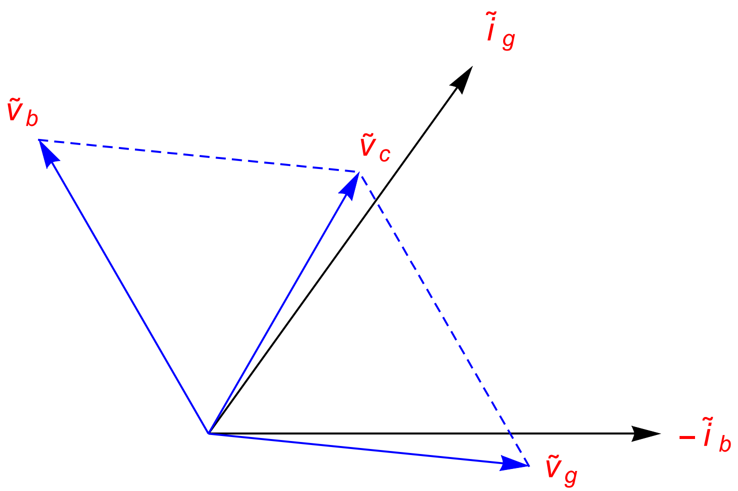


Fig. 3.13. Diagram showing the vector addition of generator and beam-loading voltages in an RF cavity.



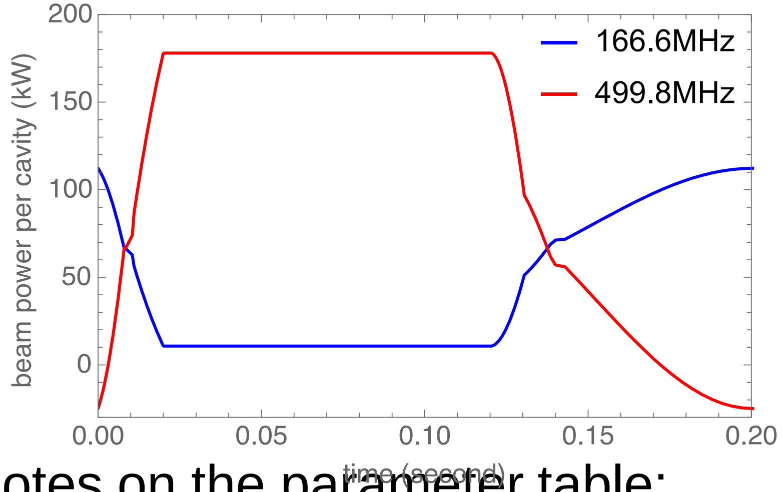
optimal β and tuning angle



optimal tuning angle but not optimal β

RF parameter table

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
Cavity Voltage at maximum beam power V (MV)	0.66	1.32
β	17293.4	9490.9
QL	28912.8	105364.
cavity filling time(μs)	55	67
optimal tuning angle ψ (degree)	-32.29	-47.77



Notes on the parameter table:

- β, QL, tuning angle ψ, are calculated values, assuming optimal coupling at maximum beam power per cavity.
  - For fundamental RF cavities, this corresponds to the operation mode.
  - For 3rd harmonic RF cavities, this corresponds to the injection mode.

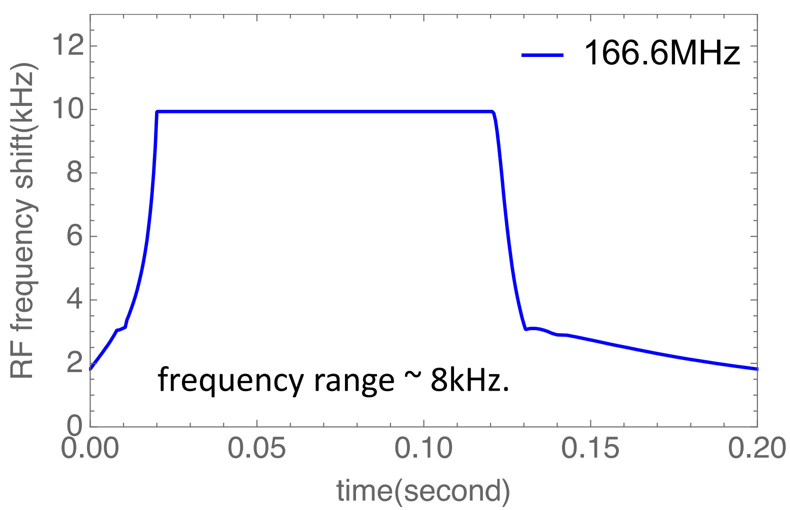
$$P_c = \frac{V^2}{2R_s}$$

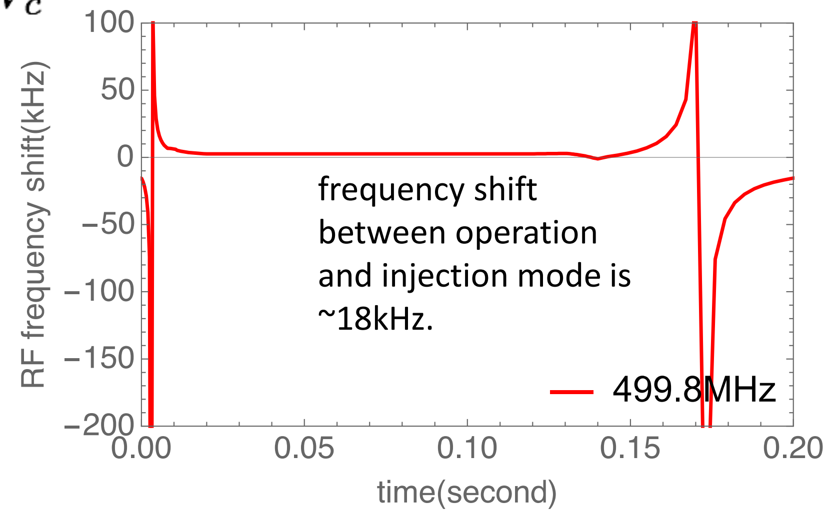
$$\beta = \frac{P_{\text{beam}}}{P_c}$$

RF control loop

- Time scales
  - cavity filling time (~ tens of μs)
  - amplitude and phase control loops response very fast, ~ tens of μs
  - frequency control loop
    - mechanical tuner: slow, ~ second
    - piezo: fast, <ms, limited dynamic range: BEPCII 500MHz cavity: ~6kHz
- In an injection period, required cavity frequency change exceed piezo range

$$\Delta f = -\frac{f_0(R/Q)I_0 \sin\phi}{2V_c}$$

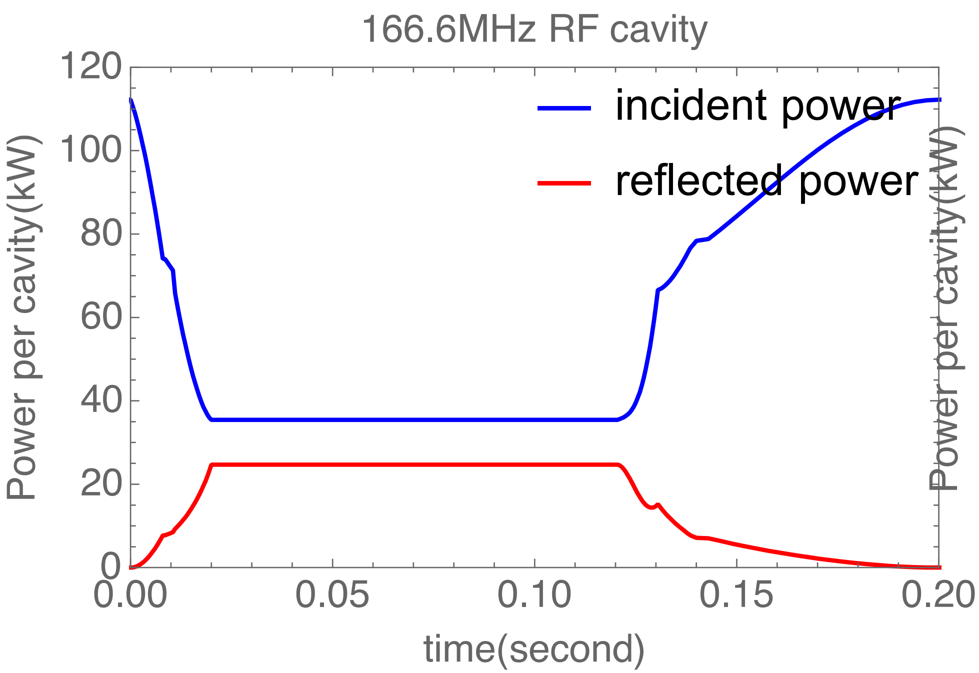


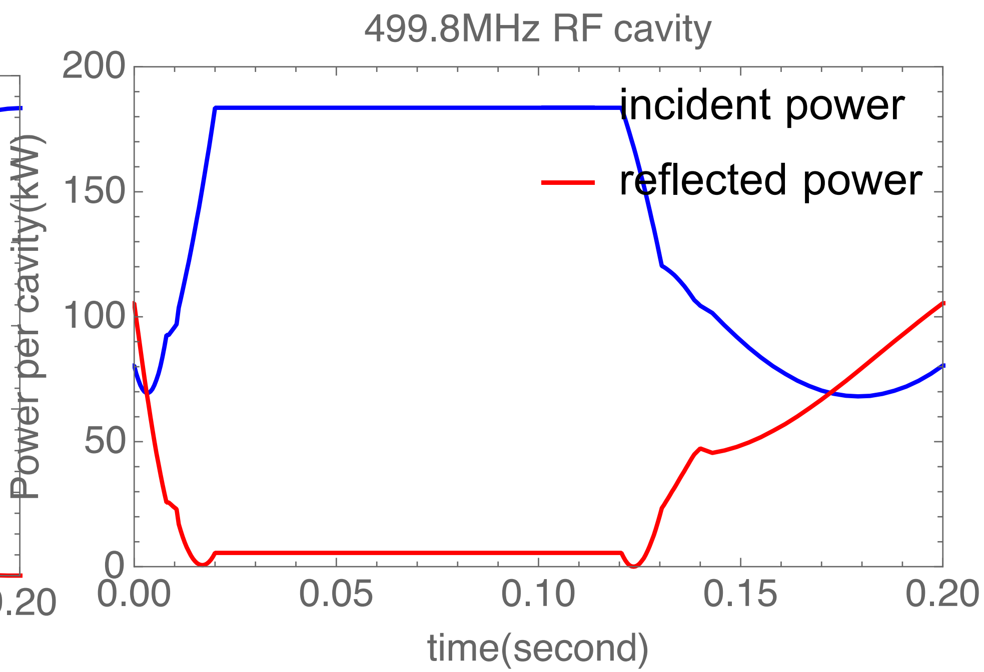


The RF power w/ fixed tuning angle during injection

Incident and reflected power in transmission line can be calculated with:

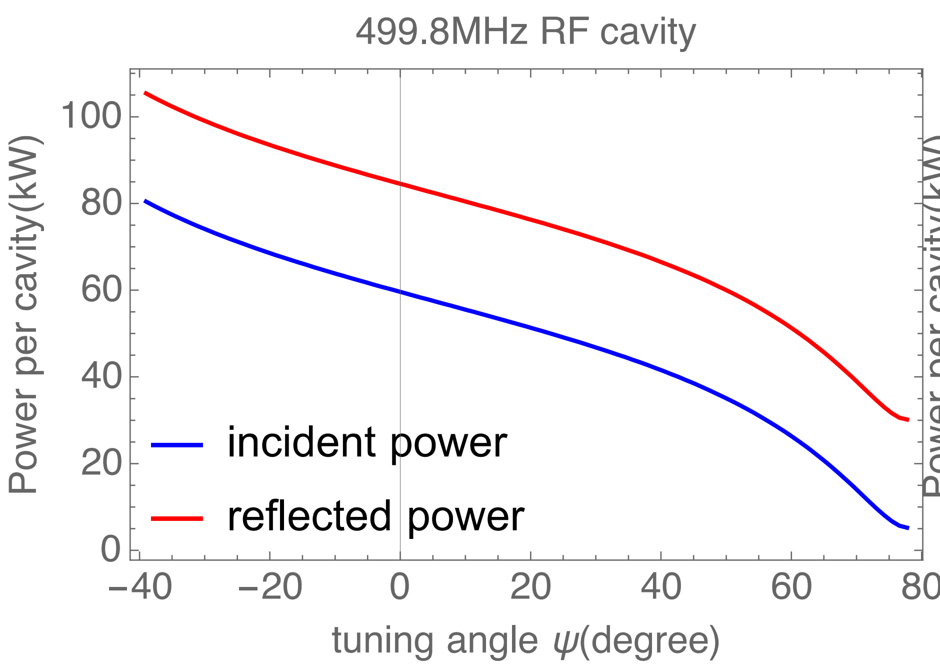
$$P_{\pm} = \frac{\beta V_c^2}{8R_s}[(1 + \frac{1}{\beta} + \frac{2R_s I_0}{\beta V_c}\cos\phi)^2 + (\tan\psi + \frac{2R_s I_0}{\beta V_c}\sin\phi)^2]$$

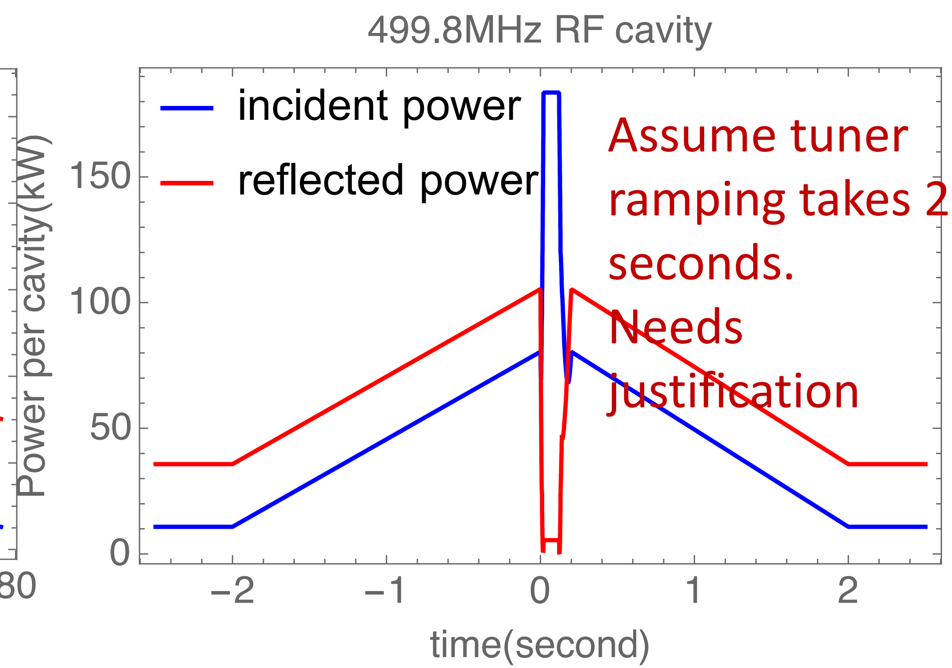




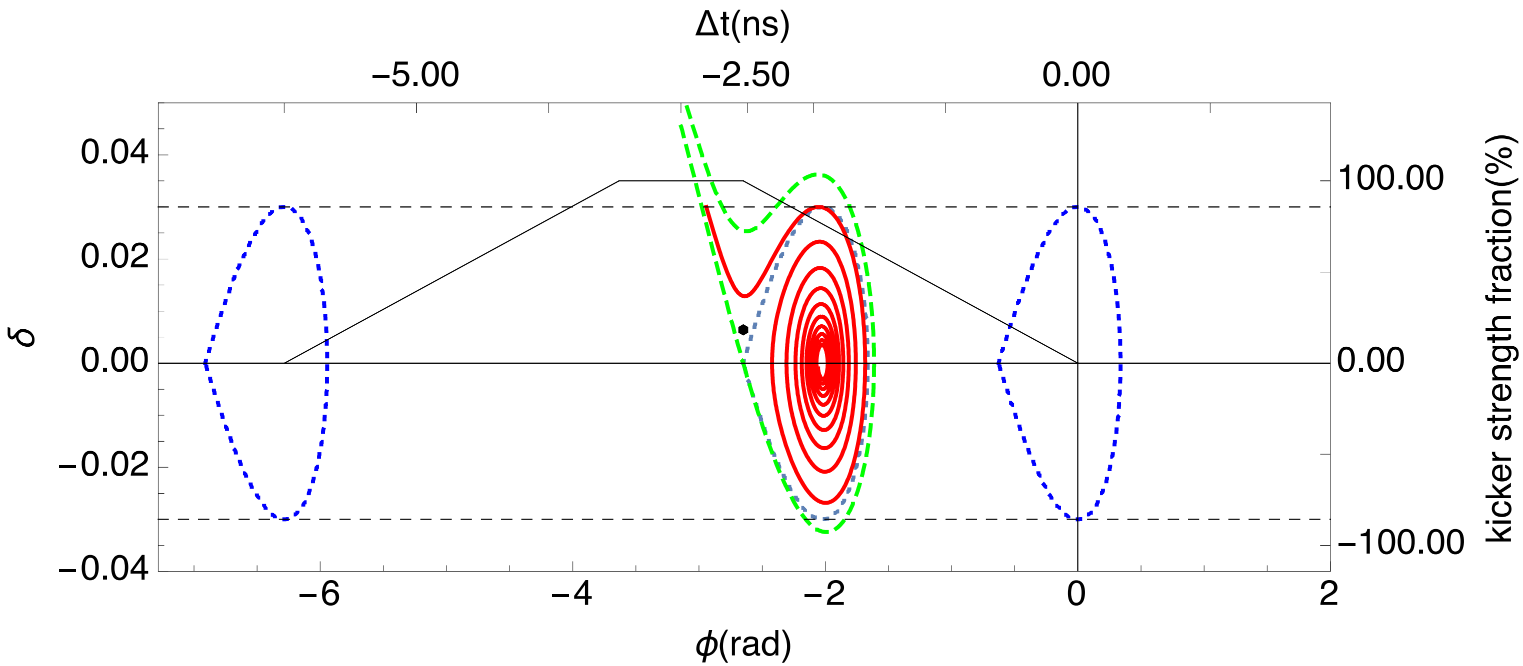
Discussion on RF control

- After injection, the **tuning angle** of harmonic cavities can be shifted from -47.8degree to 81.3 degree, with mechanical tuner, in seconds. As a result, the incident power per harmonic cavity can be reduced from 116kW, to 11.8kW.
  - Require RF amplitude and phase control to work together with frequency control, to keep the same Vc and ϕ.





Injection mode and requirements on kicker



Requirements on injection kicker system:

- Full pulse width < 6 ns
- pulse fall time < 2.5 ns

Current design: stripline kickers + high-voltage fast pulser

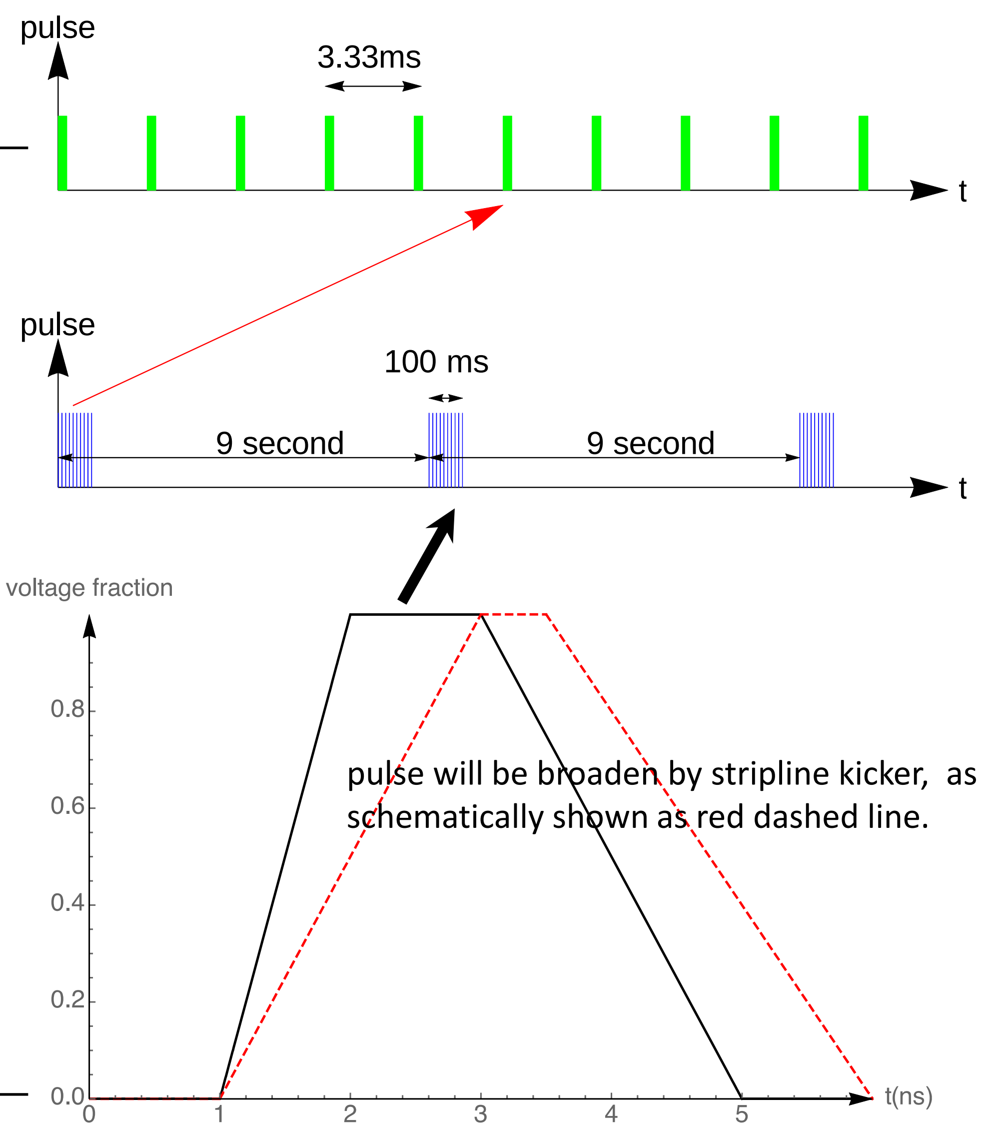
Reference:
B. I. Grishanov, *et al.*, “Very fast kicker with high repetition rate for accelerator applications”, *Nucl. Instrum. Meth. A*, vol. 396, pp. 28–34, Sep. 1997.
V. M. Efanov, *et al.*, in *Proc. IPPC’97*, pp. 988–991. FIDGmbH,http://www.fidtechnology.com

High voltage fast pulser by FID GmbH

Courtesy of Chen Jinhui

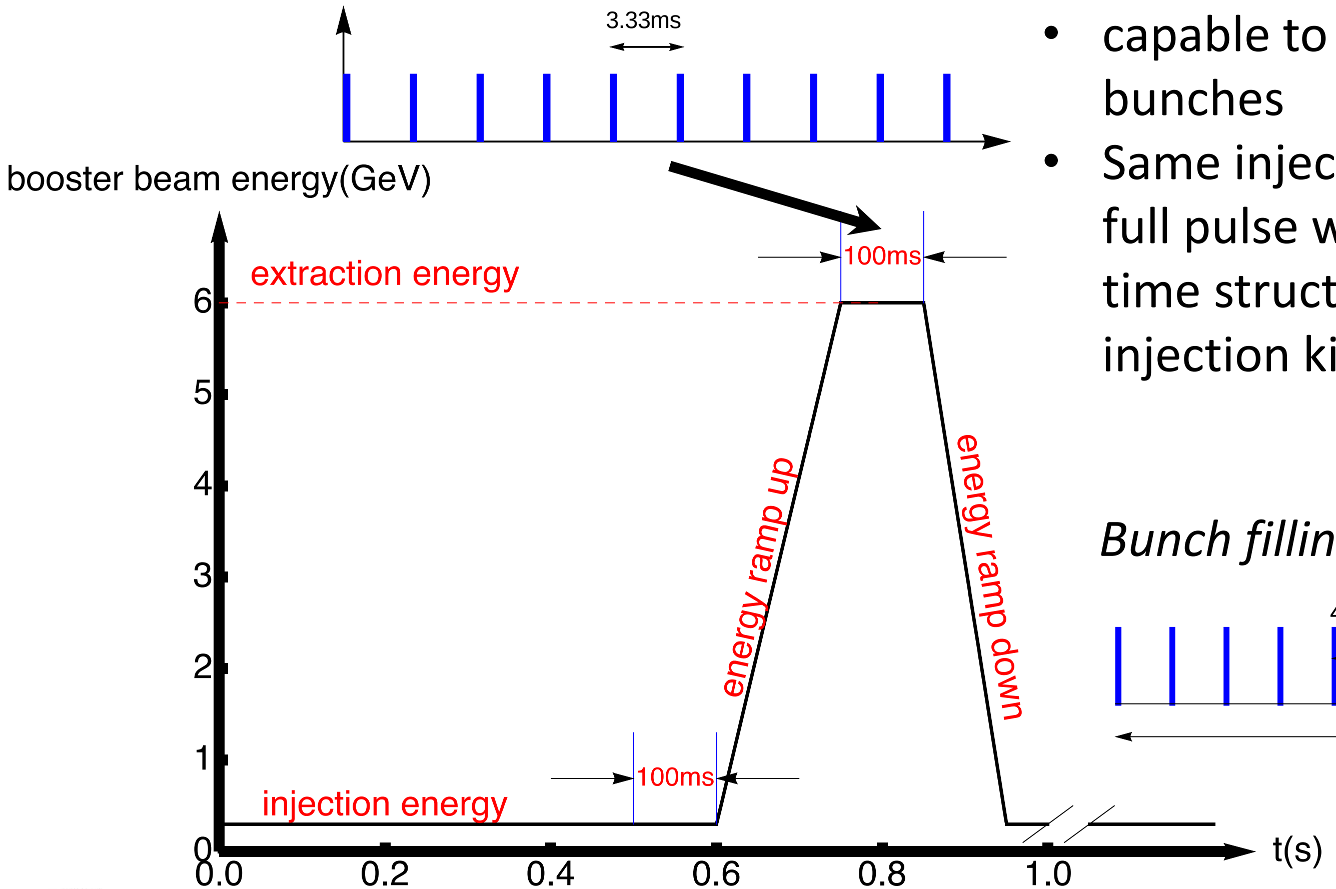
model FPG20-01MC2N4

Paramter	Value
Amplitude adjustment range	5~20kv
Amplitude stability	~1%
Rise time (5~95%)	<1ns
Fall time (95~5%)	<3ns
pulse flat-top (90%)	1~1.2ns
pulse duration at 5%	3~3.5ns(rectangle shaped pulse)
burst mode repitition rate	300Hz
macro-pulse length	2second / 100 ms
repetition rate of the macro-pulse	every 3min / 9 second

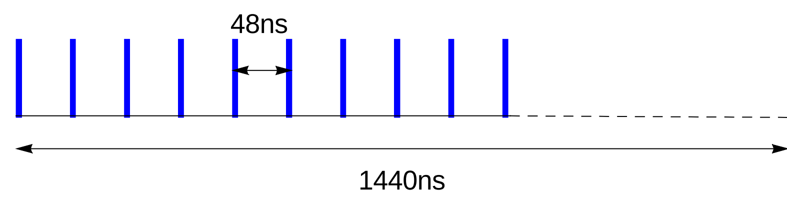


Injector specifications

- Linac
  - single bunch mode
  - repetition rate = 300 Hz
  - 2998 MHz or 2856 MHz
- Booster
  - 1/3 circumeference of main ring, 3 times larger RF frequency
  - capable of 2 Hz operation
  - capable to accommodate 30 bunches
  - Same injection & extraction kicker, full pulse width < 96 ns, similar time structure as main ring injection kicker.

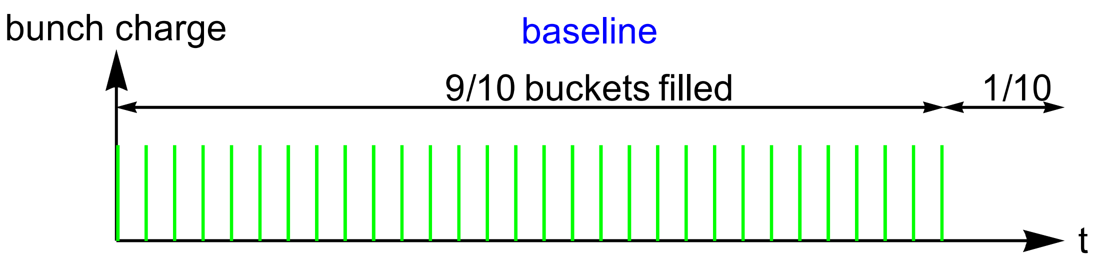


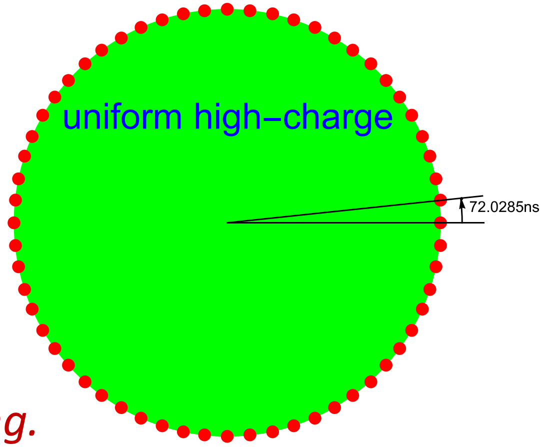
Bunch filling pattern in booster



Top-up considerations

Requirements: ~ 0.2 % beam current stability, beam current = 200mA





Preliminary estimation of beam lifetime w/ optimal lengthening.

parameters	648 bunches	60 bunches
charge	1.33 nC	14.4 nC
lifetime (during operation)	30 hours	3 hours
refill time	3.5 min	20 second
tentative injection shots in each refill	4	2
tentative bunch filled in each refill	30 * 4 = 120	30 * 2 = 60
injection time	200 ms *4	200 ms *2
total duration of each refill	9 s * 3 =27 s	9s * 1 = 9 s

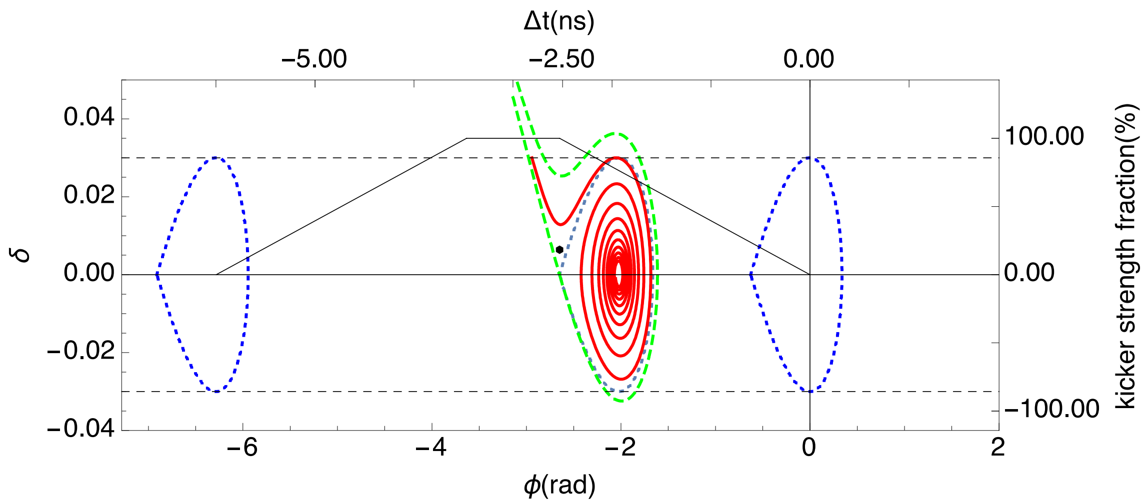
Summary

- Extensive studies have been done on various aspects of the longitudinal on-axis injection scheme with a double RF system.
- R&D on 166.6 MHz superconducting RF cavities & injection kickers are being done at IHEP.
- Underway study:
  - Simulation of dynamic aperture at the injection condition, based on which tolerances of injection errors will be analyzed.
  - Evaluation of possible collective effects with the very small bunch length during injection.
  - Estimate the impact of injection to user experiments.
- Swap-out injection scheme is also being considered.
- Alternative lattice design with high-beta insertions to accommodate off-axis pulsed-multipole injection scheme is also under way.

Thank you for your attention!

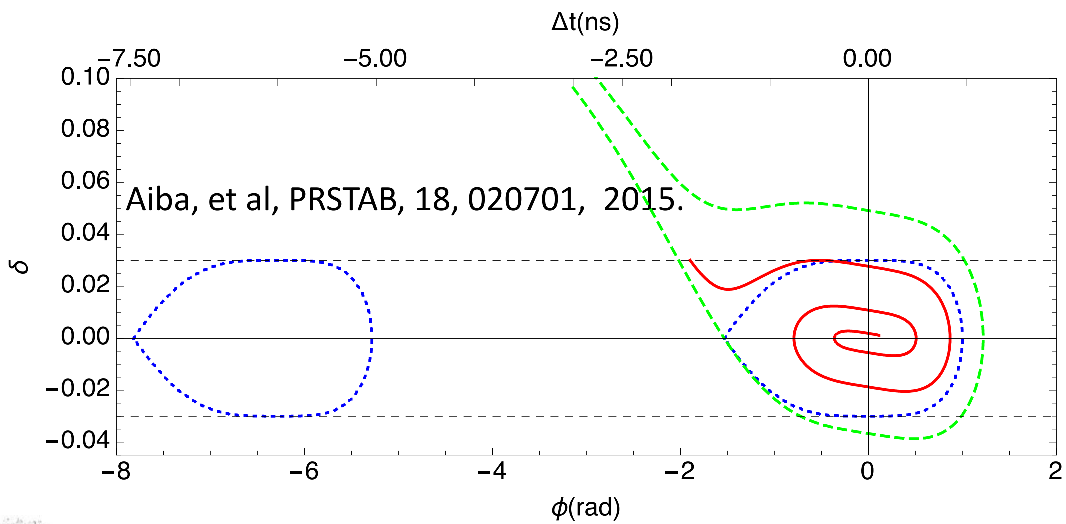
Backup

Injection mode compared to Aiba-san's scheme



Injection kicker:

- full pulse width < 6 ns
- pulse fall time < 2.5ns.



- Much smaller αc leads to more stringent requirements on MA.
- Or more stringent requirements on kicker pulse fall time -> more pieces of stripline kicker, Challenging!

RF parameters for different U0

U0 (MeV/turn)	RF bucket heights	166MHz peak power (kW)	166MHz peak voltage (MV)	500MHz peak power (kW)	500MHz peak voltage(MV)
2.0(w/o ID)	3%	112*4	0.7*4	178*2	1.4*2
2.0(w/o ID)	3.5%	112.5*4	0.7*4	155*2	1.2*2
2.5(ID in first stage)	3%	141*4	0.85*4	225*2	1.6*2
2.5(ID in first stage)	3.5%	141*4	0.85*4	196*2	1.4*2
3.0(ID in possible upgrade)	3%	169*4	1.0*4	275*2	1.9*2
3.0(ID in possible upgrade)	3.5%	169*4	1.0*4	256*2	1.8*2

For U0=2.5MeV/turn, RF bucket height=3.5%:

- peak reflected power of each 166MHz cavity =23kW
- peak reflected power of each 500MHz cavity=151kW, can be reduced to 39kW by optimal tuning after injection

SAD vs. ibsEmittance (injection mode)

Ib =200mA, 166.6 MHz cavity + 499.8 MHz cavity, 3% RF bucket height

Cases	w/o IBS	60 bunches w/ IBS		648 bunches w/ IBS	
Parameters		SAD	ibsEmittance	SAD	ibsEmittance
ex (pm)	59.32	111.26	117.98	70.18	69.77
ey (pm)	5.96	10.48	11.80	6.91	6.977
ey / ex (%)	10.04	9.42	10	9.85	10
bunch length(mm)	2.8	3.7	3.89	3.01	3.11
energy spread (1e-4)	7.96	10.55	11.06	8.57	8.84

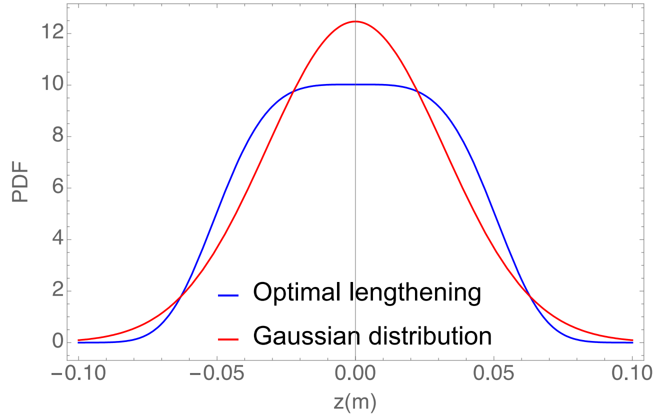
- In SAD, approximate with one 720MHz RF cavity to keep bunch length=2.8mm w/o IBS.
- The longitudinal distribution deviates from Gaussian a little, and it is good approximation to replace double RF with a single RF keeping the same bunch length.

SAD vs. ibsEmittance (operation mode)

Ib =200mA, 166.6 MHz cavity + 499.8 MHz cavity, 3% RF bucket height

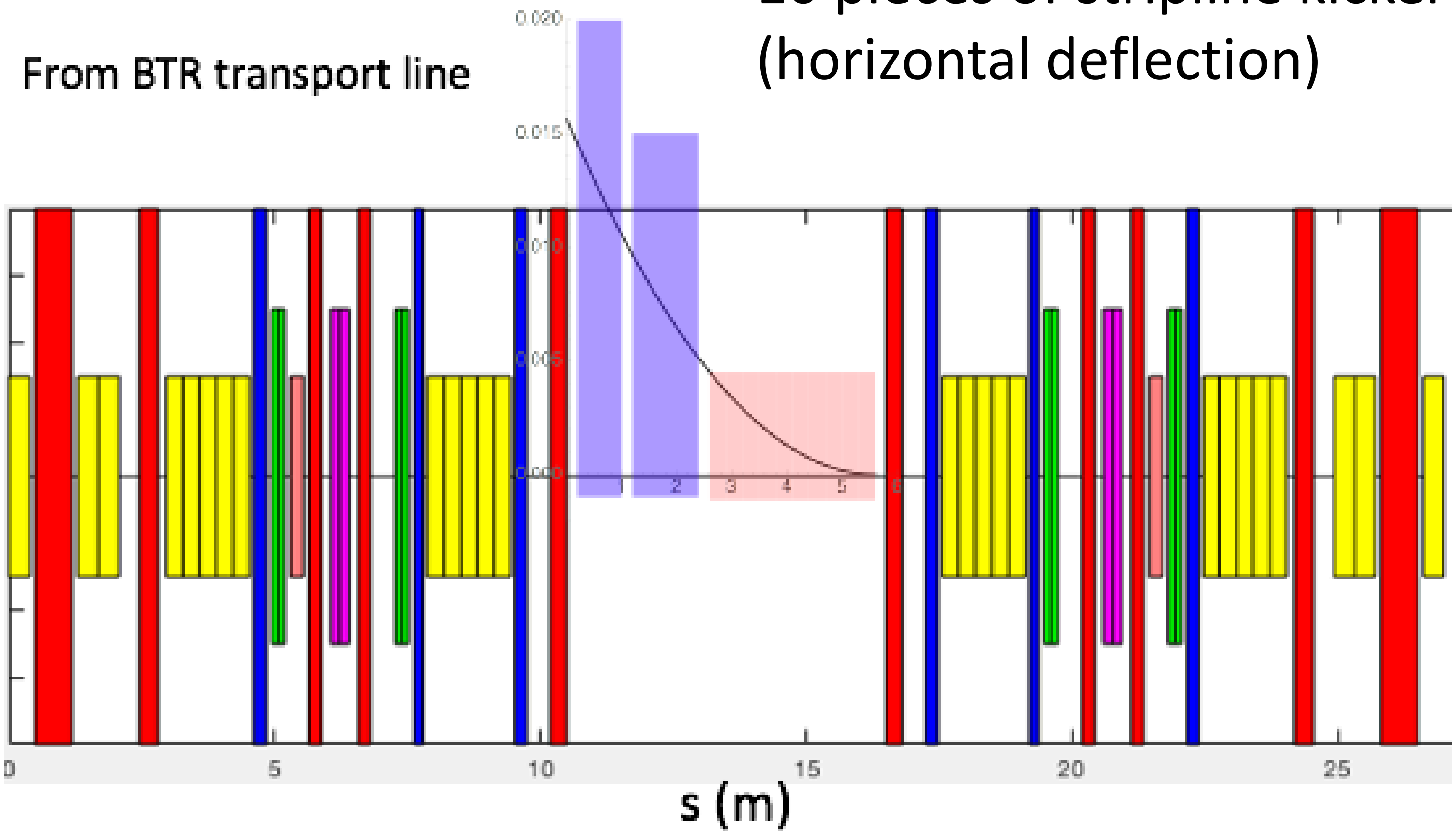
Cases	w/o IBS	60 bunches w/ IBS		648 bunches w/ IBS	
Parameters		SAD	ibsEmittance	SAD	ibsEmittance
ex (pm)	59.32	69.50	69.14	60.47	56.04
ey (pm)	5.96	6.85	6.91	6.06	5.60
ey / ex (%)	10.04	9.85	10	10.02	10
bunch length(mm)	32.0	35.11	35.41	33.03	31.50
energy spread (1e-4)	7.96	8.53	8.81	8.03	8.09

- In SAD, approximate with one 108 MHz RF cavity to keep bunch length=32 mm w/o IBS.
- Need to check with Monte-Carlo simulation available in Elegant.



Injection region layout

- Two Lambertson magnet (vetical deflection)
- 10 pieces of stripline kicker (horizontal deflection)



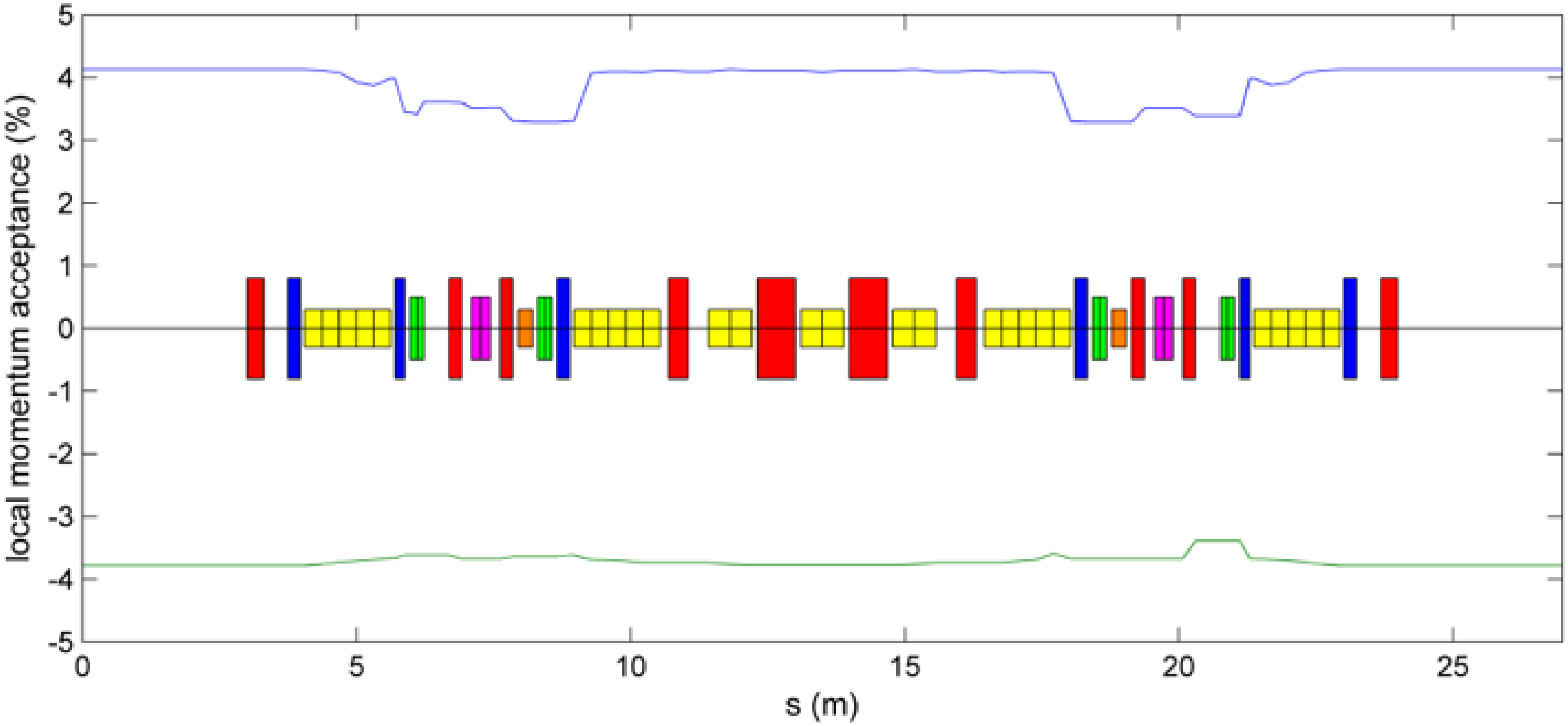
Backup

Linac main parameters

Parameter	specification
Rf frequency (MHz) (s-band)	2998.8 (or 2856)
Single bunch Charge (nC)	≥7.2 *
Energy (MeV)	≥300
Relative energy spread (%)	≤0.5 (rms)
Repetition rate (Hz)	300
geometric emittance (nm.rad)	≤70
Pulse to pulse time jitter(ps)	≤100

LMA

RF bucket height is set to 3.5%, single-frequency RF



Local momentum acceptance along a single 7BAfor the bare lattice of present nominal HEPS storage ring design, with the limitation of integer resonances into account. In this tracking, RF and synchrotron radiation are turned on.