IPAC19

中国科学院高能物理研究所
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Beam Dynamics Study in the HEPS Storage Ring

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On behalf of the HEPS Accelerator Physics Team

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Acknowledgements

HEPS Accelerator physics team includes:

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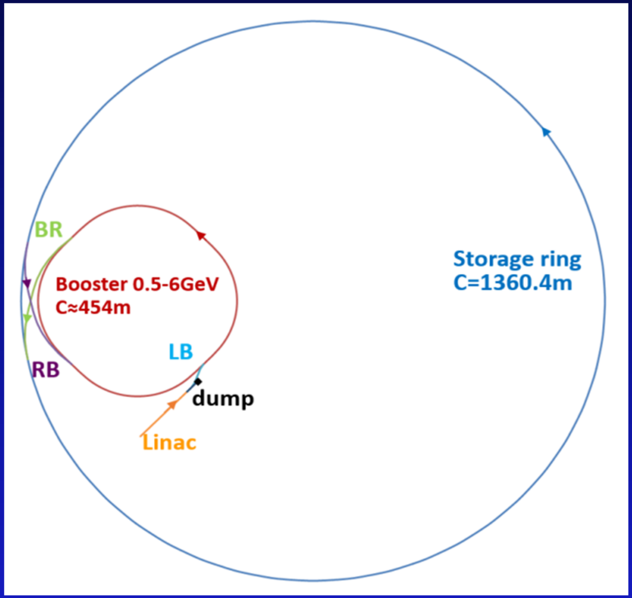
The presented work is part of that done by entire HEPS project team, led by Qing Qin, etc.

Thank worldwide experts for helpful discussions, suggestions, collaborations on HEPS design.

Outline

- *Lattice design*
  —hybrid 7BAs, high- and low- beta design
- *Nonlinear optimization*
  —Combination of MOGA and PSO
- *Injection scheme*
  —On-axis injection, accumulation in booster
- *Collective effects*
  —Single- and multi-bunch instabilities
- *Error specification and correction*
  —sextupole movers



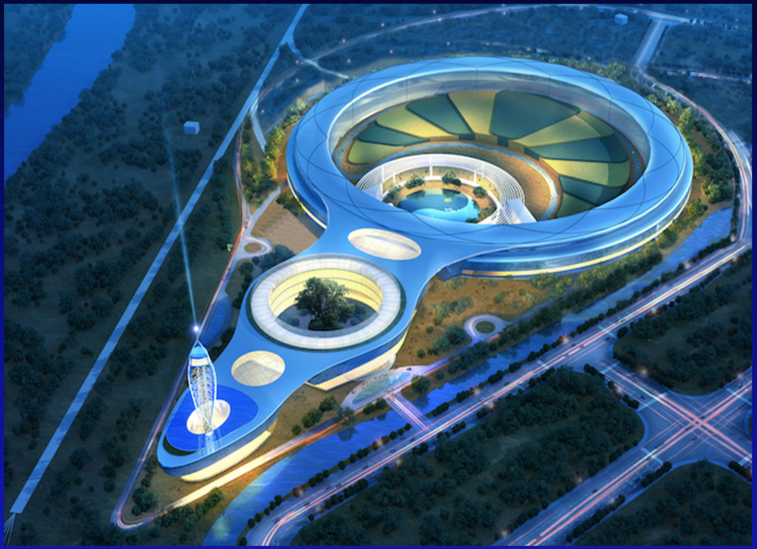
- Some issues have been studied, but will not addressed in following slides, such as dynamic error measurement, modeling and feedback; beam loss and collimation; commissioning simulation; transient injection instabilities; full coupling; etc.

High Energy Photon Source (HEPS)

The next storage ring light source of China

Milestones:

- Dec. 2017, HEPS Project Proposal Report approved
- Dec. 2018, HEPS Feasibility Study Report approved, total budget: 4.76 Billion RMB (manpower excluded), with the following goal parameters



Design goals of the HEPS light source

Main parameters	Unit	Value
Beam energy	GeV	6
Natural emittance	pm·rad	≤ 60
Brightness	phs/s/mm²/mrad²/0.1%BW	> 10^{22}
Beam current	mA	200
Injection		Top-up

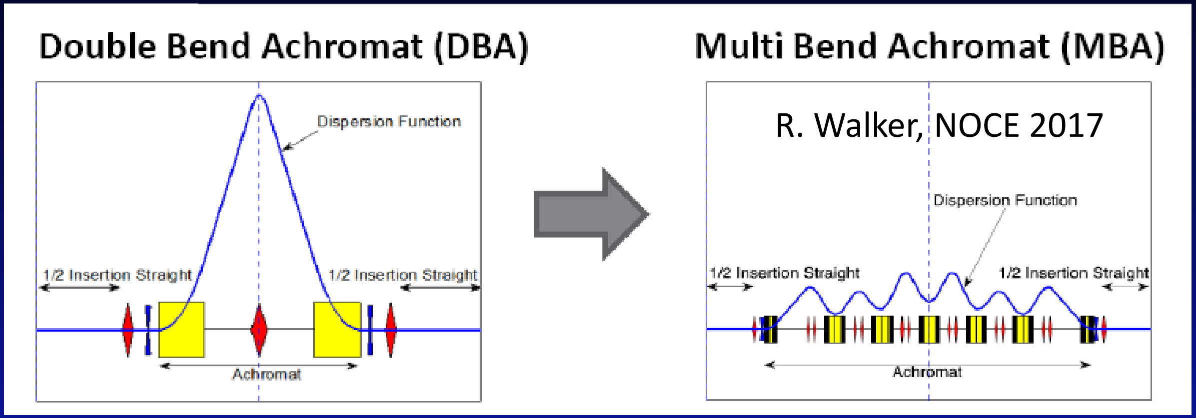
Current design satisfies the design goals

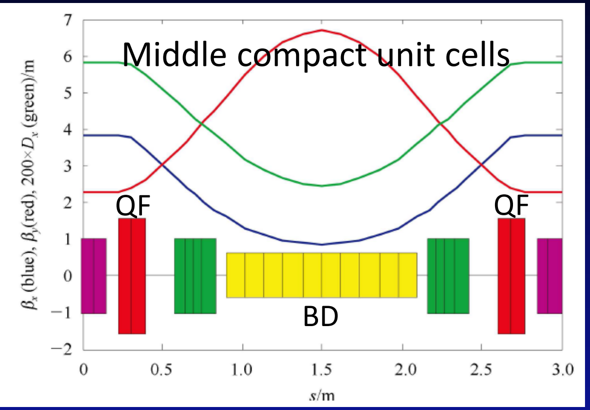
Parameters	High-brightness mode, 200 mA	High-bunch-charge mode, 200 mA [1]	Units
Beam energy	6	6	GeV
Number of bunches	680	63	
Bunch Duration (rms)	106	160	ps
Bunch spacing	6	72	ns
Emittance ratio ($\varepsilon_y/\varepsilon_x$) [2]	0.1	0.1	
Horizontal emittance	27.5	33	pm·rad
Vertical emittance	2.75	3.3	pm·rad
Horizontal beam size (rms) (high-/low-β section)	14.3/8.5	15.6/9.3	μm
Vertical beam size (rms) (high-/low-β section)	4.4/2.3	4.8/2.5	μm
Lifetime	~4	~0.8	hrs
Time between two refills	~30	~8	s

[1] In this table, we present beam parameters for the case with high-bunch-charge mode and 200 mA. Operating this mode at a lower current is under study and discussion.
[2] The Full coupling case, with emittance ratio of 1, is under study, but not presented here.

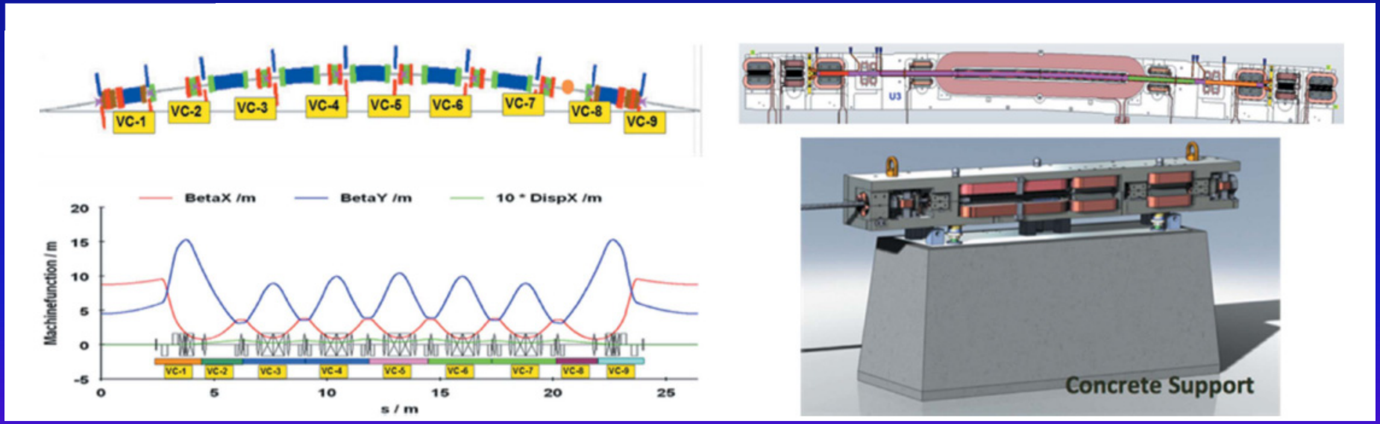
MBA: General way of reaching ultralow emittance

More dipoles, smaller bending angles, smaller dispersions





MAX IV [1]: The first MBA light source + aggressive accelerator technologies. Then ***Sirius*** **[2]** ***…***



Small-aperture magnets, NEG-coating vacuum system, 7BA integrated in single iron block

R. Hettel, *J.Synchrotron.Rad.* (2014), 21, 843-855.

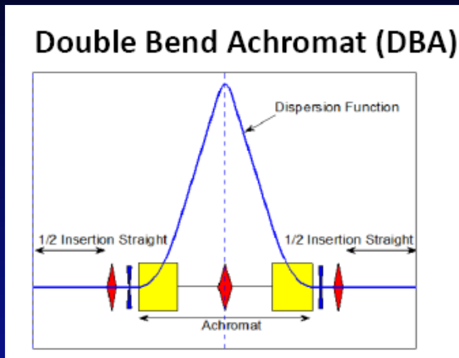
For a high energy photon source, when reducing emittance to a few tens of pm, extremely strong sextupoles will be required.

➢ ***HEPS 7BA lattice***, the available minimum emittance is about 90 pm [3].

[1] Leemann *et al.*, PRST-AB, 12, 120701, 2009; [2] e.g., Liu, IPAC17, TUXA1; [3] Jiao and Xu, *Chin. Phys. C*, 39(6), 067004, 2015.

Hybrid MBA: weaker sextupoles!

Likely a combination of DBA and MBA



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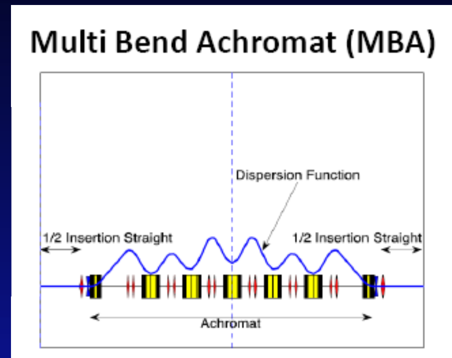
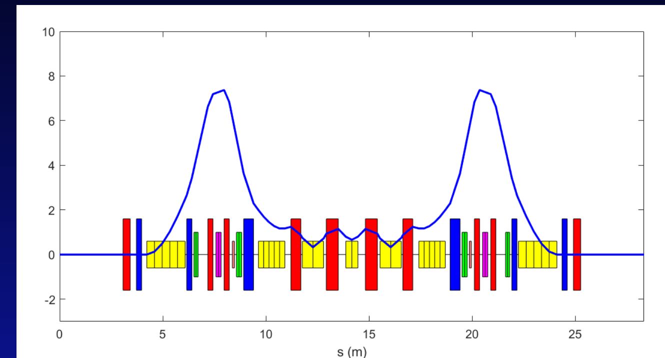
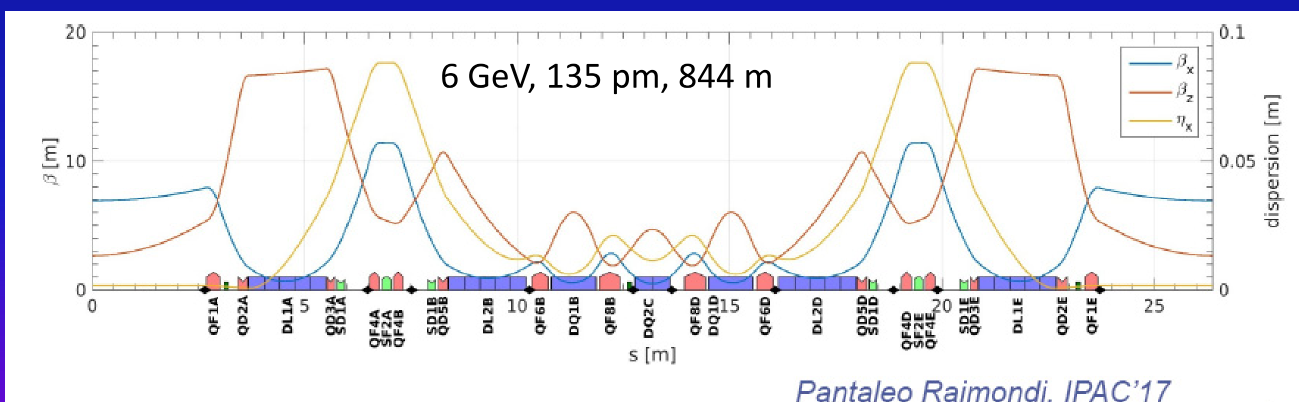




By putting all sextupoles within the dispersion bumps, sextupole strength can be well controlled. Hybrid MBA provides a good balance between chromatic correction and emittance minimization.

ESRF-EBS [1, 2]: the first to propose and use this hybrid-7BA lattice, then ***APS-U*** [3]….



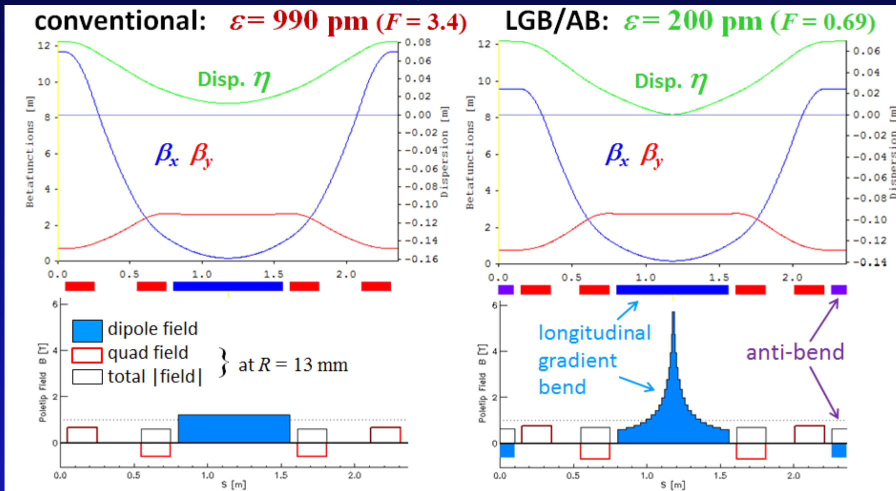
- ***HEPS hybrid-7BA lattice***, the available minimum emittance is about 45 pm [4].

[1] Farvacque et al., IPAC13, MOPEA008; [2] Raimondi, IPAC17, THPPA3; [3] Borland et al., NAPAC16, WEPOB01 ; [4] Jiao *et al.*, SAP, 2017.

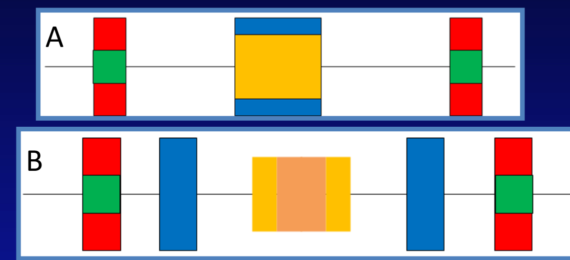
Use of Anti-bends (ABs): even lower emittance

Allows independent knob of dispersion and beta functions

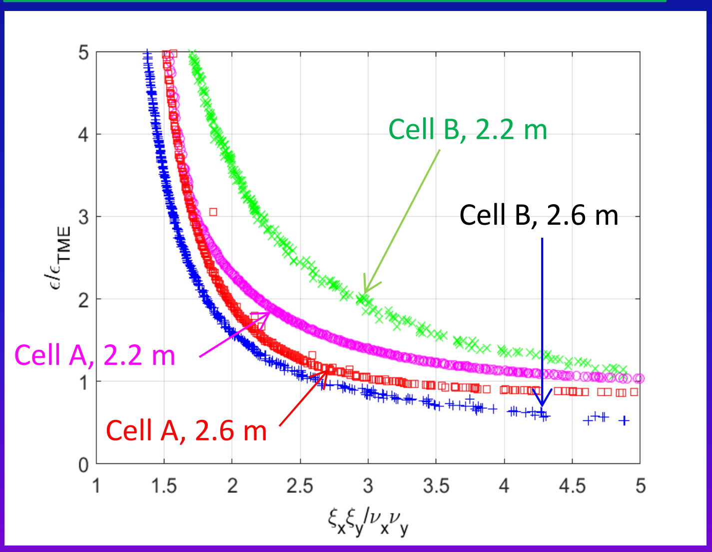
SLS-2: Adopted *BLG (or LGB)* and *AB* in one cell, emittance reduced by a factor of ~4 [1].



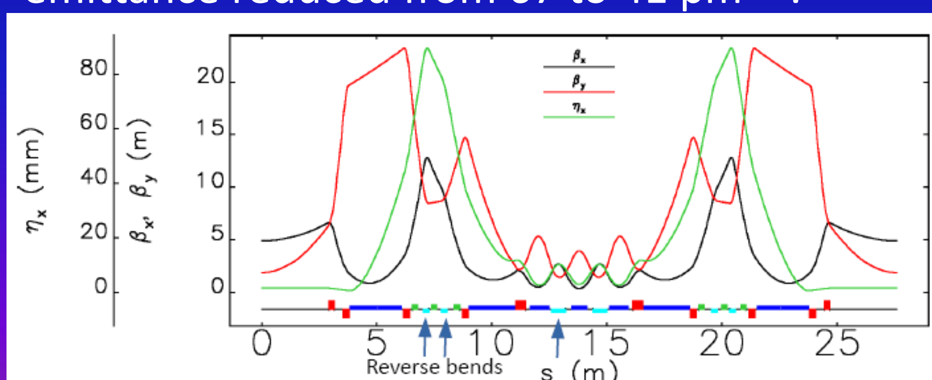
Two typical unit cells w/ ABs [3]



- Cell A can be more compact.
- Cell B promises lower emittance



APS-U: Combining *AB*s into hybrid-7BA, emittance reduced from 67 to 41 pm [2].

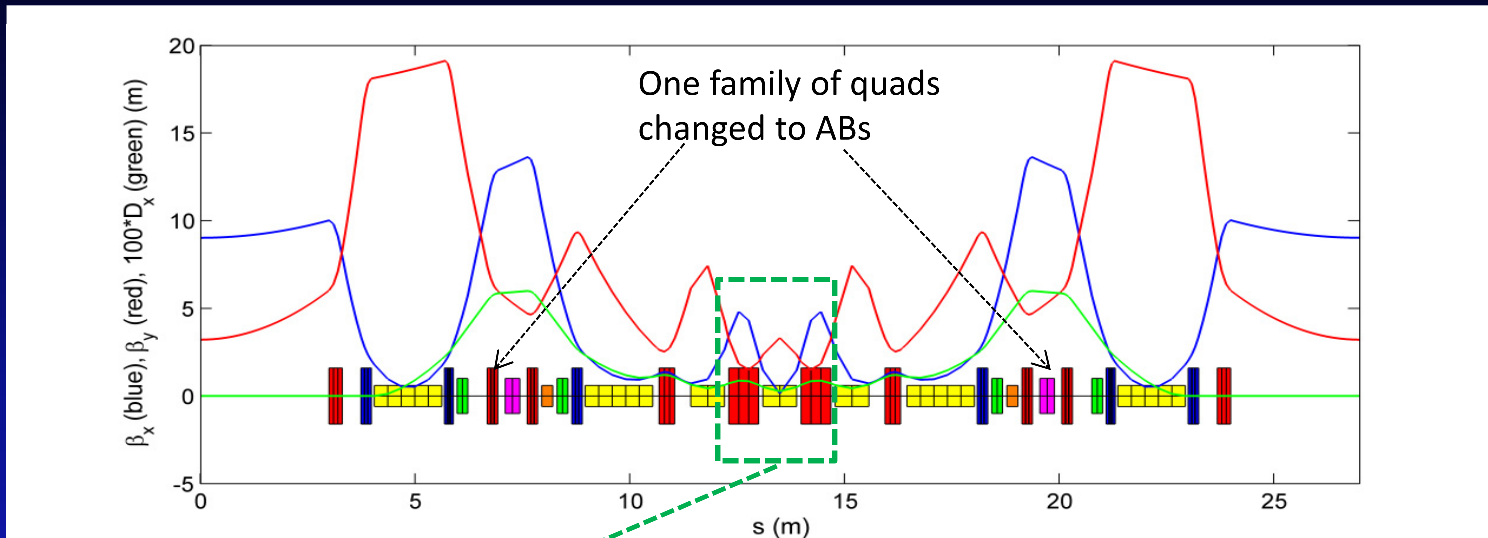


➢ ***Cell B was adopted in HEPS design***

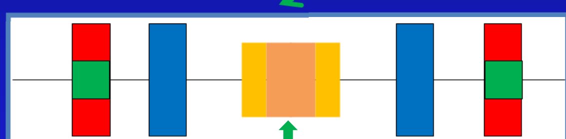
[1] A. Streun, talk in KeK, 2016.
[2] M. Borland *et al.*, NAPAC16, WEPOB01.
[3] Y. Jiao *et al.*, IPAC18, TUPMF054.

HEPS: BLG+AB cell combined in hybrid-7BA

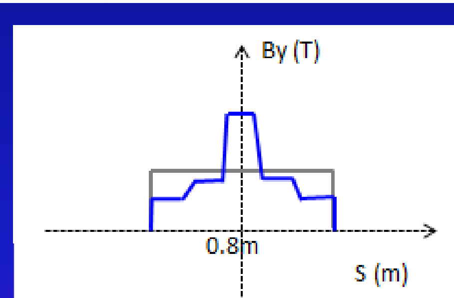
34 pm natural emittance, 1360.4 m, 48 hybrid-7BAs w/ BLGs and ABs



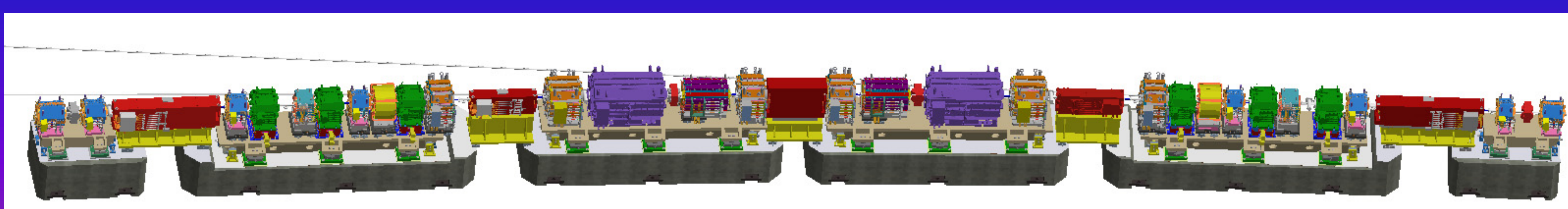
Replace the middle cell with cell B



Central slice of BLG used for bending magnet beam line



Peak field (T)	Critical photon energy (keV)	Peak power density (W/mrad^2)
0.5T	12.0	702
0.85T	20.3	1194
1T	23.9	1405
1.5T	35.9	2107
2T	47.9	2810
3T	71.8	4215
3PW(1.6T)	38.3	2349

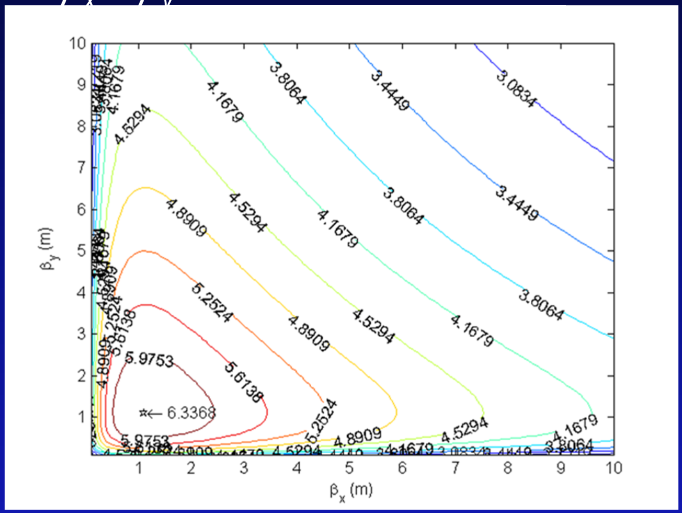


Courtesy of C. Li

HEPS design optimized for high brightness

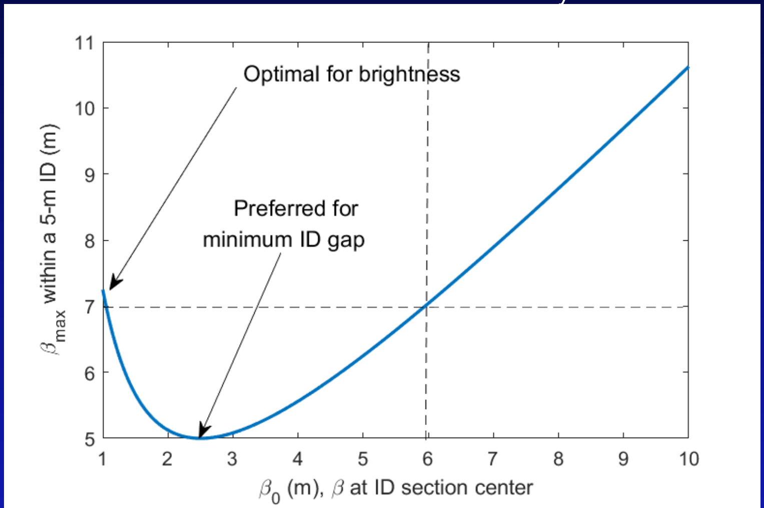
low ε, low β, small ID gap, etc. not always fulfilled at the same time

Highest possible brightness (ID gap ≡ 5 mm)
→ β_x & β_y ~ 1m at the ID section center

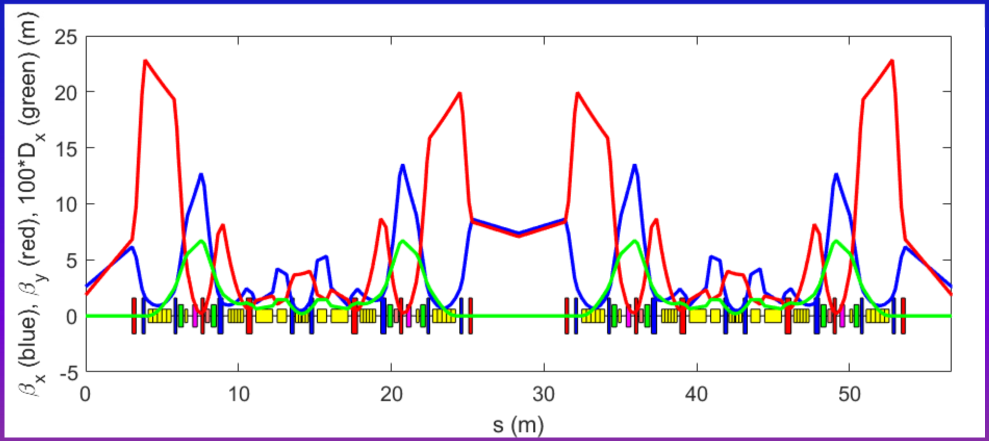


Scan based on HEPS parameters, optimized for 20 keV energy [1]

ID gap does depend on β (scales roughly as $\beta^{1/2}$)
For a 5-m ID, minimum gap → β_y ~ 2.5 m



***HEPS:** Alternating high- and low- beta sections, for high-brightness and high-flux, respectively*



48 6-m straight sections, 40 available for IDs

- *both β_x & β_y ~ 2 m at low-β section center*
- *β_y ~ 7 m at high-β section center*

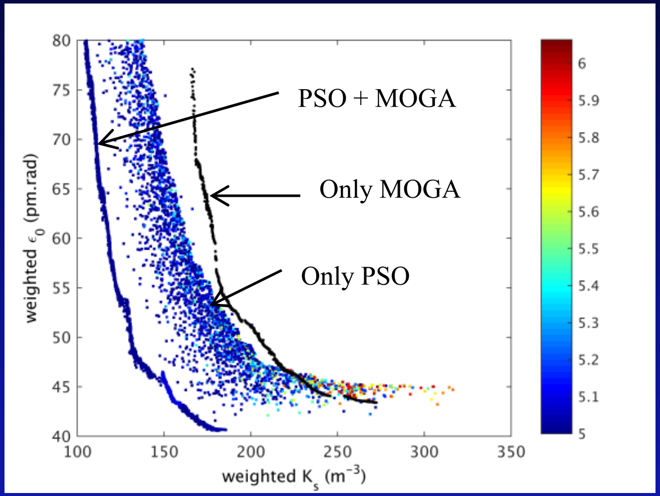
Design optimization is still under way.

[1] Y. Jiao *et al.*, IPAC18, TUPMF056 .

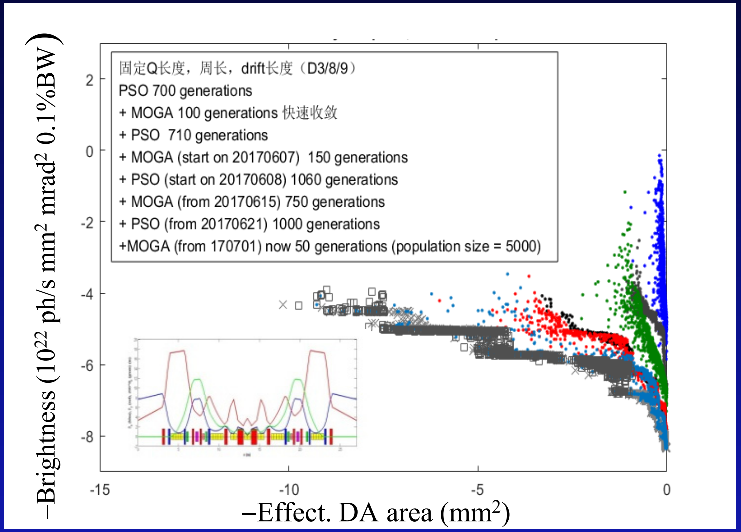
Nonlinear optimization: combined PSO & MOGA

PSO breeds more diversity, MOGA allows fast convergence

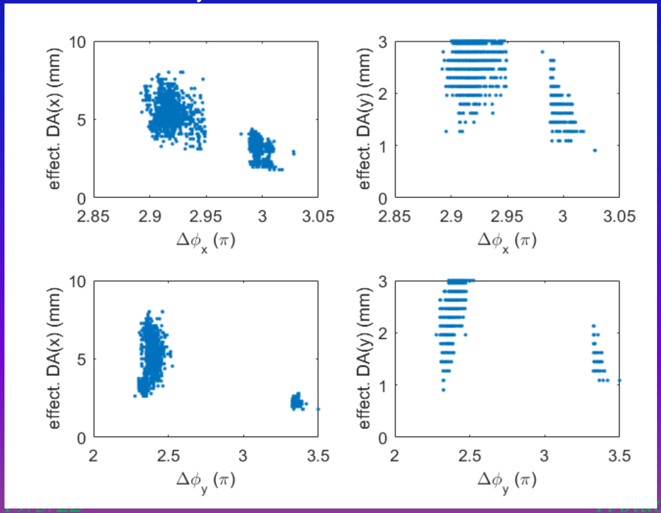
Verified with an optimization problem with known answer (Jiao & Xu, CPC, 027001, 2017)



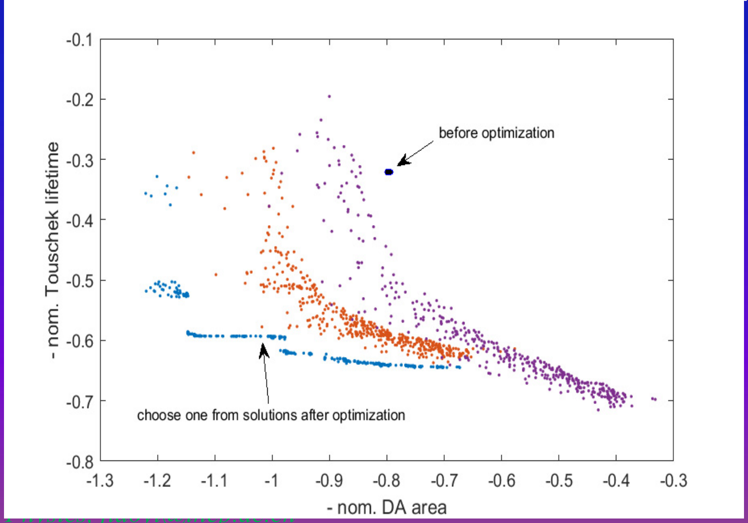
Simultaneous optimization of brightness and DA



DA depends highly on $\Delta\psi_x$ between sextupole pairs, release $\Delta\psi_y$ for higher brightness (Jiao, IPAC18)



Fix linear parameters, optimizing DA and Touschek lifetime (lifetime increased by a factor of 2)

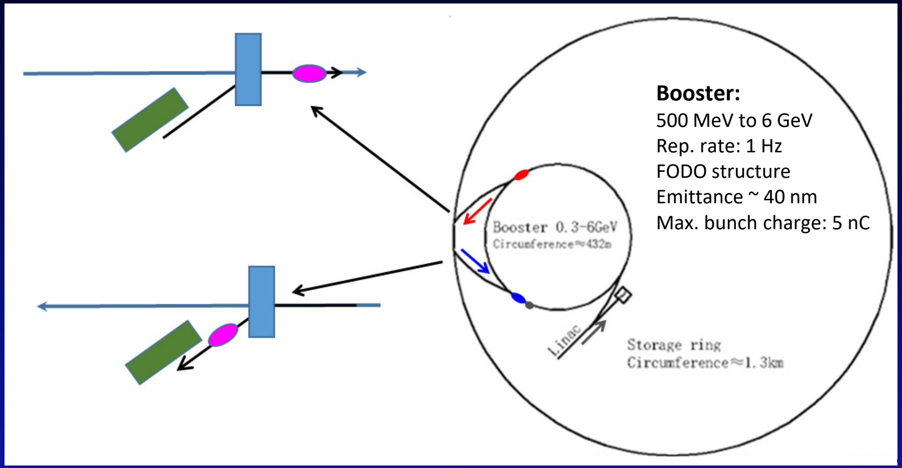


On-axis injection + high energy accumulation

On-axis swap-out injection [1]

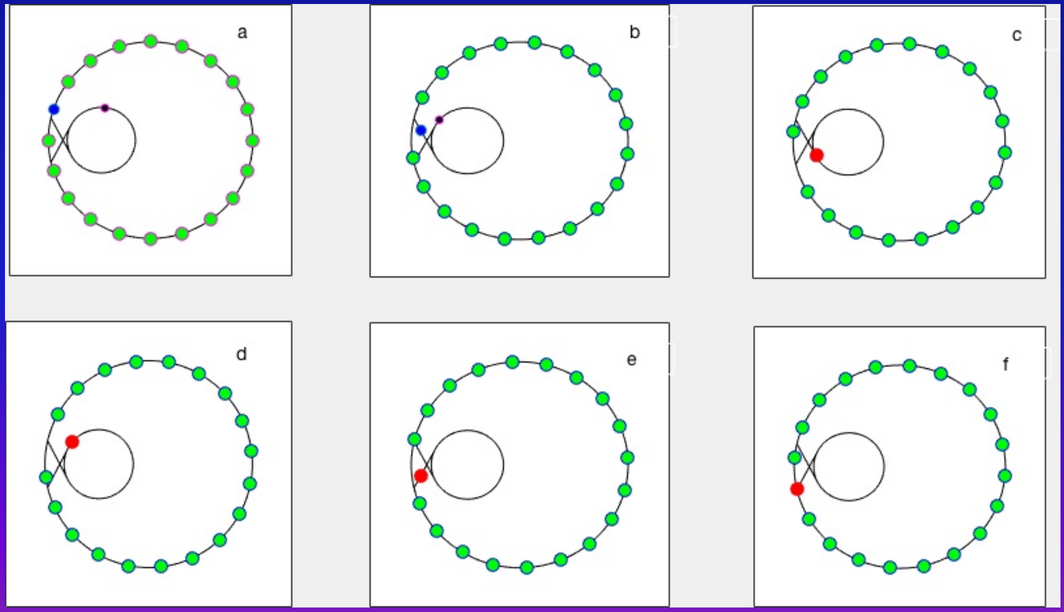
Requirements:

- Fast kicker with a pulse width of <~12 ns
- The injector (a linac + a booster) should be able to *provide full-charge bunches*
  —1.33 nC for high-brightness mode, 200 mA
  —***14.4 nC*** for high-bunch-charge mode, 200 mA



***HEPS*：** *Return transport line from ring to booster + accumulation in booster at high-energy* [2, 3]

(a) Used bunch extracted from the ring,
(b) passing through a transport line,
(c) Injected to booster, merged with an existing bunch,
(d) after about 10 thousands' revolutions in booster, extracted from the booster,
(e) passing through another transport line,
(f) re-injected to the ring



[1] *e.g.*, M. Borland *et al.*, *J. Syn. Rad.* (2014) **21** 912; [2] Z. Duan *et al.*, IPAC18, THPMF052; [3] Y. Guo *et al.*, IPAC2017, TUPAB063.

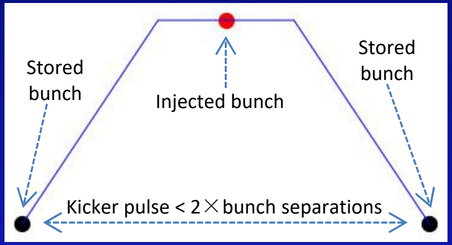
RF choice: a comprehensive consideration

166.6 MHz fundamental and 500 MHz third harmonic RF cavities

500 MHz RF cavities have been used in IHEP existing facility, the BEPC-II collider.

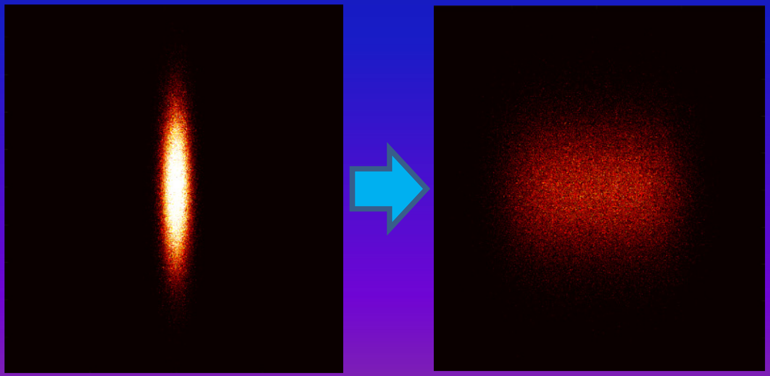
- Use a lower-frequency *166.6 MHz* RF system, to *release the requirement on pulsed kicker*

—12 ns vs. 4 ns (if using 500 + 1500 MHz RF system instead)

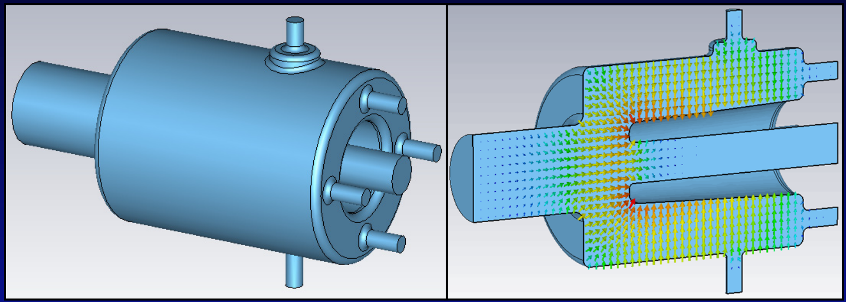


- 500 MHz RF cavities as third harmonic cavity for *bunch lengthening* and weaker collective effects

—e.g., smaller emittance growth due to IBS

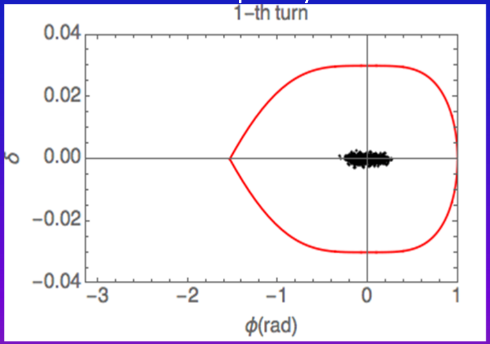


166.6 MHz SC Cavity prototype under test (Courtesy of P. Zhang)

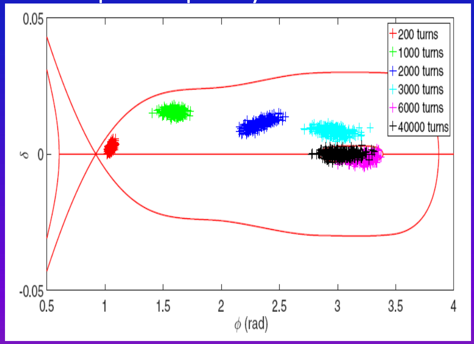


- The RF choice also allows for POP experiments of *longitudinal injection*.
  - dynamic damping double-frequency RF system (166.6 + 500 MHz)
  - Static triple-frequency RF system (166.6 + 333.2 + 500 MHz)

Double-frequency RF [1-2]



Triple-frequency RF [3]

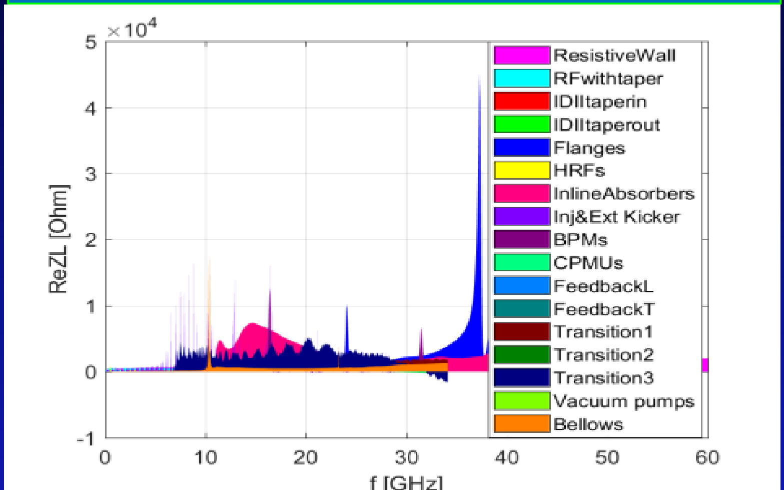


[1] G. Xu et al., IPAC16, WEOAA02; [2] Z. Duan *et al.*, eeFACT2016; [3] S. Jiang, G. Xu, PR-AB, 21, 110701.

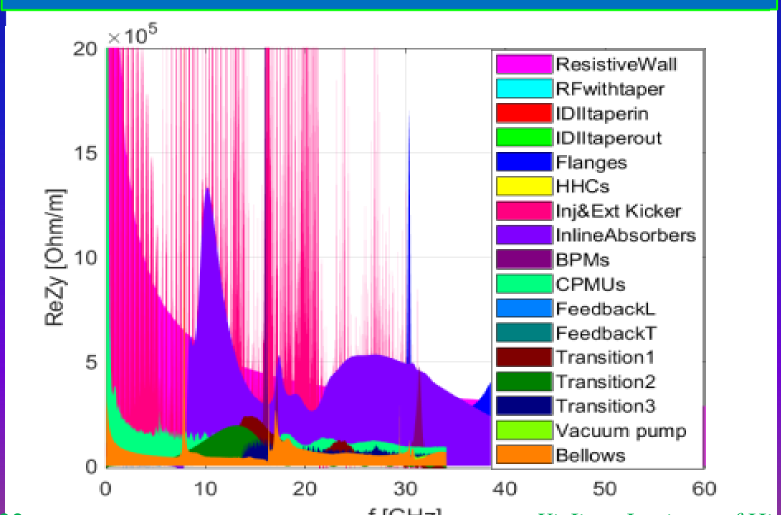
Impedance model built for instability studies

Various impedance contributors were considered, impedance optimization is under way.

Longitudinal impedance dominated by ***resistive wall and large number elements***, e.g., flanges.



Transverse impedance is dominated by the ***resistive wall impedance and Inj. &Ext. kickers.***



Longitudinal and transverse effective impedances are ***estimated at natural bunch length of 27.6 mm with HC.***

Objects	$Z_{\|\|}/n$ [mΩ]	k_l [V/pC]	k_y [kV/pC/m]
Resistive wall	38.2	1.3	11.5
RF cavities	8.6	1.2	0.11
Bellows	22.9	0.14	0.89
Flanges	42.3	5.5E-8	1.3
ID tapers	1.0	1.6E-6	0.11
Inj. & Ext. kickers	29.5	0.62	12.8
In-line absorbers	69.5	7.9E-6	2.7
BPMs	7.7	0.033	0.25
Harmonic RF	5.3	0.28	0.038
LF kicker	0.03	0.13	0.036
TF kicker	0.5	4.4E-3	0.035
In-vacuum IDs	0.03	0.032	1.5
Pumping ports	14.9	0.072	0.56
Transitions	80.3	3.4E-3	1.0
Total	326.8	3.8	32.7

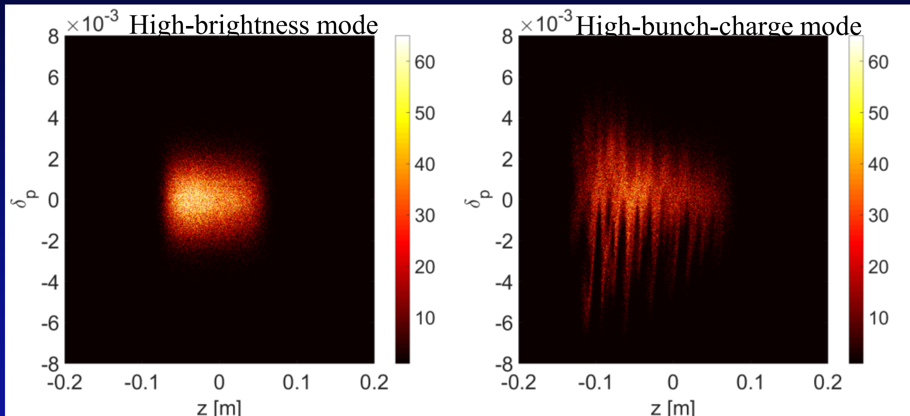
N. Wang *et al.*, IPAC17, WEPIK078

Single- and multi-bunch instabilities

Goal: single bunch charge up to 14.4 nC, average beam current up to 200 mA

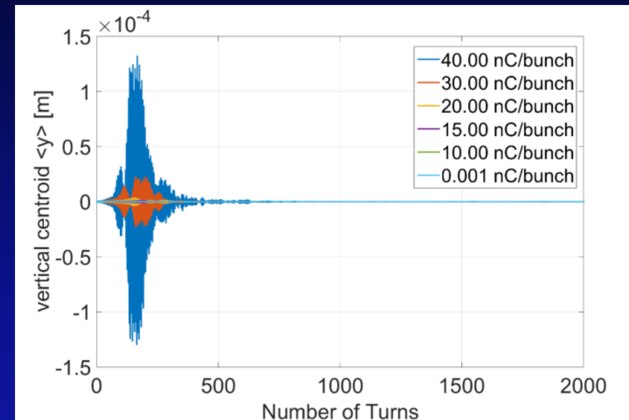
Microwave instability threshold ~ 2.2 nC.

Brightness degradation expected for high-bunch-charge mode (14.4 nC)



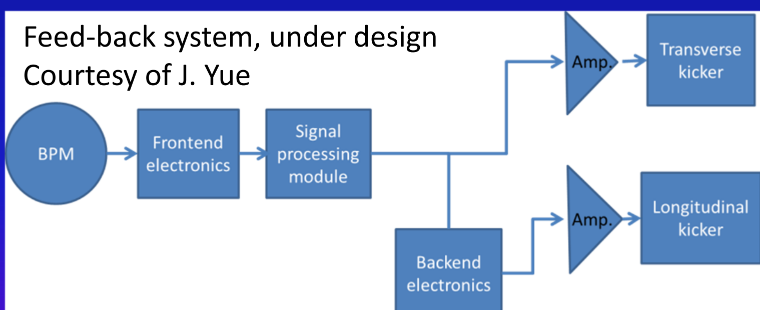
Transverse mode coupling instability I_{th}> 30 nC.

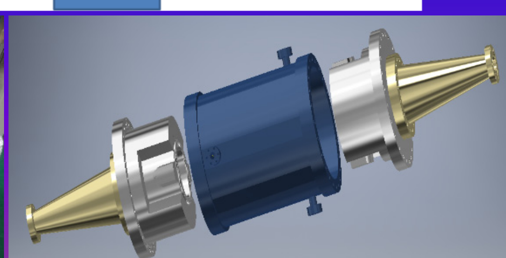
—With a large positive chromaticity (+5)

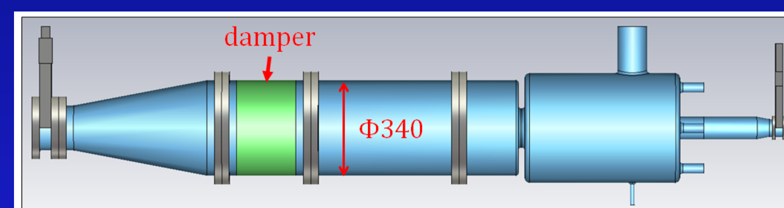


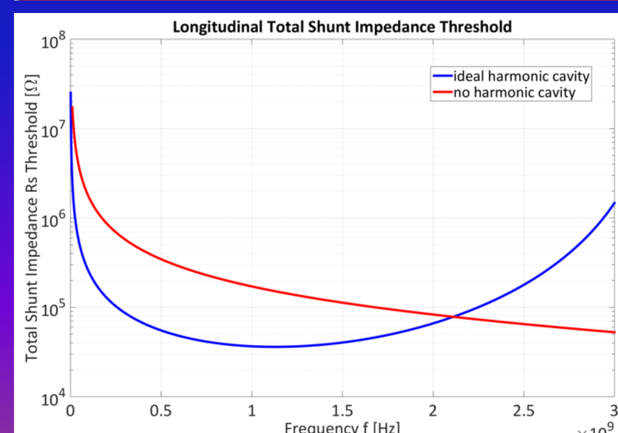
Multi-bunch instability I_{th} would be above 200 mA

—With the aid of positive chromaticity, feed-back, RF HOM damping





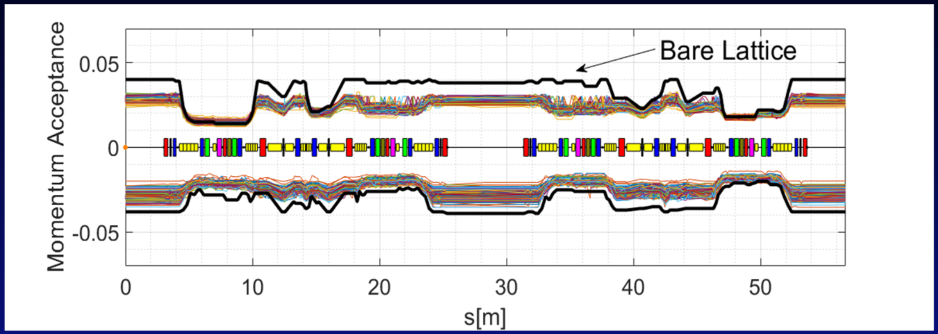




Courtesy of P. Zhang

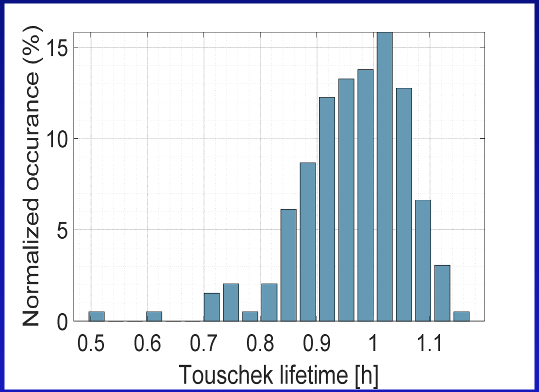
Beam lifetime

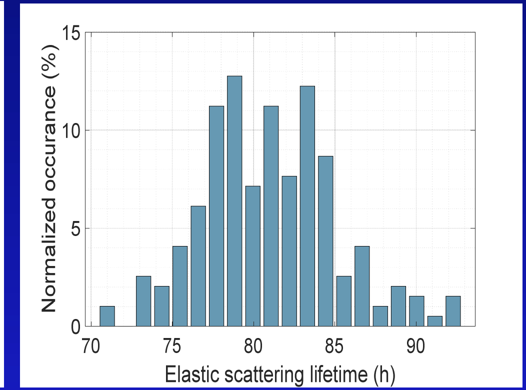
- The lifetime evaluated based on the ring acceptance in presence of practical errors,
  - ID and IBS effect included
  - Touschek and vacuum lifetime

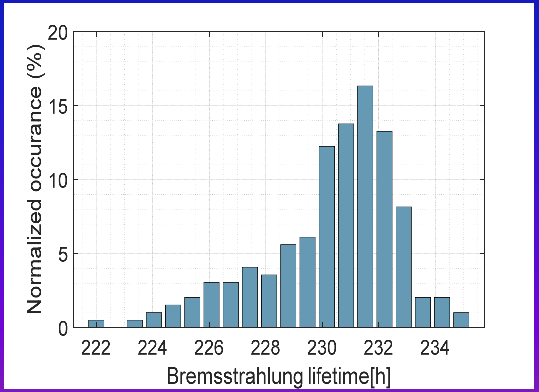


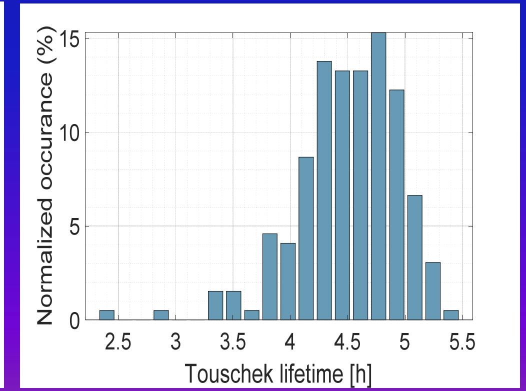
- ***Lifetime (90% chance) at 200 mA*** :
  - ~3.7 h for high-brightness mode
  - ~0.8 h for high-bunch charge mode

- ***Top-up injection*** considered
  - At 200mA, refill every 30 seconds for high-brightness mode, and every 8 seconds for high-bunch-charge mode, to keep a current stability of < 0.3%.
  - Small brightness reduction (0.1%, or 2%) in each refill period (~20 ms), but acceptable.





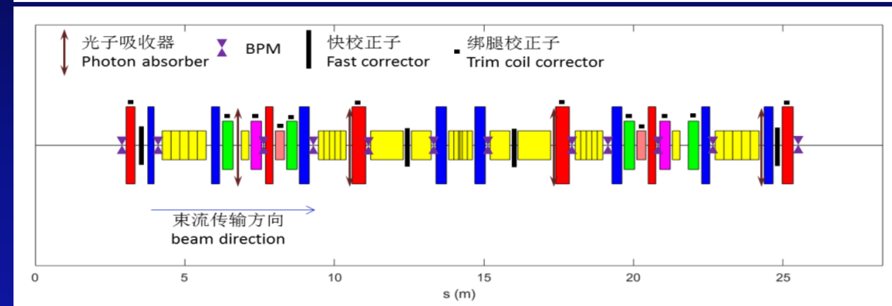


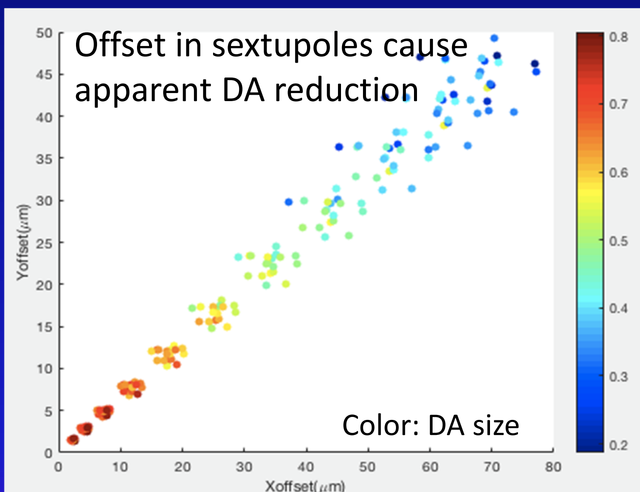


Error requirement and correction

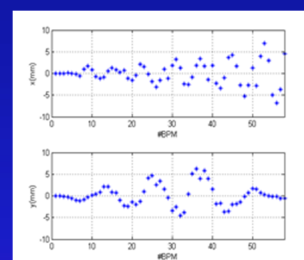
- Requirement on alignment, magnetic field errors, etc. specified.
- Number and locations of BPMs and correctors in the ring optimized and fixed.
- First turn around strategy developed [1].
- Detailed lattice calibration simulation has been done [2,3].

	Dipole	Quadrupole	Sextupole	Octupole	Girder
Transverse shift X/Y (µm)	200	30	30	30	50
Longitudinal shift Z (µm)	150	150	150	150	200
Tilt about X/Y (mrad)	0.2	0.2	0.2	0.2	0.1
Tilt about Z (mrad)	0.1	0.2	0.2	0.2	0.1
Nominal field	3e-4	2e-4	3e-4	5e-4	\

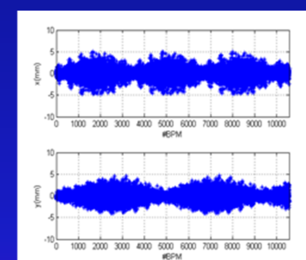




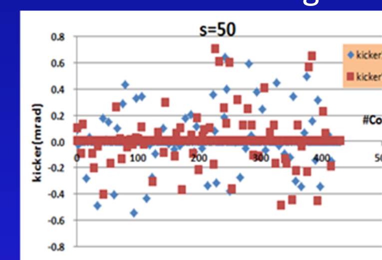
Before correct.

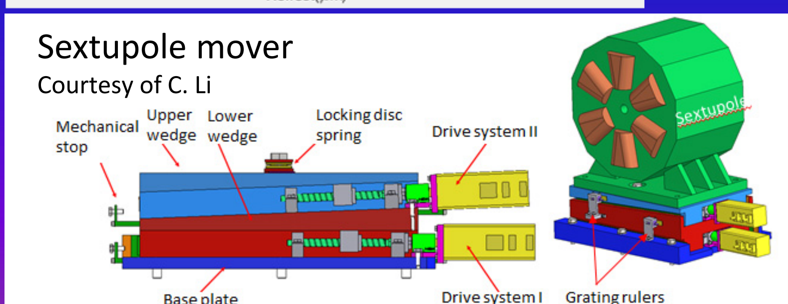


After correct.

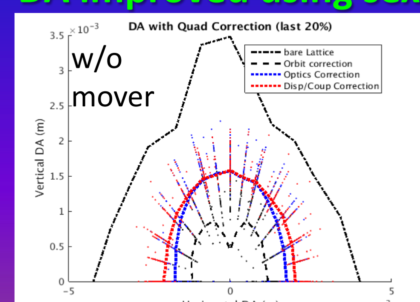


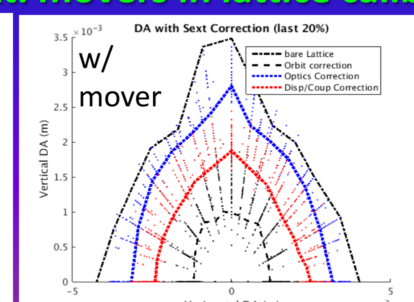
Corrector strengths





DA improved using sext. movers in lattice calibration





[1] Y.L. Zhao *et al.*, IPAC17, MOPIK082; [2] Z. Duan *et al.*, IPAC18, THPAK013; [3] D. H. Ji, *et al.*, IPAC18, THPMF054.

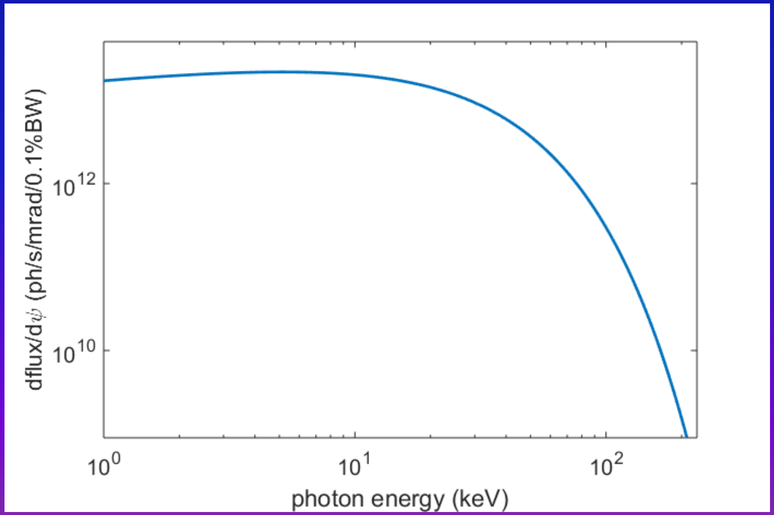
Photon beam flux and brightness

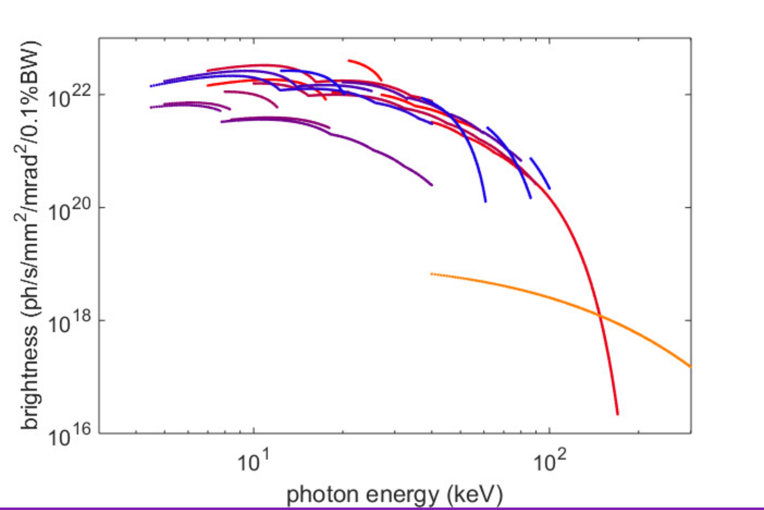
- ***More than 80 beam lines*** are expected for HEPS

- ***In the first construction phase, 14 beam lines*** will be built
  - One bending magnet beam line (middle dipole of 7BA) and 13 ID beam lines
  - Different types of IDs, such as CPMU (4), IVU(3), IAU(4), wiggler(1), APPLE-Knot (1), are planned
  - ID parameters fixed, but still under optimization for even better performance

- 4×10^{22} phs/(s·mm^2·mrad^2·0.1%BW) @~20keV, for high-brightness mode, 200 mA
  - Error effects, collective effects, etc. included.

- 50% reduction of brightness, for high-bunch-charge mode at 200 mA, due to increasing of the energy spread.





[1] X.Y. Li *et al.*, HEPS-AC-AP-TN-2018-002-V0

In Closing…

- ***Physics design basically completed for the HEPS light source.***
  - ✓ *With as many features as possible maximizing the brightness*
  - ✓ *Solutions to challenges inherent in the ultralow-emittance design*
- ***There is no show-stopper for the HEPS construction. Scheduled to start in mid-2019***
- ***Further optimization is still under way and never ends.***

Thanks for your attention!