Progress in the design and related studies on the High Energy Photon Source (HEPS)

Yi Jiao(IHEP, Beijing)
On behalf of the HEPS physical design group

July. 4, 2016

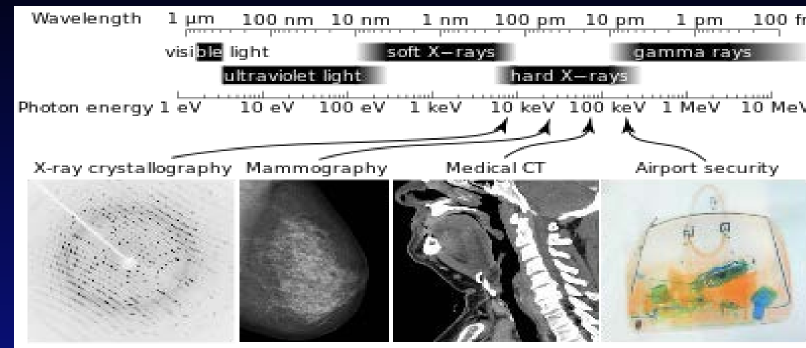
SYNCHROTRON AND FREE ELECTRON LASER RADIATION: GENERATION AND APPLICATION (SFR-2016)

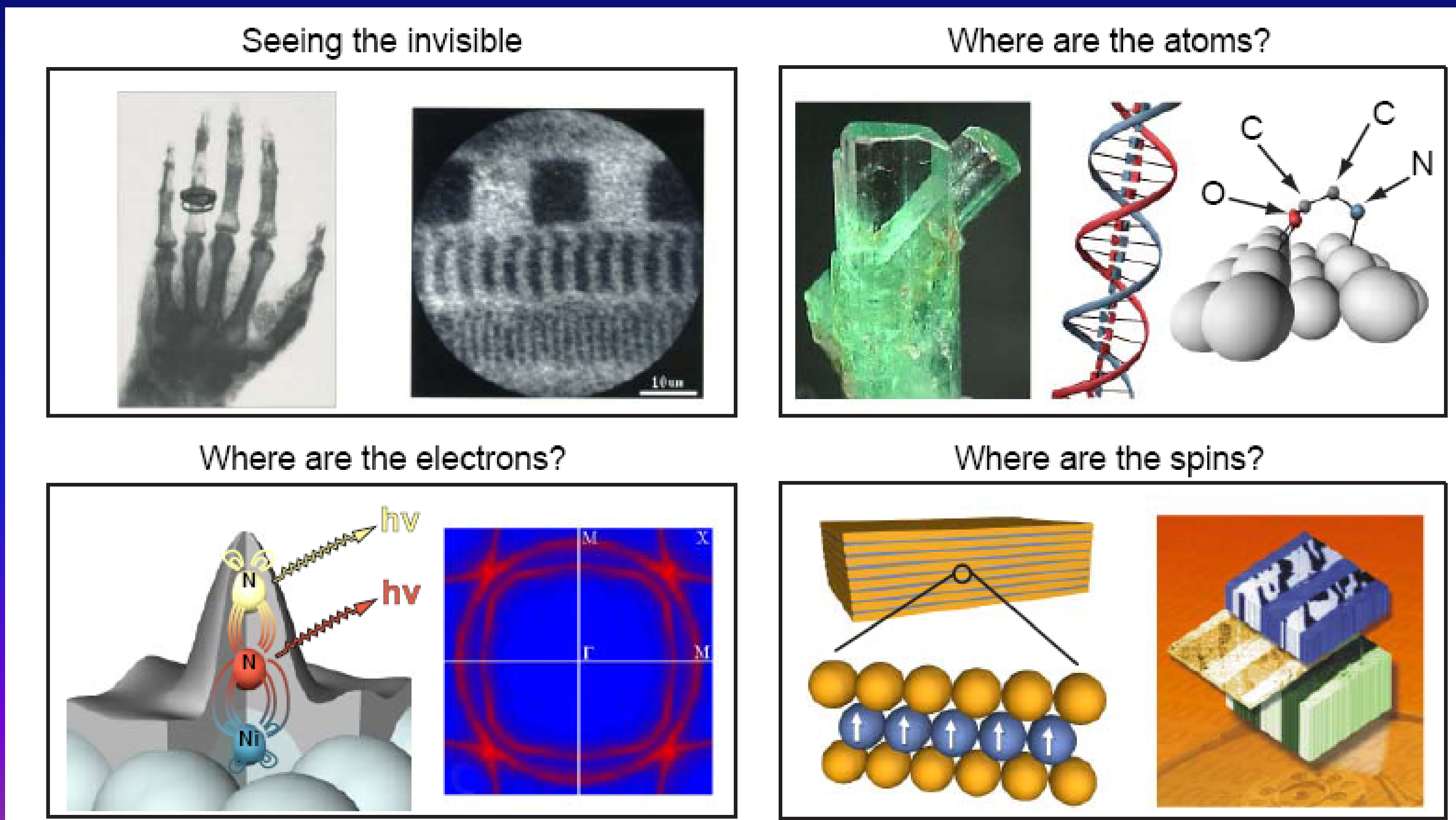
Budker Institute of Nuclear Physics SB RAS, Nobosibirsk, Russia

SFR-2016

Photons: Primary Tool to Probe Nature

Powerful light sources
are required with
widely tunable frequency range
from Infrared to X-rays!



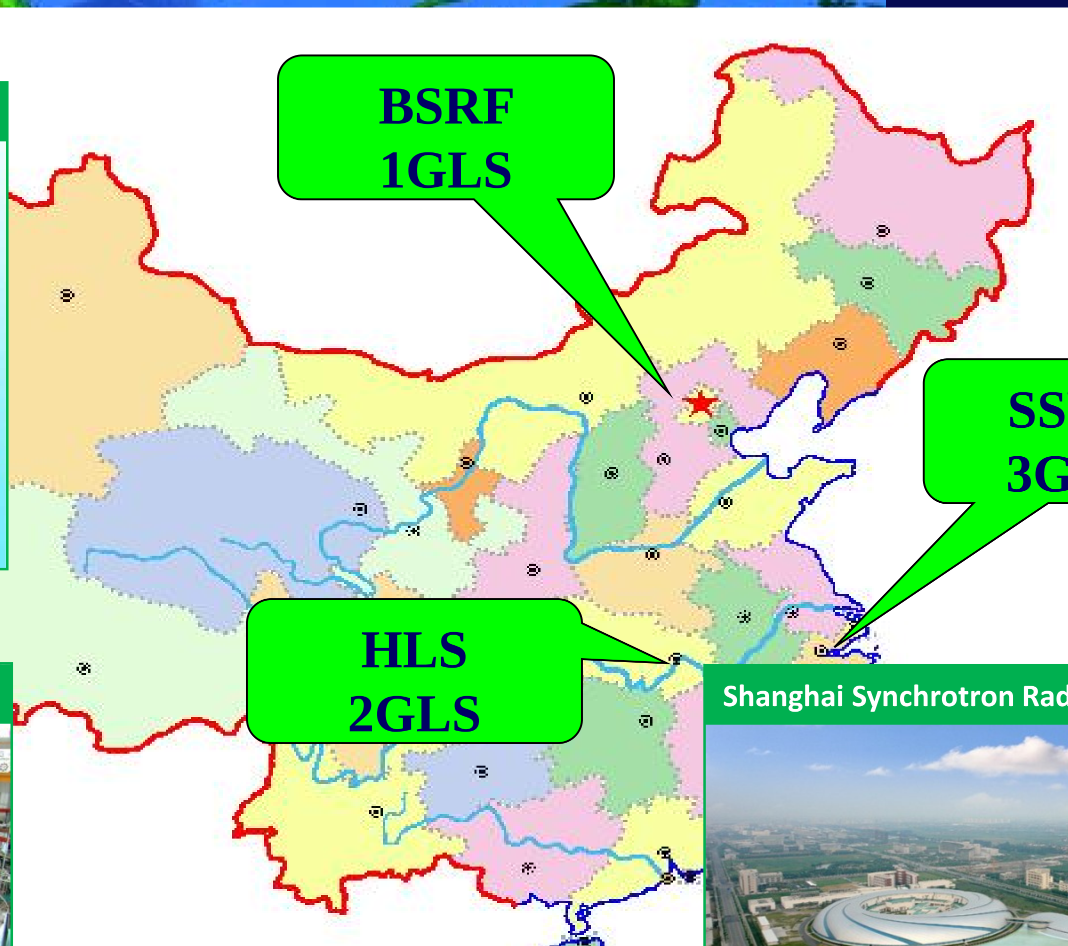


Storage Ring Synchrotron Radiation light source

Most used and successful photon science research platform worldwide

More than 50 facilities around the world!

Beijing Synchrotron Radiation Facility

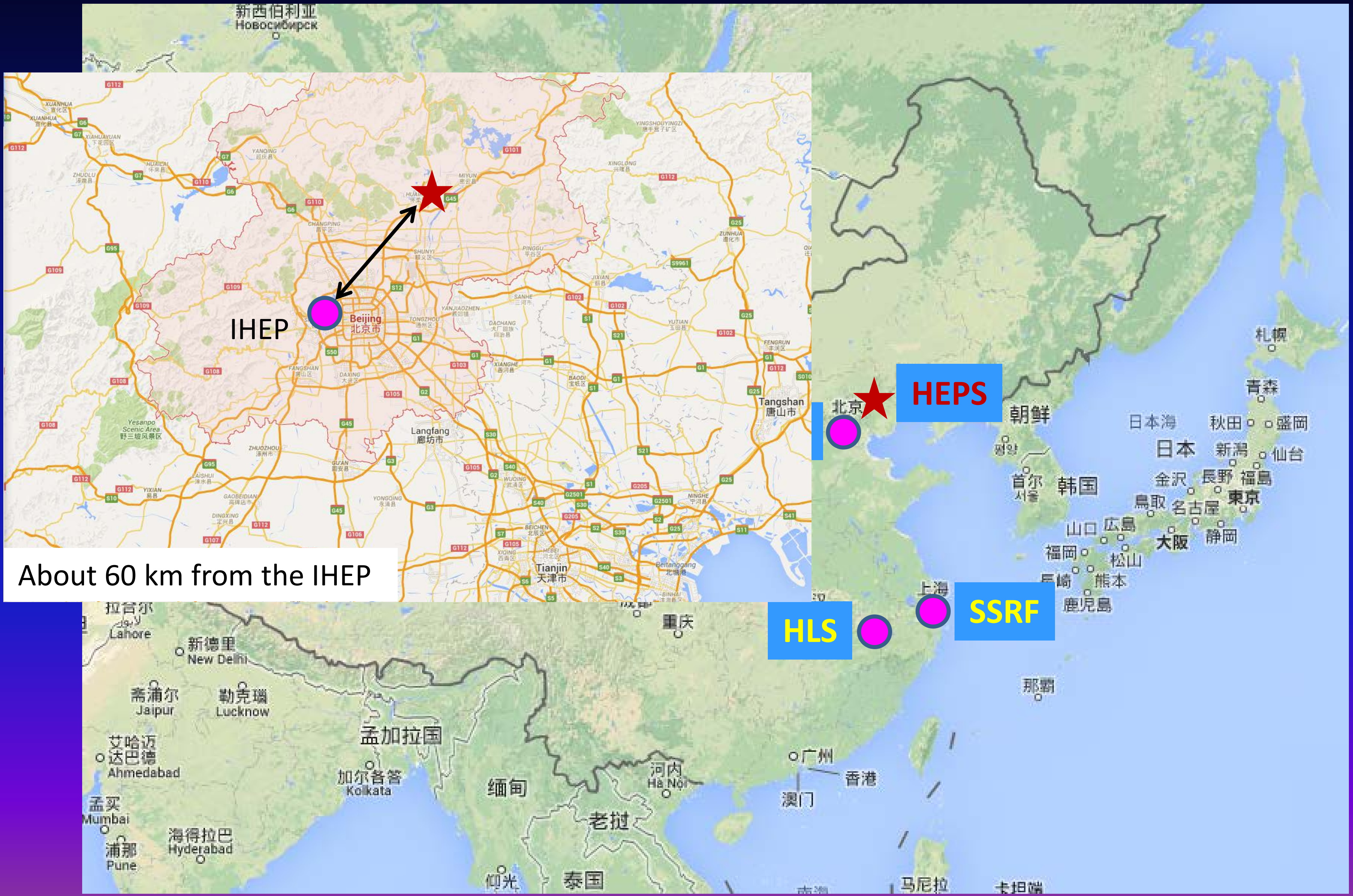


Hefei Light source

Shanghai Synchrotron Radiation Facility

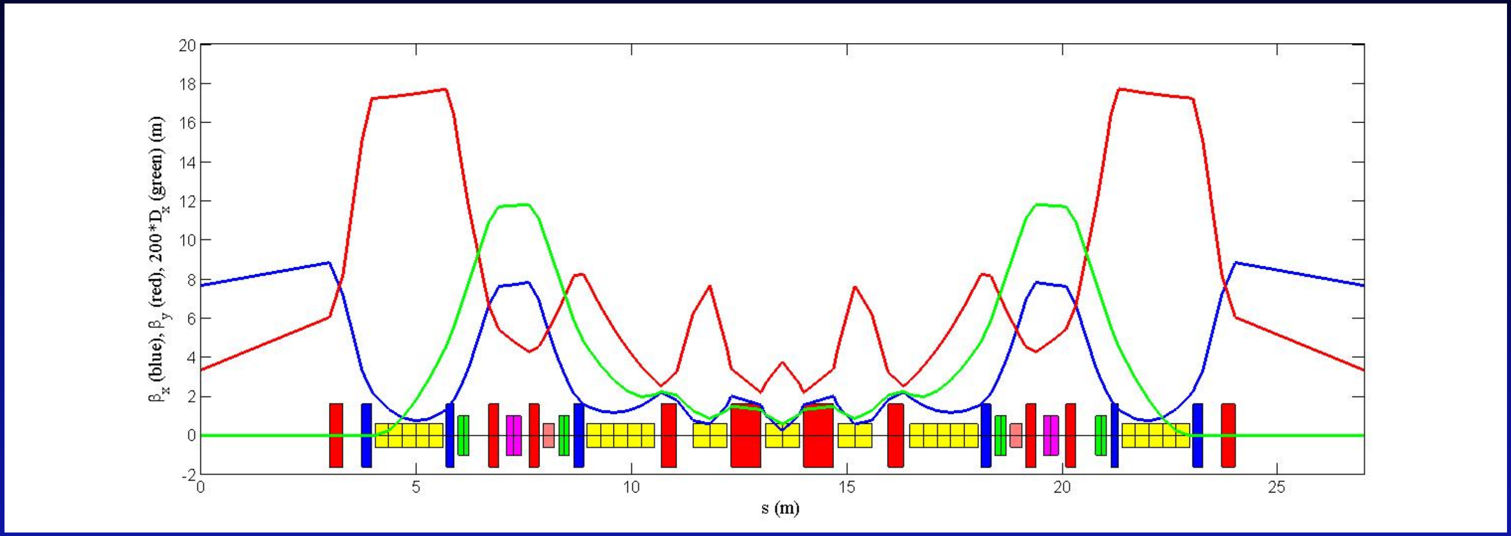
HEPS: the next ring light source in China

A new photon science research center at the north of China



Present design for the HEPS main ring

60 pm.rad @ 6 GeV, ~1.3 km



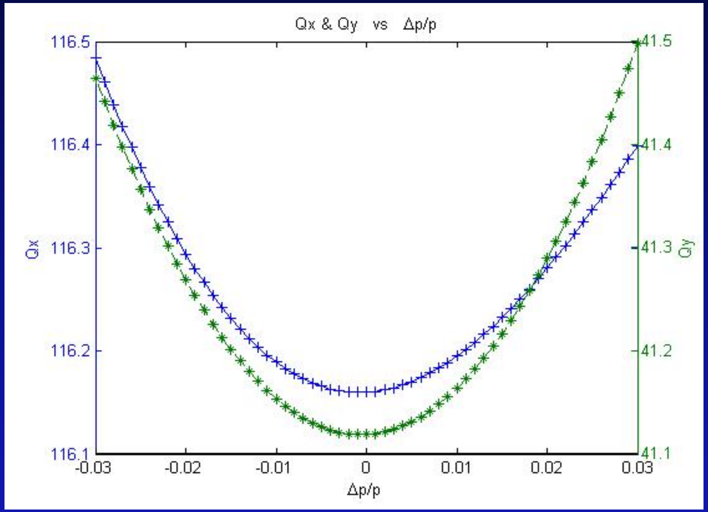
- 48 identical hybrid 7BAs. Each 7BA is about 27 m, a compact layout but with a ***6-m straight section*** for insertion device (ID);
- Four outer dipoles with long. gradients are used to create two *dispersion bumps* with all the sextupoles therein for an ***efficient chromatic correction***;
- Between each pair of sextupoles (3 families), a *-I transportation* is designed to ***cancel most of the nonlinearities*** induced by sextupoles;
- A family of octupoles is used to ***control the detuning terms***.

Present design for the HEPS main ring

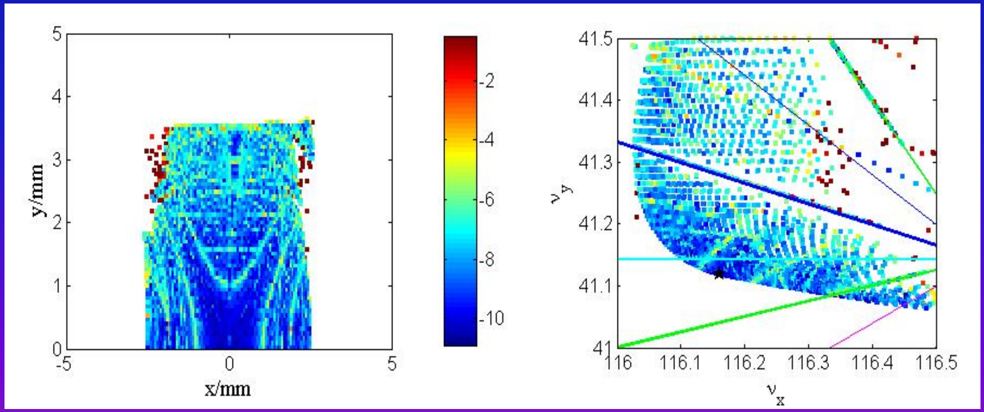
Key issues: *beam stability, injection efficiency, tolerance, other limitations*

Parameters	Unit	Value
E_0	GeV	6
I_0	mA	200
C	m	1295.6
$J_x/J_y/J_z$		1.37/1.0/1.63
ε_0	pm	59.4
$\upsilon_{x/y}$		116.16/41.12
$\xi_{x/y}$		-214/-133
7BA No.		48
L_{ID}	m	6
$\beta_{x/y}$ at ID	m	9/3.2
$\tau_{x/y/z}$	ms	18.9/25.9/15.9
U_0	MeV	1.995
σ_ε		7.97×10^{-4}
α_p		3.74×10^{-5}

Half integer resonance reached for $\delta \sim \pm 3\%$

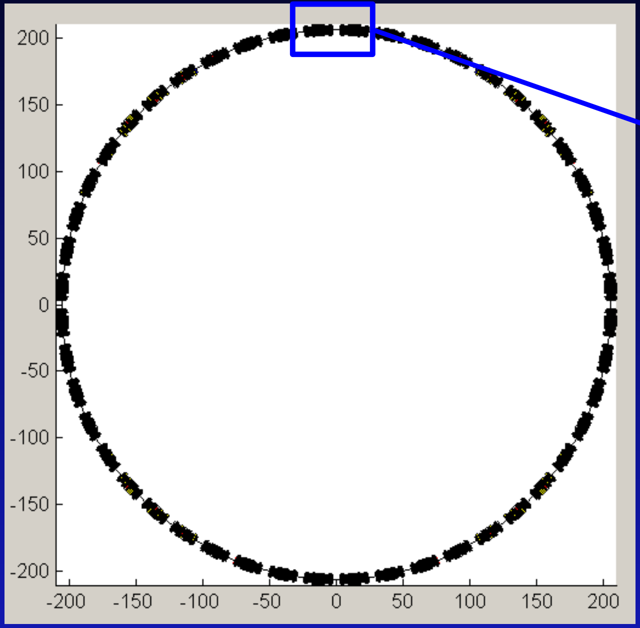


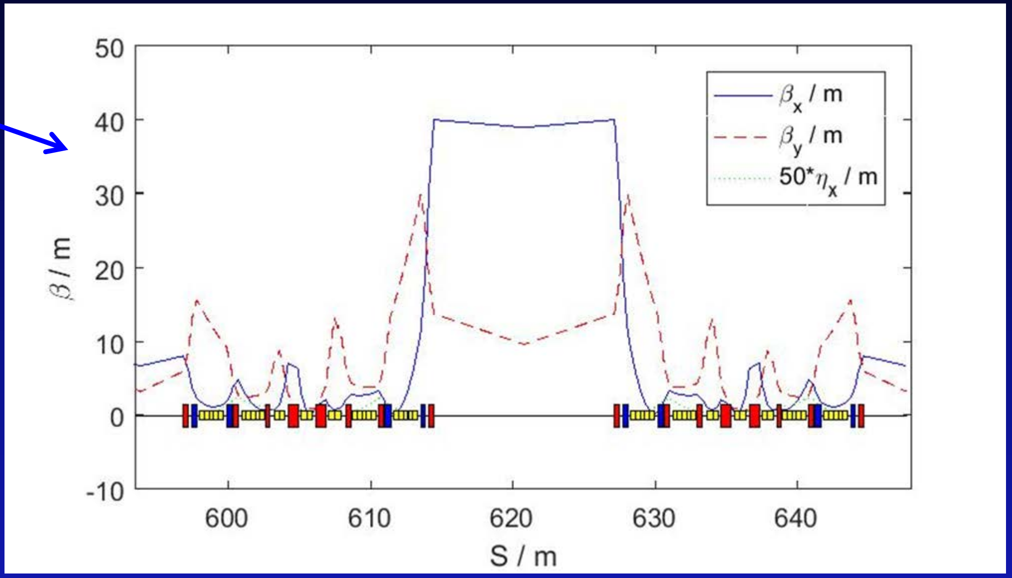
'Effective' DA ~2.5 mm in *x* and ~3.5 mm in *y* (bare lattice)



Candidate main ring design for off-axis injection

Enlarging DA by replacing a few ID sections with high-beta sections





- The two 7BAs neighboring the high-beta section are re-matched to make an ***I transportation*** with $\Delta\mu(x,y) = 2n\pi$, and without sextupole/multipoles therein, so as to restore the lattice periodicity;
- The on-momentum DA is enlarged by a factor of $(\beta/\beta_0)^{1/2}$, the square root of the ratio of the beta functions before and after optics matching;
- The $2n\pi$ phase advance does not hold for nonzero δ, leading to ***greater difficulty in MA optimization***. Sextupoles are grouped in more families and optimized to deal with this problem.

Double-frequency RF system

For longitudinal injection and to mitigate the Touschek and IBS effects

- Two candidate RF configurations were considered. They are with frequencies of ***166 and 500 MHz*** (for long. Inj.), and ***500 and 1500 MHz***.
- Double-frequency RF system promise long enough Touschek lifetime and weak IBS emittance growth
  - 200 mA beam current
  - 90% of the buckets are equally filled
  - x-y coupling 10%
  - RF parameters for a bucket height of 3.5%

Table. Beam parameters for different RF configurations.

	RF_{166}	RF_{166}^{500}	RF_{500}	RF_{500}^{1500}
Voltage (MV)	2.64	0.53	3.45	0.91
Rms bunch length (zero current) (mA)	5.49	32.1	2.48	12.1
Rms bunch length (with IBS) (mm)	5.88	32.7	2.62	12.3
Rms energy spread (with IBS) (10^{-4})	8.56	8.12	8.43	8.09
Horizontal emittance (with IBS) (pm.rad)	67.5	57.2	65.0	56.9
Touschek lifetime (h)	3.50	17.9	4.60	20.1

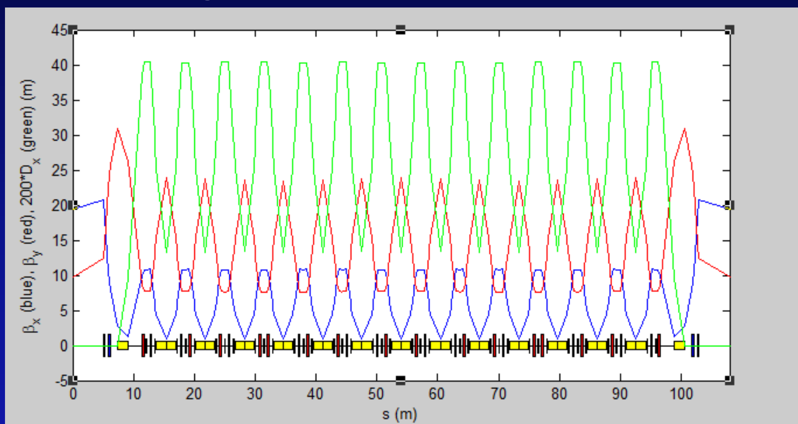
By Saike Tian

Booster: in a separate or the same tunnel ?

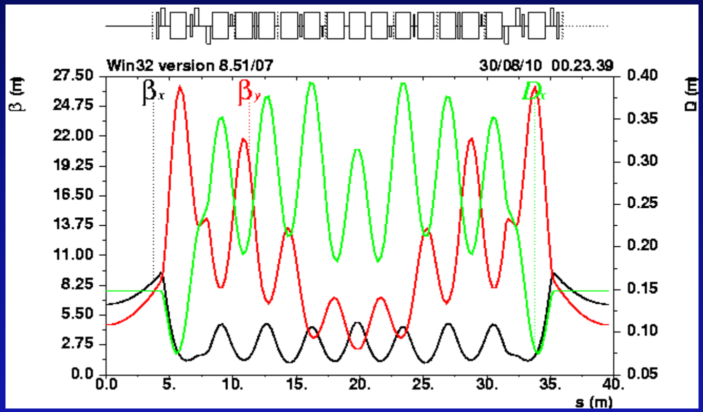
Three candidate designs and optimizations are simultaneously under way.

Two designs consider booster length of 1/3 of the main ring.

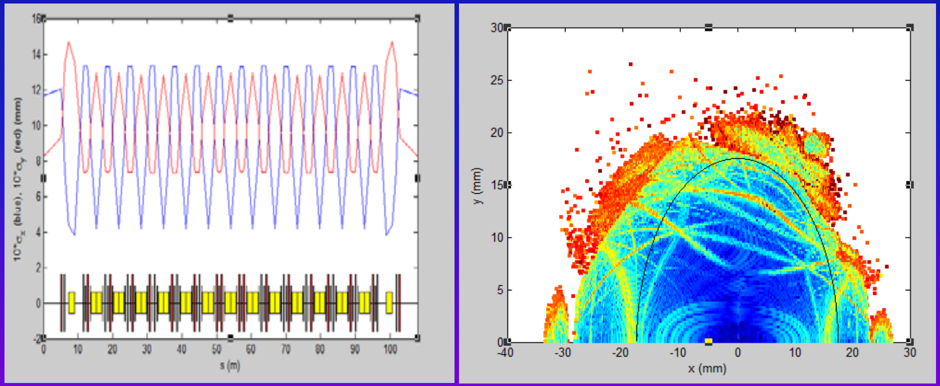
15BA design, 4.3 nm.rad @ 6 GeV, C = 432 m



NSLSII booster (37.4 nm.rad @ 3 GeV, C = 158.4 m) by BINP

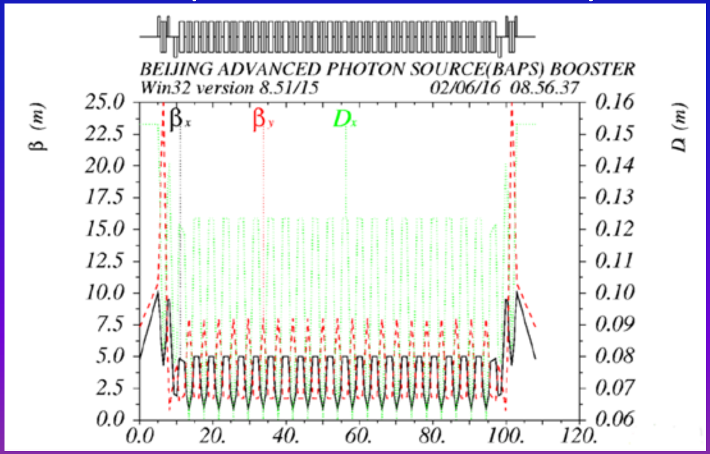


10σ(x/y) < 15 mm while DA(x/y) > 18 mm



4 nm. rad @ 6 GeV, C = 432 m

DA optimization is underway

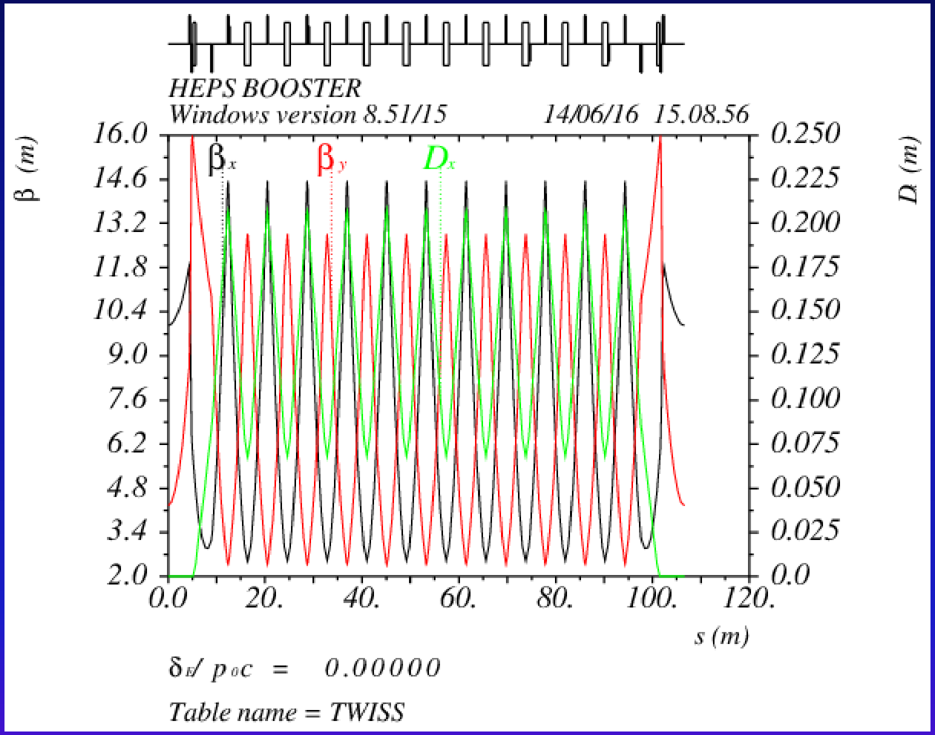


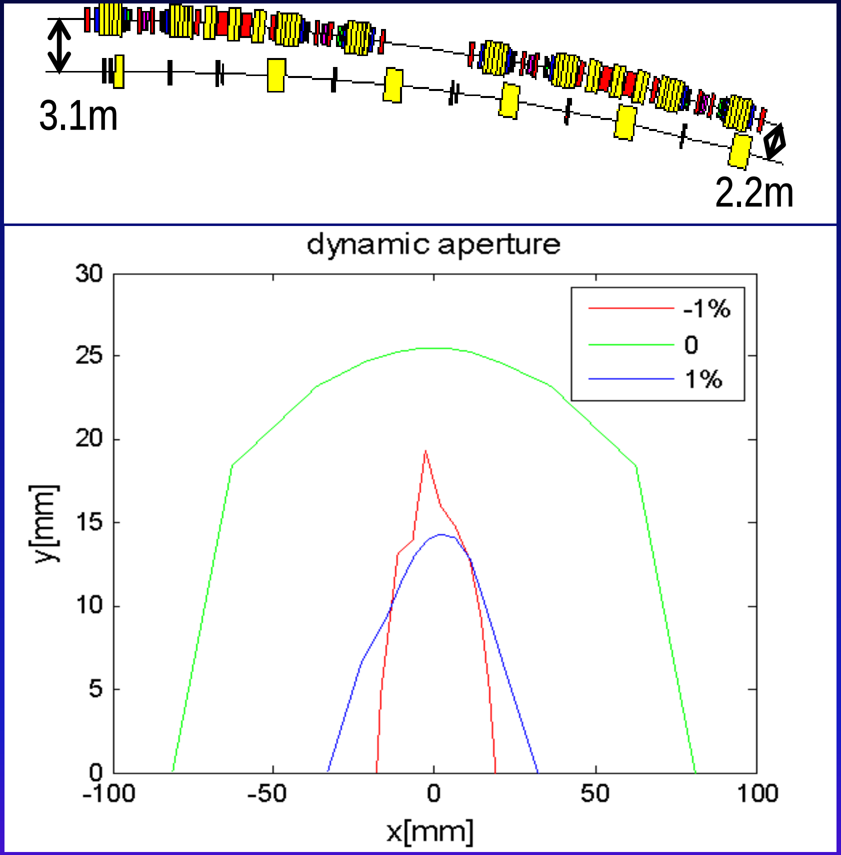
By Yuemei Peng & Yi Jiao

Booster: in a separate or the same tunnel ?

The other design shares the same tunnel as the main ring.

12BA, 2 nm.rad @ 6 GeV, C = 1249 m





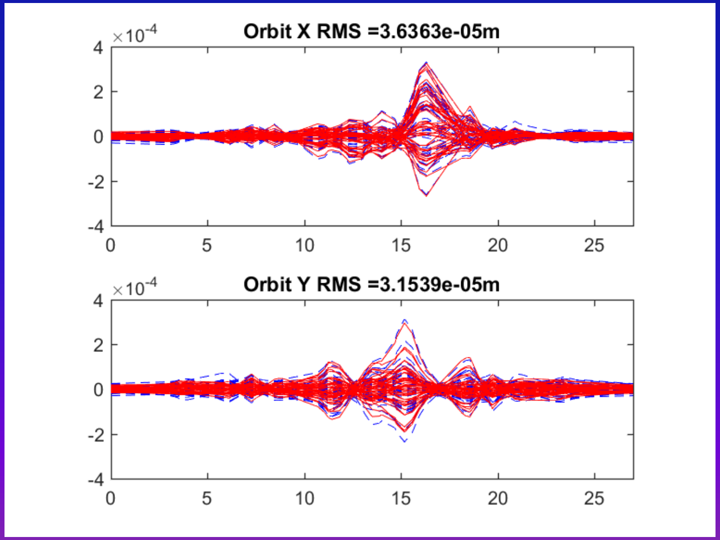
Decision will be made later, after comparing the performance as well as the cost.

By Yuanyuan Guo,
Gang Xu

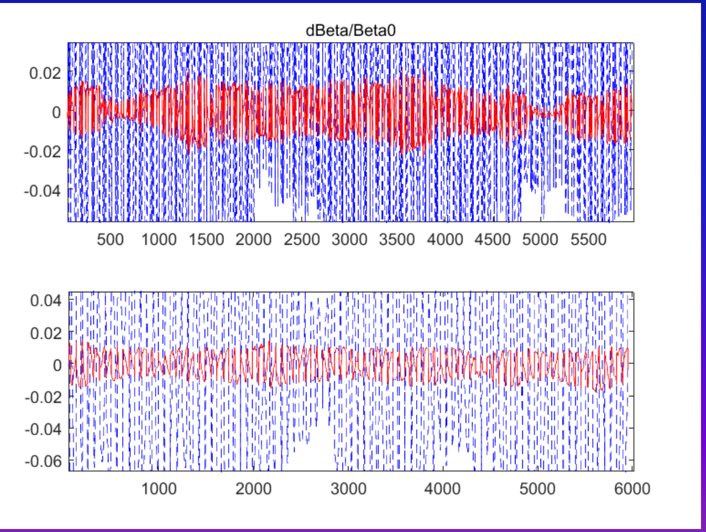
Error tolerance study

- Model various errors, then simulate the lattice calibration process
  - Nominal field error (1e-3, 2e-4, 1e-3 for B, Q, S)
  - Multipole field components (1e-3) of magnets
  - Alignment error (30 μm) and rotation (100 μrad)
  - BPM solution (0.5 μm)
- ***Alignment error (30 μm)*** has dominant effects.
- ***Dispersion and coupling correction*** is necessary. If they are not controlled, the vertical emittance can grow to 10~ 30 pm.rad.

RMS(Orbit)~=RMS(alignment Error)



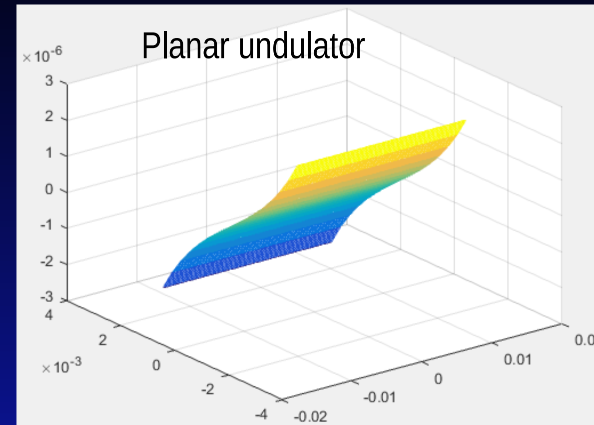
Max. Beta Beat < 1.5%



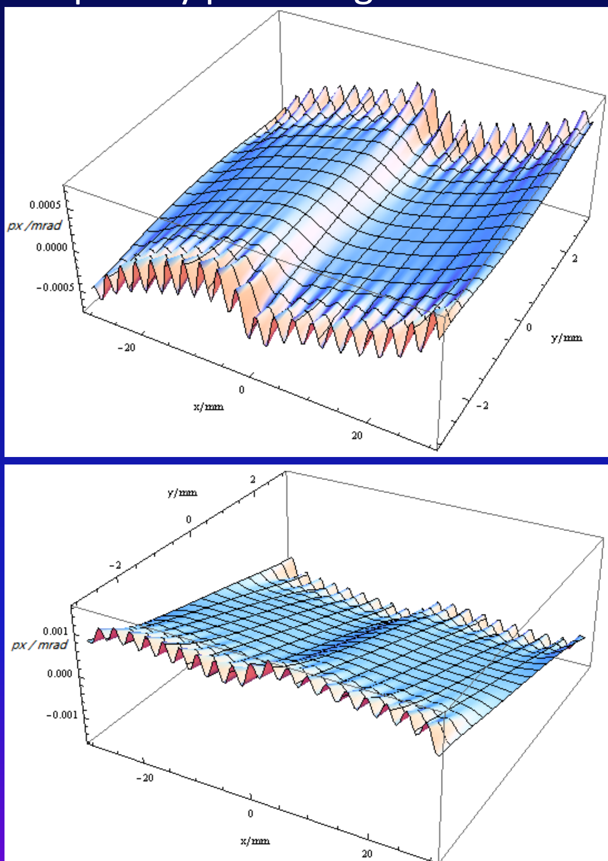
By Daheng Ji

ID effects: in an acceptable level

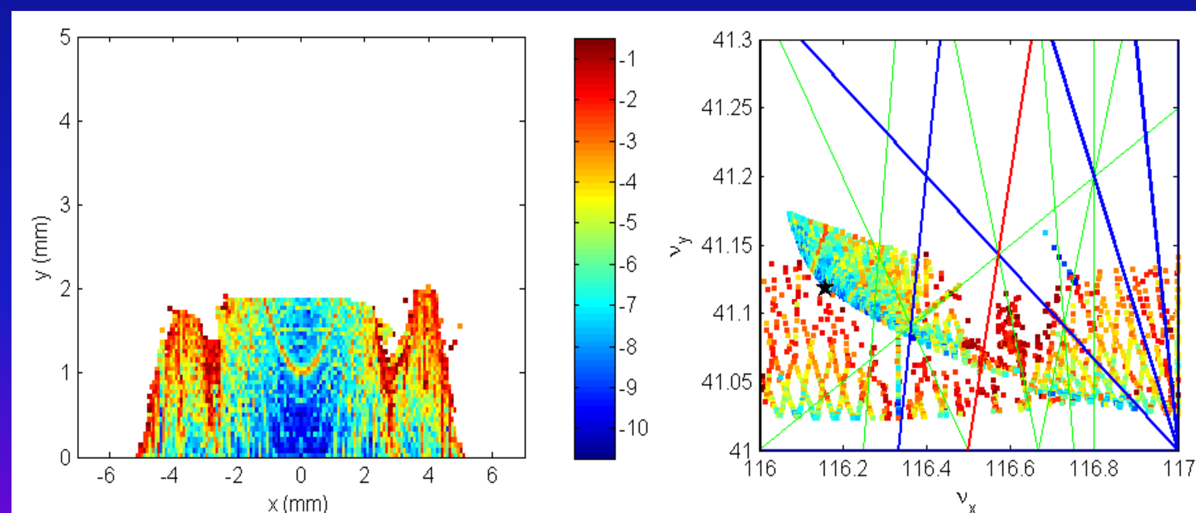
- Construct kick maps with Hamiltonian-Jacobin methods for 14 undulators to be installed in the first construction stage of HEPS



Elliptically polarizing undulator



- Induced tune shift on the order of 0.003
- ***Obvious DA reduction, but not affects on-axis inj.***



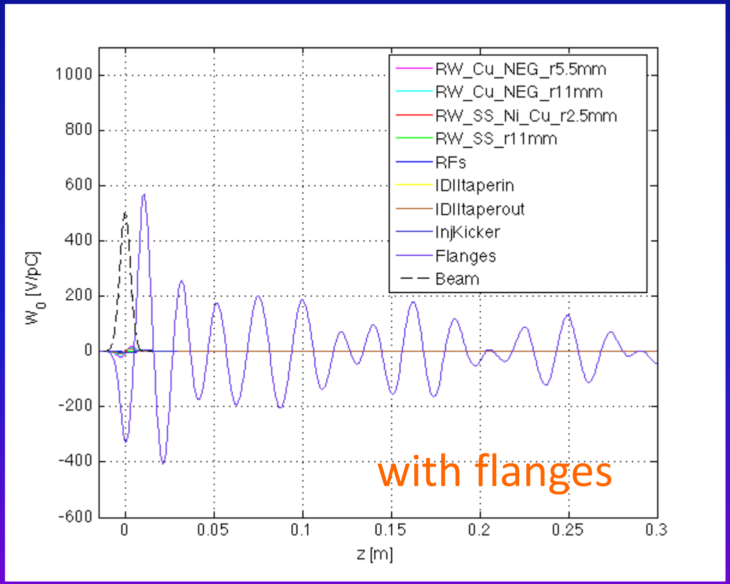
By Xiaoyu Li

Collective effects: impedance model

Preliminary impedance model obtained for instability studies

Resistive Wall		
Material	**Aperture [mm]**	**Length [m]**
Stainless Steel + Cu	11	679
Stainless Steel	11	48
Cu + NEG	11	277
Cu + NEG	5.5	180
Iron+Ni+Cu	2.5	30

Geometrical contributions	
Elements	**Number**
RF cavities	2
Flanges	1000
Injection kickers	4
B chamber	192
Antechambers	336
Undulator tapers	60 pairs



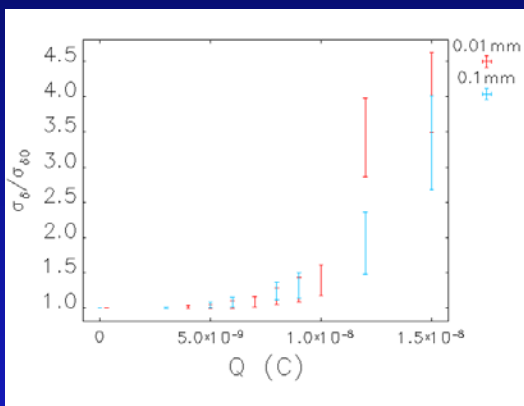
Longitudinal wake potential (σ_z =3mm)

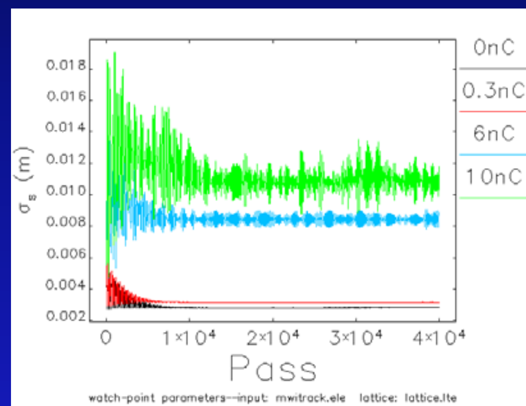
- The ***longitudinal impedance*** is dominated by ***large number elements***, e.g., flanges.
- The ***transverse impedance*** is dominated by the ***resistive wall impedance*** due to the small aperture beam pipe.
- More impedance contributors will be included in the following studies.

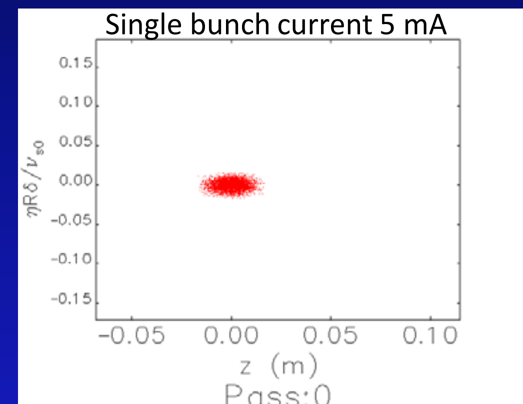
By Na Wang, Saike Tian, Xiaoyu Li

Collective effects: single bunch instability

- *Microwave instability*
  - The Keil-Schnell criterion gives threshold bunch current of 0.1mA.
  - Preliminary simulations with Elegant are performed based on the Pseudo-Green wake. Considering only the resistive wall impedance, the threshold intensity is around 1.1mA (5 nC) with harmonic cavity. Above threshold, turbulent distributions are observed.

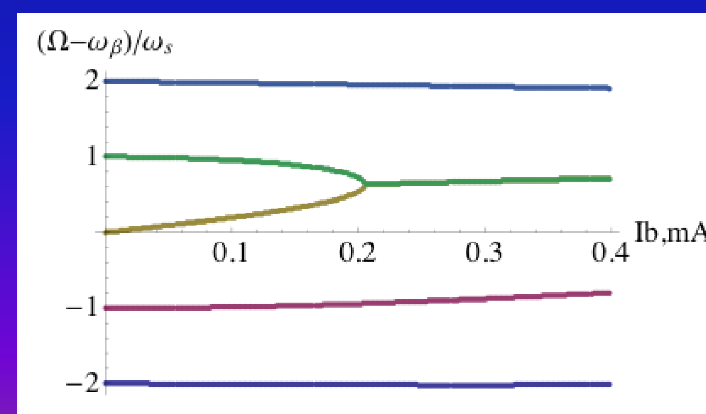






- *Transverse mode coupling instability*
  - For Gaussian bunch, the instability is evaluated with Eigen Mode analysis.
  - The threshold bunch intensity is around 0.2mA.

σ_z = 3 mm, υ_z = 0.0015, in the case with shortest σ_z during long. Inj.



By Na Wang, Zhe Duan

Several interesting topics

- What are the ***major sources*** limiting the dynamics of a DLSR, and how to deal with them?
- How to effectively and efficiently explore the ***ultimate performance*** of a special DLSR design?
- With limited ring acceptance, is it still feasible to realize ***beam accumulation*** in a DLSR?

Several interesting topics

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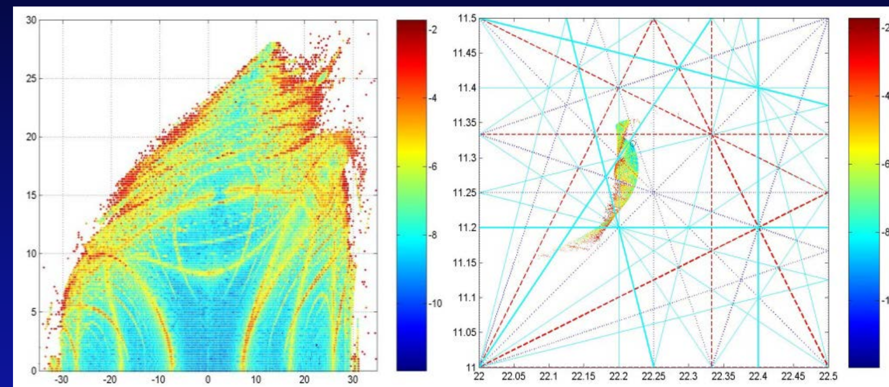
Integer & half integer resonances (IRs & HIRs)

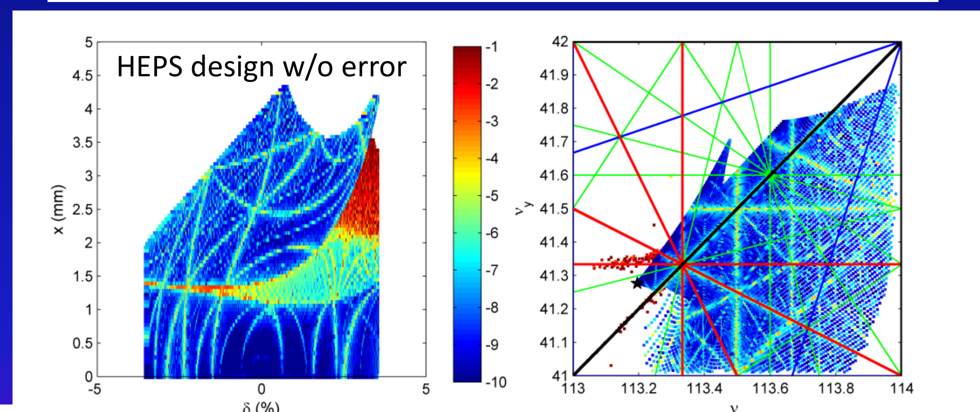
Main sources limiting the dynamics of a DLSR

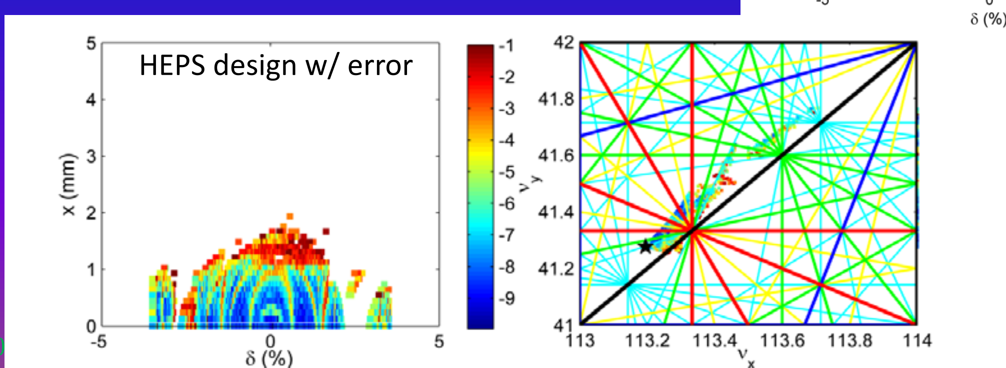
In a 3GLS, the detuning terms can be minimized, footprint far from the IR and HIRs, the dynamics limited by ***higher order resonances***



In a DLSR light source

- Stronger nonlinearities and larger detuning terms (tune shifts with amplitude and δ)
- resonances usually reached for small amplitudes and δ
- Higher order resonances are weak and has small effects.
- But, ***IRs and HIRs strongly impact the dynamics*** even for small amplitudes.





IRs and HIRs excited by linear field errors limit the available MA!

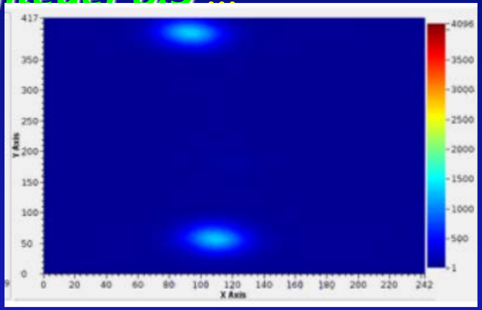
Another HEPS design with tunes of (113.20, 41.28).

Direction of breakthrough: remove HIR limitation

HIRs are less fatal to dynamics compared to IRs

- In TGLSs beam can be stored within the vertical HIR stop-band.

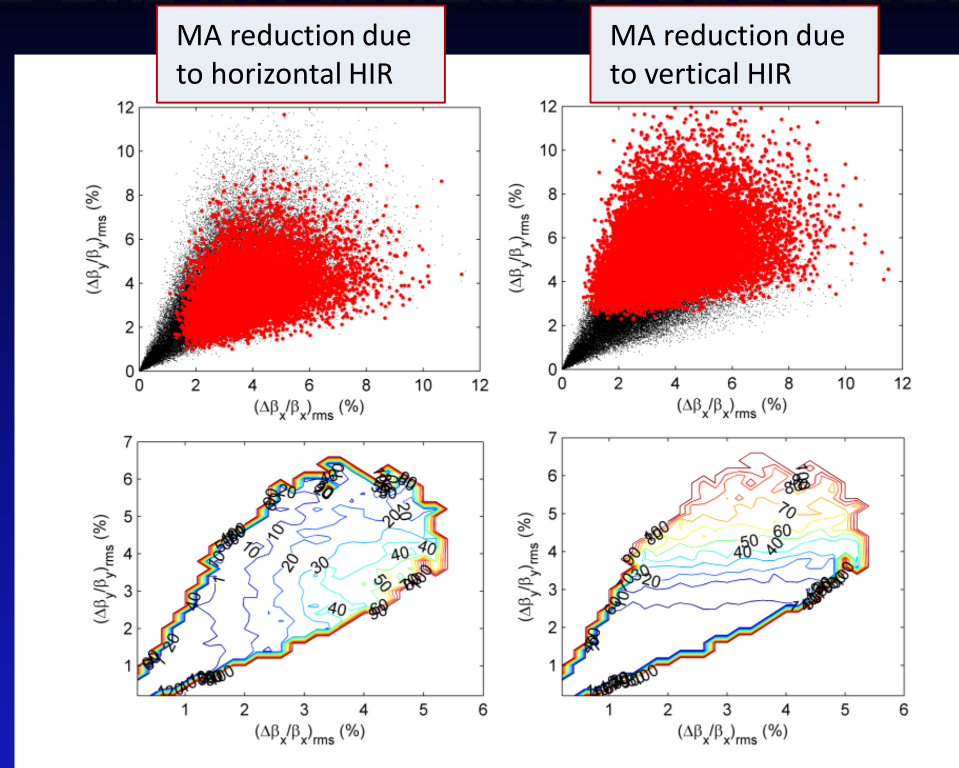
Swiss Light source (A. Streun, et al. 2001):
"…The tuning range is quite large: in the horizontal the integer 20 can be approached to 0.05, the half integer 20.5 to 0.005… *in the vertical* the integer 8 can be approached by 0.01. ***The beam is not lost on the half integer 8.5 …"***



NSLS-II (F. Willeke, 2015):
"…After optics corrections, the ***half integer stop bands can be crossed without beam loss***…" (Note: the HIR here means a vertical HIR)

- Simulation studies suggest that in DLSR it might be possible to cross HIRs without beam loss even with large errors. (APS-U, M. Borland, et al. 2015).

HIRs: can safely crossed but w/ stringent condition

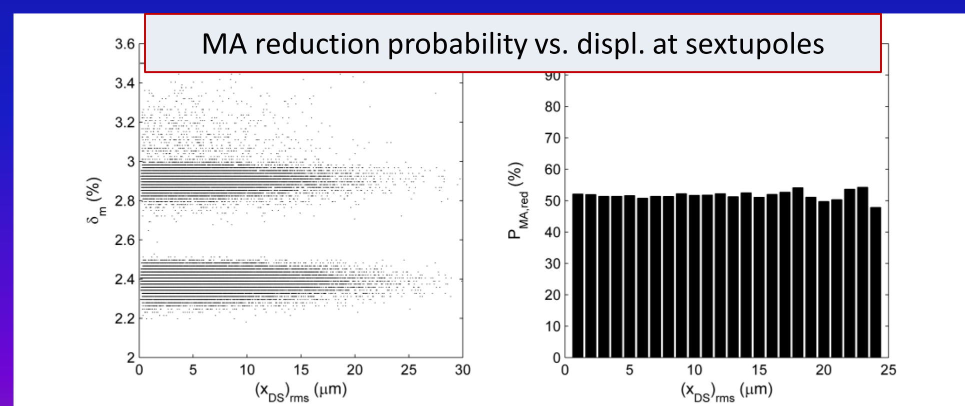


Statistical analysis based on the HEPS design (quad. field error & displacements at sextupoles):

- ***MA/DA reduction due to HIRs will not happen or with a very small probability (~1%) , if the $(\Delta\beta/\beta)_{rms}$ is below 1.5% in x and 2.5% in y planes;***

- ***Horizontal HIR is generally stronger than vertical HIR;***

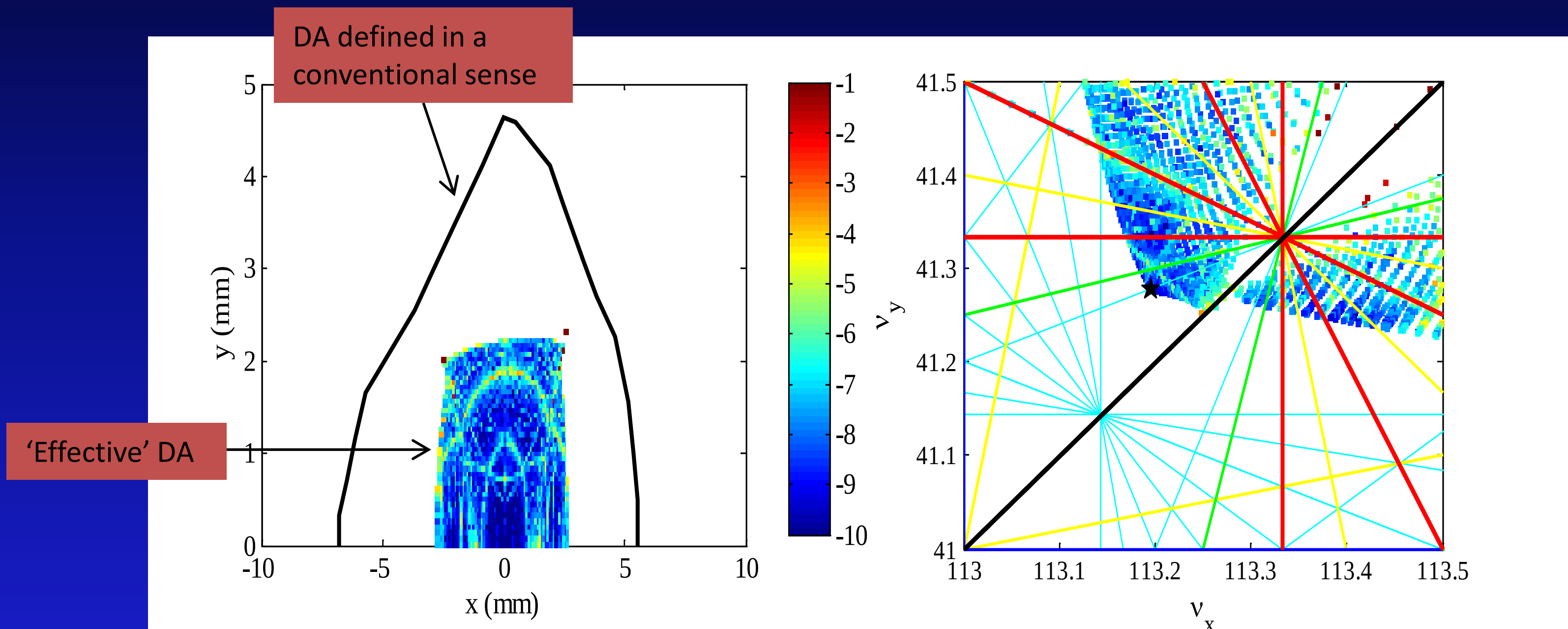
- ***The HIR effects rely only on the beta beat level, while not with the concrete error source.***



Y. Jiao and Z. Duan, arXiv:1606.07191.
Submitted to NIM-A.

'Effective' DA & MA: that limited by IRs and HIRs

This can provide a quick and reasonable measure of the realistic acceptance of a DLSR while with only the bare lattice in hand !



This will facilitate the optimization of a DLSR design, especially for the multi-objective optimizations based on numerical tracking results.

Y. Jiao and Z. Duan, arXiv:1606.07191.
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MOGA: mostly used in accelerator optimizations

MOGA: Multi-Objective Genetic Algorithm

MOGA has applied to many accelerator optimization problems.

Linac: I.V. Bazarov and C.K. Sinclair, Linac, PRST-AB, 2005; ***Ring optics***: L. Yang, et al., ring optics, NIM-A, 2009
Ring nonlinear dynamics: M. Borland, et al., PAC09, 2009. L. Yang, et al., PRST-AB, 2011.
Ring linear and nonlinear dynamics: W. Gao, et al., PRST-AB, 2011…

But when applying it to HEPS, *not effective in looking for the global optimum* in some cases.

1, MOGA (26 variables, 500 generations) based on the HEPS design, for the case with $L_{ID} \equiv 6$ m

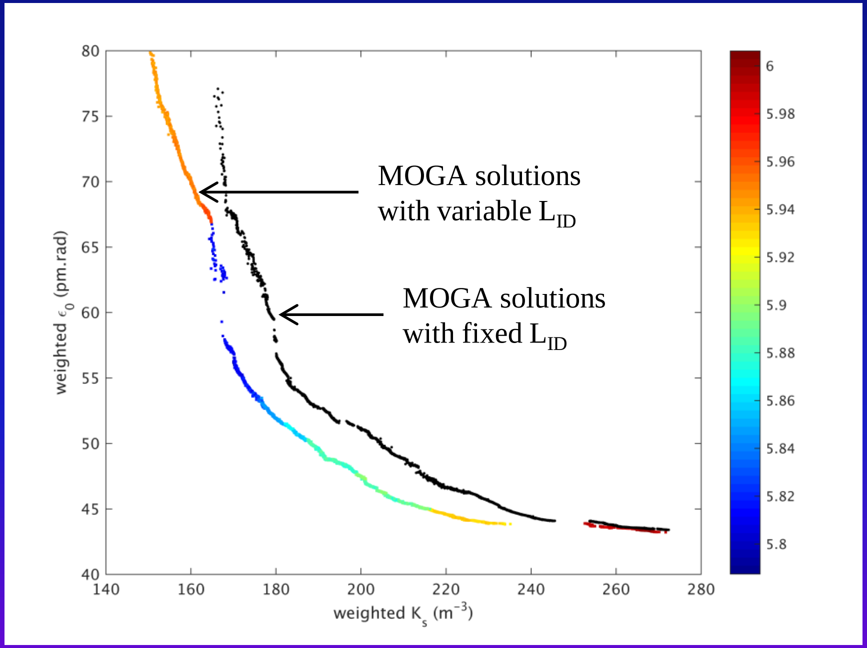
If with a shorter L_{ID}, the variables will have larger adjustment space, and one can find better results.

2, From solutions for $L_{ID} \equiv 6$ m, further optimization by varying L_{ID}

- MOGA of 800 generations
- Initial L_{ID} values: 6 m + randn × 0.1 m
- Tuning range of L_{ID} : [5, 7] m

Better solutions found with MOGA, but not the global optimum

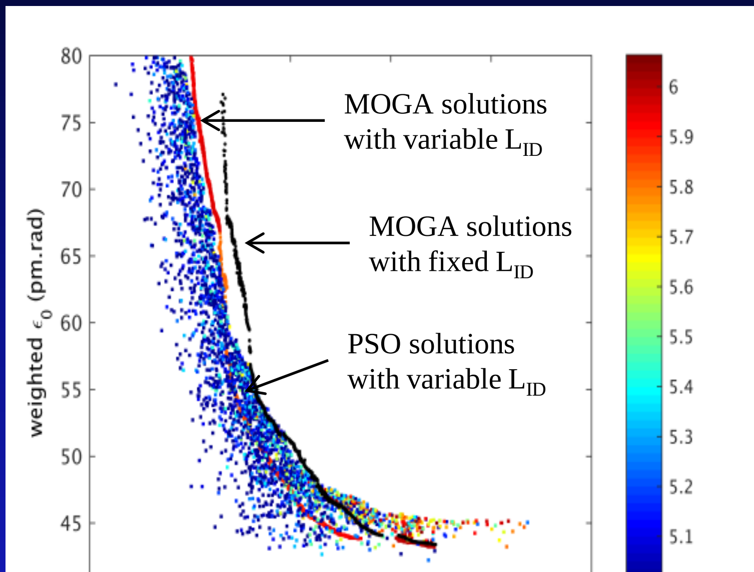
- The L_{ID} values of the final population do not exceed the L_{ID} covering range of the initial population



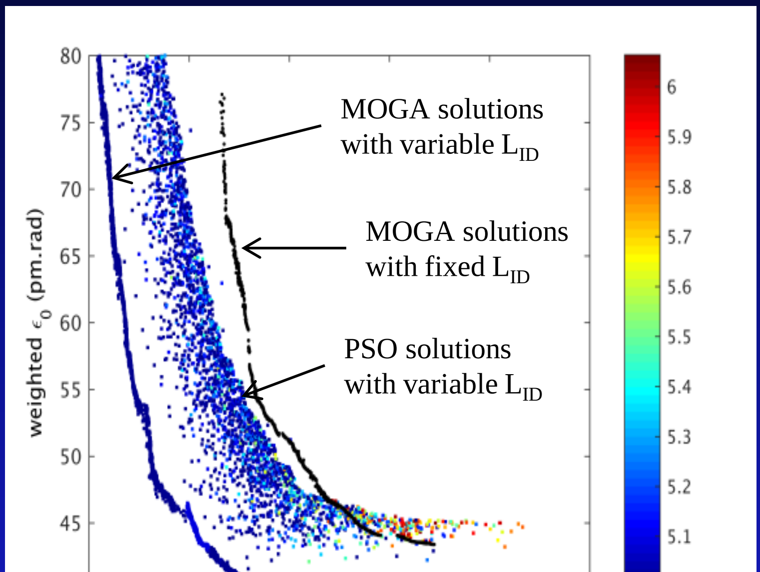
MOGA vs. PSO, particle swarm optimization

PSO: Particle Swarm optimization

Evolve with PSO for 800 generations as well



Further evolve with PSO and MOGA for 500 generations



The solutions obtained with PSO and then with MOGA accord with expectation

PSO solutions:

- **Better performance (smaller ε_0 or K_s)**
- **Most of the L_{ID} values close to 5 m**

➢ ***PSO breeds more diversity in the evolution of population***

MOGA solutions:

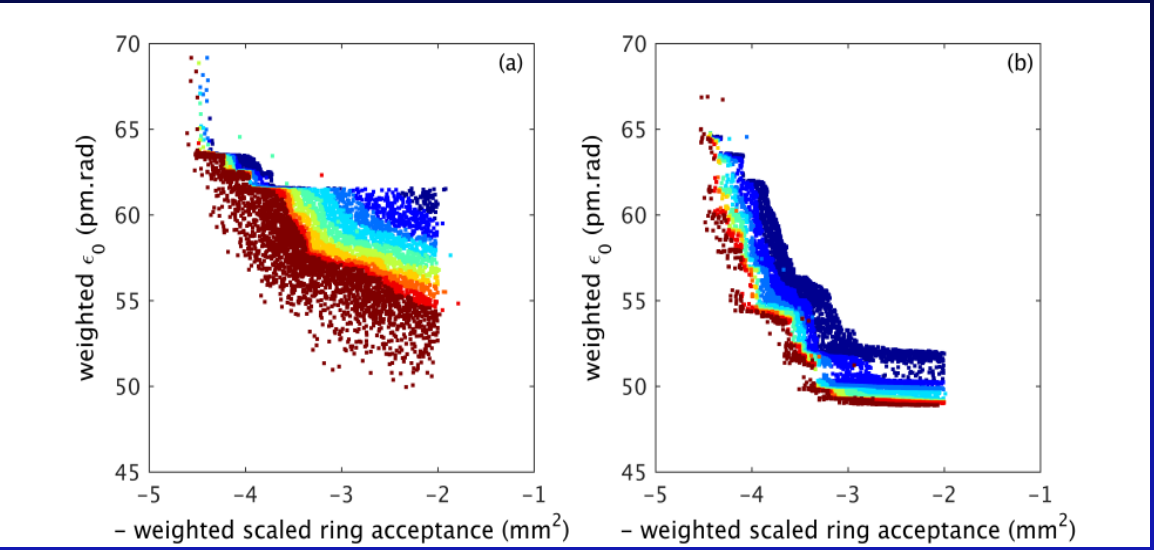
- **Better performance (smaller ε_0 or K_s)**
- **Better convergence**

➢ ***Once with enough diversity, MOGA reaches better convergence***

Combination of PSO and MOGA in HEPS design

Apply them in a successive and iterative way!

Simultaneously optimize the HEPS natural emittance and ring acceptance



- ➢Solutions continuously distributed in the objective function space;
- ➢Almost a monotonous variation of the scaled ring acceptance with the natural emittance;
- ➢The optimization enable us to find designs with ***shorter sextupoles and octupoles, lower natural emittance but larger effective DA and MA.***

Y. Jiao and G. Xu, arXiv:1605.05021 submitted to PRAB

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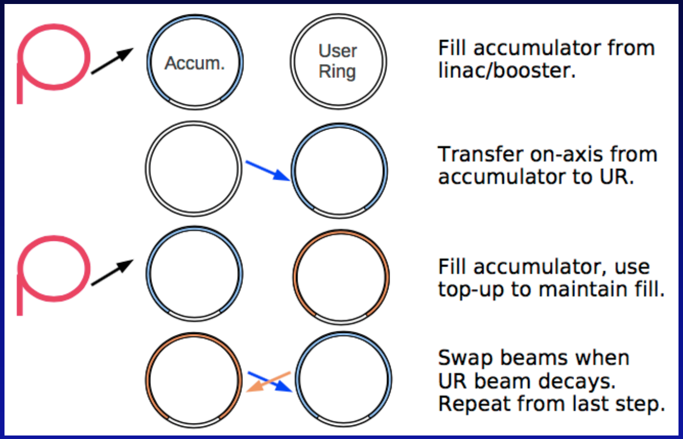
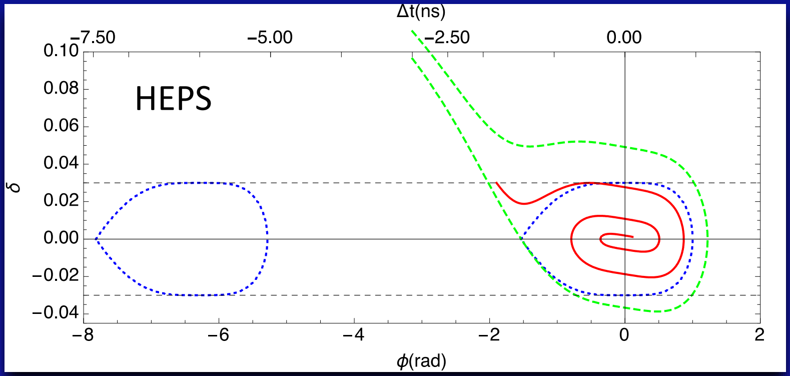
On-axis injection schemes

- The required ring acceptance of traditional off-axis is hard to achieve

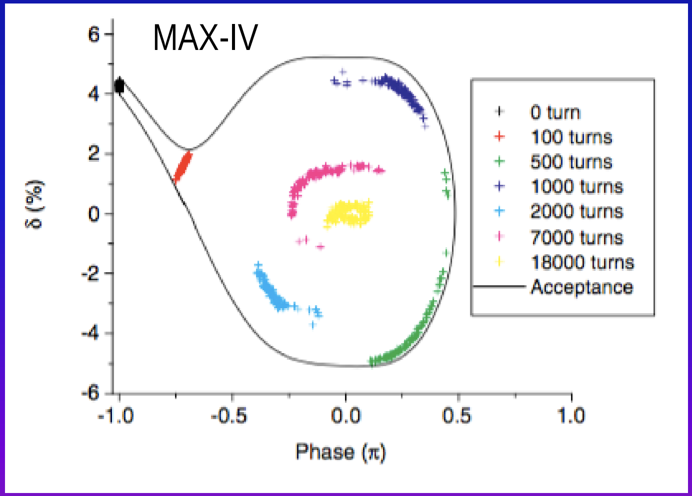
Swap-out, M. Borland, USR workshop, 2012



- Swap-out injection:
  - Requires full-charge injector
  - Not beam accumulation
  - Complexity in beam dump



Long. Inj., M. Aiba, et al., PRST-AB, 2015

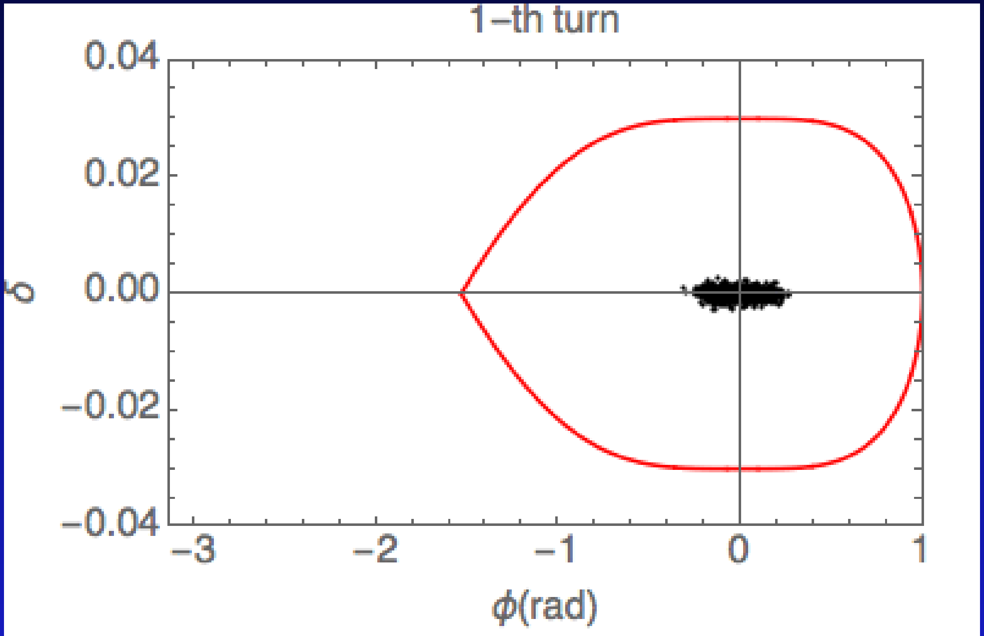


- Longitudinal injection
  - Requires large MA (> 5%).
  - Or a very challenging injection kicker (< 1.8 ns rising time).

On-axis inj. & accumulation with RF manipulation

Enabled by phase manipulation of a double-frequency RF system

RF system: 166 + 500 MHz active RF cavities; a complete injection cycle takes about 200 ms.



- ***Released kicker requirement***: *6 ns full-width and 2.5 nm rising time*
- ***Released MA requirement***: feasible with a MA of 3%
- ***Promise beam accumulation***: stored bunch always fixed in RF bucket center

G. Xu, Z. Duan, et al., IPAC16, WEOAA02.
Submitted to PRAB

HEPS physical design Group at IHEP

Prof. **Gang Xu**
Vice leader of the HEPS-TF
Leading the HEPS physical studies

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In Closing…

- *HEPS will be the next storage ring light source with high energy and low emittance in China.*
- *Physical design is going smoothly.*
- *Efforts have been made to continuously improve the ring performance!*
- *Many challenging and also interesting questions need to be explored yet…*

Thanks for your attention!

Welcome collaborations on the HEPS design and DLSR-related studies!

Backup slides

Double-frequency RF system

For longitudinal injection and mitigate the Touschek and IBS effects

- Two candidate RF configurations were considered. They are with frequencies of ***166 and 500 MHz***, and ***500 and 1500 MHz***.
- Double-frequency RF system promise long enough Touschek lifetime and weak IBS emittance growth
  - 200 mA beam current
  - 90% of the buckets are equally filled
  - x-y coupling 10%
  - RF parameters for a bucket height of 3.5%

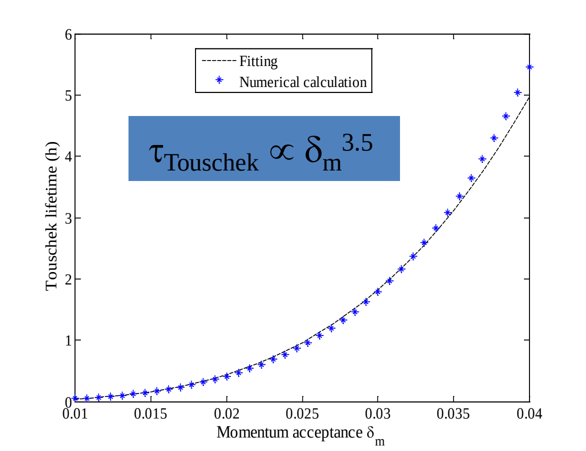

Table. Beam parameters for different RF configurations.

	RF_{166}	RF_{166}^{500}	RF_{500}	RF_{500}^{1500}
Voltage (MV)	2.64	0.53	3.45	0.91
Rms bunch length (zero current) (mA)	5.49	32.1	2.48	12.1
Rms bunch length (with IBS) (mm)	5.88	32.7	2.62	12.3
Rms energy spread (with IBS) (10^{-4})	8.56	8.12	8.43	8.09
Horizontal emittance (with IBS) (pm.rad)	67.5	57.2	65.0	56.9
Touschek lifetime (h)	3.50	17.9	4.60	20.1

By Saike Tian

On-axis long. Injection enabled by RF manipulation

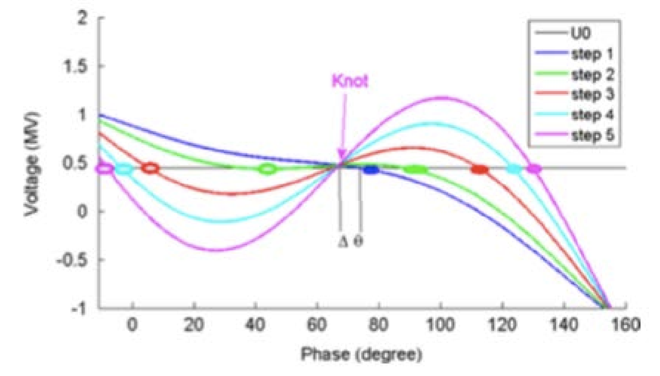

Fig. 1. Twin RF buckets creation by a double-frequency RF system with synchrotron phase deviation.

❑ B. Jiang
NIM A 814, 1,2016
voltage adjustment of 250MHz+500MHz RF cavities.

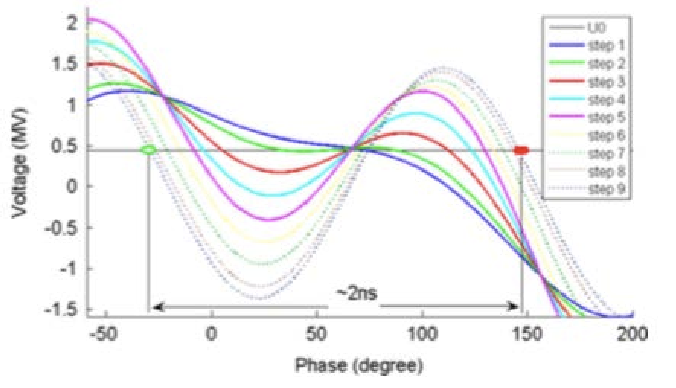

Fig. 2. Twin buckets separation.

- On-axis injection enabled by phase manipulation of a double-frequency RF system @ HEPS
  - The total four independent knobs are used through phase manipulation of RF cavities, which enables a better control of longitudinal phase space.
  - 166MHz + 500MHz active RF cavities
  - Compatible with a fast injection kicker with a 6ns full-width and 2.5ns rise time.
  - Stored bunch always fixed in RF bucket center

G. Xu, Z. Duan, et al., IPAC16, WEOAA02.
Submitted to PRAB

On-axis long. Injection enabled by RF manipulation

- A complete injection cycle takes about 200ms.
- The phase manipulation settings can be tuned according to the ring acceptance.
- Possible instability issues for very short bunch are under investigation but we believe it will not hamper the beam accumulation.
- Possible RF operation issues are also under study.