Lattice design and beam dynamics studies for the High Energy Photon Source (HEPS)

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On behalf of the HEPS physical design group

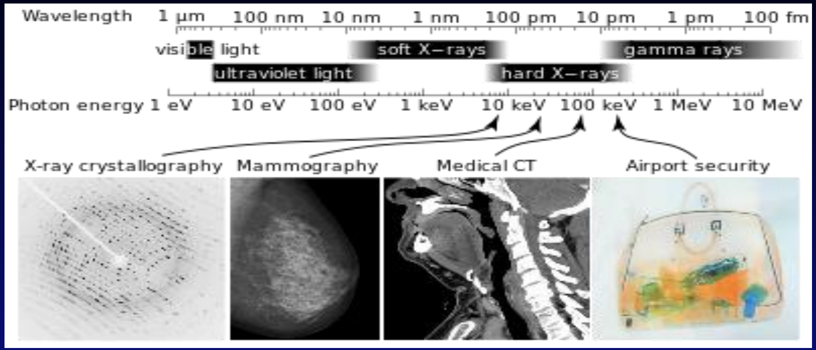
Oct. 26, 2016

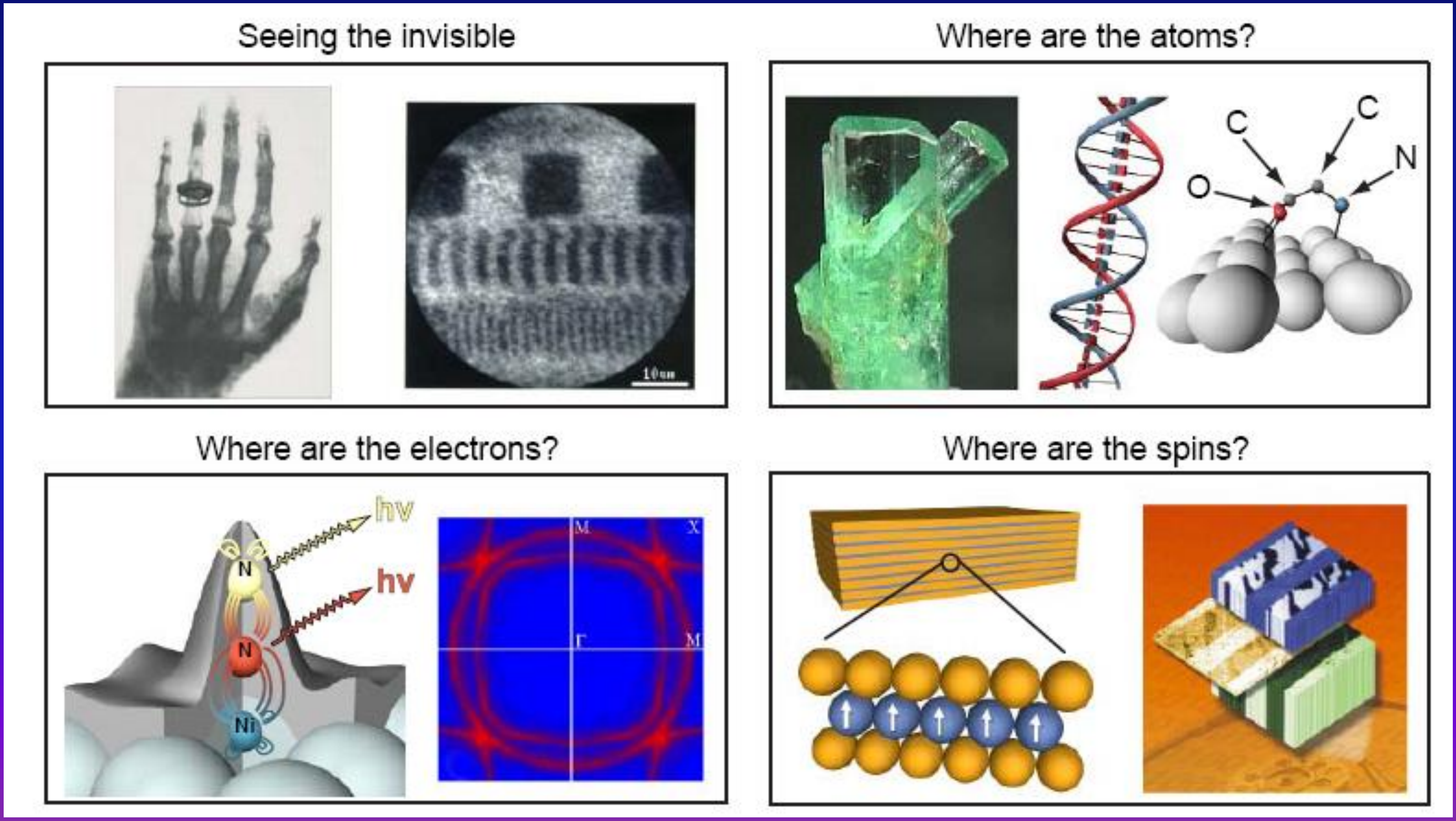
6th Low Emittance Rings Workshop (LOWeRing 2016)

Synchrotron SOLEIL, L'Orme des Merisiers Saint-Aubin - BP 48, France

Photons: Primary Tool to Probe Nature

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



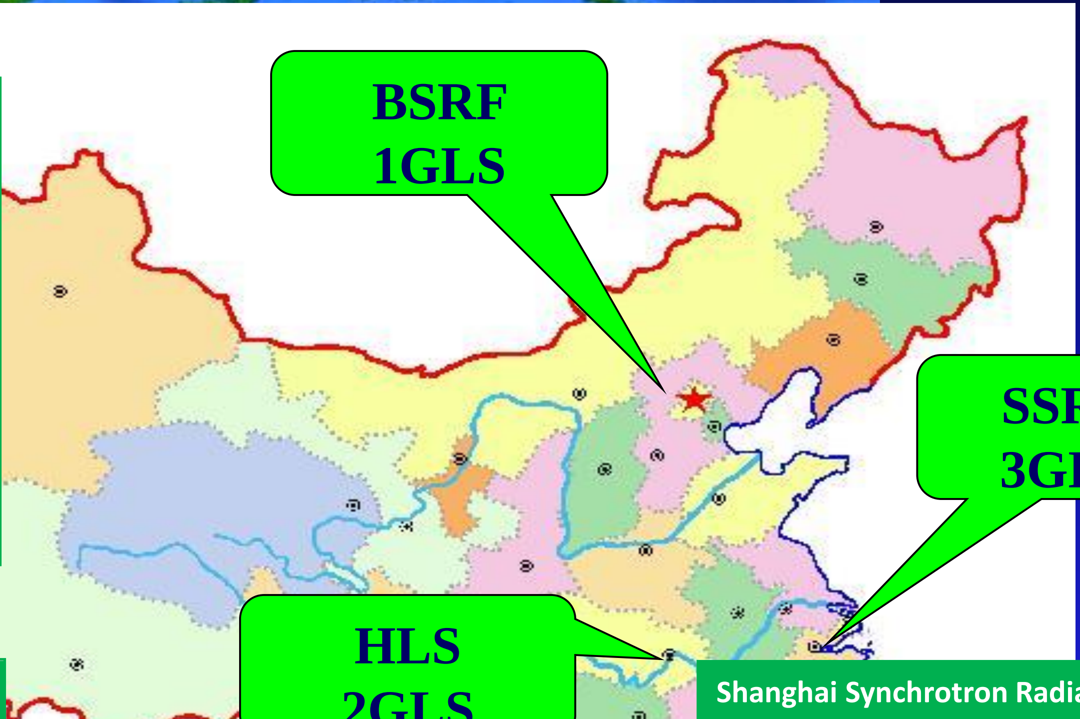


Storage Ring Synchrotron Radiation light source

Most used and successful photon science research platform worldwide

In China Mainland, 3 existing ring light sources

More than 50 facilities around the world!



Beijing Synchrotron Radiation Facility

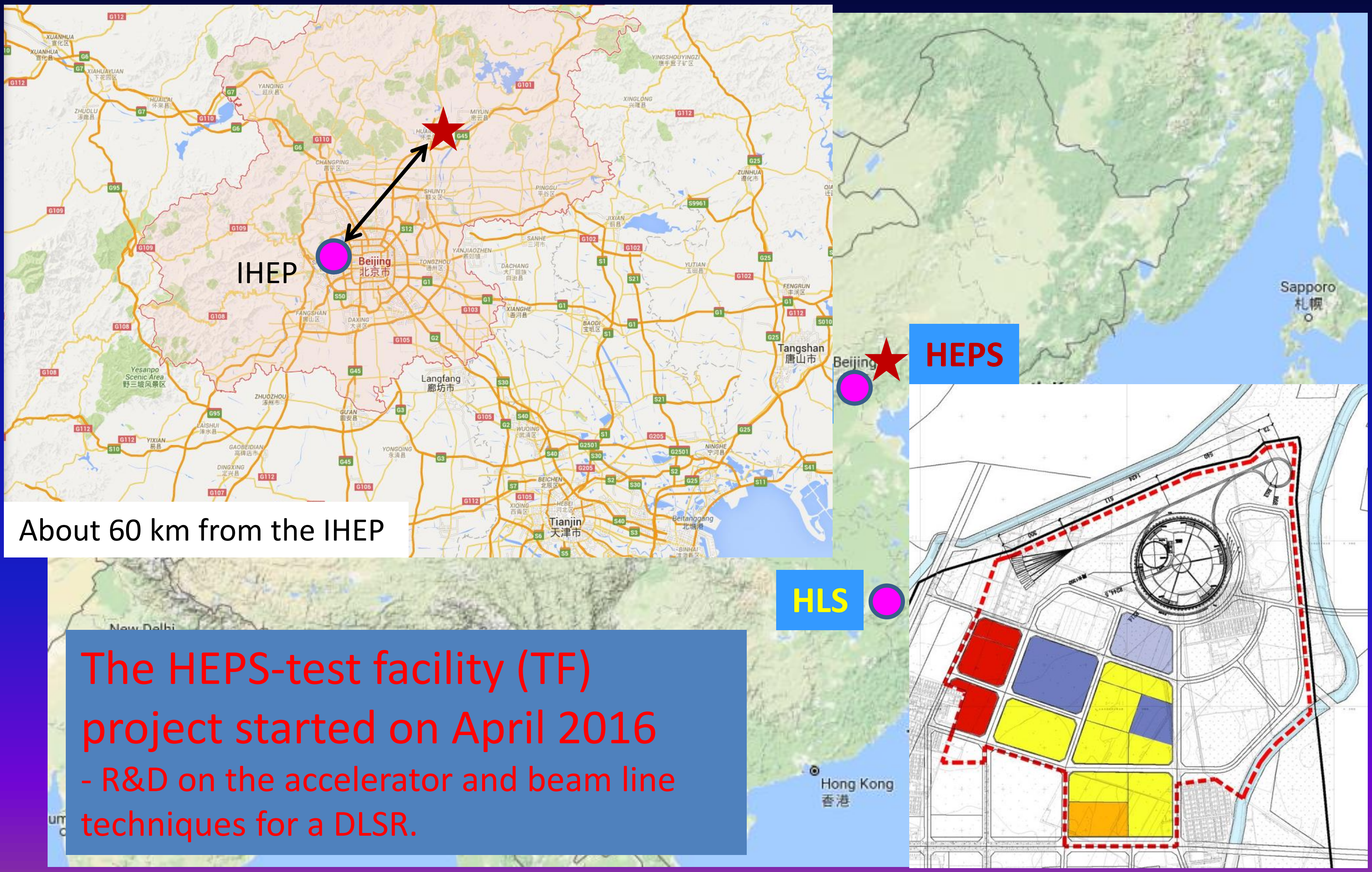
Hefei Light source

Shanghai Synchrotron Radiation Facility

Yi Jiao, Institute of High Energy Physics, jiaoyi@ihep.ac.cn

HEPS: the next ring light source in China

A new photon science research center at the north of China



The HEPS-test facility (TF) project started on April 2016

- R&D on the accelerator and beam line techniques for a DLSR.

Physical design for HEPS-TF and future HEPS project

Main goals:

- *give a final complete and 'optimal' DLSR design before construction of the HEPS project.*

  - compromise between Chinese technology level and innovation (e.g., lowest ε_0)

  - compromise between user requirements and accelerator performance

- *give a detailed parameter list and tolerance budget table for hardware systems.*

Status:

- *Reached a nominal design of the HEPS storage ring.*

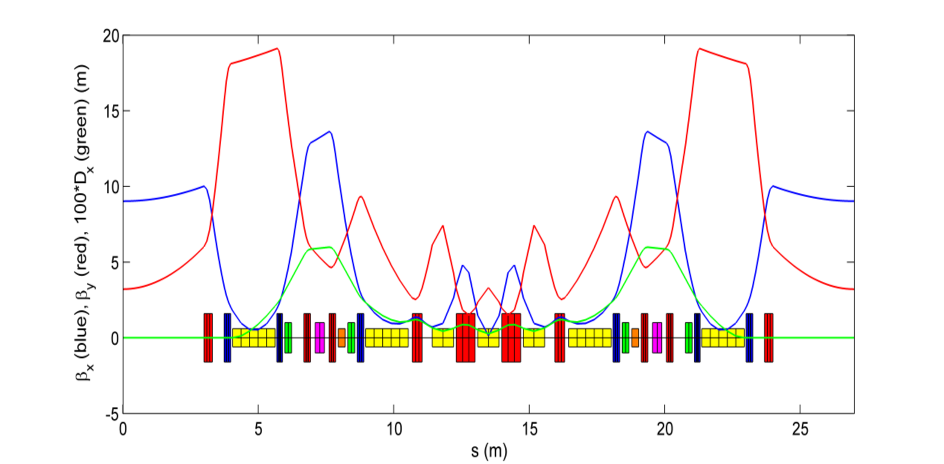
  - E = 6 GeV, ε_{x0} ~ 60 pm.rad, cir ~ 1.3 km.

- *Based on this design, injector (linac + booster) design, linear & nonlinear dynamics study, error study, on-axis injection design, collective effects study are underway. hardware R&D also launched.*

- *Alternative designs with similar or different layouts being explored in phase.*

Present nominal design of the HEPS storage ring

60 pm.rad @ 6 GeV, ~1.3 km

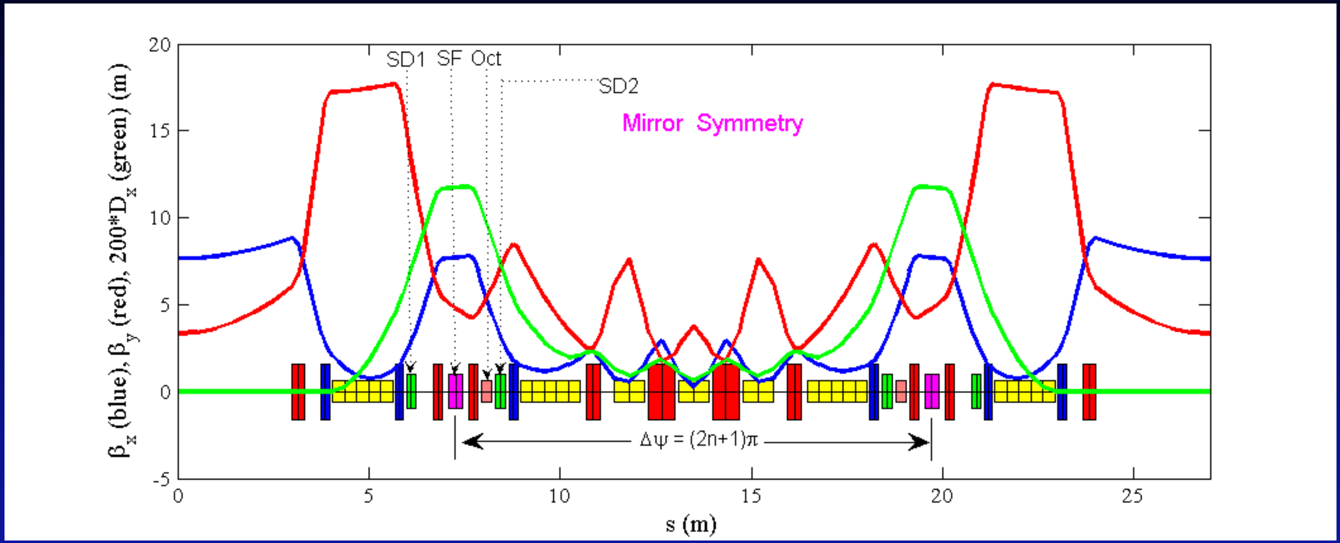


- 48 identical ***hybrid 7BAs***; Each 7BA is about 27 m.
- 48 dispersion-free ***6-m straight sections***, with beta functions of 9/3.2 m.
- 4 outer dipoles with long. Gradients; 3 inner dipoles with defocusing gradients.
- Neighboring 3 inner dipoles, high-gradient quadrupoles (~ 80 T/m).
- 6 sextupoles and 2 octupoles in one 7BA.

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}

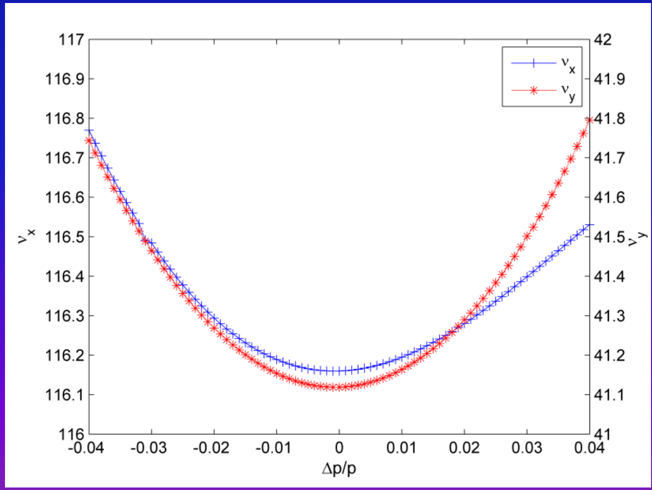
Present nominal design, nonlinear dynamics

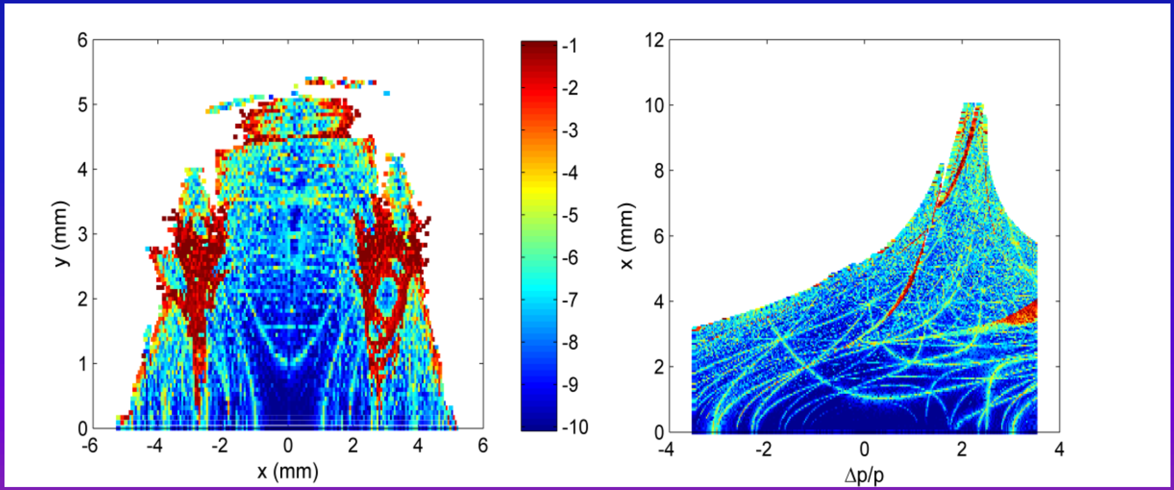
3 sextupole families & 1 octupole family, -I transportation between sextupoles.



Integer and half integer resonances can be reached at small amplitude & momentum deviation.

Tune vs. δ, ring acceptances projected in the (x, y) and (x, δ) planes, obtained with only the bare lattice



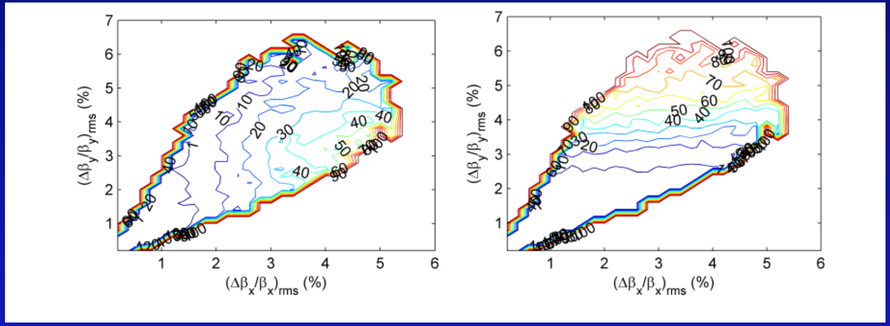


Present nominal design, nonlinear dynamics (cont.)

Impact from integer and half integer resonances should be well considered.

- ***Integer resonances***: it is generally believed ***integer resonances*** are always ***fatal to dynamics*** and can never be crossed.

- ***Half integer resonances***: it was experimentally (NSLS-II, G. Wang *et al*., IPAC16) and numerically (APS-U, M. Borland *et al*., IPAC15) shown that the ***half integer resonances can be safely crossed even with errors***. For HEPS, it was empirically found to keep the probability of MA reduction due to crossing of half integer resonances below 1%, the rms beta betas should be smaller than 1.5% in x and 2.5% in y plane.



MA reduction probability (%) for the HEPS

Left: caused by horizontal half integer resonances
Right: caused by vertical half integer resonances.

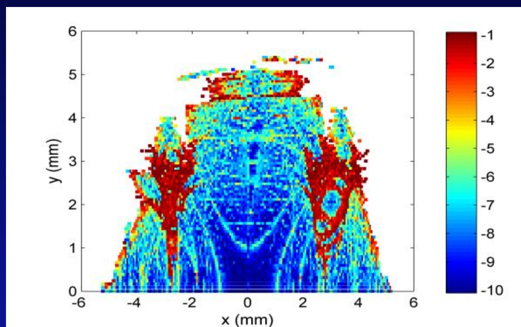
Y. Jiao, Z. Duan, NIM-A, 841, 2017

- In the preliminary design stage, we use ***'effective' DA and MA for the bare lattice*** by considering the limitation of integer and half integer resonances.
  - Within the effective DA or MA, not only the motion remains stable after tracking over a few thousand turns, but also the tune footprint is bounded by the integer and half integer resonances nearest to the nominal tunes.
  - In this way, one can avoid too optimistic estimation of the nonlinear performance of the actual machine, when having only the bare lattice in hand.

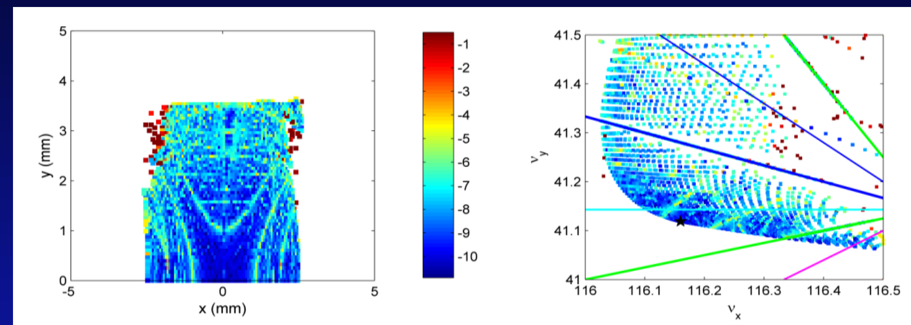
Present nominal design, nonlinear dynamics (cont.)

Conventional DA and LMA vs. effective DA and LMA

DA for the bare lattice, ~ 5 mm
(center of long straight section)



Effective DA for the bare lattice, ~ 3 mm
(center of long straight section)

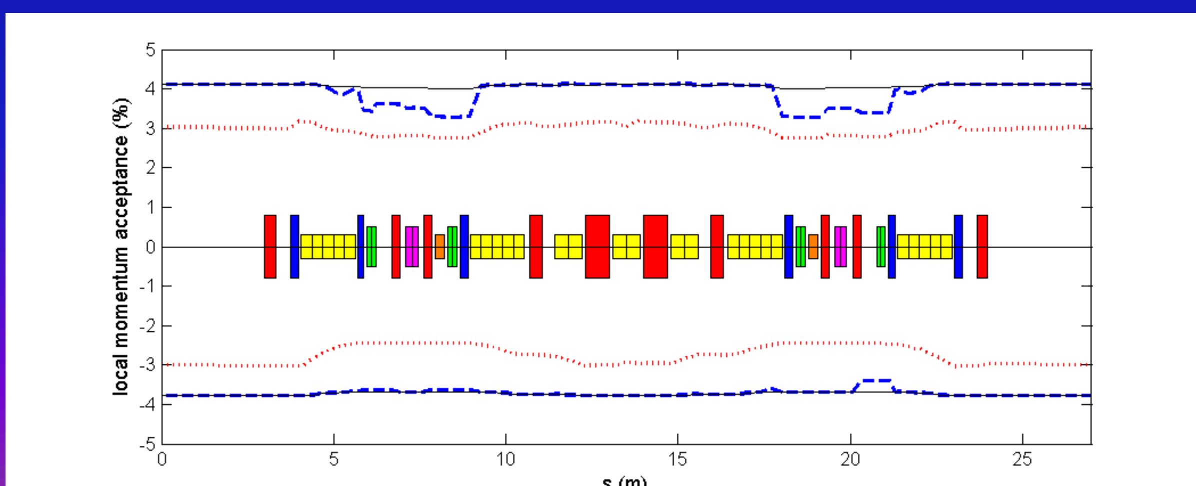


LMA along a 7BA obtained with only the bare lattice

Black: Particle loss in 2000 turns, ~ 4%

Blue: Particle loss or cross integer resonance, mostly ~4% and ~3.5% at dispersive region

Red: Particle loss or cross integer or half integer resonance (effective LMA), ~ 3% or lower



MA size closely related to the Touschek lifetime.

For HEPS, τ(Touschek) is proportional to $LMA^{3.7}$

200 mA, ~650 bunches/ 720 buckets

τ ~ 70 hrs (with LMA of 4%)

τ ~ 25 hrs (with LMA of 3%)

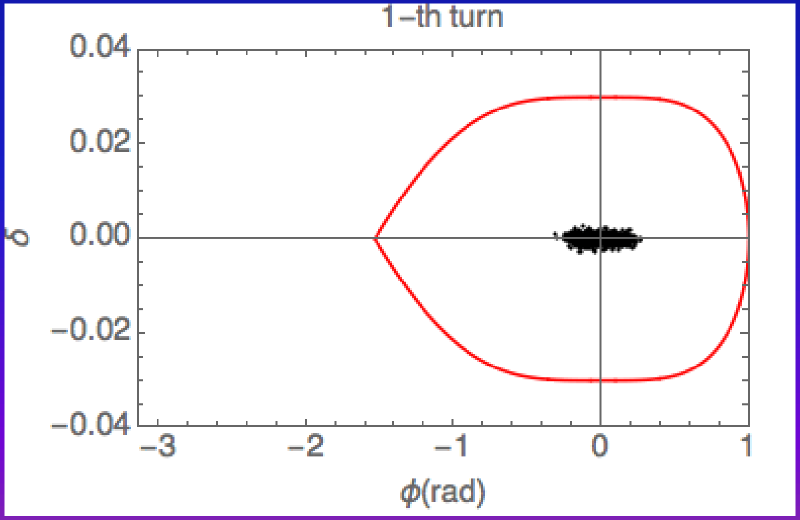
Plan to check in the presence of practical errors.

On-axis injection under consideration

Longitudinal and swap-out injection

- On-axis longitudinal injection by RF gymnastics of a double-frequency (166.6/499.8 MHz) RF system (G. Xu *et al.*, IPAC16)
  - When injection starts, first generate a new bucket near the stored bunch (in the bucket mainly determined by the fundamental RF cavities);
  - The beam coming from booster is injected into this new bucket, and then merges with the stored bunch through radiation damping effect.
  - Beam accumulation is feasible. The whole injection process takes ~200 ms.
  - During injection, a) the RF parameters need to be tuned quickly; b) the bunch length of stored beam have an obvious reduction; c) short pulse kicker and sufficient MA are required. These issues will be addressed in Dr. Duan's talk (Top-up injection schemes for HEPS).

- On-axis swap-out injection
  - Use the same kicker as the longitudinal injection.
  - Not plan to build a specific accumulator.
  - Instead, re-inject the beam of the ring to booster.
  - The booster timing system needs careful design.

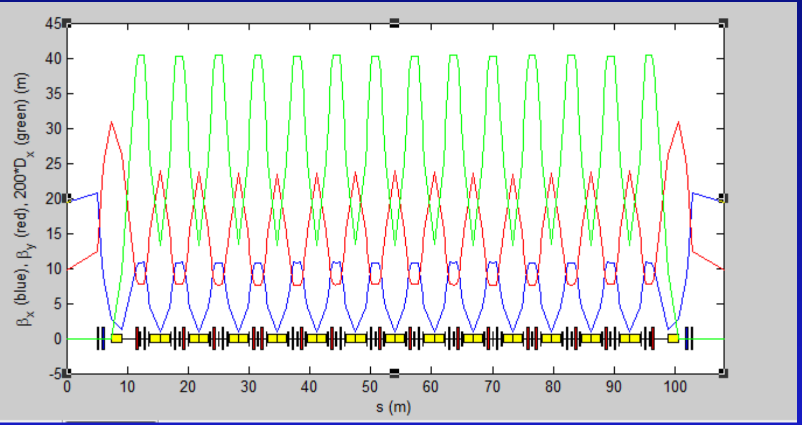


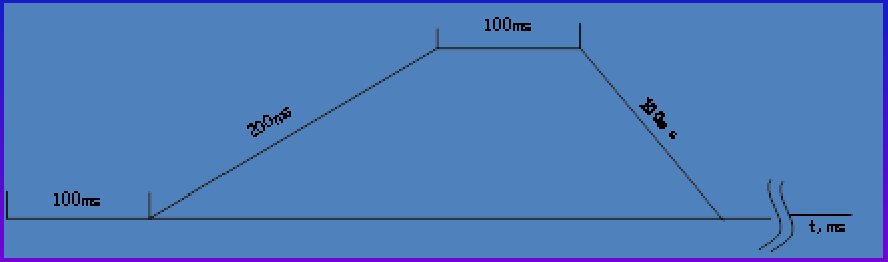
HEPS injector consideration

- Injector: Linac + booster.
- Three candidate booster designs:
  - 15BAs, 432 m, ~ 4 nm.rad @6 GeV.
  - NSLS-II type, 432 m, dipoles with quadrupole and sextupole gradients, ~ 7 nm.rad@6 GeV.
  - FODO lattice, 1279 m, ~ 2nm.rad @6 GeV.
- Recently it was determined to adopt the 15BA design.
- Timing for injection
  - Linac, 300 Hz, inject 30 bunches to booster in 100 ms.
  - Booster, 2 Hz, ramping period 500 ms.

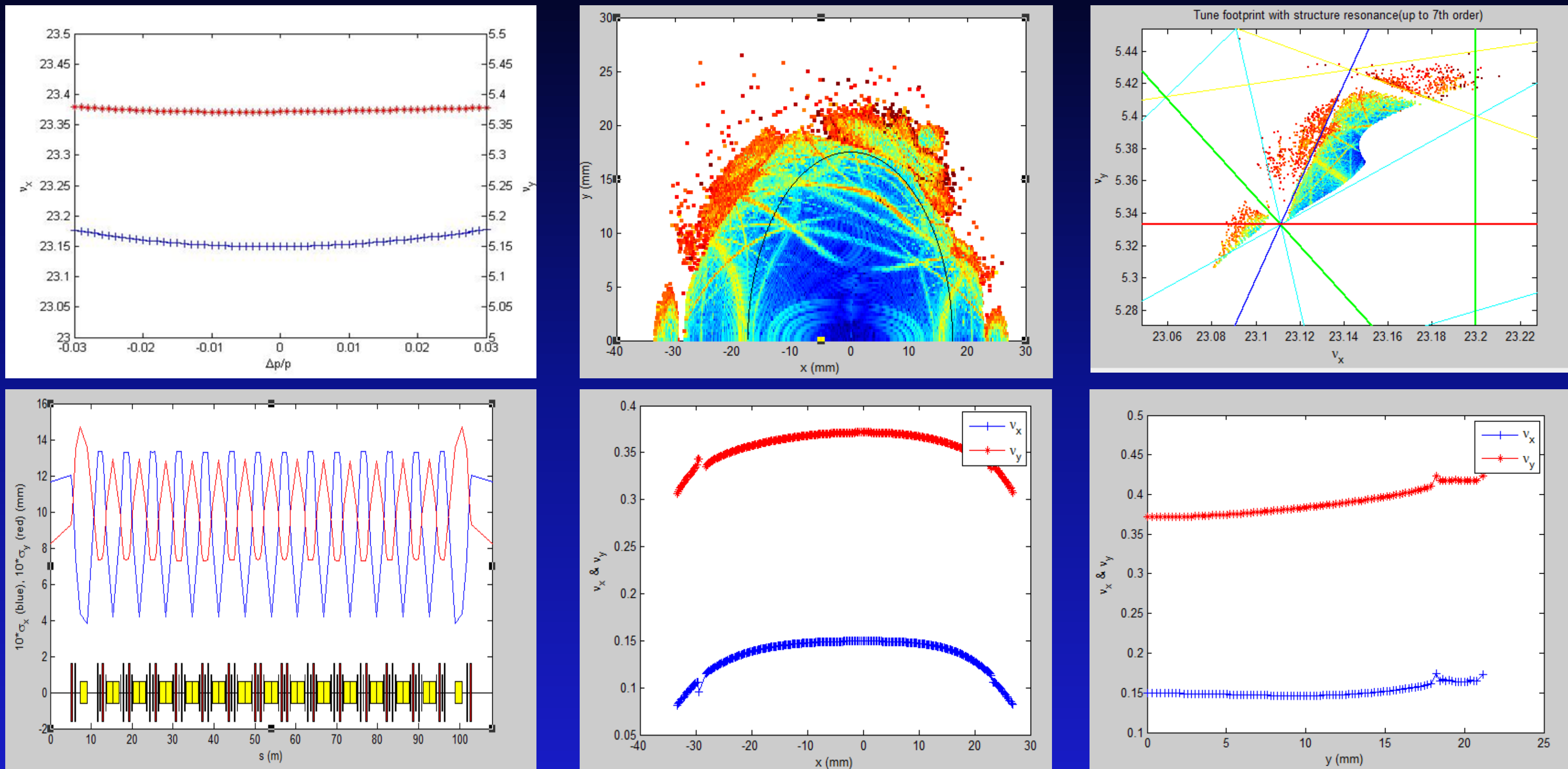
Main parameters of the Linac

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





15BA booster design: in a separate tunnel

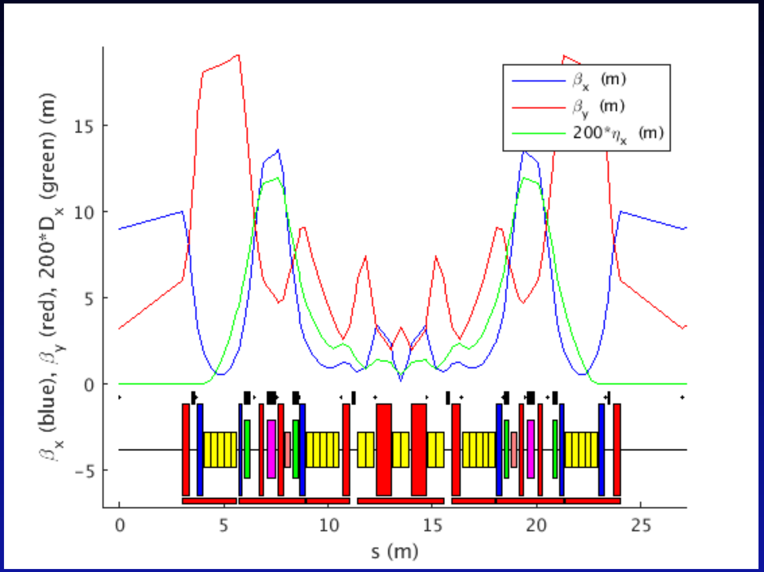


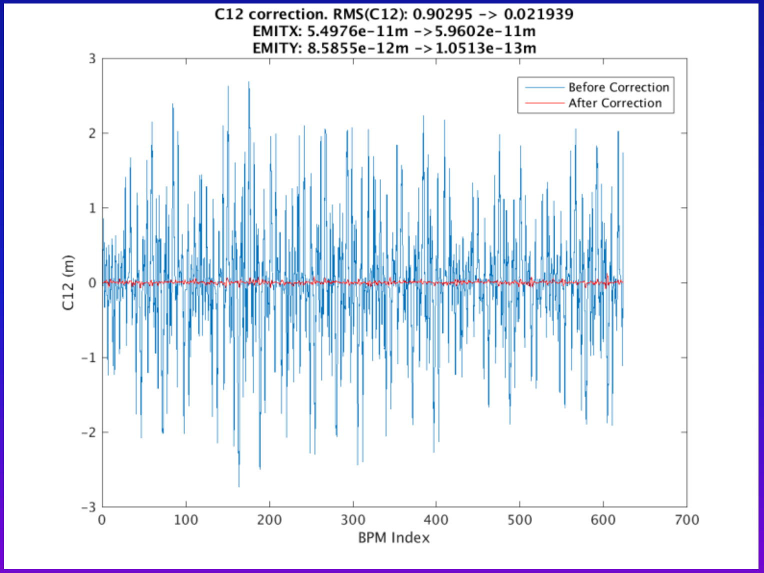
- 4.32 nm @ 6 GeV, 432 m
- Optimize the DA and MA with only chromatic sextupoles (5 families)
- 10σ(x/y) < 15 mm while DA(x/y) > 18 mm

By Yuemei Peng & Yi Jiao

Error tolerance study

- Lattice model
  - In one 7BA, 7 girders, 12 horizontal and 10 vertical correctors, 4 skew quadrupoles, and 13 BPMs
- Errors
  - Nominal field error (1e-3, 2e-4, 1e-3 for B, Q, S)
  - Multipole field components (1e-3) of magnets
  - Alignment error (30 µm on the same girder, 50 µm on different girder) and rotation (100 µrad)
  - BPM resolution (0.5 µm)
- ***Alignment error*** has dominant effects.
- ***Dispersion (Y) and coupling correction*** is necessary.
  - If they are not controlled, vertical emittance can grow to 10~ 30 pm.rad.
  - After correction with skew quadrupoles, vetical emittance can be kept below 1 pm.rad (indicated by the simulation).

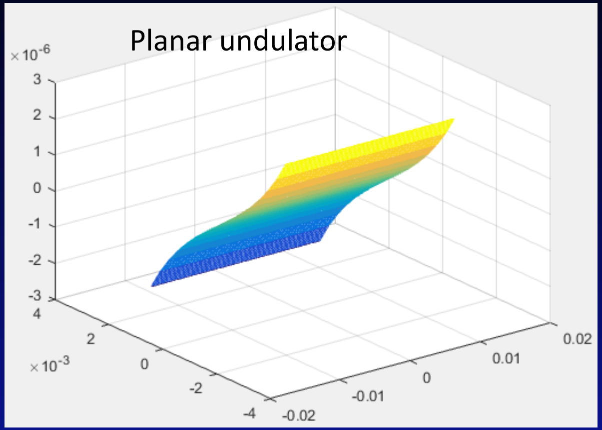


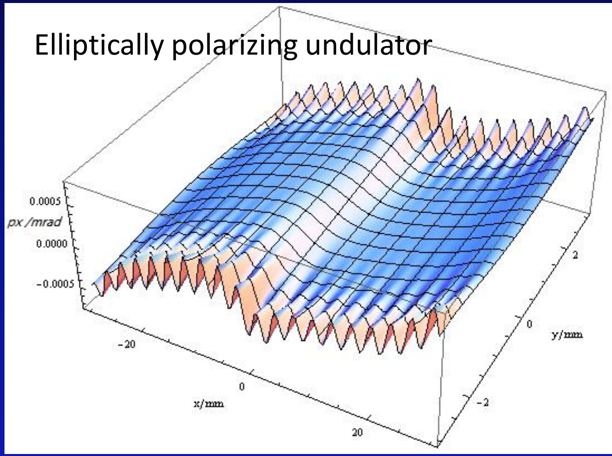


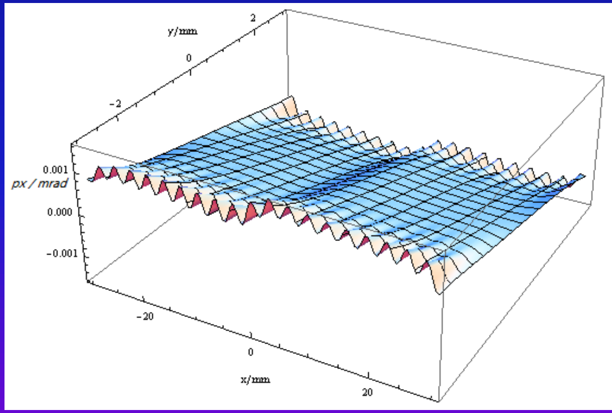
By Daheng Ji

ID effects: in an acceptable level

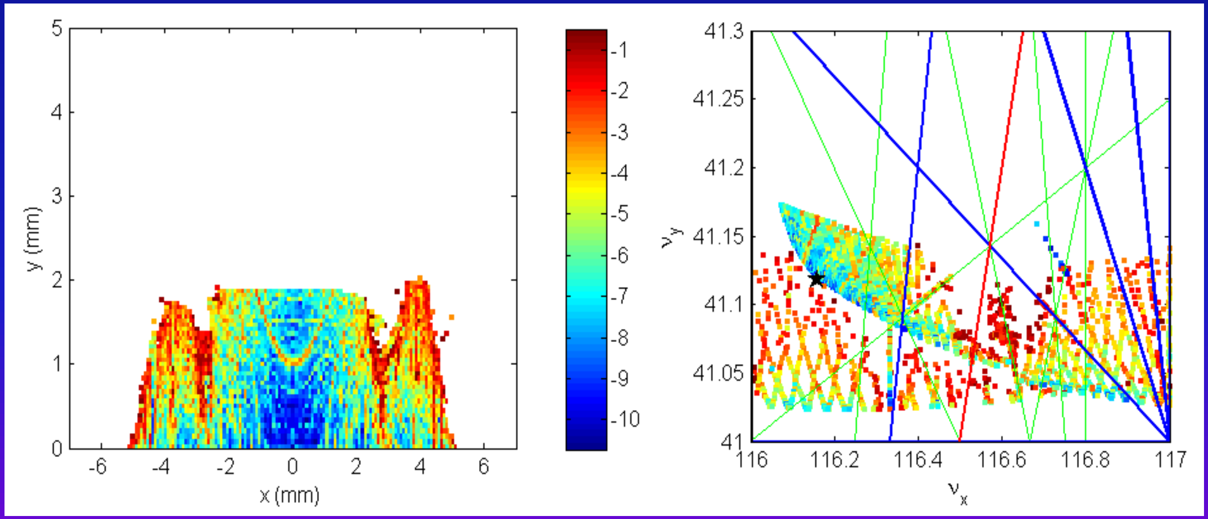
- Construct kick maps with Hamiltonian-Jacobin methods for 14 undulators to be installed in the first construction stage of HEPS.







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



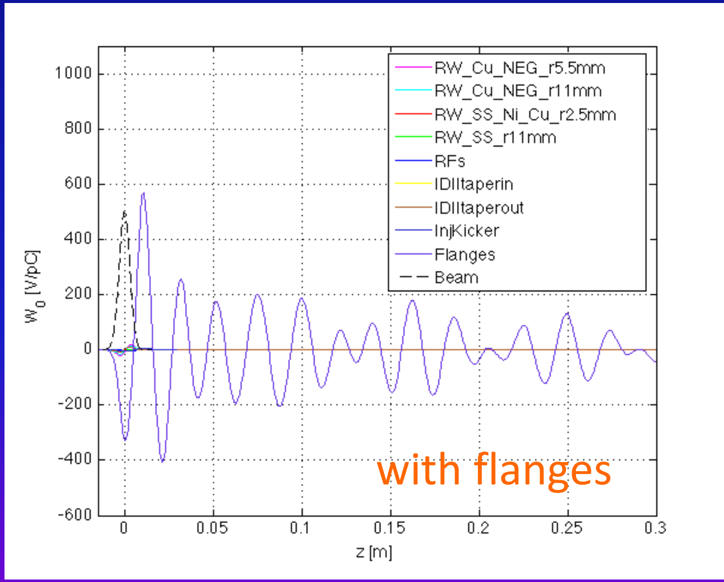
By Xiaoyu Li

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



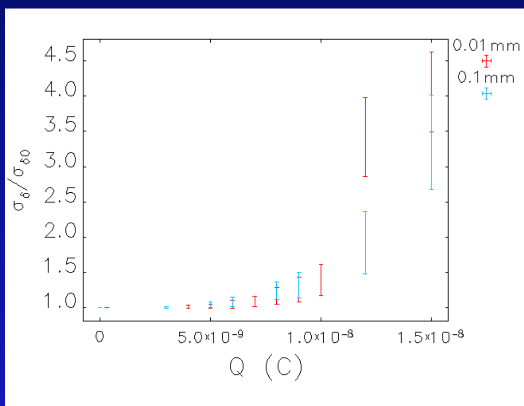
Longitudinal wake potential (σ_z =3mm)

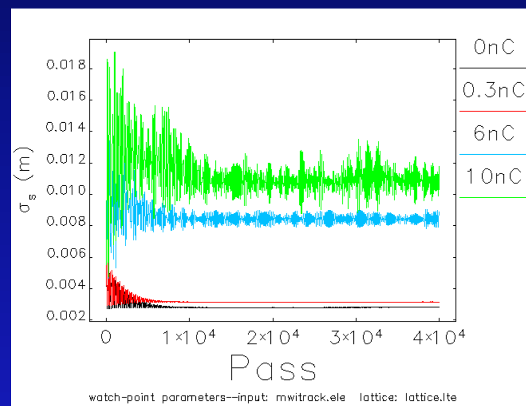
- The ***longitudinal impedance*** is dominated by ***large number elements***, e.g., flanges.
- The ***transverse impedance*** is dominated by the ***resistive wall impedance*** due to the small aperture beam pipe.
- More impedance contributors will be included in the following studies.

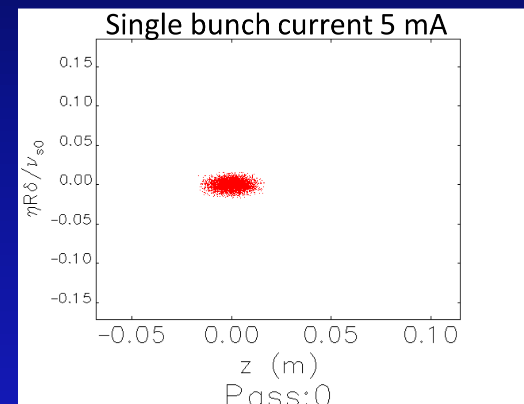
By Na Wang, Saike Tian, Xiaoyu Li

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.

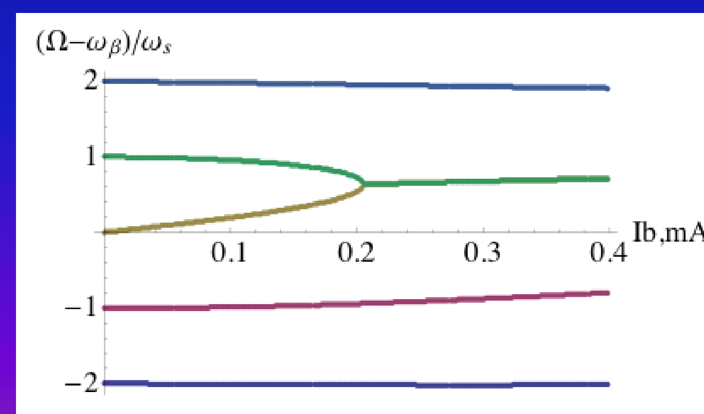






- *Transverse mode coupling instability*
  - For Gaussian bunch, the instability is evaluated with Eigen Mode analysis.
  - The threshold bunch intensity is around 0.2mA.

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



By Na Wang, Zhe Duan

Optimization with PSO and MOGA

- Test MOGA (NSGA-II) and PSO performance in an optimization problem with a known answer.

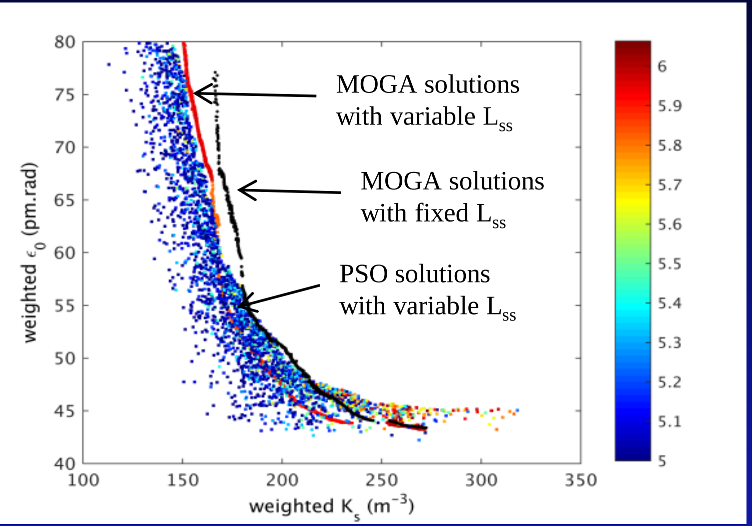
Fix the lattice structure and circumference, shortening the long straight section results in lower emittance and better dynamics?
Yes. (more room for variation of magnetic parameters).

- Generate initial seeds from the solutions optimized for a fixed straight section length, L_{ss} = 6 m.
- In the initial seeds, L_{ss} = 6 m + 0.1 m*rand, but set the variation range as [5 m, 7 m].

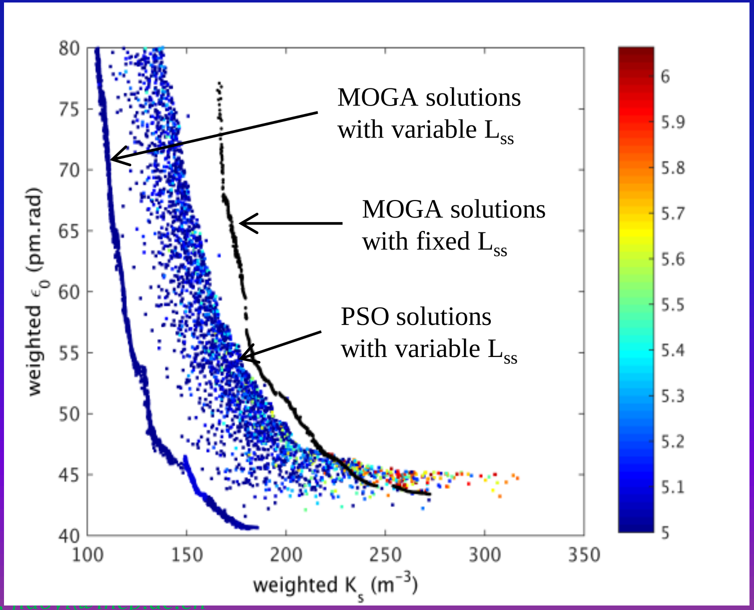
- **With only MOGA**: converge fast, but fail to find new solutions with the L_{ss} values exceeding the L_{ss} covering range of the initial population.
- **With only PSO**: succeed to find solutions with L_{ss} close to 5 m and with lower emittance, but with solutions distributed sparsely in the objective function space.
- ***With PSO and then MOGA***: good convergence and good performance.

PSO breeds more diversity. And once with enough diversity, MOGA reach very good convergence.

Evolve with PSO for 800 generations as well



Further evolve with PSO and MOGA for 500 generations

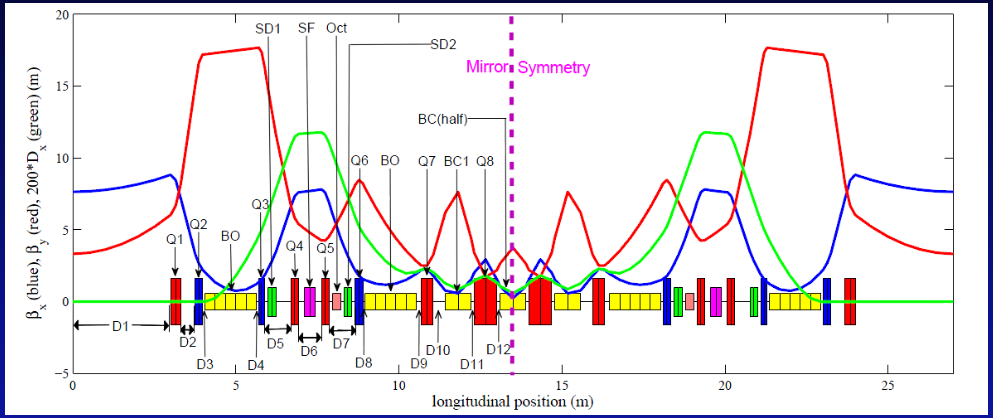


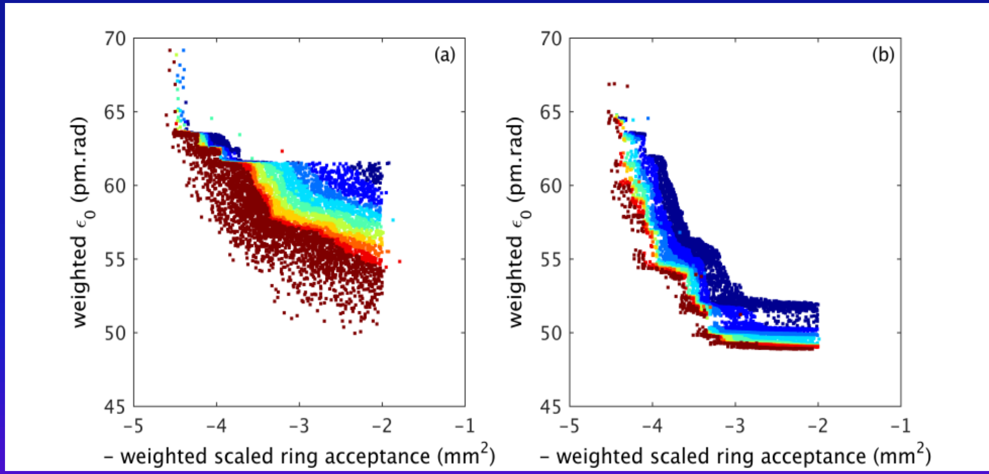
Y. Jiao and G. Xu, IPAC16

Optimize HEPS design by combining PSO & MOGA

Apply them in a successive and iterative way!

- Tuning all tunable parameters (magnetic length, strength, position), **N_{var} = 32**.
- **Two objectives**: natural emittance & scaled ring acceptance (product of the effective DA area normalized w.r.t. $\beta^{1/2}$ and the MA size)
- Consider as many **constraints** as possible to ensure desirable optics.
- Solutions continuously distributed in the objective function space;
- Almost a monotonous variation of the scaled ring acceptance with the natural emittance;
- The optimizations output designs with ***shorter sextupole & octupoles, lower natural emittance, but larger effective DA and MA*** (emittance down to ~ 50 pm.rad, effective MA up to 3.5% and meanwhile effective DA ~ 4 mm).



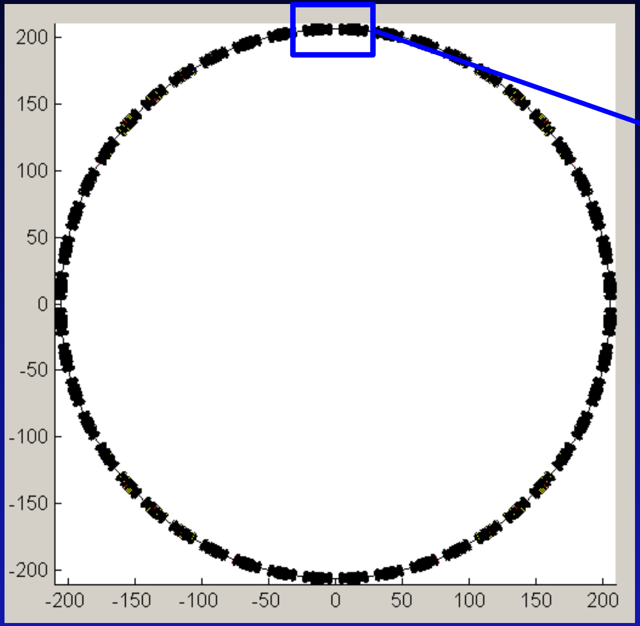


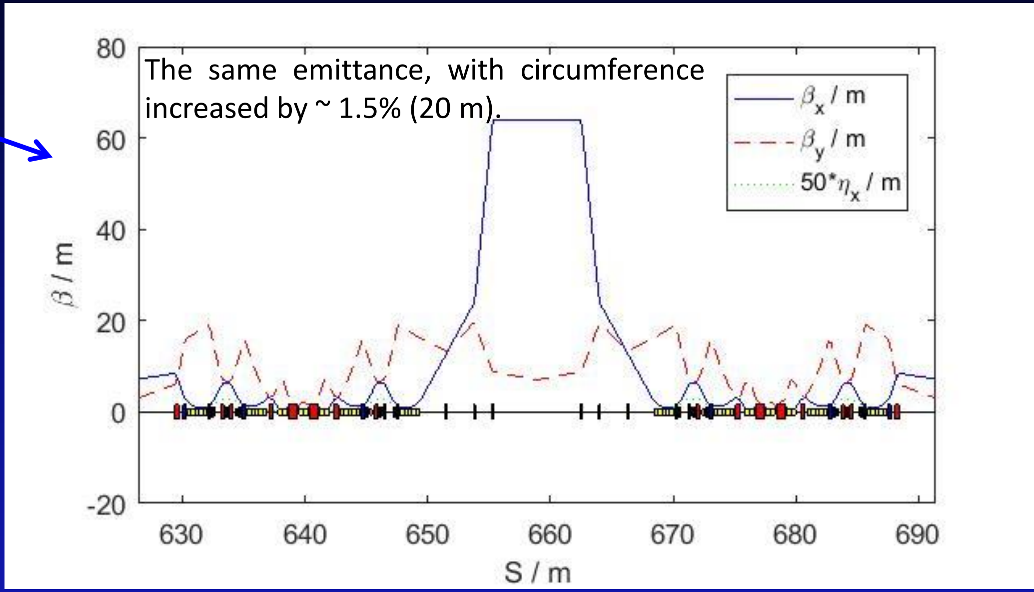
Solutions of the last iteration of MOPSO (a) and MOGA (b) in the objective function space. The population is plotted at every 100 generation and marked with different colors (from blue to red).

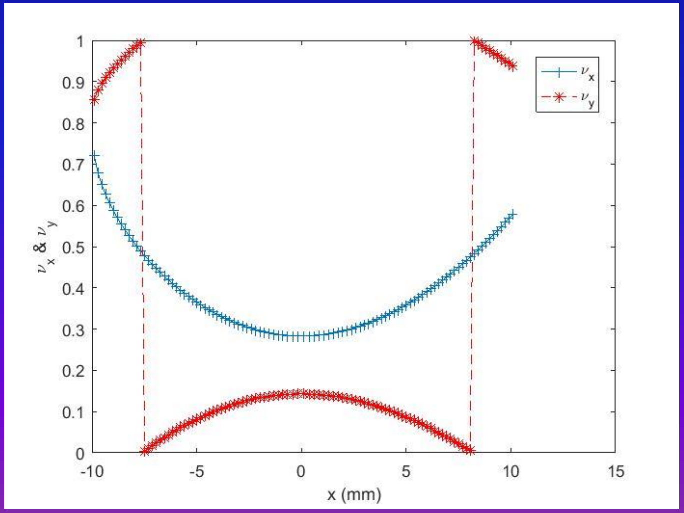
Y. Jiao and G. Xu, IPAC16, arXiv:1605.05021

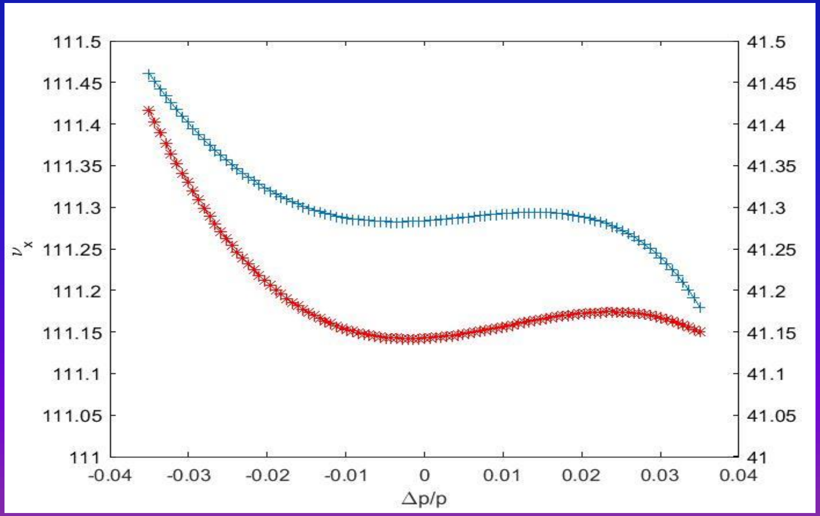
Alternative design accommodating off-axis injection

Enlarging DA by replacing two ID sections with high-beta sections









In Closing...

- *HEPS will be the next storage ring light source with high energy and low emittance in China, and the HEPS test facility has been started.*
- *A nominal design of the HEPS storage ring was reached. Based on this design, related physical studies are under way.*
- *Many challenging and also interesting issues need to be explored, and iteration of design is necessary.*

Thanks for your attention!

HEPS physical design Group at IHEP

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

Prof. **Chenghui Yu**
Head of IHEP Accel. Phys. Group