Operational Scenarios of the Chinese High Energy Photon Source Project

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Acknowledgements

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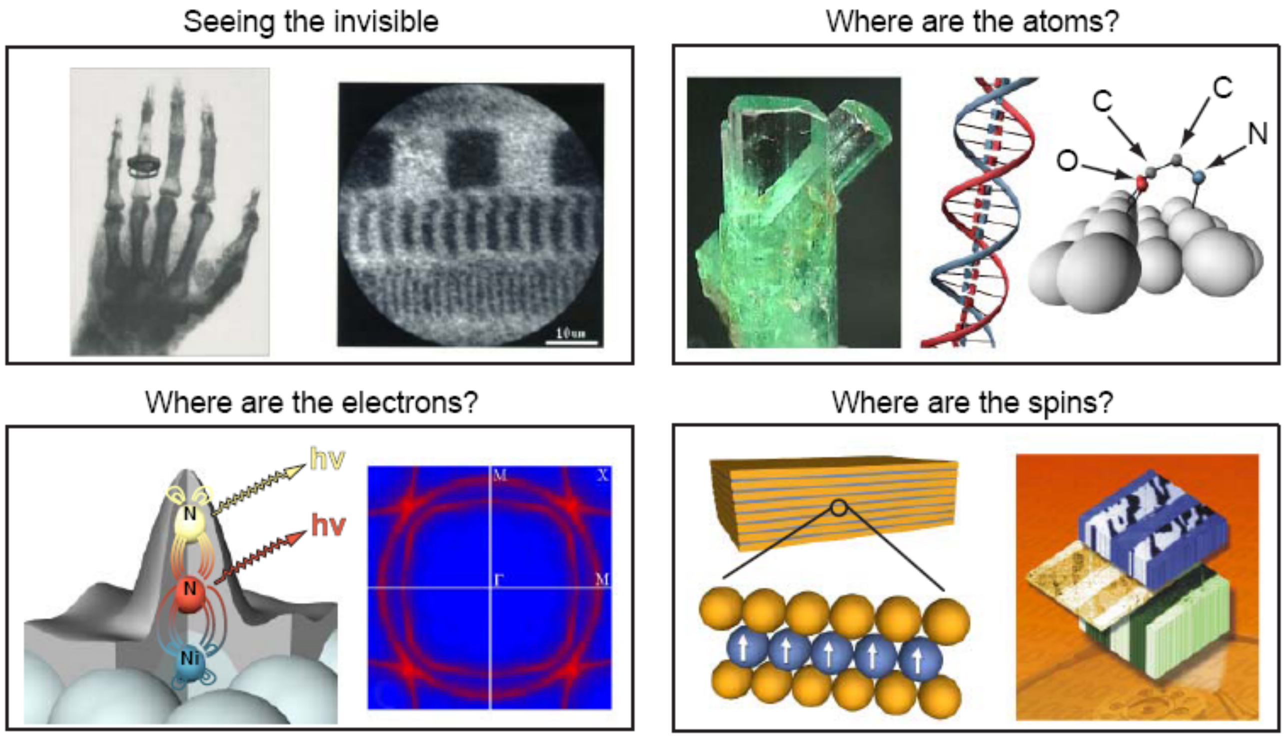
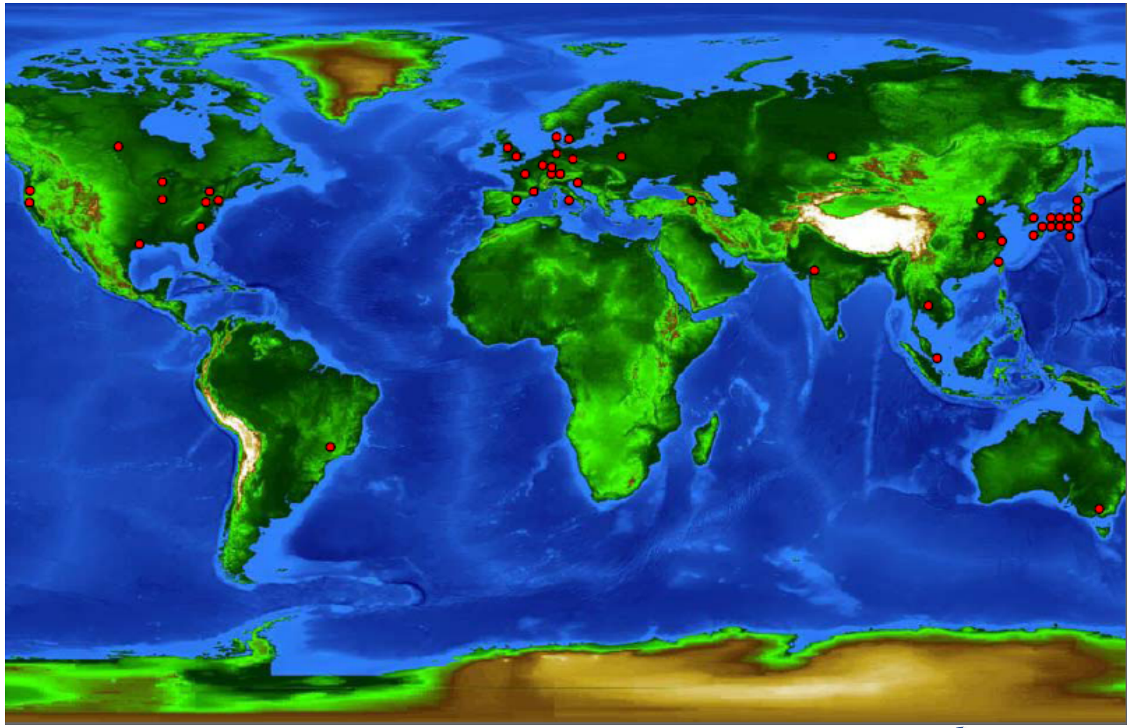
Outlines

1. Introduction
2. Accelerator physics design
3. Key technologies to HEPS
4. Project progress
5. Summary

1. Introduction

Photon source – A powerful tool to probe the nature, required with widely tunable frequency range from infrared to hard X-ray





HEPS

Storage ring-based synchrotron radiation light source

- Developed in main land China from 1980s, BEPC/BSRF, HLS to SSRF

BSRF
1GLS

Beijing Synchrotron Radiation

HLS
2GLS

Hefei Light source

SSRF
3GLS

Shanghai Synchrotron Radiation Facility

Trends of light source

MAX IV, Sweden, 528 m, 3 GeV, 0.33 nm

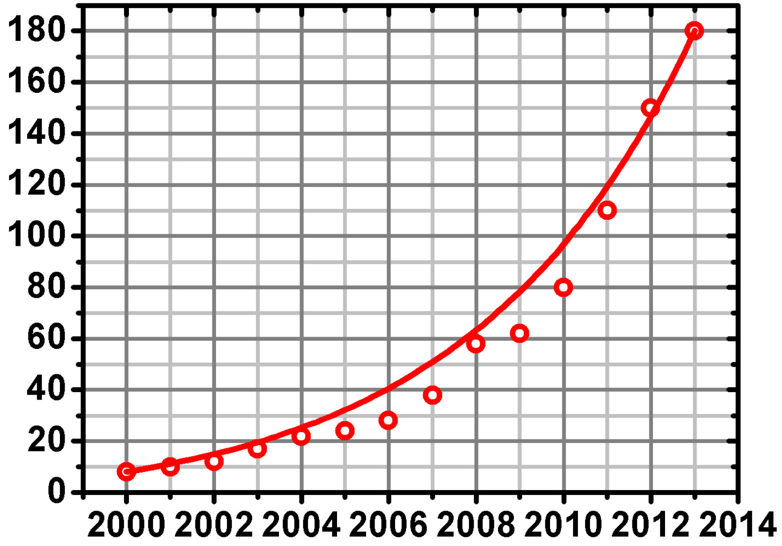
Sirius, Brazil, 518 m, 3 GeV, 0.27 nm

- ✓ Lower emittances (↘ ~0.1 nmrad)
- ✓ Higher brilliances (↗2~3 orders)
- ✓ More advanced beam lines and end-stations (Better resolutions, higher speeds, etc.)
- ✓ SR-based research centers

ESRF-EBS, France, 844 m, 6 GeV, 0.13 nm

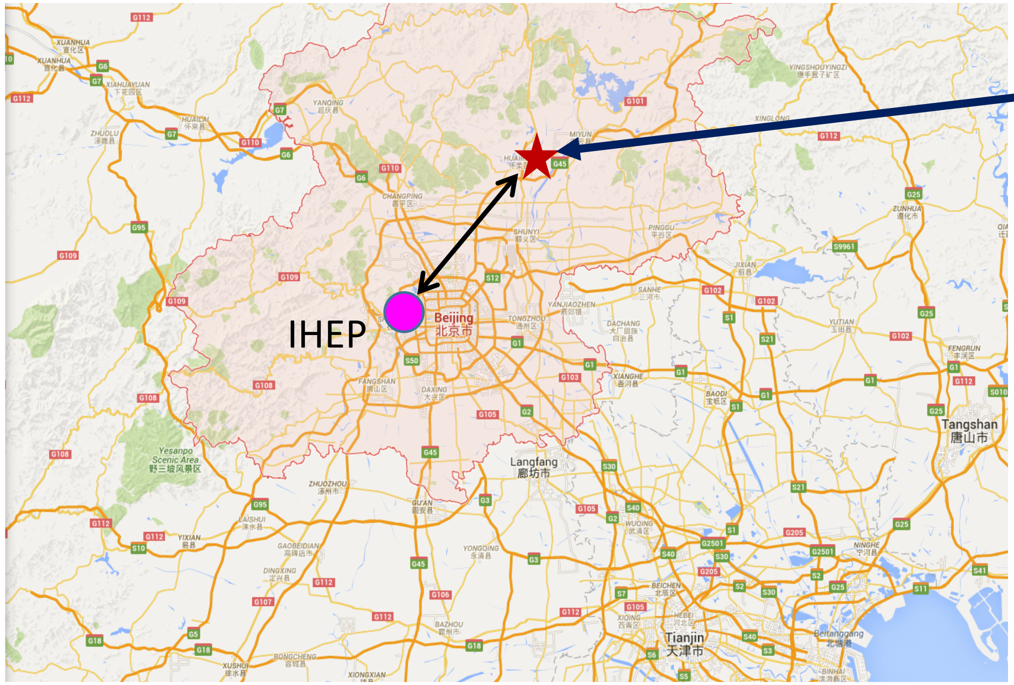
New light source in China — High energy, high brightness

- Users increased as the development of Chinese sciences and economy



e.g. Increase of structure biology users in China

A new photon science research center at the north China



About 80 km from IHEP

Two steps

- R&D of HEPS project
  - One of the 16 large scientific facilities in the list of National Development and Reform Commission in the 12^{th} 5-year plan.
  - Scheduled from 2011 to 2015, but delayed.
  - Officially started from Feb. 2016, and will be completed on Oct. 2018.
  - Total budget: 321.6 M RMB (~48 M USD)
- HEPS project
  - Passed the review of the proposals for the large scientific facility, and shortlisted the 13^{th} 5-year plan of the National Development and Reform Commission of China
  - Expected to start the construction in late 2018, completed at 2024. The whole project finished in mid-2025 after commissioning.
  - Total budget: 4.5-5 B RMB (~0.7 B USD)

Design goal of the HEPS (high energy photon source)

Main p
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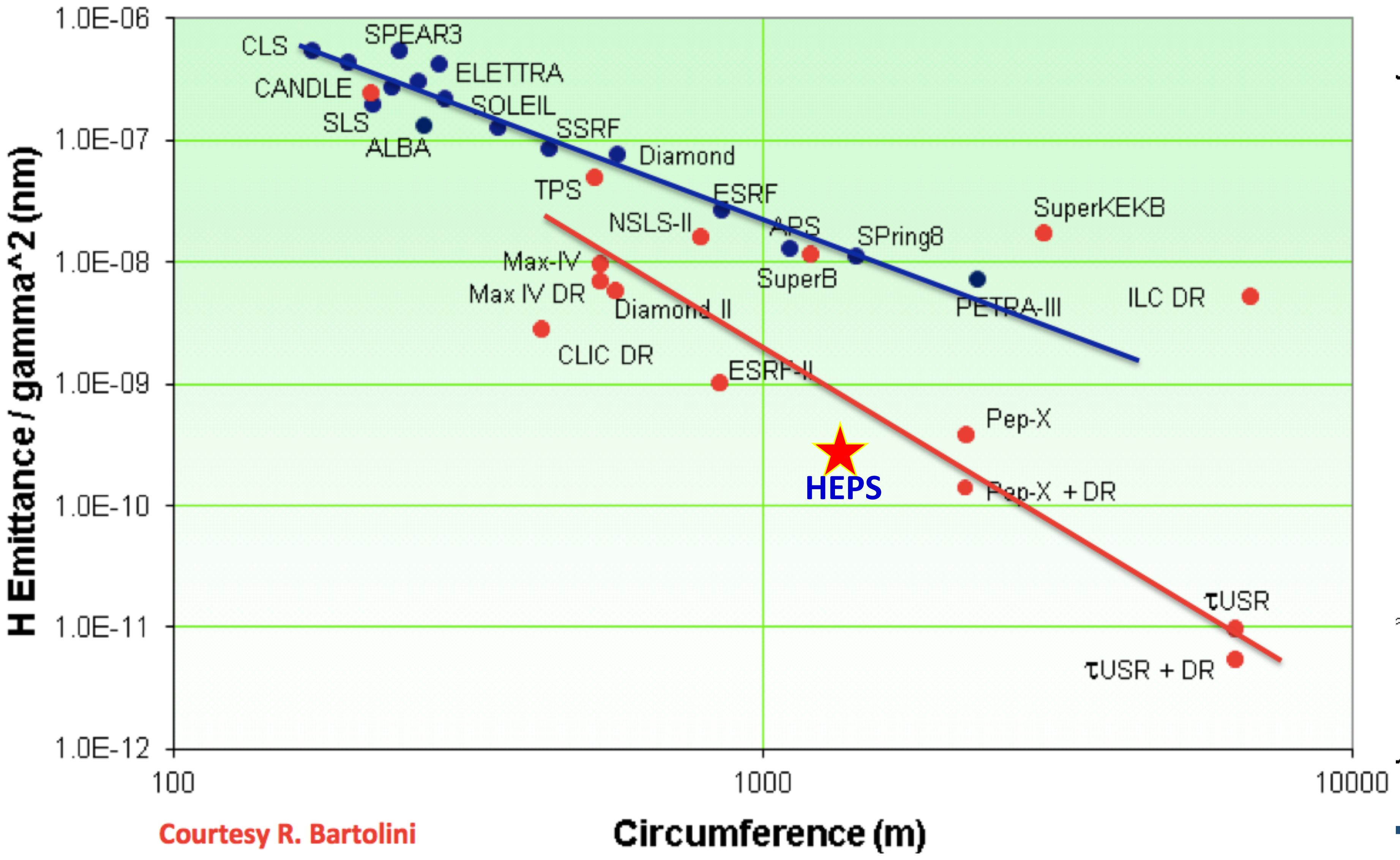
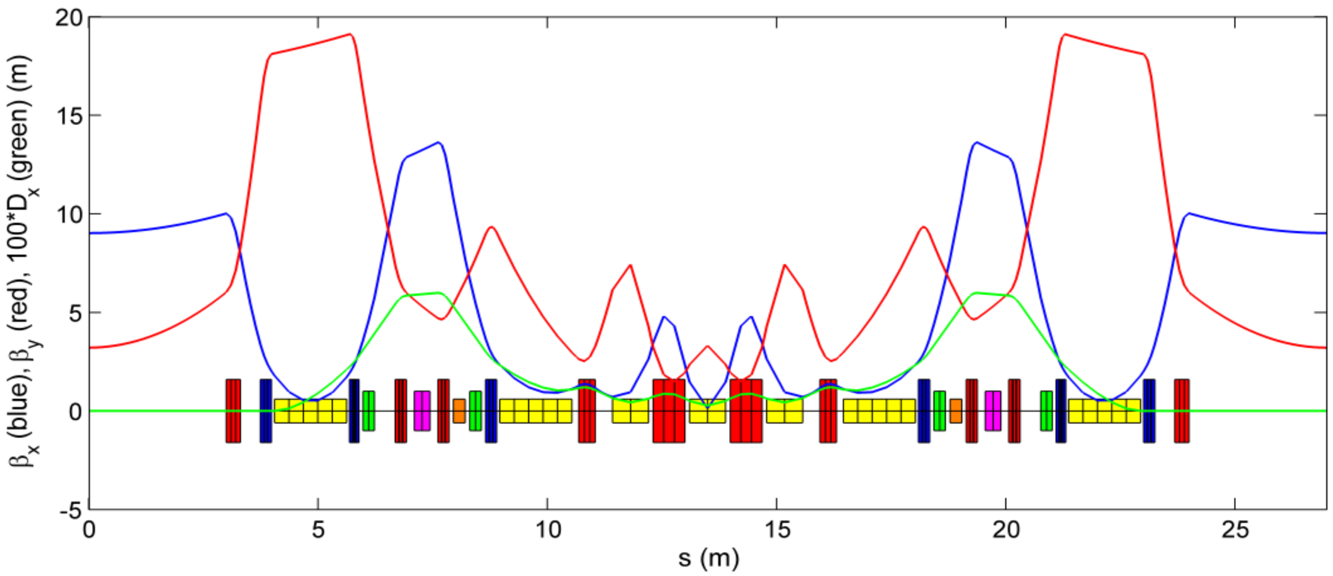
Circumfe
Emittan
Beam cu
Injectior
Brightne



≈1. 3km

2. Accelerator physics design

- Linear lattice design
  - find an optimized qusi-DLSR design for the HEPS storage ring.
    - ➢ compromised between Chinese technology level and innovations (e.g., way to get the lowest emittance)
    - ➢ compromise between user requirements and accelerator performance
  - give a detailed parameter list and tolerance budget table for hardware systems.



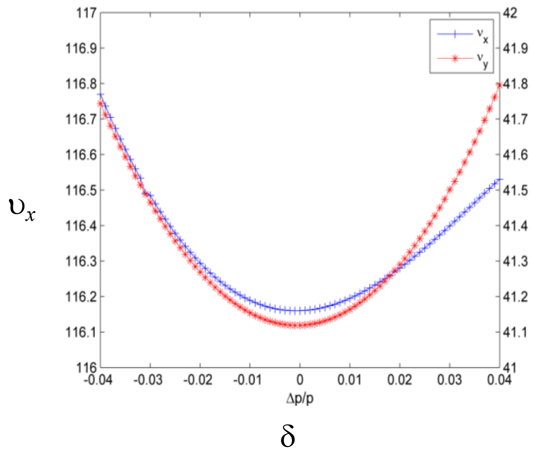
Hybrid 7-BA lattice, adopts aggressively strong focusing which results in a compact layout as well as an ultra-low emittance. This allows practical and cost effective storage ring design, even when the natural emittance is reduced down to approaching the diffraction limit of hard X-rays

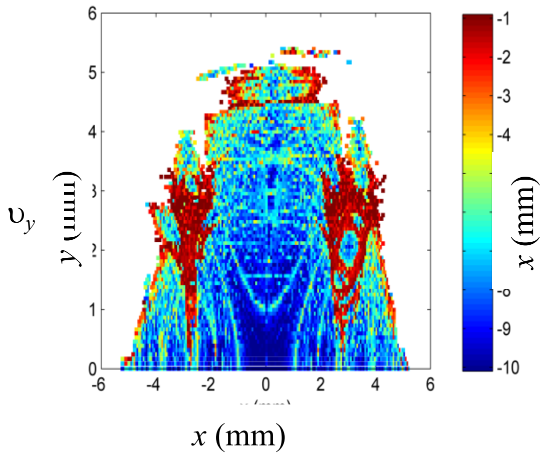
- 48 identical hybrid 7BAs.
- Each 7BA cell is about 27 m.
- 48 dispersion-free 6-m straight sections, with beta functions of 9/3.2 m.
- 4 outer dipoles with long. gradients; 3 inner dipoles with defocusing gradients.
- Neighboring 3 inner dipoles, high-gradient quadrupoles (~ 80 T/m).
- 6 sextupoles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

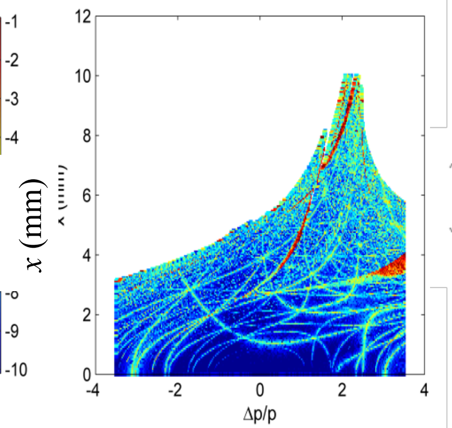
Parameter	Value	Unit
Beam energy	6	GeV
Beam current	200	mA
Circumference	1360.4	m
Partition number J_x /J_y/J_z	1.51/1.0/1.49	
Horizontal natural emittance	58.4	pm·rad
Transverse tune (x/y)	107.37/82.43	
Natural chromaticity (x/y)	-214/-133	
Corrected chromaticity (x/y)	+5/+5	
No. of cell / long straight section	48/48	
Length of LSS	6.15	m
Beta function @ mid-LSS (x/y)	8.9/4.1	m
Damping time (x/y/z)	18.3/27.8/18.7	ms
U_0 per turn (w/o ID)	1.959	MeV
U_0 per turn (w/10 IDs)	2.5	MeV
Natural energy spread	8.20×10^{-4}	
Momentum compaction factor	3.43×10^{-5}	
RF frequency	166.6/499.8	MHz
RF voltage (swap-out injection)	2.65/0.575	MV
Harmonic number	756	
Bunch length with 3rd harm. cavity	31.6	mm

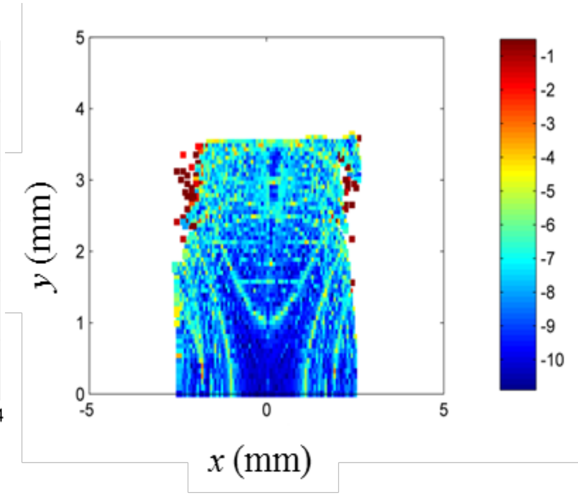
Dynamic aperture study

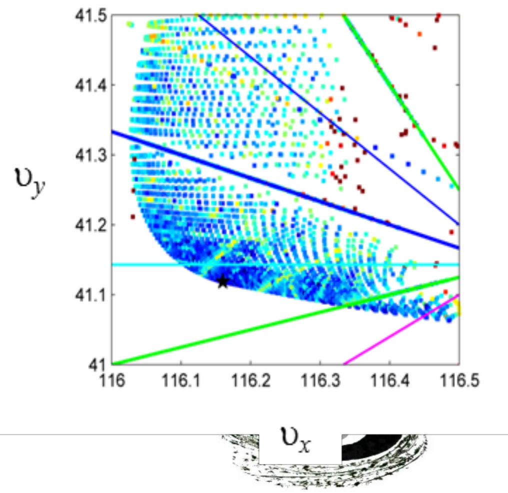
- Nonlinear optimization w/ 4 families of multipoles (grid-scan)
  - Effective on-momentum DA: ~2.5 mm in x and 3.5 mm in y;
  - effective MA: ~3%.
  - Effective DA/MA is required not only the motion remains stable after tracking over a few thousand turns (traditional definition of the DA or MA), but the tune footprint is bounded by the integer and half integer resonances nearest to the nominal tunes of the storage ring.







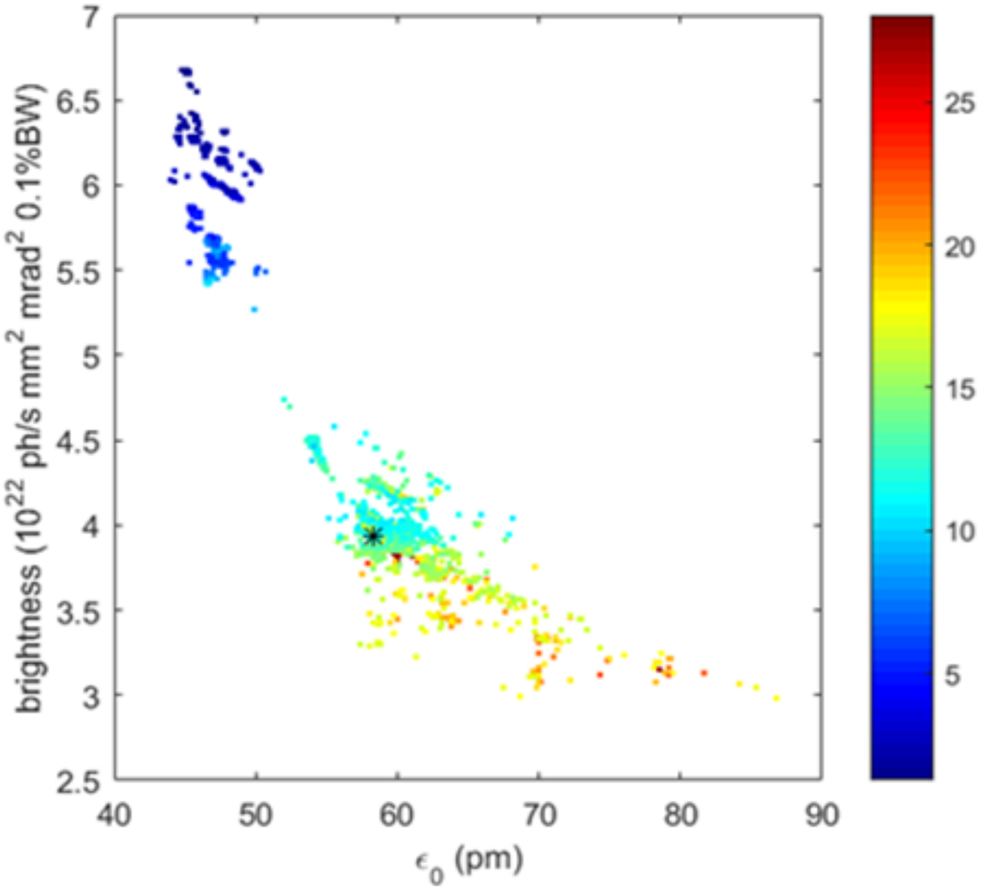




Dynamic aperture study (cont.)

- Optimization with MOPSO (combination of MOGA & PSO)
  - All tunable parameters scanned with linear/nonlinear dynamics simultaneously optimized
  - If keeping 60 pm emittance, the DA can be increased to be close to (if not larger than) 10 mm in the injection plane
  - If considering only on-axis swap-out injection, the emittance can be further pushed down to ~45 pm.rad
- Still in progress...

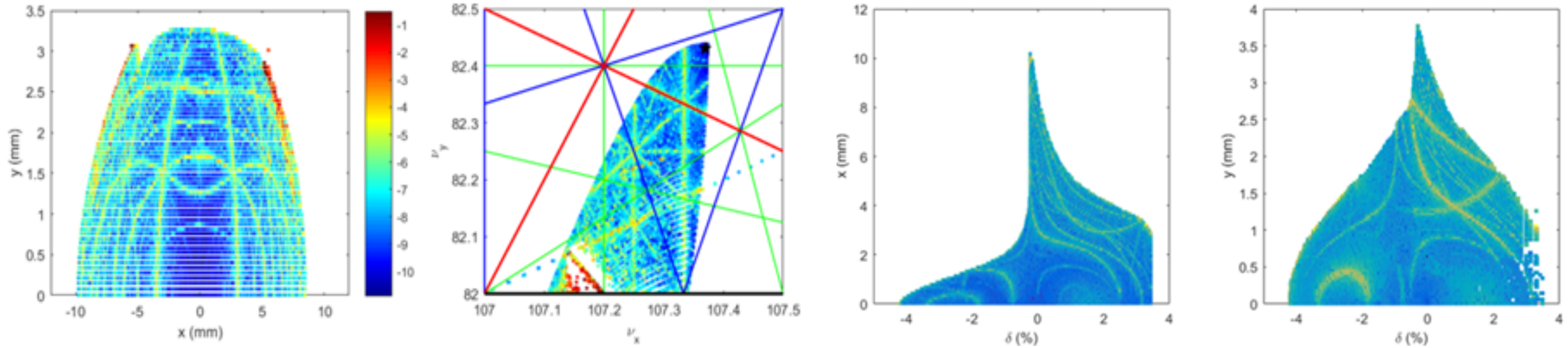
Color bar: Effect. DA area $\times$ MA/3% (mm^2)



Dynamic aperture study (cont.)

- More efforts for further progress…

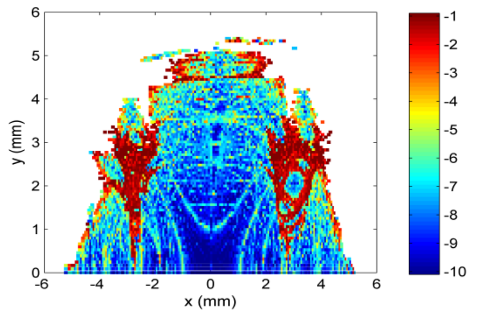
w/o high-β section, effective DA:
8/3.3 mm in x/y plane, effective MA size > 3.5%



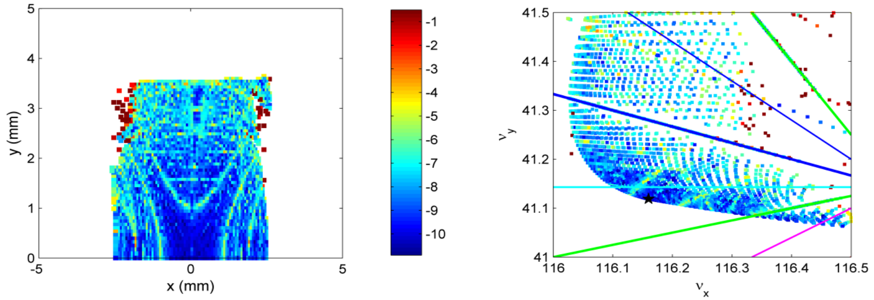
DA large enough, but can be even better

Dynamic aperture study (cont.)

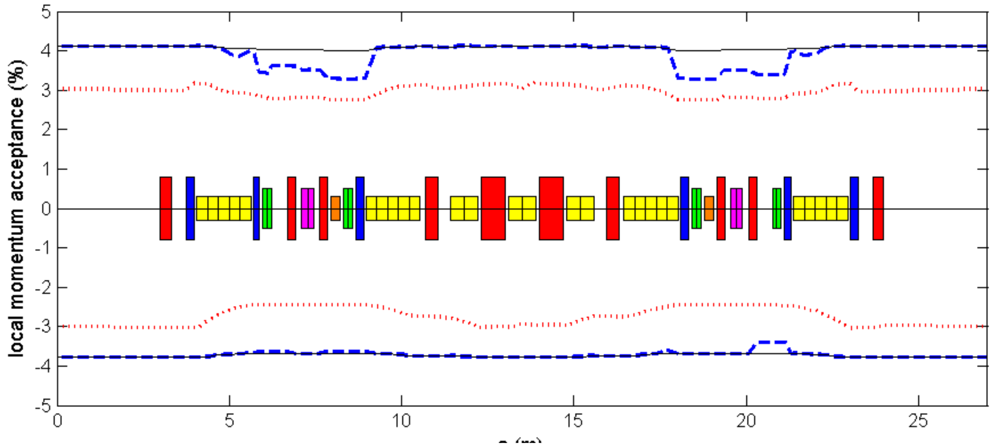
- Conventional DA and LMA vs. effective DA and LMA



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

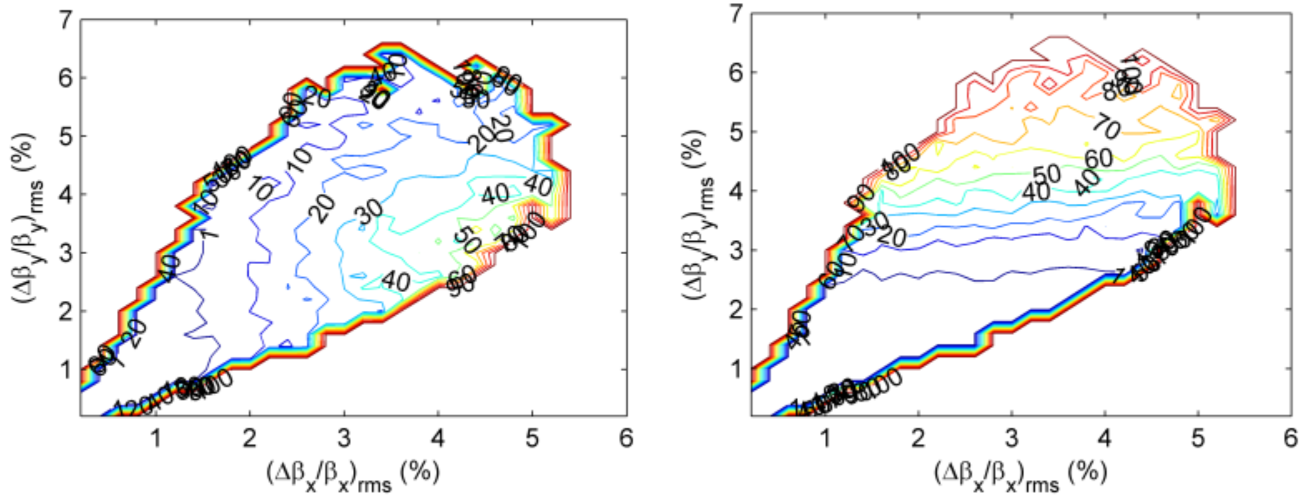
MA size closely related to the Touschek lifetime.

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%)

HEPS

Nonlinearity study



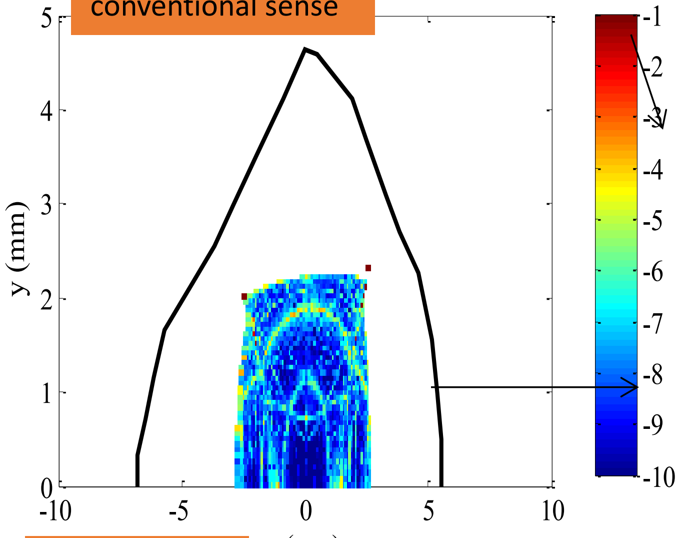
MA reduction probability (%) for the HEPS (Left: caused by horizontal half-integer resonances, Right: caused by vertical half integer resonances. Y. Jiao, Z. Duan, NIM-A, 841, 2017

- Integer resonances
  - always fatal to dynamics and can never be crossed
- Half-integer resonances
  - Experimental (G. Wang et al., IPAC16) and numerical (M. Borland et al., IPAC15) studies show that the half-integer resonances can be safely crossed even w/ errors.
  - For HEPS, keeping the probability of MA reduction due to crossing of half-integer resonances below 1%, the rms beta beating should be smaller than 1.5% in x and 2.5% in y plane, respectively.
  - 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.
  - One can avoid too optimistic estimation of the nonlinear performance of the actual machine, when having only the bare lattice in hand.

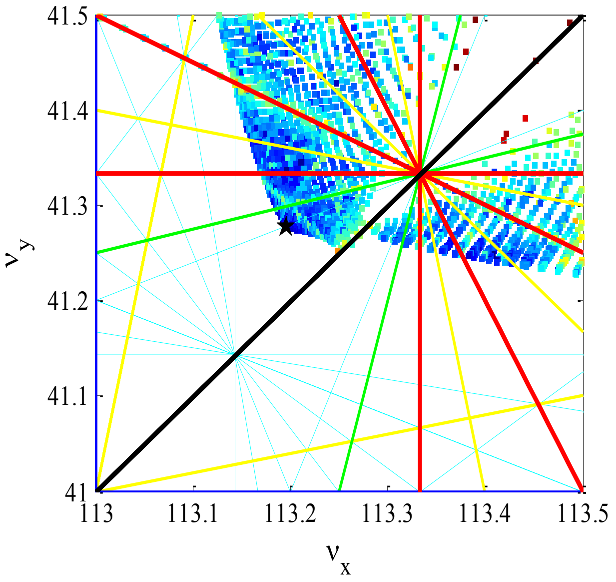
‘Effective’ DA&MA: limited by IRs and HIRs

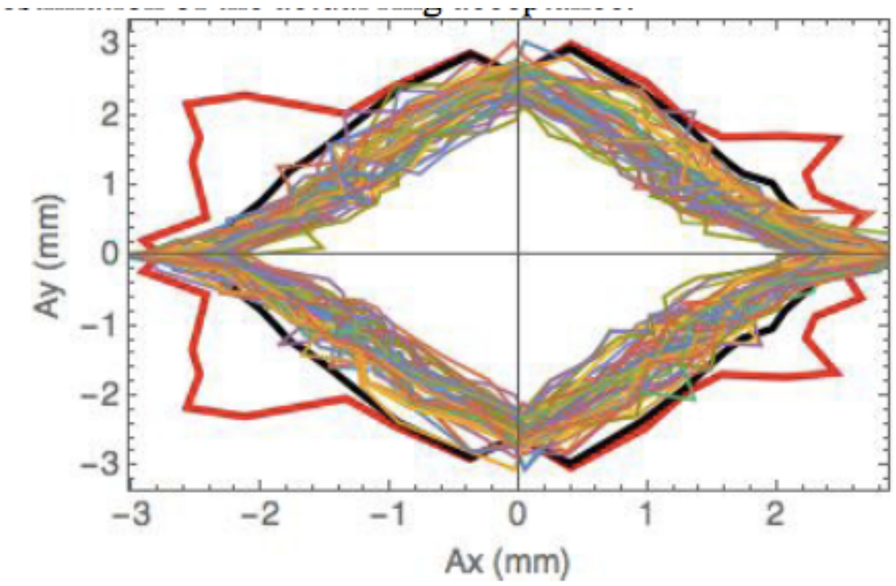
This can provide a quick and reasonable measure of the realistic acceptance of a DLSR while with only the bare lattice in hand !

DA defined in a conventional sense



‘Effective’ DA





- *This will facilitate the optimization of a DLSR design with MOGA to find multi rather than single “optimal” solutions.*
- *ated error modeling and lattice calibration can then select one most robust design from these solutions.*

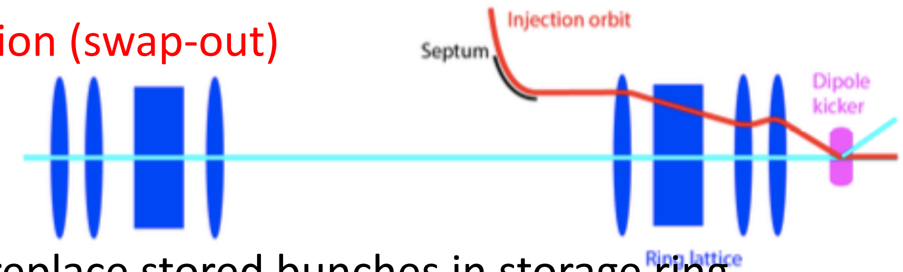
In this way, we find an efficient approach to separate the optimization and evaluation of the lattice processes.

Y. Jiao, Z. Duan and G. Xu, IPAC 2017, WEPAB055, 2706-2708.

Injection design – On-axis injection schemes

- In the lattice optimization of HEPS, there is likely a trade off between dynamic acceptance (for injection) and brightness (light source performance).
- On-axis injection schemes relax the stringent DA requirements of tranditional off-axis injection schemes, and potentially allow pursing a higher brightness.

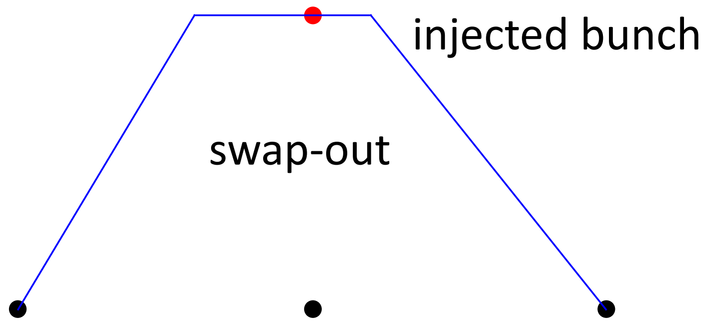
On-axis transverse injection (swap-out)



Major challenge:

A full charge injector to replace stored bunches in storage ring, in particular, HEPS timing mode requires a bunch charge of ~15 nC, generation and acceleration of such high charge bunches is nontrivial.

schematic plot of the kicker pulse shape

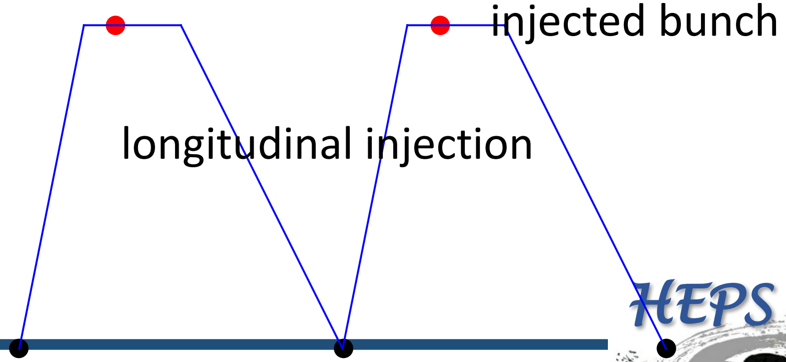


bunch spacing = 6ns for HEPS

On-axis longitudinal injection (accumulation)

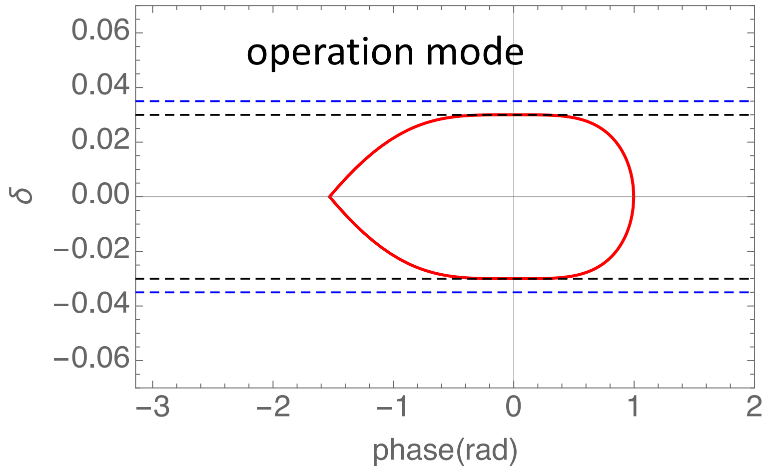
Major challenge:

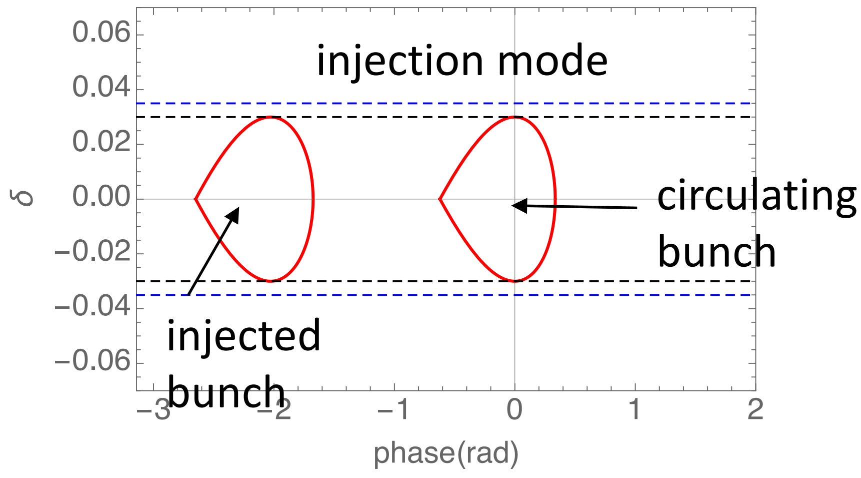
Generation of a RF acceptance region to keep both injected and stored bunch with a large enough temporal separation, so as to accommodate the kicker pulse.

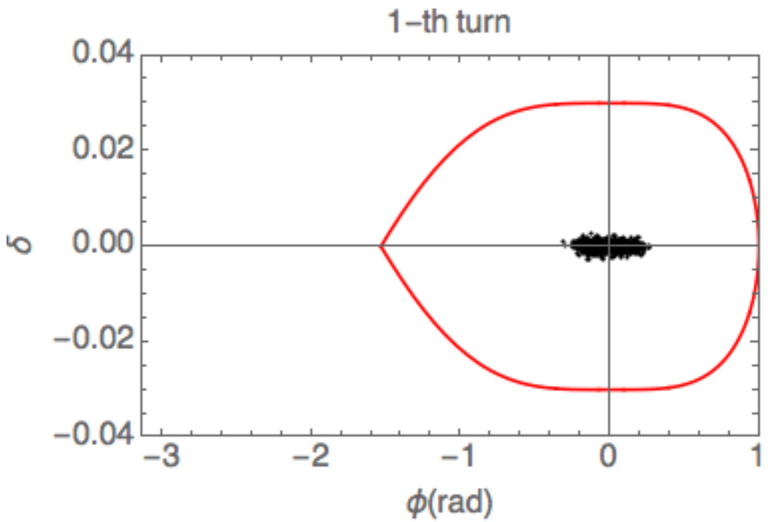


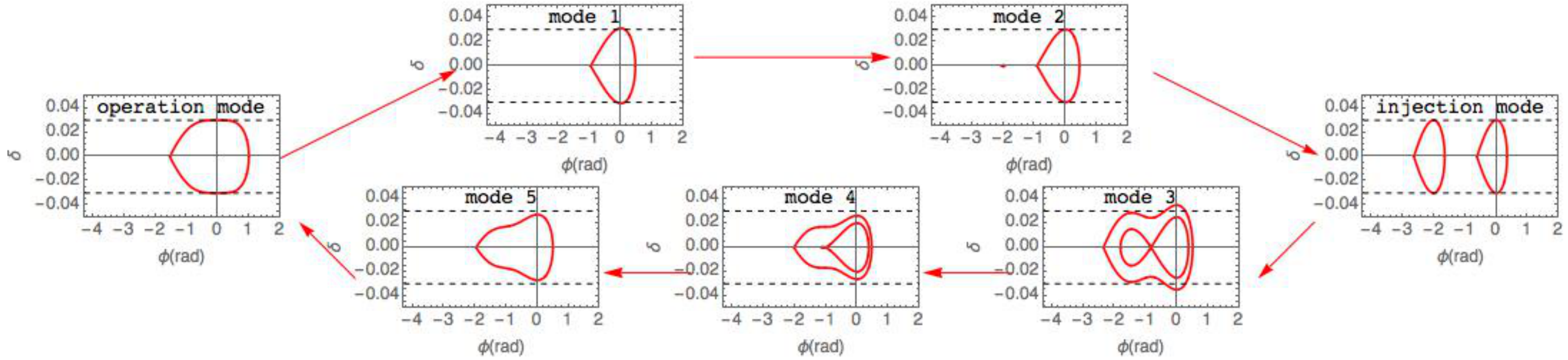
On-axis longitudinal injection schemes for HEPS (1)

- 166 MHz + 500 MHz active RF system
- Manipulation of RF voltages and phases in an injection period of ~ 200 ms



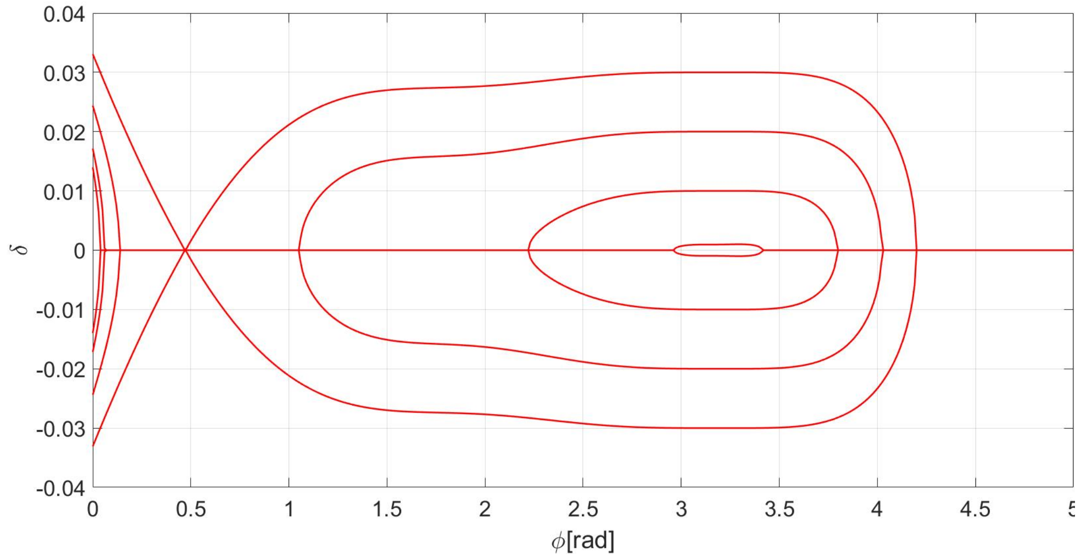


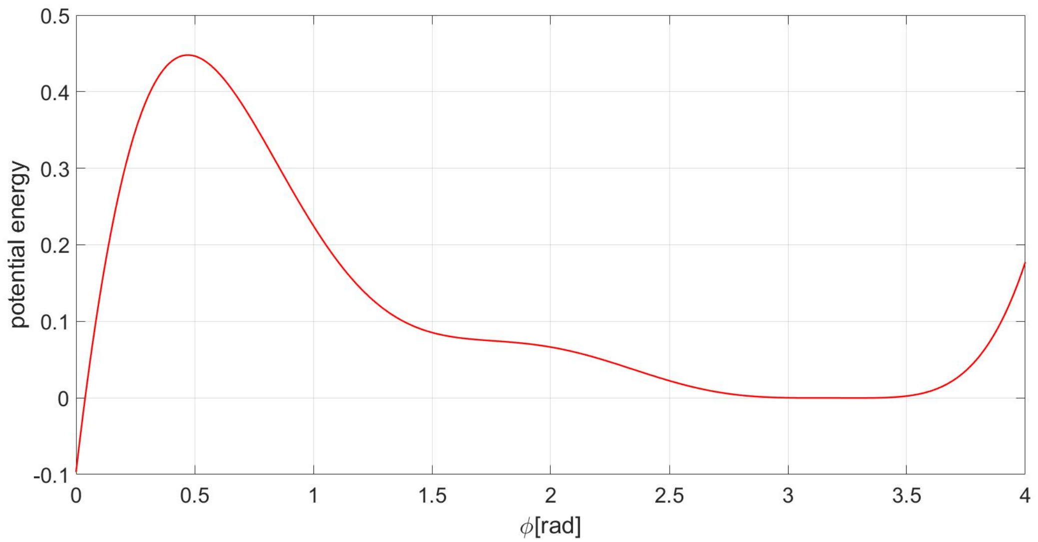




Challenges: 1. Operational issues with frequent RF ramping.
2. Substantial brightness drop (~20%) due to the short bunches at the injection mode.

On-axis longitudinal injection schemes for HEPS (2)

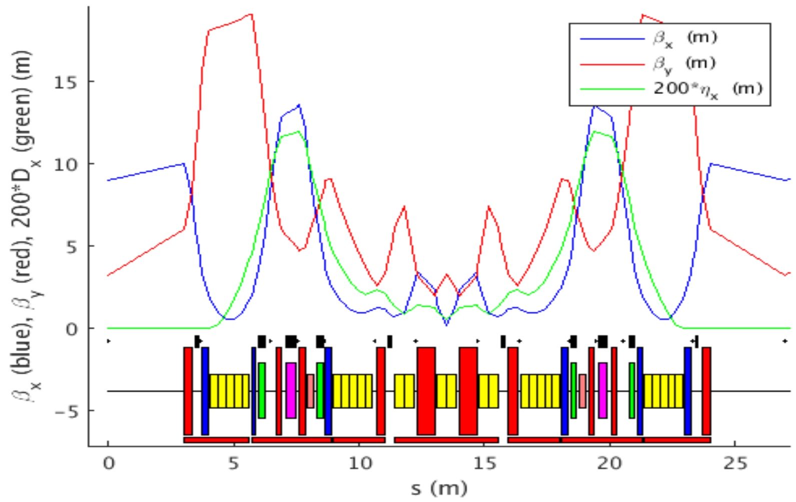


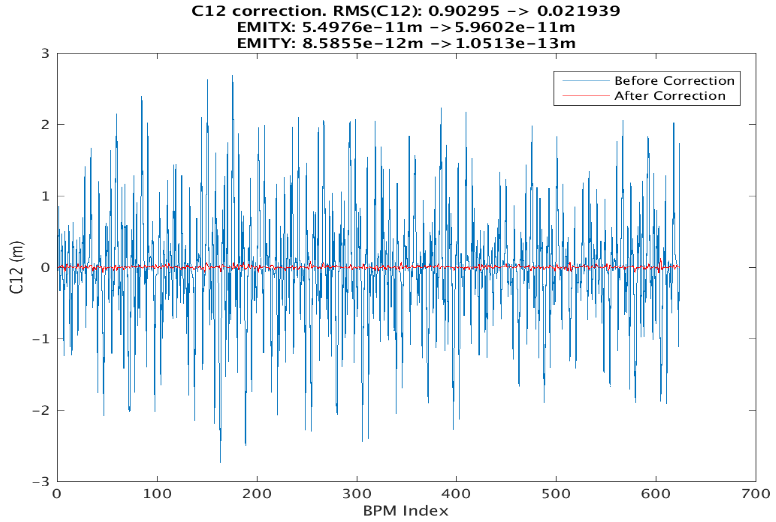


- 166 MHz + 333 MHz (2^{nd} harmonic) + 500 MHz (3^{rd} harmonic) RF systems
- A substantial increase in RF acceptance compared to what is achievable with a double RF system.
- Pro: no need for RF gymnastics, flexible choice between long / short bunch length.
- Cost: additional 333 MHz RF system
- Challenge: requires a large enough (~ 2mm) dynamic aperture at large synchrotron amplitude(~ 3%)

Error tolerance study

- Lattice model – 7-BA, 7 girders, 12 hori. and 10 vert. correctors, 4 skew quads, and 13 BPMs
- Error assign
  - Multipole field components (1e-3) of magnets
  - Alignment error (30μm on the same girder, 50μm on different girder) and rotation (100mrad)
  - BPM resolution (0.5μm)
- Alignment error is dominant
- Dispersion in vertical and coupling should be controlled by correcting with skew quads
  - From a max. 30 pm·rad increase reduced to 1 pm·rad increase.

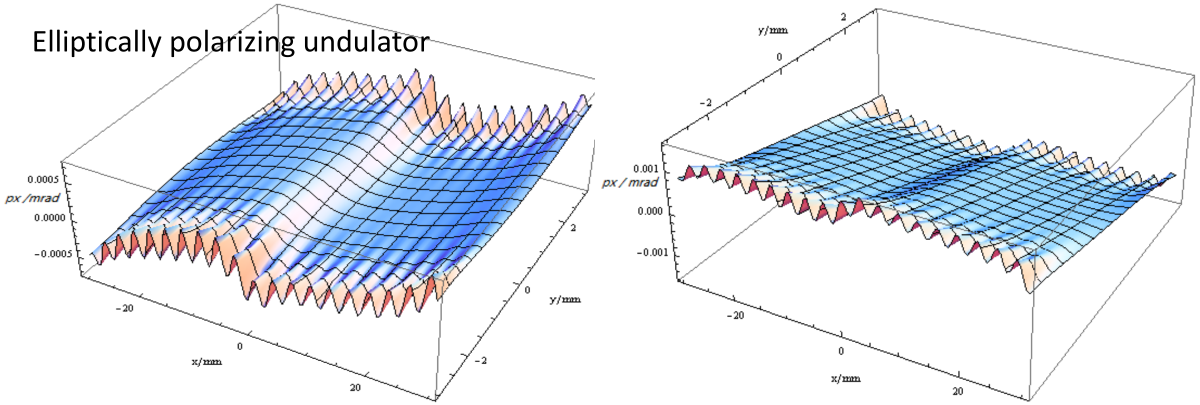


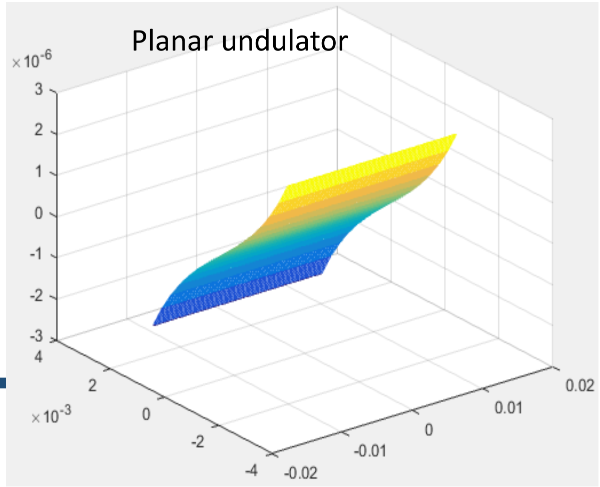


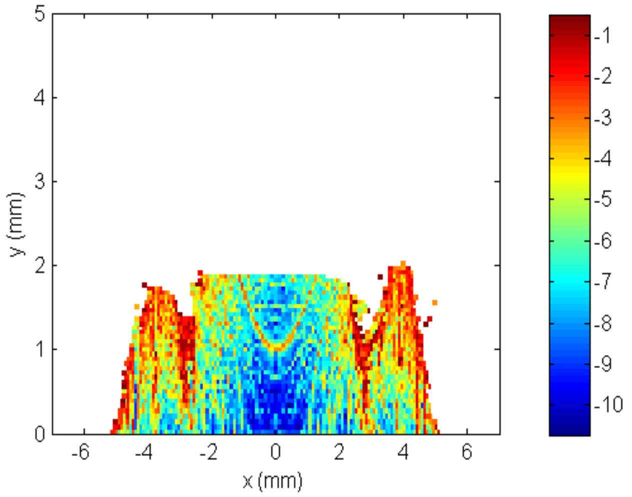
ID effect

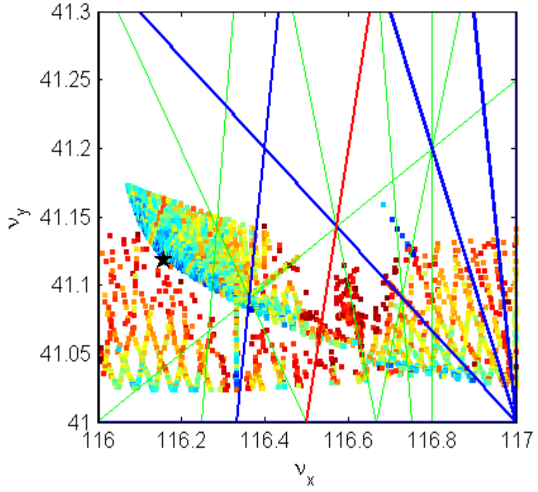
- Setup kick maps with Hamiltonian-Jacobin methods for 14 undulators to be installed in the first stage of HEPS.

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





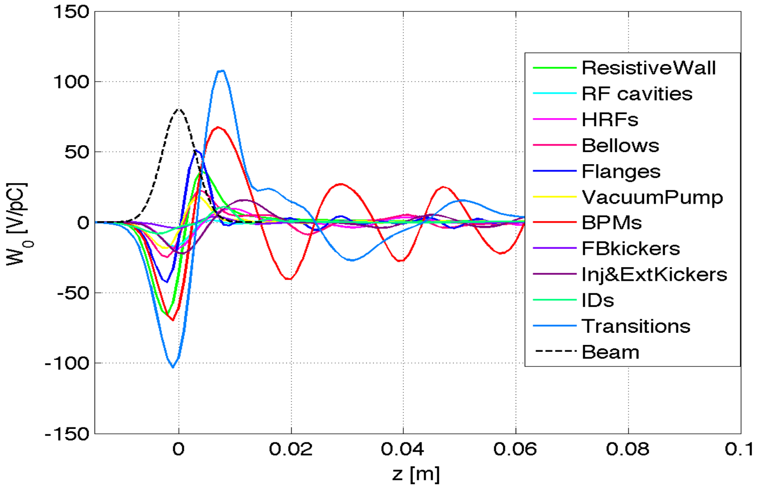




Collective effects – Impedance model

- Impedance model is setup 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



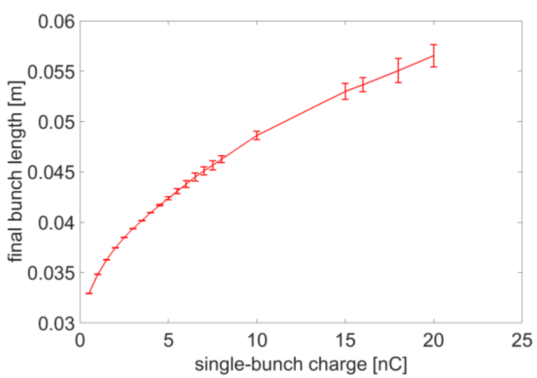
Longitudinal wake potential (σ_z =3mm)

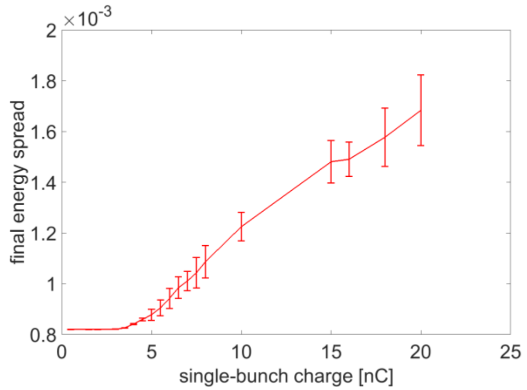
Geometrical contributions			
Elements	Number	Elements	Number
RF cavities	4	LFB kicker	1
Harmonic RFs	2	TFB kicker	1
Flanges	1000	Inj. kickers	10
Bellows	400	Ext. kickers	4
Vacuum pumps	288	IDs	15
BPMs	768	Transitions	360

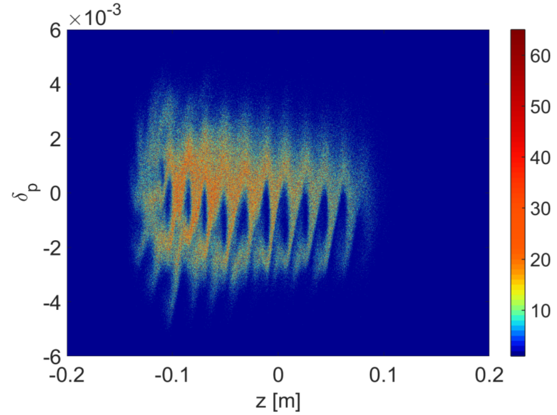
- The longitudinal impedance is dominated by large number elements, e.g., flanges, BPMs.
- The transverse impedance is dominated by the resistive wall impedance due to the small aperture of beam pipe.
- More impedance contributors will be included in the further studies.

Collective effects – single bunch instability

- Microwave instability
  - The Keil-Schnell criterion gives threshold bunch current of 0.2 mA.
  - Simulation studies shows that the threshold intensity is around 0.8 mA (3.5 nC) with harmonic cavity. Above threshold, turbulent distributions are observed.

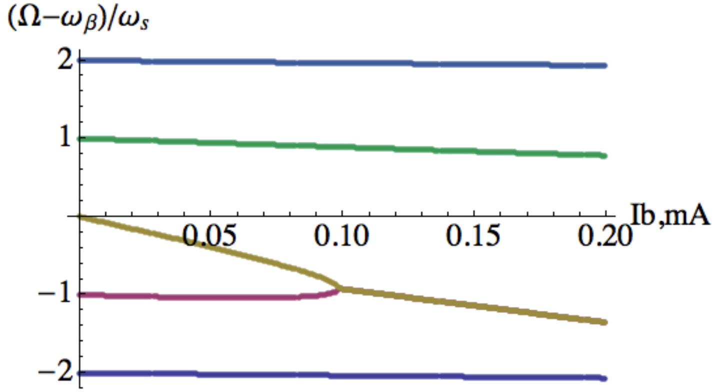






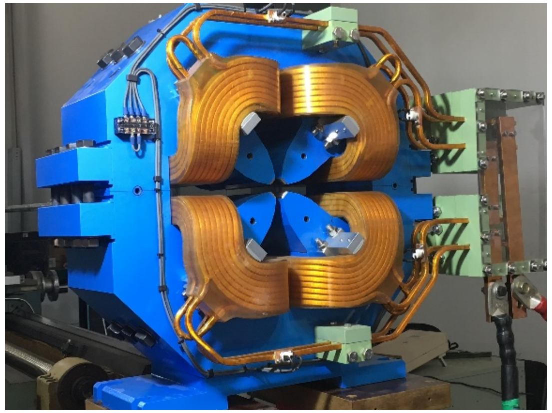
bunch charge=15nC

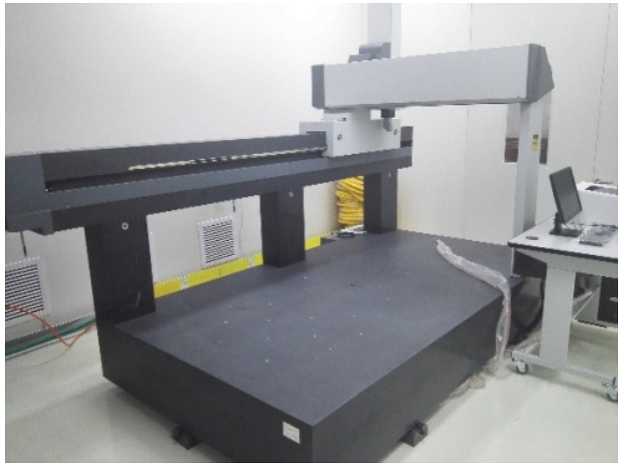
- TMCI
  - For Gaussian bunch, the instability is evaluated with Eigen Mode analysis.
  - The threshold bunch intensity is ~0.1 mA with $\xi = 0$.
  - A positive chromaticity is required.

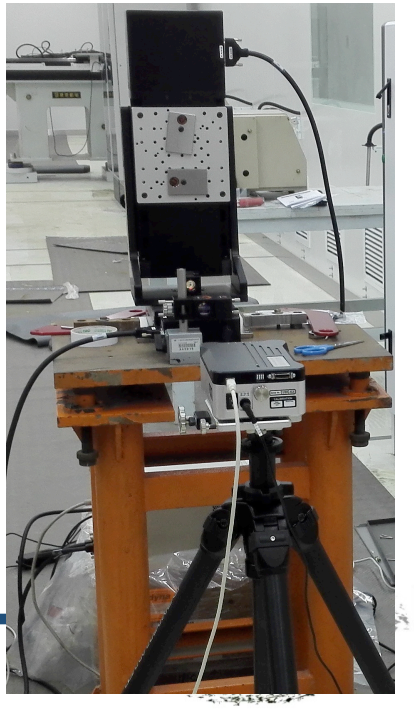


3. Key technologies to HEPS – supported by HEPS-TF

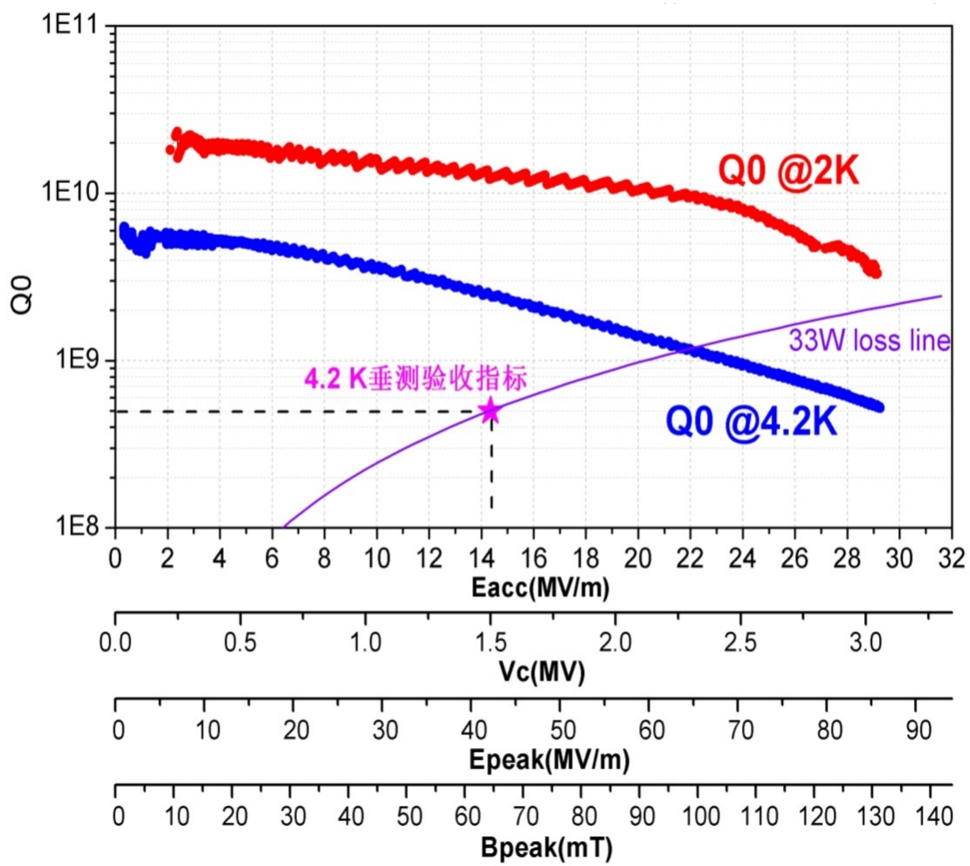
- Magnets
  - High-gradient quadrupole
  - Gradient: 88T/m
  - Longitudinal gradient dipole
  - Combined function magnets: dipole+quad





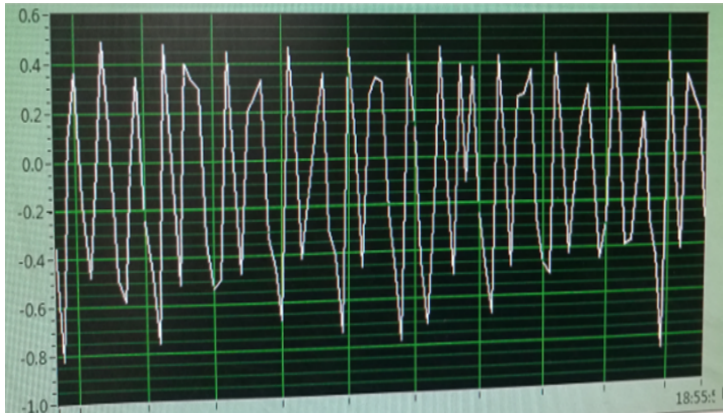


- 166.6 MHz SRF cavity – for longitudinal injection
  - Tested in March 15, 2017
  - 85 MV/m, 130 mT, 2.3 nΩ

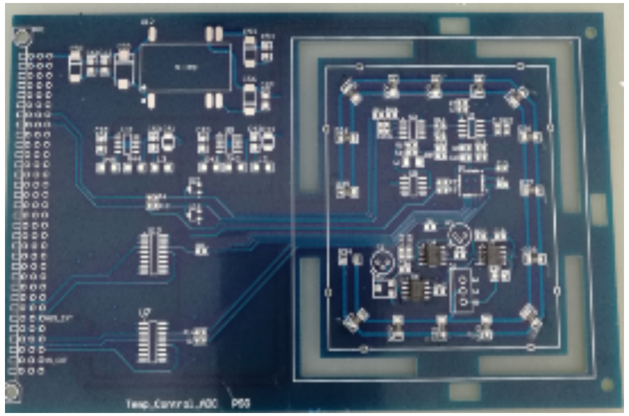


HEPS

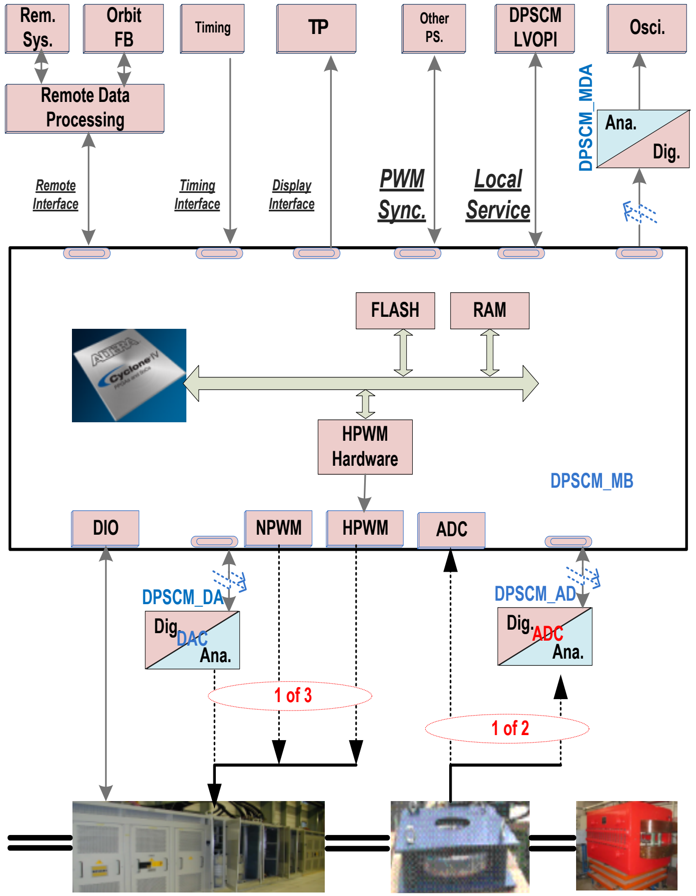
• High accurate power supplies

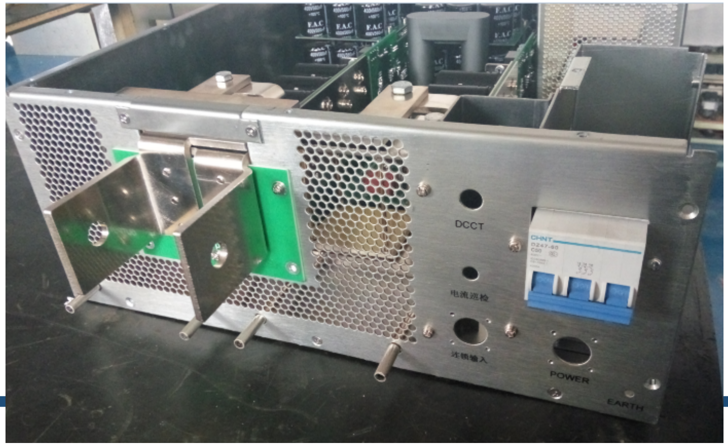


Prototype of dynamic PS (acc. =0.1%)

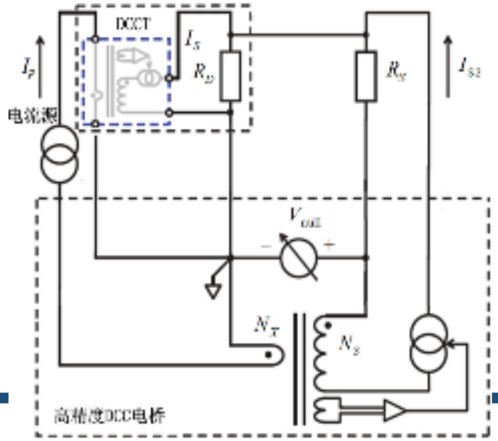


DPSCM-II high acc. ADC plate

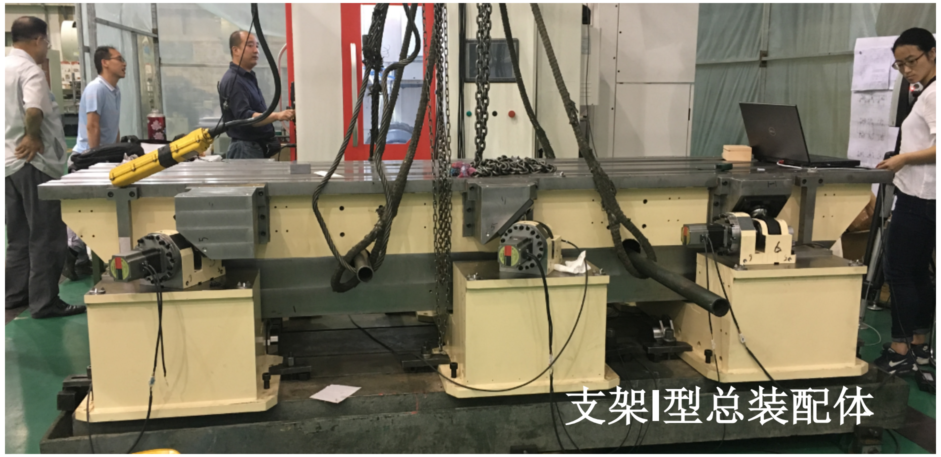


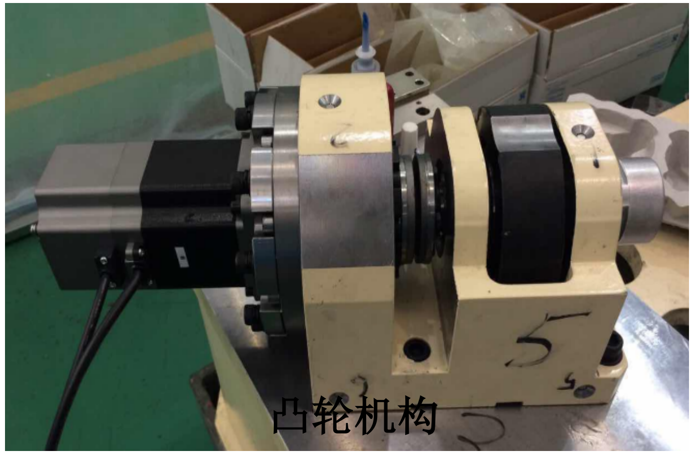


10ppm high accuracy PS

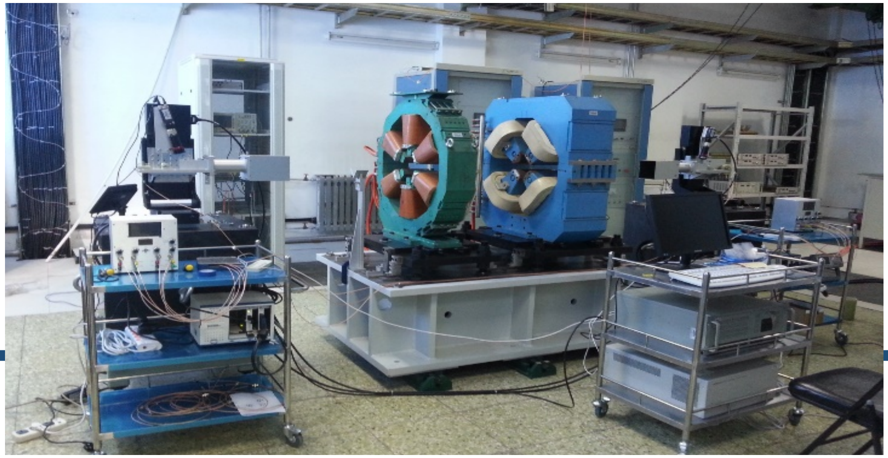


- Mechanics & alignment
  - Auto-control high precision tunable girder

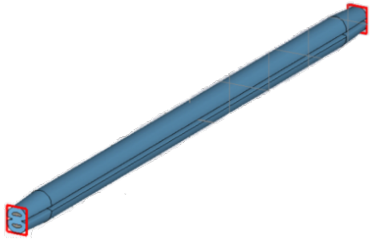
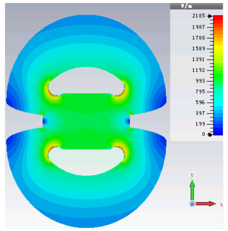
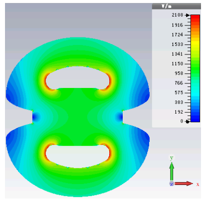
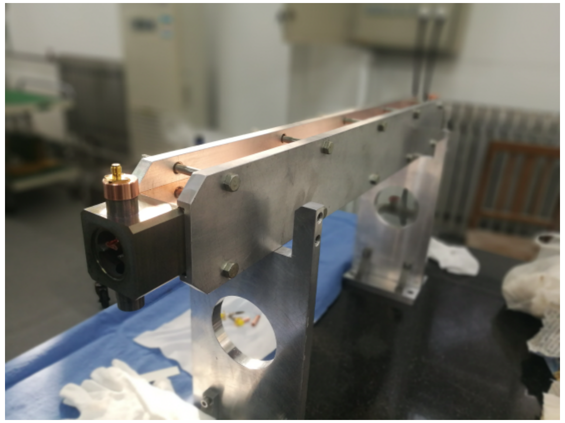
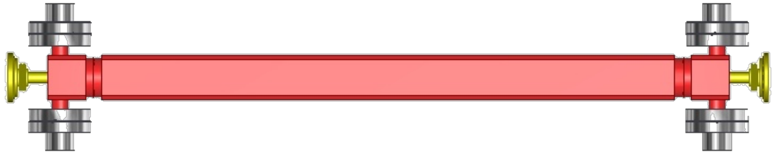
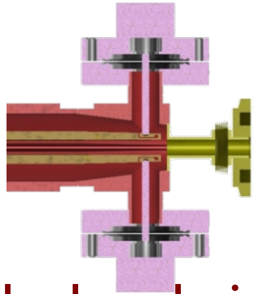




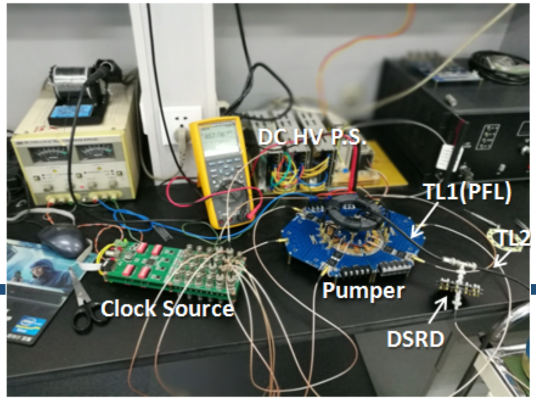
- Oscillating-line alignment tech.

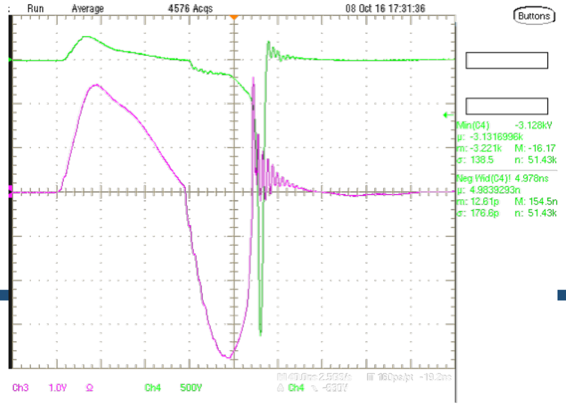


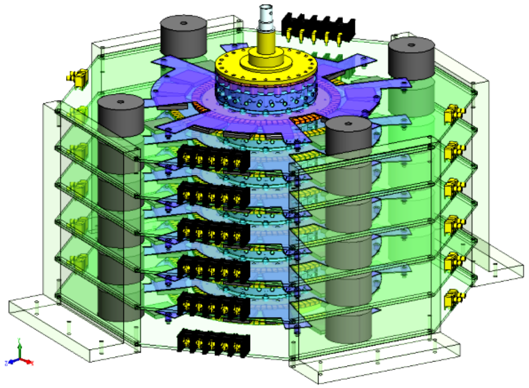
- Injection kicker & power supply
  - Physics and structure design for the strip-line kicker, on-line test

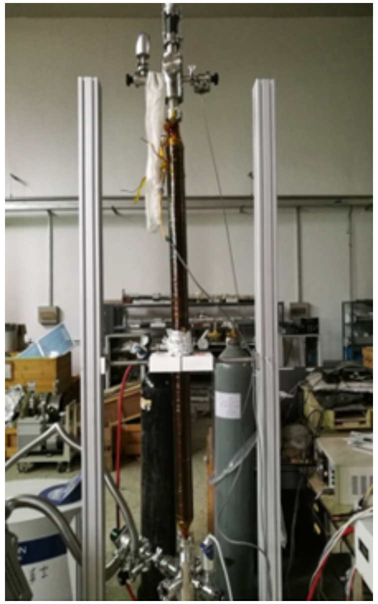
  - DSRD rapid pulse PS – Test of single-level circuit & structure design for 6-level iterated circuit







- Vacuum technique
  - NEG coating device, still in progress



国产 Ti（1mm）V（0.8mm）Zr（1mm）1:1:1

国产 Ti（1）V（0.8mm）Zr（1mm）1:1:2

进口 Ti（1mm）V（0.8mm）Zr（1mm）1:1:1

进口 Ti（1mm）V（0.8mm）Zr（1mm）1:1:2

  - Photon absorber

HEPS

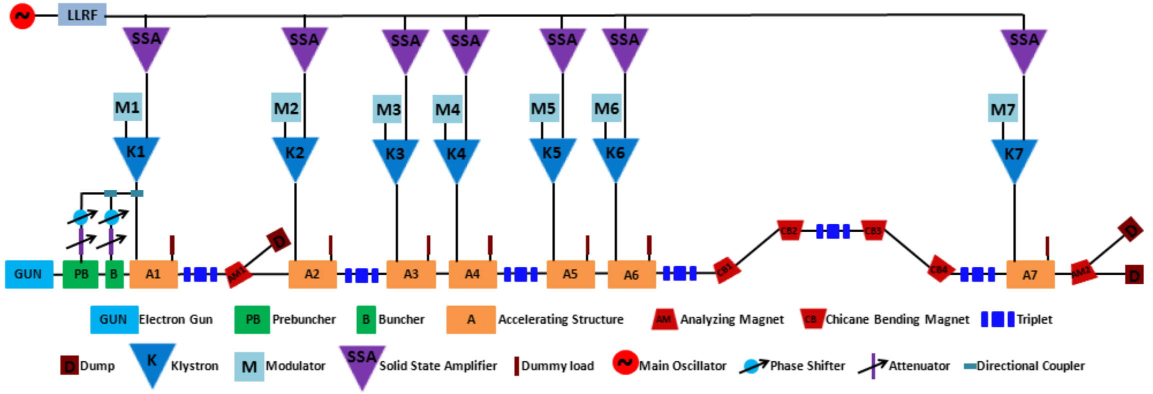
4. Project progress (HEPS)

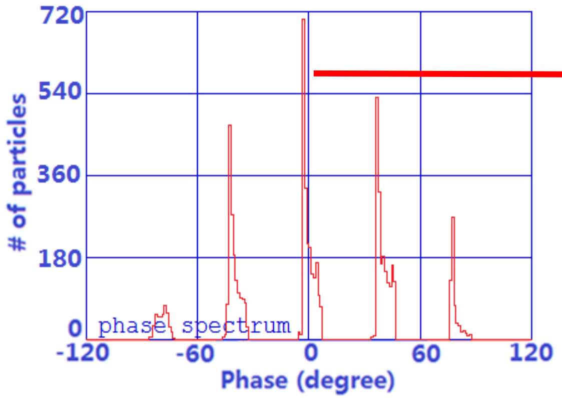
- Milestones of HEPS
  - 01/2016, CDR study & writing
  - 02/2017, CD0 completed & submitted to CAS
  - 03/2017, internal review of CD0, modify CD0 report
  - 05/2017, CD0 submitted to National Development & Reform Commission
  - 06/2017, CD1 study and report writing started
  - 26/06/2017, national review of CD0
  - 09/2017, CD0 approved & CD1 report will be submitted
  - 12/2017, national review of CD1
  - 06/2018, national review of CD2
  - 11/2018, project construction starts, and will completed in 6.5 years

Design of the injector to HEPS

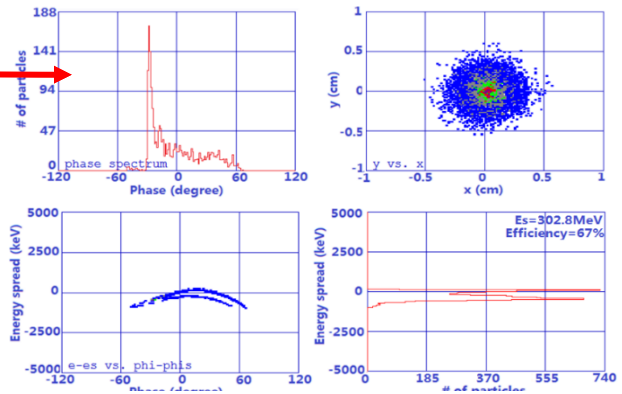
- Linac design

Electron gun, buncher, accelerating tube, etc.

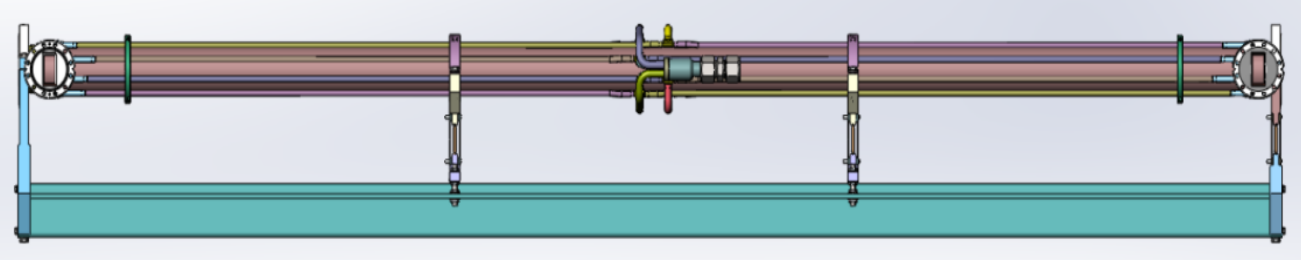


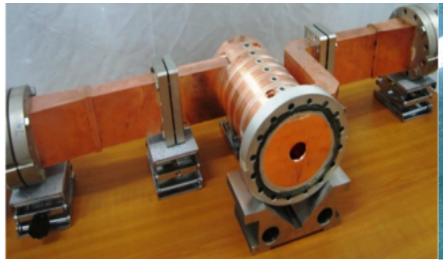


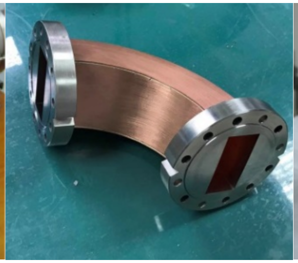
Bunch distribution at the linac exit

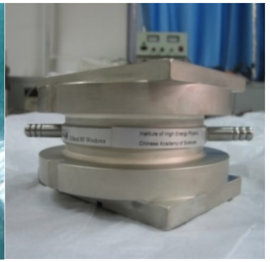


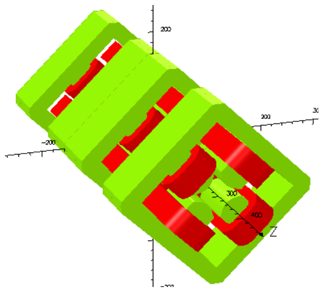
Phase & position distribution of central bunch





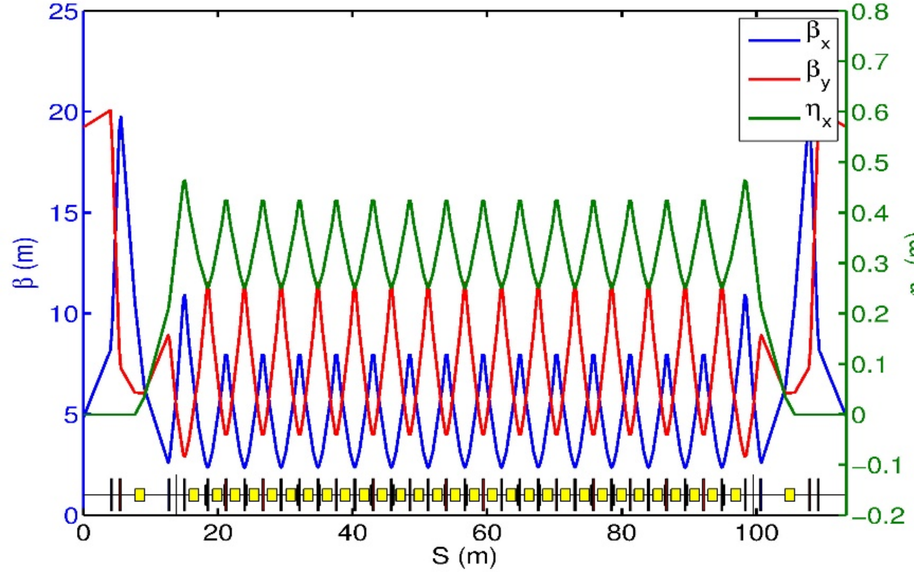


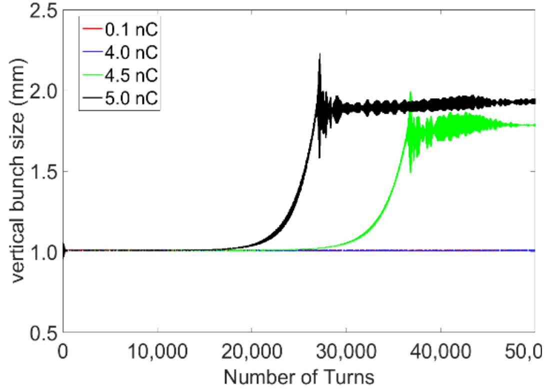




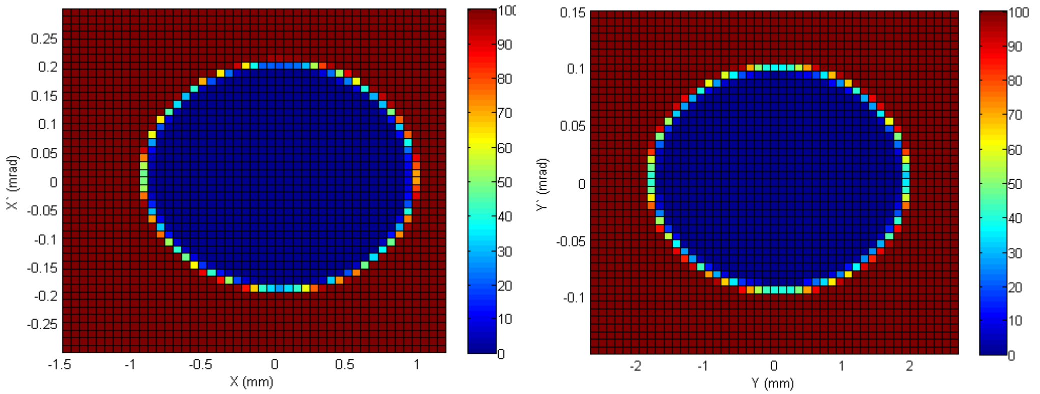
- Beam dynamics simulation & AP design
- Design of accelerating structure & MW element
- Physics design of various kind of magnets
- Design of other systems of linac

• Design of booster

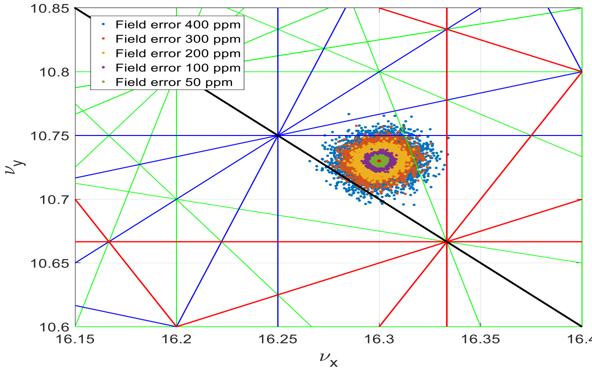




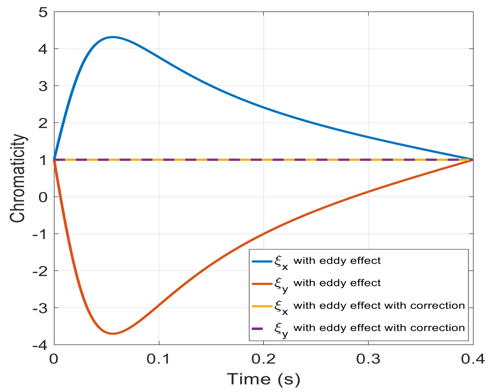
Single bunch current limit



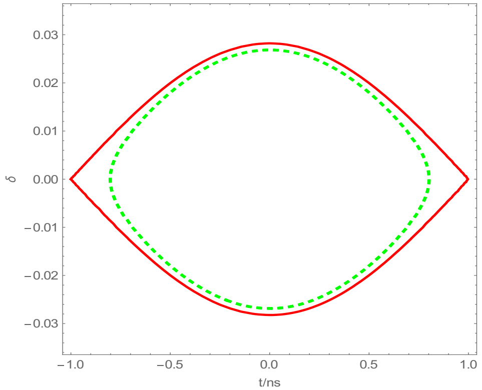
Effect on orbit error at low energy to injection



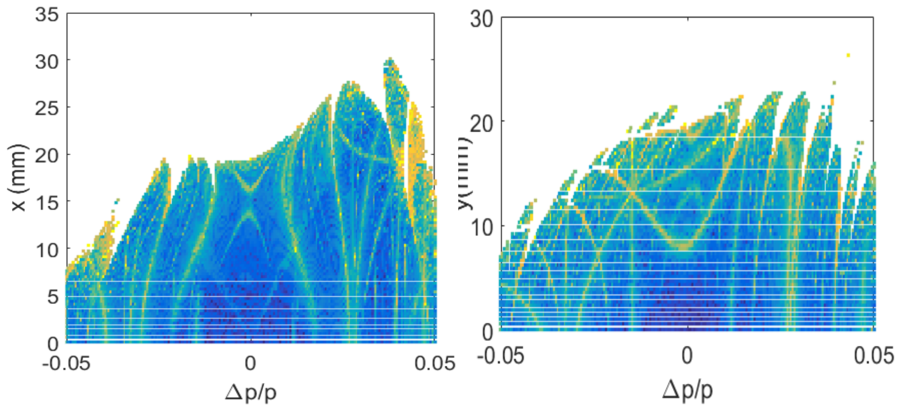
Effect of magnetic errors to tunes



Chromaticity variation due to ripple



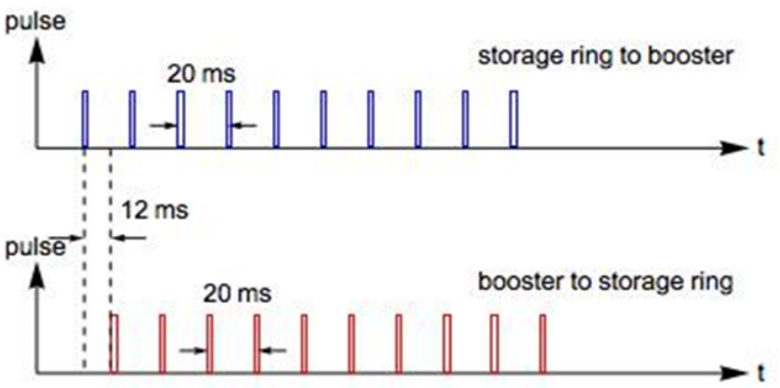
Mom. Acceptance @low energy



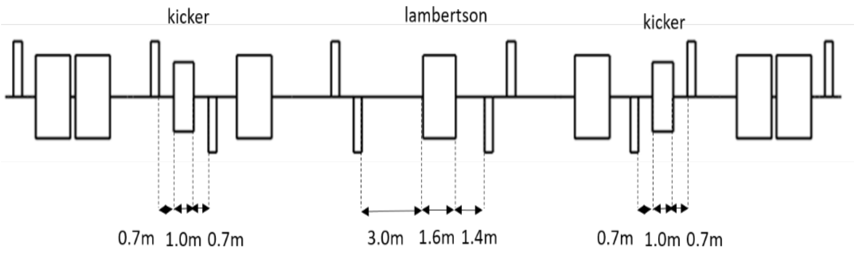
Dynamic aperture study

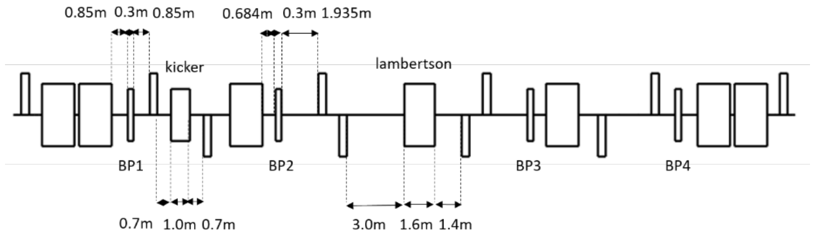
- ☐ Lattice design & nonlinear tracking study
- ☐ Magnetic errors effects to injection and beam store
- ☐ Simulation on impedance, modification of AP parameters to get required bunch charge
- ☐ Fit to the swap-out & long. on-axis injection

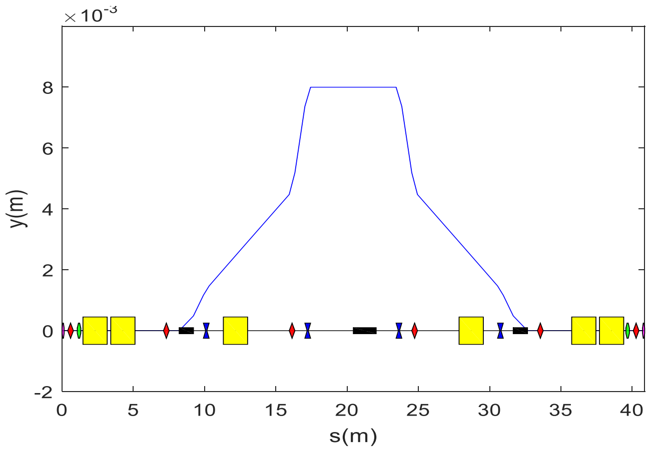
• Design on injection and extraction

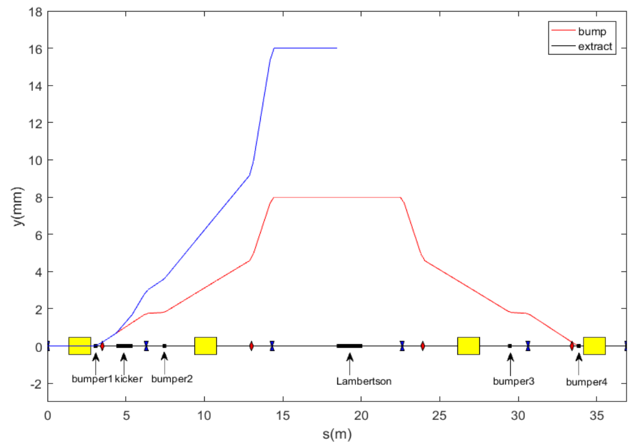


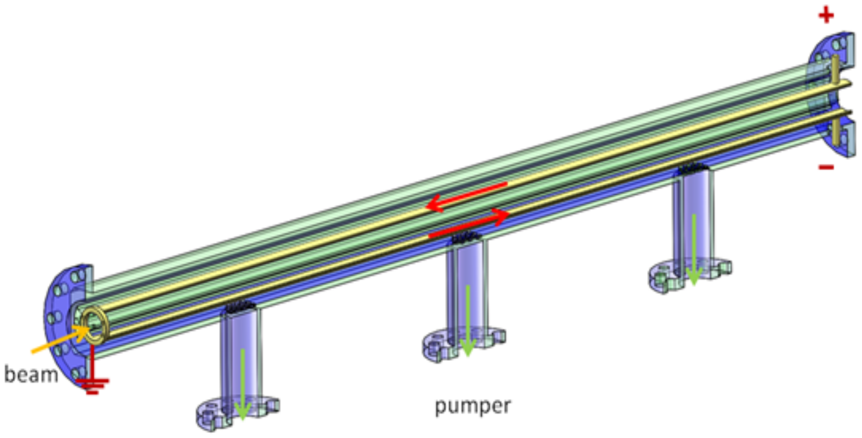
Pulse distribution at BTS line









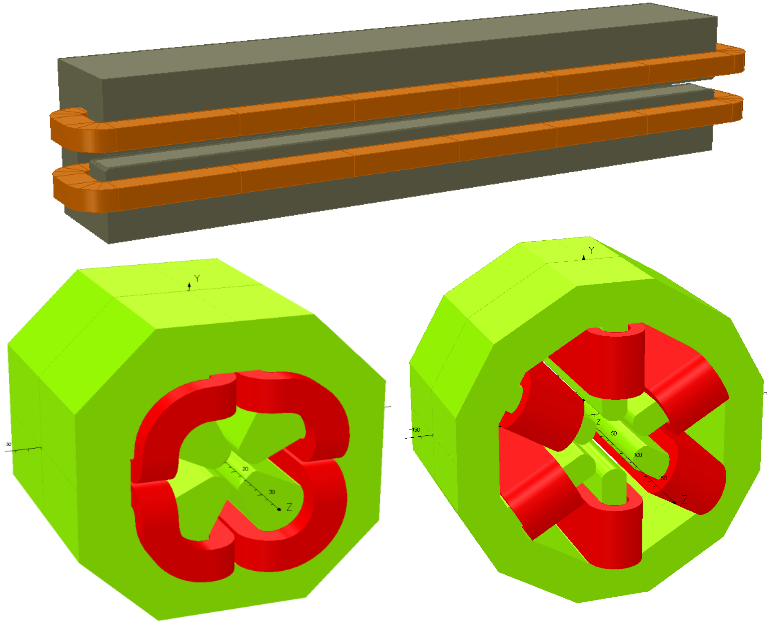


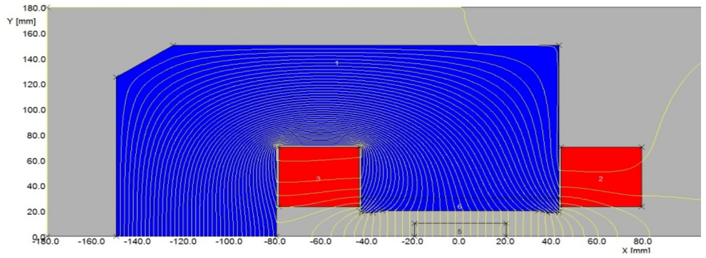
Slotted kicker

- ☐ Lattice design of injection and extraction sections
- ☐ Simulation on injection
- ☐ Physics design of key elements
- ☐ Fit the requirements of swap-out & long. on-axis injection

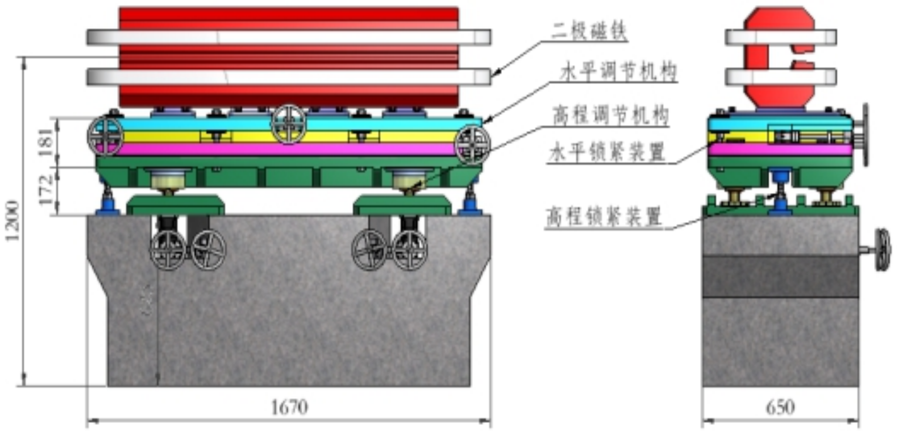
HEPS

• Design on key hardware of booster

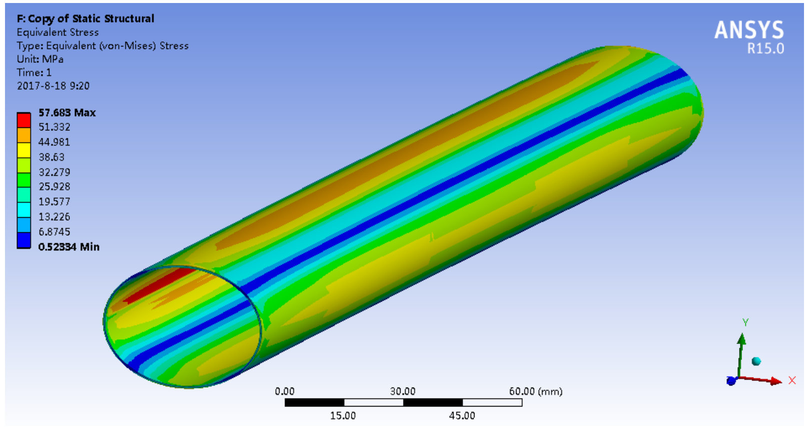




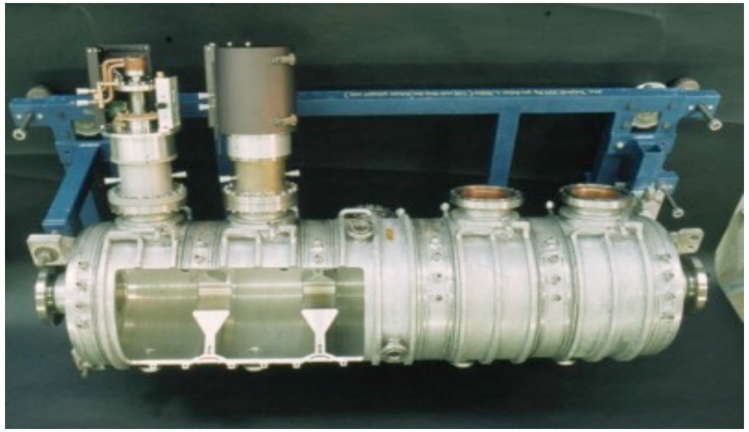
Design of various magnets



- ☐ 7 kinds of magnet support
- ☐ Injector 2D layout in general
- ☐ Linac mechanics design



- ☐ air loading & pressure analysis
- ☐ vacuum chamber design & temp. deform calculation

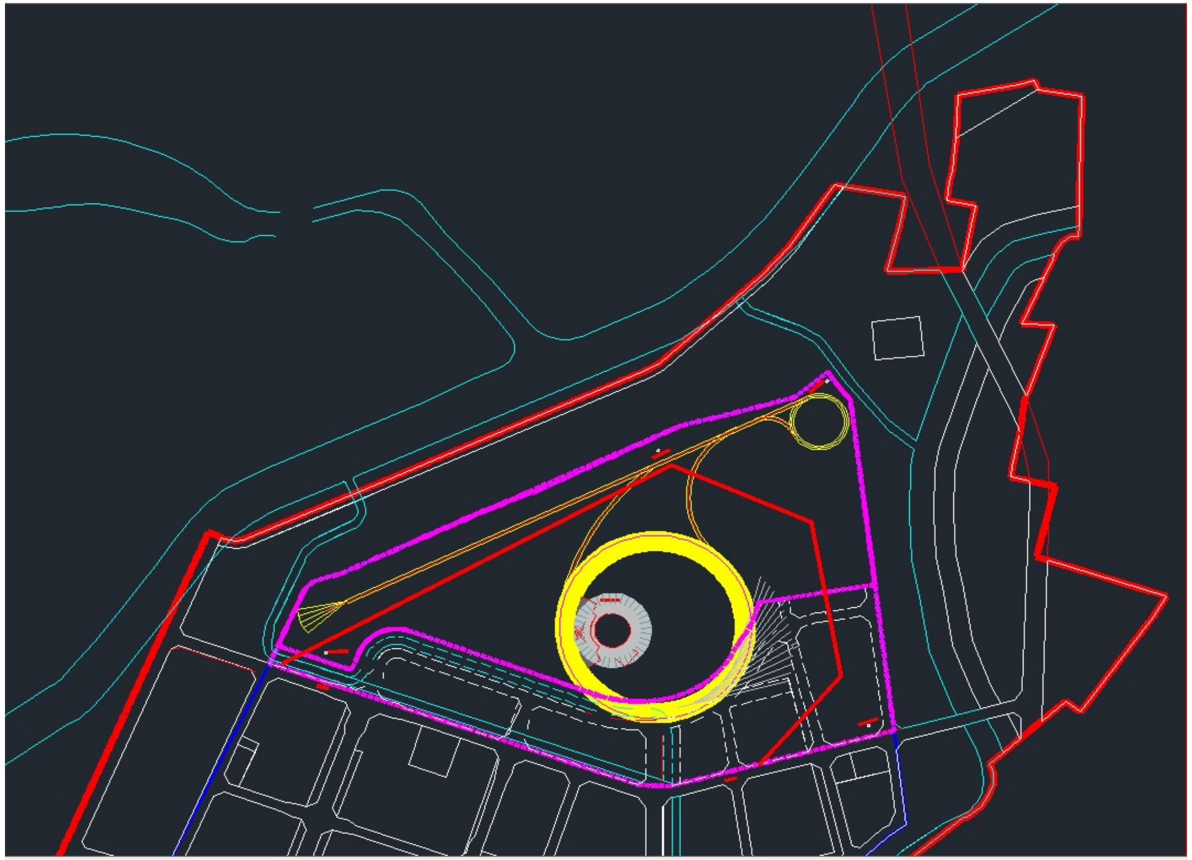


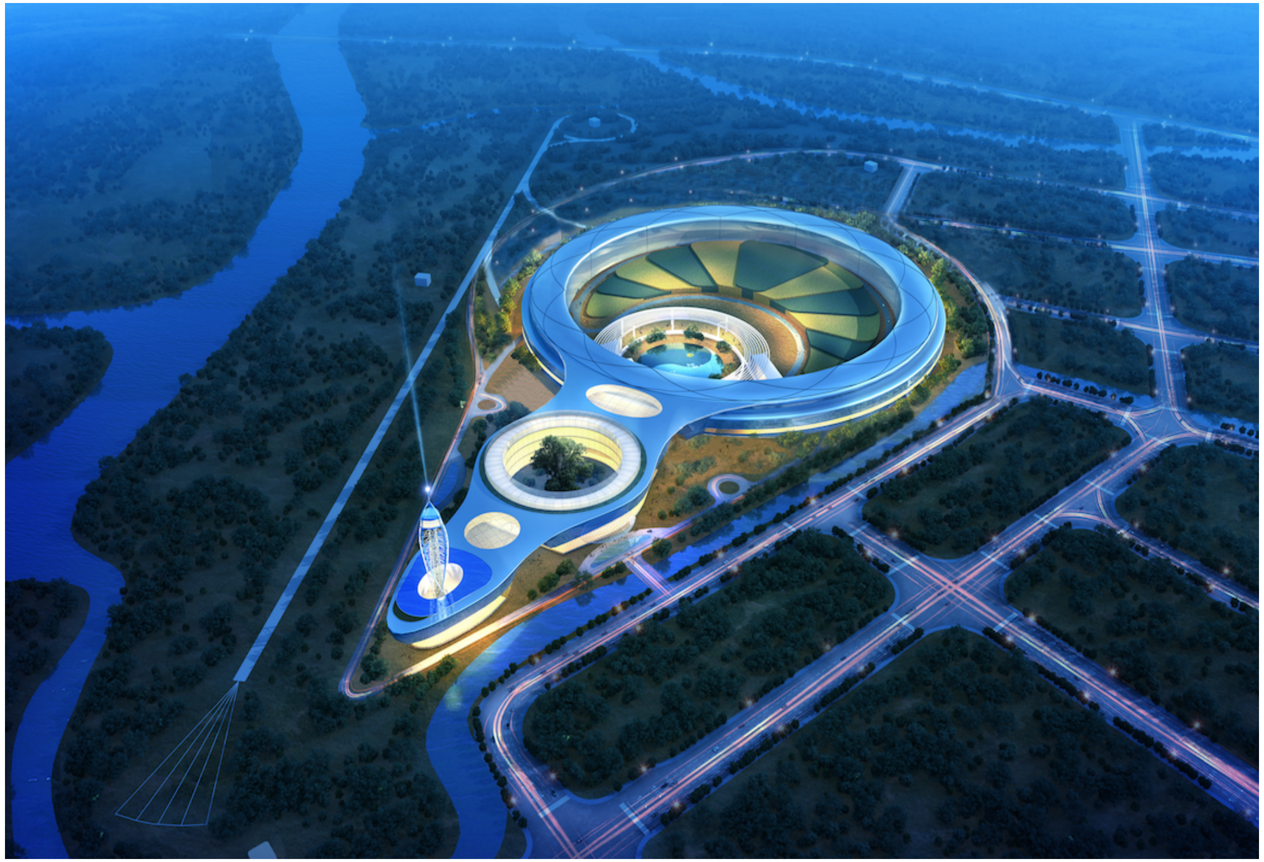
- ☐ Design on RF system integration
- ☐ HOM calculation

Beamlines for the phase-I of HEPS

1	High energy X-ray diffraction	High energy, low emmitance
2	CDI and XPCS	
3	NRS and IXS	
4	Nano-probe	
5	Time-resolved techniques	
6	Hard X-ray imaging	
7	High-pressure	
8	Protein crystallography	Large users communities
9	XAFS	
10	*In situ* surface diffraction and scattering	
11	High throughtput SAXS	
12	Ultrahigh resolution Electronic-Structure Spectroscopy	Application in industry, medicine, etc.
13	Medium energy X-ray micro-spectroscopy	
14	Structure and spectrum imaging	

Site, construction & buildings





HEPS

Platform for Advanced Photon Sciences (PAPS)

Supported by Beijing Municipality (~0.5 B RMB), 05/17 – 05/20
Research in accelerator and X-ray optic techniques
Testing infrastructure (magnets, RF, pre-alignment, vacuum, ID) of HEPS

5. Summary

- A high energy photon source is requested by users, aiming at the lowest emittance and highest brightness in the exiting synchrotron light sources.
- The R&D of the HEPS project is being carried on, and will be finished by the end of Oct 2018.
- The HEPS is scheduled to start the construction by the end of 2018, and will be completed in mid of 2025.
- The AP design and key technologies development for the HEPS are now under way.

Thanks for your attentions!