Status of two accelerator projects of Institute of High Energy Physics (IHEP)

- High Energy Photon Source (HEPS)
  - Huai-Rou district, Beijing
- China Spallation Neutron Source (CSNS)
  - Dong-guan, Guangdong province

Yao-shuo Yuan

on behalf of

Yu-hui Li and Sheng Wang

- Yu-hui Li (Deputy Director of IHEP)
- Sheng Wang   (Deputy Director of IHEP , Director of CSNS)

HEPS Commissioning Status

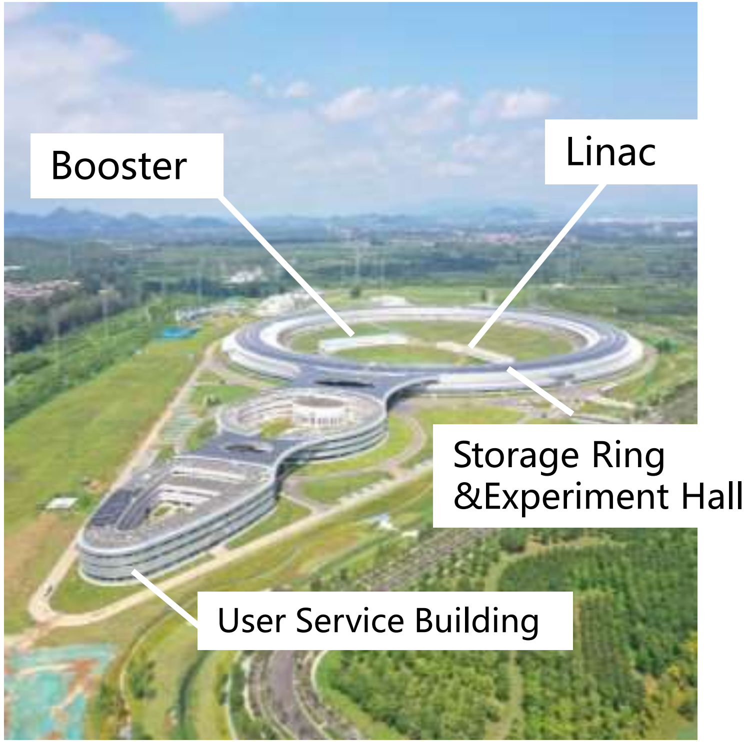
Yao-shuo Yuan
on behalf of
Yu-hui Li

01.09.2024 Frankfurt

OUTLINE

- Overview of HEPS
- Storage ring injection and first-turn trajectory correction
- Beam circulation multi-turn commissioning

Overview of the HEPS



- Fourth-generation synchrotron light sources
  - Budget 0.67 billion USD
  - more than 90 high-performance beamlines
  - provide X-rays with energy up to 300 keV
  - 10nm spatial resolution, 1MeV energy resolution
  - picosecond time resolution for high-frequency dynamic detection

Overview of the HEPS

	HEPS	APS-U	ESRF-EBS	MAX-IV	Sirius
E(GeV)	6	6	6	3	3
C(m)	1360.4	1104	844.4	528	518
Lattice	7BA	7BA	7BA	7BA	5BA
Cell	48	40	32	20	20
Emittance (pm rad)	34	42	150	330	250
Brightness	$>10^{22}$	$> 10^{22}$	$> 10^{22}$	$\sim 10^{21}$	$\sim 10^{21}$
Construction period	2019~2025	2018-2024	2015-2020	2010-2016	2015-2018

Overview of the HEPS

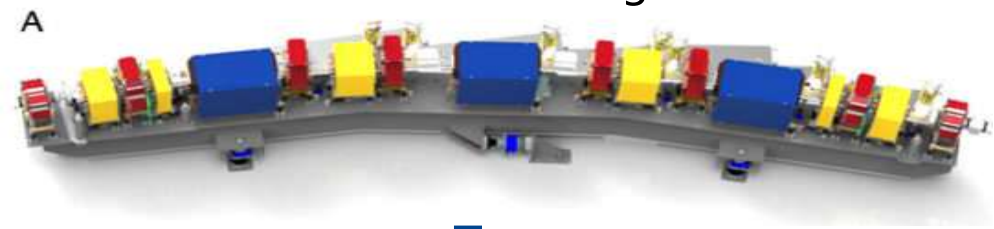
- HEPS：4th generation storage ring with 7- Bend Achromat (7BA) design

- The emittance is reduced by 1or 2 orders of magnitude
    - the X-ray diffraction limit

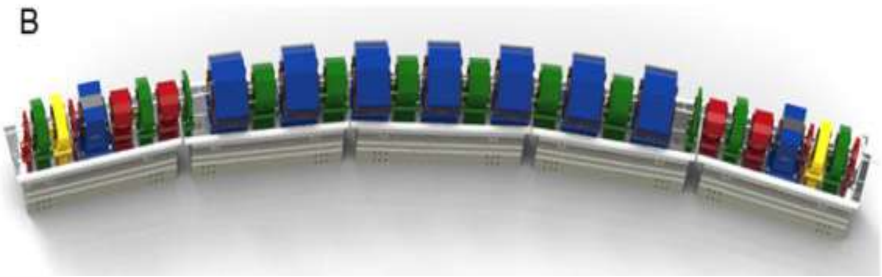
Overview of the HEPS

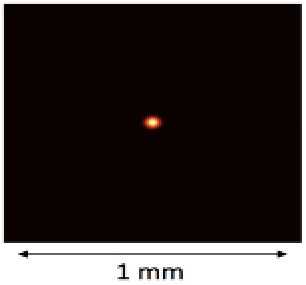
- The brightness increase by 2 to 3 orders of magnitude

3rd generation



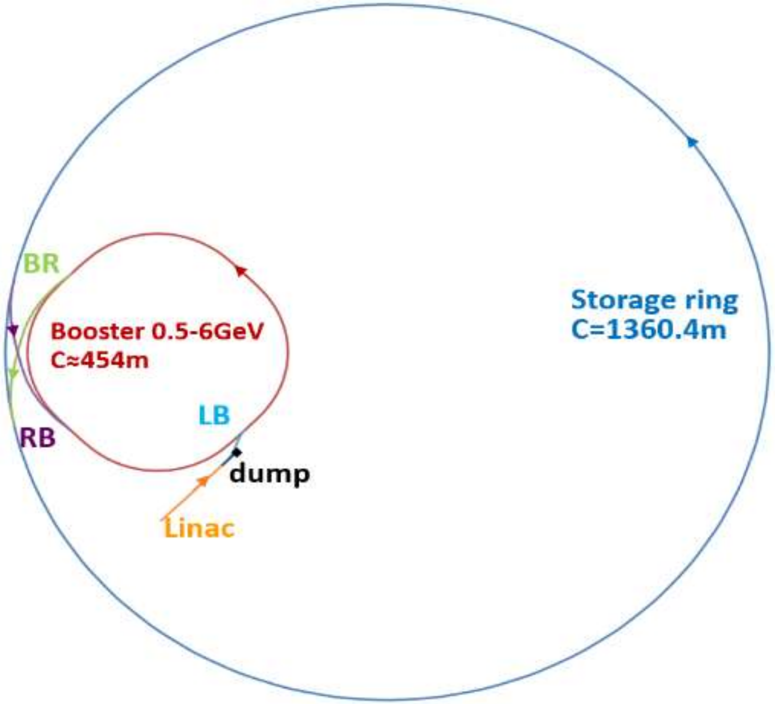
4th generation



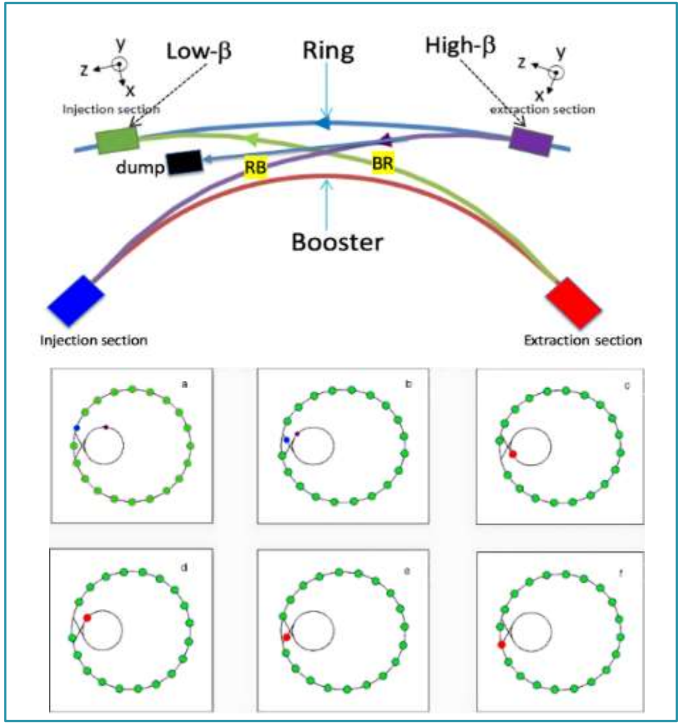


Beam Profile

Overview of the HEPS



swap-out injection



Milestones of HEPS Construction

- 2019.12 the physical design was determined
- 2021.06 installation of the first equipment
- 2022.03, the tunnel installation of the Linac
- 2022.08, the tunnel installation of the booster started
- 2023.07 beam commissioning of the booster started
- 2023.08, booster energy ramp to 6GeV
- 2024.08, beam currents higher than 10mA stored in storage ring

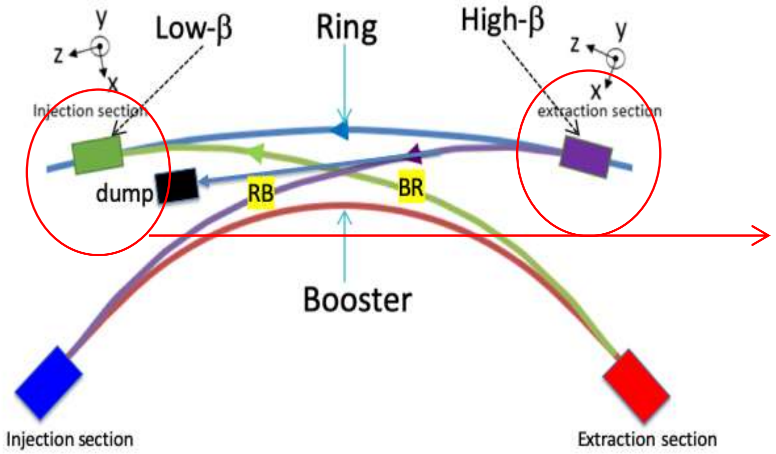
Achievements in the storage ring commissioning

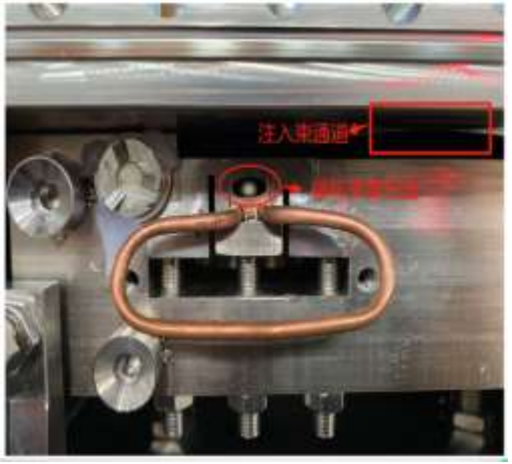
- Accelerator
  - **Low-energy linac**: 500 MeV, bunch charge > 7 nC
  - **Booster**: 6GeV, single bunch up to 5nC
  - **Storage ring**: Hardware installation completed

- Beamline
  - 14 beamlines
  - 17 end stations Installation Completed

Achievements in the storage ring commissioning

- the first step is not easy…





Lambertson septum (LMS)

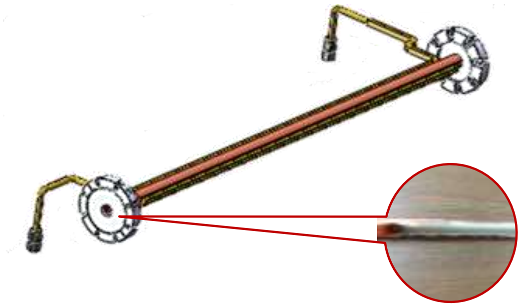
Parameters	values
Length	1.6 m
Vertical aperture	±2.5 mm

First-turn injection and trajectory correction

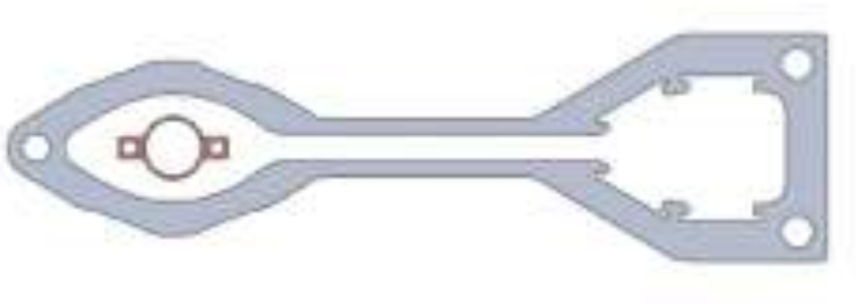
- Fourth-generation storage ring: Even if all magnets are aligned, **no stable closed orbit exists before orbit correction**
  - Traditional design: the closed orbit distortion caused by magnet alignment errors is comparable to the physical aperture of the vacuum chamber.
  - However, due to strong focusing, the orbit distortion caused by alignment errors increases significantly (tens of times higher compared to third-generation light sources).
  - To achieve ultra-low emittance, small-aperture magnets and small-aperture vacuum chambers must be used (HEPS aperture ~22 mm, NSLS-II (3rd gen) aperture ~76×25 mm).

First-turn injection and trajectory correction

- With improved magnet alignment accuracy (~3 times), challenges is still not fully addressed



HEPS arc section small-aperture vacuum chamber, ±11 mm



The vacuum chamber aperture for APS (3rd generation) is 85 × 42 mm, whereas for APS-U (4th generation), it is 26 × 26 mm.

First-turn injection and trajectory correction

➢ Some difficulties during the early stages of commissioning

- Any **hard obstruction or misalignment** in equipment installation can disrupt the electron beam's trajectory

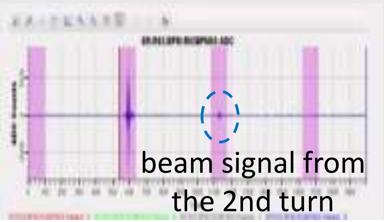
- The beam charge is low and damping occurs quickly, which reduces the accuracy of beam parameter monitoring. As a result, the available monitoring methods and their precision are limited.

- In fact, during first-turn commissioning, despite extensive preparation and calibration of the BPMs, most of the time we were observing the signals **provided by the BPMs** rather than the actual beam position information.

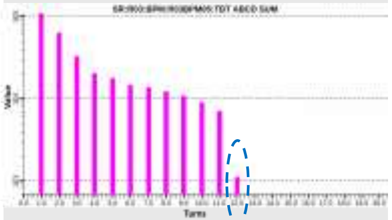
Storage ring commissioning process

07.23 — **commissioning started**

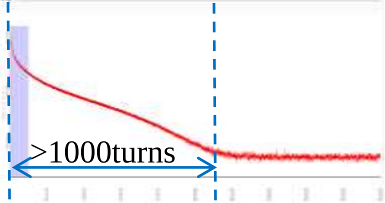
07.23 — **First turn achieved**



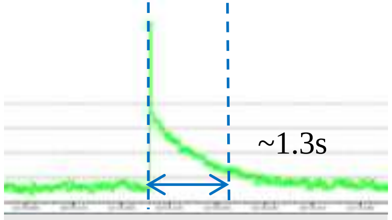
07.29 — **Beam circulates for 10 turns**



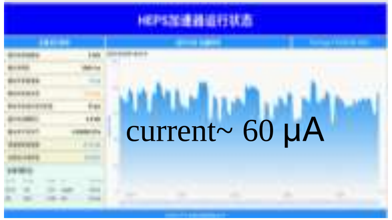
08.04 — **Beam circulates for 1000 turns**



08.06 — **First beam storage**

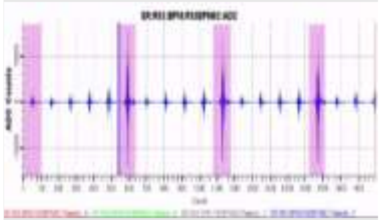


08.06 — **Beam lifetime: 1 minute**

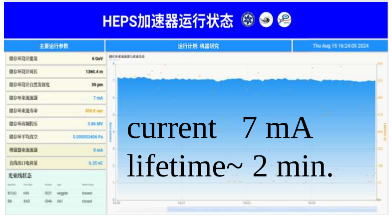


08.08 — **First multi-bunch beam storage**

current~ 0.4 mA
beam lifetime~ 1 min

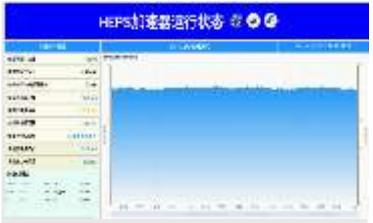


08.15 — **Current reaches 7 mA**



08.18 — **Current reaches 12 mA**

current 12 mA
beam lifetime~ 2 min



Storage ring injection and first-turn trajectory correction

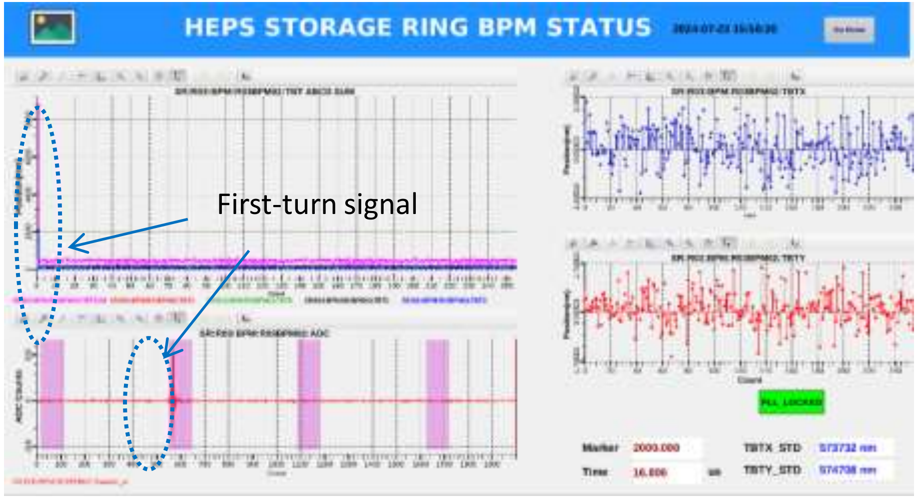
- Main challenges: Facing various uncertainties
  - 105-meter Transport Line and 1360-meter Storage Ring: Are there any "hard blockages" in the beam channel?
  - Thousands of Magnets in Transport Line and Storage Ring: Are any magnets installed with reversed polarity?
  - Alignment: Is there significant deviation from the alignment specifications

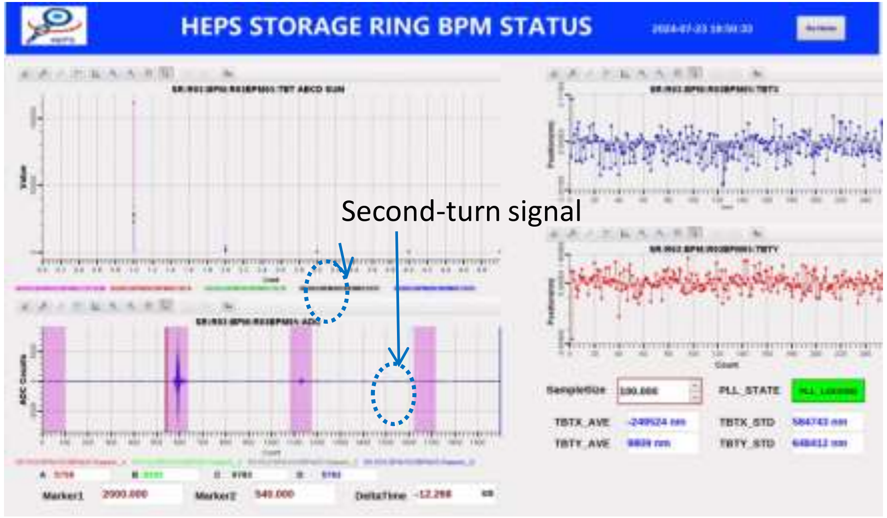
Storage ring injection and first-turn trajectory correction

- July 23: First turn of the beam successfully achieved in the storage ring
  - 11:00: Dr. Weimin Pan, Chief Engineer of the HEPS project, announces the start of the storage ring commissioning.
  - 12:25: beam commissioning starts
  - 13:20: Beam is successfully extracted from the booster and transmitted to the end of the high-energy transport line.
  - 15:10: First injection into the storage ring is achieved.
  - 19:50: The first turn of the beam in the storage ring is achieved!

Storage ring injection and first-turn trajectory correction

This indicates that the storage ring has no significant hard blockages, and the magnet polarities are correct.





Beam circulation multi-turn commissioning

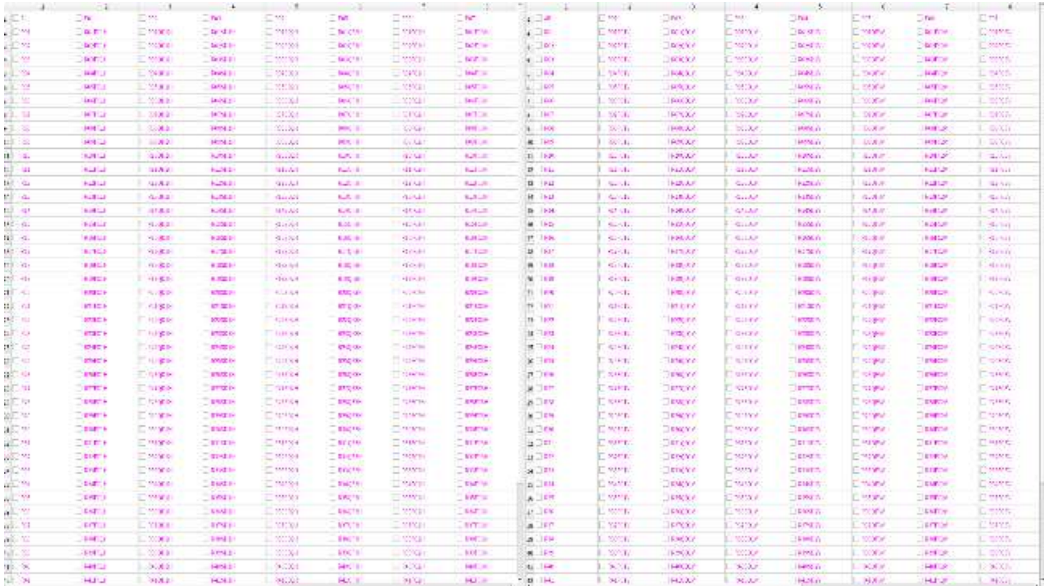
- Main challenge: Small aperture at the two LMS (1.6 m long with ±2.5 mm aperture)

- Other Difficulties
  - Radiation damping: Each time the electrons complete a cycle, there is radiation energy loss. Without correction, the trajectory will gradually damp to the center.

  - Natural Chromaticity: Large natural chromaticity causes significant deviations between the measured beam optics values and the design values. The beam optics are sensitive to energy deviations.

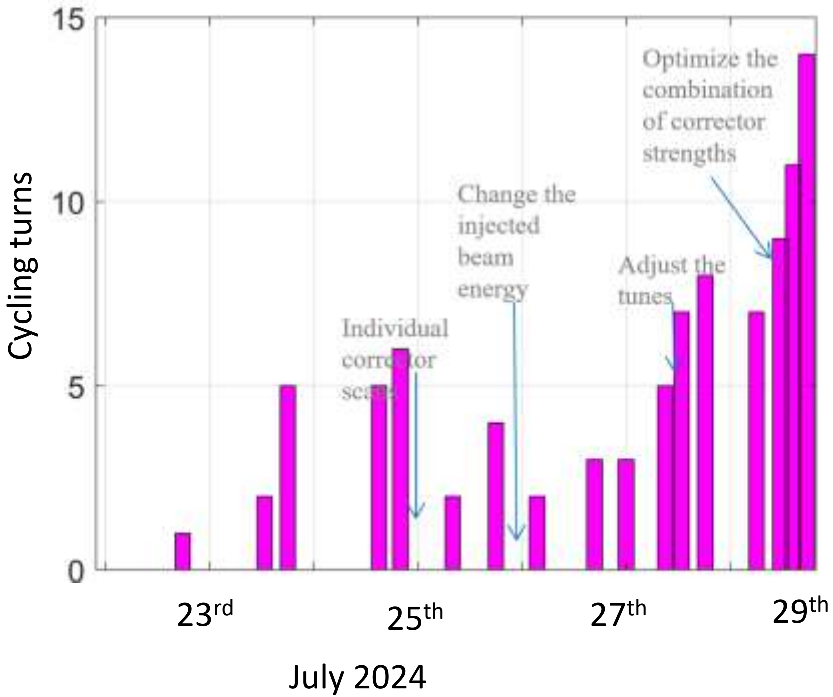
Beam circulation multi-turn commissioning

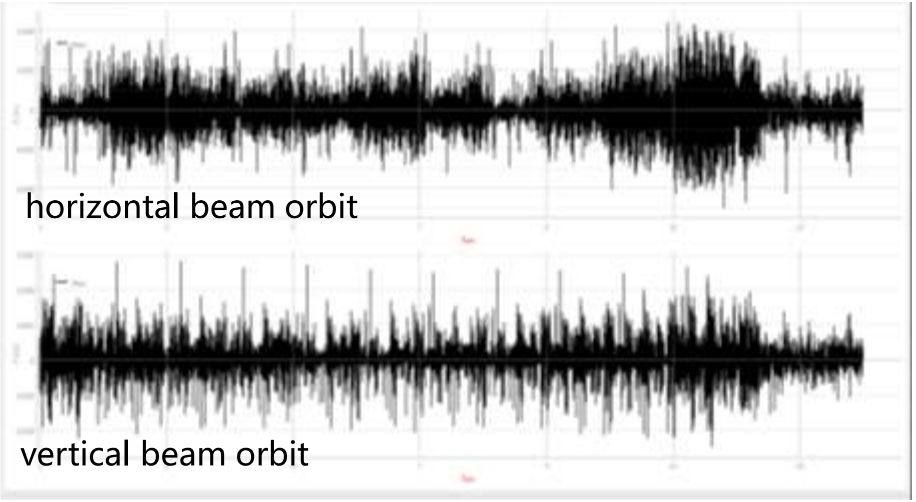
- There are over 1,000 adjustment variables just for the storage ring correctors.



Beam circulation multi-turn commissioning

➢ July 29: The electron beam in the storage ring circulated for over 10 turns





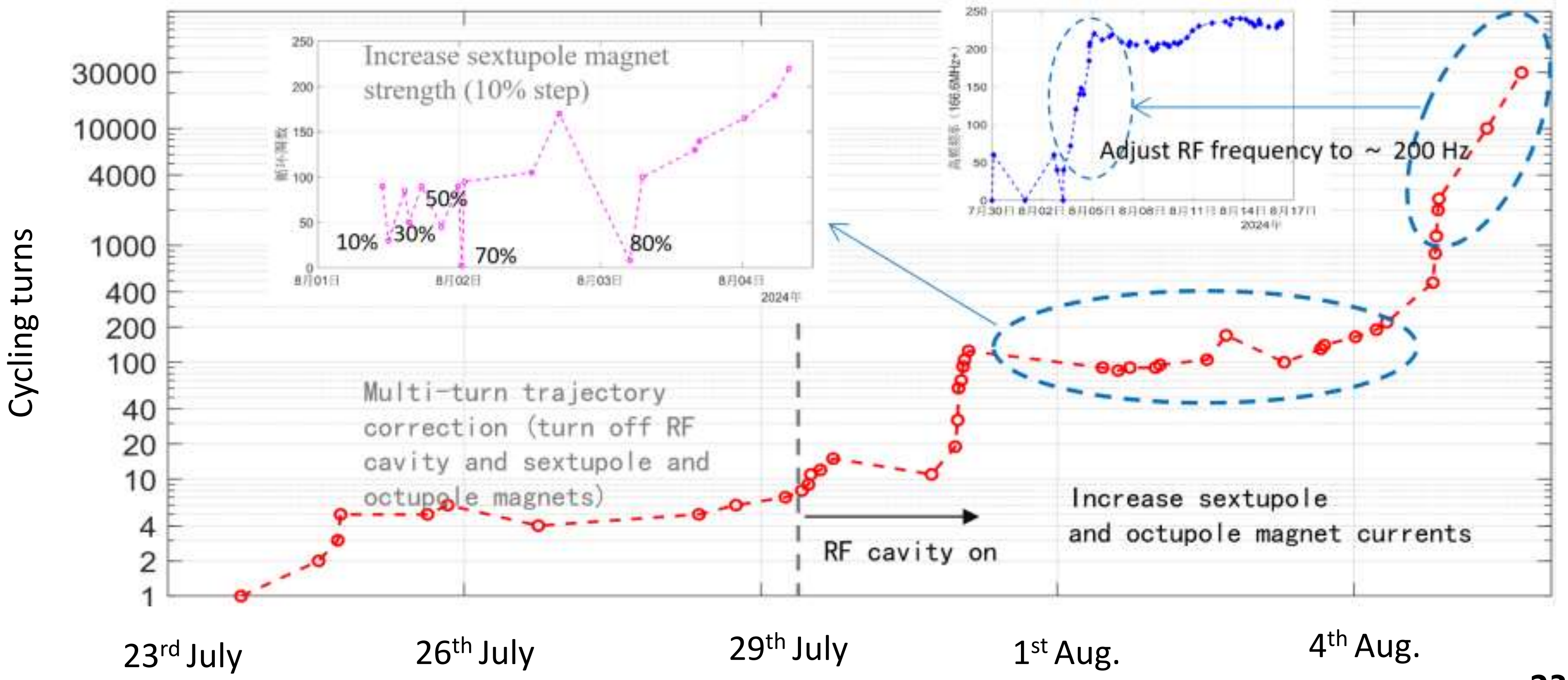
Using the correctors to reduce large oscillations in the injected beam.

Beam circulation multi-turn commissioning

- Since July 29, RF cavity has been turned on and sextupole magnet strength increased to compensate for synchrotron radiation energy loss and natural chromaticity.

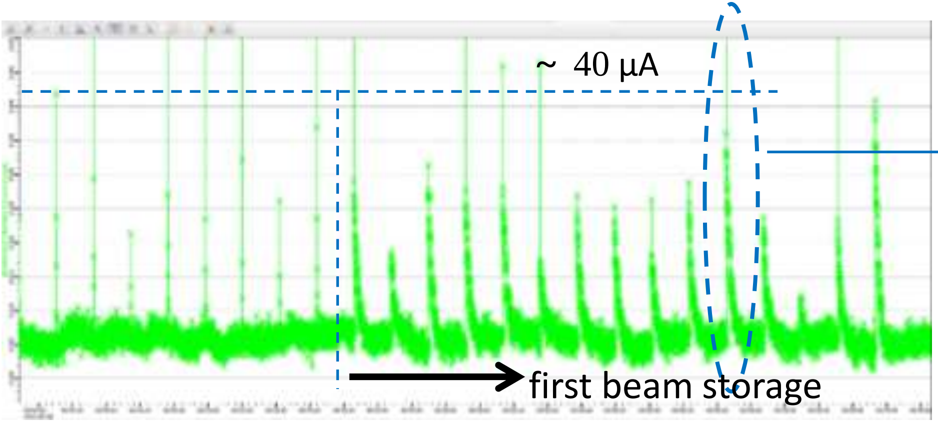
- At this stage, a parameter combination that matches the beam storage state in a larger parameter space is necessary

Beam circulation multi-turn commissioning

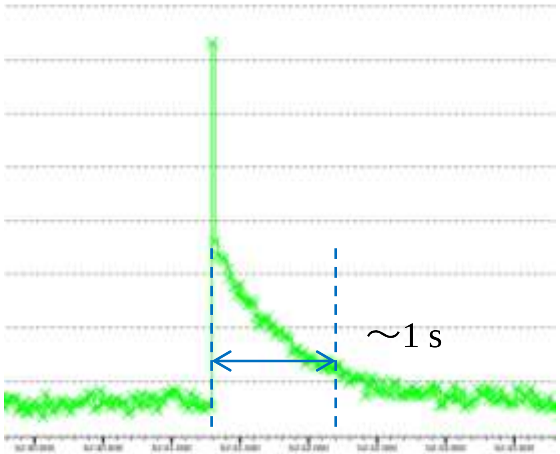


Beam circulation multi-turn commissioning

- August 6: The storage ring achieved beam storage
  - 00:50: The storage ring achieved its first beam storage, with approximately 40 μA stored for about 1 second.
  - 23:24: The beam current in the storage ring is approximately 60 μA, with a lifetime of about 1 minute.



DCCT data

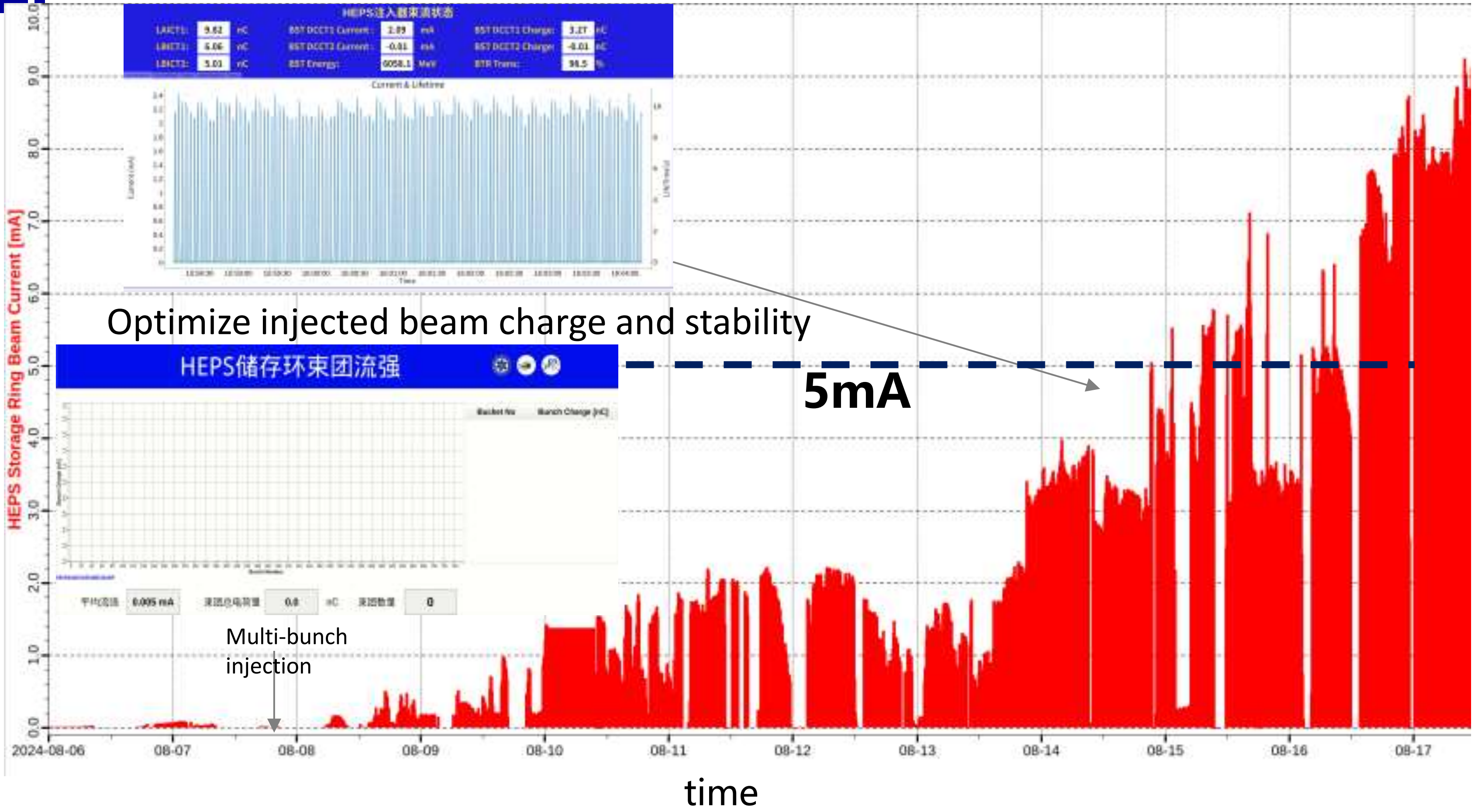


Beam circulation multi-turn commissioning

- Increase beam current and lifetime
  - Global and local orbit correction
  - Sextupole and octupole magnet strength optimization
  - Skew quadrupole magnet strength optimization
  - Vacuum lifetime optimization

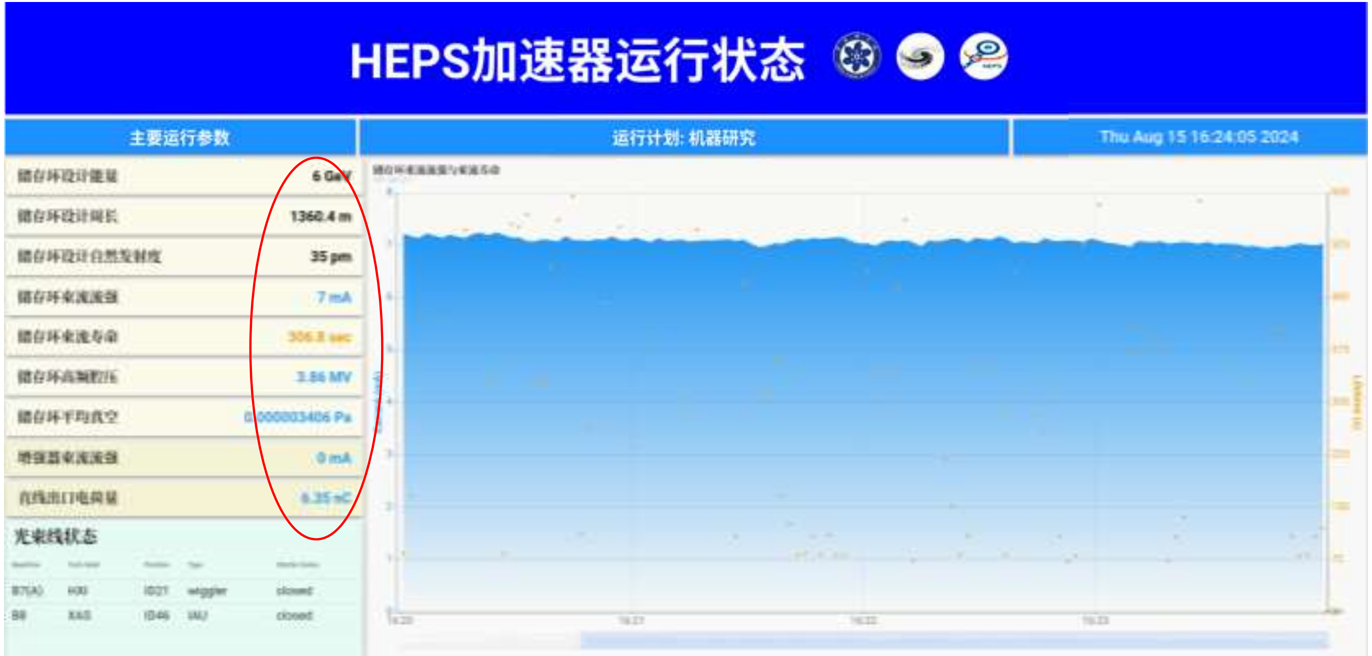
  ……

Beam circulation multi-turn commissioning



Beam circulation multi-turn commissioning

- August 15: The storage ring current exceeded 5 mA
  - 16:20: Current reached 7 mA, with a lifetime of approximately 2 minutes.



Beam circulation multi-turn commissioning

- August 18: The storage ring current exceeded 10 mA
  - 08:15: Current reached 10 mA, with a lifetime of approximately 2 minutes.
  - 20:10: Current reached 12 mA, with a lifetime of approximately 2 minutes.

Beam circulation multi-turn commissioning

	Start	first-turn	>10 turns	storage	I > 10 mA
HEPS 35 pm.rad Two ±2.5 mm aperture LMS	July 23	July 23（On the same day！）	July 29（7 days）	August 6（15days）	August 18（27 days）
Similar advanced light sources 42 pm.rad One single-sided 3 mm aperture	April 10	April 13（4days）	April 14（5days）	April 20（11days）	May 12（33days）

The results show that, compared to similar light sources, HEPS has achieved the same tasks in roughly the same amount of time despite facing greater challenges. HEPS has made a steady step in the right direction and has entered a rapid commissioning phase.

Next steps: Further improve beam quality and aim to complete the first light emission within this year

Challenging and status of the China Spallation Neutron Source

Yaoshuo Yuan

on behalf of

Sheng Wang

OUTLINE

- Overview of CSNS Project
- Upgrade project of CSNS (CSNS-II)
- Key issues and upgrade
- Conclusions

Overview of CSNS Project

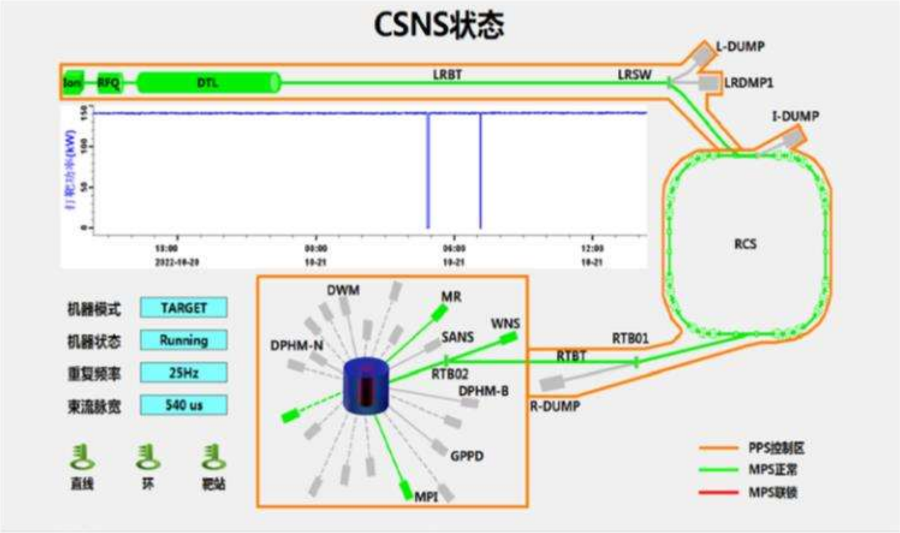
Budget: 0.26 billion USD

Location: Dongguan, Guangdong Province

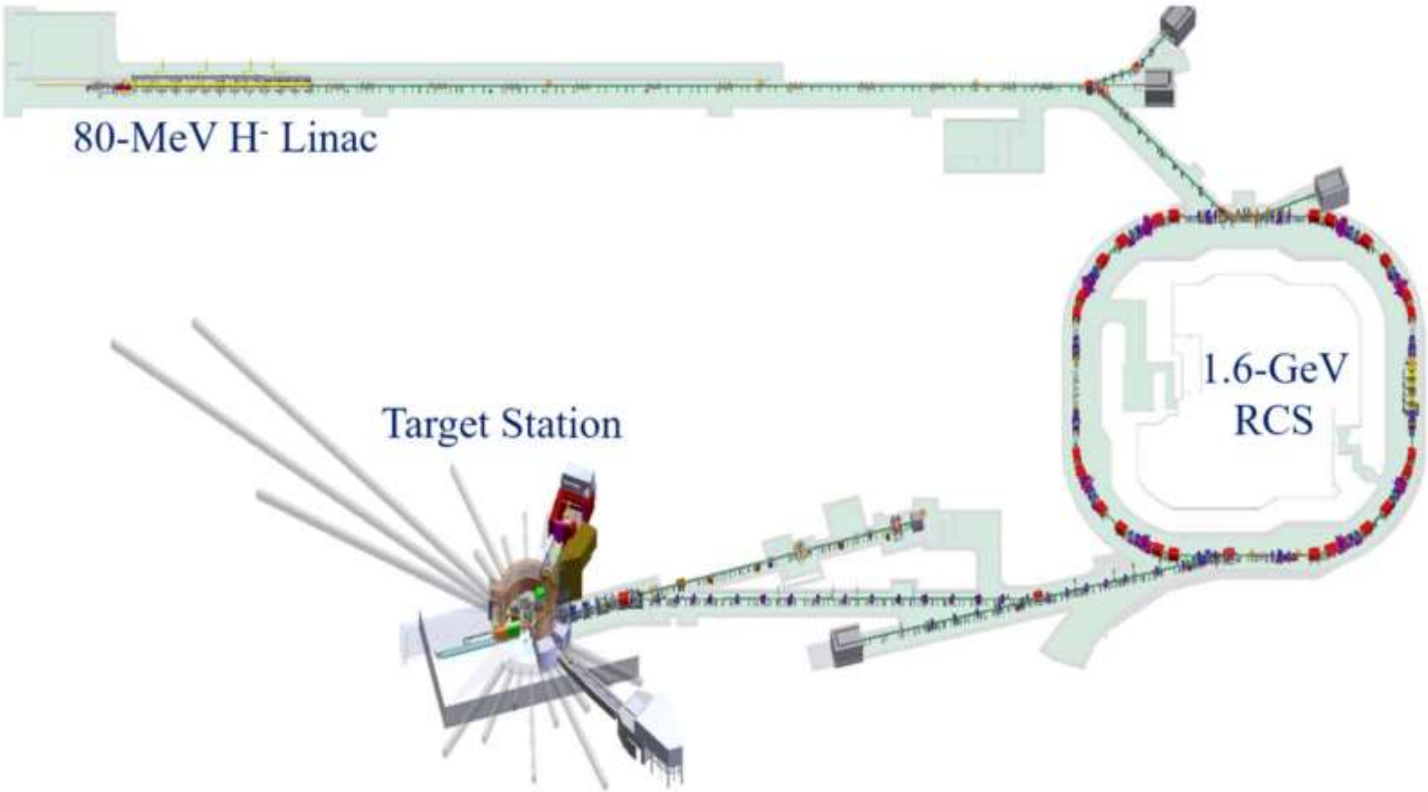
Project starts Sep. 2011

Construction period: 6.5 years

Completed in March 2018

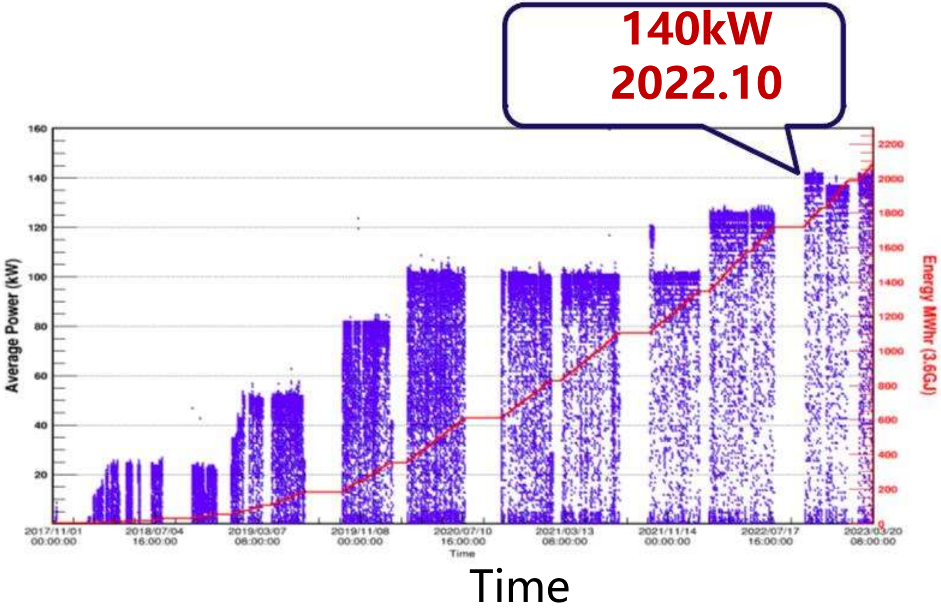


Overview of CSNS Project



Milestones

- In Mar. 2018， project construction completed, and open to users
- In Feb. 2020， the goal of 100 kw beam power was achieved
- In Feb. 2022, operation with 125 kW beam power was achieved
- In Oct. 2022 , **140 kW** beam power achieved

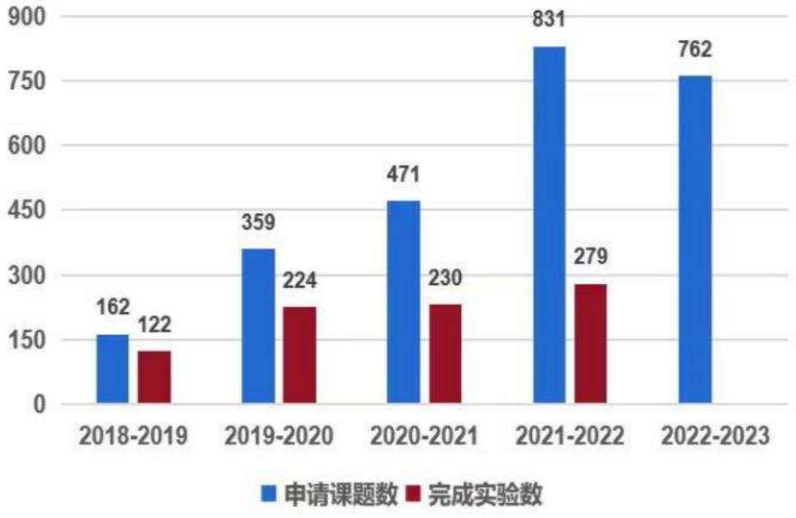


Increasing number of users

- **Since 2018**, more than 5000 users conducted experiments on the CSNS (including142 international users)

- During **2021-2022, the number of experimental proposal increased by 76%**, the passing rate is about **29%**。

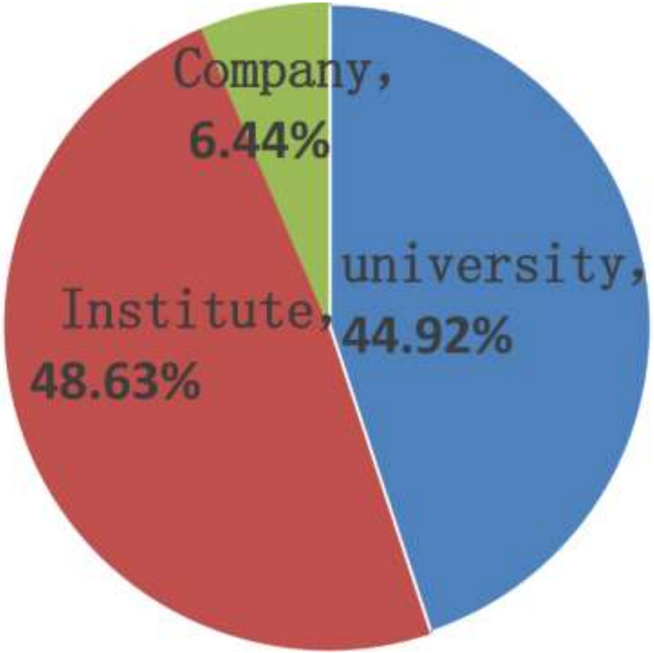
注册用户全国分布情况



Increasing number of users

- Experimental users mainly come from universities, institutes and companies.

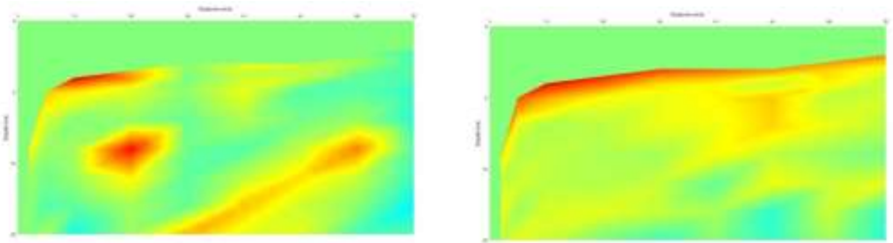
- Fruitful research fields, Including
  new resources of energy
  protein structure
  high strength alloy
  Polymer materials
  Magnetic Material



Example 1 Research on high-speed rail wheels

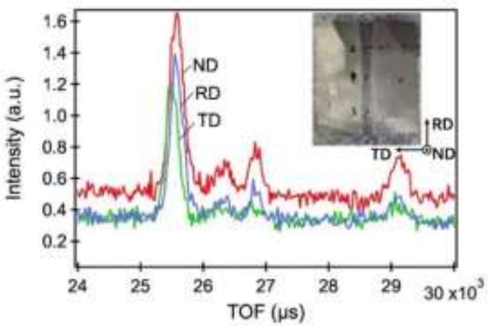
- Study on the residual stress of the wheels for the 350 km/h high-speed rail

- Detailed stress data of deep layers inside the wheels are achieved



Example 2 Research on manned submersible

- Study on the titanium alloy welds of the manned cabins
- Optimization on the welding process with lower residual stress

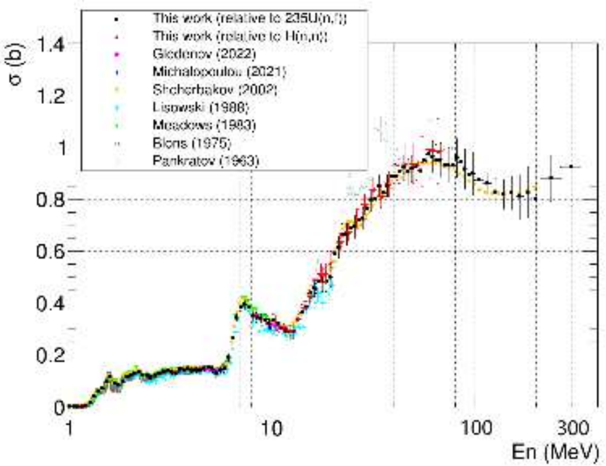


Example 3 Nuclear reaction cross-section

- ➢ Measurement of capture cross section (> 20 nuclides)
  - 169Tm, 197Au, 57Fe, nat Se, 89Y, nat Er, 162Er, 232Th, 238U, 93Nb, nat Cu, nat Lu, 113&115In,
- ➢ Total cross section measurement (> 5 nuclides)
  - 12C, 27Al, 9Be, 7Li, nat Fe

- ➢ Obtain fission cross section data of ^{232}Th in the range of 1-300 MeV, the highest energy region of the experimental nuclear reaction database EXFOR

- ➢ Invited to the IAEA Neutron Standards Technical Conference

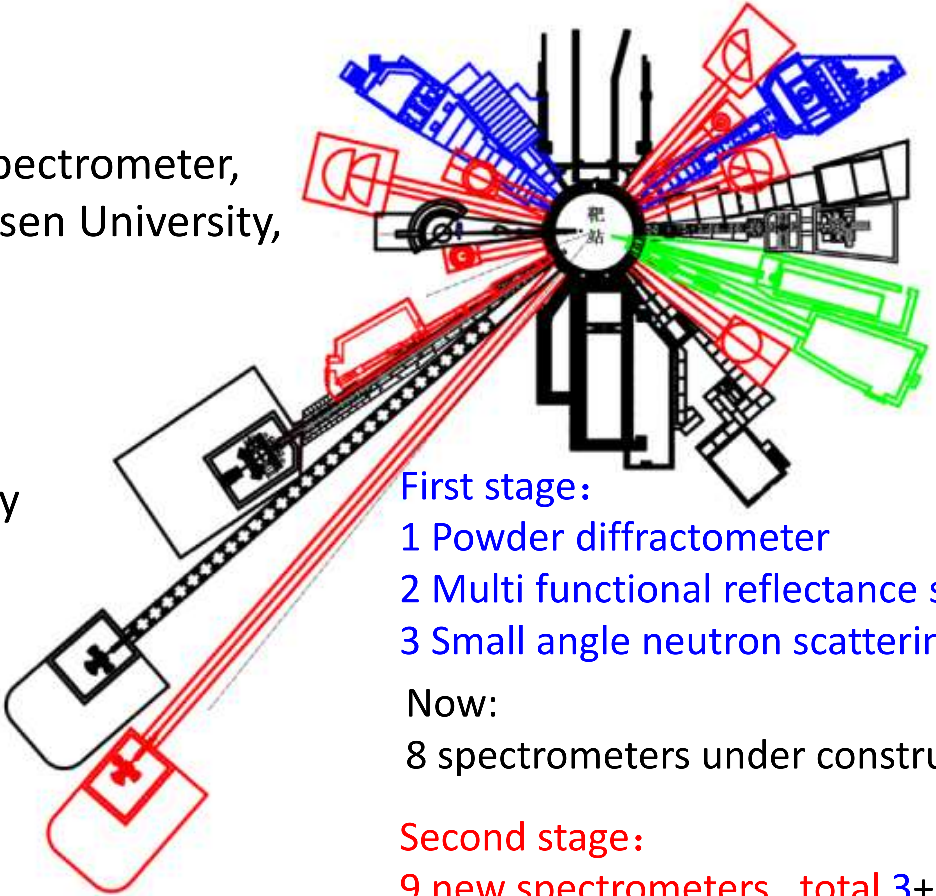


CSNS Collaboration Spectrometer

- High-energy non ballistic spectrometer, collaboration with Sun Yat-sen University, 2017

- Engineering material diffractometer，collaboration with company in Dongguan 2016

- High-resolution neutron diffractometer，collaboration with Peking University, 2016

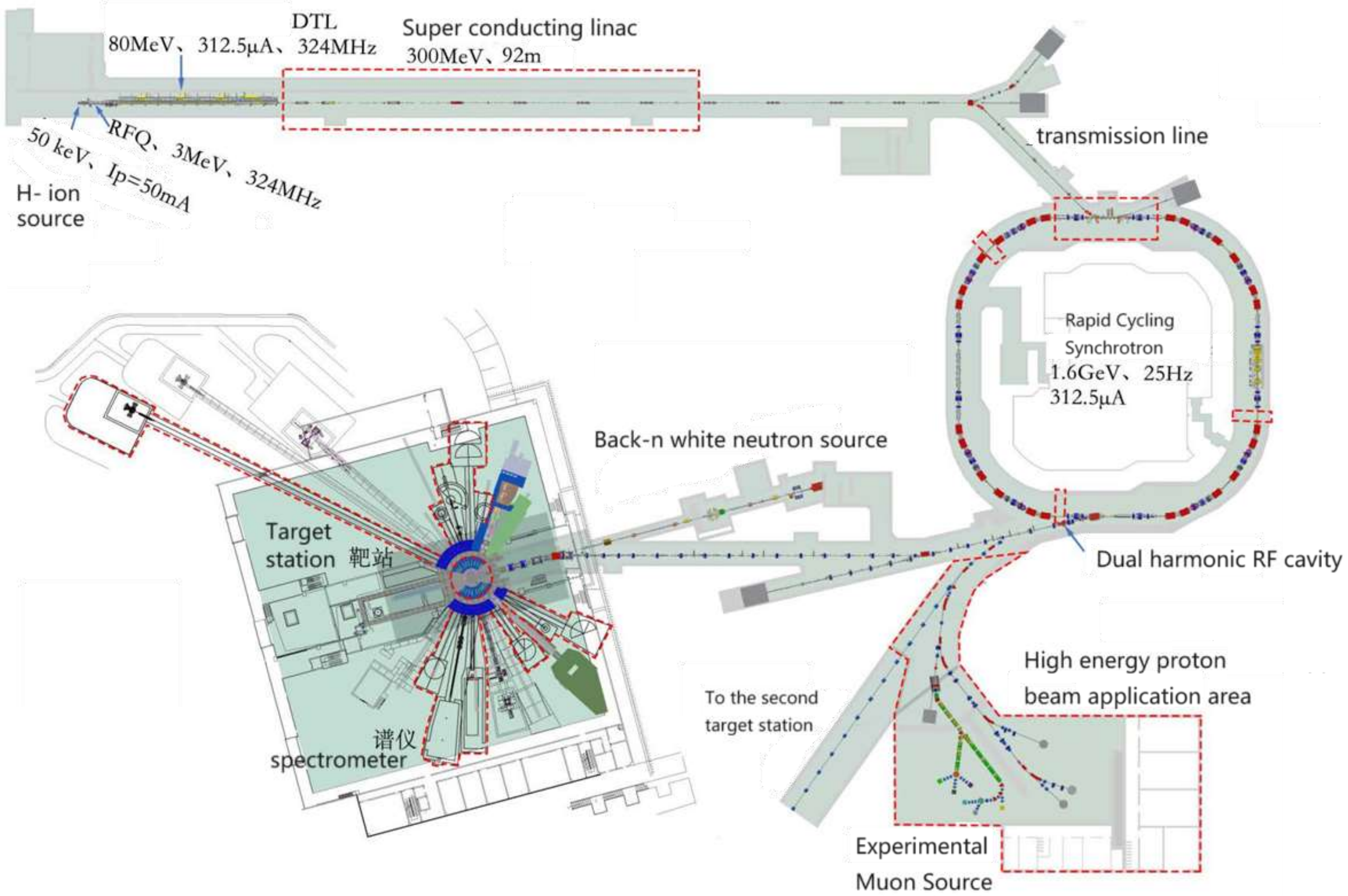


First stage：
1 Powder diffractometer
2 Multi functional reflectance spectrometer
3 Small angle neutron scattering spectrometer

Now:
8 spectrometers under construction

Second stage：
9 new spectrometers   total 3+8+9

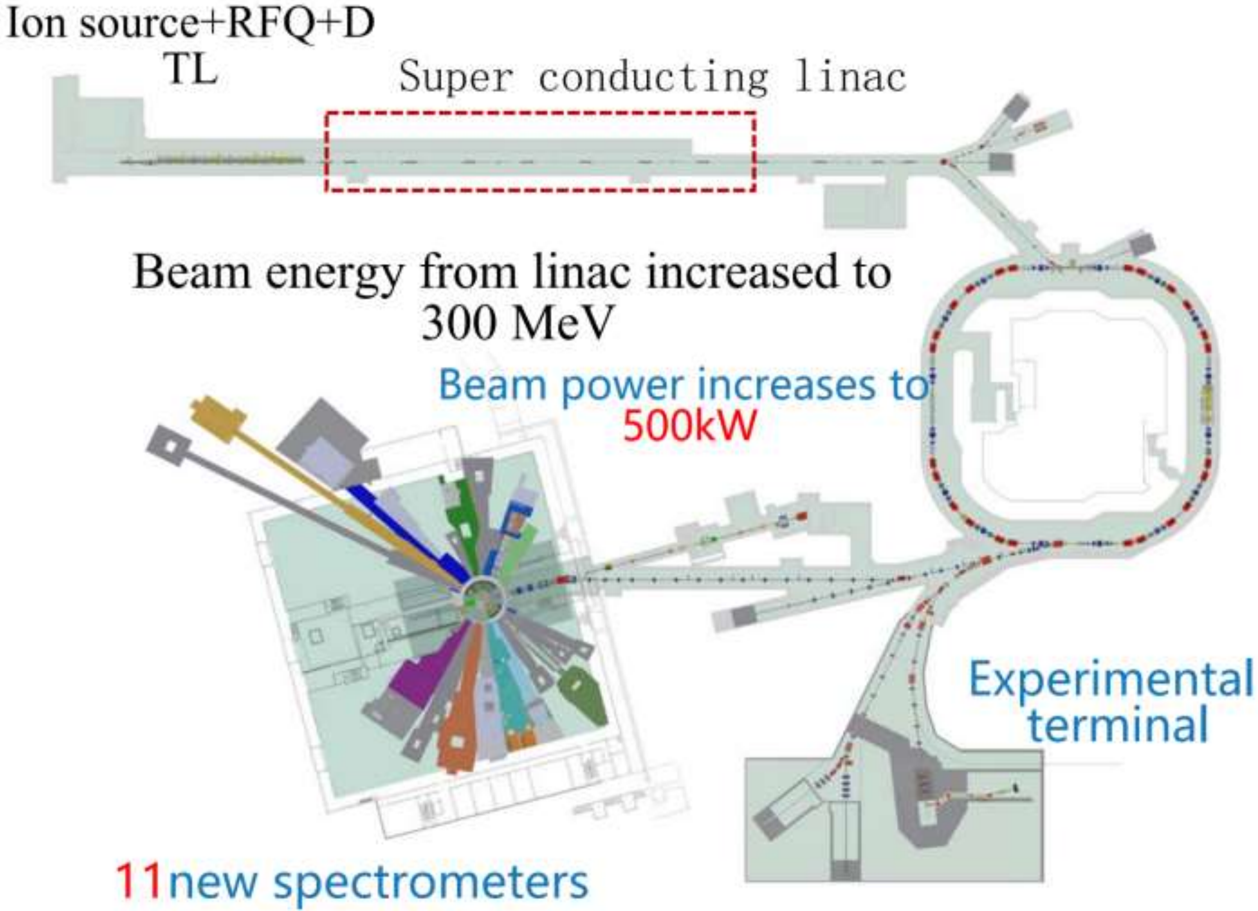
Upgrade project of CSNS (CSNS-II)



Upgrade project of CSNS (CSNS-II)

Parameters (unit)	CSNS I	CSNS II
proton beam power (kW)	100	500
Pulse repetition frequency(Hz)	25	25
Target Station number	1	1
Average beam current (μA)	62.5	312
Beam energy (GeV)	1.6	1.6
RCS injection energy (MeV)	80	300
Spectrometer Number	3	11+9

Main goal of CSNS II



Main goal of CSNS II

Beam Parameters (unit)	CSNS I	CSNS II
proton beam power (kW)	100	500
Average beam current (μA)	62.5	312
Peak beam current in linac (mA)	15	40
Frequency of the linac (MeV)	324	324 / 648
beam pulse width (μs)	400	600

Power upgrade route of CSNS

- First step Linac (80MeV) + RCS upgrade 150~200kW
  - Adoption of the dual harmonic rf cavity
  - Installation of the AC sextupoles, AC octupoles
- Second step Linac (300MeV+) + RCS upgrade 500kW
  - Beam energy in linac upgrade to 300 MeV
  - Upgrade of the injection system
  - Upgrade of the Resonant power supply system of the main dipoles in the RCS

Challenge from high beam intensity

- Circulating beam current in CSNS-II RCS is the highest among similar accelerators, e.g. 1.43 times than J-PARC !

Facility	Beam power	ΔQ (Space charge strength)
CSNS	100 kW	0.28
CSNSII	500 kW	0.19
J-PARC	1 MW	0.12
SNS	1 MW	0.08

- Space charge effect is one of the most important factor for increase of beam current/power
- Based on the experience of beam commissioning in CSNS I, beam power 500kW for CSNS II is achievable

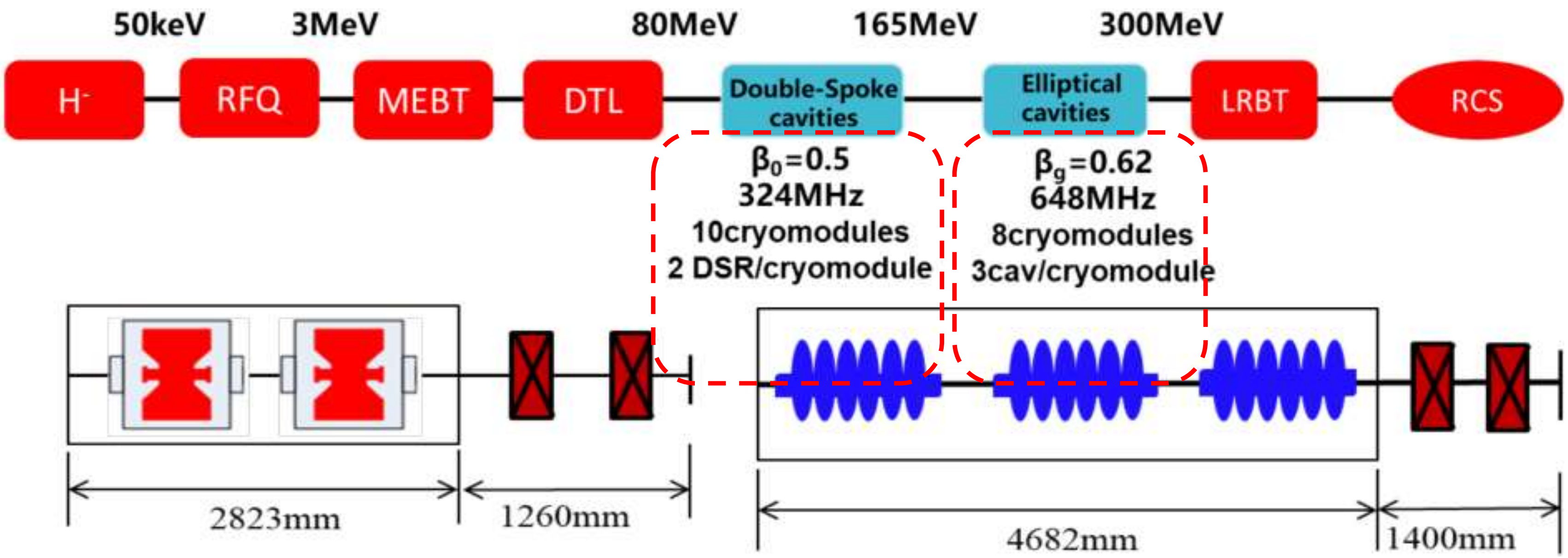
Key issues

- Peak current intensity of linac increase by 4 times
  - New type of ion source
    - High beam current
    - Low beam emittance
    - Longer service life
  - New RFQ
    higher pulse beam current
  - Super conducting linac

- RCS
  - Dual harmonic system
  - Sextupoles, octupoles
  - New injection system
  - New feedback system

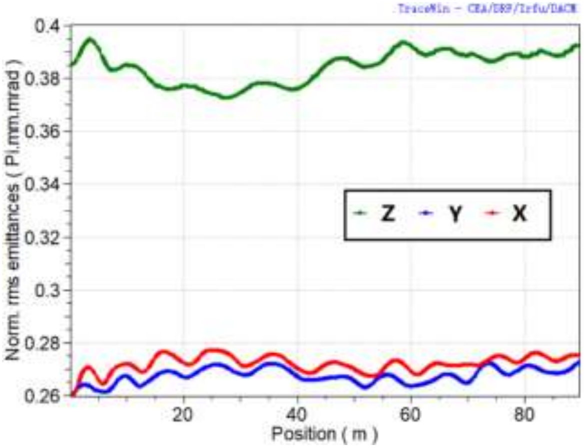
Linac upgrade

- Design and optimize the Double Spoke Cavity

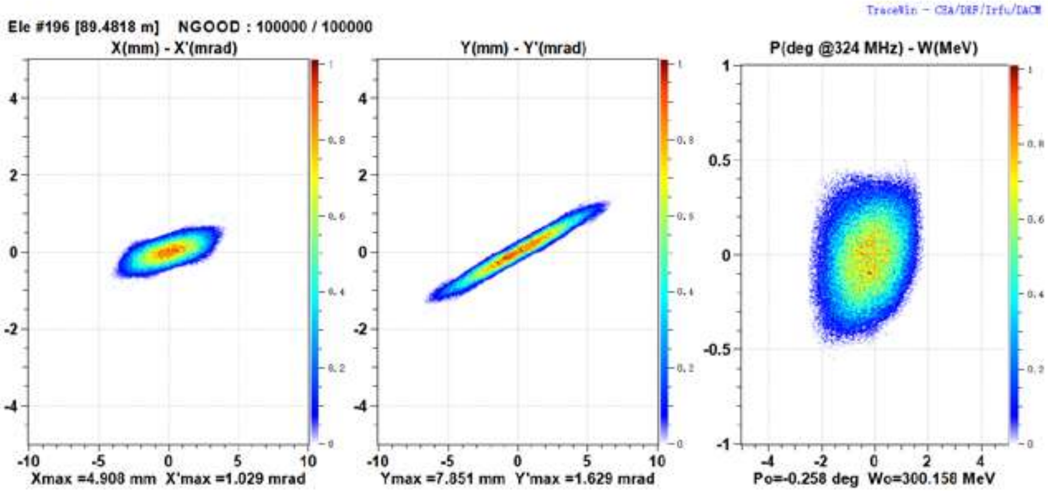


Design of the super conducting linac

- Maximum acceleration gradient
  - Spoke---9MV/m，elliptical---14.3MV/m
- Phase advance less than 90 deg
- Beam equipartitioning is considered



RMS emittance



Phase space distribution at the exit

Key issues in the RCS design

Beam power increasing

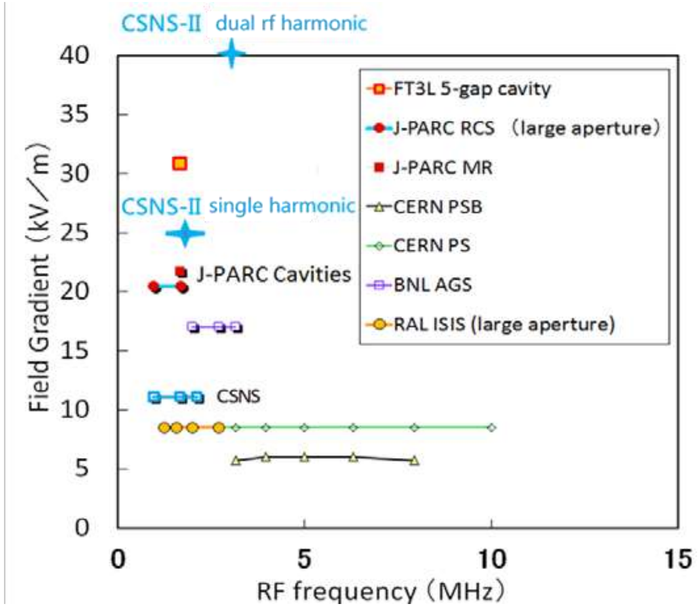
- 20 – 50 kW
  - Basic beam commissioning
- 50 – 80 kW
  - Adoption of the correlated painting injection method
- 80 – 100 kW
  - Collective effect; optimization of the chromaticity, and working point
- 100 – 125 kW
  - Upgrade the injection area, add the trim quad and sextupole
- 125 – 140 kW
  - Utilization of the dual rf harmonic system

Key Technology Development

- High-power magnetic alloy loaded rf cavity
- Ion source (50+ mA)
- Superconducting linac
- Power source

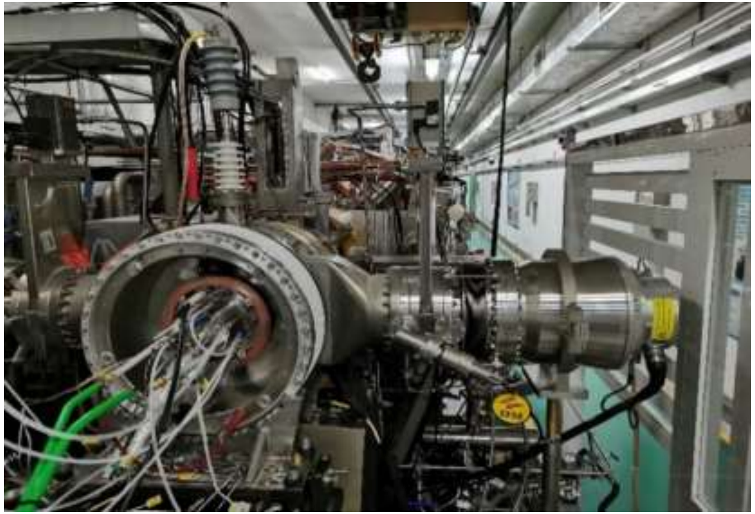
Magnetic alloy loaded rf cavity for CSNS II

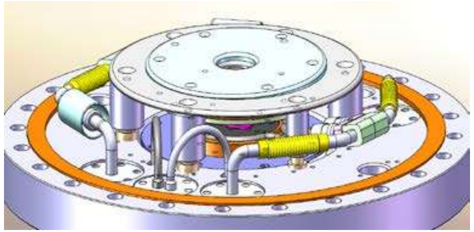
- Length 1.8 m
- Operation > 9600 hours ; variation on impedance < 3%
- Acceleration gradient 40kV/m (e.g. 80 kV)

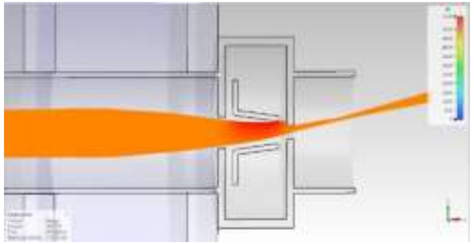


RF H$^-$ ion source

- RF-driven negative hydrogen ion source with external antenna
- Operation for 2 years, with high stability and long service life
- Test platform is built to increase the beam current and emittance
- Reduce the consumption of cesium







Prototype of the Double Spoke Cavity

- Two prototype double spoken cavities have been producted
- Vertical acceleration gradient 13MV/m
- Horizontal acceleration gradient test

Cut cavity

High power coupler
and aging test
platform

Tuner

Conclusion

- The construction of CSNS with 140 kW beam power, which higher than the design beam power goal, paves a solid way for the future CSNS II

- CSNS II project mainly consisting of 11 new neutron spectrometers and experimental terminals to enhance the power of accelerators and target stations.

- Total budget for CSNS II is 4.2 billion USD, 5 years and 9 months.

Thank you!