HEPS Injection/extraction hardware development

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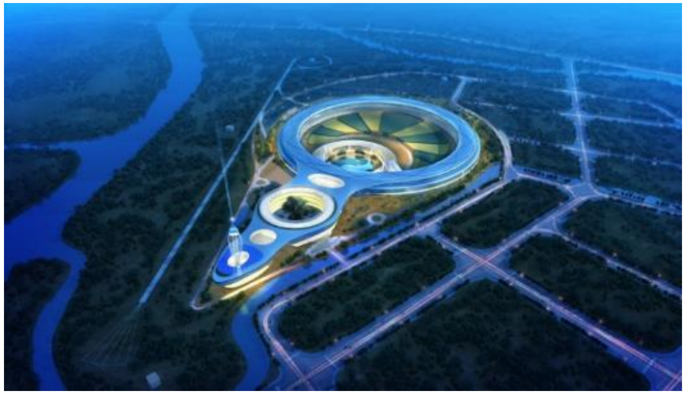
Outline

Overview of the HEPS injection and extraction systems

High Energy Photon Source

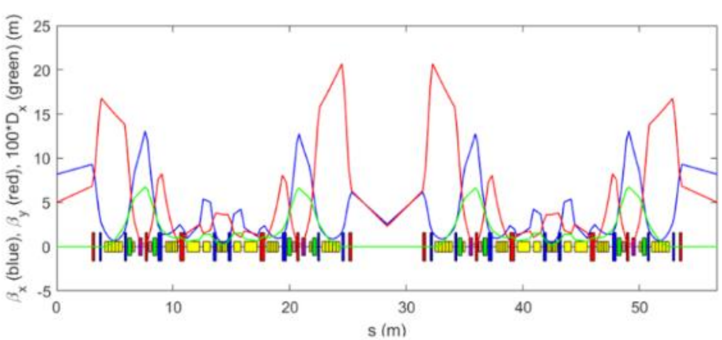
- HEPS is a typical 4th generation light source on green field in Huairou Beijing, China.
- Officially approved in Dec. 2017, the construction was scheduled to start at the end of 2018, and completed in 2024. The whole project will be finished in mid-2025 after commissioning.
- A R&D program for HEPS called HEPS-TF was started in 2016, and was completed in Sept. 2018 in order to solve some key technical issues, including some injection and extraction technologies.
- So far, the Linac has been ready to commission , the booster tunnel installation has been completed, the SR tunnel installation has been started.

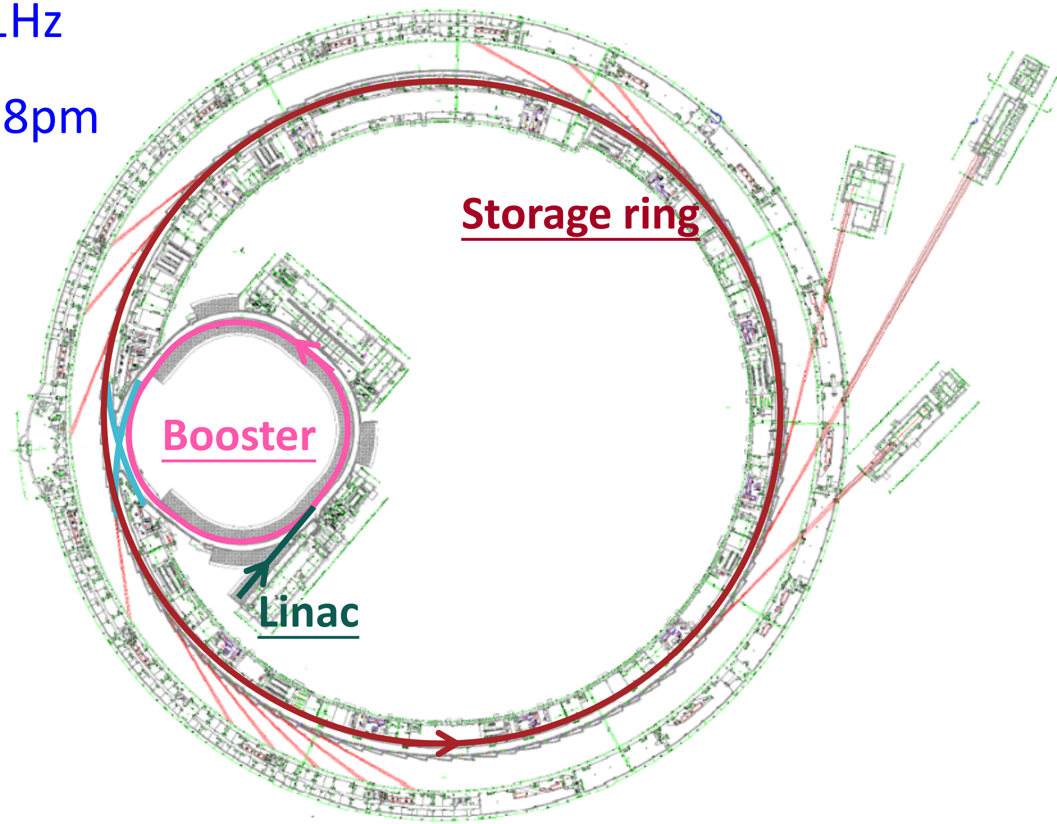


Introduction of HEPS accelerator

The HEPS accelerator complex consists of a **Linac**, several **transport lines**, a **booster ring** and **storage rings**.

- **Linac**: 0.5Gev/50Hz
- **Booster**: 0.5GeV~6GeV/454.1m/1Hz
- **Storage ring**: 6GeV/ 1360.4m, 34.8pm natural emittance
  - 48 hybrid-7BA cells, w/ BLGs and ABs
  - interleaved high-β and low-β straight sections of 6 m

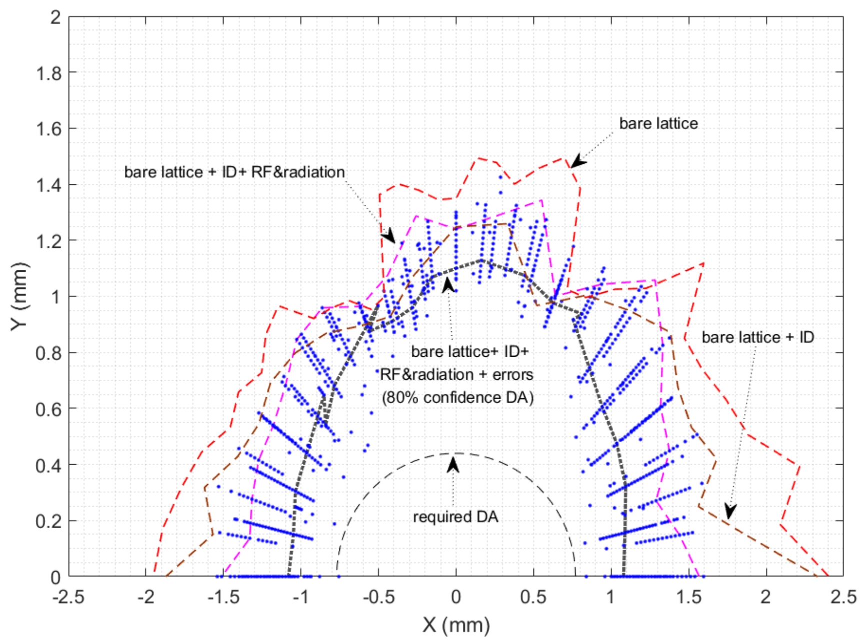


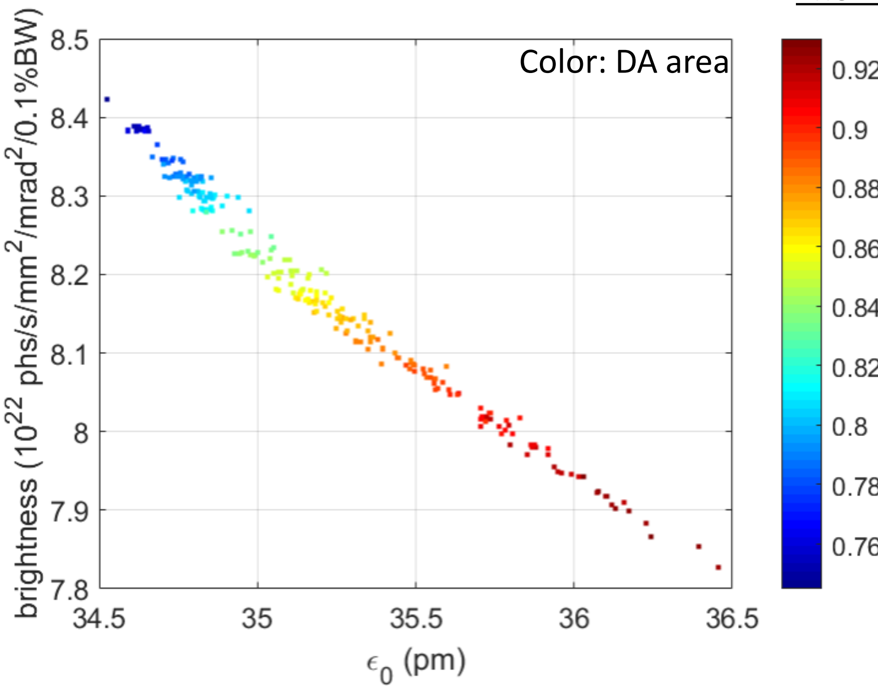


Top-up injection scheme for HEPS

- HEPS SR is a typical Low Emittance Ring (LER) with the MBA lattice. In order to achieve higher brightness, the Dynamic Aperture (DA) large enough for traditional off-axis injection is hard to reach at the same time.
- HEPS SR top-up injection scheme:
  - On-axis swap-out injection using the booster as an accumulator ring is the baseline scheme
  - Reserve possibility for on-axis longitudinal injection with dual active RF system, which frequency is 166MHz and 500MHz.

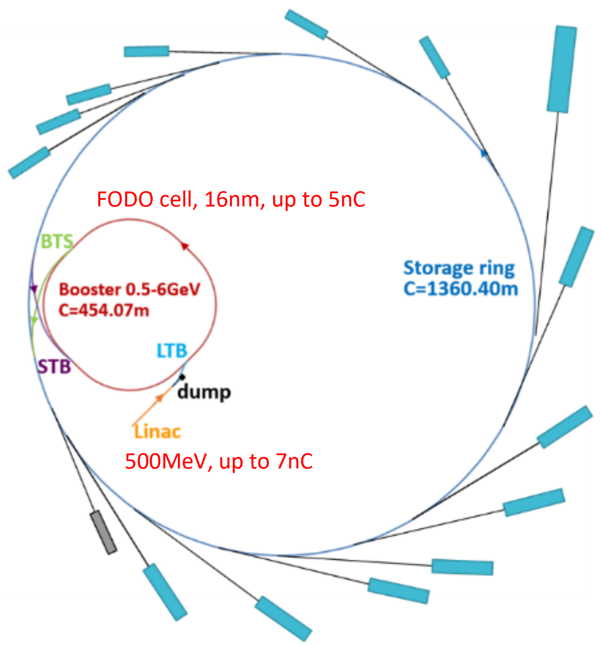
*Zhe Duan

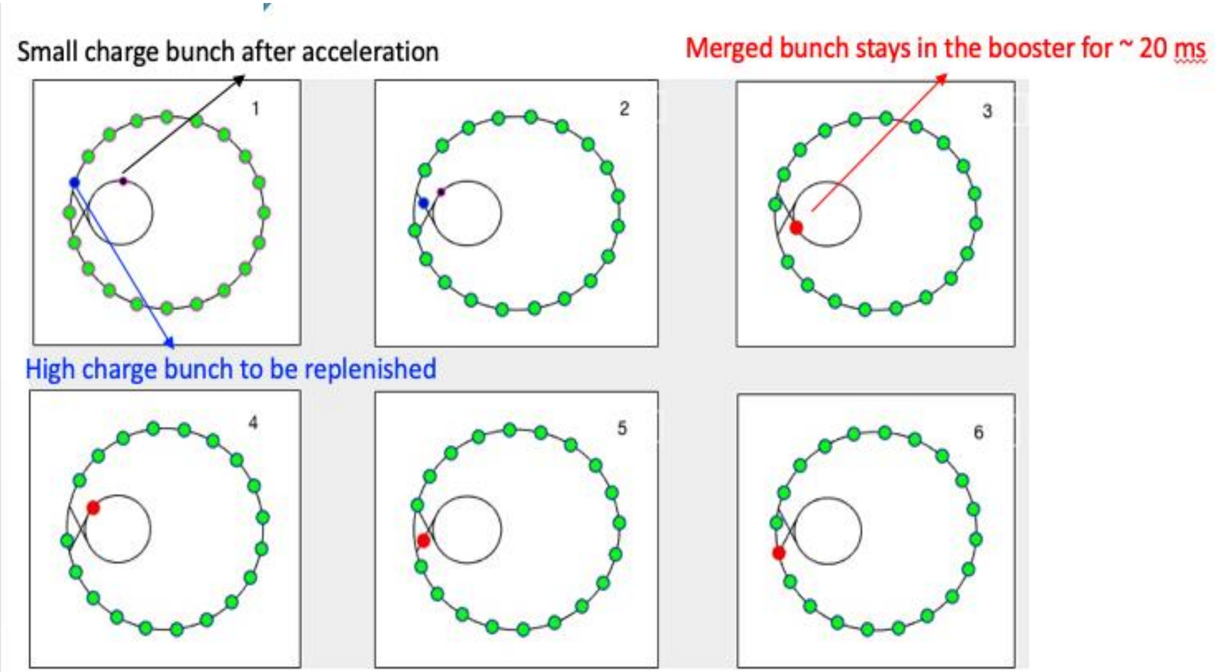




High-energy accumulation in the booster

- Major challenge of swap-out injection: a full charge injector
  - Full charge bunch prepared in an AR, injected into and accelerated in the booster (APS-U)
  - Bunch recycling w/ a dedicated AR between BR and SR (ALS-U)
  - Bunch recycling w/ booster serving as a full energy AR (HEPS) [1,2]

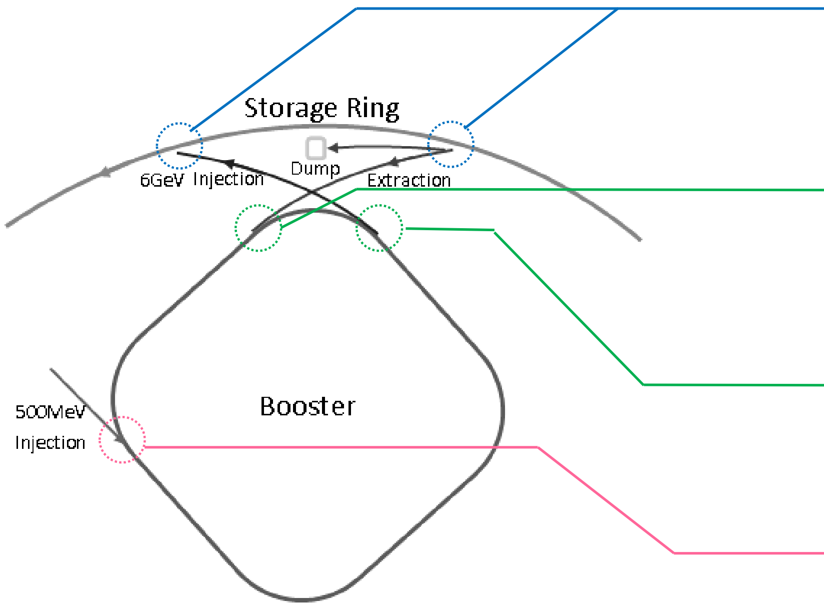




[1] Z. Duan, et al., IPAC'18, THPMF052
[2] Y. Jiao et al., J. Synch. Radiat., 25 (2018)1611

HEPS Injection & Extraction systems

The injection and extraction system of HEPS consists of 5 sub-systems.



- BTS: SR 6GeV injection system
- STB: SR 6GeV extraction system

(Bunch by bunch/on-axis swap out injection)

- STB: Booster 6GeV injection system

(Pulsed local bumped injection by 2 kickers)

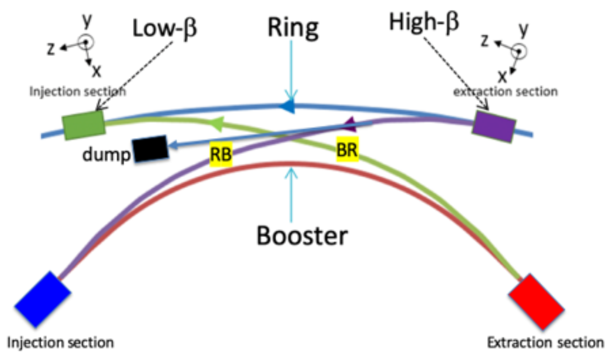
- BTS: Booster 6GeV extraction system

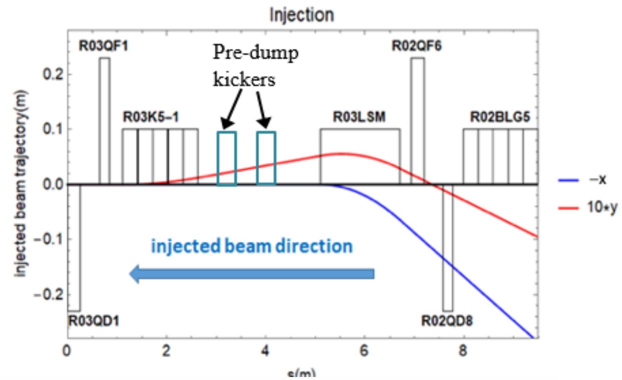
(Bunch by bunch/fast extraction assisted by 4 slow bumpers)

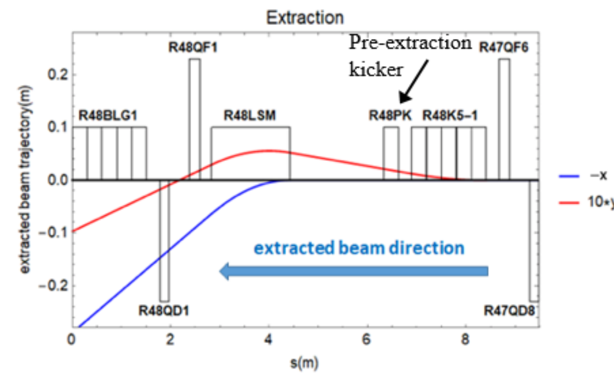
- LTB: Booster 0.5GeV injection system

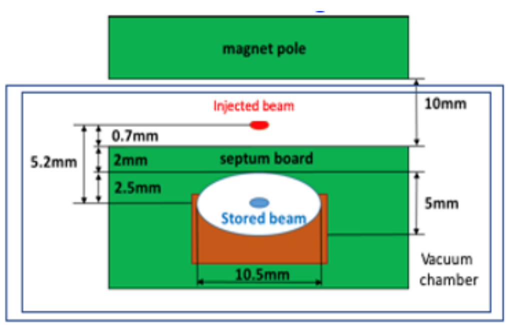
(Bunch by bunch/one turn/on-axis injection)

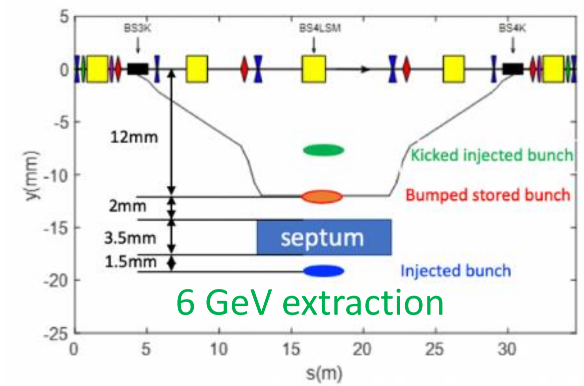
The layout of the injection & extraction sub-systems

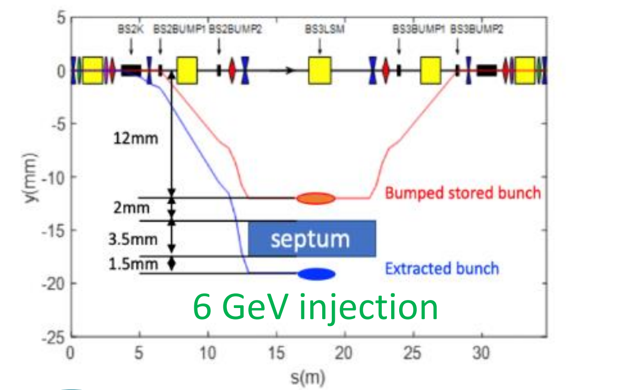


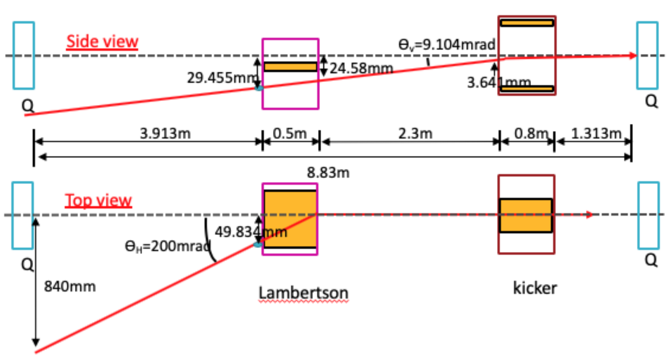


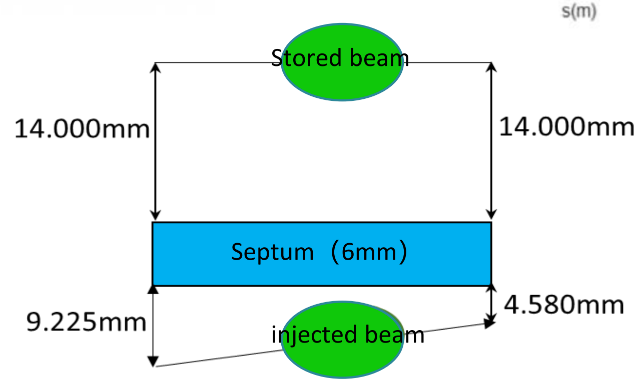








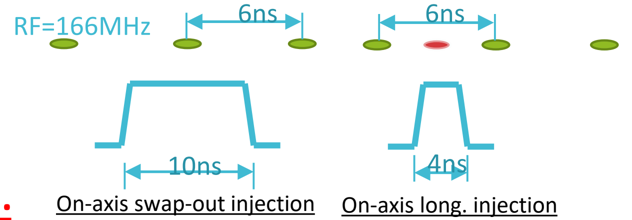




Hardware challenges of injection system

•SR injection and extraction system

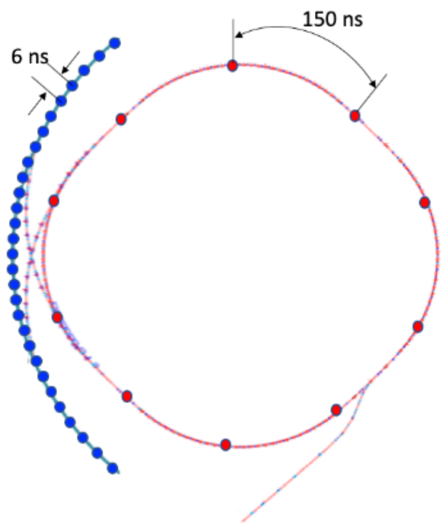
- 2 straight sections of 6 meter to accommodate injection and extraction system for 6 GeV beam manipulation.
- Fast kicker system: 300mm long strip-line kicker groups and **super fast pulser of 10ns bottom width (3%-3%)， ±15kV peak into 50ohm.**
- Thin septum: Lambertson magnet of **2mm thickness septum**



Kicker electrical pulse

•BST injection and extraction system

- kicker system: slotted-pipe kicker and **fast pulser of 300ns(at least 600ns) bottom width (10%-10%)， 2.8kA peak into 0.7μH** to inject 10 (at least 5) bunches into the BST ring in a cycling period.
- Thin septum: Lambertson magnet of **3.5mm thickness septum**
- Slow bumper: half-sine wave of 1ms bottom width(only for extraction subsystem)



Lambertson magnets

Typical requirements for HEPS LSM

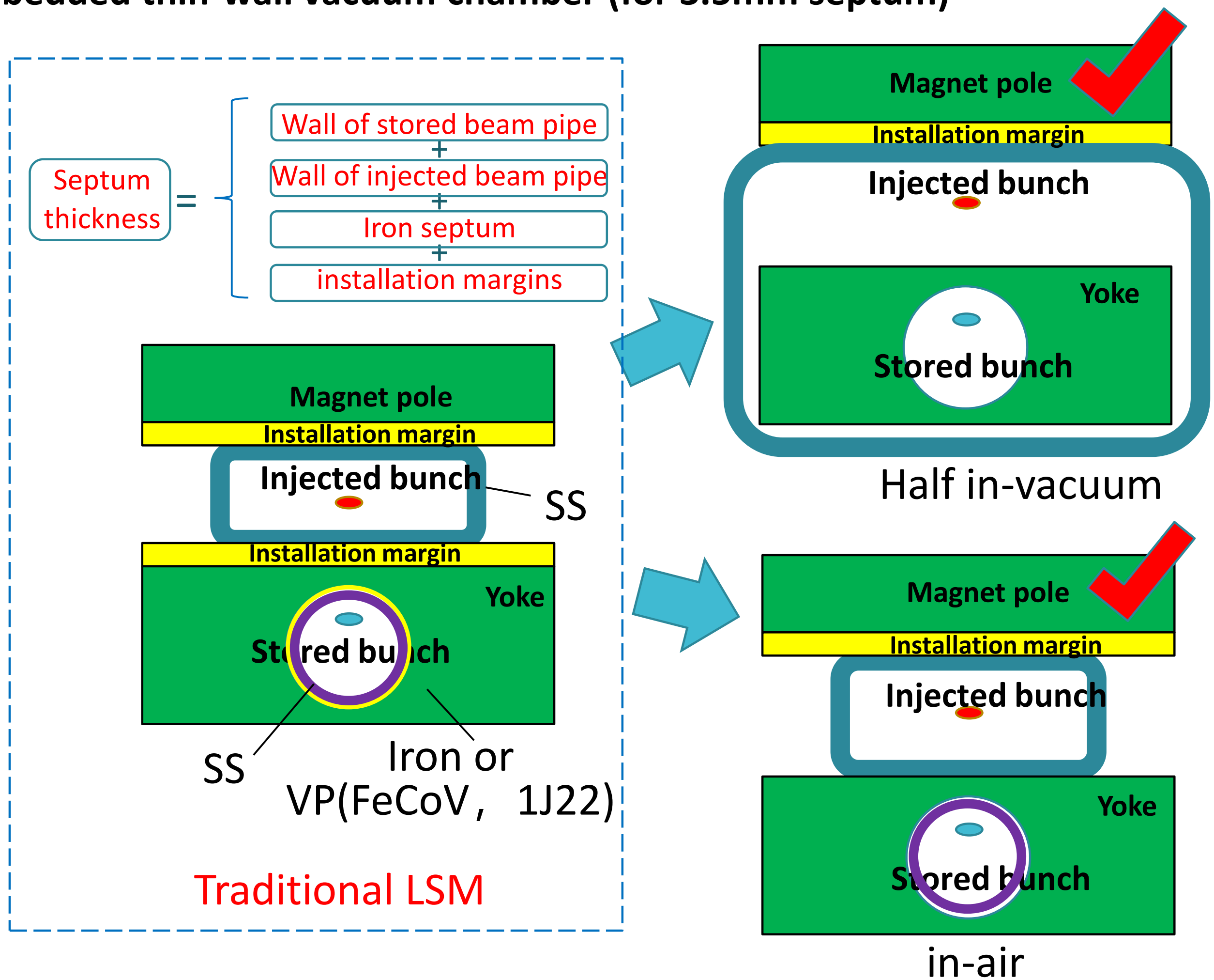
Parameters2	Unit	BST1-LSM	BST3/BST4-LSM	R48/R03-LSM
Quantity	-	1	2	2
Energy	GeV	0.5	6	6
Deflection angle	mrad	200	79.945	79.95
Insertion length	m	0.5	1.6	1.6
Magnetic field strength for injected/extracted beam	T	0.7	1	1
Min. Septum thickness （including septum board, wall of beam pipes, installation gap)	mm	≤6	≤3.5	≤2
Field uniformity	-	<±0.05%	<±0.05%	<±0.1%
Leakage field	-	$\le 1\times10^{-3}$	$\le 1\times10^{-3}$	≤0.002T·m
Clearance of stored beam at lambertson （H×V）（refer to stored beam orbit）	mm	10×10	22×28	8×5
Clearance of inj.&ext. beam at lambertson （H×V） （refer to inj.&ext. beam orbit）	mm	22×28	10×3	6×1.4
Physical aperture of stored beam vacuum chamber	mm	28×28	28×28	10.5x5

In-air

Half in vacuum

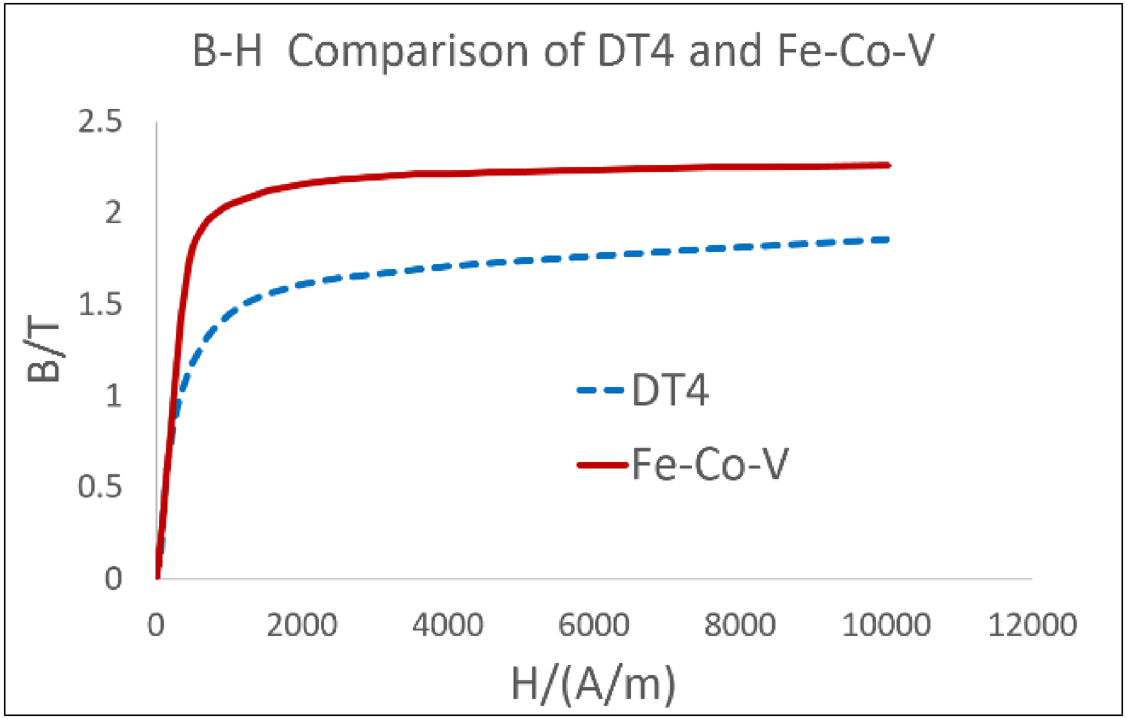
Lambertson Magnet Design Considerations

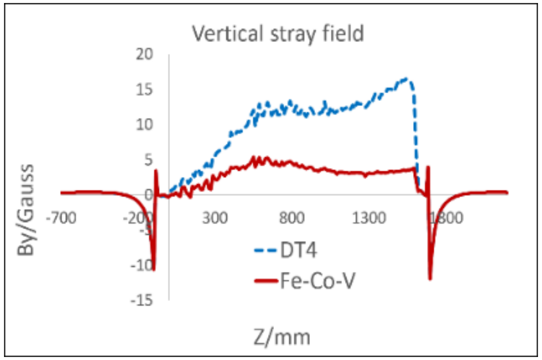
- **In order to decrease the septum thickness, 2 novel structures of magnet were proposed:**
  - **half-in-vacuum (for 2mm septum)**
  - **embedded thin-wall vacuum chamber (for 3.5mm septum)**

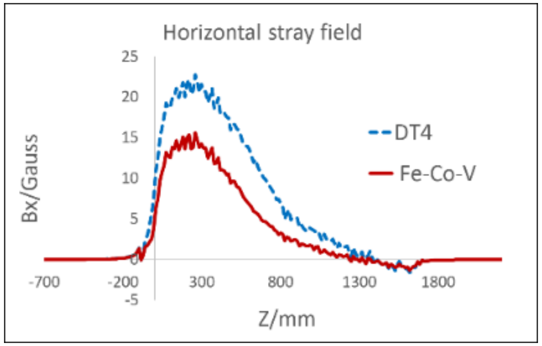


Lambertson Magnet Design Considerations

- **In order to decrease the absolute values of leakage field with thinner septum, Vanadium Permendur (FeCoV： iron50% cobalt 48% vanadium 2%, domestic brand 1J22 ） is adopted for septum board.**
  - **Higher Bs (Saturation magnetic density)**
  - **Higher μr(Relative permeability)**

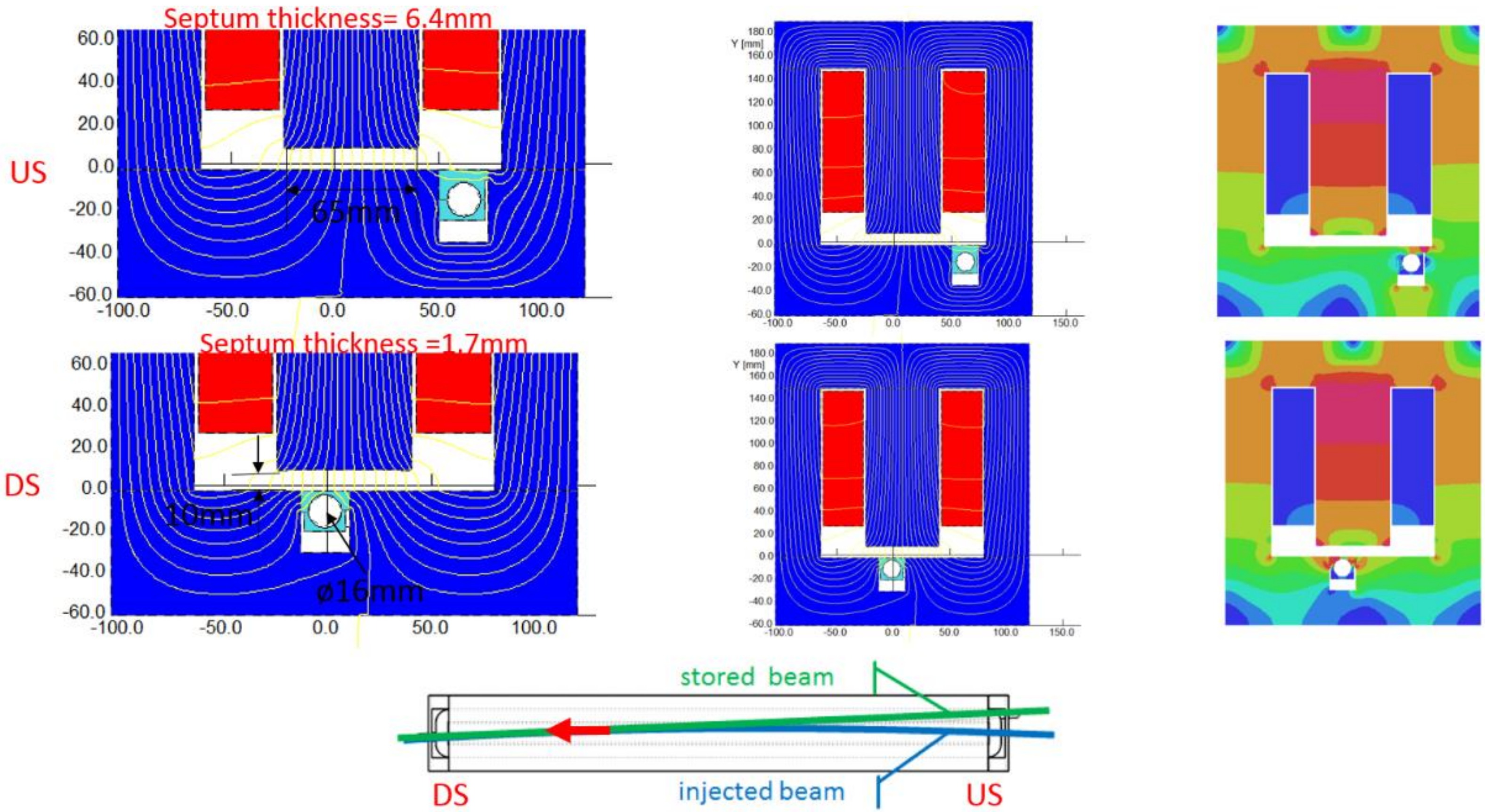






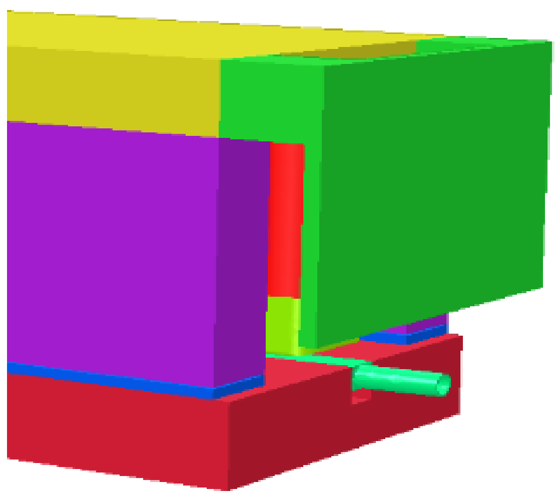
Lambertson Magnet Design Considerations

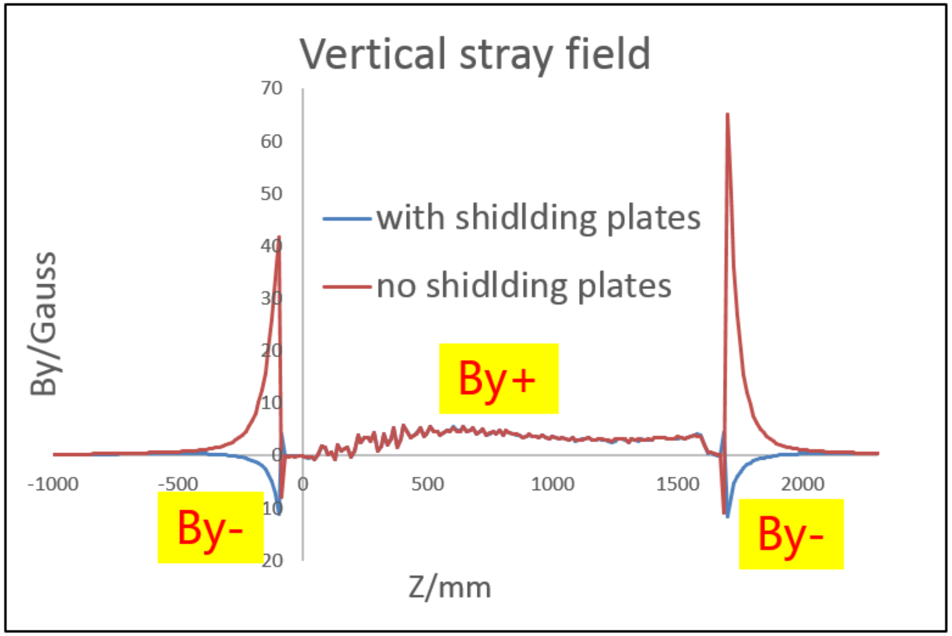
- In order to decrease the integrate leakage field, the upstream end of the stored beam chamber is located under the side leg of the yoke to create a leakage field that is opposite in sign.



Lambertson Magnet Design Considerations

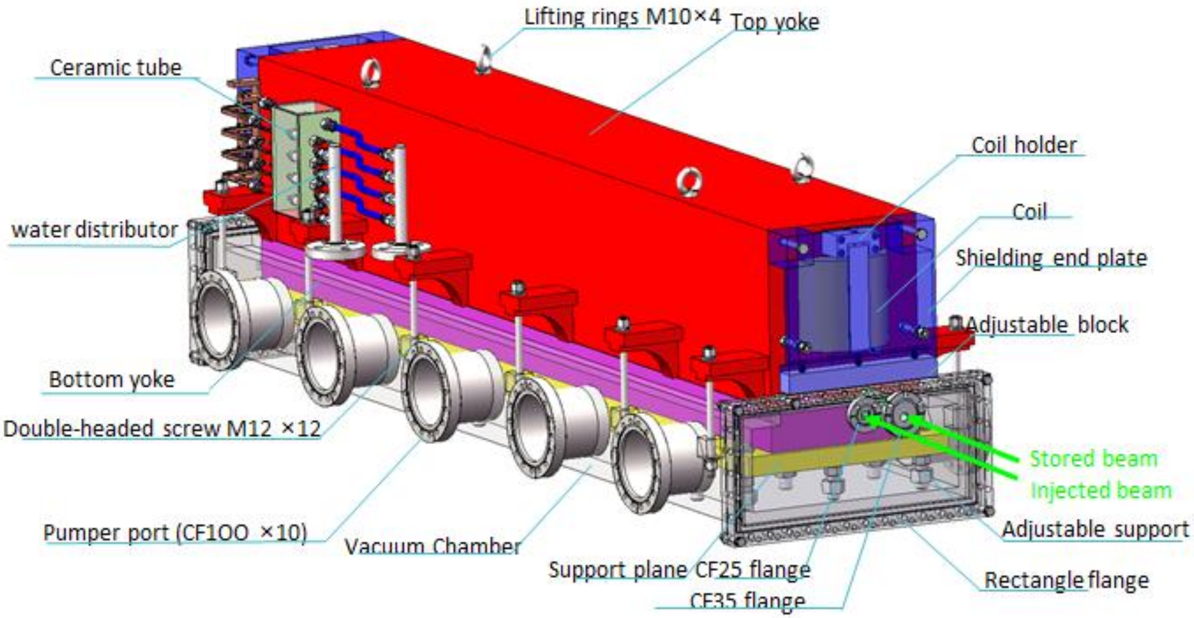
- In order to further reduce the integrate leakage field, the transition part and shielding plate design at the end of Lambertson magnet also plays an important role. With the shield plate, the leakage field in the opposite direction to the main field will be generated at the end of the magnet to cancel the leakage field in the body of magnet.

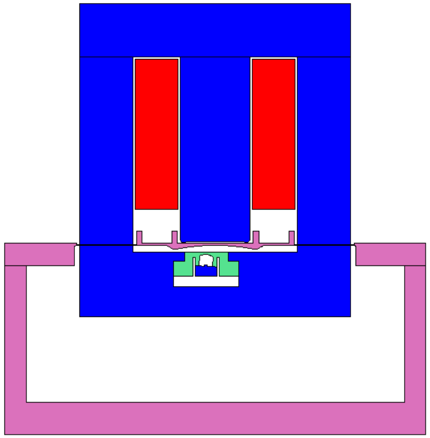


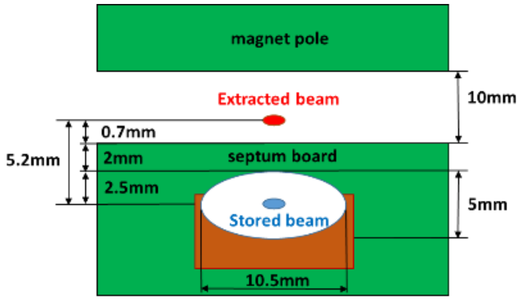


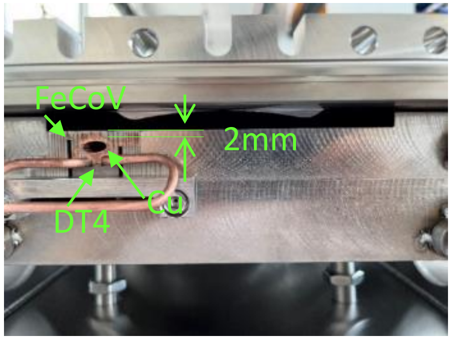
Half in-vacuum LSM R&D for HEPS SR

- Full size prototype engineering design



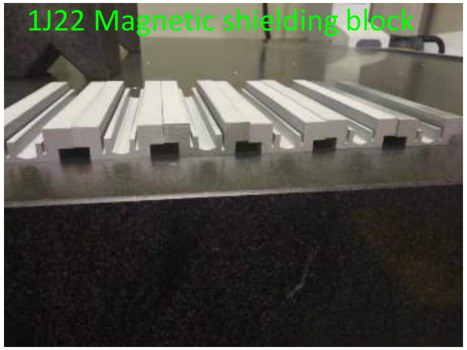






Half in-vacuum LSM R&D for HEPS SR

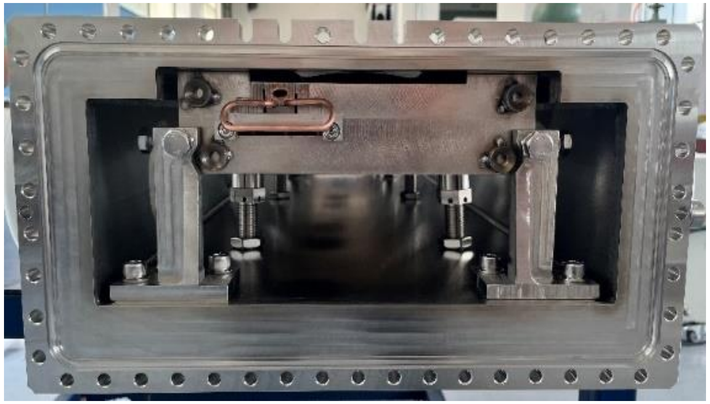
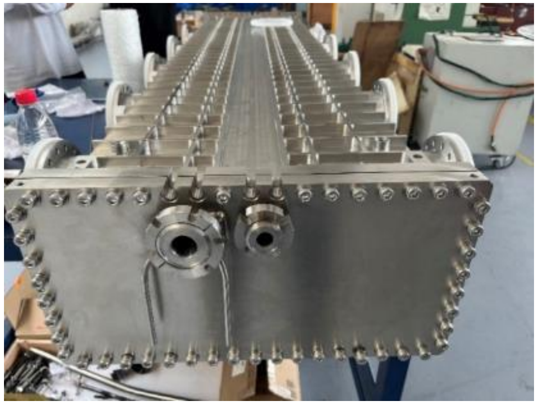
- Full size prototype:
  - Started in 2021
  - All the mechanical component processing was completed before June 2022.
  - The biggest challenge is magnetic shielding block machining because the VP is hard and brittle. Although it can be segmented processing by EDM, but annealing deformation is hard to control.

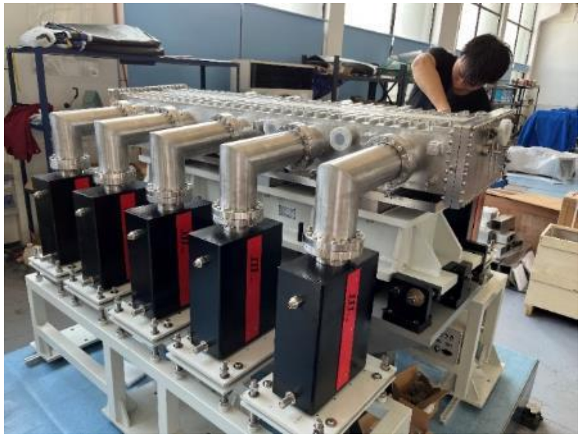


Half in-vacuum LSM prototype for HEPS

- Final assembling and vacuum testing was completed in July 2022.
- Vacuum pressure: 5.0×10^{-8}pa（vacuum chamber）, 2.2×10^{-7}pa（Transition section）

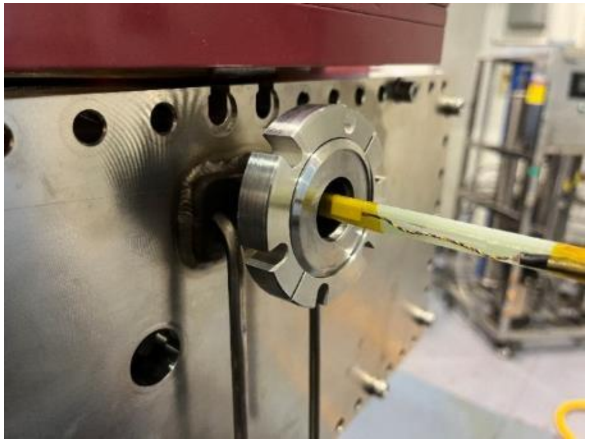


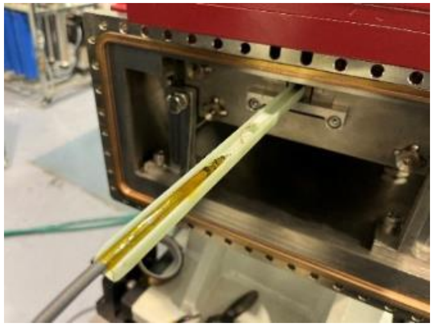



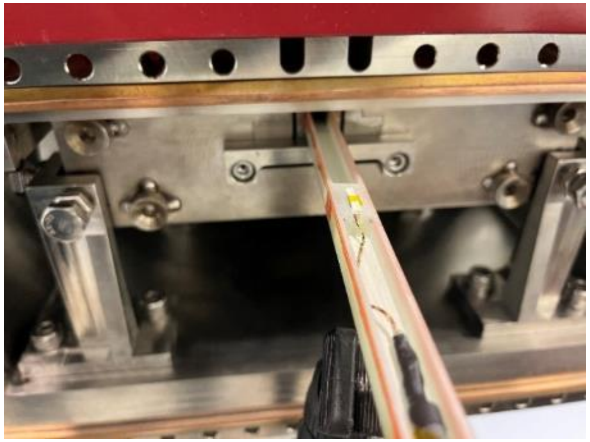


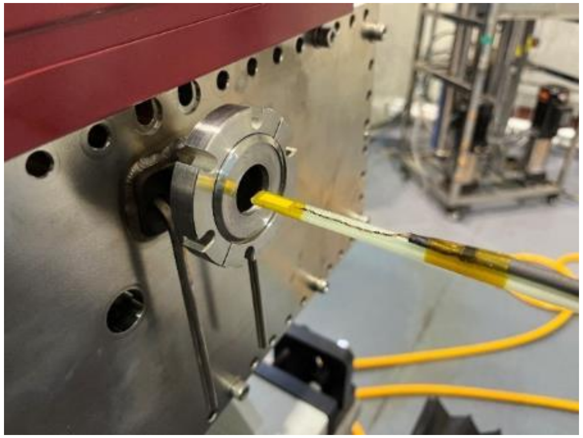

Half in-vacuum LSM prototype for HEPS

- Magnetic field measurement by Hall probe measurement system was finished successfully in Jan. 2023.





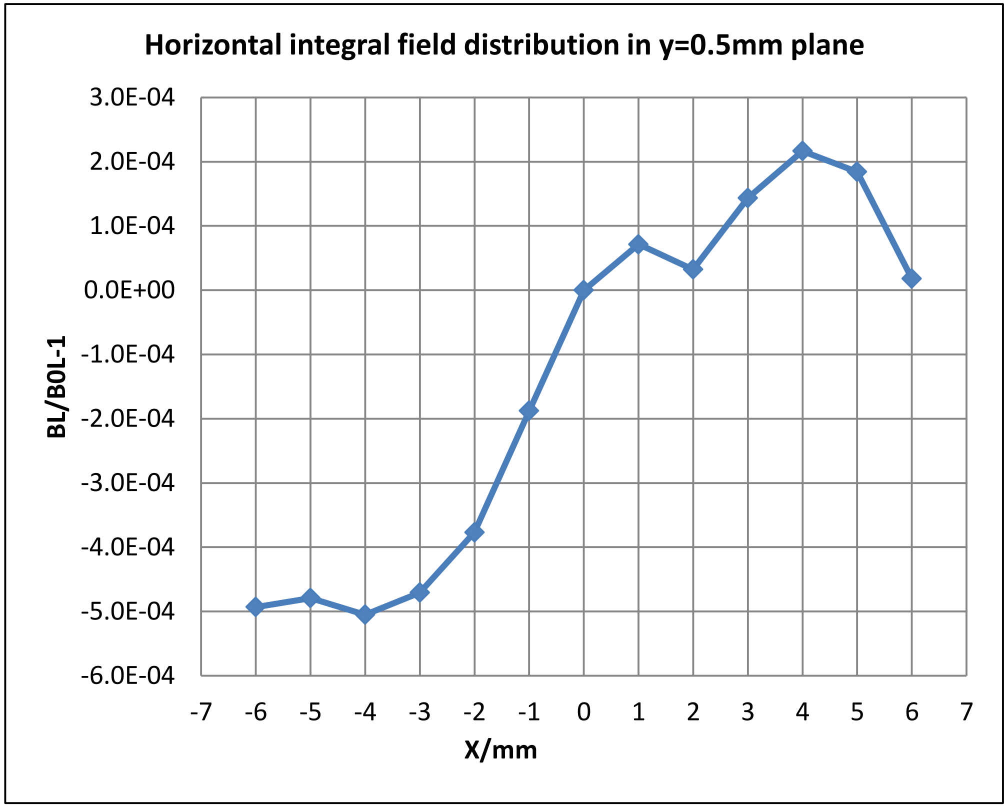


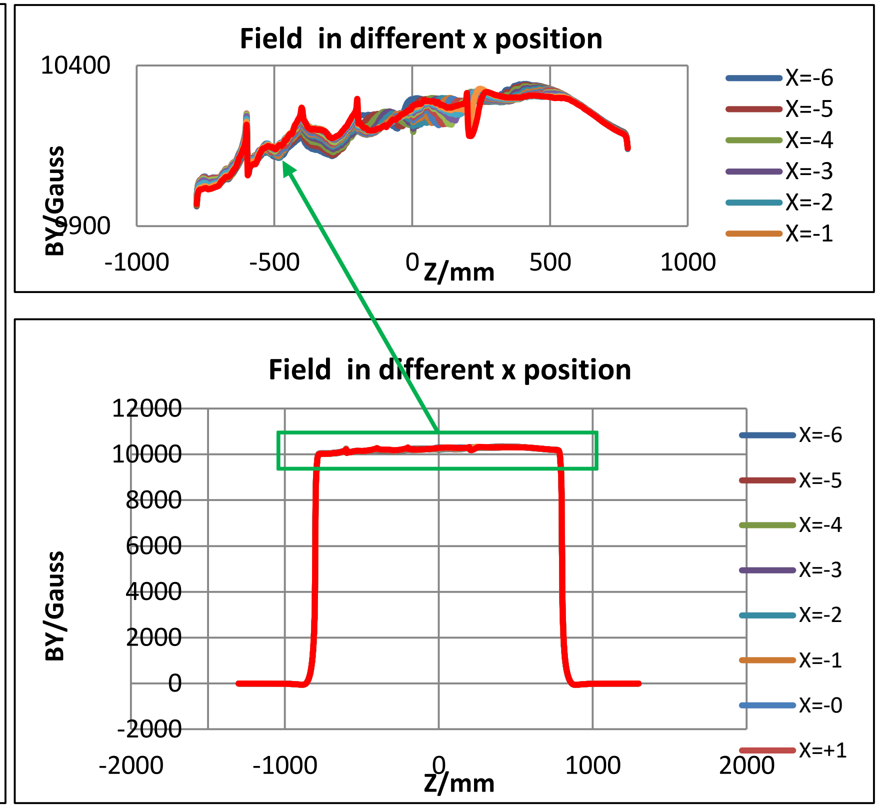


Main field distribution measurement

- All magnetic field performance of the prototype can meet the requirements of physics.

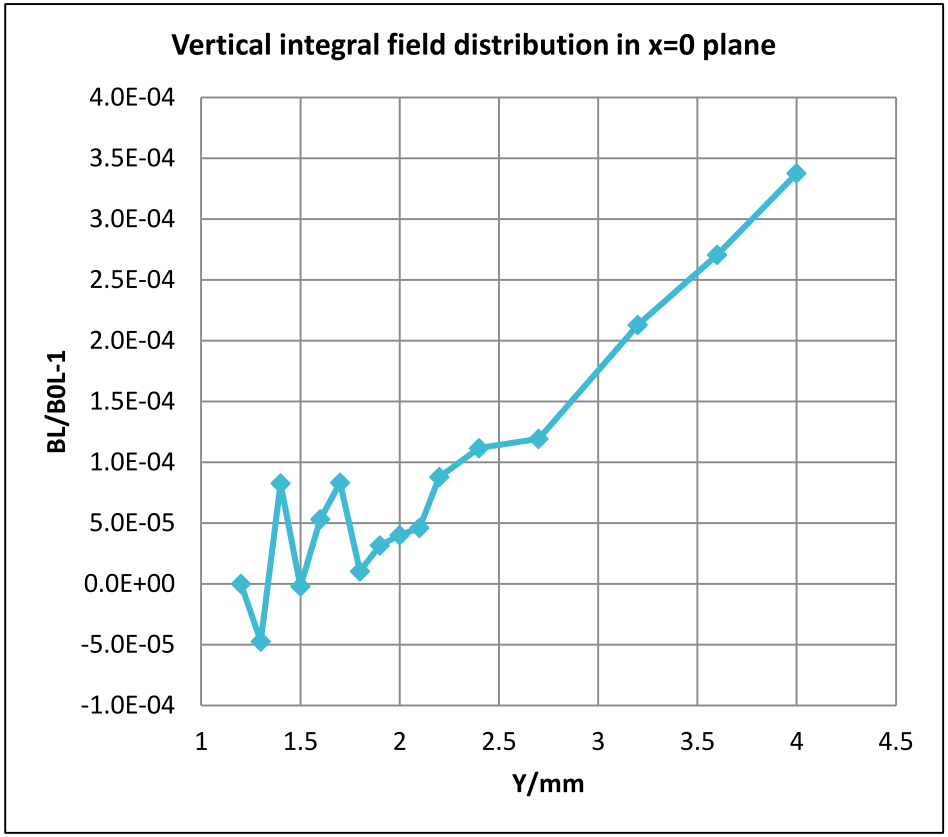
Horizontal field distribution in range x=±6mm : 7.22E-04 (<±0.1%) @ 175A

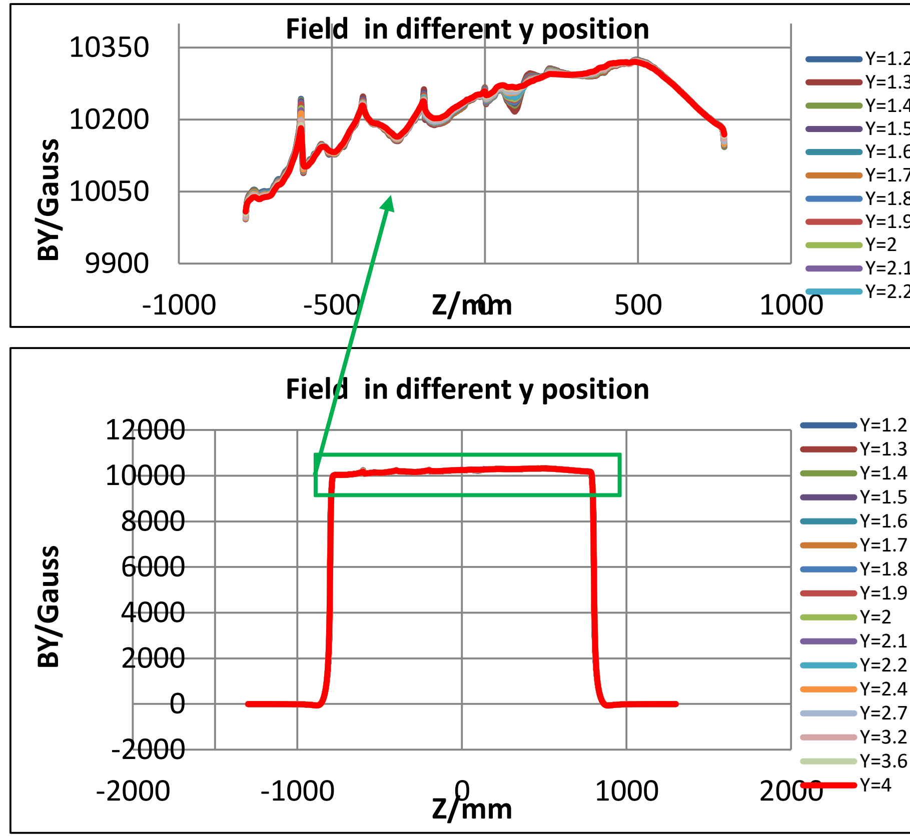




Main field distribution measurement

vertical field distribution in range 1.2mm<y<4mm： 3.85E-04 (<±0.1%) @ 175A

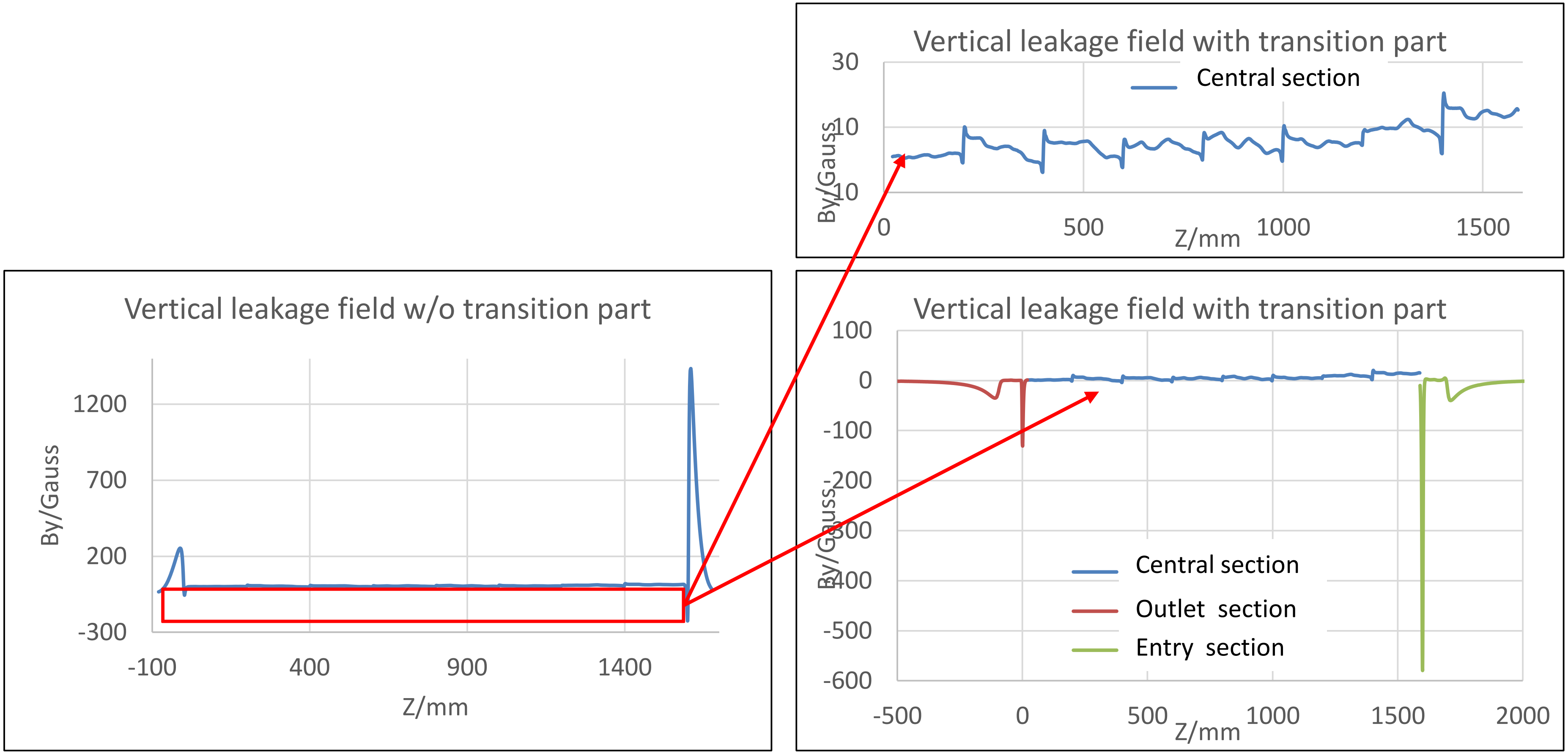




*Y=0 plane is surface of bottom polar

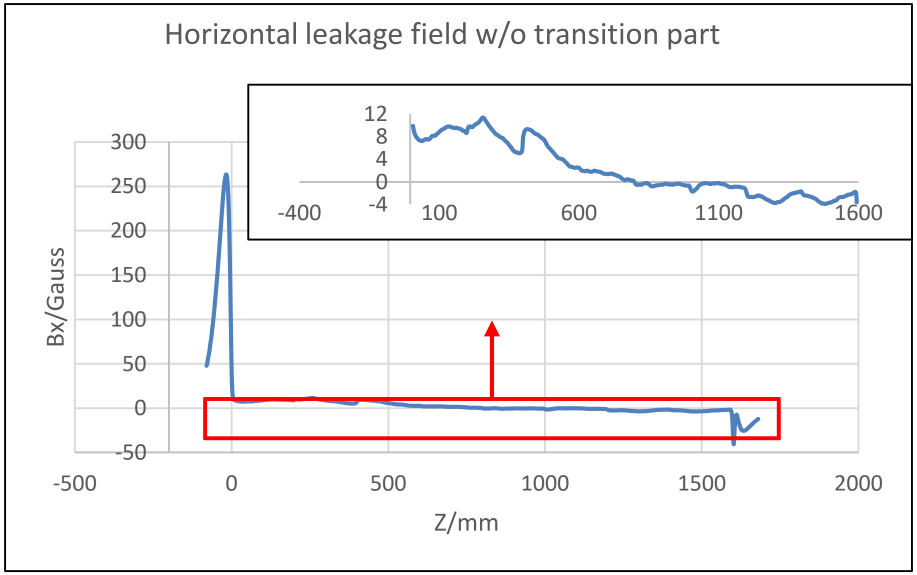
Integral leakage field measurement

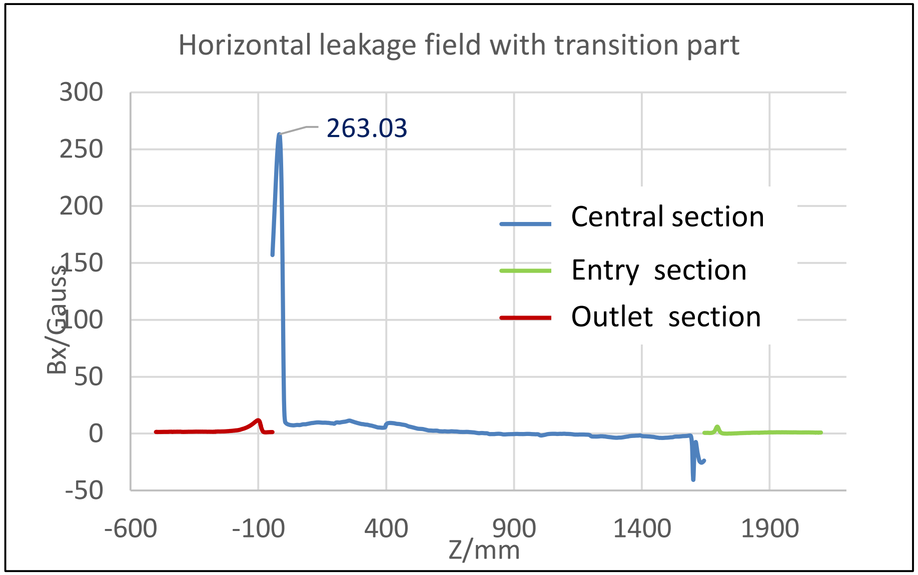
- **Vertical integral leakage field**
  - w/o transition part： integral vertical leakage filed=3.25E-03(53431Gauss·mm)， not meet requirement
  - With transition part： integral vertical leakage filed=4.3E-04 (-6997Gauss·mm)， meet requirement



Integral leakage field measurement

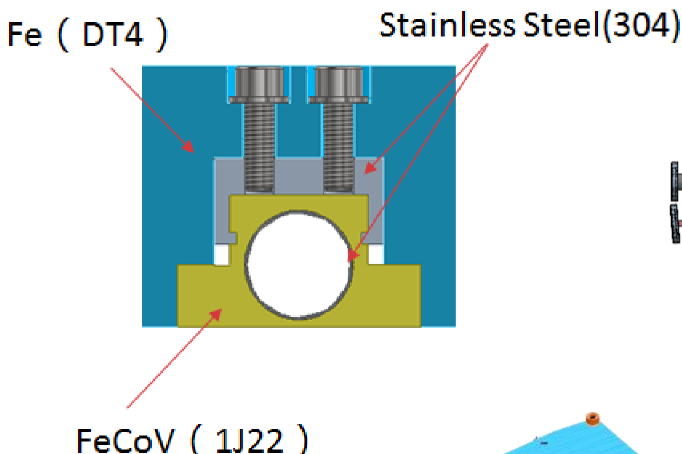
- **Horizontal integral leakage field**
  - w/o transition part： integral horizontal leakage filed=8.75E-04(14402Gauss·mm)， meet requirement
  - With transition part： integral horizontal leakage filed=8.19E-04 (13464Gauss·mm)， meet requirement

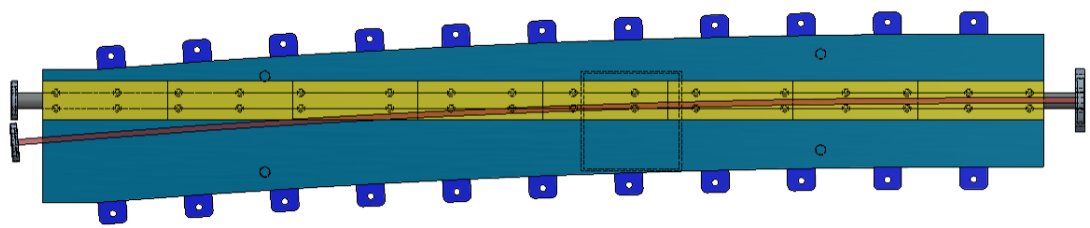


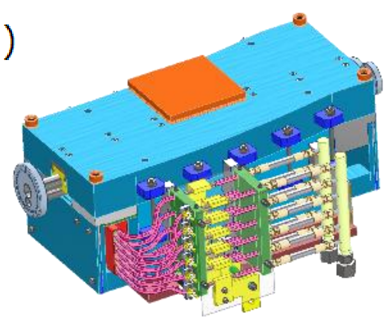


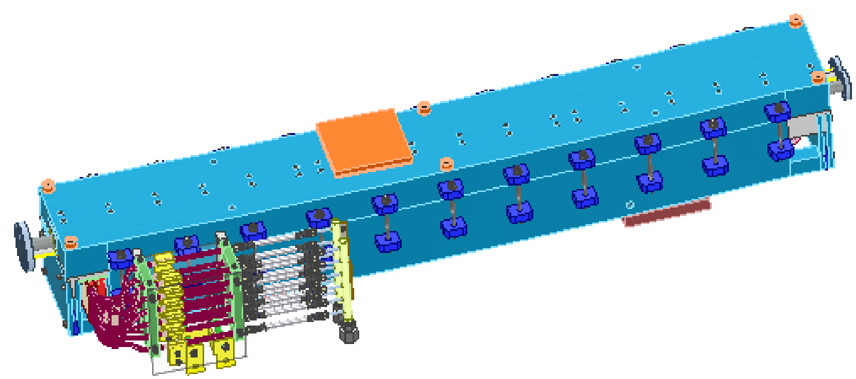
In-air LSM R&D for HEPS BST

- Feature： magnet is located in the air; total septum thickness=3.5mm， Length=1.6m
- Because FeCoV（1J22， Co50）is hard to machine, the magnetic shielding blocks must segmented processing by EDM . And that, the embedded thin wall SST vacuum chamber for stored beam is needed.





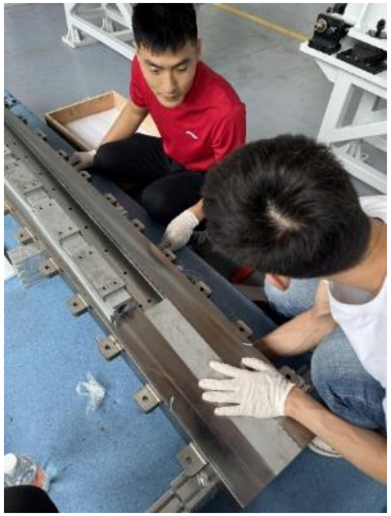




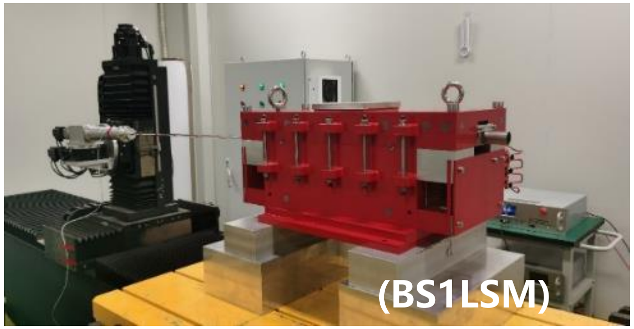
In-air LSM R&D for HEPS BST

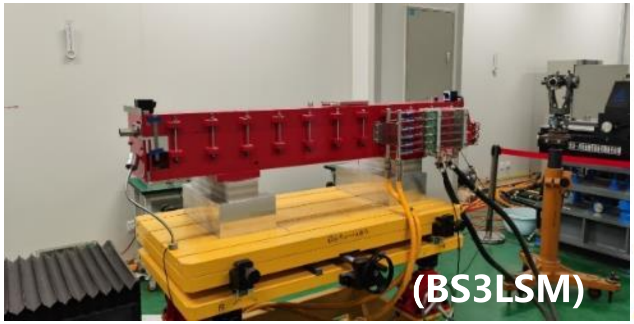
- The process of prototypes being assembled

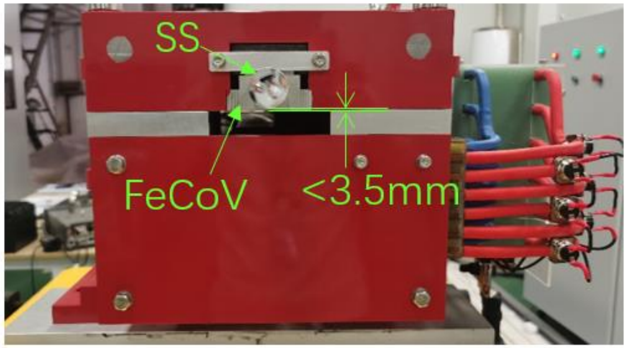





- The process of prototypes hall probe measurement

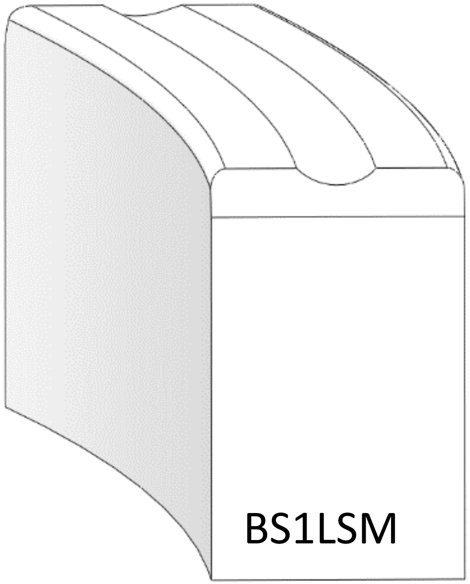


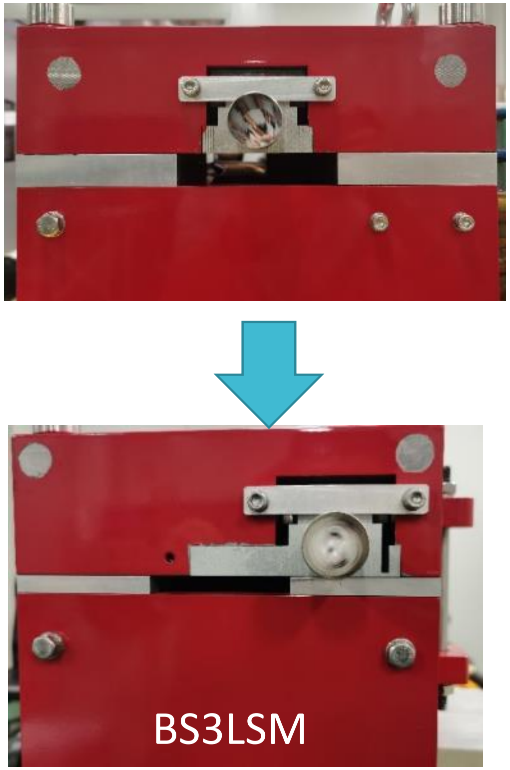




In-air LSM R&D for HEPS BST

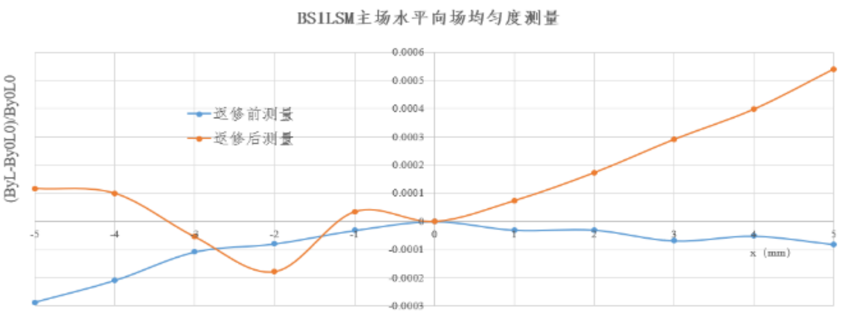
- Field measurement result shows that The gap at the joint of magnetic poles has a great influence on the leakage field and the main field distribution.
- After repair， the BS1LSM and BS3LSM have pass the second time magnetic field measurement

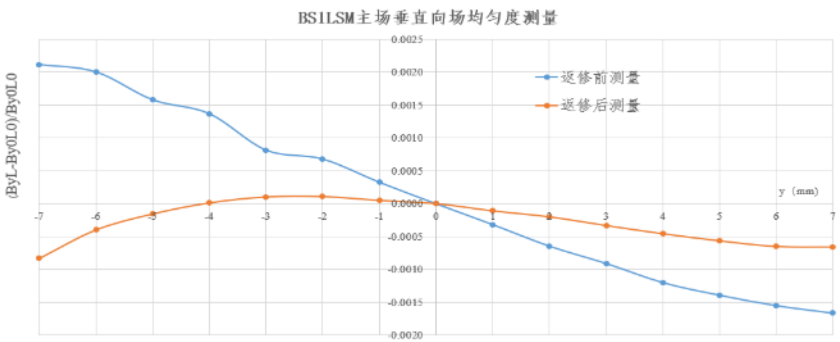


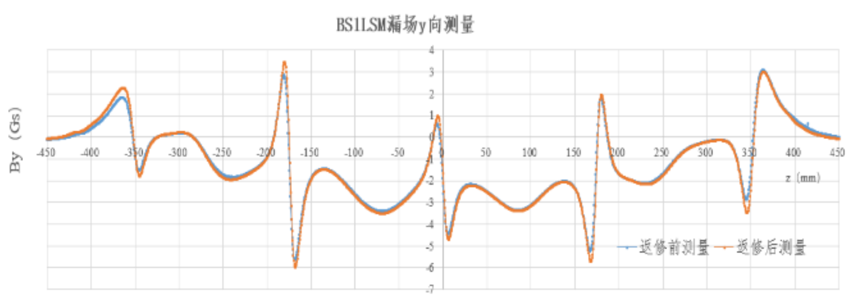


In-air LSM R&D for HEPS BST

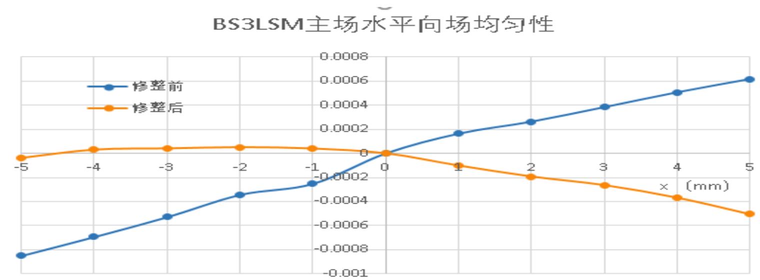
- BS1LSM:vertical main field distribution is improved from ±0.19% to ±0.0468%

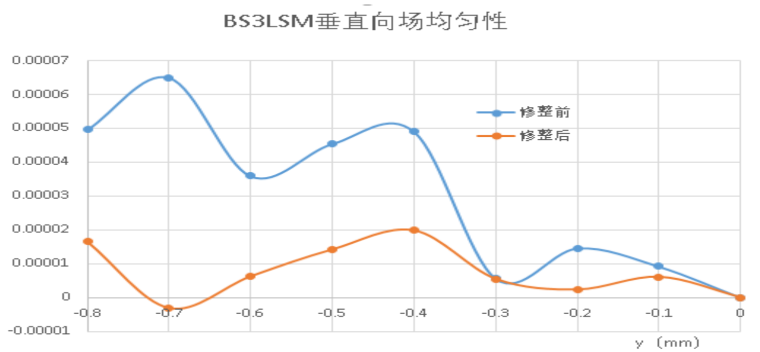


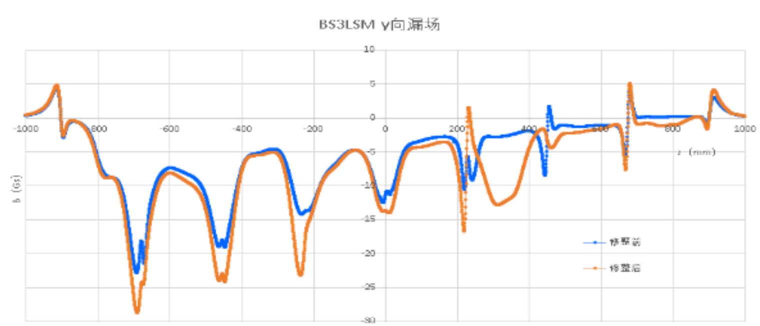




- BS3LSM:horizontal main field distribution is improved from ±0.0732% to ±0.0278%

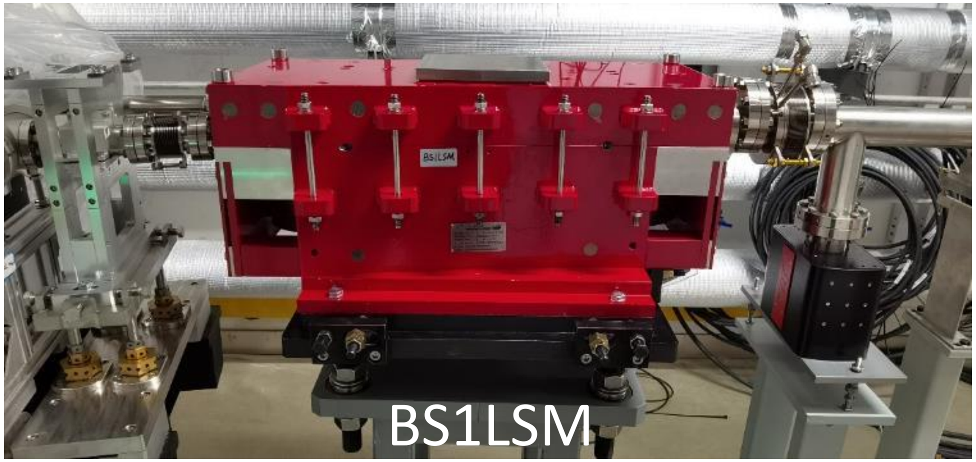


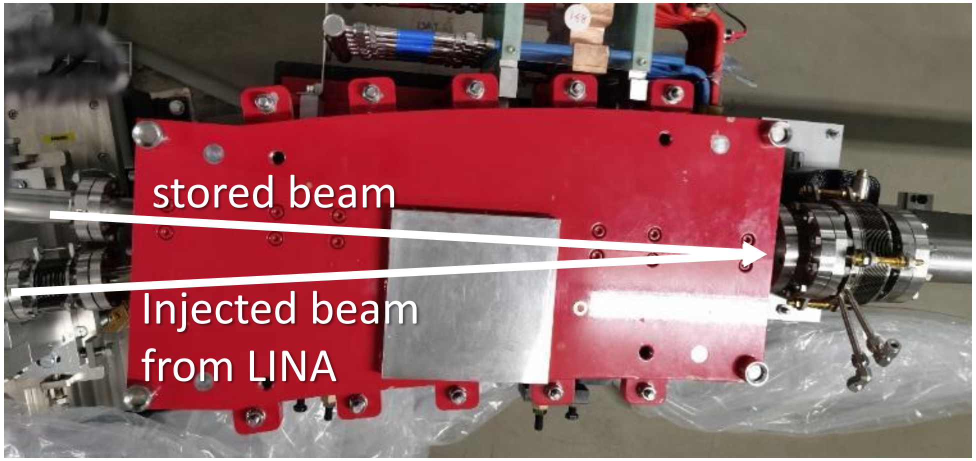




In-air LSM R&D for HEPS BST

- BS1LSM has been installed into the booster tunnel.
- BS3LSM is ready to been installed.





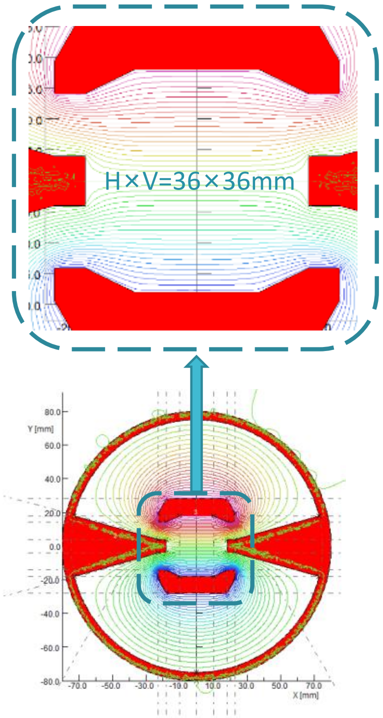
Slotted-pipe kicker system for the Booster

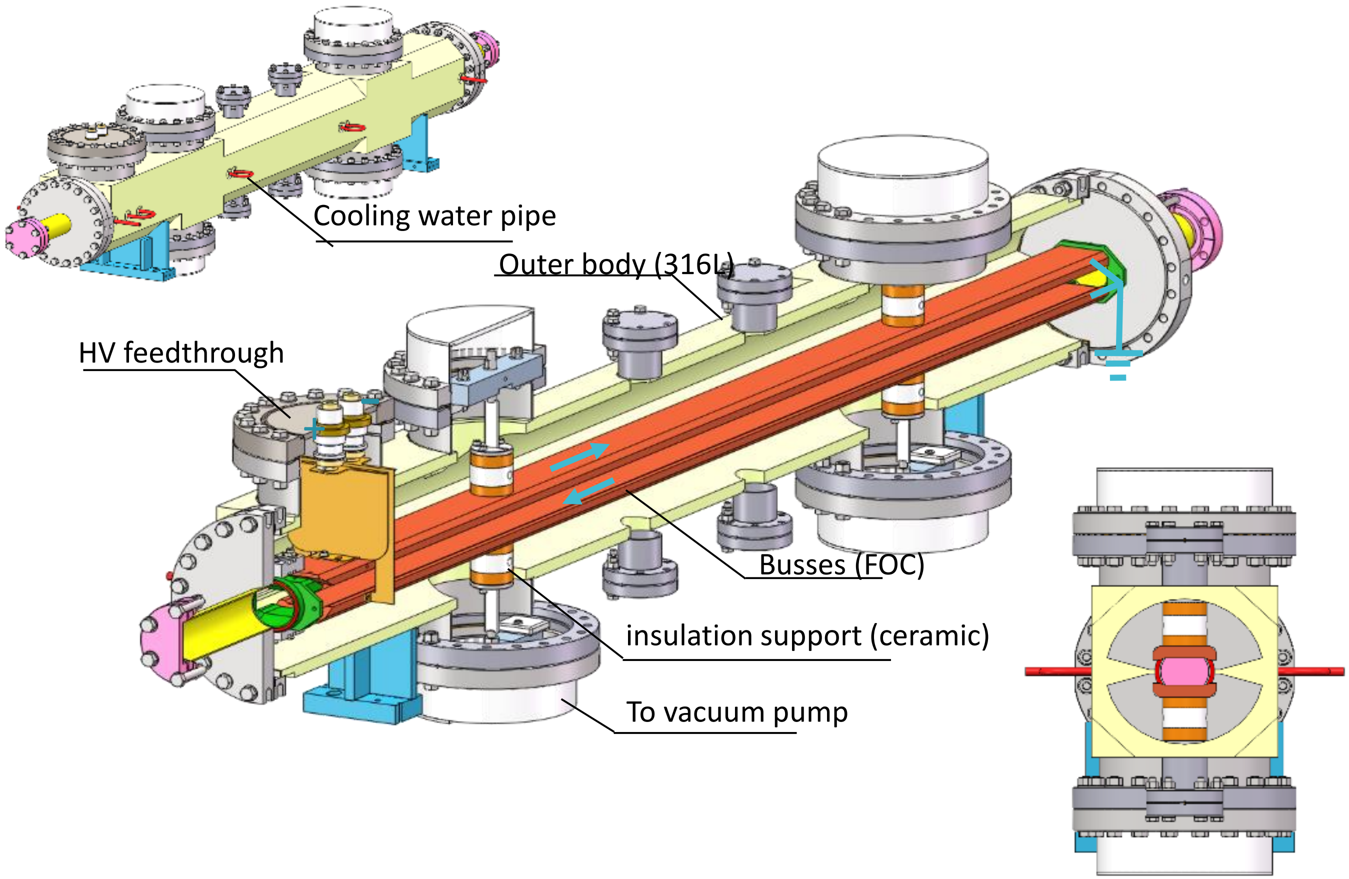
Parameters of kicker system in BST

parameter	LE-injection	HE-type I	HE-type II	HE-type III	Unit
name	BS1K	BS2K	BS3K	BS4K	-
Quantity	1	1	1	1	-
Magnetic effective length	0.8000	1.4000	1.4000	1.4000	m
Deflect direction	Vertical	Vertical	Vertical	Vertical	-
Deflect angle	9.10	1.02	1.75	1.75	mrad
Magnetic strength	0.020	0.015	0.025	0.025	T
Clearance region(H×V)	22×28	30×28	30×28	30×28	mm
Good field region(H×V)	[-6,6]×[-8,8]	[-6,6]×[-4,3]	[-6,6]×[-5,4]	[-6,6]×[-4,3]	mm
Field uniformity in good field region	x=±4,y =±5， better than±1%; x=±6,y =±8， better than±2.5%	±1%	±2%	±1%	-
Repetition rate	50	50	50	50	Hz
Amplitude repeatability	±0.5%	±0.5%	±0.5%	±0.5%	-
Pulse jitter	≤5	≤5	≤5	≤5	ns
Bottom width of half sine pulse	< 300（at least 600）	<300（at least 600）	<1000	<1000	ns
Exciting current	2160	1630	2715	2715	A
Inductance of kicker	265+200	460+200	460+200	460+200	nH

Engineering design of the slotted-pipe kicker completed

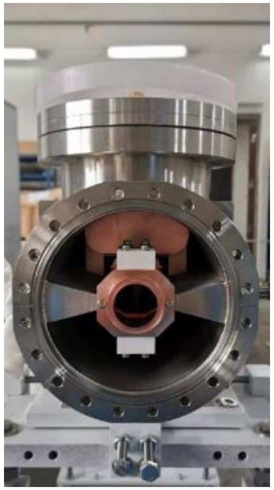
- Features： the kicker outer body is machined by EDM; One end of the busses are connected to outer body which is on ground potential level. So need a bipolar pulsed power supply. Totally 10 HV RF 50Ω cables are connected to the other end of the busses by the feedthroughs.

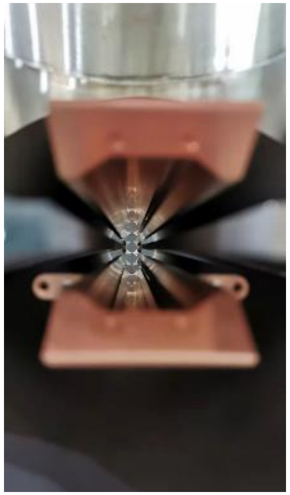


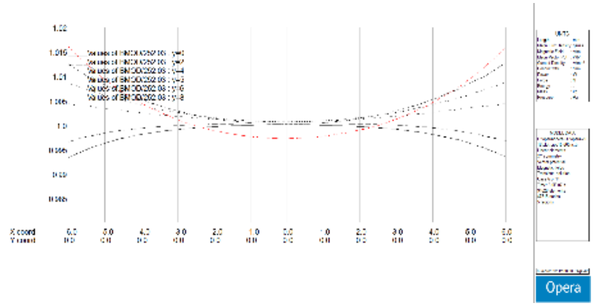


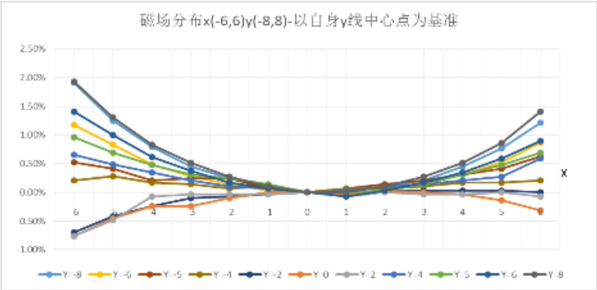
Prototype kicker for HEPS BST

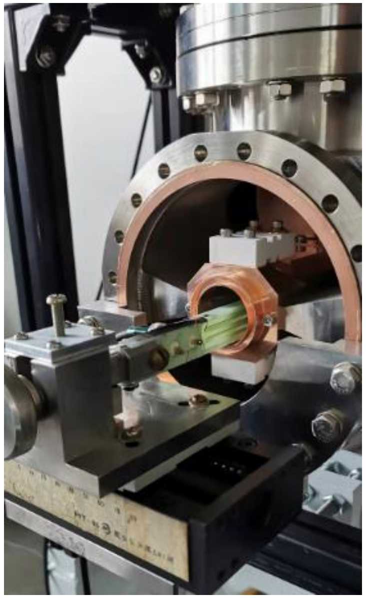
- the kicker prototype passed the vacuum assembling test and the magnetic field measurement have completed. The field distribution performance meet the requirements.









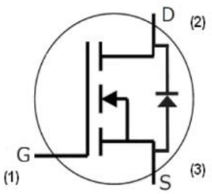


Kicker magnets installation

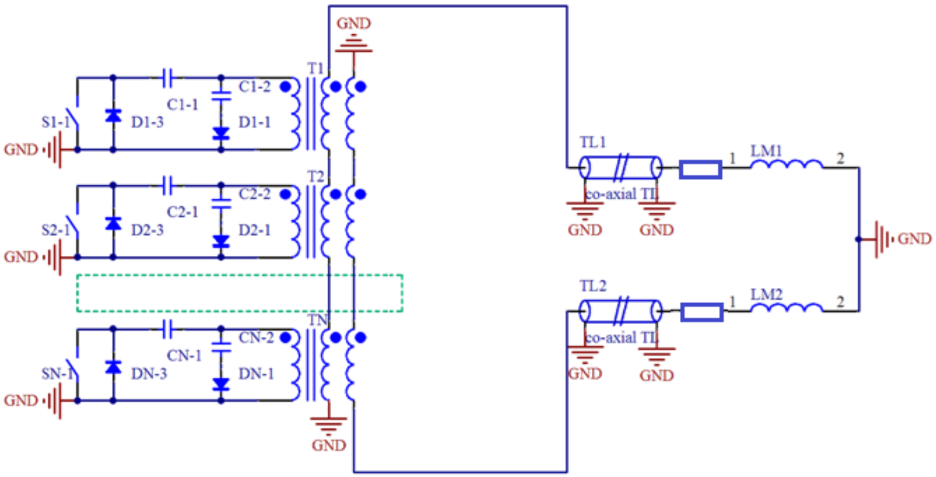
- All 4 kicker magnets for the booster injection & extraction have been installed into the booster tunnel.

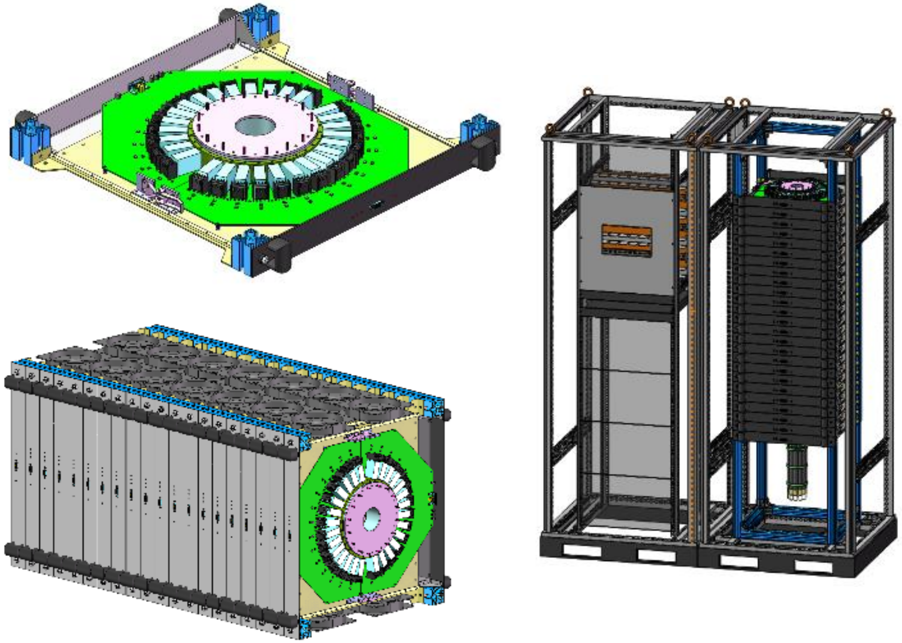



Solid-state fast kicker pulser R&D



- Scheme: 20-stage inductive adder based on SiC-MOSFETs.
- The co-axial transformer is configured as bipolar output.
- The pulser is located outside tunnel and 10 50 Ω cables with length more than 30m are applied to connect with kicker.
- Matching terminal resistor is 10Ω.

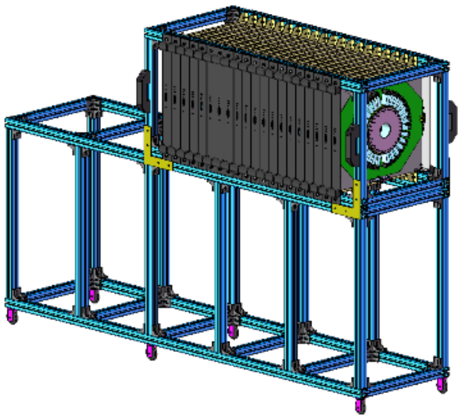
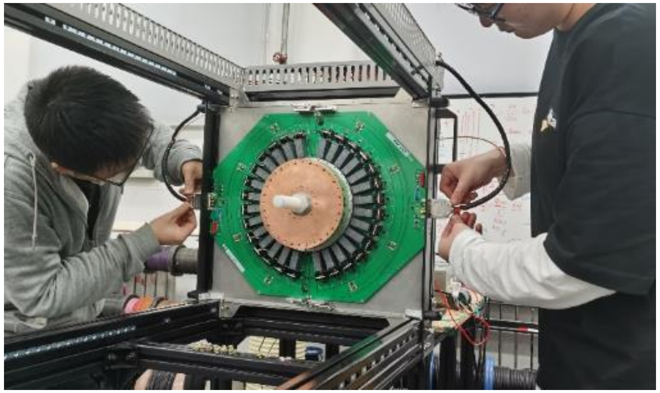
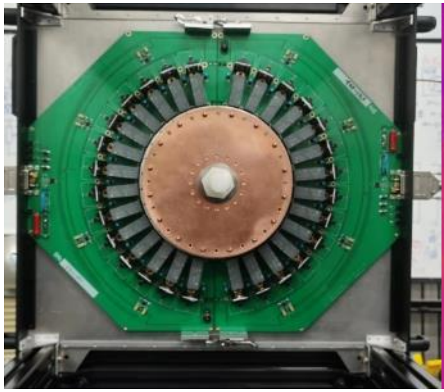
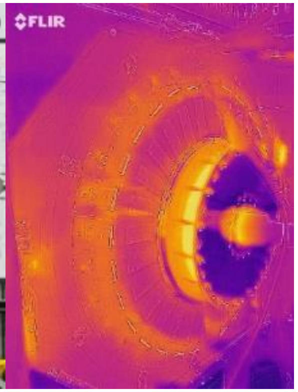


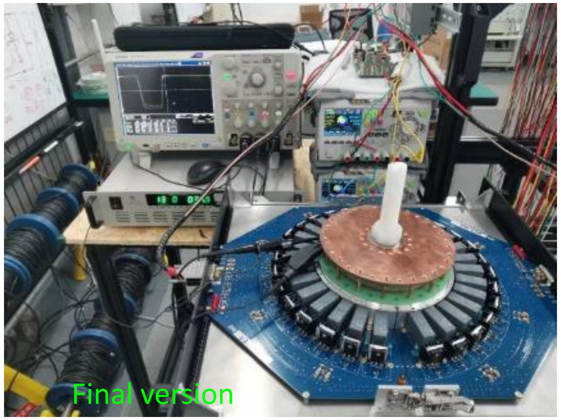


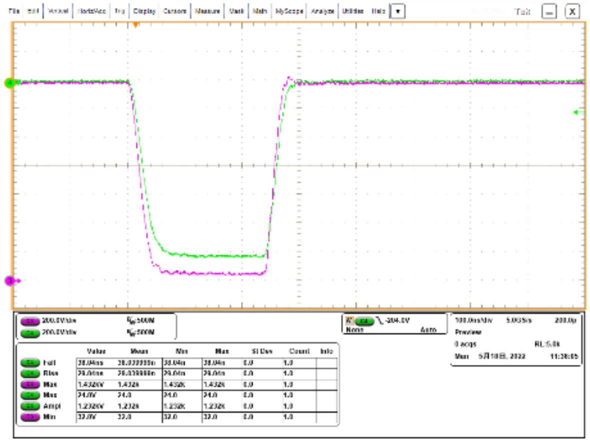
20-stage inductive adder

Pulser prototype for HEPS

- Progress： Single stage and double stages full power test has been completed （1400V into 0.5Ω）

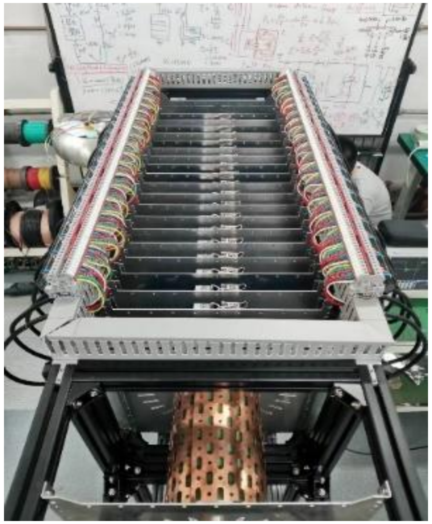


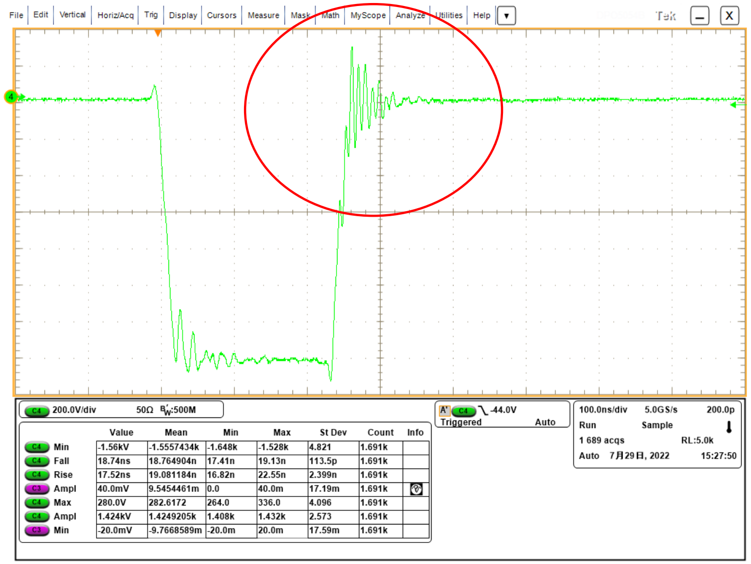


Mass production and test

Pulser prototype for HEPS

- Latest Progress： 18-stage inductive adder was tested （DC HV=800V, output pulse voltage is 14.2kV into 10Ω）.
- Due to the existence of parasitic inductance outside the adder, a reverse voltage spike with high amplitude will be induced at the tail of the pulse when MOSFET is turned off, which must be suppressed by the reverse peak absorption circuit composed of high-speed diodes, Otherwise, MOSFET overvoltage breakdown will be caused.





Strip-line kicker system for the Storage ring

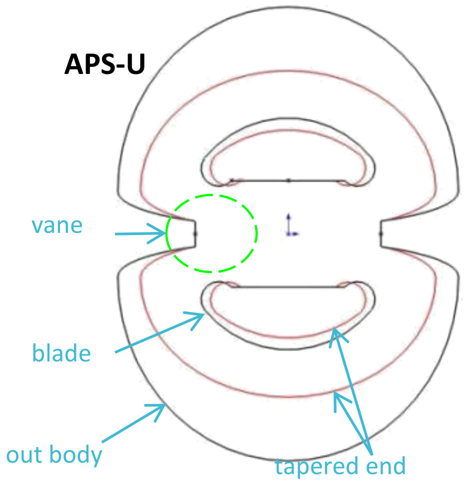
Parameters of kicker system for SR

Parameters	Unit	injection	extraction	
Name		R03K1~5	R48K1~5	R48PK
Straight section length	m	6.086	6.086	
Total kick angle	mrad	1.6108		0.2~0.075
Kick direction	-	Vertical		Horizontal
Length of Strip-line kicker electrode	mm	300		300
Gap between two electrodes	mm	8		16
Quantity of Strip-line kicker	-	5	5	1
Longitudinal space between strip-line kicker electrode	mm	6		-
Good field region	mm	x=±1.1， y= (-0.85, 2.1)		x=±0.5， y±0.4
Integral field uniformity	-	<±1%		<±1%
Odd mode impedance	Ω	50±1		50±1
Even mode impedance	Ω	<65		<65
Amplitude of electrical pulse（into 50Ω）	kV	±15		±7.5
Bottom width of electrical pulse（3%-3%）	ns	<4 *	<10	<10
FWHM(50%-50%)	ns	>2 *	>4	>4
Electrical Pulse Amplitude Stability	-	<2% (RMS)		<2% (RMS)
Repetition rate （CW）	Hz	50		50
Time jitter between electrical pulse and timing clock	ps	<200		<200
Time jitter between channels (bipolar)	ps	<100		<100

Strip-line kicker scheme

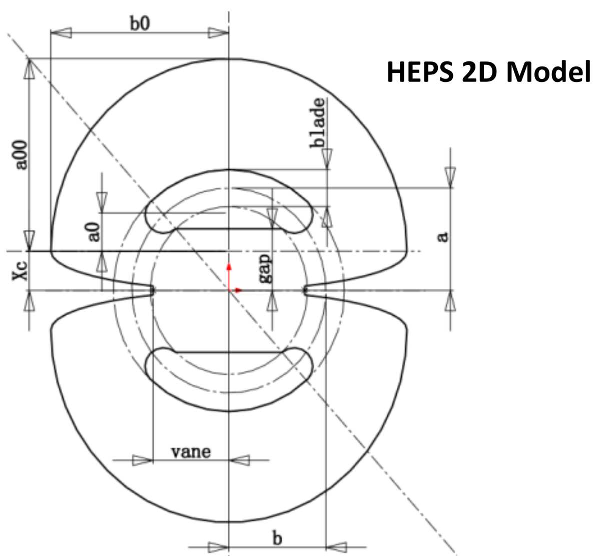
PRELIMINARY TEST RESULTS OF A PROTOTYPE FAST KICKER FOR APS MBA UPGRADE*

Figure 5: The kicker installed in the BTX beamline.



Following APS-U type strip-line kicker

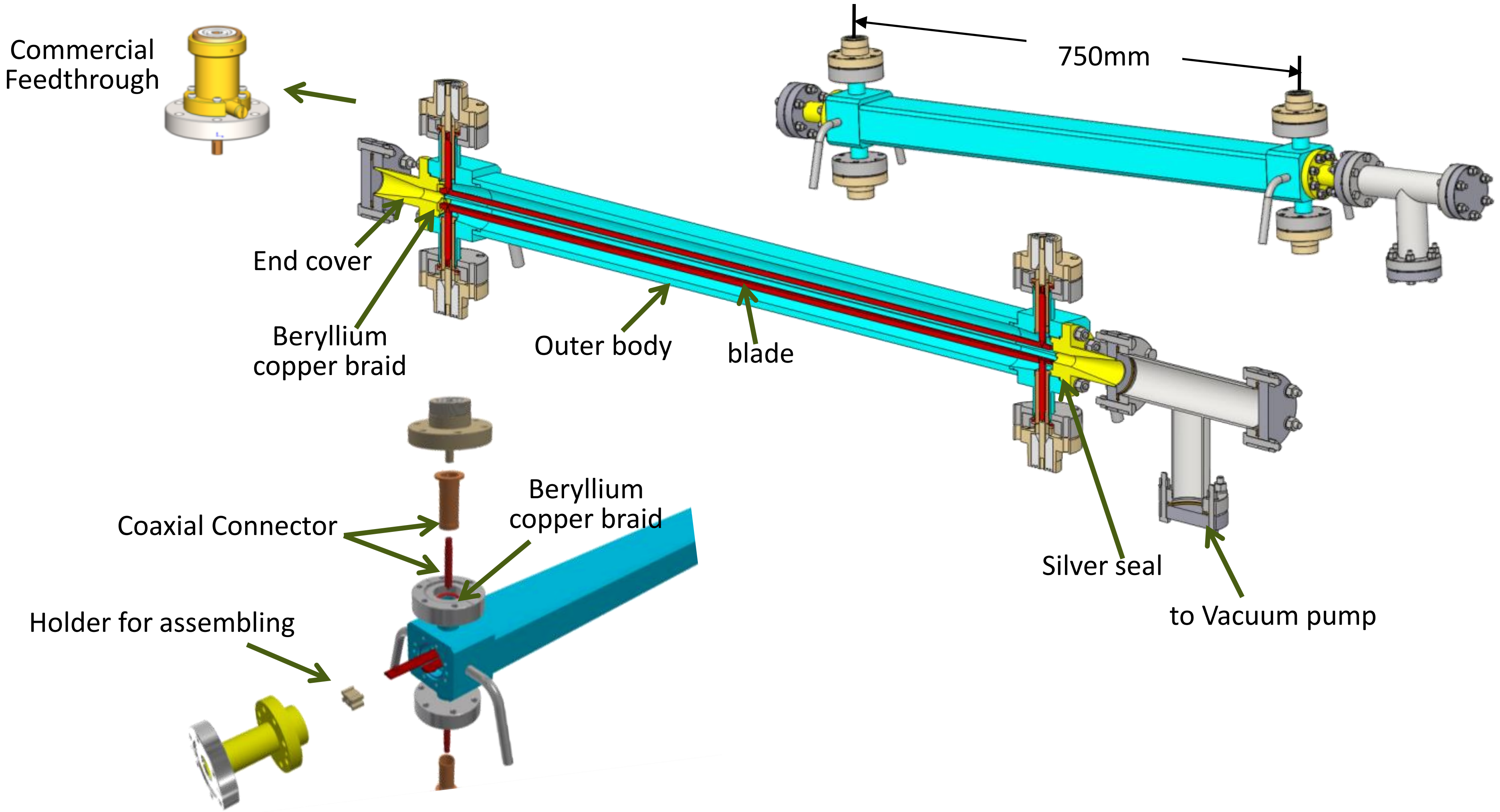
- "D" shaped blades are used to improve field-uniformity in the good field region.
- An ellipse outer body with vanes geometry is adopted to ease common-mode impedance-matching
- Tapered end sections for matching impedance to the feed-throughs.



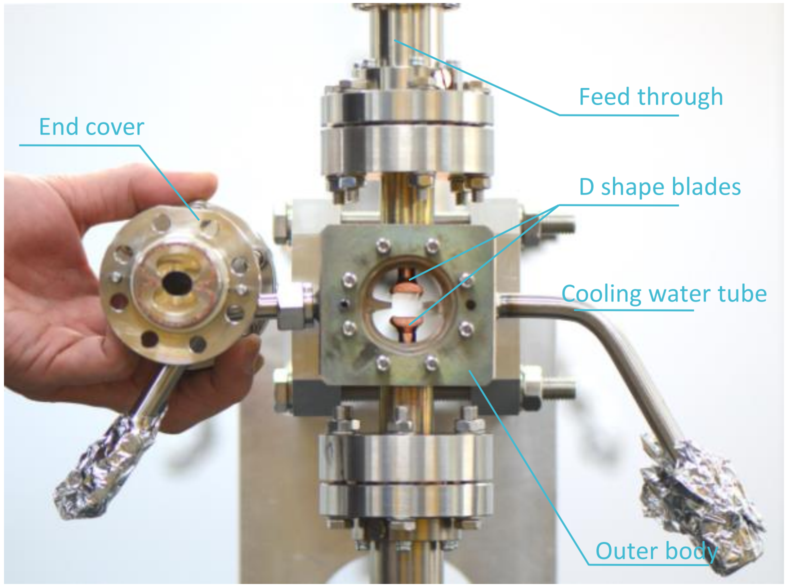
HEPS strip-line kicker prototype 2D model

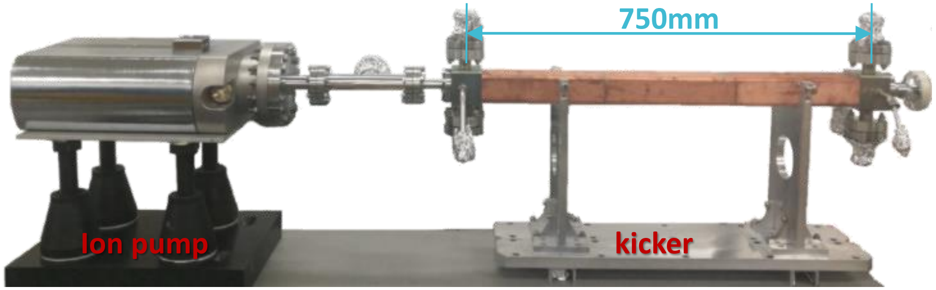
- **The strip-line blades are decided by:**
  - **a, b - axes of the center ellipse**
  - **gap=5mm – ½ distance between blades**
  - **blade=3mm – thickness of blades**
- **The outer body half shell consists of 2 half ellipses that defined by:**
  - **Center half: Xc, a0, b0**
  - **Outer half: Xc, a00, b0**
- **New parameter:**
  - **vane (>=<b)- ½ distance between Vanes**

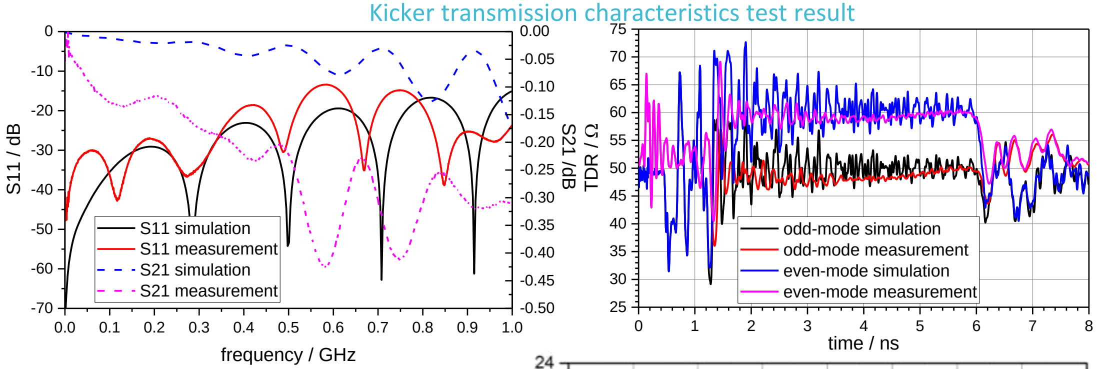
Prototype I: 750mm-long Strip-line Kicker

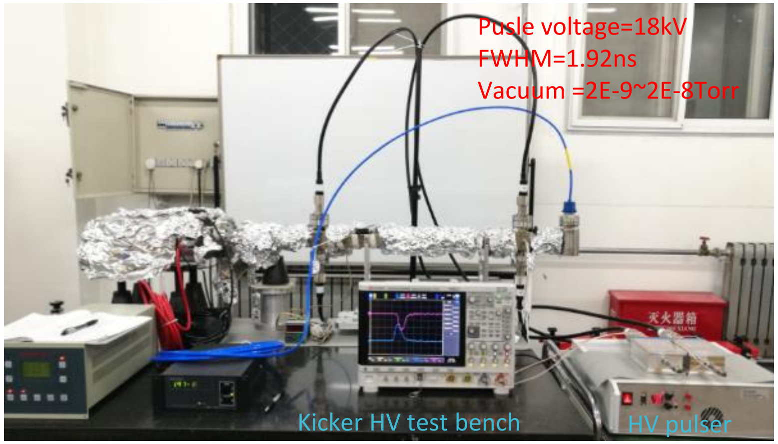


Prototype kicker completed in 2018









Kicker HV test reult：

- Kicker electrical pulse：

Rise time（10%-90%）<641ps，

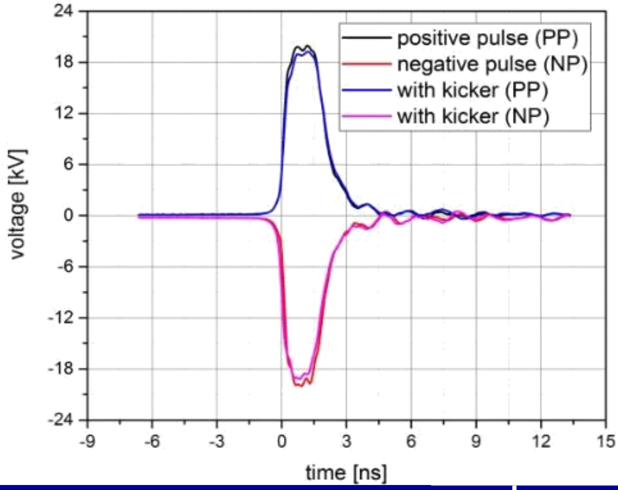
Fall time（90%-10%）<1.5ns。

- pluse edge slowing down due to

kicker insertion：

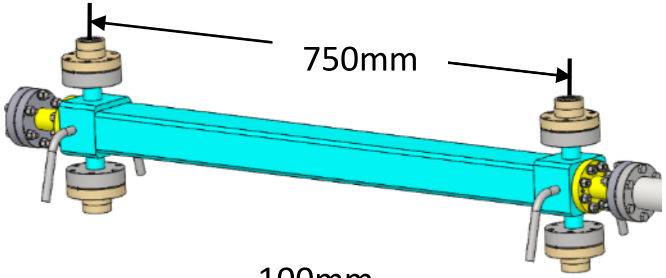
rise time (10%-90%)≈86.6ps,

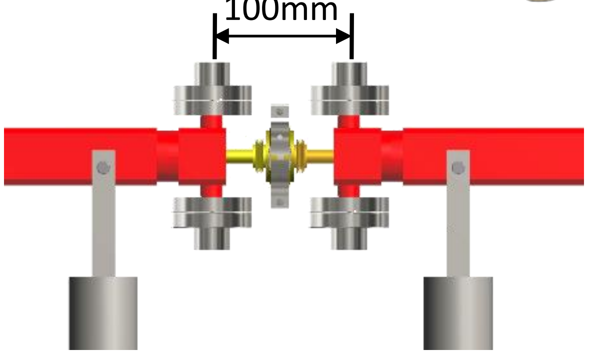
Fall time (90%-10%) ≈ 35ps。

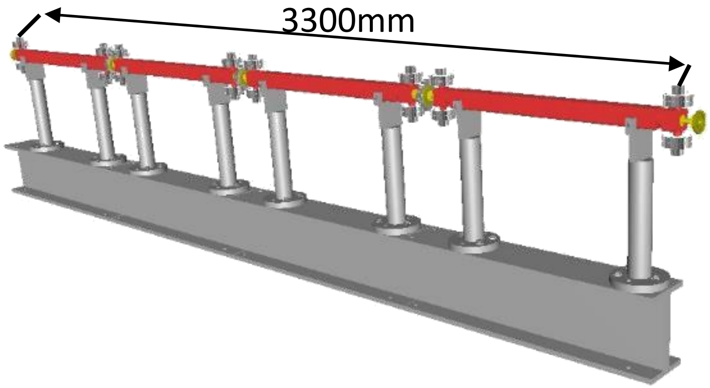


Limit longitudinal installation space

- **The HEPS prefers shorter strip-line kicker(300mm-long) to reduce difficulty of fast pulser, specially for longitudinal injection**
- **5 sets of shorter kickers and a Lambertson magnet must be installed in 6m of straight section**
- **The separated kicker structure is not fit for the shorter kicker for HEPS because of limited longitudinal space.**
- **A new compact design have to be considered.**

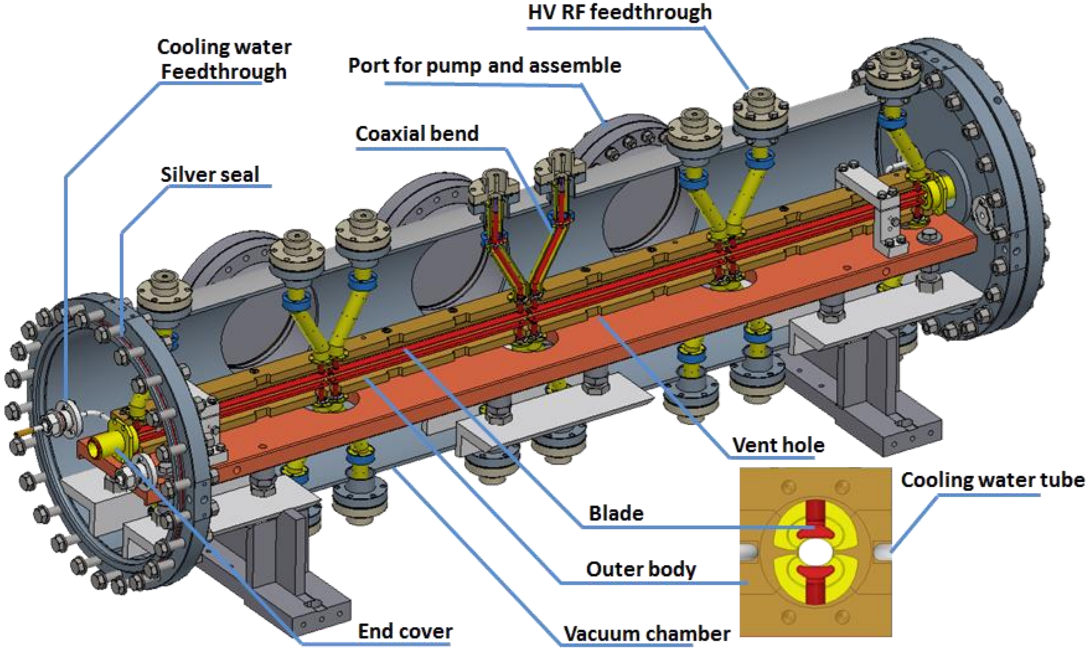






Prototype II: 300mm-long Strip-line Kicker

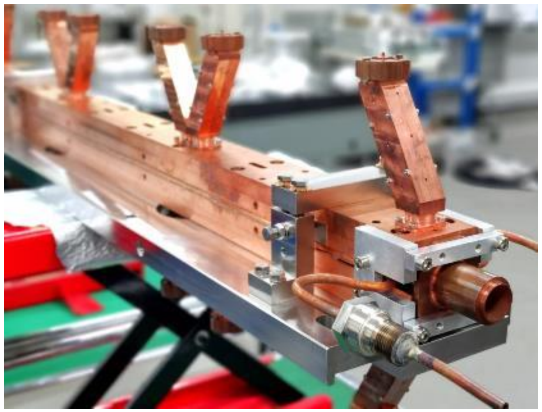
- New kicker structure with 5 cascaded kickers in a single vacuum chamber was proposed.
- The longitudinal gap between adjacent kicker blades is <6mm.
- The outer body is split into 4ps(1.2m long) which made by CNC machining from FOC.
- 300mm-long strip-line blades without taper end are also made by CNC machining from FOC.
- The coaxial bend transition parts connected blades and HV RF feedthroughs is the key point.



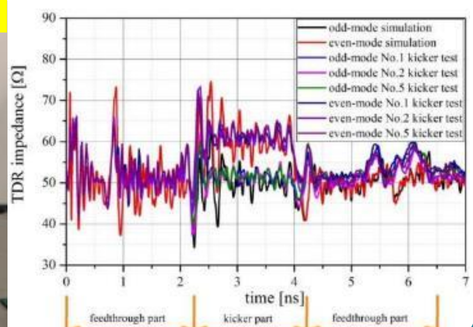
The strip-line kicker prototype completed in 2019

- Feature： 5 sets of 300mm strip-line kicker in a single module

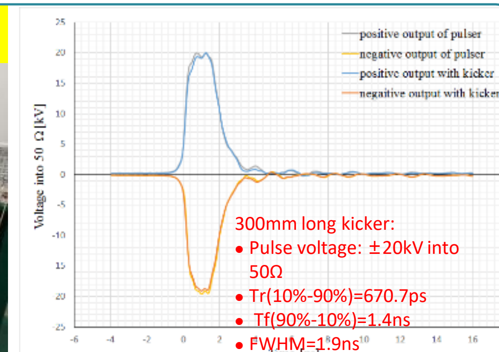
L. Wang, J.H. Chen, A 300mm long prototype strip-line kicker for the HEPS injection system, IPAC2019




TDR measurement



HV pulse testing at ± 20kV



Progress of final kicker production for HEPS

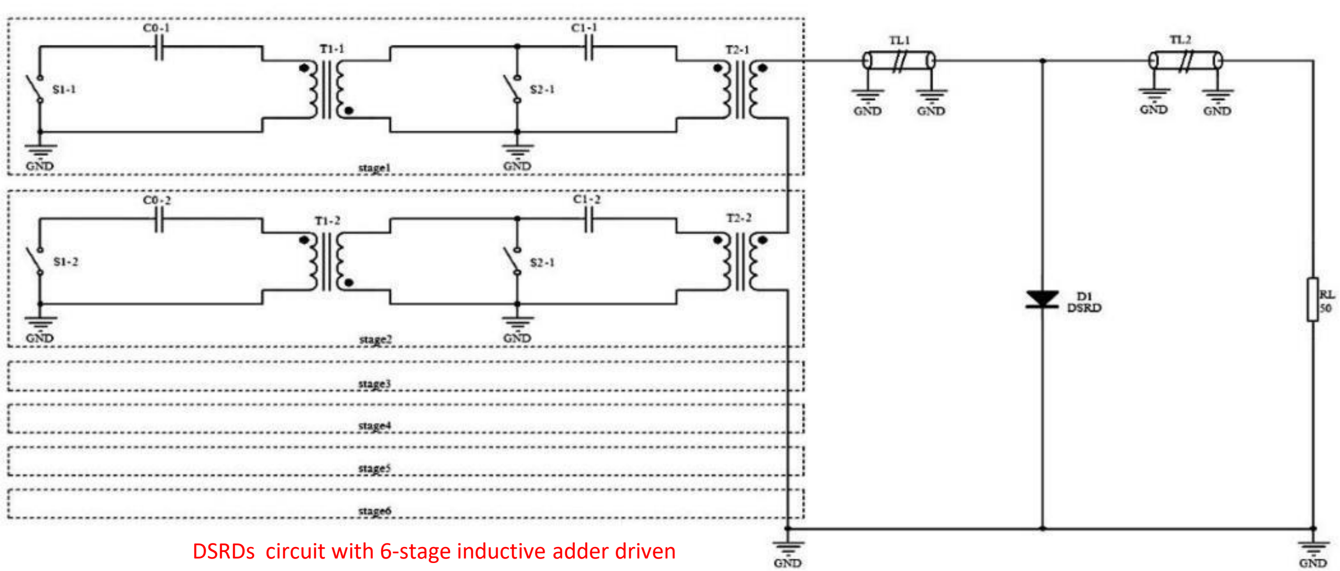
- The all mechanical machining have been completed

- first module has been assembled and passed the vacuum commissioning.

10ns-fast puler R&D

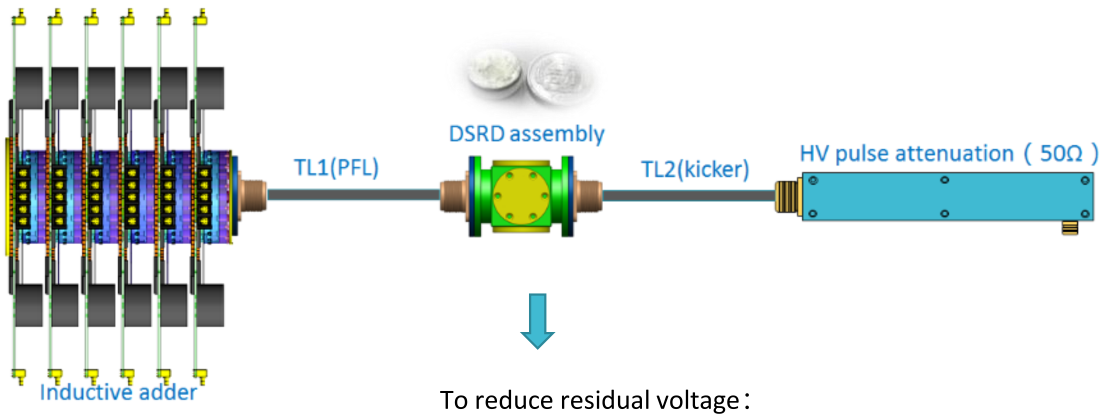
Features：

- Drift Step Recovery Diode(DSRD) [4]: Opening in sub-ns
- Chips from the Chinese vender are available ($i_p \geqslant 300A/\ V_p=10kV$)
- A 6-stage inductive adder designed as DSRD pumper circuit for 15kV:
  - avoid isolated switch driver and HV components(capacitors, switches <1kV)
  - need much fewer components compared to an inductive adder pulser
- 16 MOSFETs per stage
- 8 DSRDs(4 parallel, 2 series) switching 600A into 50 Ω;
- 0.3m long PFL(TL1) for p_w=3ns

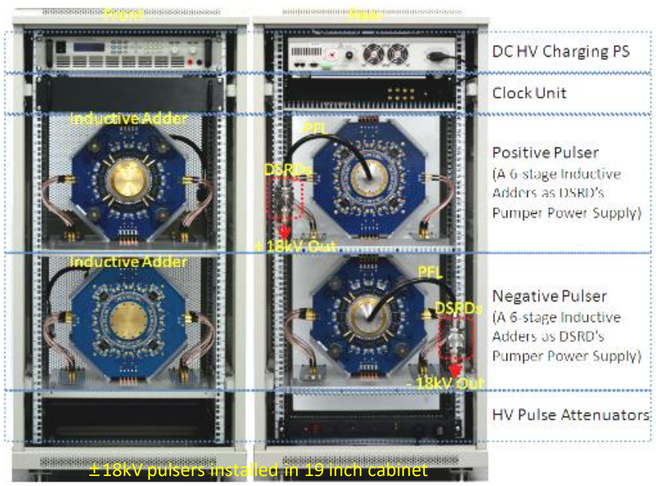


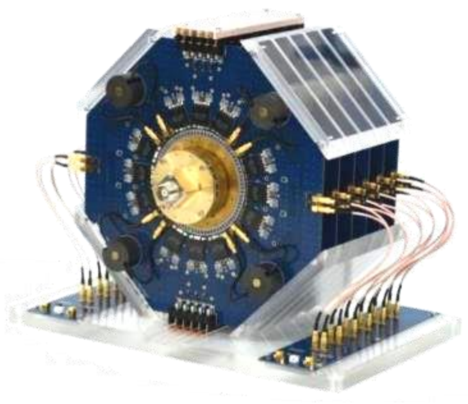
DSRDs circuit with 6-stage inductive adder driven

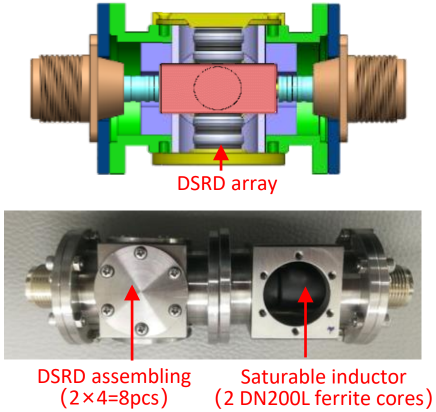
The 10ns fast pulser prototype R&D completed in 2018

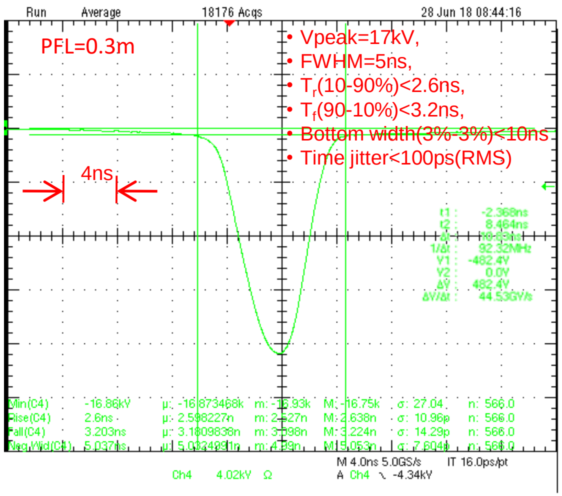


To reduce residual voltage：
•DSRD array: 4 in parallel and 2 in series
•Saturable inductor: 2 NiZn ferrite cores





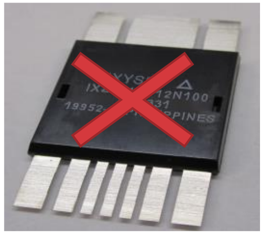




J.H. Chen, Strip-line kicker and fast pulser R&D for the HEPS on-axis injection system, NIMA 920(2019)1-6

New pumper R&D based on commercial SiC MOSFET

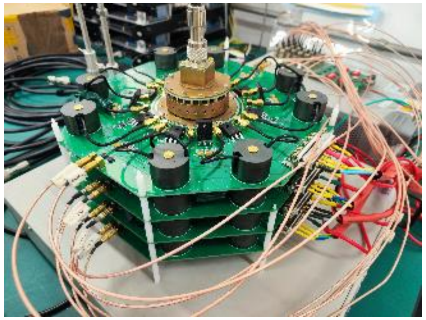
- The commercial RF-MOSFET(IXZ631DF12N100) applied in pusler prototype being in “End of Life” status
- Alternative power semiconductor SWITCH： SiC MOSFET **C2M0045170D** （CREE） with higher Vds and Id, but slower switching speed.

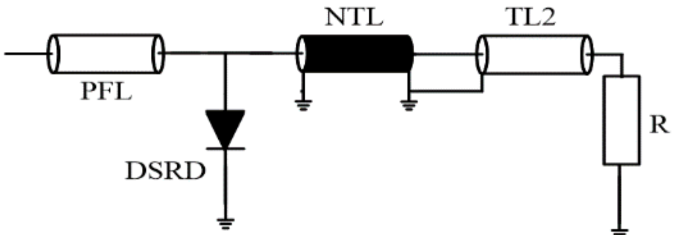


TO-247-3

V_{DS}	1700 V
I_D @ 25°C	72 A
$R_{DS(on)}$	45 mΩ

- New prototype based on SiC MOSFET was developed. A Non-linear transmission line is introduced to sharpen the pulse. The best result is the bottom width(3%-3%) of pulse is less than 10ns, the peak large than 15kV into 50ohm.





Summary

- The HEPS accelerators includes 3 injection systems and 2 extraction systems, which were designed to realize on-axis swap-out top-up injection in the storage ring with small DA.
- The injection and extraction hardware R&D activities for HEPS was initial from 2016, HEPS-TF project.
- 2 kinds of Lambertson magnet with thin septum are developed respectively for the storage ring and booster. The half-in-vacuum Lambertson magnet prototype has been completed and the in-air one was installed into the HEPS booster tunnel.
- The slotted-pipe kickers were developed successfully and also installed into the into the HEPS booster tunnel. The solid-state pulser with 300ns bottom width are still under R&D.
- 2 kind of strip-line kicker prototype were developed for the HEPS on-axis swap-out injection successfully. The final devices have been in assembling and vacuum commissioning phase. The fast pulsers based on DSRD with a 10 ns pulse width (3%-3%) was developed successfully. And a new prototype with alternative SiC MOSFET pumping circuit is in commissioning phase.

Thank you for attentions