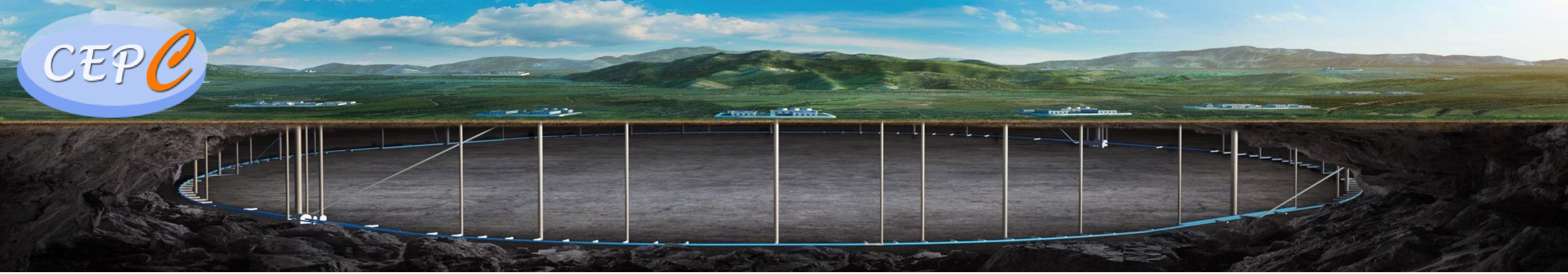

CEPC injection and extraction systems hardware R&D

Jinhui Chen

On behalf of injection & extraction team

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Introduction

- This talk is about the CEPC injection & extraction systems and related hardware R&D
- This talk relates to the TDR Ch4.3.8 (collider IE system), Ch5.3.7(booster IE system), and Ch6.4.7(Damping ring IE system)
- The content relates to the “charge letter” item 6,7,8:

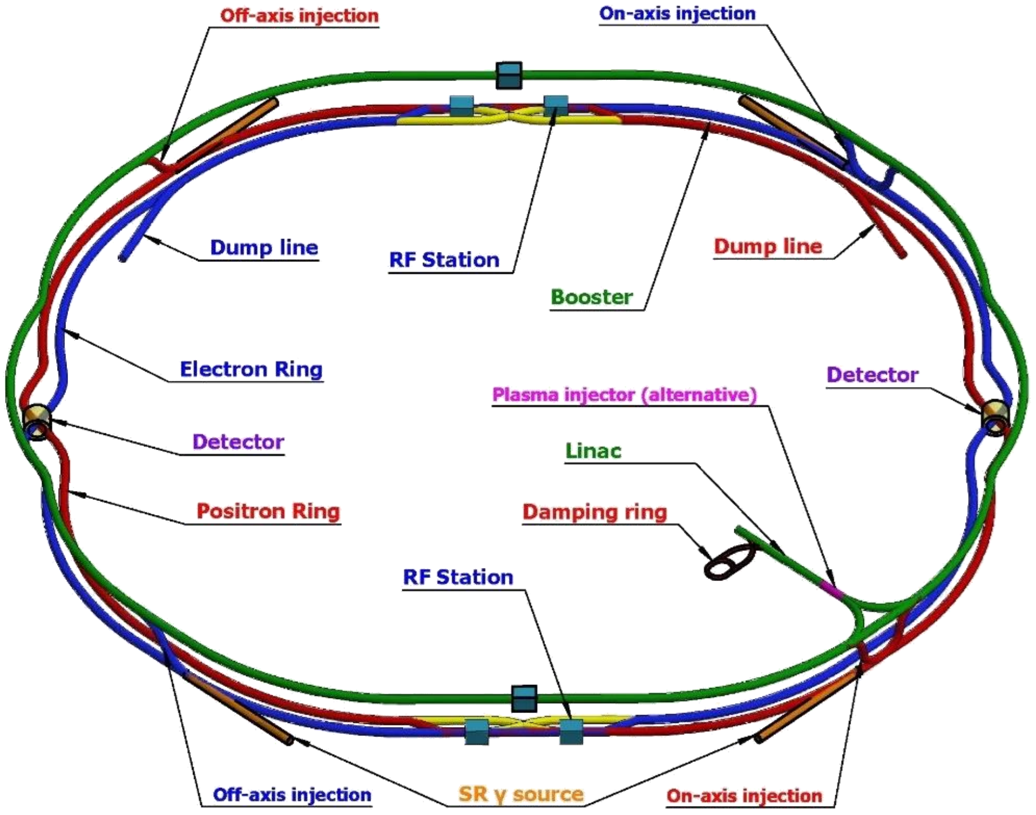
    6. Regarding the key technology research and development, are critical technologies and components of the CEPC accelerator ready or will they be ready before 2026, through the R&D program being carried out, or achieved with the Light Source project undertaken by IHEP, for the eventual realization of the CEPC?

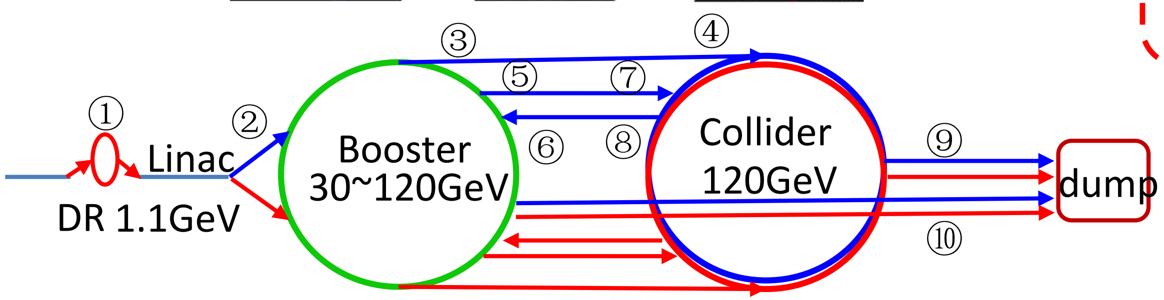
    7. What are the primary technical risks and their potential impacts on the CEPC? What are the mitigation measures that should be taken?

    8. Will the CEPC accelerator be ready for construction, after the completion of the outlined R&D program, and industrial and engineering preparation, as well as issues identified in item 7 above be properly addressed in due time?

Overview of the CEPC injection and extraction systems

Layout of the inj.&ext. systems in CEPC





The CEPC complex consists of 4 circular accelerators：

- A damping ring (1.1Gev/147m)
- A booster ring (30~120GeV/100km)
- 2 storage rings (120GeV/100km)

there are 10 injection and extraction sub-systems, including:

① DR injection and Extraction system(e+)
② Booster LE injection system (e+,e-)
③ Booster Extraction system1 (e+,e-)
④ Collider off-axis injection system (e+,e-)
⑤ Booster Extraction system2 (e+,e-)
⑥ Booster HE injection system (e+,e-)
⑦ Collider swap out injection system (e+,e-)
⑧ Collider swap out extraction system (e+,e-)
⑨ Collider beam dump system(e+,e-)
⑩ Booster beam dump system(e+,e-)

Off-axis injection
(in W and Z mode)

On-axis injection
(only in Higgs mode)

Physical requirements for CR inj.&ext. system

Parameter	Inj. and ext. (on-axis)	Injection (off-axis)	Extraction (dump)
Kicker repetition rate (Hz)	1000	1000	1000
Kicker pulse width (ns)	1360	440~2420 (Adjustable)	440~2420 (Adjustable)
Kicker flat top (ns）	-	0~1980 (Adjustable)	0~1980 (Adjustable)
Kicker rise/fall time (ns)	<680	<220	<220
Injection/extraction period (s)	0.007	1.5	1.5
Kick angle (mrad)	0.2	0.1	0.4
Kick Integral field strength (T-m)	0.08/ 0.12 ($t\bar{t}$)	0.04/ 0.06 ($t\bar{t}$)	0.16/ 0.24 ($t\bar{t}$)
Quantity of kicker group in each subsystem	1（shared by inj.and ext.）	4 (4 kicker bump)	1
Thickness of Septum (mm)	2 and 6	2 and 6	6
Defletion angle of septa (mrad)	35	26	26
Integral field strength of septa (T-m)	14.1/21.15 ($t\bar{t}$)	10.44/15.48($t\bar{t}$)	10.44/15.48($t\bar{t}$)
Quantity of septa group in each subsystem	2（inj. and ext.）	1	1
Beam pipe aperture (mm）	56	56	56

Physical requirements for BST inj.&ext. system

Parameter	LE-Injection (on- & off-axis)	HE-Extraction (off-axis)	HE-Inj./Ext. (on-axis)	HE-Extraction (dump)
Kicker repetition rate (Hz)	100	1000	1000	1000
Kicker pulse width (ns)	50	440~2420 (adjustable)	1360	440~2420 (adjustable)
Kicker flat top (ns)	-	0~1980 (adjustable)	-	0~1980 (adjustable)
Kicker rise/fall time (ns)	< 25	< 220	< 680	< 220
Inj./Extr. period (s)	60	1.5	0.007	1.5
Kick angle (mrad)	0.11	0.2	0.1	0.2
Kick Integral field strength (Tm)	0.011	0.08/ 0.12 ($t\bar{t}$)	0.04/ 0.06 ($t\bar{t}$)	0.08/ 0.12 ($t\bar{t}$)
Quantity of kicker group in each subsystem	1	1	2(inj. and ext.)	1
Thickness of Septum (mm)	5.5	6	6	6
Defletion angle of septa (mrad)	45	43	43	43
Integral field strength of septa (T-m)	0.92	17.4/26.1($t\bar{t}$)	17.4/26.1($t\bar{t}$)	17.4/26.1($t\bar{t}$)
Quantity of septa group in each subsystem	1	1	2(inj. and ext.)	1
Beam pipe aperture (mm)	56	56	56	56

Physical requirements for DR inj.&ext. system

Parameters	Injection	Extraction
Energy (GeV)	1.1	1.1
Bunch number	2/4	2/4
Min. bunch spacing (ns)	122.5	122.5
Injection /extraction mode	Bunch by bunch	Bunch by bunch
Kicker repetition rate (Hz)	100	100
Kicker pulse width (ns)	< 245	< 245
Kicker rise/fall time (ns)	< 122.5	< 122.5
Timing delay (ns)	< 122.5	< 122.5
Kicker deflection direction	Vertical	Vertical
Kicker deflection angle (mrad)	10.7	10.7
Kick integral field strength (T-m)	0.0392	0.0392
Septa deflection direction	Horizontal	Horizontal
Septa deflection angle (mrad)	120	120
integral field strength of septa (T-m)	0.44	0.44
Septa board thickness (mm)	3.5	3.5

List of the types of inj. & ext. hardware

	Sub-system	Kicker		Septa	
		Kicker Type	Kicker waveform	Septa Type	Stored beam pipe aperture /Thickness of septum
1	DR inj./ext.	Slotted-pipe kicker	Half-sine or trapezoid/245ns	Horizontal in air LMS	ϕ30/3.5mm
2	BST LE inj.	Strip-line kicker	Half-sine/50ns	Horizontal in air LMS	ϕ56/5.5mm
3	BST ext. for CR off-axis inj.	Delay-line dipole kicker	Trapezoid /440-2420ns	Vertical in air LMS	Φ56/6mm
4	CR off-axis inj.	Delay-line NLK kicker	Trapezoid /440-2420ns	Vertical in vacuum LMS	Φ56/2mm&6mm
5	BST ext. for CR on-axis inj.	Ferrite core dipole kicker	Half-sine/1360ns	Vertical in air LMS	Φ56/6mm
6	BST HE inj. for CR on-axis inj.	NLK or Pulsed sextupole	Half-sine/0.333ms	Vertical in air LMS	Φ56/6mm
7	CR swap out inj.	Ferrite core dipole kicker	Half-sine/1360ns	Vertical in air LMS	Φ56/2mm&6mm
8	CR swap out ext.	Ferrite core dipole kicker	Half-sine/1360ns	Vertical in air LMS	Φ56/2mm&6mm
9	CR beam dump	Delay-line dipole kicker	Trapezoid /440-2420ns	Vertical in air LMS	Φ56/6mm
10	BST beam dump	Delay-line dipole kicker	Trapezoid /440-2420ns	Vertical in air LMS	Φ56/6mm

Inj. & ext. system hardware R&D activities

The hardware R&D in IHEP has covered almost all types of inj. and ext. devices for CEPC. Especially for R&D projects that overlap with HEPS, all prototype developments have been completed and some devices have even entered the installation stage. The development difficulty and typical indicators of the prototypes for HEPS are comparable to those of CEPC.

- Lambertson septa magnets
  - In-air type: Septum thickness ≥3.5 mm
  - Half in vacuum type: Septum thickness =2 mm
- Kicker systems
  - Strip-line kicker and super fast pulser（PW=10~50ns）
  - Slotted-pipe kicker and fast pulser（PW=245~300ns）
  - Ferrite core kicker (with metallic coated ceramic vacuum chamber) and pusler
  - Lumped parameter dipole kicker（ half-sine/PW=1.36us）
  - Distributed parameter (delay-line) dipole kicker（ trapezoid/adjustable PW=440~2420ns ）
  - Distributed parameter (delay-line) Nonlinear kicker（ trapezoid/ adjustable PW=440~2420ns ）

Overlapping part between CEPC and HEPS

Overlapping part between CEPC and CSNS

Dedicated for CEPC

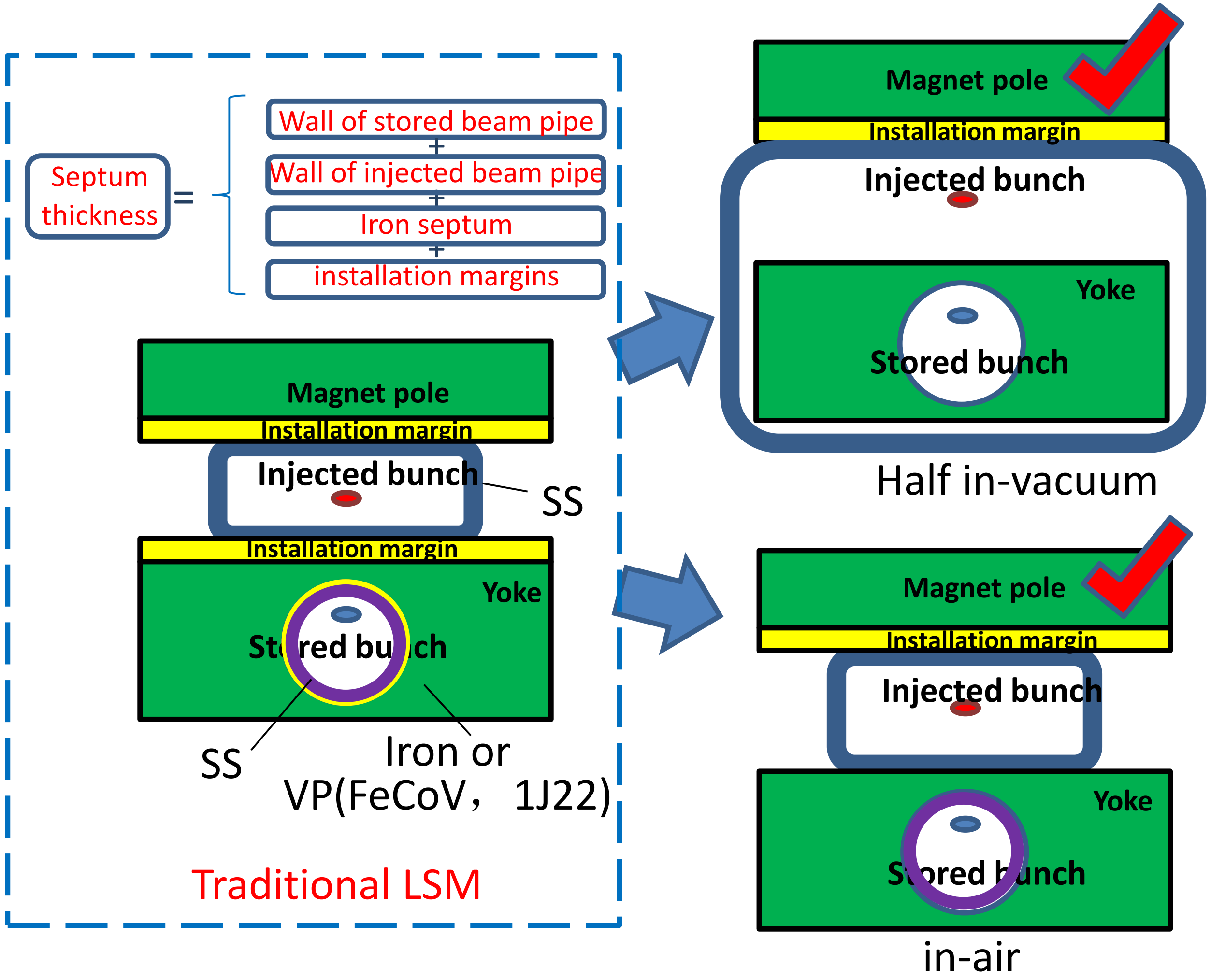
Lambertson magnet

Typical requirements for all CEPC LSMs

Parameters	Unit	DR-LSM	BST-LE-LSM	BST-HE-LSM	CR-LSM-1	CR-LSM-2	HEPS-BST	HEPS-SR
Deflection direction	-	Horizontal	Horizontal	Vertical	Vertical	Vertical	Horizontal	Horizontal
Energy	GeV	1.1	30	120	120	120	0.5/6	6
Total deflection angle	mrad	120	45	43	13	13	200/80	79.5
Total Integral field strength of septa	T-m	0.44	0.92	17.4	5.22	5.22	0.35/1.6	1.6
Deflection angle provided by a magnet	mrad	120	45	3.5	3.5	3.5	200/80	79.5
Insertion length	m	0.5	1.2	1.75	1.75	1.75	0.5/1.6	1.6
Magnetic field strength for injected/extracted beam	T	0.883	0.8	0.8	0.8	0.8	0.7/1	1
Min. septum thickness (incl. septum board, inj./ext. beam pipe wall, installation gap)	mm	3.5	5.5	6	6	2	6/3.5	2
Field uniformity	-	$< \pm 0.02\%$	$< \pm 0.02\%$	$< \pm 0.05\%$	$< \pm 0.05\%$	$< \pm 0.05\%$	$< \pm 0.05\%$	$< \pm 0.05\%$
Integral Leakage field	-	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$
Clearance of stored beam at lambertson (H×V) (w.r.t. stored beam orbit)	mm	30 × 22	30 × 50	30 × 50	-	-	22x28	8x5
Clearance of inj.&ext. beam at lambertson (H×V) (w.r.t. inj. & ext. beam orbit)	mm	22×11	18 × 29	30 × 30	20 x 20	20 x 20	10x10/10x3	6x1.4
Physical aperture of stored beam vacuum chamber	mm	30×30	56 × 56	56 × 56	56 x 56	56 x 56	28x28	8x5
Type	–	In-air	In-air	In-air	In-air	In-vacuum	In-air	In-vacuum

Lambertson Magnet Design Considerations

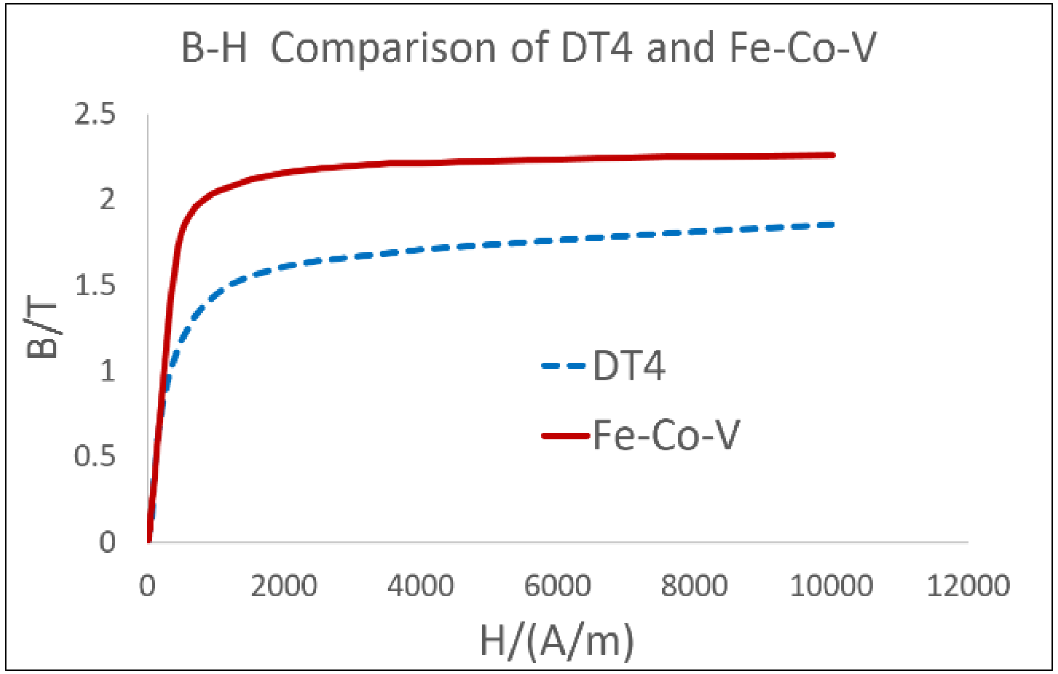
- **To realize thinner septum as possible, 2 novel structures of magnet were proposed:**

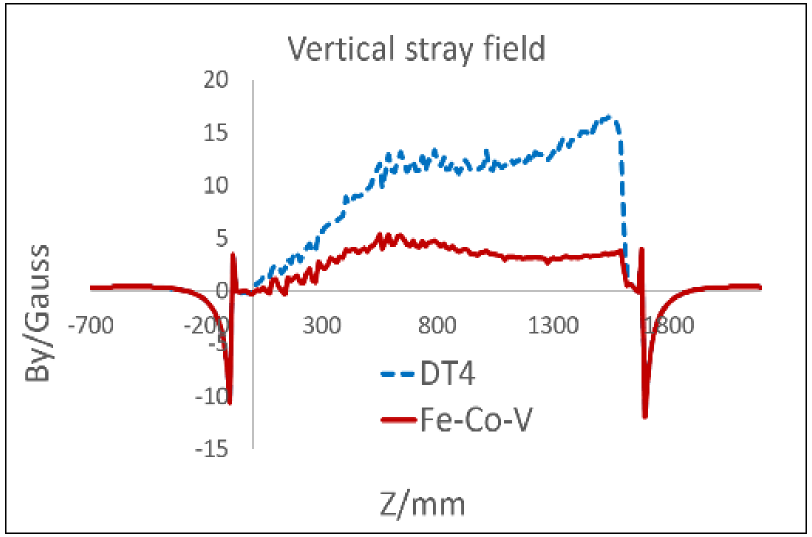


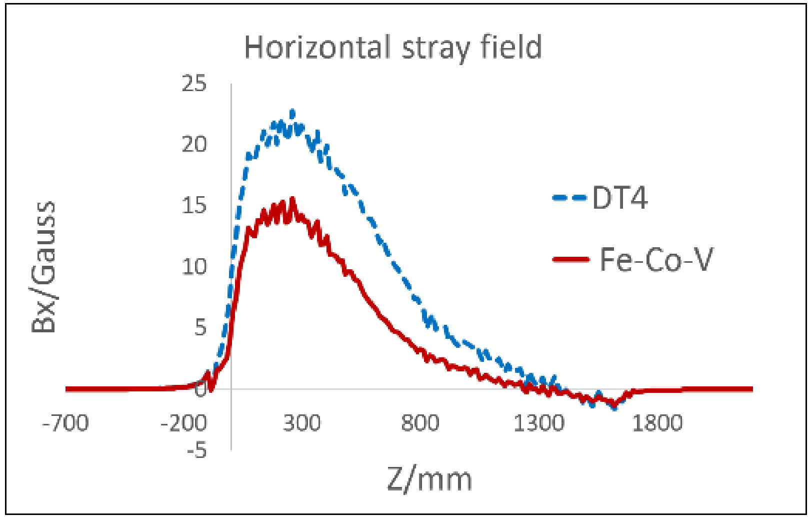
- **half-in-vacuum (for septum of 2mm)**
- **embedded thin-wall vacuum chamber (for septum≥3.5mm)**

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)**

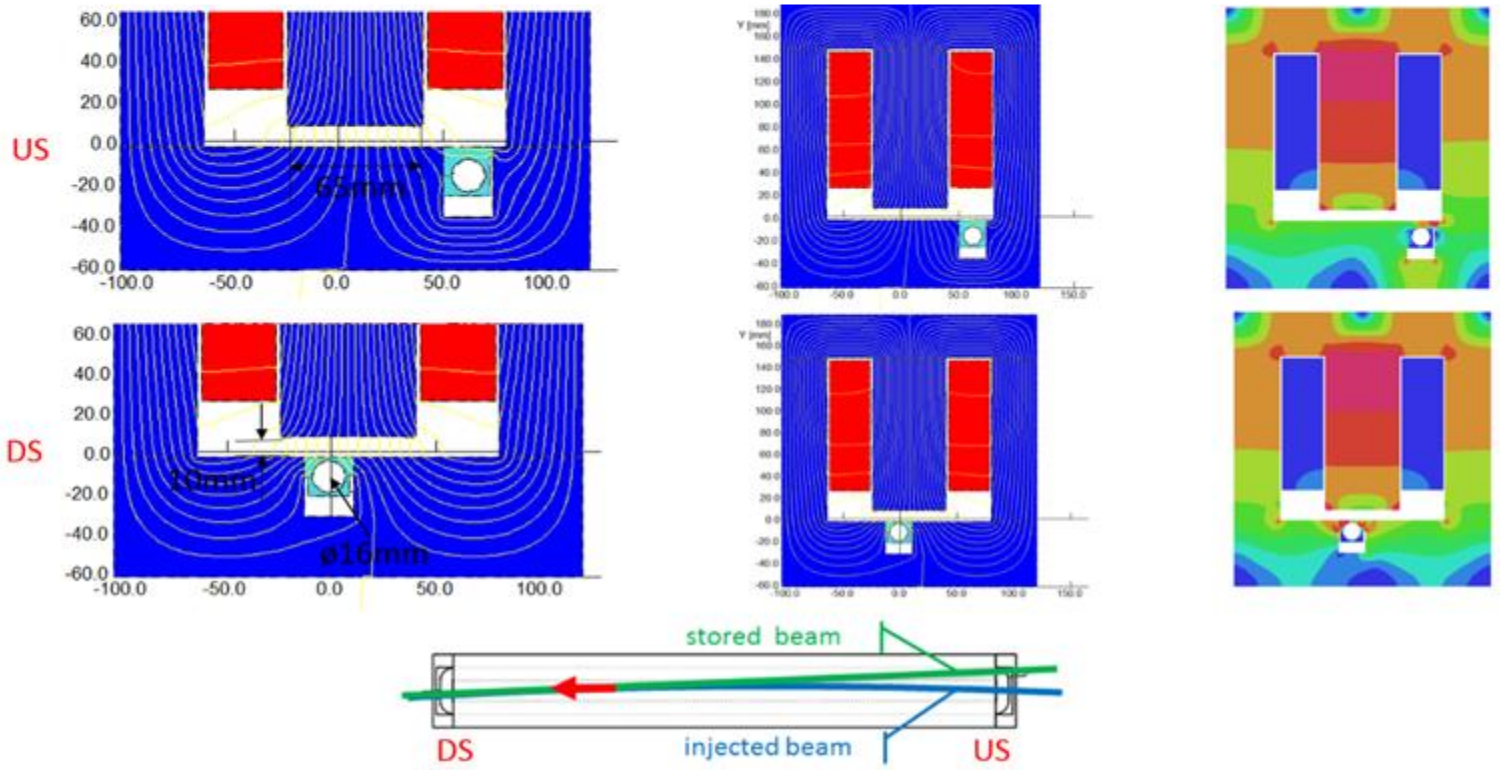


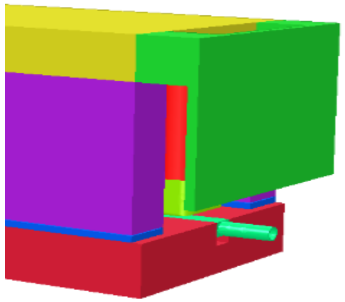


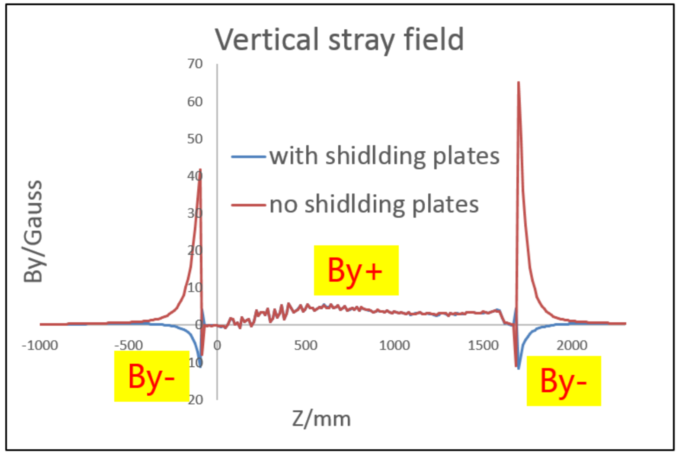


Lambertson Magnet Design Considerations

- 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.
- The transition part and shielding plate design at the end of Lambertson magnet also plays an important role to further reduce the integrate leakage field. 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.

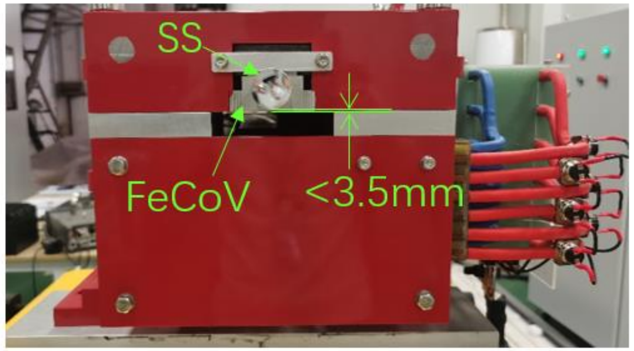


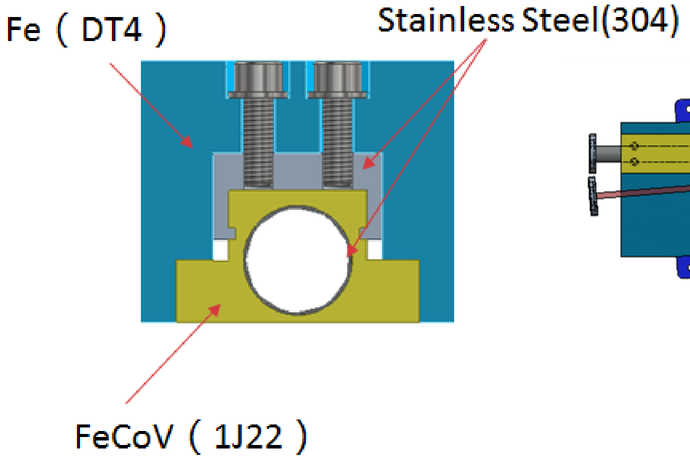


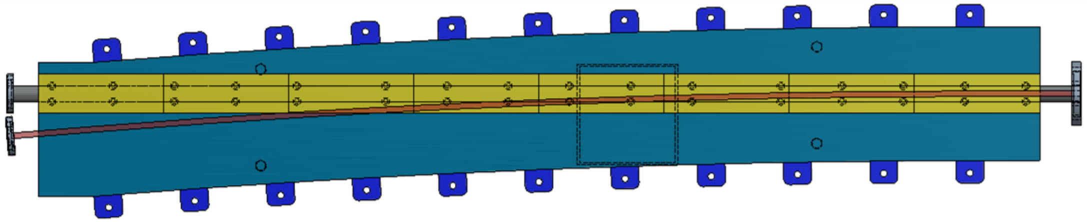


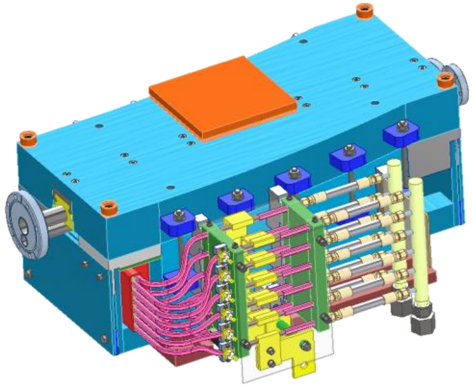
Prototype I：In-air LSM for HEPS BST

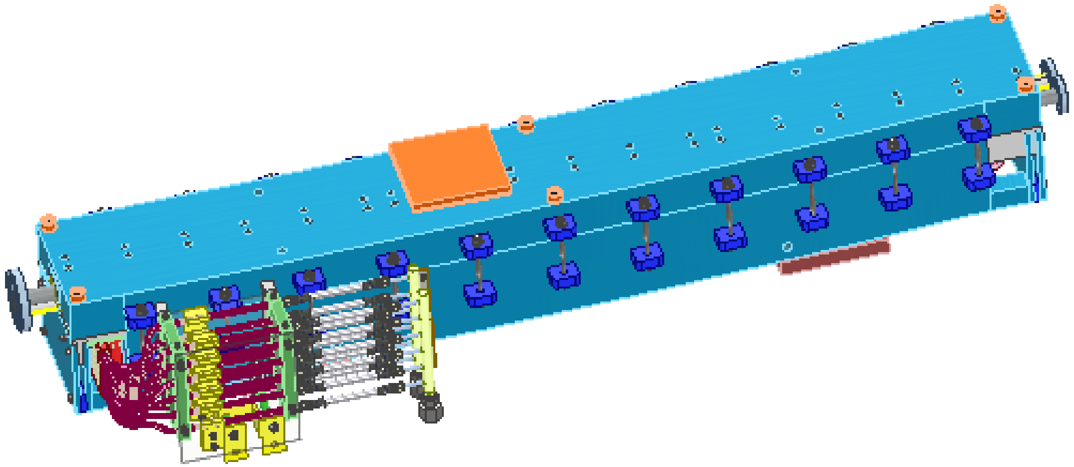
- **Features： magnet is located in the air; total septum thickness=3.5mm（2mm+0.6mm+0.6mm+0.3mm）， Length=1.6m**
- **Because FeCoV（1J22，Co50）is hard to machine, the magnetic shielding blocks must segmented processing by EDM . And that, the embedded thin wall SST vacuum chamber for stored beam is needed.**











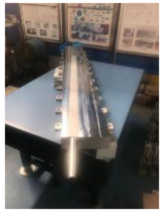
In-air LSM R&D for HEPS BST

2020 — The process testing prototype was completed







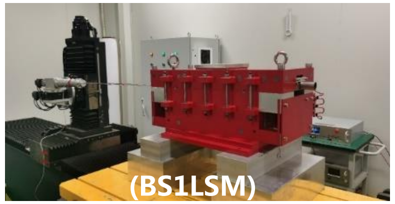



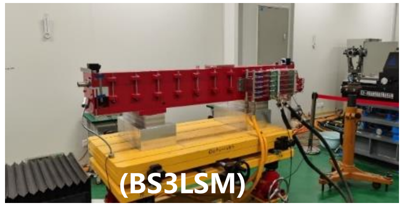
2021 — Formal magnets production

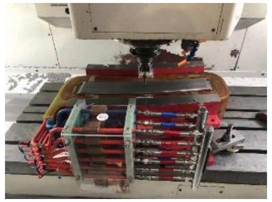



- Field measurement result shows that the gap at the joint of magnetic poles has a great influence on the leakage field and the main field distribution. After repair， the BS1LSM and BS3LSM have pass the second time magnetic field measurement

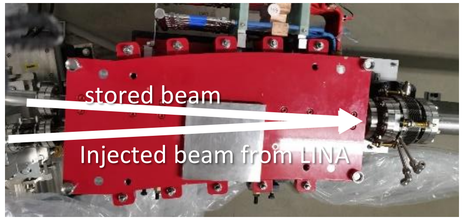
2022 — Magnetic field measurement was finished successfully





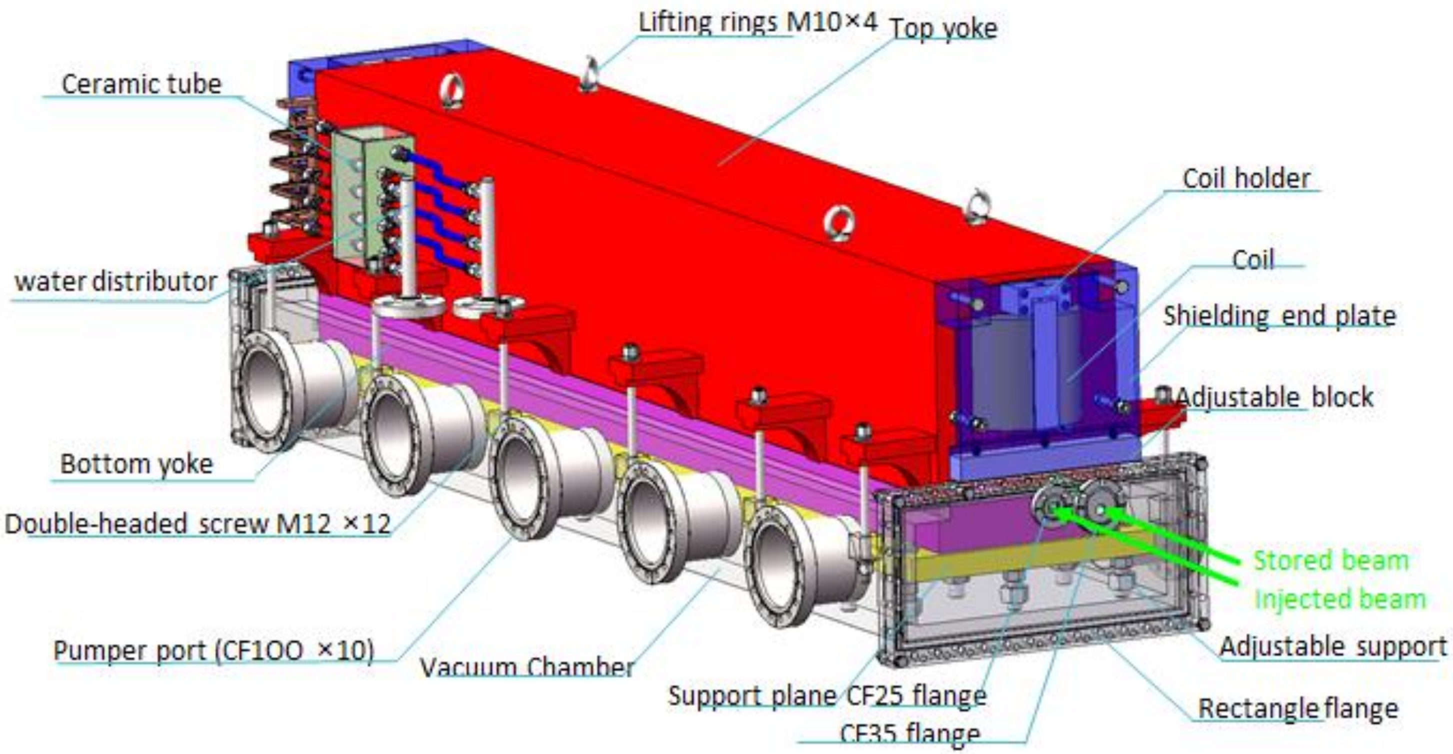



2023 — BS1LSM has been installed into the booster tunnel.BS3LSM and BS4LSM are ready to been installed.

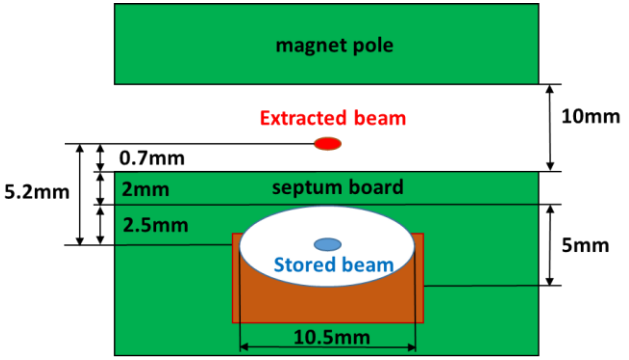


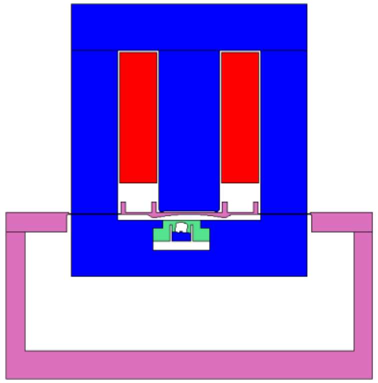
Prototype II： Half in-vacuum LSM for HEPS SR

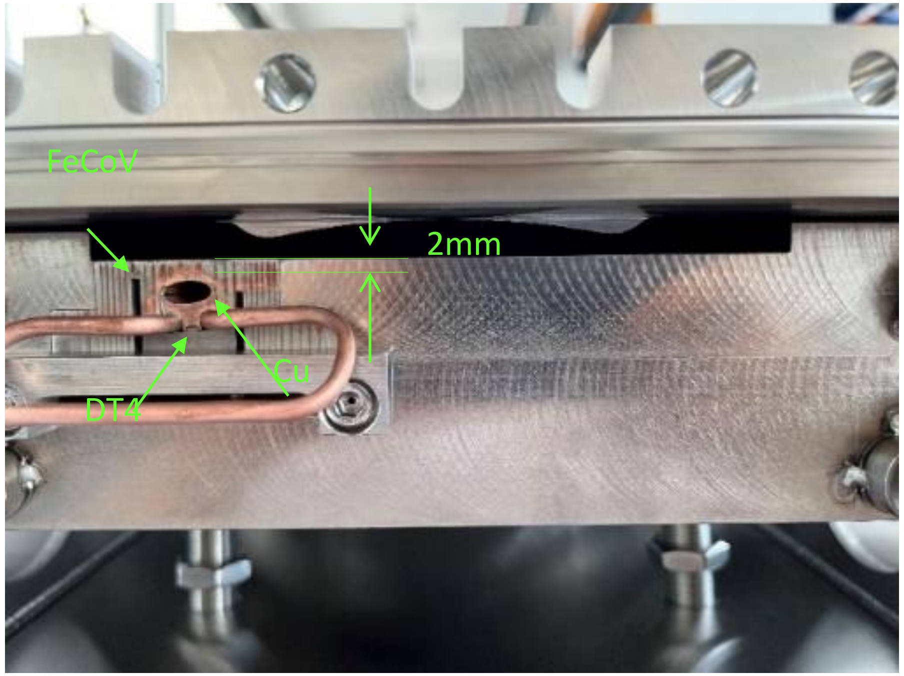
- Features： bottom part of magnet is located in vacuum; total septum thickness=2mm， Length=1.6m



Full-size prototype engineering design





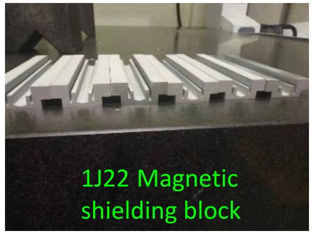


Half in-vacuum LSM R&D for HEPS SR

2021 — Full-size prototype R&D Started based on a ¼ prototype

- 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.

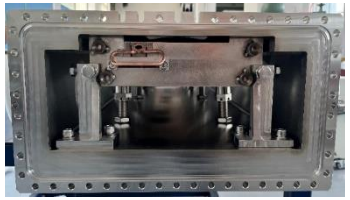
2022.6 — All the mechanical component processing was completed

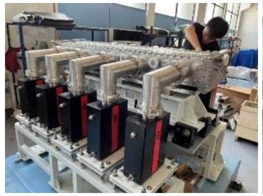


- Limited vacuum pressure: 5.0×10^{-8}pa（vacuum chamber）, 2.2×10^{-7}pa（Transition section）

2022.7 — Final assembling and vacuum testing was completed



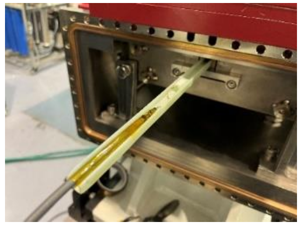


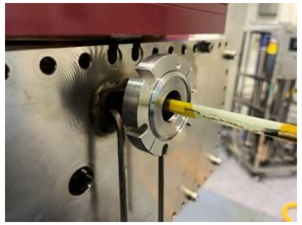
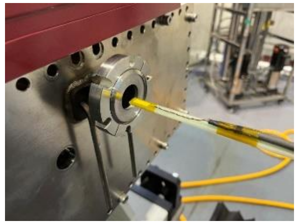




- The magnetic field measurement results are in good agreement with the simulation, meeting HEPS physical requirements.

2023.1 — Magnetic field measurement was finished successfully





Slotted-pipe Kicker system

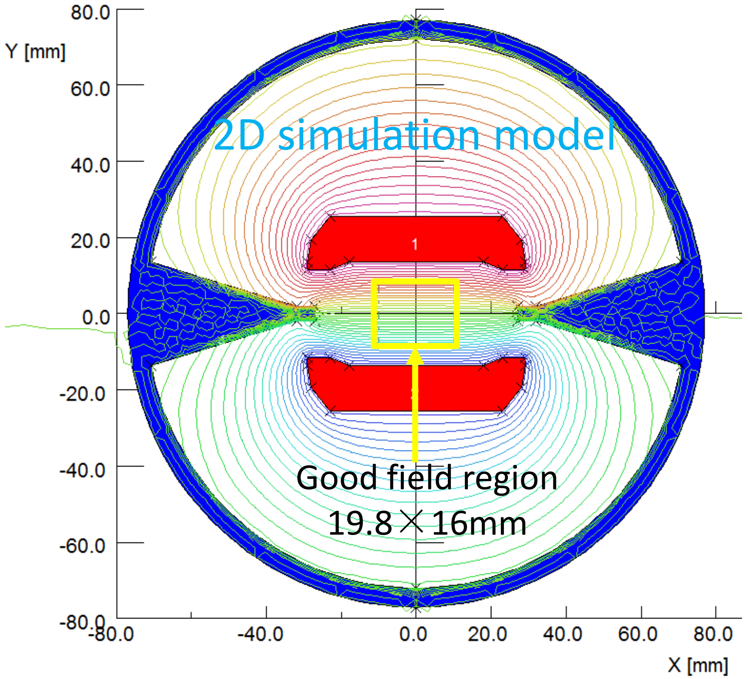
DR inj./ext. kicker design parameters

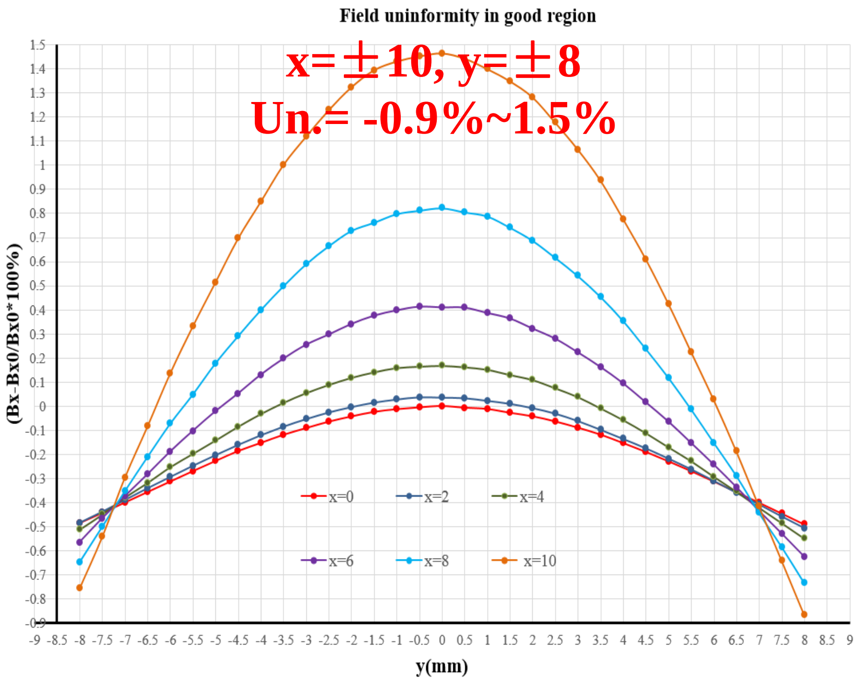
parameter	Unit	DR-kicker	HEPS-BST-kicker
Quantity	-	2	4
Type	-	Slotted-pipe kicker	Slotted-pipe kicker
Deflect direction	-	Vertical	Vertical
Beam Energy	GeV	1.1	0.5/6
Deflect angle	mrad	10.7	9.104/1.75
Magnetic effective length	m	1.4	0.8/1.4
Magnetic strength	T	0.0281	0.02/0.025
Integral magnetic strength	T·m	0.03934	0.016/0.035
Clearance region(H×V)	mm	32.8×26.6	22×28/30×28
Good field region(H×V)	mm	19.8×16	12×16/12×10
Field uniformity in good field region	-	±1.5%	±1%
Repetition rate	Hz	100	50
Amplitude repeatability	-	±0.5%	±0.5%
Pulse jitter	ns	≤5	≤5
Bottom width of pulse(5%-5%)	ns	< 245	< 300

- **The slotted-pipe kicker for CEPC DR is very similar to HEPS booster injection kicker.**

Physics design of Slotted-pipe kicker for CEPC DR

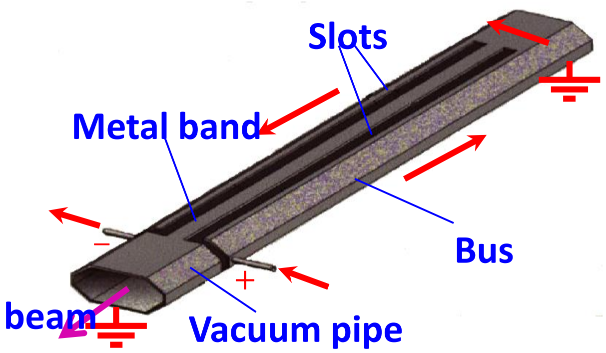
Design parameters	unit	value
Maximum voltage of coil	kV	10.622
Maximum exciting current	kA	2.4
Inductance of magnet coil	nH	387
Good field region（H×V）	mm	19.8×16
Field uniformity	-	-0.9%~1.5%



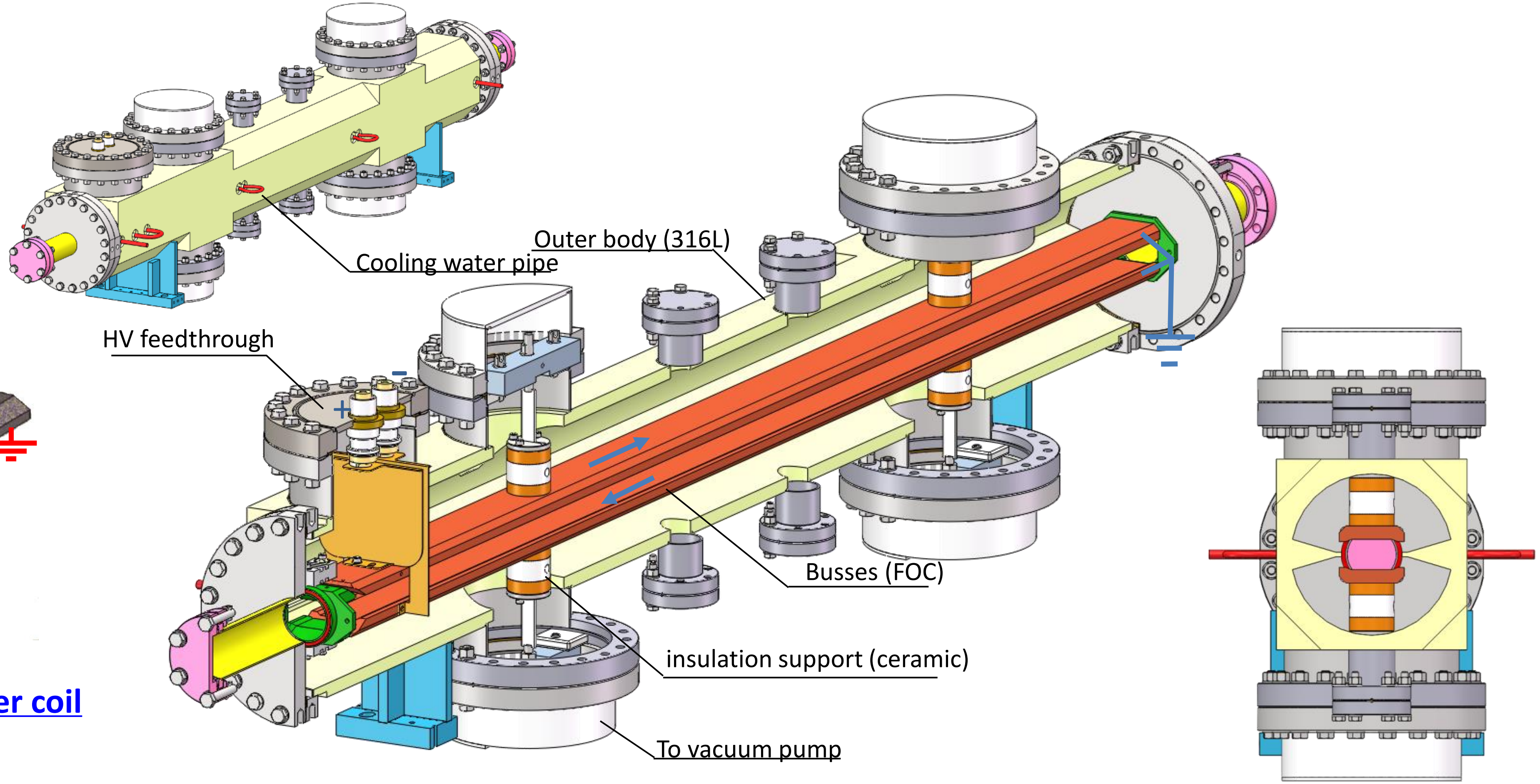


Engineer design of slotted-pipe kicker for CEPC DR

- Features： the both electrodes are electrical connected to the vacuum chamber at up-stream end, which is at ground potential. This feature is good for beam impedance. However, the kicker must be excited by a bipolar pulsed power supply.

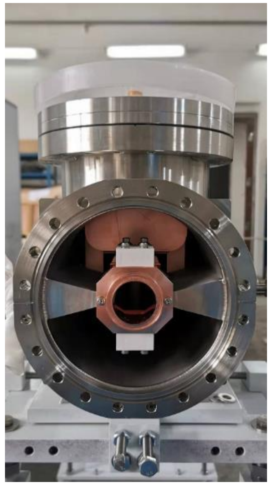


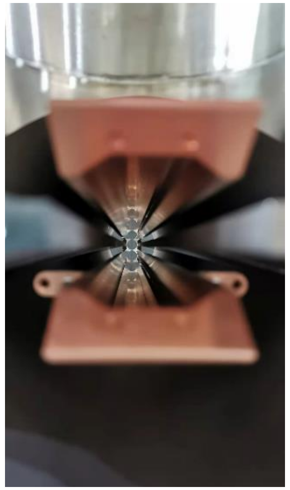
Conventional slotted–pipe kicker coil

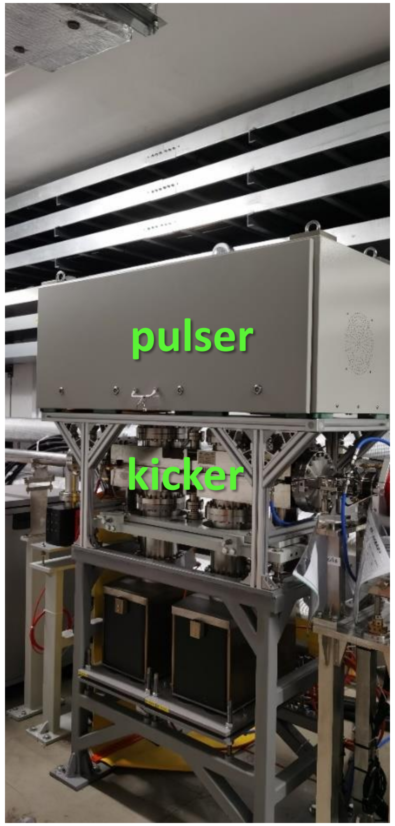


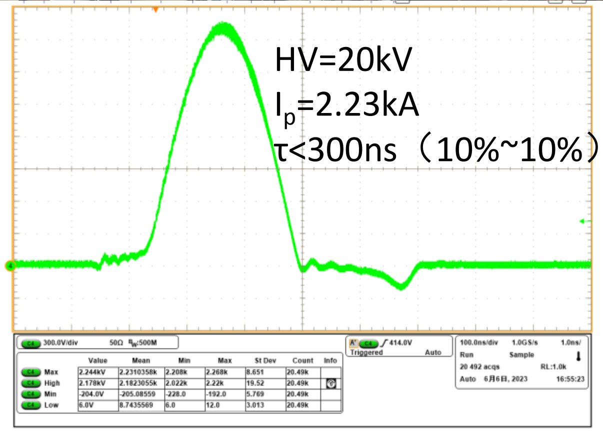
Slotted-pipe kicker R&D for HEPS BST

- All 4 formal kickers have passed vacuum test, magnetic field measurement and been installed into the tunnel.
  - The limit vacuum pressure better than 1.3×10^{-7}Pa.
  - The field distribute performance meet the requirements.
  - The kicker system has been ready for the booster beam commissioning.









Strip-line Kicker system

BST LE inj. kicker design parameters

parameter	Unit	BSTLEIK	HEPS-TF kicker prototype	HEPS-SR-kicker
Quantity	-	2×3	-	2×5
Type	-	Strip-line kicker	Strip-line kicker	Strip-line kicker
Deflect direction	-	Vertical	Vertical	Vertical
Beam Energy	GeV	30	6	6
Deflect angle	mrad	0.11	-	0.32
Length of Strip-line kicker electrode	mm	1000	750	300
Gap between two electrodes	mm	44	10	8
Odd mode impedance	Ω	50±1	50±1	50±1
Even mode impedance	Ω	<65	<65	<65
Clearance region(H×V)	mm	22×44	-	-
Good field region(H×V)	mm	12×22.6	x=±2.3， y= ±1	x=±1.1， y= (-0.85, 2.1)
Integral field uniformity	-	±2.5%	<±1%	<±1%
Amplitude of electrical pulse（into 50Ω）	kV	±12.25	±20	±15
Repetition rate	Hz	100	50	50
Amplitude repeatability	-	<2% (RMS)	<2% (RMS)	<2% (RMS)
Pulse jitter	ns	≤1	≤0.1	≤0.1
Bottom width of electrical pulse（3%-3%）	ns	< 43.3	< 10	< 10

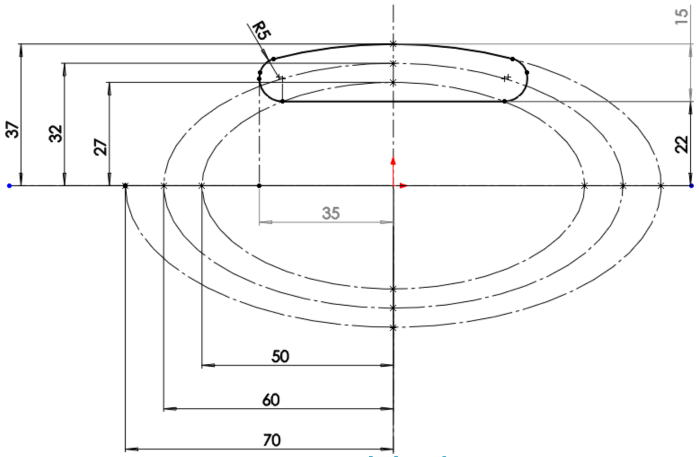
Physics design of Strip-line kicker for CEPC

- To realize injection bunch by bunch(τ=25ns)， the strip-line electrode length=1m， Electrical pulse Width 6.7ns< t_p <43.3ns（Flat-top t_{top} >6.7ns， Rise/fall Time t_r/t_f <18.3ns）
- To achieve highest geometric factor(g=0.9866) the blade width should be w=70mm, when d=44mm. Blade thickness=10mm
- Voltage between blades=24.5kV
- Outer body: distance between vanes=60mm
- Odd mode impedance Z_{odd}=50Ω, even mode impedance Z_{even}=60.5Ω

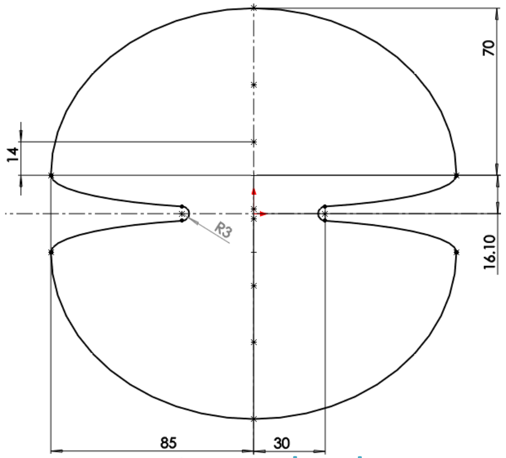
$$\boxed{\begin{cases} l < c\tau/2 \\ 2l/c < t_p < 2\tau - 2l/c \end{cases}}$$

$$\boxed{\theta = \theta_E + \theta_B = 2\theta_E = 2g\frac{eU}{E}\frac{l}{d}}$$

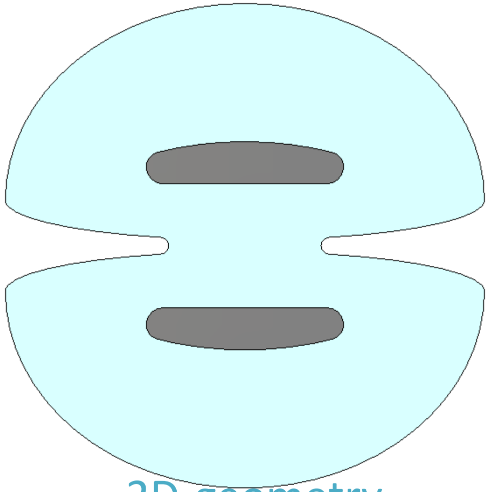
$$\boxed{g = \tanh(\frac{\pi w}{2d})}$$



blade



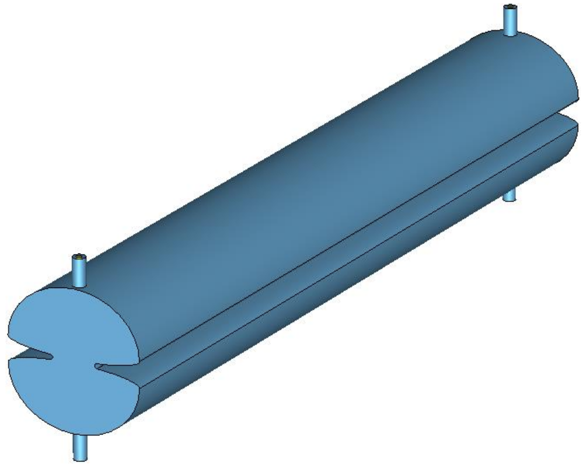
Outer body

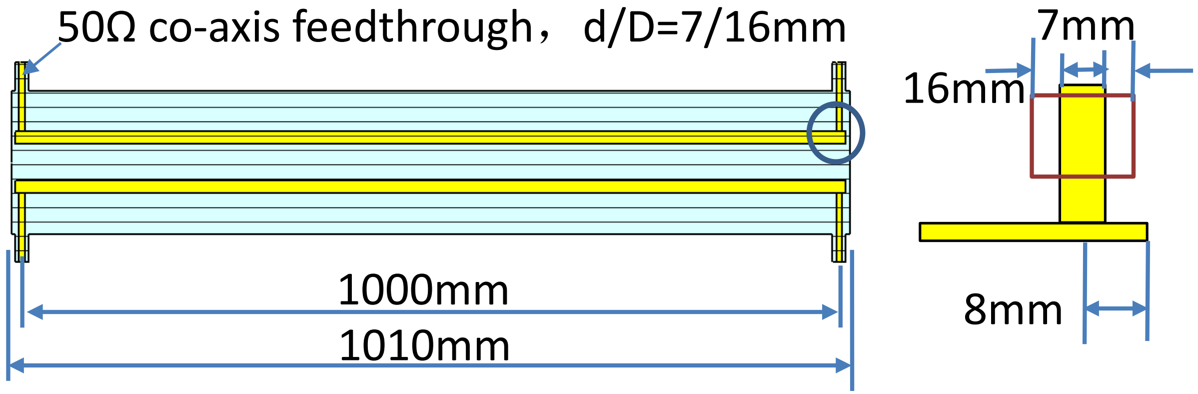


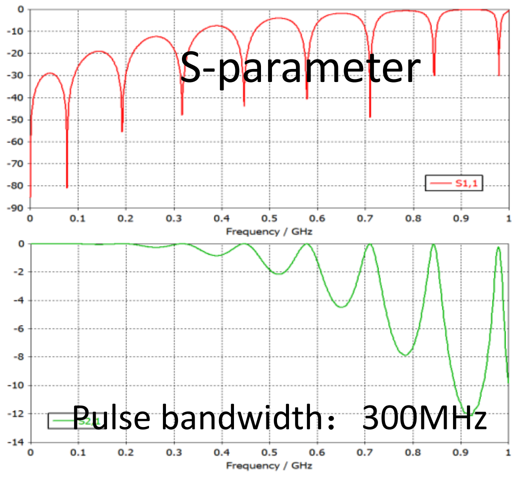
2D-geometry

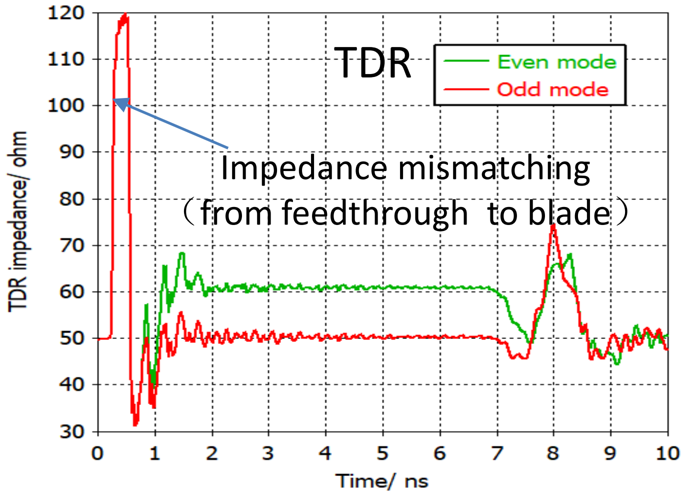
Physics design of Strip-line kicker for CEPC

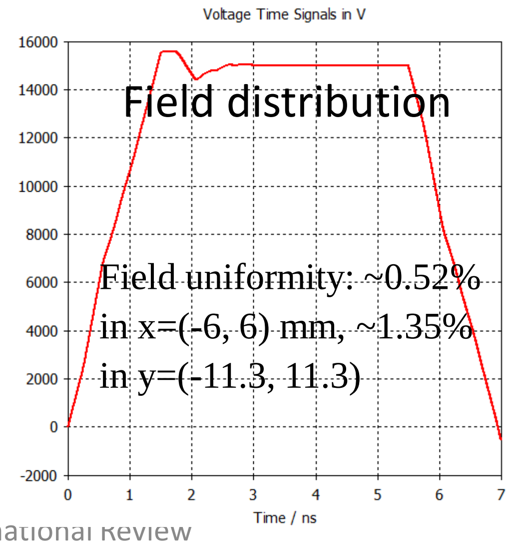
- CST-3D simulation results：

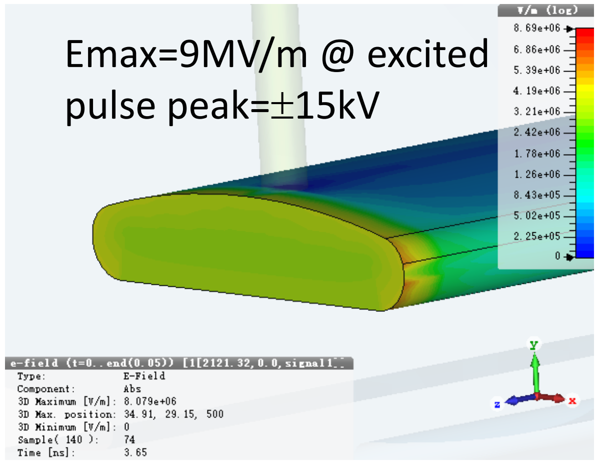




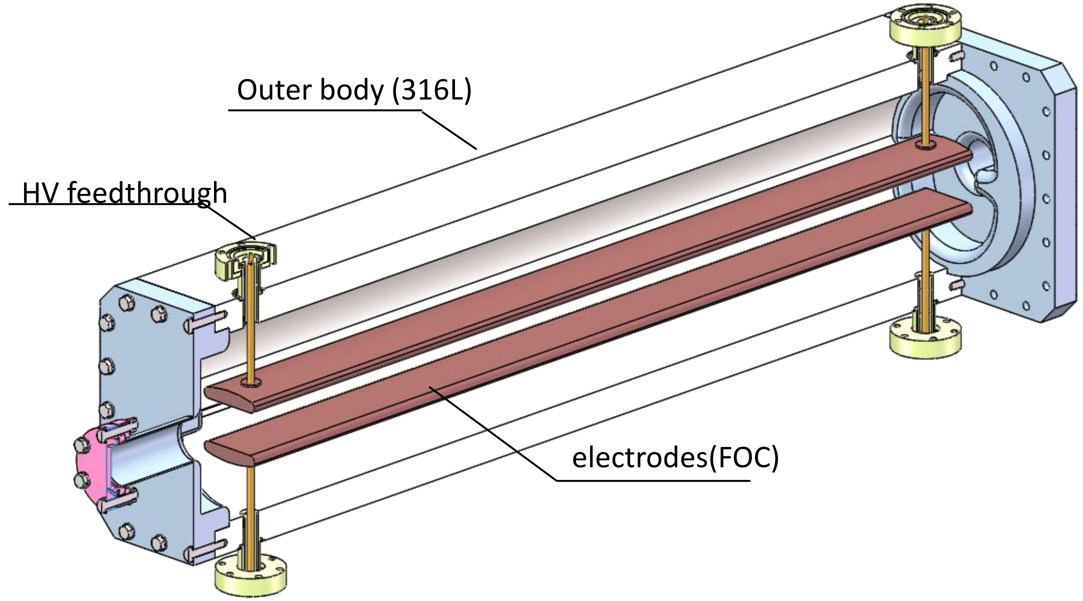


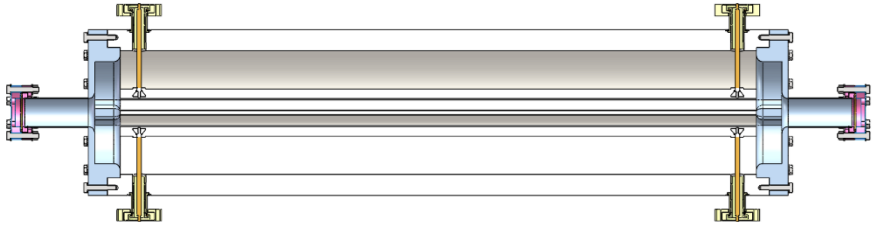


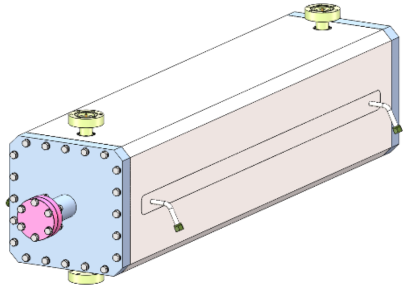


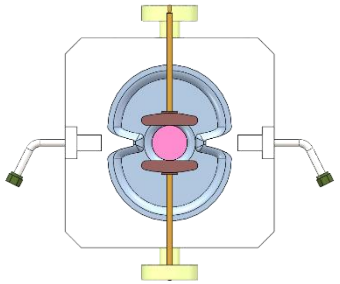


Preliminary engineer design



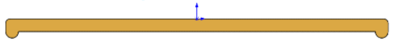






- The thicker blade made from Al is preferred due to smaller weight, stress and deformation. In the baseline design, it does not need a insulation support at the middle of the blades.

Length=1 meter

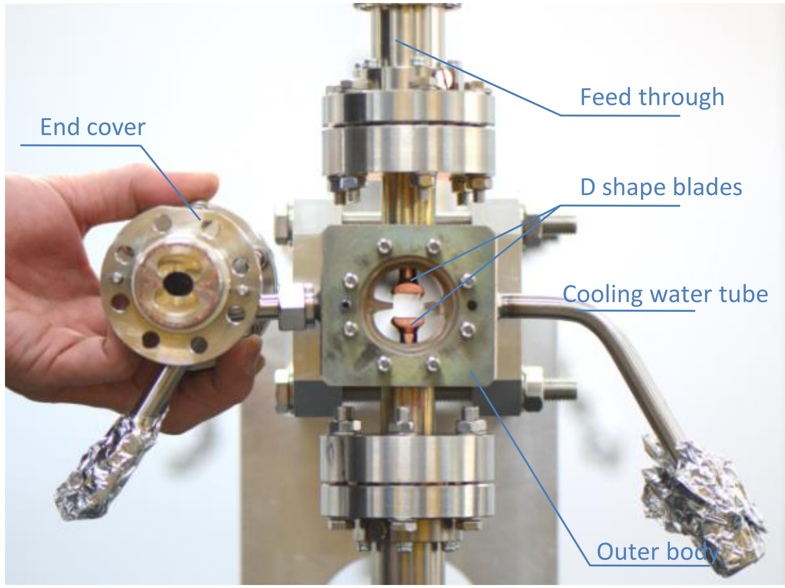


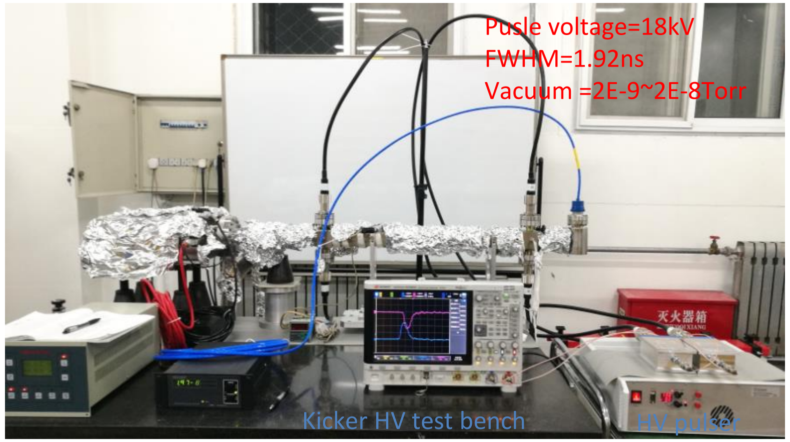
Thin blade

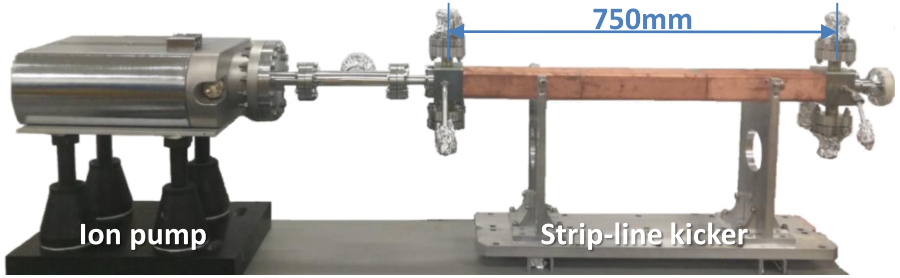
Thick blade

material	SS-316L(7.93g/cm3)			Cu(8.94g/cm3)			Al(2.7g/cm3)		
item	weight	stress	deformation	weight	stress	deformation	weight	stress	deformation
Thin blade	-	17.5MPa	0.995mm	-	19.2MPa	1.97mm	-	5.8MPa	0.961mm
Thick blade	7.27kg	6.4MPa	0.06mm	8.198kg	6.9MPa	0.12mm	2.48kg	2.1MPa	0.06mm

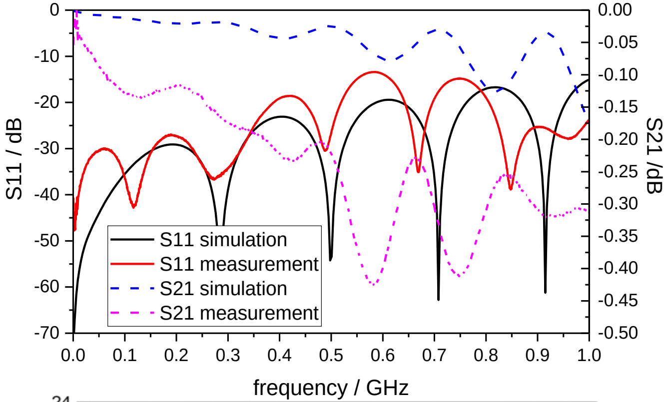
Prototype I: 750mm-long Strip-line Kicker for HEPS-TF

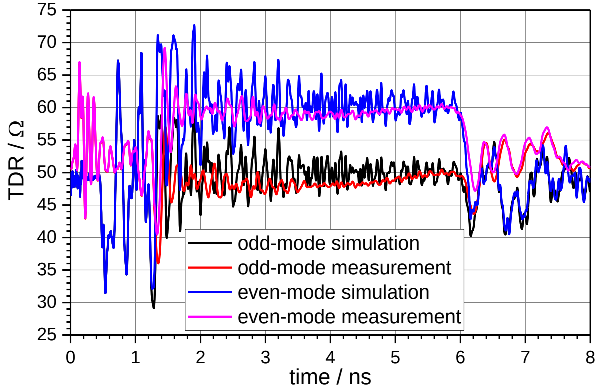


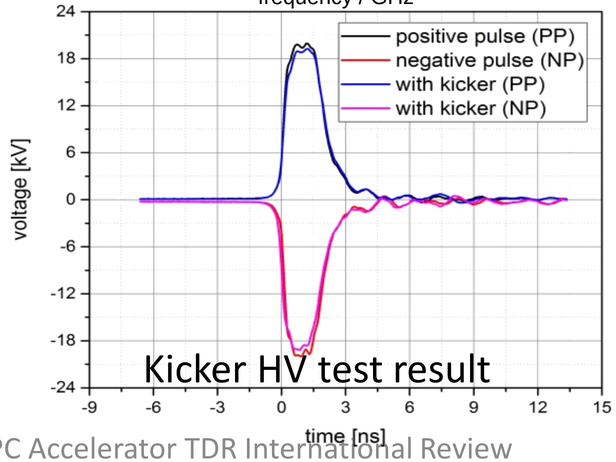




Kicker transmission characteristics test result



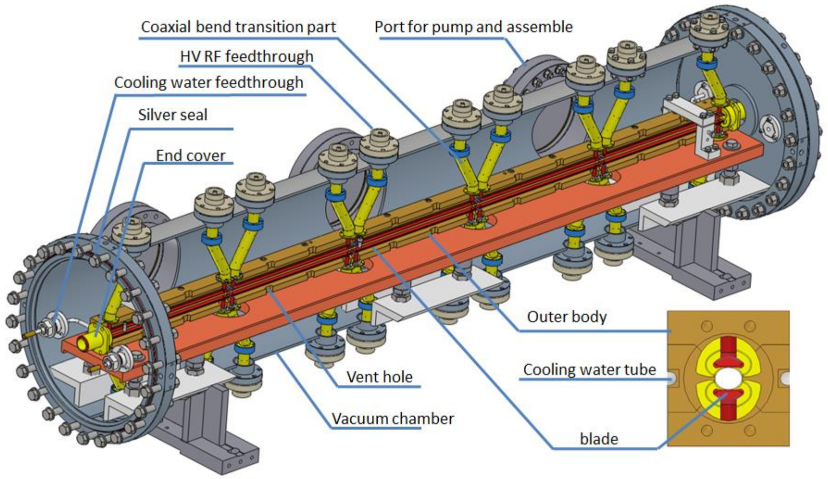


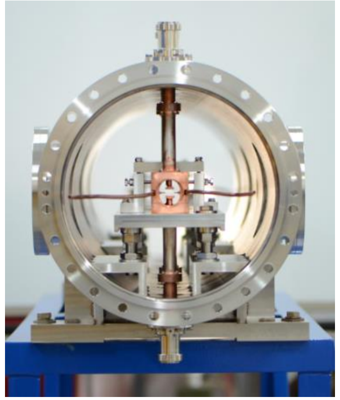


- **Kicker electrical pulse：**
  Rise time（10%-90%）<641ps
  Fall time（90%-10%）<1.5ns
- **pulse edge slowing down due to kicker insertion：**
  Rise time (10%-90%)≈86.6ps
  Fall time (90%-10%) ≈ 35ps

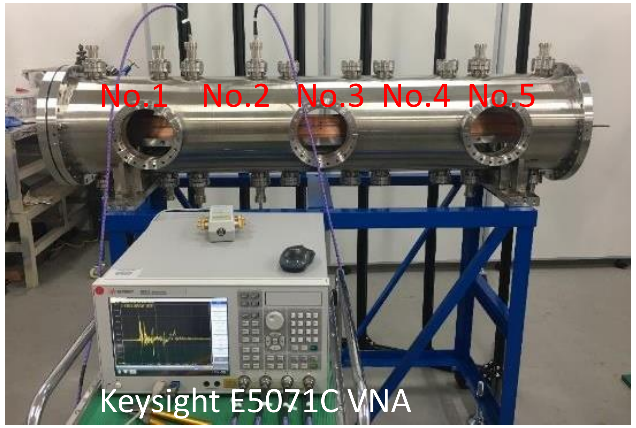
Prototype II: 300mm-long Strip-line Kicker for HEPS

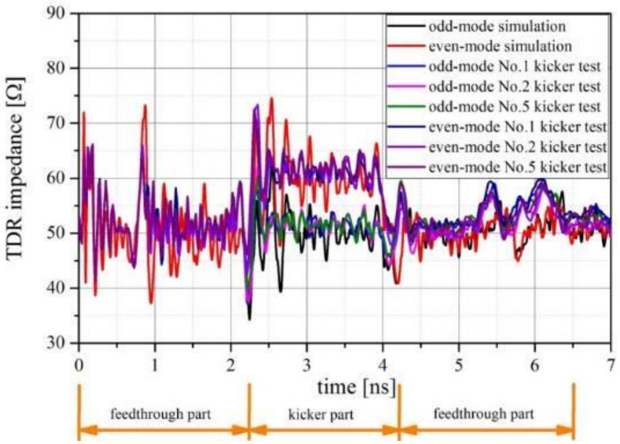
- Feature： 5 sets of 300mm strip-line kicker in a single module to save the straight section space.



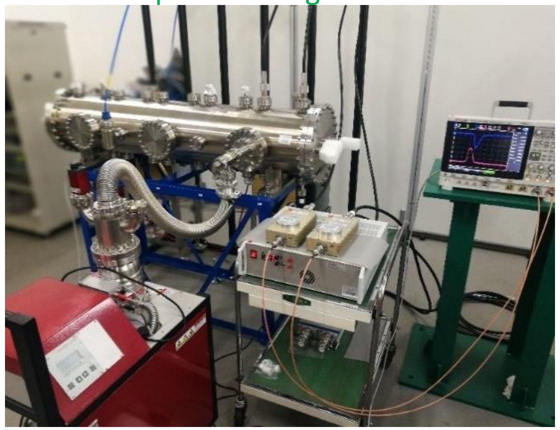


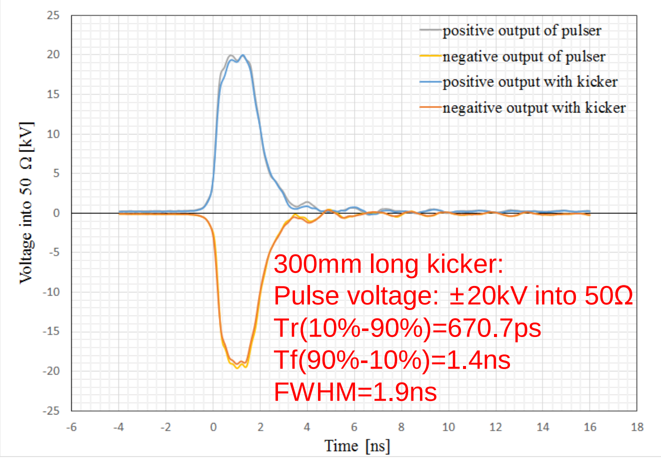
TDR measurement





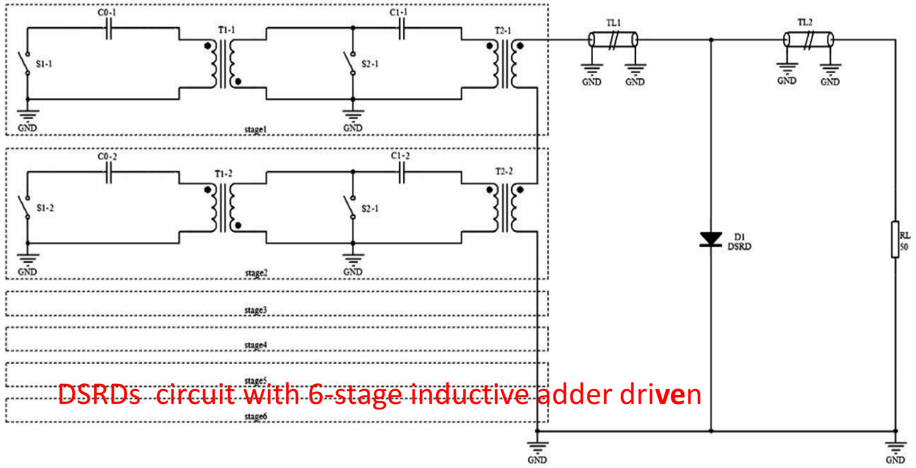
HV pulse testing at ± 20kV



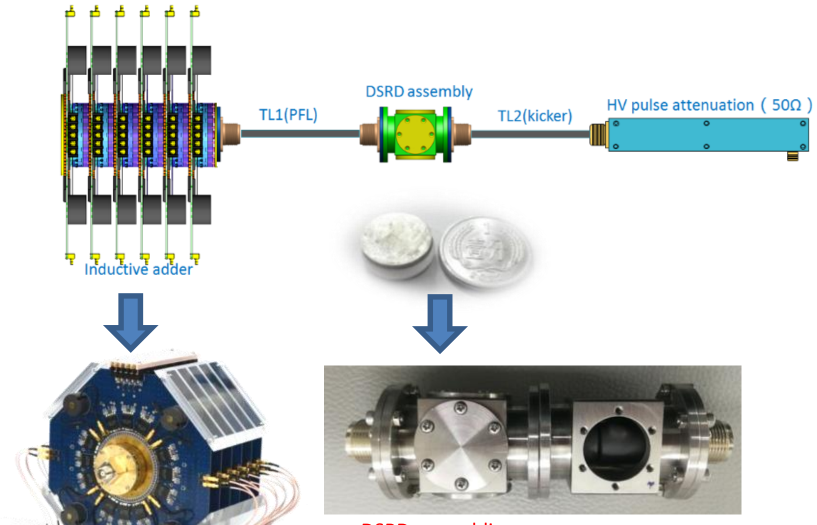


Super-fast pulser R&D

- CEPC kicker pulser requirements: Flat-top t_{top} >6.7ns, Rise/fall Time t_r/t_f <18.3ns.
- Scheme: The pulser is based on DSRDs driven by 6-stage inductive adder; The PFL length is determined as 1 meter for pulse flat-top of 10ns; the typical switching speed of DSRDs is less than 3~4ns.
- DSRD Chips from the Chinese vender are available ($i_p \geqslant 300A$/ V_p=10kV)
- A DSRD pulser prototype were developed for HEPS in house.

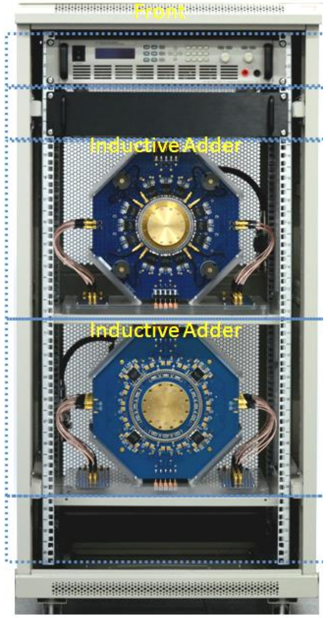


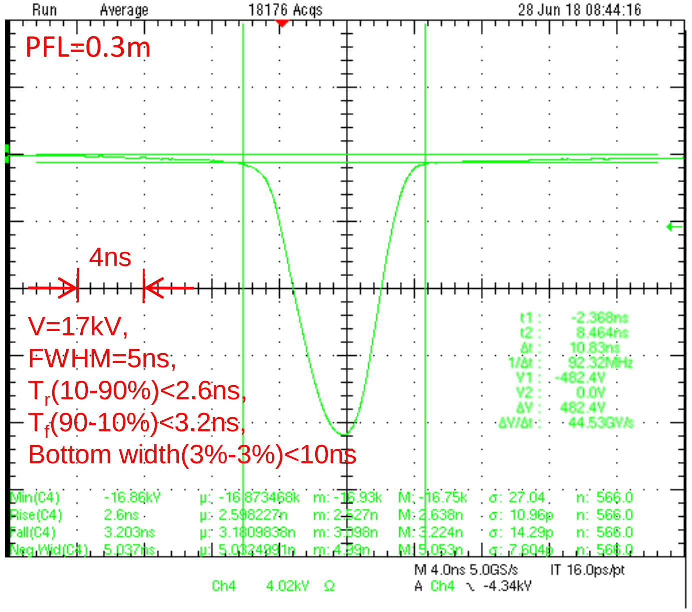
DSRDs circuit with 6-stage inductive adder driven



DSRD assembling（2×4=8pcs）

Saturable inductor（2 DN200L ferrite cores）



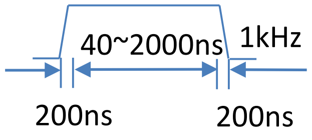


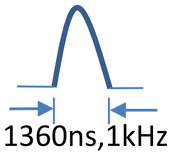
J.H. Chen, Strip-line kicker and fast pulser R&D for the HEPS on-axis injection system, NIMA 920(2019)1-6

Ferrite core kicker magnets

Design parameters of ferrite core kickers for CEPC

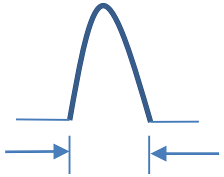
parameter	Unit	BST-EXT-kicker1/CR-inj-kicker1/dump（for CR off-axis inj.）	BST-EXT-kicker2/CR-inj-kicker2（for CR on-axis inj.）
Type	-	In-air delay-line dipole kicker	In-air lumped parameter dipole kicker
Deflect direction	-	Horizontal	Horizontal
Beam Energy	GeV	120	120
Deflect angle	mrad	0.1	0.2
Magnetic effective length	m	1	1+1
Magnetic strength	T	0.04	0.04
Integral magnetic strength	T·m	0.04	0.08
Clearance region(H×V)	mm	56×56	56×56
Good field region(H×V)	mm	50×50	50×50
Field uniformity in good field region	-	±1.5%	±1.5%
Repetition rate	Hz	1k	1k
Amplitude repeatability	-	±0.5%	±0.5%
Pulse jitter	ns	≤5	≤5
Bottom width of pulse(5%-5%)	ns	Trapezoid：440~2420	Half-sine：1360
Tr/Tf(5%-95%)	ns	<200	<680



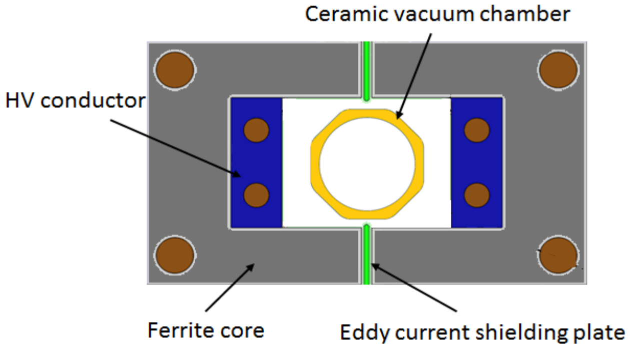


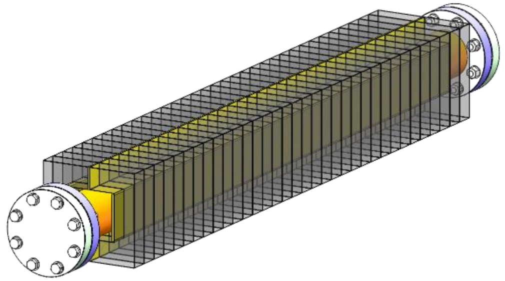
Half-sine wave kicker system

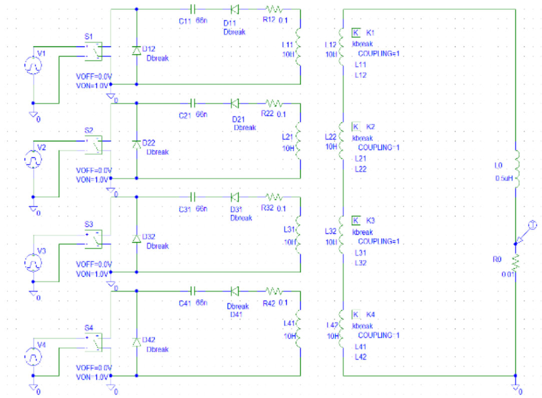
- The kicker magnet with ferrite core is preferred due to its higher exciting efficiency.
- As For 1.3us half-sine wave kicker system, the lumped parameter type kicker is adopted, because of its simpler structure and lower cost.
- To meet the requirement of repetition rate of 1kHz, a novel circuit is proposed. (LC resonance discharge inductive-adder based on IGBT and SiC-SBD)

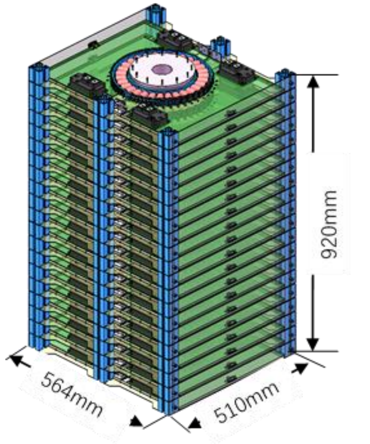


Lumped dipole kicker Parameter	Value
Magnetic field B (T)	0.04
Inner aperture of ceramic vacuum chamber (mm×mm)	56×56
Ceramic vacuum chamber outer aperture (mm×mm)	85×66
Magnet aperture w × h (mm×mm)	100×80
Length of magnet l (m)	1
Inductance of magnet L (μH)	1.6
Magnet exercitation current I (kA)	2.6
Impedance Z (Ω)	3.7
Voltage of magnet U (kV)	9.62
Pules bottom width τ (ns)	1360
Repetition rate（Hz）	1000



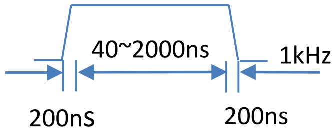


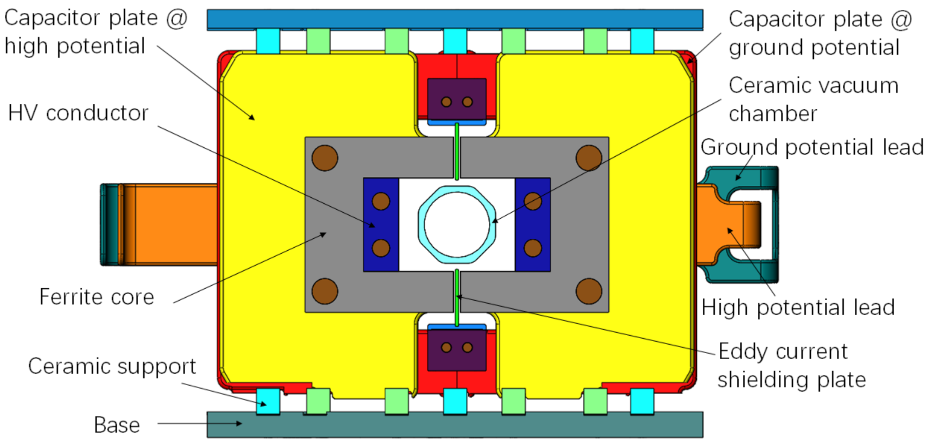




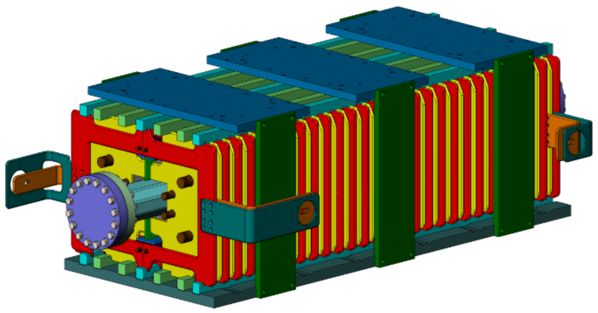
Trapezoid wave kicker system

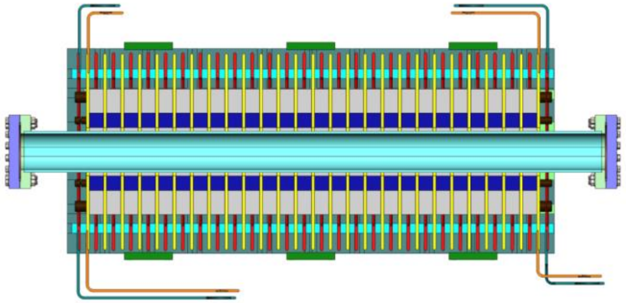
- **For trapezoid kicker system, a delay-line dipole kicker is preferred, because it can helps to achieve ideal trapezoid waveform. While, its structure is complicated.**
- **Dual-C type magnet structure is adopted for CEPC.**





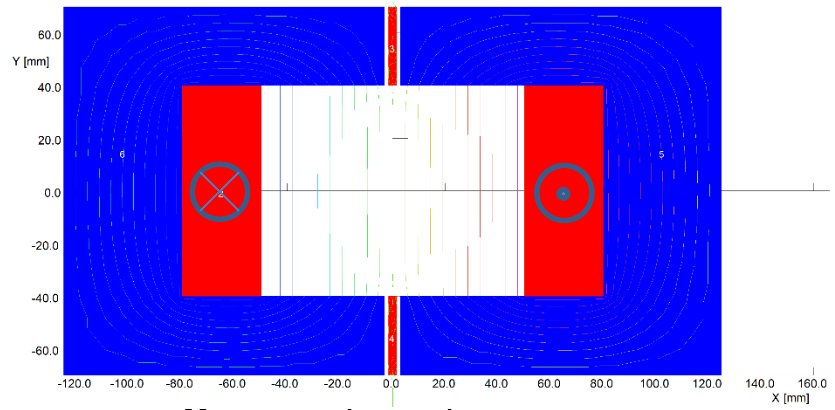
Delay-line dipole kicker Parameter	Value
Aperture of magnet (mm)	100 × 80
Longitudinal length of magnet cell (mm)	36
Cell number of magnet	26
Differential impedance of magnet (Ω)	12.5
Length of magnet (mm)	942
Total mechanical Length of magnet (mm)	1018
Inductance of magnet cell (nH)	56.6
Total inductance of magnet (nH)	1471.6
Capacitance of magnet cell (pF)	362
Total capacitance of magnet (nF)	9.412
Magnetic strength (Gs)	425
Exciting current of magnet (A)	2703
Differential voltage of magnet (V)	33791



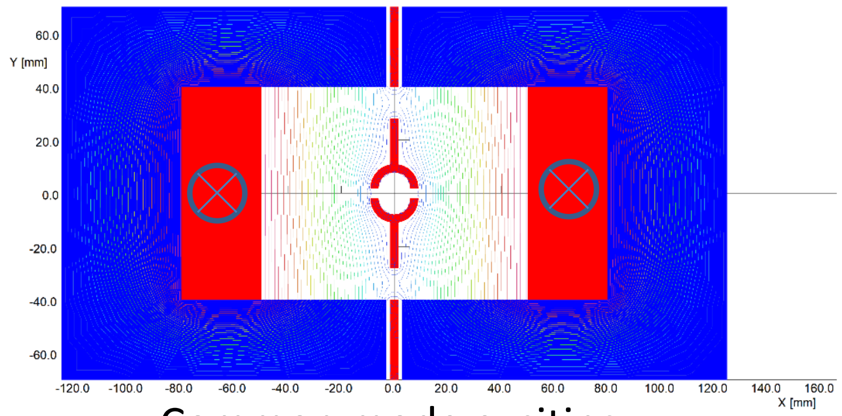


Evolution from dipole kicker to non-linear kicker

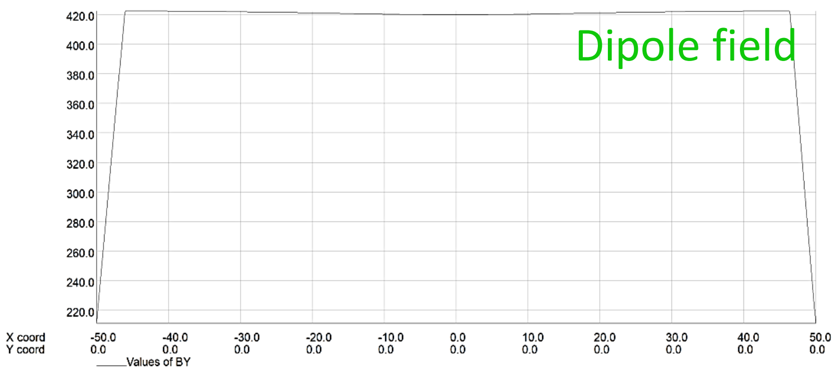
- NLK injection is a potential top-up injection scheme for CEPC, which should loose the requirement of DA.

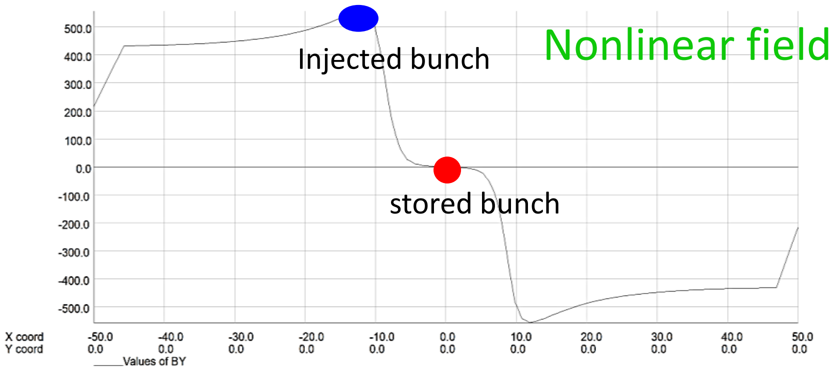


Differential mode exciting



Common mode exciting

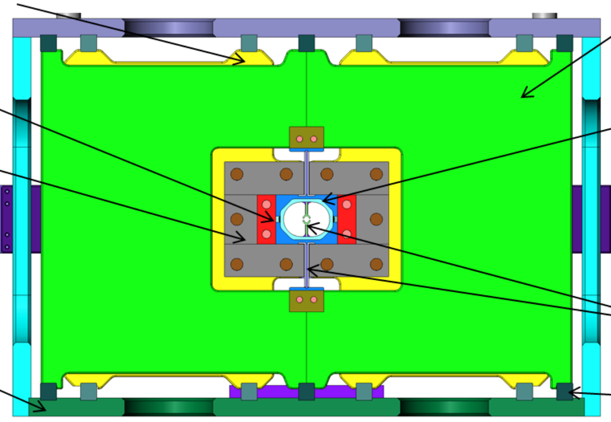


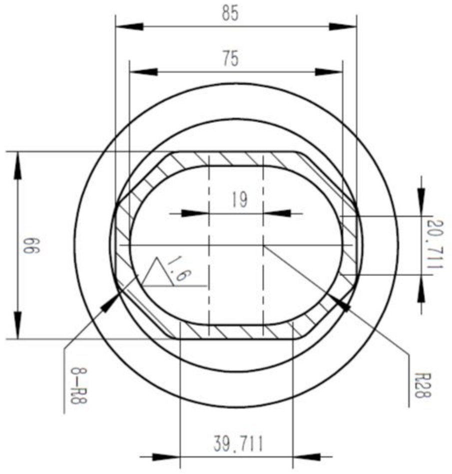


Delay-line NLK Parameter	value
Aperture of magnet (mm)	100×80
Longitudinal length of magnet cell (mm)	34
Cell number of magnet	26
Even mode impedance of magnet (Ω)	10
Length of magnet (mm)	889
Total mechanical Length of magnet (mm)	963
Inductance of magnet cell (nH)	24.1
Total inductance of magnet (nH)	630.1
Capacitance of magnet cell (pF)	241
Total capacitance of magnet (nF)	6.3
Magnetic strength (Gs)	450
Exciting current of magnet (A)	2255
Voltage between HV plate and ground potential plate (V)	22550

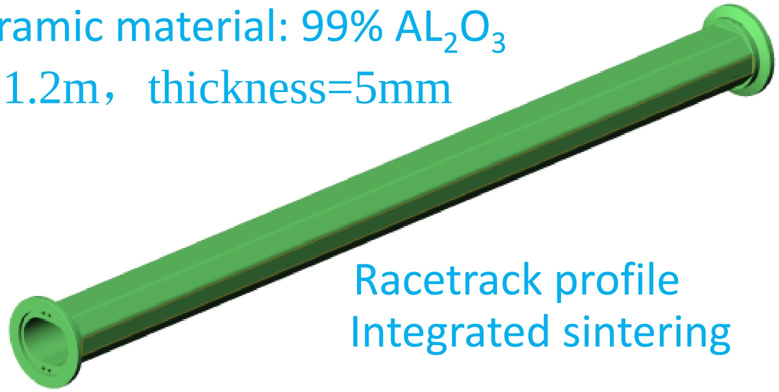
Dual-C type delay-line kicker R&D

- A delay-line kicker system is being developing, including:
    - ceramic vacuum chamber and metallic coating
    - dual-C type delay-line kicker
    - trapezoid wave solid-state pulser
- The R&D project started from 2021, and will be completed in July 2023.

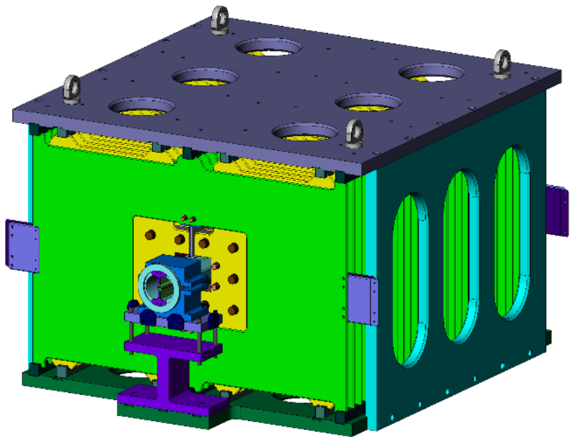


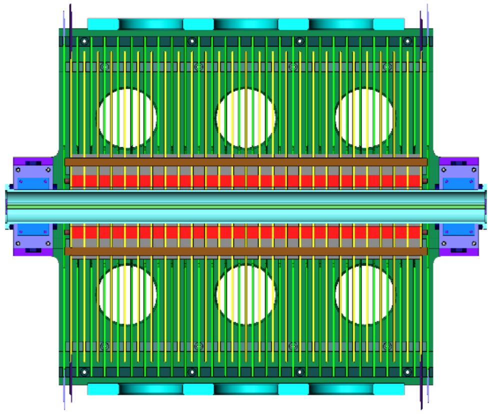


Ceramic material: 99% AL_2O_3
L=1.2m，thickness=5mm



Racetrack profile
Integrated sintering

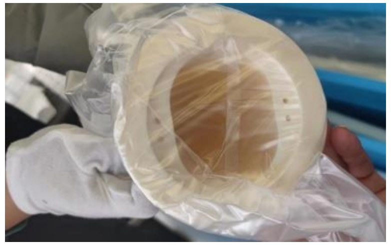
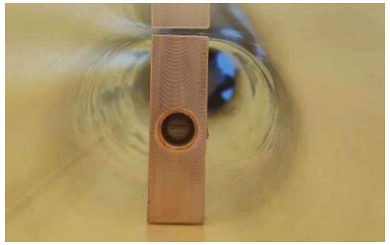




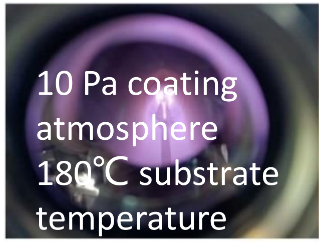
Ceramic vacuum chamber with metallic coating

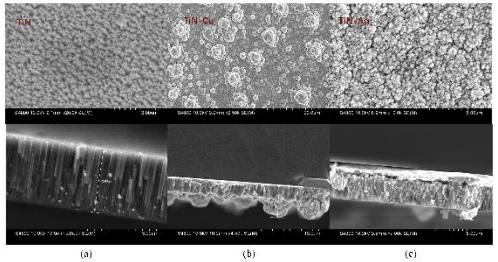
- The ceramic vacuum chamber prototypes have been fabricated by a domestic company.



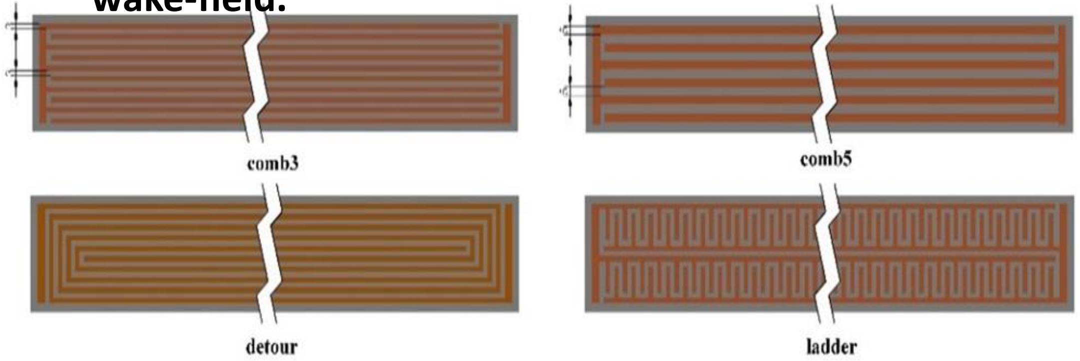



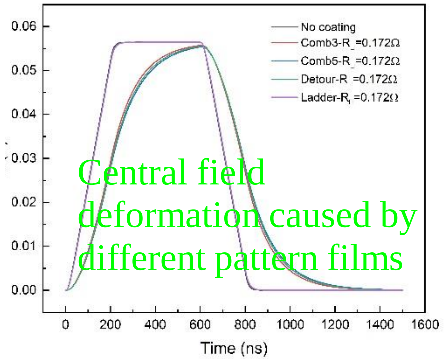
- In house， Magnetron sputter coating is applied to achieve Ti-N-Ag film, which has higher conductivity of 8.3×10^6 S/m.

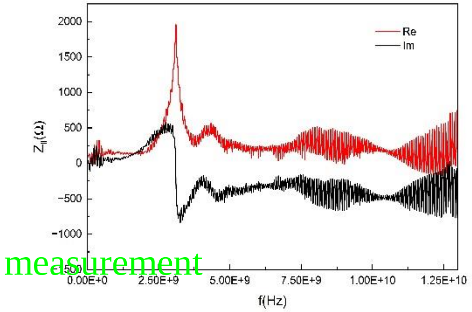


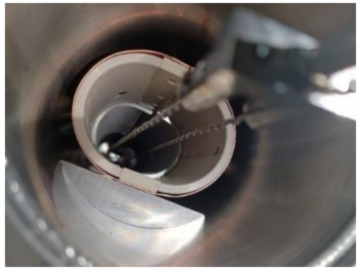
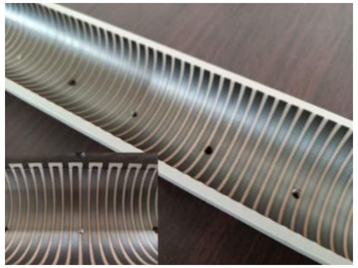



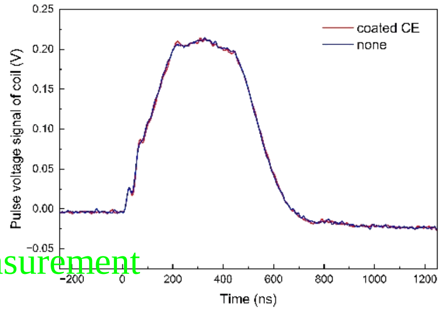
- A discontinous film of ladder pattern was achieved successfully to well balance shielding effective between pulsed B-field and beam wake-field.







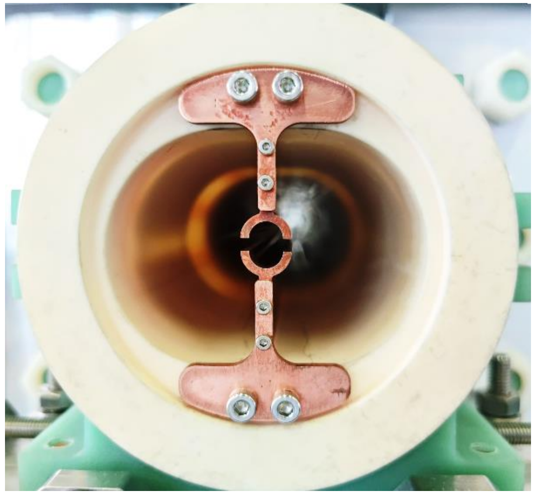
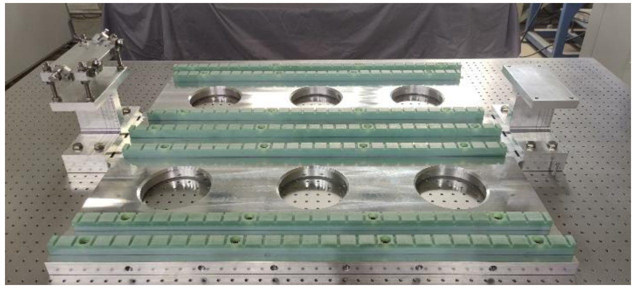
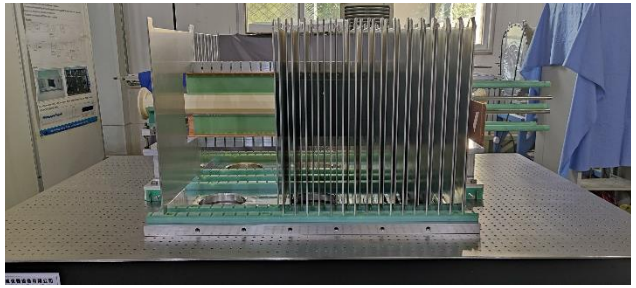
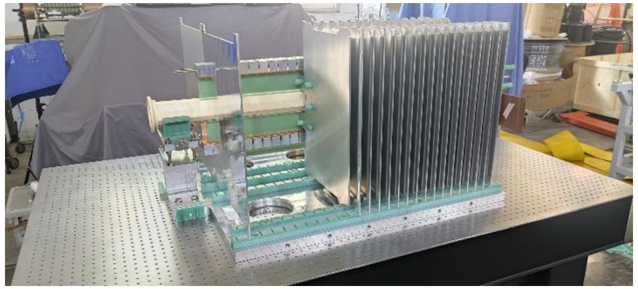
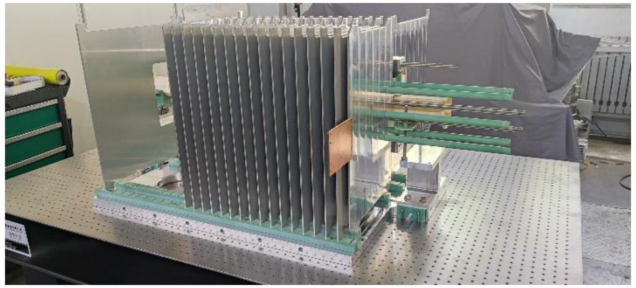


Dual-C type delay-line kicker

Latest progress:

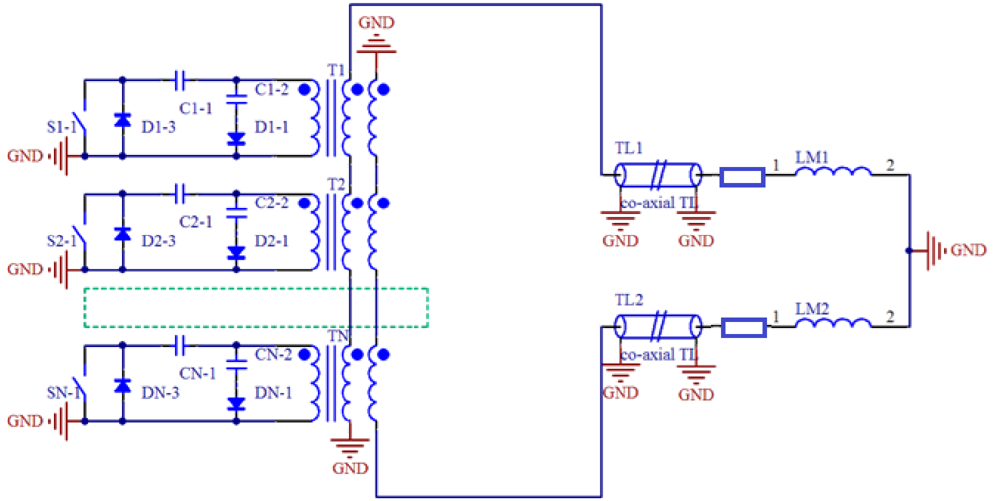
The new developed dual-c type delay-line kicker prototype was delivered from the factory , is being re-assembled at IHEP, and planed to be integrated with the pulser for magnetic field measurement.



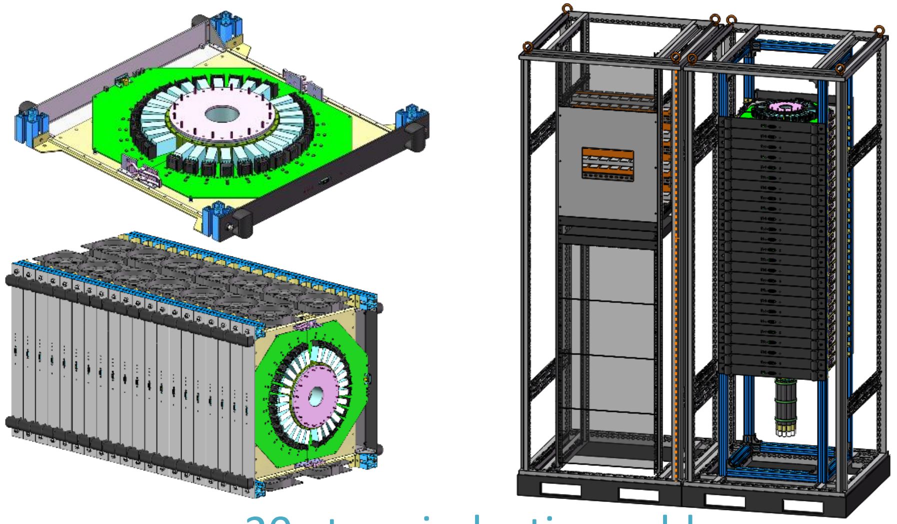







Solid-state fast kicker pulser R&D in house

- The requirements of CEPC kicker pulser：Tr/Tf(5%-5%)≤80ns
- 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.



Trapezoidal wave Pulser design Parameter	Dipole kicker	NLK
Magnet type	Dual-C delay-line	Dual-C delay-line
Aperture of magnet (mm)	100×80	100×80
Characteristic impedance of magnet (Ω)	6.25（odd mode）	10（even mode）
Exciting current (A)	2703	2255
Voltage of magnet (V)	+/-16895.5	+/+22550
Exciting mode	Differential mode	Common mode
Pulse waveform	Trapezoid	Trapezoid
Rise/fall time (ns)	200	200
Flat-top width of pulse (ns)	40~2000 adjustable	40~2000 adjustable
Filling time of magnet (ns)	117.728	63.01
Rise/fall time of pulser (ns)	80	80
Repetition rate (kHz)	1	1

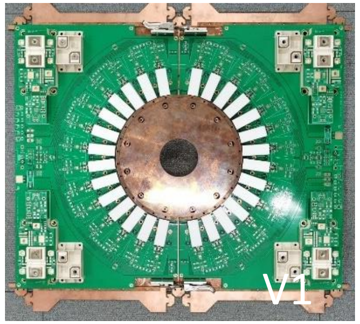


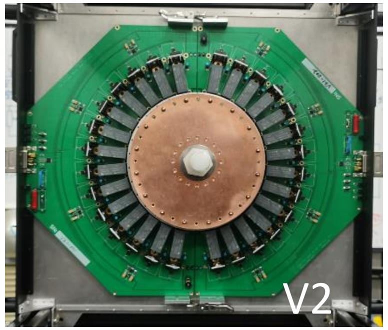
20-stage inductive adder

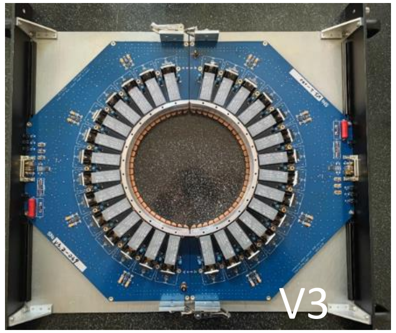
Solid-state pulser prototype

R&D status

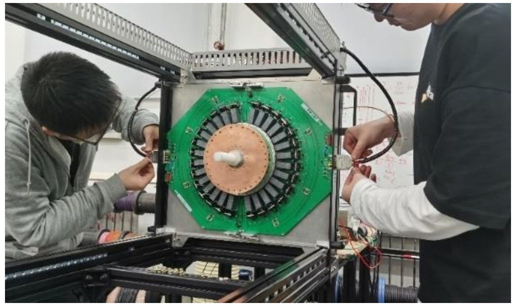
- Circuit and PCB design iteration

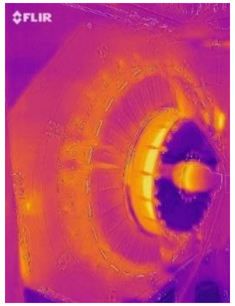


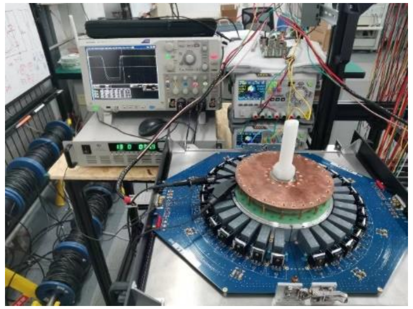


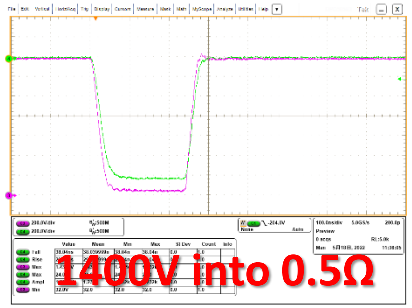


- Single stage full power test has been completed （1400V into 0.5Ω）

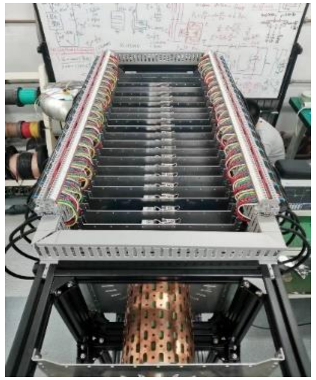


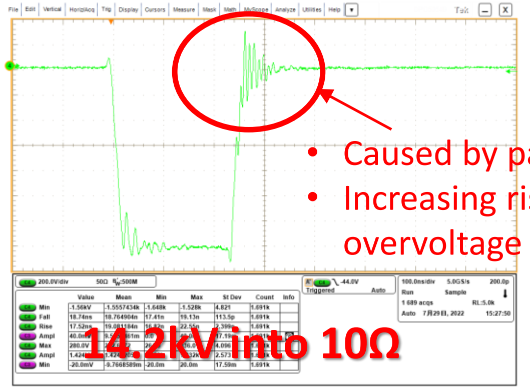






- Gradual stacking test (1→2→5→10→15→18 stages).
  18-stage adder output pulse voltage = 14.2kV into 10Ω @ DC HV=800V.





- Caused by parasitic inductance
- Increasing risk of MOSFET overvoltage breakdown

Summary

- The overview of CEPC injection & extraction system and its physical requirements were introduced.
- The types of all inj./ext. components are determined in the CEPC TDR. The hardware R&D in IHEP has covered almost all types of inj. and ext. devices for CEPC.
- For R&D projects that overlap with HEPS, including Lambertson magnet, slotted-pipe kicker and strip-line kicker, all prototype developments have been completed and some devices have even entered the installation stage. The development difficulty and typical indicators of the prototype for HEPS are comparable to those of CEPC.
- The trapezoidal wave kicker system R&D dedicated for CEPC is near the end. The full-size ceramic vacuum chamber and TiN-Ag film with ladder pattern has been achieved successfully. The delay-line kicker magnet prototype is going to be integrated with the solid-state pulser prototype for field measurement.

END

Thank you for attentions!

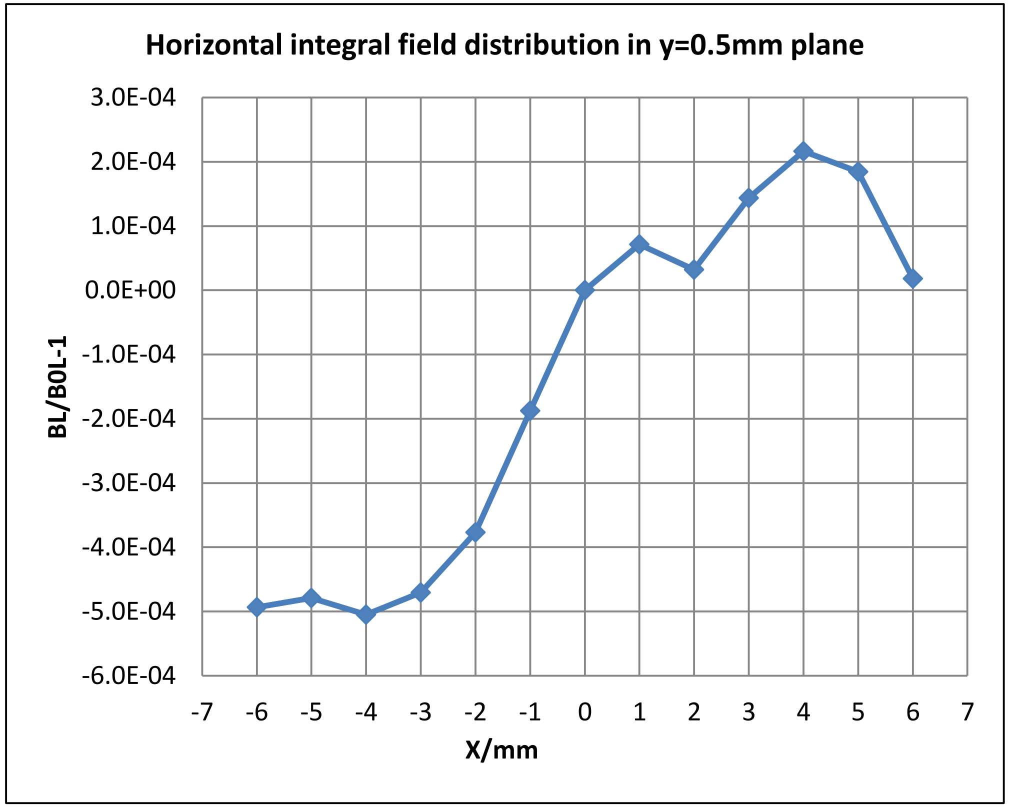
Backup slides

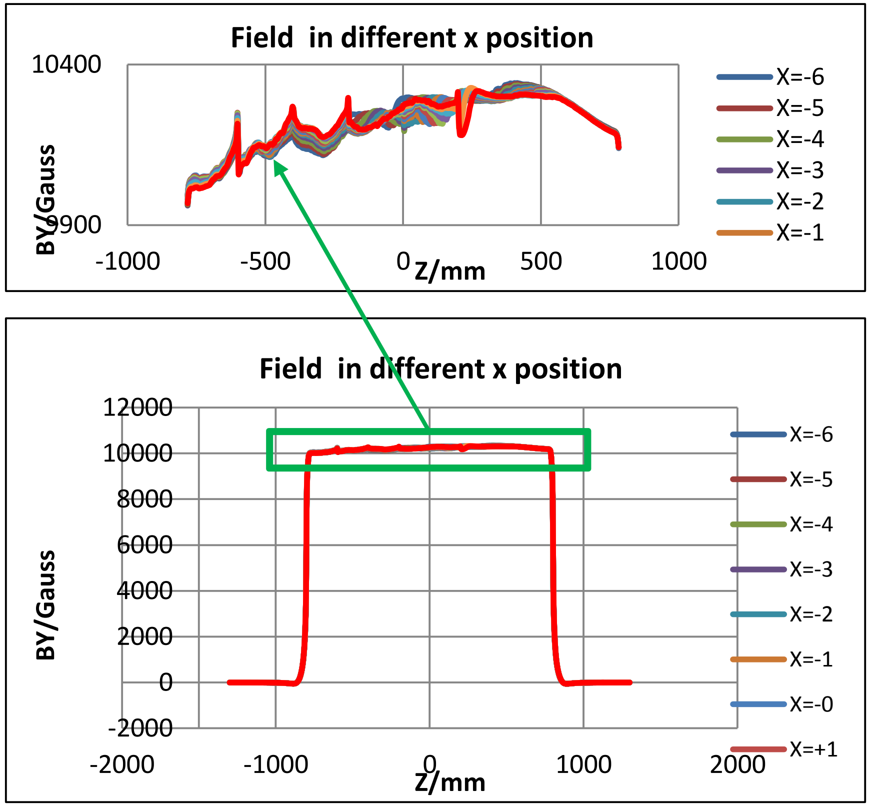
In-vacuum Lambertson

Main field distribution measurement

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

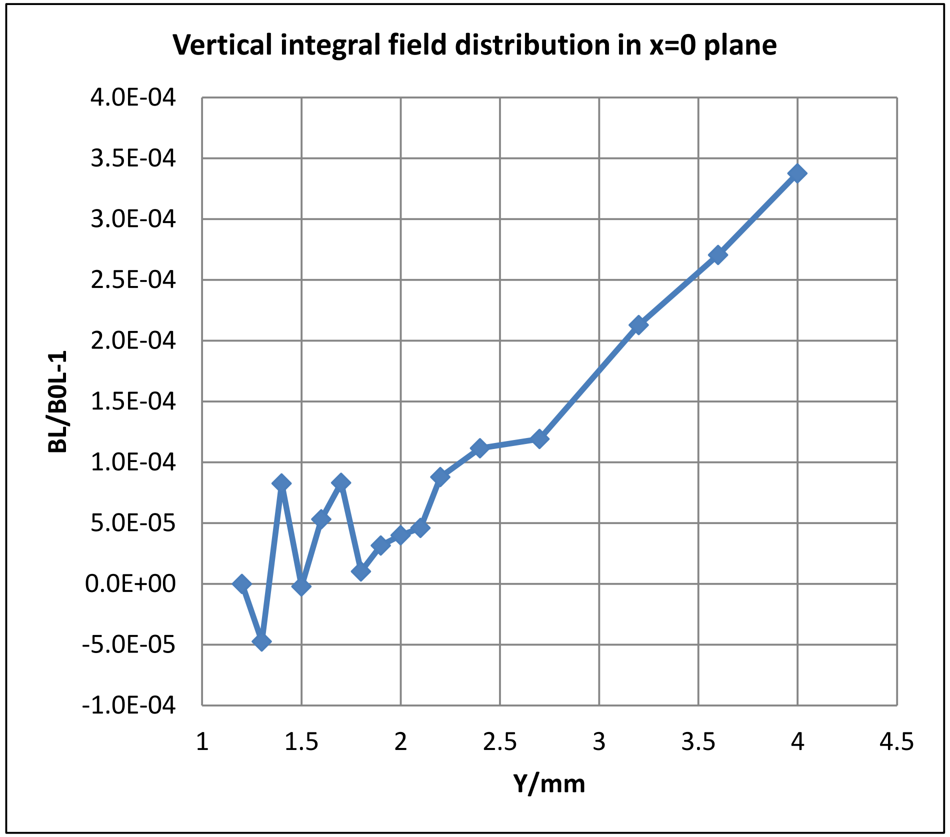
Horizontal field distribution in range x=±6mm : 7.22E-04 (<±0.1%) @ 175A



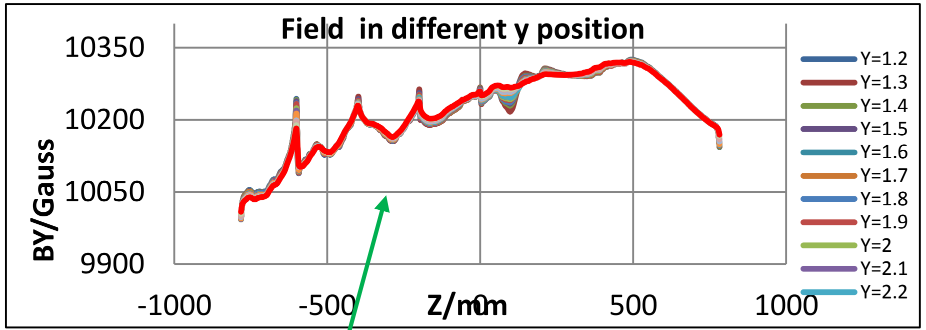


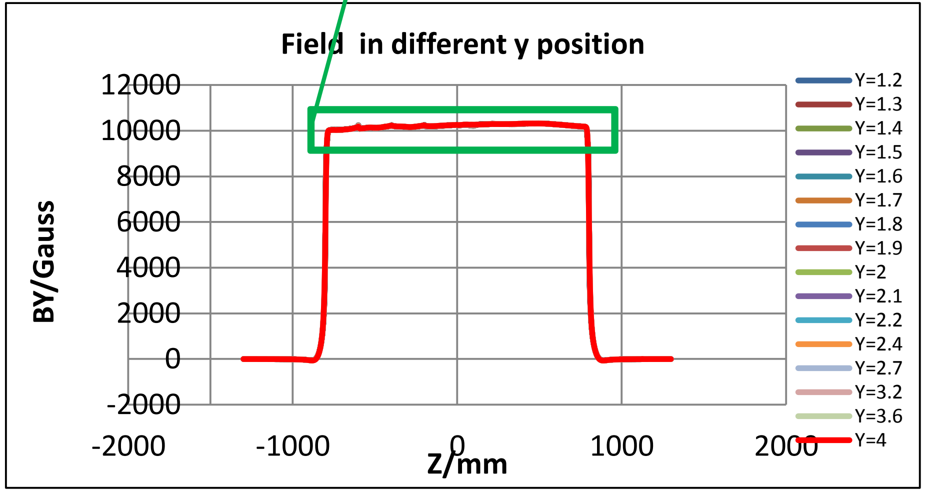
Main field distribution measurement

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



*Y=0 plane is surface of bottom polar

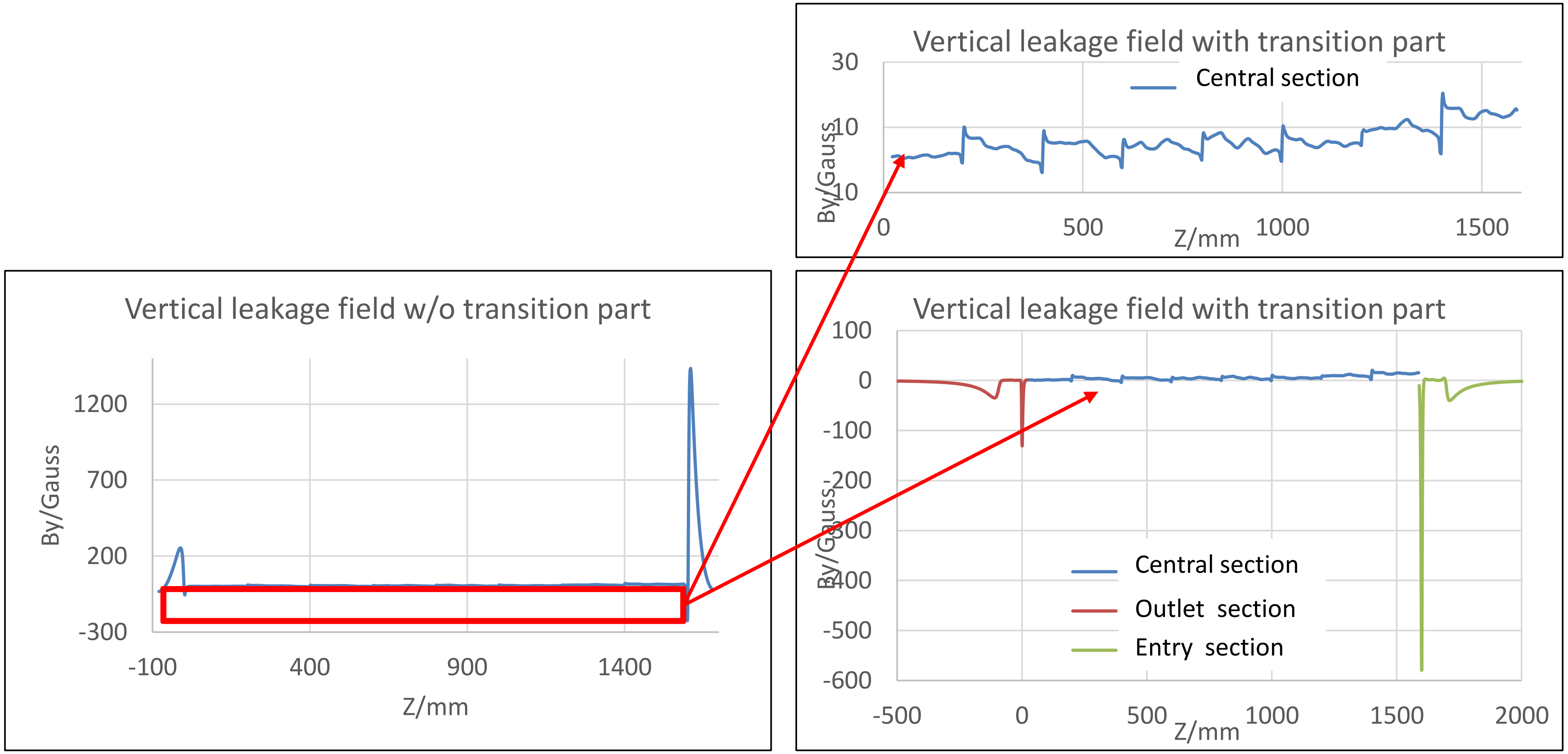




Integral leakage field measurement

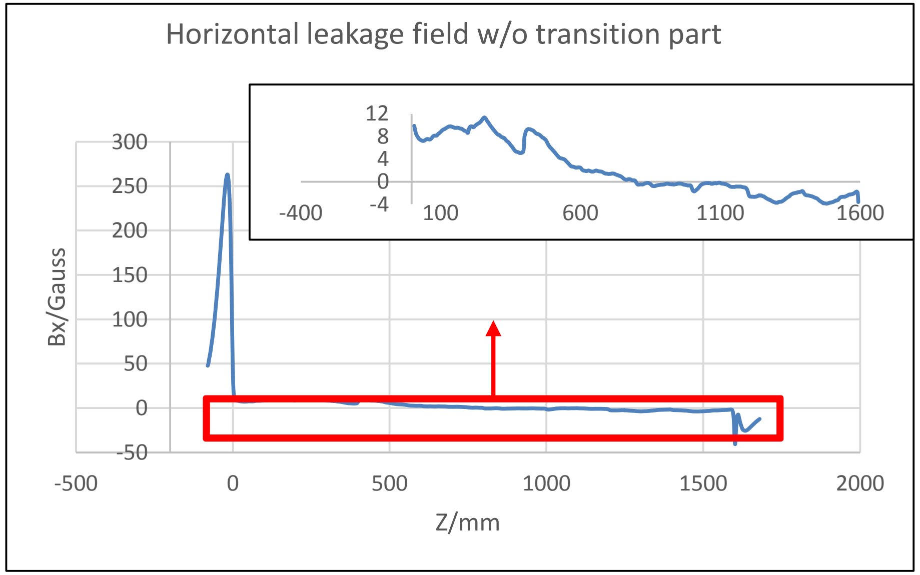
- Vertical integral leakage field

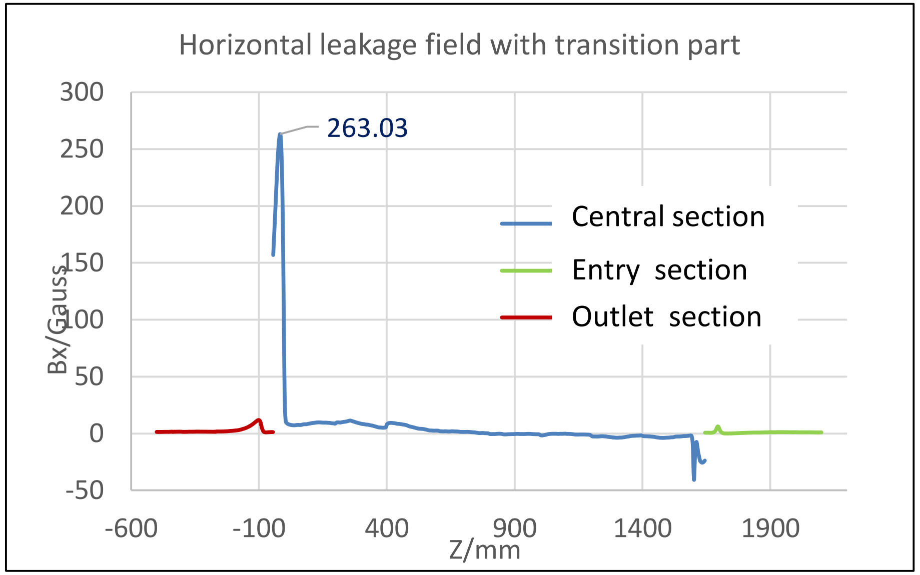
  – w/o transition part：integral vertical leakage filed=3.25E-03(53431Gauss·mm)，not meet requirement
  – With transition part：integral vertical leakage filed=4.3E-04 (-6997Gauss·mm)， meet requirement



Integral leakage field measureme

- 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

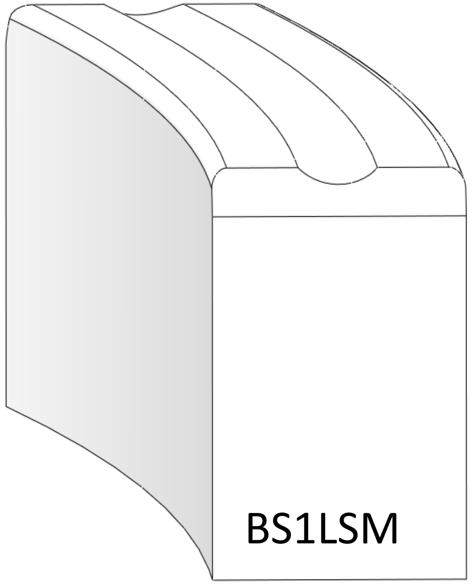


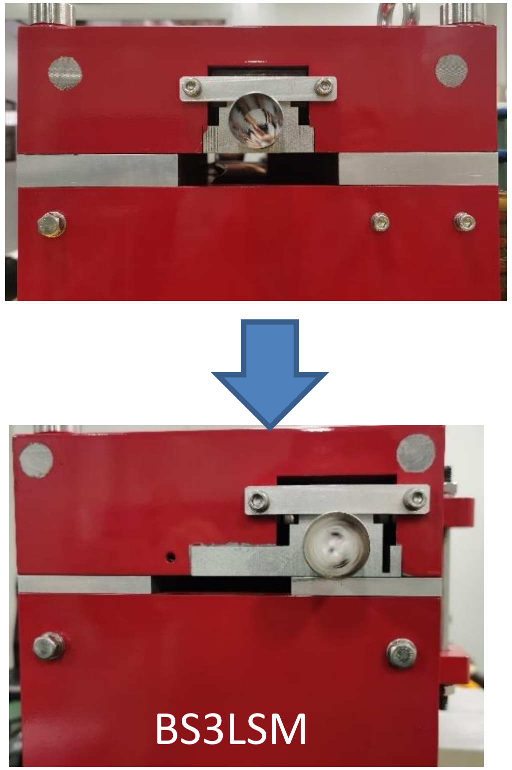


In-air Lambertson

In-air LSM R&D for HEPS BST

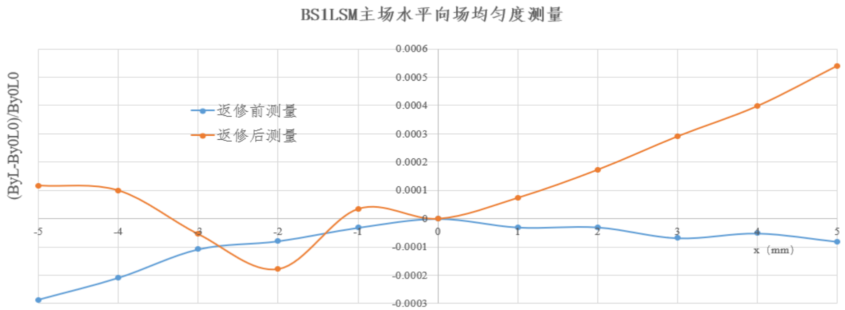
- Field measurement result shows that The gap at the joint of magnetic poles has a great influence on the leakage field and the main field distribution.
- After repair， the BS1LSM and BS3LSM have pass the second time magnetic field measurement

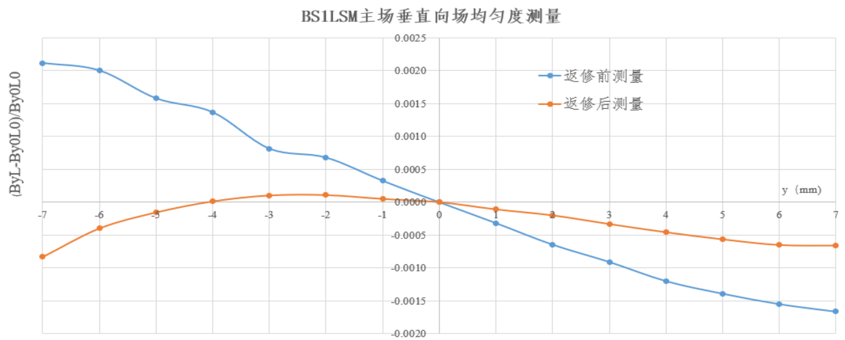


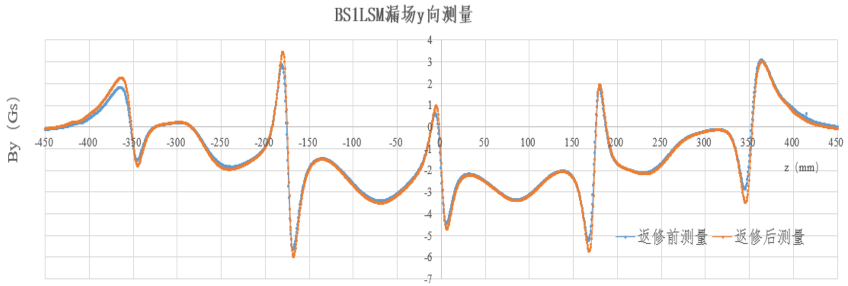


In-air LSM R&D for HEPS BST

- 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%