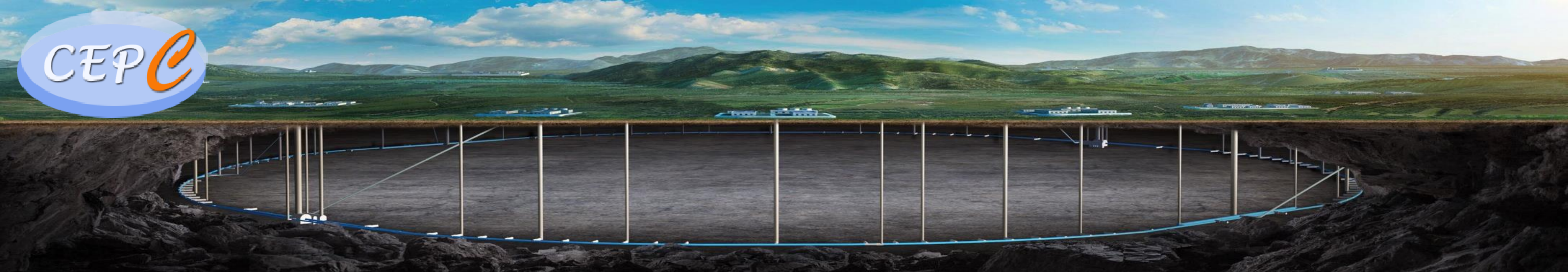

CEPC injection and extraction system

(Latest progress in EDR phase)

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Content

- Overview of CEPC Injection & extraction system
- Inj. & ext. system layout and survey design
- EDR design update of kickers
- EDR design update of septa
- New inj. & ext. tech. demonstration in HEPS beam commissioning
- Summary

1 Overview of CEPC Injection & extraction system

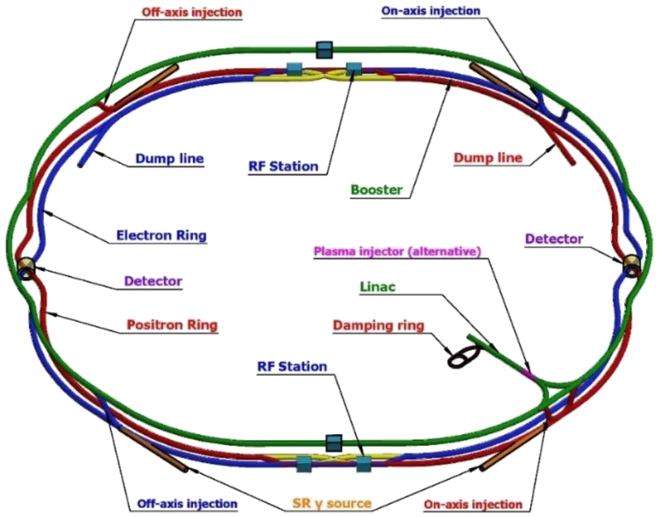
Overview of the inj.&ext. system in CEPC

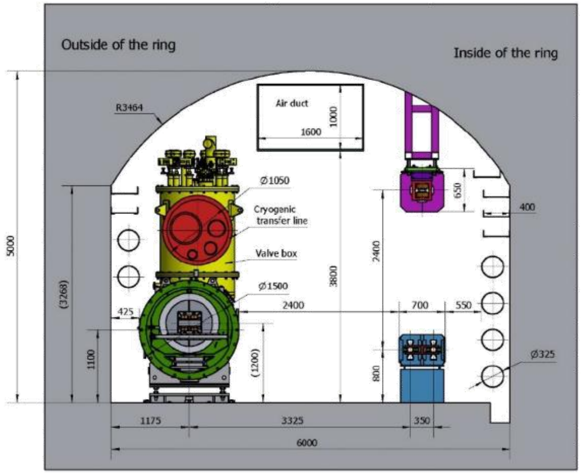
- The CEPC complex consists of 4 circular accelerators:
  - A damping ring (1.1GeV/147m)
  - A booster ring (30~120/180GeV/100km)
  - 2 storage rings (120/180GeV/100km)
- The 4 rings being linked with 14 transport lines and 10 injection & extraction sub-systems :

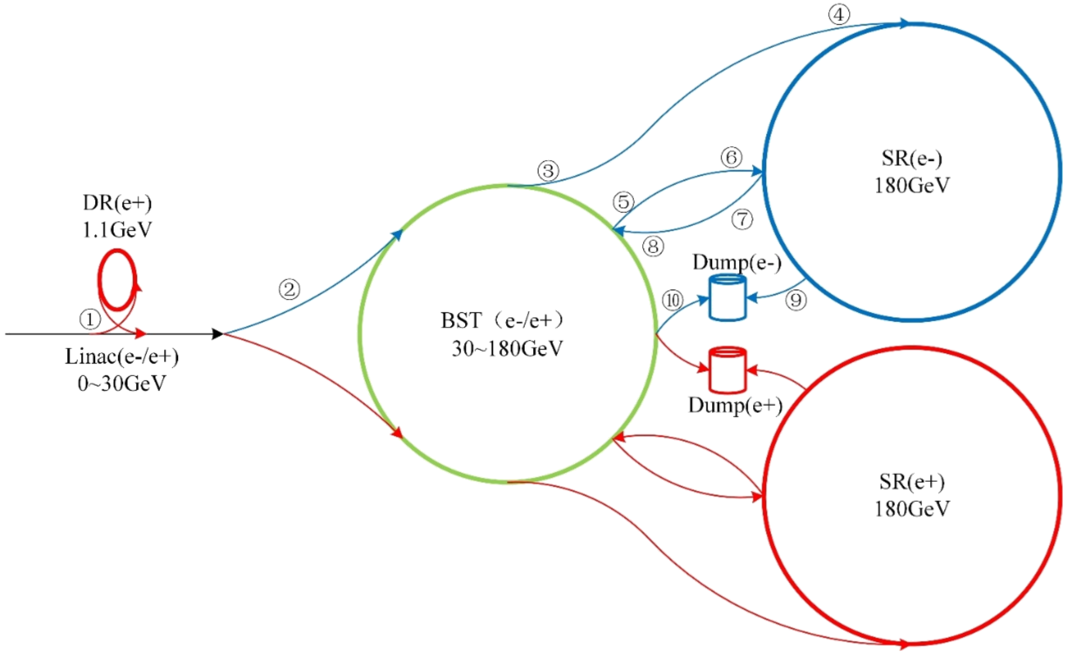
① DR injection and Extraction system(e+)
② Booster LE injection system (e+,e-)
③ Booster Extraction system1 (e+,e-)
④ Collider off-axis injection system (e+,e-)
⑤ Booster Extraction system2 (e+,e-)
⑥ Collider swap out injection system (e+,e-)
⑦ Collider swap out extraction system (e+,e-)
⑧ Booster HE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

Off-axis injection
(in W, Z and $t\bar{t}$ mode)

On-axis injection
(only in Higgs mode)

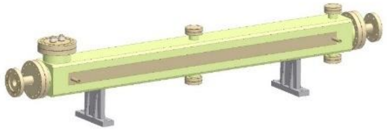


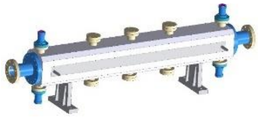


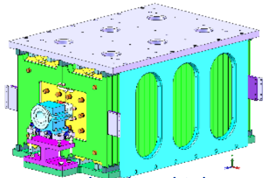


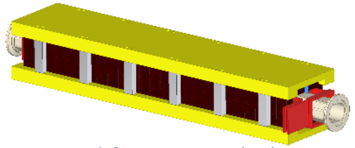
List of the types of inj. & ext. hardware

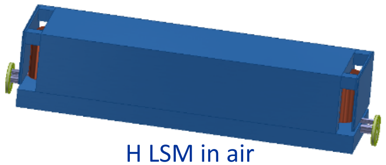
	Sub-system	Kicker		Septa	
		Kicker Type	Kicker waveform	Septum Type	Stored beam pipe aperture /Thickness of septum
1	DR inj./ext.	Slotted-pipe kicker	Half-sine /245ns	Horizontal LMS in air	ϕ30/6mm
2	BST LE inj.	Strip-line kicker	Half-sine/50ns	Horizontal LMS in air	ϕ56/10mm
3	BST ext. for CR off-axis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

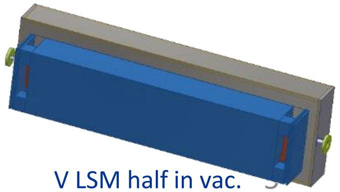

Slotted-pipe kicker


Strip-line kicker


Delay-line kicker


Lumped ferrite-core kicker


H LSM in air


V LSM half in vac.

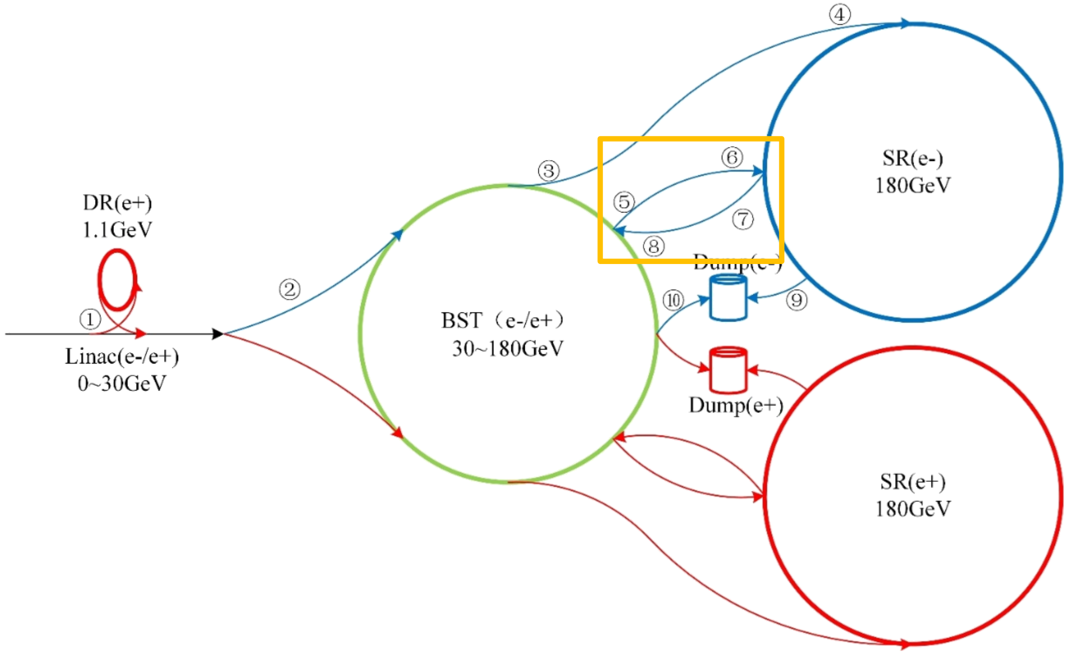
2 Layout and survey design progress status

Contributed by Xiaohao Cui, Lihua Huo, Lei Wang etc.

Overall progress status of CEPC EDR

- **Layout:** The initial layout and survey iterative designs of all 10 inj. & ext. sub-system have completed.
- **Septum:** The septa in the BST and CR are designed for a maximum energy of 180 GeV and are capable of operating in $t\bar{t}$ mode.
- **Kicker:** The kickers in the BST and CR, however, have a design maximum energy of only 120 GeV. To enable operation in $t\bar{t}$ mode, additional kickers will need to be installed in a later phase.
- The preliminary physical designs and mechanical design of all septa and kickers have been completed.

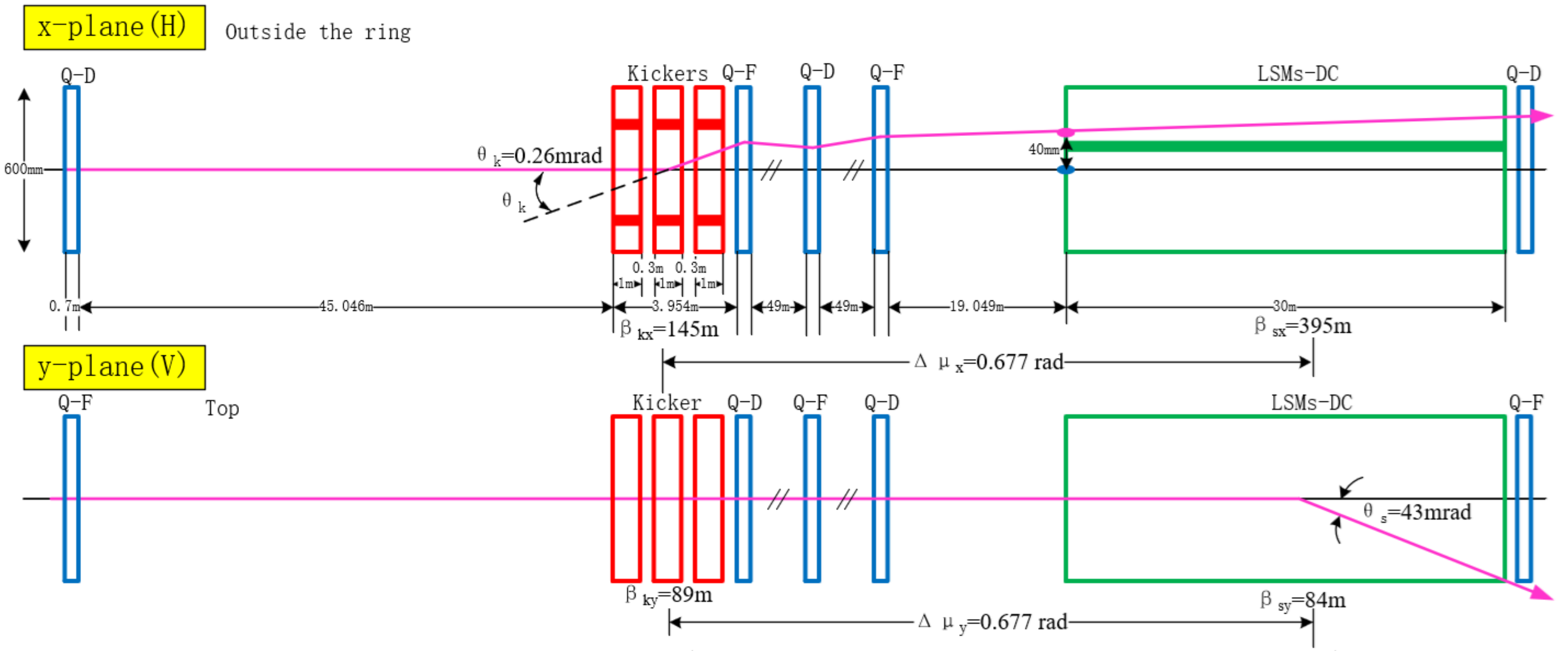
- Due to time constraints, this presentation will focus only on the layout design of the CR on-axis swap-out injection subsystem dedicated for Higgs energy mode operation.

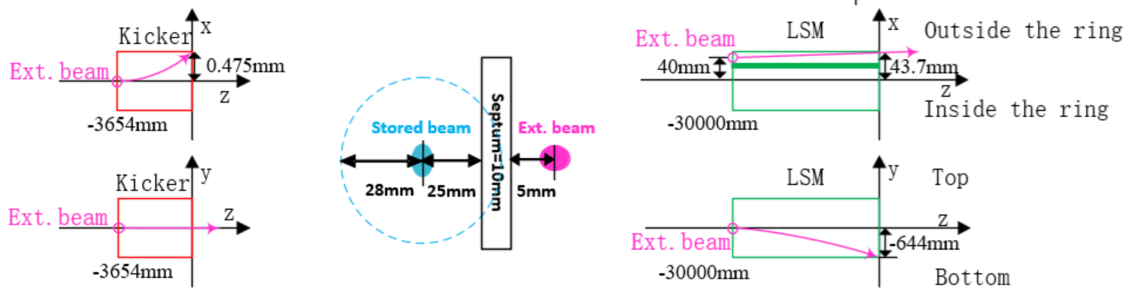


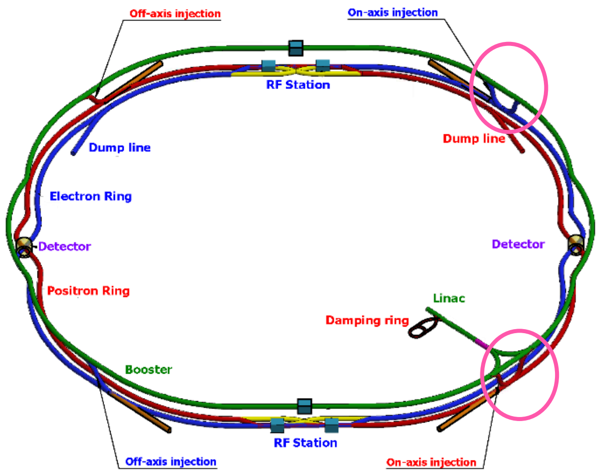
Booster extraction for CR on-axis injection

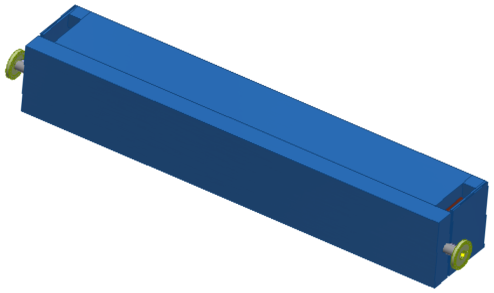
CEPC-BST-HE-extraction layout (20250314)
* layouts of e- and e+ inj. are identical
* BST HE-extraction for SR off-axis and on-axis injection are identical

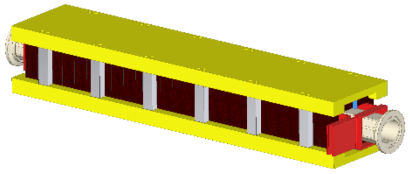
$$\theta_{kicker} = \frac{x_s}{\sqrt{\beta_k \beta_s}\sin(\mu)}$$







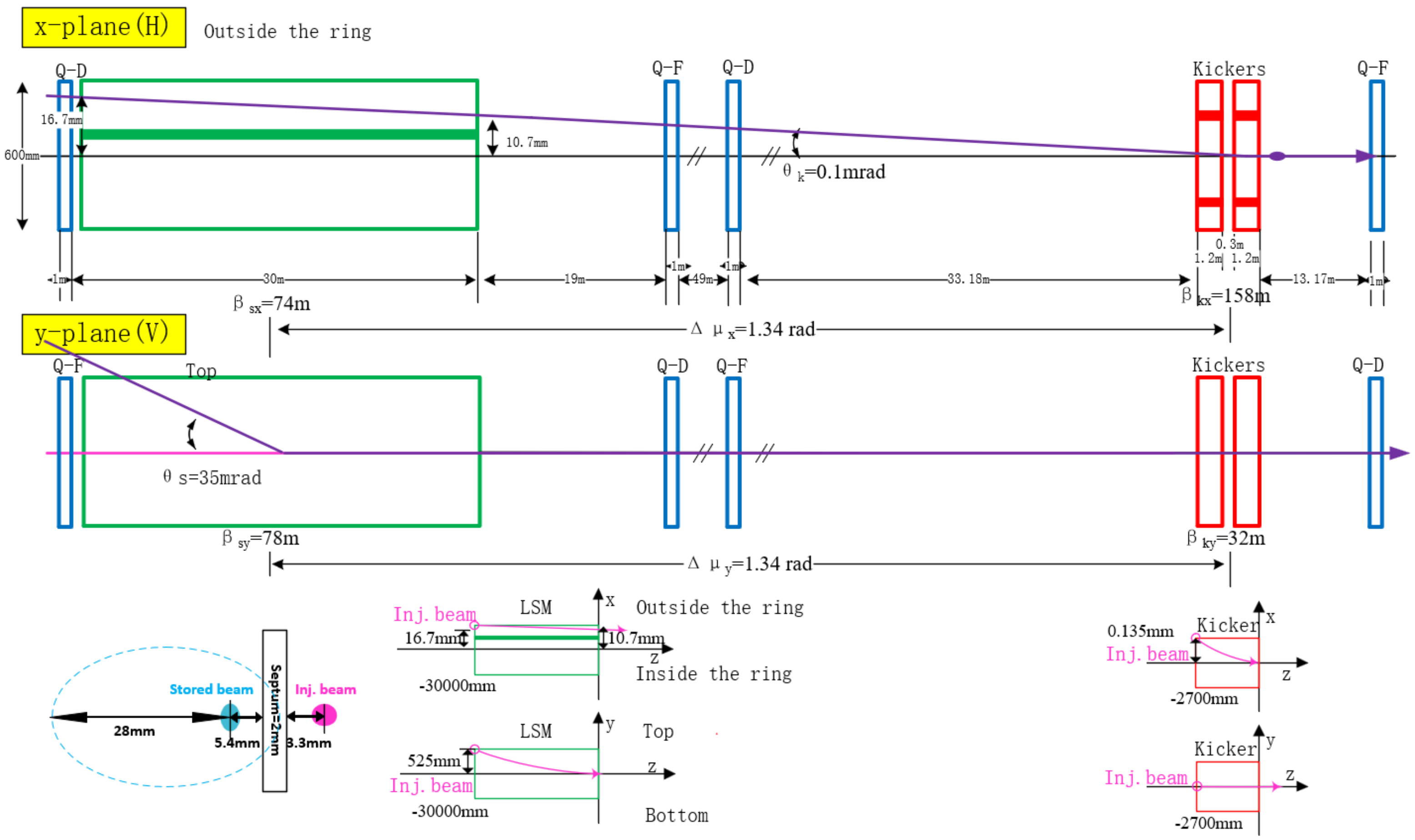


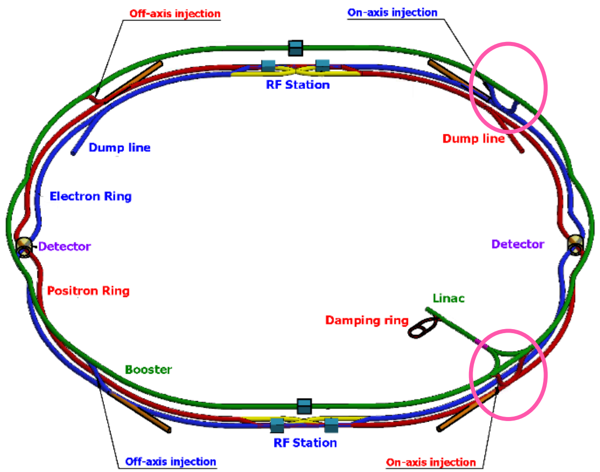


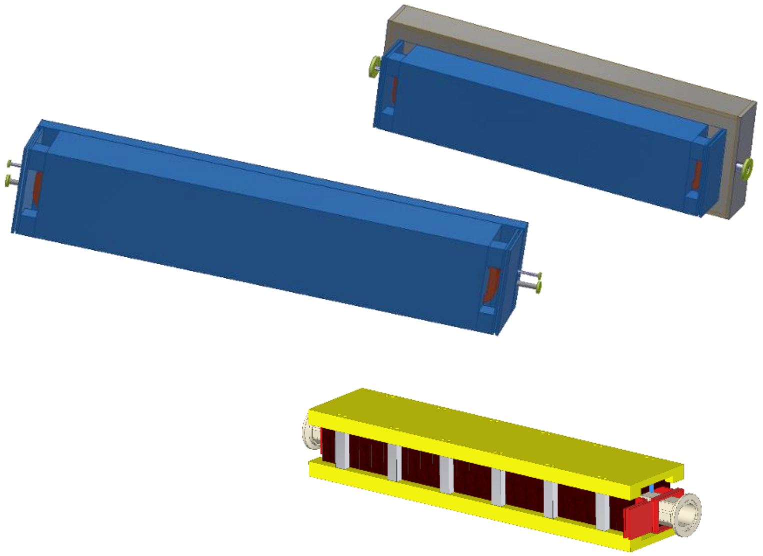
Collider on-axis injection

CEPC-SR-on-axis-inj. layout (20250318)
* layouts of e- and e+ inj. are identical

$$\theta_{kicker} = \frac{x_s}{\sqrt{\beta_k \beta_s}\sin(\mu)}$$



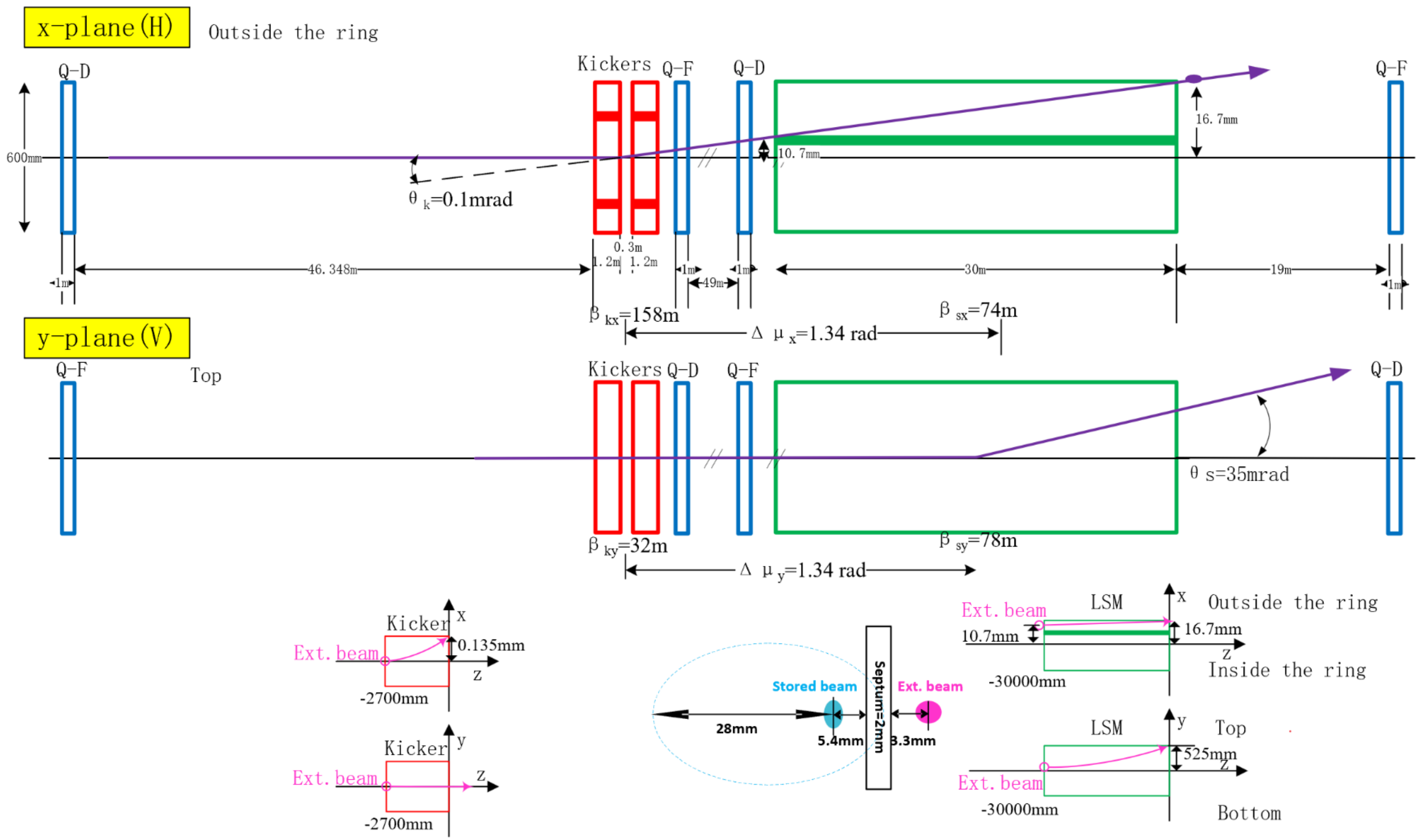


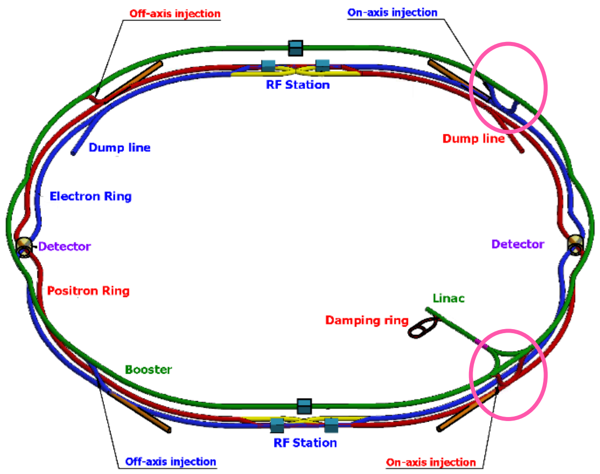


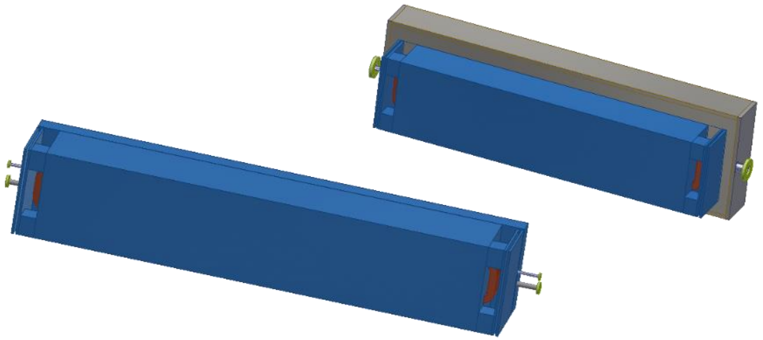
Collider on-axis extraction

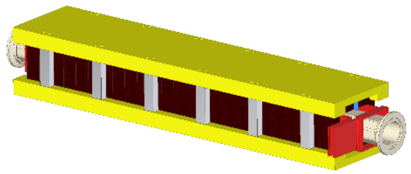
CEPC-SR-on-axis-ext. layout（20250318）
＊ layouts of e- and e+ inj. are identical

$$\theta_{kicker} = \frac{x_s}{\sqrt{\beta_k \beta_s} \sin(\mu)}$$







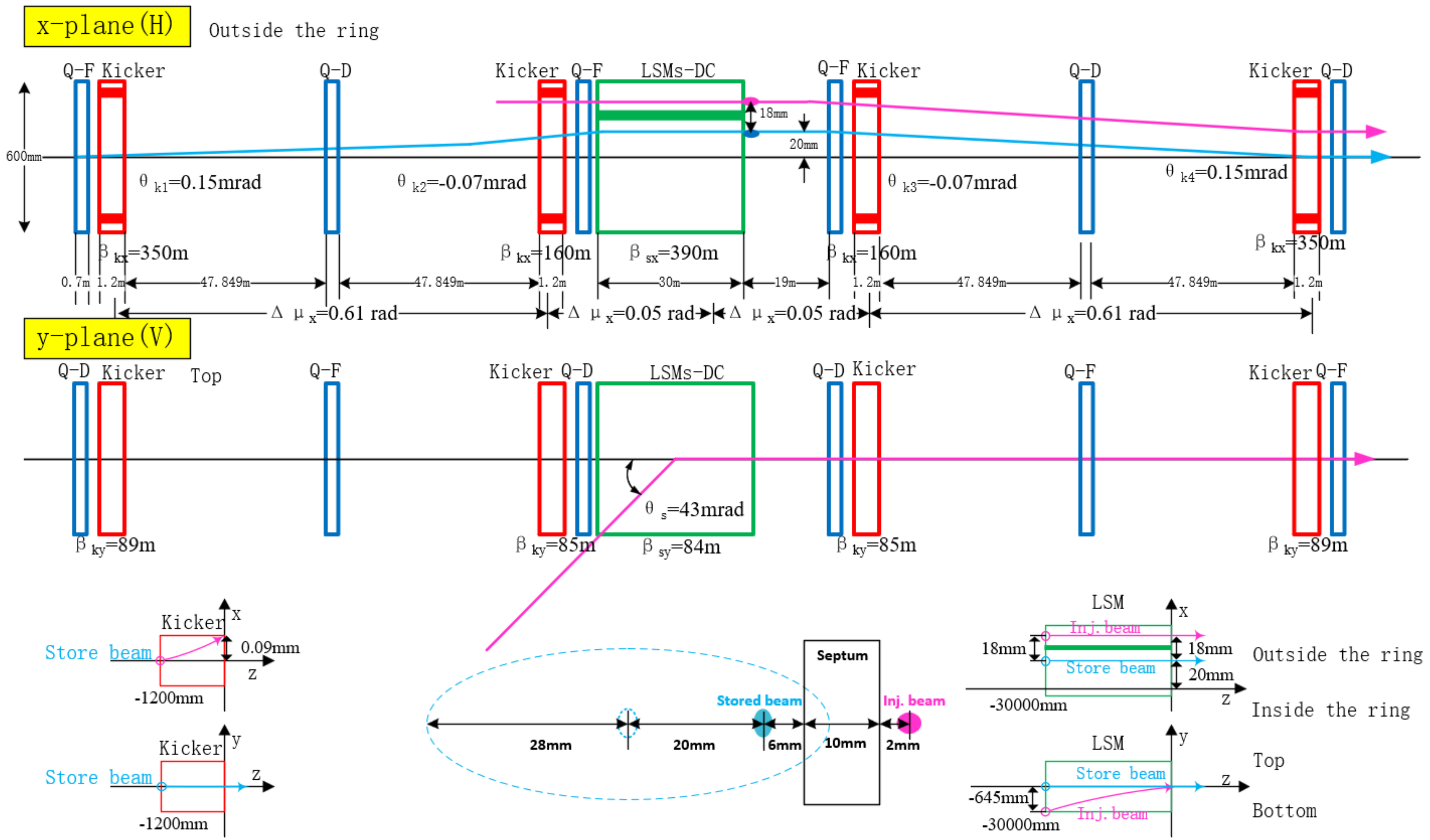


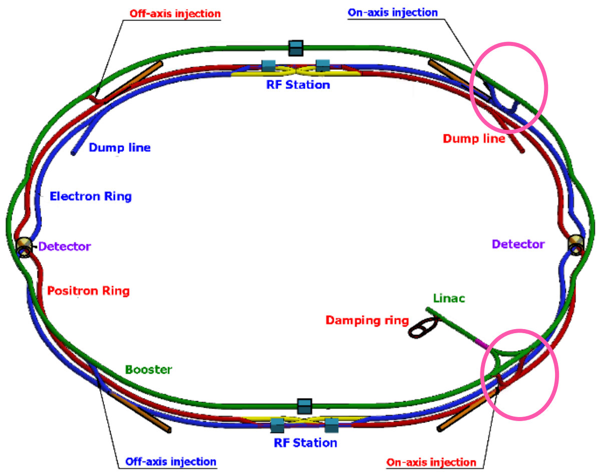
Booster re-injection from SR

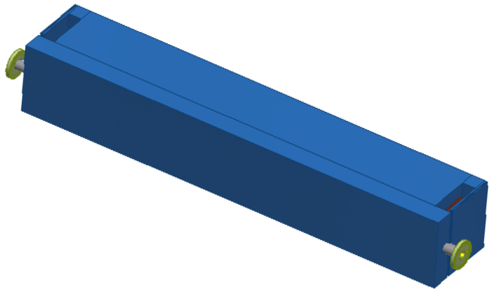
CEPC-BST-HE-inject layout (20250320)

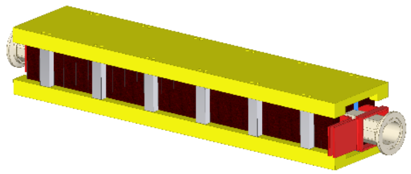
* layouts of e- and e+ inj. are identical
* BST HE-inject for SR on-axis swap out injection

$$\theta_{kicker} = \frac{x_s}{\sqrt{\beta_k \beta_s}\sin(\mu)}$$

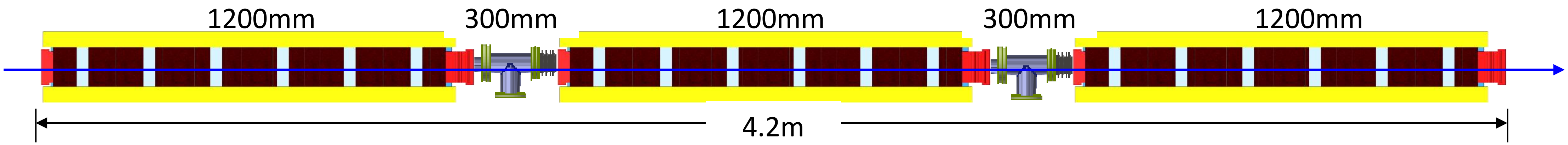




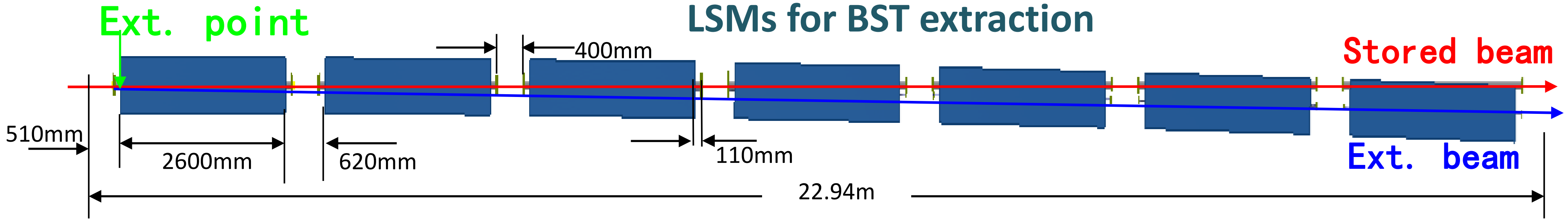




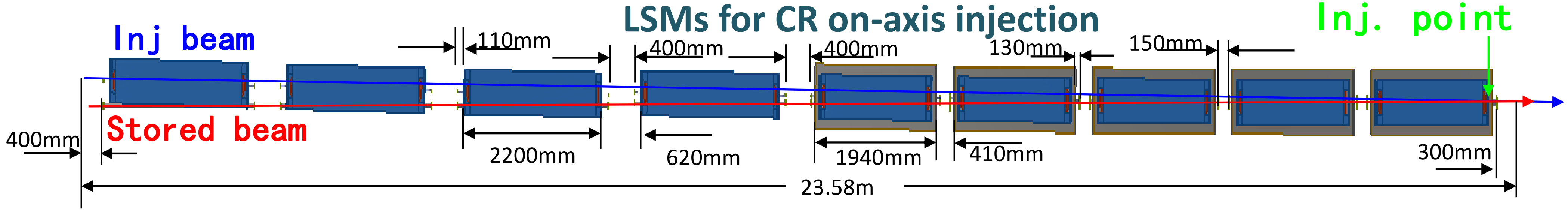
Kickers for BST extraction



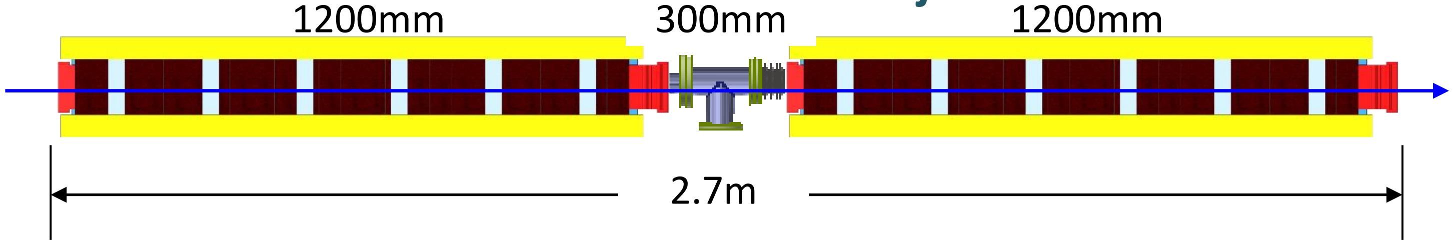
LSMs for BST extraction



LSMs for CR on-axis injection



Kickers for CR on-axis injection

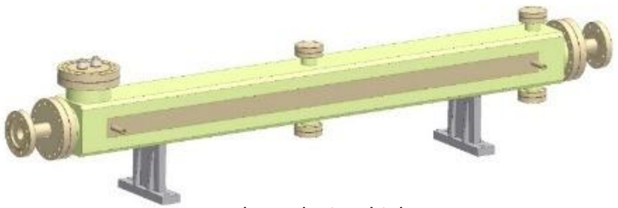


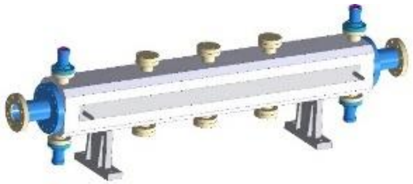
3 Kicker system EDR design update

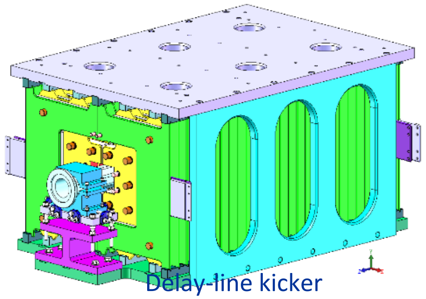
Contributed by Lei Wang，Hua Shi and Guanjian Wu

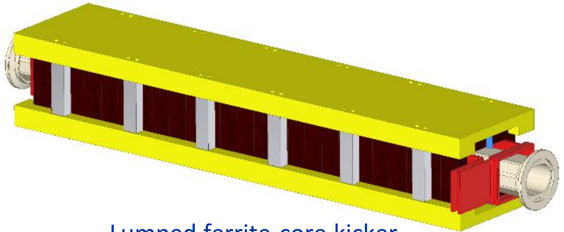
Kickers for CEPC injection & extraction

Type	Magnetic strength（T）	Quantity(e+/e-)
Slotted-pipe kicker	0.02095	2
Strip-line kicker	/	6
In-air delay-line dipole kicker	0.04	10
	0.02	12
In-air lumped parameter dipole kicker	0.035	10
	0.02	12
Total		52


Slotted-pipe kicker


Strip-line kicker


Delay-line kicker


Lumped ferrite-core kicker

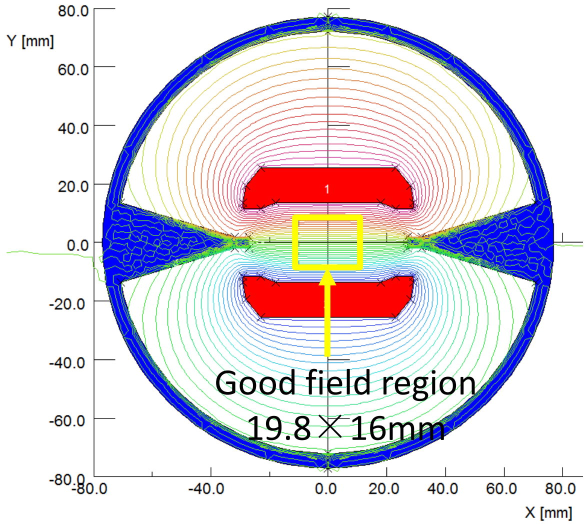
1）Slotted-pipe kicker for DR inj. & ext. system

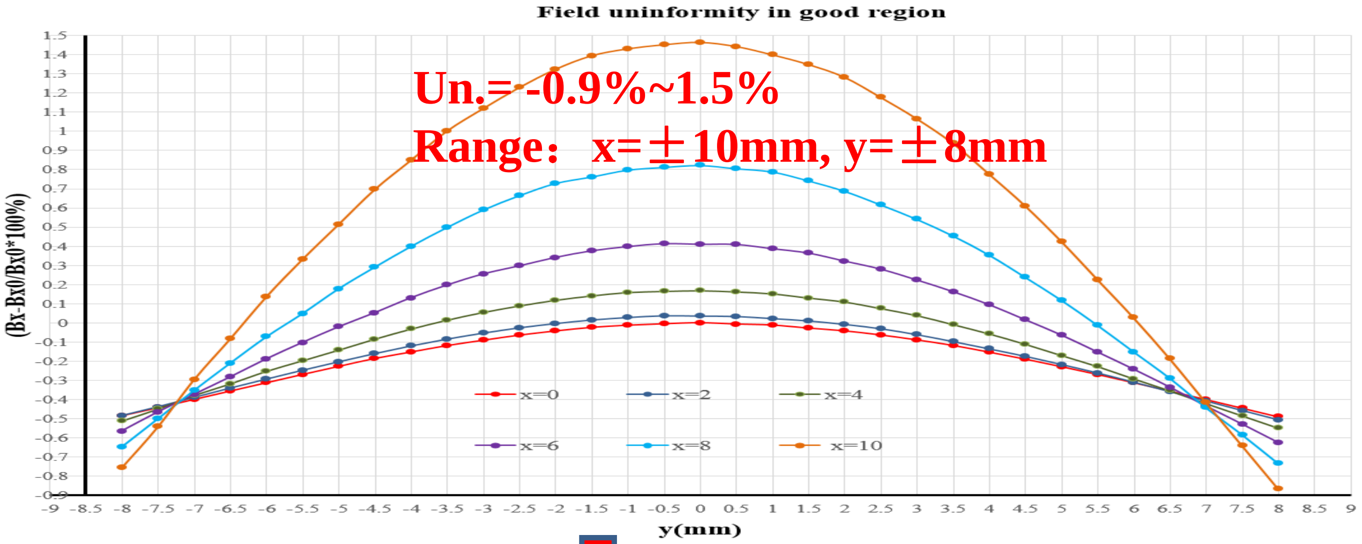
parameter	Unit	CEPC-DR-kicker	HEPS-BST-kicker
Quantity	-	1+1	1+3
Type	-	Slotted-pipe kicker	Slotted-pipe kicker
Deflect direction	-	Vertical	Vertical
Beam Energy	GeV	1.1	0.5/6
Deflect angle	mrad	8	9.104/1.75
Magnetic effective length	m	1.4	0.8/1.4
Magnetic strength	T	0.02095	0.02/0.025
Integral magnetic strength	T·m	0.0293	0.016/0.035
Clearance region(H×V)	mm	30×20	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	< 250	< 300

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

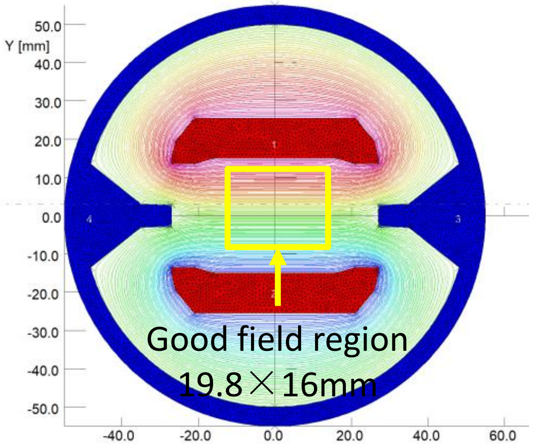
Physics design of slotted-pipe kicker for CEPC DR

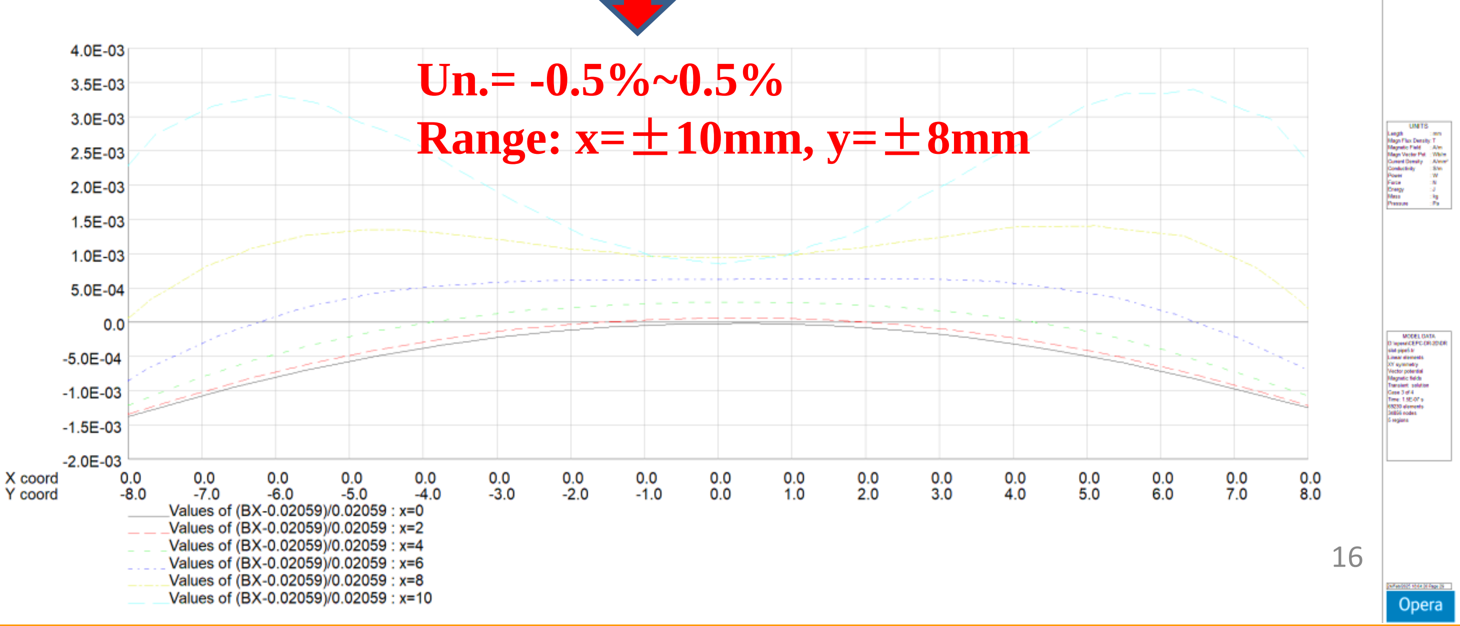
TDR





EDR



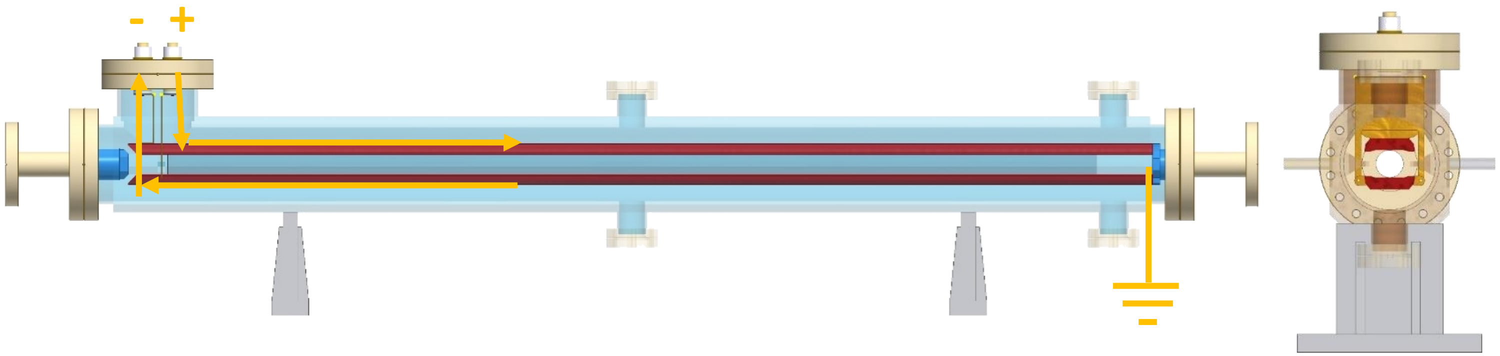


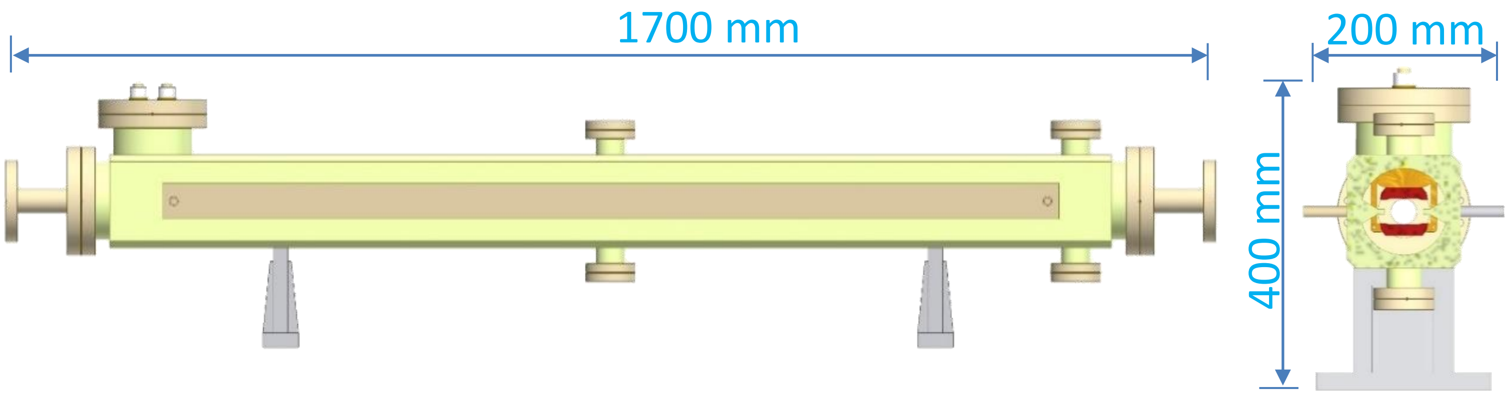
2D simulation model

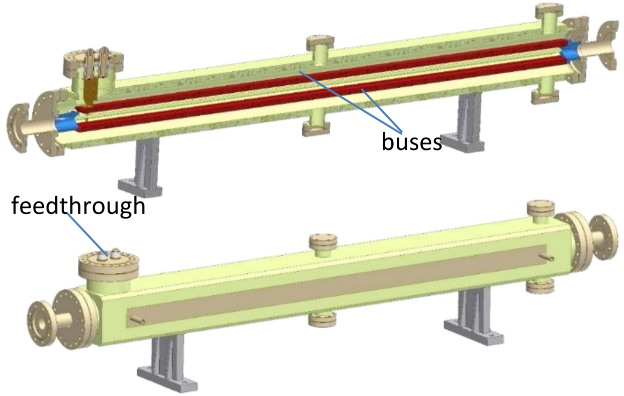
Engineer design of slotted-pipe kicker for CEPC DR

- 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.

Design parameters	unit	value
Maximum voltage of coil	kV	10.8
Maximum exciting current	kA	2.45
Inductance of magnet coil	nH	350
Good field region（H×V）	mm	19.8×16
Field uniformity	-	-0.9%~1.5%
Magnetic effective length	mm	1400
Total length	mm	1700



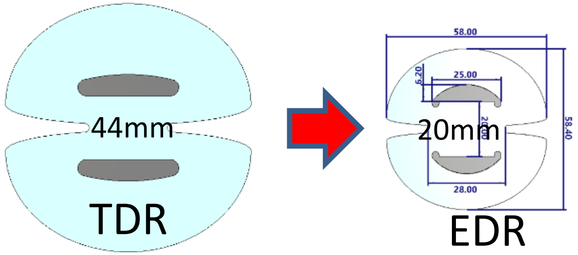




2) Strip-line kicker for BST LE injection

parameter	Unit	CEPC-BSTLEIK	HEPS-TF kicker prototype	HEPS-SR-kicker
Quantity	-	3 ×2	-	5×2
Type	-	Strip-line kicker	Strip-line kicker	Strip-line kicker
Deflect direction	-	Vertical	Vertical	Vertical
Beam Energy	GeV	30	6	6
Deflect angle of each magnet	mrad	0.0366(total 0.11)	-	0.32
Effective Length of Strip-line kicker electrode	mm	1000	750	300
Gap between two electrodes	mm	20	10	8
Odd mode impedance	Ω	50±1	50±1	50±1
Even mode impedance	Ω	<65	<65	<65
Clearance region(H×V)	mm	20×13	-	-
Good field region(H×V)	mm	10×12	x=±2.3，y= ±1	x=±1.1，y= (-0.85, 2.1)
Integral field uniformity	-	±1.5%	<±1%	<±1%
Amplitude of electrical pulse（into 50Ω）	kV	±10	±18	±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

- More flexible bunch filing patterns are achieved by using faster pulse kickers.
- The strip-line kicker for CEPC BST LE injection is very similar to HEPS-TF kicker prototype.
- The gap between 2 electrodes decreased in EDR from 44mm to 20mm.



Physics design of Strip-line kicker for CEPC

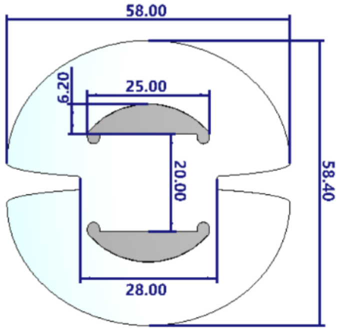
- **Length:** To realize injection bunch by bunch(τ=25ns), the strip-line electrode length=1m, electrical pulse width 6.7ns< t_p <43.3ns（Flat-top t_{top} >6.7ns， Rise/fall Time t_r/t_f <18.3ns）
- **Distance:** Minimum distanced of blades is d=20mm, which determined by beam clearance. Voltage between blades=10kV.
- **Blades:** To achieve highest geometric factor(g=0.966) the blade width should be w=25mm. Blade thickness=6.2mm.
- **Outer body:** distance between vanes =28mm
- **Impedance:** Odd-mode impedance Z_{odd}=50Ω, even-mode impedance Z_{even}=64.3Ω

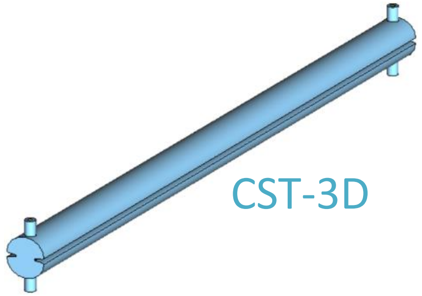
$$\begin{cases} l < c\tau/2 \\ 2l/c < t_p < 2\tau - 2l/c \end{cases}$$

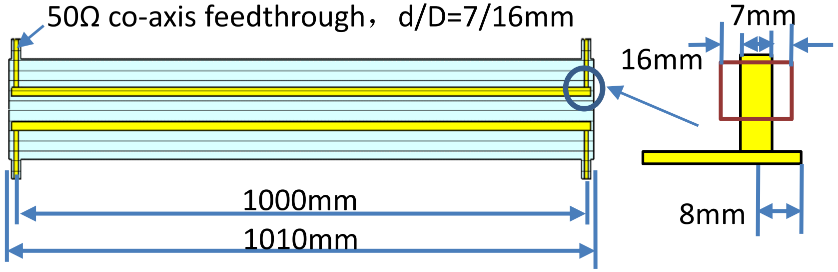
$$\theta = \theta_E + \theta_B = 2\theta_E = 2g\frac{eU}{E}\frac{l}{d}$$

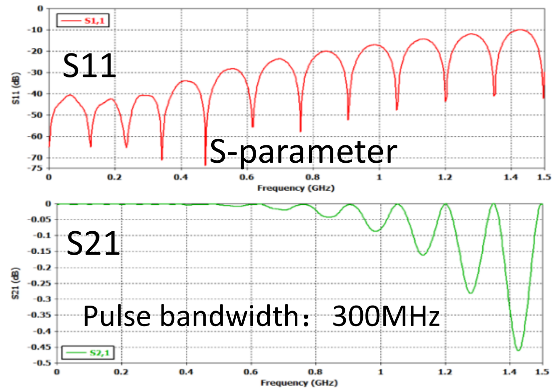
$$g = \tanh(\frac{\pi w}{2d})$$

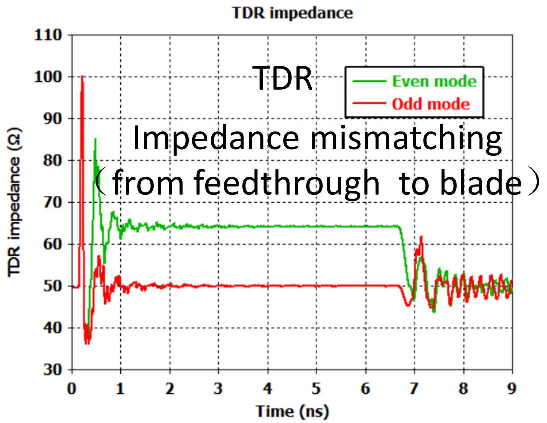
2D-geometry
Unit : mm

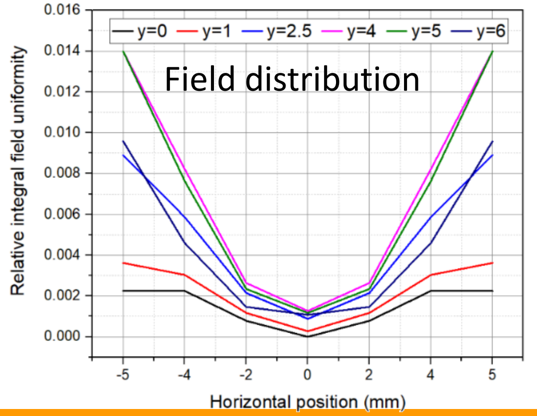


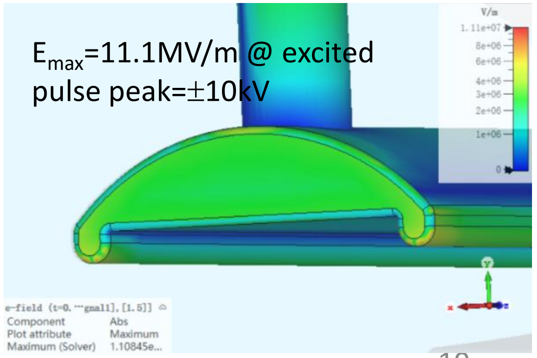




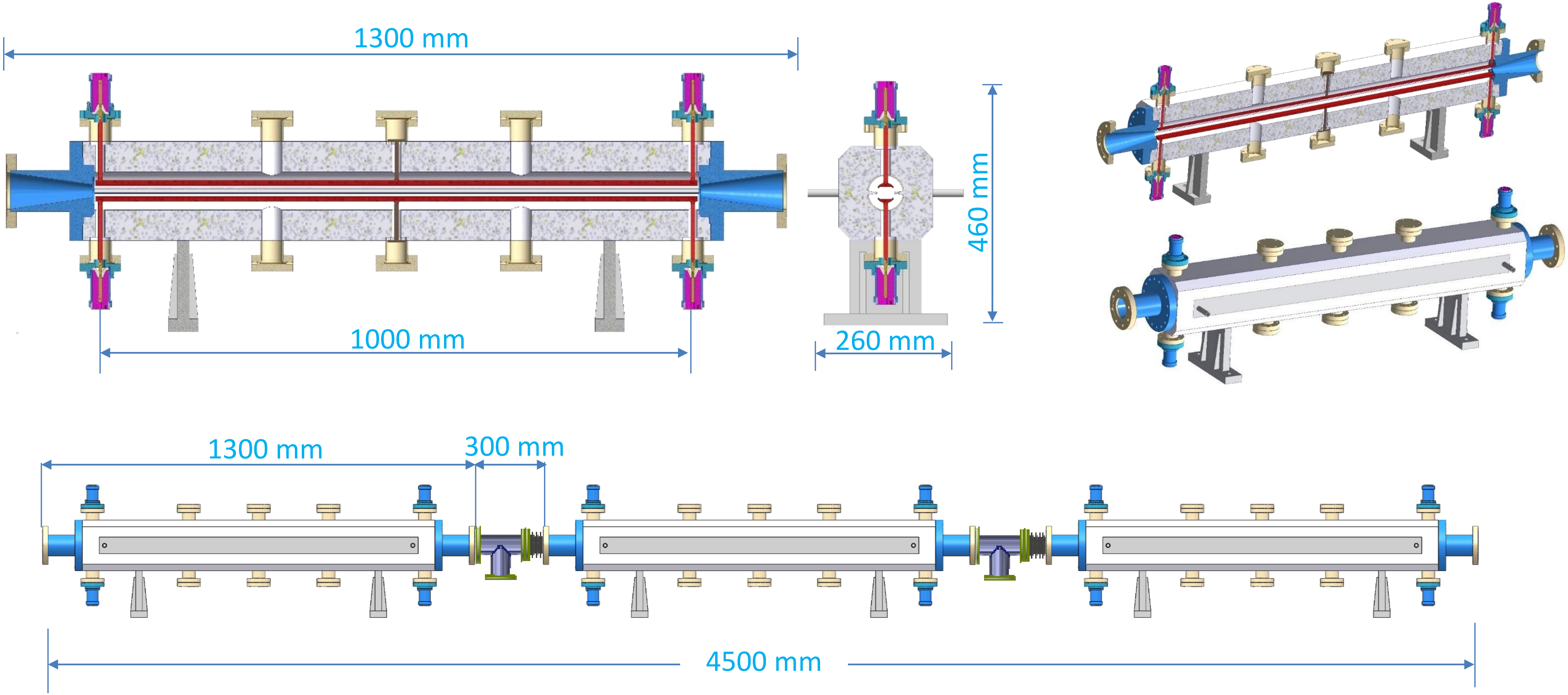






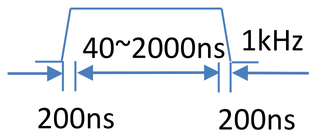


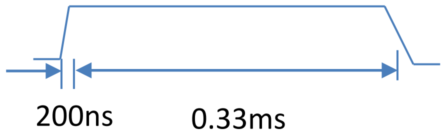
Engineer design of strip-line kicker



3) Delay-line kickers for CR off-axis inj. and ext. to dump

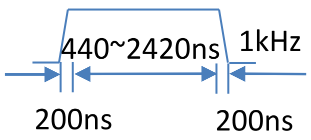
parameter	Unit	BST-ext-kicker1（for CR off-axis inj.）	BST-dump kicker	CR-inj-kicker1（for CR off-axis inj.）	CR-dump kicker
Type	-	In-air delay-line dipole kicker			
Deflect direction	-	Horizontal	Vertical	Horizontal	Vertical
Quantity(e+/e-)		3×2	2×2	4×2	2×2
Beam Energy	GeV	120	120	120	120
Deflect angle of each magnet	mrad	0.0866× 3	0.05×2	0.1×2+0.024×2	0.05×2
Magnetic effective length	m	1	1	1	1
Magnetic strength	T	0.035	0.02	0.04	0.02
Integral magnetic strength	T·m	0.035	0.02	0.04	0.02
Clearance region(H×V)	mm	20×13	20×13	50×15	13×10
Good field region(H×V)	mm	20×13	20×13	20×13	13×10
Field uniformity in good field region	-	±1.5%	±1.5%	±1.5%	±1.5%
Repetition rate	Hz	1k	-	1k	-
Amplitude repeatability	-	±0.5%	±0.5%	±0.5%	±0.5%
Pulse jitter	ns	≤5	≤5	≤5	≤5
Bottom width of pulse(5%-5%)	ns	Trapezoid：440~2420	Trapezoid：330000	Trapezoid：440~2420	Trapezoid：330000
Tr/Tf(5%-95%)	ns	<200	<200	<200	<200



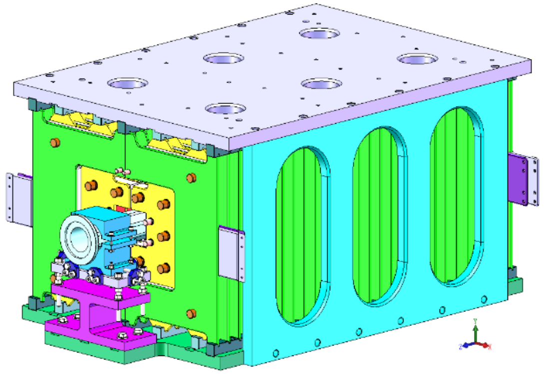


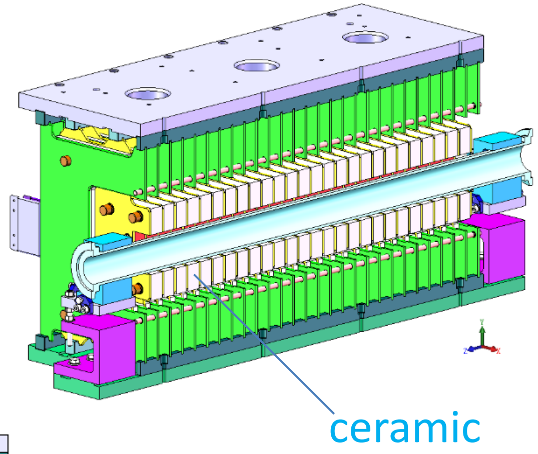
Delay-line kicker design for BST HE ext. and CR off-axis inj.

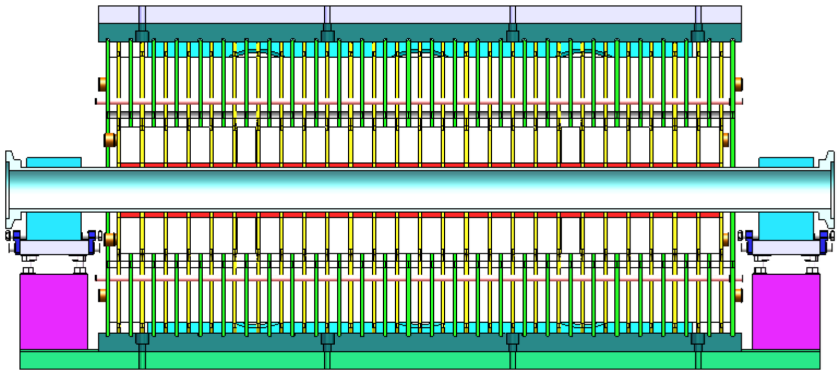
- For trapezoid kicker system, a delay-line dipole kicker is preferred, because it can helps to achieve ideal trapezoid waveform. While, its structure is complicated.
- Dual-C type magnet structure is adopted for CEPC.
- Ceramic vacuum chamber with TiN-Ag ladder pattern film is applied due to in-air magnet structure.
- Update: design a new delay-line kicker with ceramic dielectric to reduce the volume of magnet.



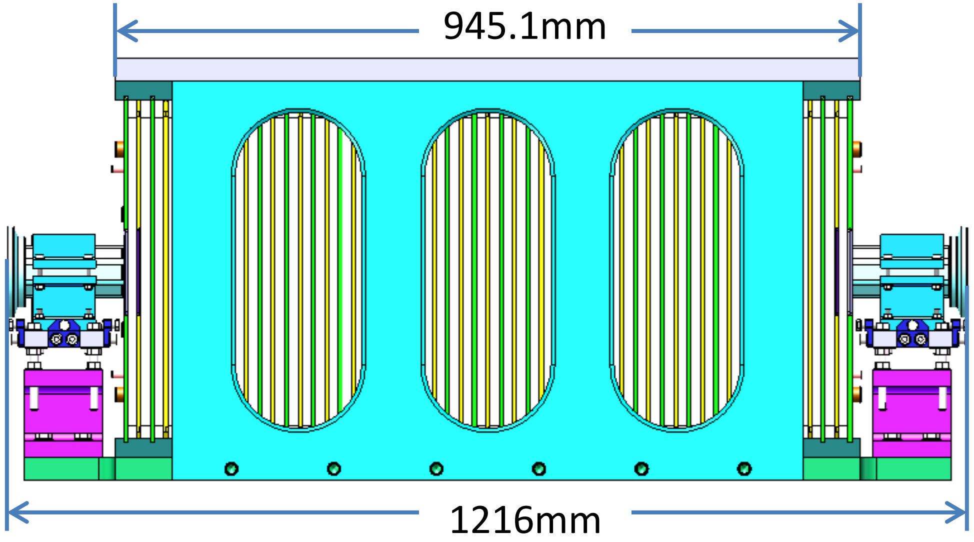
Delay-line dipole kicker and pulser Parameter	Value
Aperture of magnet (mm)	100 × 80
Longitudinal length of magnet cell (mm)	36
Cell number of magnet	26
Differential impedance of magnet (Ω)	12.5
Length of magnet (mm)	942
Total mechanical Length of magnet (mm)	1018
Inductance of magnet cell (nH)	56.6
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)	+/-16895.5
Pulse waveform	trapezoid
Rise/fall time (ns)	200
Flat-top width of pulse (ns)	40~2000 adjustable
Filling time of magnet (ns)	117.728
Rise/fall time of pulser (ns)	80
Repetition rate (kHz)	1

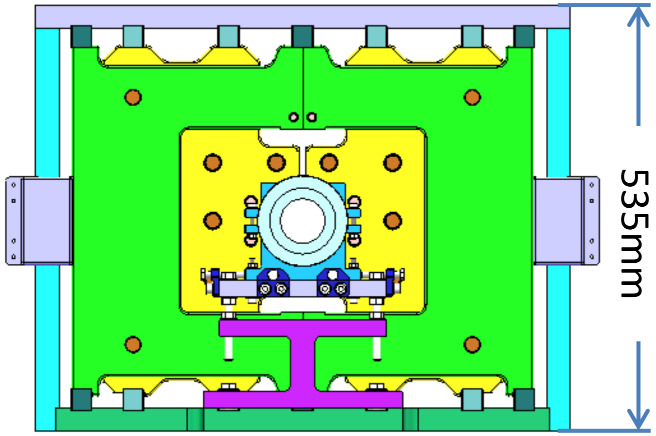


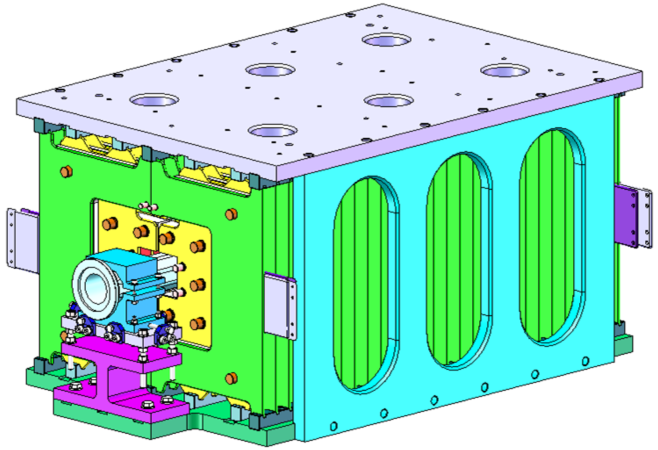


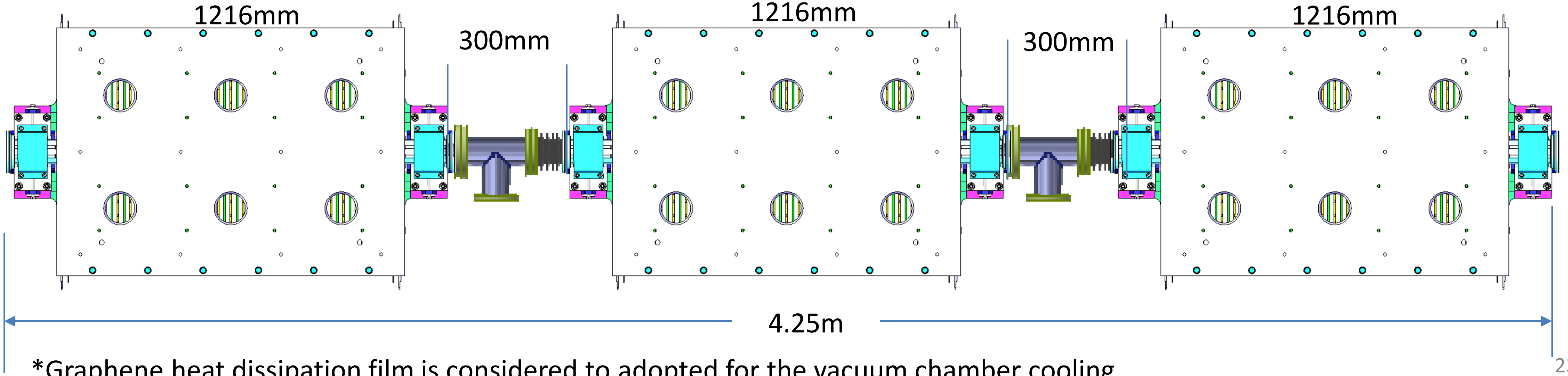


Engineer design of delay-line kicker





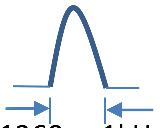




*Graphene heat dissipation film is considered to adopted for the vacuum chamber cooling.

4) Lumped parameter kickers for CR on-axis inj.

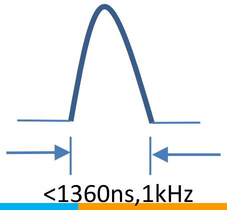
parameter	Unit	BST-EXT-kicker2（for CR on-axis inj.）	BST-HE-inj-kicker2（for CR on-axis inj.）	CR-inj-kicker2（for CR on-axis inj.）	CR-ext-kicker1（for CR on-axis inj.）
Type	-	In-air lumped parameter dipole kicker			
Deflect direction	-	Horizontal		Horizontal	
Quantity(e+/e-)		2×2	5(4)×2	2×2	2×2
Beam Energy	GeV	120	120	120	120
Deflect angle of each magnet	mrad	0.05×2	0.087+0.068×2+0.065×2	0.05×2	0.05×2
Magnetic effective length	m	1	1	1	1
Magnetic strength	T	0.02	0.035	0.02	0.02
Integral magnetic strength	T·m	0.02	0.035	0.02	0.02
Clearance region(H×V)	mm	20×13	50×15	13×10	13×10
Good field region(H×V)	mm	20×13	20×13	13×10	13×10
Field uniformity in good field region	-	±1.5%	±1.5%	±1.5%	±1.5%
Repetition rate	Hz	1k	1k	1k	1k
Amplitude repeatability	-	±0.5%	±0.5%	±0.5%	±0.5%
Pulse jitter	ns	≤5	≤5	≤5	≤5
Bottom width of pulse(5%-5%)	ns	Half-sine：1360	Half-sine：1360	Half-sine：1360	Half-sine：1360
Tr/Tf(5%-95%)	ns	<680	<680	<680	<680

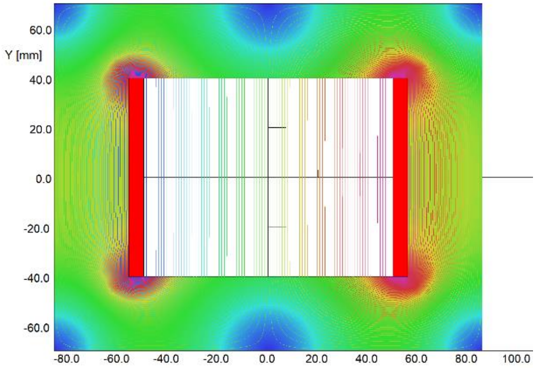


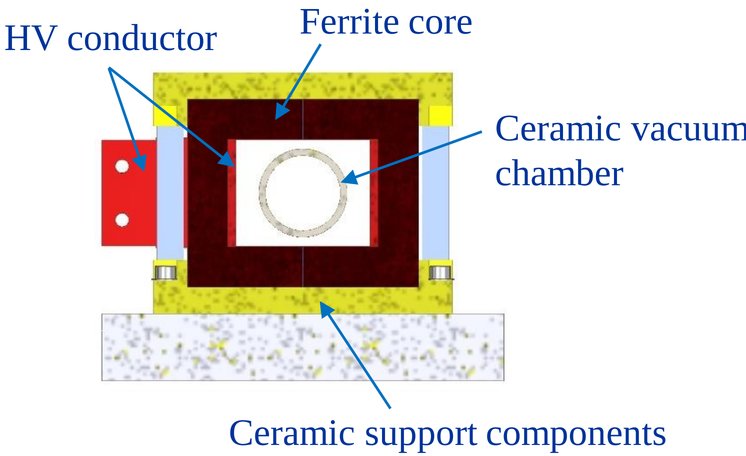
lumped parameter kicker design for BST HE ext/reinj. & CR on-axis inj.

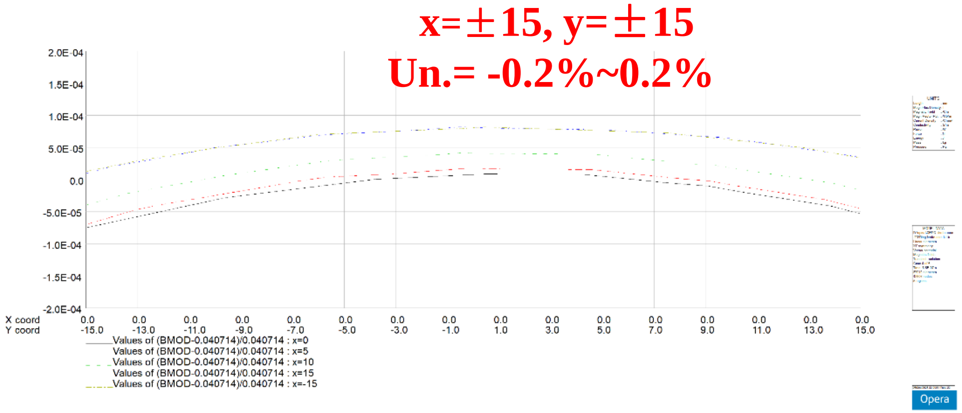
- As for 1.3us half-sine wave kicker system, the lumped parameter type kicker is adopted, because of its simpler structure and lower cost.
- The kicker magnet with ferrite core is preferred due to its higher exciting efficiency.
- Ceramic vacuum chamber with TiN-Ag continuous film is applied due to in-air magnet structure.

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

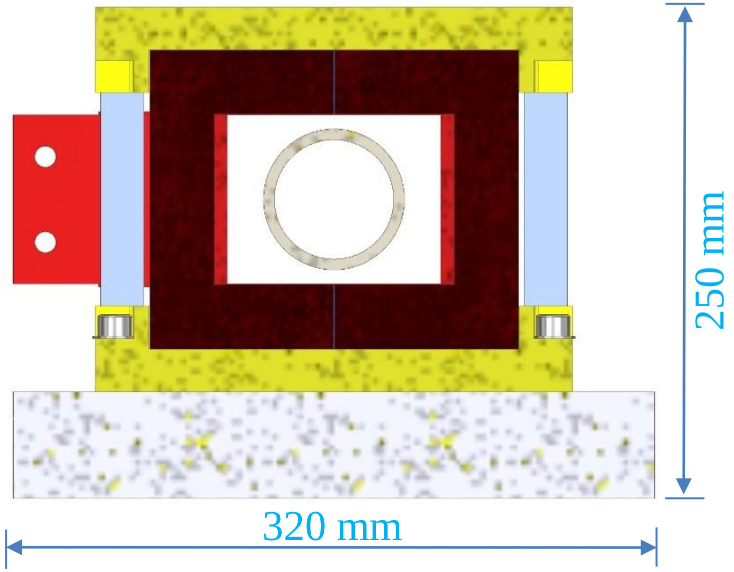


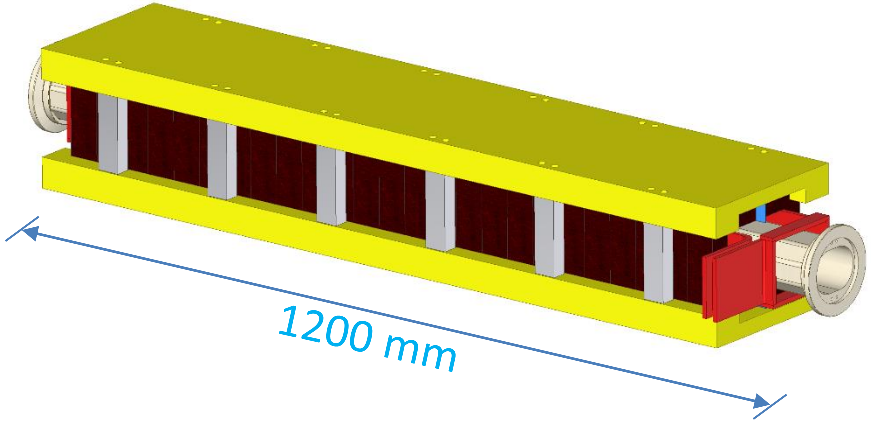


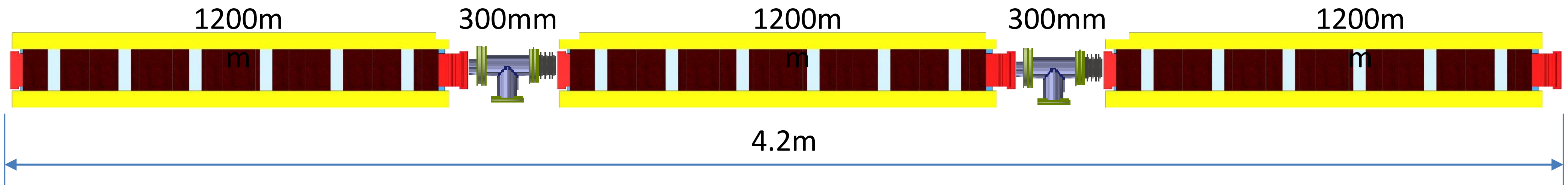




Engineer design of lumped-parameter kicker







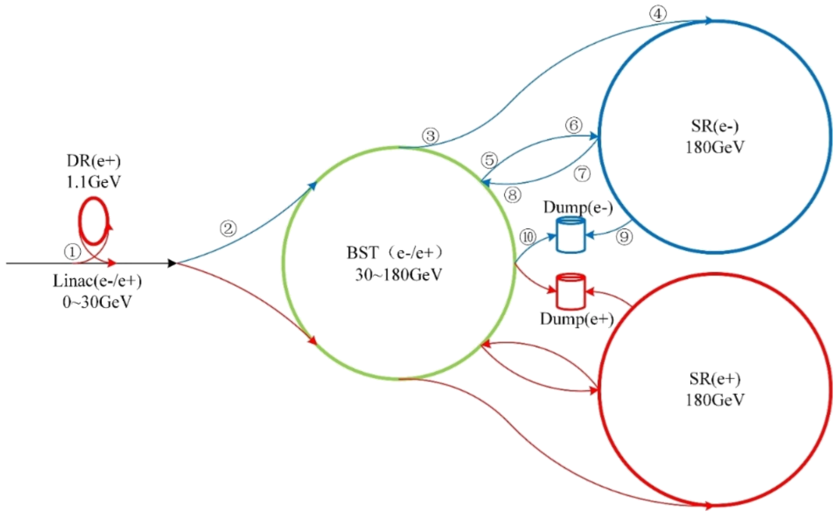
*Graphene heat dissipation film is considered to adopted for the vacuum chamber cooling.

4 Septum magnets EDR design update

Contributed by Lihua Huo

Transport lines and septa for inj.&ext. system

- Transport line： 14
- Inj&ext sub-system： 10×2=20
- Type of LSMs： in-air and half-in-vacuum
- Total quantity of septa: 134
- EDR Design progress:
  - physical models: 23
  - Mechanical models: 102



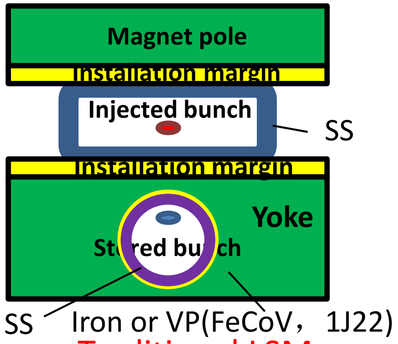
Transport line		Inj.&ext sub-systems		Septa model	Quantity
[1]	Lianc to DR e+ (LD)	1	Damping ring inj and ext	LSM (in-air)	1
[2]	DR to Linac e+(DL)	2			1
[3]	Linac to BST e+(LBP)	3	Booster Low energy inj	LSM (in-air)	3
[4]	Linca to BST e-(LBE)	4			3
[5]	BST to CR e+ off-axis inj (BCFP)	5	Booster e+ ext (off-axis)	LSM (in-air)	7
		6	Collider e+ inj（off-axis）	LSM1 (in-vac)	4
				LSM2 (in-air)	4
[6]	BST to CR e- off-axis inj (BCFE)	7	Booster e- ext（off-axis）	LSM (in-air)	7
		8	Collider e- inj（off-axis）	LSM1 (in-vac)	4
				LSM2 (in-air)	4
[7]	BST to CR e+ on-axis inj (BCNP)	9	Booster e+ ext（on-axis）	LSM (in-air)	7
		10	Collider e+ inj（on-axis）	LSM1 (in-vac)	5
				LSM2 (in-air)	4
[8]	BST to CR e- on-axis inj (BCNE)	11	Booster e- ext（on-axis）	LSM (in-air)	7
		12	Collider e- inj（on-axis）	LSM1 (in-vac)	5
				LSM2 (in-air)	4
[9]	CR to BST e+ (CBP)	13	Booster e+ high energy inj（on-axis）	LSM (in-air)	8
		14	Collider e+ ext to Booster（on-axis）	LSM1 (in-vac)	5
				LSM2 (in-air)	4
[10]	CR to BST e- (CBE)	15	Booster e- high energy inj（on-axis）	LSM (in-air)	8
		16	Collider e- ext to Booster（on-axis）	LSM1 (in-vac)	5
				LSM2 (in-air)	4
[11]	BST to Dump e+ (BDPP)	17	Booster ext to dump	LSM (in-air)	7
[12]	BST to Dump e- (BDPE)	18			7
[13]	CR to Dump e+ (CDPP)	19	Collider ext to dump	LSM (in-air)	8
[14]	CR to Dump e- (CDPE)	20			8

Total:	134

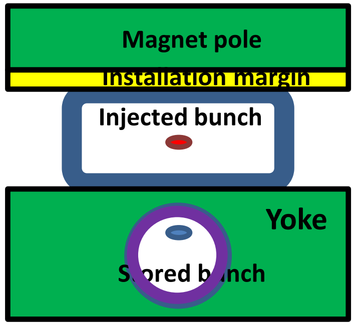
Physical requirements of all LSMs for CEPC

Subsystem	DR inj&ext	BST LE inj	BST HE ext. (off-axis)	BST HE ext. (on-axis)	BST HE re-injection	BST ext. to dump	CR off-axis injection	CR on-axis injection	CR on-axis extraction	CR ext. to dump
Operation mode	Z, W, Higgs, tt	Z, W, Higgs, tt	Z, W, Higgs, tt		Higgs, tt	Z, W, Higgs, tt	Z, W, Higgs, tt	Higgs, tt		Z, W, Higgs, tt
Max Energy （GeV）	1.1	30	180		180	180	180	180		180
Deflection direction	Horizontal	Horizontal	Vertical		Vertical	Horizontal	Vertical	Vertical		Horizontal
Total Integral field strength of septa (T-m)	0.44	4.5	12.6		12	12.6	11.68	11.6		12
Total deflection angle (m rad)	120	45	21		20	21	20	20		20
Deflection Radium (m)	4.167	133.333	800		800	800	800	800		800
Magnetic field strength for injected/extracted beam (T)	0.88	0.75	0.75		0.75	0.75	0.7/0.75	0.7/0.75		0.75
Total magnetic length (m)	0.5	6	16.8		16	16.8	16	16		16
Septum thickness (incl. septum board, inj./ext. beam pipe wall, installation gap) (mm)	6	10	10		10	5	2/3.5	2/3.5		5
Clearance of inj. & ext. beam at Lambertson (H×V) (w.r.t. inj. & ext. beam orbit) (mm)	30 × 22	30 ×30	10×5		10×5	10×10	9.2×4	6.6×4		7×6
Field uniformity in clearance of inj. & ext. beam	< ±0.05%	< ±0.05%	< ±0.05%		< ±0.05%	< ±0.05%	< ±0.05%	< ±0.05%		< ±0.05%
Clearance of stored beam at Lambertson (H×V) (w.r.t. stored beam orbit) (mm)	22 × 11	30 ×50	50 × 50		50 × 50	30 × 20	50 × 10	20 × 10		20 × 10
Integral leakage magnetic field / Integral main magnetic field	≤1×10-3	≤1×10-3	≤1×10-3		≤1×10-3	≤1×10-3	≤1×10-3	≤1×10-3		≤1×10-3
The leakage magnetic field position from septum plate in circulating tube (mm)	11	25	25		25	25	20	5.4		25

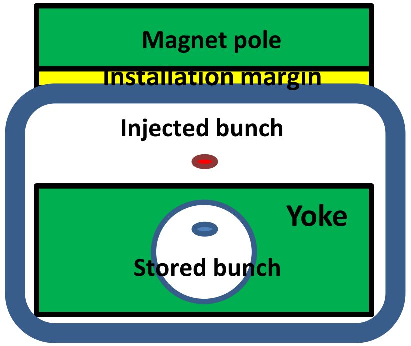
Septum thickness = Wall of stored beam pipe + Wall of injected beam pipe + Iron septum + installation margins



Traditional LSM



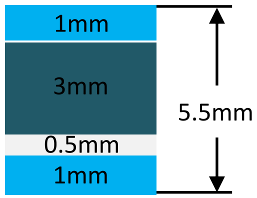
In-air（septum≥3.5mm）



Half in-vacuum（septum=2mm）

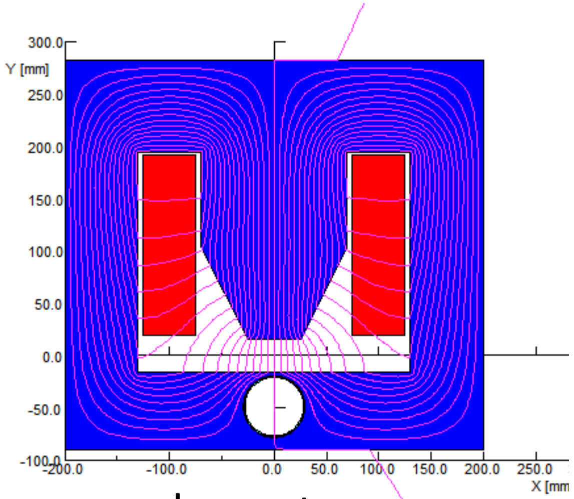
Preliminary magnet physical design of LSMs

- 2D simulation model with total thickness of septum： 5.5mm
  - Wall thickness of injected beam pipe： 1mm
  - Iron septum（DT4）： 3mm
  - Installation margin of stored beam pipe： 0.5mm
  - Wall thickness of stored beam pipe： 1mm

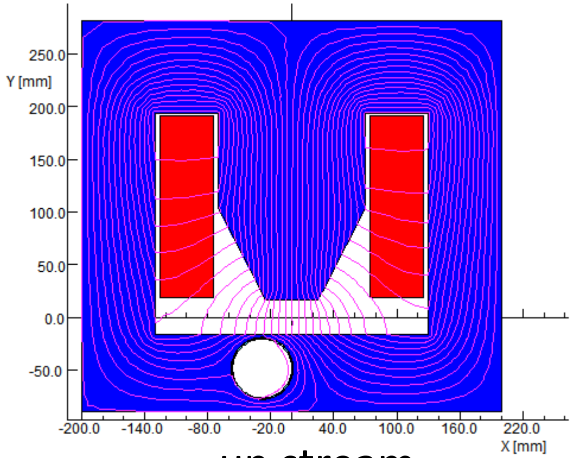


- Conclusions：
  - If main field=1T， the shielding structure don't meet requirements with any materials
  - If main field=0.9T， the shielding structure do meet requirements with DT4 vacuum chamber
  - If main field=0.8T， the shielding structure do meet requirements with any materials

➡ The main field strength is preferred less than 0.8T



down stream



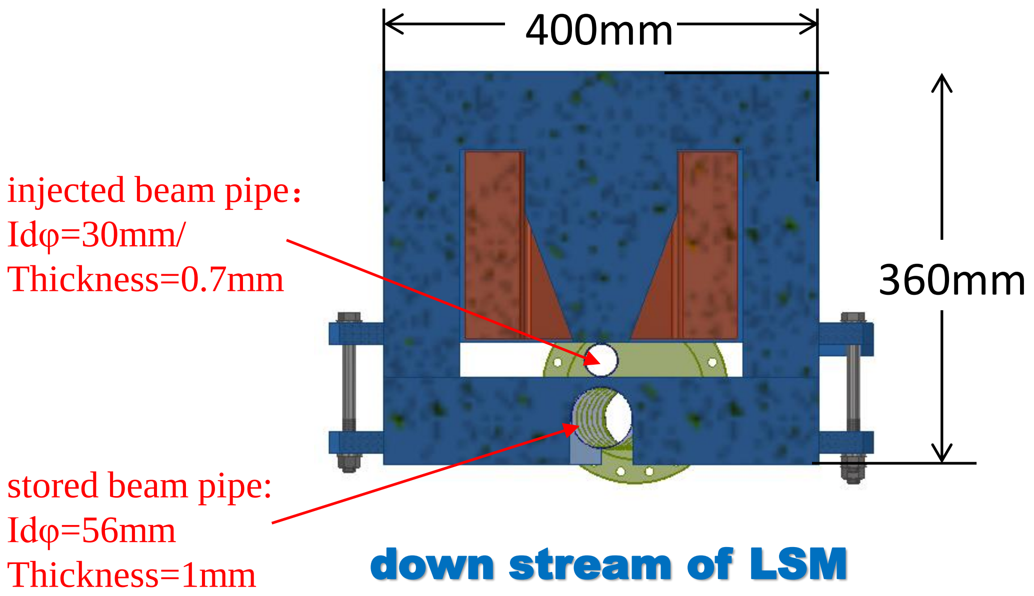
up stream

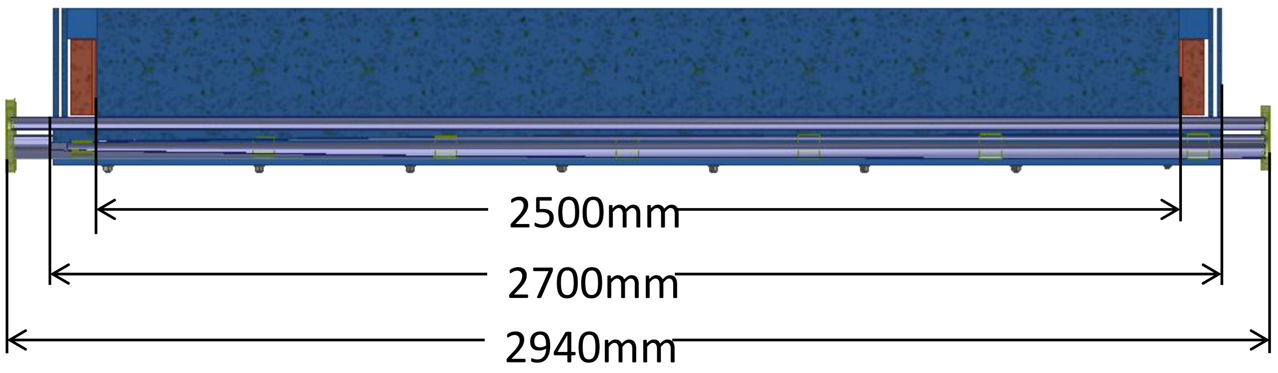
	Material of stored beam pipe	Air (Stainless Steel or copper)			1J77A			DT4			1J22
Down stream	Main field By (T)	0.80	0.89	0.999	0.8007	0.900	1.011	0.8010	0.903	1.023	1.027
	Leakage field By (T）	5.06E-04	4.69E-03	1.51E-02	1.07E-06	1.53E-03	1.10E-02	2.52E-05	2.76E-04	5.94E-03	4.46E-03
	Leakage field Bx (T）	3.03E-07	-1.99E-06	-1.76E-05	2.57E-10	-5.76E-06	6.33E-04	4.89E-09	6.06E-04	6.66E-04	6.78E-04
	Leakage field By/main field By	6.33E-04	5.25E-03	1.51E-02	1.34E-06	1.70E-03	1.08E-02	3.15E-05	2.76E-04	5.94E-03	4.46E-03
Up stream	Main field By (T)	0.80	0.905	1.037	0.8007	0.905	1.039	0.8010	0.905	1.040	1.040
	Leakage field By (T）	5.06E-04	8.39E-04	5.89E-03	1.07E-06	3.63E-06	1.58E-03	2.52E-05	2.99E-05	4.27E-04	2.63E-04
	Leakage field Bx (T）	3.03E-07	2.45E-04	-5.83E-03	2.57E-10	2.13E-06	-2.22E-03	4.89E-09	-3.37E-04	-1.25E-03	-1.10E-03
	Leakage field By/main field By	6.33E-04	9.26E-04	5.68E-03	1.34E-06	4.01E-06	1.52E-03	3.15E-05	3.30E-05	4.11E-04	2.53E-04

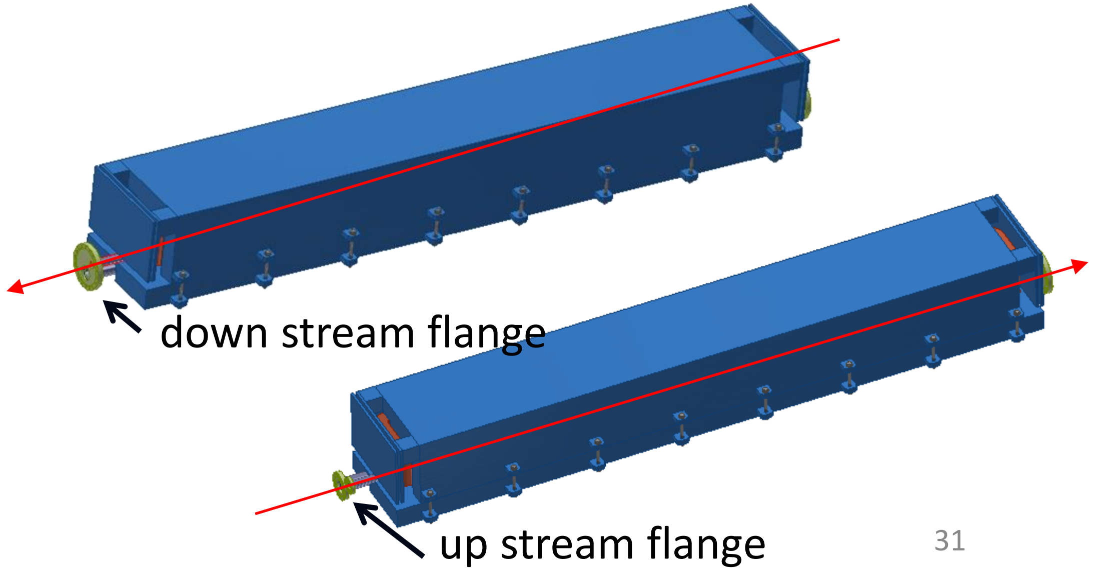
Data In red represent not meeting requirements

Preliminary mechanical design of LSM

- The mechanical length of a single magnet is must less than **2.7 meters**, mainly considering the following points:
  - Machining and manufacturing capability of the magnet core(solid iron + deep hole drilling)
  - Assembly and alignment errors of the magnet
  - Weight considerations for individual magnets
  - Processing, assembly and vacuum achievement of beam pipes
  - Measurement of the magnetic field (Hall point measurement)





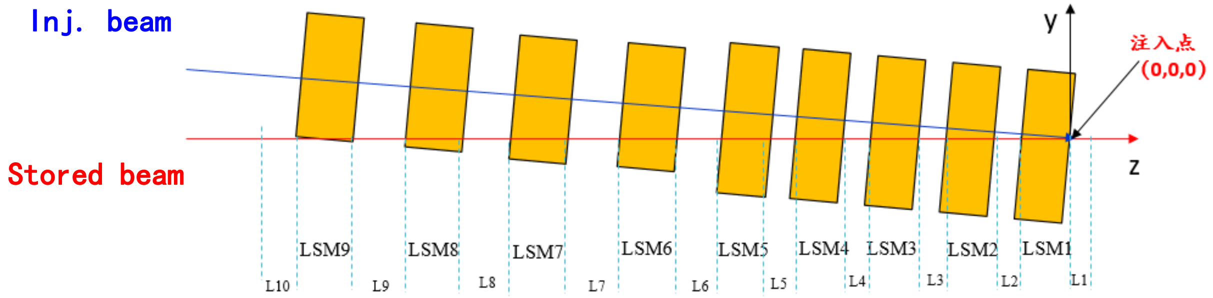


Magnet designs of all of LSMs for CEPC

Sub-system	DR inj&ext	BST LE inj	BST ext. (on-axis)	BST ext. (off-axis)	BST HE re-inj.	BST ext. to dump	CR off-axis inj.		CR on-axis inj.		CR on-axis ext.		CR ext. to dump
Type	H-in air	H-in air	V-in air	V-in air	V-in air	H-in air	V-in vac	V-in air	V-in vac	V-in air	V-in vac	V-in air	H-in air
Thickness of septum(mm)	6	10	10	10	10	5	2	3.5	2	3.5	2	3.5	5
Quantity per group	1	3	7	7	8	7	4	4	5	4	5	4	8
Deflection angle (m rad)	120	15	3	3	2.5	3	2	3	2	2.5	2	2.5	2.5
Gap of magnet(mm)	20	36	20	20	15	20	20	20	15	15	15	15	15
Integral main field strength (T*mm)	440	1500	1800	1800	1500	1800	1120	1800	1120	1500	1120	1500	1500
Field strength of magnet (T)	0.88	0.75	0.75	0.75	0.75	0.75	0.7	0.75	0.7	0.75	0.7	0.75	0.75
Magnetic effective length (mm)	500	2000	2400	2400	2000	2400	1600	2400	1600	2000	1600	2000	2000
Main field uniformity	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%	≤±0.05%
Integral leakage field/main field	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%	≤0.1%
Size of coil wire (mm)	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4	7x7 Ø4
Turn number of coil	96	224	144	144	80	144	108	144	56	80	56	80	80
Resistance of coil (m Ω)	68.25	519.73	519.73	519.73	170.69	375.8	195.78	375.8	99.55	173.69	99.55	173.69	170.69
Inductance of magnet(H)	0.06	0.73	0.65	0.65	0.22	0.65	0.24	0.65	0.09	0.22	0.09	0.22	0.22
Voltage drop (V)	10.04	50.12	31.94	31.94	19.54	31.32	20.3	31.32	14.93	19.54	14.93	19.54	19.54
Exciting current (A)	147.17	96.43	85	85	112.5	83.33	103.7	83.33	150	112.5	150	112.5	112.5
Power consumption (kW)	1.48	4.83	2.72	2.72	2.2	2.61	2.11	2.61	2.24	2.2	2.24	2.2	2.2
Current density of coil (A/mm²)	4.14	2.71	2.39	2.39	3.16	2.34	2.92	2.34	4.22	3.16	4.22	3.16	3.16
Pressure of cooling water (kg/cm2)	6	6	6	6	6	6	6	6	6	6	6	6	6
Number of water channel	4	14	12	12	10	12	9	12	7	10	7	10	10
Velocity of water flow (m/sec)	3.1	1.34	1.47	1.47	2.07	1.47	1.82	1.47	2.32	2.07	2.32	2.07	2.07
Flow of water (ml/sec)	0.31	0.23	0.22	0.22	0.26	0.22	0.21	0.22	0.2	0.26	0.2	0.26	0.26
Temperature rise (° C)	2.26	4.91	2.92	2.92	2.02	2.8	2.45	2.8	2.62	2.02	2.62	2.02	2.02
Length of magnet (mm)	700	2240	2600	2600	2200	2600	1940	2600	1940	2200	1940	2200	2200
Width of magnet (mm)	440	580	450	450	410	440	481	450	444	380	444	380	400
Height of magnet (mm)	340	500	440	440	400	450	580	440	580	400	580	400	410

Design example: LSMs for CR on-axis injection system

- e+ inj region： 9 sets of LSM
- LSM1~LSM5： half-in-vac (septum=2mm)
- LSM6~LSM8： in-air(septum=3.5mm)



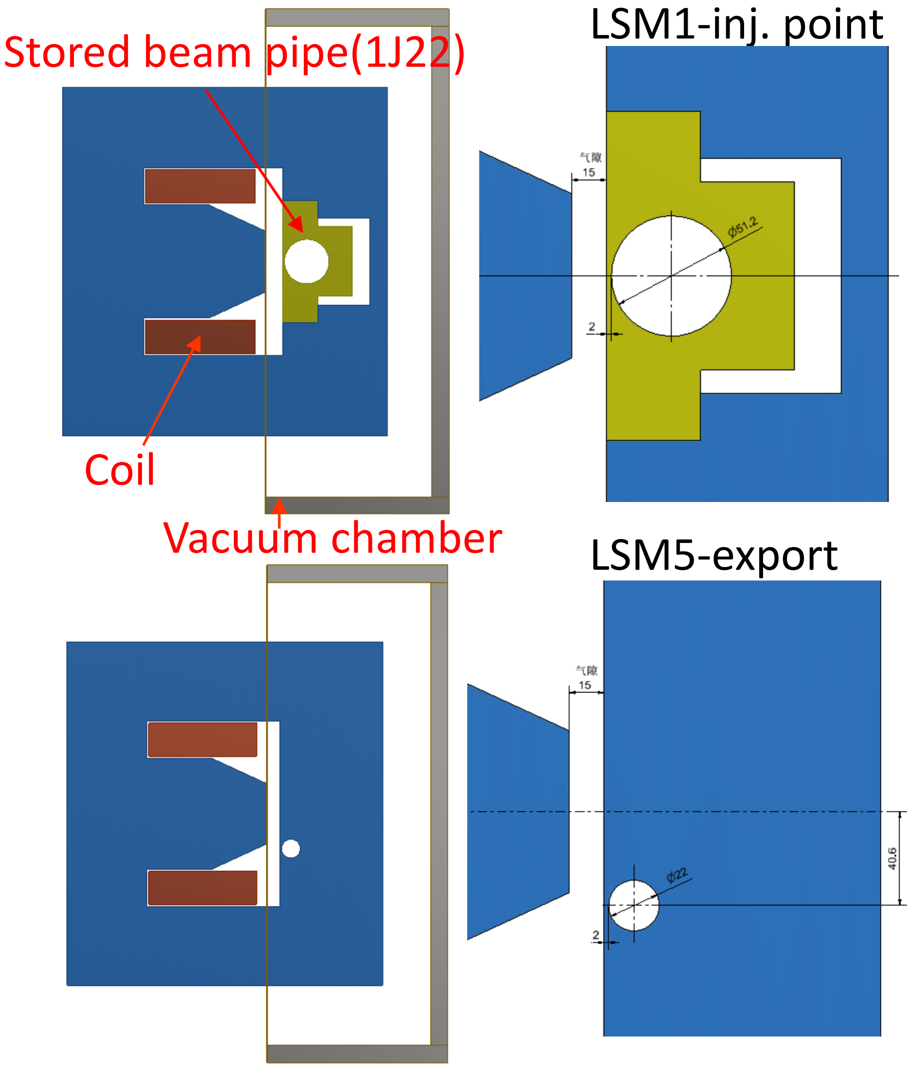
Length of straight section of inj. beam （mm）

L10	LSM8	L9	LSM8	L8	LSM7	L7	LSM6	L6	LSM5	L5	LSM4	L4	LSM3	L3	LSM2	L2	LSM1	L1
610	2000	820	2000	820	2000	820	2000	910	1600	750	1600	750	1600	750	1600	750	1600	600

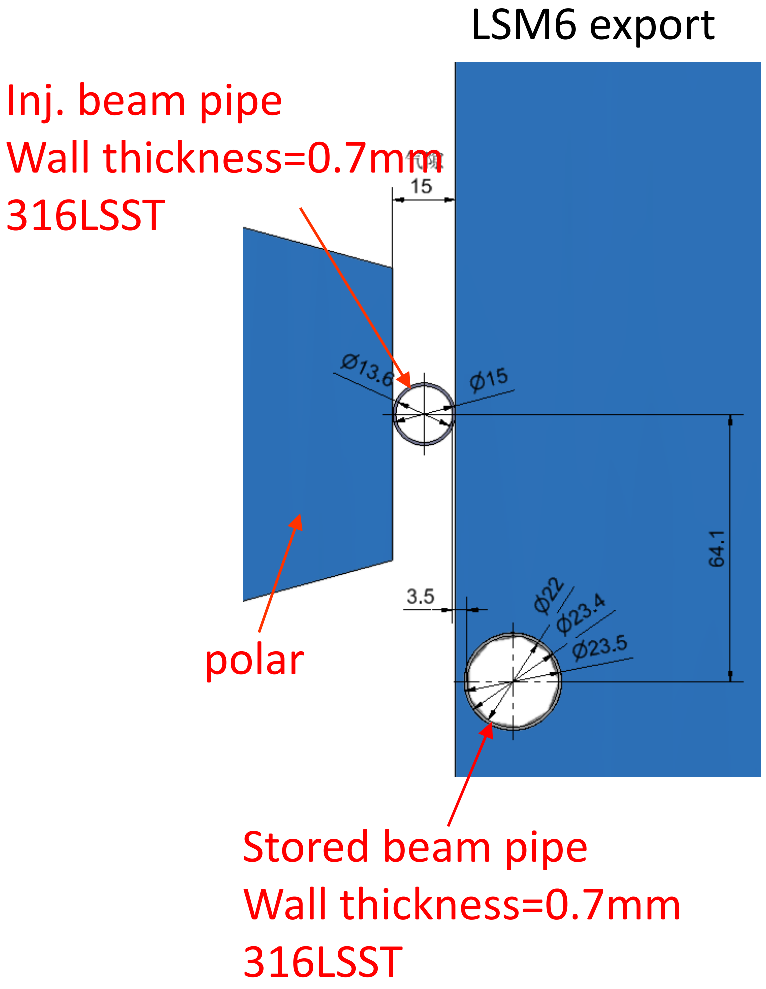
Mode	Higgs	tt
Energy （GeV）	120	180
Deflection direction	Vertical	
Total Integral field strength of septa (T-m)	7.733333	11.6
Total deflection angle (m rad)	20	
Deflection Radium (m)	800	
Magnetic field strength for injected/extracted beam (T)	0.46667/0.5	0.7/0.75
Total magnetic length (m)	16	
Septum thickness (incl. septum board, inj./ext. beam pipe wall, installation gap) (mm)	2/3.5	
Clearance of inj. beam at Lambertson (H×V) (w.r.t. inj. beam orbit) (mm)	6.6 x 4	
Field uniformity in clearance of inj. beam	< ±0.05%	
Clearance of stored beam at Lambertson (H×V) (w.r.t. stored beam orbit) (mm)	20 x 10	
Integral leakage magnetic field / Integral main magnetic field	$\leq 1 \times 10^{-3}$	
The leakage magnetic field position from septum plate in circulating tube (mm)	5.4	

The LSMs for CR on-axis injection

- **LSM1~LSM5: half-in-vacuum, septum=2mm**



- **LSM6~LSM9: in-air, septum=3.5mm**

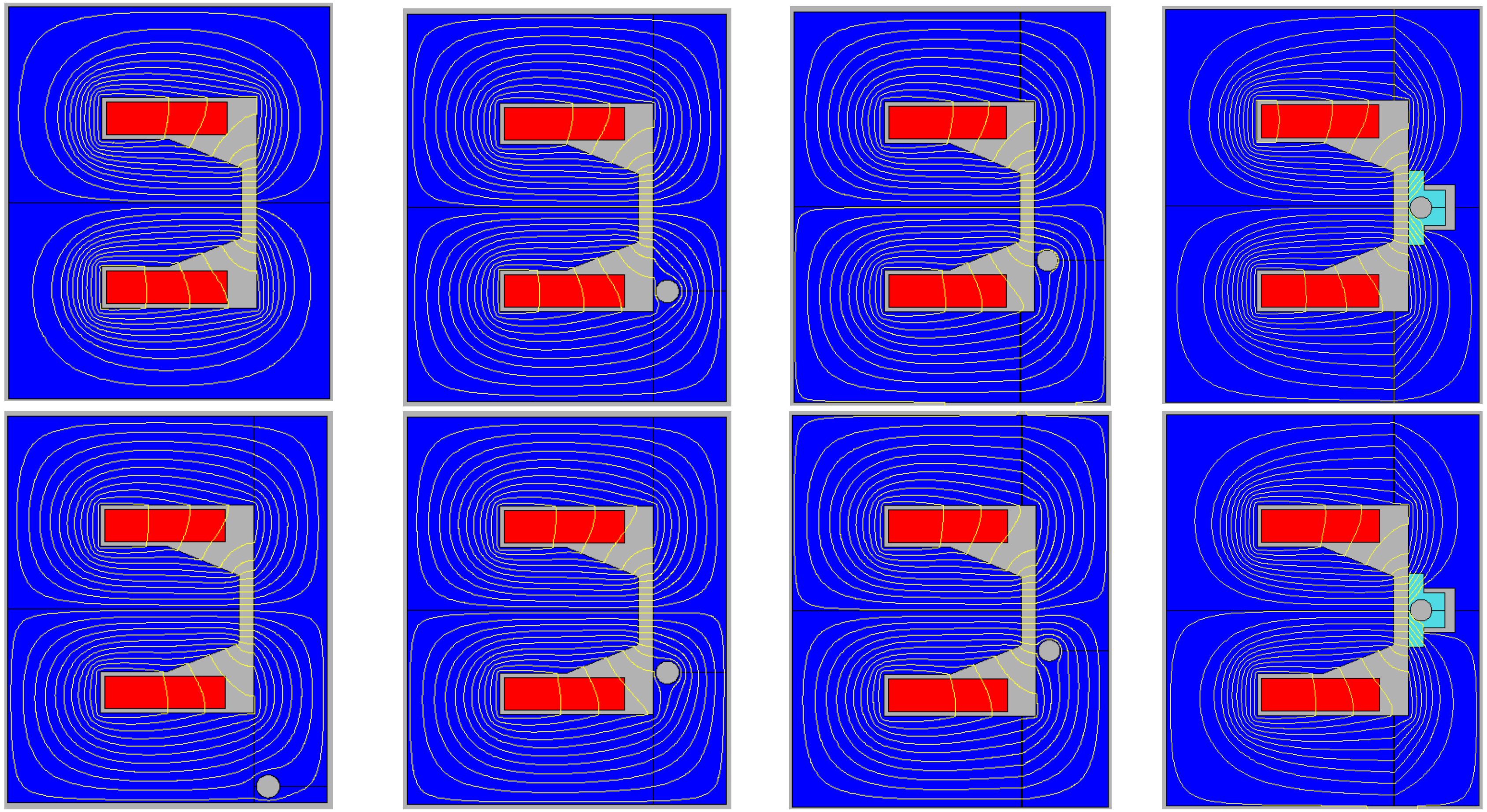


Physical design of the LSMs for CR on-axis injection

LSM8 LSM6 LSM5 LSM1

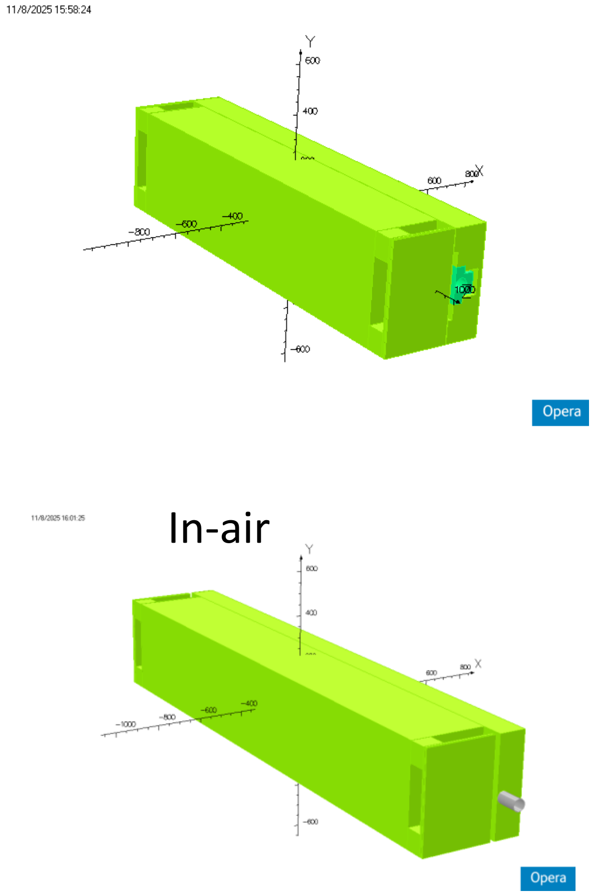
import

export



2D model in Opera

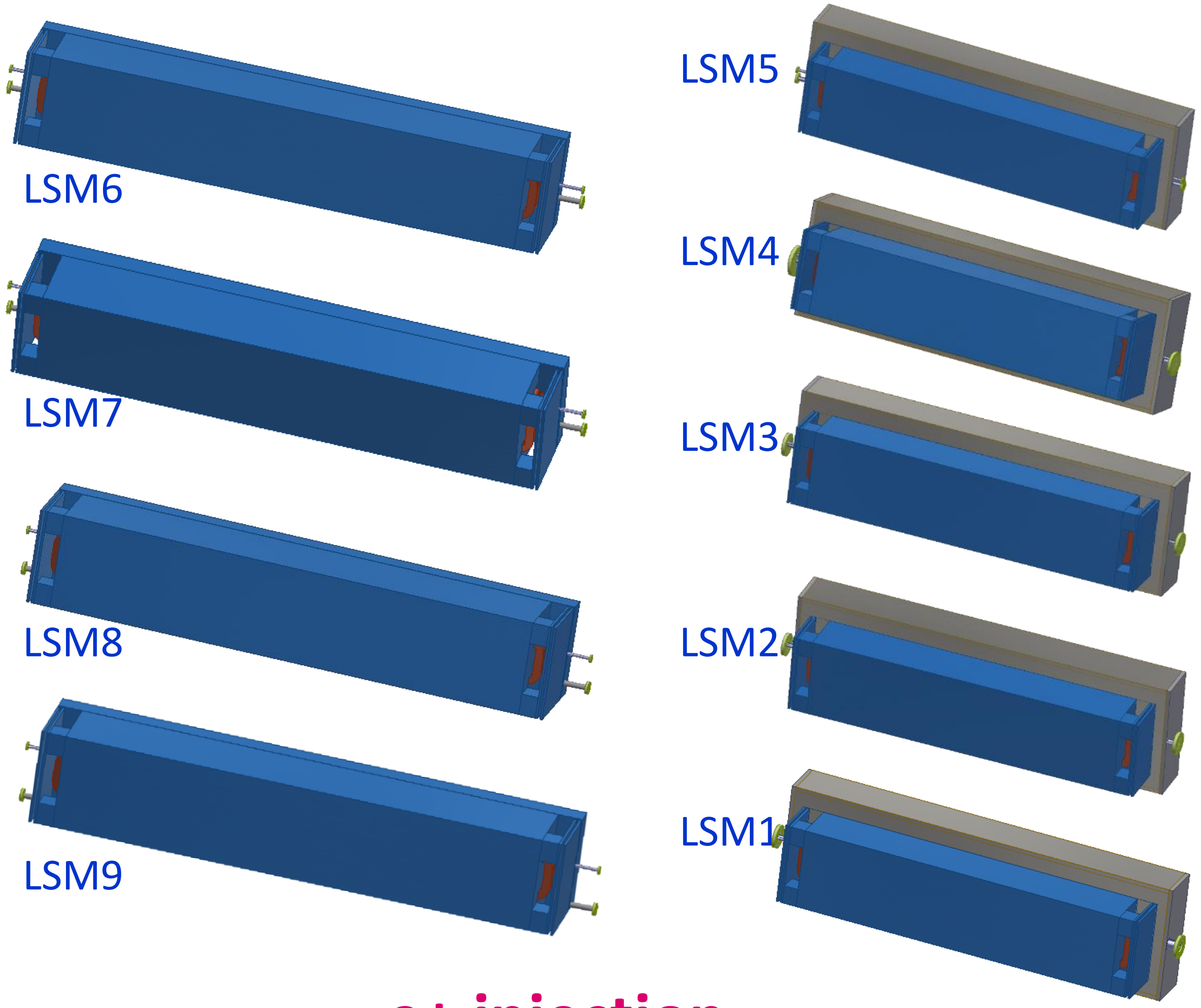
Half-in-vacuum



3D model in Opera

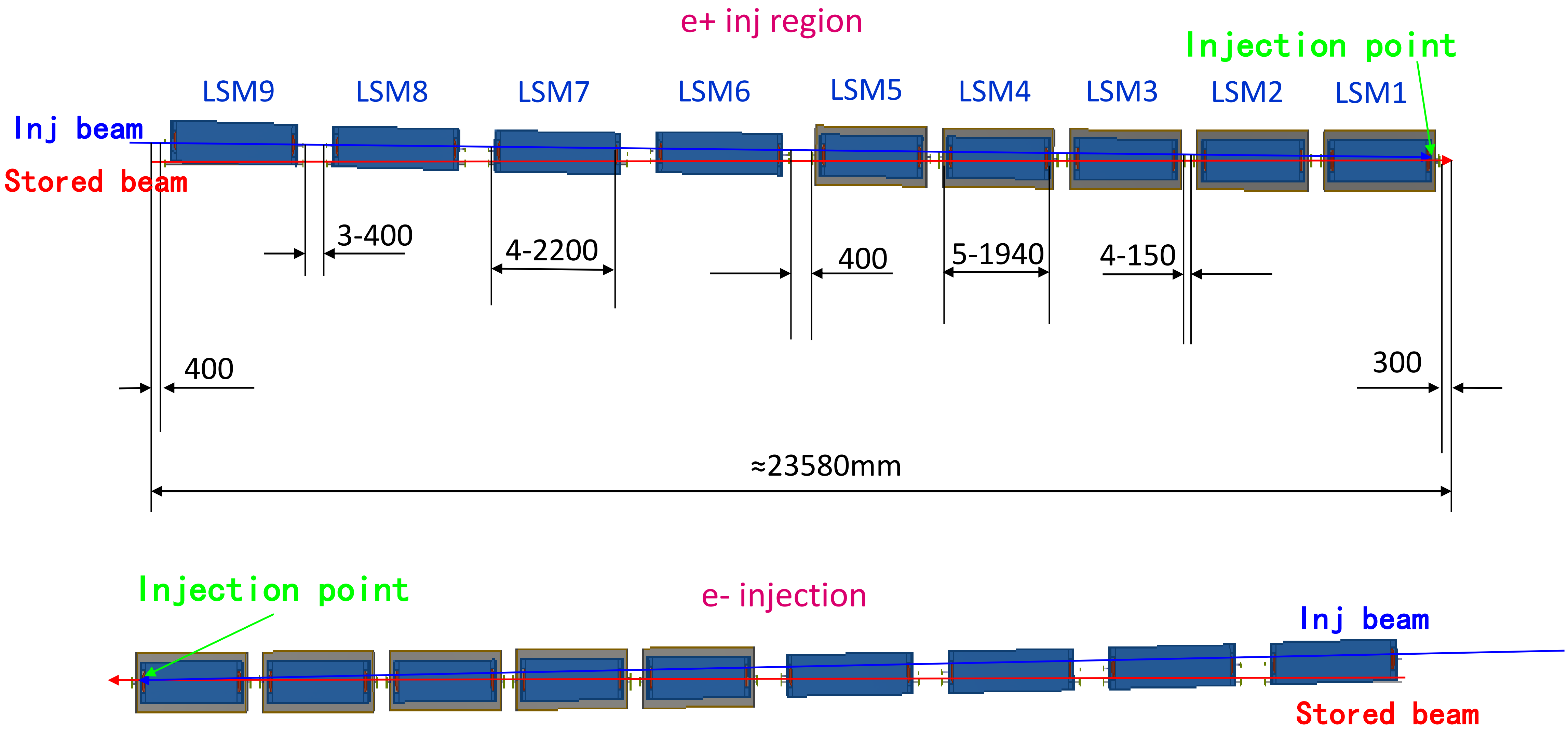
Mechanical design of LSMs for CR on-axis injection

Quantity per group	5	4
Thickness of septum (mm)	2	3.5
Deflection angle (m rad)	2	2.5
Gap of magnet(mm)	15	15
Integral main field strength (T*mm)	1120	1500
Field strength of magnet (T)	0.7	0.75
Magnetic effective length (mm)	1600	2000
Main field uniformity	≤±0.05%	≤±0.05%
Integral leakage field/main field	≤0.1%	≤0.1%
Size of coil wire (mm)	7x7 Ø4	7x7 Ø4
Turn number of coil	56	80
Resistance of coil (m Ω)	99.55	173.69
Inductance of magnet(H)	0.09	0.22
Voltage drop (V)	14.93	19.54
Exciting current (A)	150	112.5
Power consumption (kW)	2.24	2.20
Current density of coil (A/mm2)	4.22	3.16
Pressure of cooling water (kg/cm2)	6	6
Number of water channel	7	10
Velocity of water flow (m/sec)	2.32	2.07
Flow of water (ml/sec)	0.20	0.26
Temperature rise (° C)	2.62	2.02
Length of magnet (mm)	1940	2200
Width of magnet (mm)	444	380
Height of magnet (mm)	580	400



e+ injection

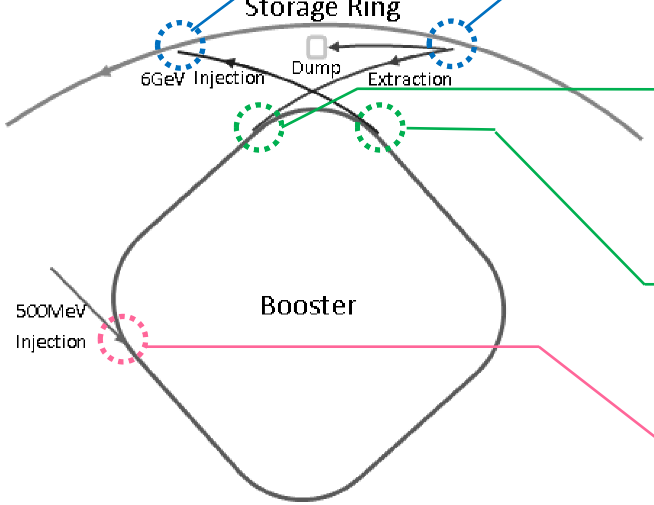
Layout of 9 LSMs in CR on-axis injection region



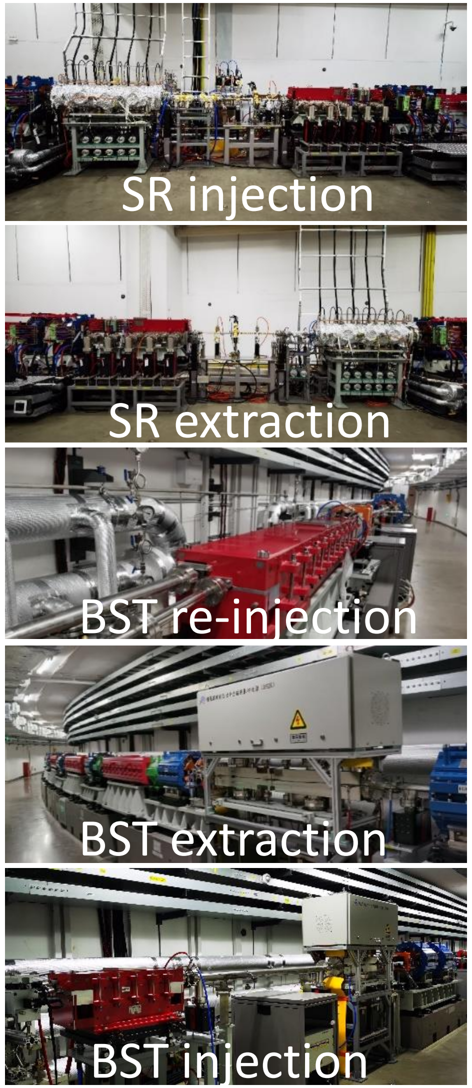
5 Inj. & ext. tech. demonstration in HEPS beam commissioning

High Energy Photon Source

Overview of injection & extraction system of HEPS



- BTS: **SR 6GeV injection system**/WBS:AB-0102 (Bunch by bunch/for on-axis swap-out or longitudinal injection)
- STB: **SR 6GeV extraction system**/WBS:AB-0101 (Bunch by bunch/for on-axis swap-out injection)
- STB**: BST 6GeV injection system**/WBS:AB-0203 (Pulsed local bump injection with 2 kickers)
- BTS: **BST 6GeV extraction system**/WBS:AB-0201 (Bunch by bunch/fast extraction with 4 slow bumpers assisted)
- LTB: **BST 0.5GeV injection system**/WBS:AB-0202 (Bunch by bunch/on-axis /one turn injection)

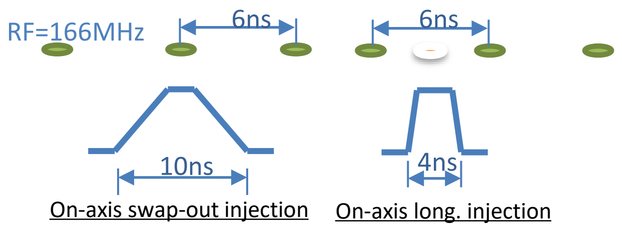


Highlight feature:

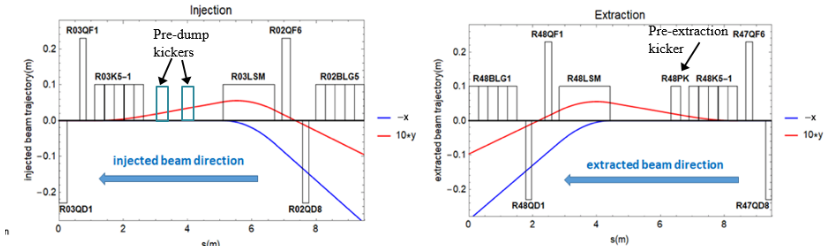
SR on-axis swap-out top-up injection based on beam accumulating in the full-energy booster.

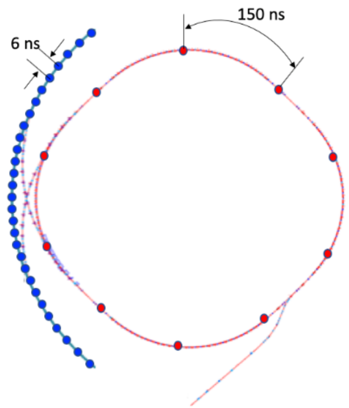
Challenges of HEPS inj. & ext. system

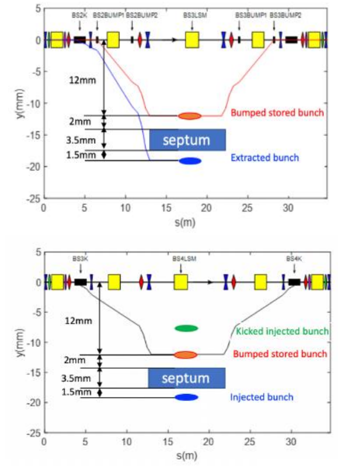
- Top-up injection physics solutions（due to small DA）:
  - short-term goal: on-axis swap-out injection with the full-energy BST as accumulating ring. **(baseline)**
  - Long-term goal: on-axis longitudinal injection with harmonic cavities.
- SR injection & extraction system:
  - 2 straight sections with length of only 6 meters applied to accommodate inj.&ext. components for 6 GeV beam manipulation.
  - Fast kicker system: 5-cell 300mm long strip-line kicker module with 8mm gap and **super fast pulser with pulse bottom width of 10ns/4ns (3%-3%), ±15kV peak voltage into 50Ω allowing to charge all the buckets.**
  - Thin septum: Half-in-vacuum Lambertson magnet with **septum as thin as 2mm**, high vacuum achievement with small beam physic aperture.
- BST injection & extraction system:
  - kicker system: slotted-pipe kicker with large physic aperture and **fast pulser with pulse bottom width of 300ns (at least 600ns, 10%-10%), 2.8kA peak current into 0.7μH** to inject 10 (at least 5) bunches into the BST ring in a cycling period.
  - Thin septum: Lambertson magnet with **thickness septum of 3.5mm**
  - Slow bumper: half-sine wave pulse with bottom width of 1ms and consistent waveform (only for extraction subsystem)



Electrical pulse for fast kicker







Hardware for HEPS injection & extraction system

Hardware	Type	Quantity	Typical parameters	Features	Status
BST kicker magnet	Slotted-pipe kicker	4+1	300ns/450ns/1us	In-vacuum	On-line operation
BST kicker pulser	Thyratron based	4+1	300ns/450ns/1us	Made in house	On-line operation
BST bump magnet	Laminated core	4	1ms	In-air	On-line operation
BST bumper pulser	IGBT based	4	1ms	Made in house	On-line operation
BST septum magnet	Lambertson	3	Septum=3.5mm	In-air/DC	On-line operation
SR septum magnet	Lambertson	2+1	Septum=2mm	Half in-vacuum/DC	On-line operation
SR kicker	Strip-line kicker	2	300mm/8mm/±15kV/V	5-cell module	On-line operation
SR pre-ext. kicker	Strip-line kicker	1	300mm/16mm/±8.4kV/H	In-vacuum	On-line operation
SR fast kicker pulser	DSRD+MOSFET based	22	10ns/±17kV	Made in house	On-line operation
SR fast kicker pulser	FID based	5	4ns/±20kV	Commercial	On-line operation
SR pre-dump kicker	Slotted-pipe kicker	2	4.5us/half sine/H+V	In-vacuum	On-line
SR pre-dump kicker pulser	IGBT based	2	4.5us/half sine	Made in house	Off-line test

- **Most of the hardware technologies are applied in the CEPC.**

Milestone of inj. & ext. system installation and commissioning

- 2023/02/09: To complete 4 bumpers,BS1LSM,BS1K,BS2k,BS3K,BS4K installation
- 2023/06/06: To complete BS1K pulser installation and commissioning
- 2023/07/23: Success in BST 1st phase beam commissioning with BST LE injection system
- 2023/10/23: To complete BS2K,BS3K,BS4K,4 bumpers pulsers installation and commissioning
- 2023/12/18: To complete BS3LSM,BS4LSM installation
- 2024/05/17: Success in BST beam extraction commissioning
- 2024/05/29: To accept all hardware of SR inj.&ext. and enter final installation stage
- 2024/07/01: To complete vacuum connection of all SR devices
- 2024/07/23: Success in SR 1st phase beam commissioning with the backup kicker(450ns)
- 2024/08/24: Success in SR extraction to dump with fast kickers (10ns)
- 2024/09/12: Success in SR 2nd phase beam commissioning with the final kickers(10ns)
- 2024/12/25: Success in SR extraction to BST with fast kickers (4ns)
- 2024/12/28: Success in BST full-energy re-injection
- 2025/01/02: Success in on-axis swap-out injection with beam accumulating by full-energy BST
- 2025/09/26: HEPS accelerator passing national acceptance testing successfully

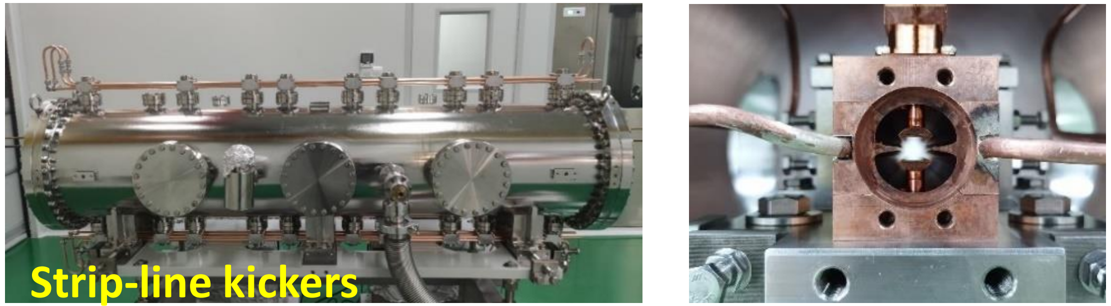
HEPS IAC review report 2025

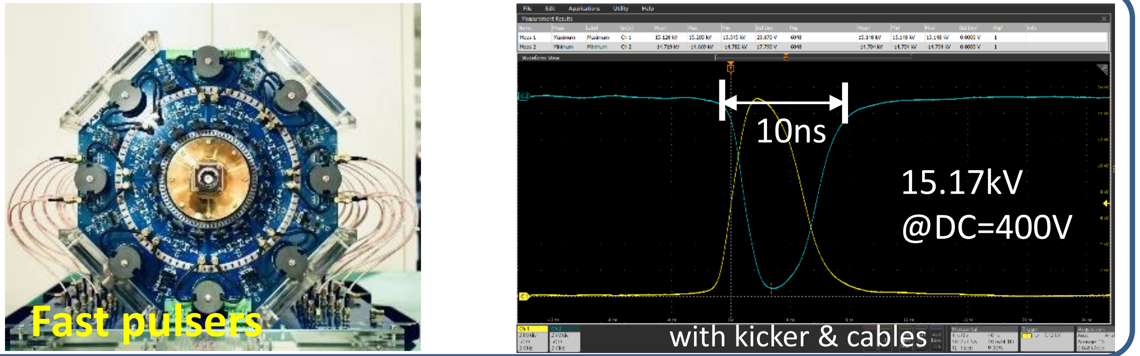
HEPS IAC review report in Jan.2025

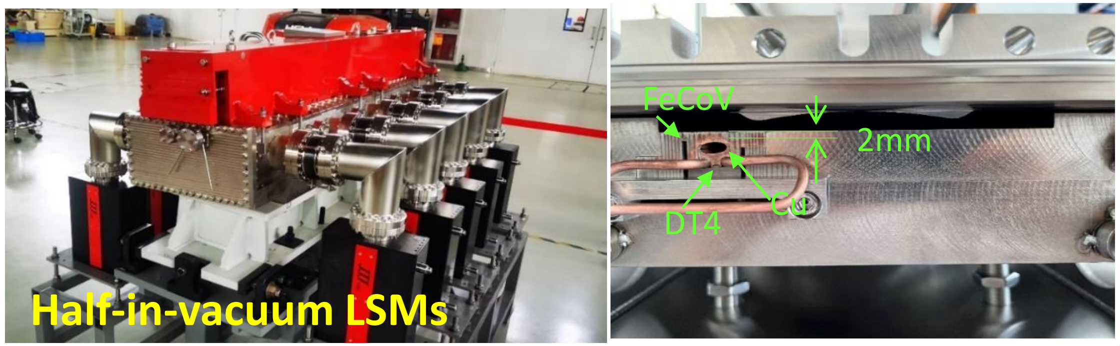
Status and Commissioning Progress of HEPS Accelerator (Ping He)

Comments / Findings

- Impressive progress was made since 2018.
    a. Linac and booster commissioned
    b. Outstanding advances in ring commissioning
    c. swap-out injection/extraction, a critical concern of the past, now in routine operation
    d. measured emittance reached x+y = 80 pm-rad
- Two most demanding tasks, accomplished only by careful dedicated team work.
- Demonstrated confidence to take on and complete innovations
    a. 166 MHz SRF, swap-out injection, AK, Mango undulators, fast pulsers, half-in-vacuum Lambertson







Summary

- The inj. & ext. system layout designs and hardware designs for the CEPC were discussed.
- The layout and hardware design iteration of CEPC inj.&ext. system has be updated, including kickers and Lambertson magnets. The preliminary mechanical designs of the most magnets with dimensions were presented.
- Most key inj. & ext. technologies applied in the CEPC were demonstrated in the HEPS beam commissioning.

END

Thank you for attentions!