CEPC Injection/Extraction Hardware Design Towards TDR

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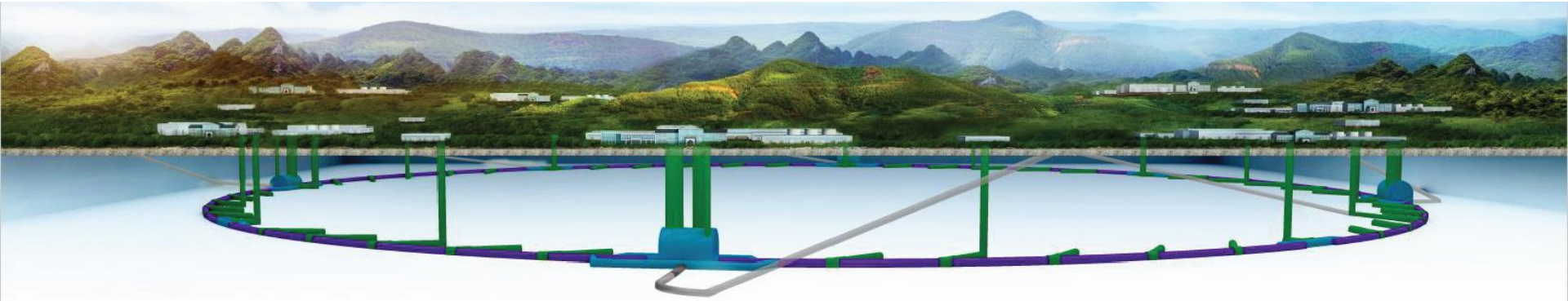
Injection group

2021-1-20



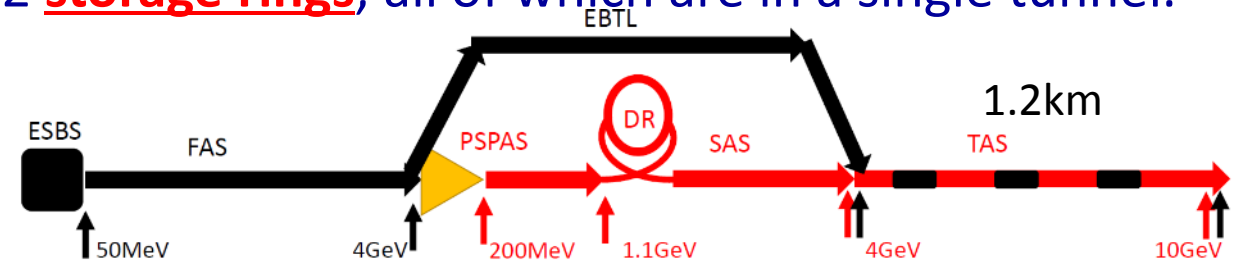
Outline

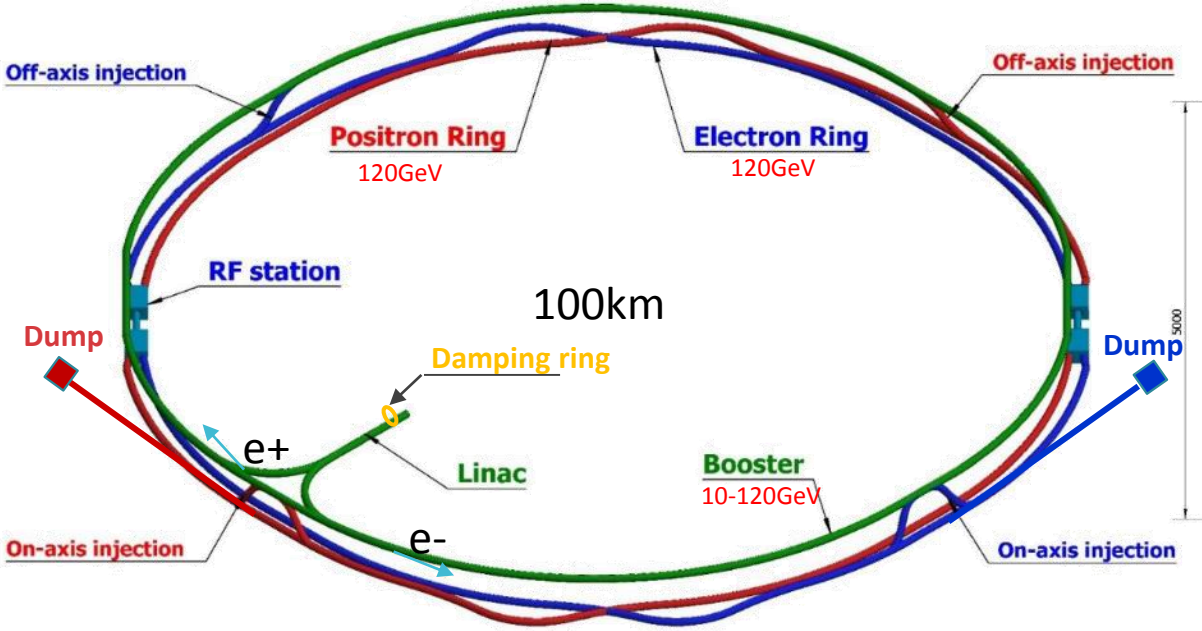
1. Overview of CEPC Inj./Ext. systems
2. DR Inj./Ext. system hardware design towards TDR
3. BST LE inj. system hardware design towards TDR
4. BST HE ext. system hardware design towards TDR
5. Summary

Overview of the CEPC injection and extraction systems

Layout of the accelerator complex

The CEPC accelerator complex consists of a **Linac**, which including a small **damping ring** for positron beams, several **transport lines**, a **booster ring** and 2 **storage rings**, all of which are in a single tunnel.





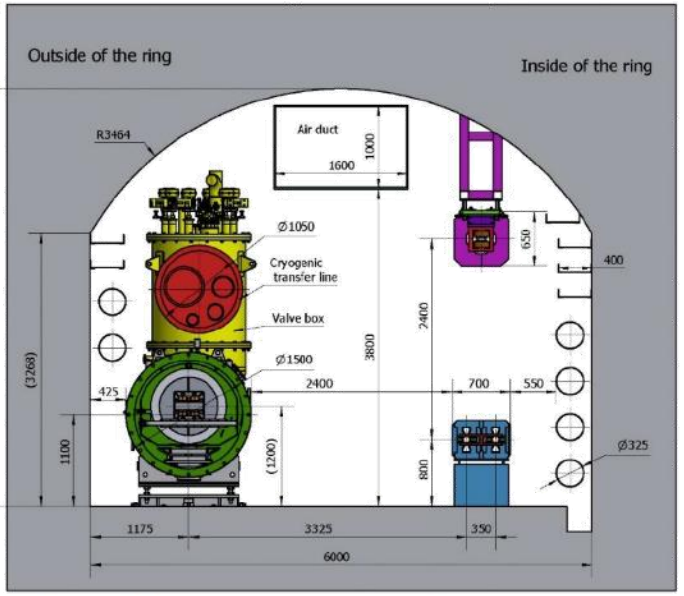


Figure 2.1: Tunnel cross section in the arc region

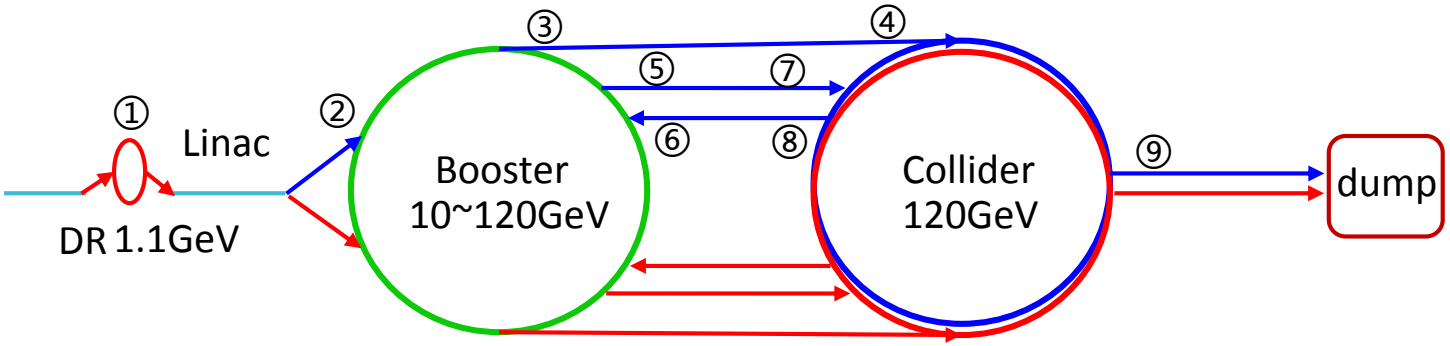
CEPC injection and extraction systems

There are 9 injection and extraction sub-systems in CEPC accelerator complex, 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-)

→ Off-axis injection (in W and Z mode)

→ On-axis injection (only in Higgs mode)

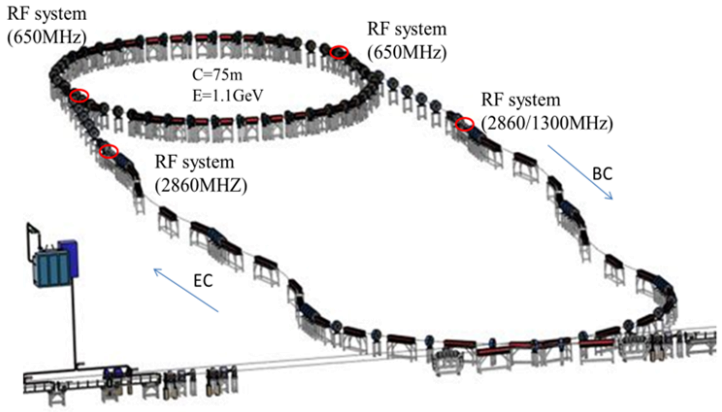


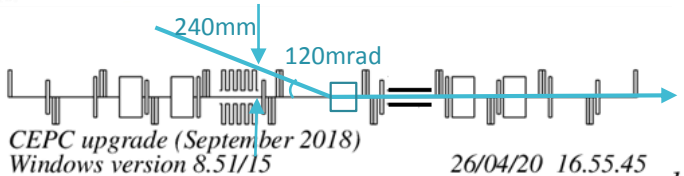
Main types of inj.&ext. hardware

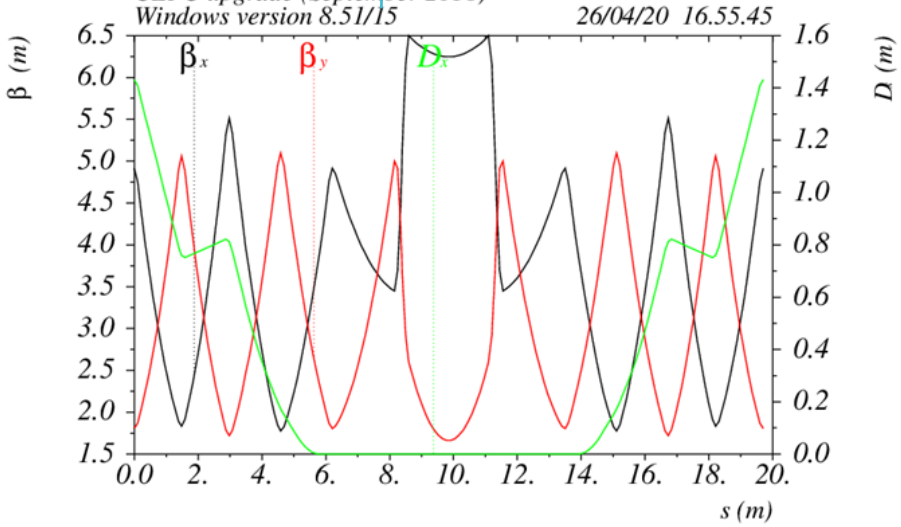
	Sub-system	Kicker Type	Kicker waveform	Septa Type	Thickness of septum
1	Damping ring inj./ext.	Slotted-pipe kicker	Half-sine/250ns	Horizontal LMS	ϕ22/3.5mm
2	Booster LE inj.	Strip-line kicker	Half-sine/50ns	Horizontal LMS	ϕ55/5.5mm
3	Booster ext. for CR off-axis inj.	Delay-line dipole kicker	Trapezoid /440-2420ns	Vertical LMS	Φ55/6mm
4	Collider off-axis inj.	Delay-line NLK kicker	Trapezoid /440-2420ns	Vertical LMS	Φ75x56/2mm
5	Booster ext. for CR on-axis inj.	Ferrite core dipole kicker	Half-sine/1360ns	Vertical LMS	Φ55/6mm
6	Booster HE inj.	NLK or Pulsed sextupole	Half-sine/0.333ms	Vertical LMS	Φ55/6mm
7	Collider swap out inj.	Ferrite core dipole kicker	Half-sine/1360ns	Vertical LMS	Φ75x56/6mm
8	Collider swap out ext.	Ferrite core dipole kicker	Half-sine/1360ns	Vertical LMS	Φ75x56/6mm
9	Collider beam dump	Delay-line dipole kicker	Trapezoid /440-2420ns	Vertical LMS	Φ75x56/6mm
10	RF region beam separating	Delay-line dipole kicker	CW square / 165us,50%	Horizontal Copper septa	Φ75x56/10mm

DR Inj./Ext. system hardware design towards TDR

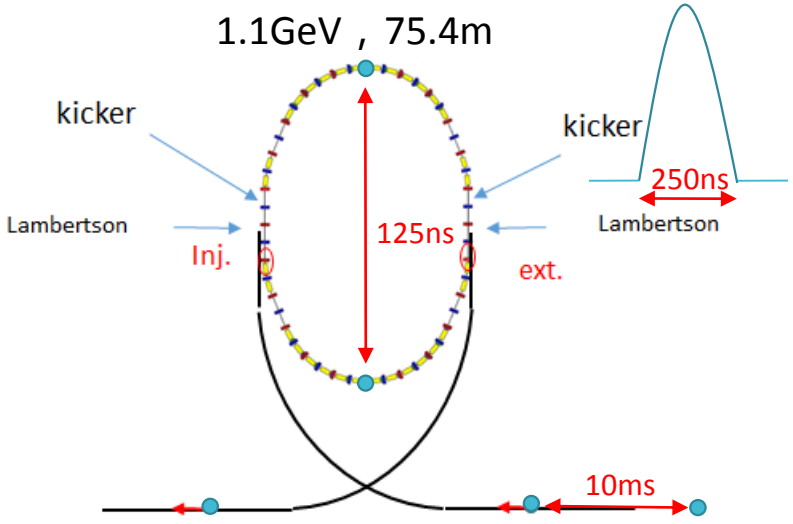
Damping ring injection and extraction system





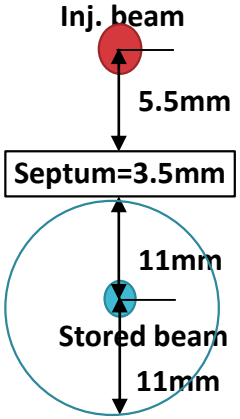


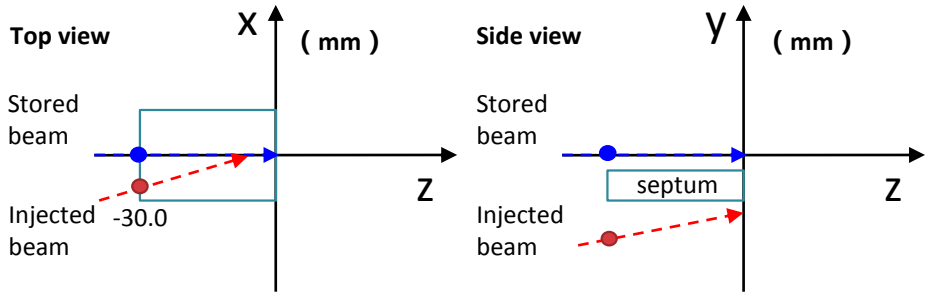
- Damping ring is dedicated to decrease emittance of positron beams
- Double bunches are stored at the same time
- On-axis bunch-by-bunch injection
- Hardware：Vertical slotted-pipe kicker、horizontal LSM



LSM requirements for DR

Parameters	Unit	DR-LSM
Quantity	-	2
Energy	GeV	1.1
Horizontal deflection angle	mrad	120
Insertion length	m	0.5
Magnetic field strength for injected/extracted beam	T	0.883
Min. Septum thickness（including septum board, inj./ext. beam pipe wall, installation gap)	mm	3.5
Field uniformity	-	<±0.05%
Leakage field	-	≤1×10^{-3}
Clearance of stored beam at lambertson（H×V）（refer to stored beam orbit）	mm	36.4×22
Clearance of inj.&ext. beam at lambertson（H×V）（refer to inj.&ext. beam orbit）	mm	22×11
Physical aperture of stored beam vacuum chamber	mm	22×22

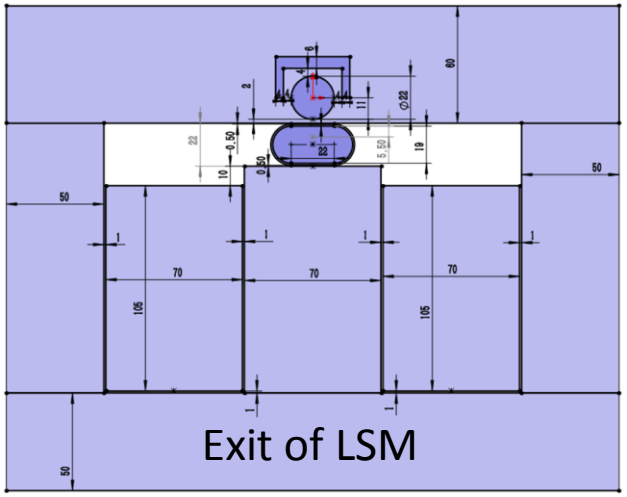


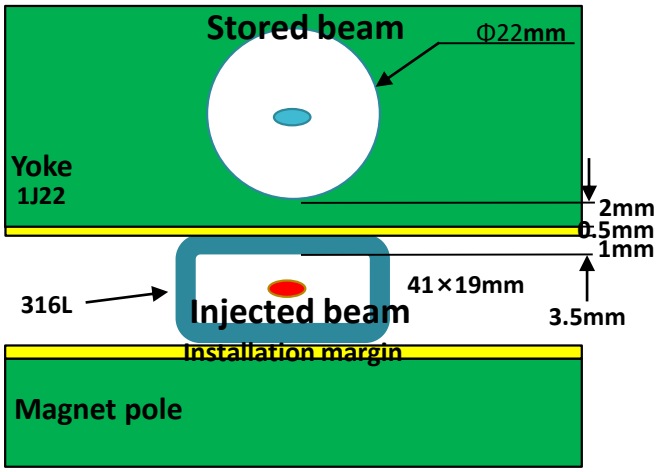


Injected beam	X(mm)	Y(mm)	Z(mm)
LSM in	-30.0	-23.75	-500.0
LSM out	0	-20	0

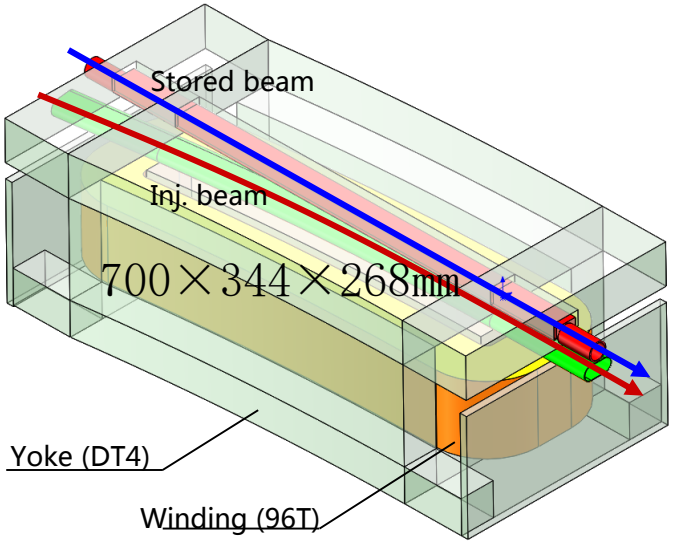
Stored beam	X(mm)	Y(mm)	Z(mm)
LSM in	0	0	-500.0
LSM out	0	0	0

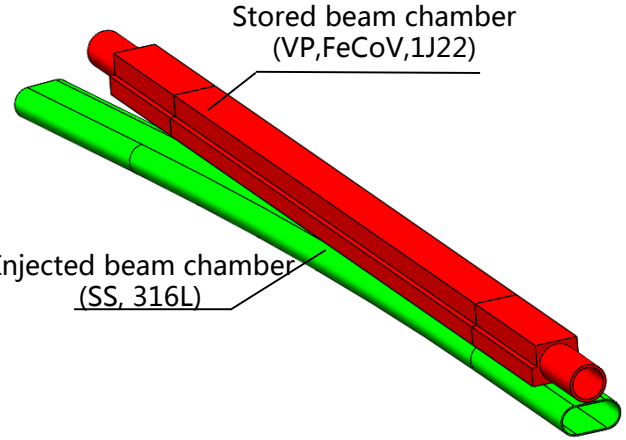
LSM physics design



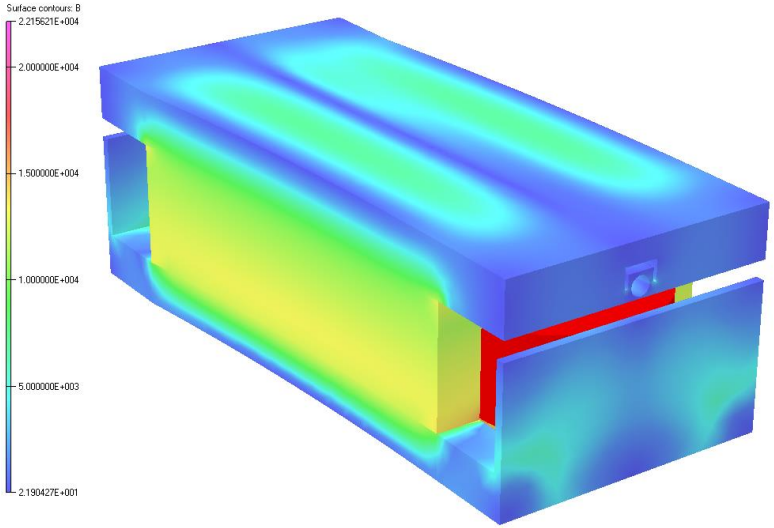


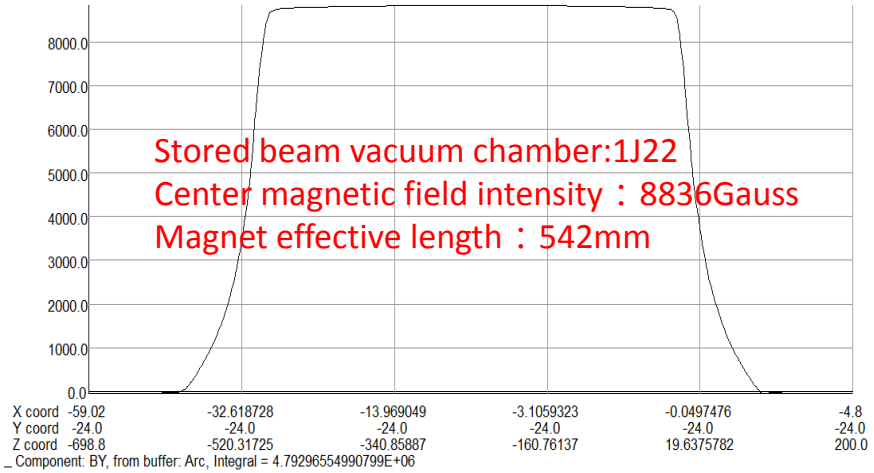
- Stored beam pipe(VP) inner diameter= ø22mm, Thickness=2mm
- Injected beam pipe (SS): W=41mm, H=19mm, Thickness=1mm
- Septum Thickness=2+1+0.5=3.5mm
- Magnet gap: 22mm
- Winding: W=70mm,H=105mm,T=96
- Exciting current=166A
- Inductance=0.0228H





3D simulation

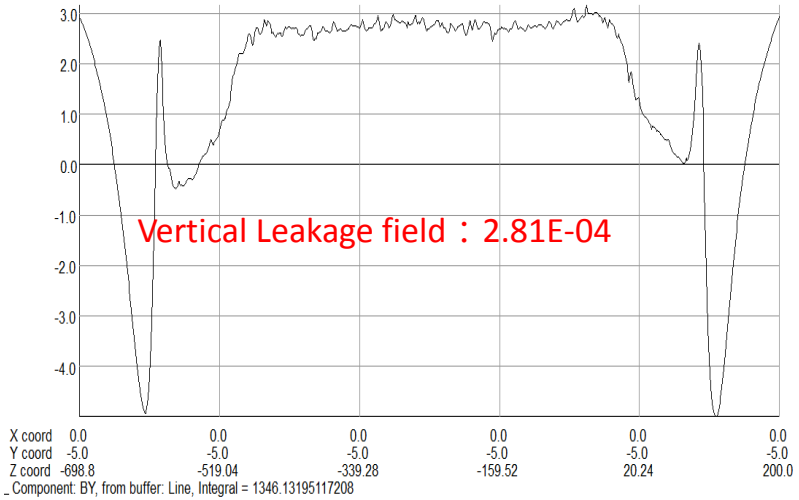




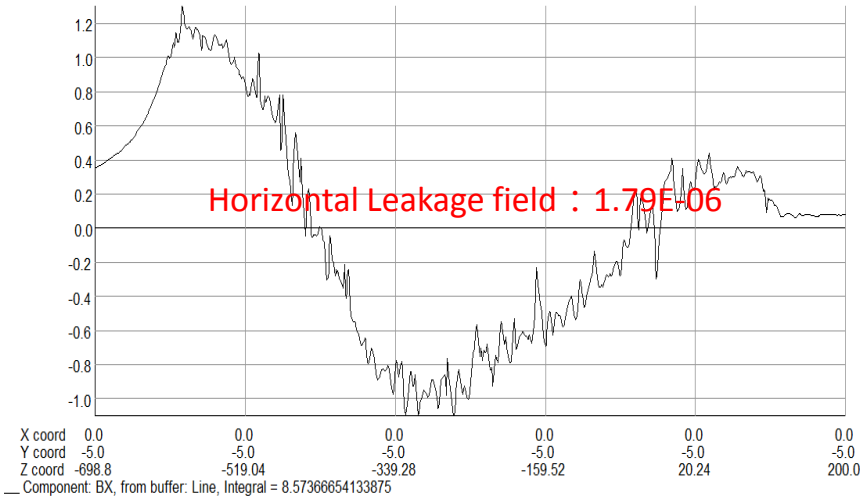
Stored beam vacuum chamber:1J22

Center magnetic field intensity：8836Gauss

Magnet effective length：542mm



Vertical Leakage field：2.81E-04



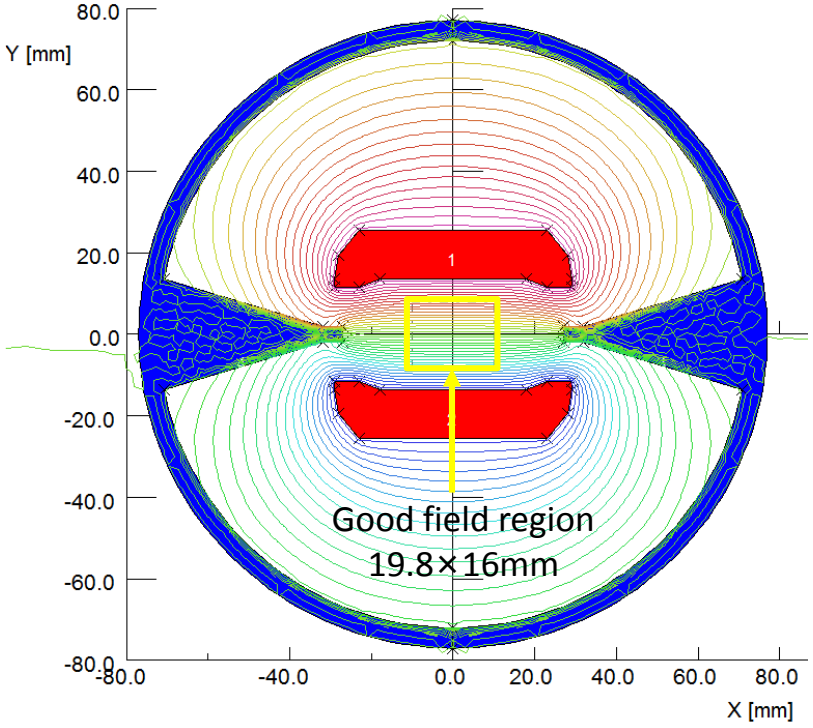
Horizontal Leakage field：1.70E-06

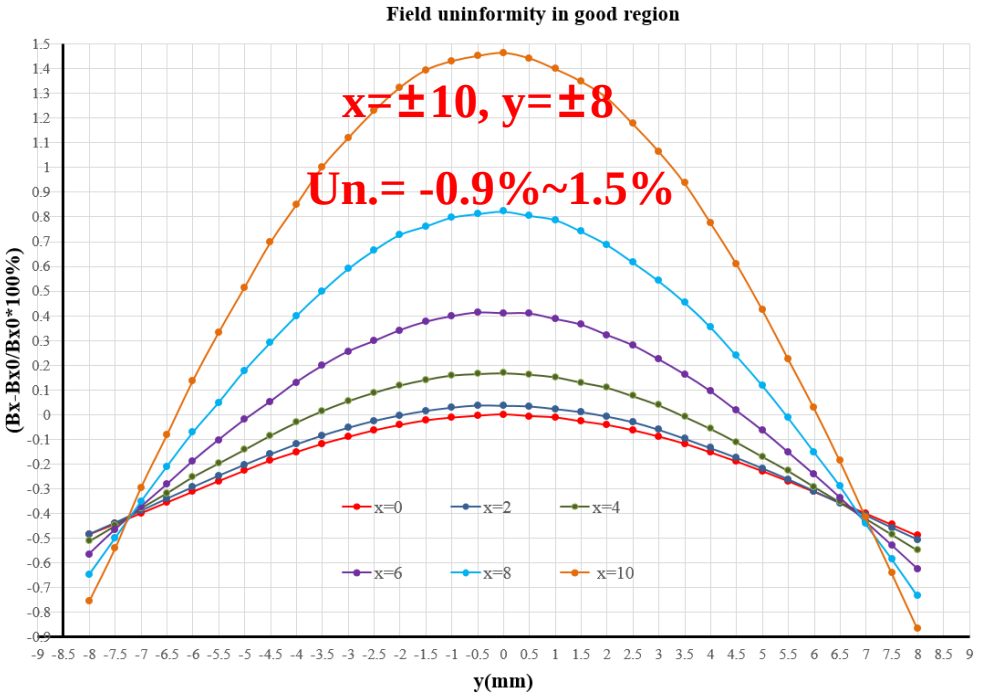
DR inj./ext. kicker design parameters

parameter	Unit	DR-kicker
Quantity	-	2
Type	-	Slotted-pipe kicker
Deflect direction	-	Vertical
Beam Energy	GeV	1.1
Deflect angle	mrad	10.7
Magnetic effective length	m	1.4
Magnetic strength	T	0.0281
Integral magnetic strength	T·m	0.03934
Clearance region(H×V)	mm	32.8×26.6
Good field region(H×V)	mm	19.8×16
Field uniformity in good field region	-	±1.5%
Repetition rate	Hz	100
Amplitude repeatability	-	±0.5%
Pulse jitter	ns	≤5
Bottom width of half sine pulse(5%-5%)	ns	< 250

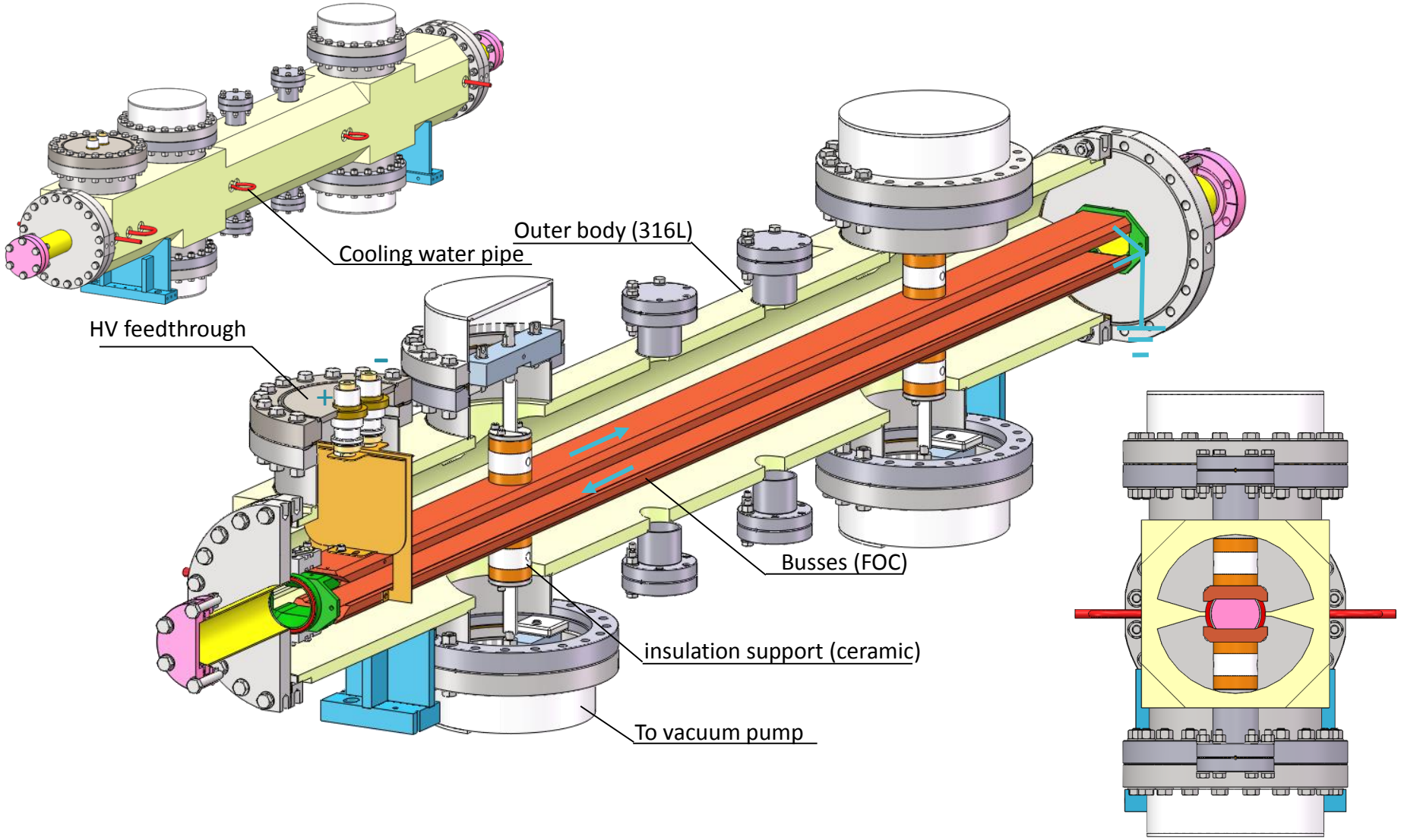
Magnet physics design

- 2D simulation model
- Max. voltage of coil: Umax=10622V
- Max. exciting current: Imax=2400A
- Magnet coil inductance=387nH
- Good field region: 19.8×16mm
- Field uniformity: -0.9%~1.5%



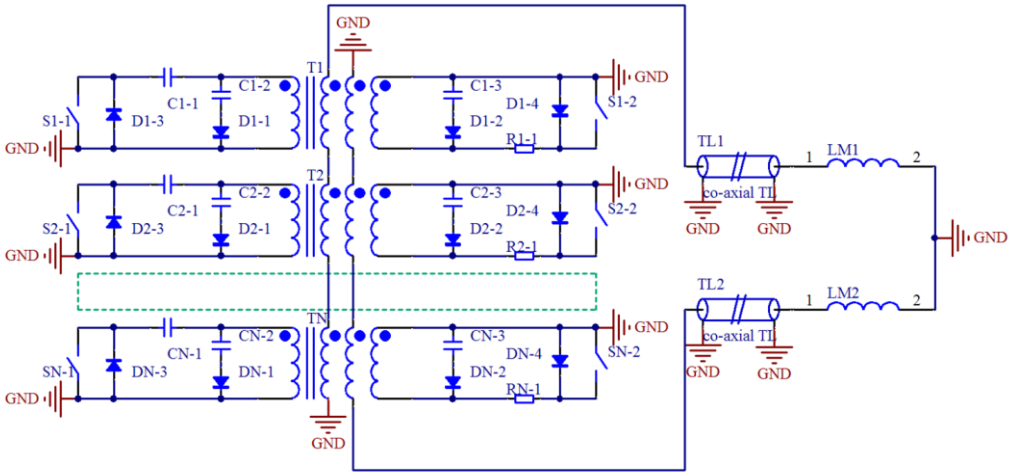


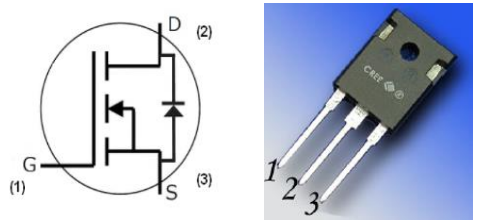
Slotted-pipe kicker engineer design

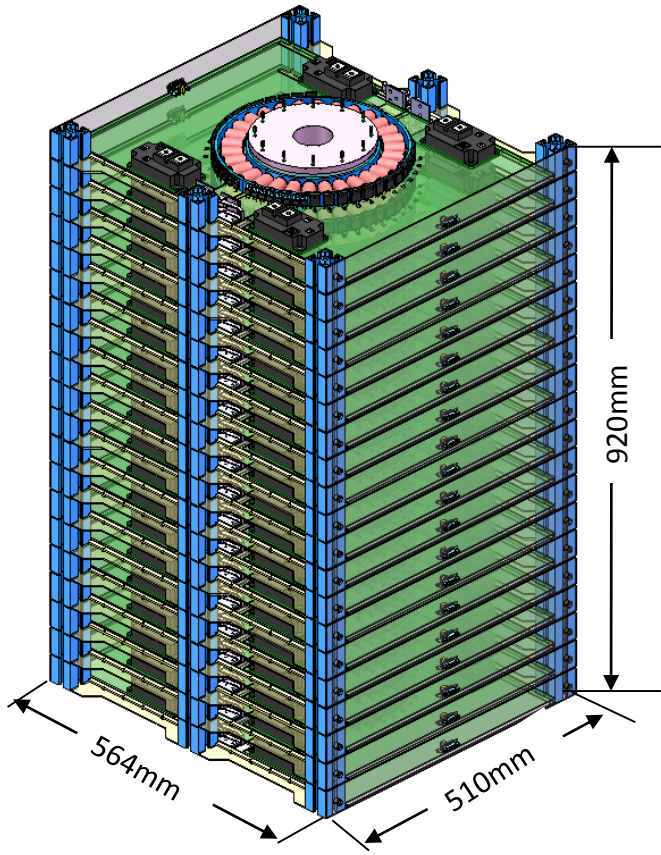


250ns-fast kicker pulser design

- 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 cables with length of 30m are applied to connect to kicker.
- Due to short end of the slotted-pipe kicker, the reflection energy should be return to the pulser.
- A proper absorption circuit must be designed at pulser end.





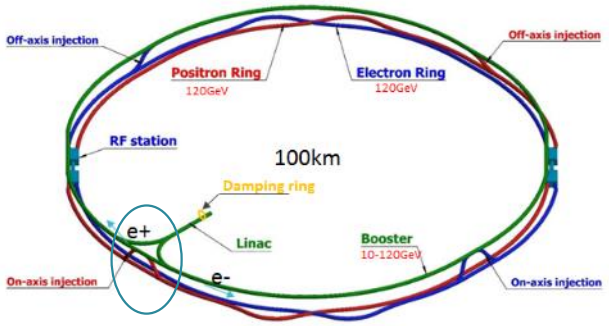


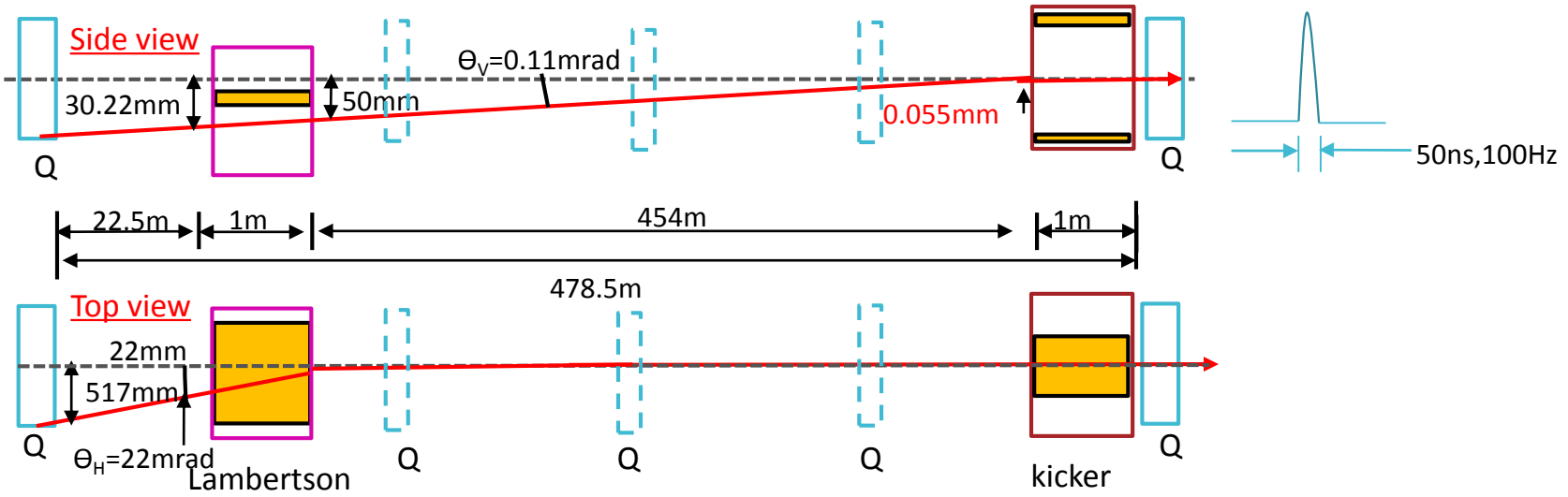
20-stage inductive adder

BST LE Inj. system hardware design towards TDR

Booster LE injection system

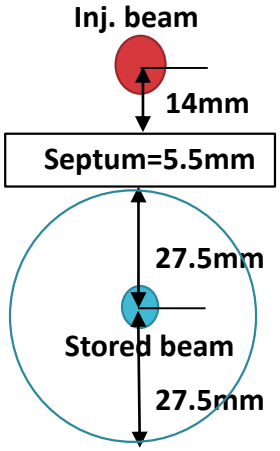
- On-axis bunch-by-bunch injection
- Hardware：
  - **Kicker:** vertical strip-line kicker driven by fast pulser
  - **Septa:** horizontal Lambertson magnet

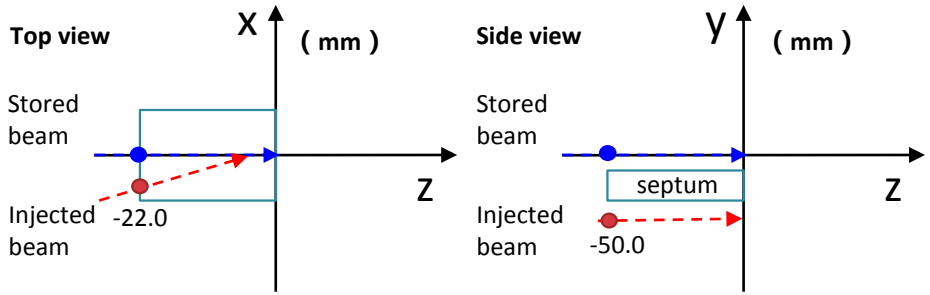




LSM requirements for BST LE inj. system

Parameters	Unit	DR-LSM
Quantity	-	2
Energy	GeV	10
Horizontal deflection angle	mrad	22
Insertion length	m	0.8
Magnetic field strength for injected/extracted beam	T	0.9175
Min. Septum thickness（including septum board, inj./ext. beam pipe wall, installation gap)	mm	5.5
Field uniformity	-	<±0.02%
Leakage field	-	≤1×10^{-3}
Clearance of stored beam at lambertson（H×V）（refer to stored beam orbit）	mm	30×50
Clearance of inj.&ext. beam at lambertson（H×V）（refer to inj.&ext. beam orbit）	mm	18×29
Physical aperture of stored beam vacuum chamber	mm	55×55

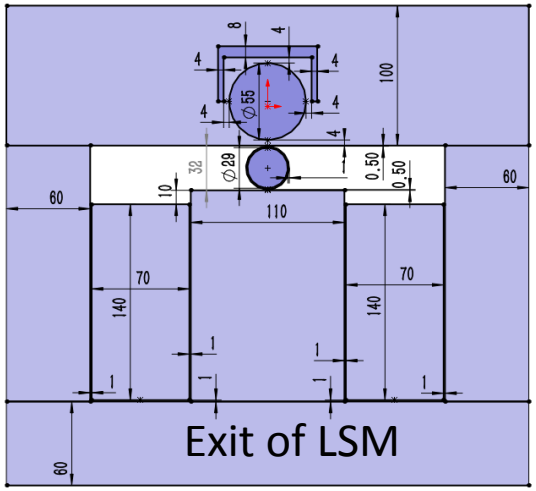


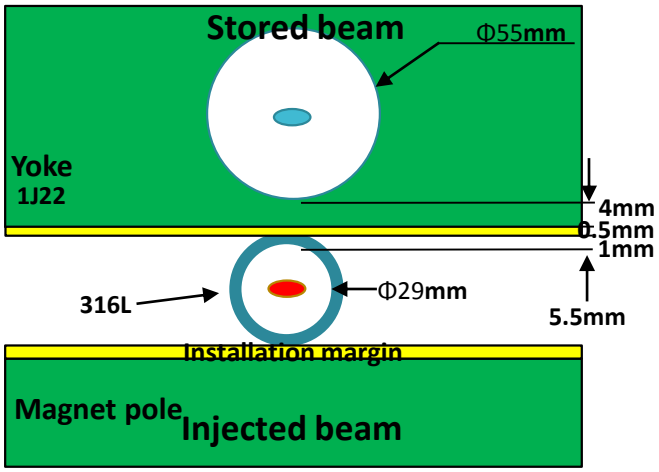


Injected beam	X(mm)	Y(mm)	Z(mm)
LSM in	-22.0	-50	-800.0
LSM out	0	-50	0

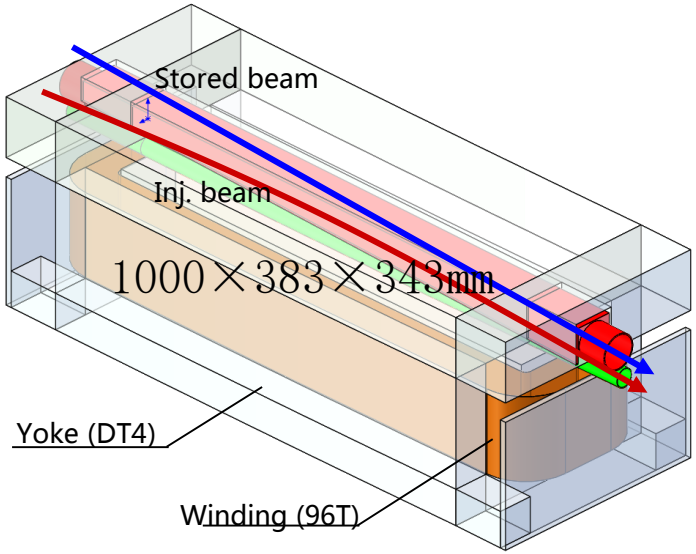
Stored beam	X(mm)	Y(mm)	Z(mm)
LSM in	0	0	-800.0
LSM out	0	0	0

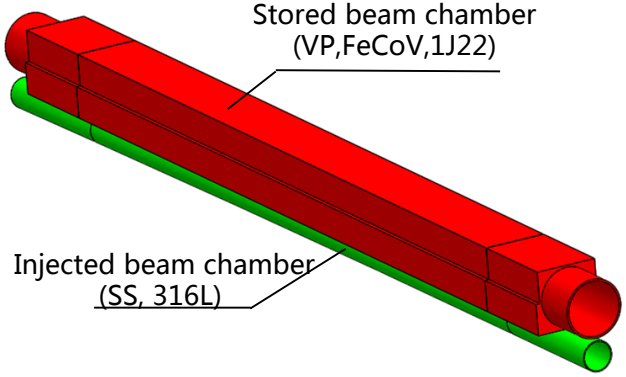
LSM physics design



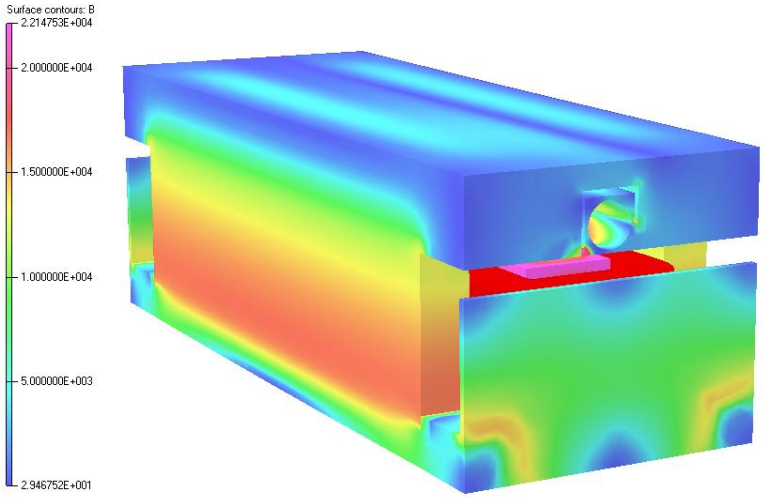


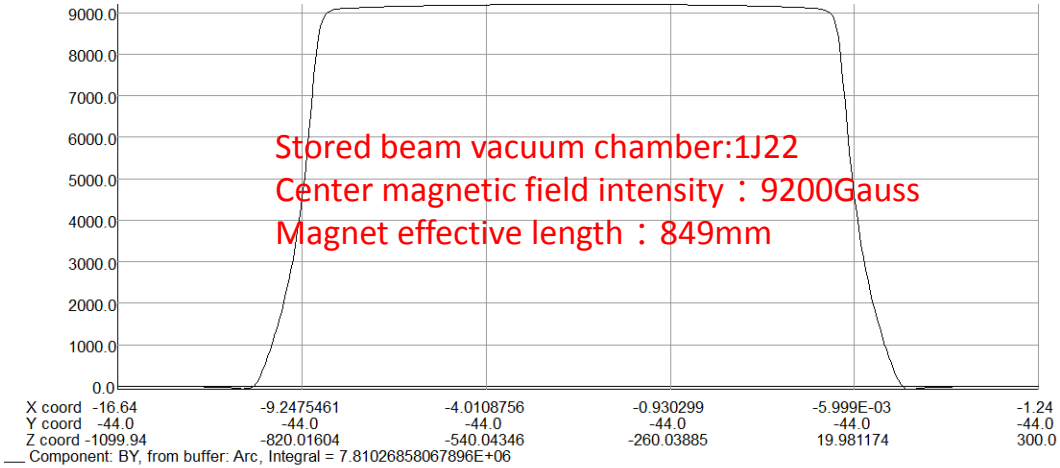
- Stored beam pipe(VP) inner diameter= ø55mm, Thickness=4mm
- Injected beam pipe (SS): inner diameter=ø29mm, Thickness=1mm
- Septum Thickness=4+1+0.5=5.5mm
- Magnet gap: 32mm
- Winding: W=70mm,H=140mm,T=128
- Exciting current=188A
- Inductance=0.0682H





3D simulation

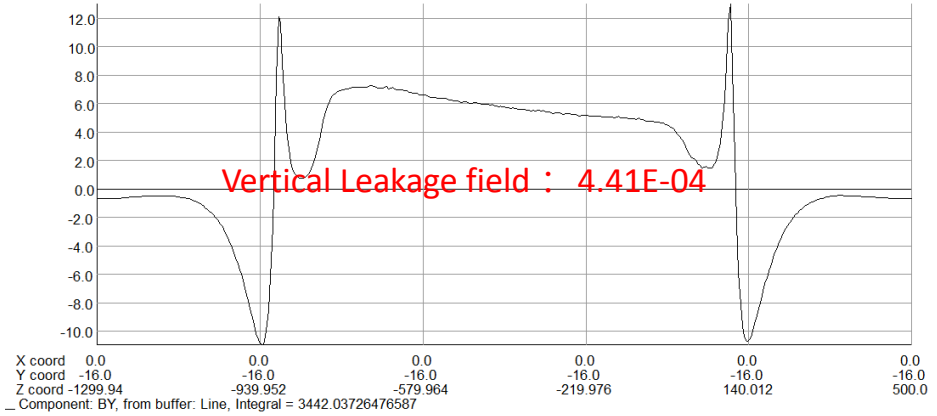




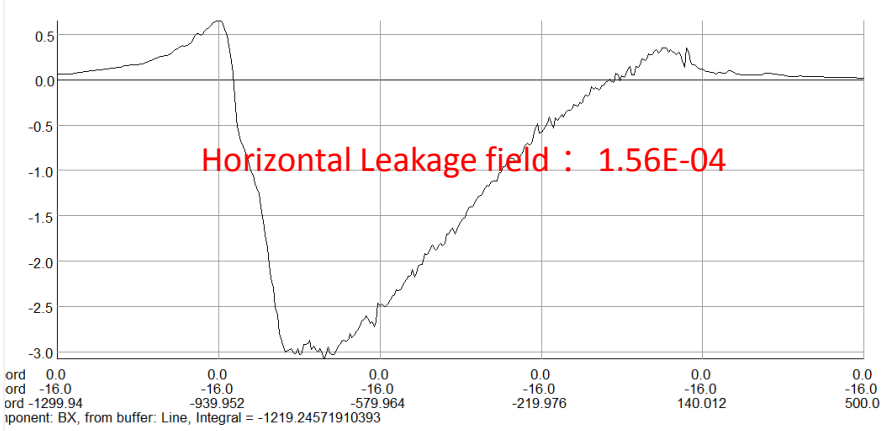
Stored beam vacuum chamber:1J22

Center magnetic field intensity：9200Gauss

Magnet effective length：849mm



Vertical Leakage field： 4.41E-04



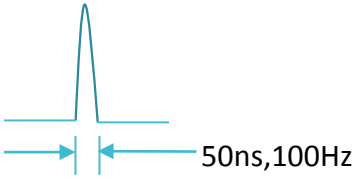
Horizontal Leakage field： 1.56E-04

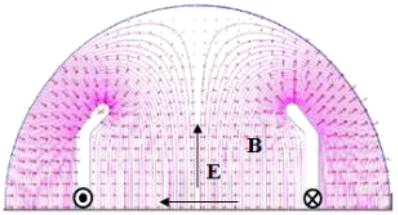
BST LE inj. kicker design parameters

parameter	Unit	Booster Low Energy injection kicker
name	-	BSTLEIK
Quantity	-	2
Type	-	Strip-line kicker
Deflect direction	-	Vertical
Beam Energy	GeV	10
Deflect angle	mrad	0.11
Length of Strip-line kicker electrode	mm	1000
Gap between two electrodes	mm	44
Odd mode impedance	Ω	50±1
Even mode impedance	Ω	<65
Clearance region(H×V)	mm	22×44
Good field region(H×V)	mm	12×22.6
Integral field uniformity	-	±2.5%
Amplitude of electrical pulse（into 50Ω）	kV	±12.25
Repetition rate	Hz	100
Amplitude repeatability	-	<2% (RMS)
Pulse jitter	ns	≤1
Bottom width of electrical pulse（3%-3%）	ns	< 50

Strip-line kicker design for booster LE inj.

- Kick strength
  - Total kick angle: θ=0.11mrad
  - E=10GeV, d=44mm, g=1 =>U*L>24.2kV·m
  - Total strip-line kicker electrode length L=1m =>U>24.2kV(or ±12.1kV)



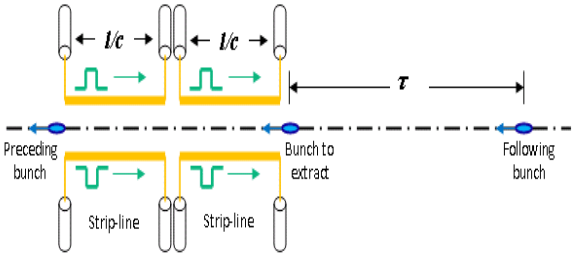


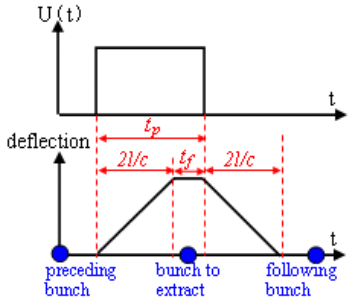
$$F_{E+B} = 2\frac{Uq}{d} \qquad \theta = \theta_E + \theta_B = 2\theta_E = 2g\frac{eU}{E}\frac{l}{d}$$

$$g = \tanh(\frac{\pi w}{2d}) \qquad \tanh(x) = \frac{e^{2x}-1}{e^{2x}+1}$$

Here, θ is kick angle(rad); E is beam energy(eV); U is applied pulse voltage for both electrodes(V); l is strip-line length; d is the distance between the electrodes, g is the geometry factor, determined by the shape of the electrode. w is the strip-line width.

- Kick speed
  - Min bunch spacing - τ=25ns
    - Electrode length l<3.75m => l= 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

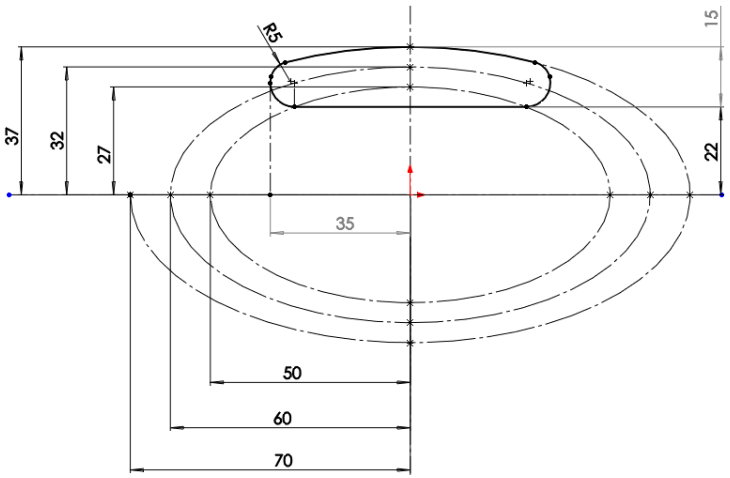




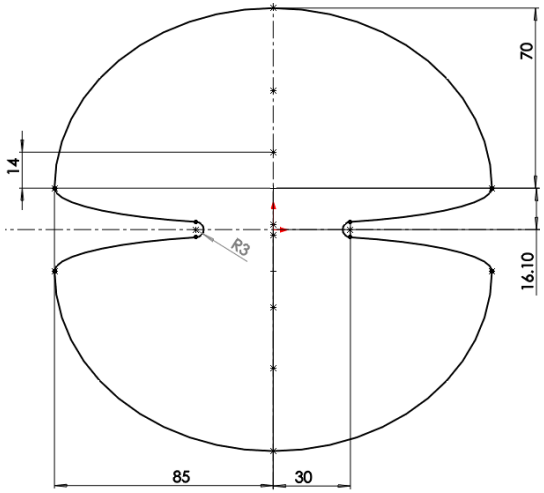
$$\begin{cases} l < c\tau/2 \\ 2l/c < t_p < 2\tau - 2l/c \end{cases}$$

Kicker physics design

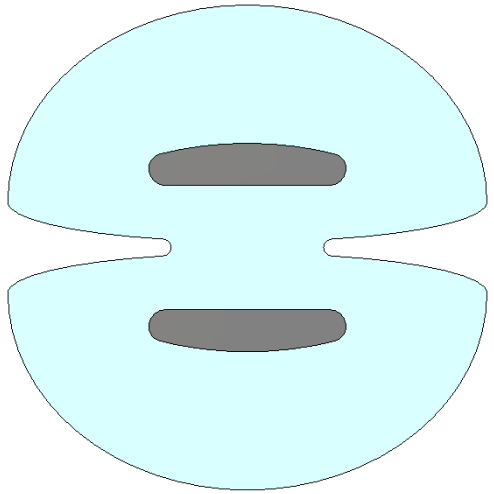
- To achieve highest geometric factor(g=0.9866) the blade width should be w=70mm, when d=44mm.
- Blade length=1m，thickness=10mm
- Voltage between blades=24.5kV
- Outer body: distance between vanes=60mm
- Odd mode impedance Zodd=50Ω, even mode impedance Zeven=60.5Ω



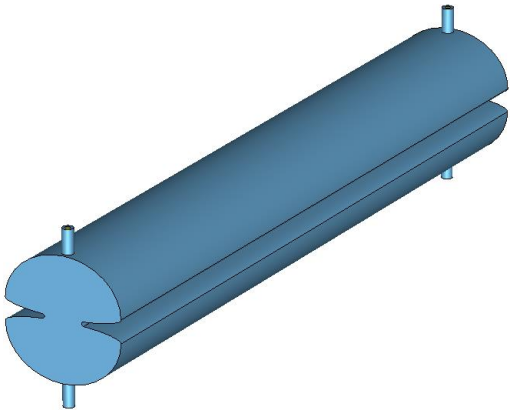
blade

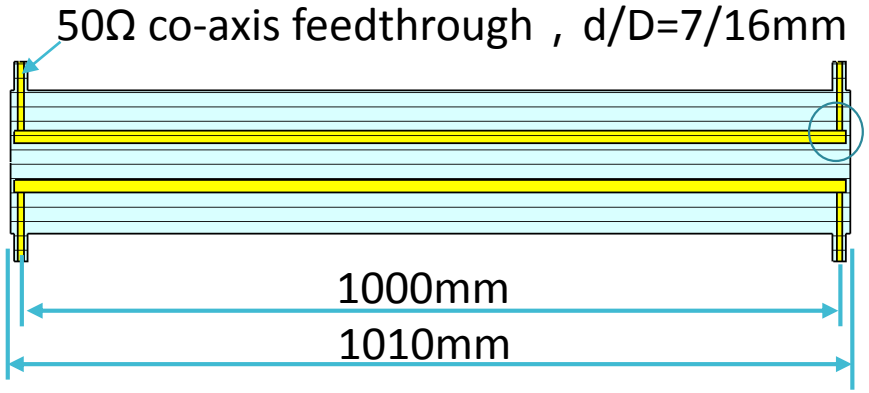


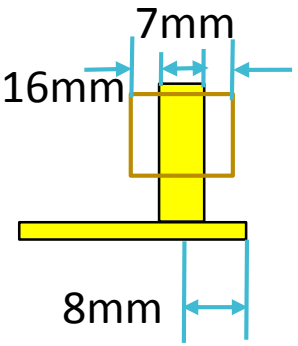
Outer body

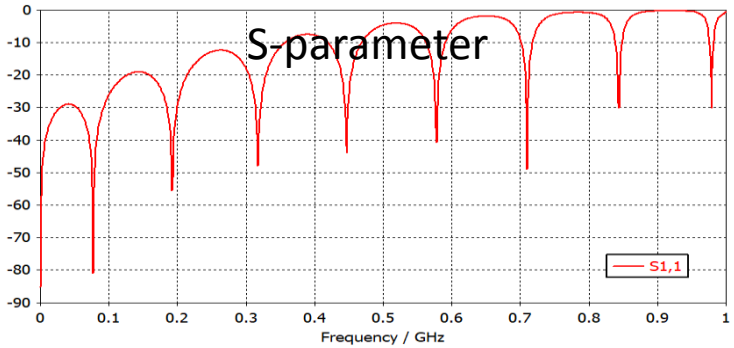

2D-geometry

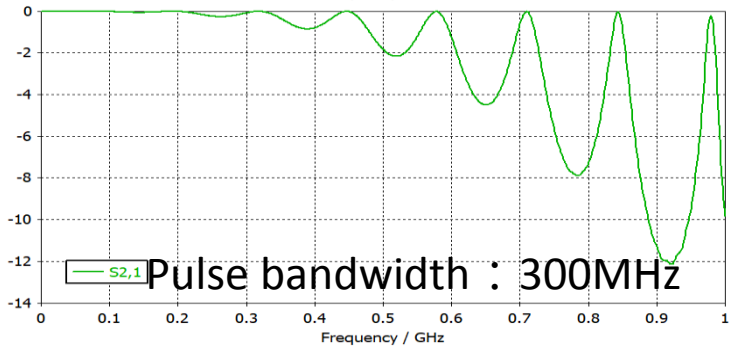
3D simulations

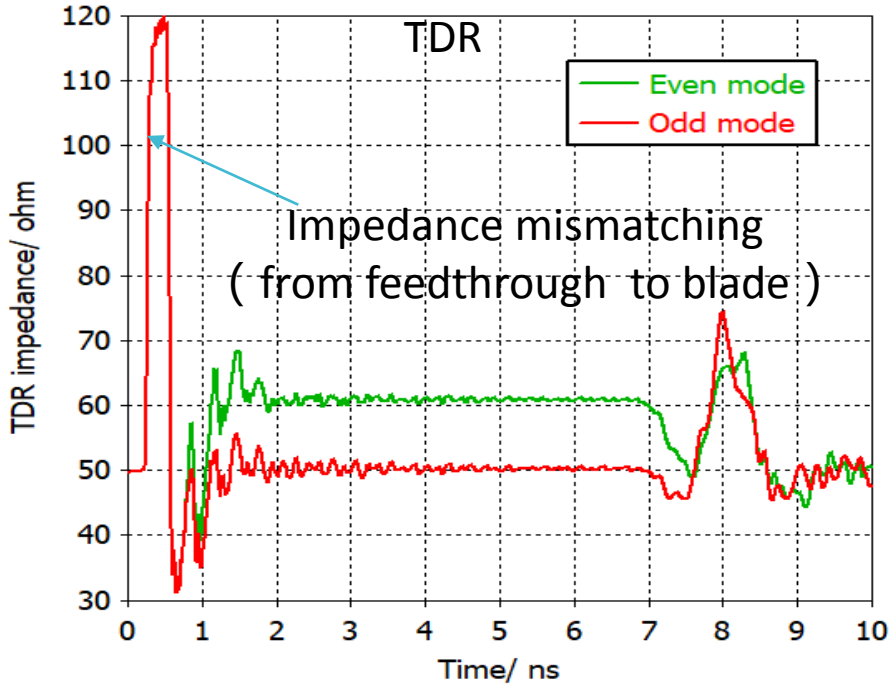






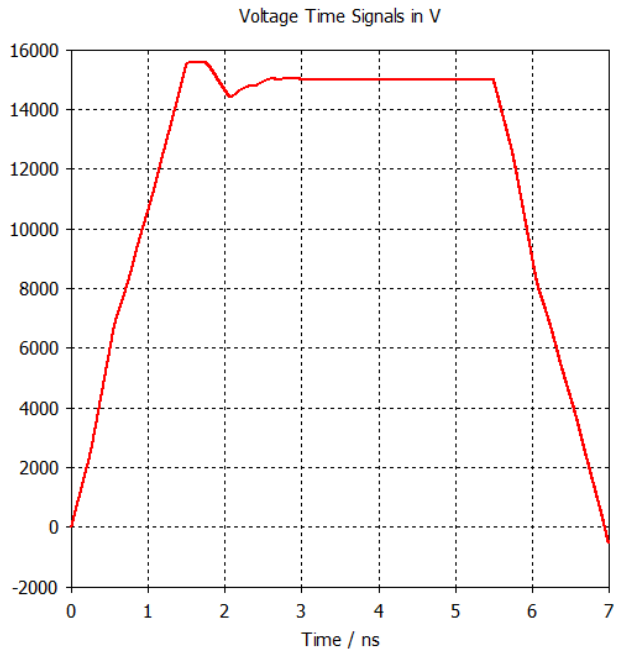


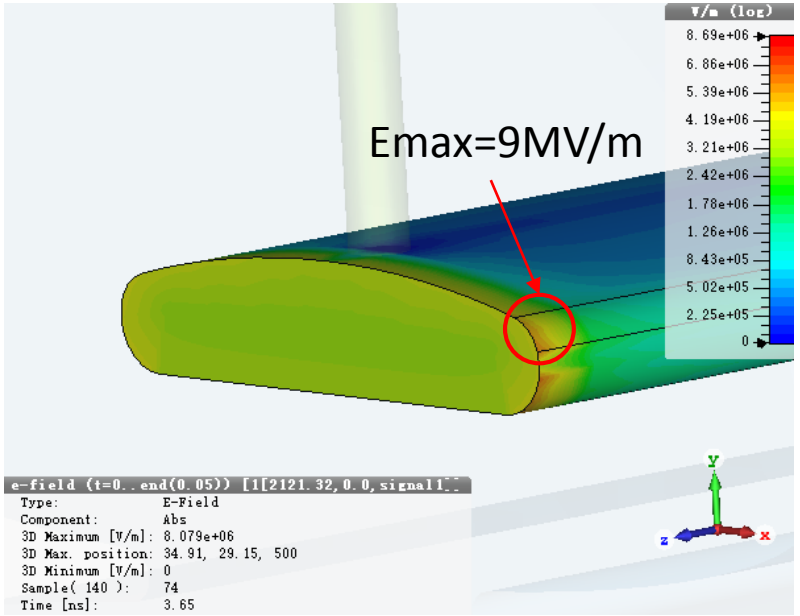




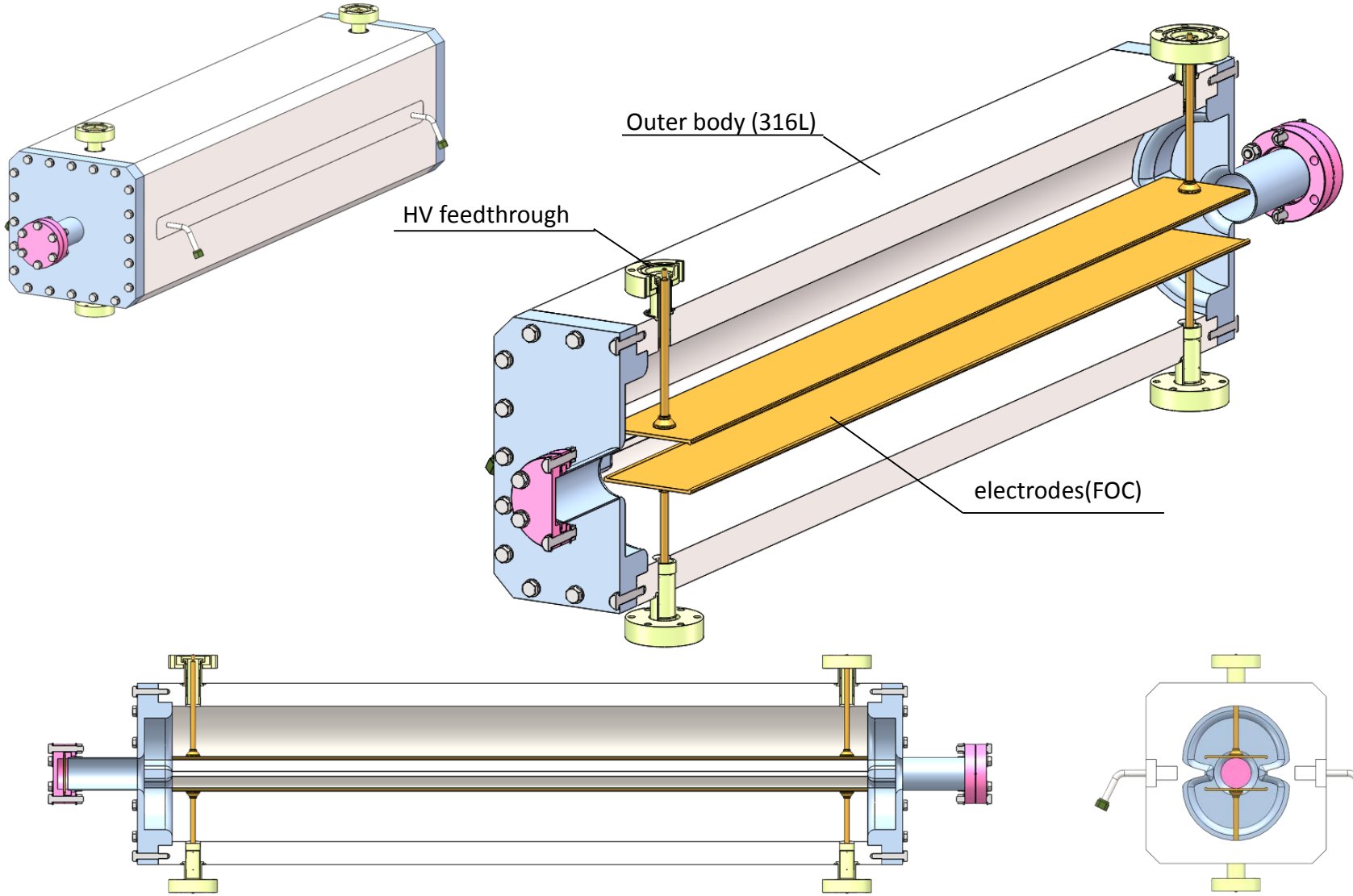
3D simulations

- Field uniformity: ~0.52% in x=(-6, 6) mm, ~1.35% in y=(-11.3, 11.3)
- Emax=9MV/m @ excited pulse peak=±15kV





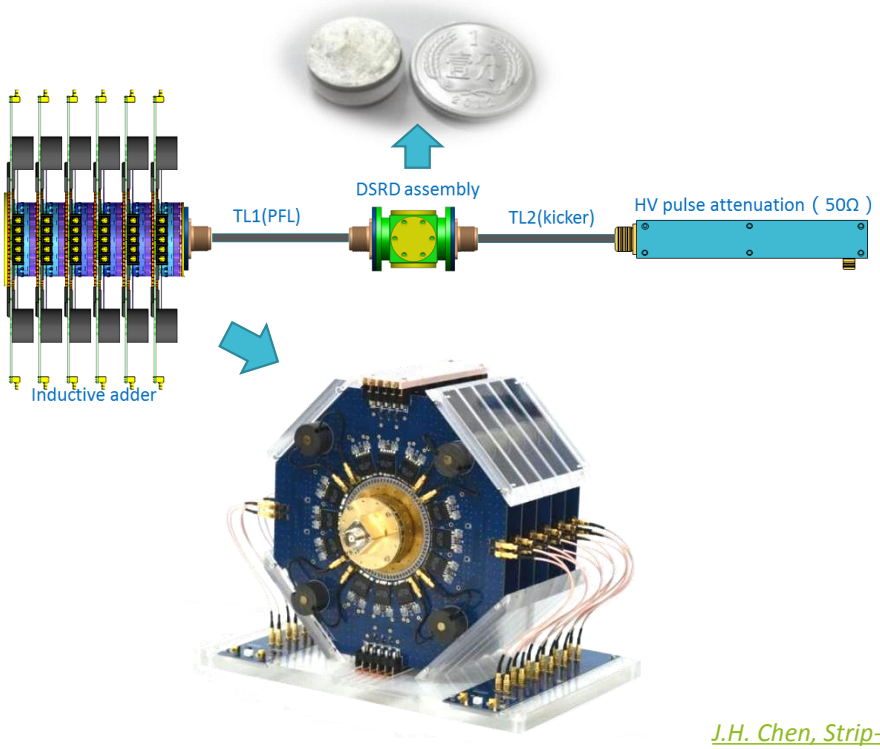
Strip-line kicker engineer design

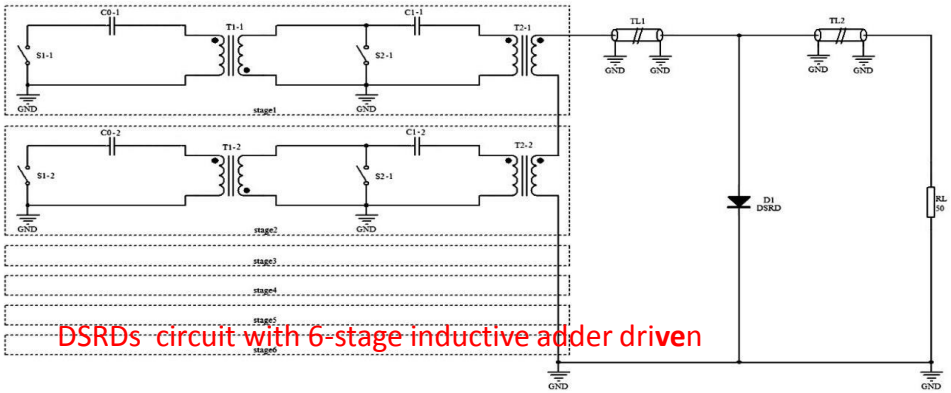


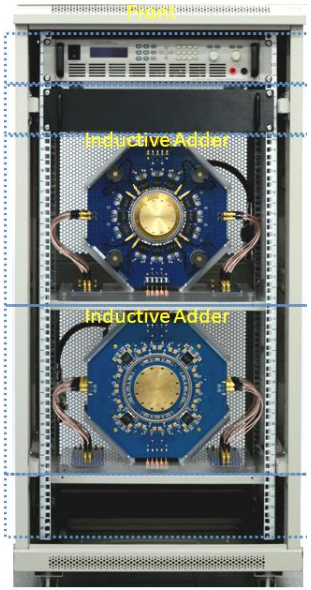
50ns-fast puler design

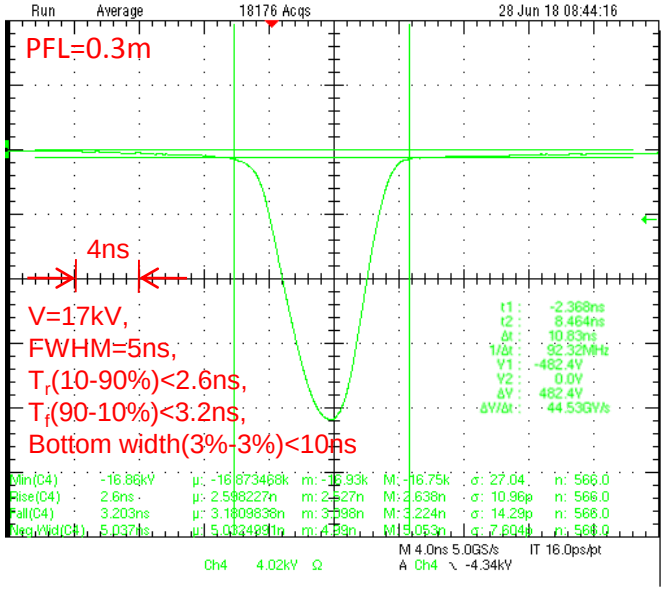
- Scheme: pulser based on DSRDs driven by 6-stage inductive adder;
- The similar hardware was developed in HEPS-TF project.

Drift Step Recovery Diode









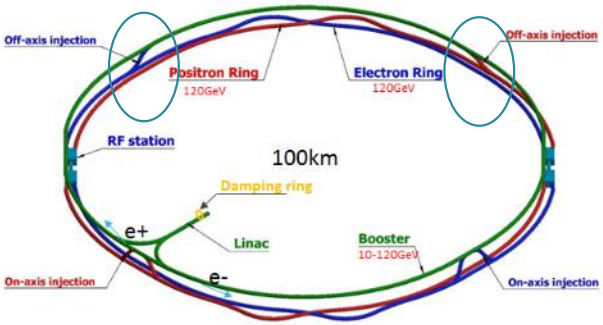
J.H. Chen, Strip-line kicker and fast pulser R&D for the HEPS on-axis injection system, NIMA 920(2019)1-6

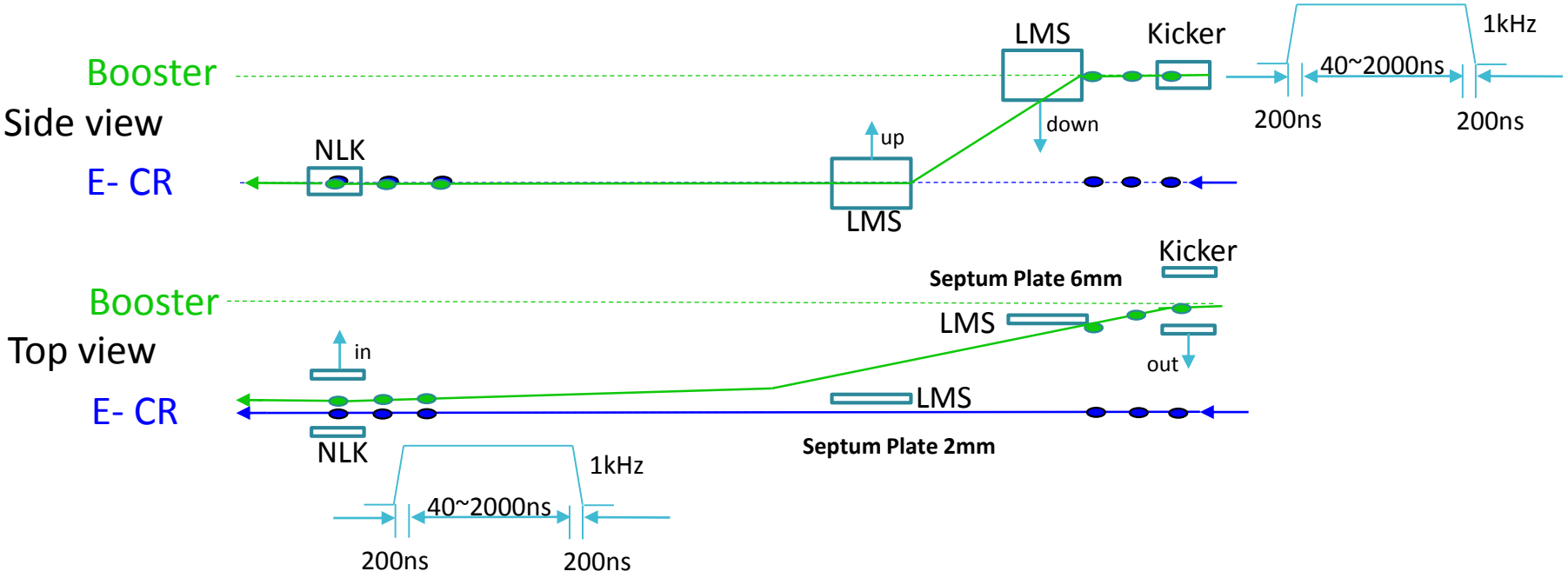
BST HE Ext. systems hardware design towards TDR

BST-HE-Ext. for CR off-axis injection

- Train by train or bunch-by-bunch extraction

1. **Kicker:** horizontal out-vacuum delay-line dipole kicker(coating ceramic vacuum chamber) driven by PFN-based solid-state pulser
2. **Septa:** vertical Lambertson magnet

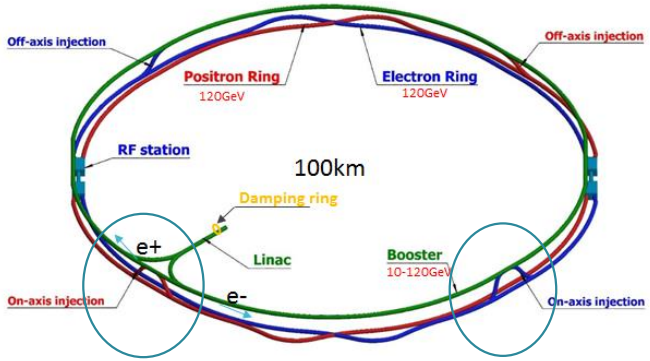


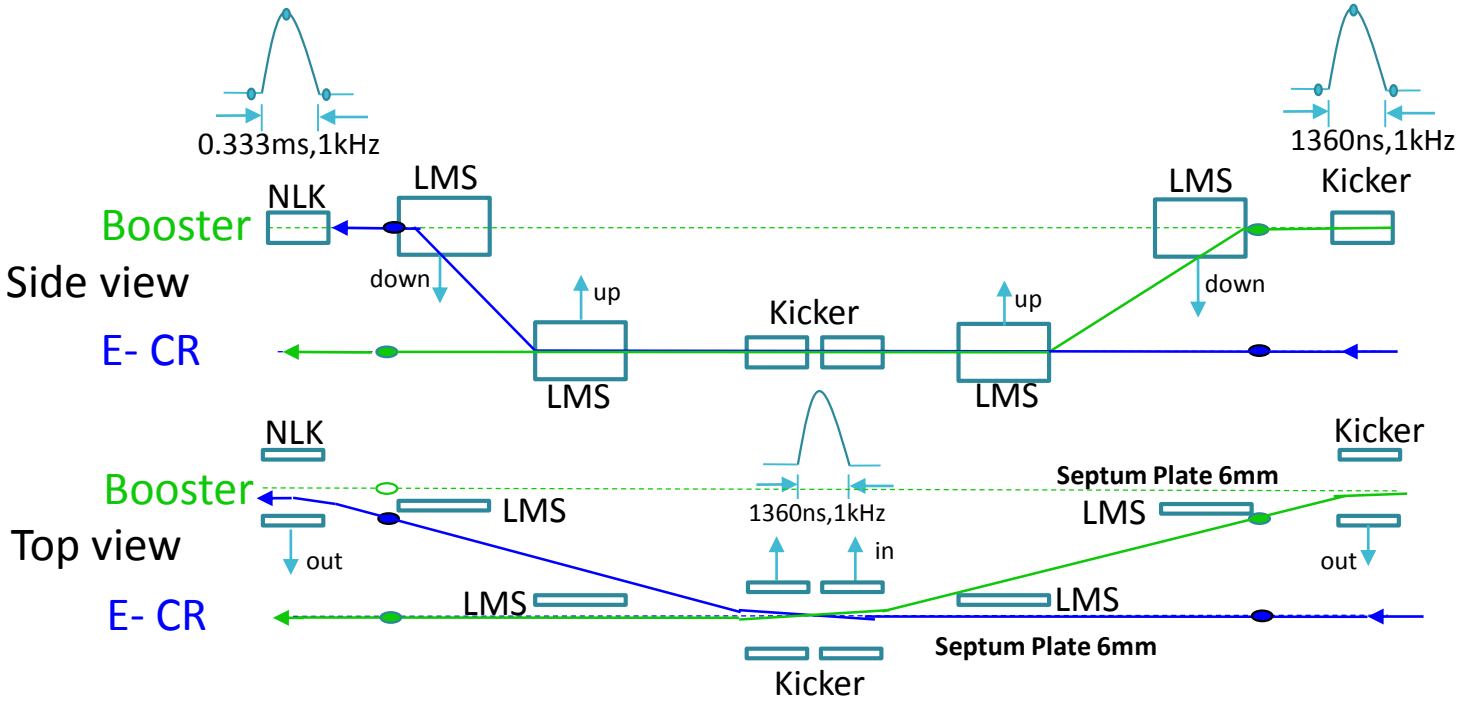


BST-HE-Ext. for CR on-axis swap-out injection

- Bunch-by-bunch extraction

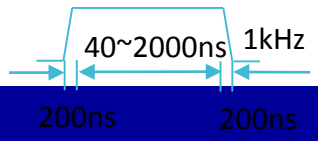
1. **Dipole kicker:** horizontal ferrite core out-vacuum kicker+coating ceramic chamber+LC resonance pulser
2. **Inj. NLK:** horizontal NLK or Pulsed sextupole+coating ceramic chamber+LC resonance pulser
3. **Septa:** Vertical Lambertson magnet

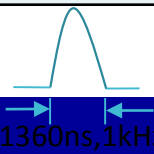




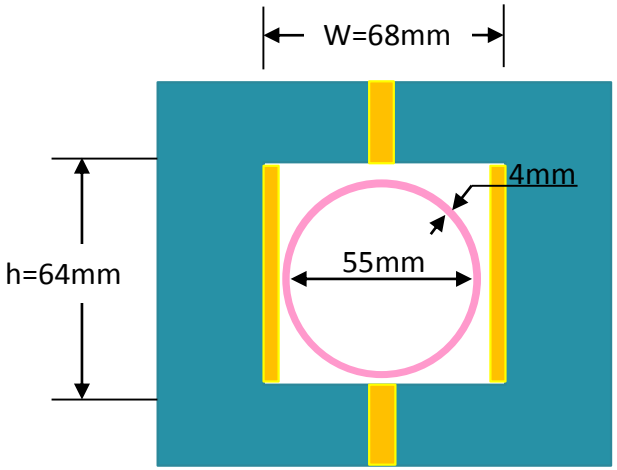
BST EXT kicker design parameters

parameter	Unit	BST-EXT-kicker1 (for CR off-axis inj.)	BST-EXT-kicker2 (for CR on-axis inj.)
Quantity	-	2	2
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	0.2	0.1
Magnetic effective length	m	1.4	0.7
Magnetic strength	T	0.06	0.06
Integral magnetic strength	T·m	0.08	0.04
Clearance region(H×V)	mm	55×55	55×55
Good field region(H×V)	mm	?	?
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





Kicker magnet physics design



$$L=\mu_0 \frac{w}{h} l = 4\pi \times 10^7 \times \frac{68}{64} \times 1.4 = 1.8683\mu H$$

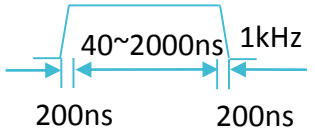
$$I=\frac{B}{\mu_0} h = \frac{0.06}{4\pi\times10^{-7}} \times 0.064 = 3.056kA$$

$$Z = 10\Omega$$

$$U=I\cdot Z = 3000 \times 10 = 30kV$$

$$\tau = \frac{L}{R} = \frac{1.87 \times 10^{-6}}{10} = 187ns$$

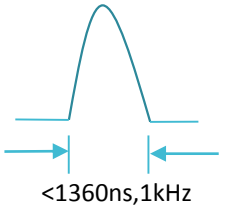
- Lumped parameter kicker with shorted end : Tr（5%-95%）=3τ=561ns
- Lumped parameter kicker with matched resistor : Tr（5%-95%）=3τ/2=280.5ns
- Delay-line kicker with matched resistor : Tr（5%-95%）=τ=187ns

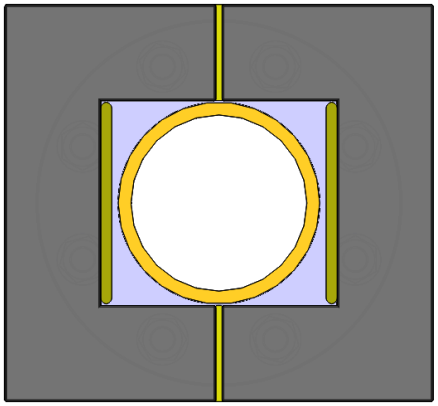


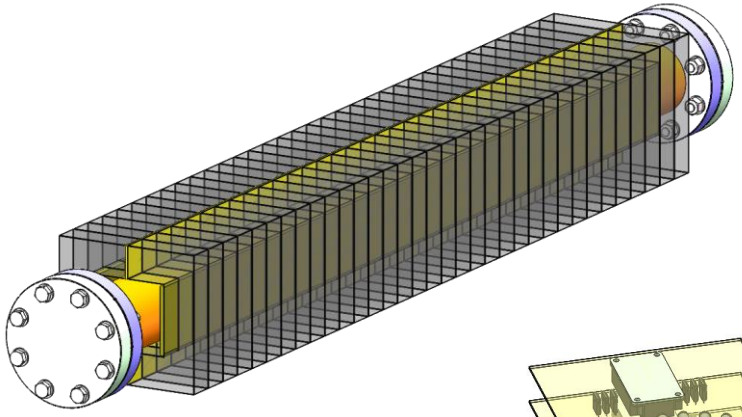
Lumped parameter dipole kicker magnet

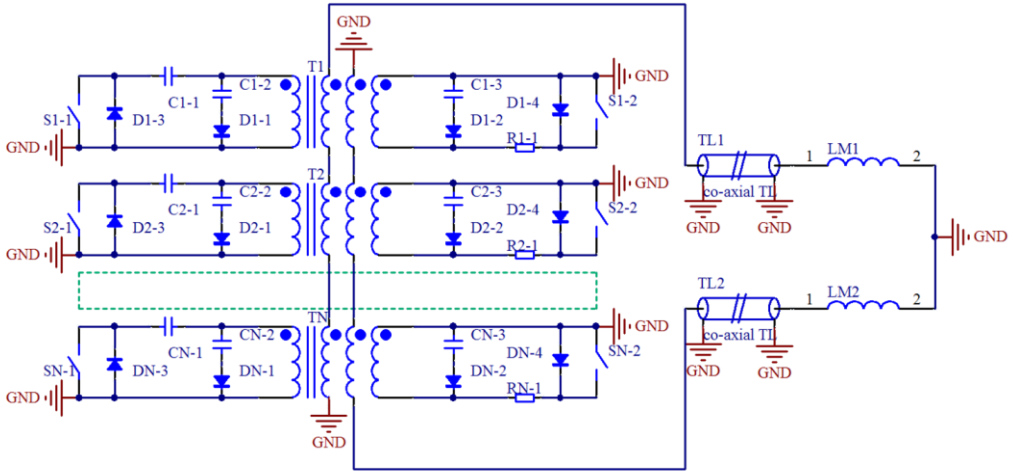
Features:

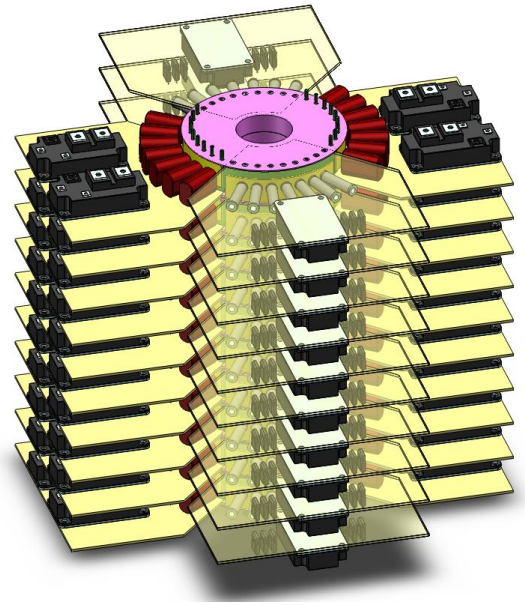
- Out-vacuum **kicker** with metallic coating ceramic vacuum chamber
- Pulser: Inductive adder based on IGBTs.







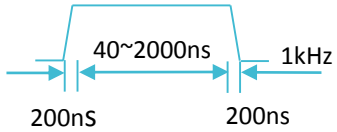




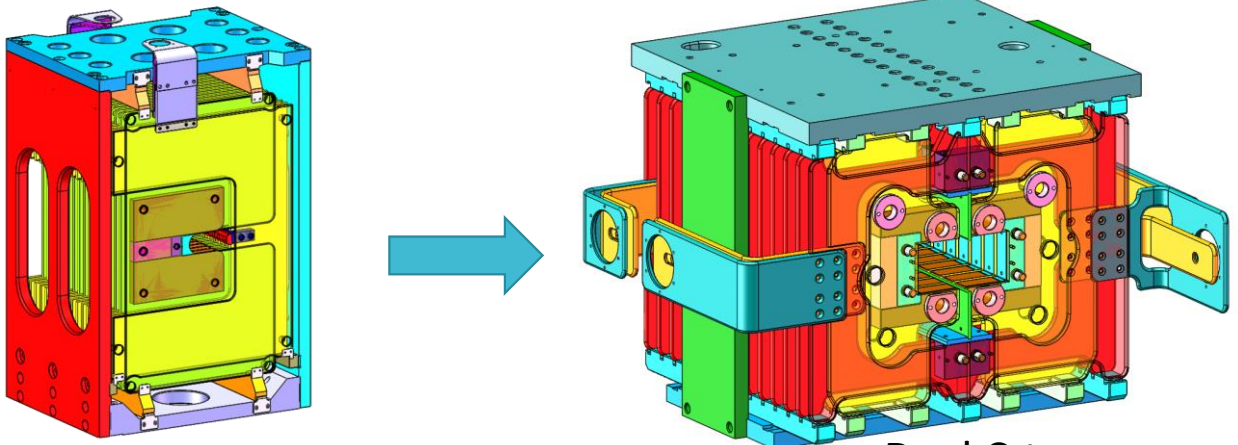
Distributed parameter (delay-line) dipole kicker

Features:

- The structure of delay-line kicker is complicated, but helps to achieve ideal trapezoid waveform.
- ceramic vacuum chamber with special pattern metallic coating
- Pulser: adjustable pulse width inductive adder or Marx generator based on SiC MOSFET

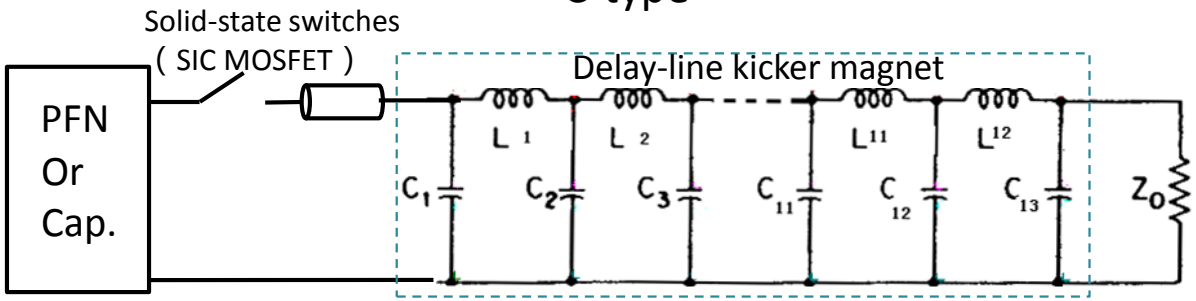


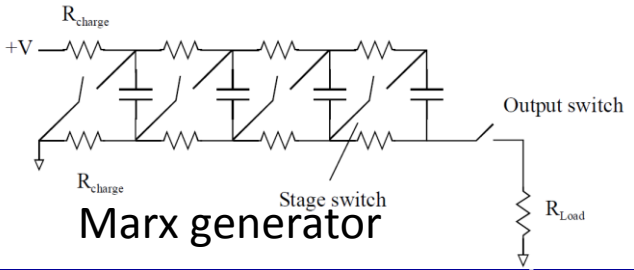
challenges



C-type

Dual C-type





Marx generator

Summary

- There are 9 injection and extraction sub-systems in CEPC accelerator complex. The types of all inj./ext. components are figured out.
- The hardware designs towards TDR are being carried out.
- So far , the kickers and the Lambertson septas preliminary designs for the damping ring , the booster low energy inj. system are completed. The kickers for high energy ext. sub-systems are being designed.

END

Thank you for attentions!!!

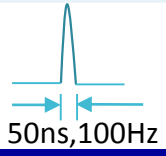
Backup slides

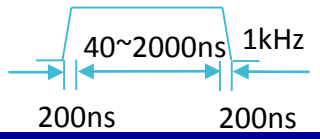
Booster Ring

Booster operating mode	Higgs			W		Z	
Beam energy（GeV）	10	120		10	80	10	45.5
Function	Injection（both）	Extraction（off-axis）	Inj./Ext.（on-axis）	Injection（off-axis）	Extraction（off-axis）	Injection（off-axis）	Extraction（off-axis）
Bunch number	242（in half ring）		7（in half ring）	1524（uniform）		6000	
Min. bunch spacing （ns）	680		23800	220		25	
Bunch number per train× train number	-		-	-	-	80×75	
Train spacing （ns）	-		-	-	-	2460	
Injection（extraction）mode	Bunch by bunch			Bunch by bunch		Bunch by bunch	Train by train
Kicker repetition rate (Hz)	100	1000		100	1000	100	1000
Kicker pulse width (ns)	1360			440		50	<6900
Kicker flat top（ns）	-			-		-	>1980
Kicker rise（fall）time (ns)	<680			<220		<25	<2460
Timing delay(ns)	<680		<23800	<220		<2460	<4400
injection（extraction）period (s)	2.42	0.242	0.007	15.24	1.5	60	0.075
Kick angle (mrad)	0.11	0.2	0.1	0.11	0.2	0.11	0.2
Kick Integral field strength (Tm)	0.004	0.08	0.04	0.004	0.05	0.004	0.03
Beam pipe aperture Φ（mm）	55						

Considering the compatibility of three operating modes:

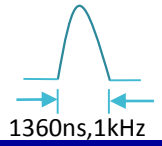
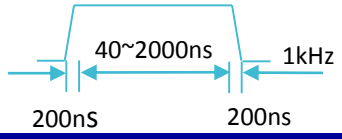
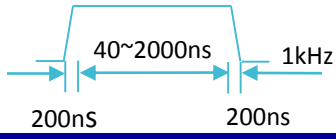
Function	LE-Injection（both）	HE-Extraction（off-axis）	HE-Inj./Ext.（on-axis）
Kicker repetition rate (Hz)	100	1000	1000
Kicker pulse width (ns)	50	440~2420(Adjustable)	1360
Kicker flat top（ns）	-	0~1980(Adjustable)	-
Kicker rise（fall）time(ns)	<25	<220	<680
injection（extraction）period (s)	60	1.5	0.007
Kick angle (mrad)	0.11	0.2	0.1
Kick Integral field strength (Tm)	0.004	0.08	0.04
Beam pipe aperture Φ（mm）	55	55	55





Collider ring

Booster operating mode	Higgs			W		Z	
Beam energy（GeV）	120			80		45.5	
Function	Injection（off-axis）	Injection（on-axis）	Extraction（dump）	Injection（off-axis）	Extraction（dump）	Injection（off-axis）	Extraction（dump）
Bunch number	242（in half ring）- 7			1524（uniform）		12000	
Min. bunch spacing （ns）	680			220		25	
Bunch number per train× train number	-			-		80×150	
Train spacing （ns）	-			-		245	
Injection（extraction）mode	Bunch by bunch			Bunch by bunch		Train by train	
Kicker repetition rate (Hz)	1000			1000		1000	
Kicker pulse width (ns)	1360			440		<2460	
Kicker flat top（ns）	-			-		>1980	
Kicker rise（fall）time (ns)	<680			<220		<245	
Timing delay(ns)	<680	<23800	<680	<220		<4400	
injection（extraction）period (s)	0.242	0.007	0.242	1.5		0.15	
Kick angle (mrad)	0.1	0.2	0.2	0.1	0.2	0.1	0.2
Kick Integral field strength (Tm)	0.04	0.08	0.08	0.027	0.05	0.015	0.03
Beam pipe aperture HxV（mm）	75×56						

Considering the compatibility of three operating modes:

Function	Injection（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	0.2
Kick Integral field strength (Tm)	0.08	0.04	0.08
Beam pipe aperture HxV（mm）	75×56	75×56	75×56