14th ANPhA Board meeting and Symposium

Preliminary concept design of EicC accelerator

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28-29 June 2019, Jeju • Korea

Outline

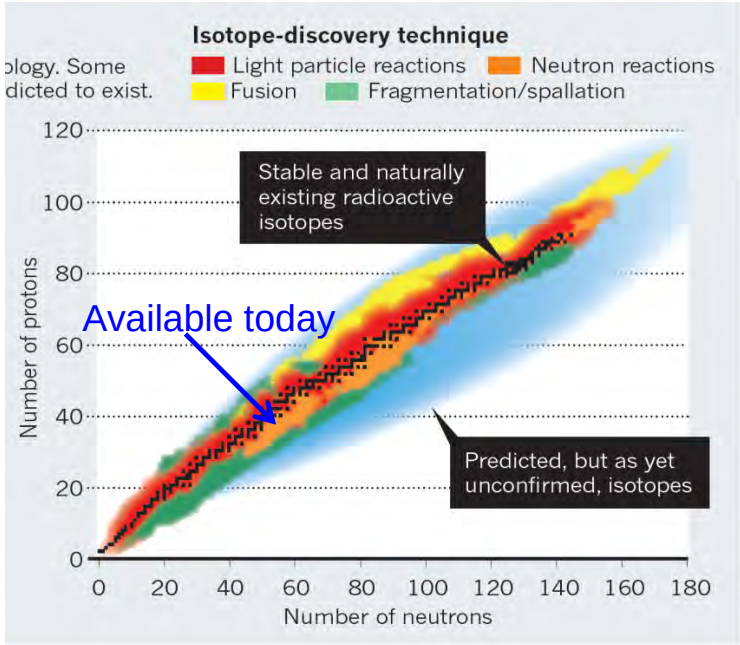
1. HIAF introduction and status
2. EIC proposals in the world
3. Concept design of EicC accelerator
4. Interaction region and luminosity concept
5. Cost estimation and schedule
6. Summary

HIAF introduction and status

High-Intensity Heavy Ion Accelerator Facility-HIAF

HIAF introduction and status

Next-generation high intensity facilities are required for advances in nuclear physics and related research fields:



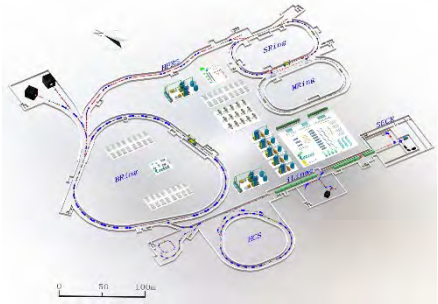
Fascinating and crucial questions

- To explore the limit of nuclear existence
- To study exotic nuclear structure
- Understand the origin of the elements
- To study the properties of High Energy and Density Matter

……

Next-generation facilities are being constructed or proposed worldwide:

- SPIRAL2 at GANIL in Caen, France
- FAIR at GSI in Darmstadt, Germany
- FRIB at MSU in the U.S.
- NICA at JINR, Dubna, Russia
- EURISOL in Europe

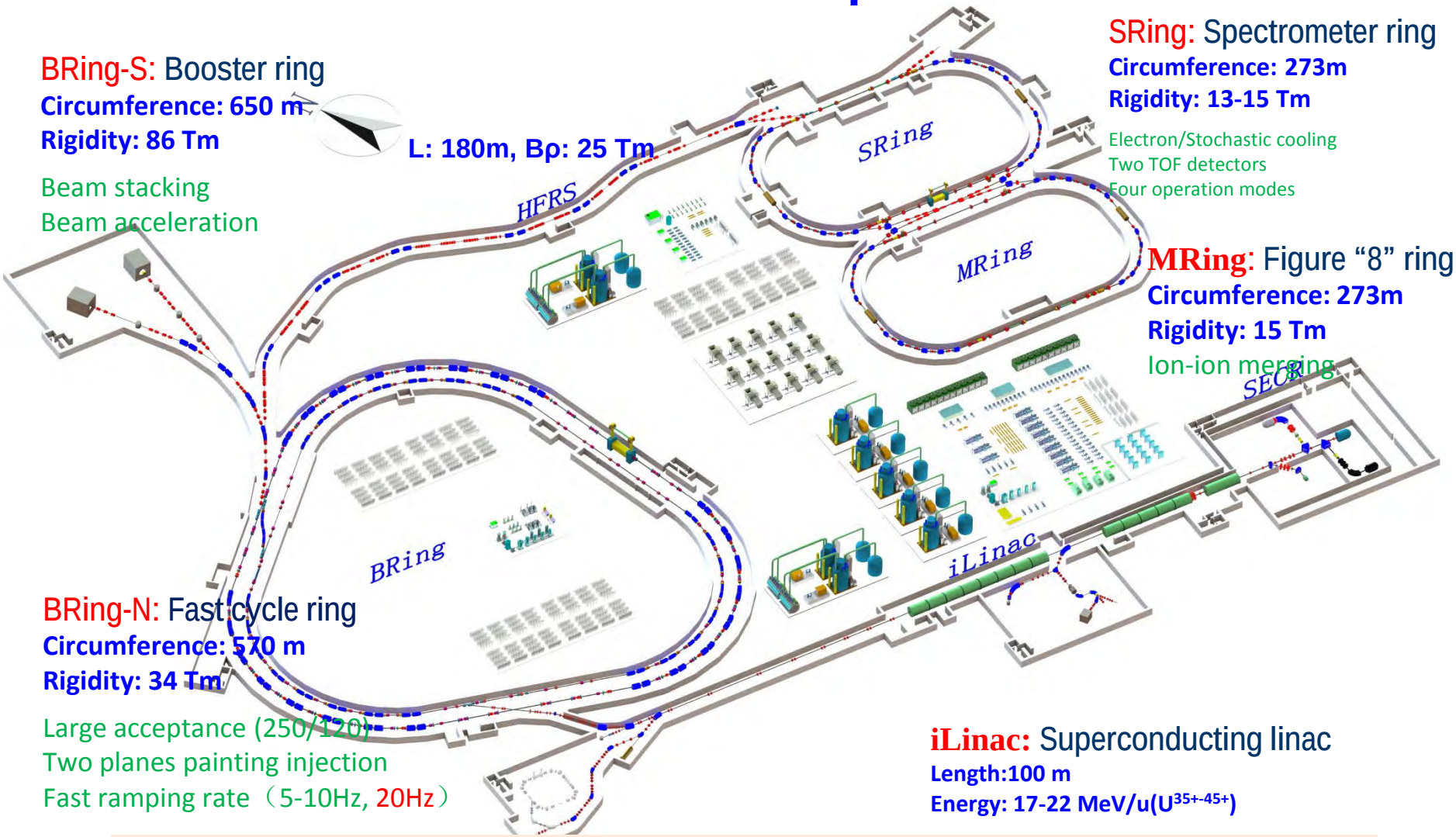


High Intensity Heavy-ion Accelerator Facility

HIAF in China

HIAF introduction and status

Main accelerator components



BRing-S: Booster ring
Circumference: 650 m
Rigidity: 86 Tm

Beam stacking
Beam acceleration

L: 180m, Bρ: 25 Tm

SRing: Spectrometer ring
Circumference: 273m
Rigidity: 13-15 Tm

Electron/Stochastic cooling
Two TOF detectors
Four operation modes

MRing: Figure "8" ring
Circumference: 273m
Rigidity: 15 Tm
Ion-ion merging

BRing-N: Fast cycle ring
Circumference: 570 m
Rigidity: 34 Tm

Large acceptance (250/120)
Two planes painting injection
Fast ramping rate（5-10Hz, 20Hz）

iLinac: Superconducting linac
Length:100 m
Energy: 17-22 MeV/u($U^{35+-45+}$)

These tunnels will be built in a cut and cover method and will be filled with 5 m overlay of soil. This conforms to the requirements of radiation safety.

HIAF introduction and status

Unprecedented parameters and unique features:

Highest beam Intensity （Comparison with HIRFL）:

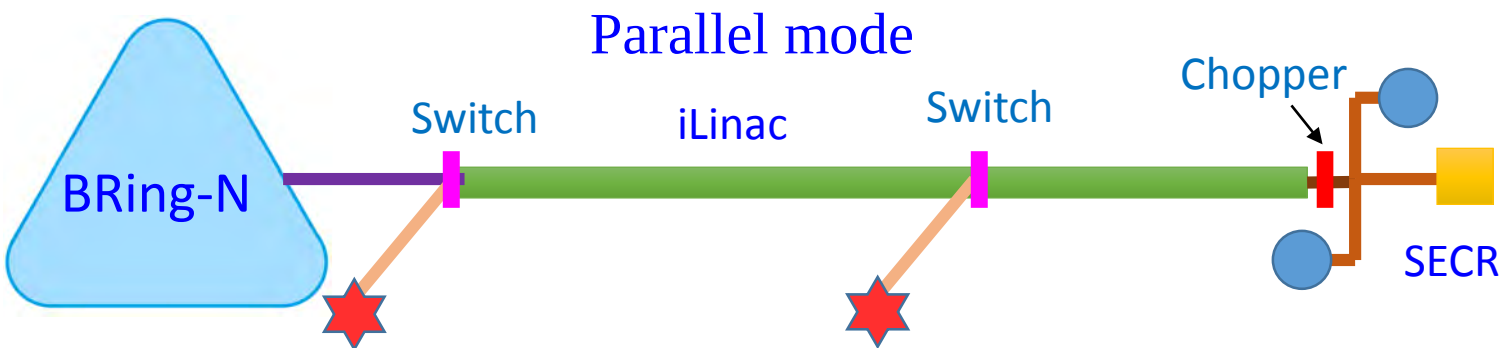
- **Primary beam intensity increases by x 1000 - x 10000**
- **Secondary beam intensity increases by up to x 10000**
- **Highest heavy ion beam intensity in the world**

Precisely-tailored beams - Precision frontiers

- **Beam cooling (**Electron, Stochastic, laser; high quality, very small spot **)**
- **Beam compression (**Ultra-short bunch length: 50-100ns**)**
- **Super long period slow extraction (**Super long, high energy, quasi-continuous beam **)**

Versatile operation modes:

- **Parallel operation, beam splitting (** increase of target time, high integrated luminosity**)**



Heavy ion beam intensity

	Ions	Energy	Intensity
SECR	$^{238}U^{35+}$	14 keV/u	0.05-0.1 pmA
iLinac	$^{238}U^{35+}$	17 MeV/u	0.028-0.05 pmA
BRing-N	$^{238}U^{35+}$	0.8 GeV/u	~2.0×10^{11} ppp
BRing-S	$^{238}U^{35+}$	2.3 GeV/u	~1.0×10^{12} ppp
	$^{238}U^{76+}$	5.8 GeV/u	~5.0×10^{11} ppp
	$^{238}U^{92+}$	7.3 GeV/u	~5.0×10^{11} ppp
SRing	RIBs: neutron-rich, proton-rich	0.84 GeV/u(A/q=3)	~10^{9-10} ppp
	Fully stripped heavy ions H-like, He-like heavy ions	0.8 GeV/u($^{238}U^{92+}$)	~10^{11-12} ppp

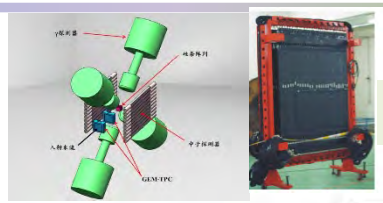
Heavy ion beam intensity

The highest pulse heavy ion beam intensity in the world

Institute	Machine	Planned Intensity	Achieved Intensity	Ion species	Repetition rate
BNL	AGS Booster		5×10^{9}	Au^{32+}	
CERN	LEIR		9×10^{8}	Pb^{54+}	
JINR	NICA Booster	4×10^{9}		Au^{32+}	
GSI	SIS18	1.0×10^{11}	3×10^{10}	U^{28+}	2.7Hz
FAIR	SIS100	4.0×10^{11}		U^{28+}	
IMP	HIAF-BRing-N	2.0×10^{11}		U^{35+}	5-10Hz, 10-20Hz
IMP	HIAF-BRing-S	1.0×10^{12} 2.0×10^{12}		U^{35+}	

HIAF introduction and status

Experiment terminals

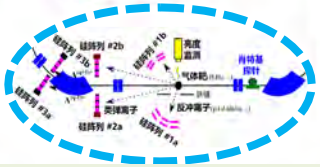


RIBs physics station

HFRS

External target station

High Energy Density Physics
Nuclear Matter study-CEE
Hypernuclear
High energy irradiation



e-ion recombination spectroscopy

SRing

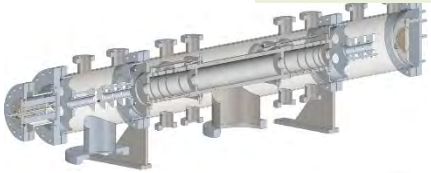
High precision spectrometer ring

MRing

BRing-S

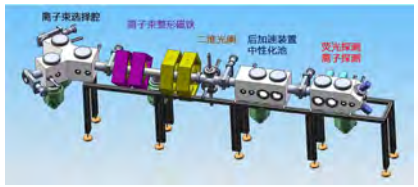
BRing-N

Ion-Ion Merging

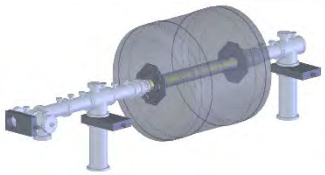


iLinac-100 **iLinac-25**

SECR



Low energy irradiation



Low energy nuclear structure terminal

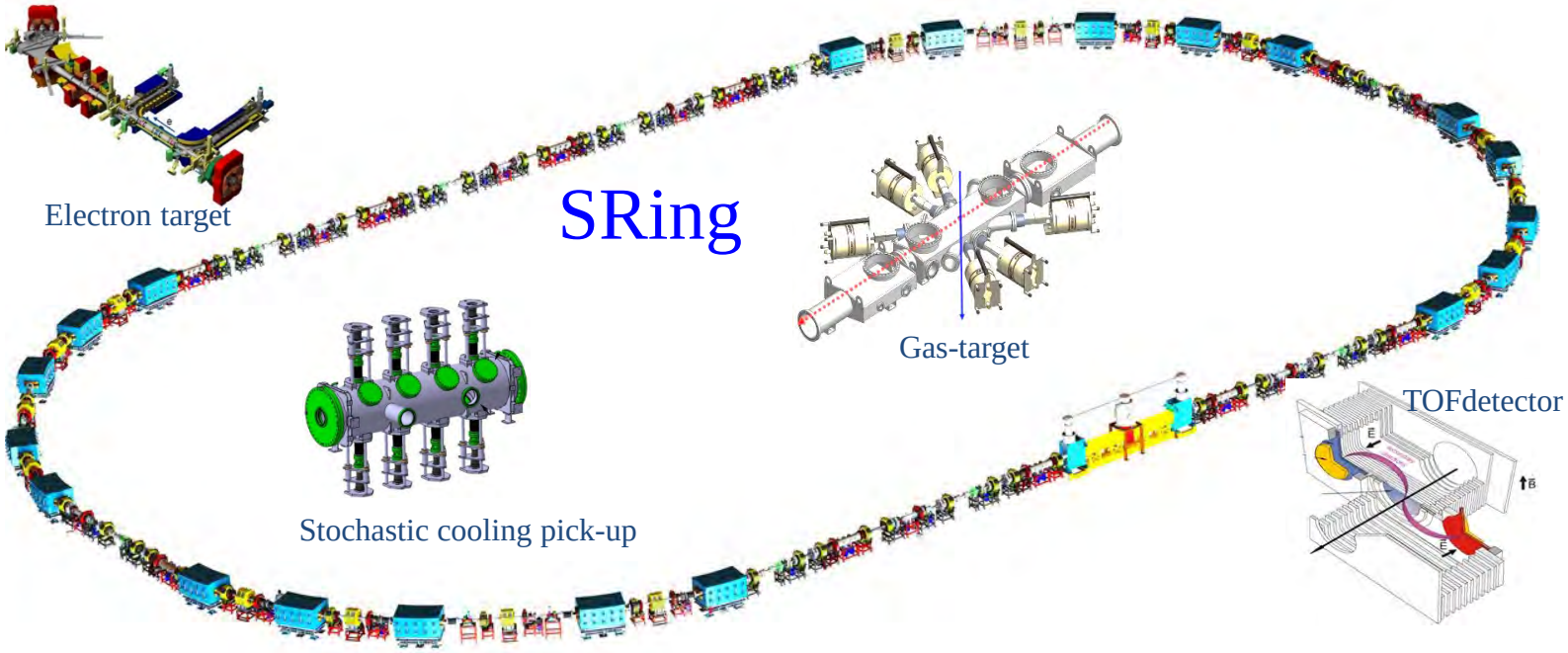
HIAF introduction and status

Unique feature-1 Multi-function storage ring

Key devices
- Electron cooling
- Stochastic cooling
- Two TOF detectors
- Electron target

Operation modes
- Isochronous mode
- Normal Mode
- Internal-target Mode
- Ion-ion merging Mode

Experiment programs
- Gas-jet target experiments
- DR experiments
- IMS & SMS
- Ion-ion merging experiments

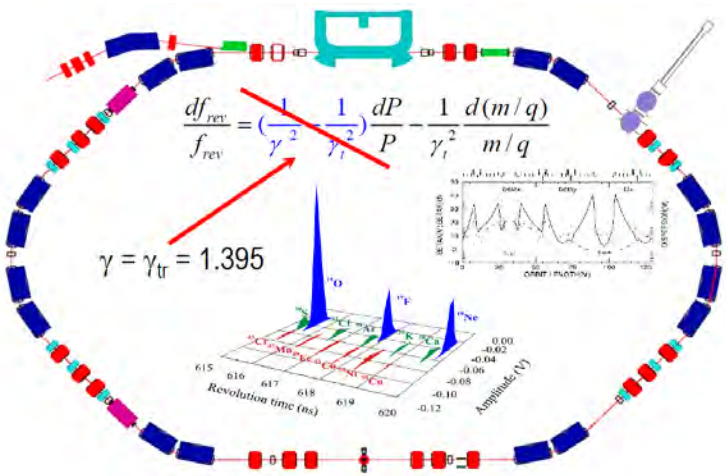


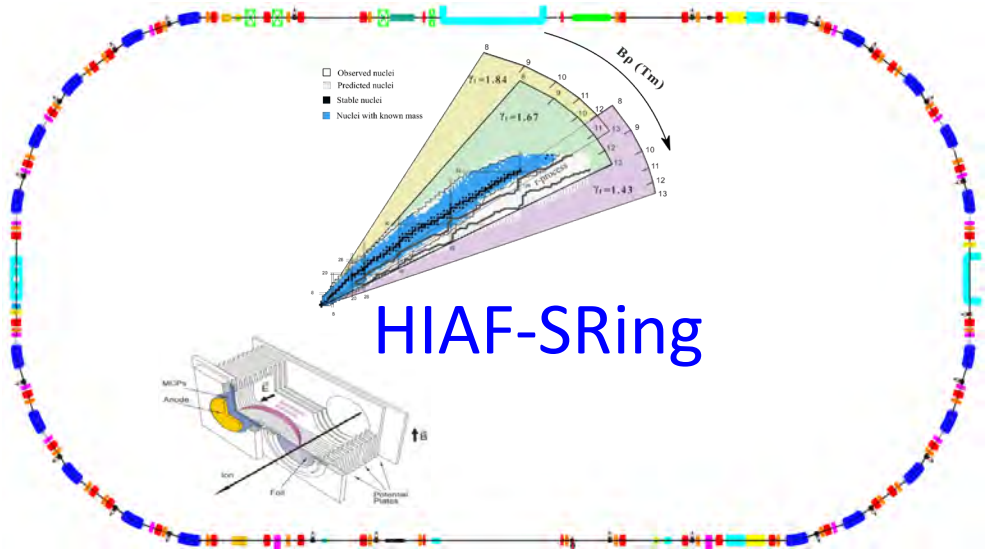
Precision frontiers machine for in-ring experiments

HIAF introduction and status

Isochronous mode with two TOF

HIRFL-CSRe





Beams: ^{58}Ni, ^{78}Kr, ^{86}Kr and ^{112}Sn

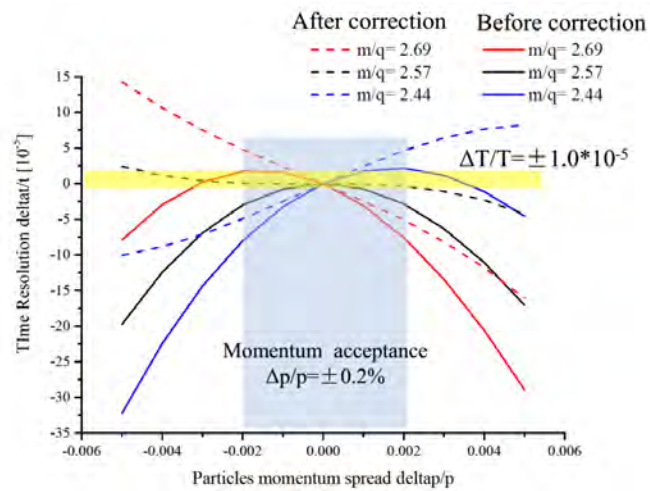
43 masses are measured

Measured for the first time: 16

Precision improved: 27

Precision achieved: $\Delta M/M \sim 10^{-7}$

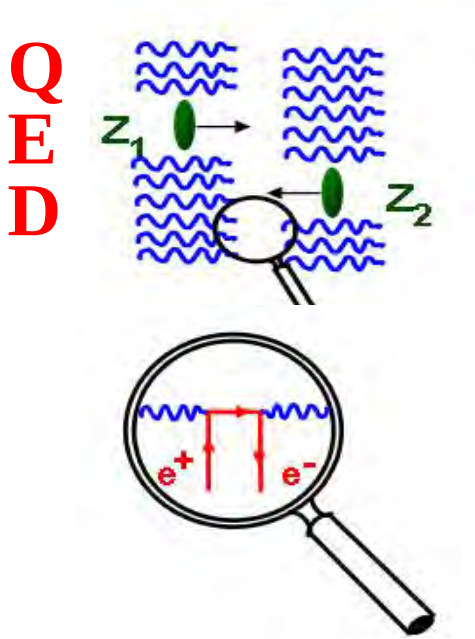
Demonstrated the TOF mode first time in the world

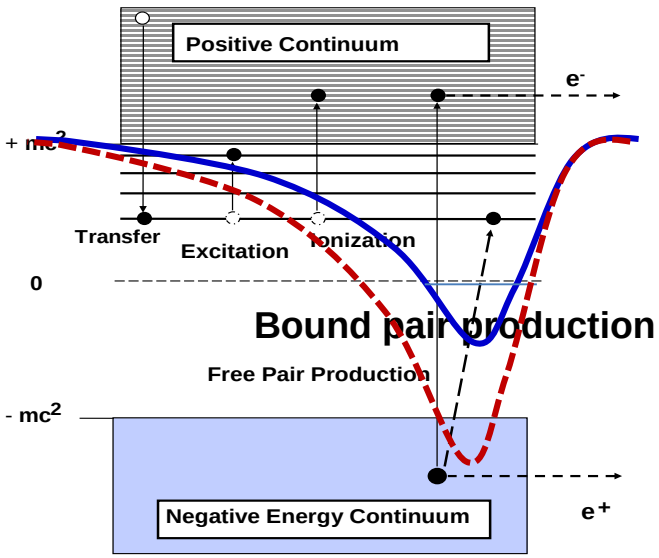


$\Delta M/M \sim 10^{-7}$-10^{-8}

Unique feature-2 **First figure-8 shape ring for ion-ion merging**

Spontaneous electron–positron pair production





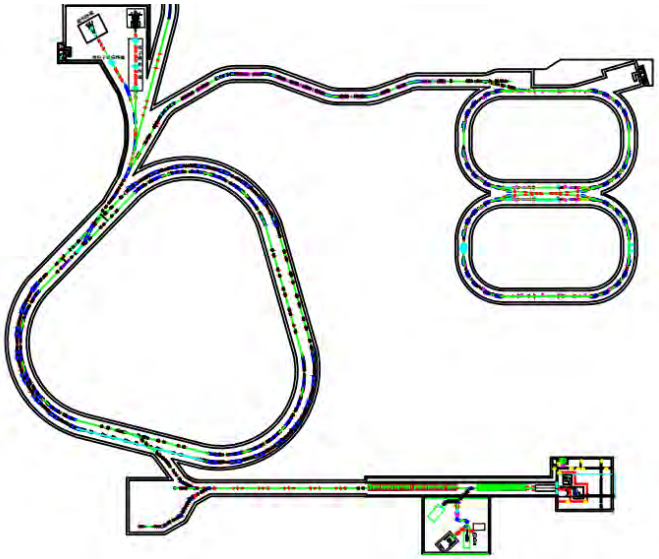
- A fundamental question of QED-spontaneous electron-positron pair creation in supercritical Coulomb fields
- Theory prediction: occur in the collisions of two very heavy ions with the total atomic number Z1 + Z2 ≥ 173.
- Failed to observe in fixed target experiments due to the interference of extranuclear electrons.

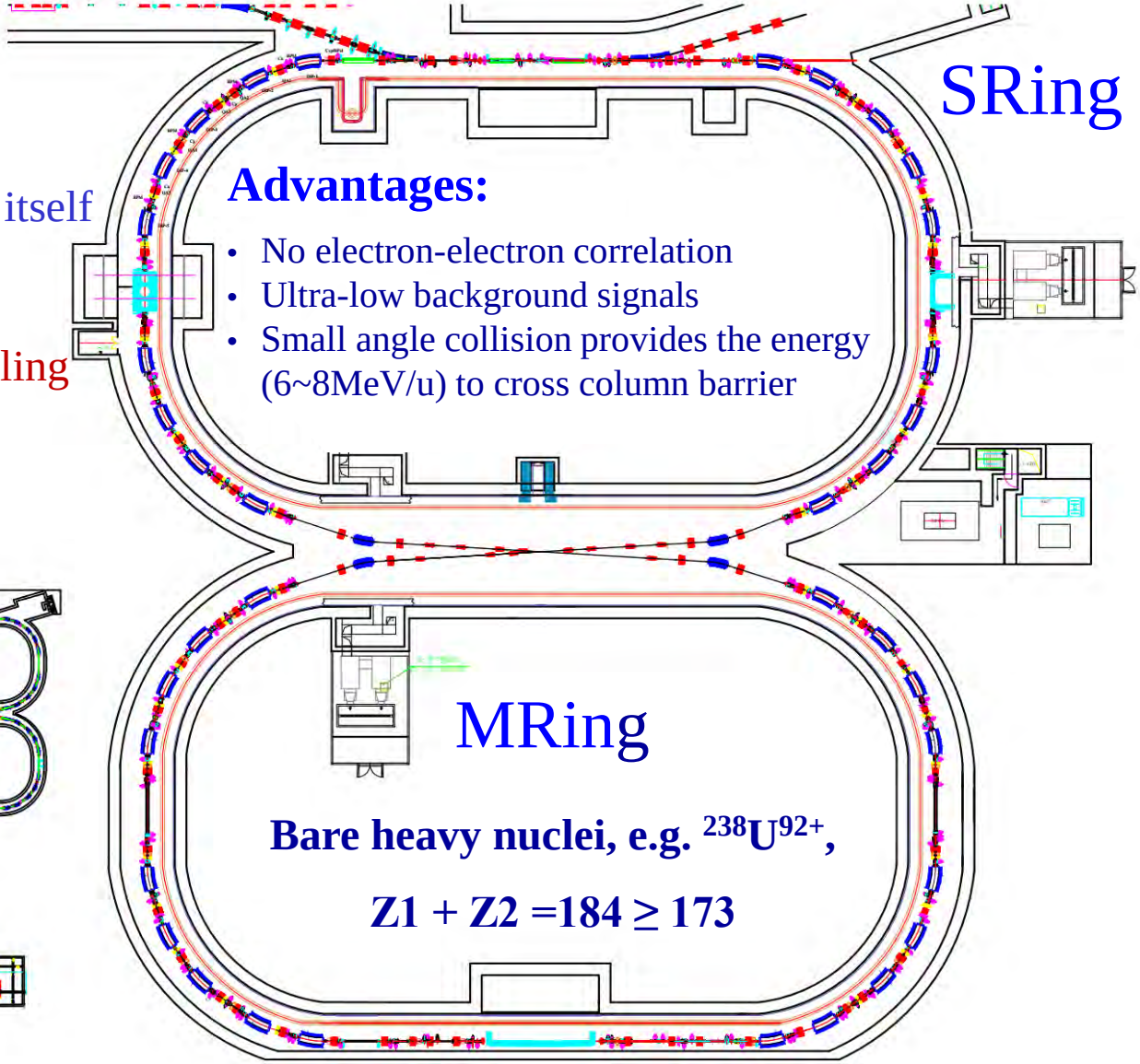
HIAF introduction and status

First figure-8 shape ring for ion-ion merging: pair production

Unique features:

- "8" shape ring
- Coasting beam merging with itself scheme
- Based on SRing
- Sharing the injection and cooling system
- No powerful RF system





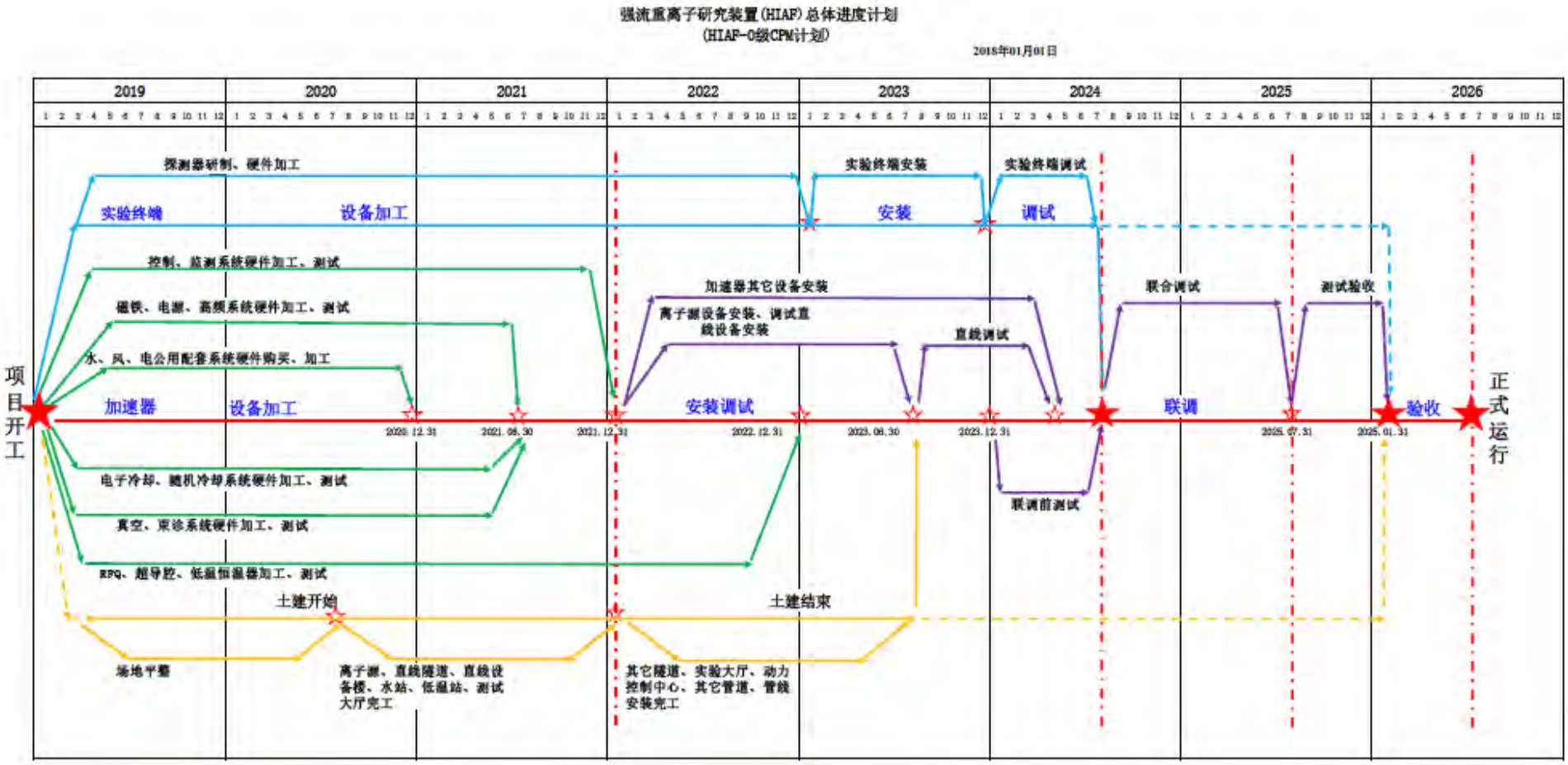
Advantages:

- No electron-electron correlation
- Ultra-low background signals
- Small angle collision provides the energy (6~8MeV/u) to cross column barrier

Bare heavy nuclei, e.g. $^{238}U^{92+}$,

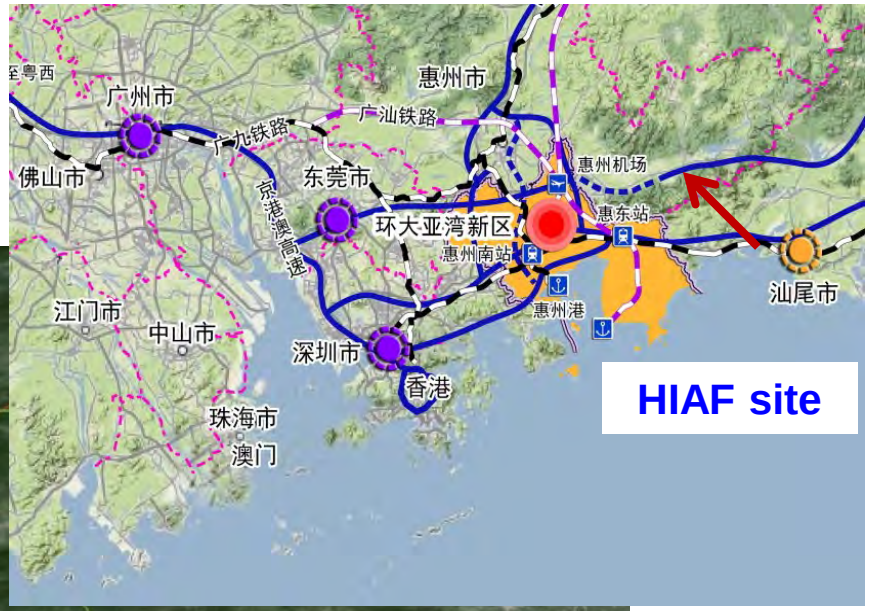
$Z1 + Z2 = 184 \geq 173$

Schedule


强流重离子研究装置(HIAF)总体进度计划
(HIAF-0级CPM计划)
2018年01月01日
2019
2020
2021
2022
2023
2024
2025
2026
探测器研制、硬件加工
实验终端安装
实验终端调试
实验终端
设备加工
安装
调试
控制、监测系统硬件加工、测试
磁铁、电源、高频系统硬件加工、测试
水、风、电公用配套系统硬件购买、加工
加速器其它设备安装
离子源设备安装、调试直线设备安装
直线调试
联合调试
测试验收
项目开工
加速器
设备加工
安装调试
联调
验收
正式运行
2020.12.31
2021.06.30
2021.12.31
2022.12.31
2023.06.30
2023.12.31
2025.07.31
2025.01.31
电子冷却、随机冷却系统硬件加工、测试
真空、束诊系统硬件加工、测试
RFQ、超导腔、低温恒温器加工、测试
联调前测试
土建开始
土建结束
场地平整
离子源、直线隧道、直线设备楼、水站、低温站、测试大厅完工
其它隧道、实验大厅、动力控制中心、其它管道、管线安装完工

New campus


HIAF site


惠州市
广州市
广汕铁路
广九铁路
佛山市
东莞市
惠州机场
京港澳高速
环大亚湾新区
惠东站
惠州南站
惠州港
汕尾市
江门市
中山市
深圳市
香港
珠海市
澳门
HIAF site


十里银滩
"十二五"装置
惠州核电优选
HIAF
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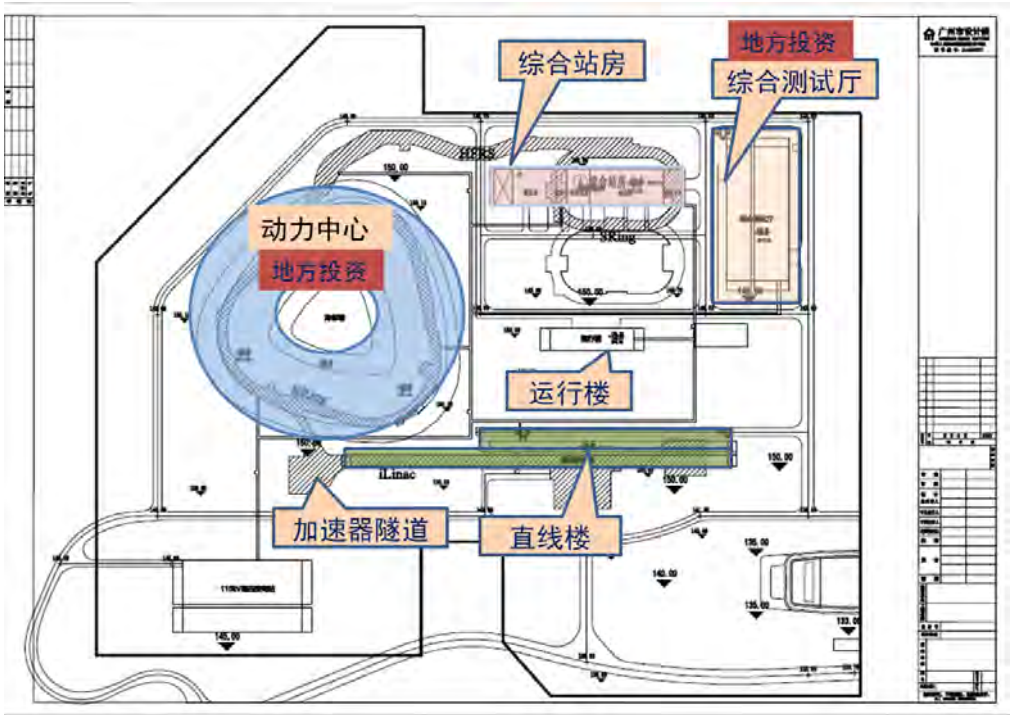
9.71 公里
Google earth

Present status



HIAF园区主要建筑平面布置图

HIAF introduction and status

Present status

Present status

Outline

1. HIAF introduction and status
2. EIC proposals in the world
3. Concept design of EicC-1 accelerator
4. Interaction region and luminosity concept
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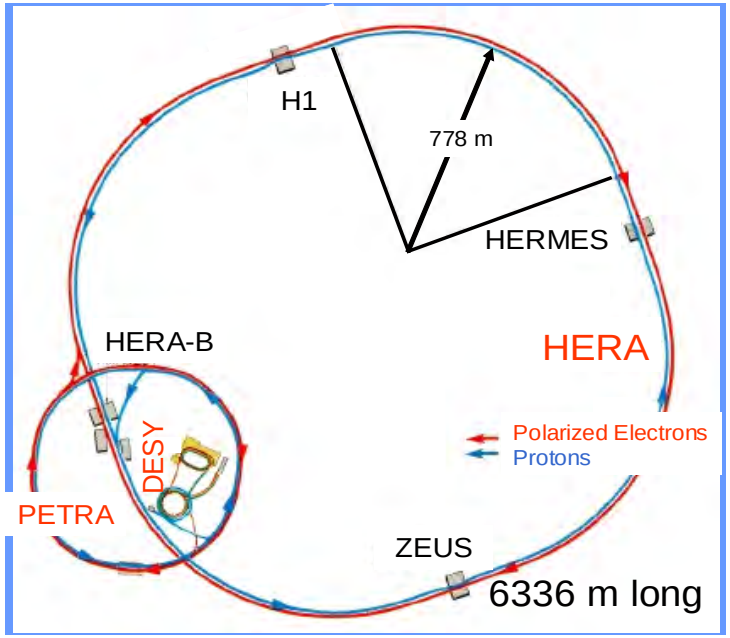
HERA: First EIC machine in the world



		Lepton	Proton
Energy	GeV	27.5	920
Intensities	mA	60	180×10^{11}
Magnetic field	T	0.15	1.5
Acc. voltage	MV	130	2
e-polarization	%	50 to 70	--

Final luminosity
$(1.5 \text{ to } 5) \times 10^{31}$ cm^{-2}s^{-1}

A Ring-Ring (polarized) Lepton-Proton collider with 320 GeV CM energy

1981 Proposal
1984 Start construction
1991 Commissioning, first Collisions
1992 Start Operations for H1 and ZEUS,
➔ 1st exciting results with low luminosity
1994 Install East Spin Rotators
➔ Longitudinal polarized leptons for HERMES
1996 Install 4th Interaction region for HERA-B
1999 High Luminosity Run with electrons
2000 High efficient luminosity production:100 /pb/y
2001 Install luminosity upgrade,
Spin Rotators for H1 and ZEUS
2003 Longitudinal polarization in high energy collisions
2007 End of a highly successful program

Tunnel: 5.2 m diameter

EIC proposals in the world

RHIC ➔ eRHIC

FAIR ➔ ENC

HIAF ➔ EicC

CEBAF ➔ JLEIC

LHC ➔ LHeC

HERA

Beam parameters and science goals

LHeC	eRHIC	JLEIC	EicC
7TeV+60GeV	255(p)+15.9(e)GeV	100(p)+5 (e)GeV	20(p)+3.5 (e) GeV
Unpolarized	E_{cm}: 126 GeV	100(p)+10 (e)GeV	100(p)+10 (e) GeV
E_{cm}: 1296 GeV		E_{cm}: 45/63 GeV	E_{cm}: 16.7/45 GeV

The High-Energy/Nuclear Science of LHeC

Overarching Goal: lepton-proton at the TeV Scale

Hunt for quark substructure & high-density matter (saturation)

High precision QCD and EW studies and possible implications for GUT

The Nuclear Science of eRHIC/MEIC

Overarching Goal: Explore and Understand QCD:

Map the spin and spatial structure of quarks and gluons in nucleons

Discover the collective effects of gluons in atomic nuclei

(role of gluons in nuclei & onset of saturation)

The Nuclear Science of EicC

Overarching Goal: Explore Hadron Structure

Map the spin and spatial structure of valence & sea quarks in nucleons

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Machine Design Goal

Present baseline:

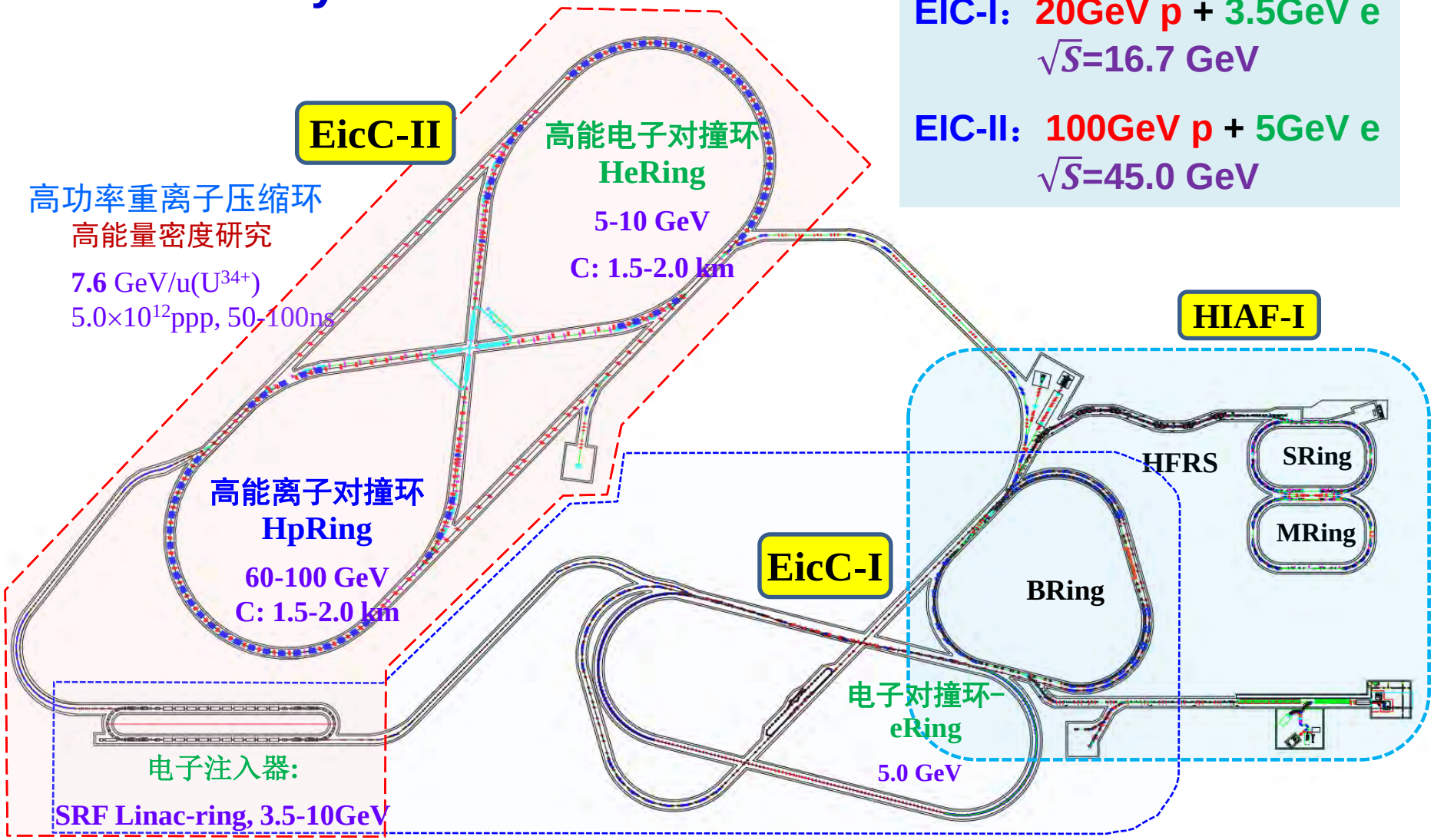
- **Energy:** 3.5 GeV/electron, 20 GeV/proton **First phase-EicC-1**
  5-10 GeV/electron, 60-100 GeV/proton **Second phase-EicC-2**
- **Ions:** Polarized light ions (p, d, ^{3}He), unpolarized heavy ions up to Uranium
  High polarization for both beams, 80% for electron, and 80% for proton
- **Layout :** Ring-Ring collision mode
  New figure “8” shape ring for ion
  Racetrack shape for electron
  Electron injector based on SRF Linac-Ring
- **Cooling strategy :**
  Conventional DC cooling for pre-cooling
  Bunched electron cooling for high energy stage based ERL
- **Luminosity :**
  (2-4)x10^{33} cm-^{2}s^{-1} **First phase-EicC-1**
  1x10^{34} cm-^{2}s^{-1} **Second phase-EicC-2**

The preliminary concept design of EicC

The whole layout of EicC

EIC-I：20GeV p + 3.5GeV e
$\sqrt{S}$=16.7 GeV

EIC-II：100GeV p + 5GeV e
$\sqrt{S}$=45.0 GeV



离子对撞环 - pRing
20 GeV， C: 1347 m Polarized proton

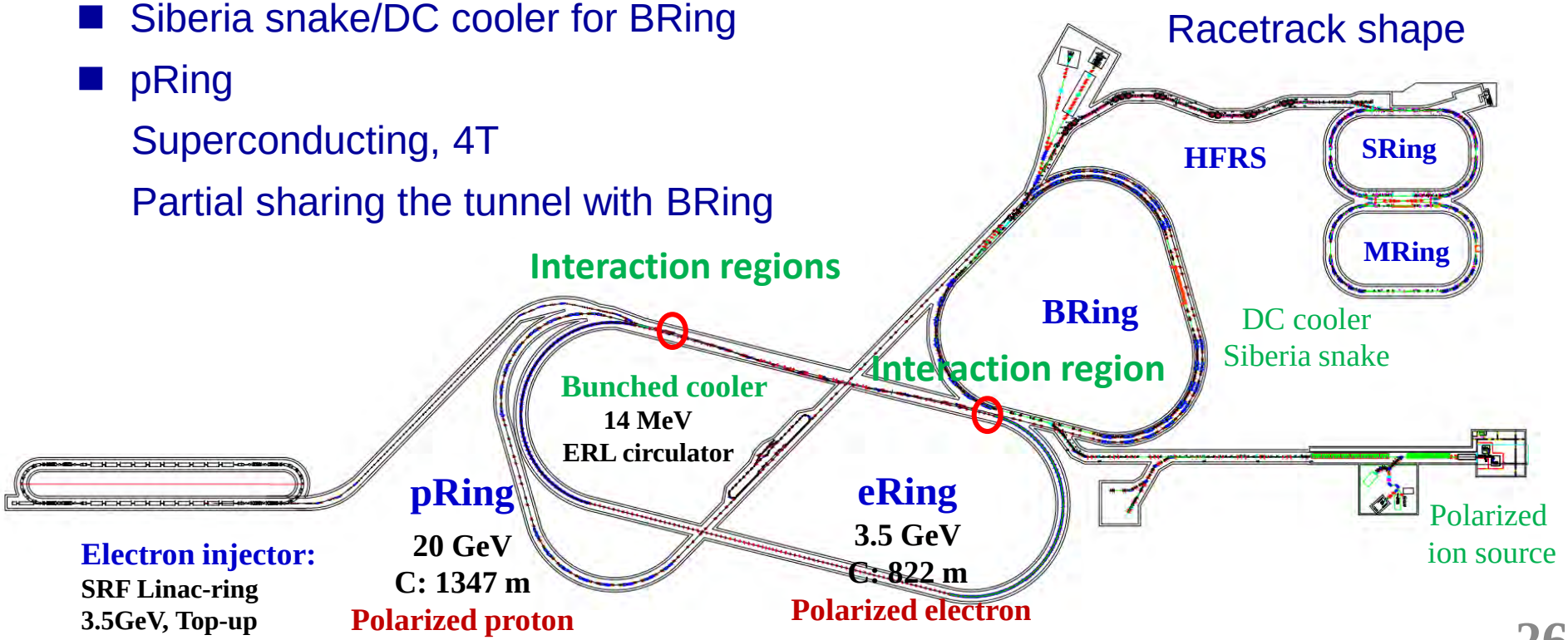
The whole layout of EicC-1

Main changes

- Figure-8 shape ion collider with four long straight sections
- Two interaction points for detectors, electron cooling, RF system
- The high luminosity 2 x10^{33} cm^{-2}s^{-1}, **4 x10^{33} cm-^{2}s^{-1}**

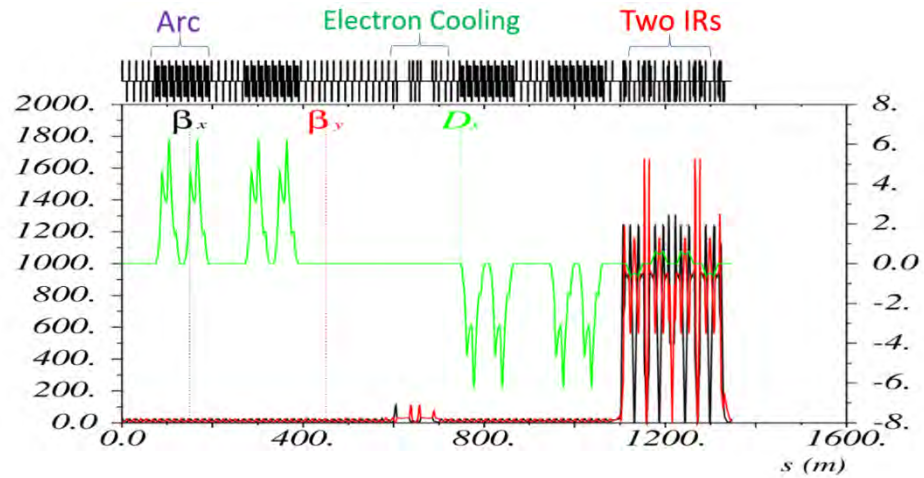
EicC-I New construction

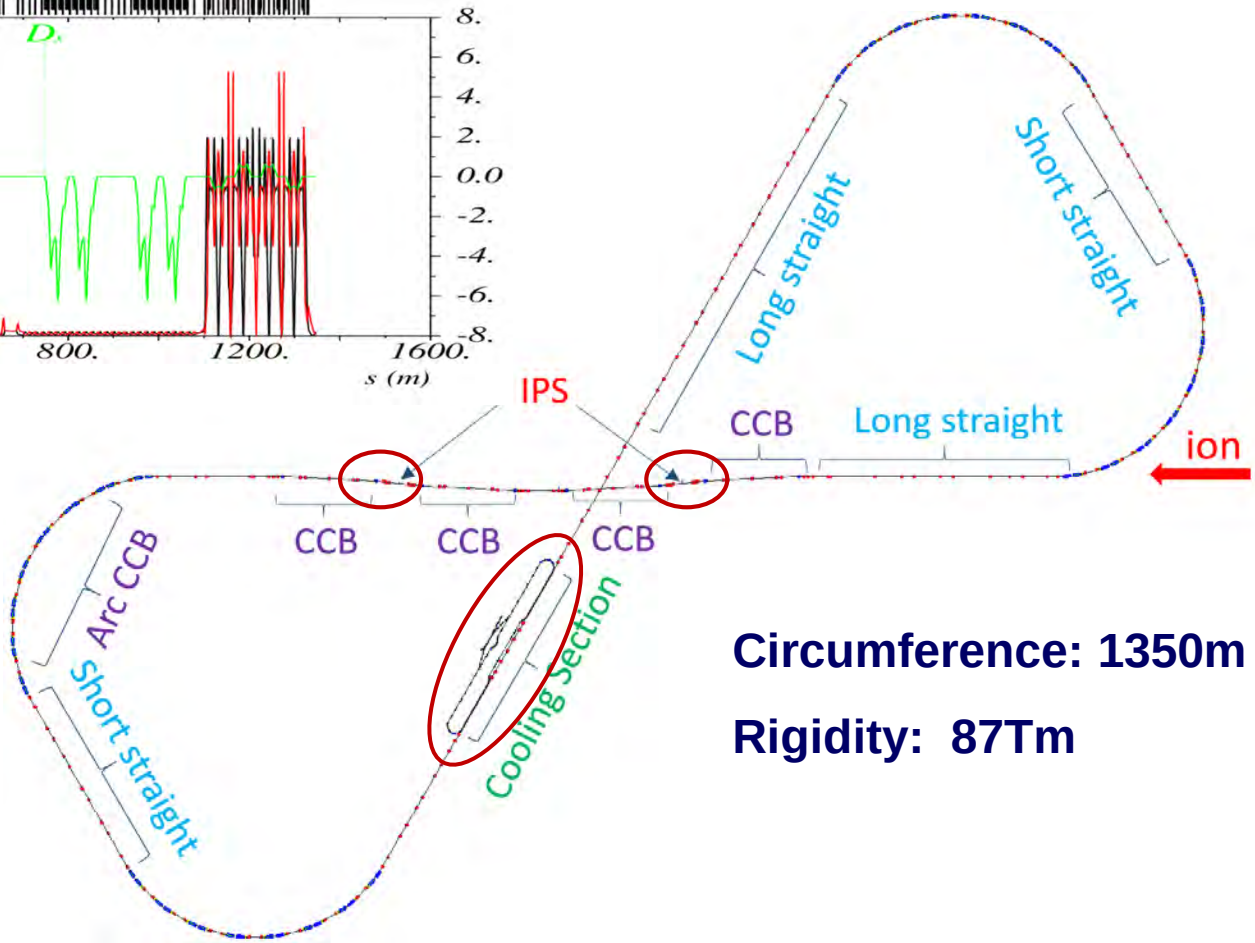
- polarized ion source
- Siberia snake/DC cooler for BRing
- pRing
  Superconducting, 4T
  Partial sharing the tunnel with BRing
- e injector
  SRF Linac-ring
- eRing
  Racetrack shape



Ion Collider Layout and Optics- pRing

- FD type lattice cell in arcs - not standard FODO, dynamic vacuum effects
- Dedicated Chromaticity Compensation Blocks (CCB) in arcs
- Long straight sections for two **IPs, RF, cooler**



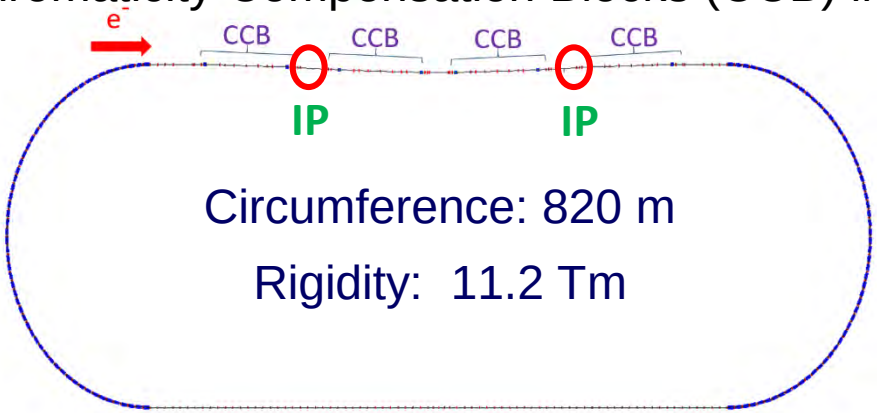


Circumference: 1350m

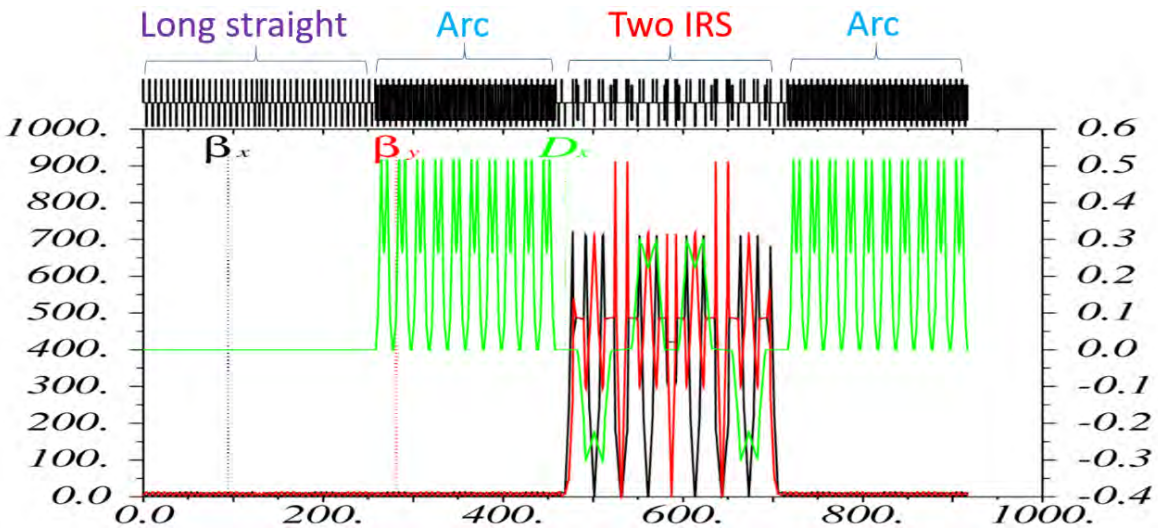
Rigidity: 87Tm

Electron Collider Layout and Optics- eRing

- FODO-cell arcs, racetrack shape
- Dedicated Chromaticity Compensation Blocks (CCB) in arcs



The whole layout of the electron collider-eRing



Optics of the whole electron collider-eRing

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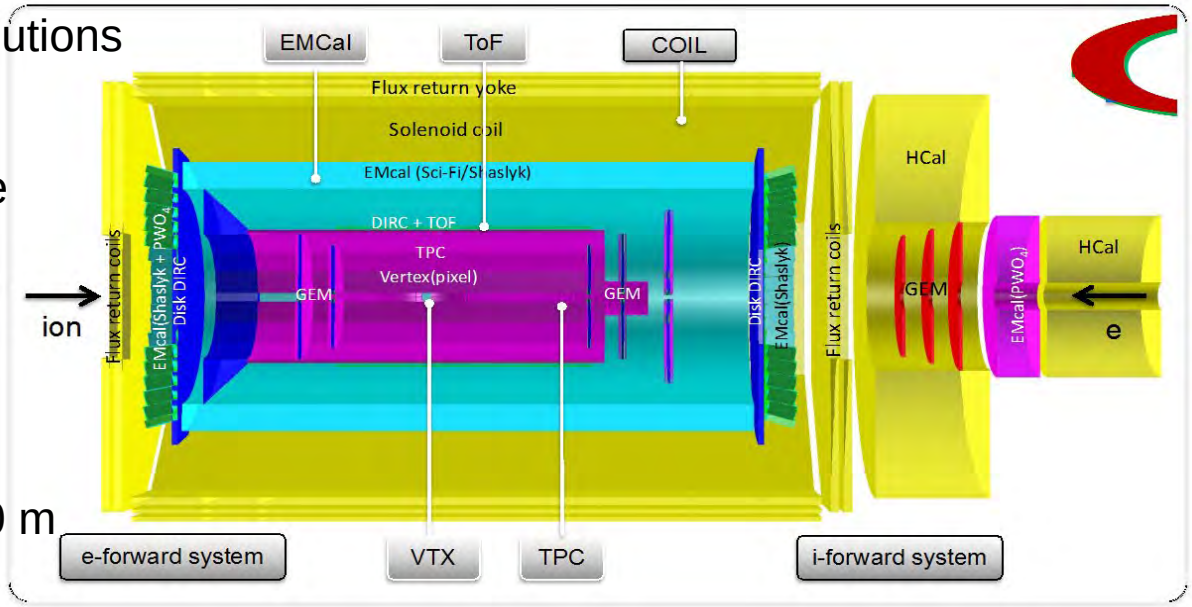
Interaction Regions Design

IR design requirements:

- Small β* for high luminosity
- Limited IR chromaticity contributions
- Large detector acceptance
  - ➔ Large quadrupole aperture

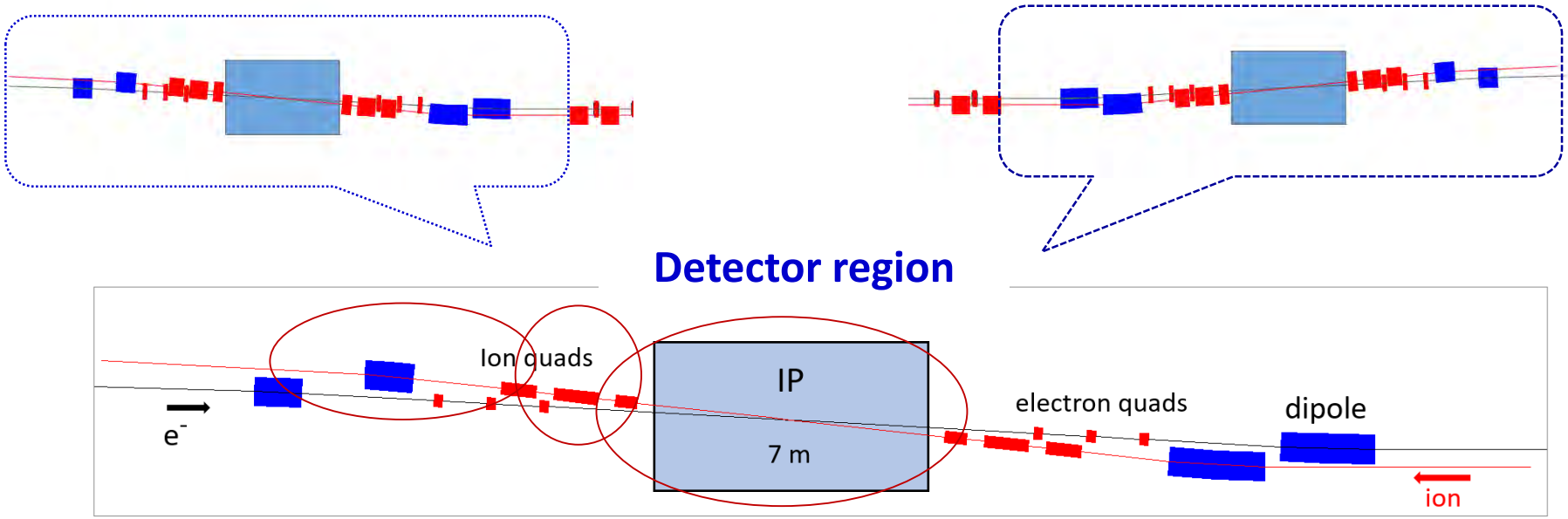


EicC-1 detector system

- Accommodate spectrometer in the low-β optics
- No accelerator magnets +/-7.0 m
- Avoid synchrotron radiation:
  - no electron bends on the forward side
  - absorb SR far from IP
  - need mask against backscattered SR photons
- Accommodate spin rotators, spin matching
- Space for luminosity monitor, neutron detector, “Roman Pots”

Interaction Regions Layout

- Two interaction points and 7m free straight section for each point
- 50 mrad crossing angle
- Two Mirror-symmetric Interaction Regions



Forward hadron detection

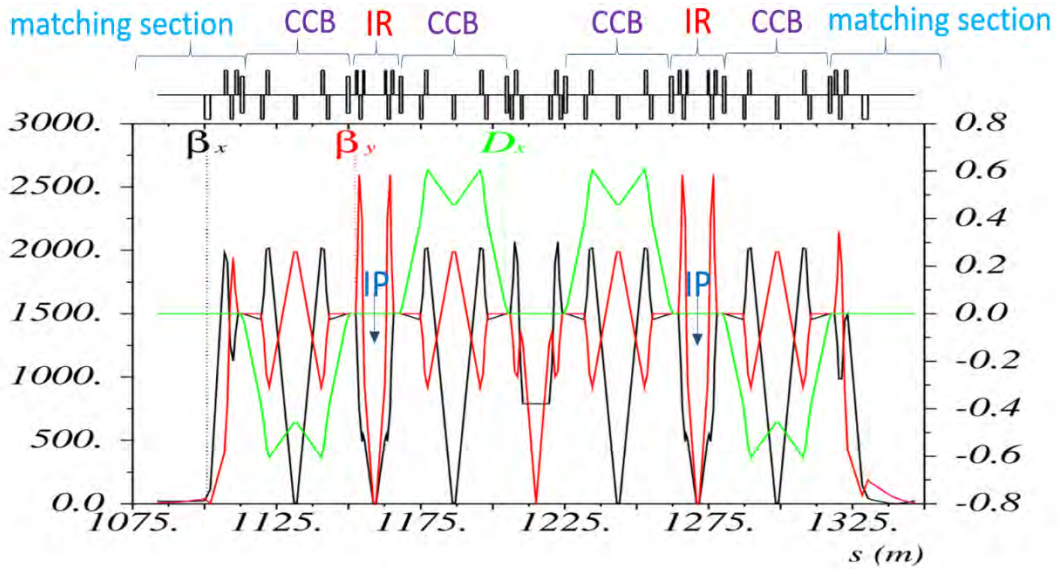
Forward electron detection

Schematic layout of the interaction region

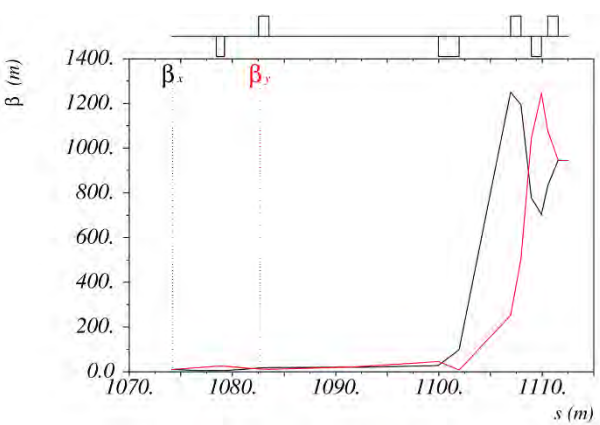
Interaction Region Optics - pRing

➢ Interaction Region

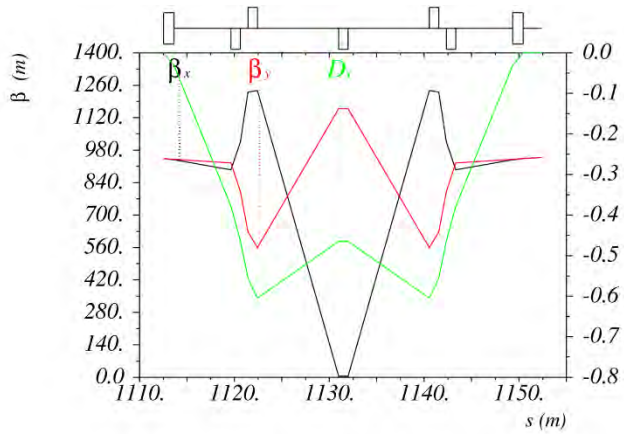
- Symmetric optic design and no dispersion at IPS
- Two Interaction Regions based on Final Focusing Blocks(FFB)
- Three CCBs with dispersion suppression and chromaticity compensation



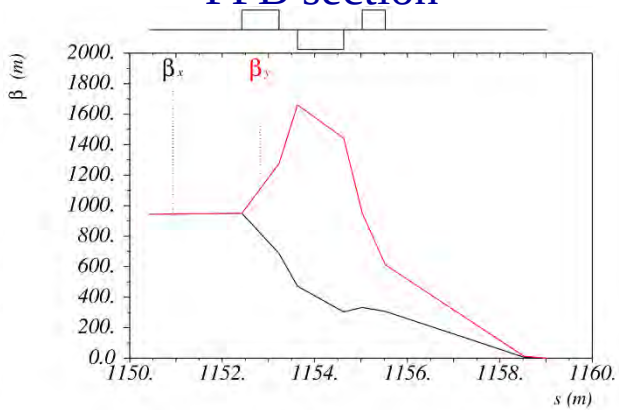
Matching section



CCB section

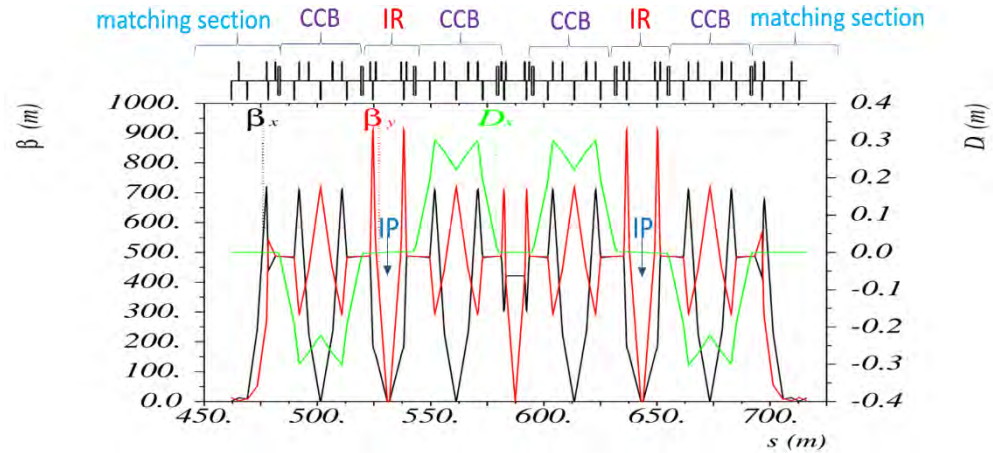


FFB section

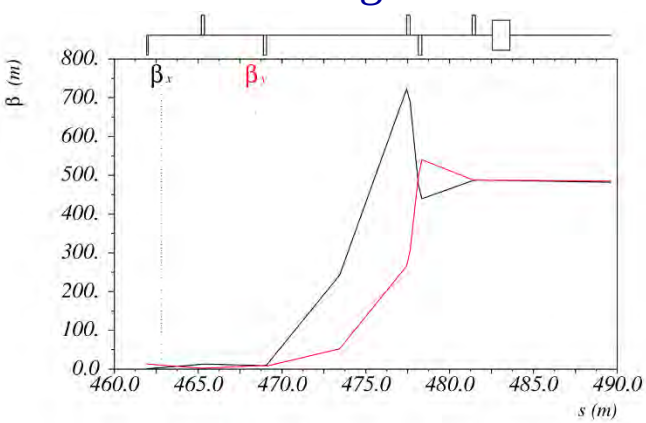


Interaction Region Optics - eRing

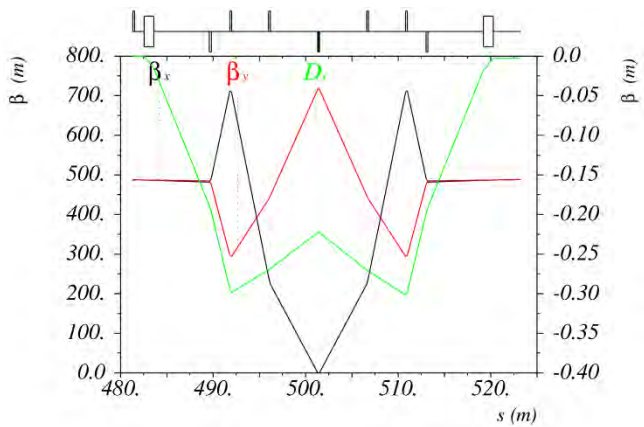
- IR design feature similar to proton
  - Symmetric optic design and no dispersion at IPS
  - Two Interaction Regions based on Final Focusing Blocks(FFB)
  - Three CCBs with dispersion suppression and chromaticity compensation



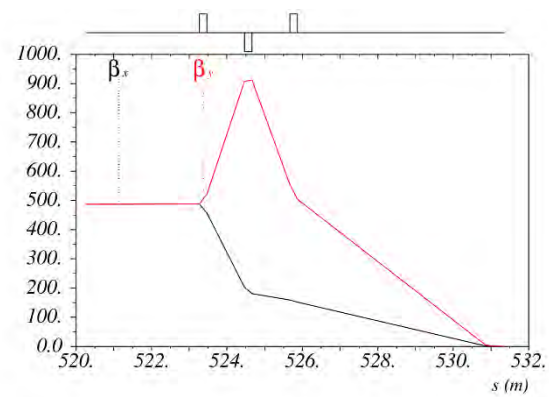
Matching section



CCB section



FFB section



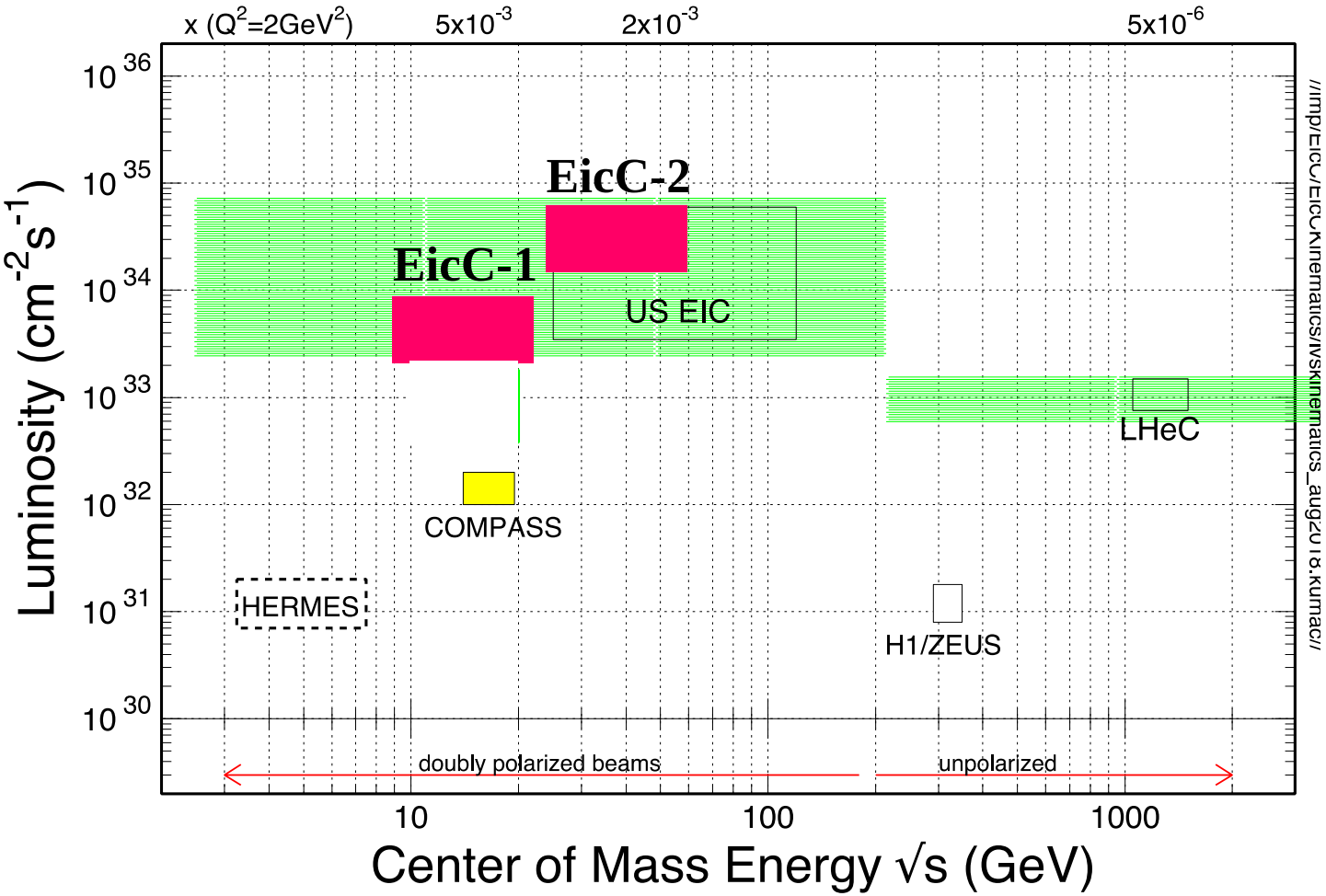
Luminosity concept

EicC-I: 25GeV p + 3.5GeV e

$\sqrt{S}$=18.7GeV

Luminosity: 2.0×10^{33} cm^{-2}s^{-1}

4.0×10^{33} cm^{-2}s^{-1}



Basic strategy and design principles

Limitation of the state-of-art

- The stored beam currents are up to 0.5A for protons or ions and 3A for electrons
- The hadron beam-beam tune-shift is limited to 0.03/interaction point
- The direct space-charge tune-shift of ion beams is limited to 0.06

$$L = \frac{N_p N_e f_c}{4\pi\sigma_x\sigma_y} H$$

$$N_p f_c \propto I_p$$
$$N_e f_c \propto I_e$$

$$\Rightarrow \quad L \propto \frac{I_p I_e}{f_c}$$

$\sigma_x\sigma_y$ also increase, but smaller impaction than f_c

Strategy of EicC-1

- More particles in a single bunch.
- A lower collision frequency.
- Crab-crossing
- Adjust emittance simultaneously due to IBS.

Basic strategy and design principles

- The main challenge of EicC is IBS

IBS rate

$$\frac{1}{\tau} \propto \frac{N_p}{\boxed{\varepsilon_x \varepsilon_y \sigma_{dp/p} \sigma_s}}$$

Volume of 6 phase space

- If N_p increase m times, let IBS rate keep constant, Then

$$\varepsilon_x \propto m^{\frac{1}{3}}, \varepsilon_y \propto m^{\frac{1}{3}}, \sigma_{dp/p} \propto m^{\frac{1}{6}}, \sigma_s \propto m^{\frac{1}{6}}$$

- Luminosity

$$\boxed{L = \frac{N_p N_e f_c}{4\pi\sigma_x\sigma_y} H \propto \frac{m m^{\frac{1}{m}}}{m^{\frac{1}{3}} m^{\frac{1}{2}}} = \sqrt{m}}$$

Basic strategy and design principles

	Old		New	
particle	**p**	**e**	**p**	**e**
circumference(m)	1350	876	1350	820
energy(GeV)	25	3.5	25	3.5
Bρ(T·m)	87	11.7	87	11.7
$f_{collision}$(MHz)	750		**30**	
particles per bunch($\times 10^{10}$)	0.5	2.6	**10.4**	**62.5**
ε_x, ε_y(nm·rad, rms)	100/60	10	**300/180**	**60**
β^*_x/β^*_y (m)	0.024/0.012	0.24/0.072	**0.04/0.02**	**0.2/0.06**
bunch length(m)	0.02	0.01	0.035	0.02
dp/p	5e-4		8.5e-4	
Beam-Beam Parameter ξ_y	0.002	0.007	0.011	0.04
Laslett tune shift	0.01	—	0.05	—
energy loss per turn(MeV)	—	0.32	—	0.32
total SR power(MW)	—	1.0	—	1.0
SR linear power density(kW/m)	—	3.7	—	3.6
current(A)	0.6	3.1	0.5	3.0
crossing angle(mrad)	50		50	
hourglass	0.87		0.85	
Luminosity($cm^{-2}s^{-1}$)	**0.5×10^{33}**		**2.0×10^{33}**	

Luminosity increases by 4 times

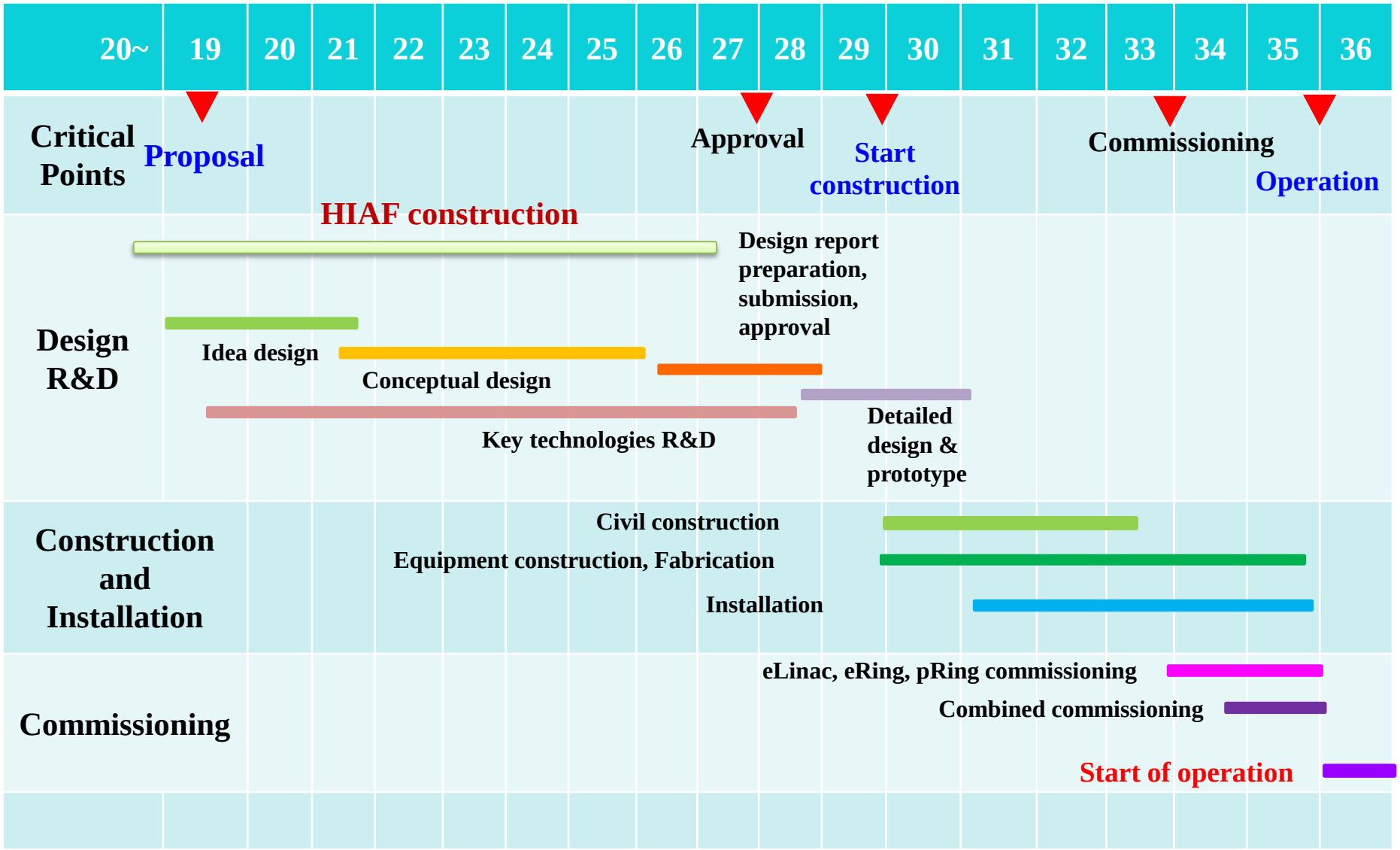
Outline

1. HIAF introduction and status
2. EIC proposals in the world
3. Concept design of EicC-1 accelerator
4. Interaction region and luminosity concept
5. Cost estimation and schedule
6. Summary

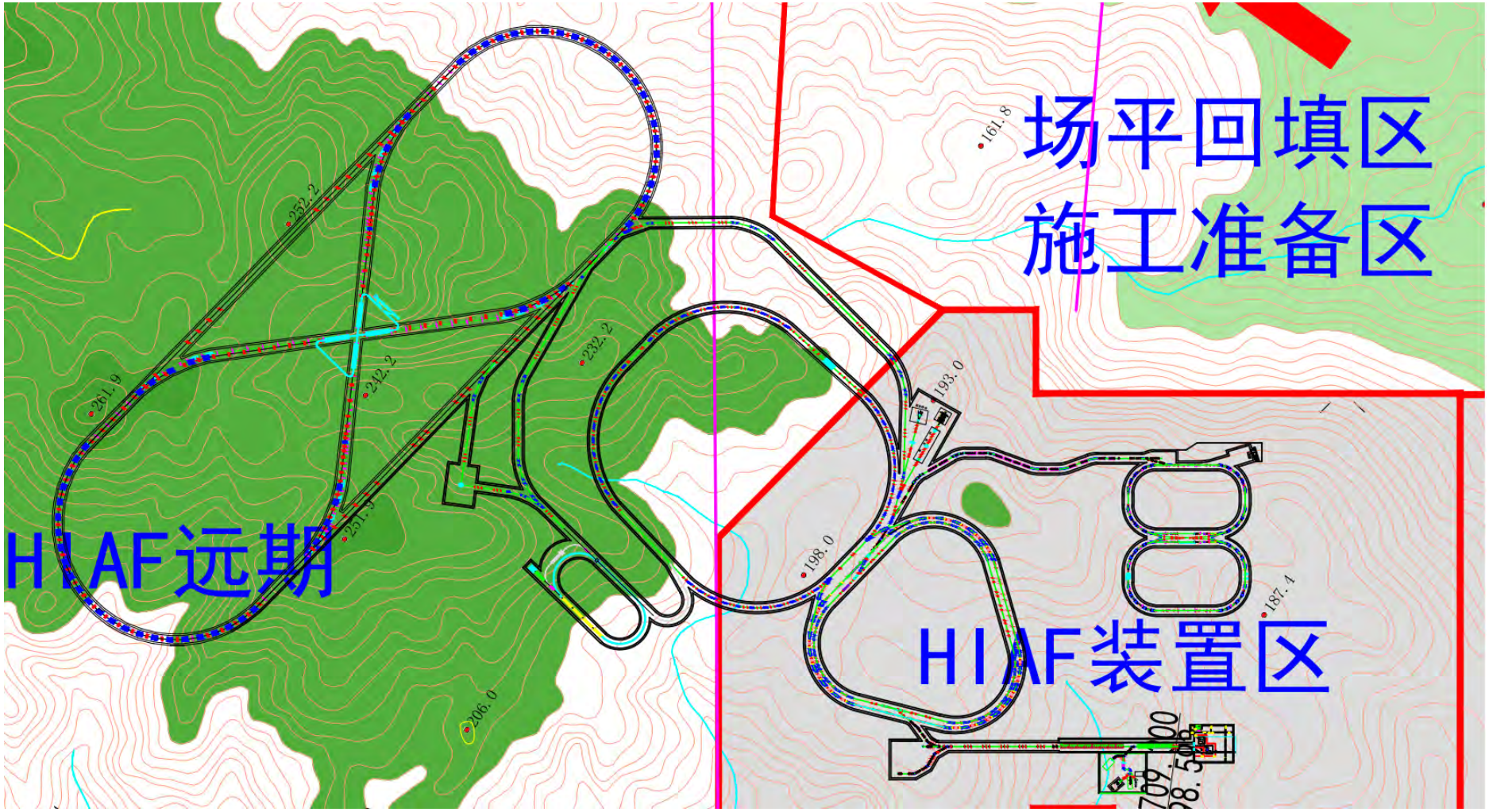
EicC-1 cost estimation

Items	1st phase (MRMB)
HIAF update	**560**
eLinac	**550**
eRing	**600**
pRing	**800**
Beam transfer line	**400**
Experiment setups	**1000**
Cryogenics	**450**
Civil engineering	**550**
Tunnel construction	**600**
Contingency cost	**500**
Total of facility	**6010**

Schedule of EicC-1



Campus for EicC



Outline

1. HIAF introduction and status
2. EIC proposals in the world
3. Concept design of EicC-1 accelerator
4. Interaction region and luminosity concept
5. Cooling strategy and design
6. Summary

Summary

- Based on the HIAF accelerator complex, a concept design of EicC-1 accelerator design was presented. The new design mainly focused on the scientific requirements, such as luminosity, interaction region.
- This is a preliminary concept design and provides a basis for performance evaluation, technical risk assessment and cost estimation.
- The design will be further optimized and improved. More details should be investigated, especially cooling scheme and stimulation studies.
- The polarization issue is not covered by this presentation, for polarization in BRing, the Siberia Snakes will be used and figure 8 shape ring for ion collider ring-pRing.
- A series of beam dynamics and technical challenges for EicC. Prototypes of key technologies or components will be developed step by step.

Thanks for your attention!

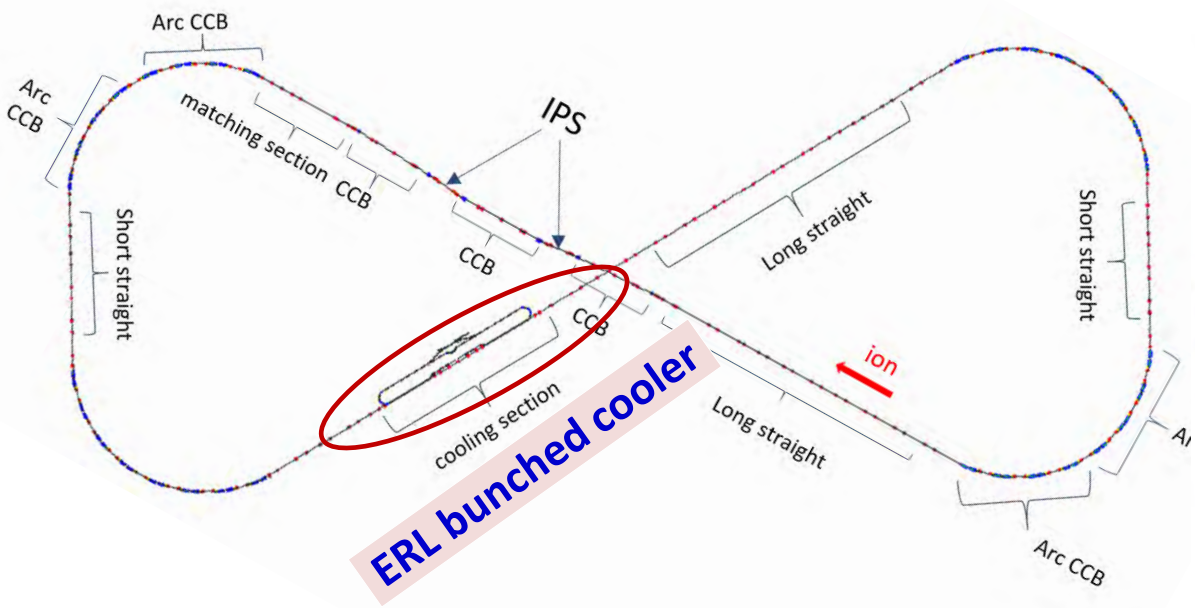
Cooling strategy

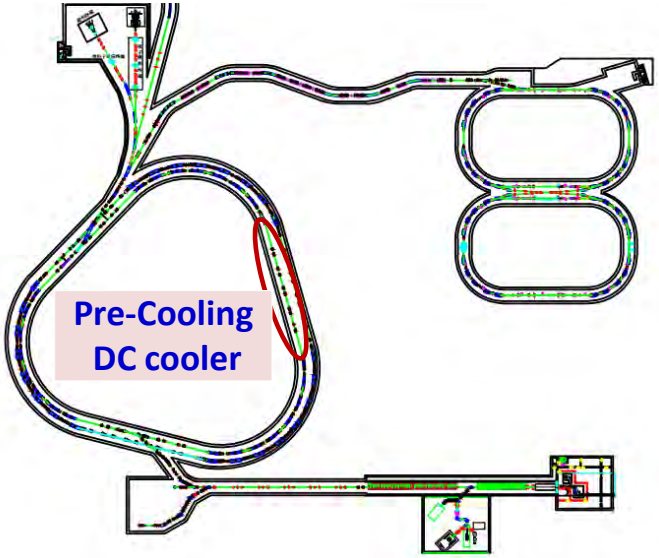
Cooling

- Small emittance and short bunch (with strong SRF)
- Enabling ultra strong final focusing and crab crossing
- Suppressing IBS, expanding high luminosity lifetime

Two stages cooling scheme:

- **Pre-Cooling:** Booster-BRing-N, 2GeV, Conventional DC cooler
- **Collision cooling:** Proton collider-PRing, 25 GeV, ERL bunched cooler

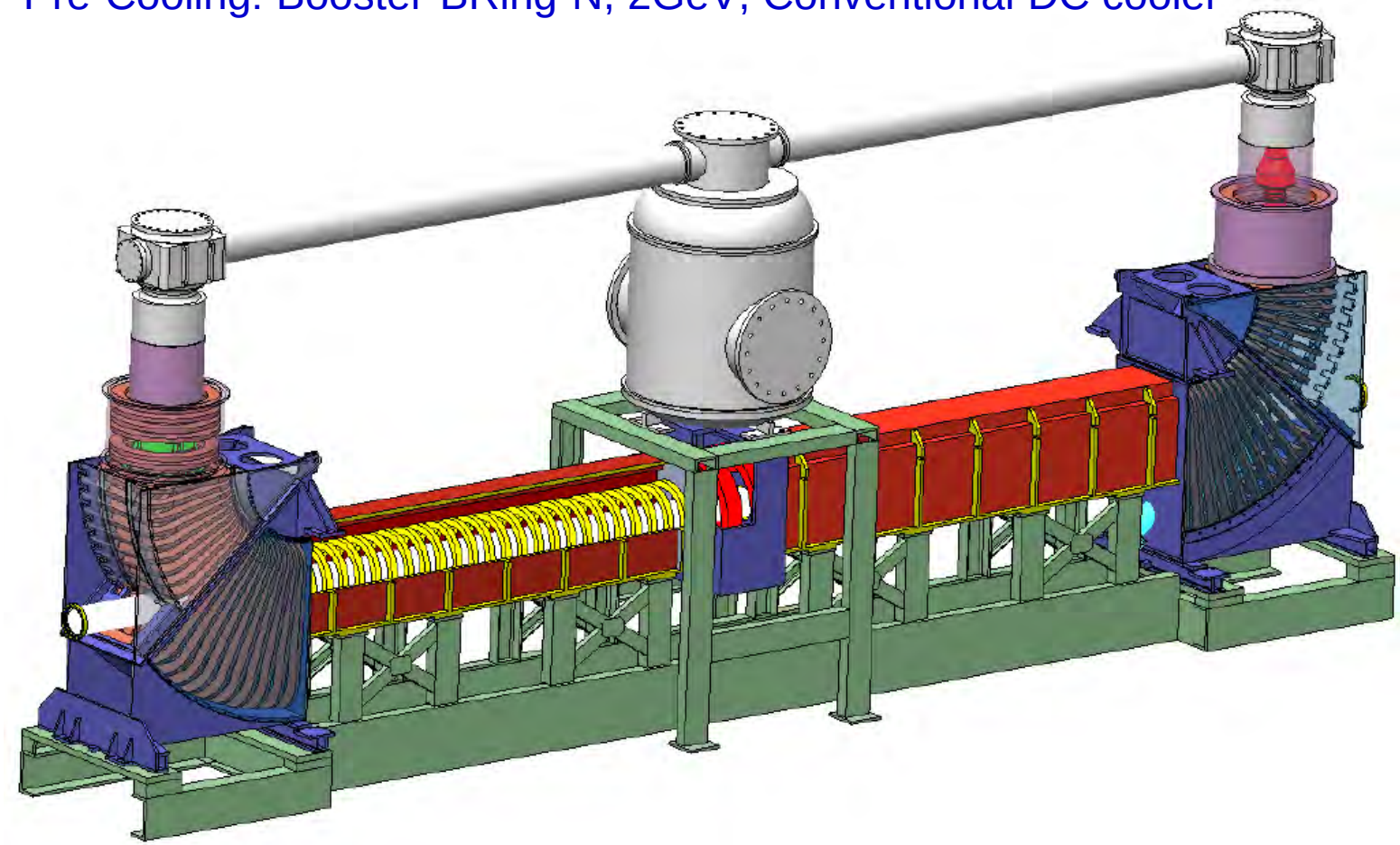




Cooling strategy

Pre-cooling design:

- Pre-Cooling: Booster-BRing-N, 2GeV, Conventional DC cooler

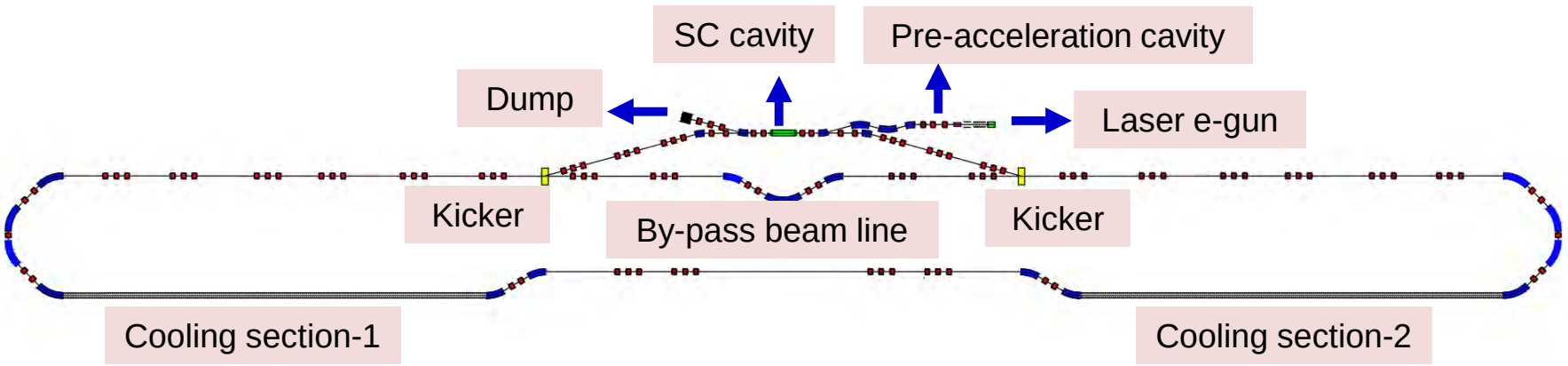


Such a cooler is technically well developed and readily available

Cooling strategy

Collision cooler design:

- **Collision cooling:** Proton collider-pRing, 25 GeV, ERL bunched cooler



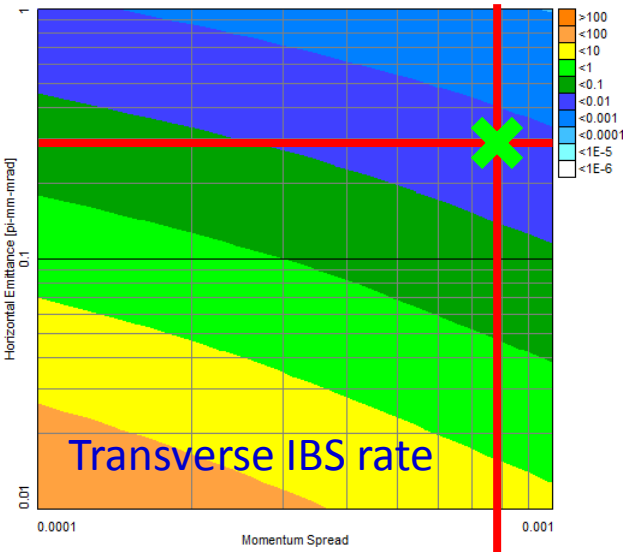
Sketch of EicC collision cooling design

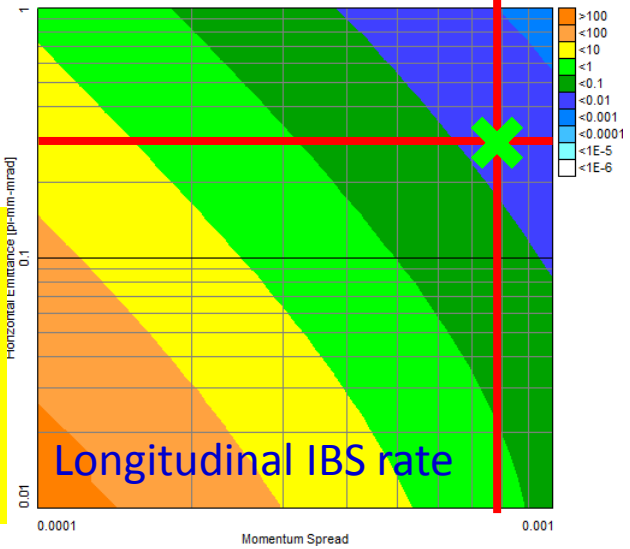
Gun type	NCRF	RMS energy spread	5×10^{-4}
RF frequency	700 MHz	RMS bunch length	200 ps
PRF	2 MHz	Cooling section	50m
Charge /bunch	4 nC	Cryostat number	1
Inject energy	2 MeV	Cryostat length	1.5m
Cooling energy	14 MeV	Circumference of circulating ring	160m
Transerse rms normalized emittance	2.5πmm mrad	Bunch frequency in circulating ring	30 MHz

EicC luminosity parameters

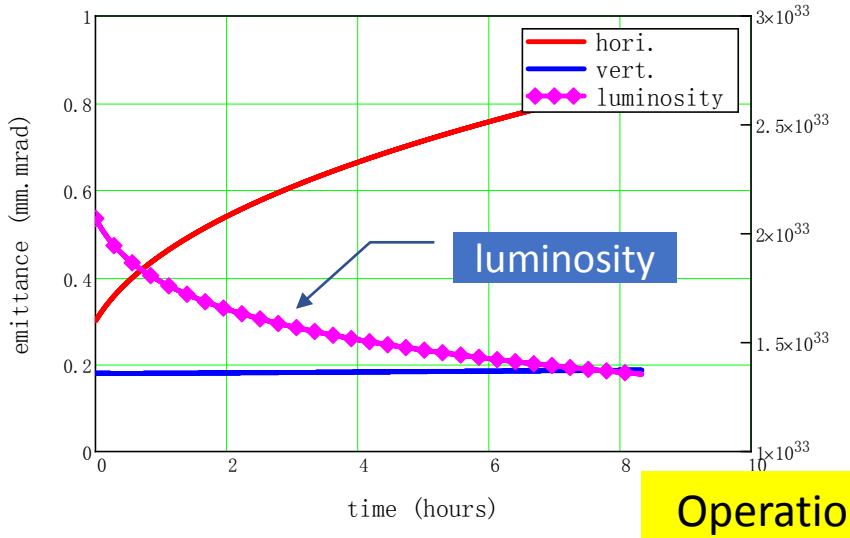
	p	e
circumference(m)	1350	820
energy(GeV)	25	3.5
Bρ(T·m)	87	11.7
$f_{collision}$(MHz)	30	30
particles per bunch($\times 10^{11}$)	1.04	6.25
ε_x, ε_y(nm·rad, rms)	300/180	60
β^*_x/β^*_y (m)	0.04/0.02	0.2/0.06
bunch length(m)	0.035	0.02
dp/p	8.5e-4	
Beam-Beam Parameter ξ_y	0.011	0.04
Laslett tune shift	0.05	—
energy loss per turn(MeV)	—	0.32
total SR power(MW)	—	1.0

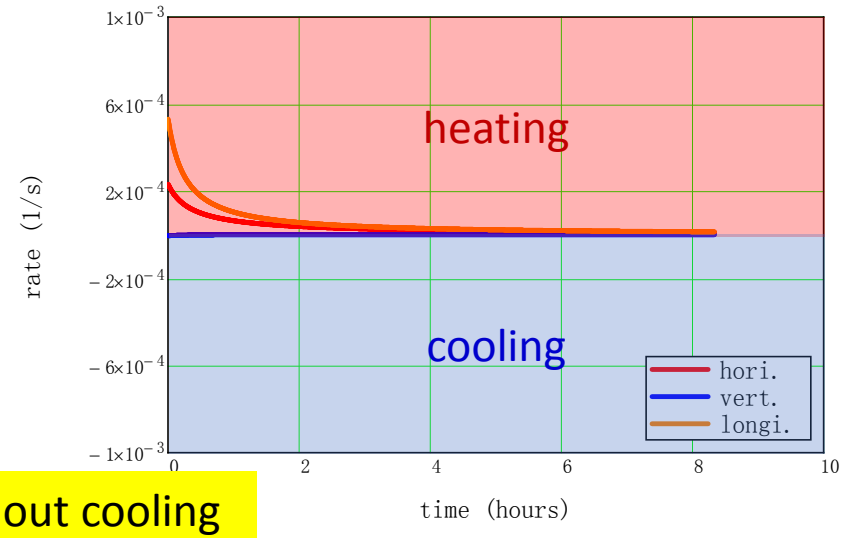
- The IBS growth rate is estimated around ***1.2 h^{-1}***
- A beam cooling rate should be the same as IBS growth rate, to suppress the emittance growth in operation.



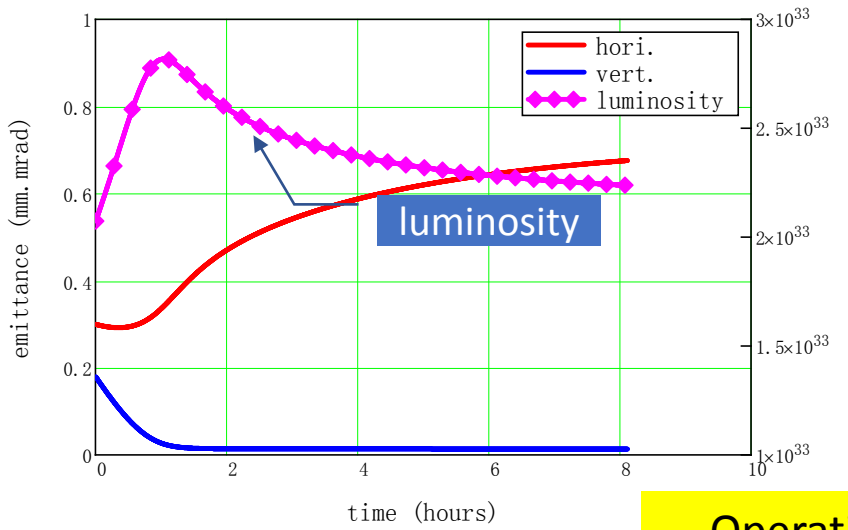


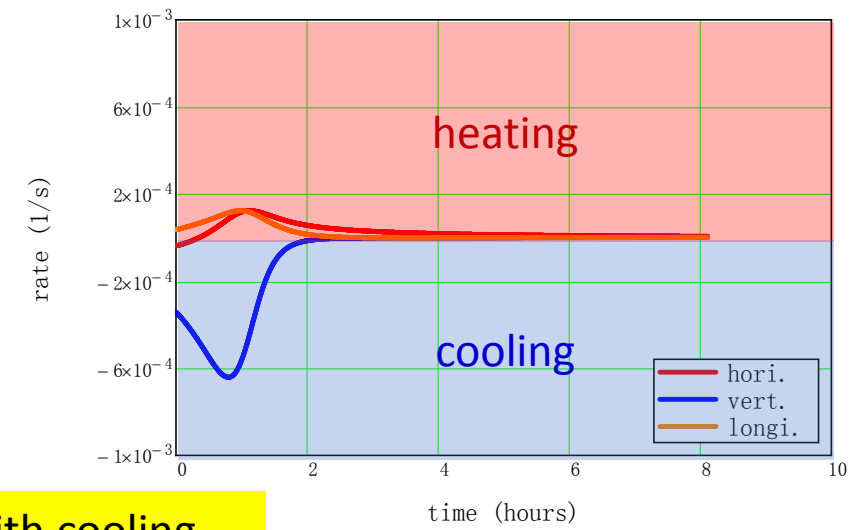
EicC proton beam cooling





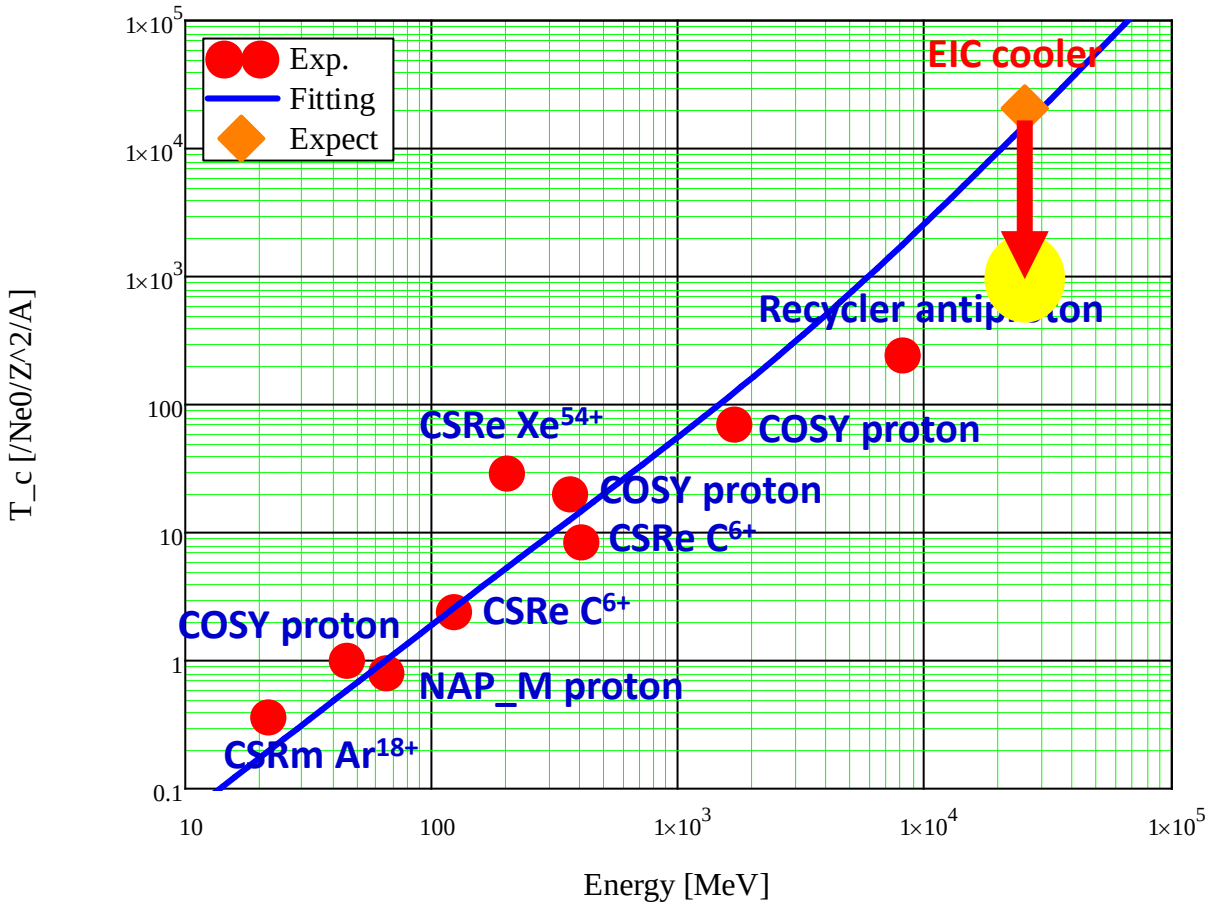
Operation without cooling





Operation with cooling

Cooling rates footprint (expt.)



The cooling rates $1/T_c$ are normalized by Z^2/A to an electron density n_e of $10^8\ cm^{-3}$

$$\frac{1}{T_c} = 4 r_e r_p n_e \eta_c c \frac{1}{\gamma^2} \left(\frac{1}{\beta^2 \gamma^2 \theta_\perp^2 + \beta^2 \theta_\parallel^2 + \theta_{eff}^2} \right)^{\frac{3}{2}} \frac{Z^2}{A} \ln \xi \quad \propto n_e \frac{Z^2}{A} \frac{1}{\gamma^2 \beta^3}$$

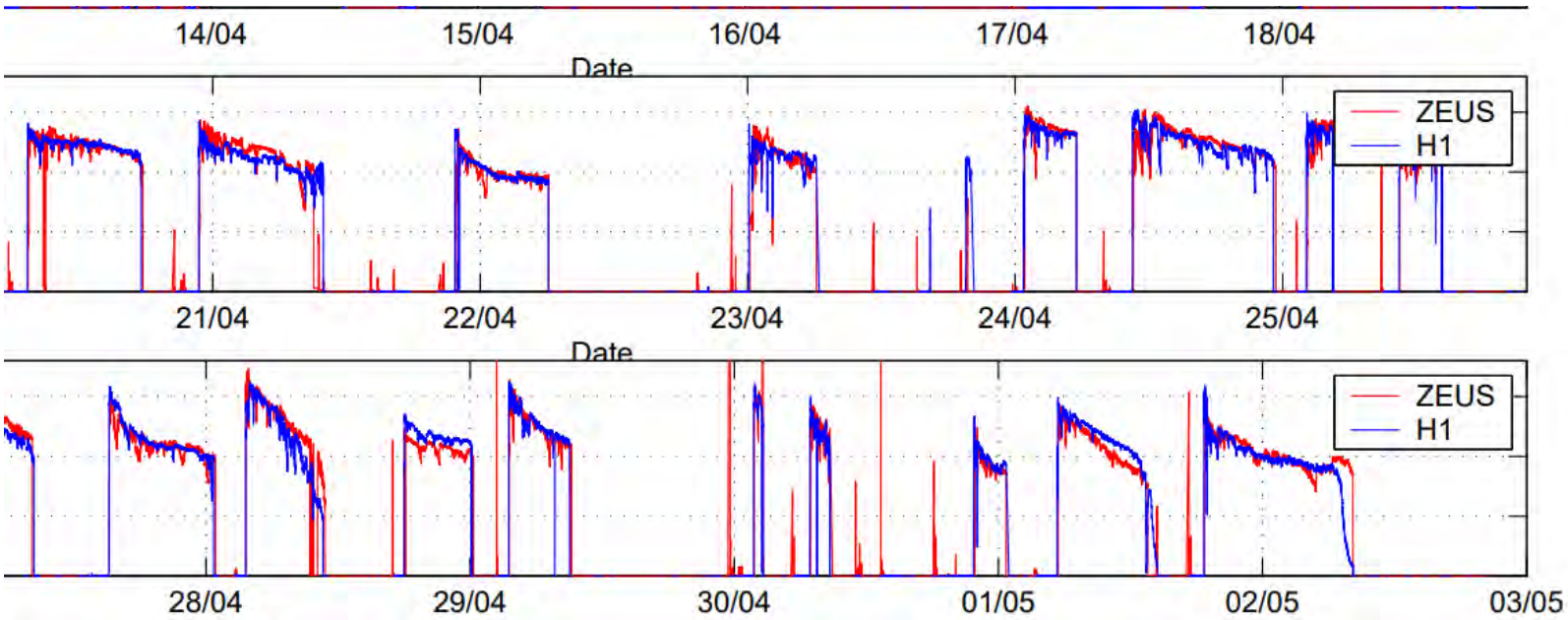
Bunched beam cooling

- **The bunched beam cooling based on ERL design relies on adapting several new concepts/schemes and integrating an array of cutting-edge accelerator technologies for delivering high performance to meet the cooling needs. A successful demonstration of these new concepts/schemes and development of various key supporting technologies are still very challenging. In this case, this cooling scheme is a big risk of EicC-1**

- **An alternative design without ERL collision cooling is also under active evaluation for high integrated luminosity with fast cycling mode and it provides a backup approach.**

Operation mode and integrated luminosity

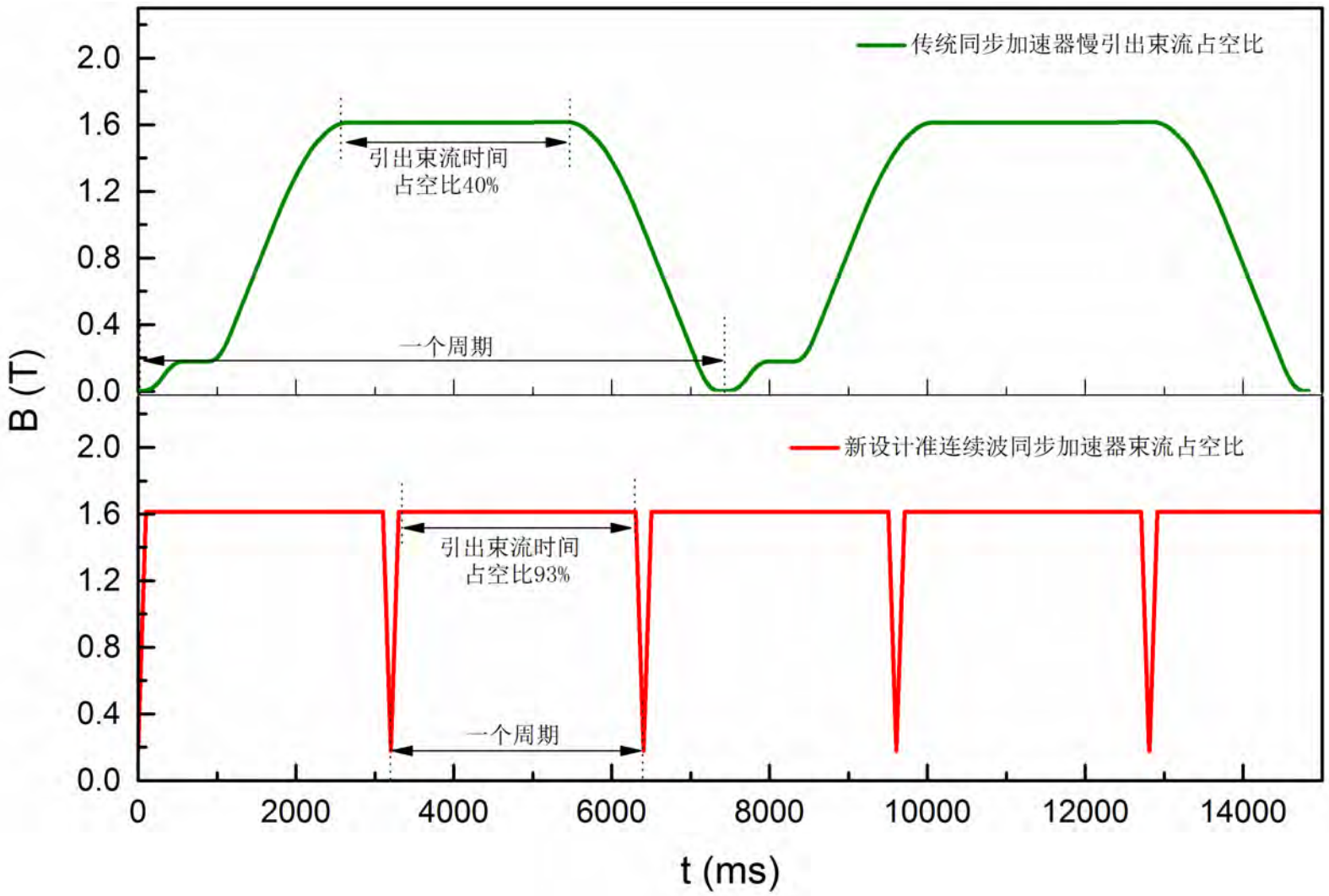
➢ The normal integrated luminosity mode



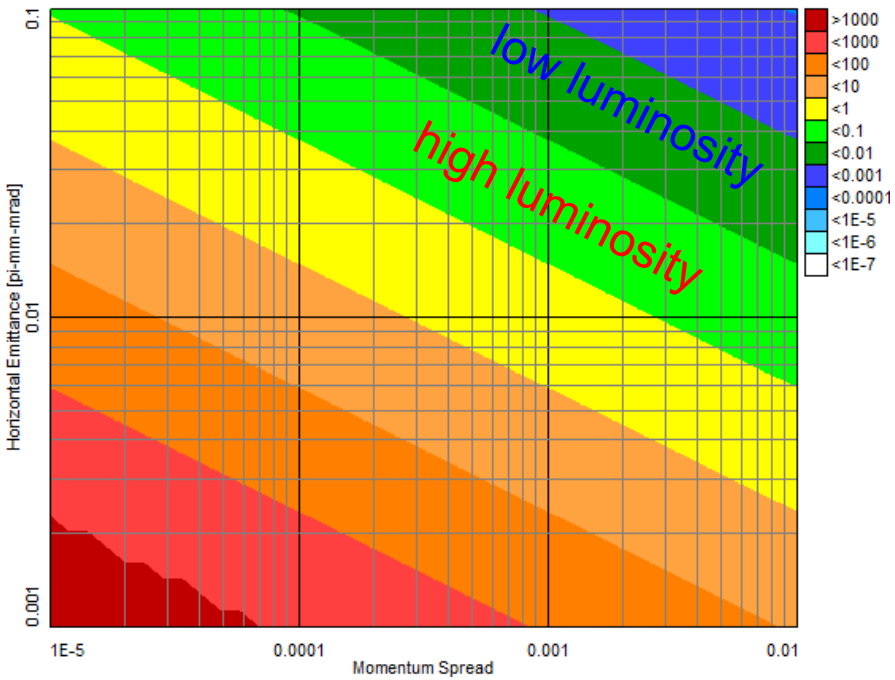
	LHC	RHIC	HERA	EicC-1
Injection	20 min	1 min	20 min	1-2s
Acceleration	18 min	130 s	30 min	4s
Collision	~ 15 h	~ 8 h （Max10 h）	~ 10 h	~ 2 h
Ions	p-p	Au-Au	p-e	p-e

Operation mode and integrated luminosity

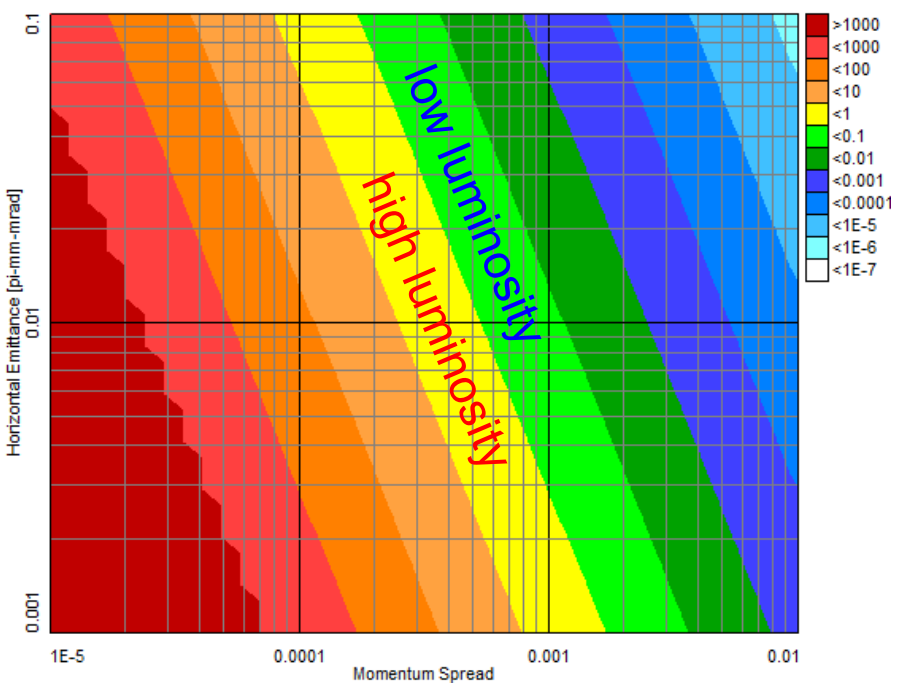
➢ **The new integrated luminosity scenario**



Cooling strategy



transverse

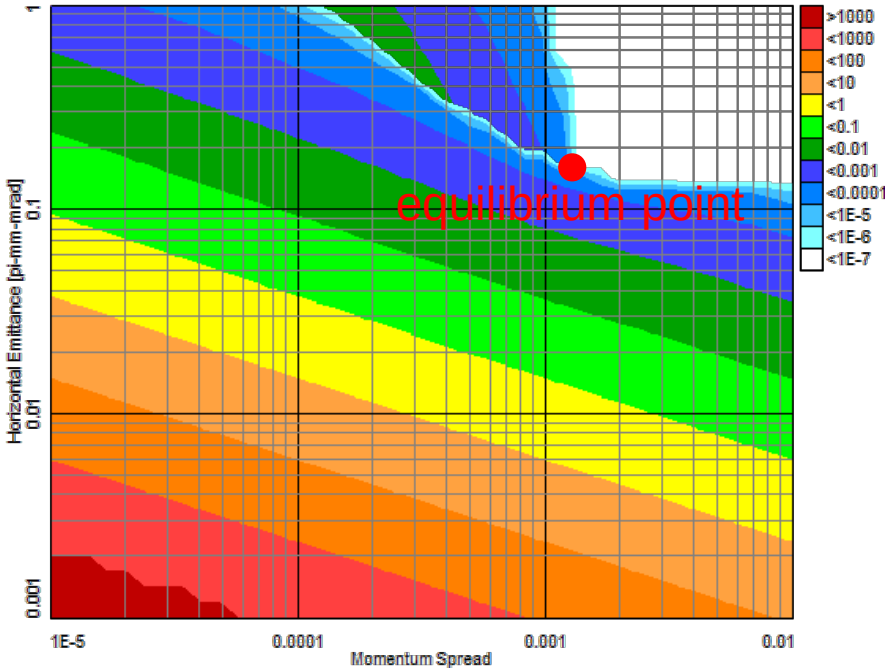


longitudinal

in principle, a fast cooling is necessary for low luminosity mode ($t_{cooling}$ < 1000 sec) and high luminosity ($t_{cooling}$ < 100 sec)
the big challenge!

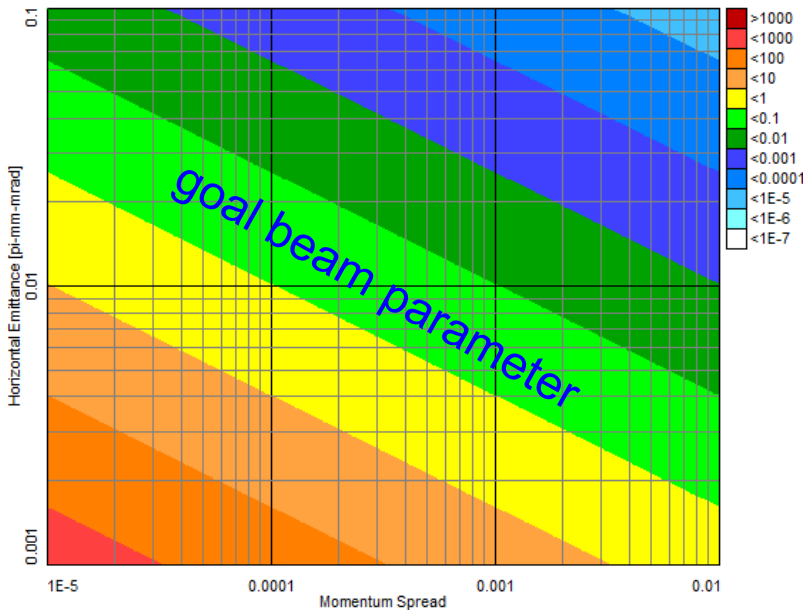
energy scaling from Recycler 8.9 GeV/c p cooling: $t_{cooling}$ =3000 sec

Cooling strategy

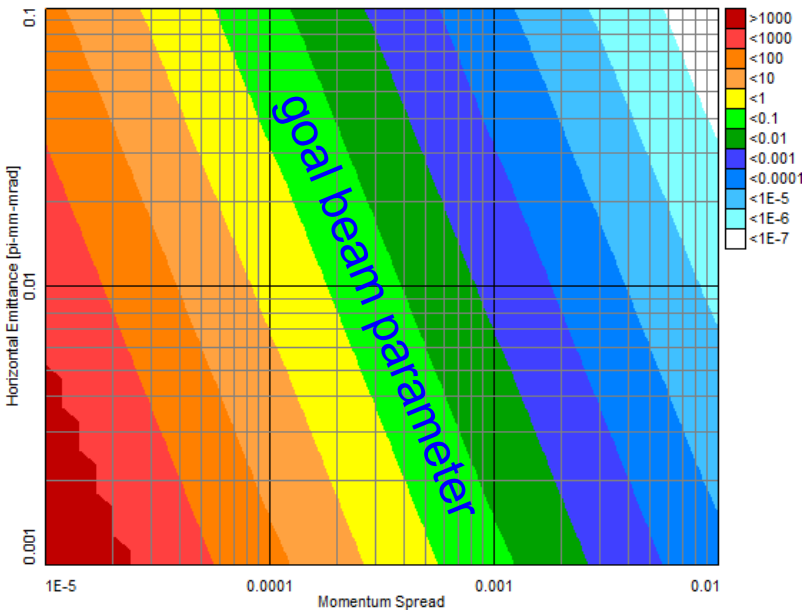


电子束能量	10.89 MeV
电子束团长度	20 mm
电子束团动量分散	10^{-4}
电子束团半径	2 mm
电子束团发射度	0.04 urad
电子束团峰值流强	4.7 A
电子束团密度	$1.7\times10^{14}cm^{-3}$

	p	e
circumference(m)	1200	1200
energy(GeV)	60	5
Bρ(T·m)	203	16.7
$f_{collision}$(MHz)	500	500
particles per bunch($\times 10^{10}$)	1	3.2
ε_x, ε_y(nm·rad, rms)	10/2	5/1
β^*_x/β^*_y (m)	0.05/0.01	0.1/0.02
bunch length(m)	0.012	0.01
Beam-Beam Parameter ξ_y	0.01	0.076
Laslett tune shift	0.06	—
energy loss per turn(MeV)	—	2.2
total SR power(MW)	—	5.7
SR linear power density(kW/m)	—	18
current(A)	0.8	2.56
crossing angle(mrad)	50	
hourglass	0.88	
Luminosity($cm^{-2}s^{-1}$)	1.1×10^{34}	



transverse



longitudinal

10 sec < $t_{cooling}$ < 100 sec is needed for 60 GeV EIC!

$$\frac{1}{\tau_{cool}} \propto \frac{Z^2}{A} \frac{n_e L_c}{\beta^3 \gamma^5 \theta_{rel}^3}$$

	p	e
circumference(m)	1200	1200
energy(GeV)	60	5
Bρ(T·m)	203	16.7
$f_{collision}$(MHz)	750	750
particles per bunch($\times 10^{10}$)	0.5	3.2
ε_x, ε_y(nm·rad, rms)	100	10
β^*_x/β^*_y (m)	0.02/0.01	0.2/0.1
IBS rate	0.0003(H,V),0.0018(L)	—
bunch length(m)	0.03	0.01
dp/p	3e-4	
Beam-Beam Parameter ξ_y	0.0015	0.01
Laslett tune shift	0.005	—
energy loss per turn(MeV)	—	0.33
total SR power(MW)	—	1.3
SR linear power density(kW/m)	—	5.2
current(A)	0.6	3.9
crossing angle(mrad)	50	
hourglass	0.75	
Luminosity($cm^{-2}s^{-1}$)	0.5×10^{33}	