The Upgrade Plan of BEPCII Using Crab-Waist Technology

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for the BII-U+ team

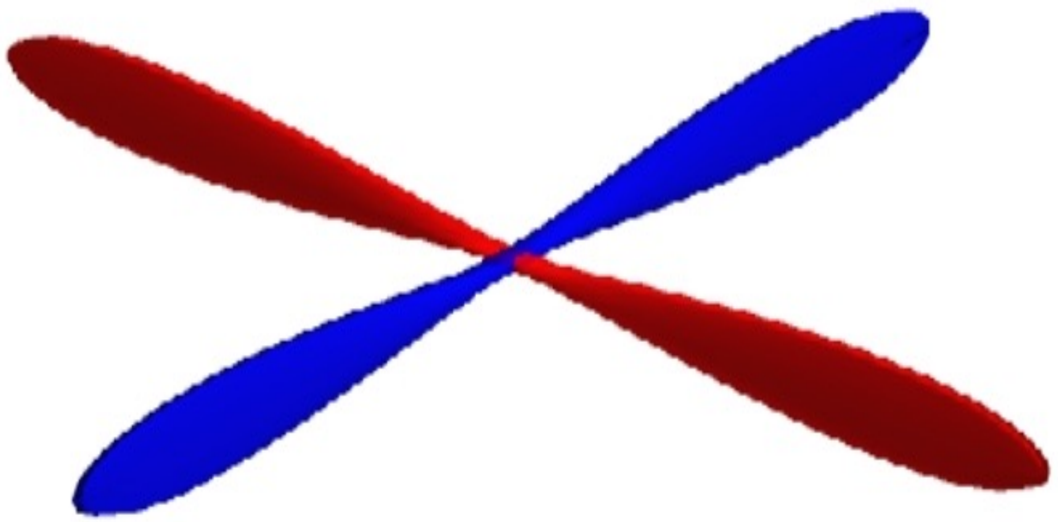
Outline

- Introduction to Crab-Waist, BEPCII, BEPCII-U, and BEPCII-UP (BII-U+)
- Benefits to BESIII Physics with CW
- BEPCII-UP
- Summary

What and why Crab Waist?

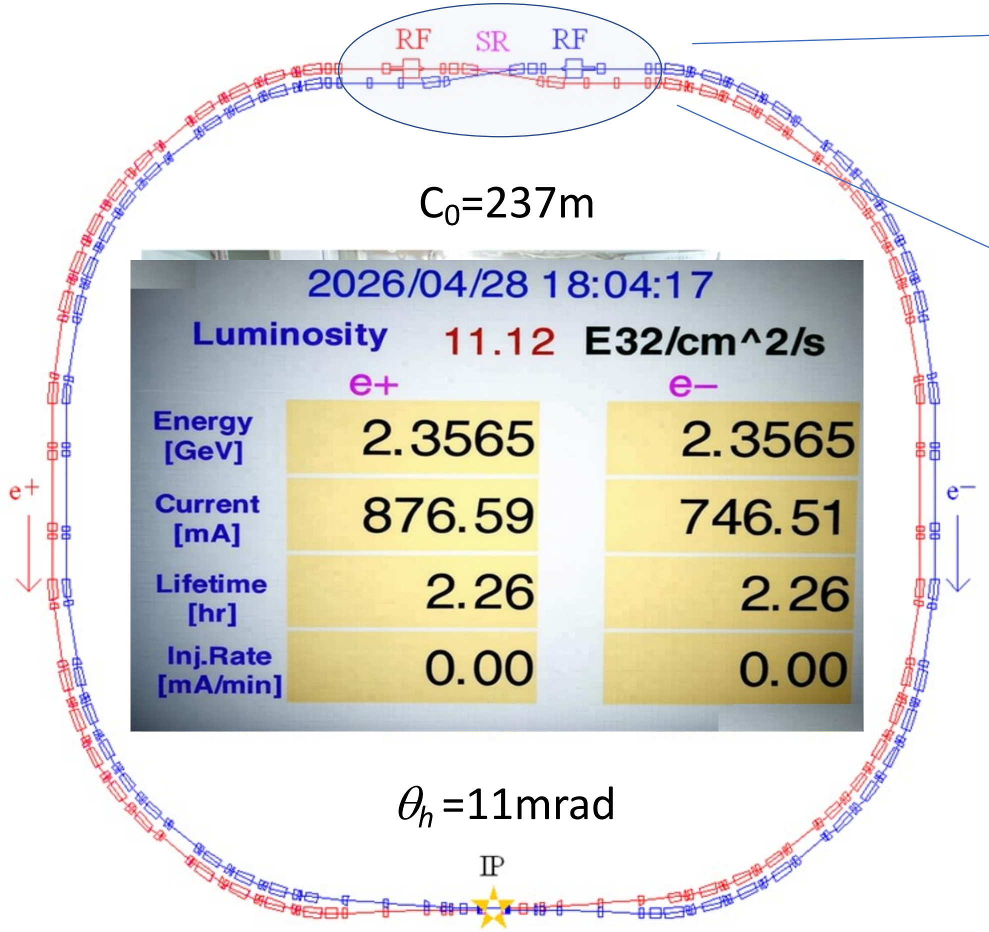
- The Crab Waist collision concept was first tested and successfully demonstrated at DAFNE in Italy.
- Crab Waist has the potential to significantly enhance luminosity.
    - Large Piwinski angle
    - Small β_y*
    - Crab sextupoles
- Crab Waist is the preferred scheme for achieving high luminosity in next-generation colliders (SuperKEKB, CEPC, FCC, STCF…).
- No new facility in next 5-year, … …

Test of "Crab-Waist" Collisions at the DA Φ NE Φ Factory, Physical review letters, 2010, Vol.104 (17), Article 174801

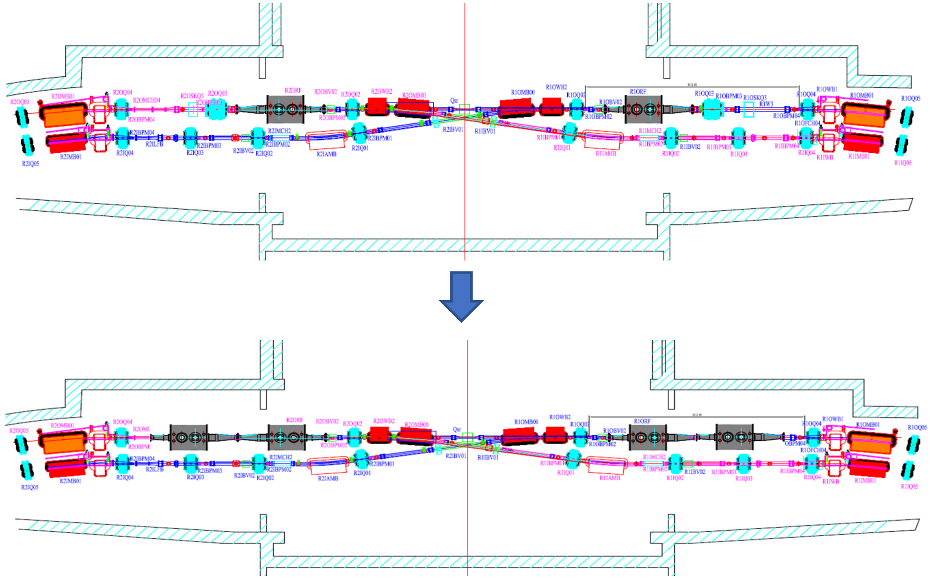


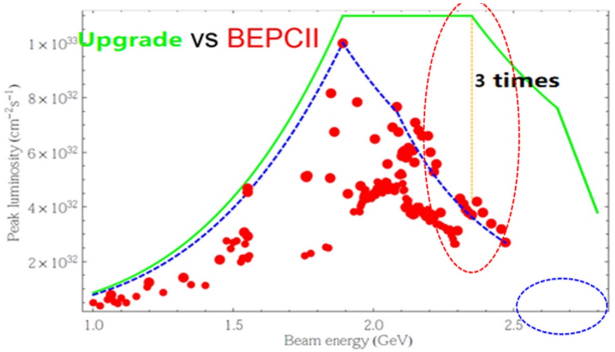
BEPCII and BEPCII-U

- **BEPCII: double ring e+e- collider (2005 -)**
  - 0.92 GeV~2.47 GeV

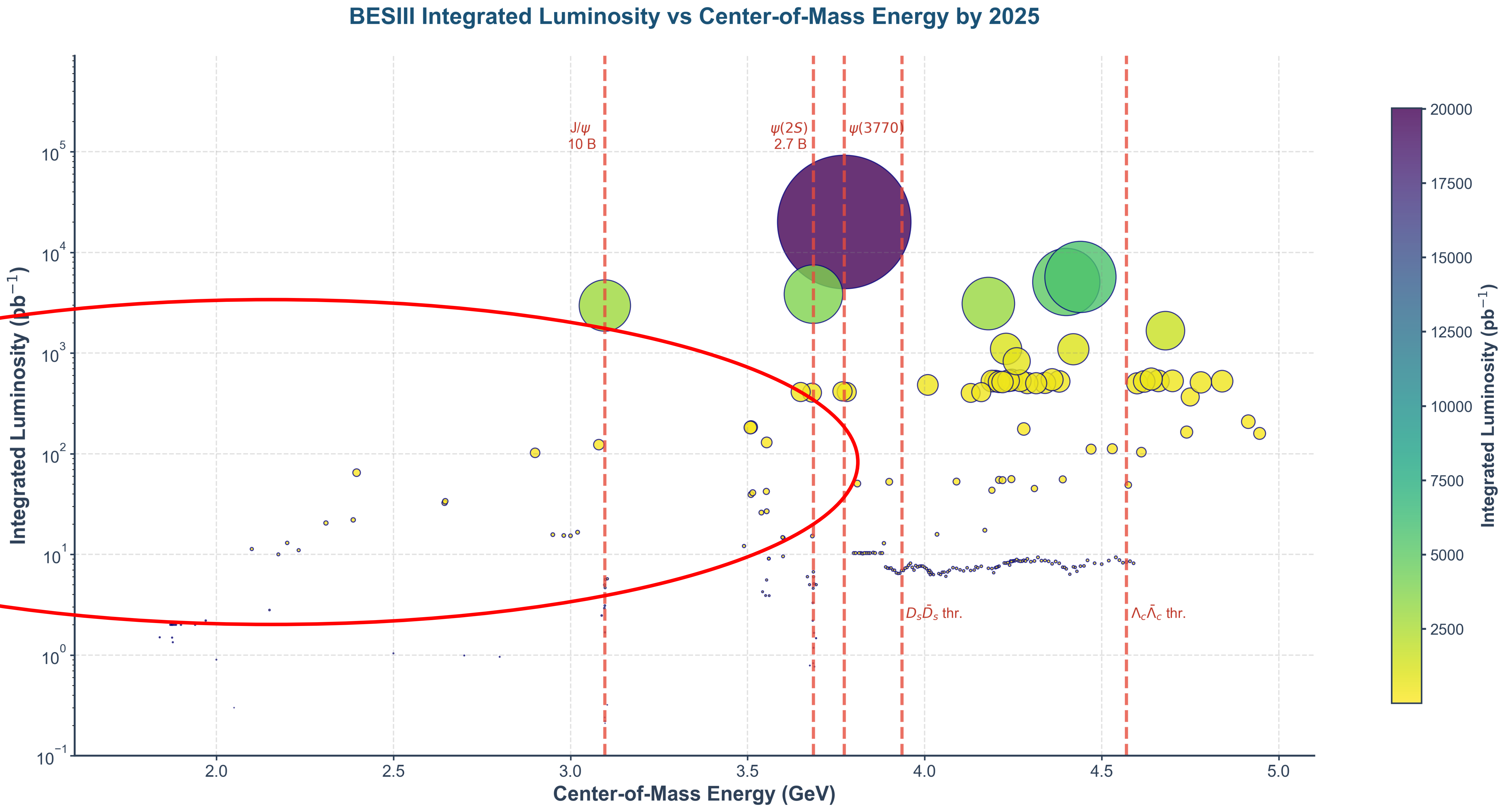


Performance upgraded at high energy (2021~2025)





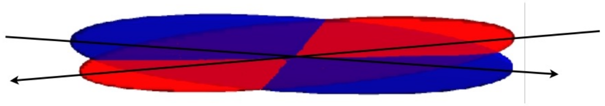
- L×3 @ 2.35GeV ✔
- Max. beam energy: 2.47GeV → 2.80GeV



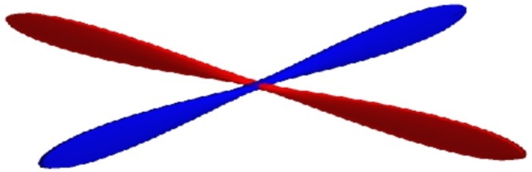
BESIII Integrated Luminosity vs Center-of-Mass Energy by 2025
J/ψ
10 B
ψ(2S)
2.7 B
ψ(3770)
$D_s\bar{D}_s$ thr.
$\Lambda_c\bar{\Lambda}_c$ thr.
Integrated Luminosity (pb^{-1})
Center-of-Mass Energy (GeV)

BEPCII Crab Waist scheme

BEPCII/U



BEPCII Crab Waist



Design study supported by IHEP

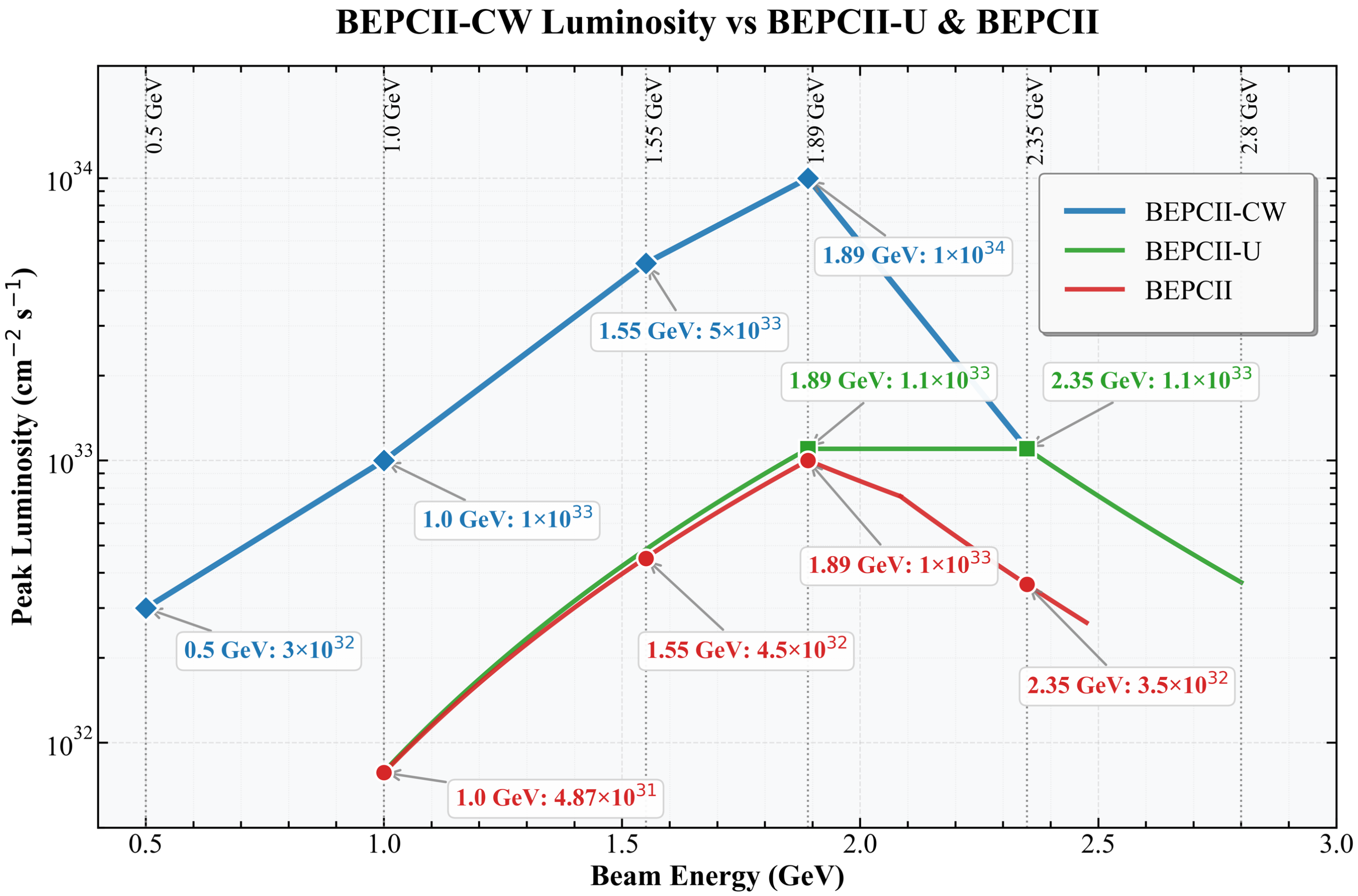
Innovation funding ~ 1.8 M RMB.

1. IR: Crab Waist collision

2. Inner ring Inj. region: insert wigglers

3. Linac: Compact damping ring

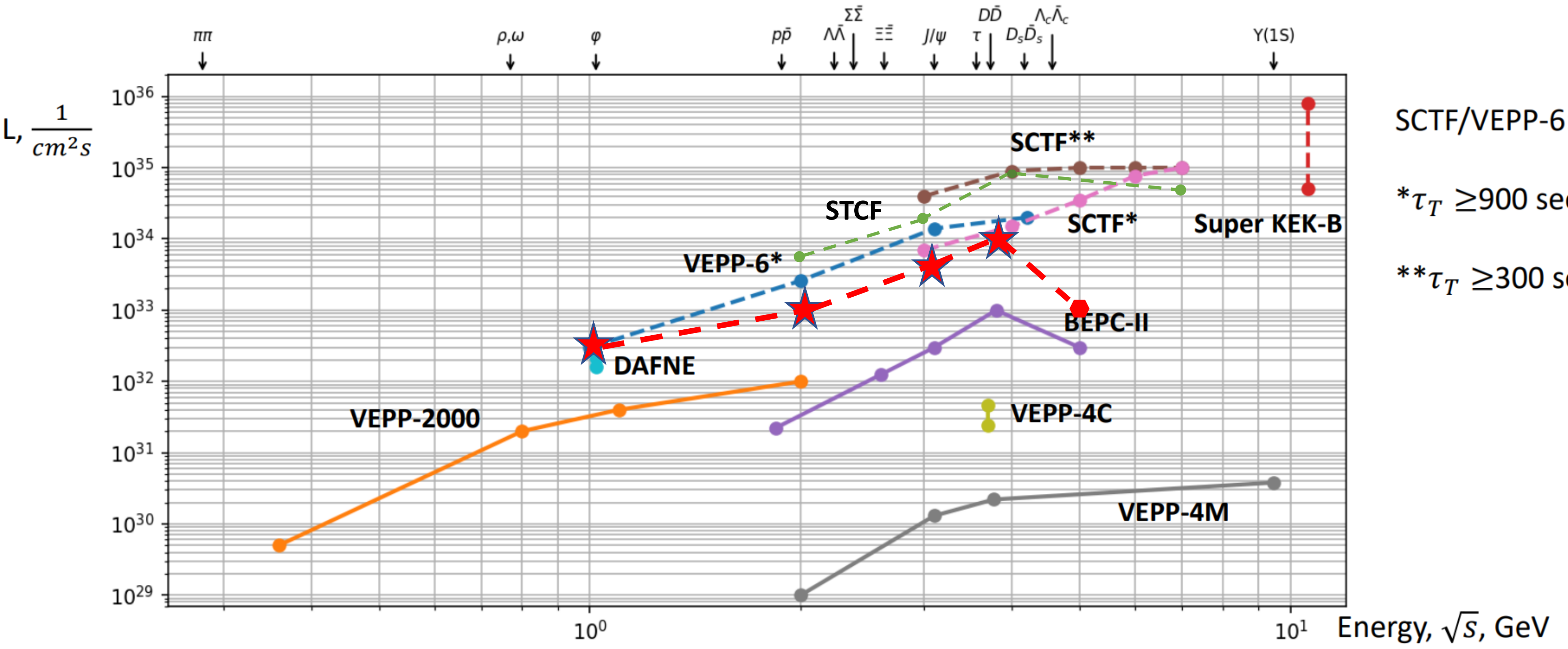
BEPCII Crab Waist performance outlook



- The specifications at each energy are very preliminary.
- Parameters and lattice design need to be carefully optimized for each energy.
- Accelerator design is focusing on 1.89 GeV firstly.

- Luminosity may increase by ×10 below 1.89 GeV.
- Operation below 1 GeV is enabled.

e+e- colliders at a glance



SCTF/VEPP-6:

$^*\tau_T \geq 900$ sec

$^{**}\tau_T \geq 300$ sec

Ref: Ivan Logashenko @FTCF2025（November 24, 2025）

Physics potential with CW

- With CW upgrade
  - 0.1 B $D\bar{D}$ pair → 1 B $D\bar{D}$ pair (20 → 200 /fb)
  - 2.7 B psi(2S) → 30 B psi(2S)
  - ~~J/psi: EMC/DAQ cannot handle with such a high event rate : ->30 kHz~~
- Physics topics
  - ✓ Pure leptonic decay of D meson: $|V_{cd}|$, $|V_{cs}|$, decay constants, …
  - ✓ Semi-leptonic decay of D meson: $|V_{cd}|$, $|V_{cs}|$, light hadron spectroscopy
  - ✓ Hadron decays of D meson： CP violation, strong phase, Quantum entanglement
  - ✓ Psi(2S) sample: 1 J/psi in 2 psi(2S) events, $\eta_c(2S)$, $\eta_c(1S)$, h_c, χ_{cJ}, …
    - ✓ Light hadron spectroscopy
    - ✓ Rare decay searches: LFV, weak decays, …
    - ✓ Charmonium transitions and decays
  - ✓ χ_{cJ} and τ scan
  - ✓ … …

Benefits to BESIII Physics with CW

Physics potential at low energy region

Nucleon Form Factors near Threshold

Energy Range: 1.7 - 2.0 GeV

Measurement of e+e- → ppbar/nnbar cross sections and extraction of nucleon form factors.

Strange Hadron Physics

Energy Range: 1.5 - 3.0 GeV

Precision study of hadrons containing strange quarks (e.g., Λ, Σ, Ξ).

High-Precision R-Scan

Energy Range: 1.0 - 2.0 GeV (Precision < 5%)

Precision measurement of the R value (σ_had/σ_mumu) in the center-of-mass energy region.

phi Vector Meson Line Shape

Energy Range: 0.9 - 1.3 GeV

Detailed line shape scan of the phi(1020) meson in the specified region.

Exclusive Hadronic Cross Sections

Energy Range: 1.0 - 2.0 GeV

Measurement of exclusive channels (e.g., pipi, KK, LambdabarLambda) and their form factors.

rho-omega Scan

Energy Range: 0.5 - 1.0 GeV

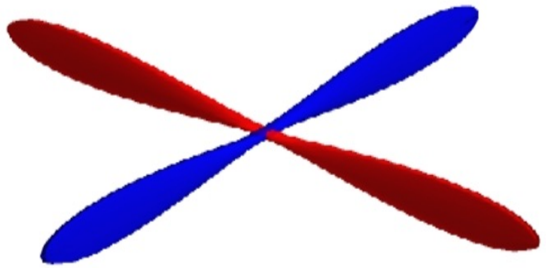
Precision scan focusing on the e+e- → pi+pi- cross section measurement.

Luminosity upgrade with CW@1.89GeV

CW: small ε_x & DW: I_b=7.5 mA ➔ 12.5 mA, ξ_y=0.04 ➔ 0.09

$$L(\mathrm{cm}^{-2}\mathrm{s}^{-1}) = 2.17\times10^{34}(1+R)\xi_y \frac{E(GeV)k_b I_b(A)}{\beta_y^*(cm)}$$

CW: β_y^* =1.35 cm ➔ 0.5 cm



(L_{CW}/ L_{BEPCII}) =(13.5/5) ×(0.09/0.04) × (12.5/7.5)=10.1

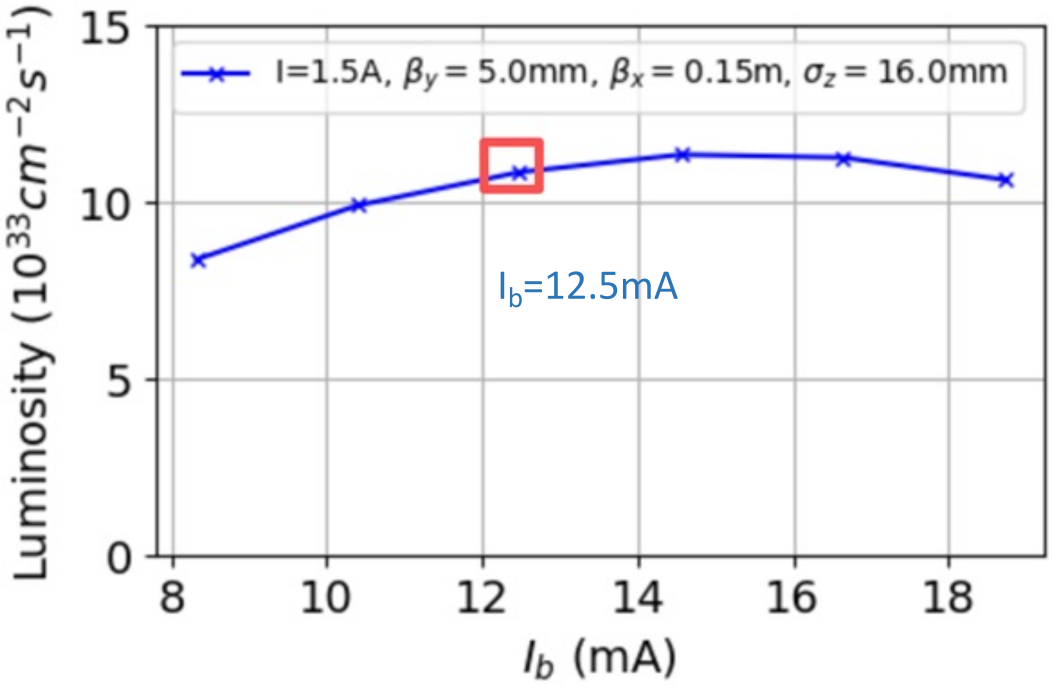
$L_{BEPCII}=1.0\times10^{33}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ➔ L_{CW} ~10×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

1.89GeV BEPCII Crab Waist parameters（w. 3.0 T wiggler）

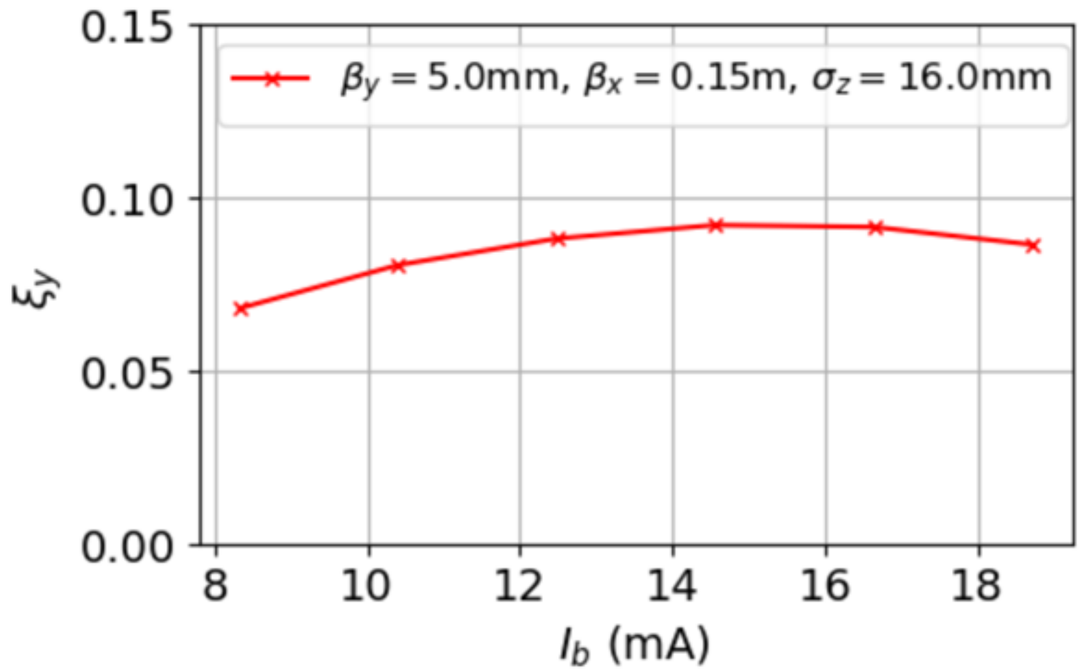
	BEPCII (L_0=1E33cm^{-2}s^{-1})	BEPCII-CW (10×L_0)
Circumference [m]	237	
Peak luminosity [$10^{33} cm^{-2} s^{-1}$]	1	10.9
β_x^*/β_y^* [m]	1/0.0135	0.15/0.005
Total current [mA]	886	1500
Bunch current [mA]	7.5	12.5
Bunch number	118	120
Beam-beam para. ξ_x/ $\xi_{y,\mathrm{lum}}$	0.029/0.04	0.01/0.088
Emittance [nmrad]	120/0.6	55/0.193
Damping time [ms]	24.7/24.7/12.3	13.9/14.6/7.45
Coupling facter [%]	0.5	0.35
Longitudinal tune $\boldsymbol{\nu_s}$	0.032	0.040
Natural energy spread [%]	0.05	0.082
Natural bunch length $\boldsymbol{\sigma_{z,0}}$ [mm]	11.5	13.3
Bunch length $\boldsymbol{\sigma_z}$ [mm]	13.5	16
Half crossing angle [mrad]	11	18.1
Piwinski angle	0.47	3.19
Working point	7.509/5.575	8.550/7.576

Beam-beam simulation (1.89 GeV)

Luminosity vs. bunch current



Beam-beam para. vs. bunch current



Total current is fixed at 1.5A with different bunch current.

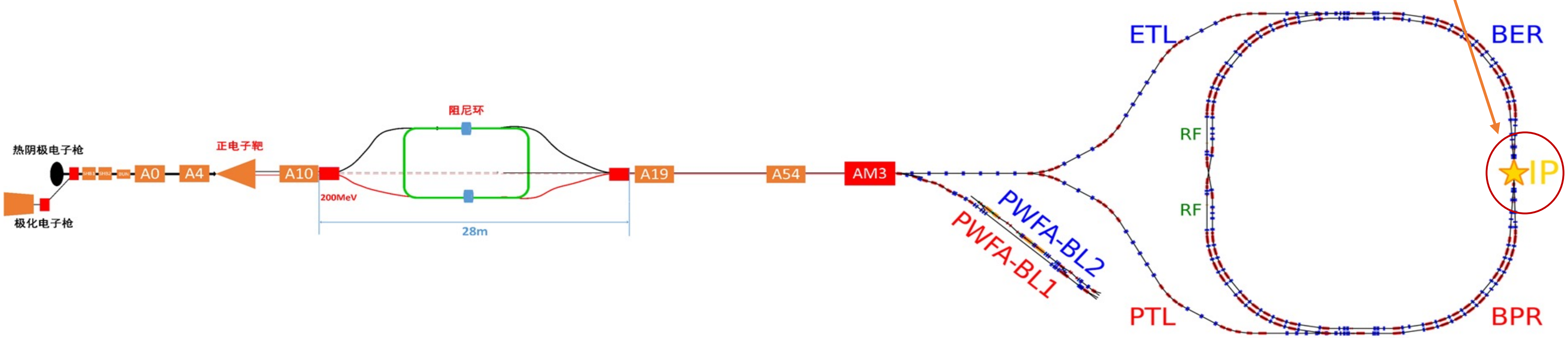
BEPCII: bunch current I_b=7.5mA, total current I=886mA

Lower energy parameters @ 1.55GeV/ 1.0GeV/0.5GeV

	BEPCII-Crab Waist-3.6T (1.55GeV)	BEPCII-Crab Waist-3.6T (1.0GeV)	BEPCII-Crab Waist-3.6T (0.5GeV)
RF voltage [MV]	1.5	1.1	1.0
SR power/beam [kW]	107.4 (43.1 in arc)	19.5 (4.5 in arc)	1.4 (0.1 in arc)
Total current [mA]	795	464	160
Peak luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	50	10	3
β_x^*/β_y^* [m]	0.15/0.005	0.15/0.005	0.15/0.005
Bunch current [mA]	6.6	3.9	0.9
Bunch number	120	120	180
Beam-beam para.ξ_x/ $\xi_{y,\mathrm{lum}}$	0.006/0.102	0.005/0.089	0.006/0.09
Emittance [nmrad]	27/0.095	12.5/0.1	3.3/0.052
Damping time [ms]	18/18/9	37.7/37.7/19	93/93/47
Coupling factor [%]	0.35	0.8	1.6
Longitudinal tune ν_s	0.032	0.044	0.059
Bucket Height [%]	0.35	0.8	1.6
Natural energy spread [%]	0.086	0.076	0.014
Natural bunch length $\sigma_{z,0}$ [cm]	1.77	1.8	1.1
Bunch length σ_z [cm]	1.86	1.9	1.2
Half crossing angle [mrad]	18.1	18.1	18.1
Piwinski angle	5.3	7.9	9.8

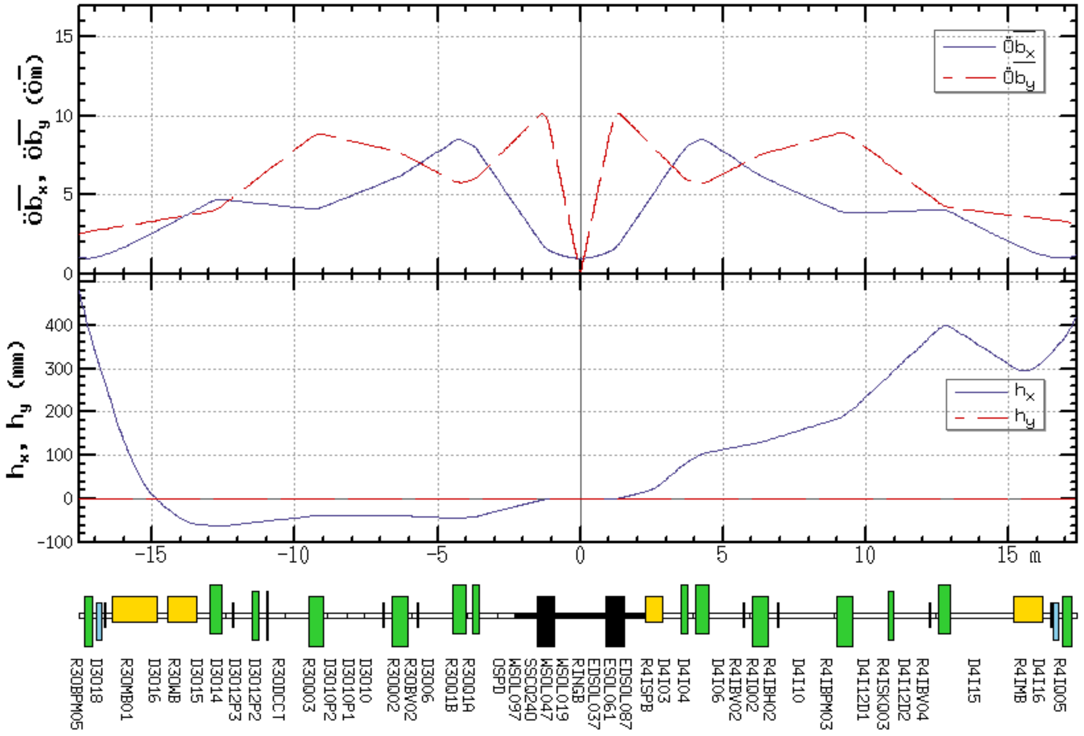
To test luminosity performance at various Piwinski angles → B-B parameters & CW commissioning experience.

1. IR: Crab Waist collision

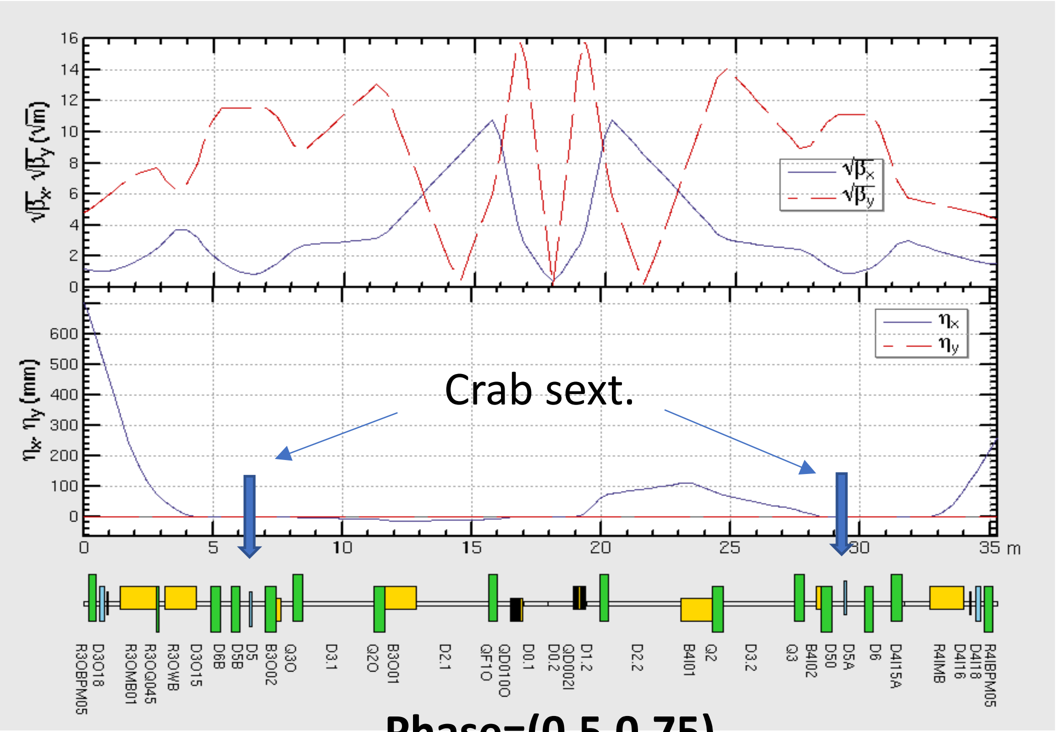


IR comparison@1.89GeV (1 m/15 mm → 0.15 m/5 mm)

BEPCII



BEPCII-CW



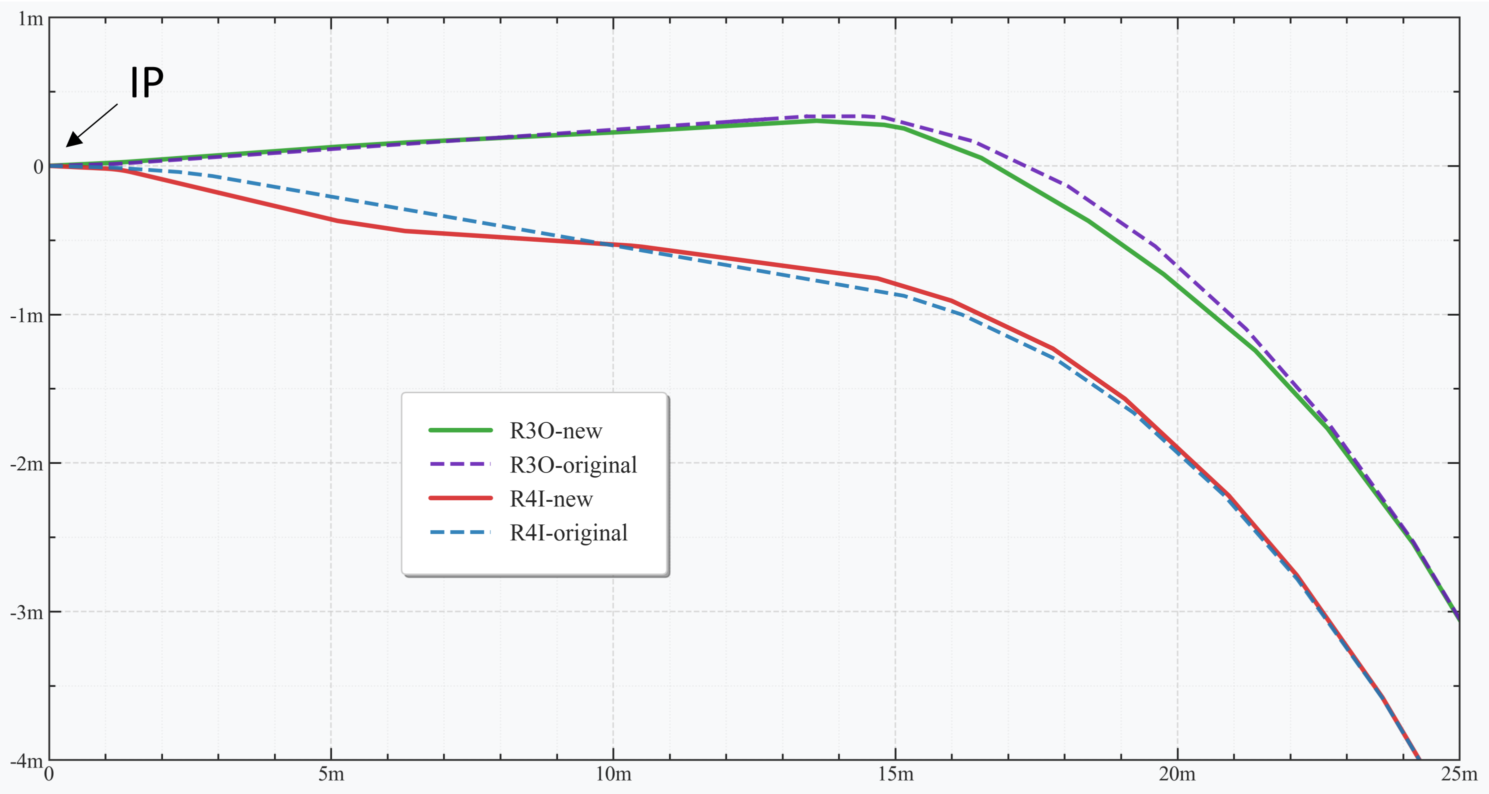
Phase=(0.5,0.75)

- The interaction region design has already taken into account the boundaries of the BESIII detector and the accelerator geometry.
- The upgrade is localized to approximately ±23 meters on either side of IR.

Geometry changes in the interaction region

- The Geometry difference from BEPCII is localized in ±23 meters region.
- The new accelerator geometry does not conflict with the existing BEPCII tunnel.

Y (m)



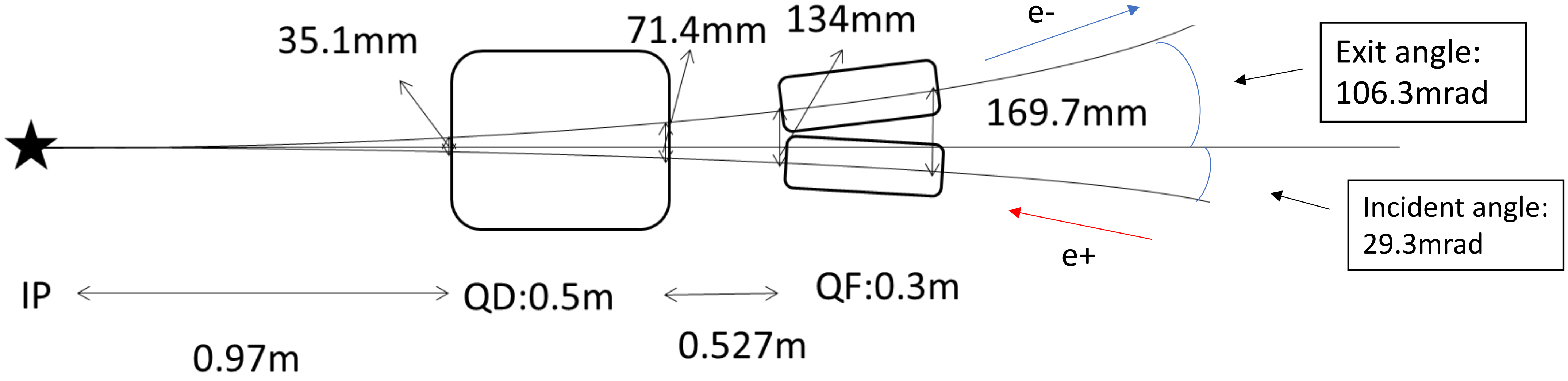
X (m)

Half crossing angle=18.1 mrad (11 mrad @BEPCII/BEPCII U)

BEPCII-CW Asymmetric IR design

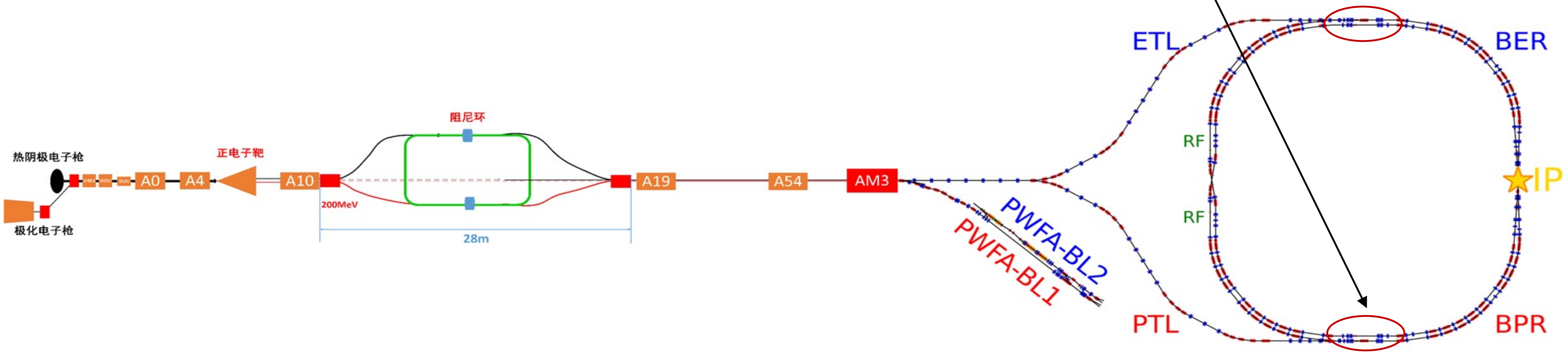
- **BII-CW（1.89GeV）：**
  QD(single aperture): B’= 21.5 T/m & B=0.34 T
  QF(twin aperture): B’=21.0 T/m
- **Correcting coils to cancel the alignment error：**
  -- skew quad & correctors

- The new IR SC quadrupole magnet will replace the existing SCQ.
  - ✓ BEPCII： QD (single aperture)
  - ✓ BEPCII-CW： QD (single aperture) + QF (double aperture)



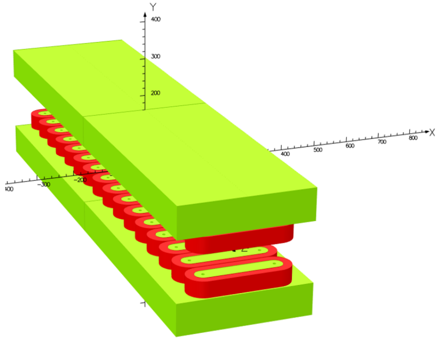
- **No direct SR light from the upstream will hit the central Beryllium pipe.**

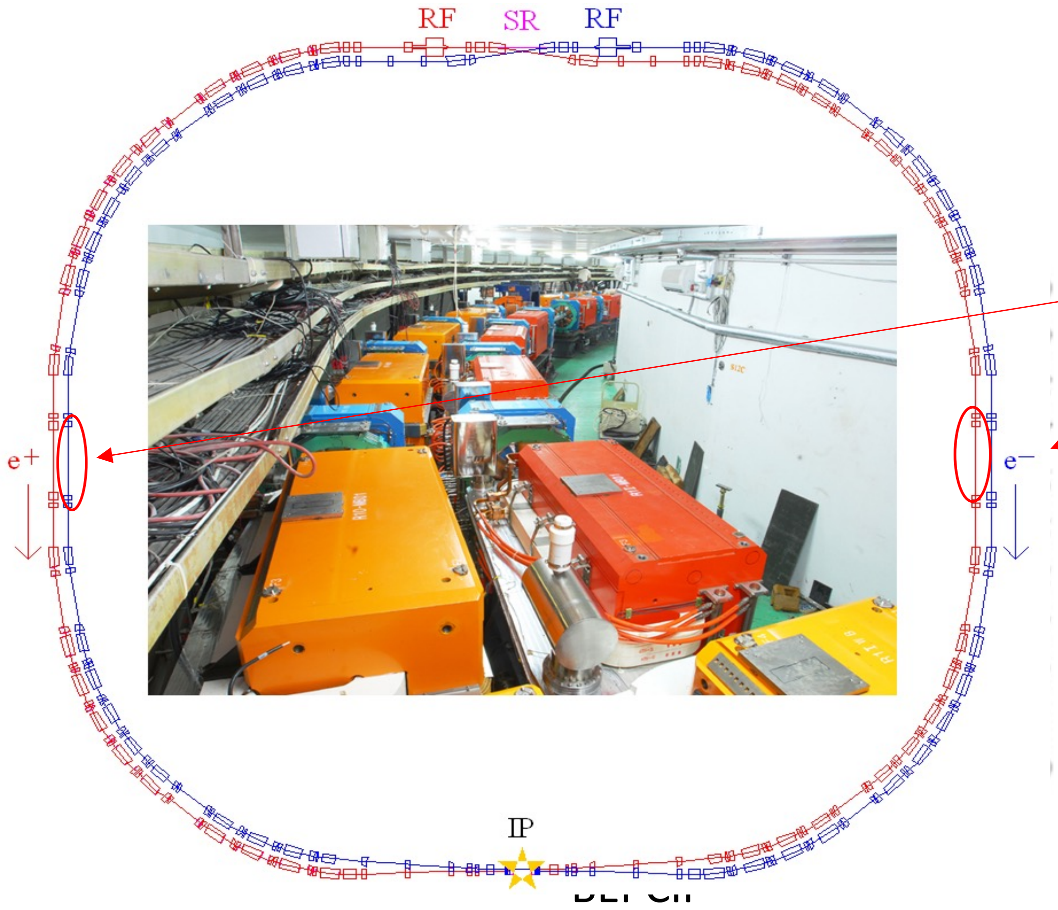
2. Inner ring Inj. region: insert wigglers

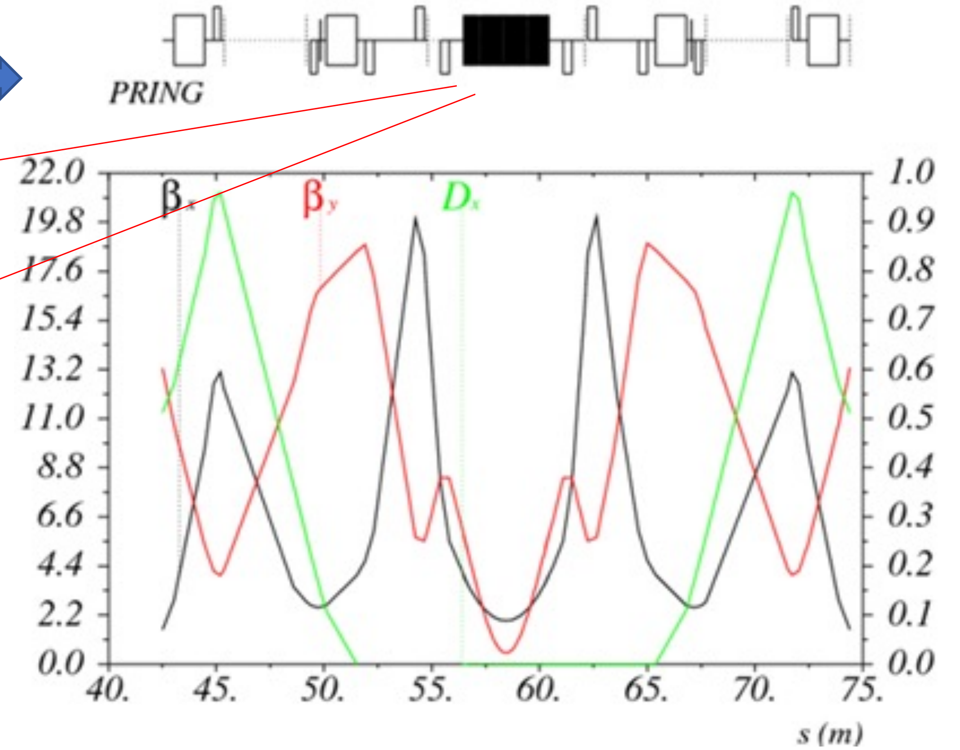


Insertion of SC wiggler at inj. region of inner ring

- Increase SR damping → smaller emittance, larger Piwinski angle
- shorter damping time → higher beam-beam limit





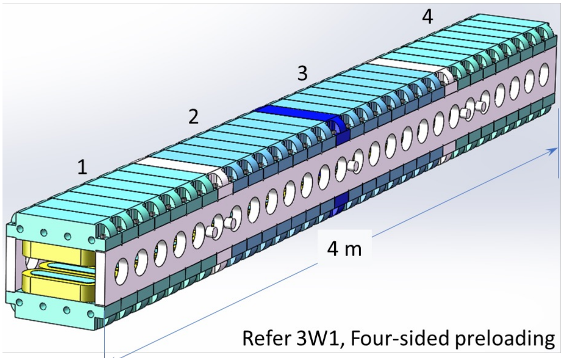


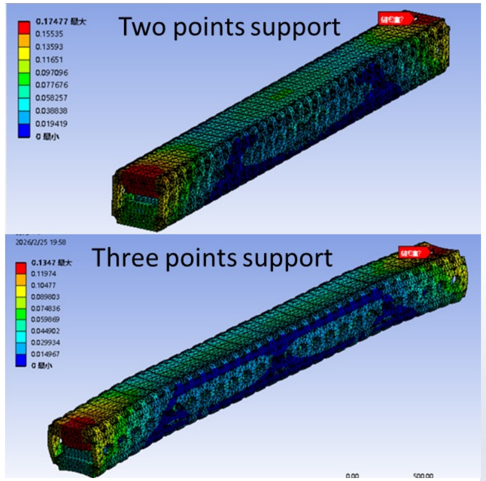
BEPCII-CW

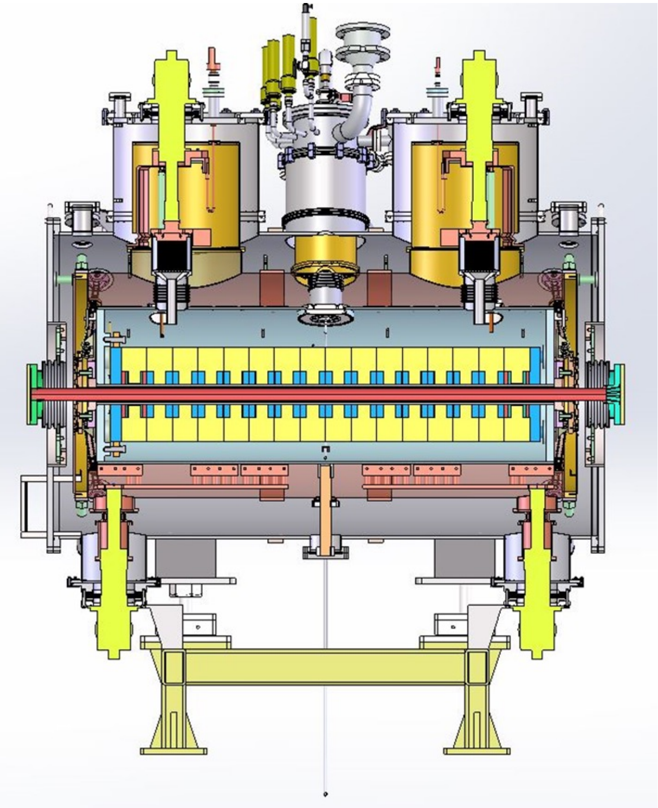
SC wiggler

SCW250 main parameters

- λu = 250 mm, L=4m
- Gap = 64 mm
- B = 3.6 T (Max: 4.4T)



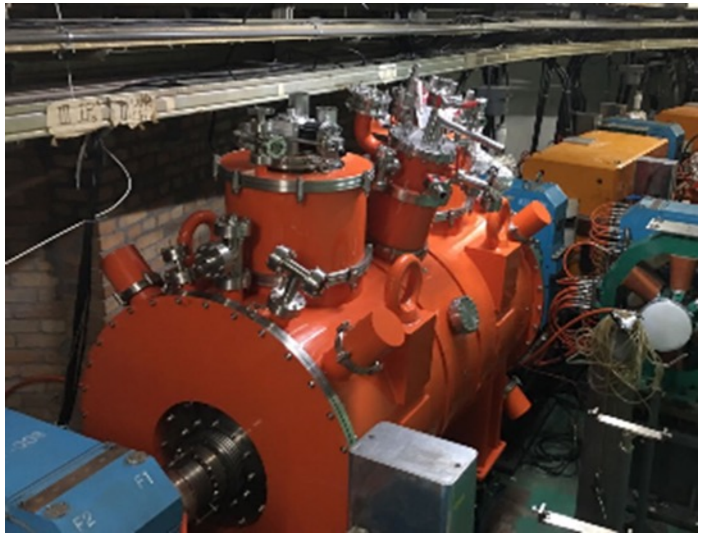




Cryostat based on the compact cryocooler

3W1 experience on BEPCII

- 3W1 was produced by IHEP, installed on BEPCII in 2019
- The first domestically produced SC wiggler with operation.
- **λu = 190mm， L=1.36m**
- **Gap= 68mm**
- **B= 2.6T**



3W1 in BEPCII tunnel

Key Parameters at 1.89 GeV (w. 3.6 T wiggler)

A direct comparison of the baseline BEPCII and the upgraded BEPCII-CW configurations at 1.89 GeV, demonstrating the significant performance leap enabled by advanced beam optics and the Crab Waist collision scheme.

Peak Luminosity (10^{33} $cm^{-2}s^{-1}$)

BEPCII (Baseline)	BEPCII-CW (Upgrade)
1.0	**10.9**(10× Boost)

βy* (Vertical Beta Function, cm)

BEPCII	BEPCII-CW
1.35	**0.50**(High Focusing)

Bunch Current (mA)

BEPCII	BEPCII-CW
7.5	**12.5**(67% Increase)

Piwinski Angle (Crab Waist Signature)

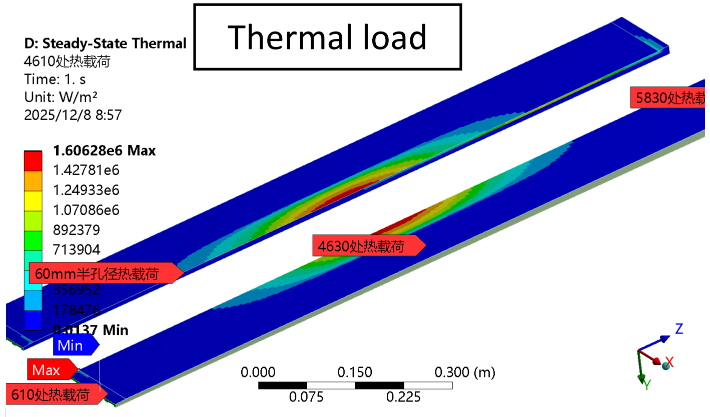
BEPCII	BEPCII-CW
0.47	**3.19**(Scheme Enabled)

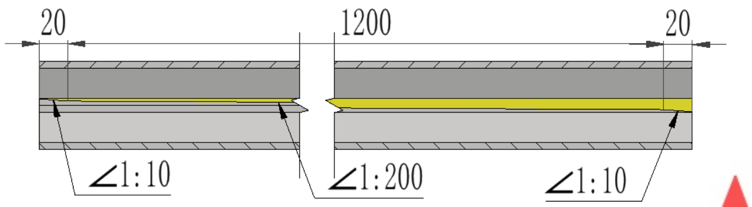
Wiggler synchrotron radiation absorber

➢ Strong SR power downstream of wiggler may destroy the accelerator equipment, locally absorbed with a dedicated absorber.

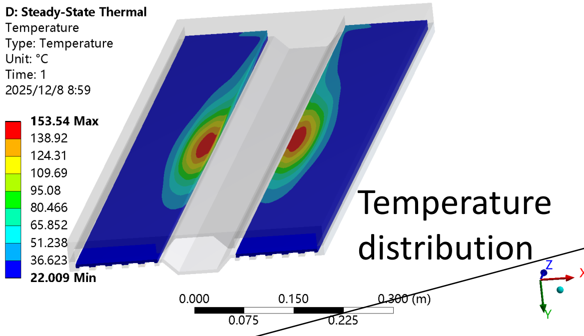
- 2-stage absorber (with vertical beveled surface)
- Total SR power： ~142kw

Thermal load

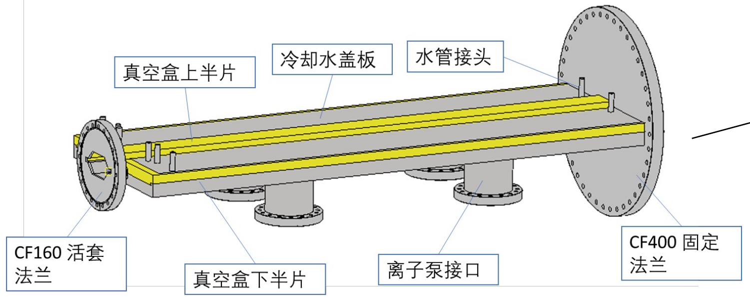


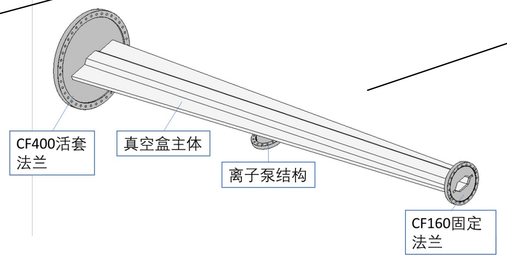


Beveled structure

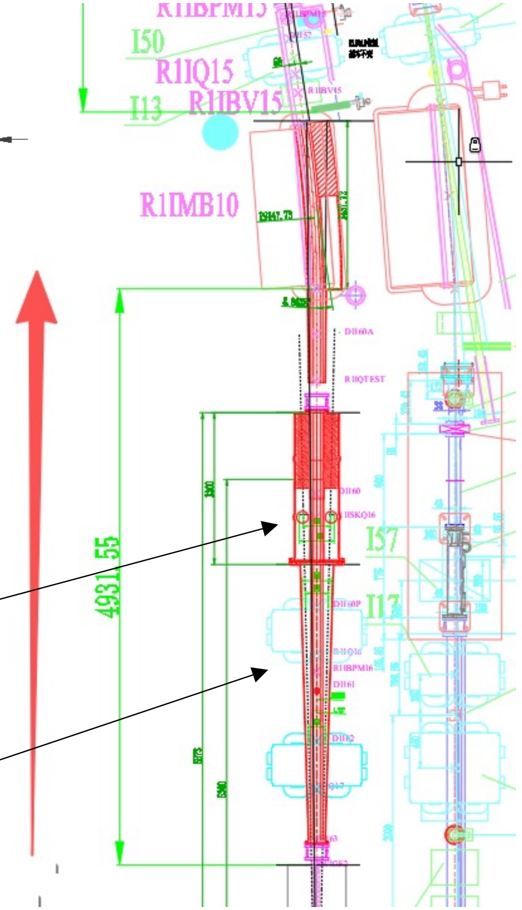


Temperature distribution





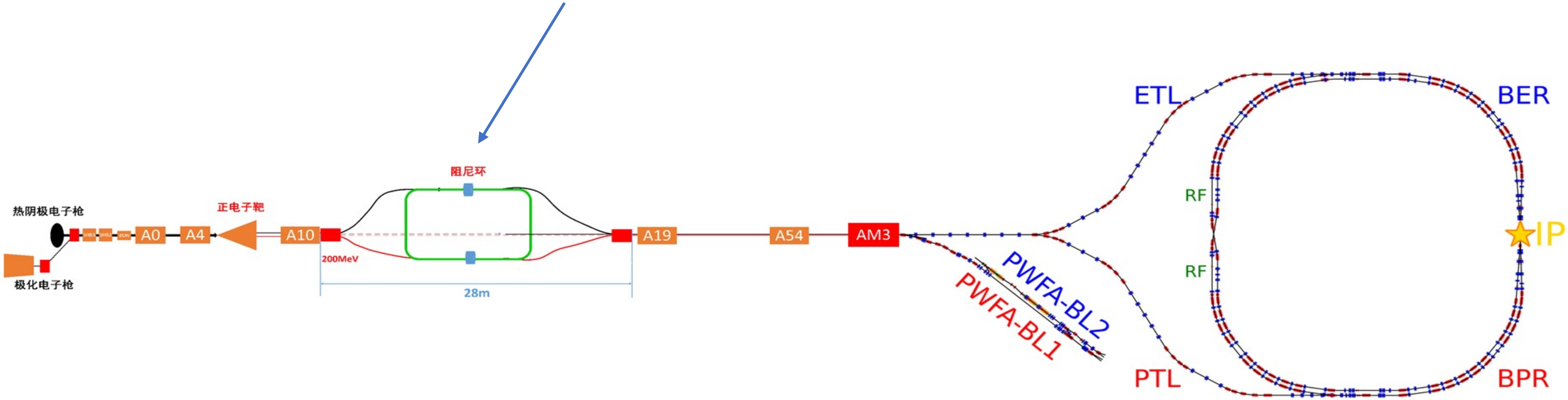
SR light



Stage 2

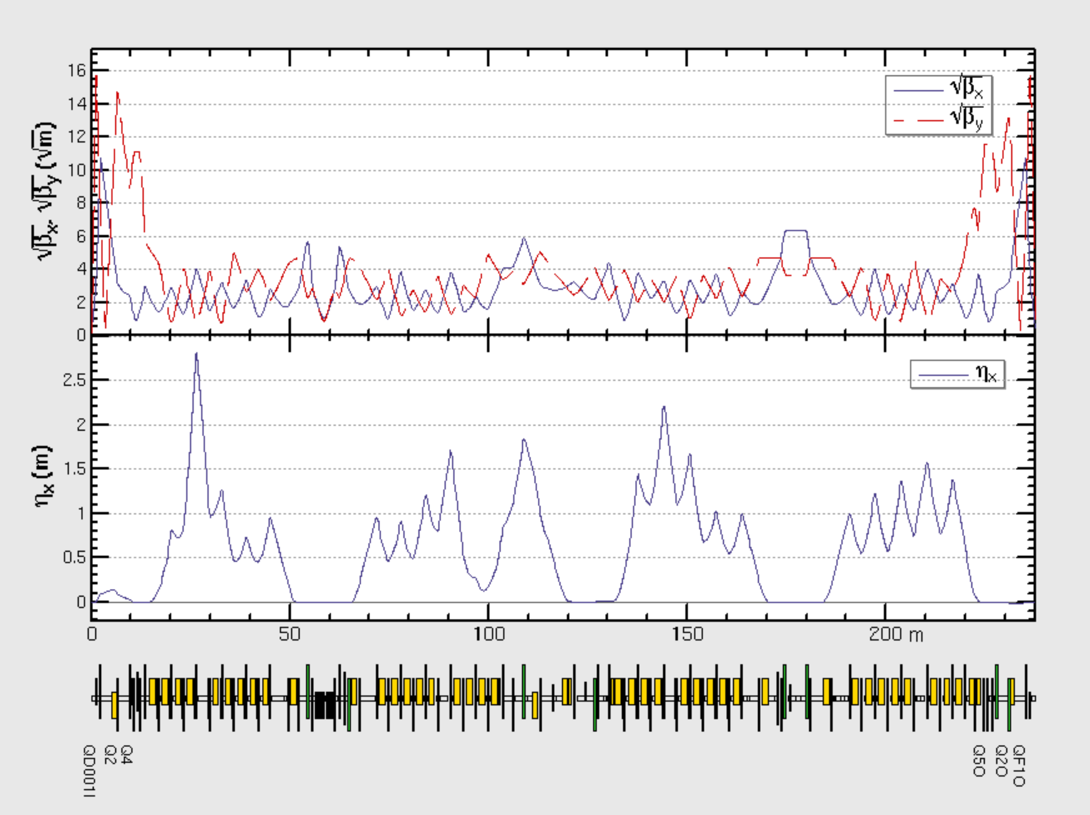
Stage 1

3. Linac: Compact damping ring



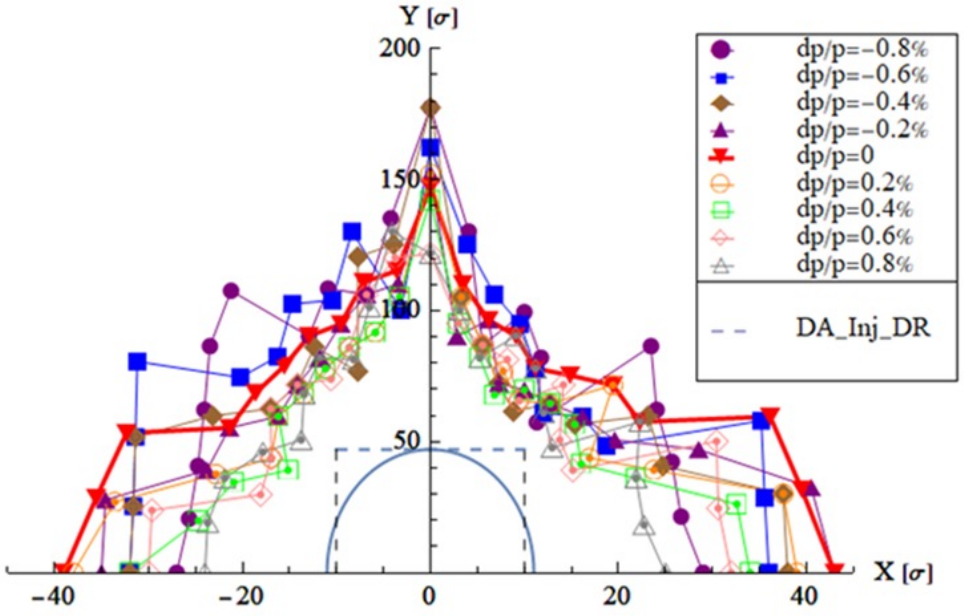
Whole ring lattice & DA @1.89 GeV (β*=0.15m/5mm)

- No local chromaticity correction due to limited space.



Working point: 8.55/7.58

62% crab + 3T wiggler



- DA requirement by injection @1.89GeV
  - Without DR: 14σx, 136σy (εy= 0.0035εx)
  - With DR : 10.5σx, 47σy (εy= 0.0035εx)

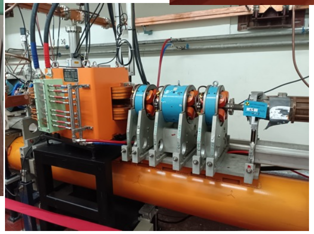
- Damping ring supports the achievement of the Crab Waist's high-luminosity goal.

BEPCII Linac upgrade with damping ring

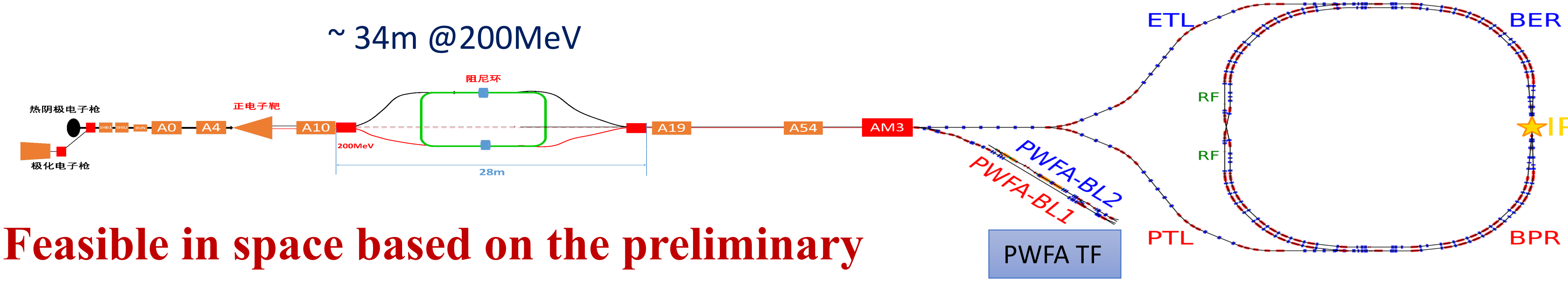
➢ **Damping ring reduces the emittance of linac injector — new highlight**

a) High luminosity operation @1.89GeV.
b) Explore physics（R scan）at low energy region.
c) Improve performance of PWFA TF.
d) Top up injection @1.89GeV can be tested.

Damping ring

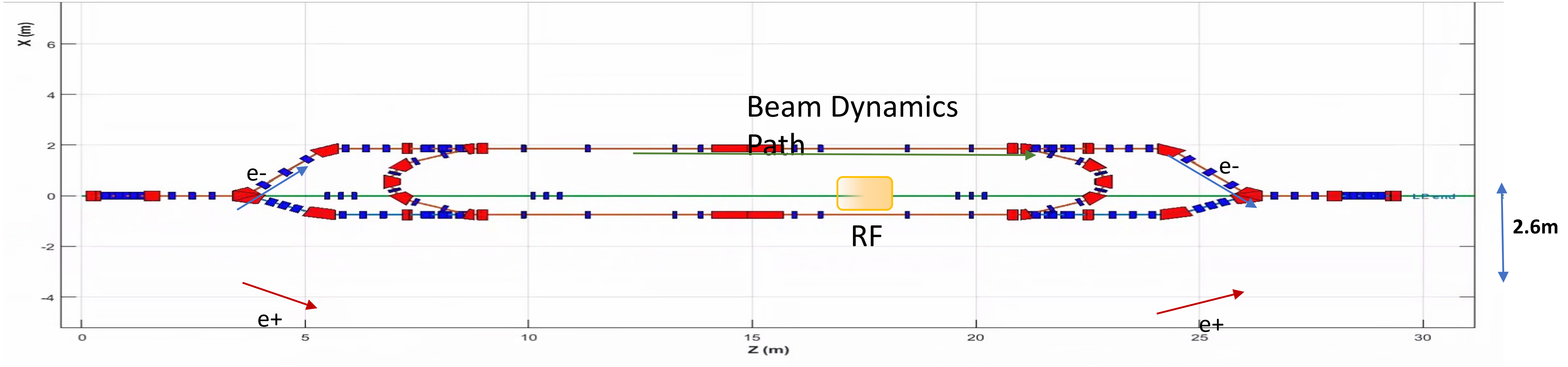


~ 34m @200MeV



➢ **Feasible in space based on the preliminary lattice design** (tunnel width: 3.5m)

Engineering Design: Damping Ring (DR)



Mission: Upgrade beam quality for high luminosity while ensuring operational continuity.

01. Beam Quality Enhancement

Reduces beam emittance (size) before injection, delivering a high-quality beam to the storage ring—critical for achieving the target luminosity.

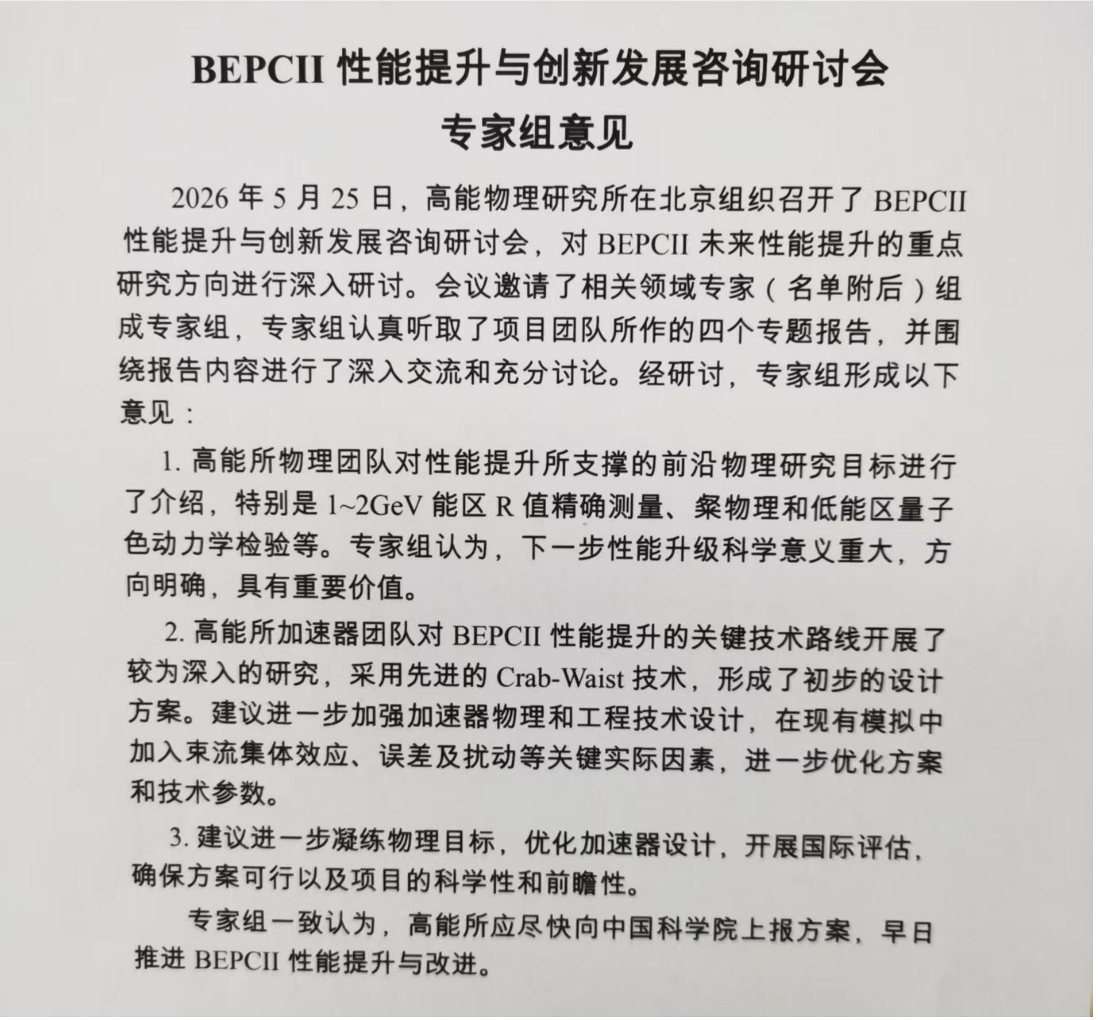
02. Space-Optimized Lattice

The DR lattice is compactly designed to fit entirely within the existing tunnel space, avoiding costly and time-consuming civil engineering modifications.

03. Non-Disruptive Commissioning

Commissioning of the DR will run parallel to BEPCII's routine physics operations, ensuring no downtime or interruption to ongoing experimental programs.

Next steps



BEPCII 性能提升与创新发展咨询研讨会

专家组意见

2026 年 5 月 25 日，高能物理研究所在北京组织召开了 BEPCII 性能提升与创新发展咨询研讨会，对 BEPCII 未来性能提升的重点研究方向进行深入研讨。会议邀请了相关领域专家（名单附后）组成专家组，专家组认真听取了项目团队所作的四个专题报告，并围绕报告内容进行了深入交流和充分讨论。经研讨，专家组形成以下意见：

1. 高能所物理团队对性能提升所支撑的前沿物理研究目标进行了介绍，特别是 1~2GeV 能区 R 值精确测量、粲物理和低能区量子色动力学检验等。专家组认为，下一步性能升级科学意义重大，方向明确，具有重要价值。

2. 高能所加速器团队对 BEPCII 性能提升的关键技术路线开展了较为深入的研究，采用先进的 Crab-Waist 技术，形成了初步的设计方案。建议进一步加强加速器物理和工程技术设计，在现有模拟中加入束流集体效应、误差及扰动等关键实际因素，进一步优化方案和技术参数。

3. 建议进一步凝练物理目标，优化加速器设计，开展国际评估，确保方案可行以及项目的科学性和前瞻性。

专家组一致认为，高能所应尽快向中国科学院上报方案，早日推进 BEPCII 性能提升与改进。

➢ Domestic Expert Consultation Meeting (May 25th , 2026)

(Consultation Symposium: BEPCII Performance Upgrade and Innovation)

1. BEPCII further performance upgrade is scientifically significant, with a clear direction and substantial value.
2. The accelerator team has developed a preliminary design, though further optimization is still required.
3. It is recommended to further refine the physics goals, optimize the accelerator design, and conduct an international review.

Conclusion: IHEP should submit the proposal to the CAS as soon as possible to ensure the timely advancement of the BEPCII performance upgrade.

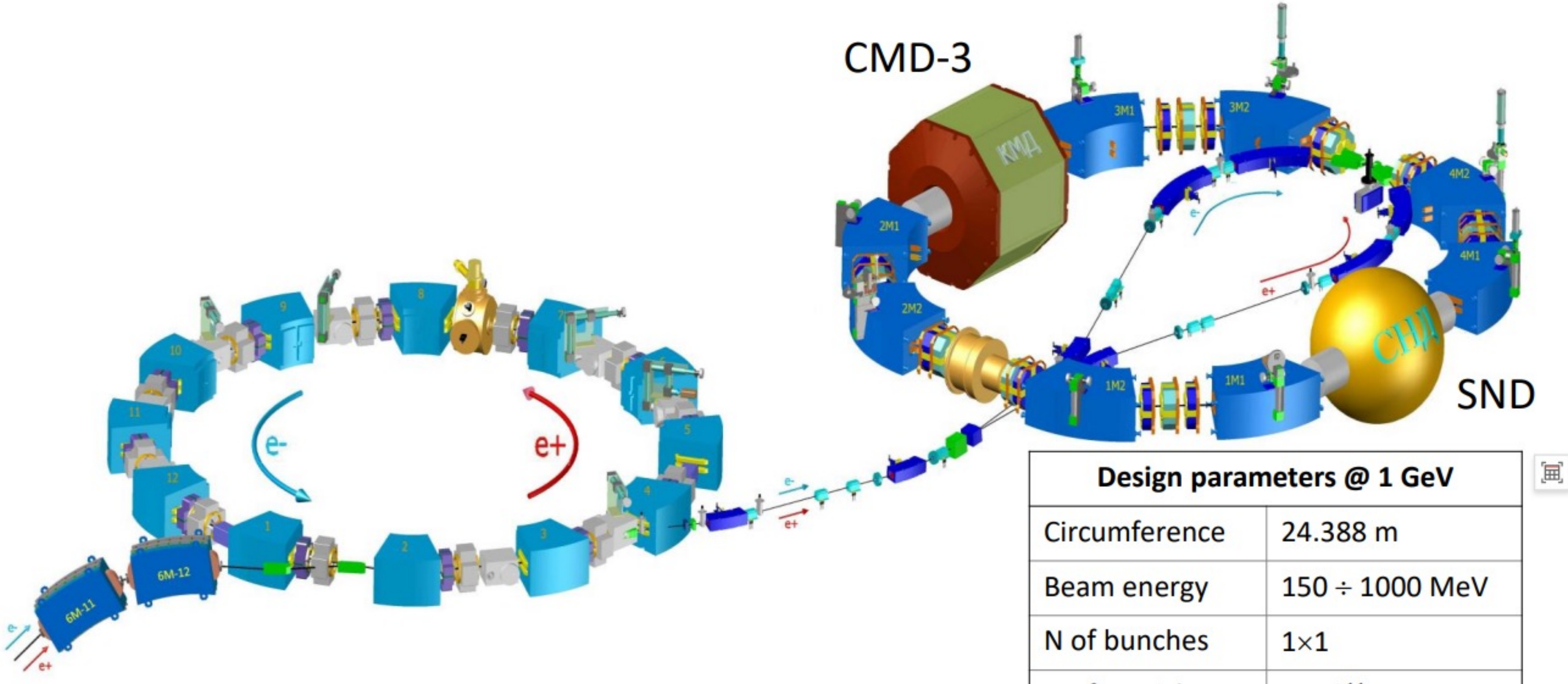
Summary

- A preliminary design for the BEPCII Crab-Waist upgrade.
- Preliminary feasible approaches to addressing the key technical challenges.
- The CW upgrade could enhance the luminosity and enable low energy operation of the BEPCII.
- Gaining valuable experience on Crab Waist which is vital for the CEPC and STCF
- IHEP innovation project supports the pre-study and pursuing 先导A of CAS
- Working on …
  - **Accelerator physics**: error effects, DA, beam-beam effect, lattice optimization at different energy, beam lifetime, background, luminosity tuning, damping ring design, clock/timing …
  - **Key technology**: IR SC quadrupole (incl. installation/alignment), SC wiggler, wiggler SR absorber …
  - **Detector**: possible improvement

Back up

World's highest luminosity @ 1 GeV

VEPP-2000



Design parameters @ 1 GeV	
Circumference	24.388 m
Beam energy	150 ÷ 1000 MeV
N of bunches	1×1
N of particles	1×10^{11}
Betatron tunes	4.14 / 2.14
Beta*	8.5 cm
Luminosity	1×10^{32} cm^{-2}s^{-1}

Our goal: 1×10^{33} cm^{-2} s^{-1} @1GeV

World-highest luminosity below 2 GeV (except at φ)

Experimental program:

- Exclusive $e^+e^- \to hadrons$ at $\sqrt{s} \leq 2.007$ GeV (spectroscopy of uds hadrons, dynamics,…)
- Related to muon (g-2)
- $p\bar{p}$, $n\bar{n}$ threshold
- Other topics

1 fb^{-1} collected per detector

Ref: Ivan Logashenko @FTCF2025（November 24, 2025）

Russia's Next Plan (VEPP-6)

- e^+e^- collider - J/ψ factory and beyond
  - Beam energy from <0.5 to 1.6 GeV (J/ψ) (2.1 GeV)
  - Luminosity $\mathcal{L} \approx 10^{34}\ cm^{-2}c^{-1}$ @ 1.6 GeV
  - Located at BINP (Novosibirsk)
- General purpose detector
- Physics
  - J/ψ decays, physics of light hadrons

    $5 \times 10^{11}\ J/\psi$: $5 \times 10^{8}\ \eta$, $3 \times 10^{9}\ \eta'$, $10^{10}\ a_2/f_2$, $10^{9}\ \Lambda\bar{\Lambda}$,...
  - Baryon thresholds
  - Measurement of $e^+e^- \to hadrons$, direct/ISR

E, MeV	500	1000	1550	2100
Π, m	388			
2θ, mrad	50			
β_x^*/β_y^*, mm	150/3			
I_{tot}, A	0.4	0.78	1.5	1.5
ε_x, nm	66	34	31	31
$\varepsilon_y/\varepsilon_x$	0.006			
ξ_x/ξ_y	0.005/0.03	0.008/0.05	0.01/0.1	0.01/0.1
$T_{Touschek}$, s	900	900	1100	2000
$\mathcal{L}$, $10^{32}\ cm^{-2}s^{-1}$	**3** DAΦNE: 2-4	**26** VEPP-2000: 0.9	**140** BEPCII: 3.1	**200** BEPCII: 10

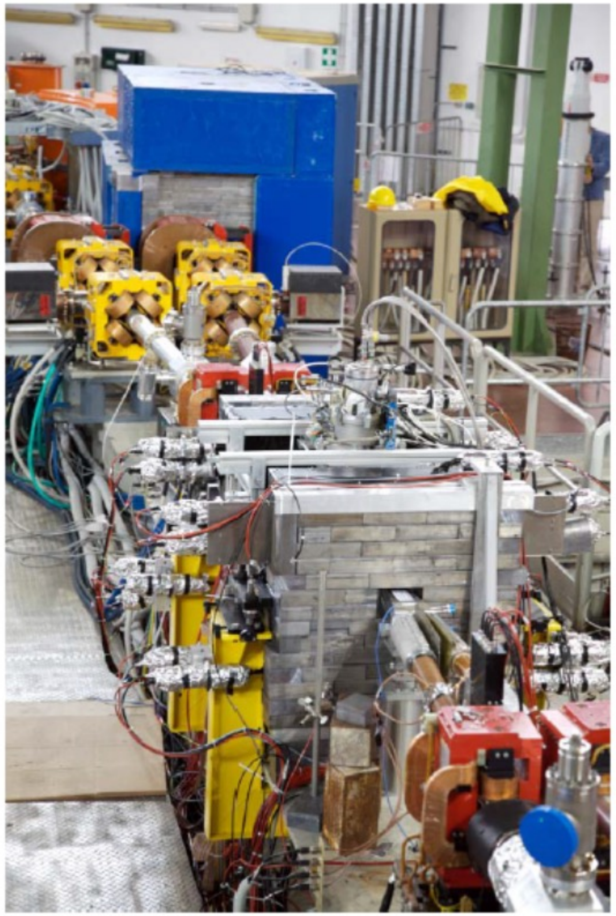
- BEPCII-CW plan is highly similar to VEPP-6.

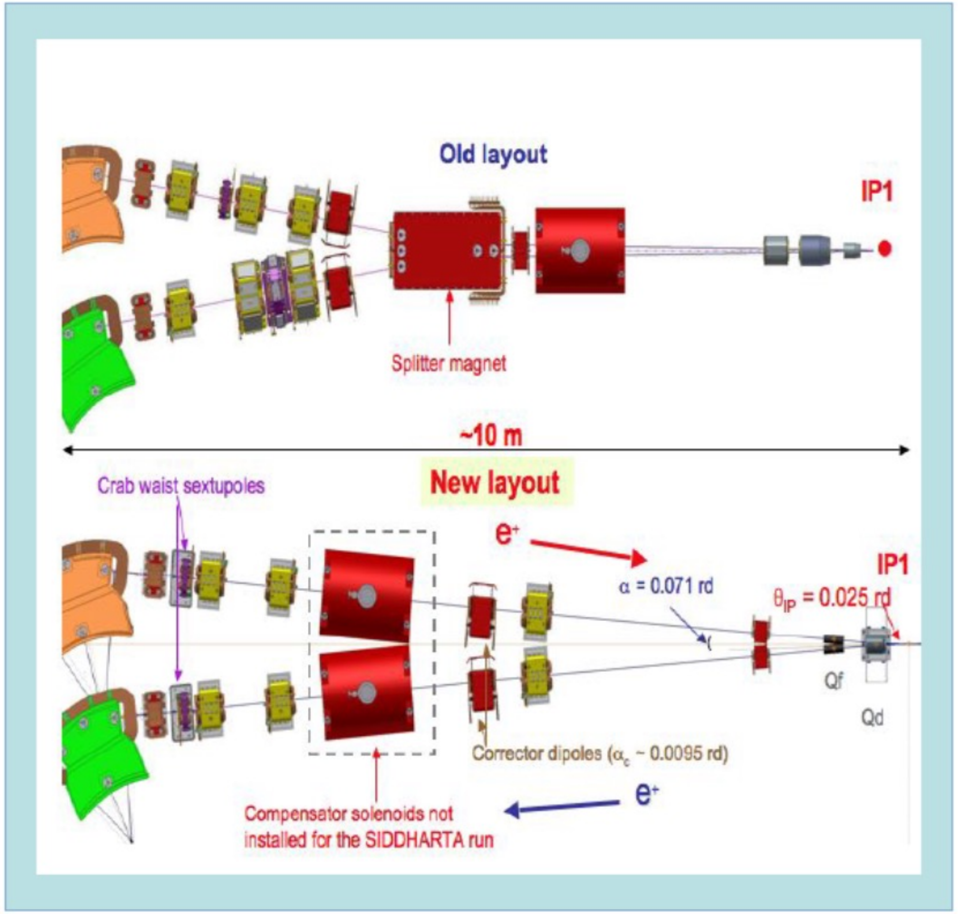
Ref: Ivan Logashenko @FTCF2025（November 24, 2025）

DAΦNE's experience @ 0.5GeV

- Highest luminosity: 4.5×10^{32} cm^{-2} s^{-1}, Circumference: 98m

	DAΦNE FINUDA	DAΦNE Upgrade
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mm×mrad)	0.34	0.20
β_x^* (cm)	170	20
σ_x^* (mm)	0.76	0.20
$\Phi_{Piwinski}$	0.36	2.5
β_y^* (cm)	1.70	0.65
σ_y^* (μm)	5.4 (low current)	2.6
Coupling, %	0.5	0.5
I_{bunch} (mA)	13	13
N_{bunch}	110	110
σ_z (mm)	22	20
L ($cm^{-2}s^{-1}$) x10^{32}	1.6	5





Beam-beam simulations with lattice

BEAMBEAM : emity=416nm

weak strong+ lattice

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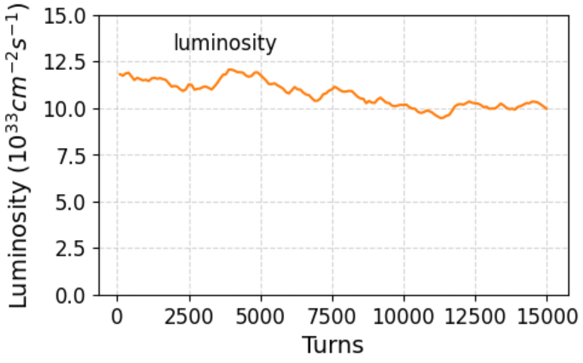

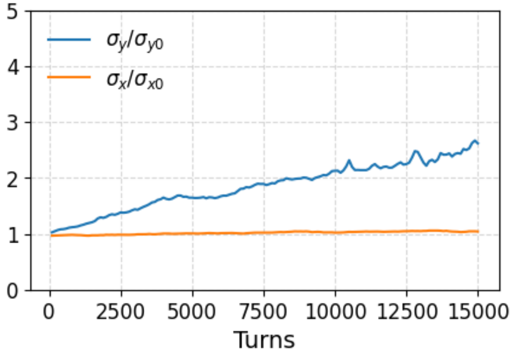

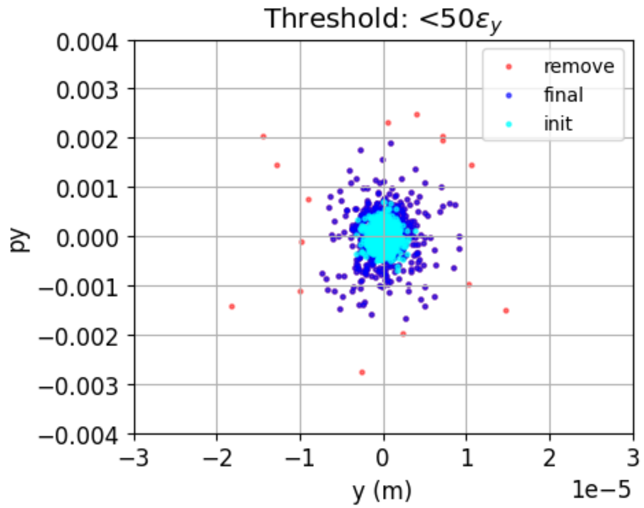

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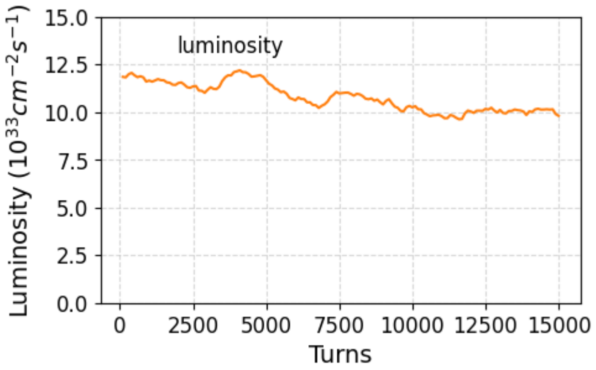

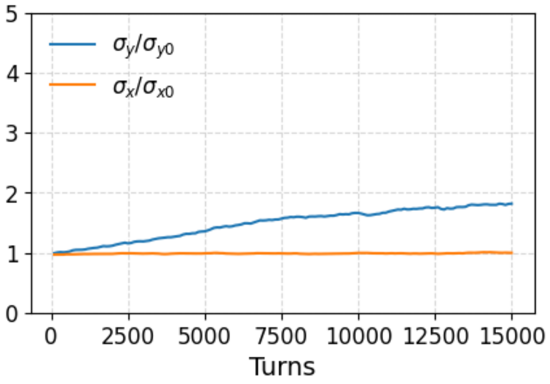

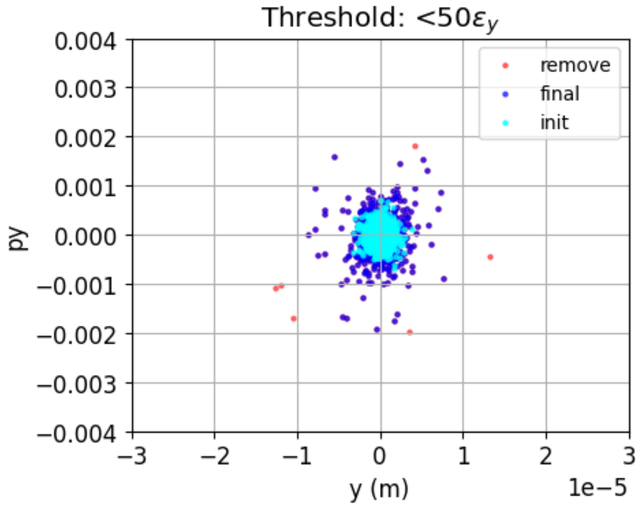

Damping ring parameters

DR V2.0	Collision mode		PWFA TF	
	e-	e+	e-	e+
Energy (MeV)	200			
Circumference （m）	34			
Bunch charge (nC)	1	0.07	1~2	0.5
Repetition （Hz）	50		1	
Bunch number	15		1	
Bending radius (m)	0.51			
B0 (T)	1.3			
U0 (keV/turn)	0.28			
Damping time x/y/z (ms)	68/163/266			
δ0 (%)	0.044			
ε0 (mm.mrad)	4.5			
Inj σz (mm)	1.39	1.66	1.39	1.66
Extract σz (mm)	2.0	2.0	2.1	2.1
εinj (mm.mrad)	500	2500	500	2500
εext x/y (mm.mrad)	37/16	9/50	47/5	21/3
δinj /δext (%)	0.5/0.10	0.9 /0.13	0.5 /0.044	0.9 /0.044
Storage time (ms)	300		>1000	

RF cavity： 1.5m*0.6m*0.6m

RF parameters	
RF frequency (MHz)	500
RF voltage (MV)	1.6
Energy acceptance by RF(%)	3.9
harmonic	56

Fast Kicker: 14 ns (bottom width)

Crab cavity vs. crab waist