Feasibility study of future BEPCII upgrade with crab waist scheme

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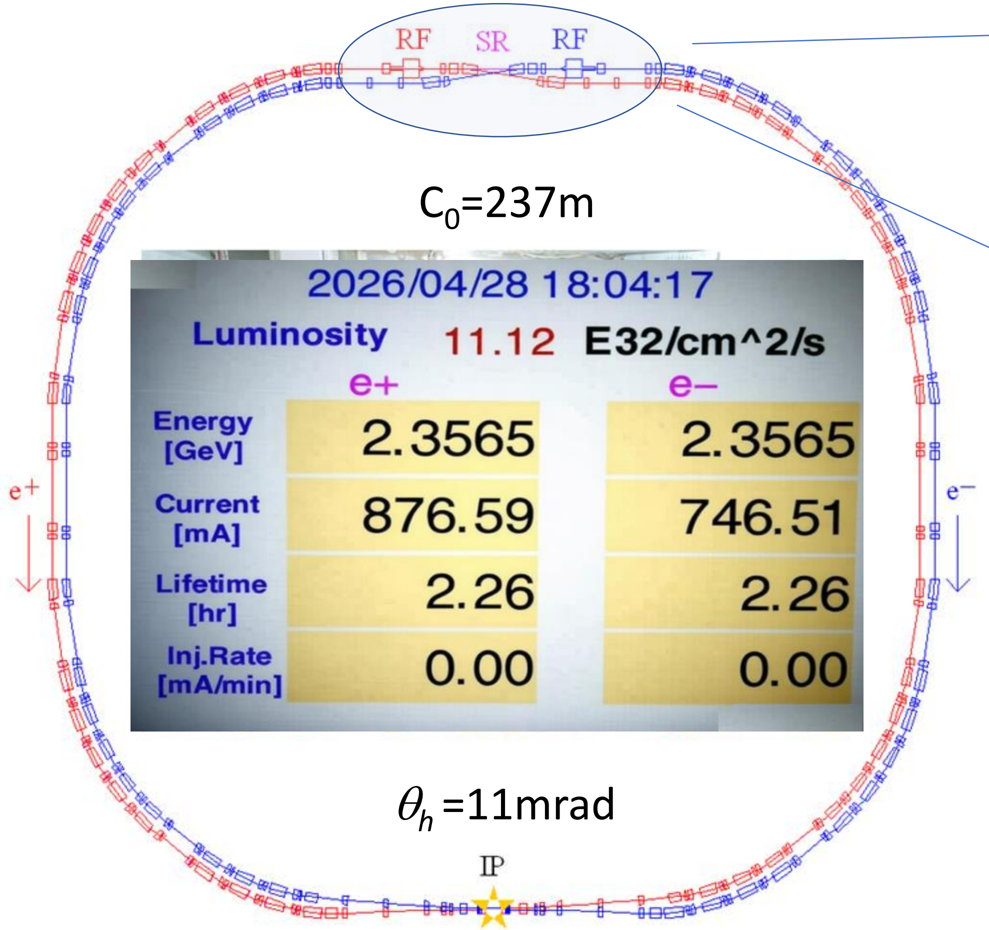
On behalf of BEPCII-UP team

Outline

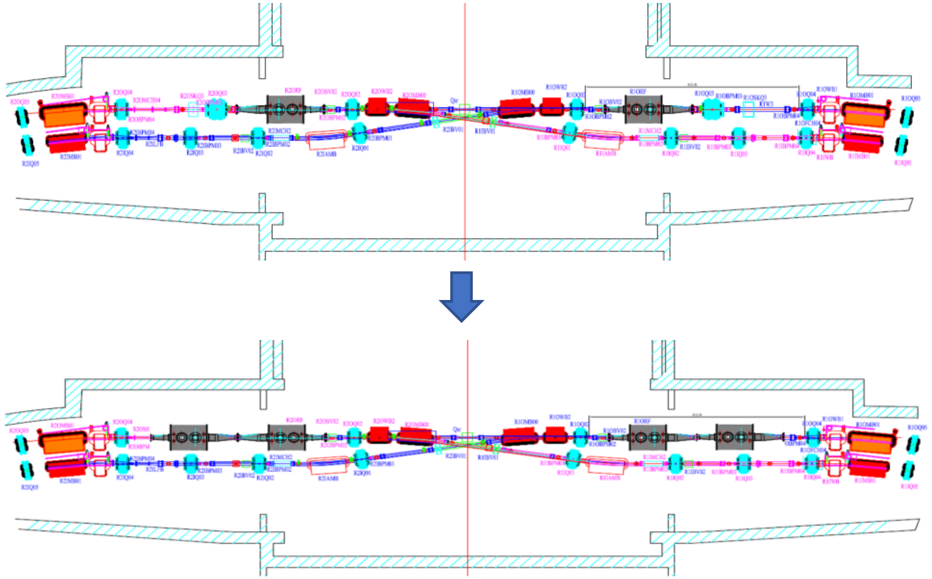
- Crab waist scheme being considered for BEPCII
- Benefits to BESIII Physics with CW
- Design and development of BEPCII with CW (intended for a future upgrade)
- Possible international collaborations
- Summary

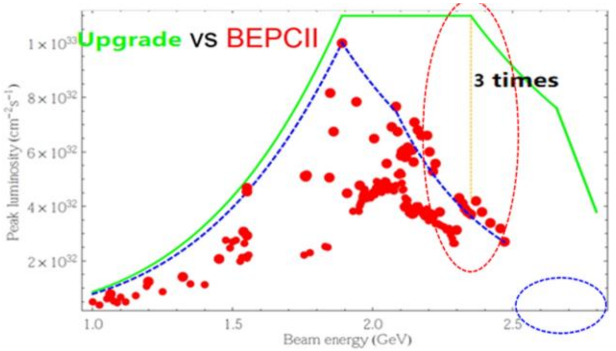
BEPCII

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



- **Performance upgraded at high energy (2021~2025)**





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

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 betay*
  - Crab sextupoles
- Crab waist is the preferred scheme for achieving high luminosity in next-generation colliders (SuperKEKB, CEPC, FCC, STCF…).

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

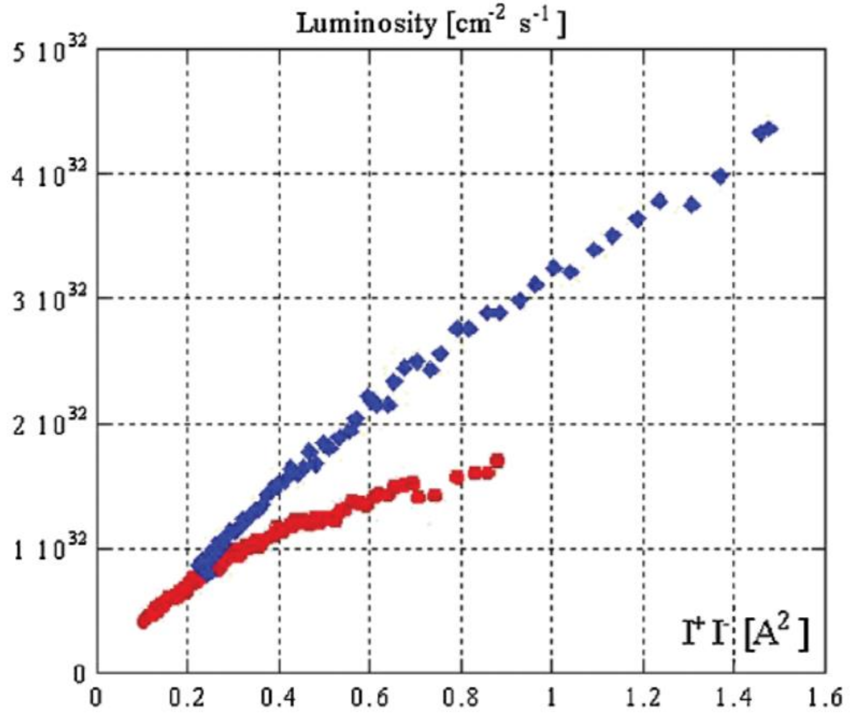
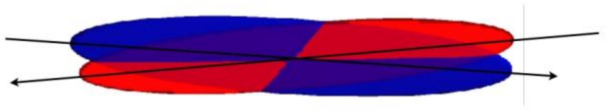


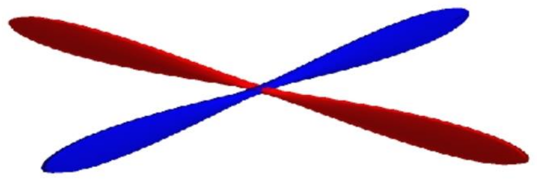
FIG. 4 (color). Measured luminosity as a function of beam current product for crab sextupoles on (blue) and off (red).

BEPCII crab waist scheme

BEPCII/U



BEPCII crab waist

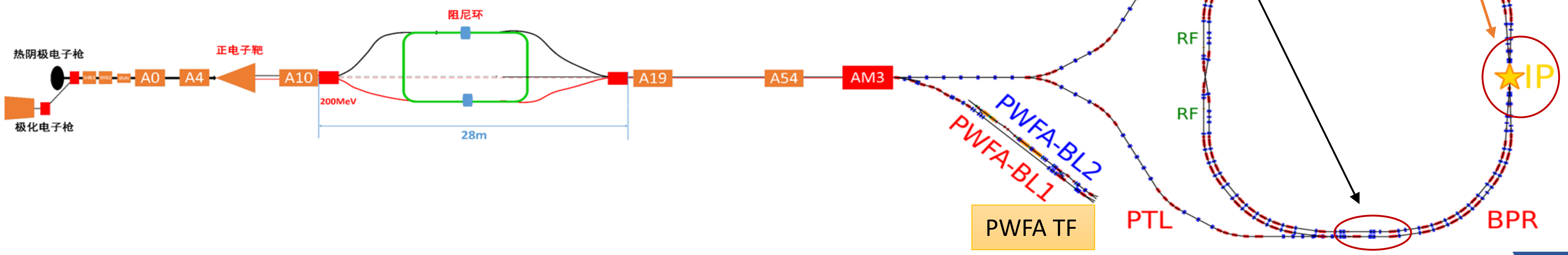


- Design study supported by IHEP Innovation funding since 2025.

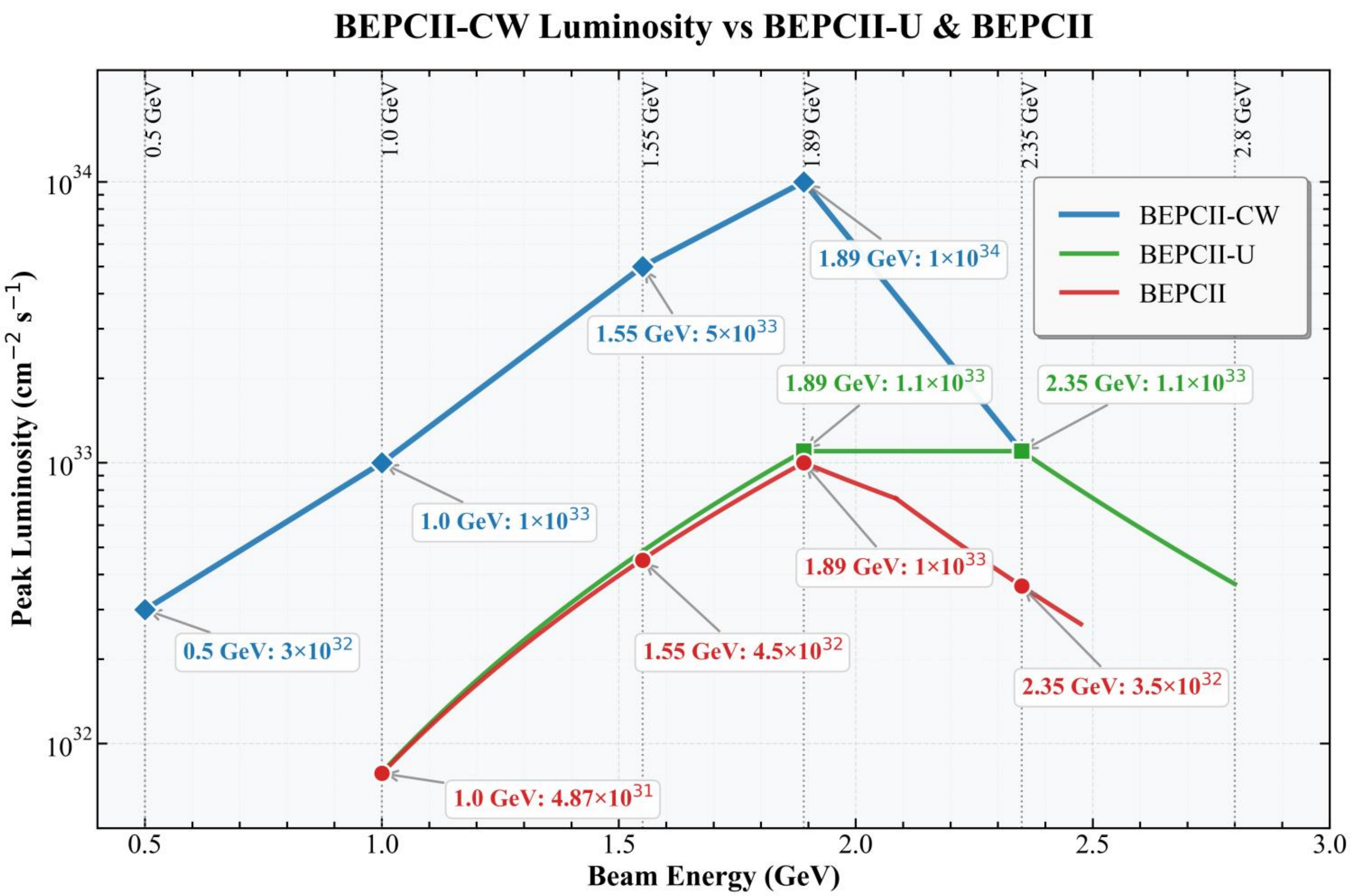
1. IR: crab waist collision

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 1.89GeV,.
- Operation below 1GeV is enabled

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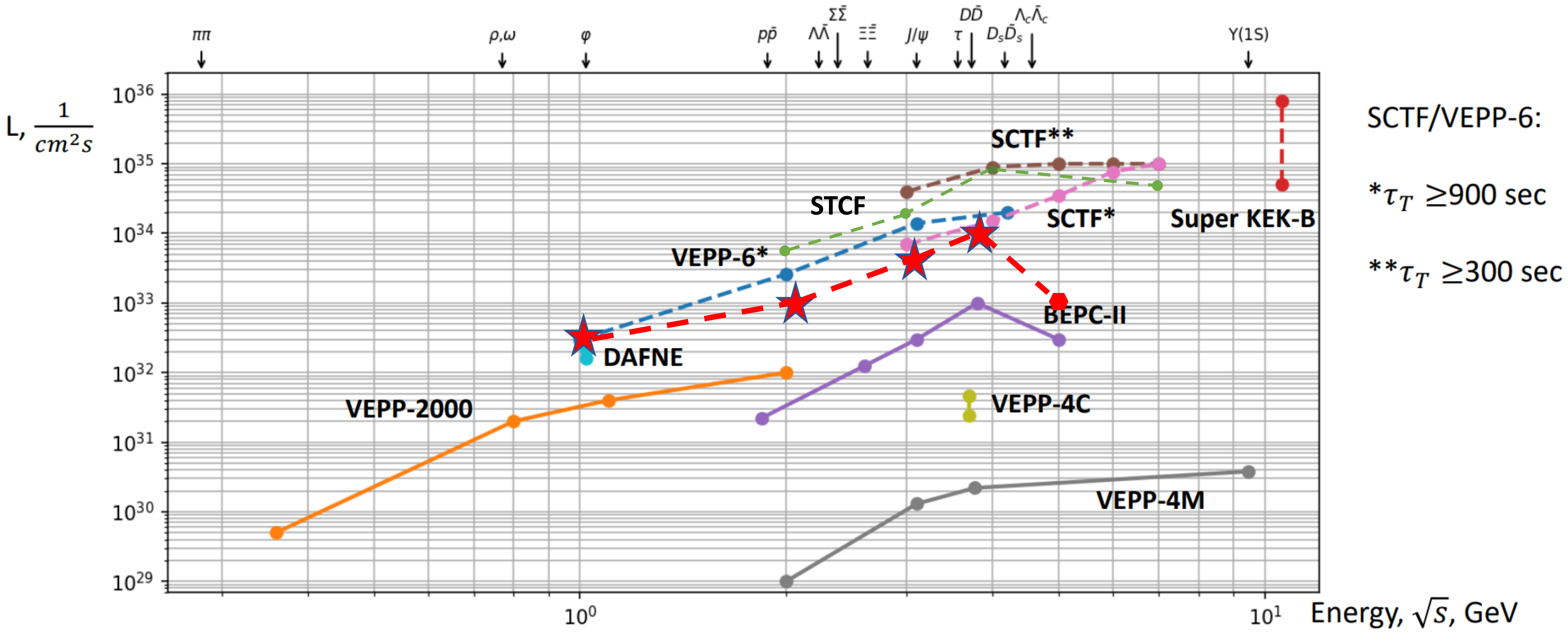
e+e- colliders at a glance



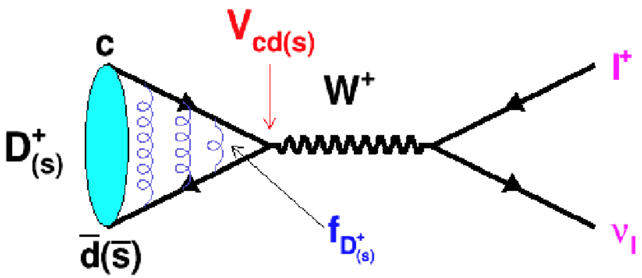
Ref: Ivan Logashenko @FTCF2025（November 24, 2025）

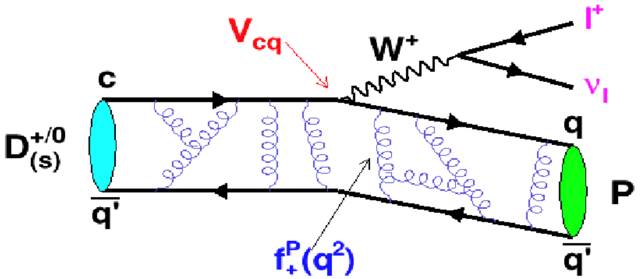
Benefits to BESIII Physics with CW

Charm physics with x10 data at 3.77 GeV

Haibo Li, Gang Li

- With CW upgrade: 0.1 B $D\bar{D}$ pair → 1 B $D\bar{D}$ pair
- Physics topics
  - ✓ Pure leptonic decay of D meson: precision measurement of $|V_{cd}|$, $|V_{cs}|$, decay constants, search for lepton flavor violation, …
  - ✓ Semi-leptonic decay of D meson: precision measurement of $|V_{cd}|$, $|V_{cs}|$, search LFV, and light hadron spectroscopy studies
  - ✓ Hadron decays of D meson: CP violation, strong phase, Quantum entanglement
  - ✓ New physics searches: rare decay, radiative decay, invisible particles, FCNC, …
  - ✓ … …





$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi}|V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}}\left(1-\frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2$$

Benefits to BESIII Physics with CW

Physics potential at low energy region

Haibo Li, Gang Li

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: 0.4 - 1.0 GeV

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

Strategy of luminosity upgrade with CW@1.89GeV

CW: small ε_x & DW: I_b=7.5mA → 12.5mA, 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^* =13.5mm → 5mm

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

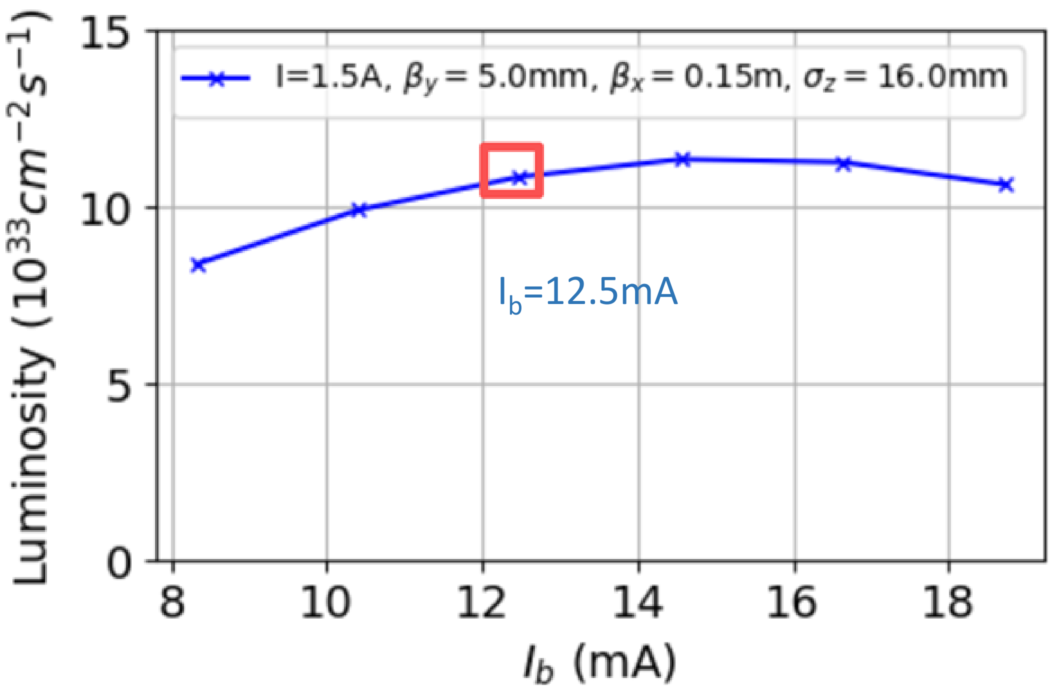
L_{BEPCII}=1.0×10 ^{33} cm^{-2}s^{-1} → L_{CW} ~10×10 ^{33} cm^{-2}s^{-1}

1.89GeV BEPCII crab waist parameters（w. 3.0T wiggler）

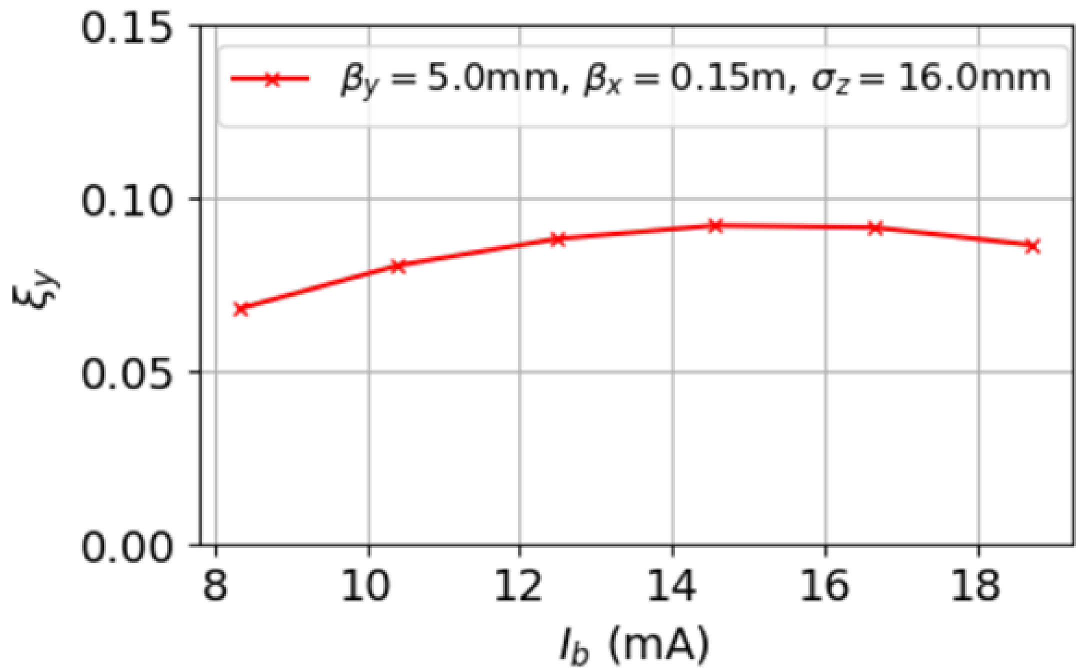
	BEPCII (L_0=1E33cm^{-2}s^{-1})	BEPCII-CW ($10\times L_0$)
Circumference [m]	237	
Peak luminosity [$10^{33} cm^{-2} s^{-1}$]	1	10.9
β_x^*/β_y^* [m]	1/0.0135	0.15/0.005
Total current [mA]	910	1500
Bunch current [mA]	8.3	12.5
Bunch number	110	120
Beam-beam para. ξ_x/ $\xi_{y,\mathrm{lum}}$	0.029/0.04	0.01/0.088
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

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=8.3mA, total current I=910mA

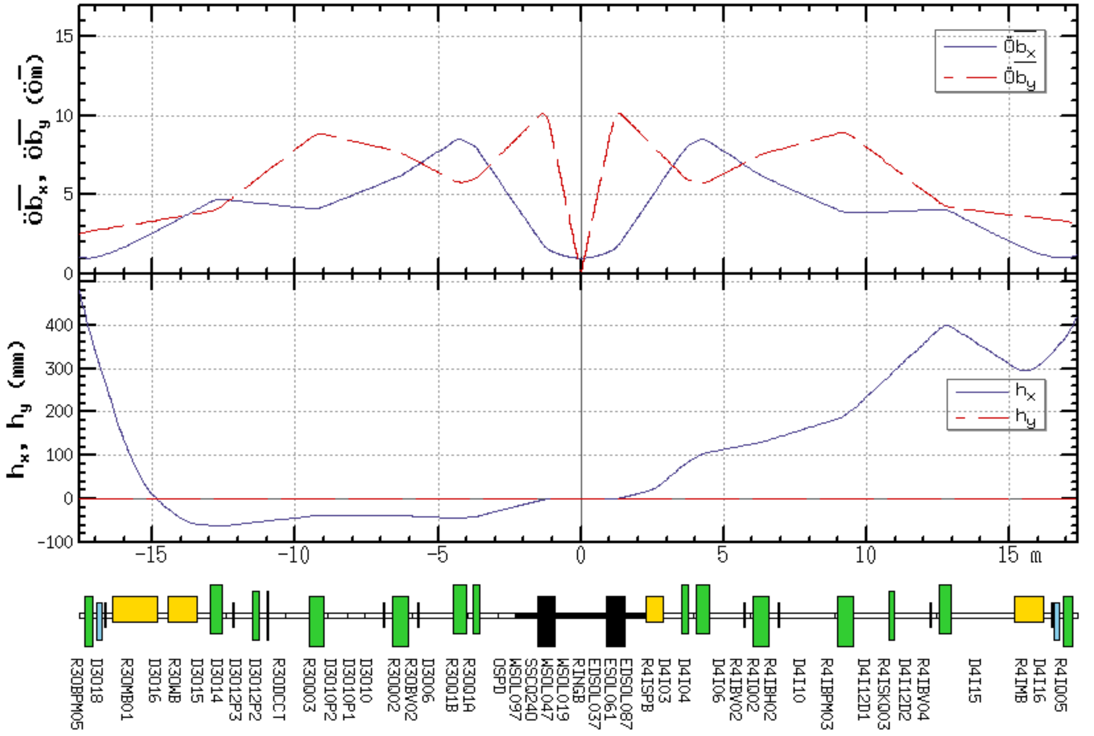
Lower energy parameters @ 1.55GeV/ 1.0GeV/0.5GeV

	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 [$\mathbf{10^{32}cm^{-2}s^{-1}}$]	50	11	3
$\boldsymbol{\beta_x^*/\beta_y^*}$ [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.$\boldsymbol{\xi_x}$/ $\boldsymbol{\xi_{y,\mathrm{lum}}}$	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 $\boldsymbol{\nu_s}$	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 $\boldsymbol{\sigma_{z,0}}$ [cm]	1.77	1.8	1.1
Bunch length $\boldsymbol{\sigma_z}$ [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

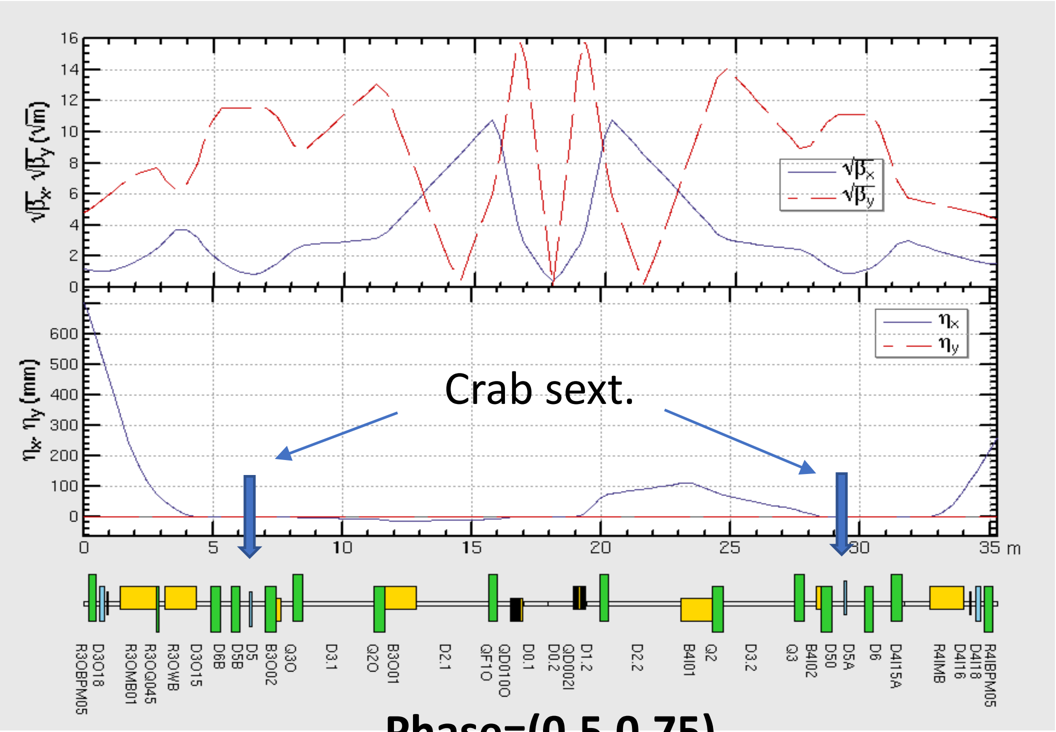
To test luminosity performance at various Piwinski angles → b-b parameters & CW commissioning experience.

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

BEPCII



BEPCII-CW

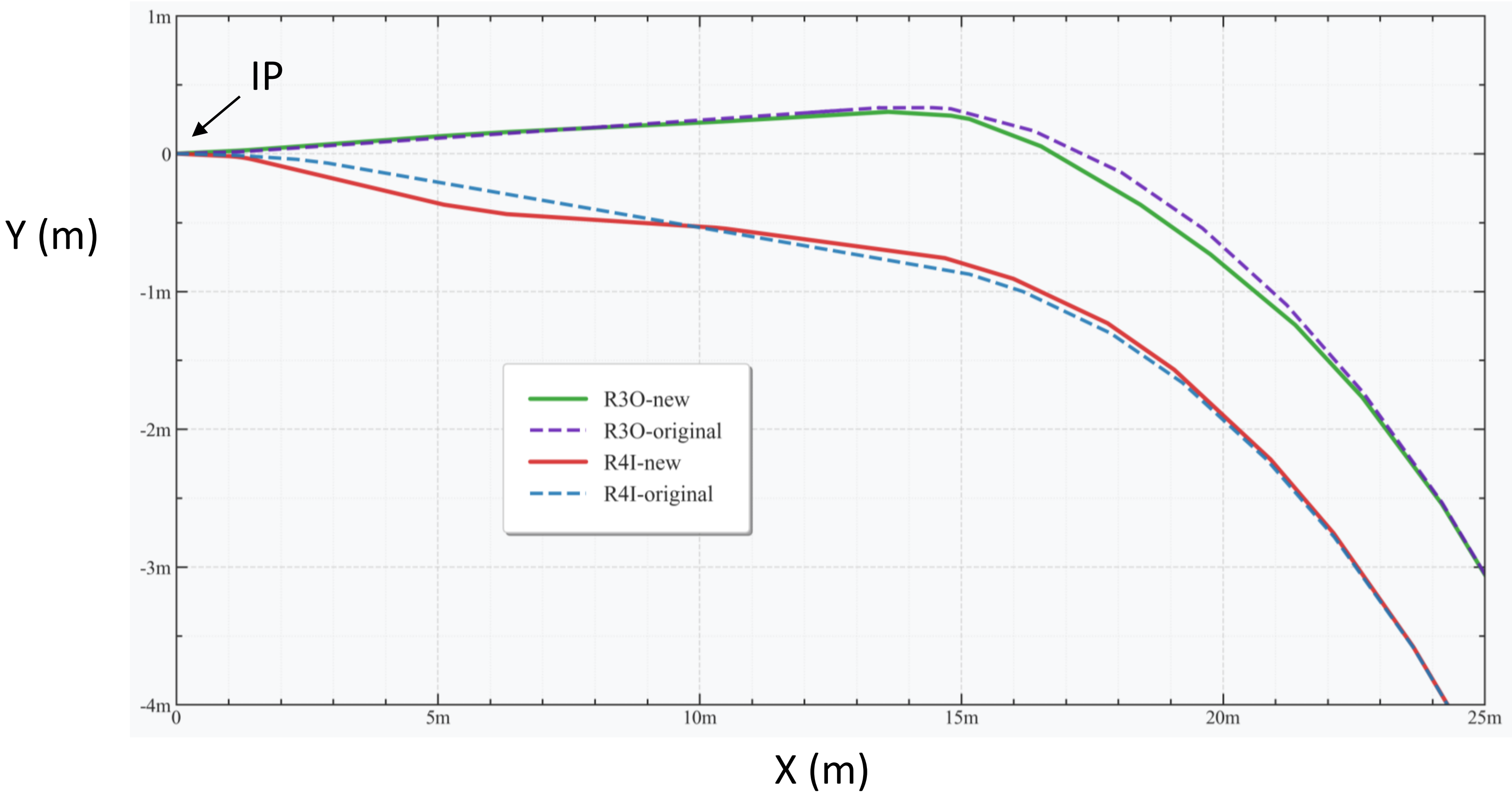


Phase=(0.5,0.75)

- **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.



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

BEPCII-CW Asymmetric IR design

- **BII-CW（1.89GeV）：**

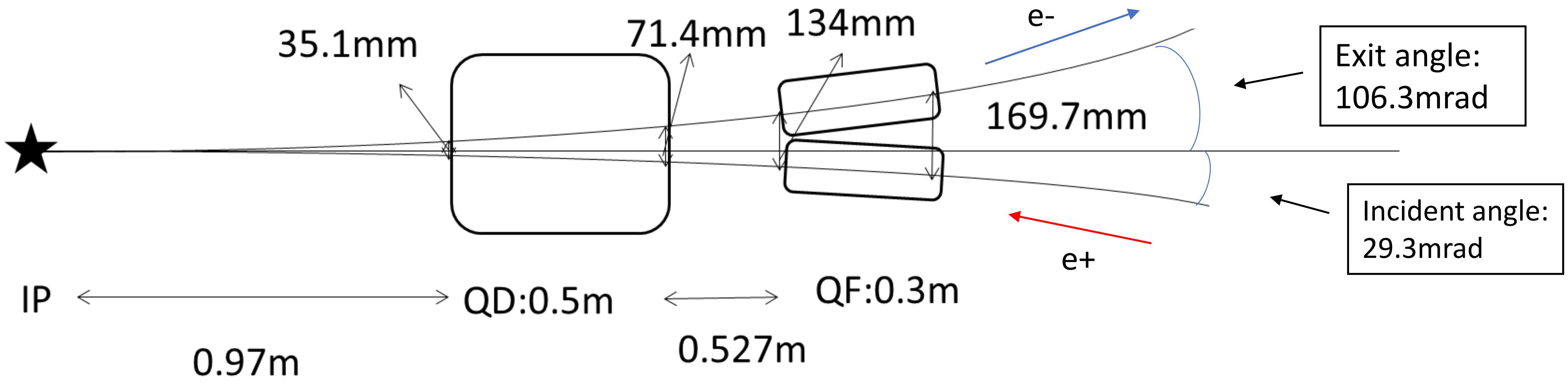
  QD(single aperture): B'= 21.5 T/m & B=0.34 T

  QF(twin aperture): B'=21.0 T/m

- **Correcting coils to cancel the alignment error：**

  -- skew quad & correctors

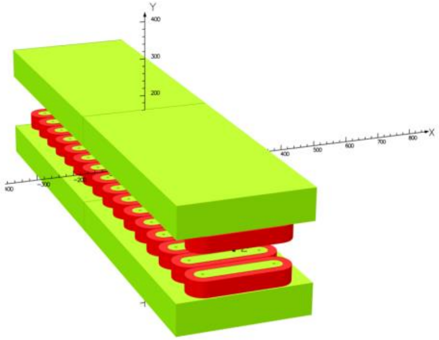
- The new IR SC quadrupole magnet will replace the existing SCQ.
  - ✓ BEPCII： QD （single aperture）
  - ✓ BEPCII-CW： QD （single aperture） + QF （double aperture）

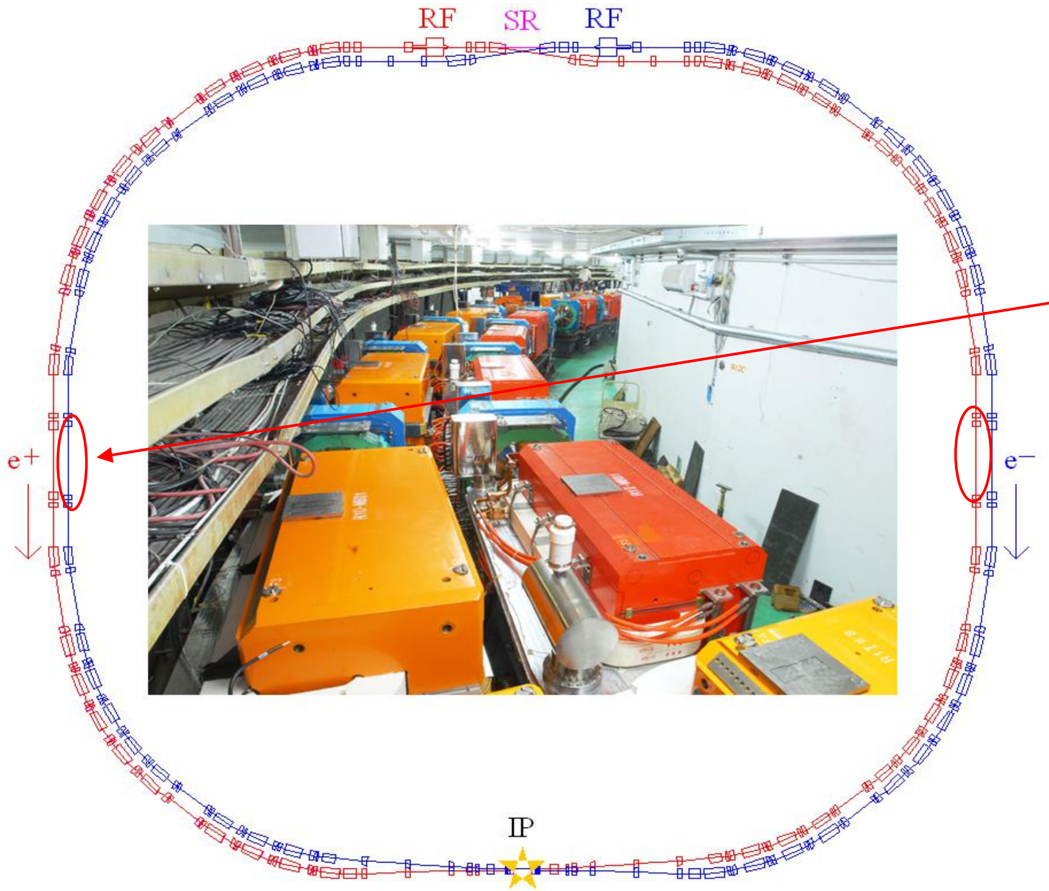


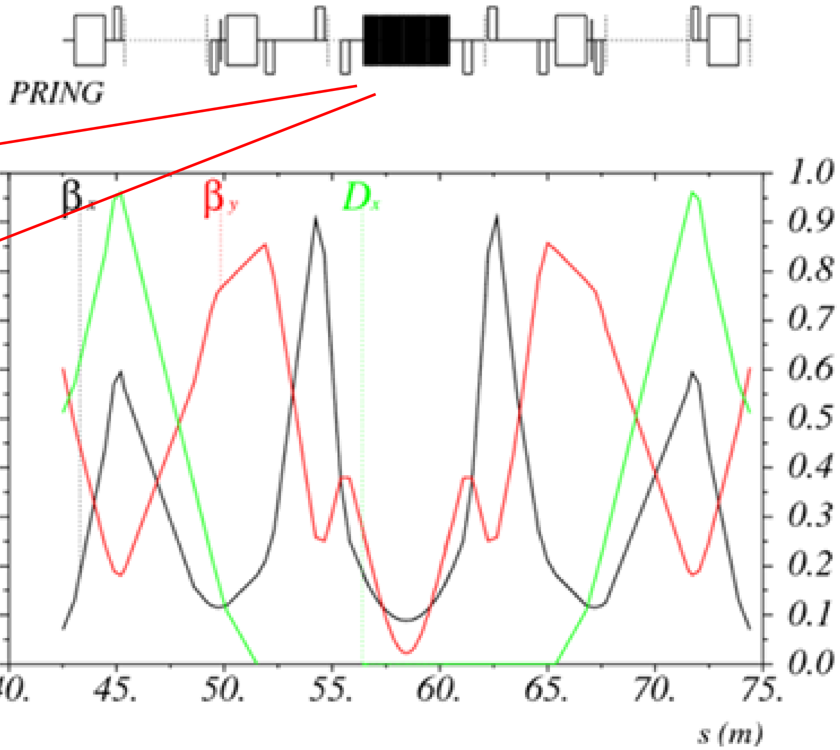
- **No direct SR light from the upstream will hit the central Beryllium pipe.**

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





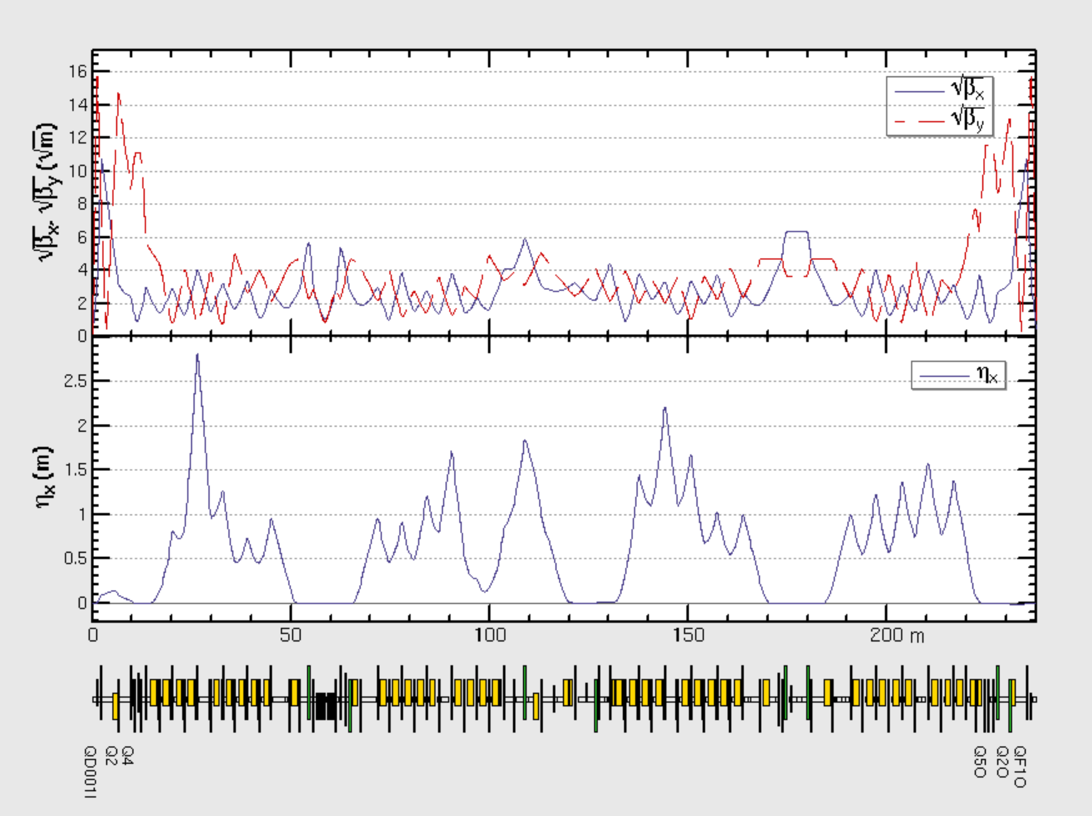


BEPCII-CW

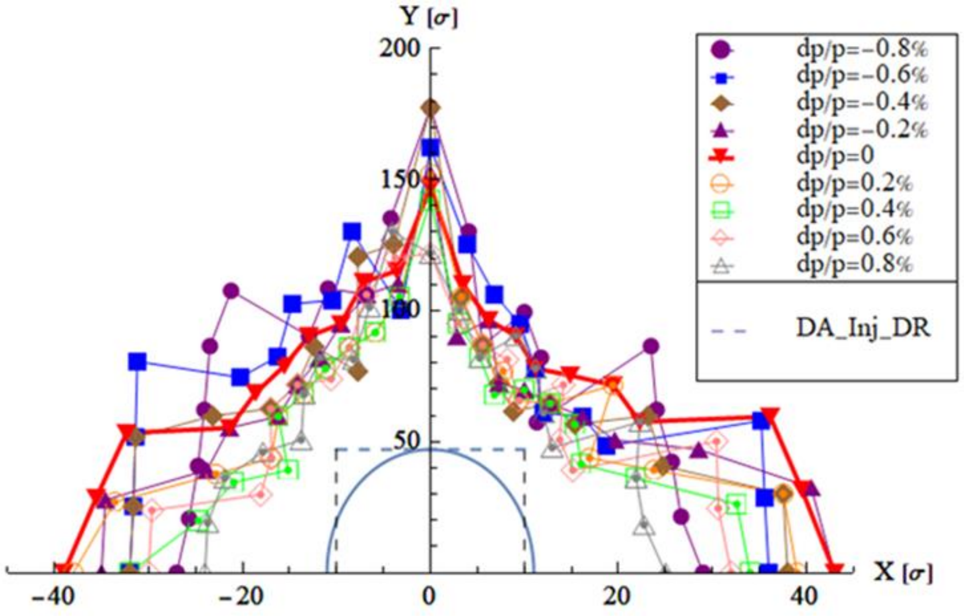
Whole ring lattice & dynamic aperture (β^*=0.15m/5mm)

- No local chromaticity correction due to limited space.

62% crab + 3T wiggler



Working point: 8.55/7.58



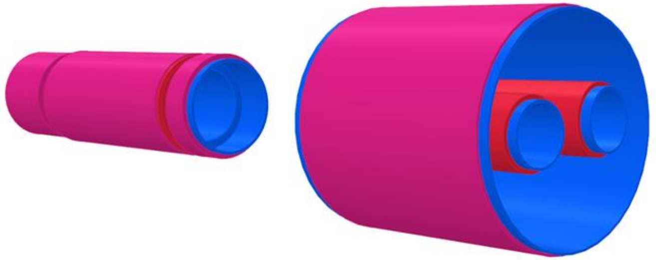
- DA requirement by injection @1.89GeV
  - Without DR: 14σx, 136σy (εy= 0.0035εx)
  - With DR : 10.5σx, 47σy (εy= 0.0035εx)

- Damping ring supports the achievement of the crab waist's high-luminosity goal.

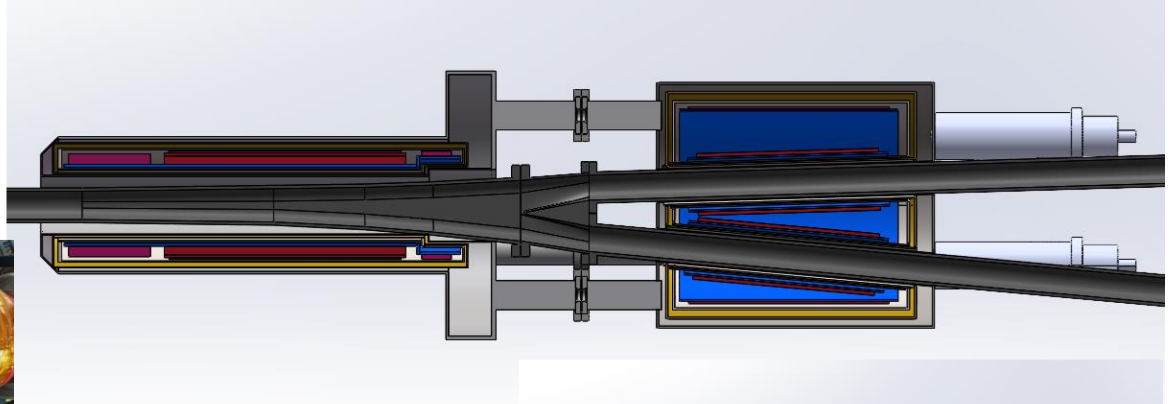
IR SCQ

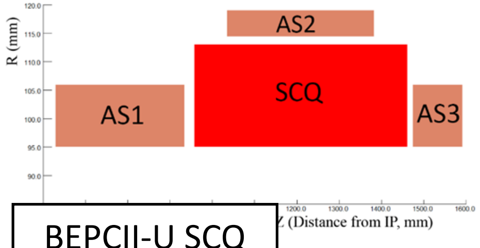
➢ Magnet baseline： NbTi technology

- QD： serpentine winding
- QF： CCT

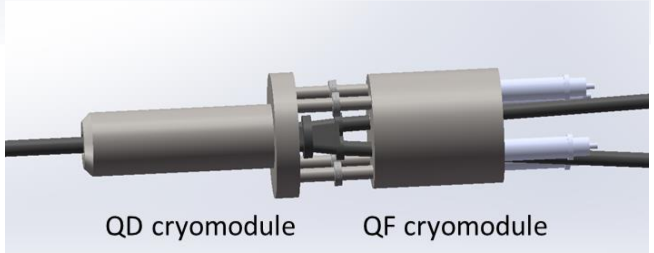


➢ Separate cryomodule for QD & QF





BEPCII-U SCQ



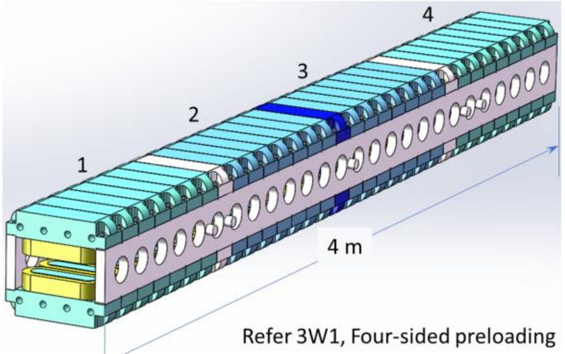
➢ SCQ experience on BEPCII-U

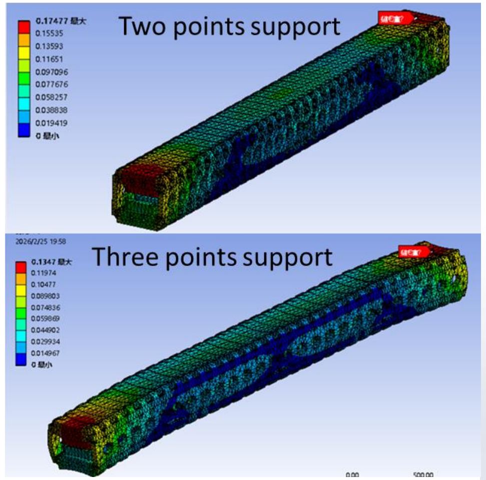
- Two SCQ was produced by IHEP, installed on BEPCII-U in 2025
- The first domestically produced SCQ with operation.
- **R=190mm， B’=25T/m @ 2.8GeV**
- **Anti-solenoid: 2.85T**

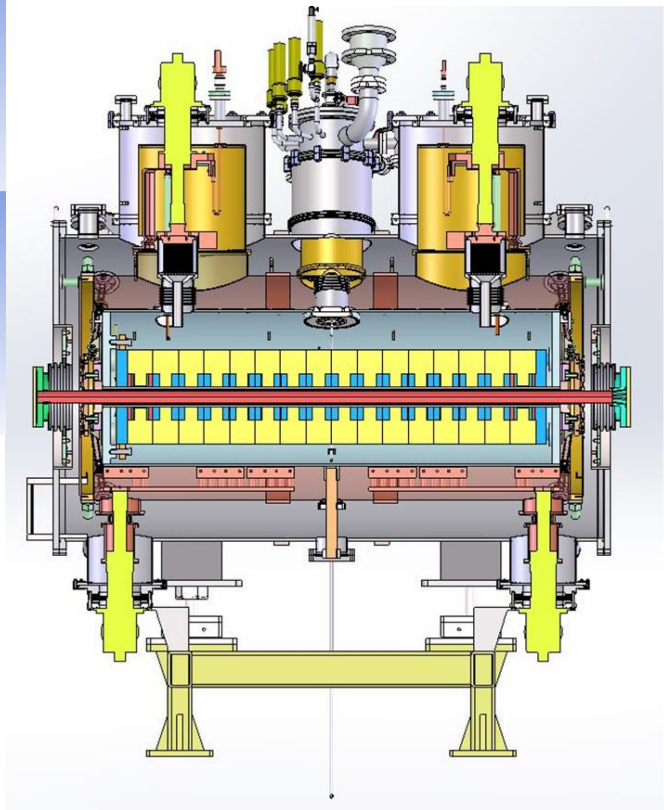
SC wiggler

SCW250 main parameters

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



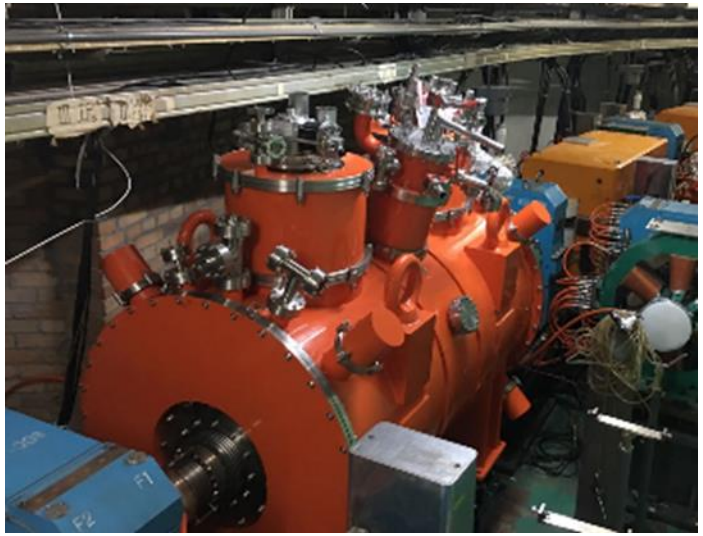




Cryostat based on the compact cryocooler

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**

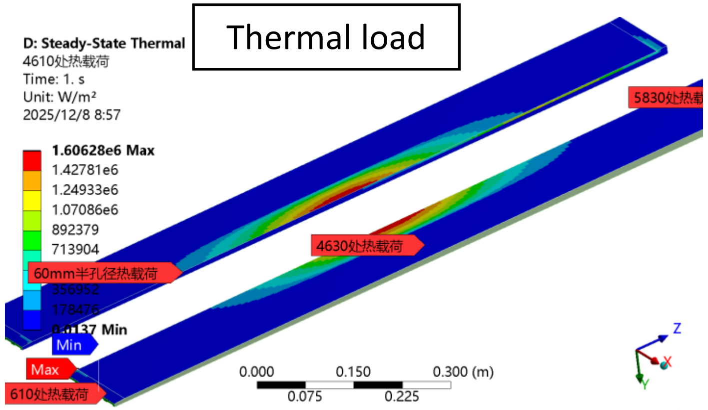


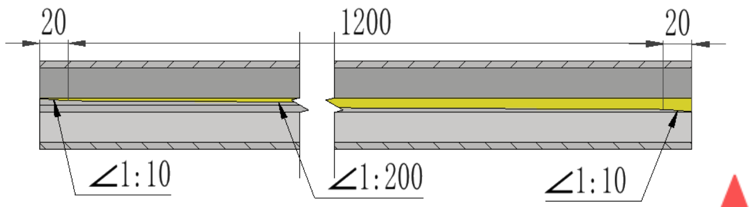
3W1 in BEPCII tunnel

Wiggler synchrotron radiation absorber

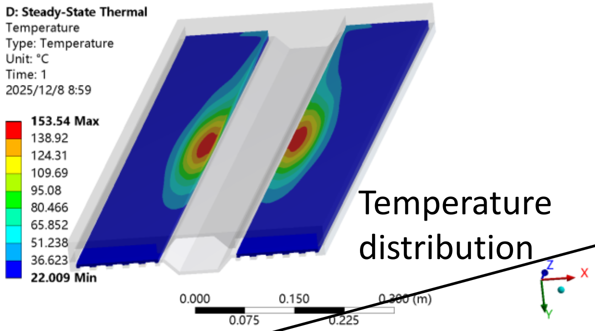
➢ Strong SR power downstream of wiggler may destroy the accelerator equipment, locally absorbed with a dedicated absorber.

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

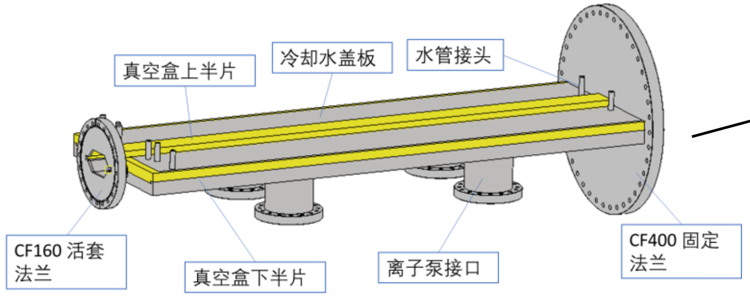


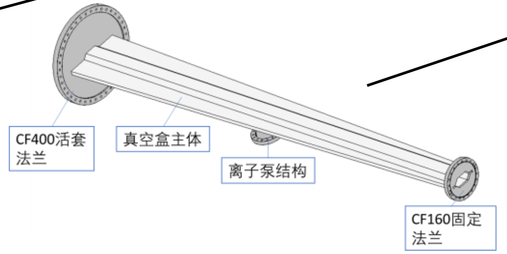


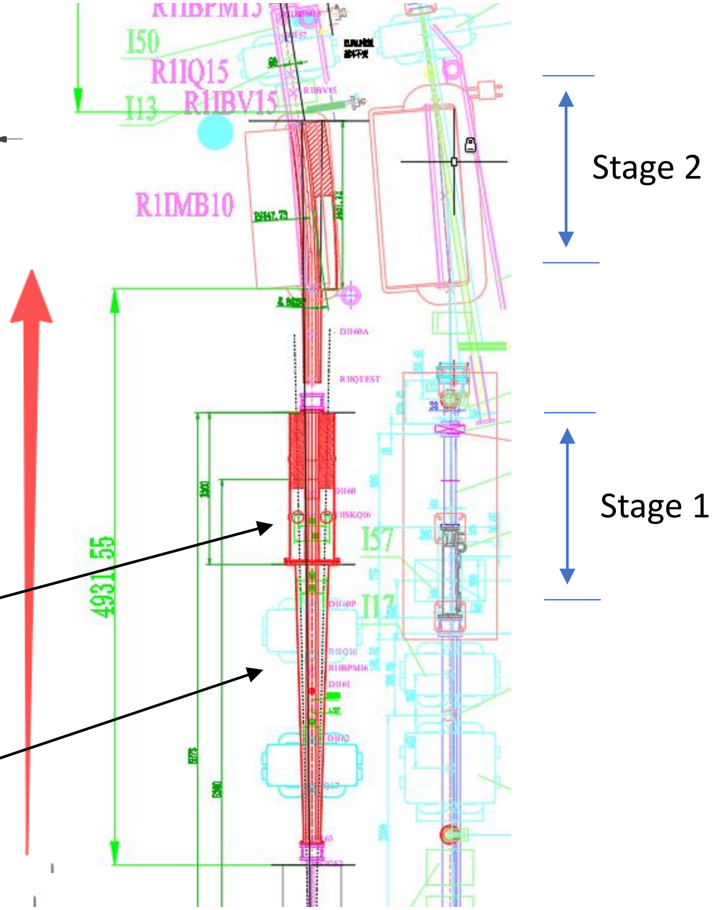
Beveled structure



Temperature distribution



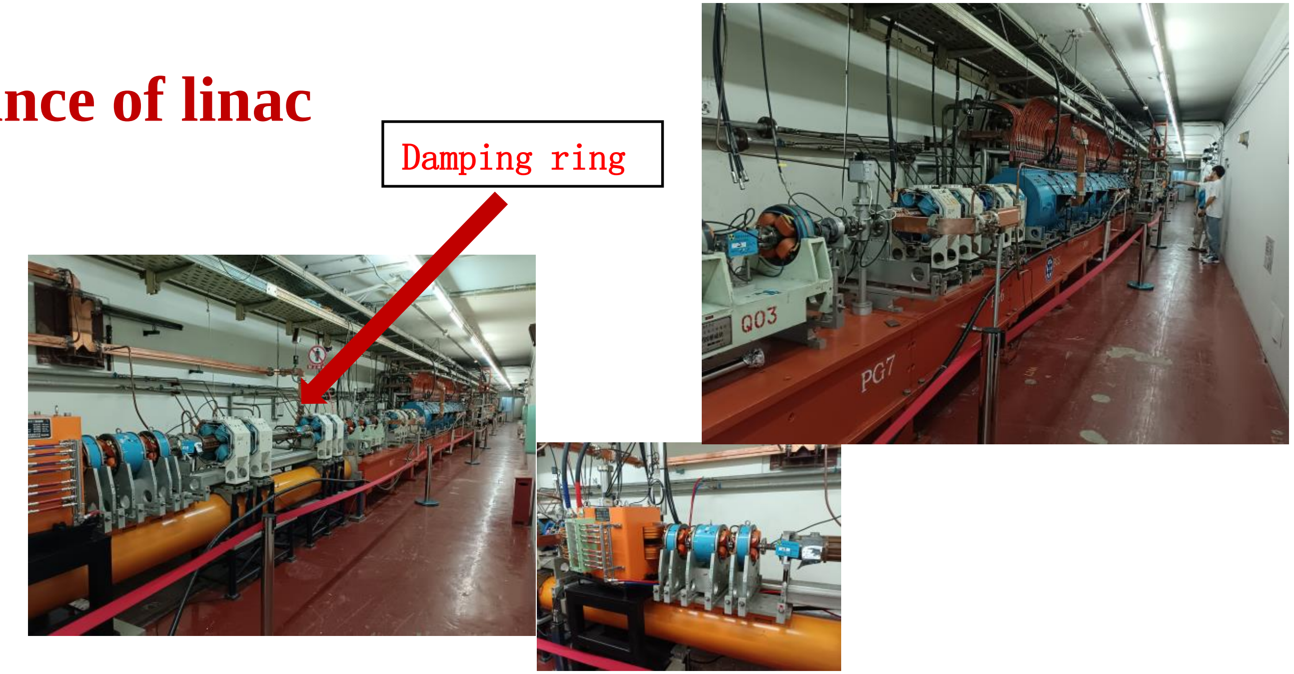




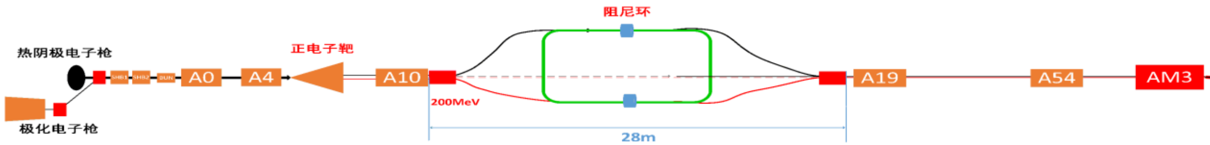
BEPCII Linac upgrade with damping ring

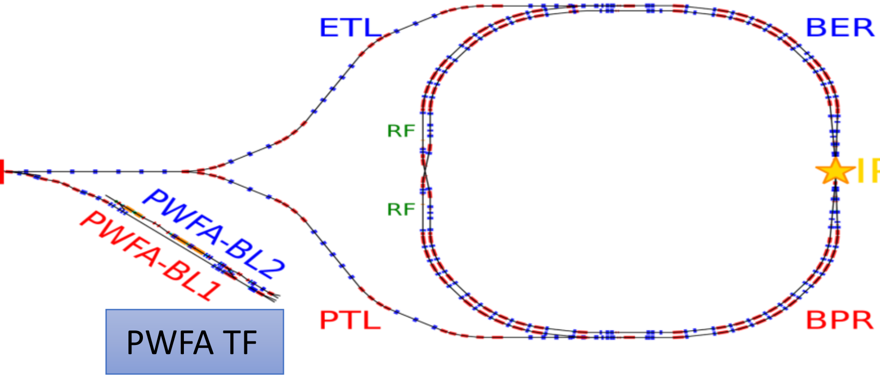
➢ Damping ring reduces the emittance of linac injector — new highlight

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.



~ 34m @200MeV

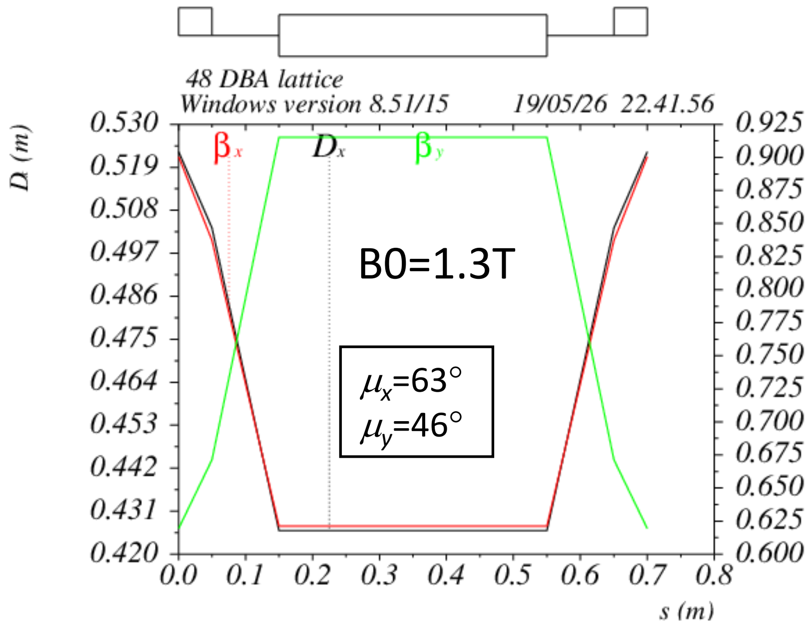


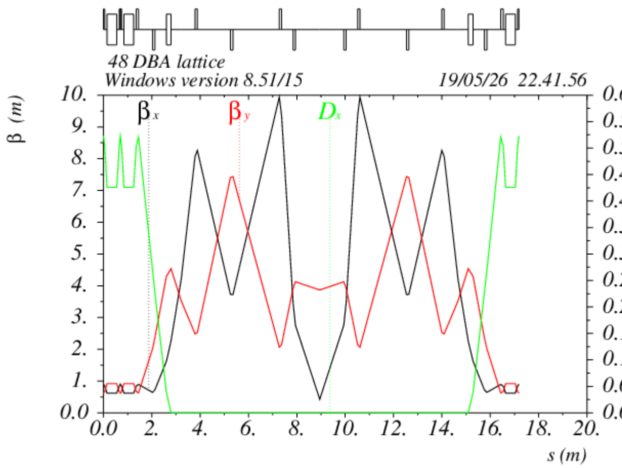


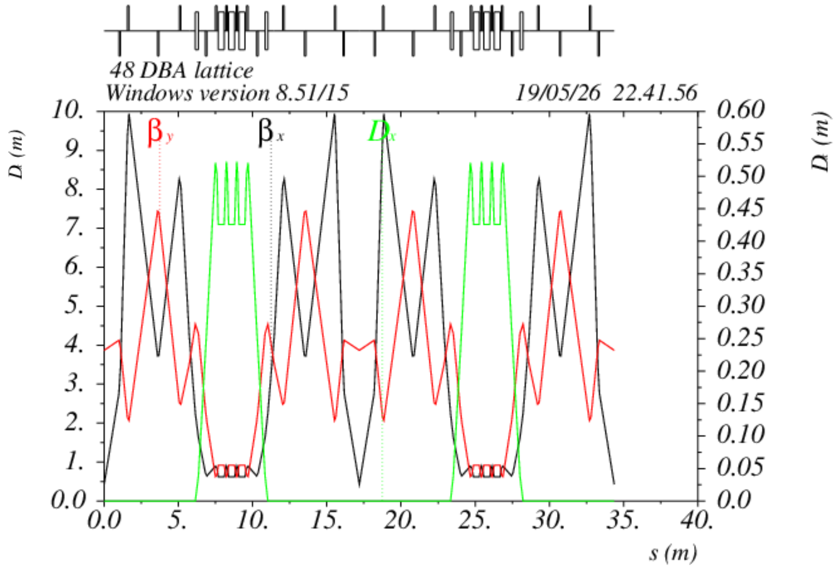
➢ Feasible in space based on the preliminary lattice design

(tunnel width: 3.5m)

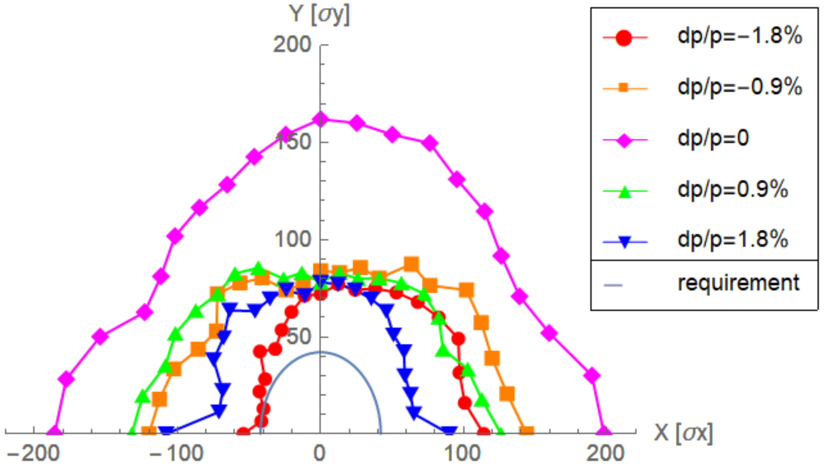
Preliminary damping ring lattice

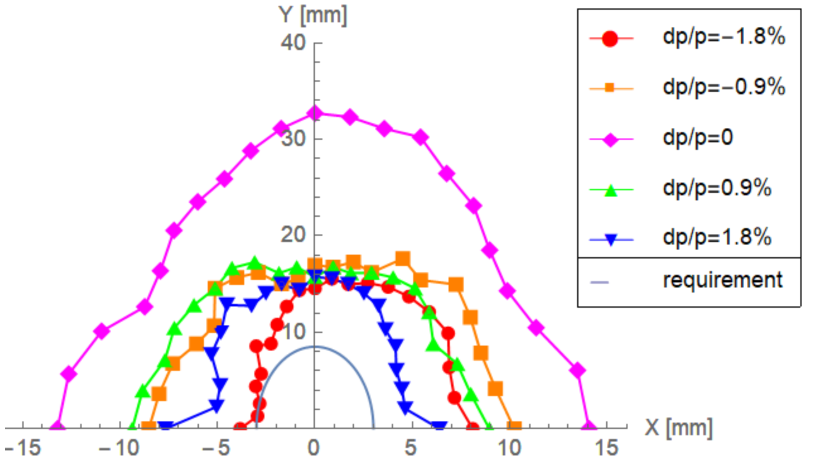




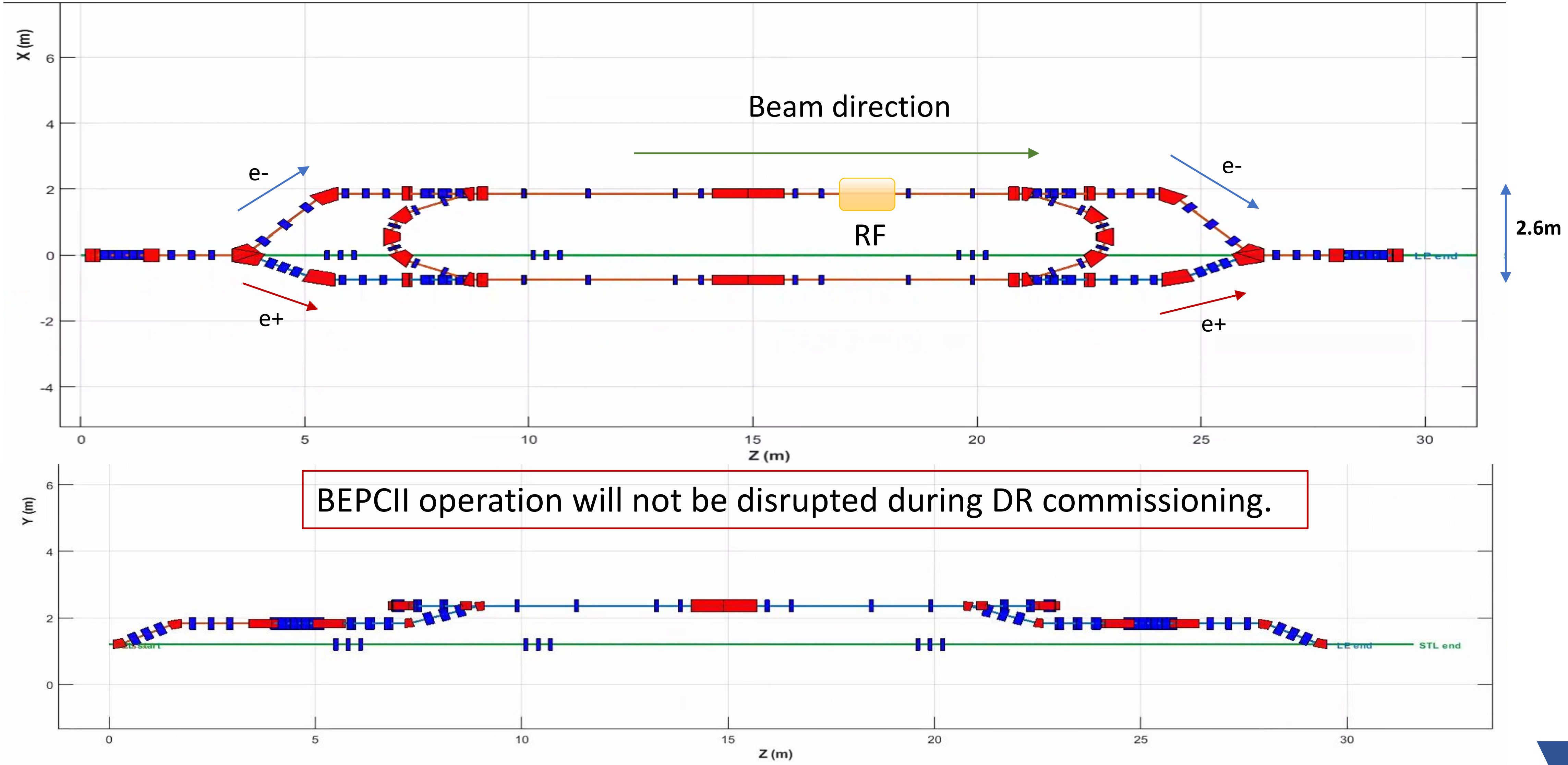


- **Combined magnets**
  – compact structure
  - B+QD+SD
  - QF+SF
- DA requirement (blue ellipse): 2 times of e+ inj. beam size





Damping ring survey



Possible collaborations

- Tunning & Operation related with crab waist scheme
- Beam-beam simulations based on APES
- IP luminosity feedback and fast luminosity monitoring technics
- ML-AI algorithms and realistic modelling (digital twins)
- Monochromatization scheme on BEPCII/CEPC
- Background & MDI
- Upgrading injection systems (damping ring, PWFA injector)

Summary

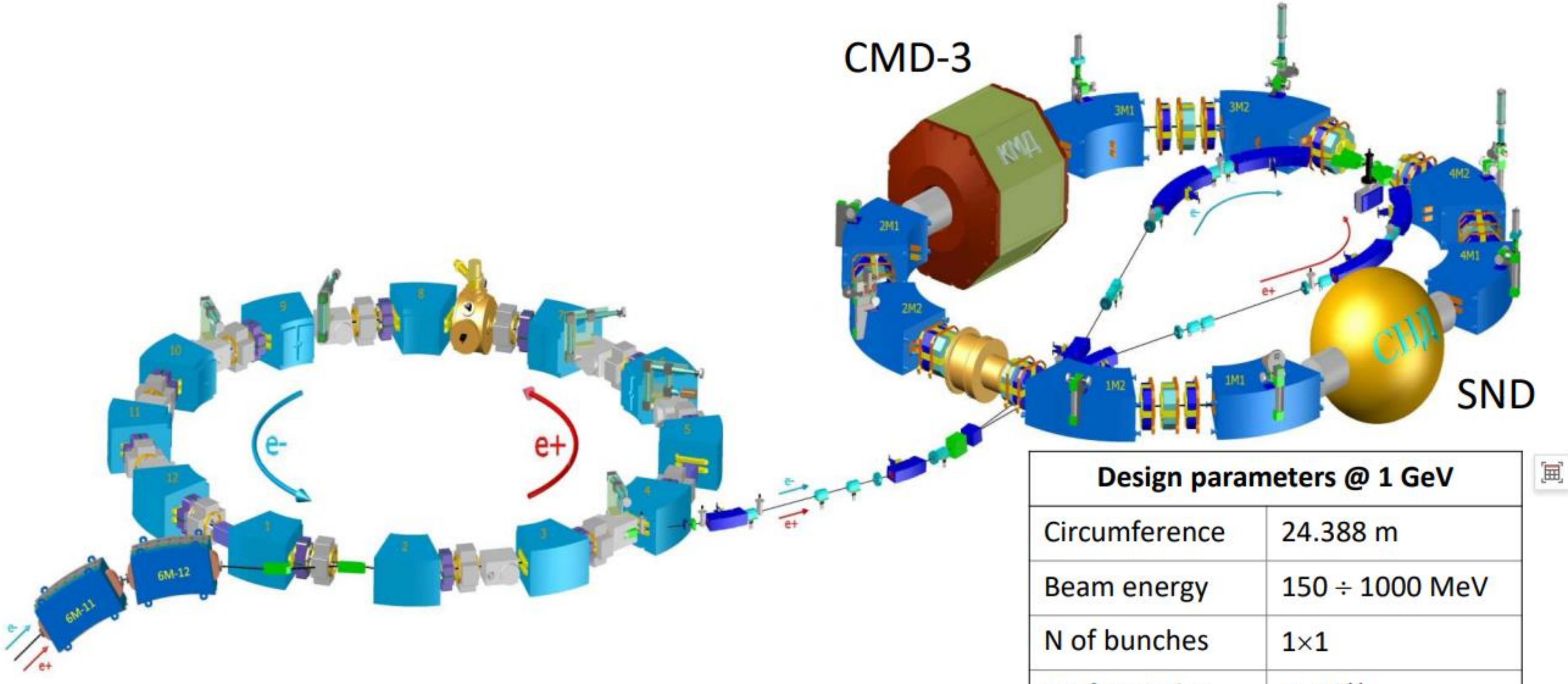
- A preliminary design for the BEPCII Crab-Waist upgrade has been presented.
- Initial feasible approaches to addressing the key technical challenges have been identified.
- The crab waist upgrade may enhance the performance (×10, enabling low energy operation) of the BEPCII.
- Gaining valuable experience on crab waist scheme which is vital for future circular e+e- colliders.
- We are 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

Thank you!

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}

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

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

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

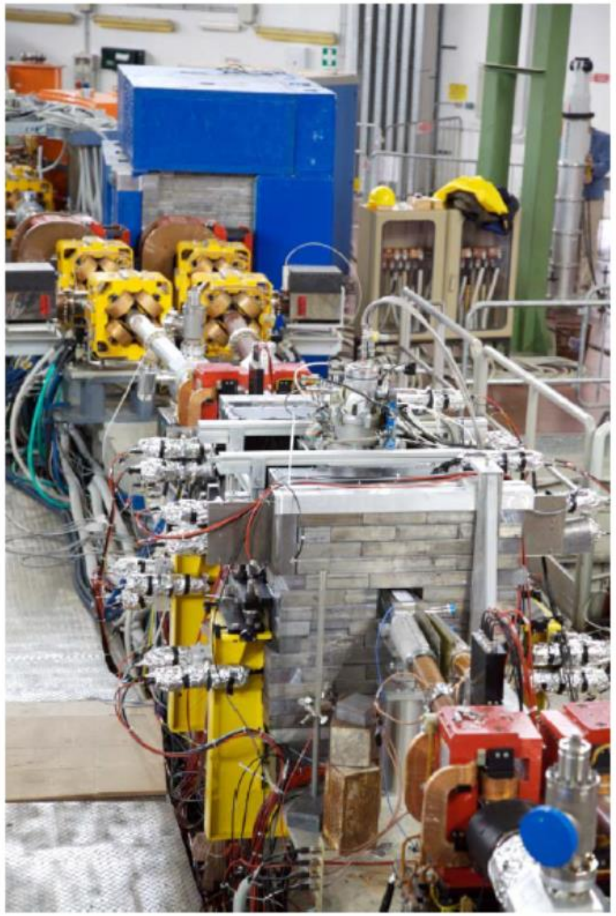
- BEPCII-CW plan is highly similar to VEPP-6.

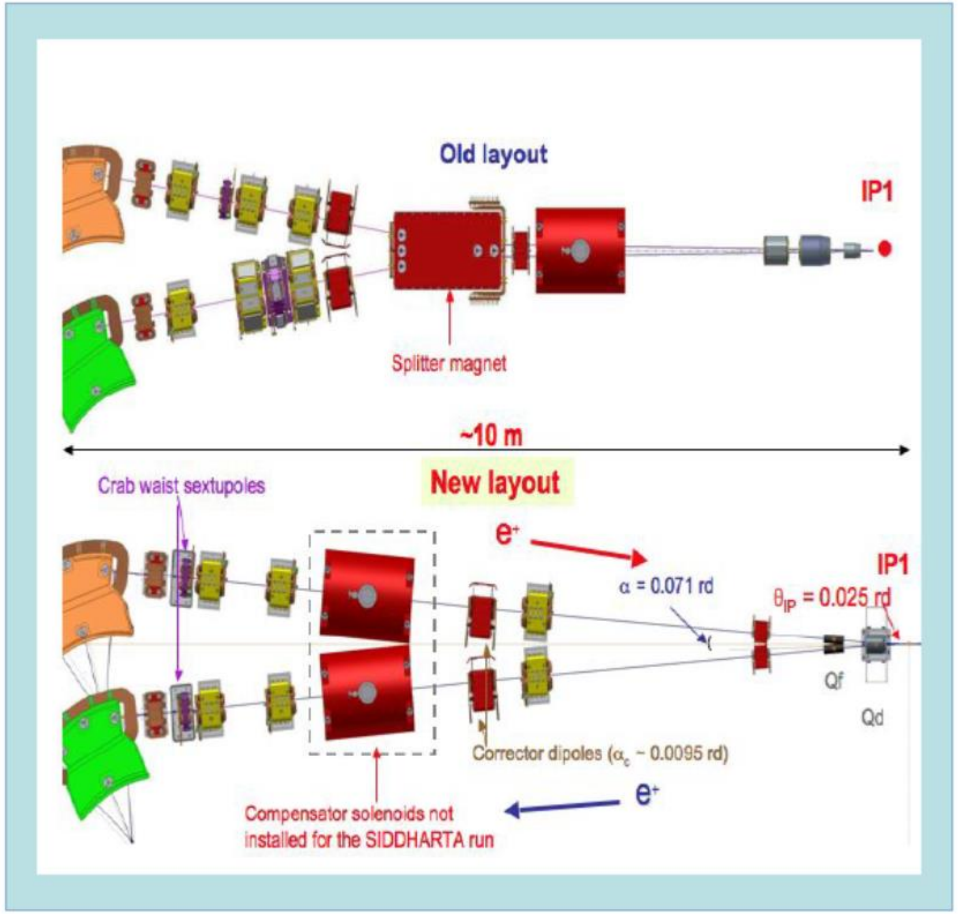
Ref: Ivan Logashenko @FTCF2025（November 24, 2025）

DAΦNE's experience @ 0.5GeV

- Highest luminosity: $4.5\times10^{32}\ cm^{-2}\ s^{-1}$, 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



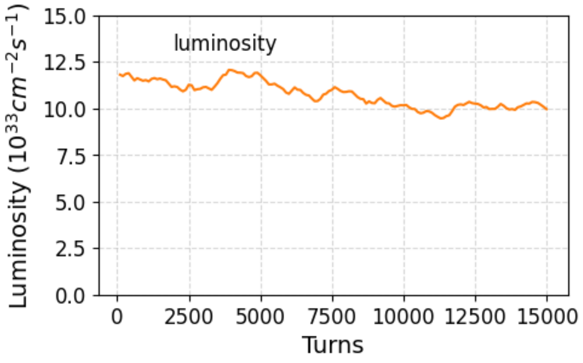


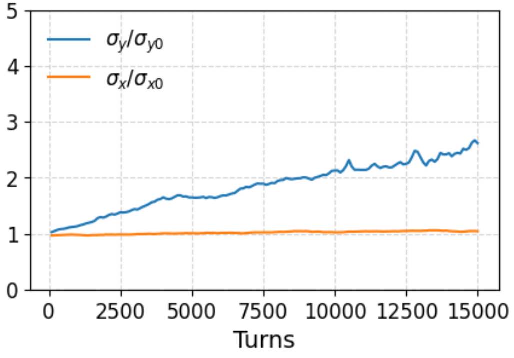
Beam-beam simulations with lattice

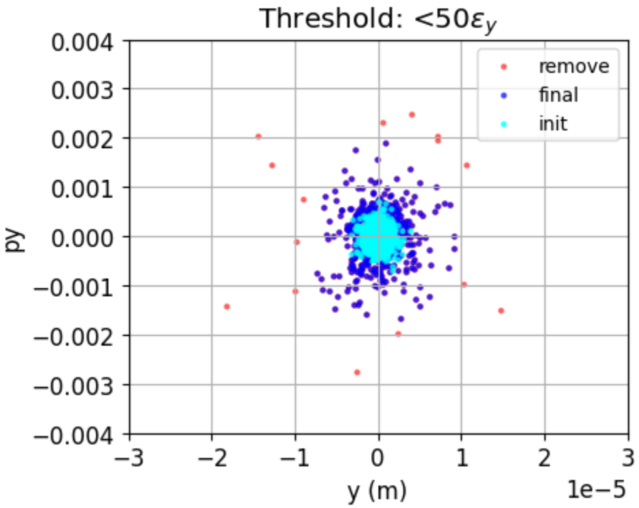
BEAMBEAM : emity=416nm

weak strong+ lattice

bpr.ZXv4.lat







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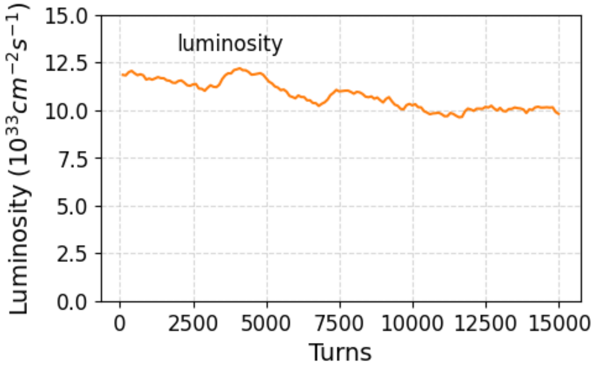
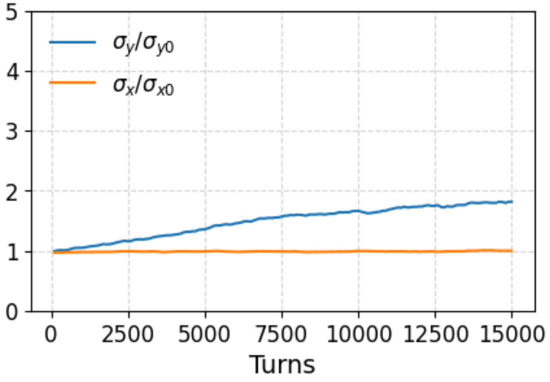
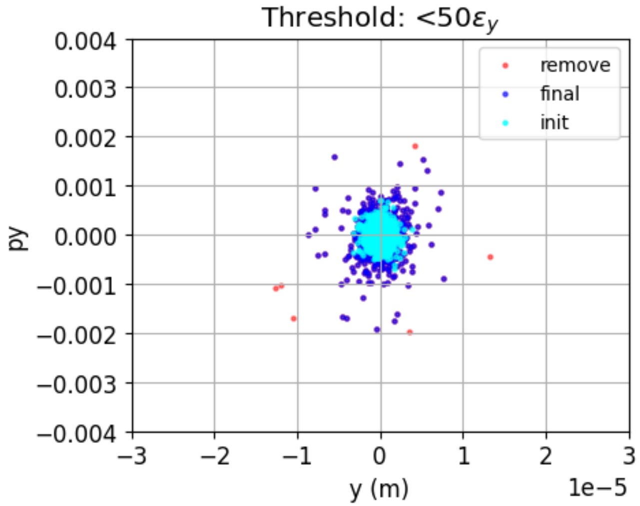
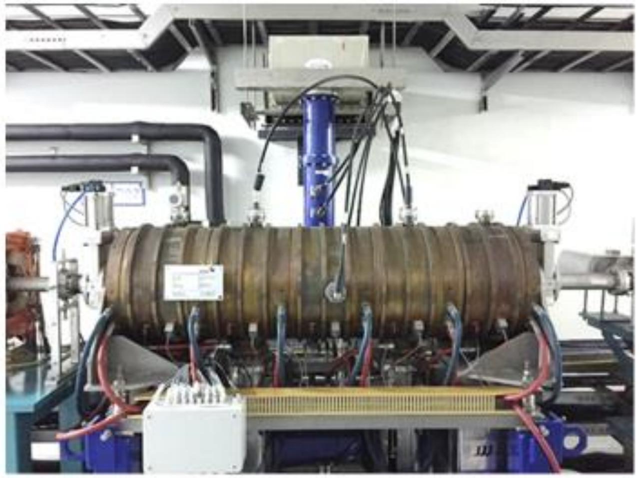






Damping ring parameters

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			
$\delta 0$ (%)	0.044			
$\varepsilon 0$ (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)