The FCC (e^+e^-) Studies with a Focus on Turkey's Contribution

FCC Workshop
2nd of April, 2022

Ozgur ETISKEN (Kırıkkale University)

Thanks to: Prof. Dr. Abbas Kenan Ciftci (İEU), Prof. Dr. Rena Ciftci (Ege Ü.), Doç. Dr. Fatih Yaman (İYTE) and Dr. Salim Ogur (ADAM) for their slides about contribution from Turkey

and the FCC-e^+e^- injector working groups for the whole studies

Remotely due to Covid-19 pandemic

Outline

- Introduction
- FCC-e^+e^- injector complex
- FCC-e^+e^- pre-injector design
  - e-source and linac
  - Positron source
  - Damping ring
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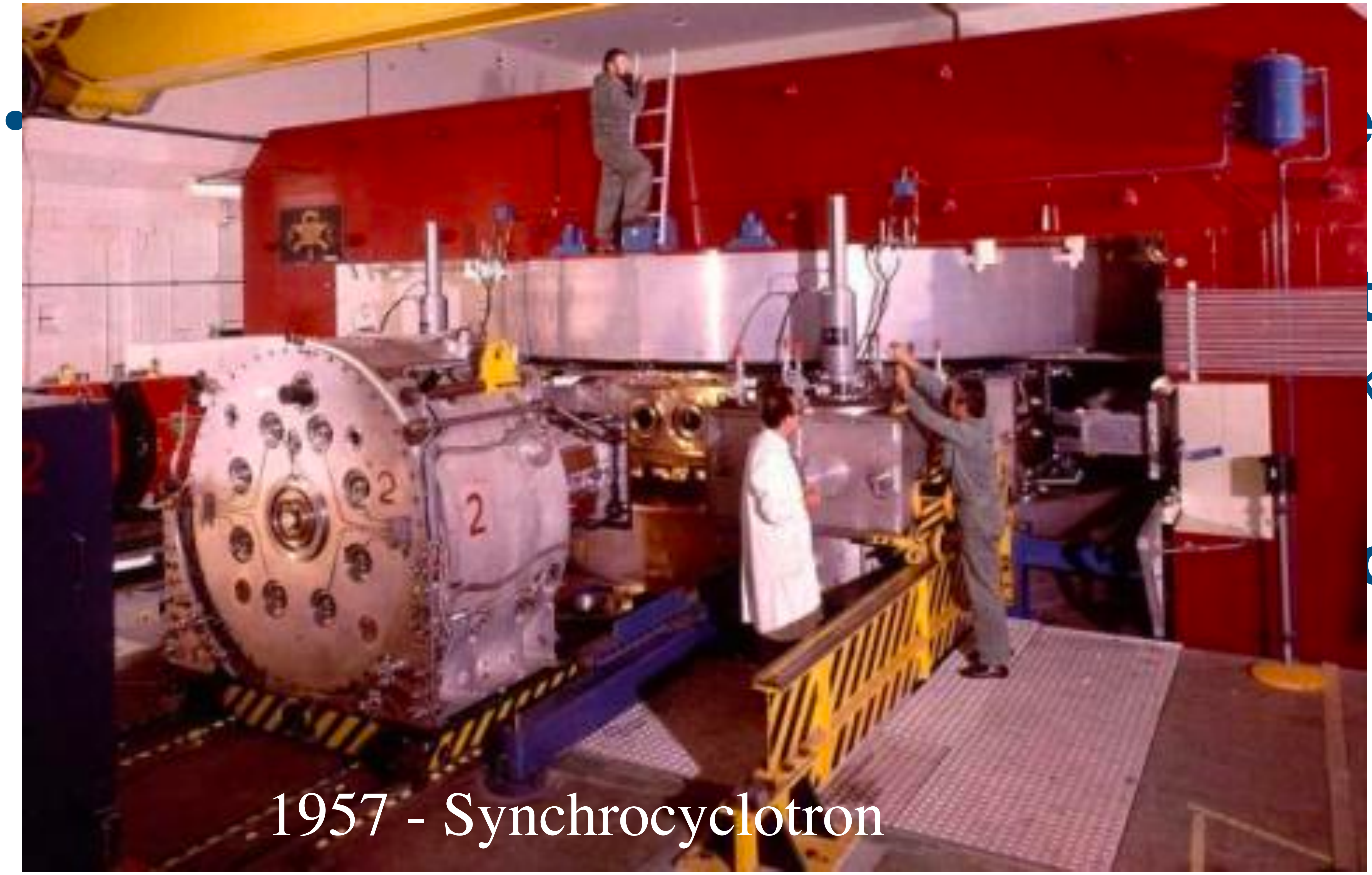
Introduction

- CERN was established by 12 founder members in 1954 with the following mission:
  - **Provide** a unique range of **particle accelerator facilities** that enable research at the forefront of human knowledge.
  - Perform world-class **research in fundamental physics**.
  - **Unite people** from all **over the world** to push the frontiers of science and technology, **for the benefit of all**.

Introduction



1957 - Synchrocyclotron

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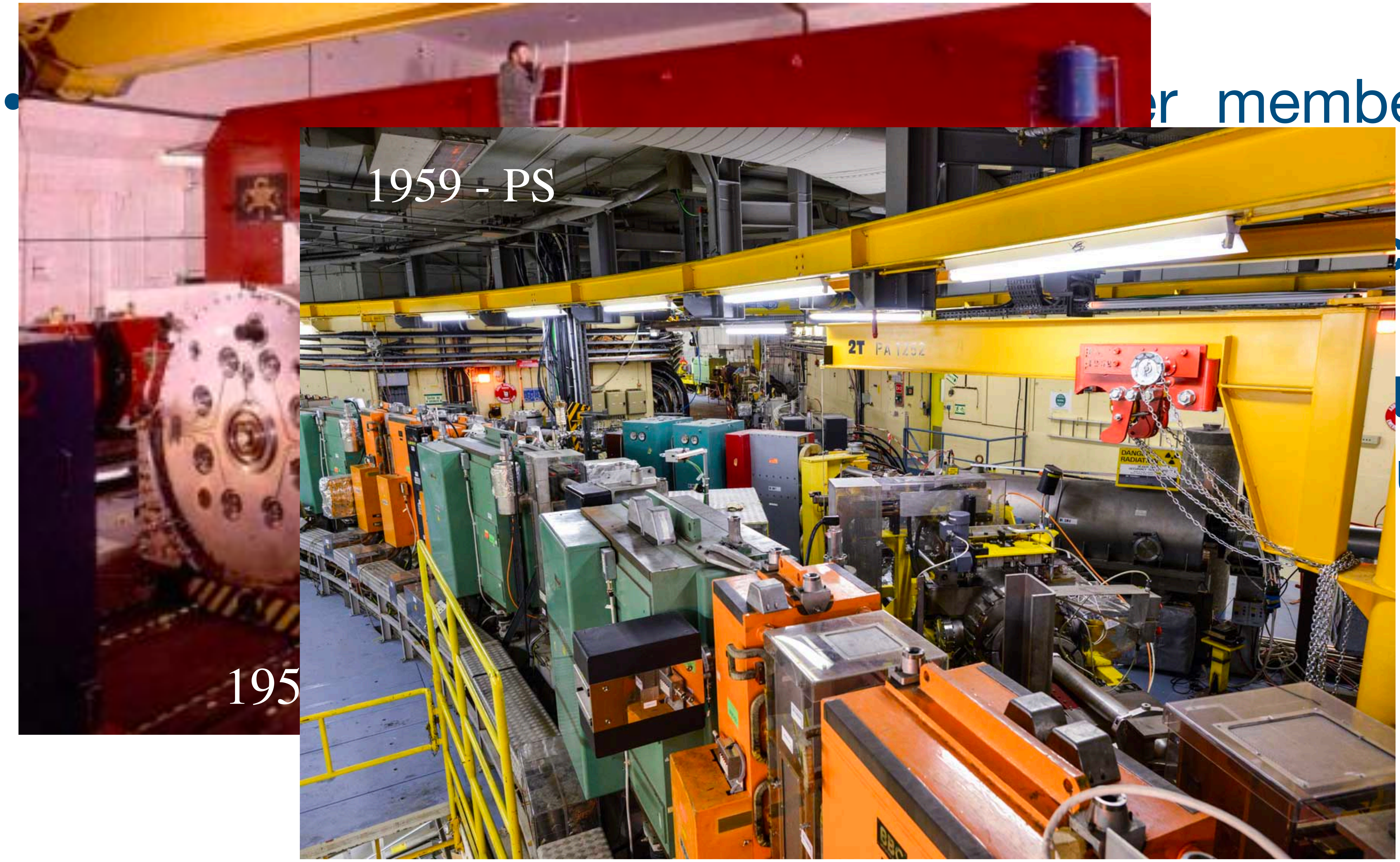

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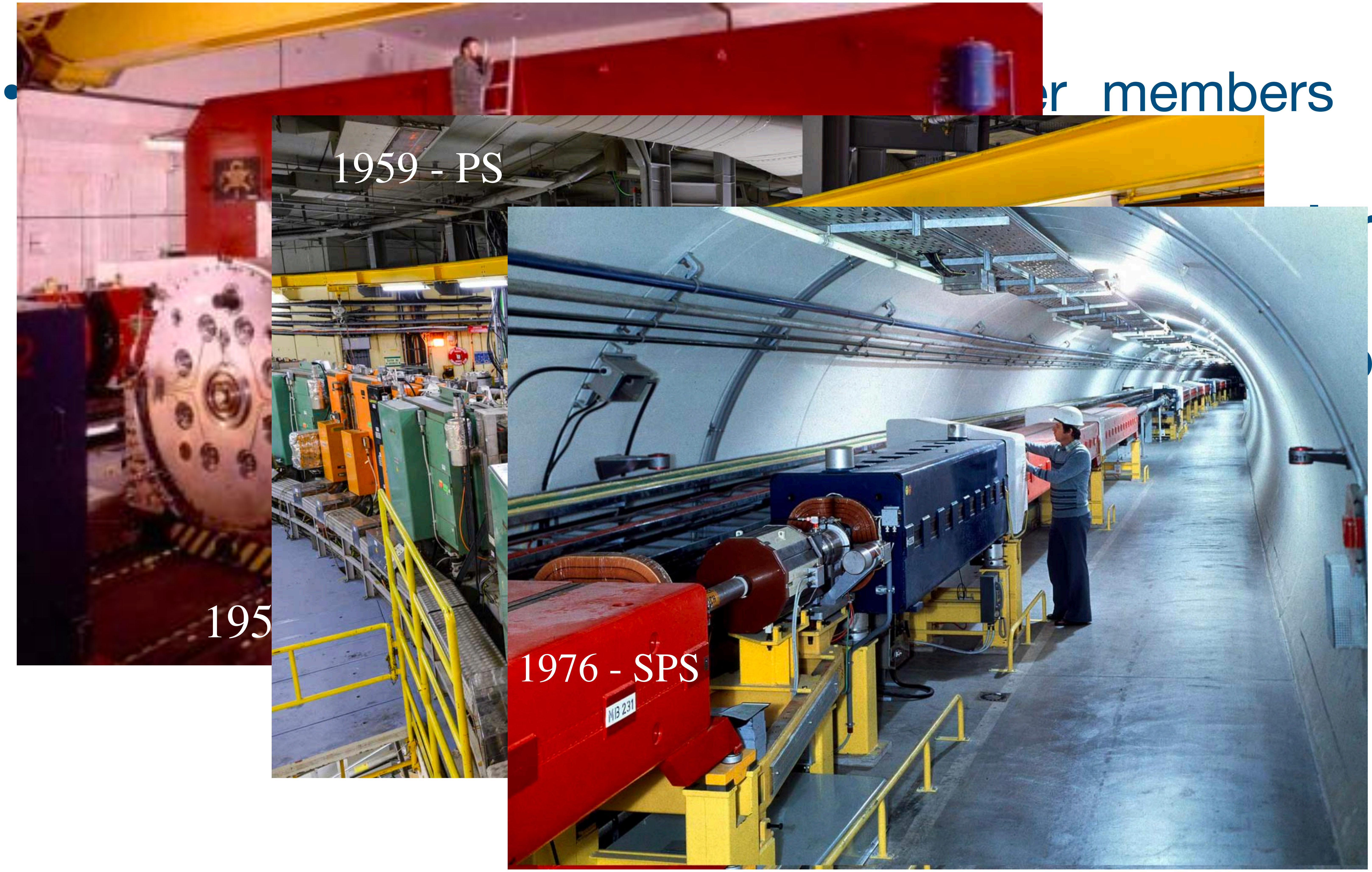

6.9 km

FUTURE CIRCULAR COLLIDER

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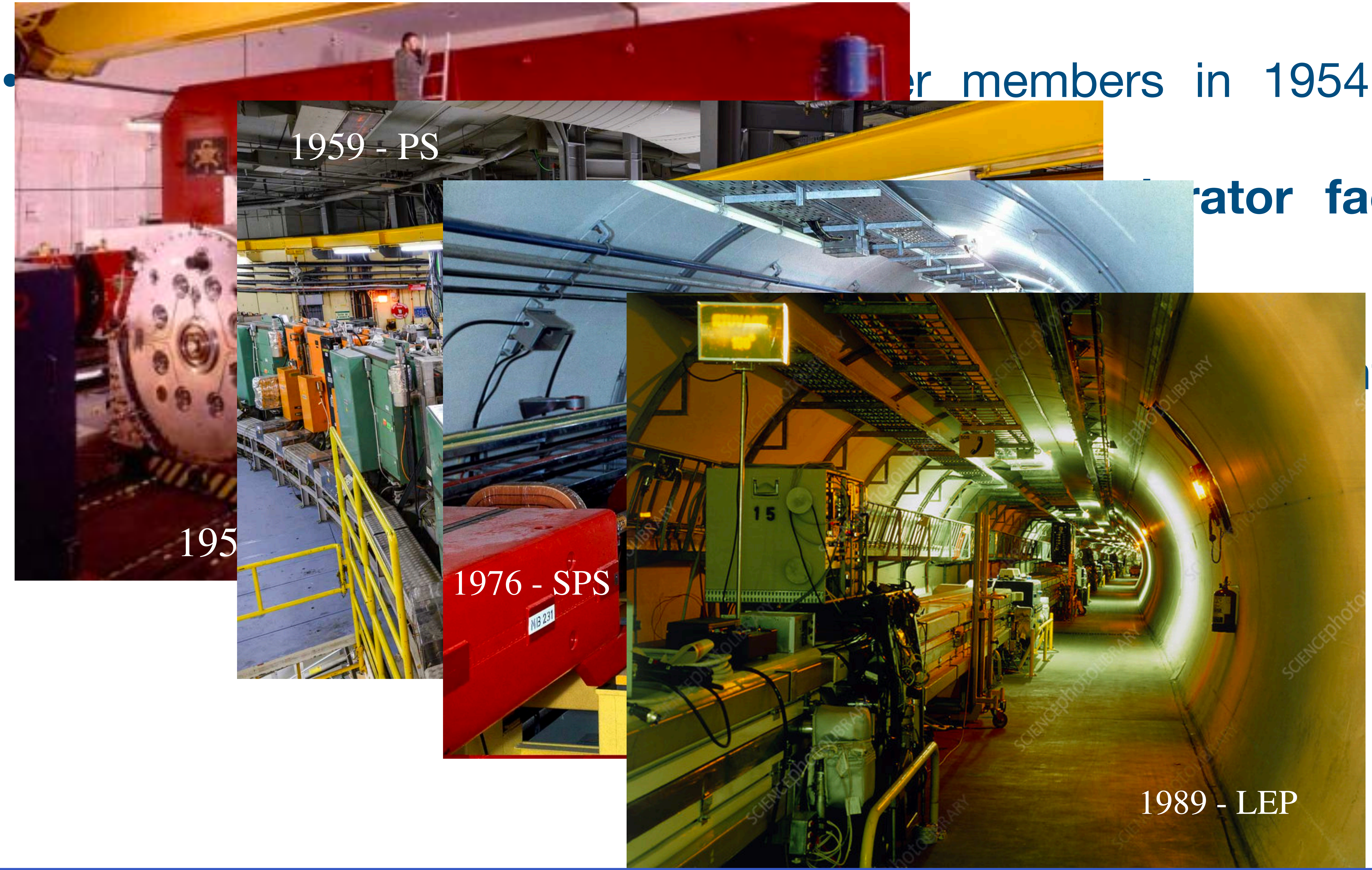

→ **27 km**

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ESPPU (European Strategy for Particle Physics) 2013

“**Europe** needs to be in a position to **propose** an ambitious **post-LHC** accelerator project at CERN by the time of the next Strategy update" and that CERN should undertake design studies for accelerator projects in a global context, with emphasis on **proton-proton** and **electron-positron** high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide".

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ESPPU 2020

"**Europe**, together with its international partners, should investigate the technical and financial feasibility of a **future hadron collider** at **CERN** with a centre-of-mass energy of at least 100 TeV and with an **electron-positron Higgs and electroweak factory** as a **possible first stage**. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

Introduction

- The future may be calling for the **F**uture **C**ircular **C**ollider (**FCC**)…

Introduction

- FCC - **Conceptual Design Reports**, published in 2019 by more than **1350** contributors: FCC Physics Opportunities, FCC-ee, FCC-hh, HE-LHC.
- **144** Institutes and **30** companies from **34** countries have been contributing to the project.
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Michael Benedikt and Frank Zimmermann, FCC Week 2021

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The FCC-e^+e^- Project

- The FCC-e^+e^- is a design project of a circular collider of around 100 km circumference.
  - Center of energies of the collider ring varies between **91.2 and 365 GeV.**

- General precision machine for the investigations of the **Z, W, Higgs and top particles**.

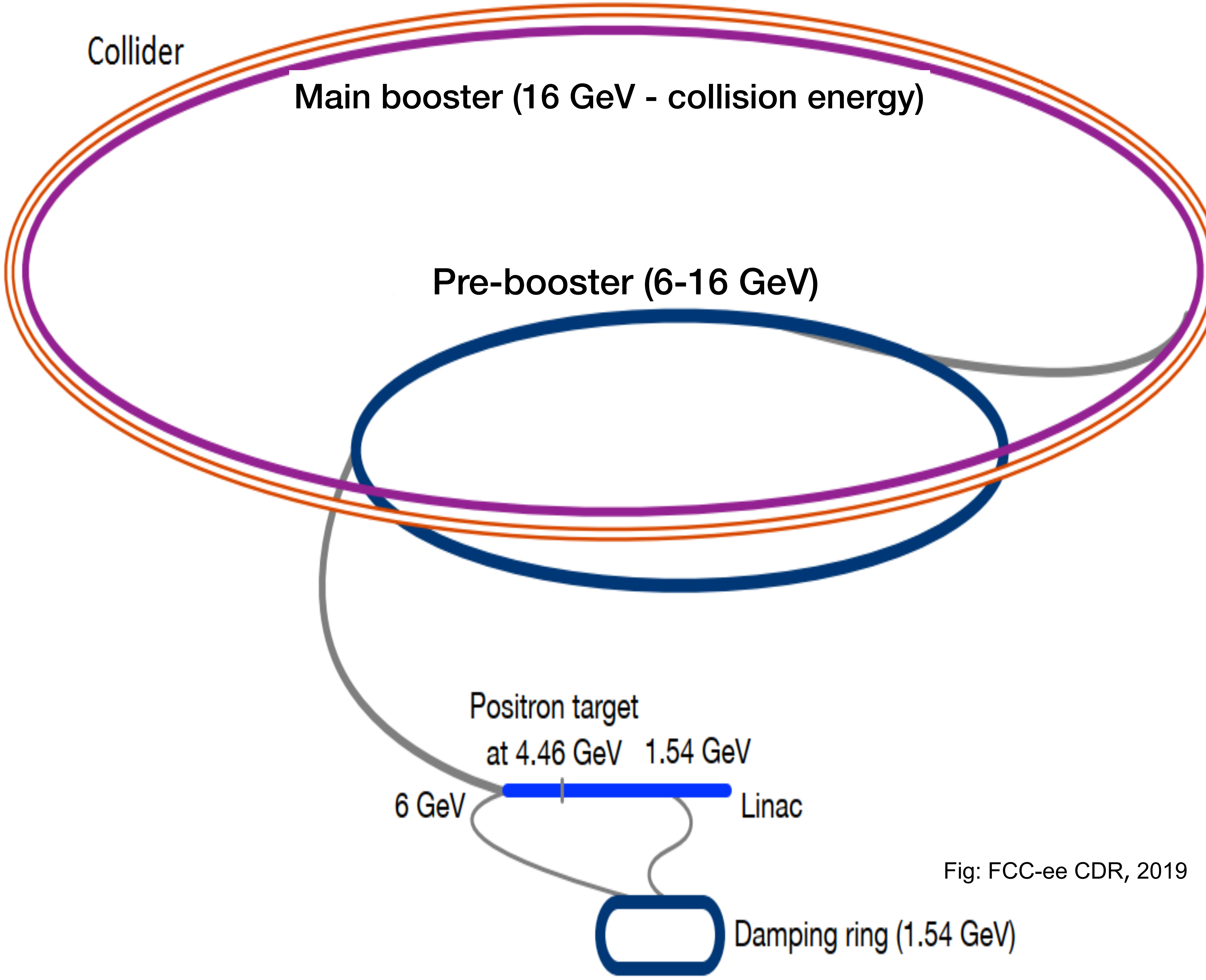

Fig: FCC-ee CDR, 2019

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    - Positron production
  - **Damping ring @ 1.54 GeV**
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  - **Pre-booster ring up to 16 GeV**
    - SPS (baseline)
    - Alternative design
  - **Main booster ring**

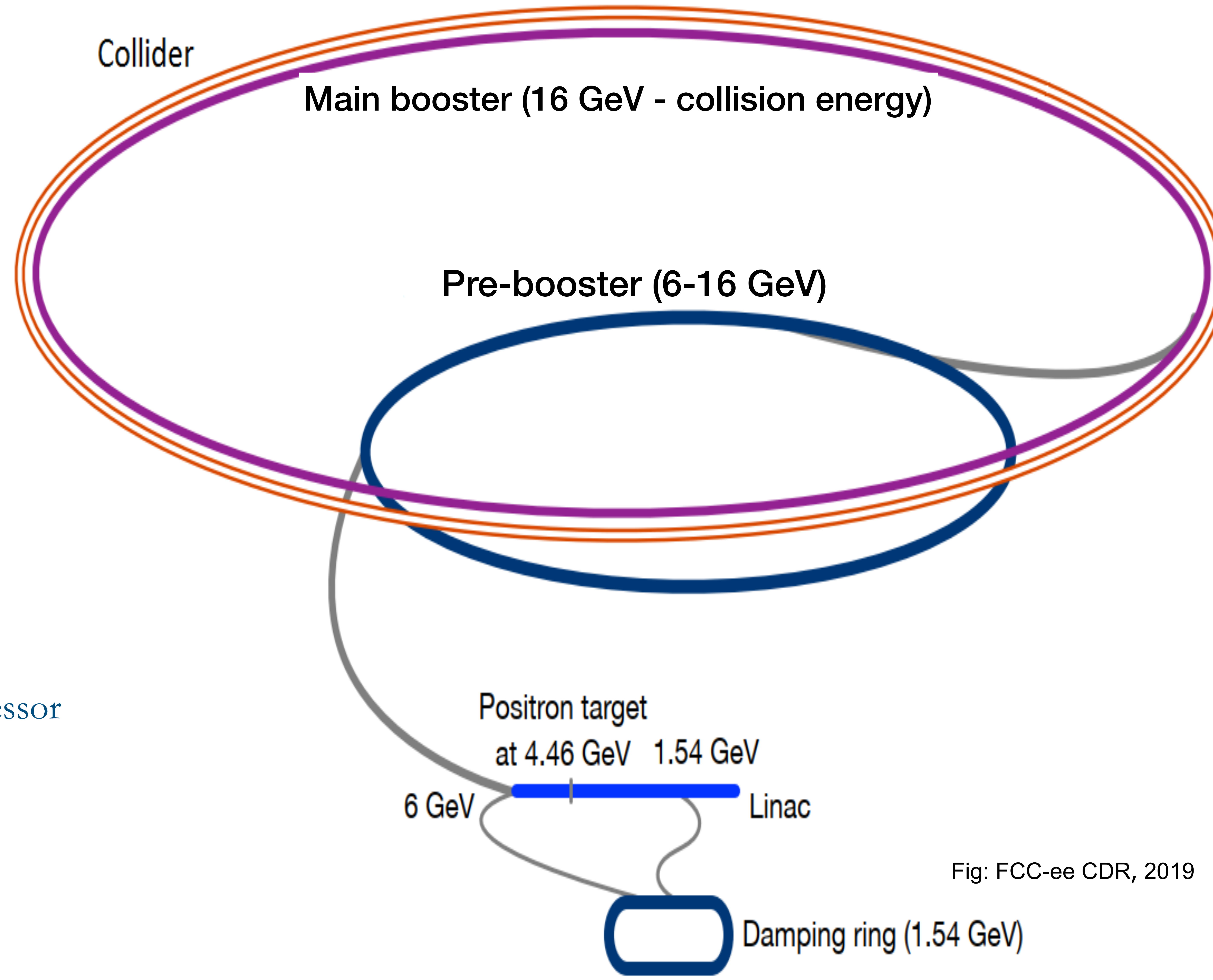

Fig: FCC-ee CDR, 2019

Motivation

The motivation of this presentation is to summarize the studies related to the FCC-ee with a focus of contribution from Turkish scientists.

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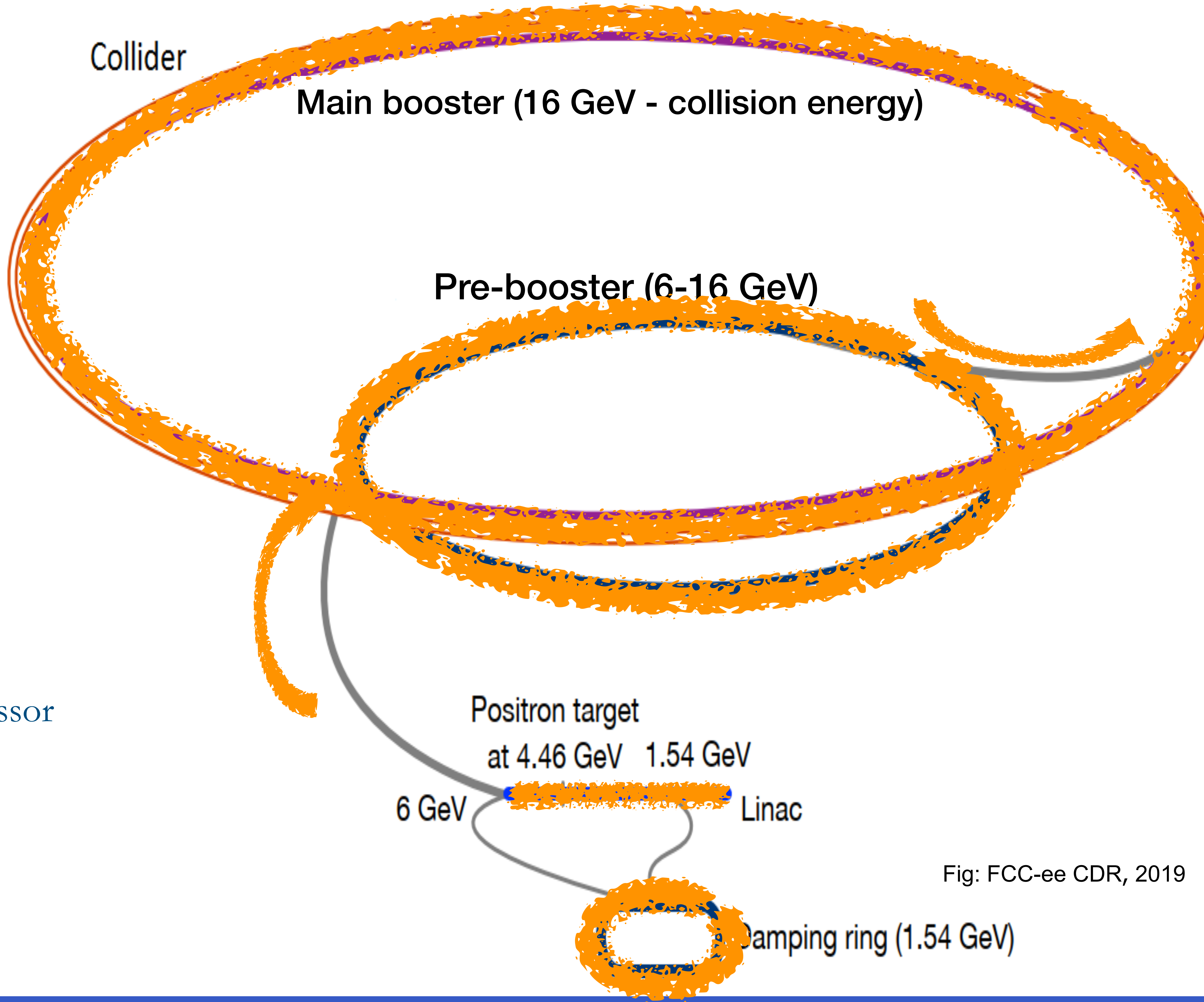

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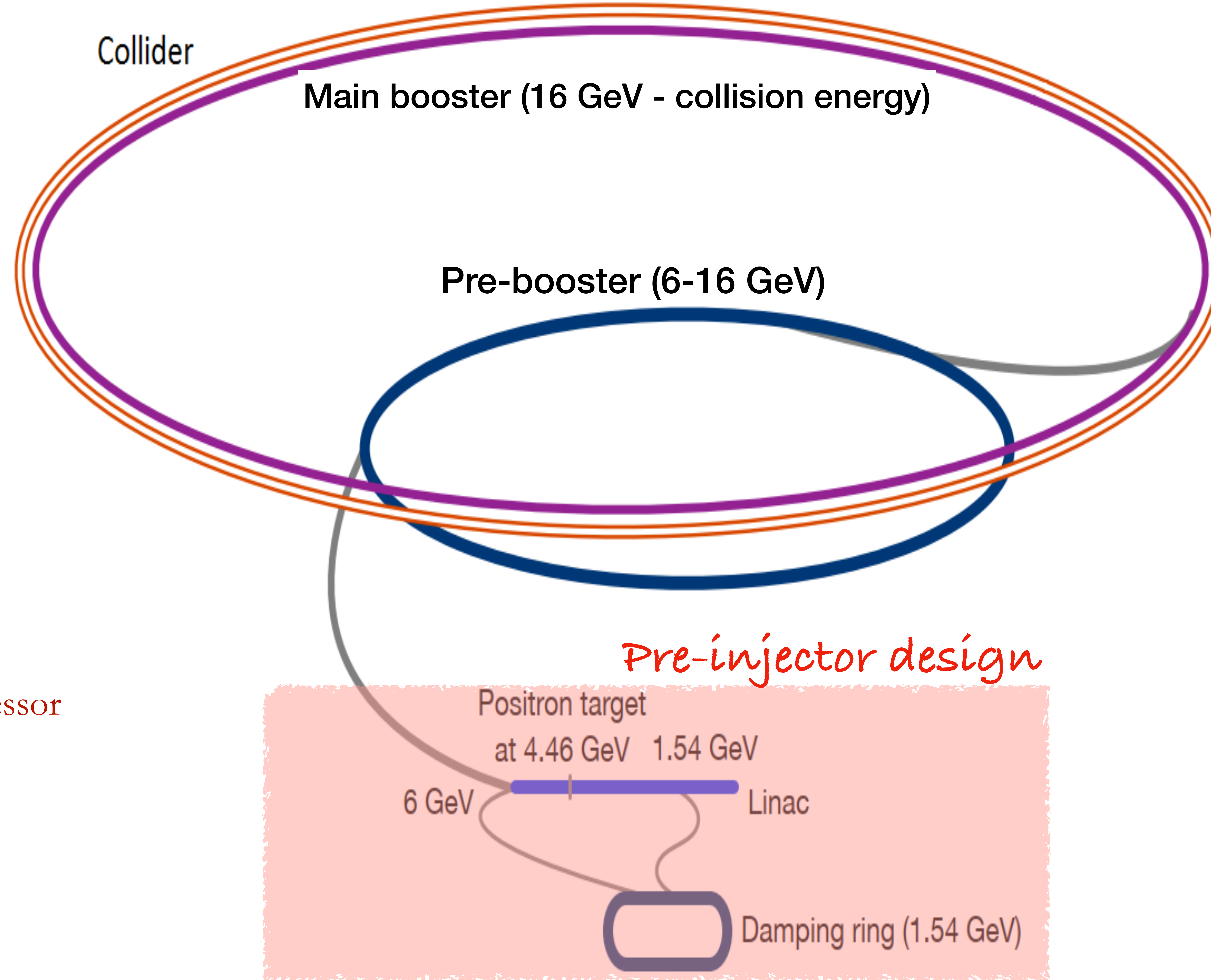

The pre-injector complex

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Design revision is ongoing!

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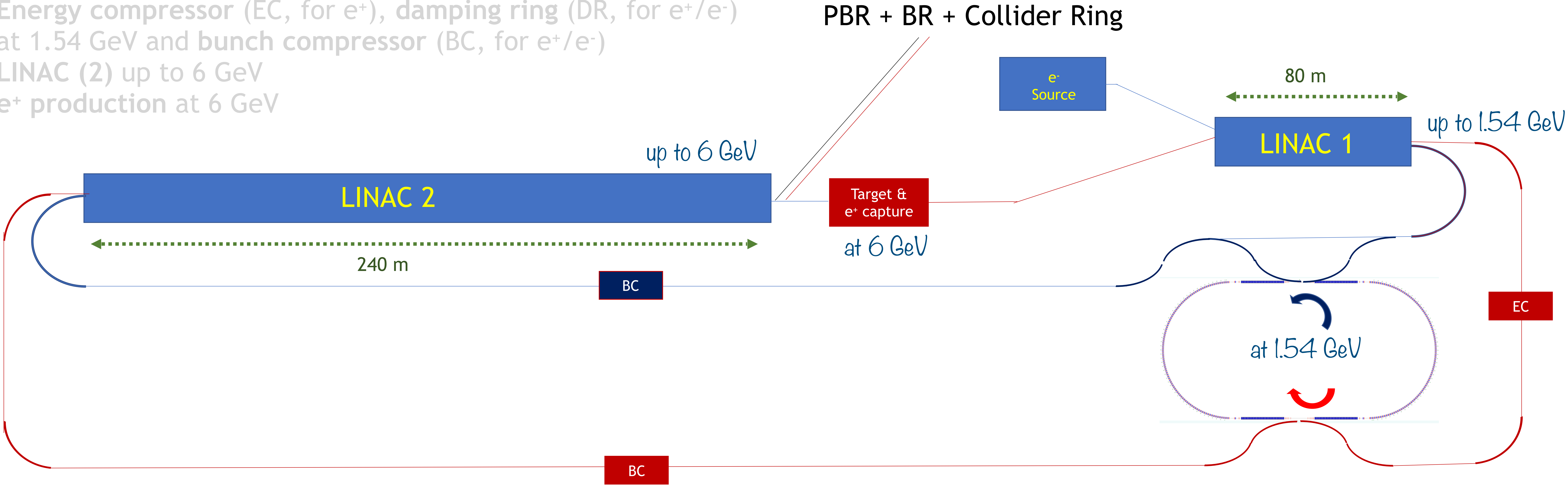

C. Milardi, et. al., FCC-ee Injector Design/CHART Coordination meeting, 2021

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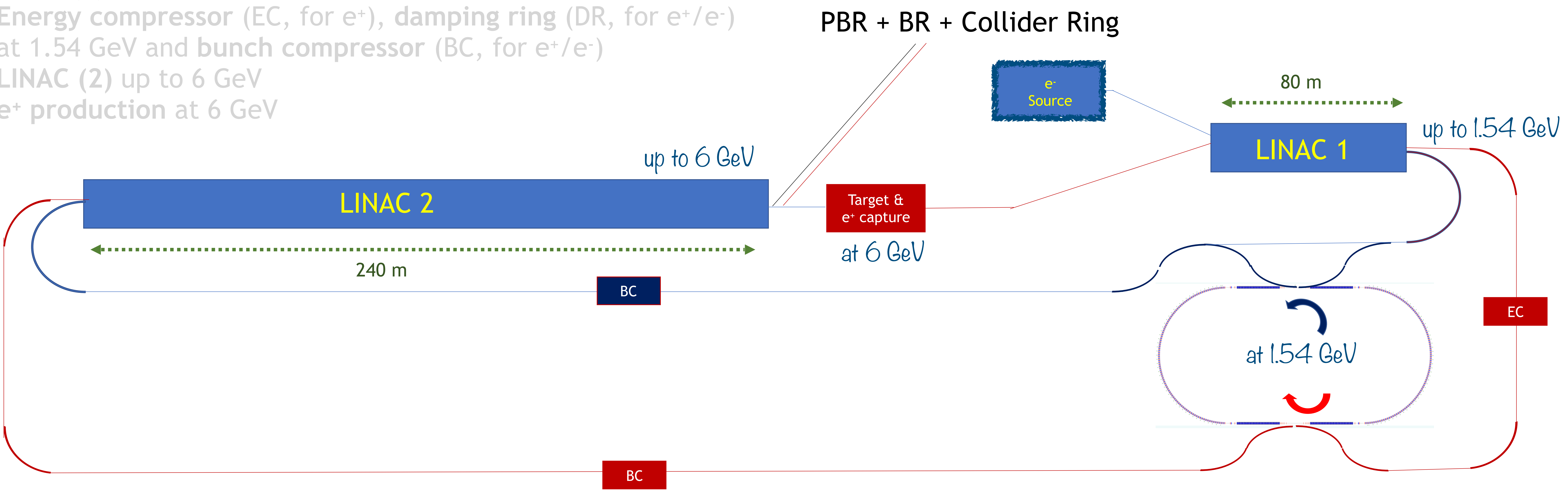

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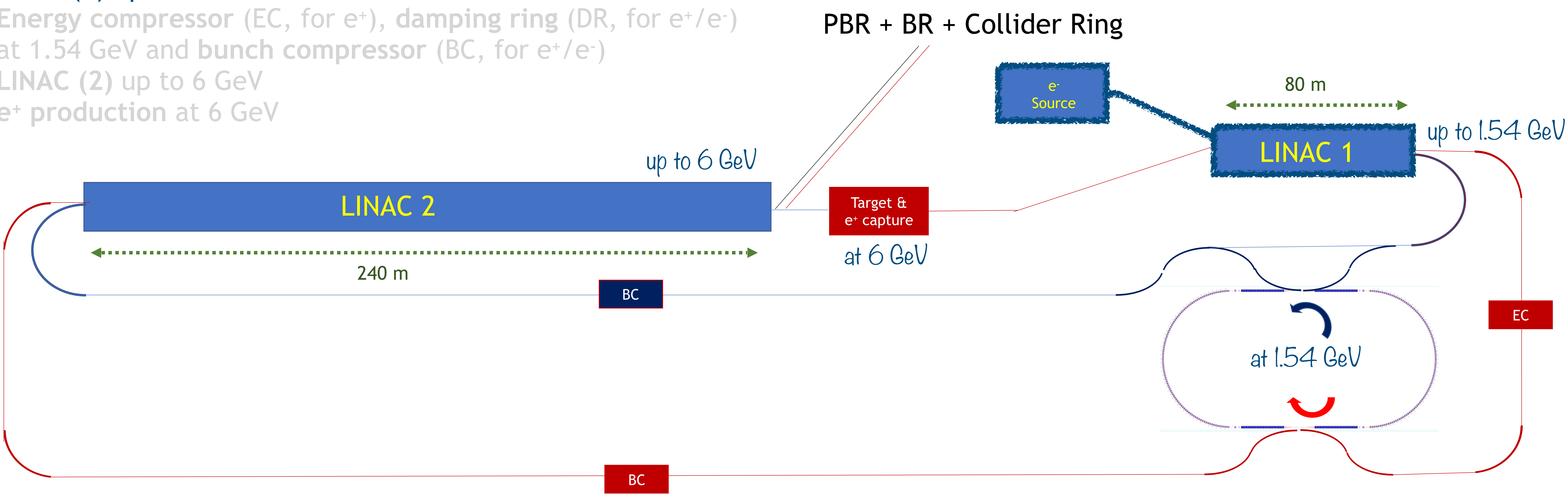

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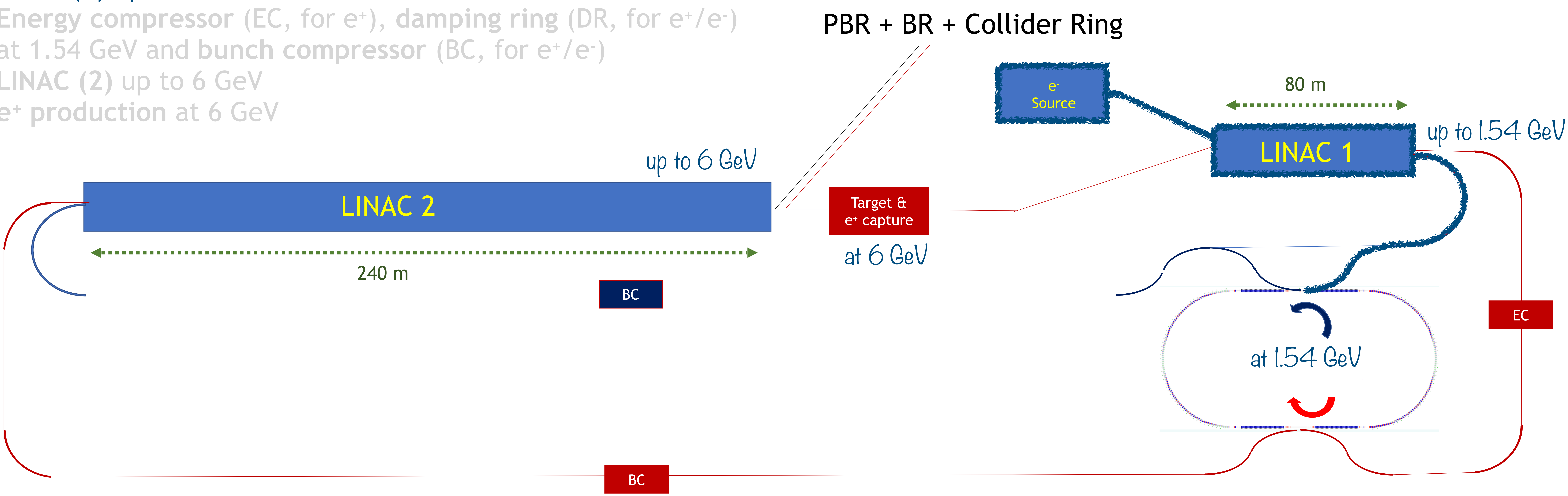

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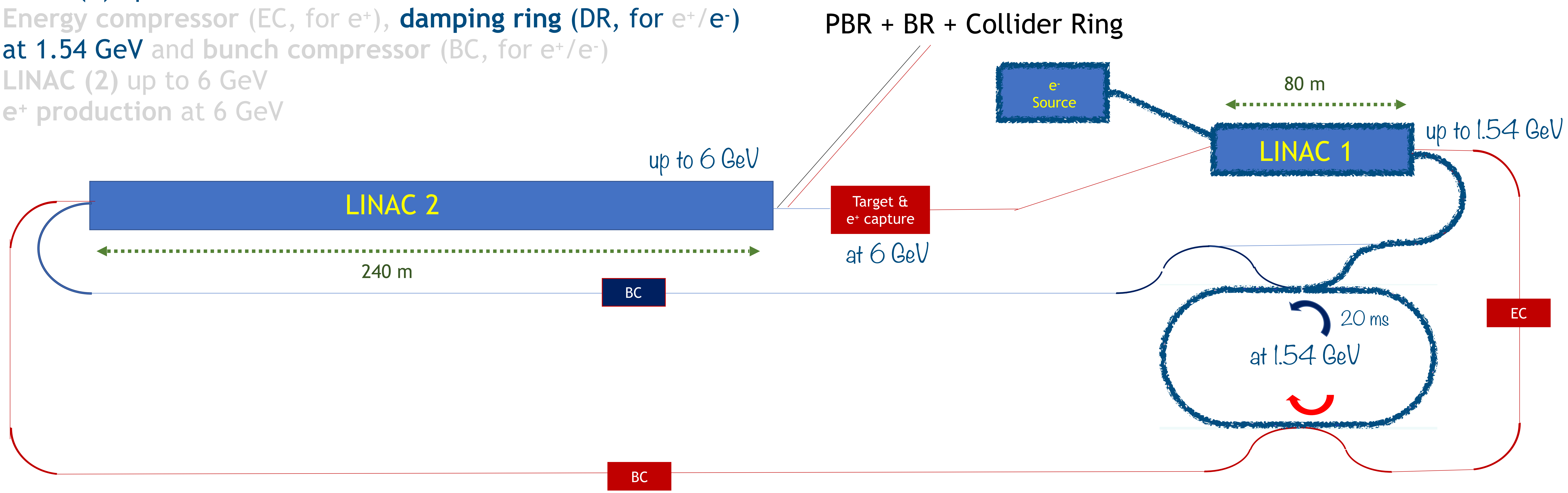

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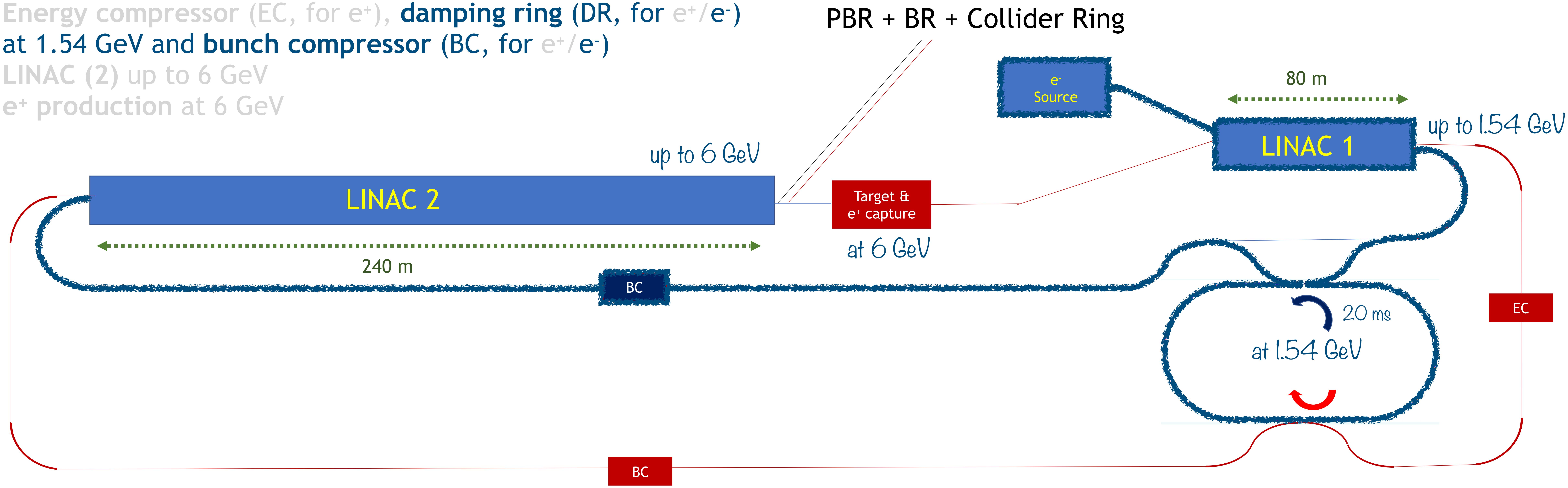

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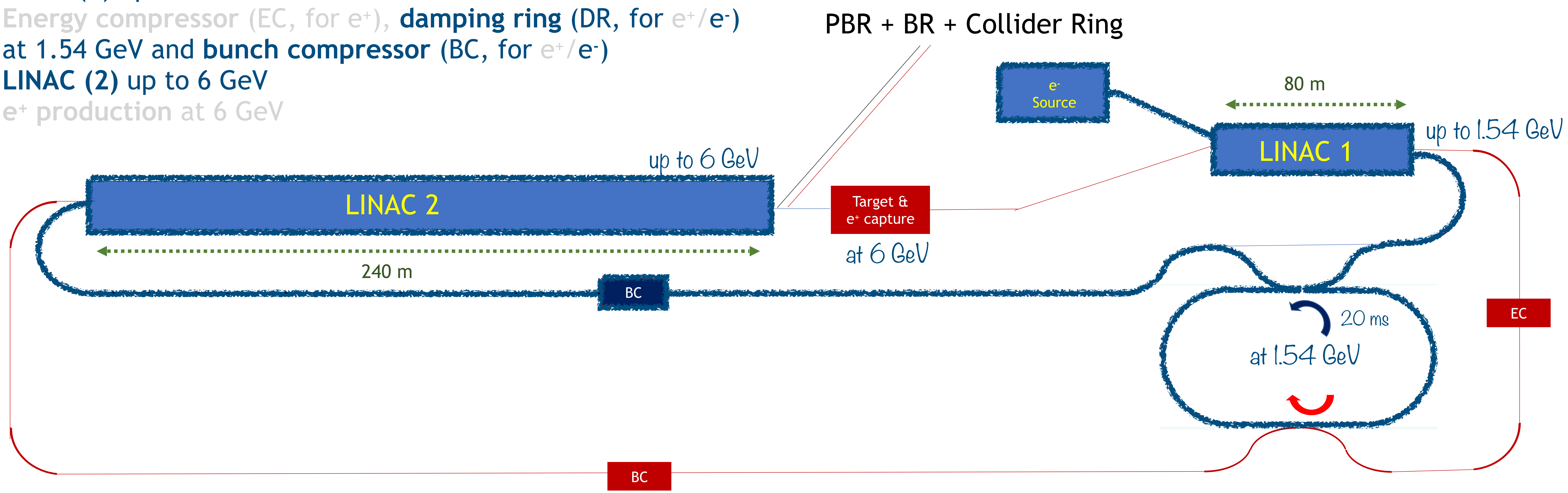

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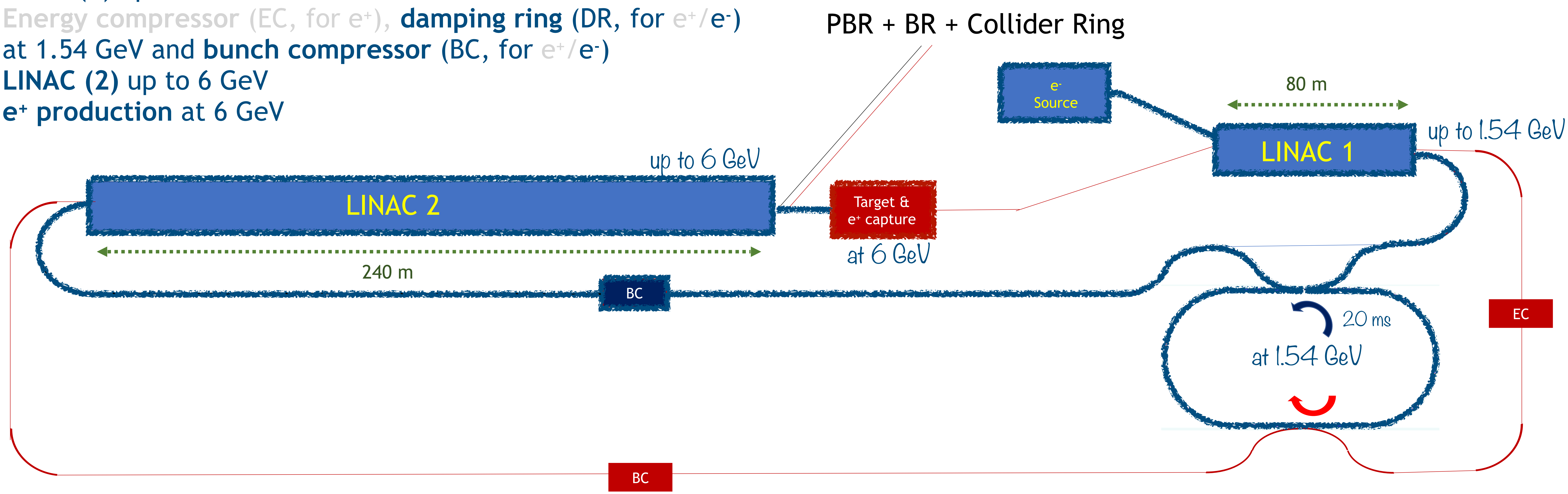

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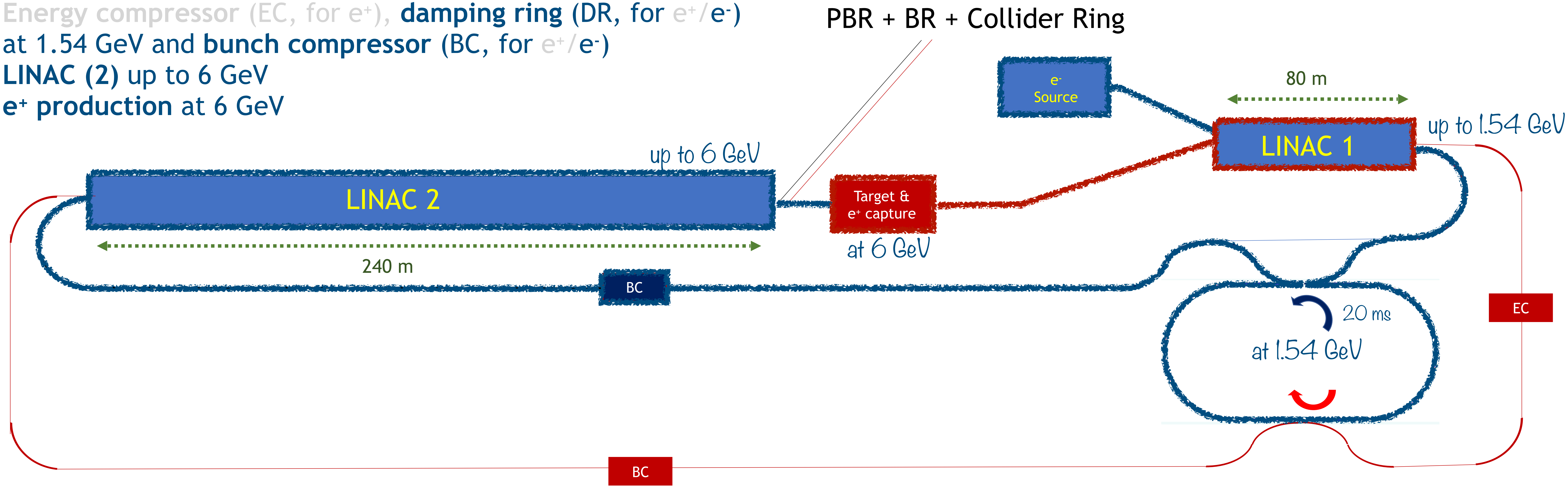

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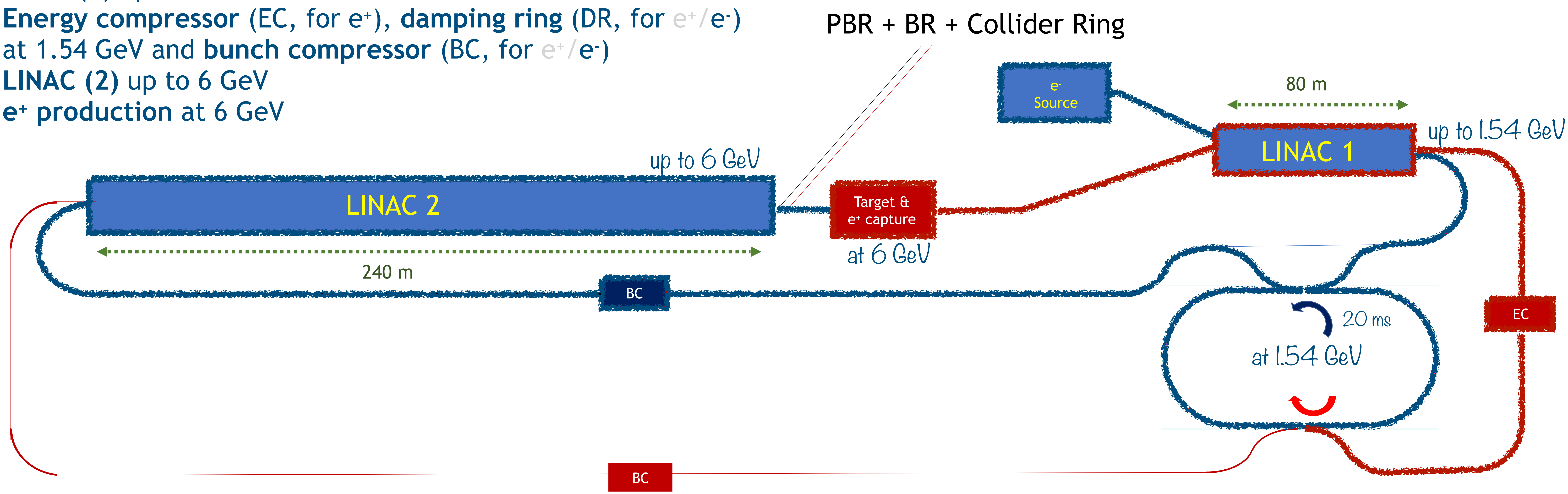

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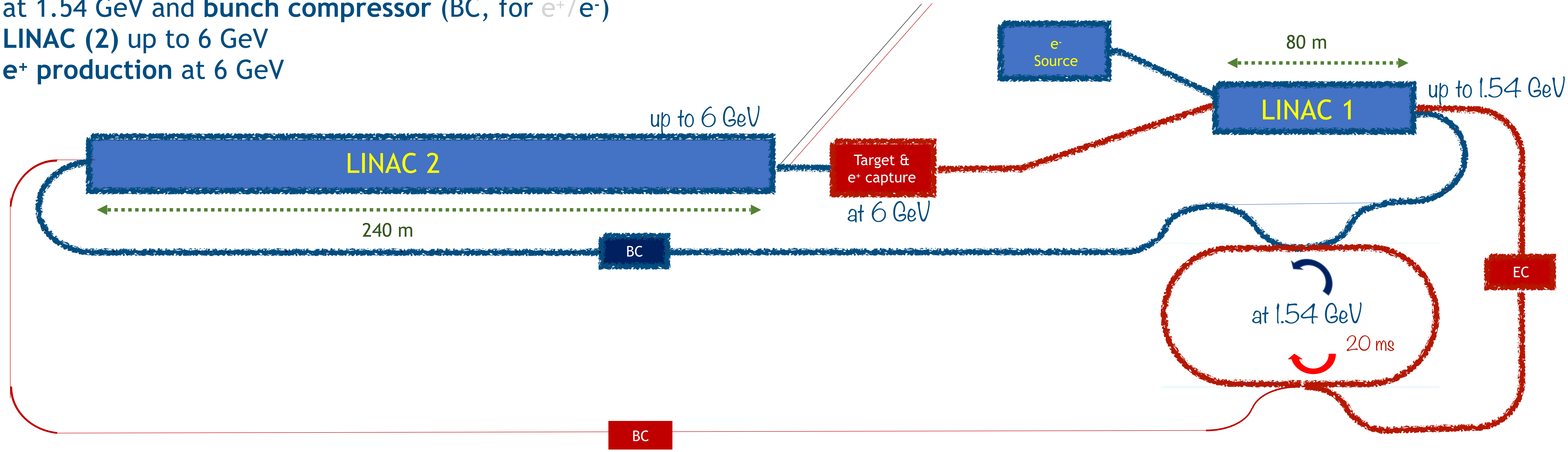

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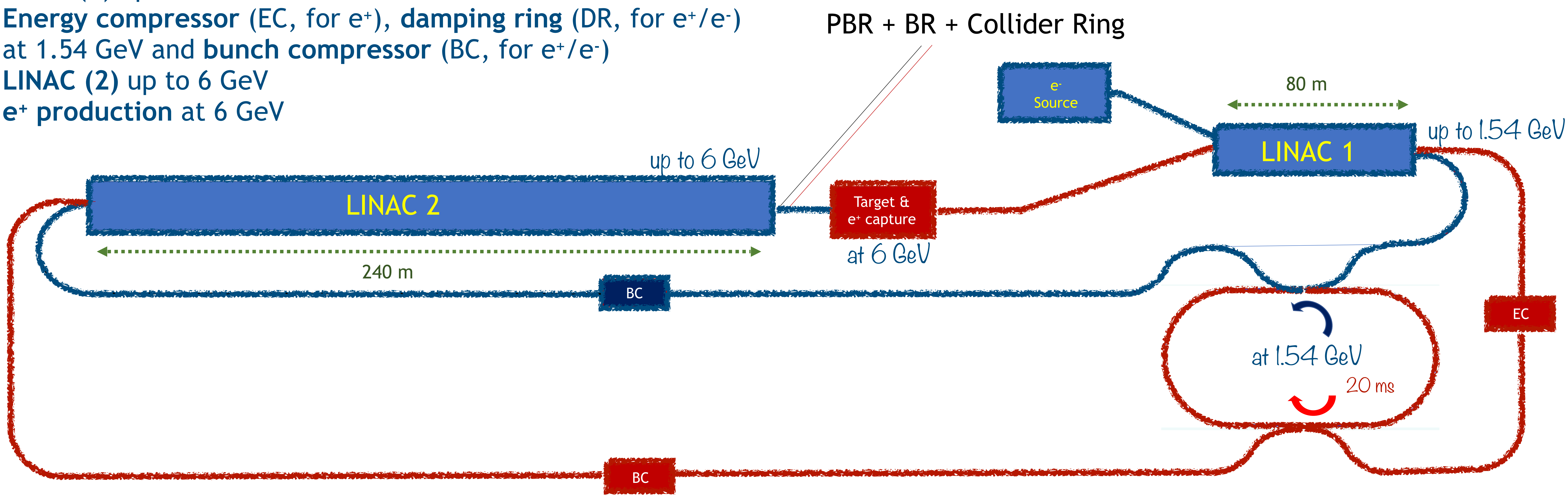

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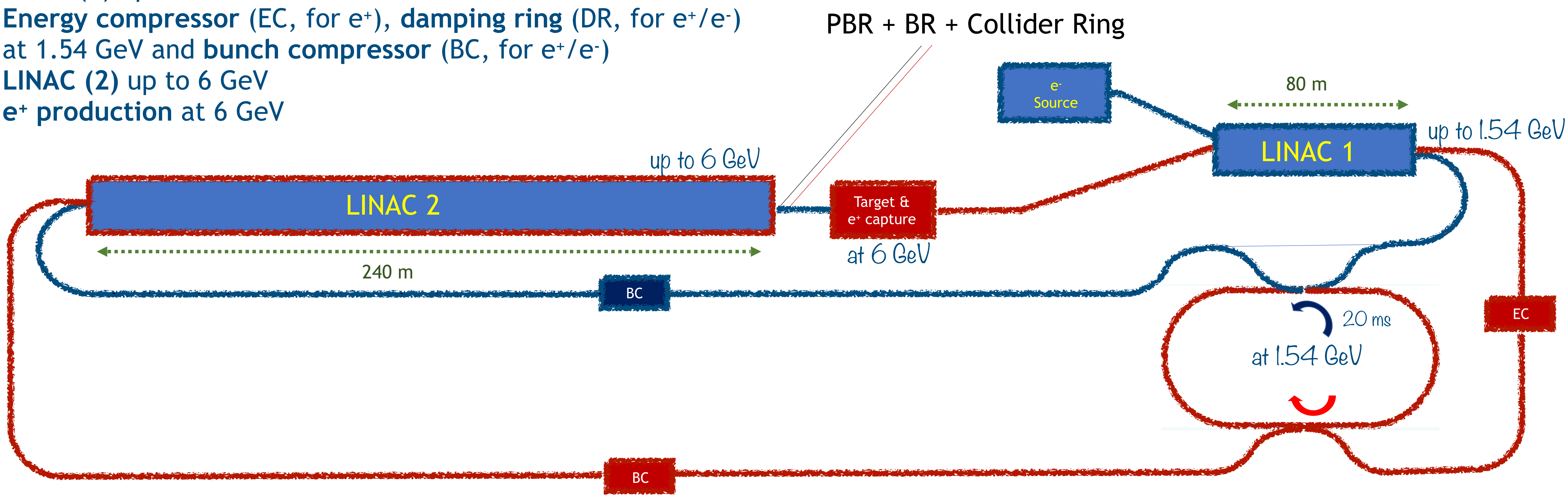

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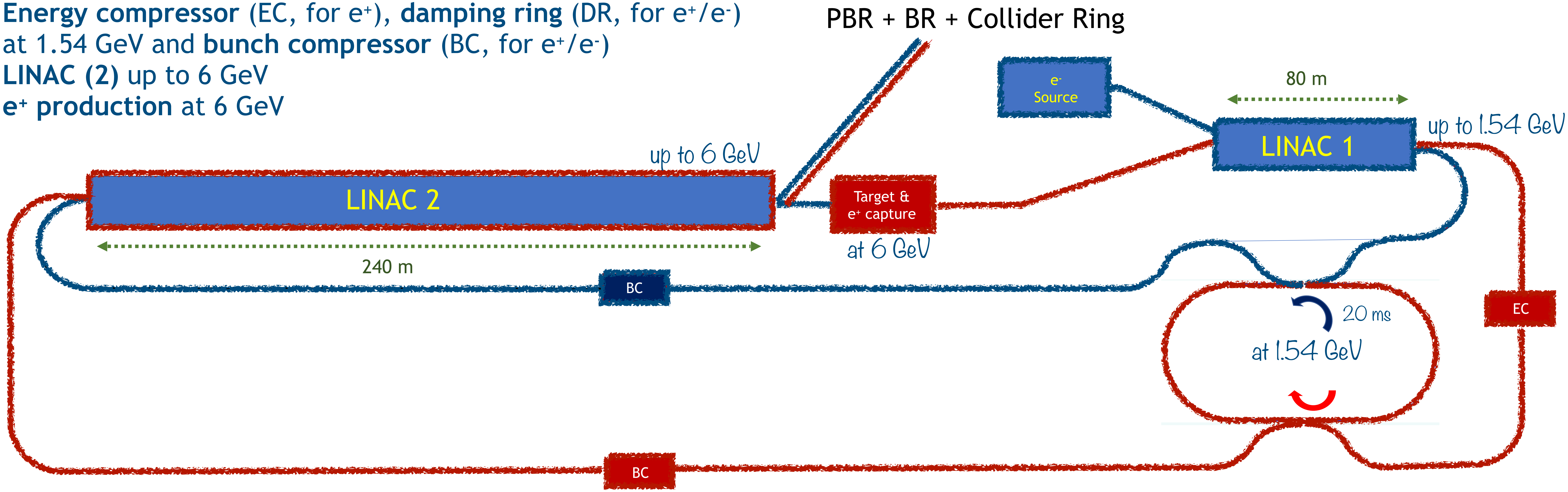


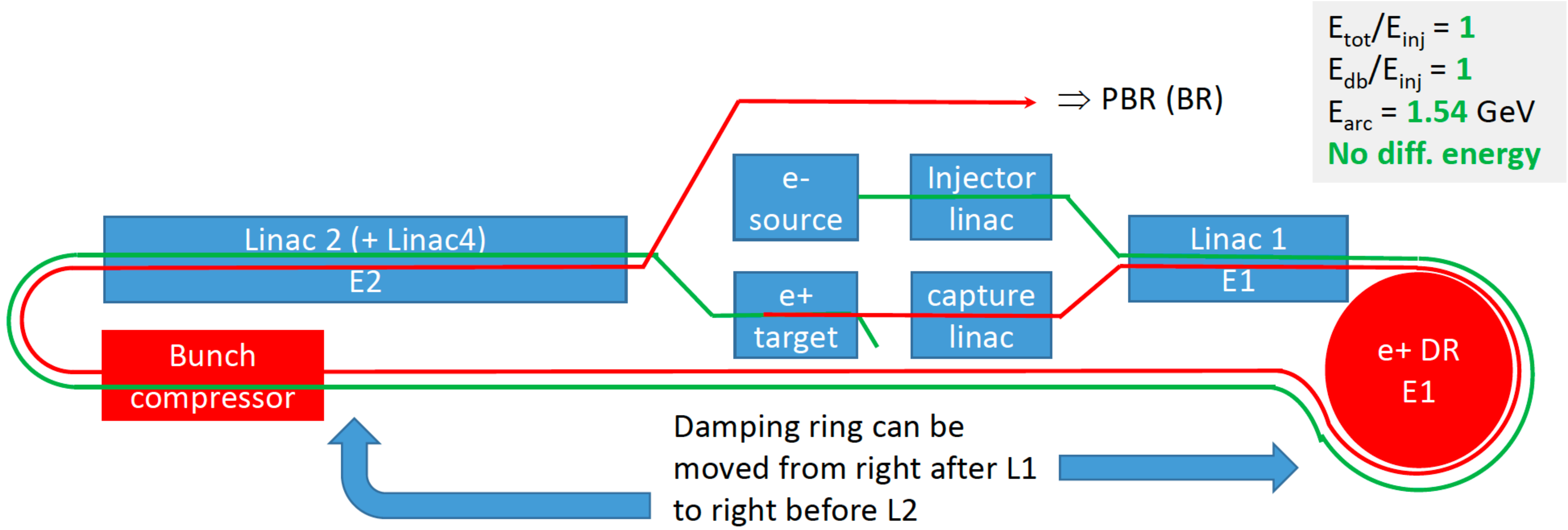
C. Milardi, et. al., FCC-ee Injector Design/CHART Coordination meeting, 2021

e-source and linac

- The custom built **RF e-source** has a normalized transverse emittance of <10 μm , and can provide up to 6.5 nC of charge at **around 10 MeV**.
- Apart from RF e-source for the low e- beam, a **thermionic gun** will also be utilized in order to supply 10 nC of bunch charge for positron beam.

A.M. Barnyakov, D.A. Nikiforov, A.E. Levichev (BINP) (CDR)

- The normal conducting linac will be fed by two electron sources (the RF source for the low emittance e- beam and the thermionic source with higher charge for positrons production).
- The linac consists of S-Band structures accelerating the beam up to 6 GeV.



Alexej Grudiev et. al., FCC Week 2021

Linac up to 1.54 GeV

Parameter	Result
length	79.1 m
number of cavities and quadrupoles	21 and 14
final emittance without errors (x/y)	2.7/3.8 nm
average extracted emittance (x/y)	5.5/6.0 nm
average longitudinal emittance	1.9 μm
final rms bunch length, en. spread	1 mm, 0.2%

Linac up to 6 GeV (1.54-6 GeV)

Parameter	Value
length of the accelerator	248.5 m
number of cavities and quadrupoles	60 and 12
bunches per RF pulse	2 (4*)
injected emittance (x/y)	1.9/0.4 nm
final emittance w/o errors (x/y)	0.48/0.10 nm
average extracted emit. (x/y)	0.55/0.11 nm
average extracted emit. (long.)	1.1 μm
final rms bunch length, spread	0.4 mm, 0.5%

S. Ogur et al.

Damping ring

- The **purpose** of the damping ring design is to **accept** the **1.54 GeV beam** coming from the linac (1), **damp the positron/electron beams** and provide the **required beam characteristics** for injection into the linac (2).

- The DR design was done by **S. Ogur** and **K. Oide** and the design was taken over (early 2021) by **C. Milardi, O. Blanco, A. De Santis**.

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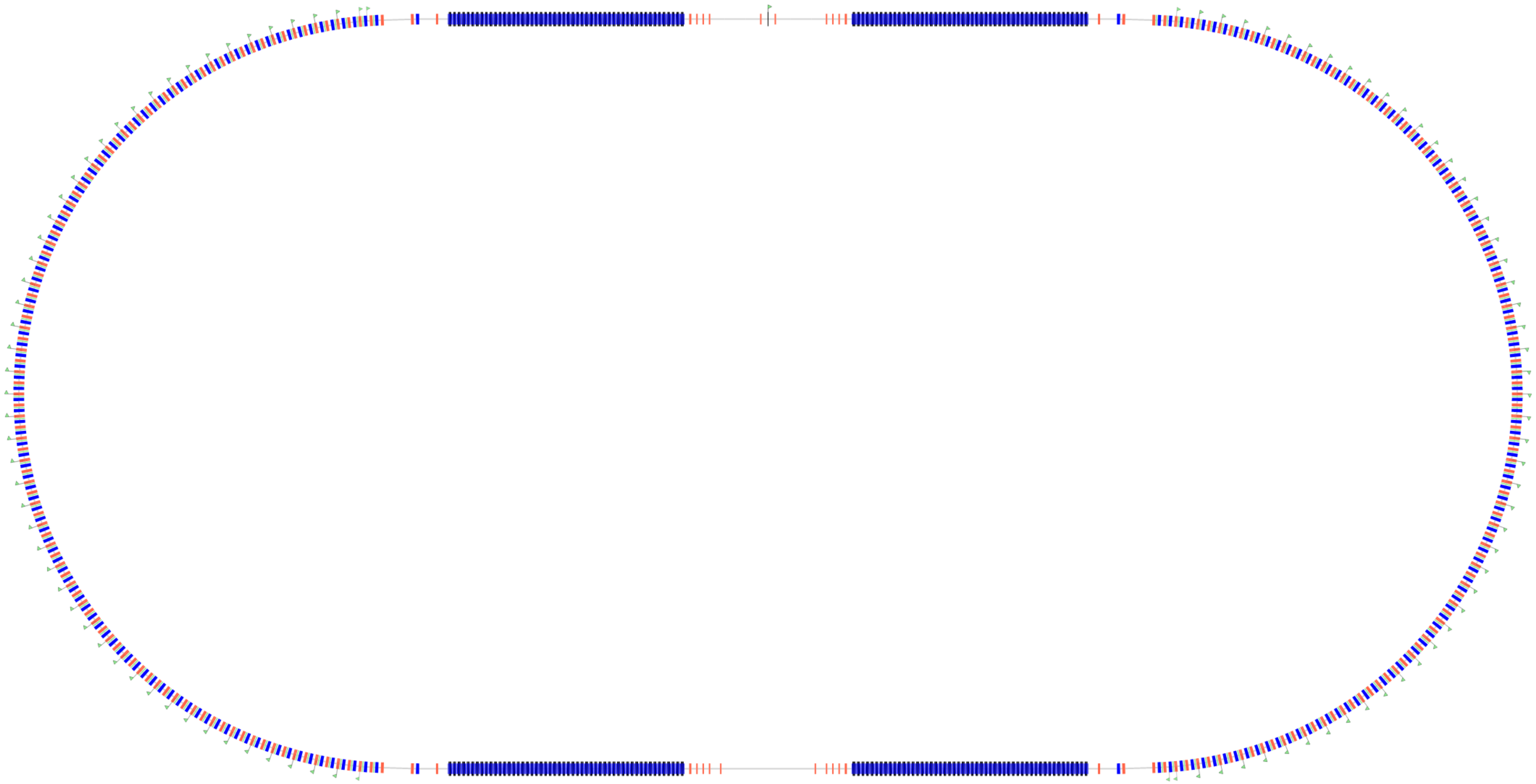

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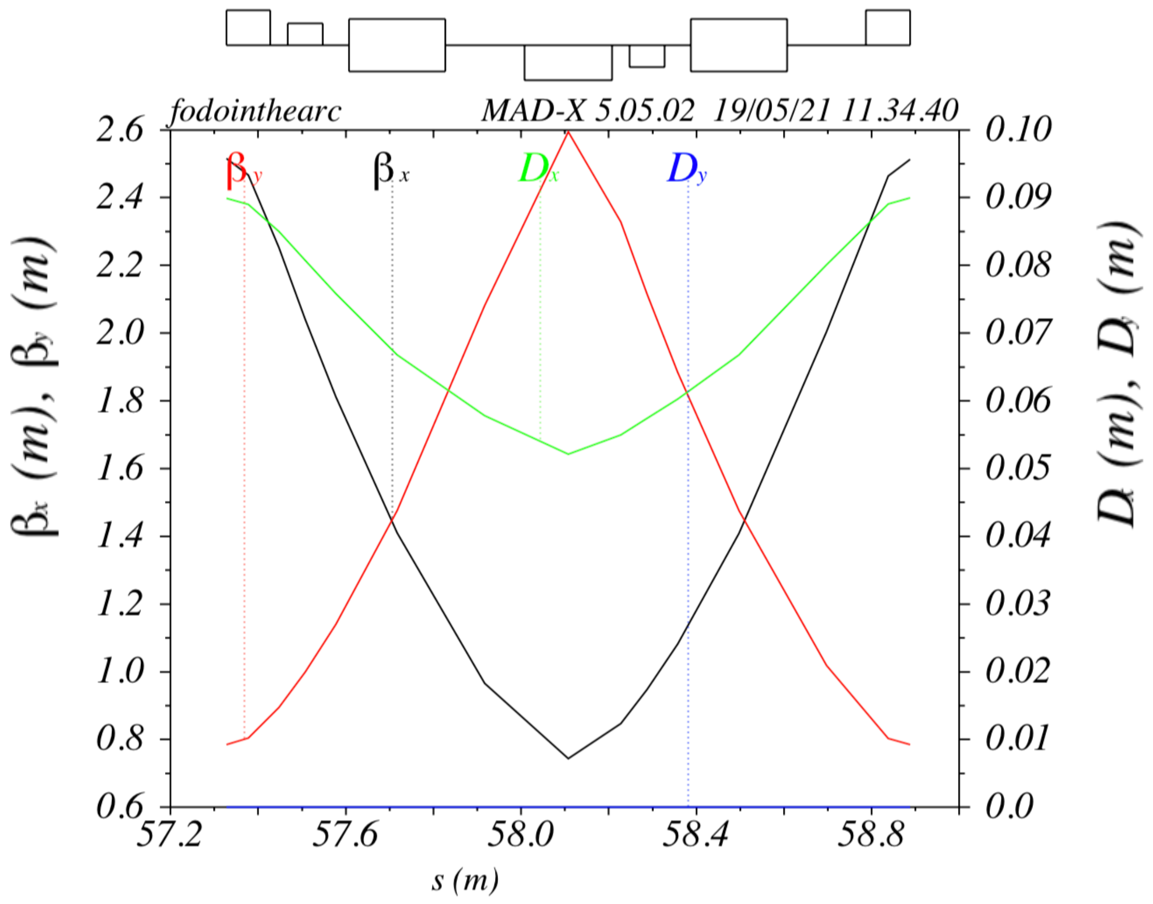

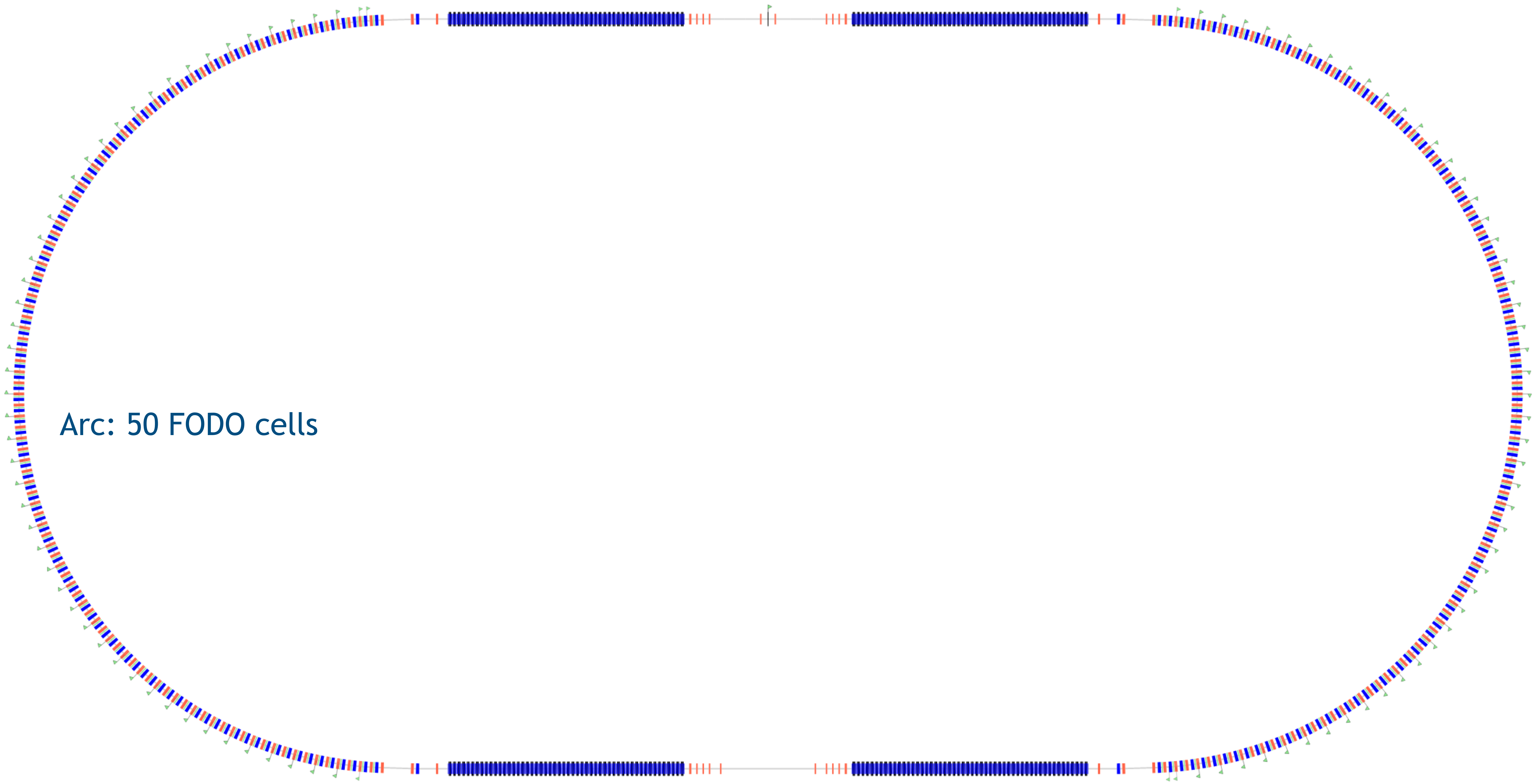

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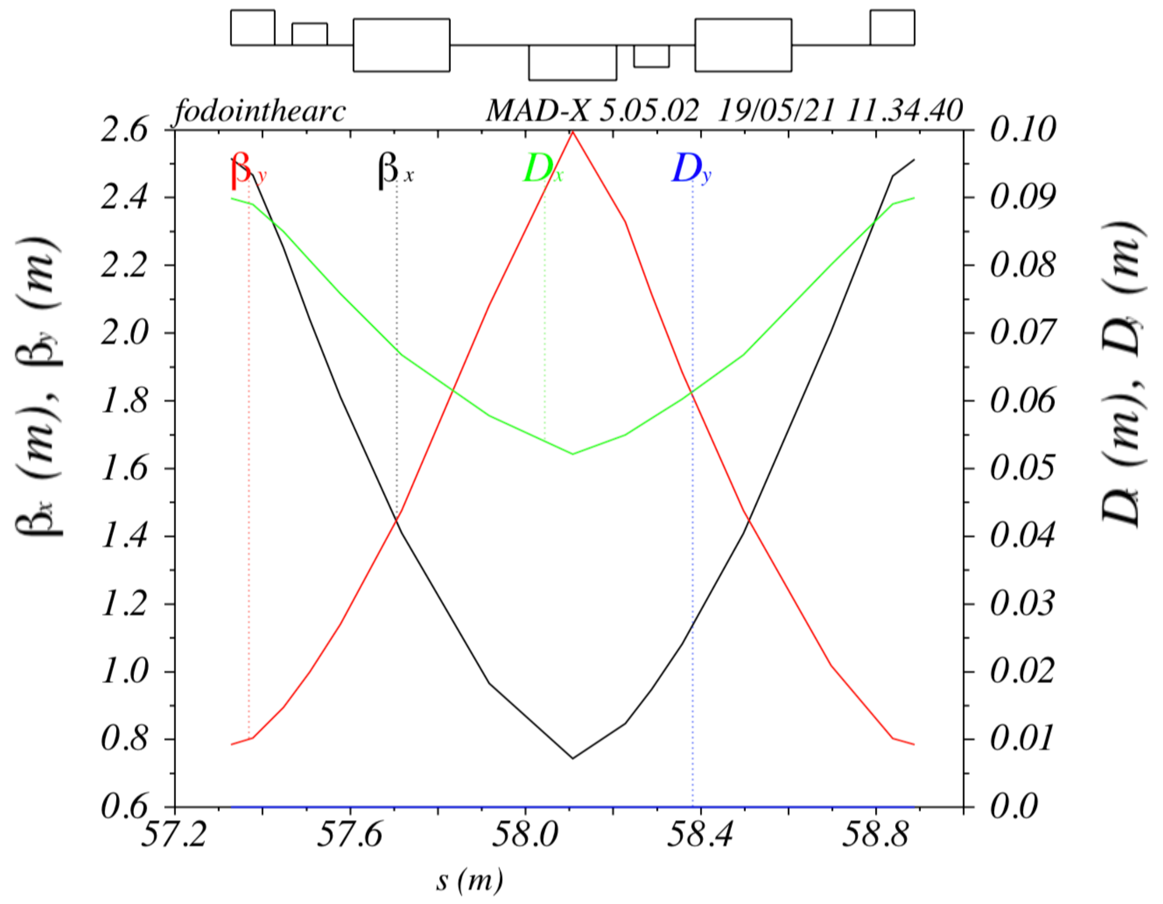
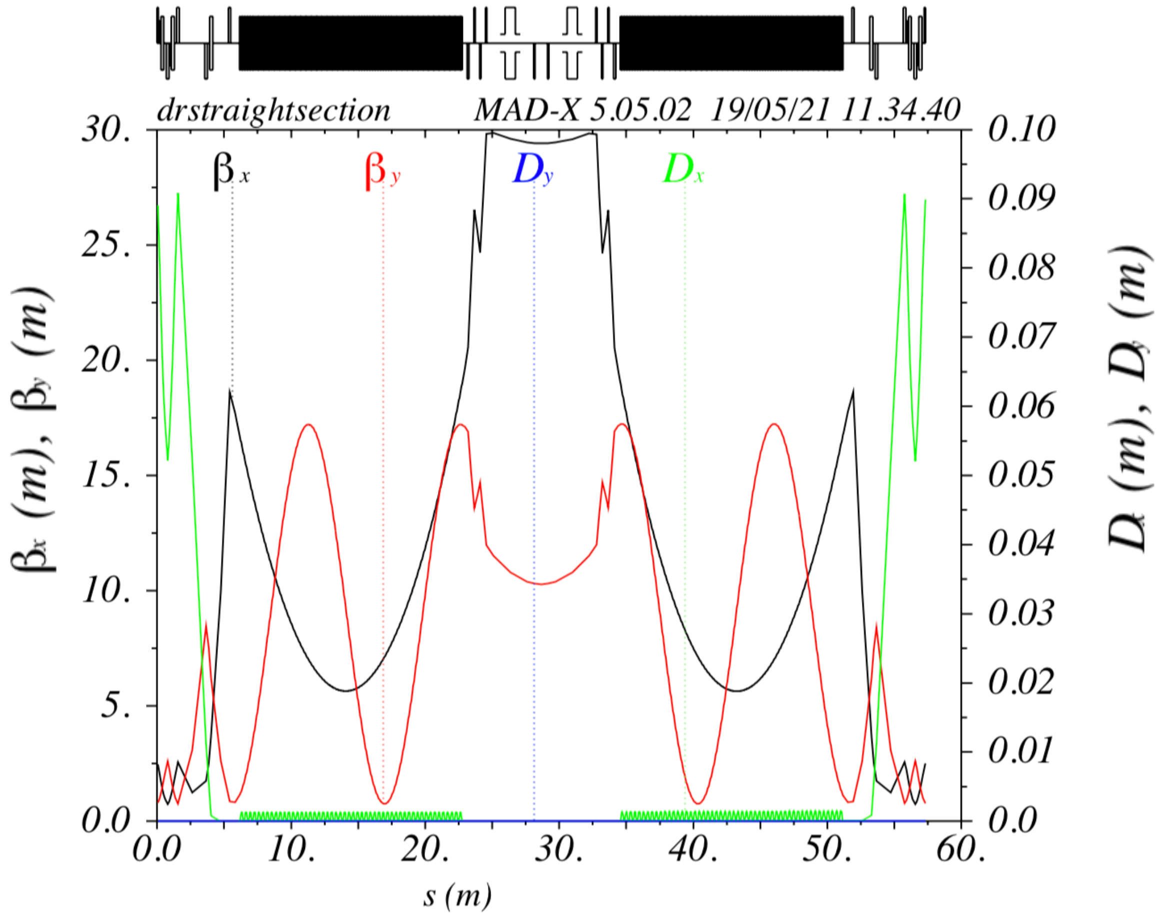
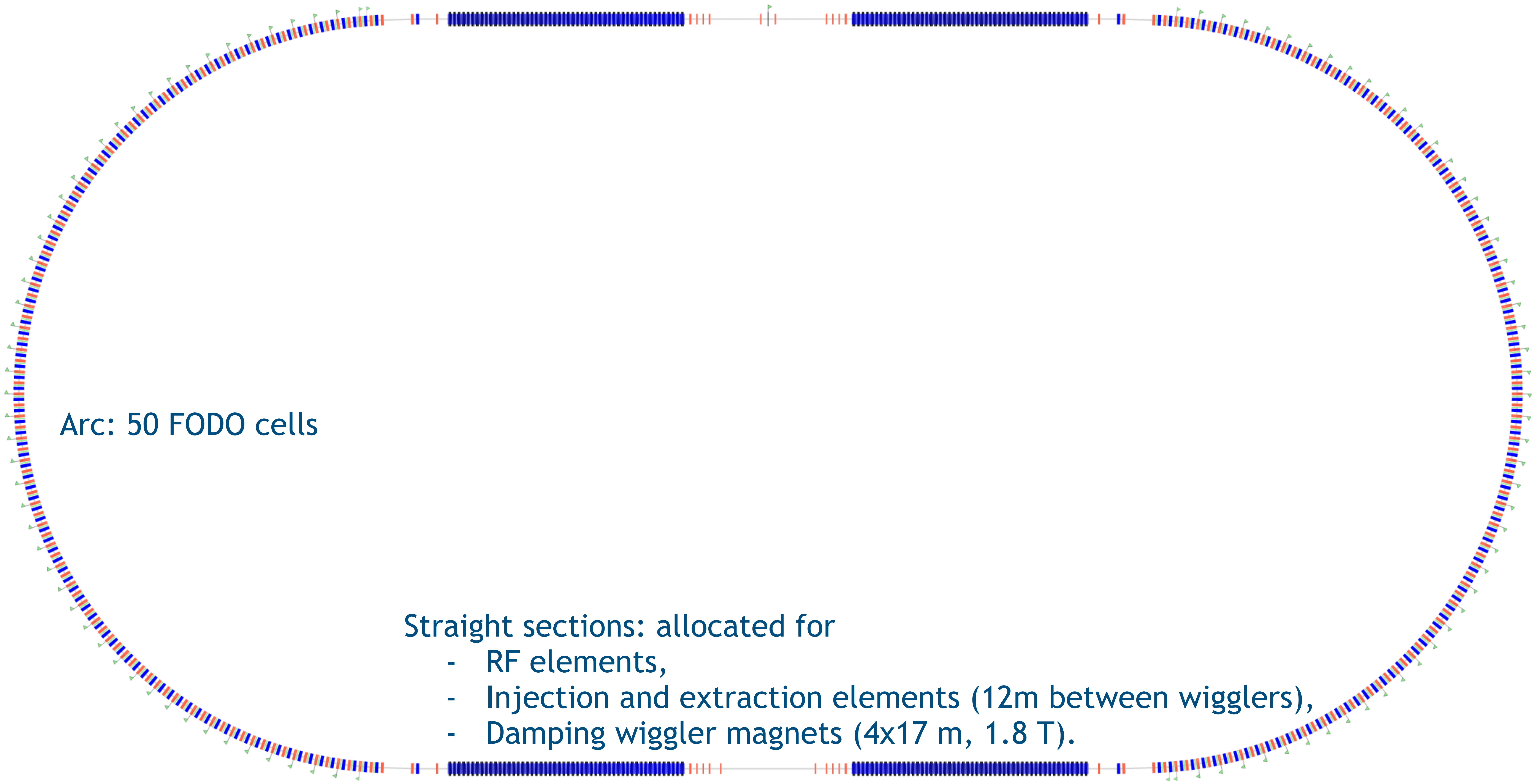
- The DR design was done by **S. Ogur** and **K. Oide** and the design was taken over (early 2021) by **C. Milardi, O. Blanco, A. De Santis**.







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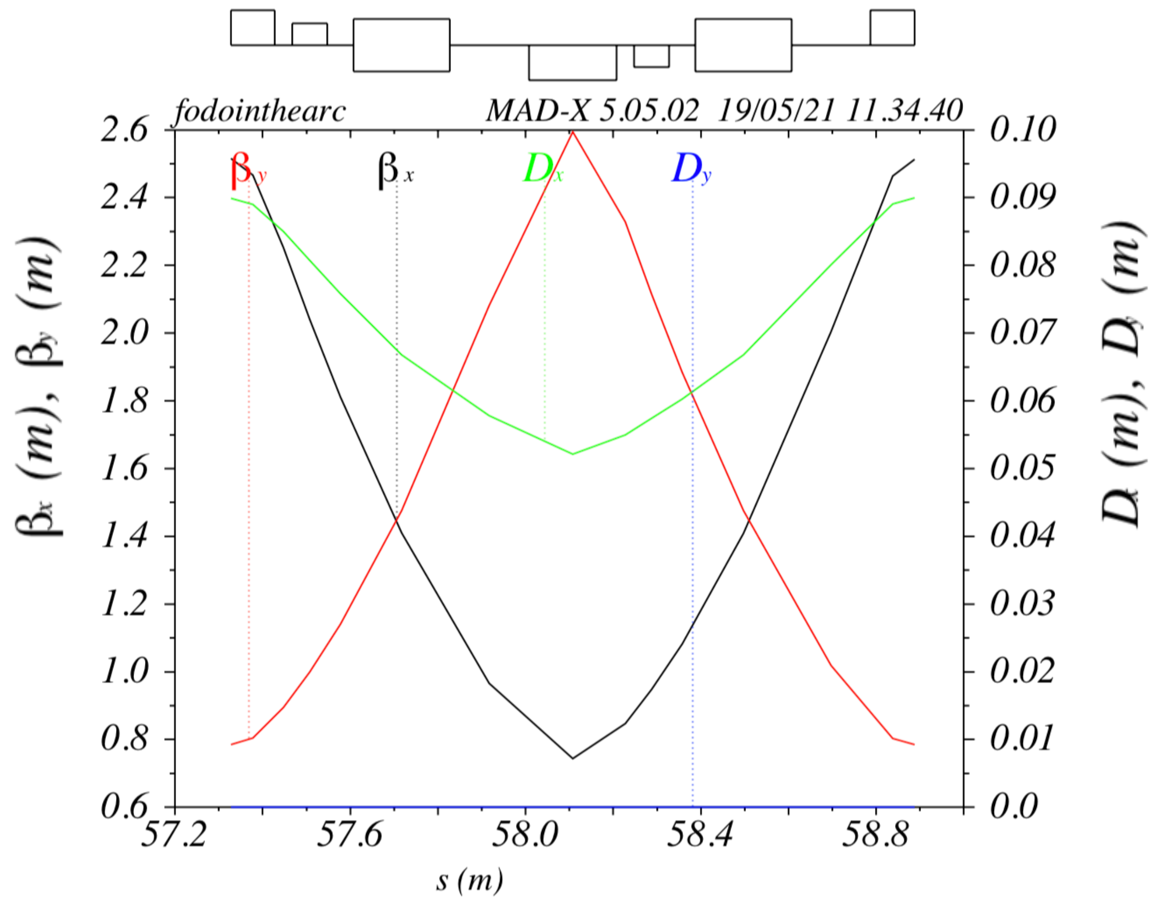

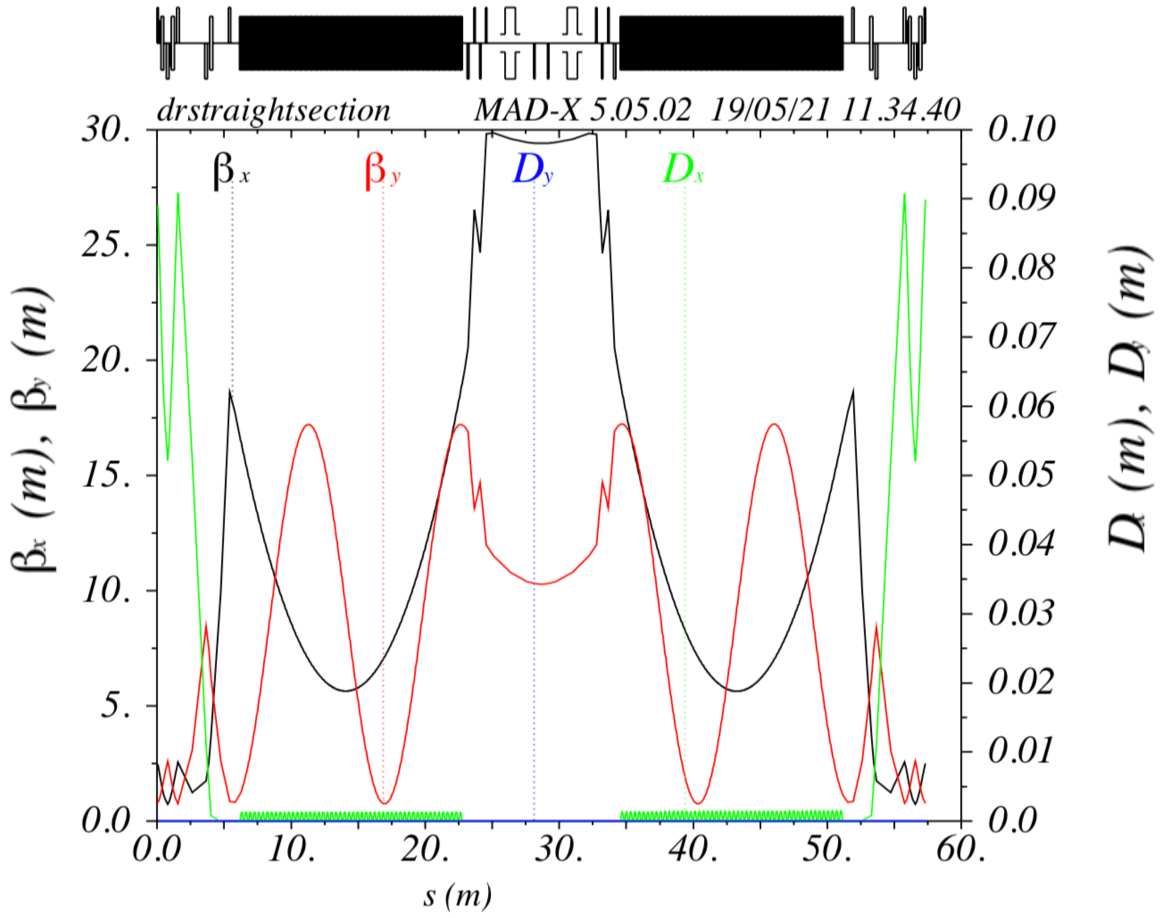

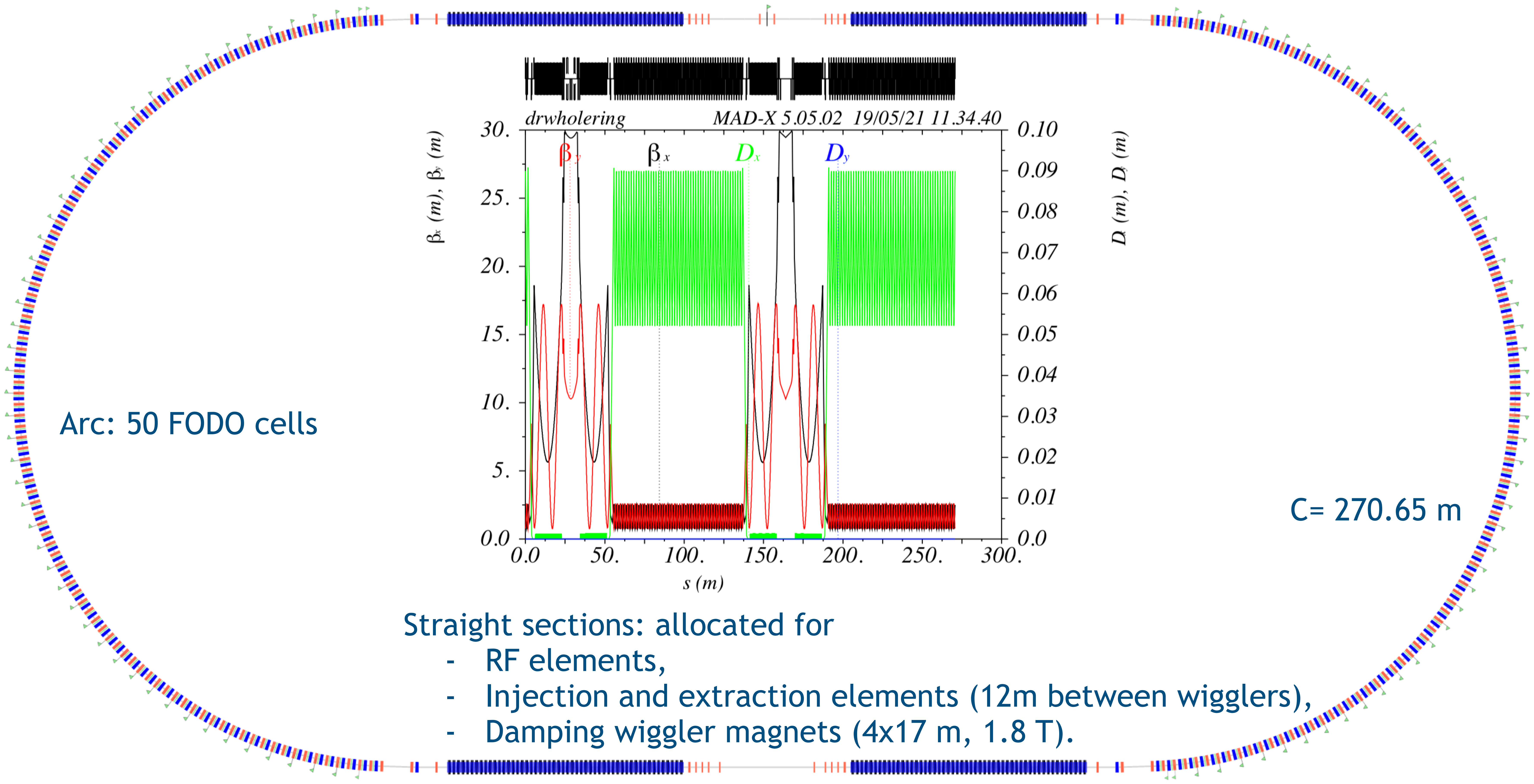

Straight sections: allocated for
- RF elements,
- Injection and extraction elements (12m between wigglers),
- Damping wiggler magnets (4x17 m, 1.8 T).

Damping ring

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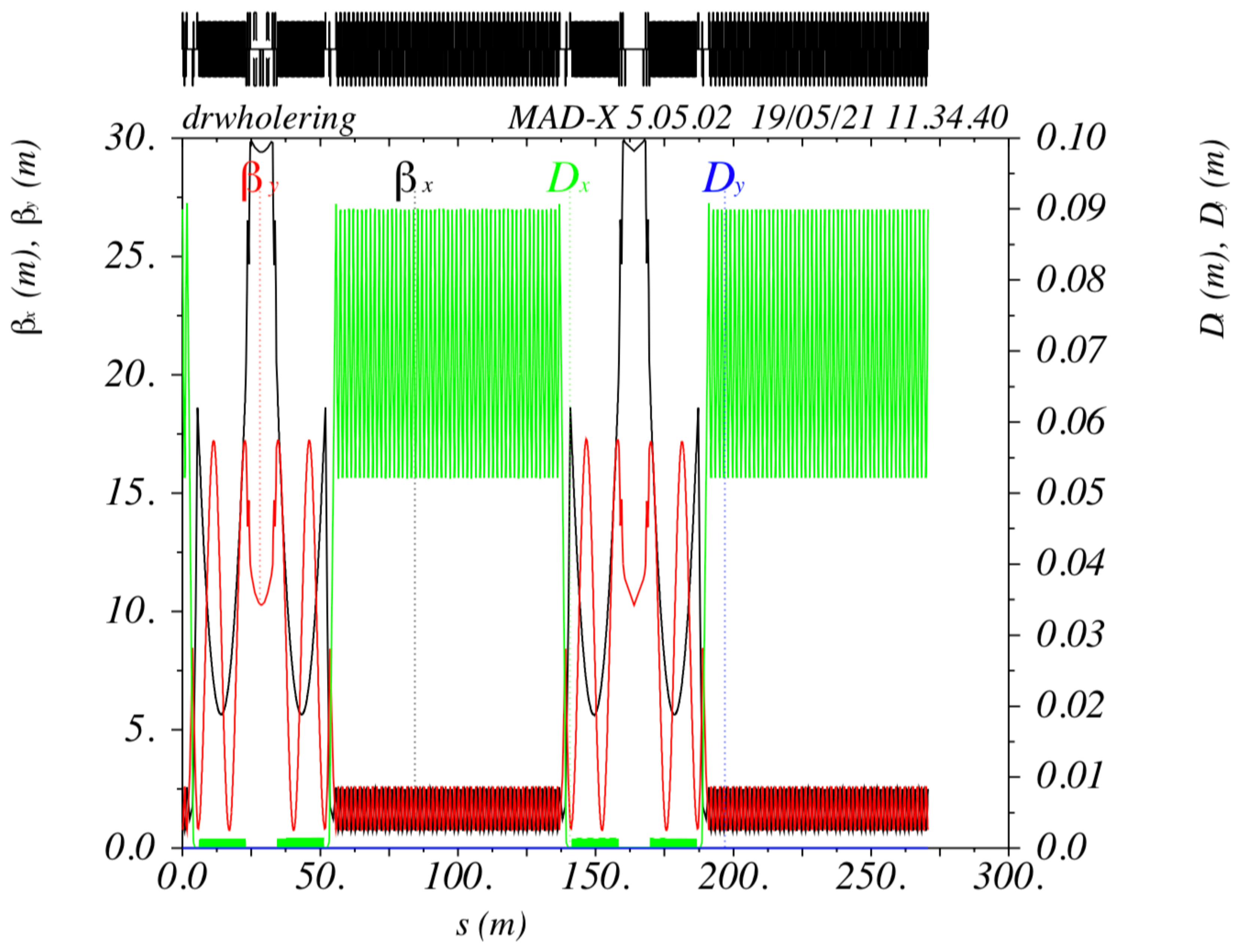
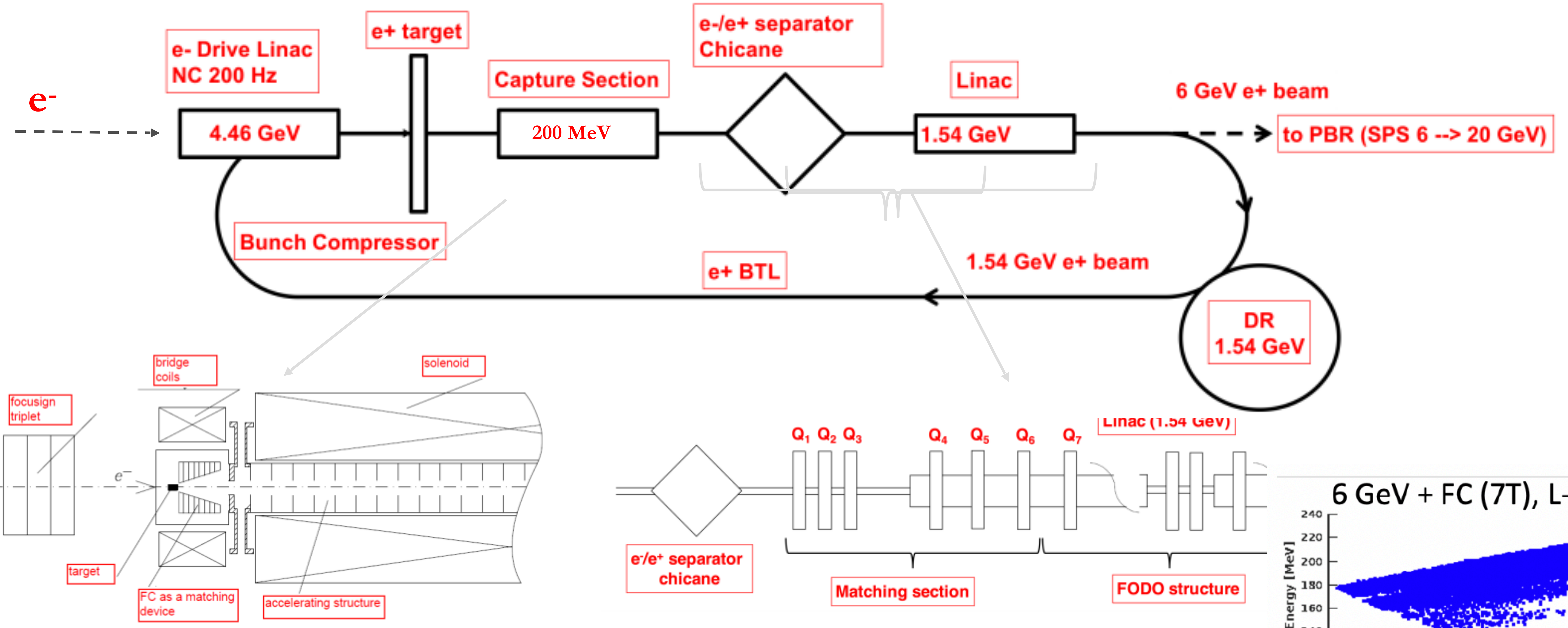
Parameter	Symbol	Damping Ring
Energy	E [GeV]	1.54
Circumference	C [m]	270.65
Eq. geo. emittance	ε_x [nm.rad]	1.25
Eq. bunch length	σ_z [mm]	3.19
Eq. momentum spread	σ_δ ($x10^{-2}$)	0.074
Damping time	τ_h [ms]	5.9
Harmonic number	h	360
Momentum Compaction factor	α_c ($x10^{-3}$)	1.49
Tune (h/v)	$Q_{x,y}$	22.57/23.61
Tune (s)	Q_s	0.019
Energy loss per turn	U_0 [MeV]	0.47
Bunch population	N_b ($x10^{10}$)	$2.13x10^{10}$
Stored time	t_s [ms]	20
Beam Current	I [mA]	188
Bunch spacing	ΔT_b [ns]	18
Number of bunches	n_b	50
RF frequency	F_{rf} [MHz]	400
RF Voltage	V_{rf} [MV]	4
Bending magnet length	l_{bend} [m]	0.219
Number of bending magnets	N_{bend}	212
Bending radius	ρ (m)	7.38
Bending magnet field	B_{dipole} [T]	0.69
Wiggler magnet length (total)/field	Lw [m]/Bw [T]	68/1.8
Number of wiggler magnets	Nw	4 (x17 m)



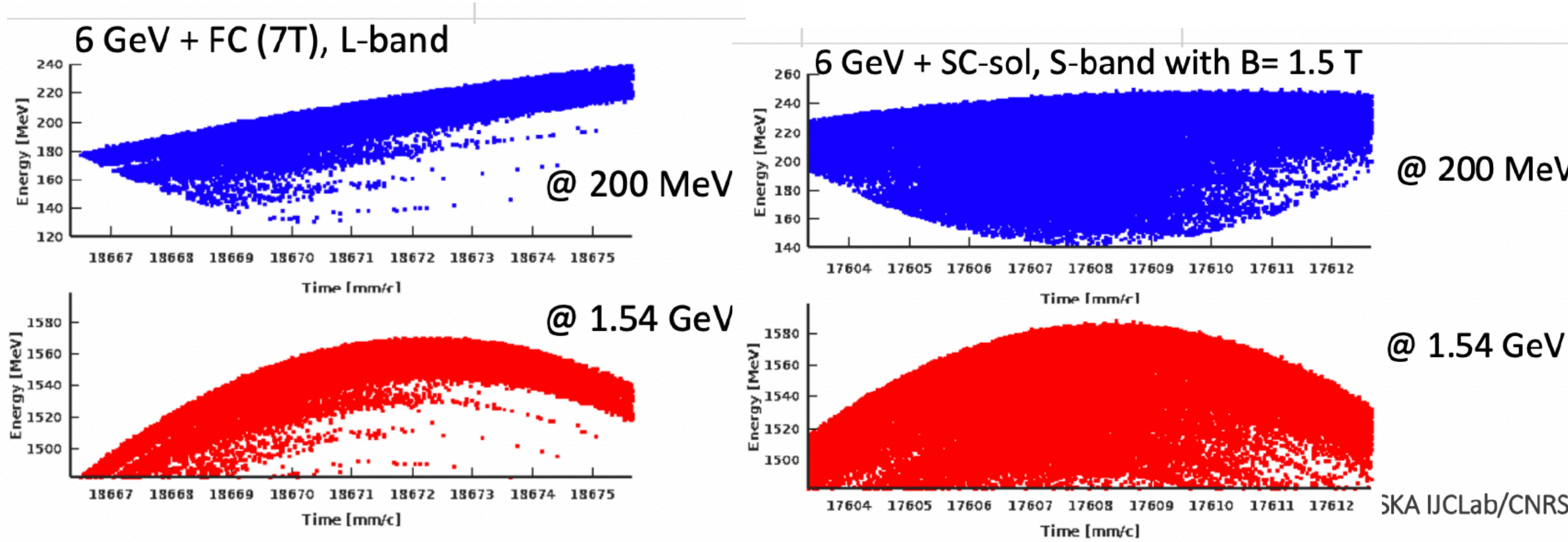
Contribution to the design revision, O. Etisken

Positron production



- **Same linac** used for positron production @ **4.46 GeV** with bunch intensity of **4.2 x 10^10** particles. Positron beam emittance are reduced in DR @ **1.54 GeV.**
- After target, the capture section is composed of an AMD followed by the capture linac embedded in a DC solenoid magnetic field used to accelerate the beam until about 200 MeV.
- Presented studies show that the comparable positron yield (**1 N_{e+}/N_{e-}**).

CDR



Beam energy, GeV	6					
Number of bunches	**2**	**10**	**15**	**20**	**30**	**40**
e+ bunch charge @200 MeV, e+	4,2E+10	4,2E+10	4,2E+10	4,2E+10	4,2E+10	4,2E+10
e+ yield	2,3	2,3	2,2	2,1	1,8	1,2
Bunch charge, e-	**1,8E+10**	**1,8E+10**	**1,9E+10**	**2,0E+10**	**2,4E+10**	**3,4E+10**
Bunch length (rms), mm	1	1	1	1	1	1
Bunch transv. size (rms), mm	**0,5**	**0,65**	**0,9**	**1,15**	**1,7**	**2,5**
Bunch separation	tens of ns	tens of ns	tens of ns	tens of ns	tens of ns	tens of ns
Repetition rate (max), Hz	100	100	100	100	100	100
Beam power, kW	3,5	17,3	27,4	38,4	69,1	130,6
Emittance (normalsed max), mm.rad	<1	<1	<1	<1	<1	<1
Energy spread, %	< 1	< 1	< 1	< 1	< 1	< 1
PEDD (target), J/g	**8,6**	**32**	**32**	**32**	**32**	**32**
Deposited power (target), kW	**0,6**	**3,3**	**5,1**	**7,2**	**13**	**25**

FCPPL Workshop, 2021

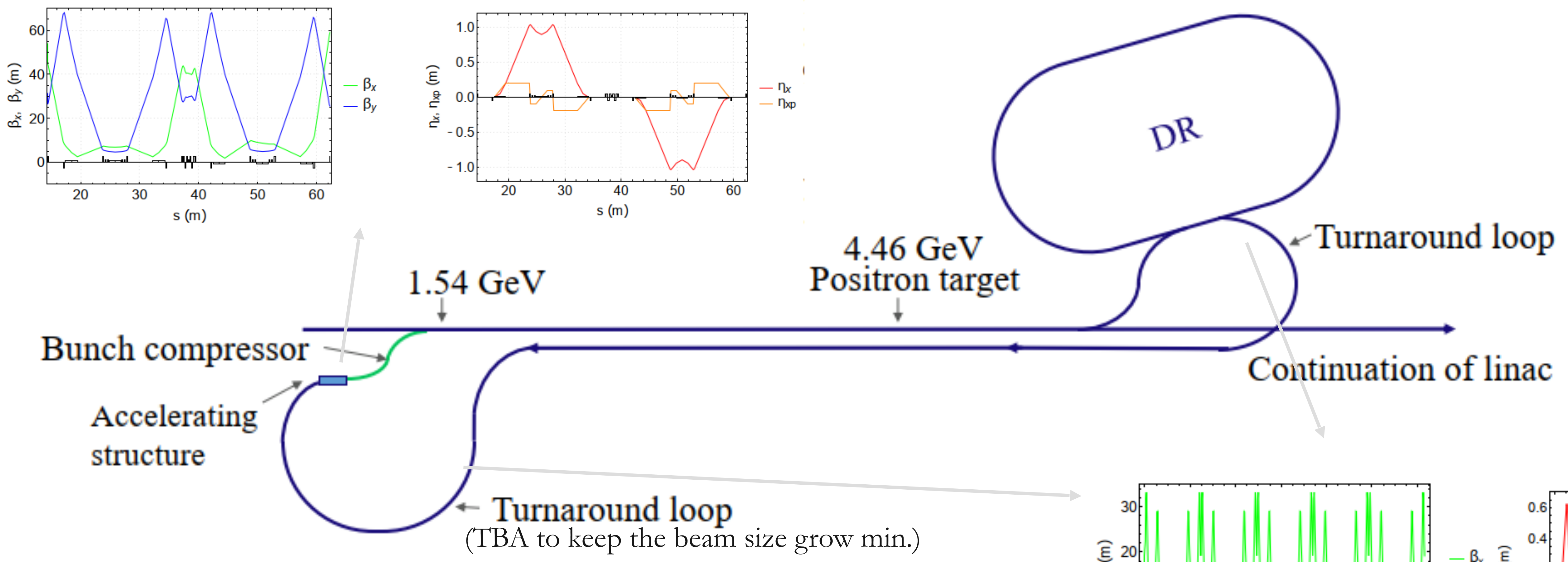
- conventional or hybrid targets?
- irradiation tests at Mainzer Mikrotron
- machine learning will be implementing for capture and optics
- demonstrator for e+ production and capture to be built at PSI/ SwissFEL in 2024-2025.

S. Ogur, I. Chaikovska, P. Martyshkin et al. (LAL)

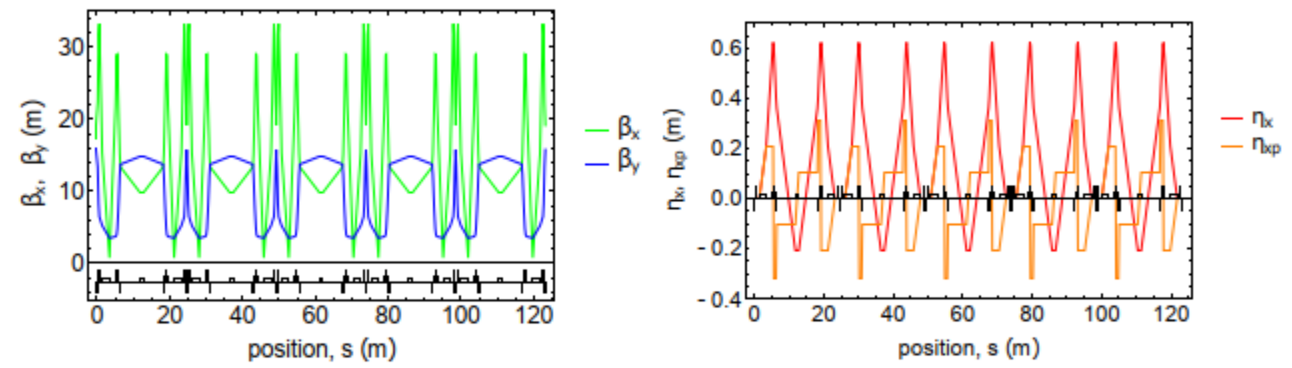
FCC Week, 2021

Bunch compressor

- FCC-e^+e^- injector requires two 180^0 turnaround loops to transport the positron beam from the damping ring to the lower energy section of the linac.
- In addition, **bunch compression** is required to reduce the RMS bunch length from **5mm to 0.5 mm**, prior to injection into the linac. Following the second loop, before the beam is injected back into the linac, is the location of the bunch compressor.



Design revision is ongoing by INFN team with a potential contribution from O. Etisken



(a) (b)

Beam parameters at the damping ring exit

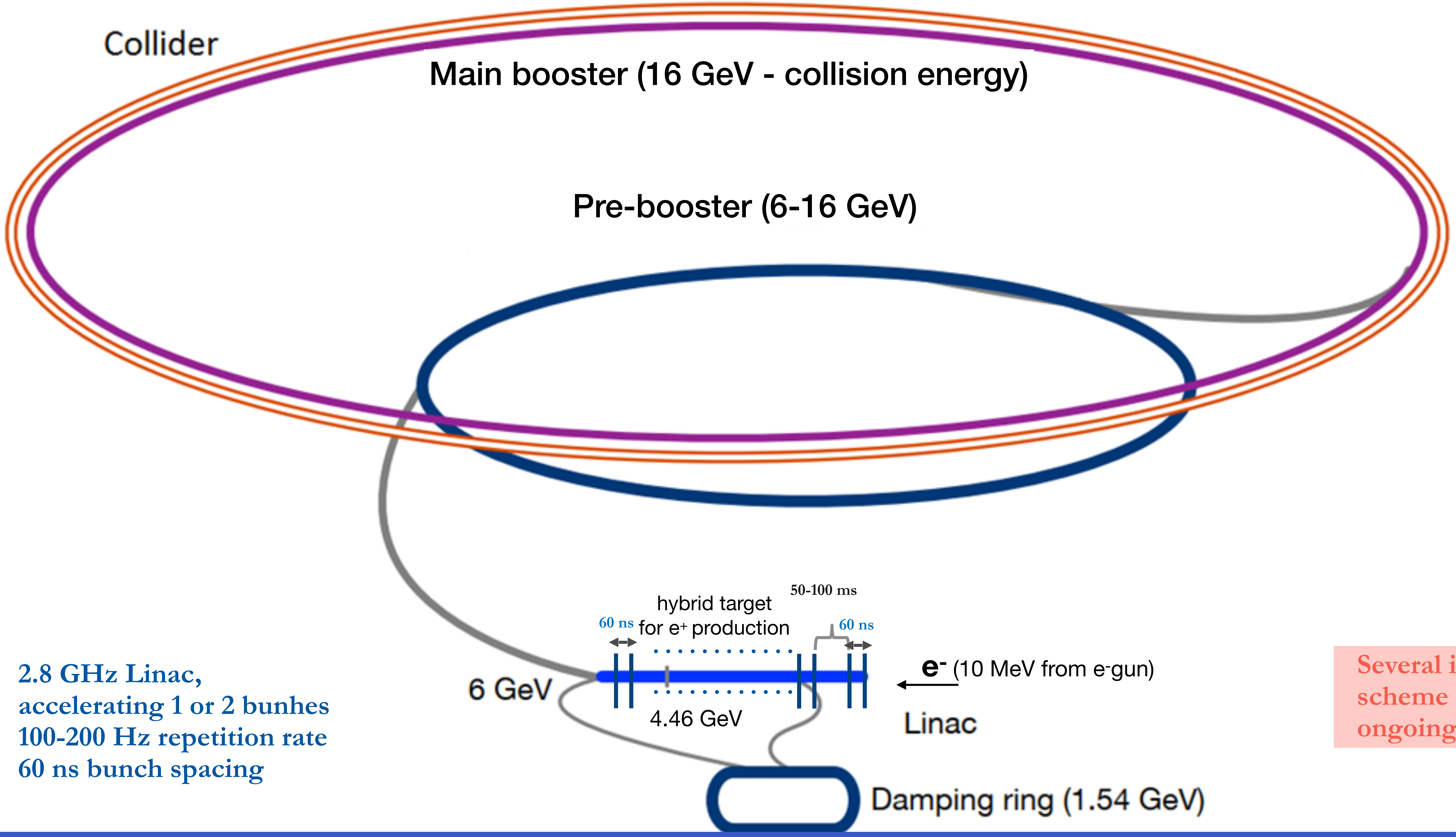
Property	Symbol	Value	Units
Beam energy	E_0	1.54	GeV
Bunch charge	Q	4.80	nC
Bunch length, initial	$\sigma_{z,i}$	5.00	mm
Energy spread	$\frac{\sigma_E}{E_0}$	0.10	%
Horizontal emittance	ϵ_x	1.81	nm rad
Vertical emittance	ϵ_y	0.37	nm rad

- CSR cancellation techniques were applied to minimize the emittance growth across the compressor to 6.8%.

CDR

T. K. Charles et al. (CERN)

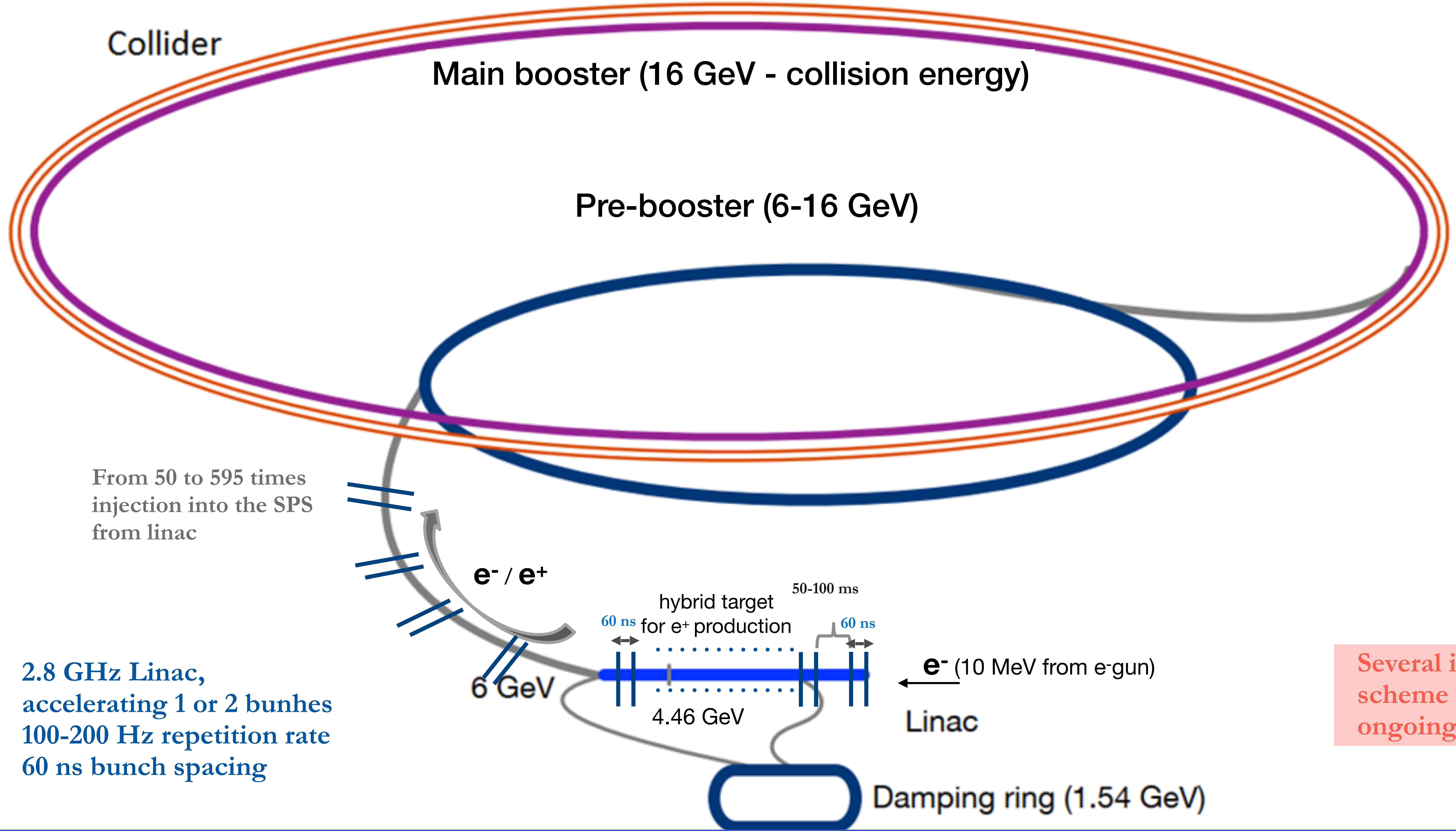
Injection filling scheme



2.8 GHz Linac,
accelerating 1 or 2 bunhes
100-200 Hz repetition rate
60 ns bunch spacing

Several injection filling scheme discussions are ongoing!

Injection filling scheme



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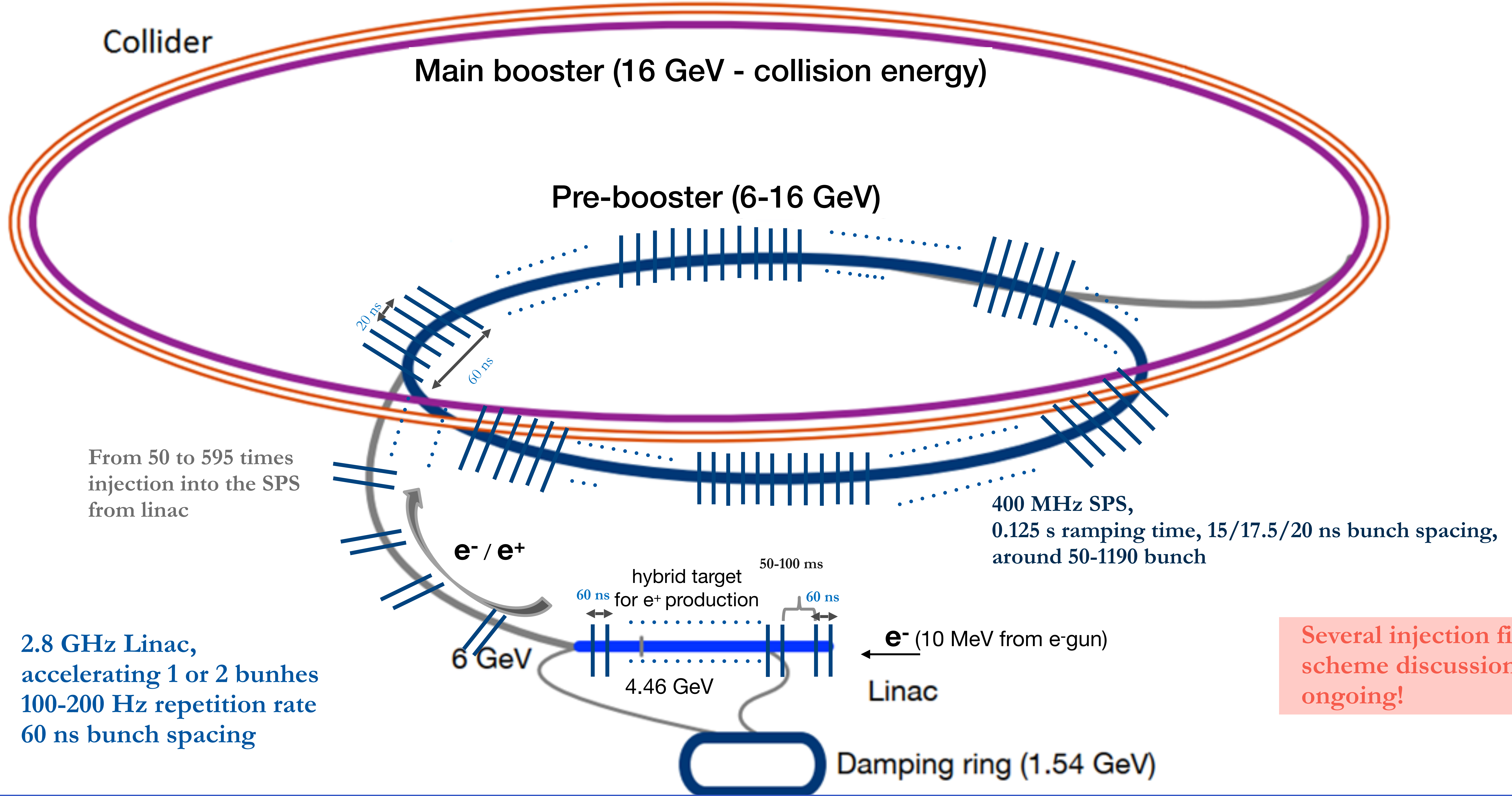

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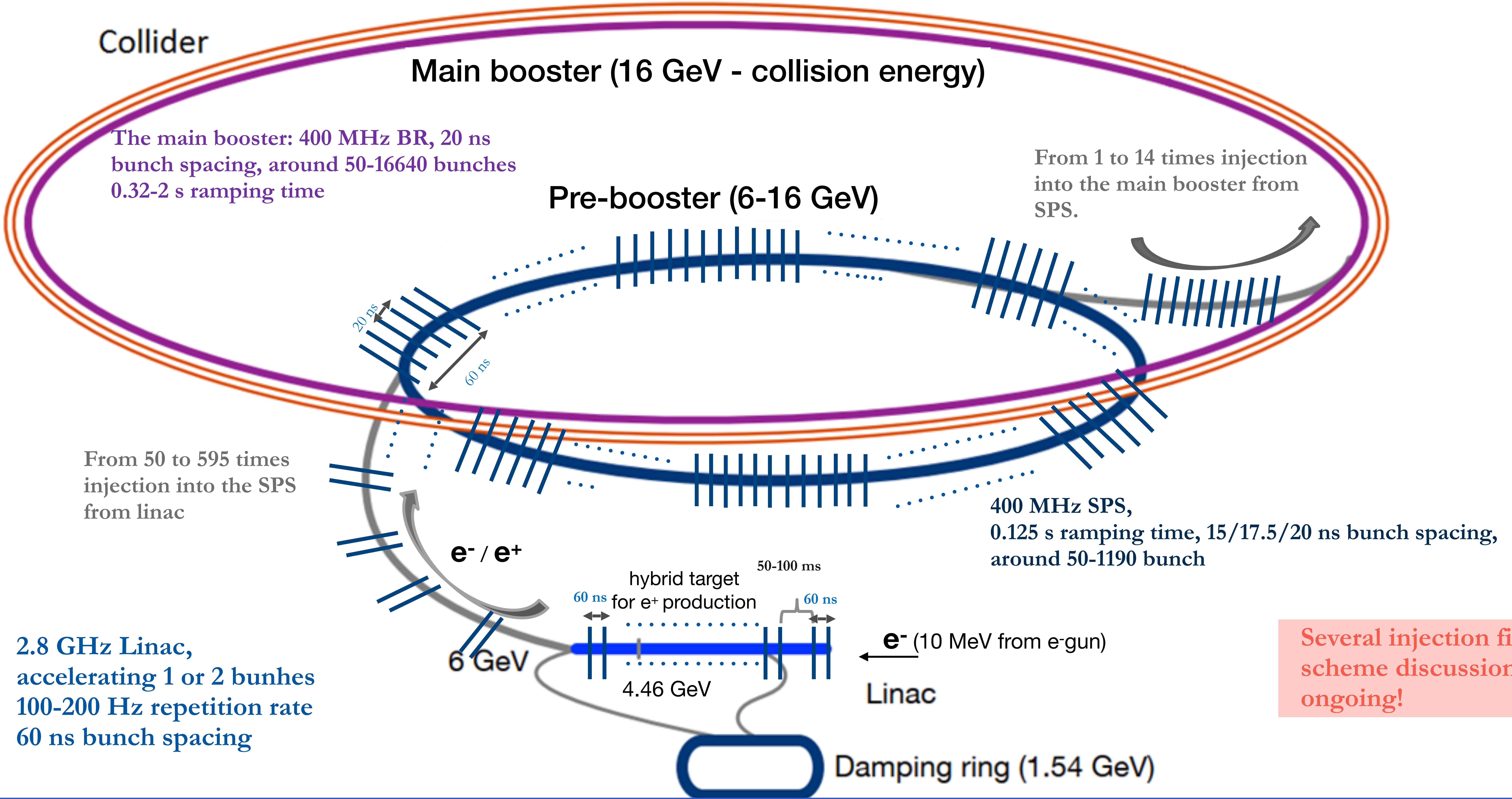

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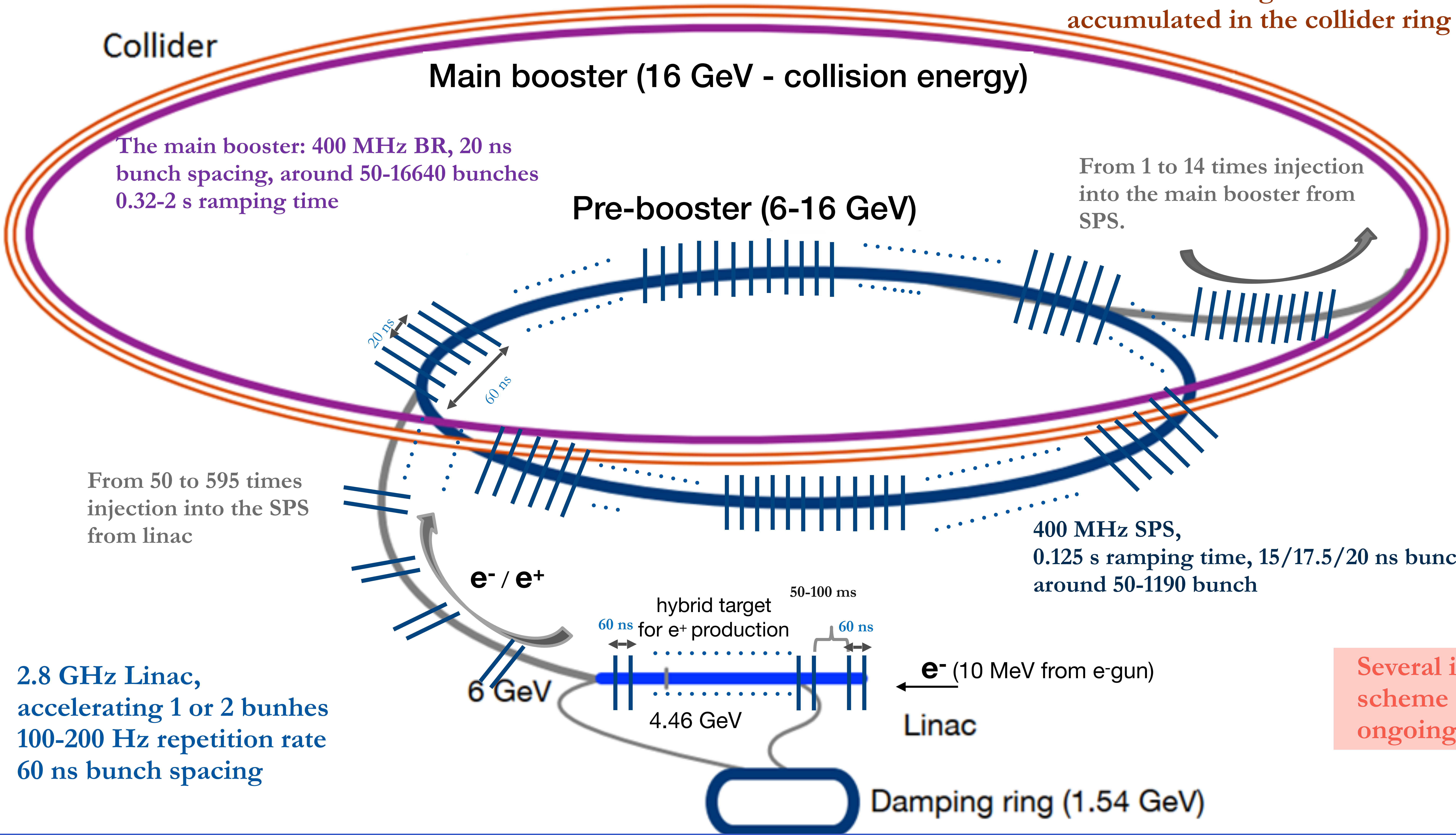
Injection filling scheme

The bunch charge is accumulated in the collider ring



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FUTURE CIRCULAR COLLIDER

Outline

- Introduction
- FCC-e^+e^- injector complex
- FCC-e^+e^- pre-injector design
  - e-source and linac
  - Positron source
  - Damping ring
- **Pre-booster ring design for FCC-e^+e^- injector complex**
  - SPS as FCC-e^+e^- pre-booster ring
  - Conceptual design of an alternative pre-booster ring
- Collective effect calculations
- More options for the injector complex
- Main booster ring
- Physics + Design + Prototyping
- Conclusion

Requirements for the PBR

- The **purpose** of this design is to **accept** the **6 GeV beam** coming from the linac, **increase** the beam **energy** up to **16 GeV** and provide the **required beam characteristics** for injection into the main booster ring.

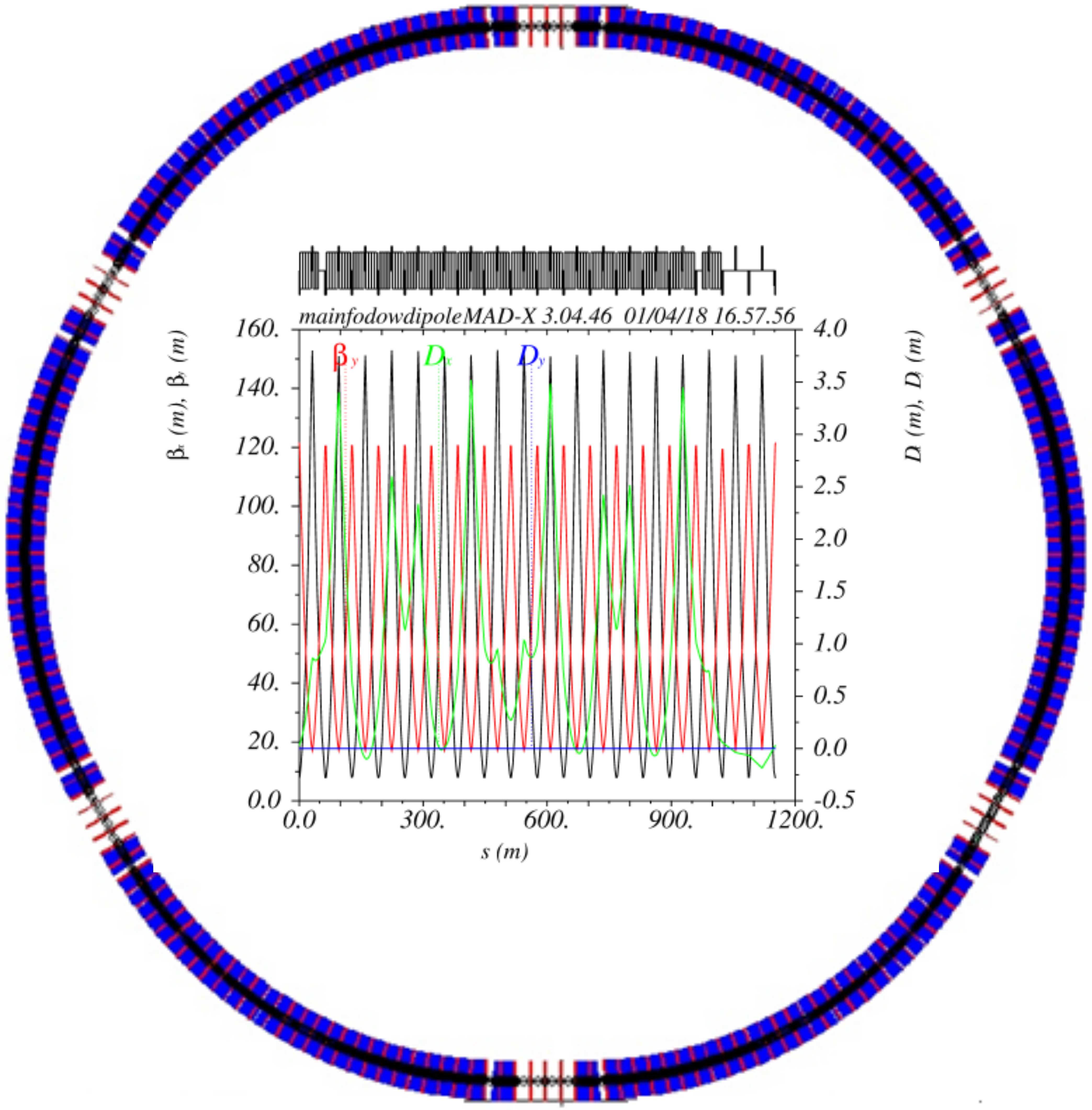
Requirements for the PBR

- The **purpose** of this design is to **accept** the **6 GeV beam** coming from the linac, **increase** the beam **energy** up to **16 GeV** and provide the **required beam characteristics** for injection into the main booster ring.

- The required beam characteristics, defined by the **BR** and the **linac**, are summarized in the table below.

Paramaters	Requirements	
Injection energy [GeV]	6	→ Linac
Extraction energy [GeV]	16	→ BR
Damping time @injection (hor.) [s]	0.1	→ Injection filling scheme
Geo. emittance @extraction (hor.) [nm.rad]	5	→ BR
Energy acceptance @injection [%]	1.5	→ Linac
Dynamic aperture @injection (hor.) [mm]	6.5	→ Injection method and linac
Energy spread @extraction [%] (rms.)	0.3	→ BR

SPS as FCC e^+e^- PBR



- The **Super Proton Synchrotron** (SPS) is the second-largest machine in CERN's accelerator complex.
- The SPS was initially used as a **hadron** collider and later as the injector of the **lepton** collider (LEP).
- Currently, it operates as the injector of the **large hadron collider (LHC).**
- It consists of **6 arcs and 6 straight** sections: each **super-period** is composed of **18 FODO** cells.
- The circumference is around **6.9 km.**
- Naturally, considered as the **baseline** option for the PBR of the FCC-e^+e^-.

FUTURE CIRCULAR COLLIDER

Essential modifications

- The existing machine is evaluated for the FCC-e^+e^- based on an energy scaling of the SPS and taking into account the design requirements for the PBR.

- Accordingly, two main challenges were revealed:
  - The **extraction** horizontal geometric **emittance** is **74 nm.rad** which is much larger than the required one,
  - The synchrotron radiation **damping time** at injection for the **SPS** is **1.8 s** which is much longer than the **0.1 s** required for the pre-booster ring and should be shorten seriously for the efficiency of the injection oscillation.

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- Several methods may be applied to reduce the horizontal emittance in a circular accelerator.

- However, **minimum modifications can be applied to the current machine,** since it has currently been providing beams for several experiments.

- In this regard, the horizontal emittance must be reduced while keeping the existing SPS lattice design.

Essential modifications

- The horizontal emittance expressed by the second and fifth synchrotron radiation integrals is given by:

$$\epsilon_0 = c_q \gamma^2 \frac{I_5}{J_x I_2}$$

$$I_2 = \oint \frac{1}{\rho^2} ds \qquad I_5 = \oint \frac{\mathcal{H}_x}{\rho^3} ds$$

$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2$$

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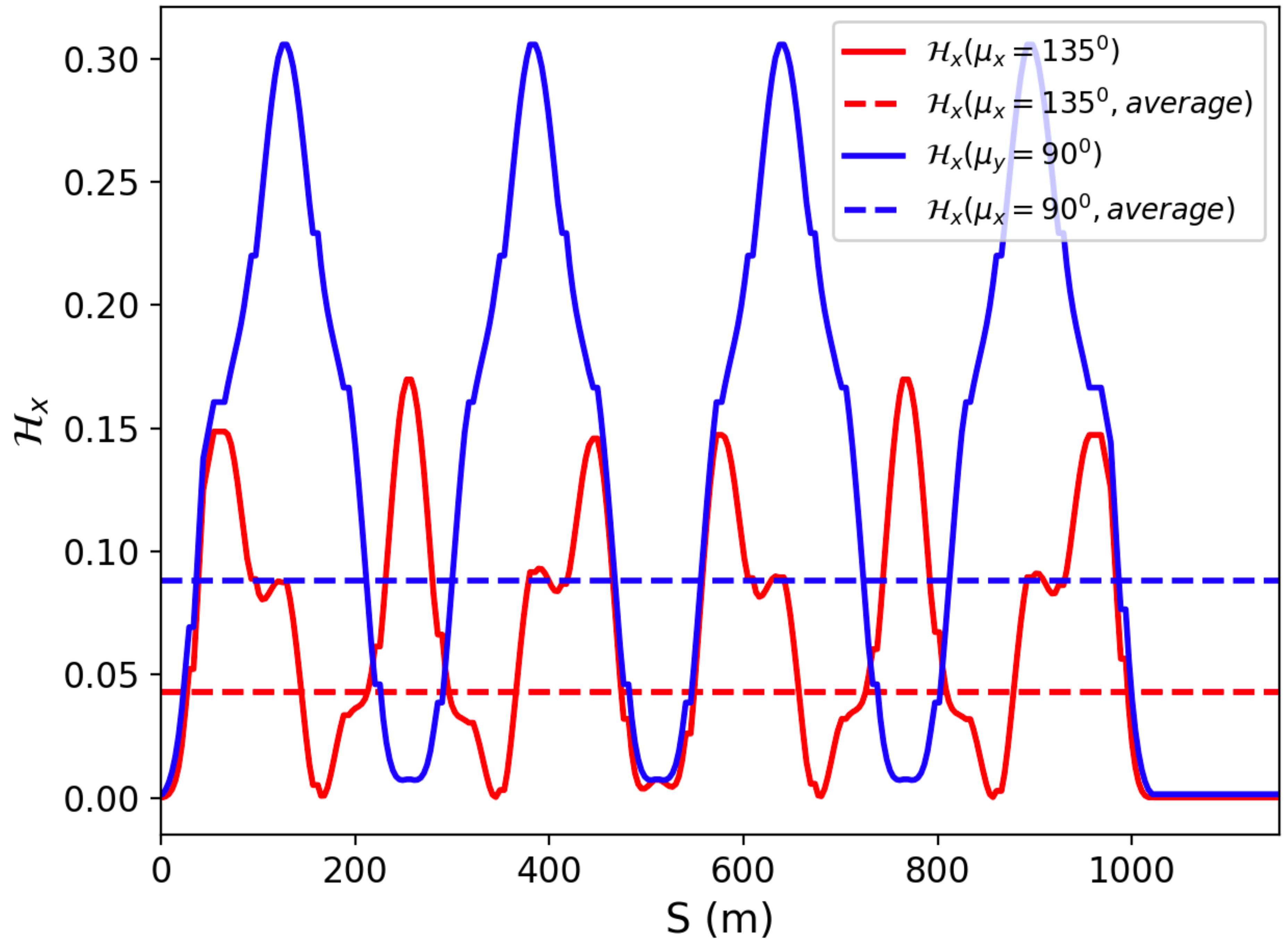

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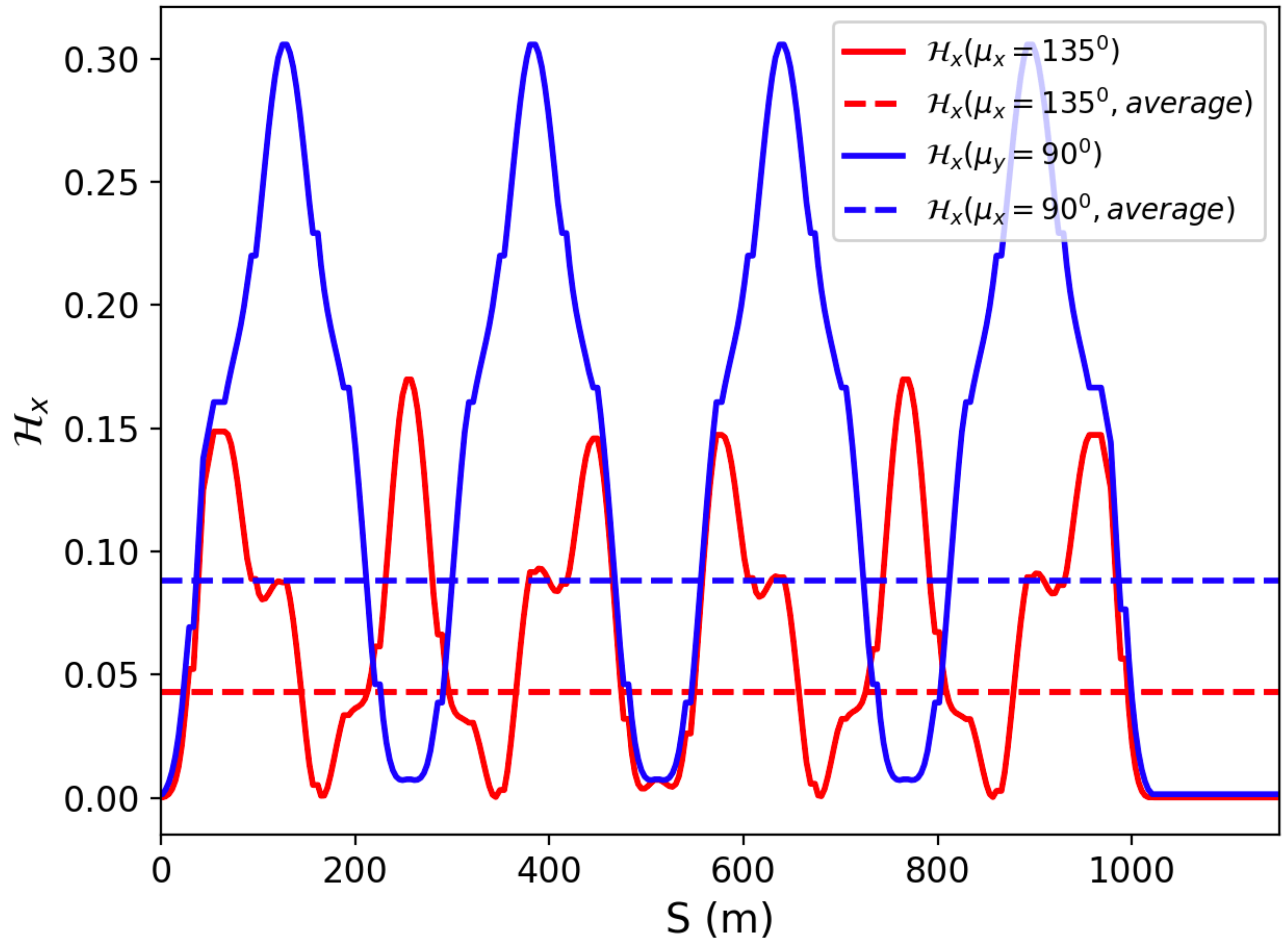
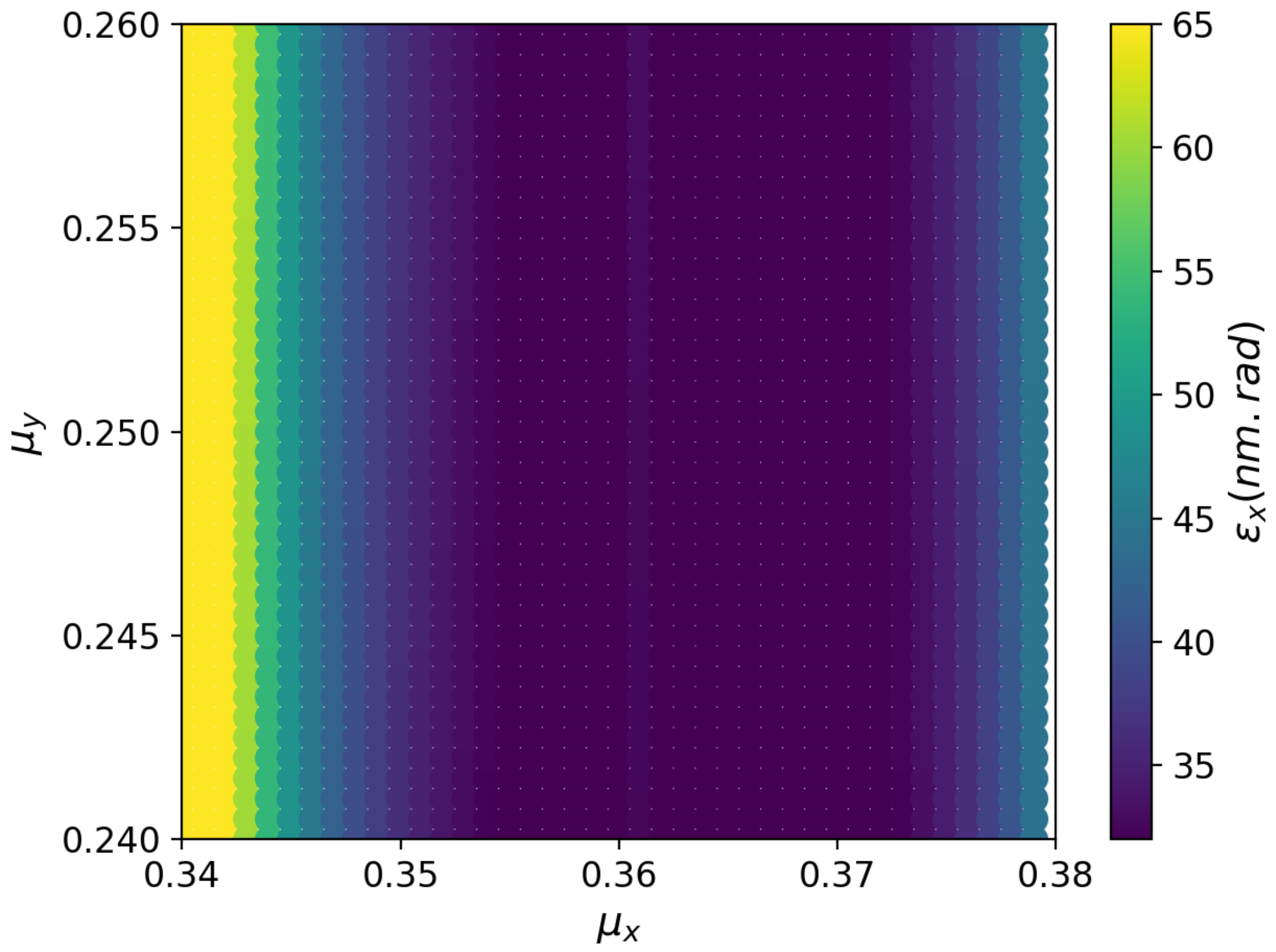


- Thus, it is possible to reduce the emittance seriously by means of phase advance optimization only.

Phase advance scanning for the SPS

- The **nominal phase advance** of the SPS is around **90 degrees** per cell.
- The existing phase advance **cannot** provide the required **horizontal emittance**.
- A numerical parametrization of the equilibrium horizontal emittance with the horizontal and vertical phase advance of the FODO cell was performed.



- The optimum phase advance is around 135^0, achieving an **emittance of 34 nm.rad** at extraction, which is **seven times larger** than the requirement of 5 nm.rad.

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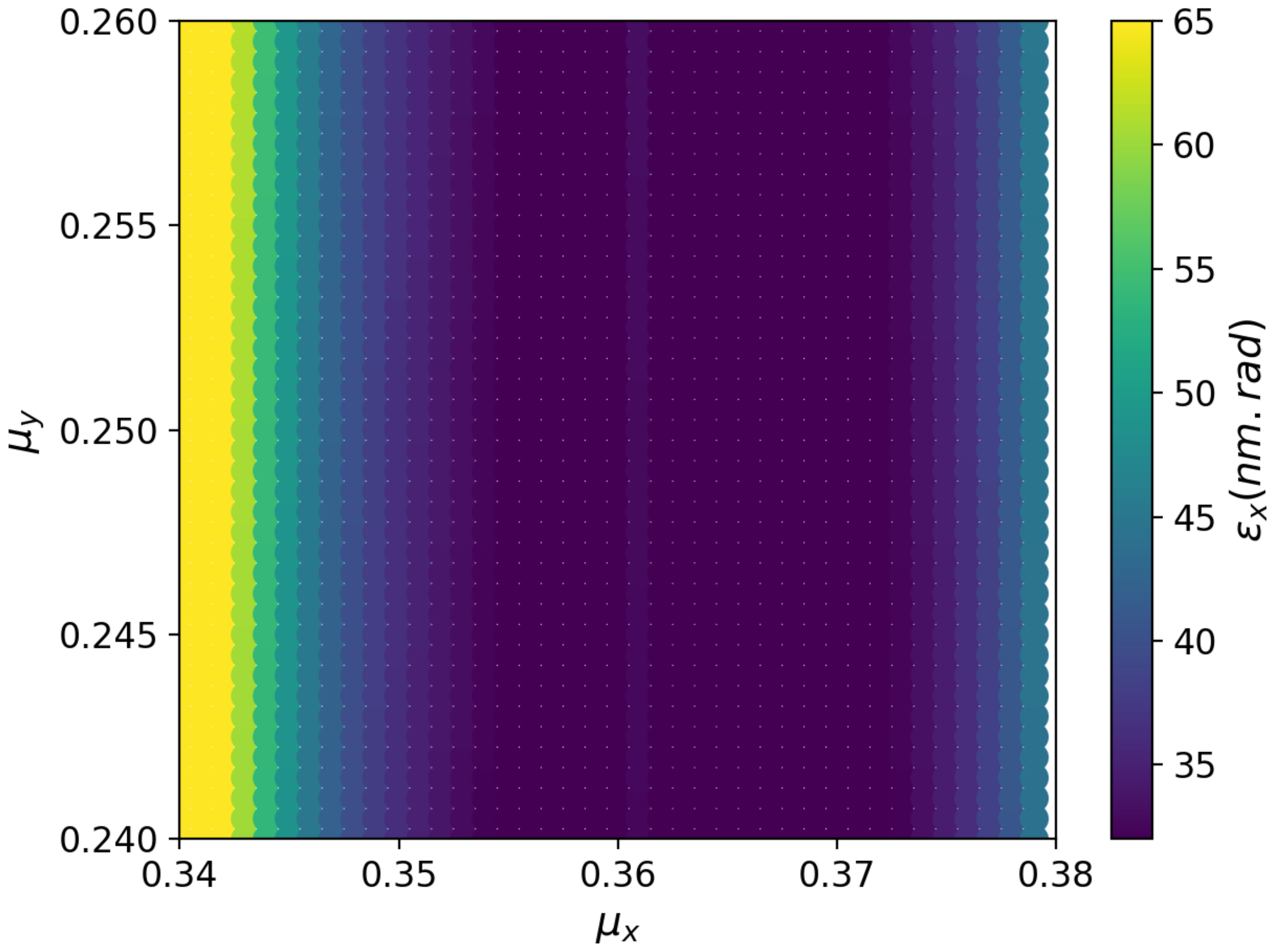

SPS Parameters * *phase advance is close to 135^0		Requirements
SPS Bending radius [m]	741.63	
SPS injection energy [GeV]	6	
SPS extraction energy [GeV]	16	
Dipole length	6.26	
Bending field @ injection [Gauss]	269.811	
Bending field @ extraction [Gauss]	899.3703	
Emittance @ injection [m.rad]	4.8×10^{-9}	
Emittance @ extraction [nm.rad]	34	5
Energy Loss / turn @ injection [MeV]	0.154	
Energy Loss / turn @ extraction [MeV]	7.8	
Transverse Damping time @ injection [s]	1.79	0.1
Natural chromaticity h/v	-72/-40	

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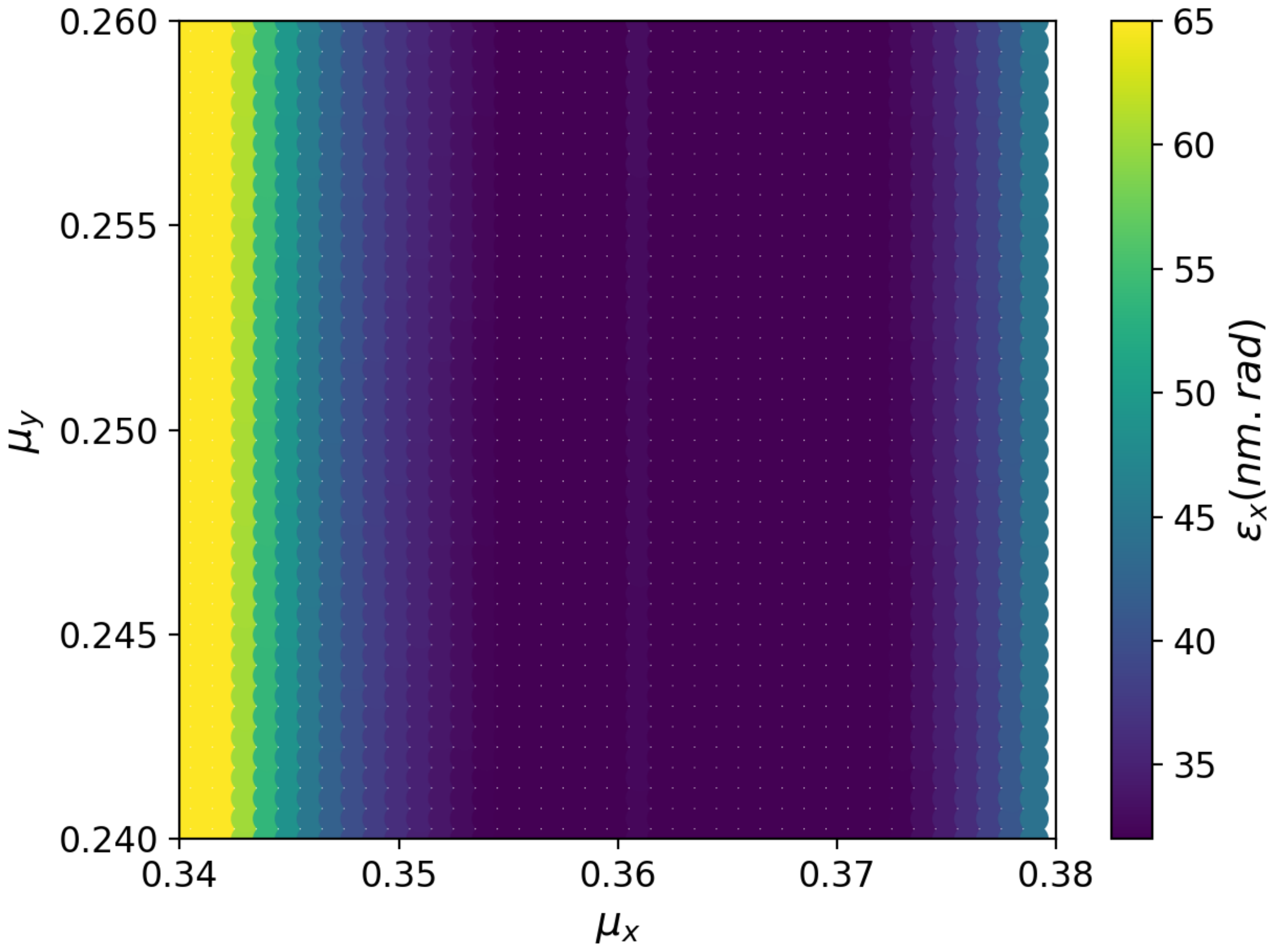

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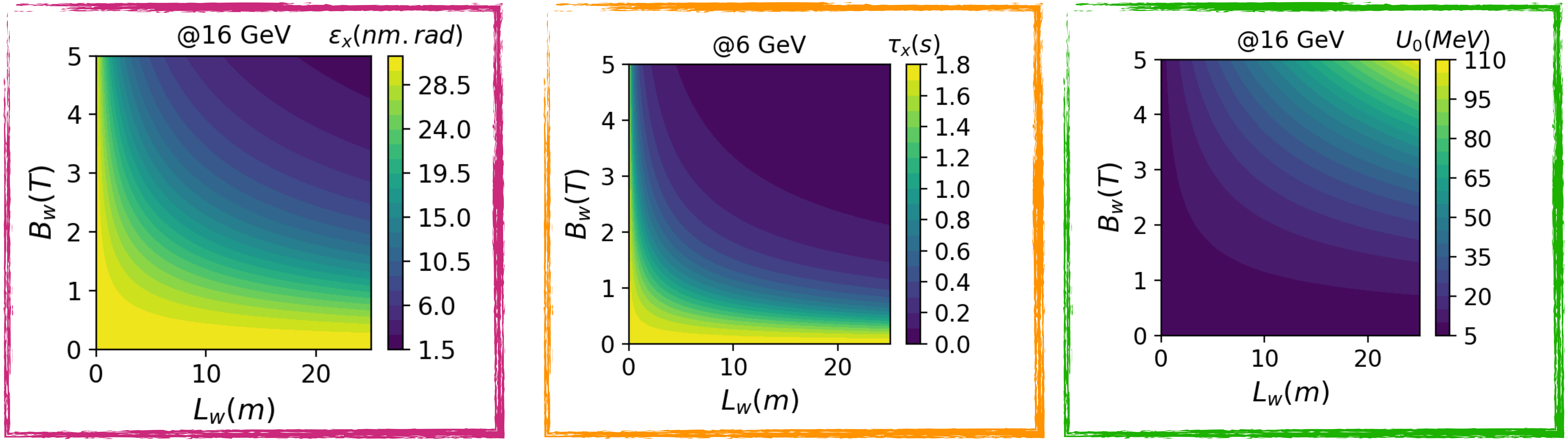
- **1.79 s damping time** is much **longer** than needed.

- To overcome these limitations, the insertion of **damping and Robinson** wiggler magnets is proposed.

Damping W. magnets



- Analytical Parameterization of the **horizontal emittance (ε_x)**, **damping time (τ_x)** **and energy loss per turn (U_0)** with the **wiggler peak field** and total **length.**

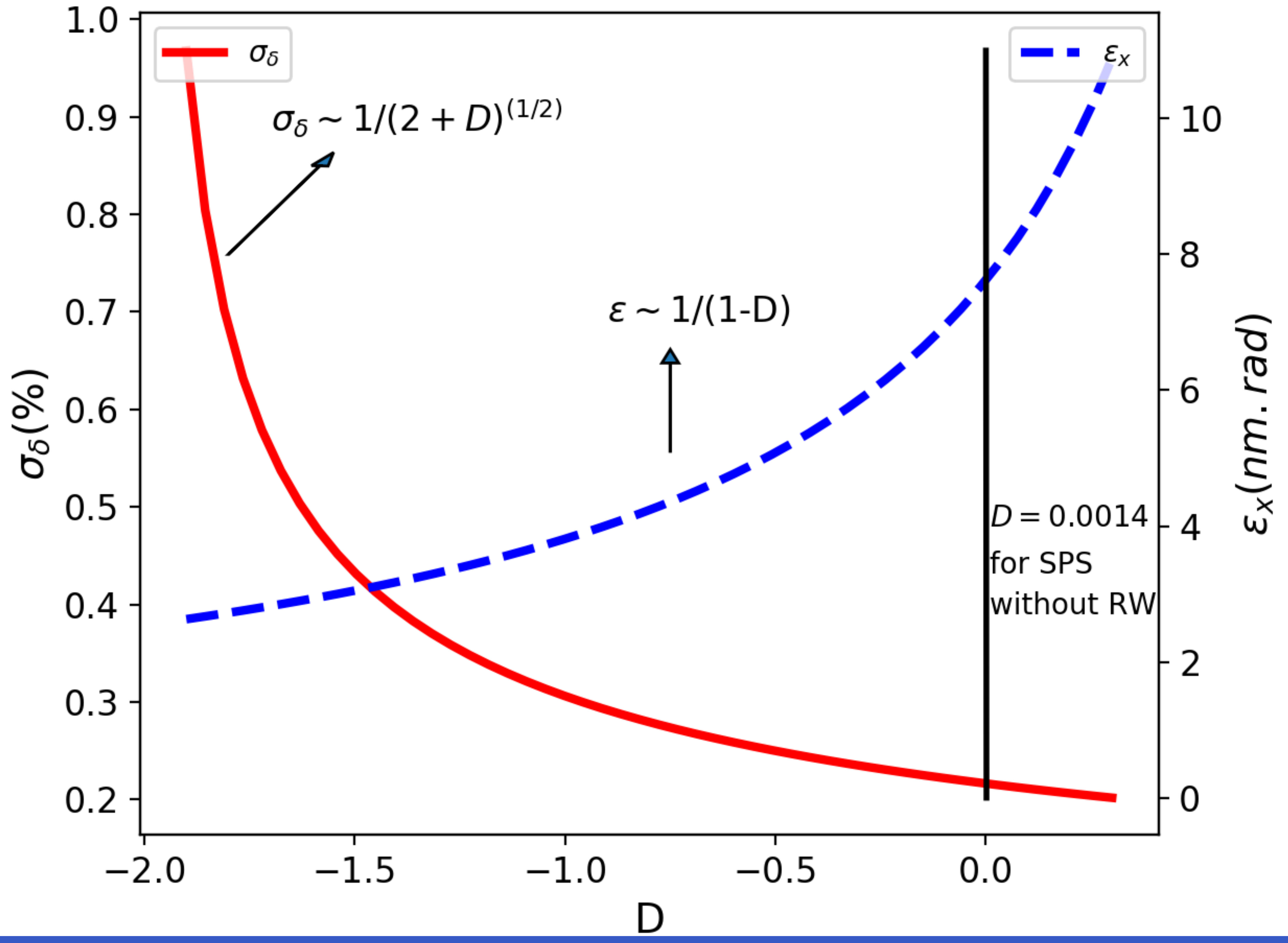
- The required horizontal emittance at extraction and damping time at injection can be achieved for a total wiggler length of 23m and 3.5T peak field.

- For this choice, the **energy loss per turn is however very large (>60MeV).**

FUTURE CIRCULAR COLLIDER

Robinson W. magnets

- The **Robinson wiggler** (RW) is composed by a series of combined function magnets.
- It impacts the damping partition ($D = I_4/I_2$) by modifying the 4th synchrotron radiation integral (I_4).



- By introducing a RW (and thus modifying the damping partition number) the **horizontal emittance** can be significantly decreased, while the **energy spread** is increased.

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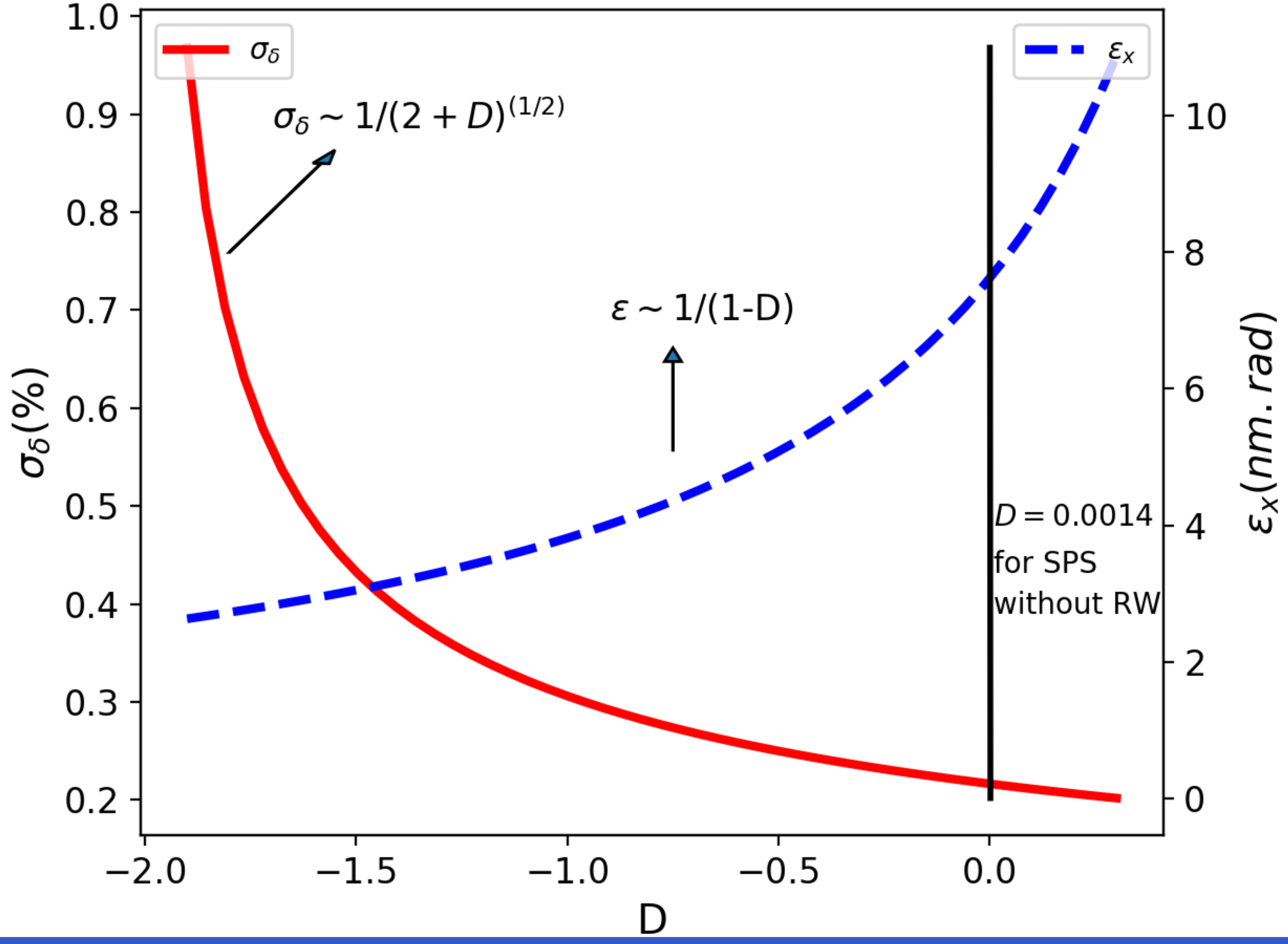


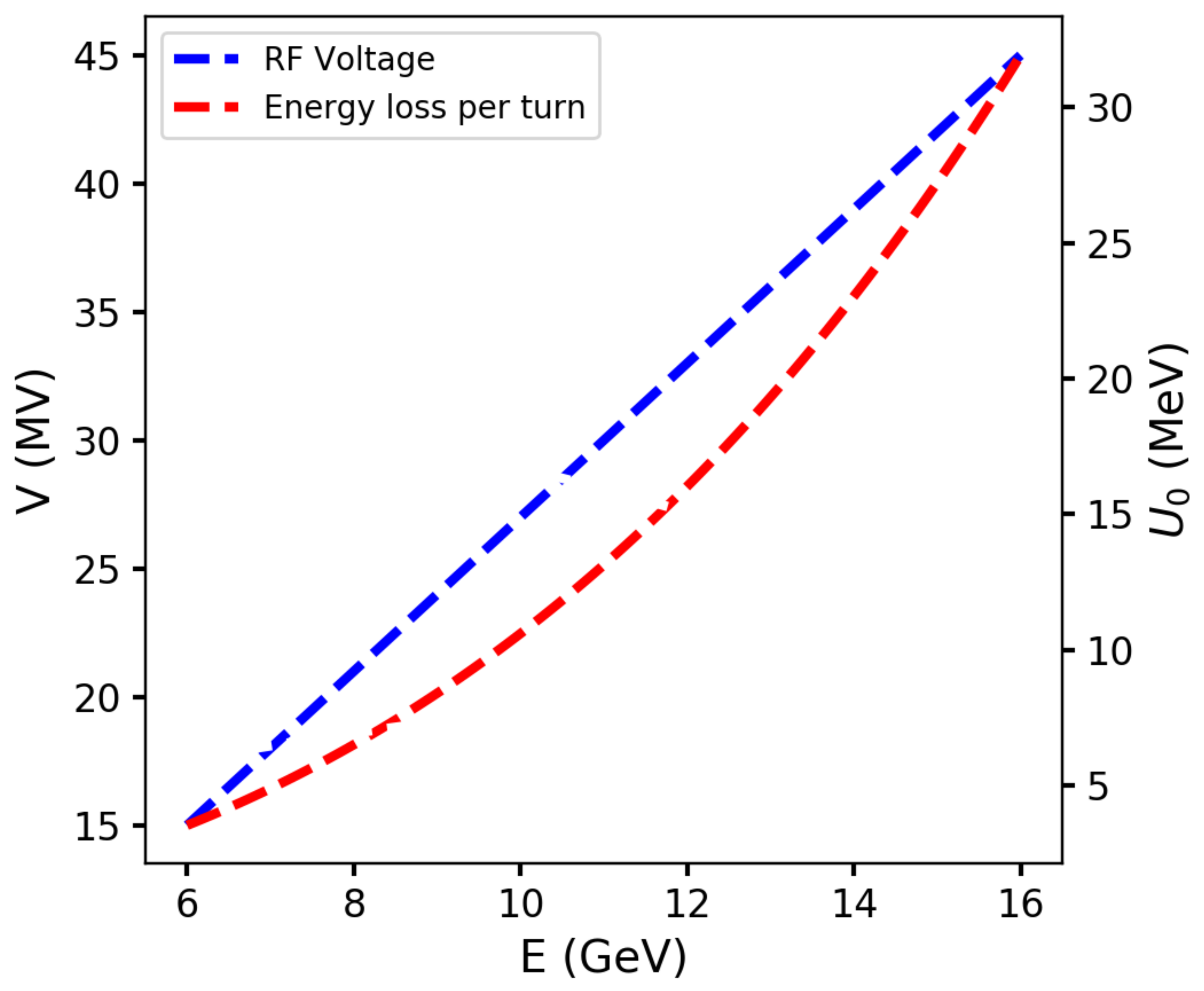
- By introducing a RW (and thus modifying the damping partition number) the **horizontal emittance** can be significantly decreased, while the **energy spread** is increased.

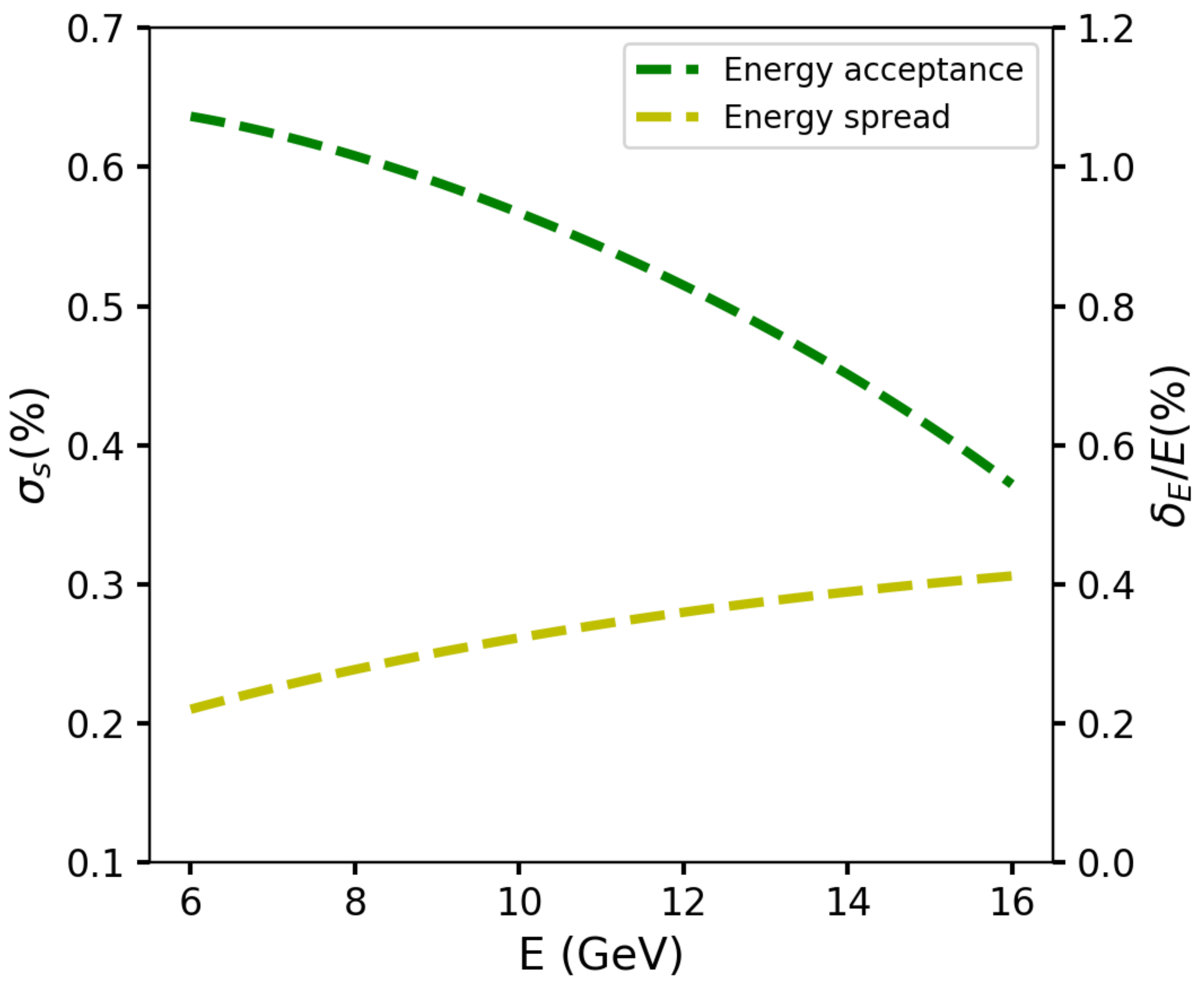
- There is an energy spread **limit (0.3 %) coming from the acceptance of the main BR.**
- The required emittance at extraction can be achieved, while keeping the energy loss per turn in acceptable levels, by using **a combination of damping and Robinson** wiggler magnets.

Energy Acceptance

- The value of the **maximum momentum deviation**, for which a particle may have and **still** undergo **stable synchrotron oscillation**, is called the **momentum acceptance** of the accelerator.

- The energy acceptance of the SPS, at the PBR injection energy, is defined by the mechanical aperture constraints and the limit is 1.0 % at injection for the chosen phase advance.





- The minimum **RF voltage** required for assuring the **1.0% energy acceptance** is **15 MV** at injection and increases up to **45 MV** at extraction energy.
- Challenging RF system is needed.

Dynamic aperture

- Nonlinear effects are introduced by adding sextupoles magnets to the design to correct the chromaticity.
- Maximum stable oscillation amplitudes in x-y spaces due to non-linear fields generate the dynamic aperture.
- The dynamic aperture (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects.
- The working point of a ring is chosen to be away from resonance lines. In order to find a good working point, first, a phase advance optimization study was performed.

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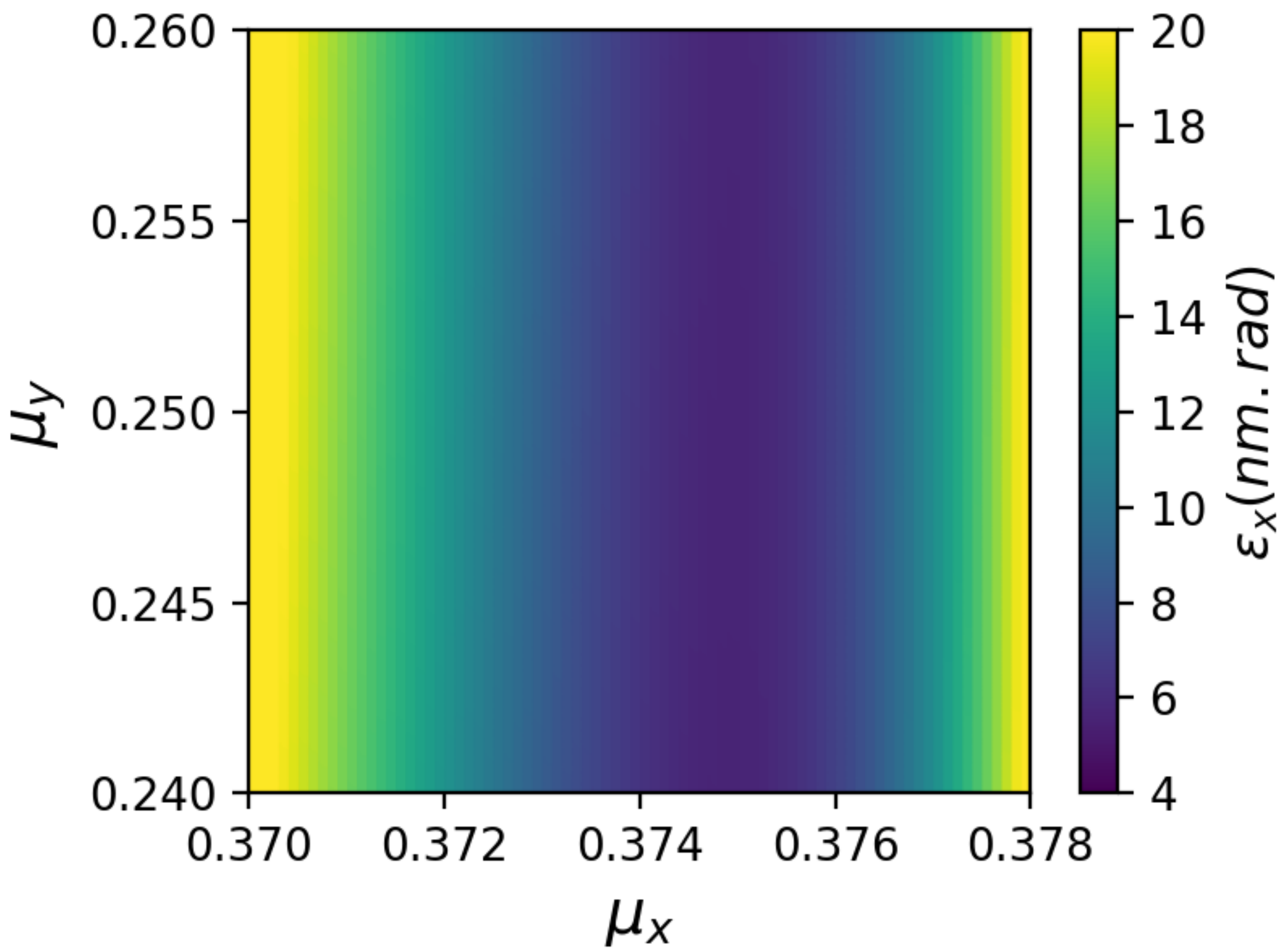
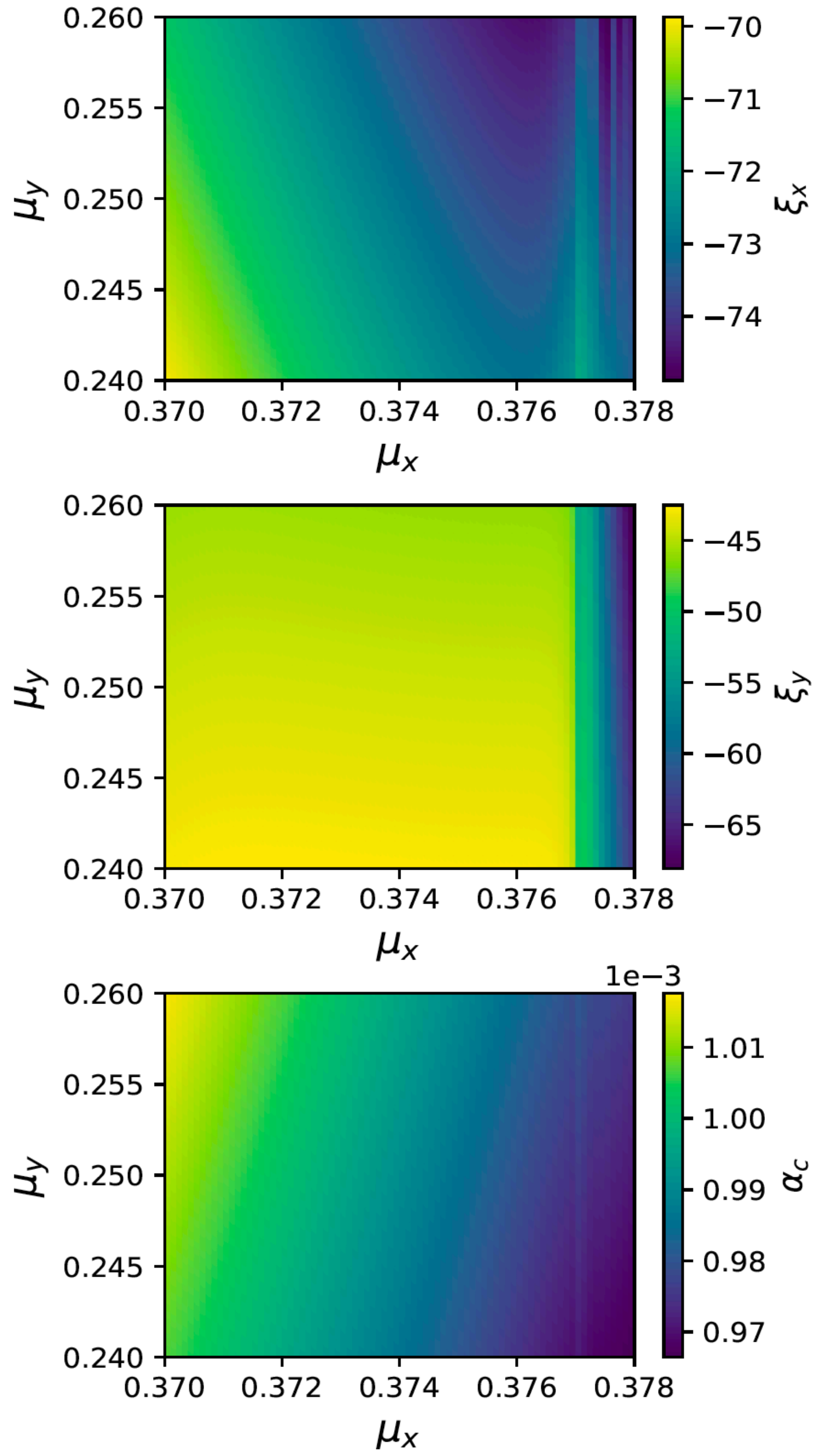
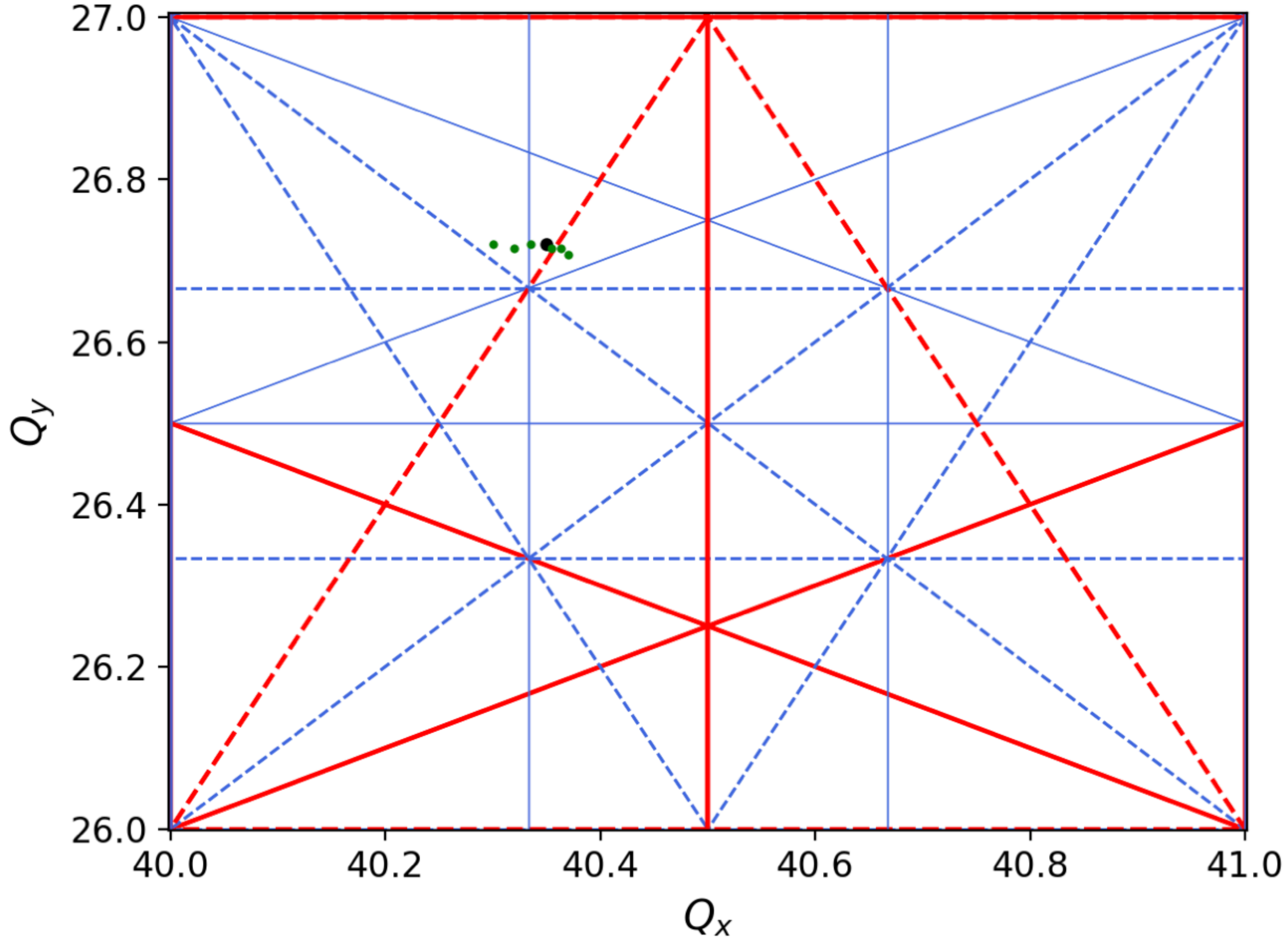




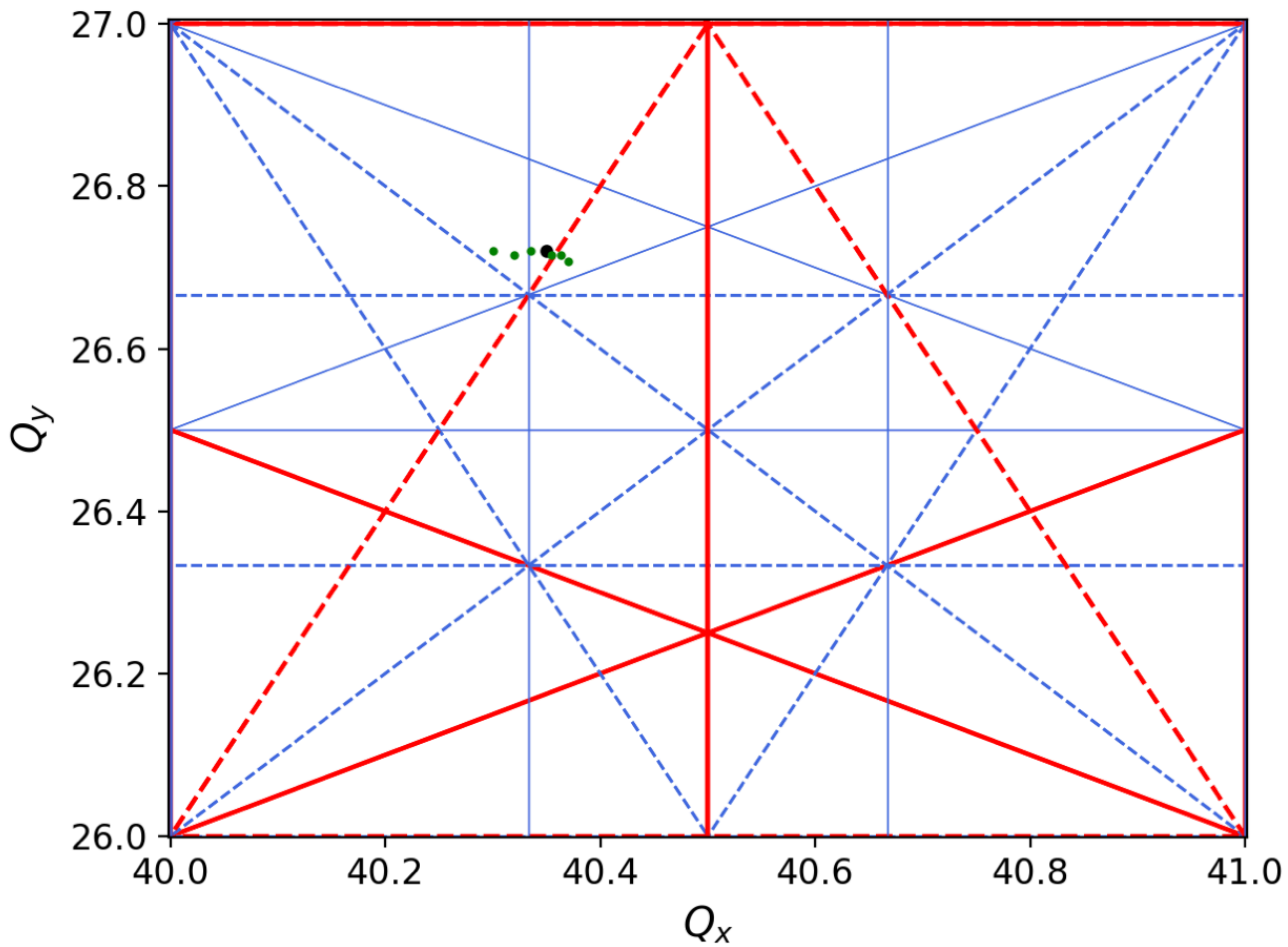
FUTURE CIRCULAR COLLIDER

Dynamic aperture

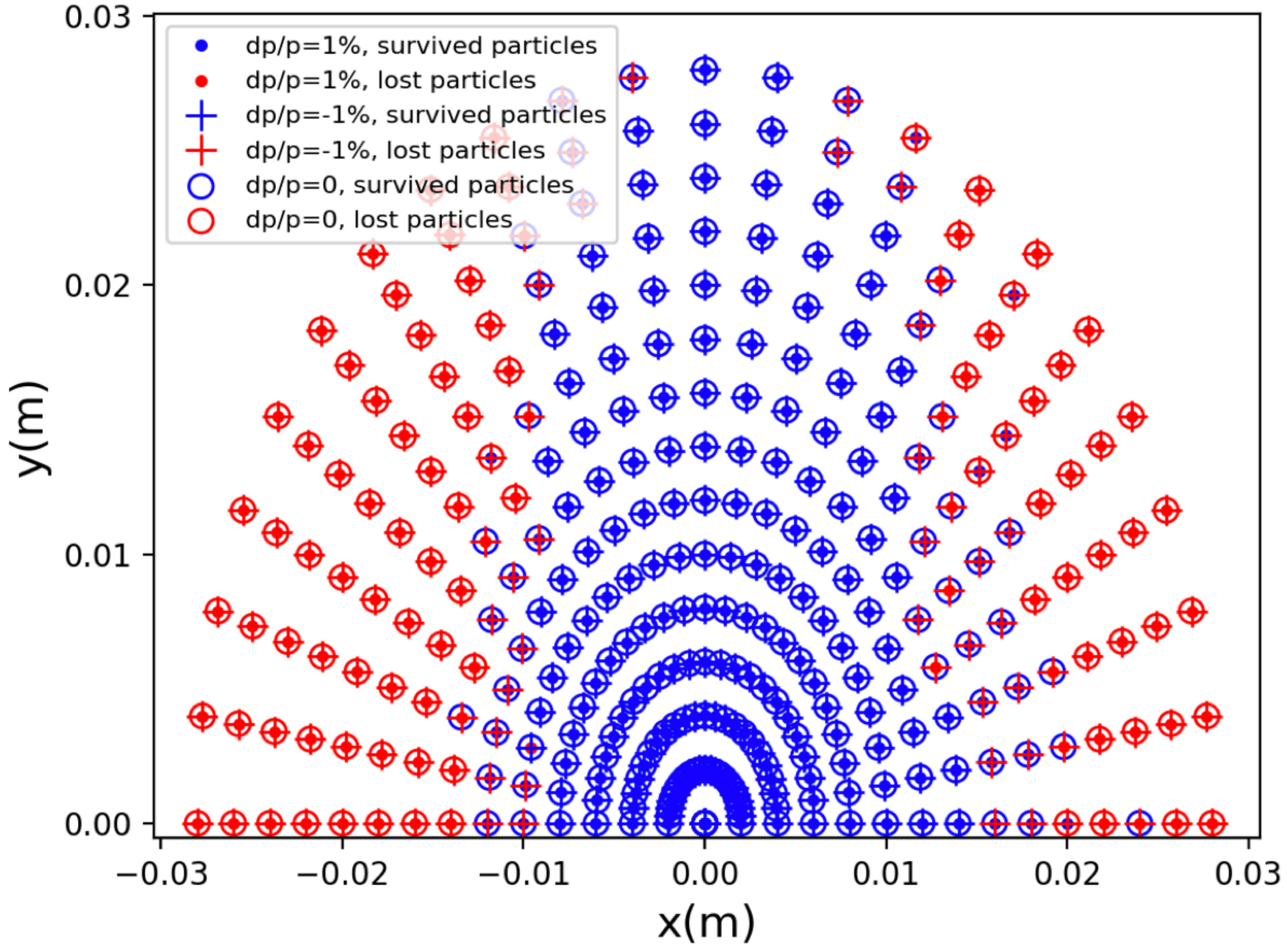


- Tune working point on a resonance diagram up to 3th order
- Systematic **(red)**, non-systematic **(blue)**, normal **(solid)** and skew **(dashed)** resonances
- **Black point** shows the working point and **green points** shows the tune shift with off momentum up to +/-1.0 %

Dynamic aperture



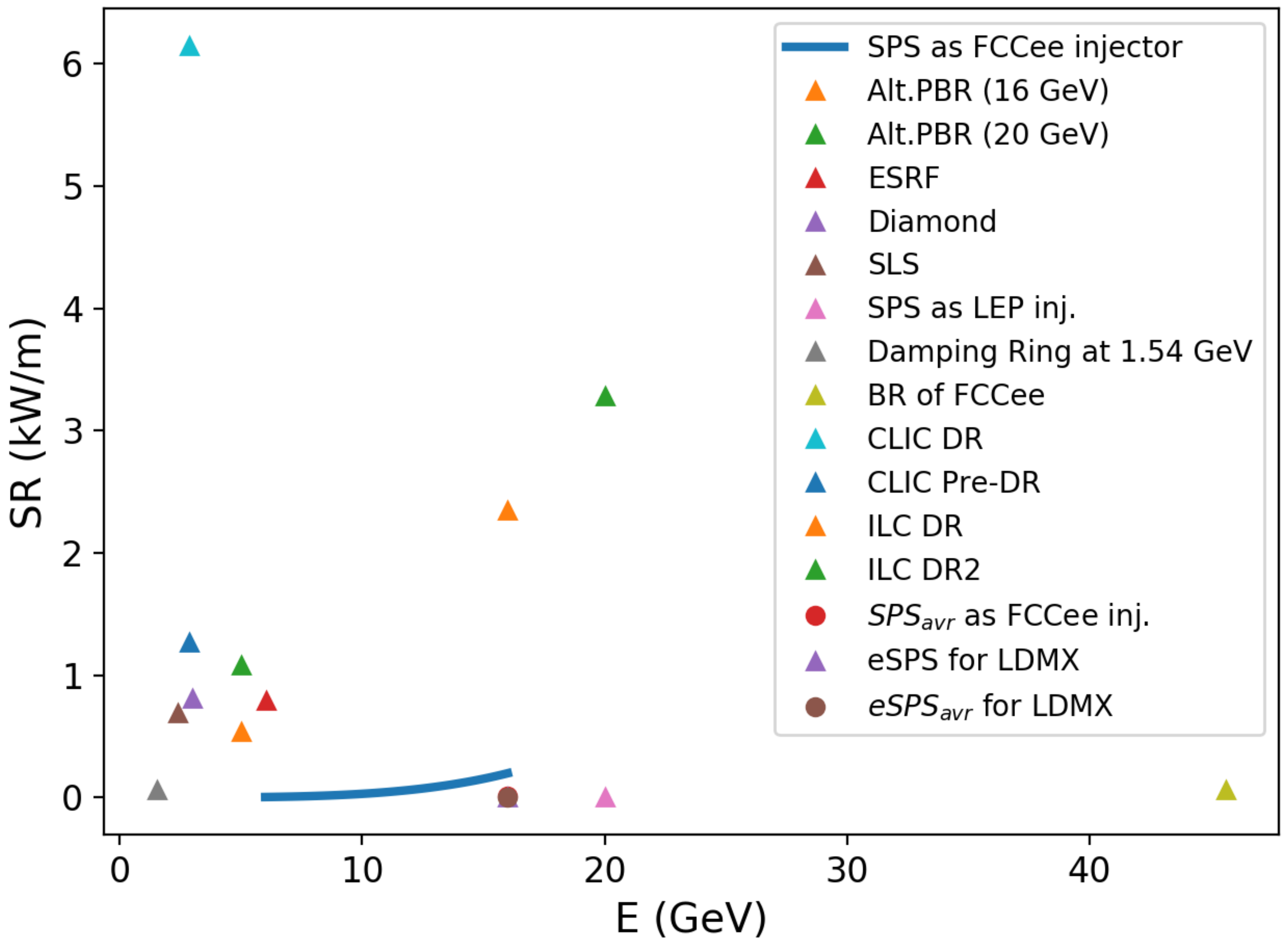
Tune working point on a resonance diagram up to 3th order. Systematic (red), nonsystematic (blue), normal (solid) and skew (dashed) resonances.



Dynamic aperture for different momentum deviations (up to +/-1.0%).

- Particles with different initial conditions were tracked for 4400 turns (around one damping time),
- Sufficient dynamic aperture including off-momentum particles up to +/-1.0 % are achieved for the SPS.

Synchrotron radiation power

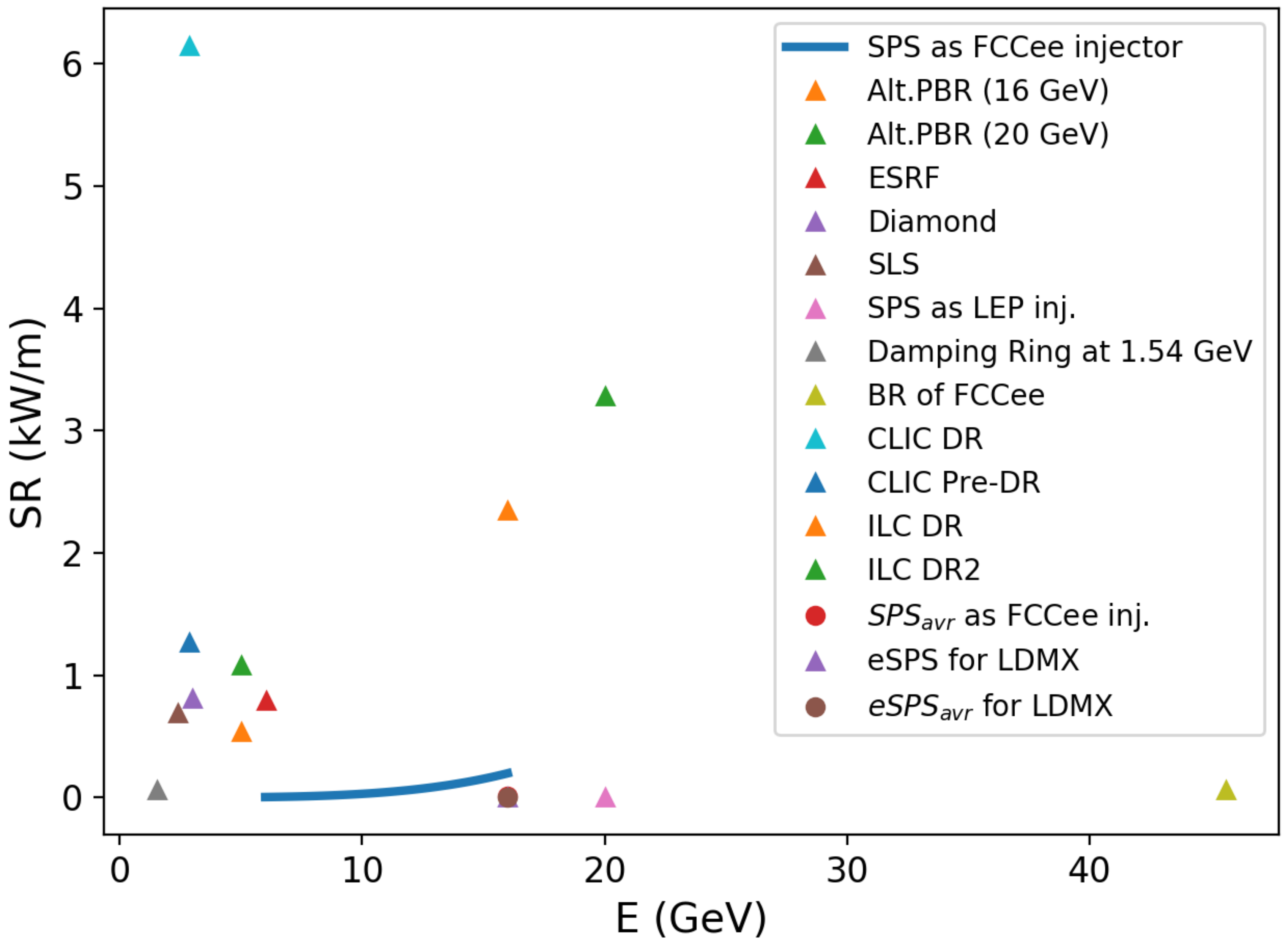


- Strong Synchrotron radiation (SR) may penetrate the vacuum chamber and disturb the vacuum level.
- The **SR power** is proportional to the energy loss per turn ***(U_0)***, total beam current ***(I_{tot})*** and inversely proportional to the circumference ***(C)***:

$$P_{sr}\ [W/m] = \frac{U_0[eV] \cdot I_{tot}[A]}{C[m]}$$

- The PBR ring will operate in a strong SR regime. SR power considerations should be taken into account at this early design stage.

Synchrotron radiation power



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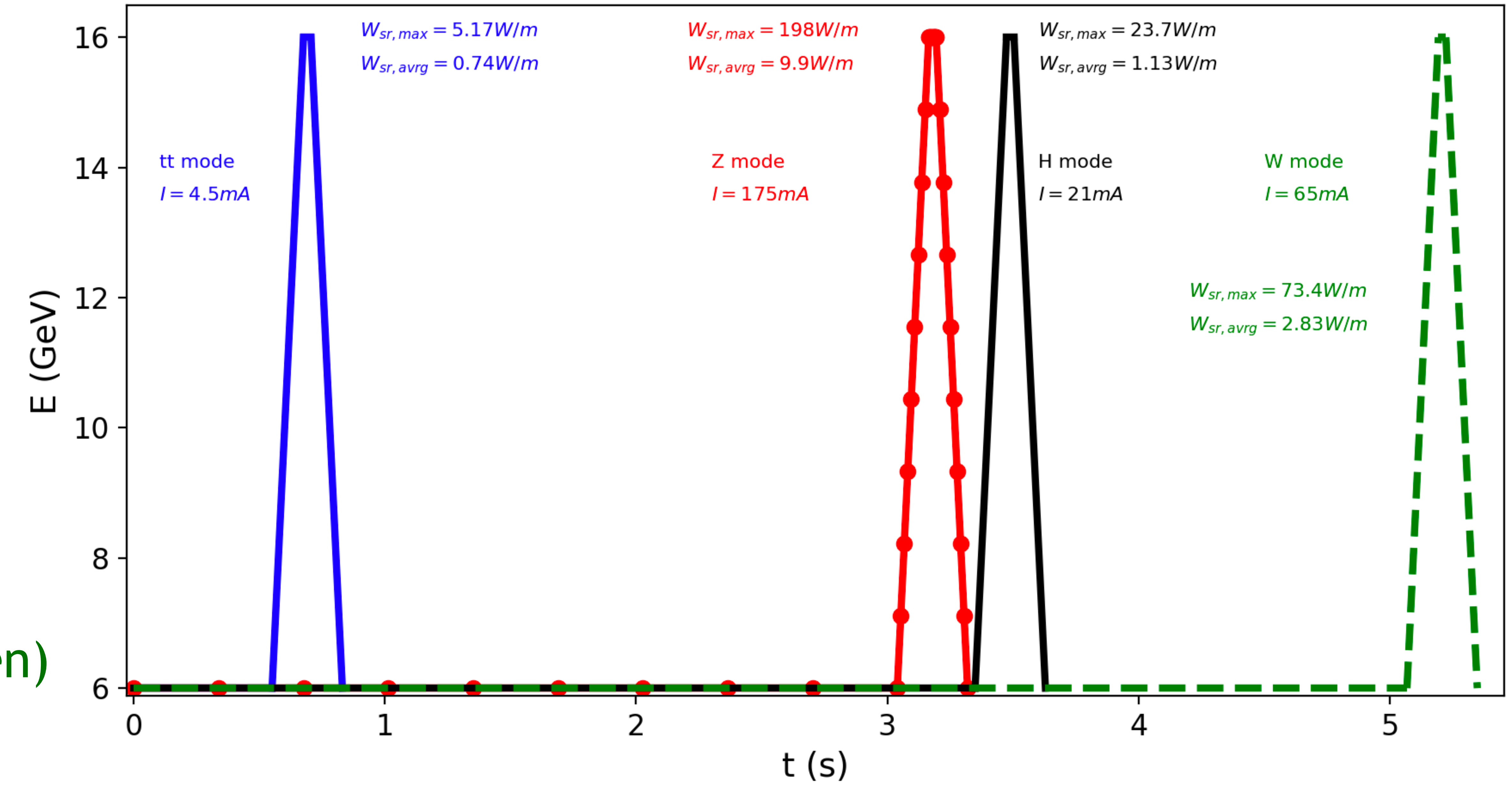
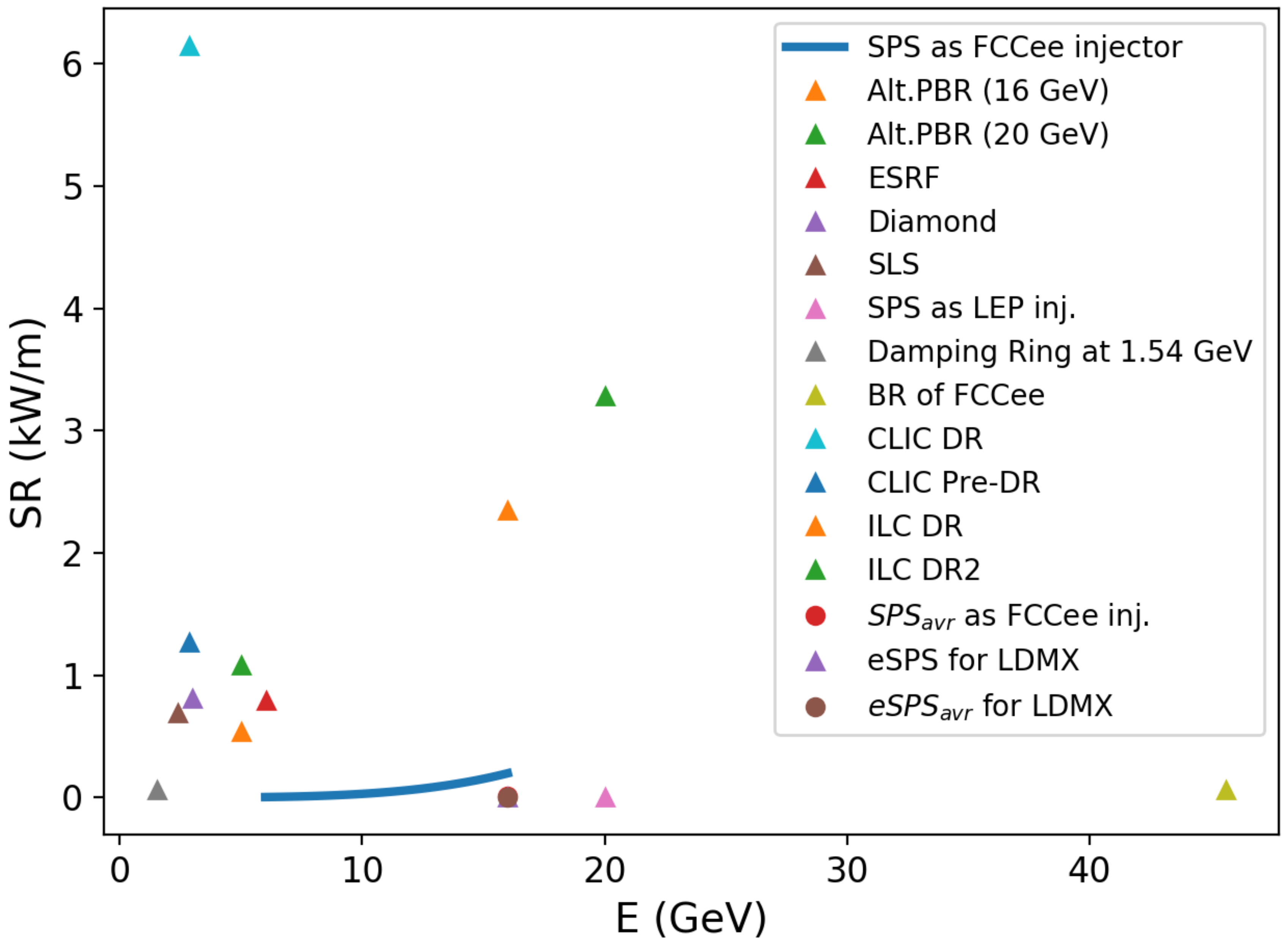


The cycle length of the PBR corresponding to four different modes: tt (blue), Z (red), H (black), W (green)

Synchrotron radiation power



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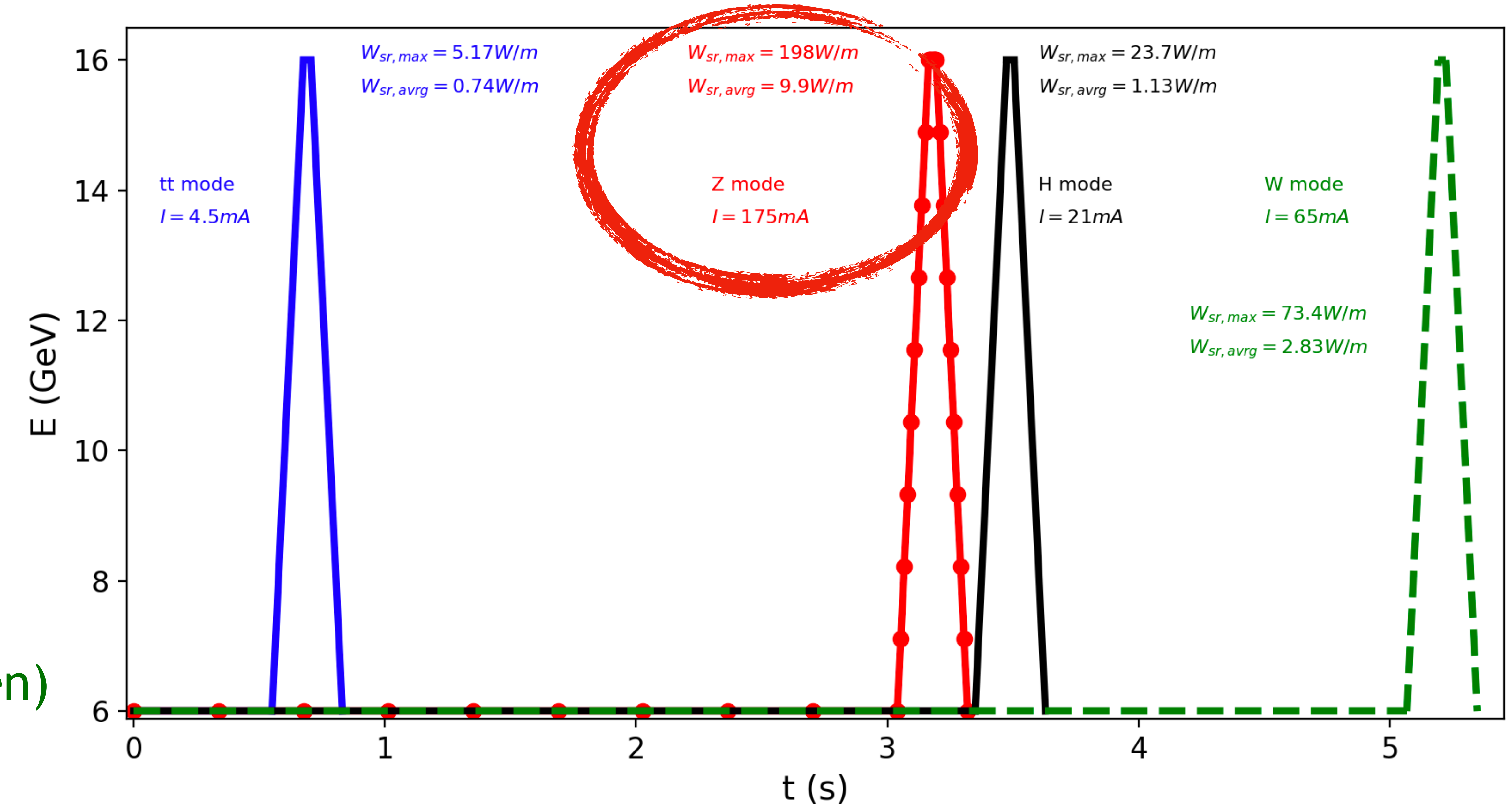
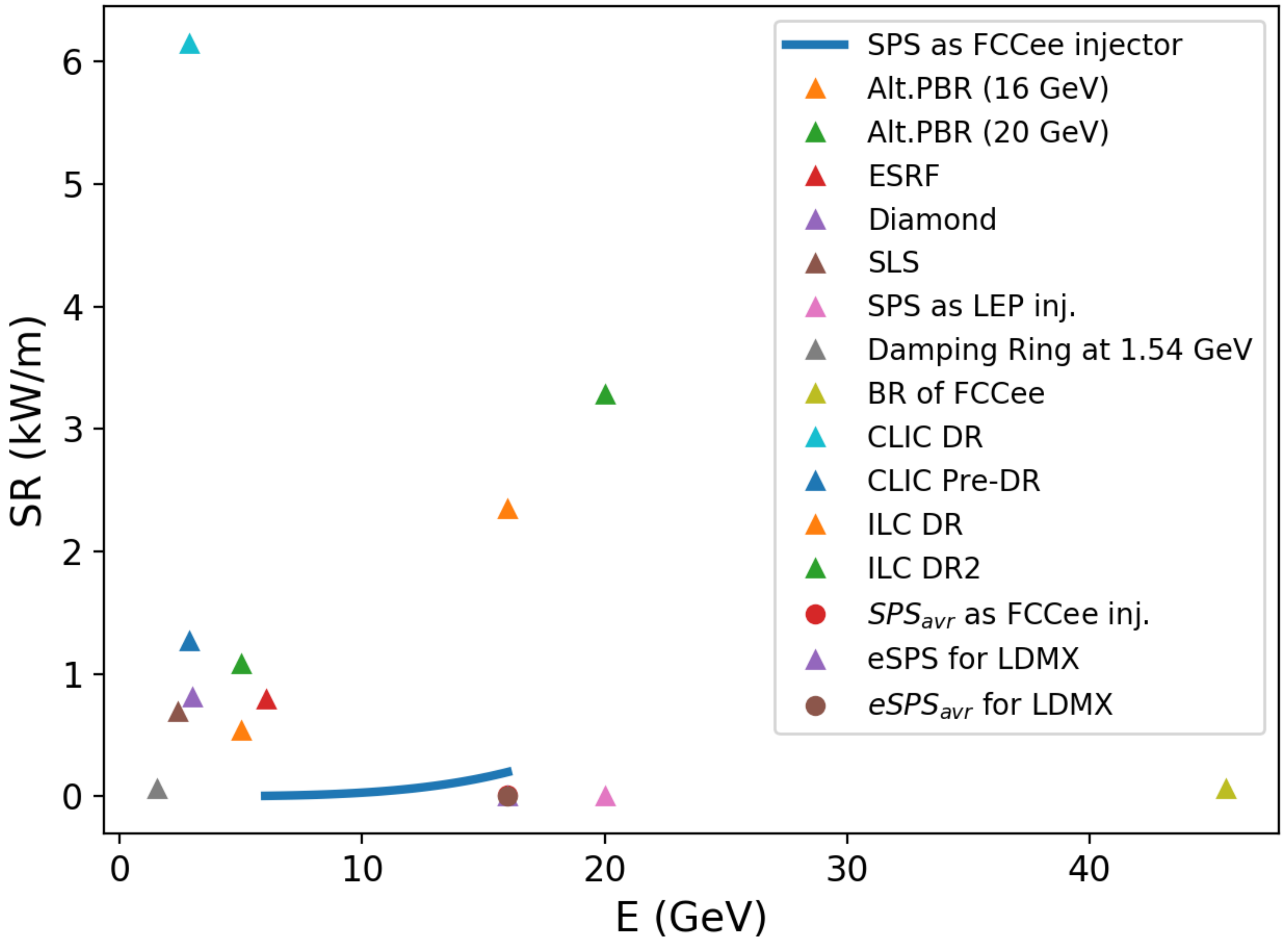


The cycle length of the PBR corresponding to four different modes: tt (blue), Z (red), H (black), W (green)

Synchrotron radiation power



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$$P_{sr}\ [W/m] = \frac{U_0[eV] \cdot I_{tot}[A]}{C[m]}$$

- The PBR ring will operate in a strong SR regime. SR power considerations should be taken into account at this early design stage.

Parameters	**SPS for LEP**	**SPS for FCC**
Extraction energy [GeV]	20	16
SR due to dipole magnets only(W/m)	1.85	198
Average SR due to dipole magnets only (W/m)	0.024	8.1
SR due to dipole and damping wiggler (W/m)	-	809
Average SR due to dipole and damping wiggler (W/m)	-	107
Beam current (mA)	0.45	7-160

- The existing vacuum chamber of the SPS cannot sustain such power loads.
- A **new vacuum system, using properly cooled chambers and absorbers is needed** [Private communication with R. Kersevan].

SPS parameter list

- Based on all the considerations summarized in this presentation, the beam parameters of the SPS ring as the FCC e+e- injector complex are summarized in the table below.

Parameters	Symbol	Injection	Extraction
Beam energy	E [GeV]	**6**	**16**
Geo. emittance [nm.rad] (hor.)	ϵ_x [nm . rad]	0.73	**5.6**
Bunch length	σ_z[mm]	41	55
Momentum spread	σ_δ	0.3 x 10^{-2}	**0.38 x 10^{-2}**
Circumference	C [m]	6911.5	
Harmonic number	h	9215	
Mom. comp. factor	α_c	0.98 x 10^{-3}	
Tunes [h/v/s]	$Q_{h/v}$	40.38/26.7/0.08	
Energy loss per turn	U_0 [MeV]	3.4	**31.5**
Damping times [h/v/l]	$\tau_{h/v/l}$ [s]	**0.03/0.03/0.015**	0.01/0.01/0.005
RF frequency	F_{rf} [MHz]	400	
RF voltage	V_{rf} [MV]	15	45
Bending magnet length	l_{bend} [m]	6.26	
Field of bending magnet	B_{dipole} [T]	0.026	0.071
Nat. chromaticity	$\xi_{h/v}$	-72/-40	
Number of bending magnets	N_{bend}	744	
Number of damping wiggler	N_{dw}	6	
Period of damping wiggler	λ_{dw} [m]	0.05	
Field of damping wiggler	B_{dw} [T]	3.5	
Length of damping wiggler	l_{dw} [m]	12.15	
Length of Robinson wiggler magnet (in total)	l_{rw} [m]	6	
Field of Robinson wiggler magnet	B_{rw} [T]	0.5	
Number of Robinson wiggler magnet	N_{rw}	3	
Energy acceptance	$\frac{\delta E}{E}$ [%]	1.0	

Different energy discussions

- The extraction energy was planned as 20 GeV in the earlier stages of the project.
- As this option leads to a very large energy loss per turn, different extraction energy options were investigated and the results are summarized below.

	20 GeV option			
	@ injection		@ extraction	
	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler
Emittance (nm.rad)	**1.03**	4.88	5.92	54.25
Energy loss per turn (MeV)	**9.96**	0.15	128.0	19.09
Damping time (s)	0.012	1.79	**0.003**	0.048
Energy spread (%)	**%0.3**	%0.01	%0.60	%0.06
RF Voltage (MV)	**35**		160	
Damping wiggler B[T] / L [m]	6 / 12.15			
Robinson wiggler B[T] / L [m]	0.5 / 12			

Different energy discussions

- The extraction energy was planned as 20 GeV in the earlier stages of the project.
- As this option leads to a very large energy loss per turn, different extraction energy options were investigated and the results are summarized below.

	20 GeV option				18 GeV option			
	@ injection		@ extraction		@ injection		@ extraction	
	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler
Emittance (nm.rad)	**1.03**	4.88	**5.92**	54.25	**0.95**	4.88	**5.60**	43.9
Energy loss per turn (MeV)	**9.96**	0.15	**128.0**	19.09	**6.97**	0.15	**73.9**	12.5
Damping time (s)	**0.012**	1.79	**0.003**	0.048	**0.01**	1.79	**0.005**	0.06
Energy spread (%)	**%0.3**	%0.01	**%0.60**	%0.06	**%0.35**	%0.01	**%0.5**	%0.05
RF Voltage (MV)	**35**		**160**		**30**		**90**	
Damping wiggler B[T] / L [m]	6 / 12.15				5 / 12.15			
Robinson wiggler B[T] / L [m]	0.5 / 12				0.5 / 12			

Different energy discussions

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- As this option leads to a very large energy loss per turn, different extraction energy options were investigated and the results are summarized below.

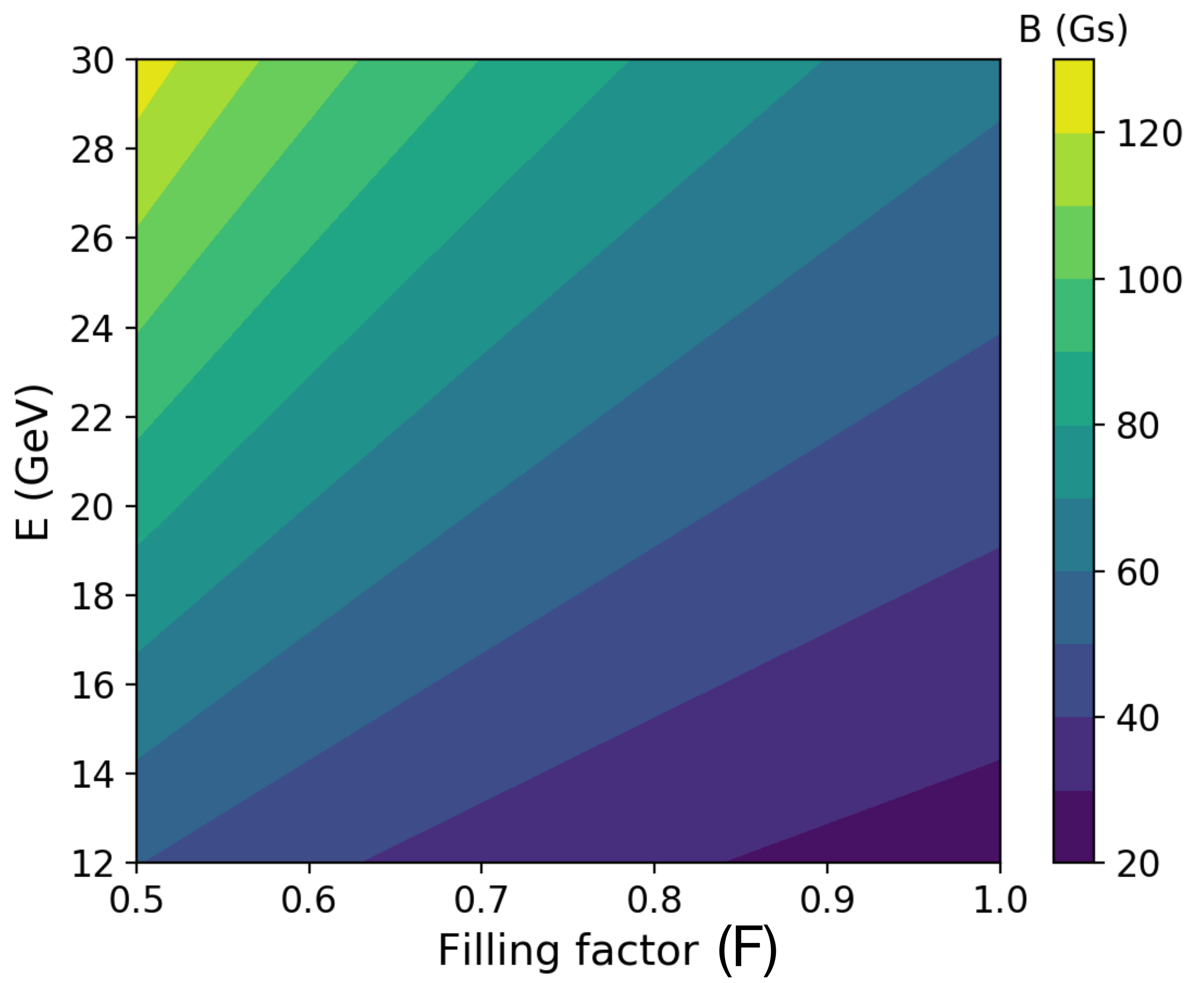
	20 GeV option				18 GeV option				16 GeV option			
	@ injection		@ extraction		@ injection		@ extraction		@ injection		@ extraction	
	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler	w/ wiggler	w/ out wiggler
Emittance (nm.rad)	**1.03**	4.88	**5.92**	54.25	**0.95**	4.88	**5.60**	43.9	0.73	4.88	5.64	34.7
Energy loss per turn (MeV)	**9.96**	0.15	**128.0**	19.09	**6.97**	0.15	**73.9**	12.5	3.49	0.15	31.5	7.82
Damping time (s)	**0.012**	1.79	**0.003**	0.048	**0.01**	1.79	**0.005**	0.06	0.03	1.79	0.01	0.09
Energy spread (%)	**%0.3**	%0.01	**%0.60**	%0.06	**%0.35**	%0.01	**%0.5**	%0.05	%0.3	%0.01	%0.38	%0.05
RF Voltage (MV)	**35**		**160**		**30**		**90**		25		40	
Damping wiggler B[T] / L [m]	6 / 12.15				5 / 12.15				3.5 / 12.15			
Robinson wiggler B[T] / L [m]	0.5 / 12				0.5 / 12				0.5 / 6			

- It becomes clear that the 16 GeV option provides a reasonable energy spread, energy loss per turn and emittance at the same time.

Outline

- Introduction
- FCC-e^+e^- injector complex
- FCC-e^+e^- pre-injector design
  - e-source and linac
  - Positron source
  - Damping ring
- **Pre-booster ring design for FCC-e^+e^- injector complex**
  - SPS as FCC-e^+e^- pre-booster ring
  - Conceptual design of an alternative pre-booster ring
- Collective effect calculations
- More options for the injector complex
- Main booster ring
- Physics + Design + Prototyping
- Conclusion

Parameter Scaling

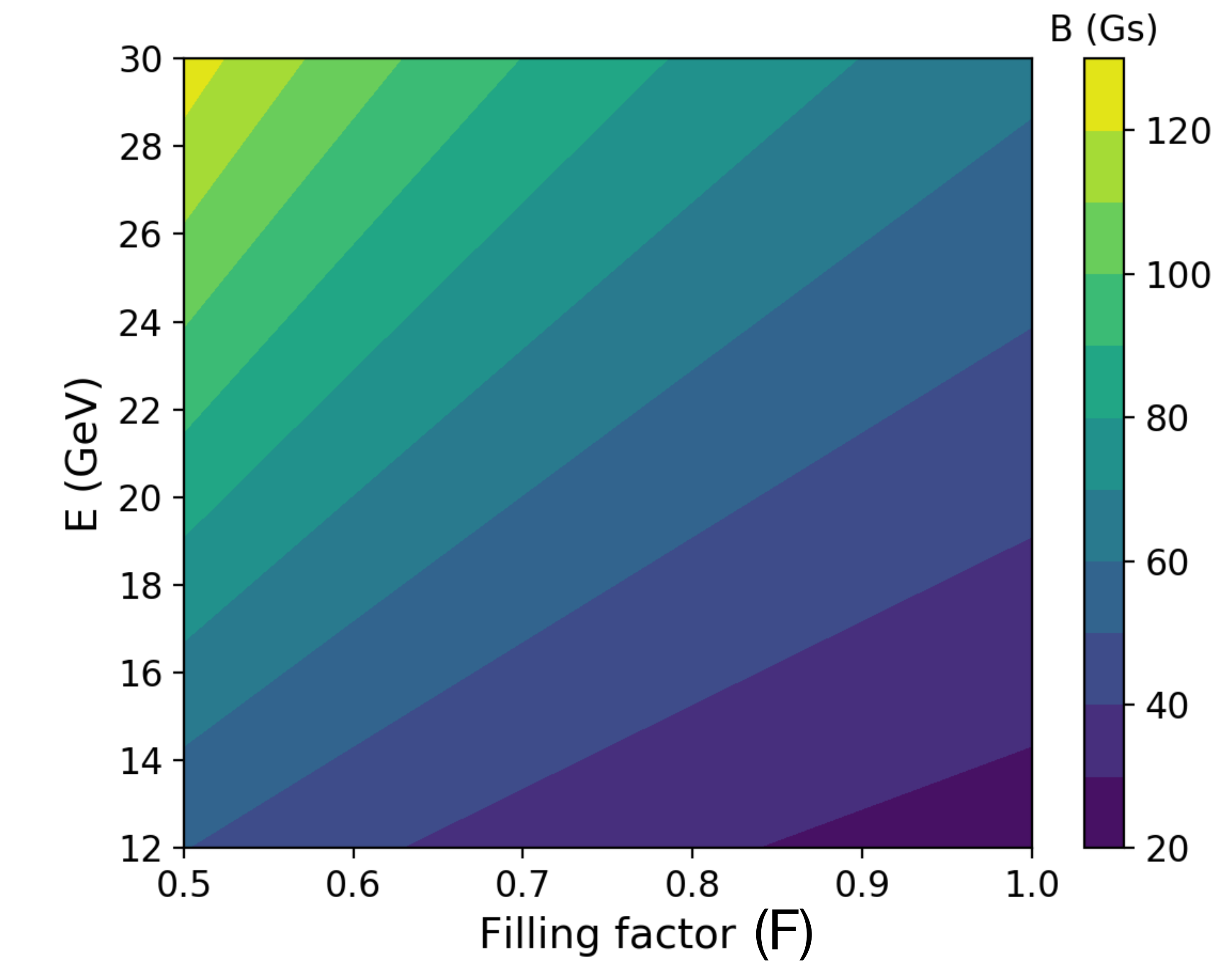


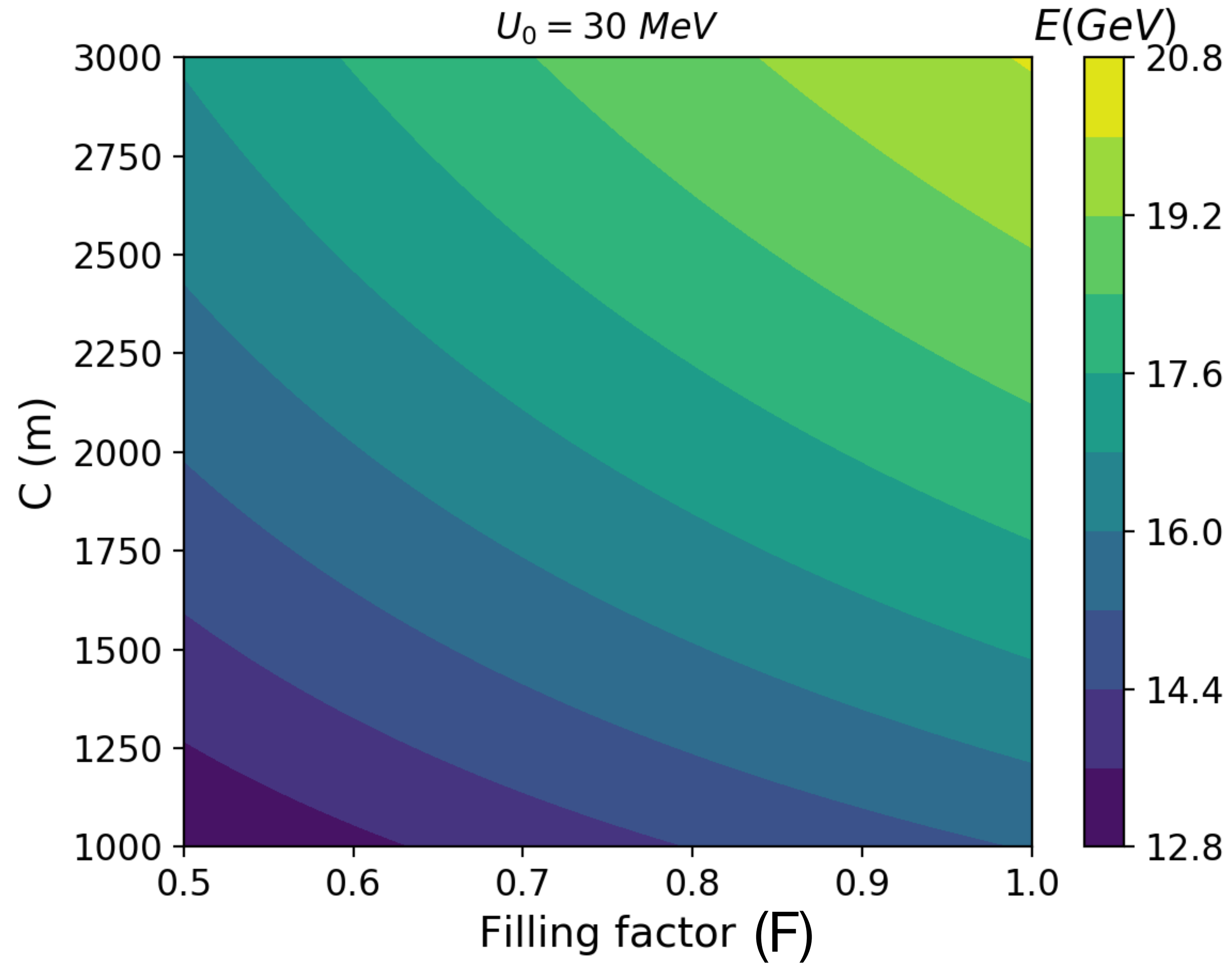
- The extraction energy of the PBR is defined by the main BR.

$$B = \frac{2\pi E}{FCc} \quad ; \quad F = \frac{N.l}{C}$$

- A lowest limit of 50 Gauss was considered for the dipole magnet field (B) of the main BR
- Based on the above considerations, the extraction energy of the PBR was set to 16 GeV (18 GeV and 20 GeV options were also studied)

Parameter Scaling





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- Based on the above considerations, the extraction energy of the PBR was set to 16 GeV (18 GeV and 20 GeV options were also studied)

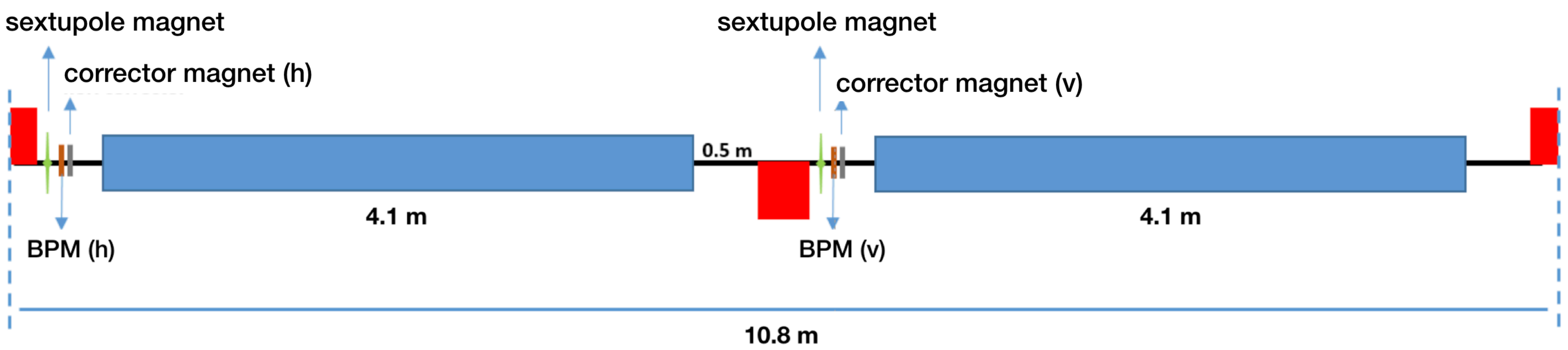
- For an energy loss per turn (U_o) of 30 MeV and an extraction energy of 16 GeV, the required machine circumference (C) of the alternative PBR design was estimated around **2 km**.

$$U_0 = \frac{2\pi C_\gamma E^4}{FC}$$

Main cells in the lattice

- A FODO type cell is chosen.
- The cell consists of two 4.1 m-long dipoles sandwiched between quadrupoles with 30 cm length.
- The natural chromaticity is compensated by two families of 20 cm long sextupoles in the arcs of the ring.
- Zero-dispersion straight sections (designed with identical bending-free cells) in order to accommodate the RF system, injection and extraction.

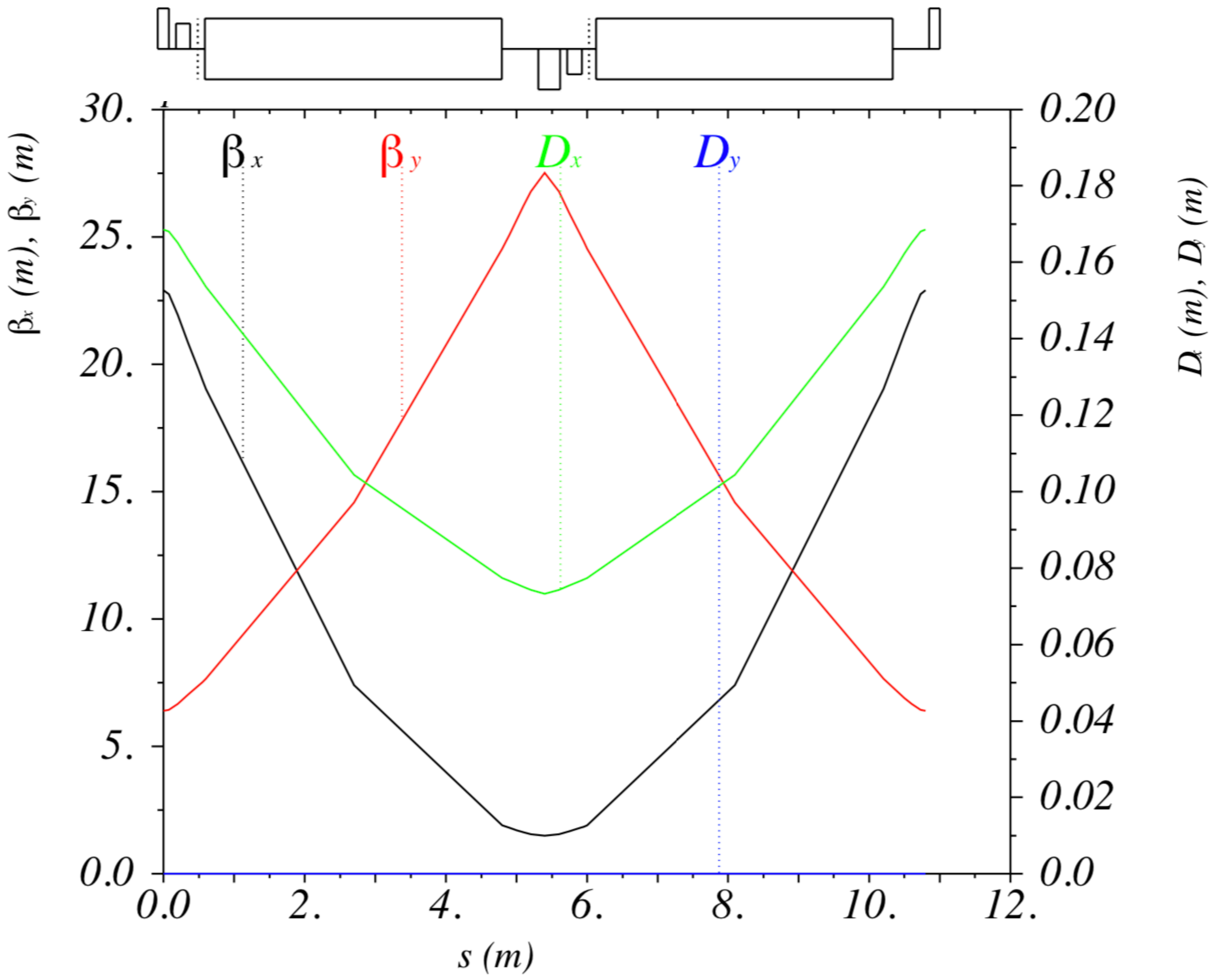
Parameters	Value
Number of bending magnets	304
Magnet length [m]	4.1
Bending angle [degree]	1.18
Max. magnetic field [T]	0.27
Min. magnetic field [T]	0.1



Main cells in the lattice

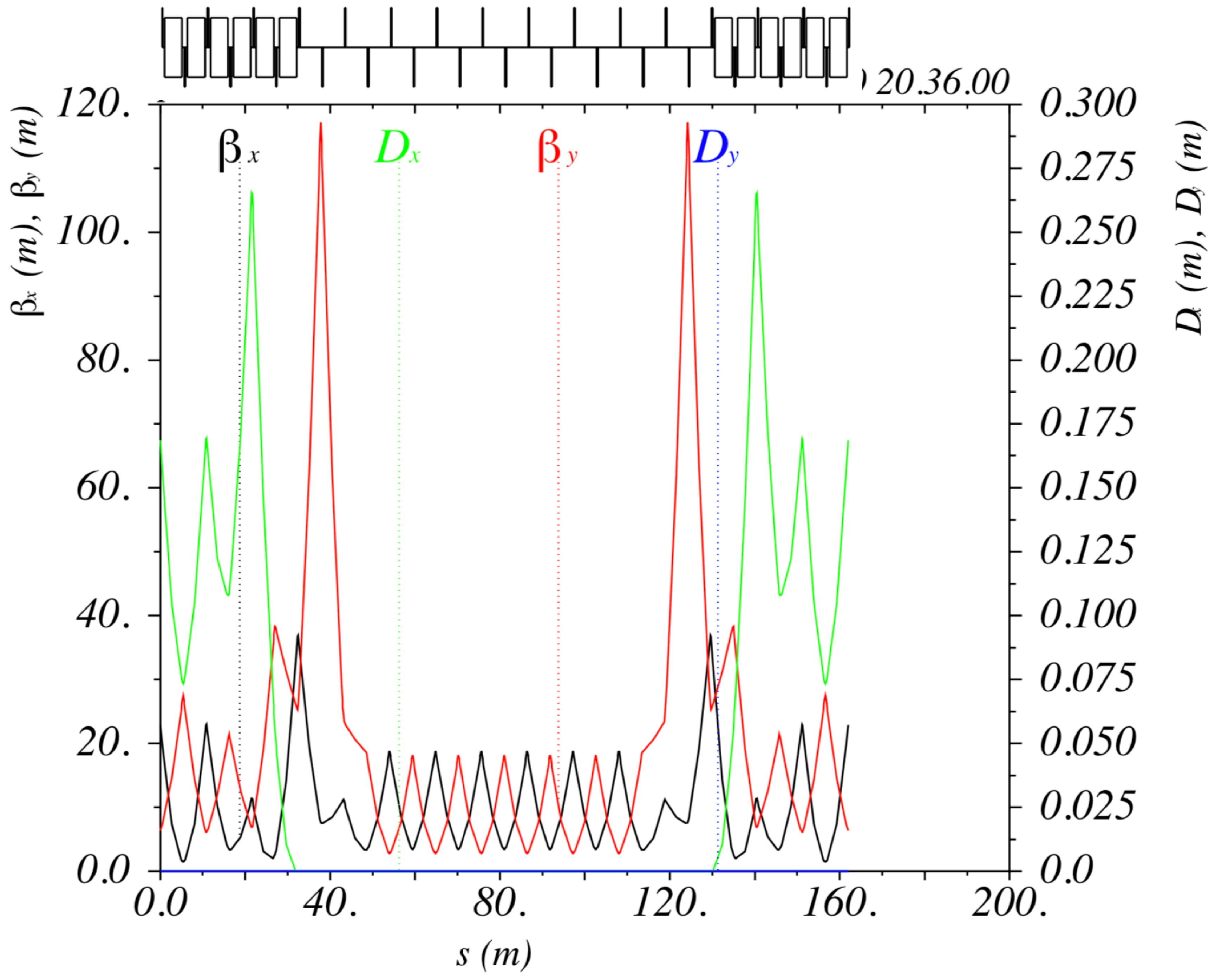
- **FODO cell:** sequence of focusing and defocusing quadrupoles which are separated by drift or dipole magnets

- One **arc** of the alternative PBR consists of **32 FODO** cells



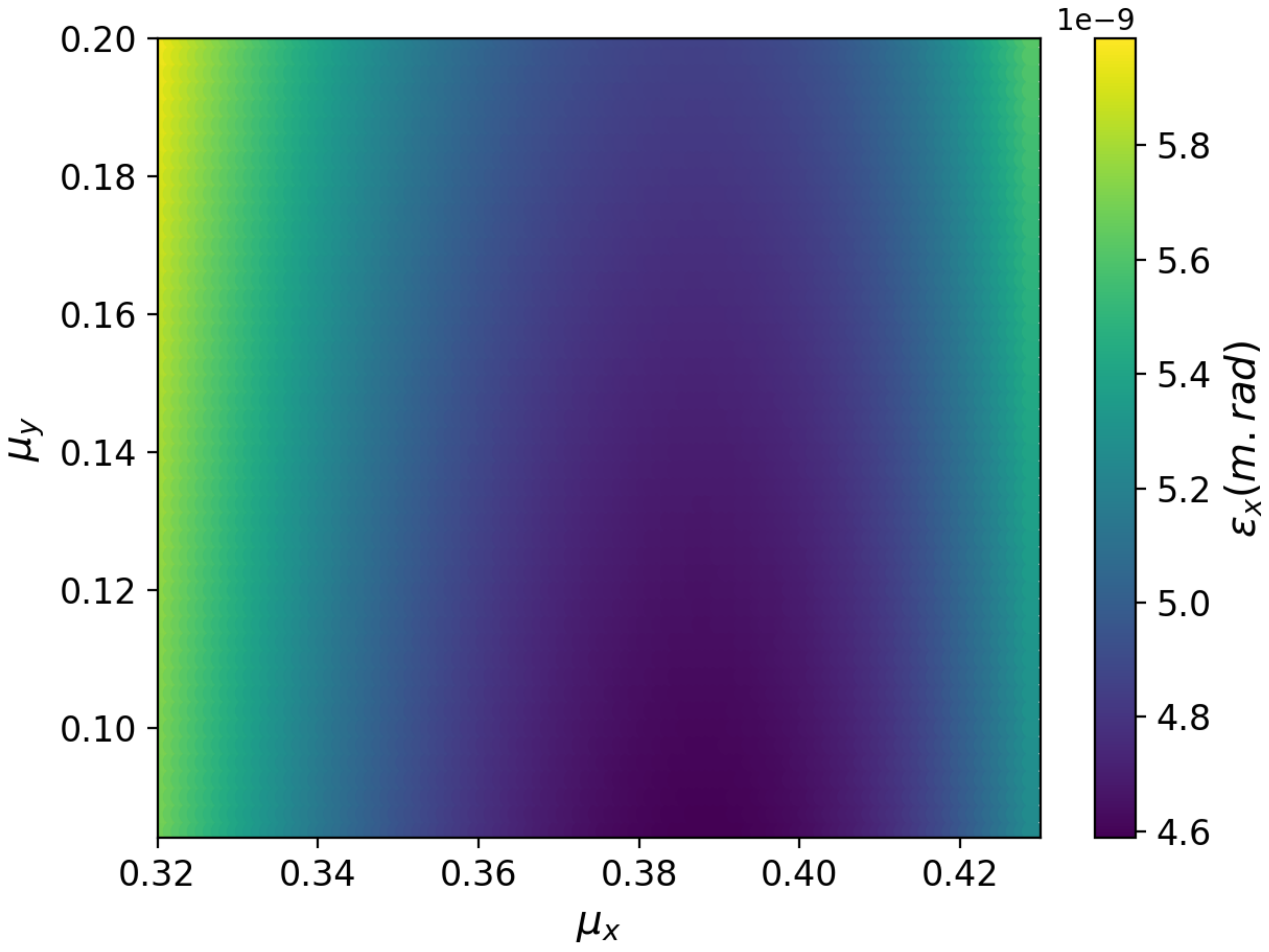
- **Straight sections** (5 cells) allocated for
  - **RF** elements
  - **Injection** and **extraction** elements
  - Possible **insertion devices** if needed

- **Matching section:**
  - For betatron and dispersion functions matching between the arc and straight section



Phase advance optimization

- h/v **emittance** is mainly determined **by the dipoles in the arcs** of the ring.
- A numerical parametrization of the equilibrium horizontal emittance with the horizontal and vertical phase advances of the arc FODO cell was performed.



- **The minimum emittance** can be achieved for a horizontal phase advance of $\sim$ **0.383**.
- Minimal dependence on the vertical phase advance.

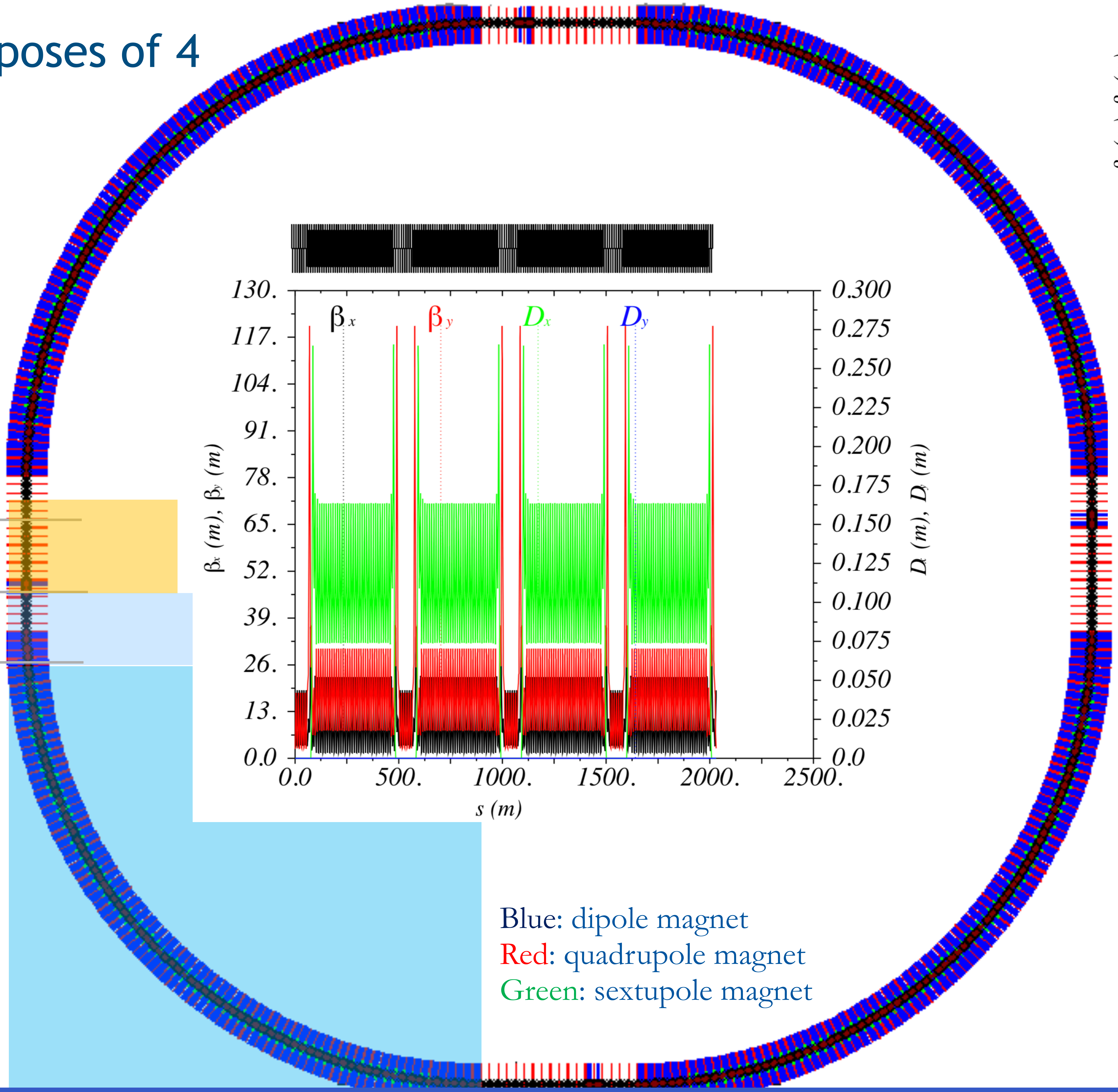
Layout of the alternative PBR

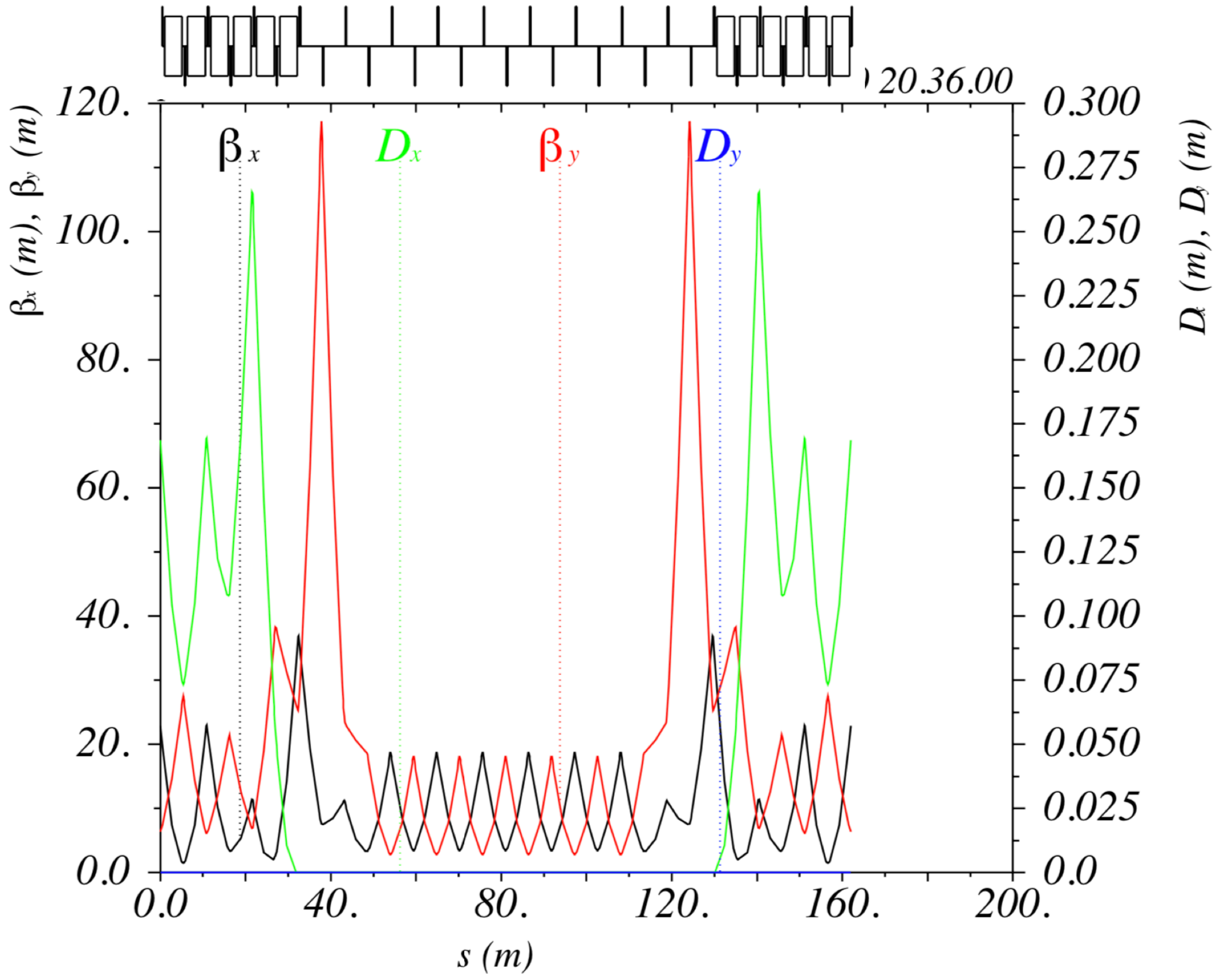
The design of the PBR composes of 4 arcs and 4 straight sections.

Zero-dispersion section
cells with close to 90⁰ phase advance

Dispersion suppressor and beta matching area

Arc: 32 FODO cells with optimum phase advance for low emittance





Straight sections:
- 5 cells,
- Allocated for
  - RF elements,
  - Injection and extraction elements,
  - Possible insertion devices if needed.

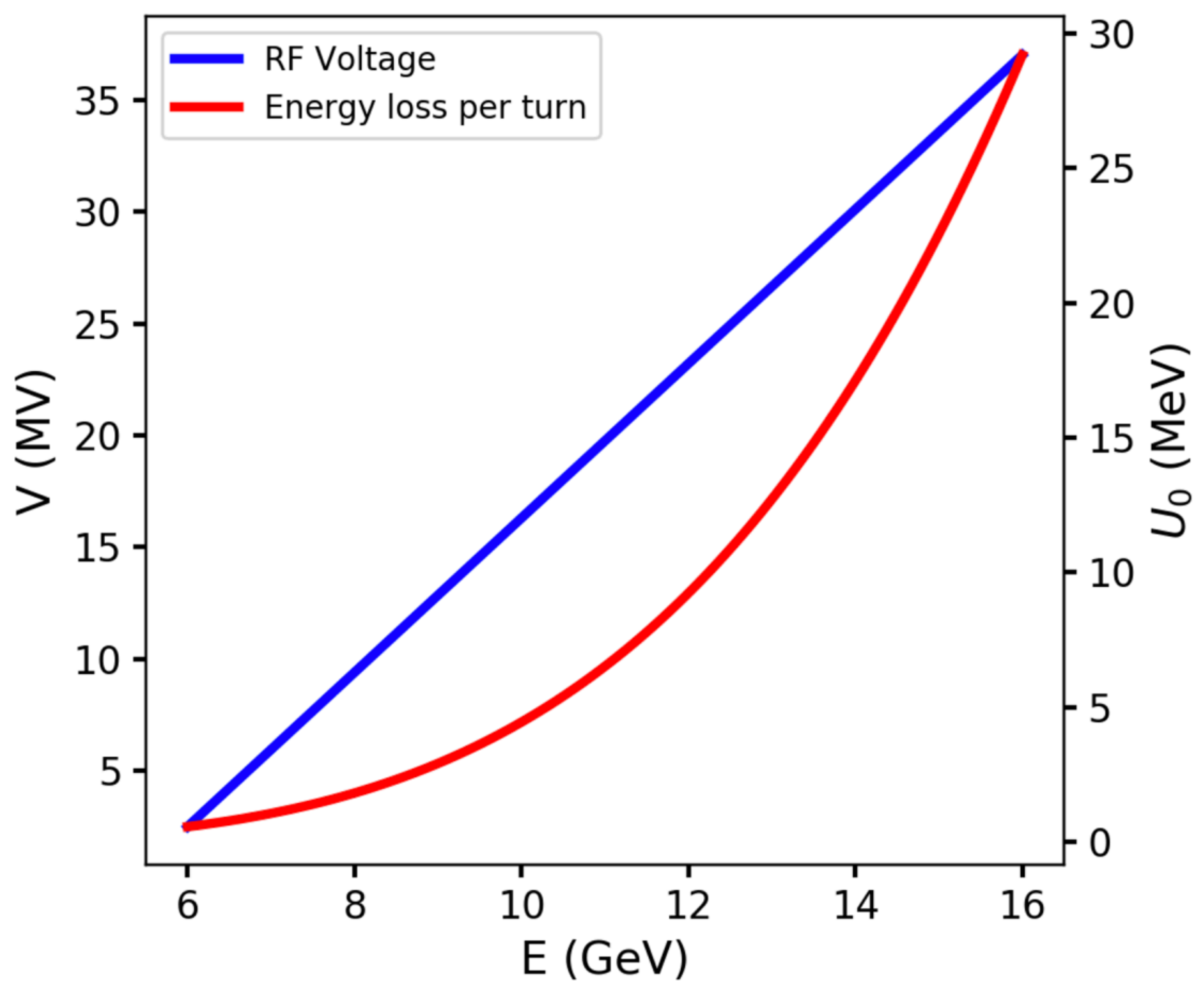
Energy Acceptance

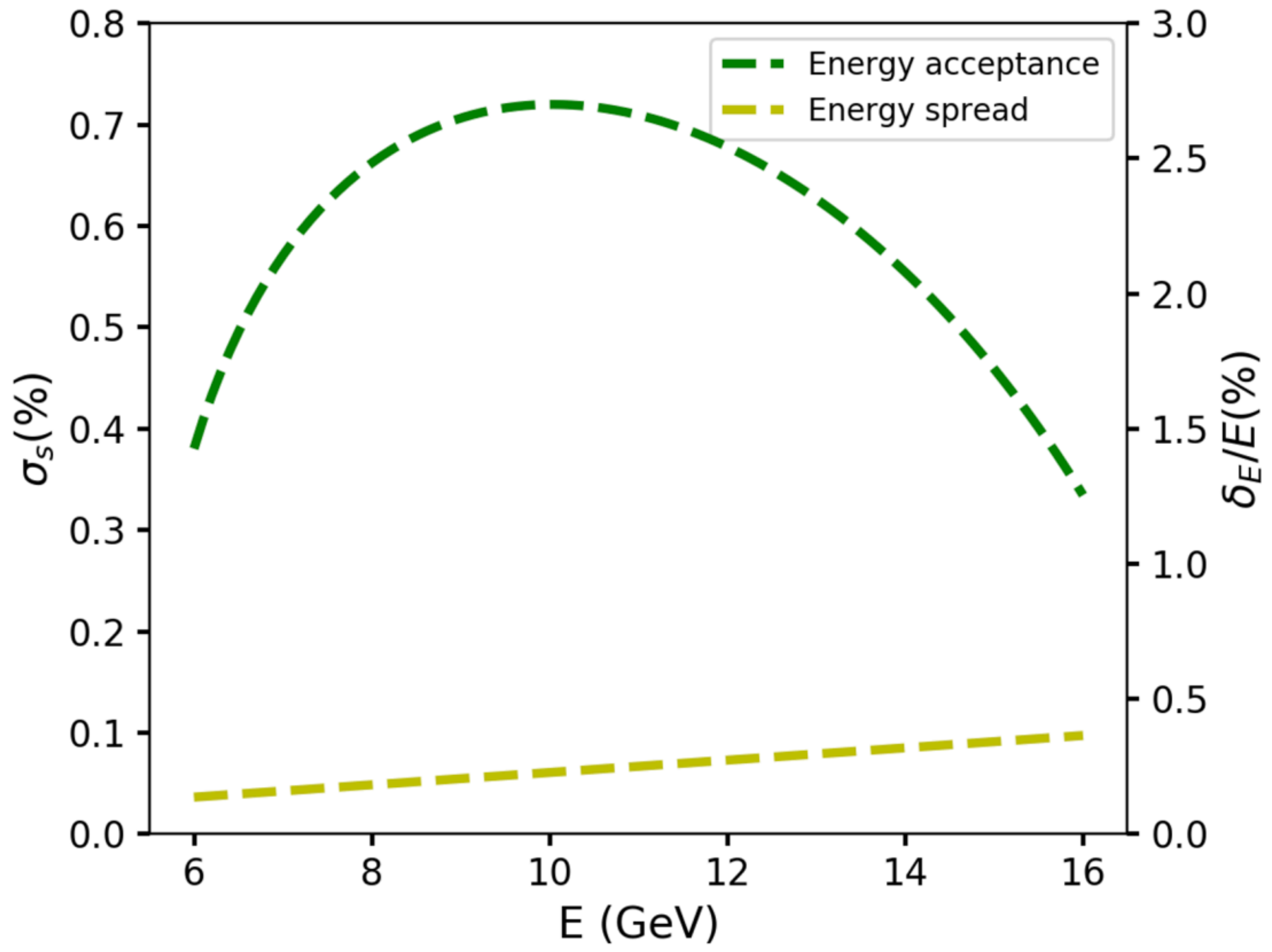
- The value of the **maximum momentum deviation**, for which a particle may have and **still** undergo **stable synchrotron oscillation**, is called the **momentum acceptance** of the accelerator.

- Considering the maximum energy spread of the beam extracted from the linac, the energy acceptance is aimed to be **1.5%** for the PBR design at the injection energy to be able to accept the incoming beam safely.

$$\left(\frac{\delta_E}{E}\right)^2 = \left[\frac{qV}{\pi h \alpha_c E_o}((2cos\phi_s) + (2\phi_s - \pi)sin\phi_s)\right]$$

$$\phi_s = arcsin\left(\frac{U_0}{V_0}\right)$$





- Therefore, the minimum RF voltage is calculated **as 2.5 MV** to assure **1.5%** energy acceptance at injection and it increases up to **37 MV** at extraction energy.

Imperfections

- Machine imperfections can have an important impact on the beam dynamics.
- Realistic alignment and main field and multipole field errors were applied.

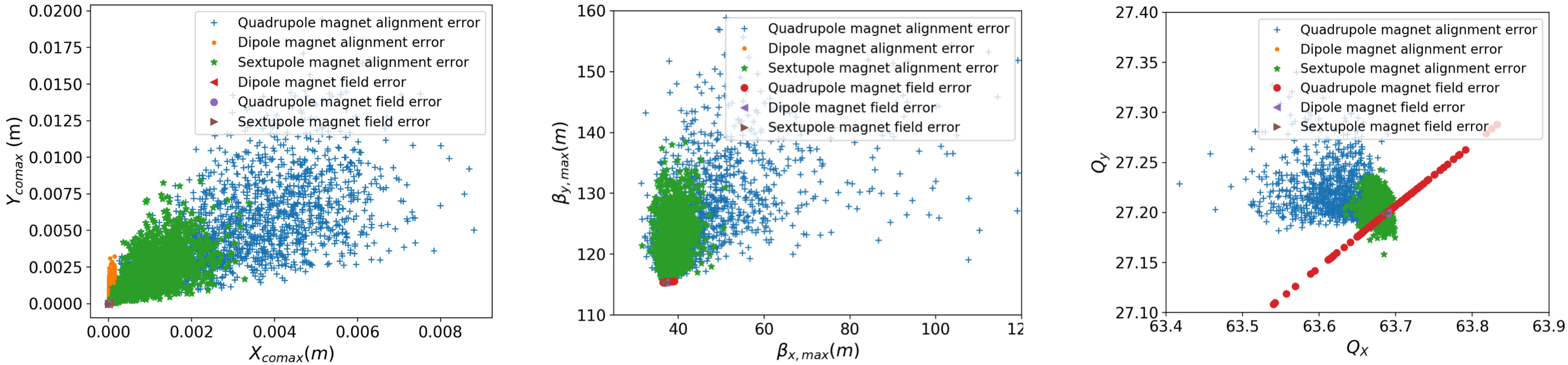
Magnets	dx (μm)	dy (μm)	dz (μm)	dphi (μrad)	dtheta (μrad)	dpsi (μrad)
Dipole	100	100	100	100	100	100
Quadrupole	100	100	100	100	100	100
Sextupole	100	100	100	100	100	100

Magnets	Main field errors
Dipole	10^{-3}
Quadrupole	10^{-3}
Sextupole	10^{-3}

Reference: H. Ghasem, F. Antoniu, S. Papadopoulou, Y. Papaphilippou, "Update on CLIC DR design", CLIC Workshop, 2017.

Magnets	Order	Systematic	Random
Dipole	2	10^{-4}	10^{-3}
	3	$1.5x10^{-4}$	10^{-3}
	4	0	10^{-3}
	5	$5x10^{-5}$	10^{-3}
	6	0	10^{-3}
	7	$5x10^{-4}$	10^{-3}
	8	0	10^{-3}
	9-20	0	10^{-3}
Quadrupole	3-5	0	10^{-3}
	6	10^{-6}	10^{-3}
	7-9	0	10^{-3}
	10	10^{-7}	10^{-3}
	11-13	0	10^{-3}
	14	10^{-8}	10^{-3}
	15-17	0	10^{-3}
	18	10^{-8}	10^{-3}
	19-20	0	10^{-3}
Sextupole	4-8	0	10^{-3}
	9	10^{-6}	10^{-3}
	10-14	0	10^{-3}
	15	10^{-7}	10^{-3}
	16-20	0	10^{-3}

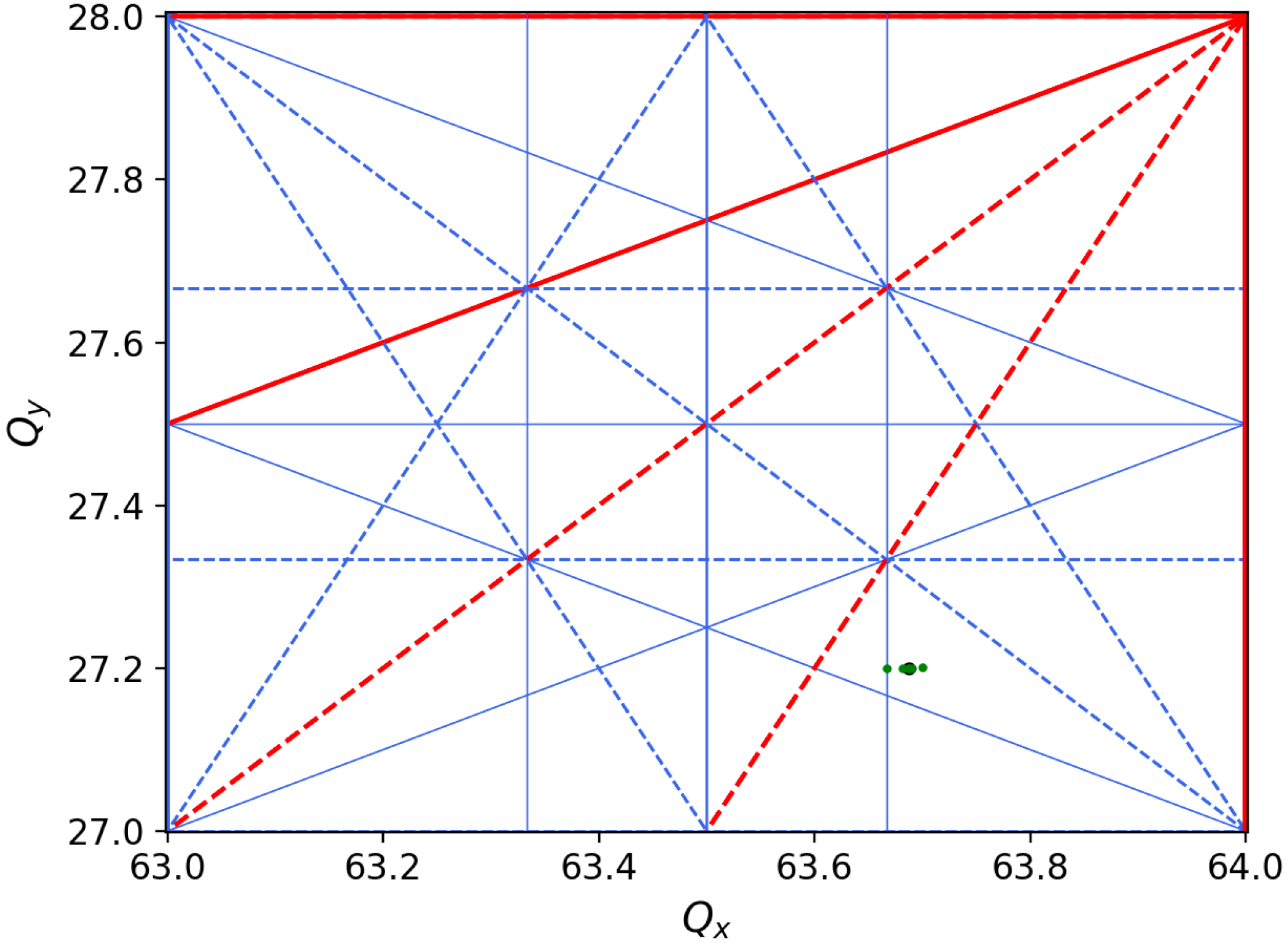
Impact of alignment and field errors



- Impact of different magnet errors (dipole, quadrupole, sextupole) on the orbit, optics and tune.
- The orbit and beta distortion is dominated by the quadrupole alignment errors.
- Quadrupole alignment and field errors are the main source of optics and tune distortions.

Dynamic aperture

- The **dynamic aperture** (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects.



- Tune **working point** on a resonance diagram up to **3th order**
- Systematic **(red)**, non-systematic **(blue)**, normal (solid) and skew (dashed) resonances
- **Black point** shows the working point and **green points** shows the tune shift with off momentum up to +/-1.5 %

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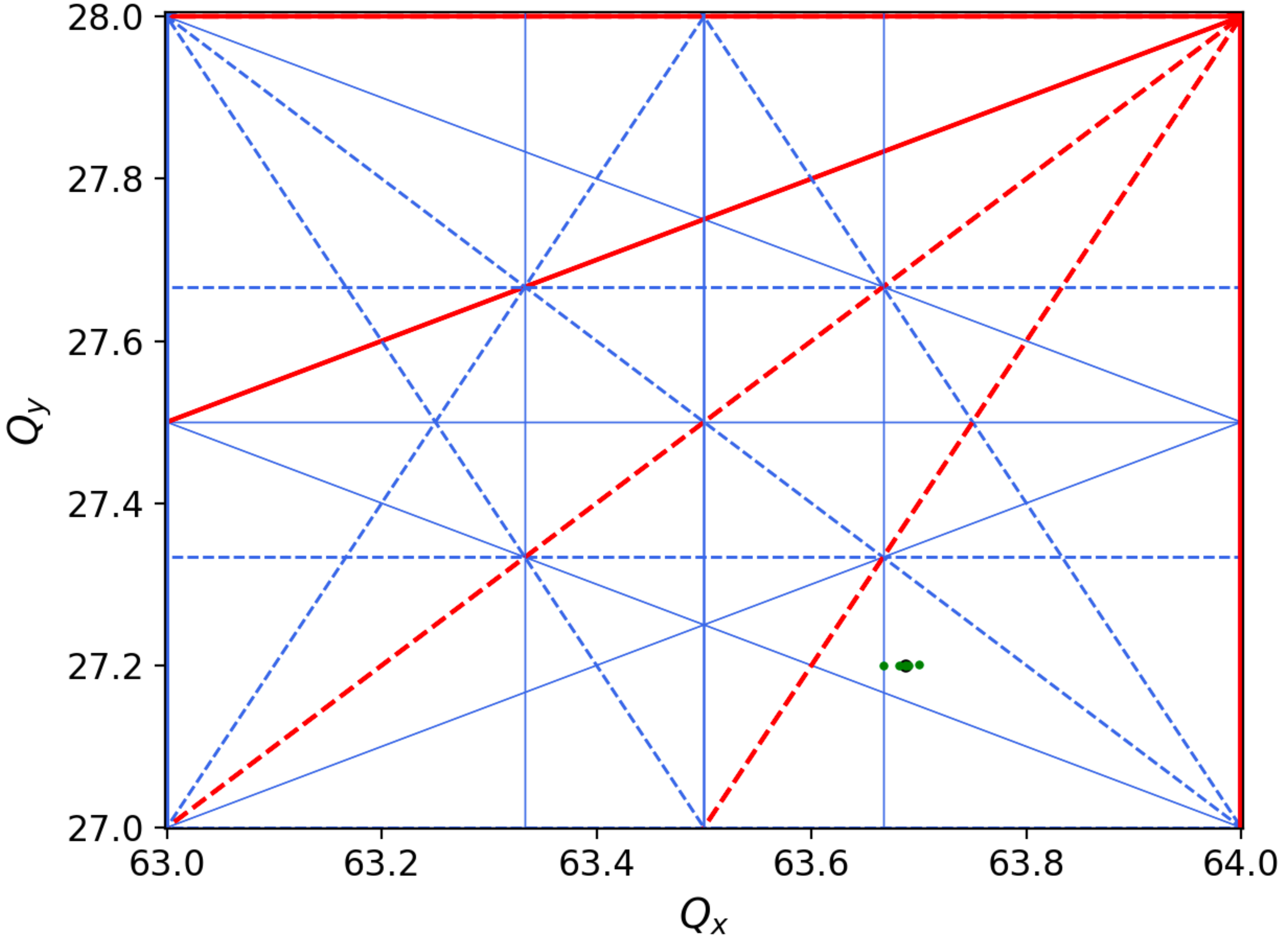

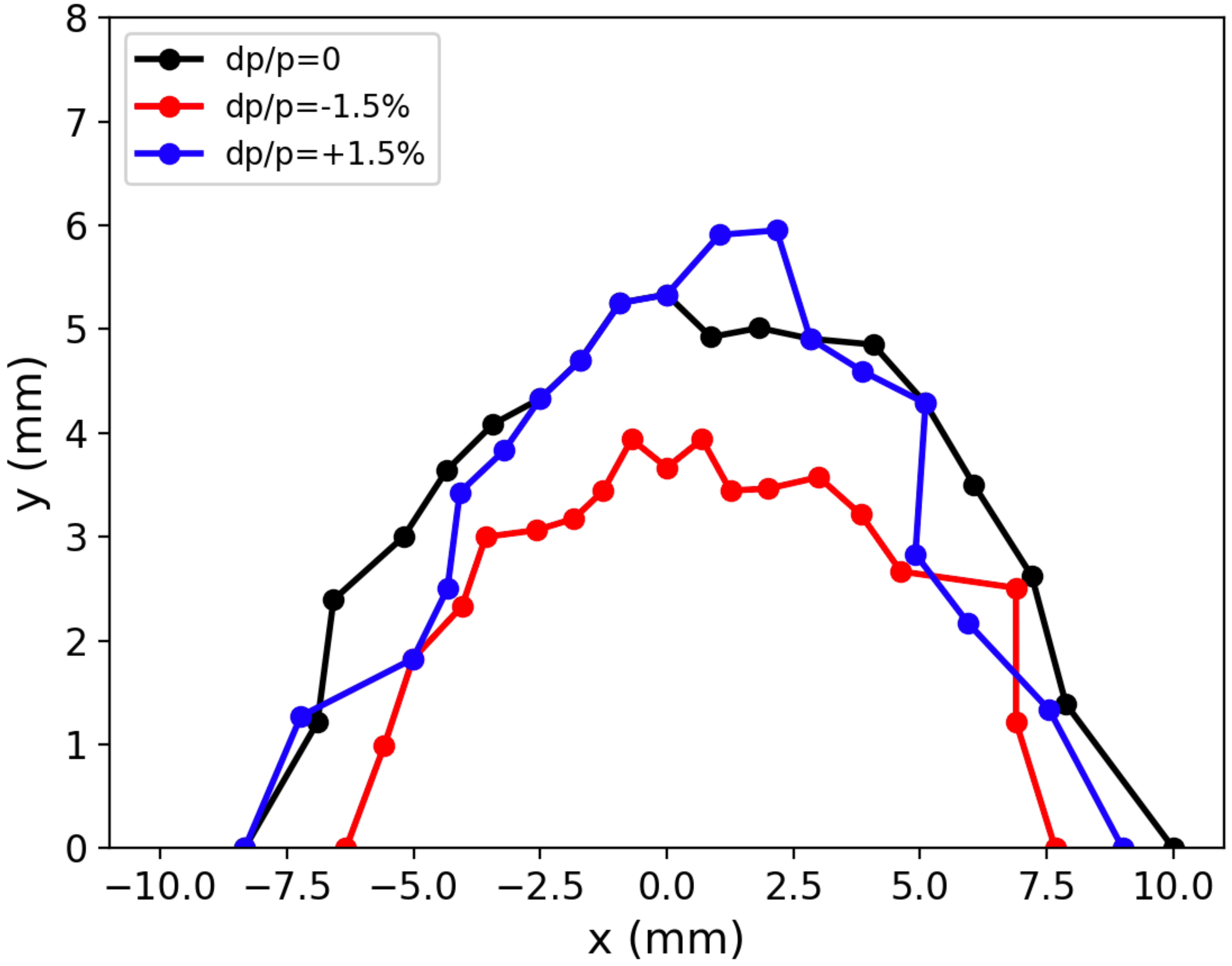

- Particles with different initial conditions were tracked for **26000 turns** (around 1 damping time).

Dynamic aperture

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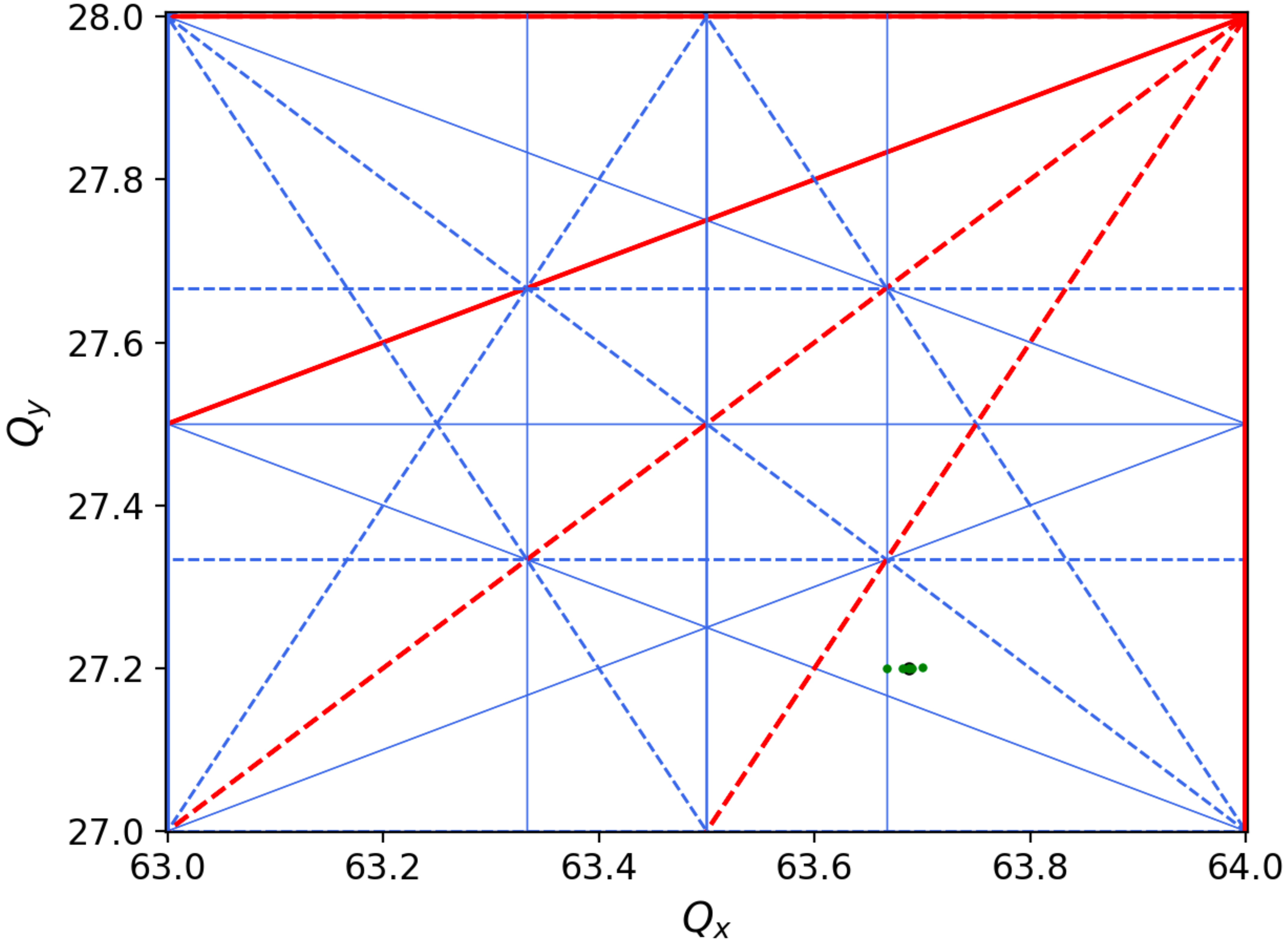

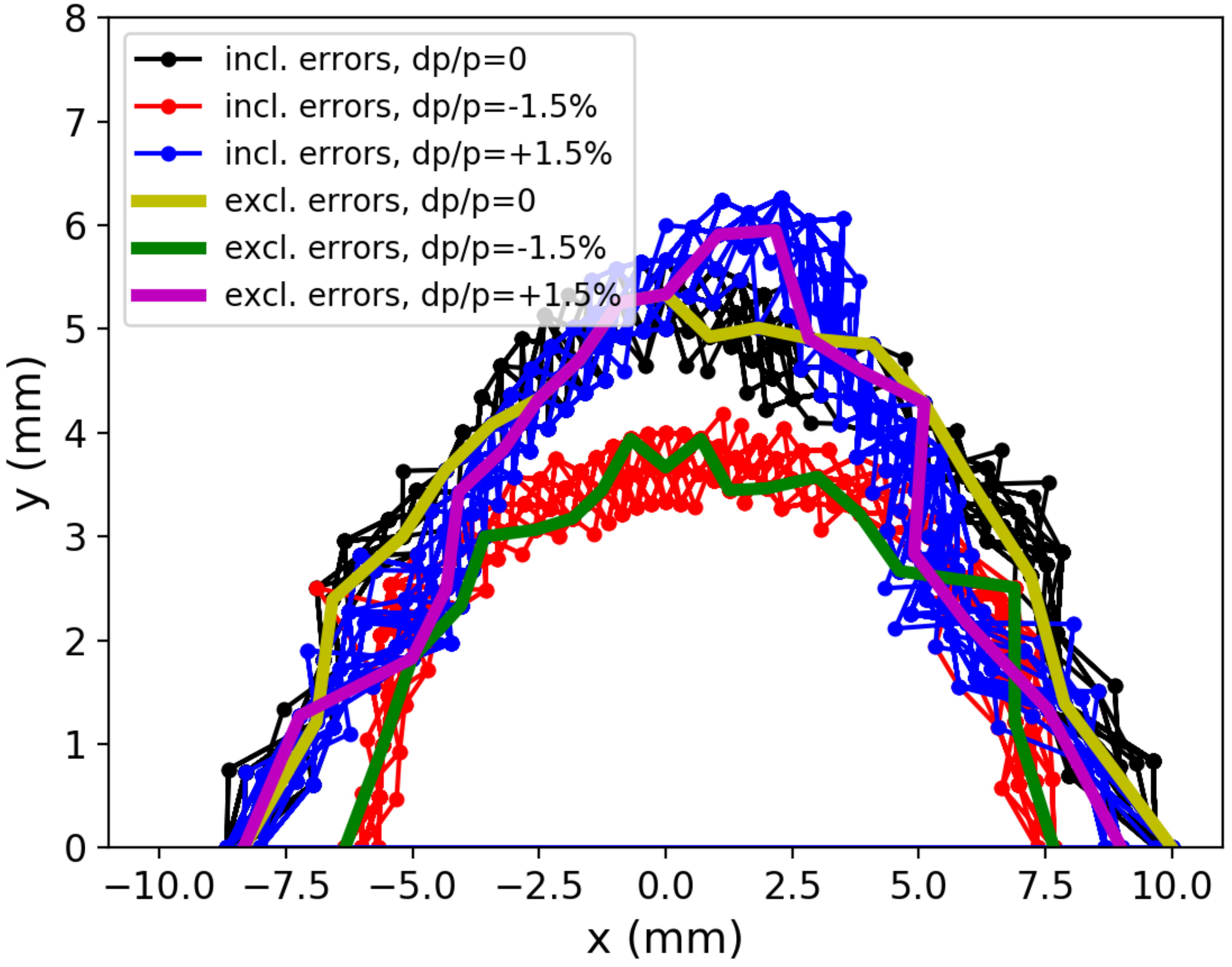

- Particles with different initial conditions were tracked for **26000 turns** (around 1 damping time) including errors.
- The DA of the alternative PBR including machine and magnet imperfections is adequate for off-axis injection.

Frequency Map Analysis

Parameters

- Based on all the considerations summarized in this presentation, the beam parameters of the alternative pre-booster ring of the FCC e^+e^- injector complex are summarized in the table below.

Parameters	**Symbol**	**Injection**	**Extraction**
Beam energy	*E [GeV]*	6	16
Geo. emittance [nm.rad] (hor.)	ϵ_x [nm . rad]	0.66	4.74
Bunch length	σ_z[mm]	5.9	7.2
Momentum spread	σ_δ	0.3 x 10^{-3}	0.97 x 10^{-3}
Circumference	*C [m]*	2030.4	
Harmonic number	*h*	2706	
Mom. comp. factor	α_c	0.32 x 10^{-3}	
Tunes [h/v]	$Q_{h/v}$	63.687/27.199	
Energy loss per turn	U_0 *[MeV]*	0.57	29.22
Damping times [h/v/l]	$\tau_{h/v/l}$ [s]	0.18/0.18/0.09	0.01/0.01/0.005
RF frequency	F_{rf} *[MHz]*	400	
RF voltage	V_{rf} *[MV]*	2.5	37
Bending magnet length	l_{bend} *[m]*	4.1	
Field of bending magnet	B_{dipole} *[T]*	0.1	0.27
Nat. chromaticity	$\xi_{h/v}$	-99/-59	
Number of bending magnets	N_{bend}	304	
Dynamic aperture (h/v)	*DA [mm]*	6.3/3.8	-
Energy acceptance	$\frac{\delta E}{E}$ [%]	1.5	-

FUTURE CIRCULAR COLLIDER

Different energy discussions

- As it was discussed and explained, the limit for the extraction energy comes from **the magnetic field of the main booster ring**.
- Since the main booster ring has a very **large circumference** (~98 km), the field of the dipole magnets become low at its injection energy.
- The extraction energy is planned **16 GeV** as a baseline for the alternative PBR; however, different options such as **18 GeV** and **20 GeV** have been also considered and discussed.

Parameters	**Option 1**	**Option 2**	**Option 3**
Extraction energy [GeV]	16	18	20
Circumference [m]	2030	2240	2644
Injection energy [GeV]	6	6	6
Geo. emittance [nm.rad] (hor.) @extraction	4.74	4.63	5.01
Energy loss per turn [MeV] @extraction	29.22	41.36	57.8
Damping time (hor.) [s] @injection	0.18	0.21	0.1
Energy spread [%] (rms.) @extraction	0.097	0.1	0.12
RF voltage [MV] @extraction	37	50	67
Damping wiggler field [T]	-	-	1.3
Damping wiggler length (total) [m]	-	-	16.2

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- **Collective effect calculations**
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- Main booster ring
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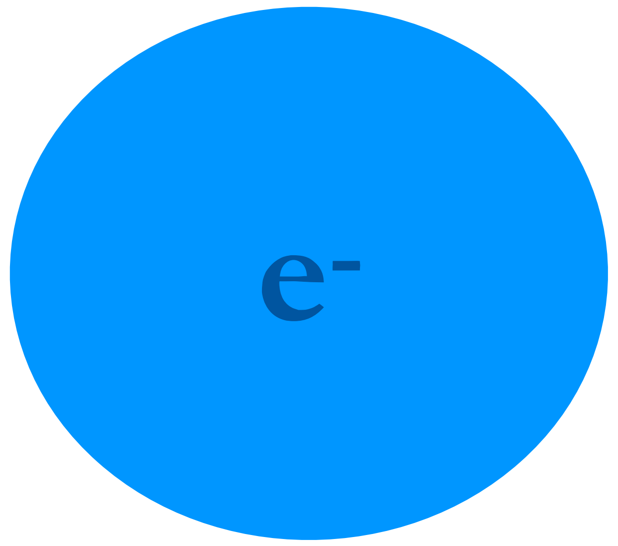
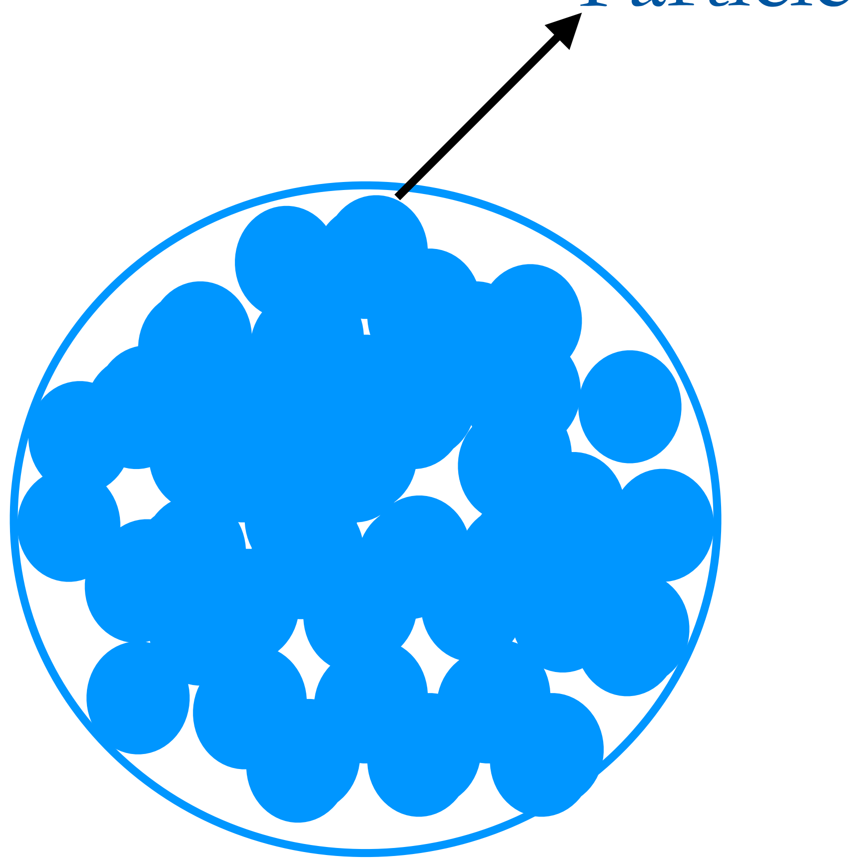
Collective effects



particle

Particles are not traveling alone in an accelerator.

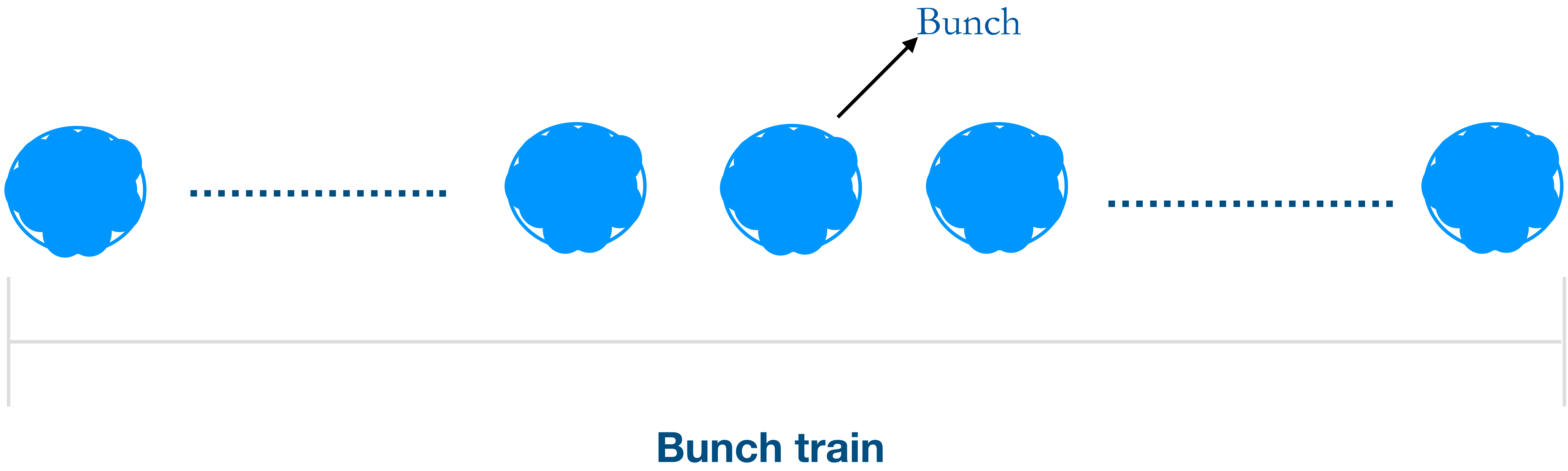
Collective effects



Bunch

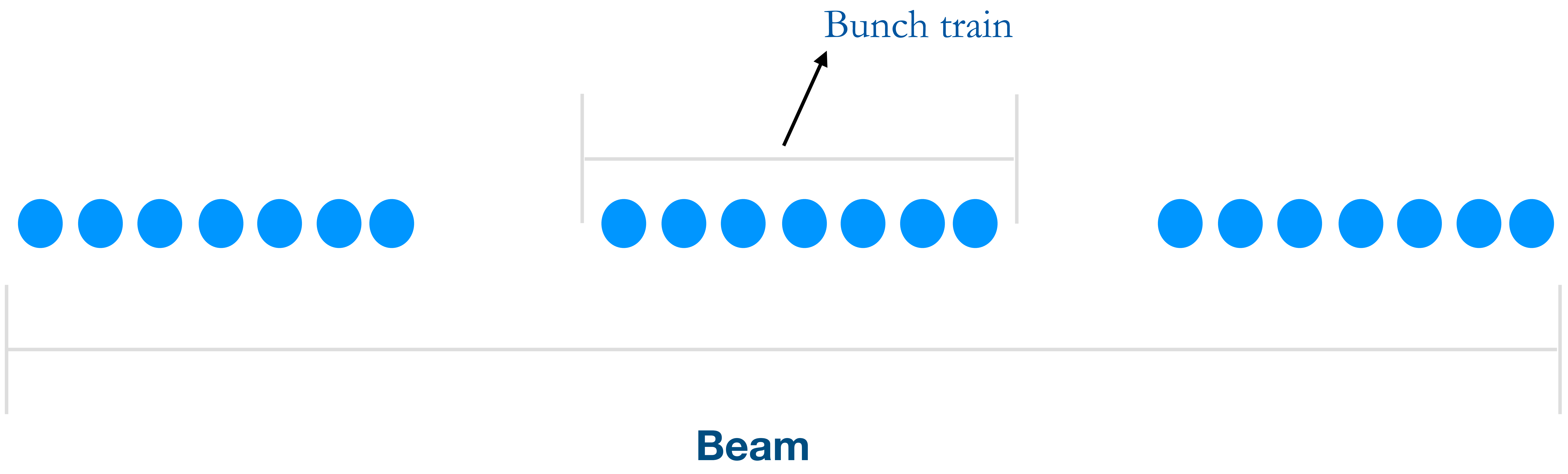
Many particles are traveling together in a bunch.

Collective effects



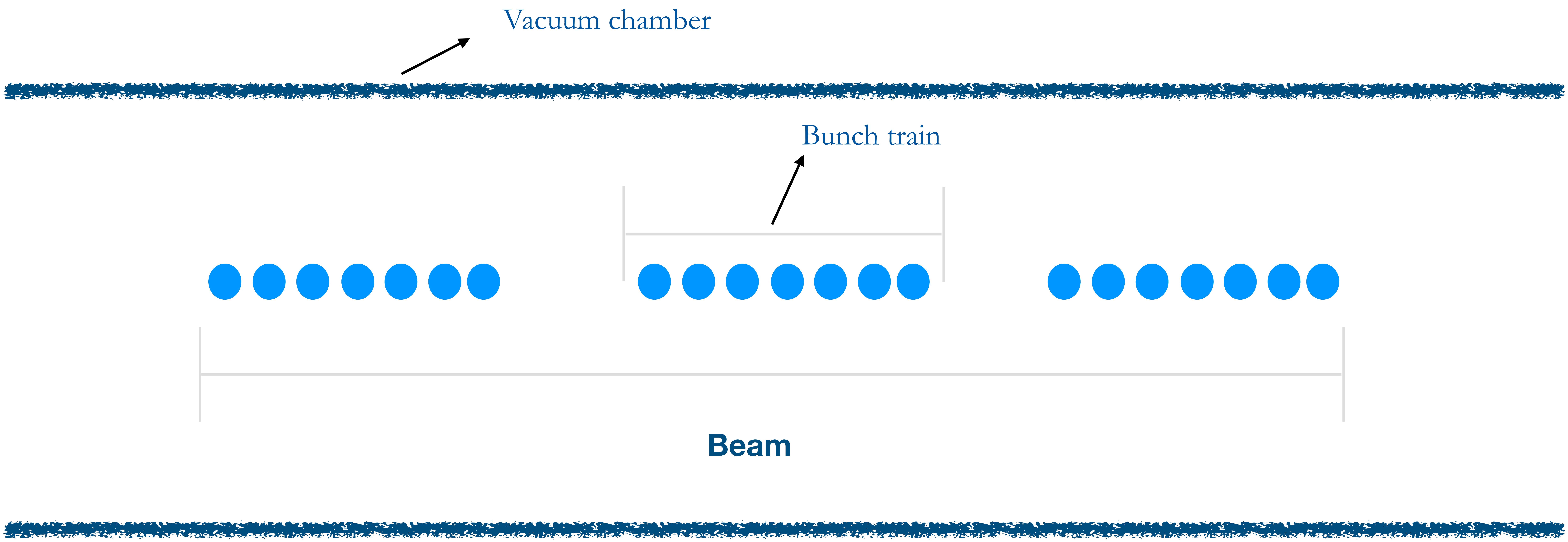
Bunches travel together with specific bunch space in the accelerator as bunch train.

Collective effects



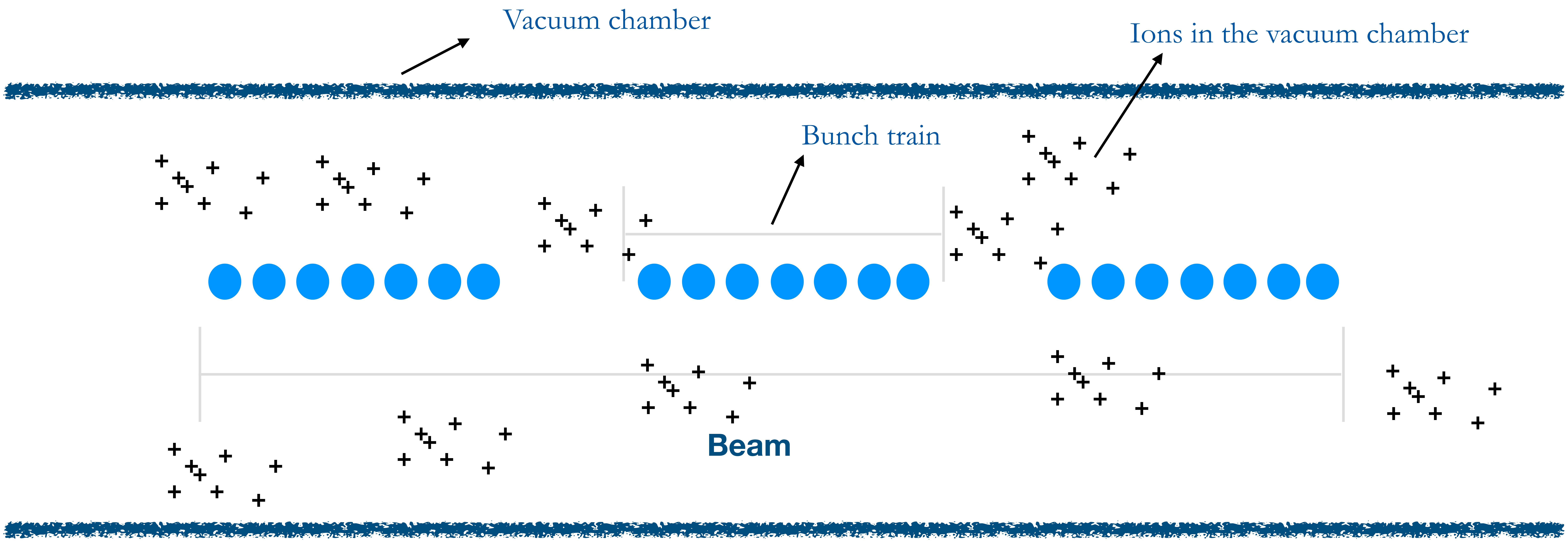
Many trains (or one) travel as beam.
Particles, bunches, bunch trains may have effect on each other.

Collective effects



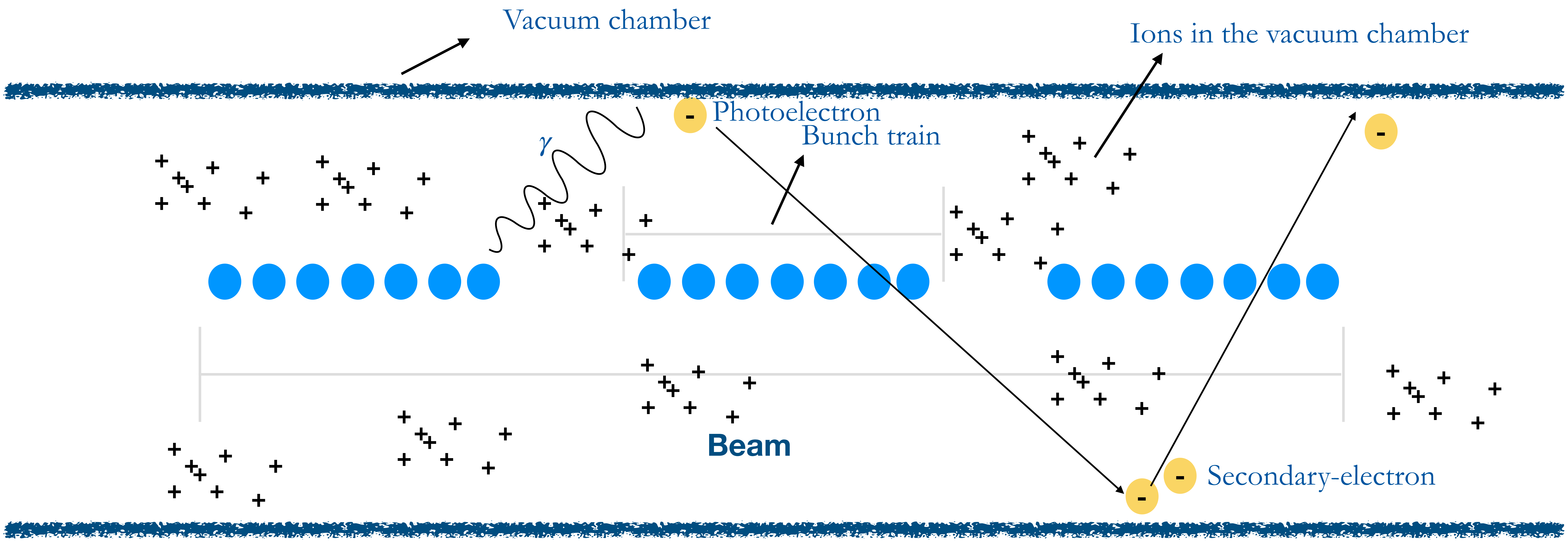
The beam travels in a vacuum chamber.
So, the vacuum chamber may effect the beam.

Collective effects



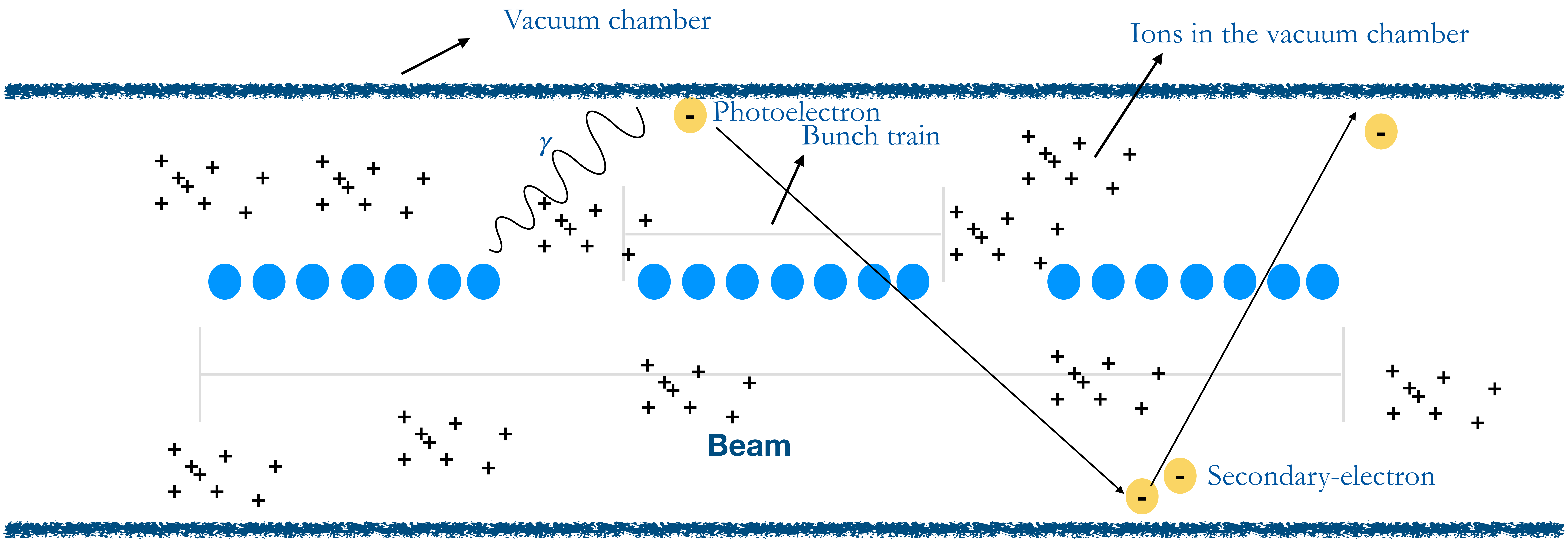
Although, it is a vacuum chamber, there are still ions in it!
So, these ions may effect the beam.

Collective effects



Or the photons (emitted from traveling particles) or ionized gases may create electrons and these primary electrons may create secondary electrons.
The electron clouds may effect the beam.

Collective effects



All these (and more) effects are known as **collective effects**.

Collective effect estimates

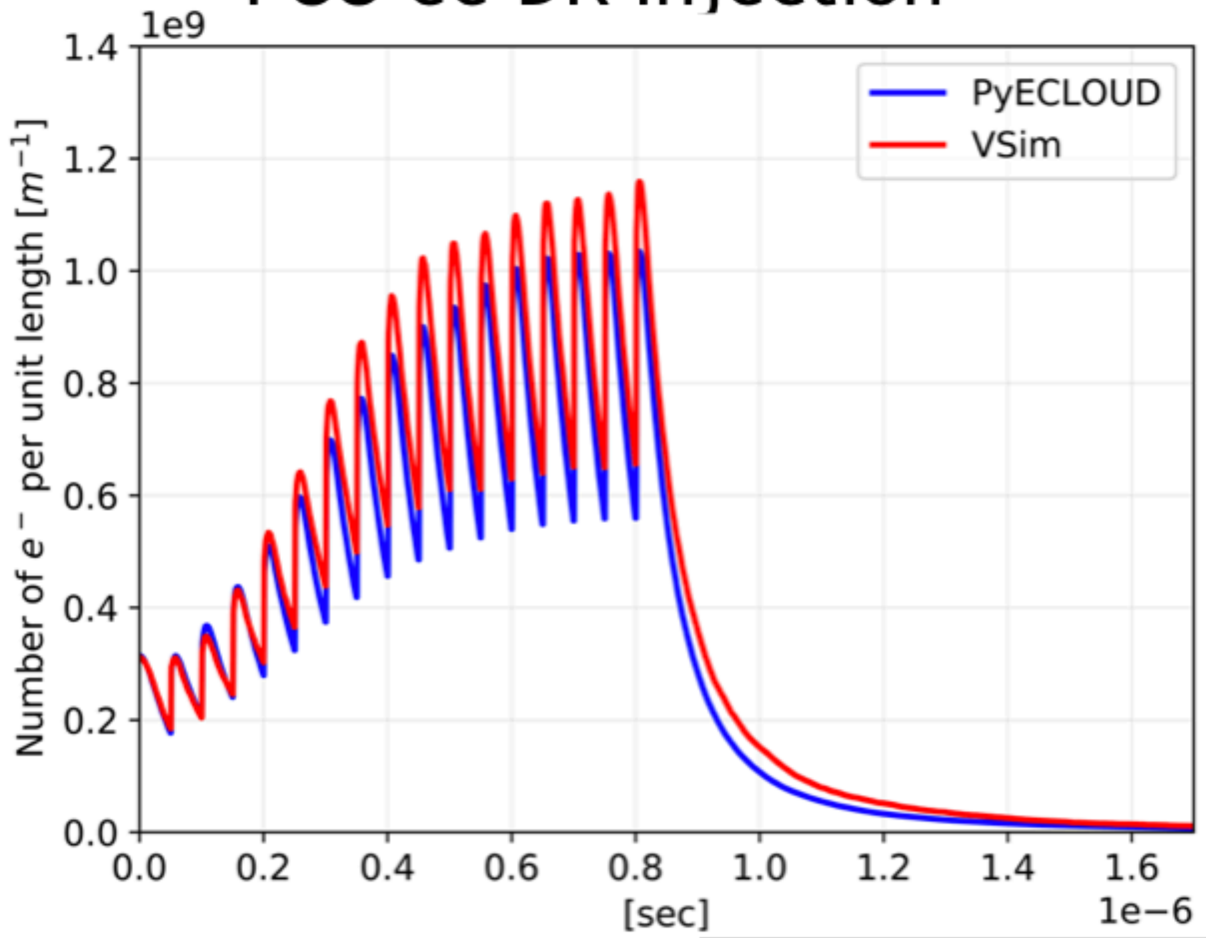
- Collective effects can limit the ultimate performance of any accelerator. In this respect, an **analytical estimation** of **intensity thresholds** have been performed both for the SPS and the alternative PBR designs.
- Based on the analytical estimations, **no major limitations** are expected from **space charge**, **longitudinal micro-wave inst.** and **e-cloud.**
- Concerning the **TMCI**, the transverse impedance **exceeds** the instability **threshold** for the **SPS** at the equilibrium state at injection energy and extraction energy. Detailed simulations should follow addressing this subject.
- Fast rise times were computed for the fast ion instability rise times: **134** and **61** for **the SPS** and **alternative PBR**, respectively. These rising times can be compensated with a feedback system, provided that **10^{-11} mbarr SPS vacuum pressures** and **10^{-10} mbarr alternative ring** vacuum chamber are achieved.
- Therefore, the current **vacuum pressure** of the **SPS** needs to be considerably **improved**.

Parameters	Alternative PBR	SPS as PBR
ΔQ_y - @inj.	0.0032	0.0005
ΔQ_y - @eq.	0.028	0.018
ΔQ_y - @ext.	1.6 x 10^{-4}	1.6 x 10^{-5}
Emit. growth by IBS at inj. (%)	9	6
$Z_0^{\|\|}$ [Ω]	1	6.4
$(Z_0^{\|\|}/n)_{th}$ [Ω] - @inj.	57.92	1167
$(Z_0^{\|\|}/n)_{th}$ [Ω] - @eq.	1.44	31.14
$(Z_0^{\|\|}/n)_{th}$ [Ω] - @ext.	10.11	100
$Z_0^{\|\|}$ [Ω]	1	6.4
$Z_t^{\perp}$ [MΩ/m]	0.79	9.77
Z_{th} [MΩ/m] @inj.	5.28	29.6
Z_{th} [MΩ/m] @eq.	8.95	7.10
Z_{th} [MΩ/m] @ext.	37	8.97
ΔQ_{ion}	0.002	0.009
τ_{inst} [t_{rev}]	134	61
ρ_{neutr}[10^{11}/m^3]	12.55	7.06
ρ_{th} [10^{11}/m^3] @inj.	2.84	11.30
ρ_{th} [10^{11}/m^3] @eq.	1.62	1.43
ρ_{th} [10^{11}/m^3] @ext.	1.68	3.67
ΔQ_x @neut. (Inj/Eq.)	0.003	0.035
ΔQ_y @neut. (Inj/Eq.)	0.005	0.035
ΔQ_x @neut. (Ext.)	0.001	0.01
ΔQ_y @neut. (Ext.)	0.002	0.01
Stupakov parameter	568	3.78
σ_z [cm]	0.59	4.1
Condition 1 [cm]	0.015	5000
Condition 2	6433	18525

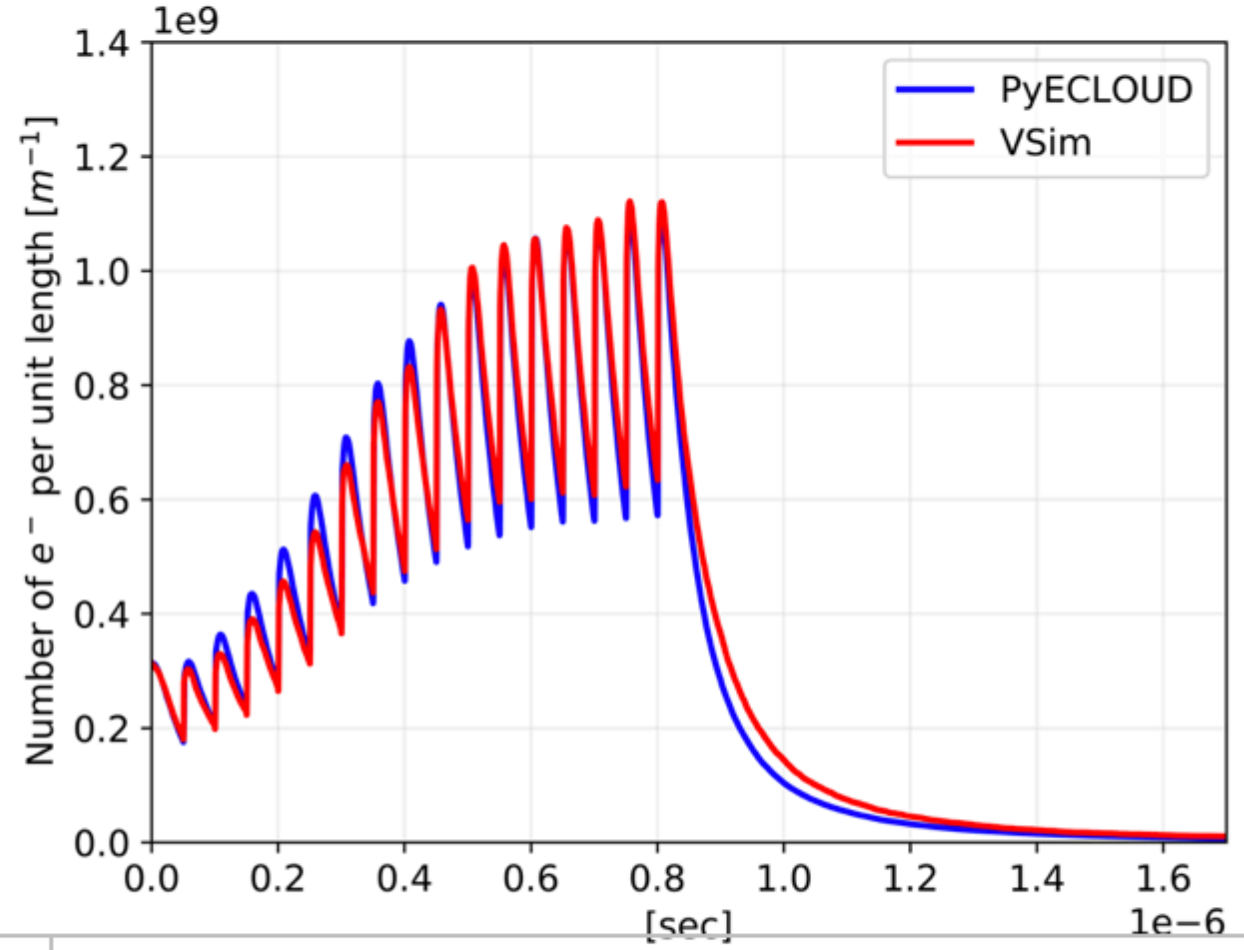
e-cloud build up studies

Comparisons (Furman-Pivi Model, total SEY=2.1, initial e⁻ =1e12 [e⁻/m³])

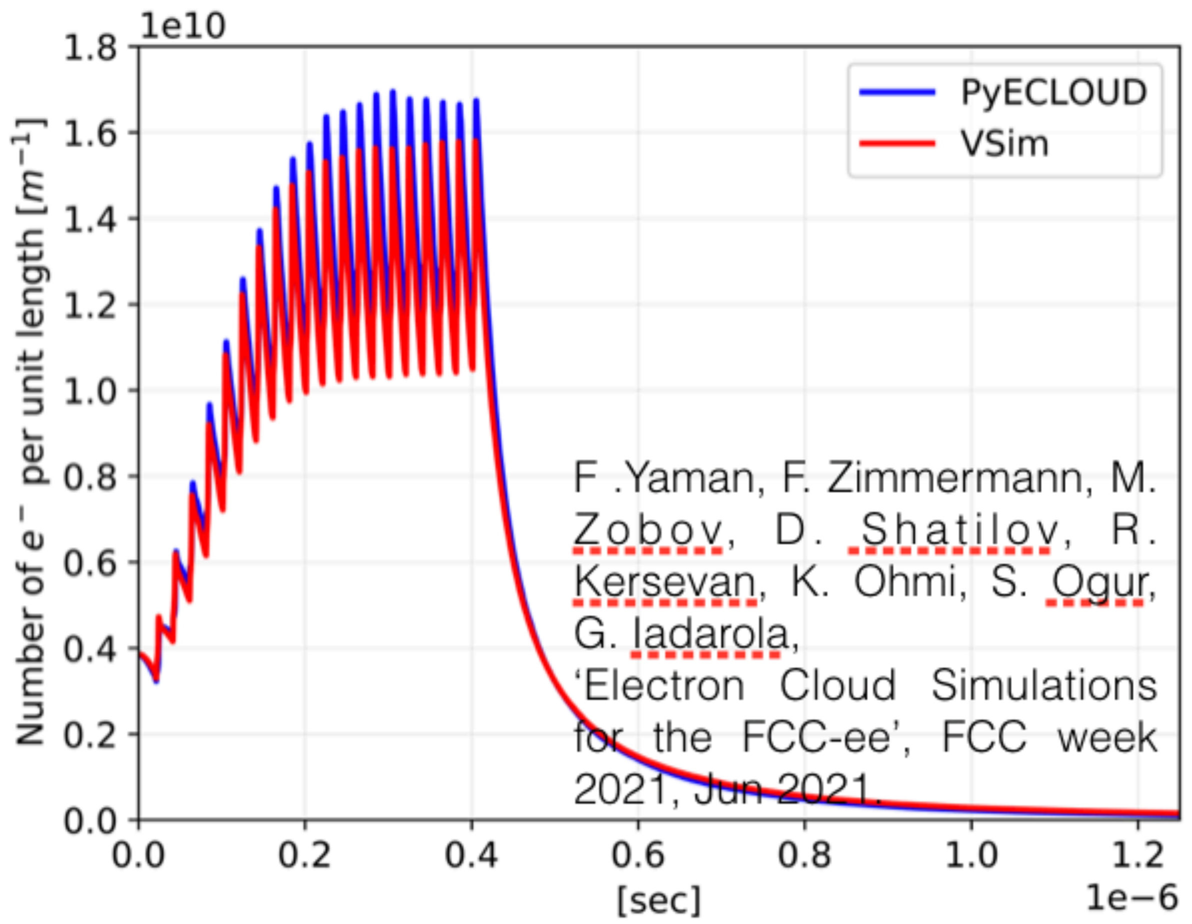
FCC-ee DR Injection



FCC-ee DR Extraction



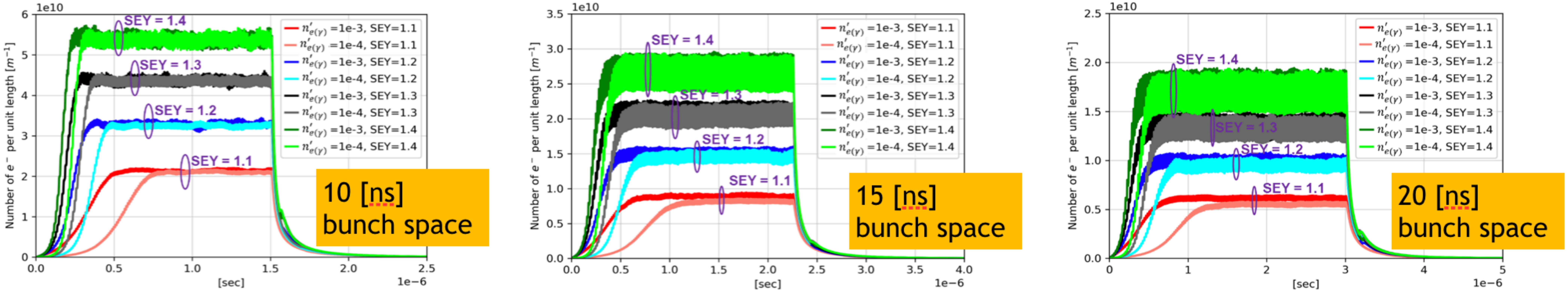
FCC-ee Collider arc dipole



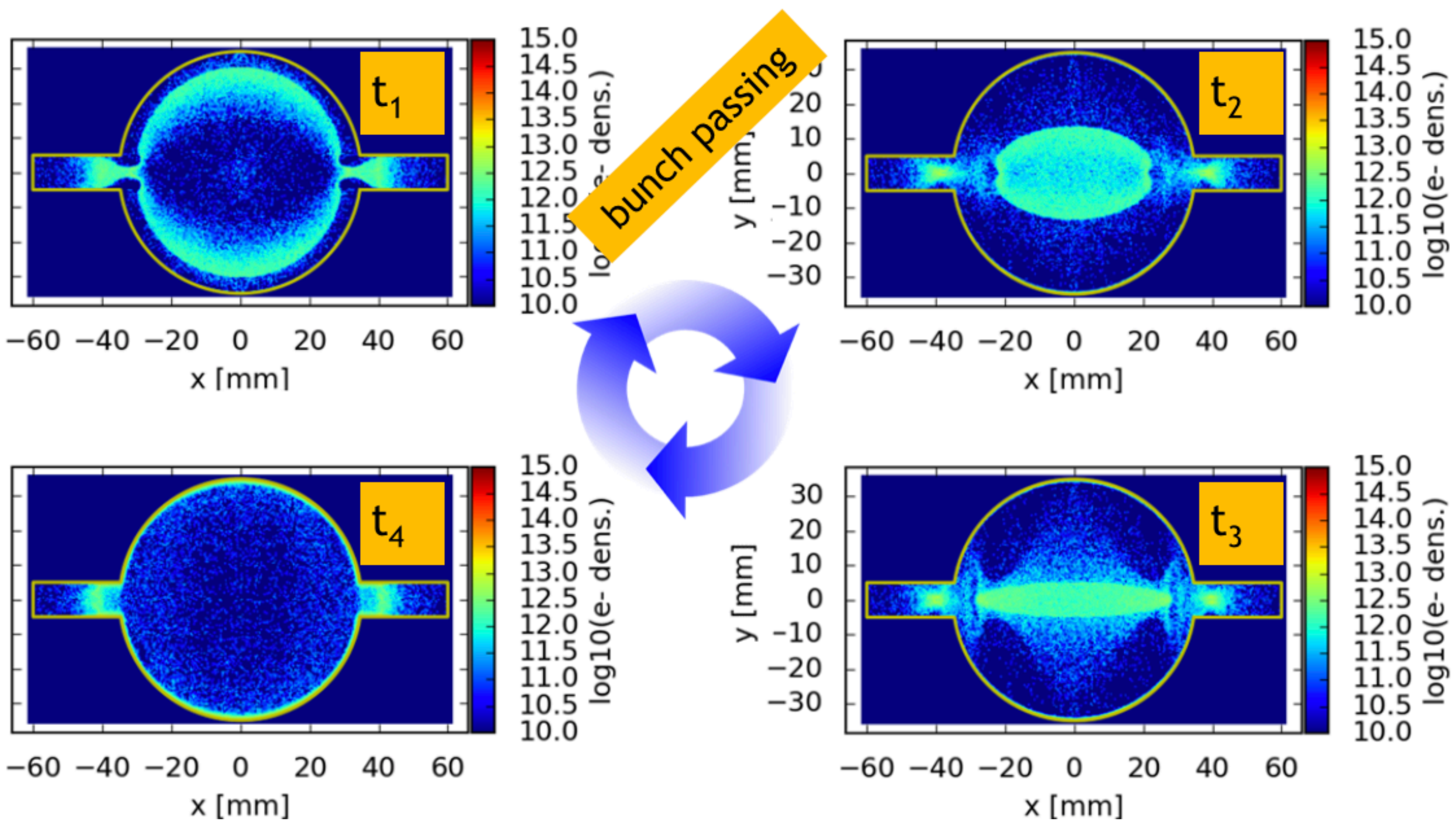
	FCC-ee DR Injection	FCC-ee DR Extraction	FCC-ee collider arc dipole
beam energy [GeV]	1.54	1.54	45.6
bunch spacing [ns]	50	50	20
bunches per train	2	2	20
trains per beam	8	8	1
r.m.s. bunch length (σ_z) [mm]	3.4	2.1	3.5
h. r.m.s. beam size (σ_x)	2.2 [mm]	98 [μm]	120 [μm]
v. r.m.s. beam size (σ_y)	2.8 [mm]	47 [μm]	7 [μm]
number of particles / bunch	2.2 x 10^{10}	2.2 x 10^{10}	1.7 x 10^{11}
bend field [T]	1.8	1.8	0.01415
beam pipe radius [mm]	10	10	35

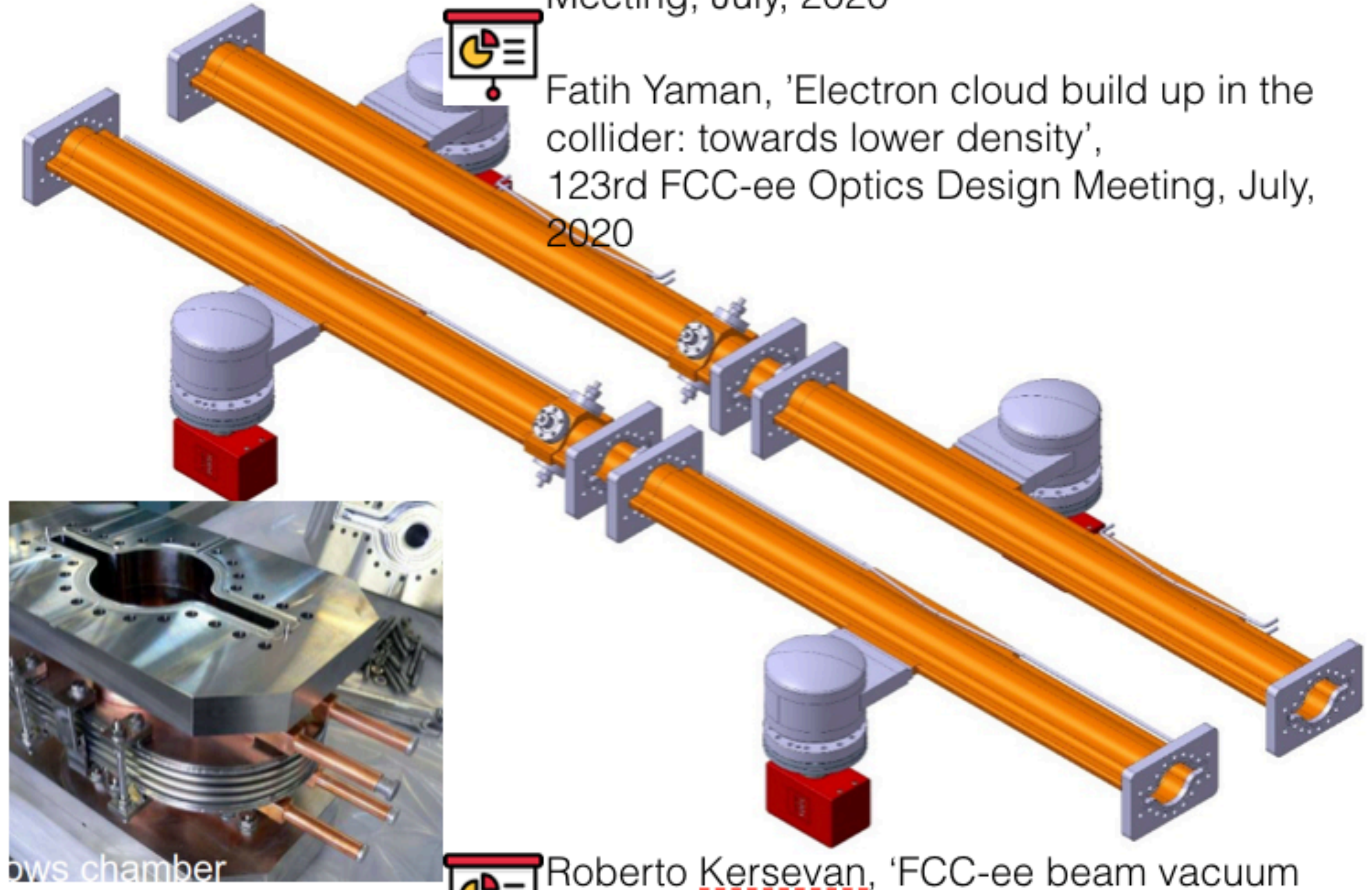
e-cloud build up studies

circular beam pipe resi



electron distribution for circular beam pipe with winglets





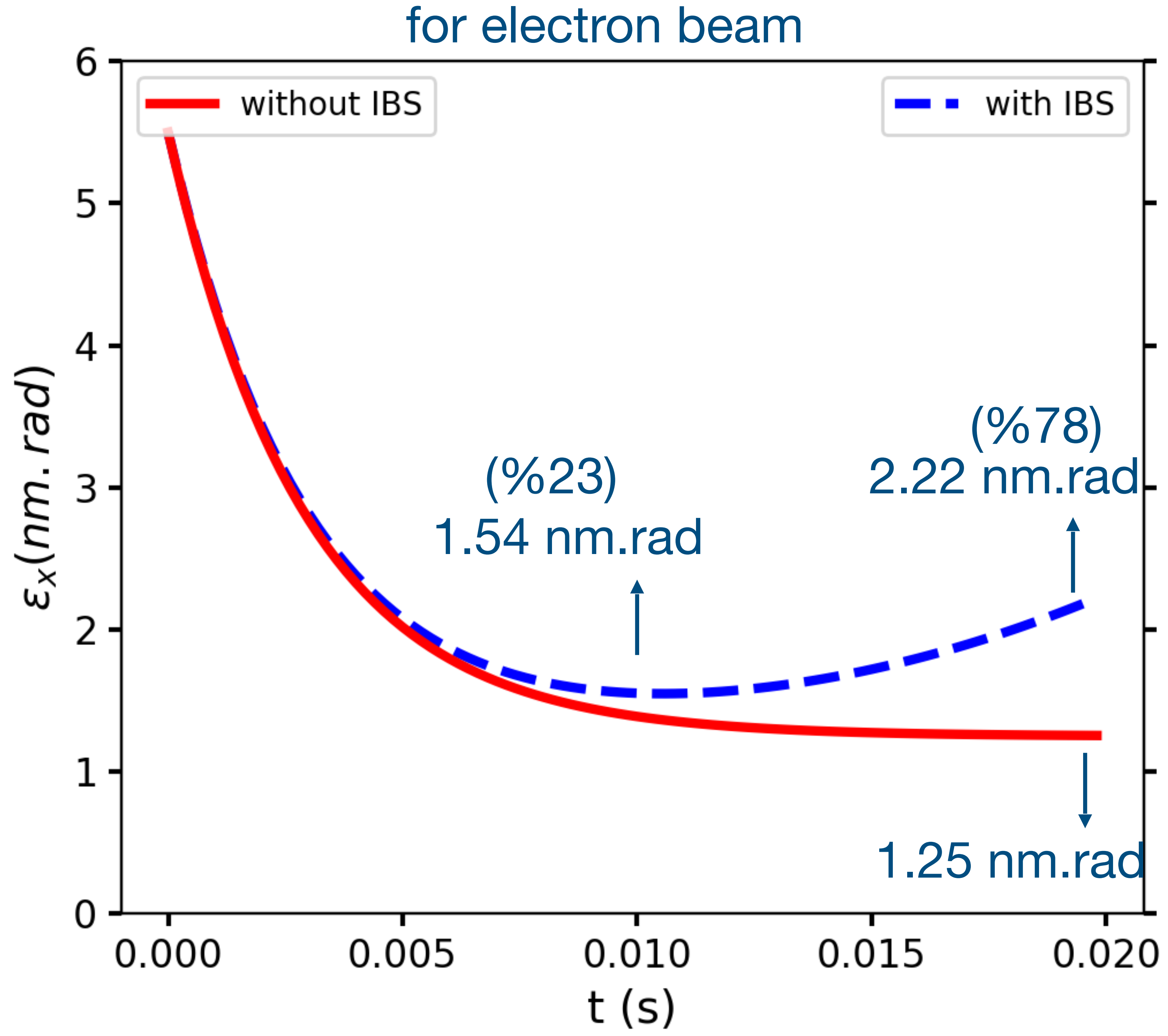
Fatih Yaman, 'Electron-Cloud Simulations for the FCC-ee Collider Arcs and for the e+ Damping Ring' 121st FCC-ee Optics Design Meeting, July, 2020

Fatih Yaman, 'Electron cloud build up in the collider: towards lower density', 123rd FCC-ee Optics Design Meeting, July, 2020

Roberto Kersevan, 'FCC-ee beam vacuum concept: the beam pipe of FCC-ee' FCC Week 2018 Amsterdam, April 2018

Intra-beam scattering

- **Intra-beam Scattering** (IBS) refers to the **binary Coulomb scattering** events **between the particles** within a beam, leading to the re-distribution of the phase space. Above transition, **IBS** can lead to **emittance blow-up** in all three planes.



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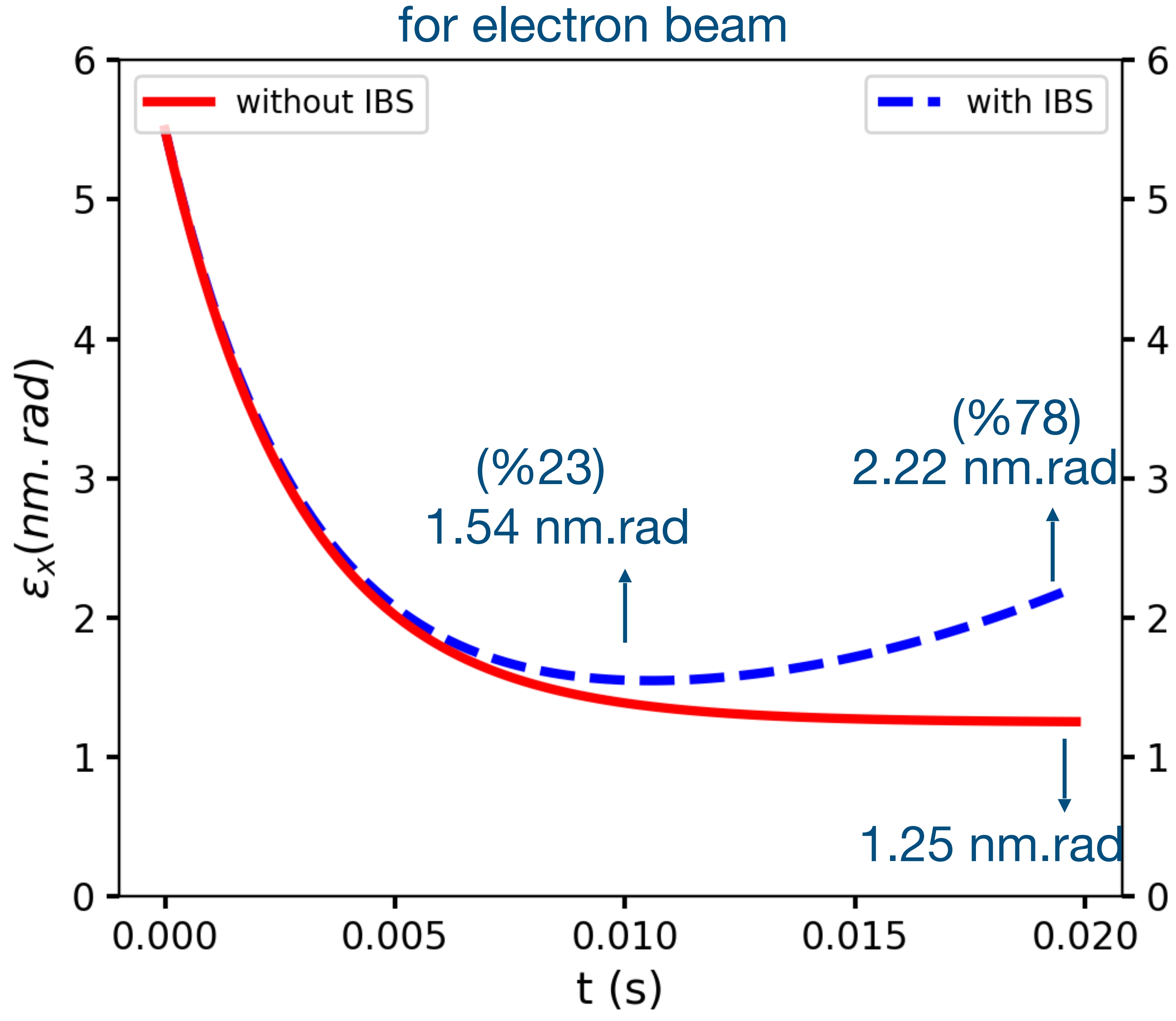

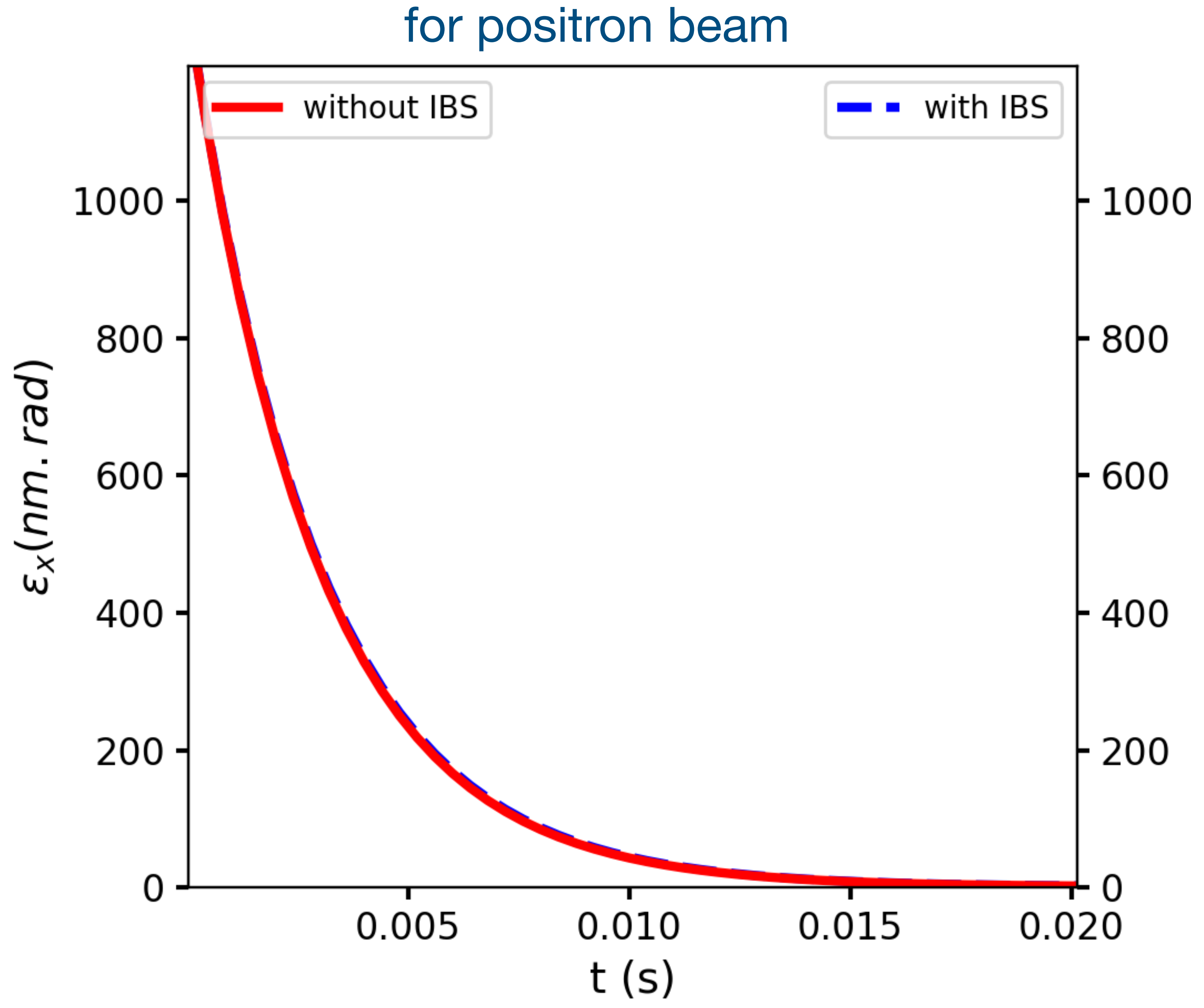

Parameter	**DR**
Emit. growth by IBS @inj. (e^-) [%]	78
Emit. growth by IBS @inj. (e^+) [%]	6

- The **emittance growth** with respect to the natural equilibrium emittance (without IBS) at the end of the injection plateau is around **78 % and 6%** for the electron and positron beams.
- In both cases, the extraction emittances are within the limit for the DR.

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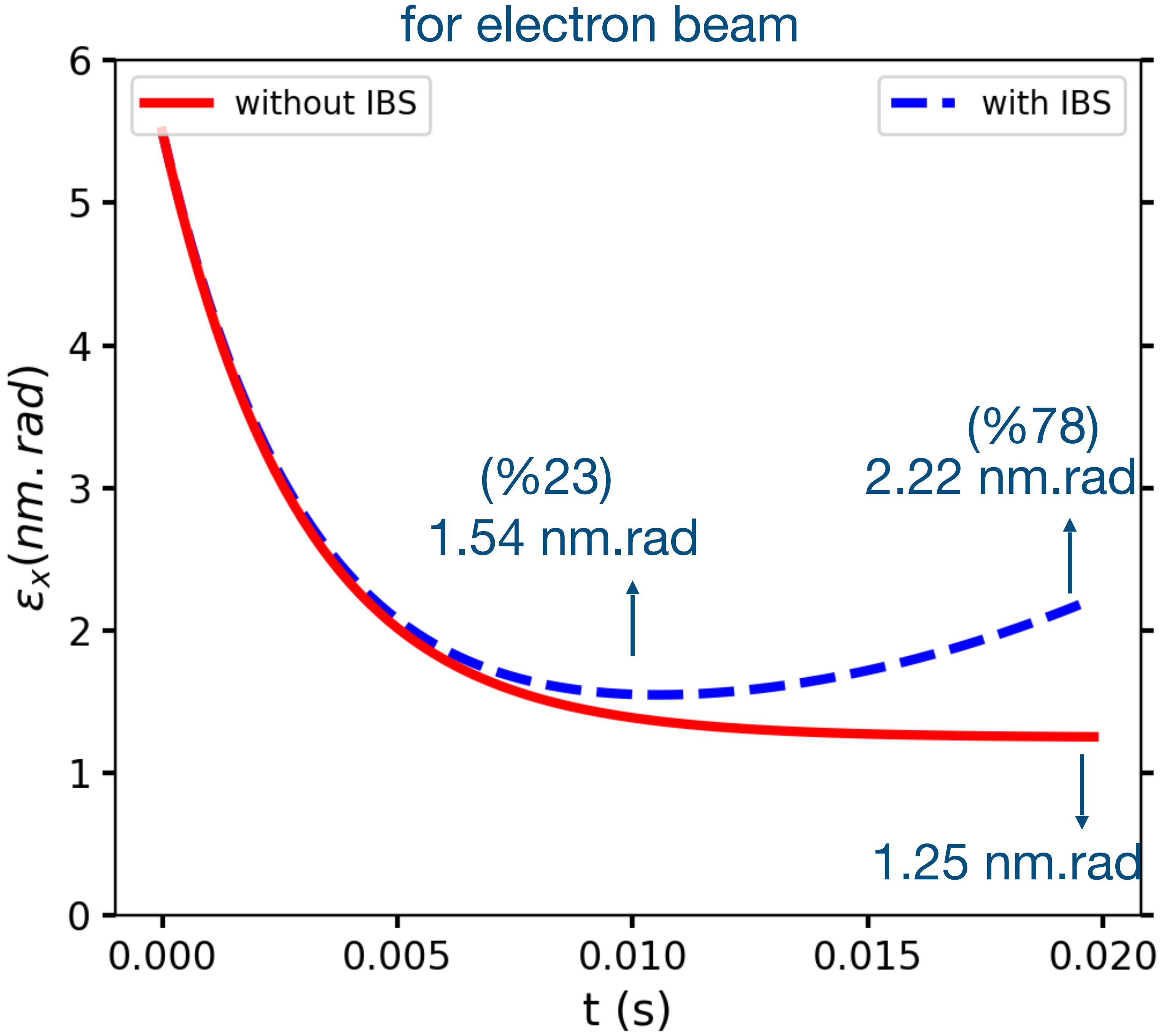

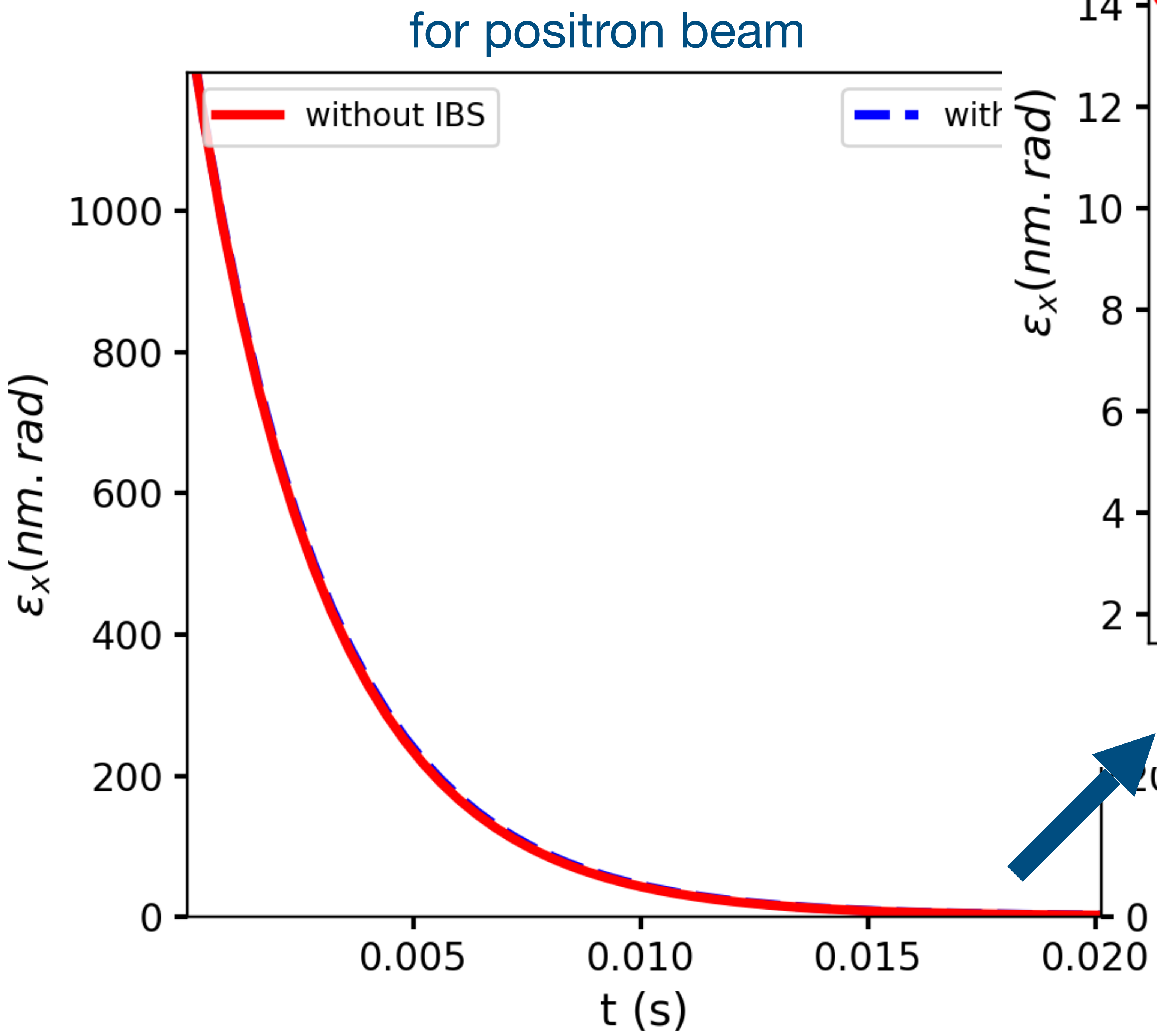

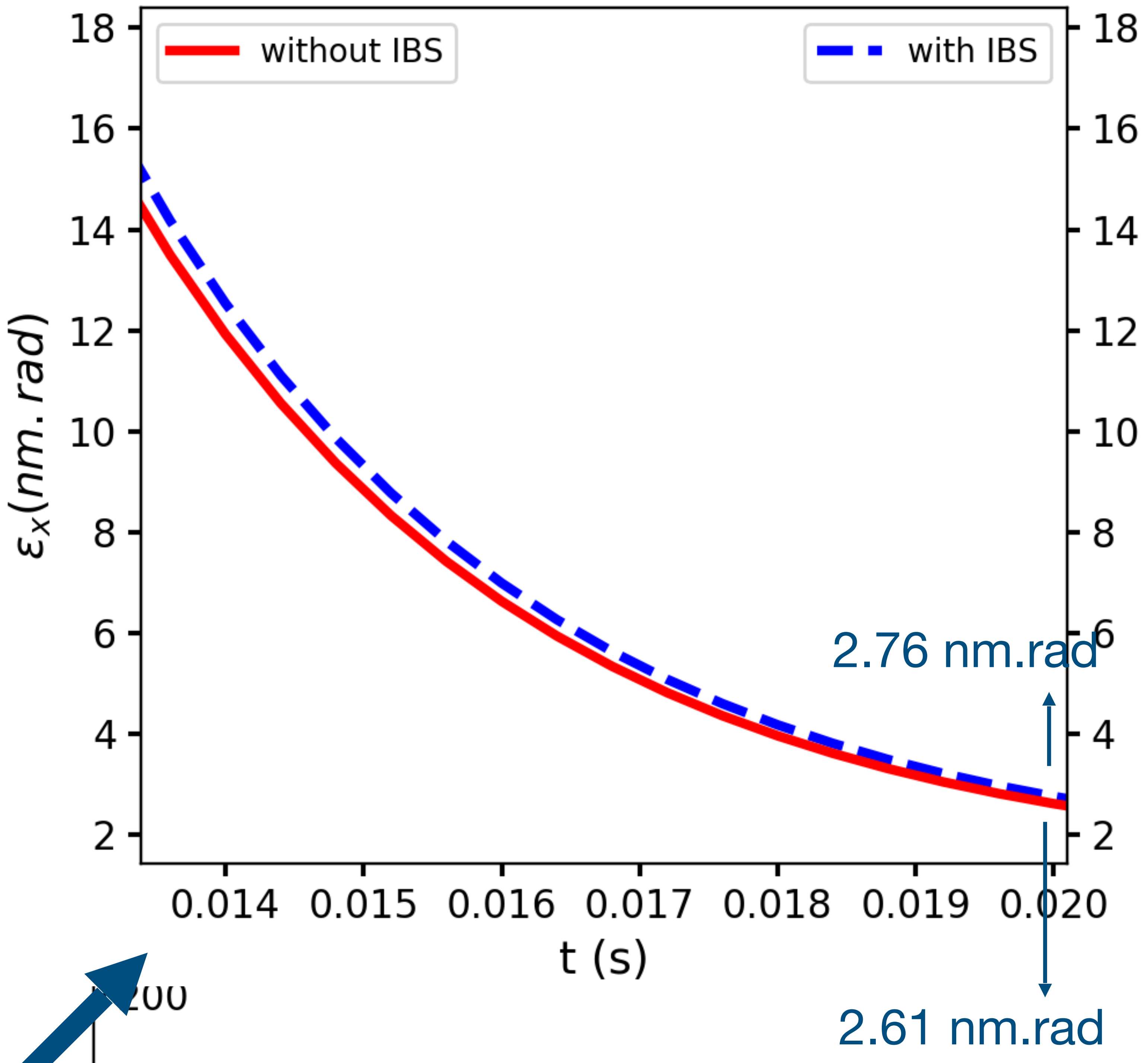

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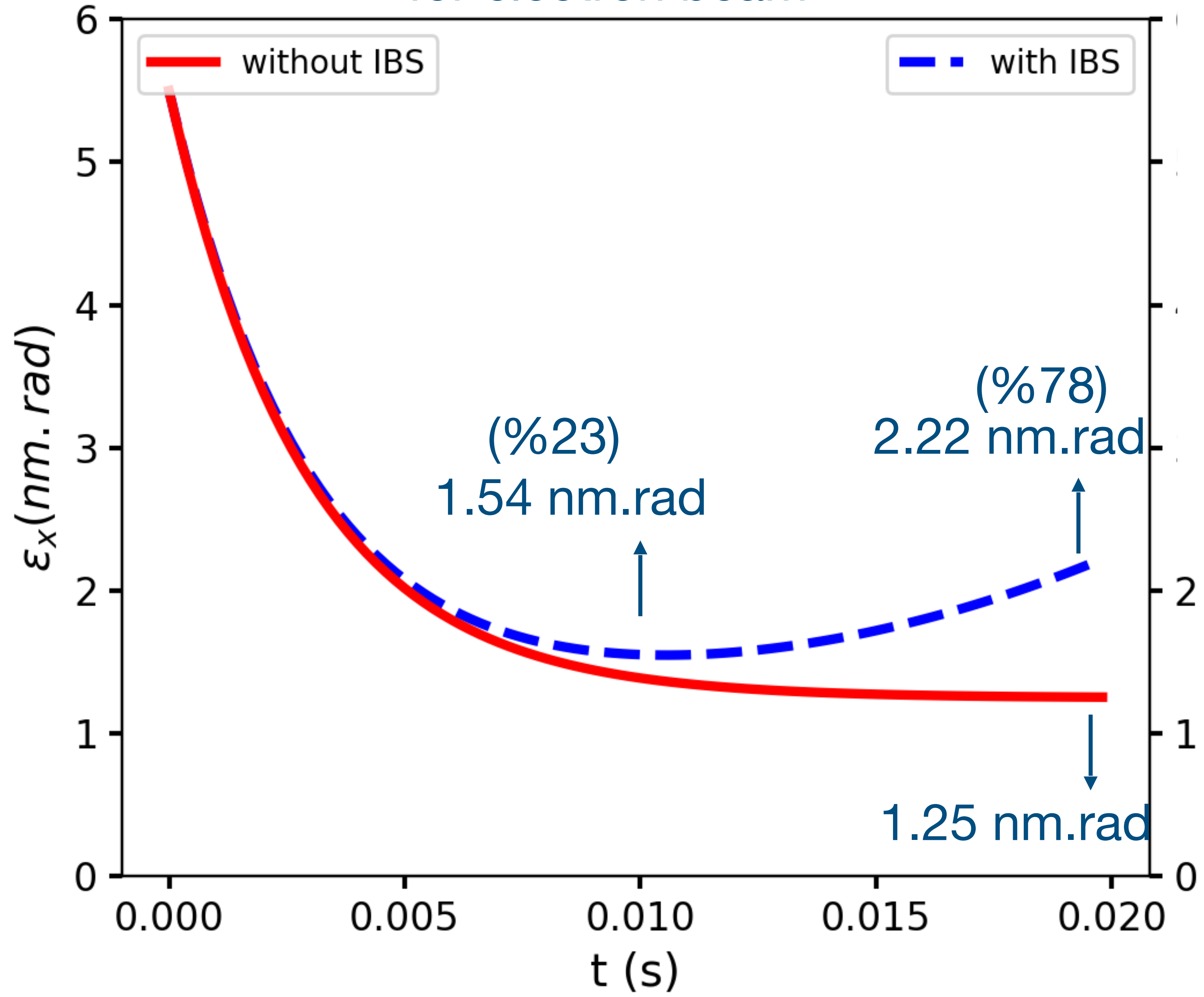
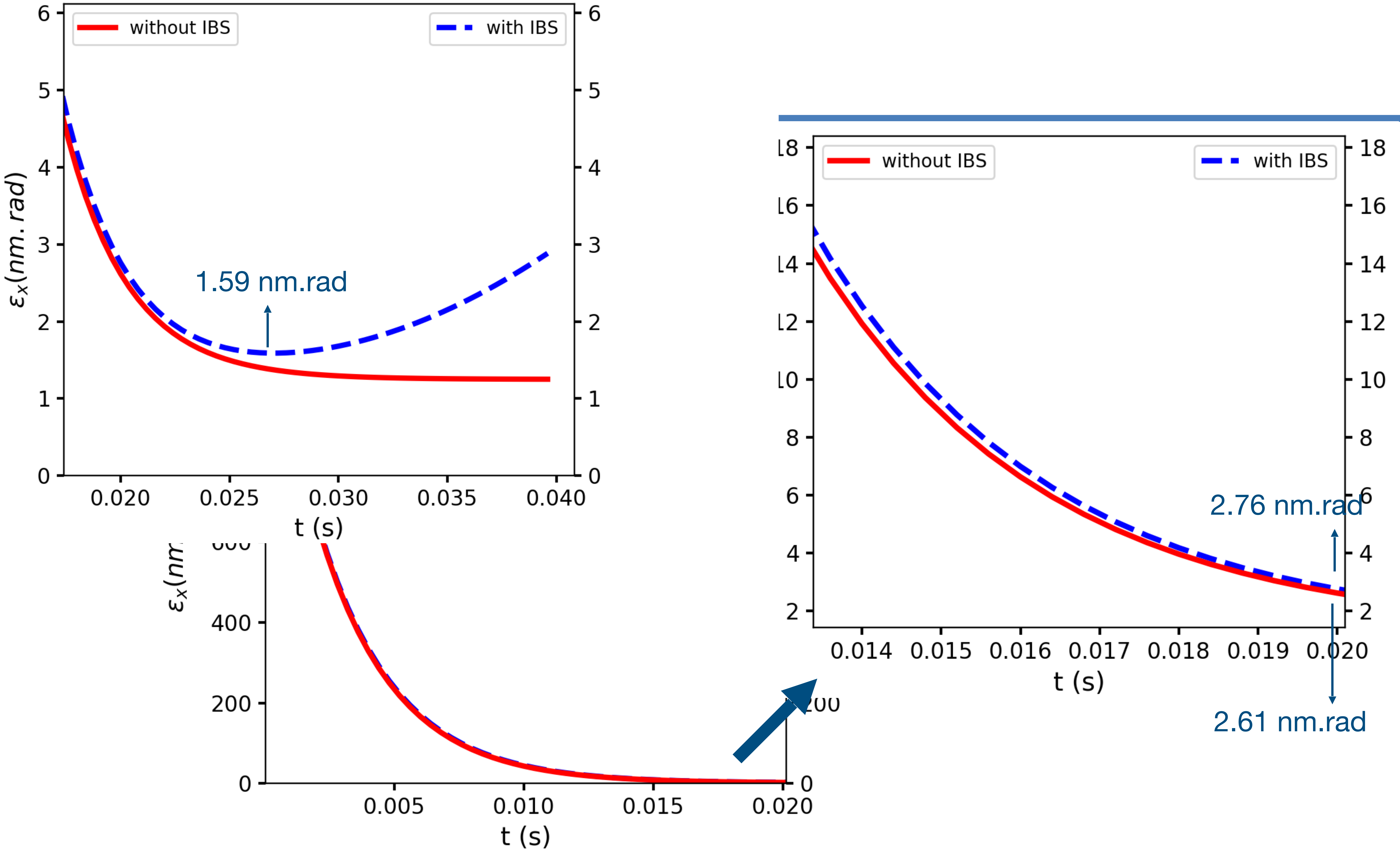
Intra-b

- **Intra-beam Scattering** (IBS) refers to
  to the re-distribution of the phase spa

for electron beam





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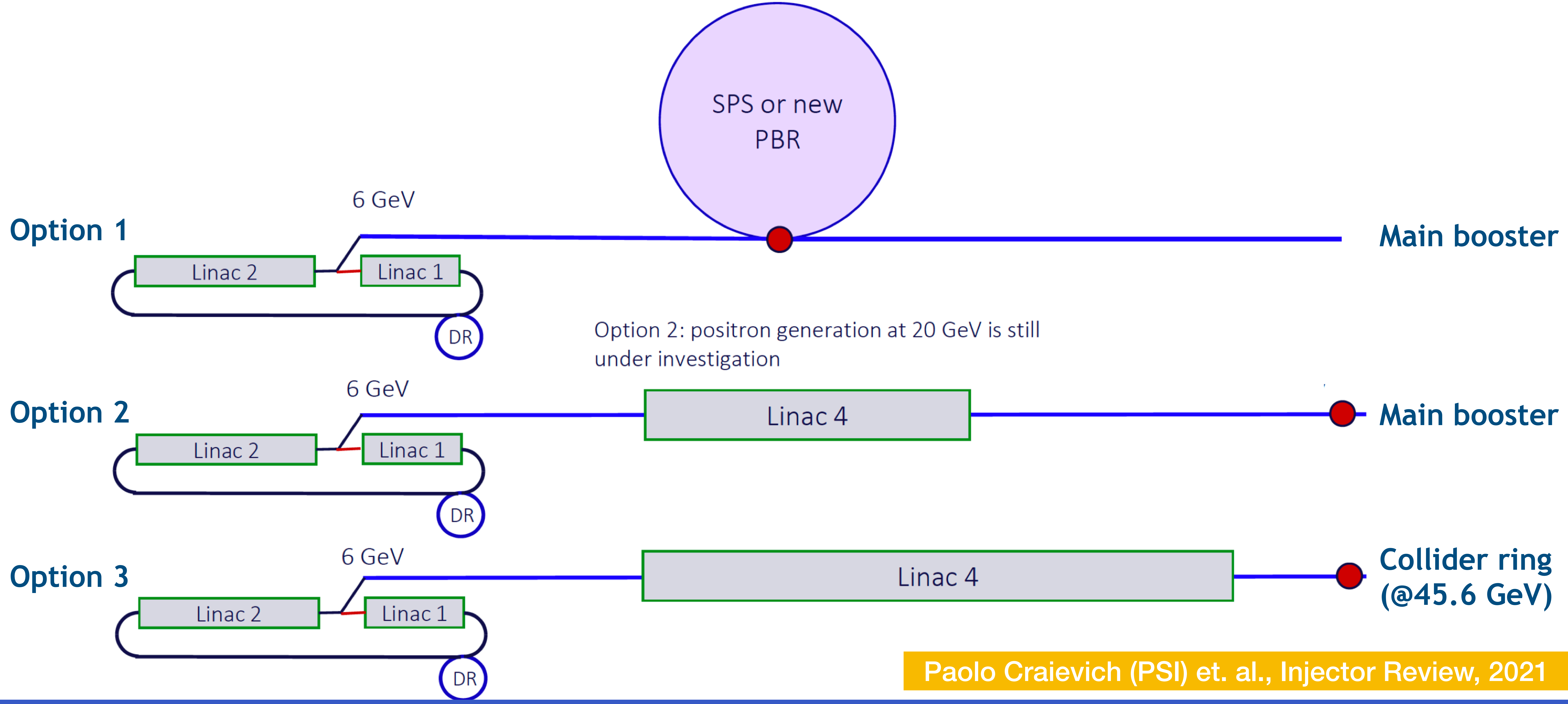
- Introduction
- FCC-e^+e^- injector complex
- FCC-e^+e^- pre-injector design
    - e-source and linac
    - Positron source
    - Damping ring
- Pre-booster ring design for FCC-e^+e^- injector complex
    - SPS as FCC-e^+e^- pre-booster ring
    - Conceptual design of an alternative pre-booster ring
- Collective effect calculations
- **More options for the injector complex**
- Main booster ring
- Physics + Design + Prototyping
- Conclusion

More options

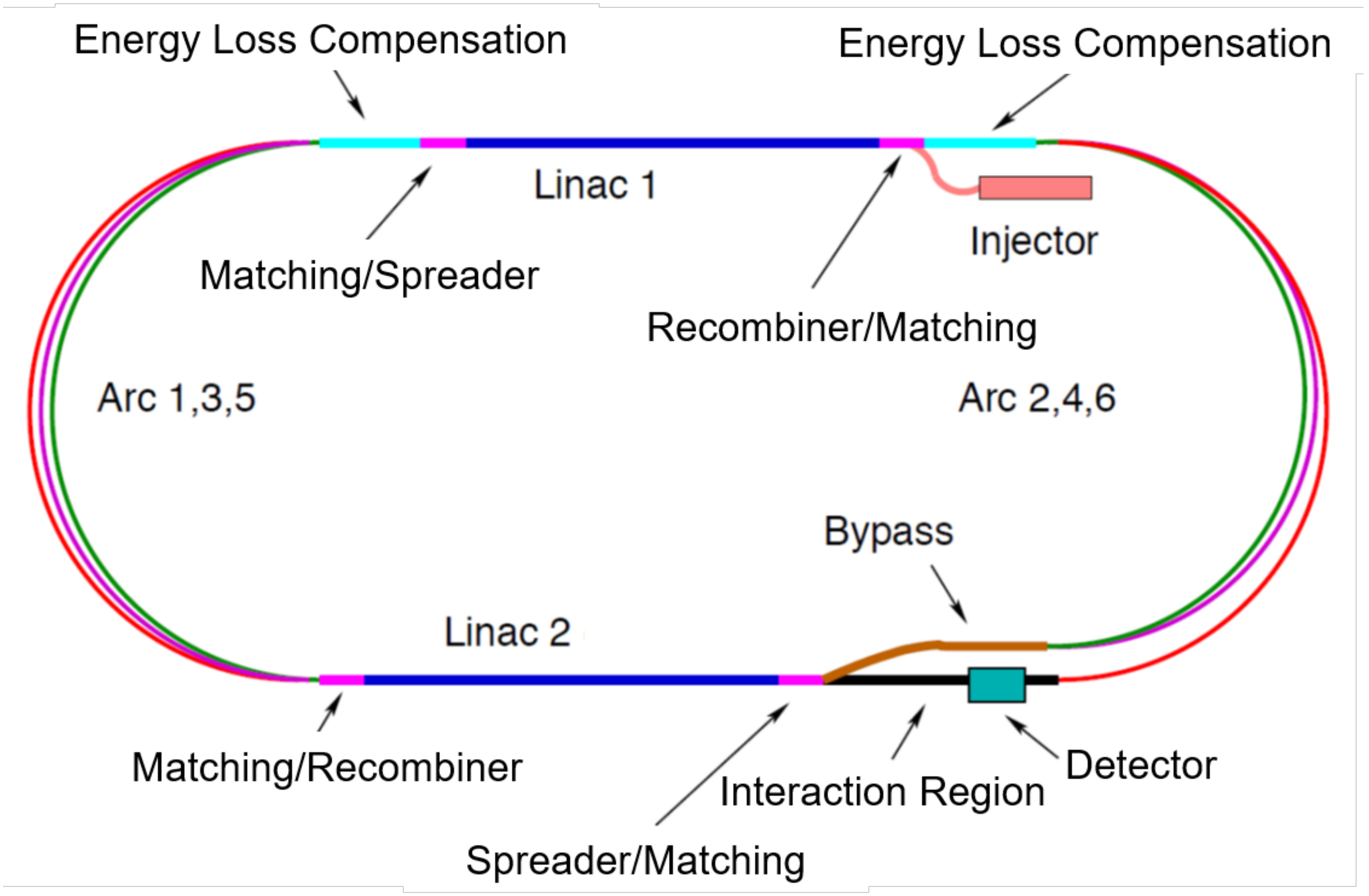
- More options have been under consideration for the injector complex since the early studies before CDR.



Paolo Craievich (PSI) et. al., Injector Review, 2021

LHeC-RLI as FCC-ee Injector

- LHeC (Large Hadron Electron Collider) - Recirculating Linac Injector (RLI) is also evaluated for the FCC-ee as injector.



- Based on **2 Linacs** with **3 recirculating arcs (~5.3 km in total)**, with **max. energy** of **~49 GeV** (60 GeV with longer version)
- Could be used for **full energy top-up injector** for FCCee-Z mode and **pre-injector** for other modes
- Small footprint **PERLE-like version** could be used as **pre-injector** to (P)BR~**6-20GeV**

Next steps:

- **Refine parameters** to include **low power/energy** options
- **Positron production** scheme (including **damping ring**)
- Detailed **beam dynamics design**

Yannis Papaphilippou et. al., FCC Week, 2021

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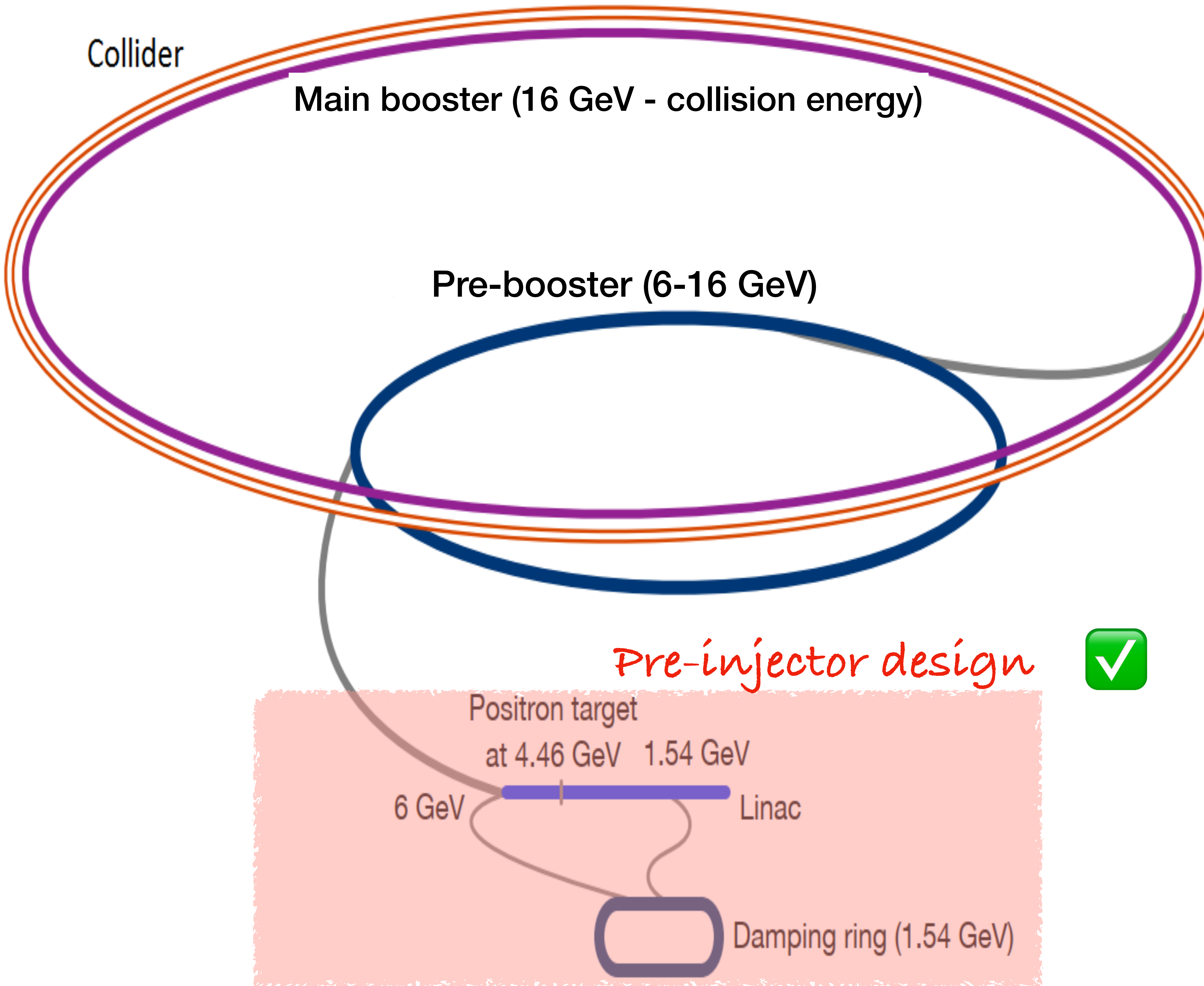
The FCC-e^+e^- Project

- The FCC-e^+e^- is a design project of a circular collider of around 100 km circumference.
    - Center of energies of the collider ring varies between **91.2 and 365 GeV.**
- General precision machine for the investigations of the **Z, W, Higgs and top particles**.
- The **injector complex** consists of:
    - **e-gun**
    - **Linac**
        - up to 6 GeV
        - Positron production
    - **Damping ring @ 1.54 GeV**
        - Bunch compressor
    - **Pre-booster ring up to 16 GeV**
        - SPS (baseline)
        - Alternative design
    - **Main booster ring**



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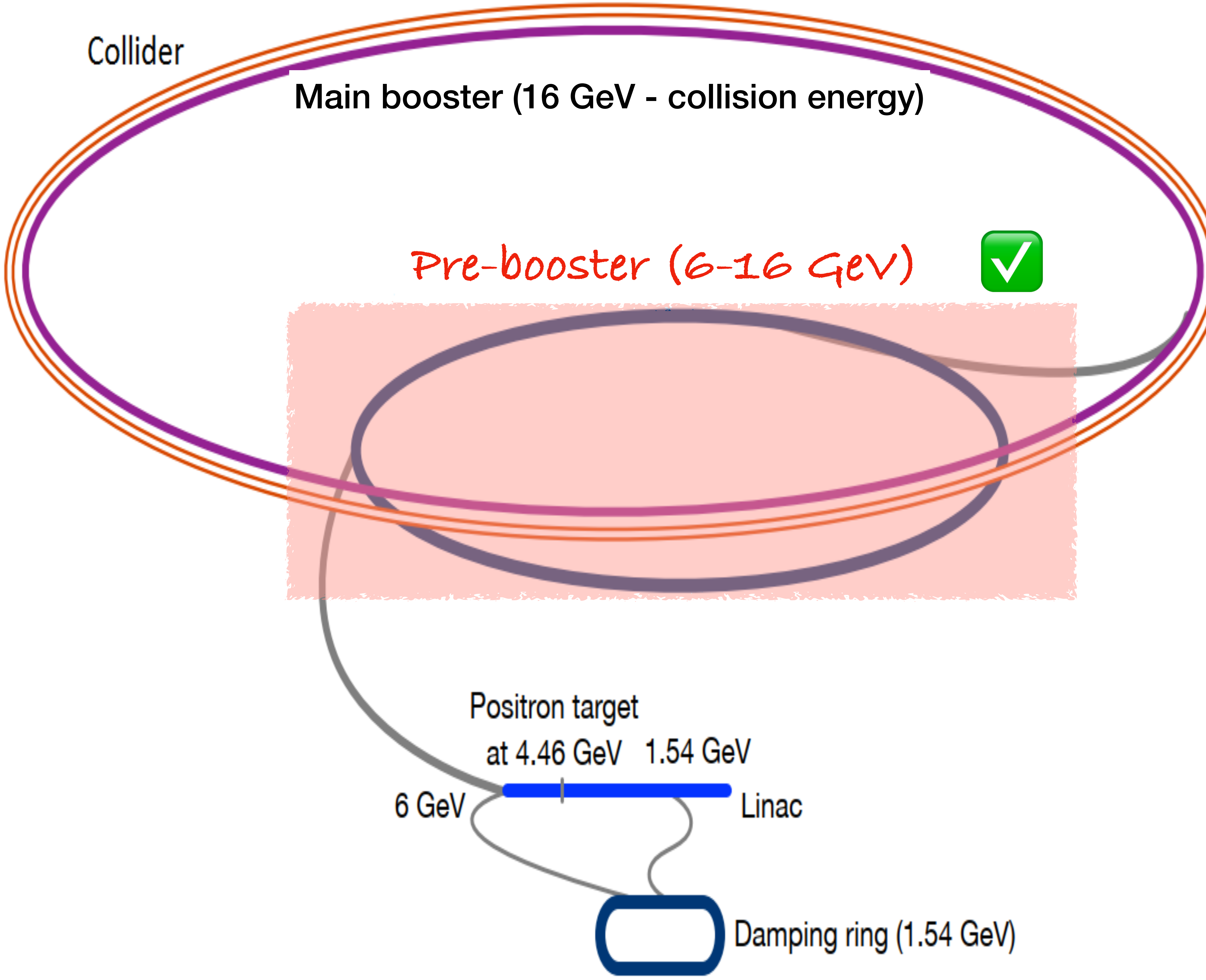

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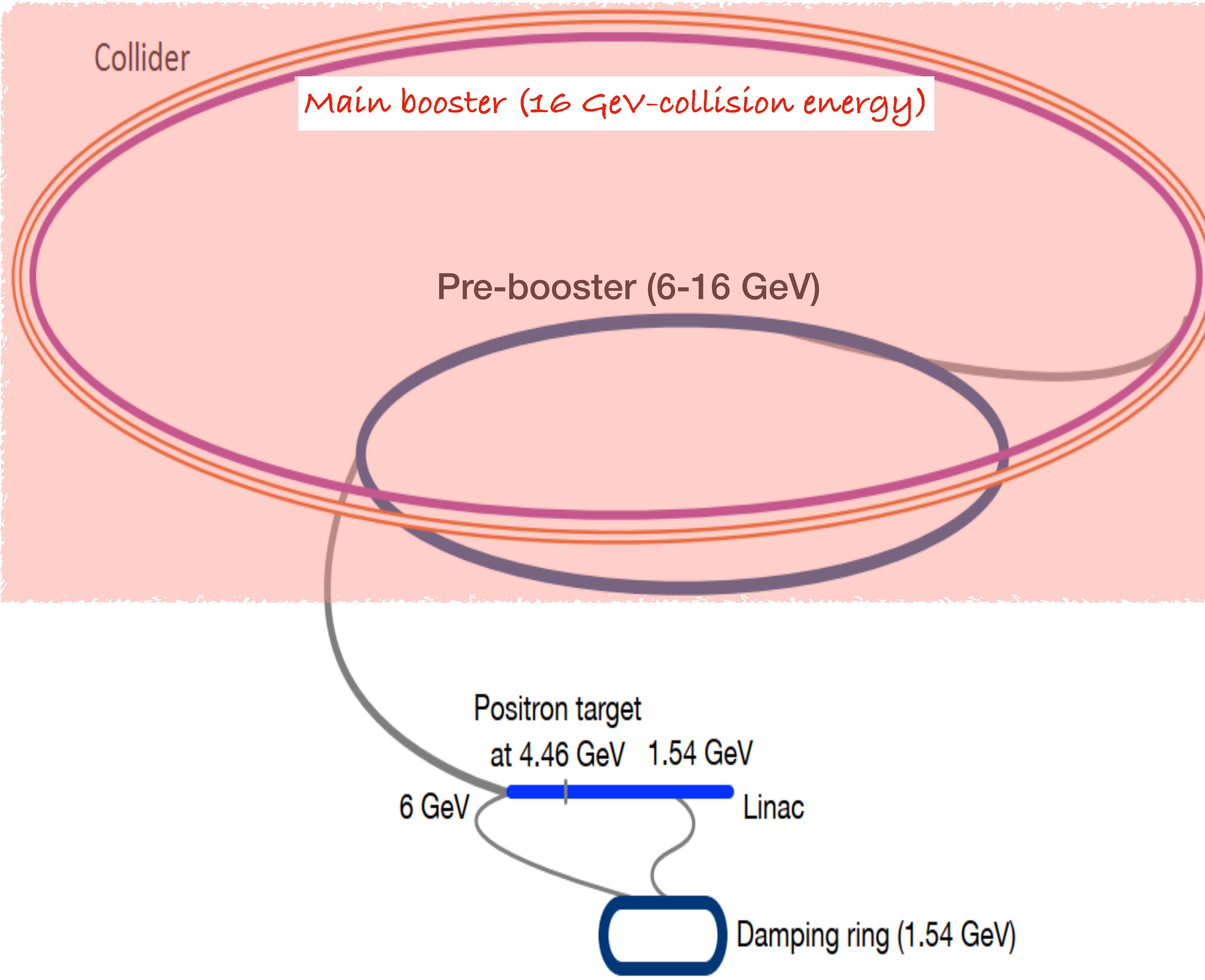
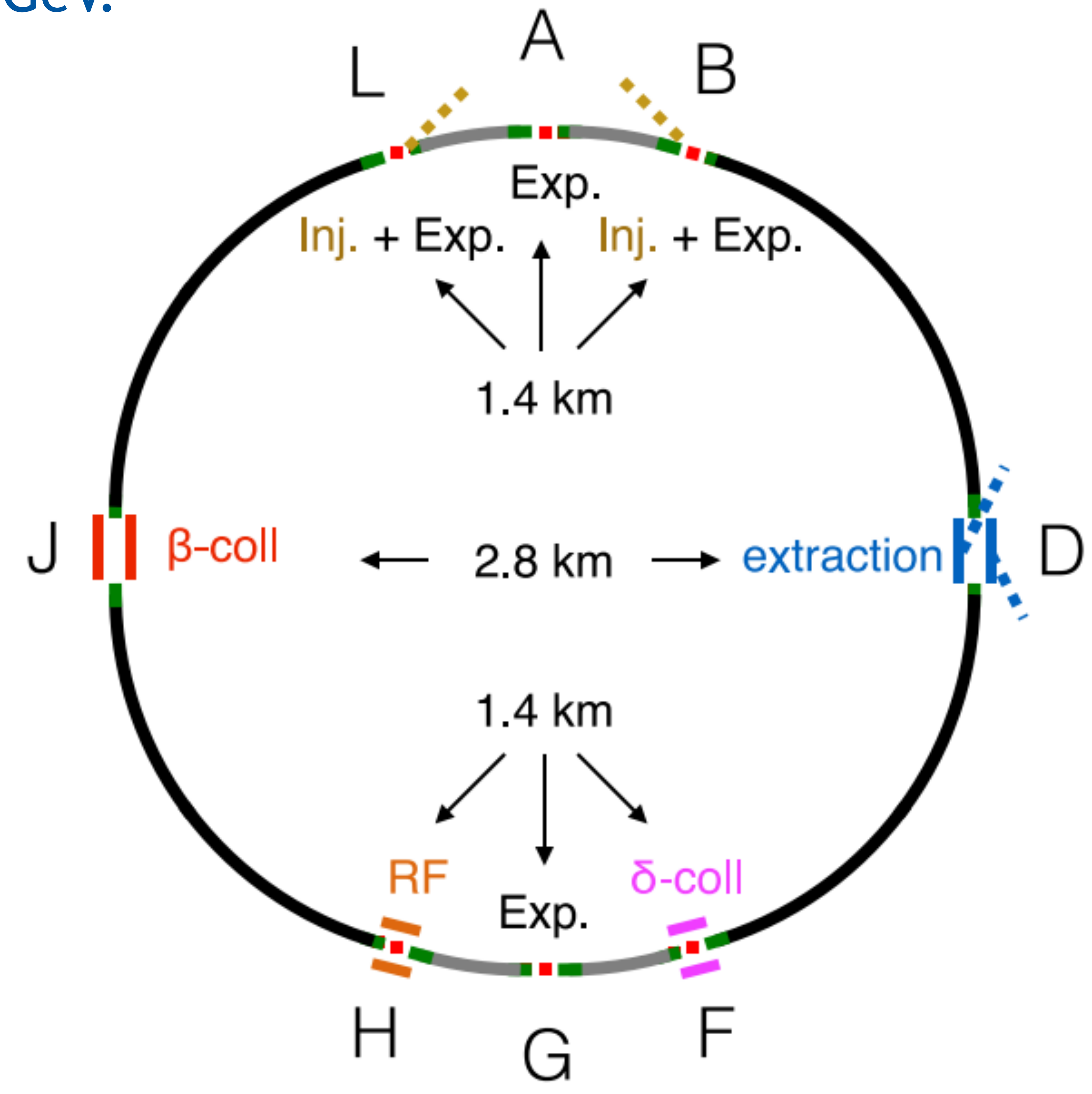
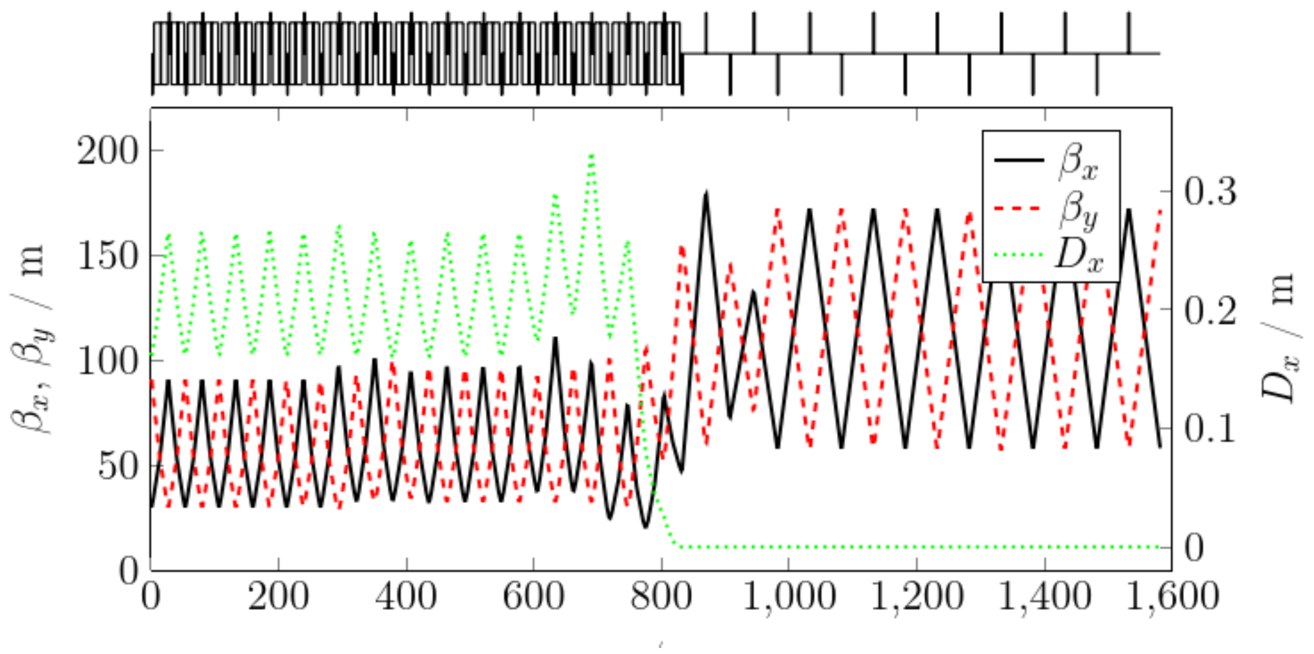


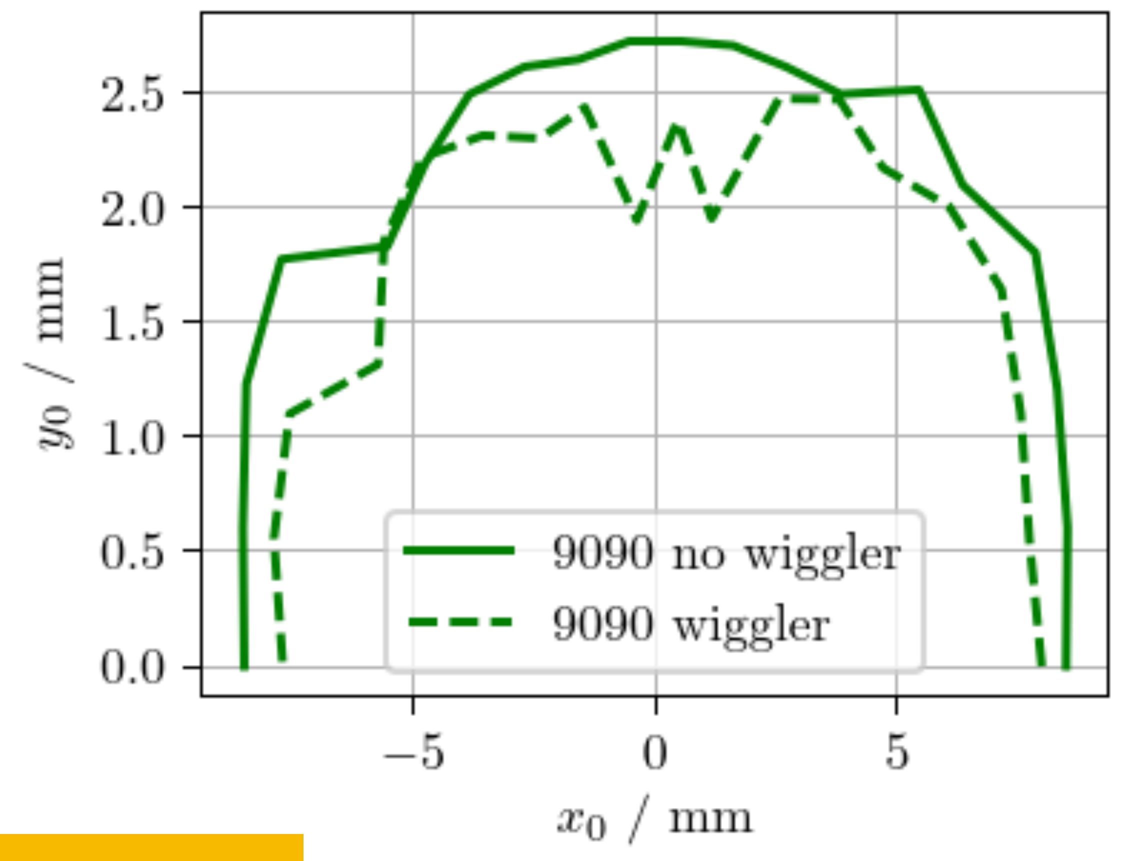
Main booster

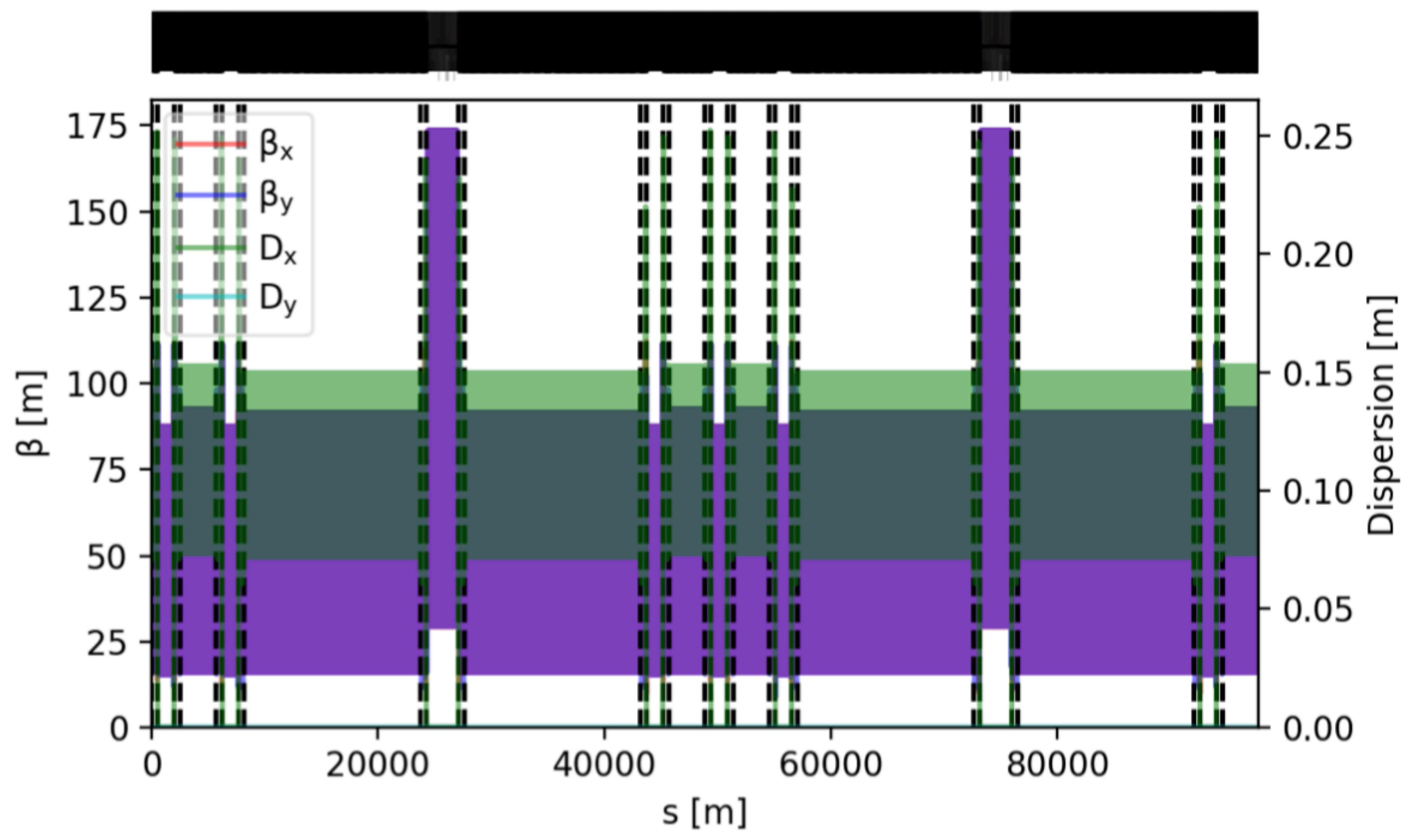
- The last stage of the FCC-e⁺e⁻ injector chain is a ~98 km full energy injector housed in the same tunnel as the collider.
- The magnetic lattice is of FODO structure. Two optics are used: first, a $90^0/90^0$ optics for the operation at 120 GeV and 182.5 GeV, second, a $60^0/60^0$ optics for 45.5 and 80 GeV.



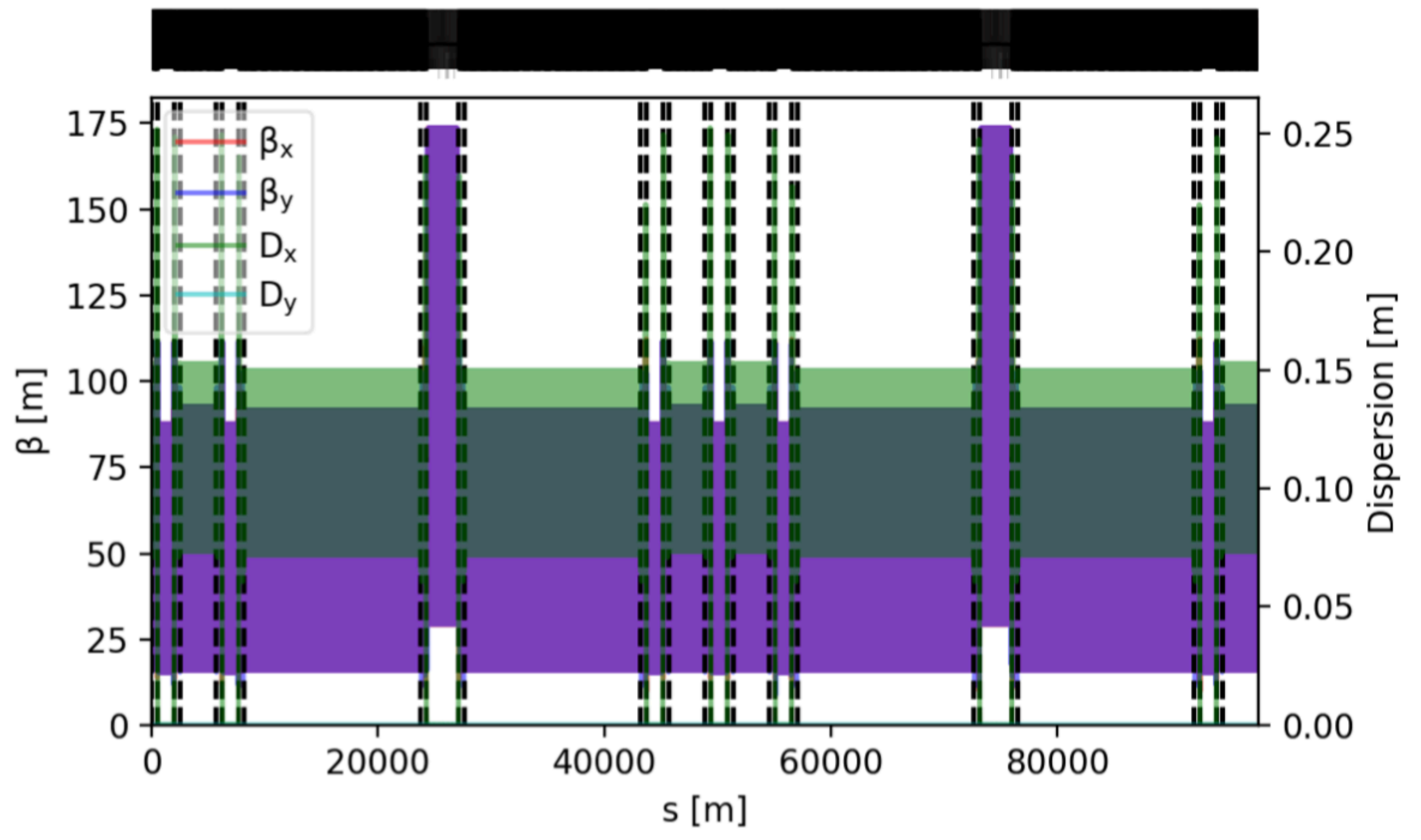
A. Chance (CEA), B. Harer (KIT) et. al.







Contribution to the IBS calculations, O. Etisken et. al.



Outline

Design + Physics + Prototype

<u>İzmir Ekonomi ve Ege Üniversitelerinin 2018 de hazırladığı ancak yönetmelik ve mevzuat sebebiyle beklemekte olan ortak projesi</u>

- 2018 yılı Nisan ayında CERN FCC Projesi ile İzmir Ekonomi Üniversitesi ve CERN FCC Projesi ile Ege Üniversitesi arasında ikili işbirliği protokolleri imzalanmıştır. (2021 yılının Kasım ayında protokoller yenilenmiştir.)
- Bu kapsamda İzmir Ekonomi Üniversitesi ve Ege Üniversitesi ile birlikte "CERN'ün Gelecek Dairesel Çarpıştırıcısında (FCC) Tasarım, Prototip Üretimi ve Fizik Araştırmaları" isimli proje başvurusunu hazırlamıştır.

A. Kenan Ciftci, IEU, Rena Ciftci, Ege Ü.

Design + Physics + Prototype

FCC Projesinde vereceğimiz katkılar nelerdir?

- FCC-ee'nin ana halkasının vakum odacığının prototipinin Türkiye'de üretimi ve testleri,
- FCC-ee için prebooster halkanın tasarımı,
- FCC-ee için amorf hedeften damping halkasına pozitron üretim zincirinin tasarımı,
- 3-3-1 Modellerinin öngördüğü yeni fermiyonların ve ayar bozonlarınn FCC-hh ve FCC-he'de gözlenme potansiyelinin araştırılması yapılacaktır…

A. Kenan Ciftci, IEU, Rena Ciftci, Ege Ü.

Design + Physics + Prototyping

Proje Yürütücüsü → Prof.Dr. Abbas Kenan Çiftçi
İzmir Ekonomi Ü. Fizik

Doç. Dr. Rena Çiftçi
Ege Ü. Fizik ← Yürütücü Yardımcısı ve Ege Üniversitesi Koordinatörü

Prof. Dr. Cüneyt Çeliktaş EÜ. Fizik	Prof. Dr. Nadide Kazancı EÜ. Fizik	Doç. Dr. Gürsoy Bozkurt Akgüç İEÜ Fizik	Dr. Öğr. Üy. Özge Sağlam İEÜ Makine Müh.
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Danışmanlar:

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A. Kenan Ciftci, IEU, Rena Ciftci, Ege Ü.

Design + Physics + Prototype

- Bu projenin tamamlanması sonucunda Türkiye'nin ve Türk şirketlerinin Vakum odacığı üretme kapasitesi CERN tarafından tescillenmiş olacaktır.
- Böylece ~2030 civarında çıkılacak ihalede 400 km (FCC-ee'nin ana ve booster halkaları) uzunluğunda (yaklaşık 1,5 Milyar CHF) vakum tüplerinin ihalelerine şirketlerimiz katılabilecekler
- Benzer şekilde teknolojiyi öğrendiğimiz için FCC-hh'nin (yaklaşık 3 Milyar CHF) vakum tüplerinin de ihalelerine katılabileceğiz
- Dünyada üretilecek hızlandırıcıların vakum tüplerini üretmeye de talip olabiliriz.
- Ultra Vakum teknolojisinin öğrenilmesi ile Türkiye'de bilim ve teknolojinin gelişiminde öngörülemeyecek katkıları bekliyoruz.
- Projemizde katkı verecek şirketler CERN tarafından tanınacak (akredite olacaklar) böylece vakum tüpü dışındaki ihalelere de katılabileceklerdir.
- NEG kaplama tekniğinin Türkiye haklarını alabileceğiz.

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Outline

- Introduction
- FCC-e^+e^- injector complex
- FCC-e^+e^- pre-injector design
  - e-source and linac
  - Positron source
  - Damping ring
- Pre-booster ring design for FCC-e^+e^- injector complex
  - SPS as FCC-e^+e^- pre-booster ring
  - Conceptual design of an alternative pre-booster ring
- Collective effect calculations
- More options for the injector complex
- Main booster ring
- Physics + Design + Prototyping
- **Conclusion**

Özet ve Sonuç

- **FCC-e$^+$e$^-$** (**enjektör kompleksi** odaklı) çalışmaları, farklı seçenekleri de kapsayacak şekilde **tanıtıldı**.

- **Türkiye'den bilim insanlarının** ellerinden gelenin en iyisini vererek **2016** yılından beri projeye, bir çok kısmına ve çeşitli konularda, dahil olarak aktif bir şekilde katkı vermekte olduğu ve katkı vermeye devam edeceği görünmektedir! :
    - Doğrusal hızlandırıcı (**tasarım**),
    - Pozitron üretimi (**tasarım+deneysel çalışma**),
    - Sönümleme hızlandırıcısı (damping ring) (**tasarım**, **kolektif etki hesaplamaları**),
    - Ön-enerji öteleyici hızlandırıcısı (pre-booster ring) (**tasarım**),
    - Ana-enerji öteleyici halkası (main booster ring) (**IBS hesaplamaları**),
    - Çarpıştırma halkası (collider ring) (**injection filling scheme**, **e-cloud hesaplamaları**).

- Türkiye'de bilim insanlarının (İzmir Ekonomi ve Ege Üniversitesi) **önemli bir projesi** ise **2019** yılından beri değerlendirilmeyi **bekliyor**!
    - **Prototip** + **tasarım** + **fizik çalışmaları**.

FUTURE CIRCULAR COLLIDER

Özet ve Sonuç

- **FCC-e$^+$e$^-$ (enjektör kompleksi** odaklı) çalışmaları, farklı seçenekleri de kapsayacak şekilde **tanıtıldı**.

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Thank you!