COLLECTIVE EFFECTS ESTIMATES FOR THE CURRENT DAMPING RING DESIGN OF THE FCC-e^+e^-

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Outline

- **Introduction**

- **Review of the latest pre-injector layout and the DR design**

- **Estimations of collective effects for the DR of FCC-ee injector complex:**

  ✳Space charge (SC)
  ✳Intra-beam scattering (IBS)
  ✳Longitudinal micro-wave instability (LMI)
  ✳Transverse mode coupling instability (TMCI)
  ✳Ion effects
  ✳e-cloud
  ✳Coherent synchrotron radiation (CSR)

- **Conclusion**

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Introduction

- 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 and energy compressor
  - **Pre-booster ring up to 16 GeV**
    - SPS (baseline)
    - Alternative design
  - **Main booster ring**

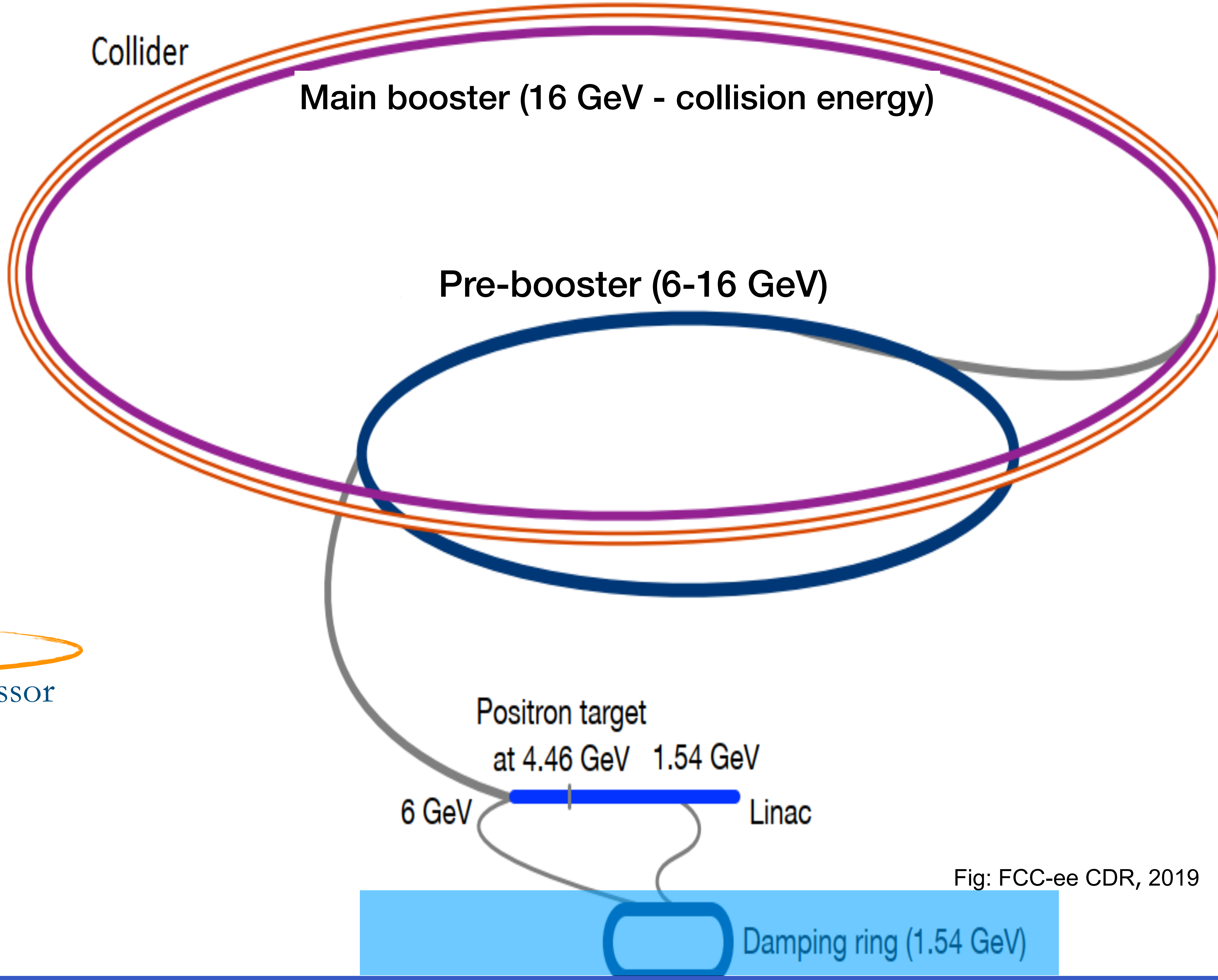

Fig: FCC-ee CDR, 2019

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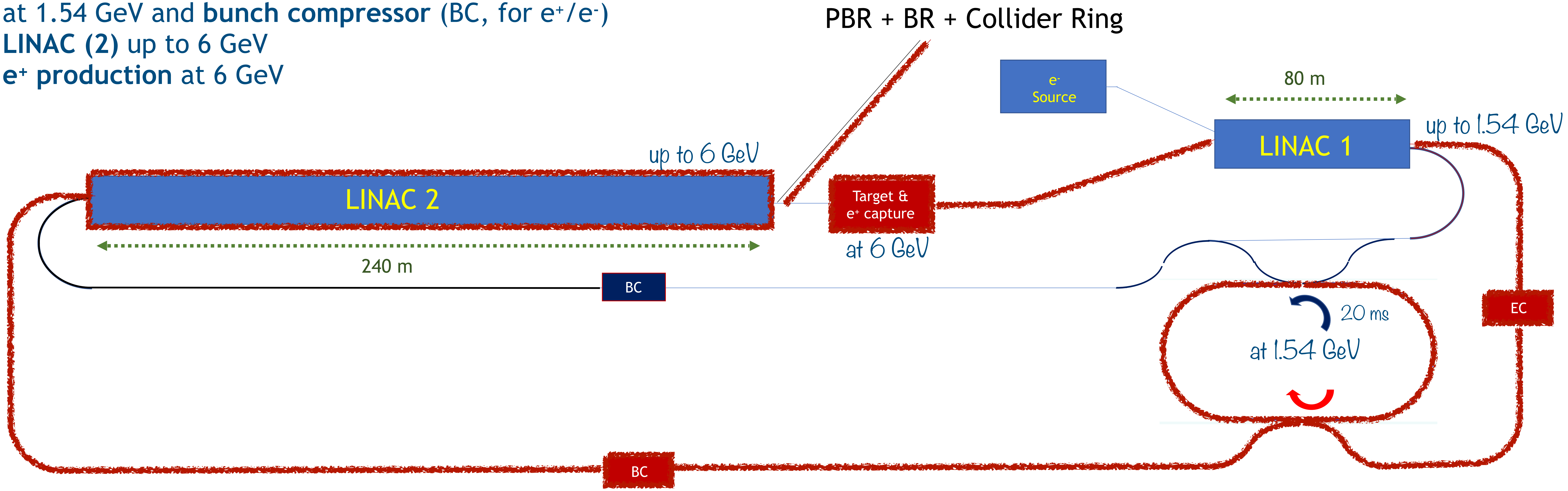
Review of latest version of the pre-injector complex

The latest proposed version of the **injector complex** consists of:

- **e⁻ source**
- **Linac (1)** up to 1.54 GeV
- **Energy compressor** (EC, for e⁺), **damping ring** (DR, for e⁺/e⁻) at 1.54 GeV and **bunch compressor** (BC, for e⁺/e⁻)
- **LINAC (2)** up to 6 GeV
- **e⁺ production** at 6 GeV



Review of latest version of the 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 study was taken over (early 2021) by **C. Milardi, O. Blanco, A. De Santis.**

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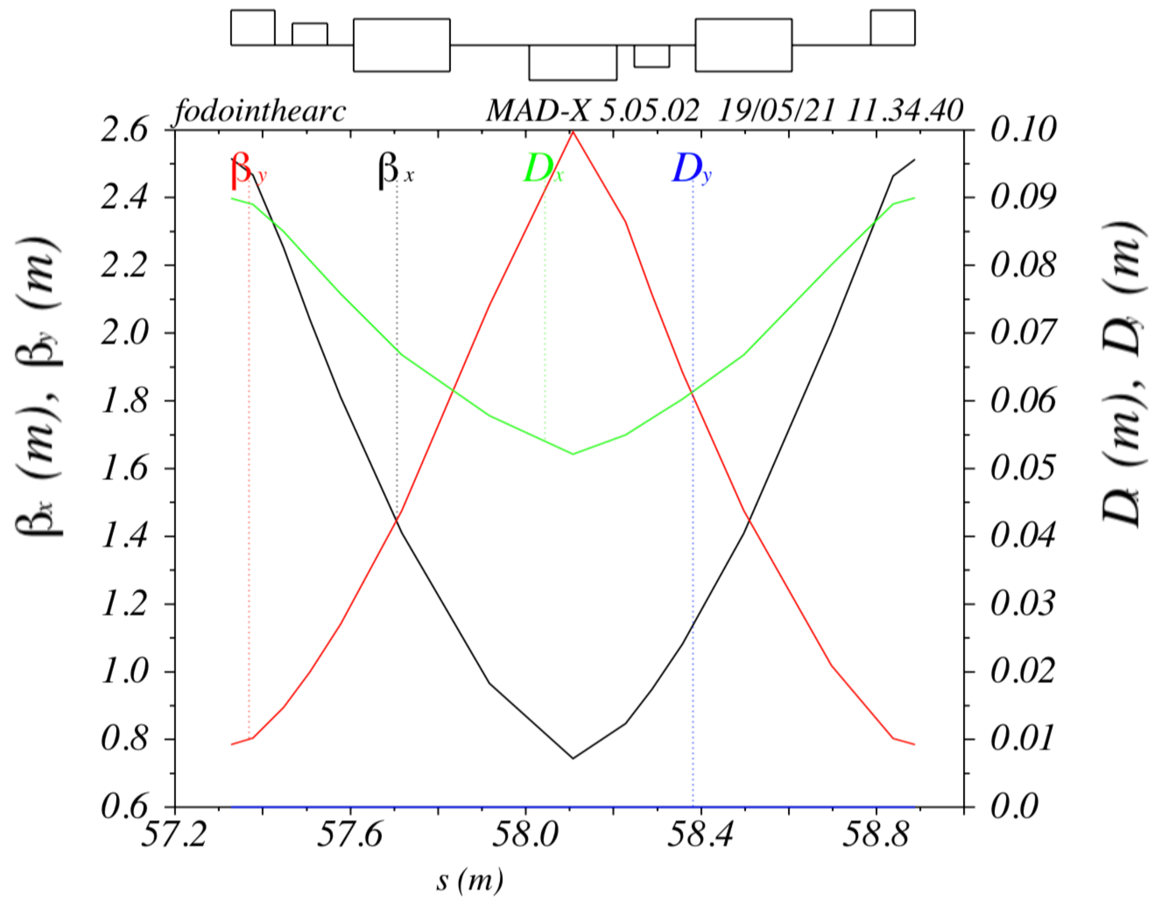

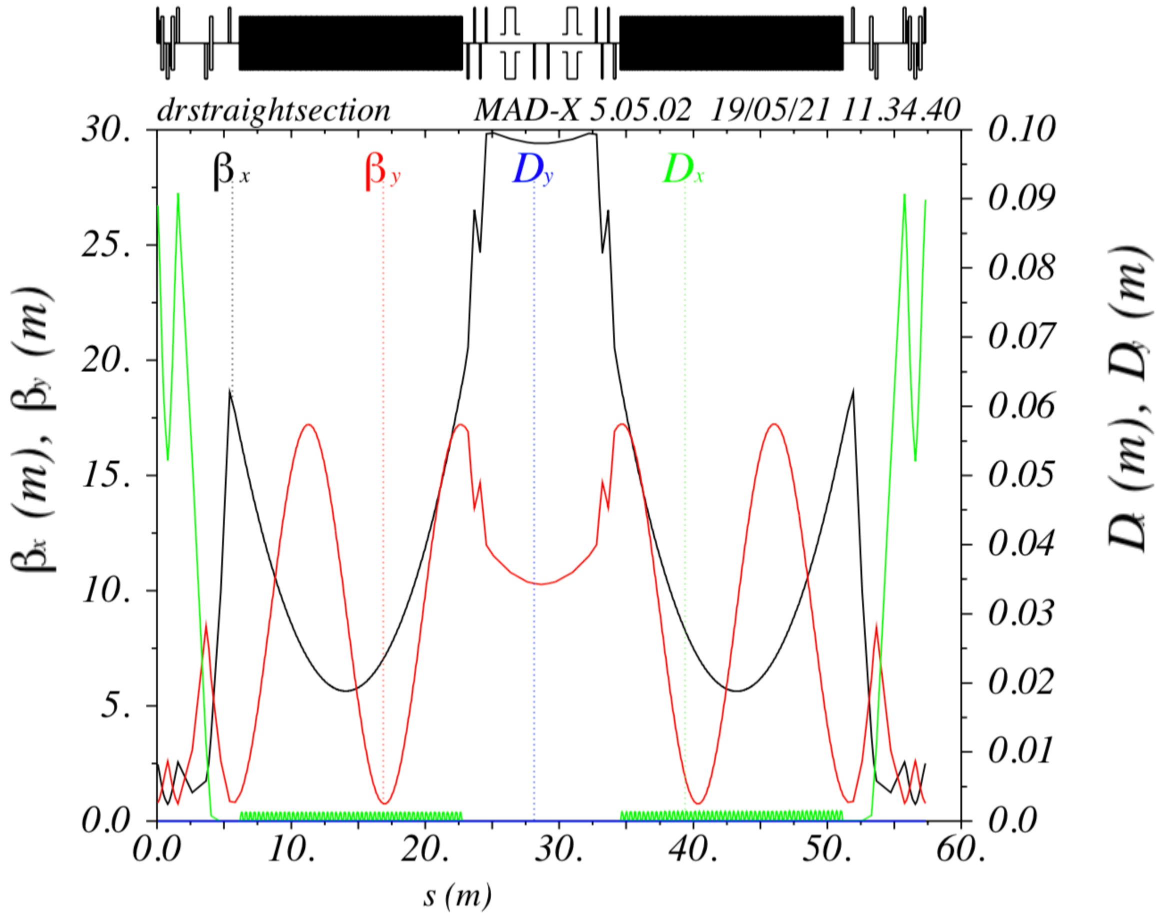

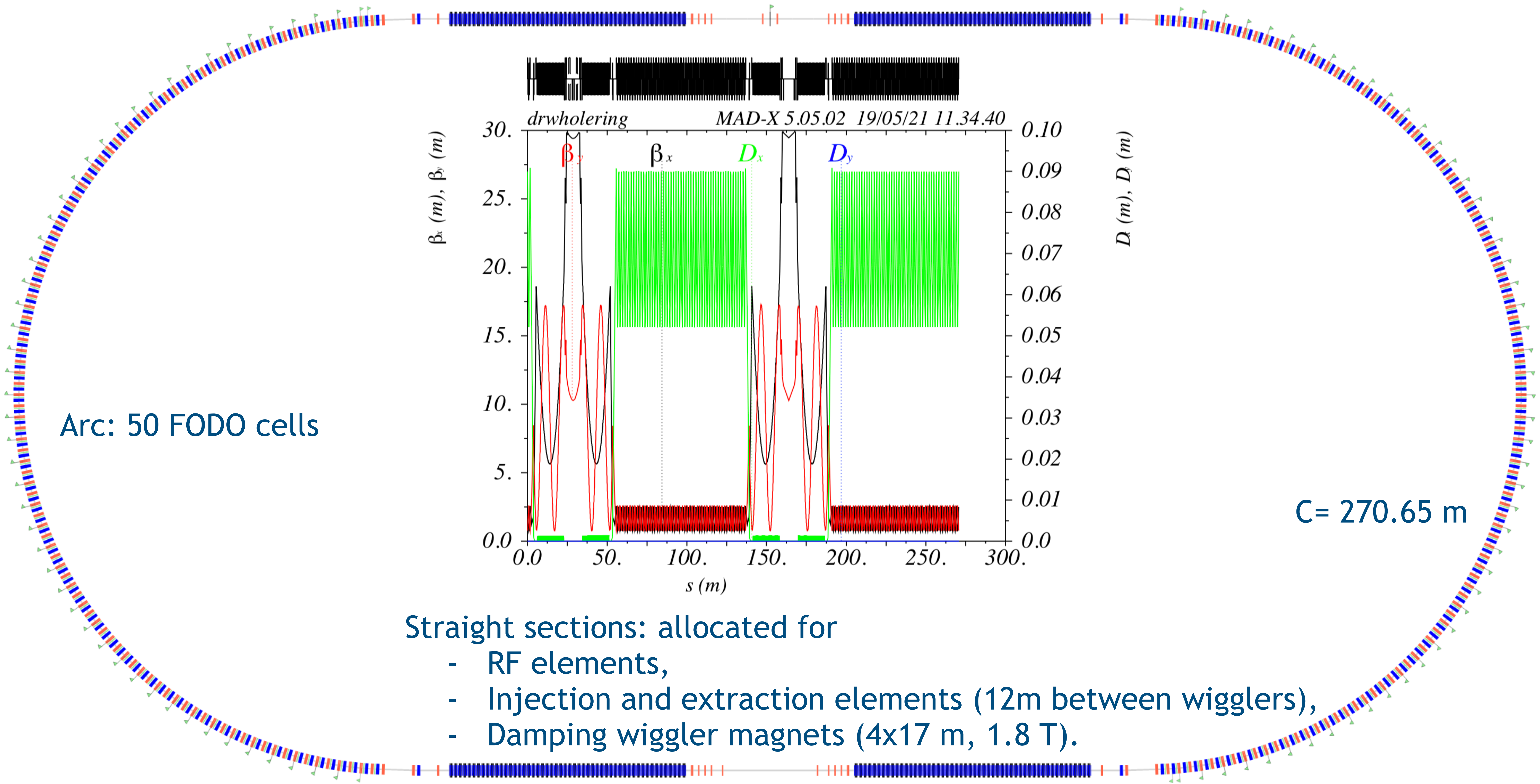

Arc: 50 FODO cells

C= 270.65 m

Straight sections: allocated for

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

Beam parameters of the DR

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)
Chamber radius	b [m]	0.01
Injected parameters		
Emittance (e^-/e^+)	ε_x [nm]/[µm]	5.5/1.29
Emittance (e^-/e^+)	ε_y [nm]/[µm]	6/1.22
Momentum spread (e^-/e^+)	σ_δ $(x10^{-2})$	0.2/5
Bunch length (e^-/e^+)	σ_z [mm]	1/3.4

The constants which are needed for the calculations

Constant	Symbol	Value
Electron radius	r_e [m]	$2.81794x10^{-15}$
Vacuum impedance	Z_0 [Ω]	375
Electron charge	e [C]	$1.602x10^{-19}$
Electron charge	e [A.s]	$1.5x10^{-19}$
Speed of light	c [m/s]	$3x10^{8}$
Proton radius	r_p [m]	$1.54x10^{-18}$
Alfven current	I_A [A]	17045
Conductivity (Al)	σ $[\Omega^{-1}m^{-1}]$	$3.77x10^{7}$

1. **S. Ogur**, IPAC 2019 proceeding (doi:10.18429/JACoW-IPAC2019-MOPMP002)
2. **F. Yaman**, e-cloud presentation, Optic Meeting-120

Space charge

- The incoherent **tune spread** caused by the **Space Charge (SC)** effect can lead to the interaction of the beam with resonances and consequently to beam degradation.

- An **analytical expression** for the incoherent SC tune spread for Gaussian bunches is given by:

$$\delta Q^{inc}_{x,y} = -\frac{N_b r_e C}{(2\pi)^{\frac{3}{2}}\beta^2\gamma^3\sigma_z\sqrt{\epsilon_{x,y}}}\left\langle \frac{\sqrt{\beta_{x,y}}}{\sqrt{\beta_{y,x}\epsilon_{y,x}+D_{y,x}{}^2\sigma_\delta{}^2}+\sqrt{\epsilon_{x,y}\beta_{x,y}}}\right\rangle$$

N_b= bunch population, r_e= electron radius, C = circumference, σ_z= beam length,
$\varepsilon_{x,y}$= h/v emittance (geo.), D_x= dispersion, σ_δ= momentum spread

Parameter	**DR**
$\delta Q_{x/y}$ - @inj. (e^-)	0.004/0.003
$\delta Q_{x/y}$ - @inj. (e^+)	$1.8\text{x}10^{-4}/1.04\text{x}10^{-5}$
$\delta Q_{x,y}$ - @eq. (e^- and e^+)	0.01/0.09

- The maximum value is computed after the beam reaches the equilibrium emittance values in all planes: **δQ_y^{inc}=-0.09**.

- This may cause issue due to resonance crossing. It should be taken into account on the working point choice.

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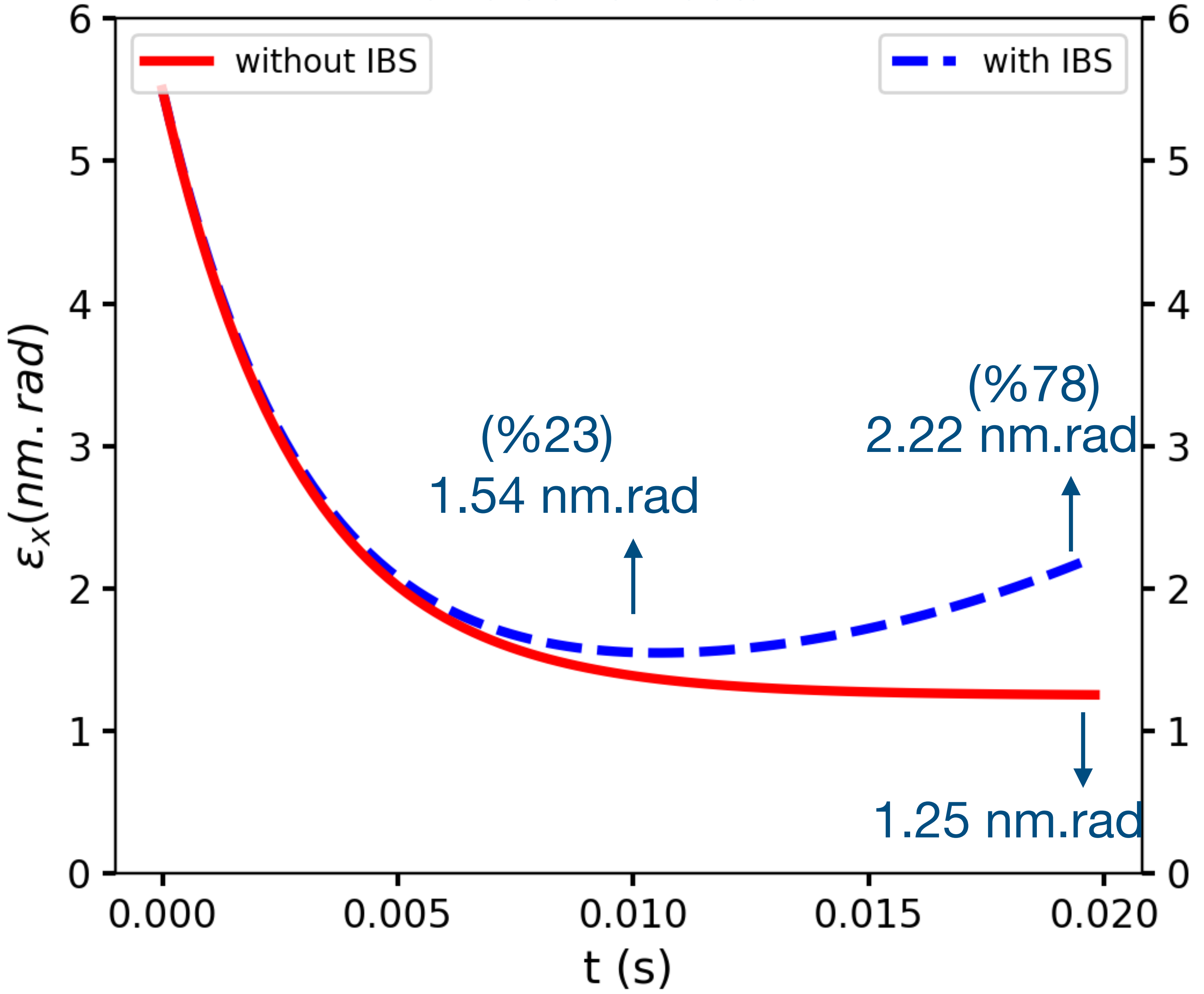
Intra-beam scattering

- **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.

for electron beam



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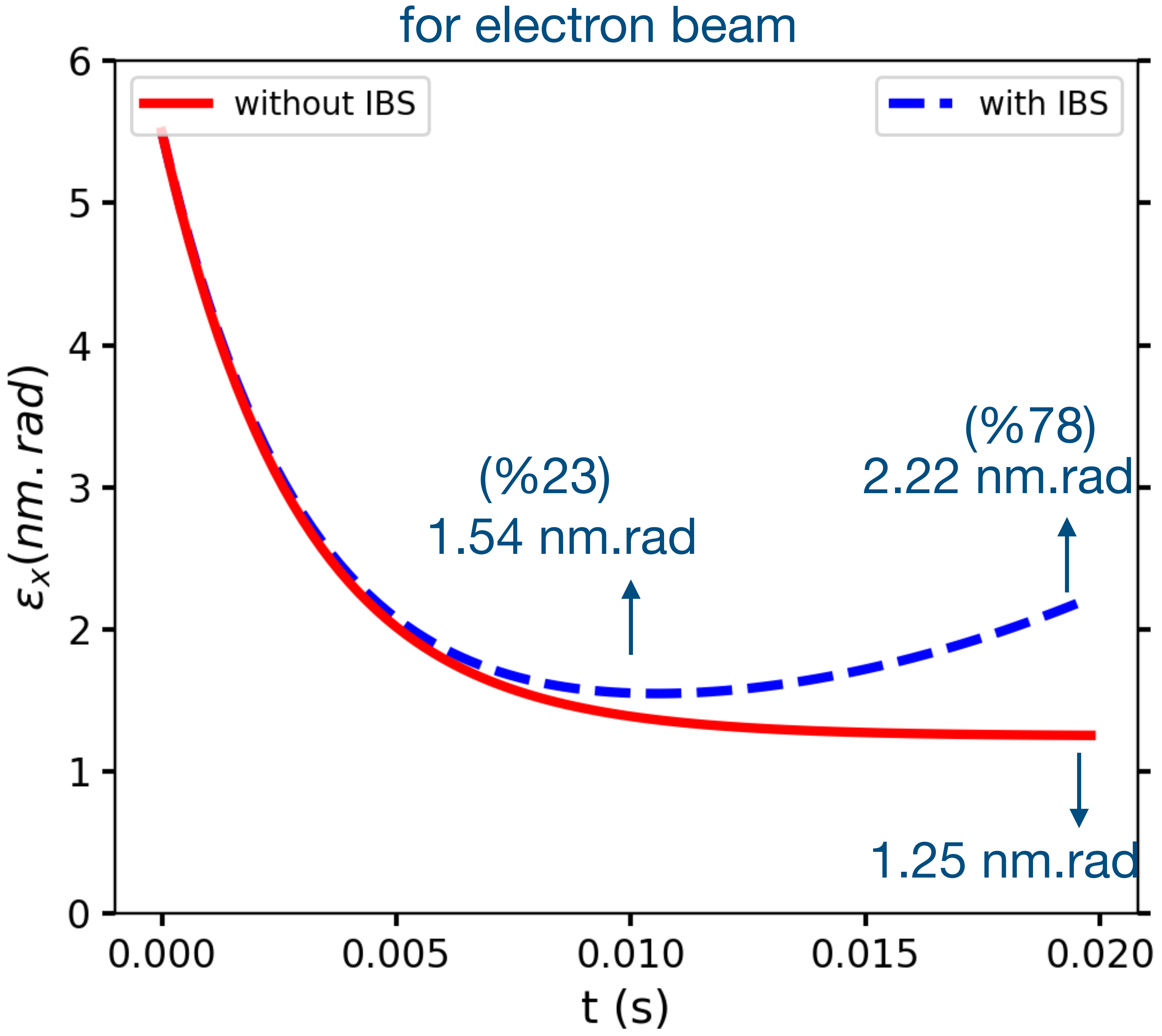
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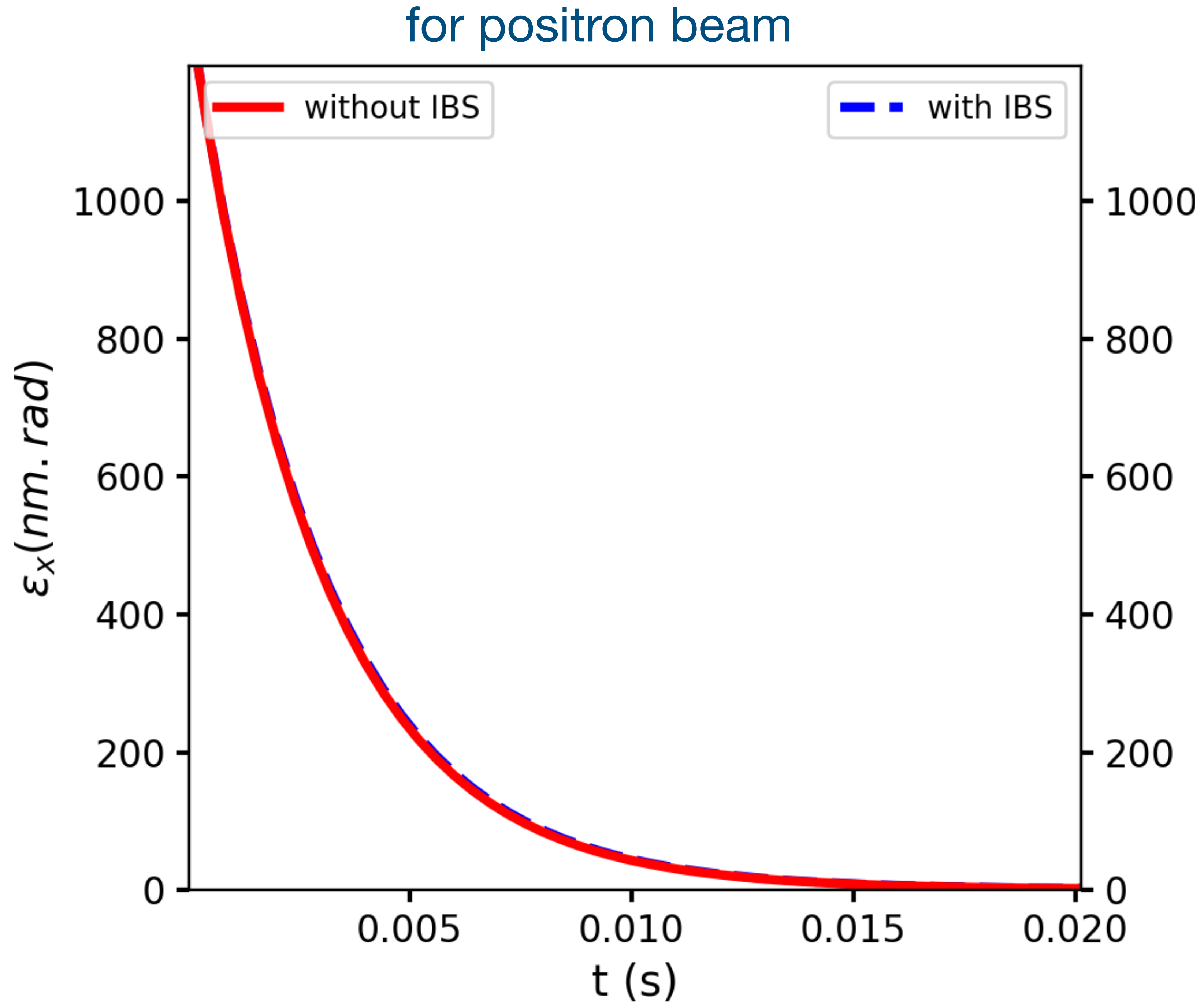
for positron beam

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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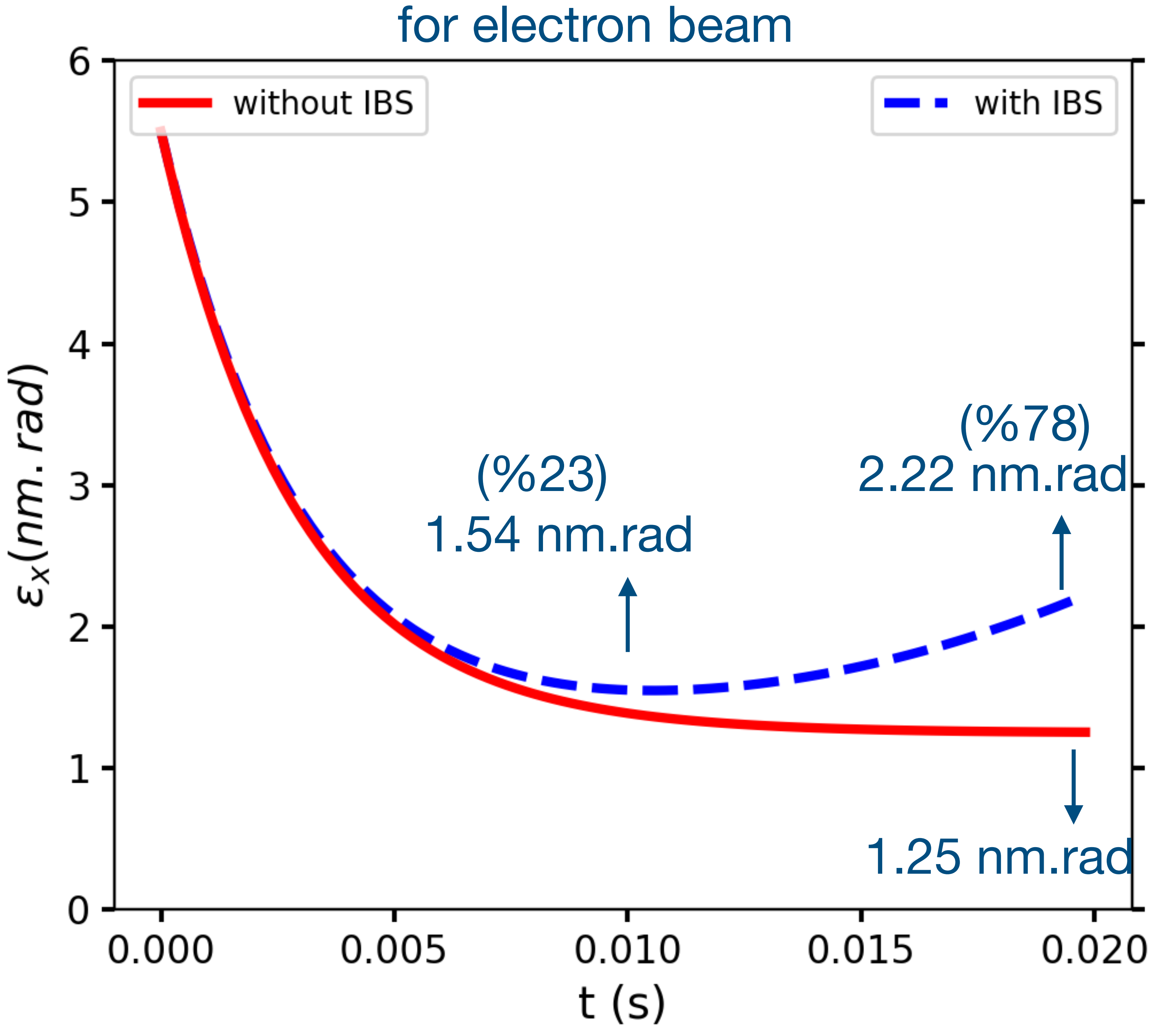

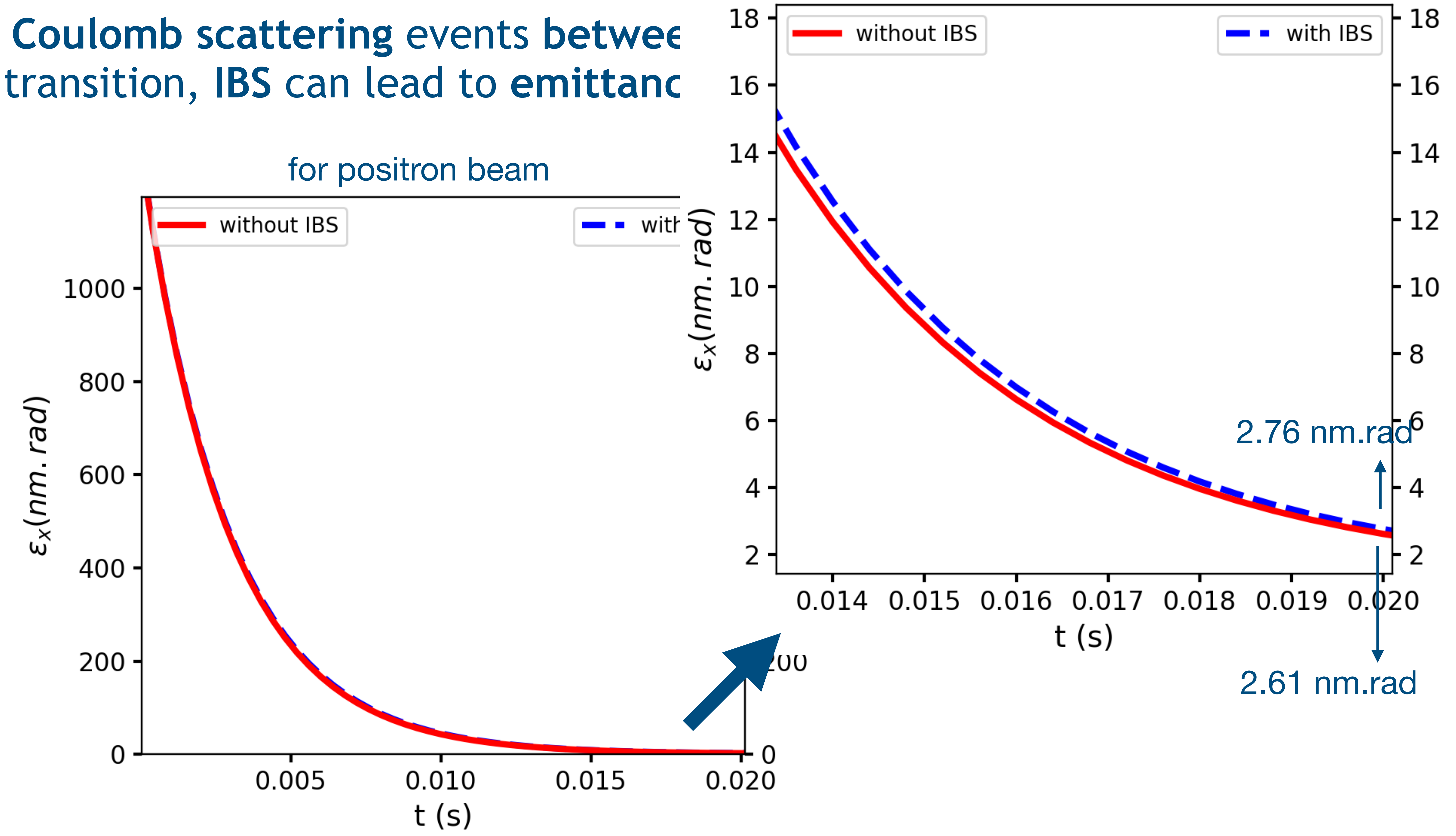

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Intra-b

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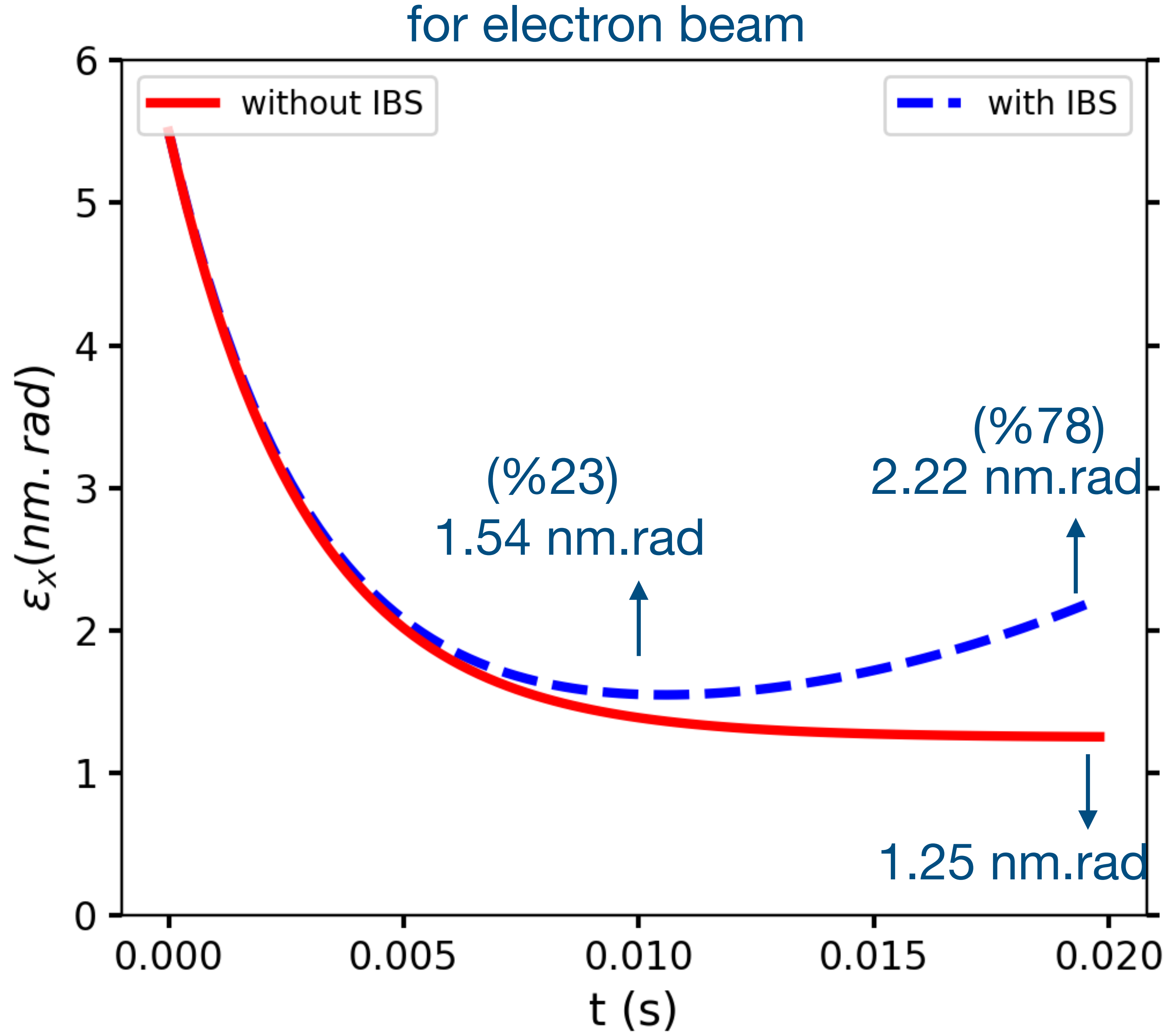

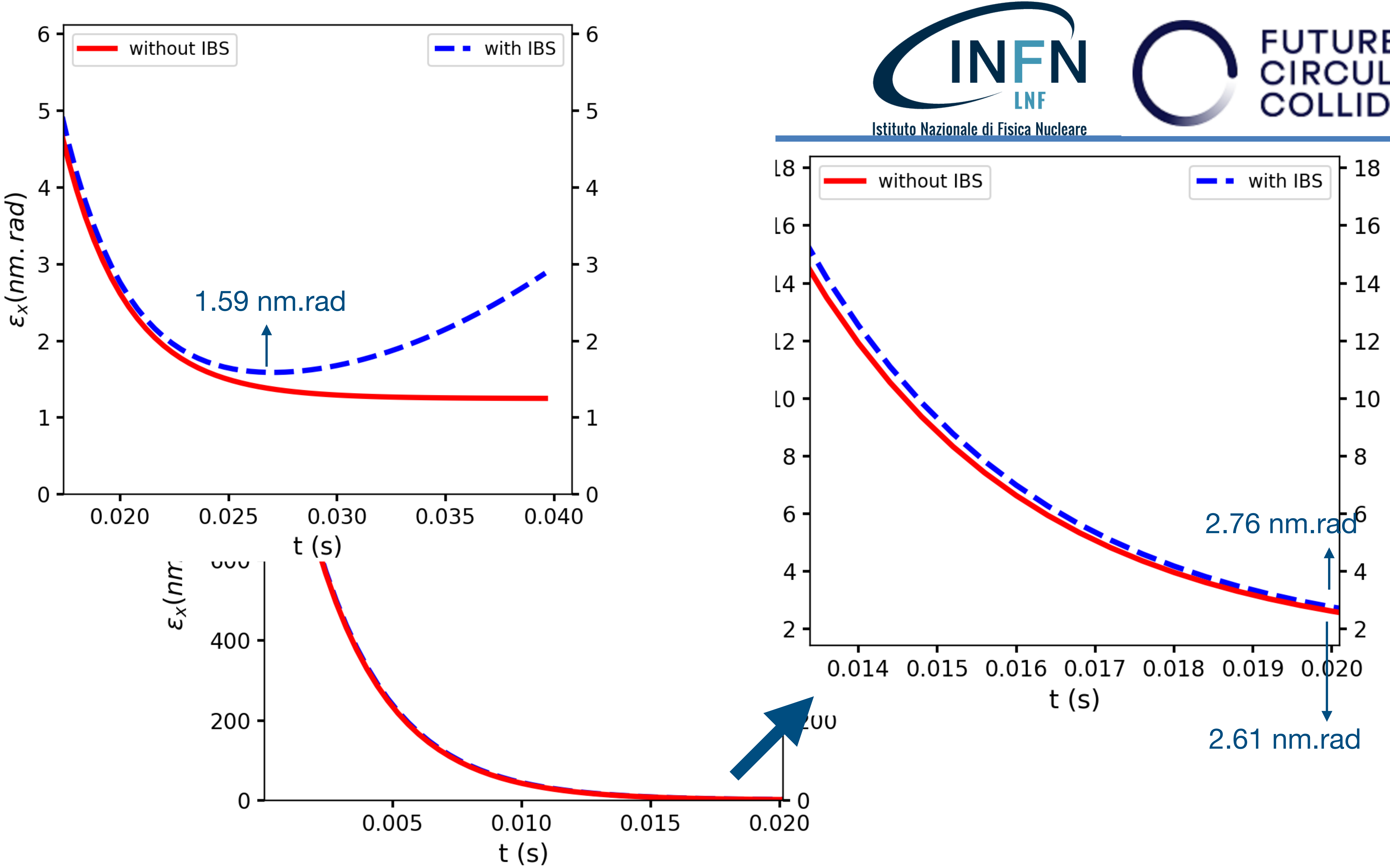

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Longitudinal micro-wave instability

- A **broad-band impedance**, representing the effect of all discontinuities of the beam pipe, can cause a **microwave instability.** According to the **Boussard criterion**, the corresponding **threshold impedance** is given by:

$$\frac{Z_0^{||}}{n} = Z_0 \frac{\pi}{2} \frac{\gamma \alpha_c \sigma_\delta^2 \sigma_z}{N_b r_e} \left(\frac{b}{\sigma_z} \right)^2$$

Z_0= the impedance of free space

Parameters	DR
$Z_0^{||}$ [Ω]	1
$(Z_0^{||}/n)_{th}$ [Ω] - @inj. (e^-)	14
$(Z_0^{||}/n)_{th}$ [Ω] - @inj. (e^+)	2585
$(Z_0^{||}/n)_{th}$ [Ω] - @eq.	0.1

- 1 Ω longitudinal impedance is assumed, as the design of modern accelerators can easily allow for an impedance of that magnitude.
- The Boussard threshold impedance was calculated at injection for positron and electron beams, at the end of the injection plateau.
- The results are summarized in the table: 14 Ω, 2585 Ω and 0.1 Ω.
- **For the equilibrium state, the Boussard criterion is below than the longitudinal impedance. If the vacuum chamber radius is increased to around 35 mm (needs discussion with experts), it become 1.25 Ω which become well above than the impedance.**

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Transverse Mode Coupling Instability

- The **transverse impedance** of the machine can drive **the head-tail instability** (HTI) and/or the **transverse mode coupling instability** (TMCI).

- The **TMCI threshold** for a broad-band resonator impedance is given by:

$$R_{th}[k\Omega/m] = \frac{0.6E[GeV]Q_sQ}{\beta_y[m]Q_b[C]\sigma_t[ps]f_r^2[GHz]}$$

$Q_b = N_b\, e$ ($e=1.602\times10^{-19}$), $f_r=W_r/2\pi$
$W_r=c/b$, σ_t [ps]$=\sigma_z/c$

- The **transverse impedance** is linked to the **longitudinal impedance** through:

$$Z_t^{\perp} = \frac{C}{\pi b^2}\frac{Z_0^{||}}{n}$$

Parameters	**DR**
$Z_t^{\perp}$ [MΩ/m]	**0.95**
R_{th} [MΩ/m] @inj. for e$^-$	12.06
R_{th} [MΩ/m] @inj. for e$^+$	3.54
R_{th} [MΩ/m] @eq.	3.78

- The **transverse impedance** of the **DR** is estimated **below the calculated thresholds.**

Ion effects

- **Ions** can be created in the vacuum chamber from the interaction of charged particles in the beam with the residual gas in the beam pipe.

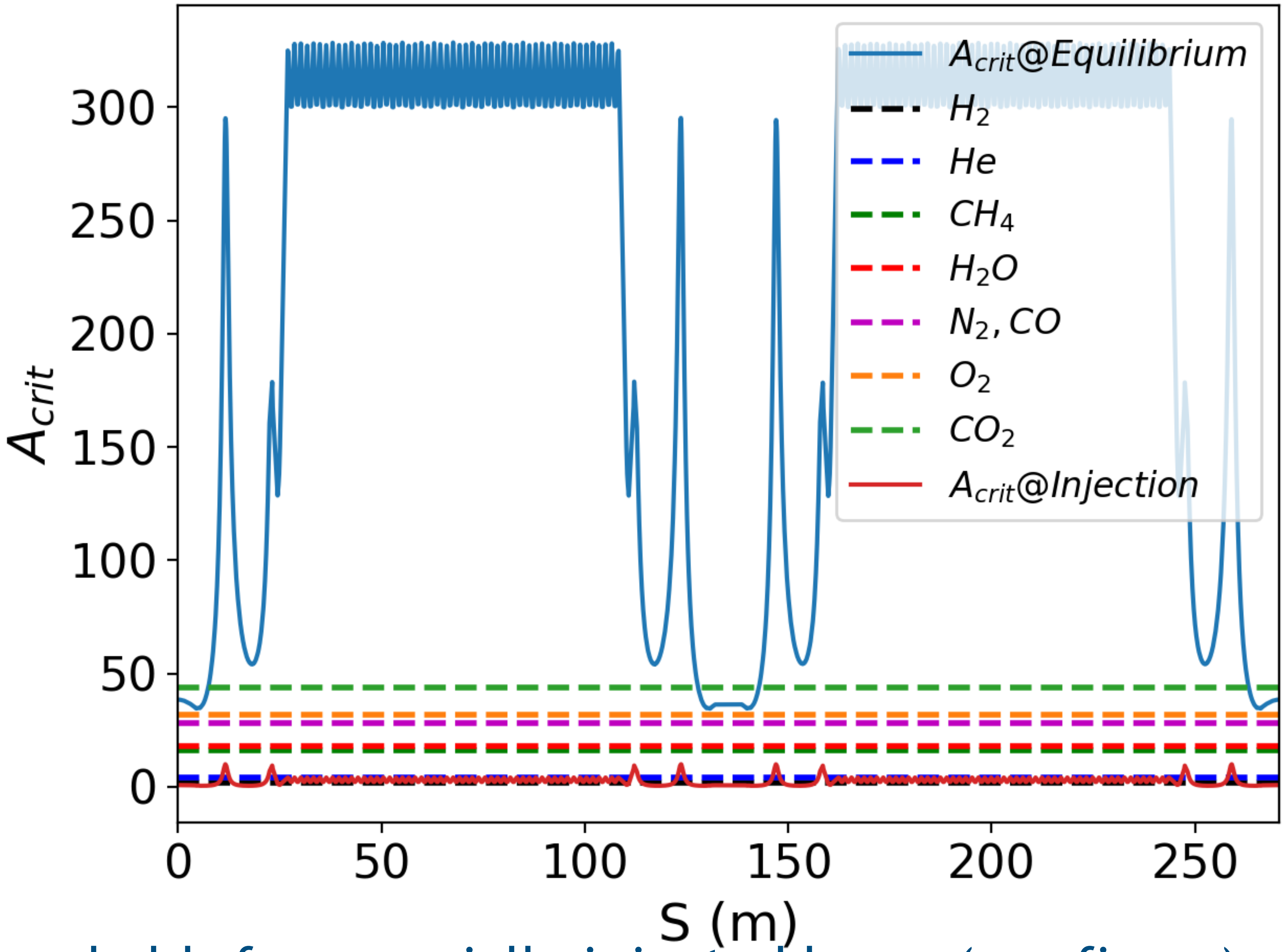
- These ions can be **trapped** and **accumulated** by the fields of the electron beam and eventually can lead to **beam instability**.

The critical mass: $$A_{crit} \cong \frac{N_b \Delta T_b c r_p}{2\sigma_y(\sigma_x + \sigma_y)}$$

Tune shift at the end of the train: $$\delta Q_{ion} \cong \frac{N_b n_b r_e C}{\pi \gamma \sqrt{\epsilon_x \epsilon_y}} \left(\frac{\sigma_{ion} p}{k_B T}\right)$$

The rise time of FII given by: $$\tau_{inst} \cong \frac{0.1 \gamma \sigma_x \sigma_y}{N_b n_b c r_e \beta_y \sigma_{ion}} \left(\frac{k_B T}{p}\right) \left(\sqrt{\frac{8}{\pi}}\right)$$

Parameters	**DR**
δQ_{ion} @inj./@eq.	0.003/<<
τ_{inst} [t_{rev}] @inj./eq.	770/14



- The **trapping condition** is lower than almost all the possible ions' thresholds for especially injected beam (see figure).
- **10^{-9} mbar is needed** in the DR in order to provide long enough rise time (to be compensated with a feedback system).
- Max. **tune shift** by ions (see table, 0.003) is **small** (with 10^{-9} mbar pressure).
- The FII **rise times:** 14 t_{rev} which can be compensated with a **feedback system**.

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e-cloud

- The ***e*-cloud** instability mostly arises for ***e***$^+$ beams.
- When free electrons in the vacuum chamber get accelerated in the electromagnetic field of the beam and hit the chamber walls, electron amplification can occur through the multipacting effect.
- The e$^-$ build up saturates when the attractive beam field is compensated by the field of the electrons, at a **neutralization density**.
- The single bunch ***e*-cloud instability** (ECI) occurs **above the e$^-$ density threshold.**

Neutralization density:

$$\rho_{neutr} = \frac{N_b}{L_{sep}\pi b_x b_y}$$

L_sep [m] is the bunch spacing

Threshold density for the instability:

$$\rho_{th} = \frac{2\gamma Q_s}{\sqrt{3} Q r_e \beta_y C} \quad ; \quad Q = min(7, \frac{w_e \sigma_z}{c})$$

Angular oscillation frequency of the electrons interacting with the beam:

$$w_e^2 = \frac{N_b r_e c^2}{2\sigma_z \sigma_y(\sigma_x + \sigma_y)}$$

Parameters	**DR**
ρ_{neutr}[10^{11}/m^3]	**125.06**
ρ_{th} [10^{11}/m^3] @inj.	1634
ρ_{th} [10^{11}/m^3] @eq.	22.06

- The **neutralization density exceeds** the **threshold** for at the equilibrium state. **This should be investigated with detailed simulations.**
- **The e-cloud simulations which were done by F. Yaman for the previous design should be revised for better understanding.**

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- The single bunch ***e*-cloud instability** (ECI) occurs **above the e$^-$ density threshold.**

I had a meeting with F. Yaman last week.
He agreed on revising the previous calculations and taking a step further together.

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Coherent synchrotron radiation

- **Coherent synchrotron radiation** (CSR) occurs if the **SR wavelength is comparable to the bunch length.**
- The **CSR** may lead to a **micro-bunching instability** under the following **conditions:**

$$\sigma_z \geq 0.5\rho\Lambda^{-3/2} \qquad and \qquad \frac{\rho}{b} \leq \Lambda$$

ρ is the bending radius, Λ is known as the Stupakov-Heifets parameter

The Stupakov-Heifets parameter is given by:

$$\Lambda = \frac{N_b r_e \rho\sqrt{2\pi}}{C|\alpha_c|\sigma_z \gamma \sigma_\delta^2}$$

Parameters	**SPS**
Stupakov parameter @eq.	**3.18**
ρ/b @eq.	0.73
$0.5\rho\Lambda^{-3/2}$ (m)@eq.	0.65
σ_z(m) @eq	0.003
Stupakov parameter @inj. e^-/e^+	**0.22/0.0001**
ρ/b @inj. e^-/e^+	0.73
$0.5\rho\Lambda^{-3/2}$ (m) @inj. e^-/e^+	33.8/>>
σ_z(m) @inj. e^-/e^+	0.001/0.0034

- The instability conditions were calculated and presented in the table above, **showing that no CSR instability is expected.**

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CONCLUSION

- In this study, **analytical estimates** of various **collective effects** were presented for the FCC-e^+e^- **DR** design.
- **No major limitations** are expected due to **IBS, TMCI and CSR**.
- Concerning the **SC**, the tune shift at the equilibrium state might be an issue.
- The Boussard criterion is below the longitudinal impedance assuming a vacuum chamber radius of 10 mm. 35 mm radius is needed.
- It was shown that the **neutralization density exceeds** the **e-cloud instability threshold** for the equilibrium state.
- The **fast rise times** of the FII can be compensated with a **feedback system**, provided a vacuum pressure of **10^{-9} mbar** are achieved **for the DR**.

CONCLUSION

- In this study, **analytical estimates** of various **collective effects** were presented for the FCC-e^+e^- **BR** design.
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Thank you

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