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COLLECTIVE EFFECT ESTIMATES FOR THE FCC e^+e^- PRE-BOOSTER RING

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INTRODUCTION

The FCC-e^+e^- injector complex needs to produce and to transport a high intensity e^+e^- beam at a fast repetition rate for topping up the collider at its collision energy. **Two different options** are under consideration **as pre-accelerator**: using the existing **SPS** or designing a completely **new ring**. The purpose of this paper is to present the updated studies of the pre-booster ring design and parameter choice, focusing in particular on **first estimates** with respect to **collective effects**.

Alternative Pre-booster Ring Design

The alternative design of the PBR composes of **4 arcs and 4 straight sections**. Each arc consists of 35 FODO cells while the straight sections consist of 5 FODO cells each, with adequately allocated space for the RF, damping wigglers (DW), injection and extraction elements.

The damping time of the PBR is reduced to **0.1 s** from **0.26 s** with a **wiggler** peak field of **1.3 T** and a total wiggler length of **16.2 m**. Two DW magnets per cell are installed in each straight section.

SPS as Pre-booster of FCC-e^+e^-

Two main proposals are made in order to reduce the **damping times** at injection and reach the required **emittance** at extraction:

- moving the horizontal **phase advance** to around **135^0 ($3\pi/4$)** for a FODO,
- inserting **damping** and **Robinson wiggler** magnets.

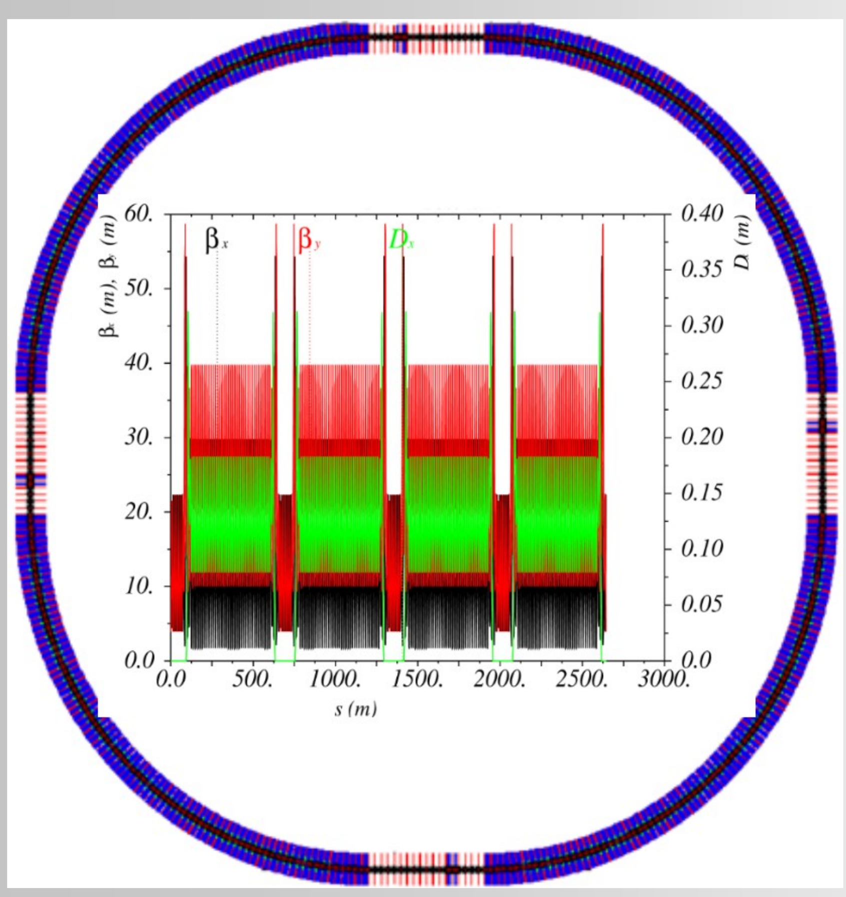


Figure 1: Layout and optics functions of the alternative PBR.

Parameters	Symbol	Alternative PBR	SPS
Energy	E (GeV)	6	6
Geo. Emittance (Eq.)	$\varepsilon_{(x,y)}$ [10^{-9} m.rad]	0.20/0.20*0.01	0.73/0.73*0.01
Bunch length	σ_z [m]	0.013	0.041
Momentum spread	σ_δ	$0.9*10^{-3}$	$0.3*10^{-2}$
Bunch spacing	ΔT_b [ns]	20	20
Bunch population	N_b	$2.66*10^{10}$	$2.13*10^{10}$
Circumference	C [m]	2644	6911.5
Coupling	[%]	0.01	0.01
Mom. Comp. factor	α_c	$0.28*10^{-3}$	$0.98*10^{-3}$
Number of bunches	N_b	520	2080
Tunes	$Q_{x,y,s}$	71.78 /25.24/0.01	40.38/26.71/0.08
Energy loss per turn	E_0 [MeV]	1.025	3.4
Damping times	$\tau_{(x,y,z)}$ [s]	0.1/0.1/0.05	0.1/0.1/0.05
RF frequency	F_{rf}	400	400
RF voltage	RF [MV]	3.6	25
Bend length	L_{bend}[m]	5.31	6.26*4
Chamber radius	b [m]	0.03	0.04
Number of bends	N_{bend}	328	744
Wiggler length	L_w [m]	16.2	12.15
Wiggler field	B_w [T]	1.3	3.5
Number of wigglers	N_w	8	6
Injected parameters	**Symbol**	**From linac**	
Emittance	$\varepsilon_{(x,y)}$ [10^{-9} m.rad]	0.55/0.11	
Mom. Spread	σ_δ	$1.2*10^{-2}$	
Bunch length	σ_z [m]	0.01	

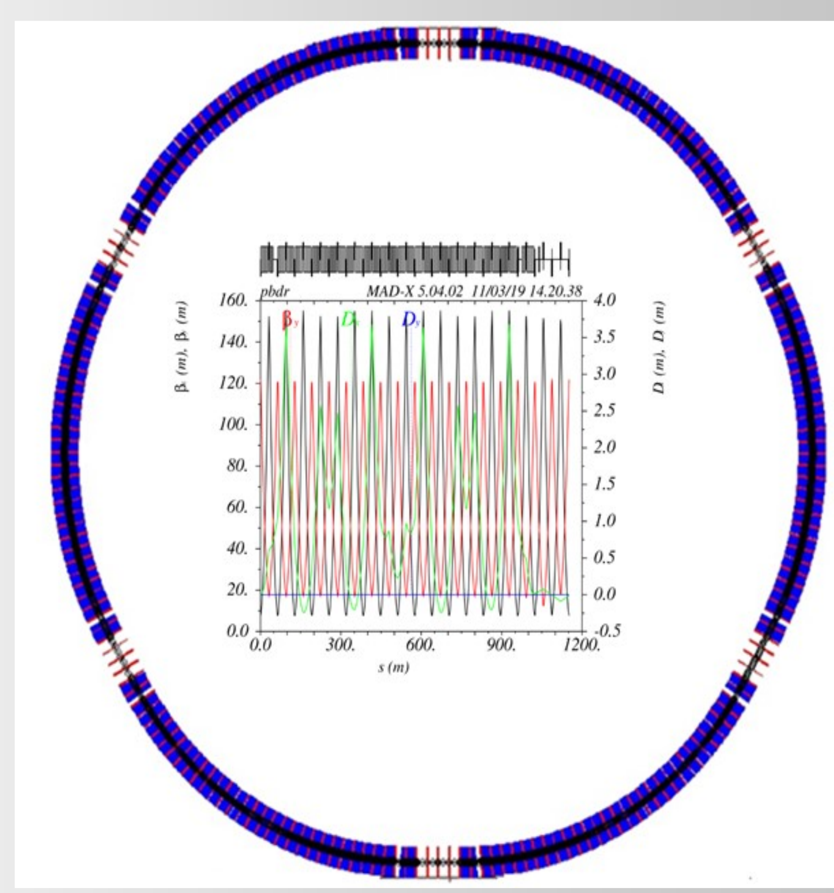


Figure 2: Layout and optics functions of the SPS as FCC e^+e^- PBR.

Analytical calculations for collective effects

Space charge

The space charge effect may cause **tune shift** and **emittance growth**. Here, the incoherent (direct) space charge tune spread is calculated analytically:

$$\Delta Q_y^{inch} = \frac{N_b r_e C}{(2\pi)^{3/2}\gamma^3\sigma_z}\sqrt{\frac{1}{\varepsilon_y}}. < \frac{\sqrt{\beta_y}}{\sqrt{\beta_x\varepsilon_x + D_x^2\sigma_\delta^2 + \sqrt{\varepsilon_y\beta_y}}} >$$

	Alternative PBR	SPS as PBR
ΔQ_y @ inj.	0.005	0.0003
ΔQ_y @ eq.	0.075	0.018

The tune shift in the vertical plane is calculated for the injected parameters and equilibrium state at injection energy.

Space charge is not expected to be a limitations for the FCC e^+e^- PBR.

Longitudinal μ-wave instability

The resistive wall impedance of the vacuum chamber may cause a source of **longitudinal microwave instability** and **transverse mode coupling instability (TMCI)**. A broad band impedance (short lived wake) is expected to cause microwave instability above a threshold. The threshold for the longitudinal microwave instability can be evaluated:

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

	Alternative PBR	SPS as PBR
$Z_0^{\|\|}$ [Ω]	1	6.4
$(Z_0^{\|\|}/n)_{th}$ [Ω] @ inj.	267	2075
$(Z_0^{\|\|}/n)_{th}$ [Ω] @ eq.	1.15	31.14

The threshold of the long. microwave instability **(Boussard criterion)** is **higher** than **the longitudinal impedance** for both the SPS and the alternative PBR.

Transverse mode coupling instability (TMCI)

In the transverse plane, head-tail interaction through a wake field can drive the bunch unstable. **The threshold (R_{th})** of strong head tail instability (also known as **TMCI**) can be estimated by:

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

The transverse impedance is linked to the longitudinal one;

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

	Alternative PBR	SPS as PBR
$Z_0^{\|\|}$ [Ω]	1	6.4
$Z_t^{\perp}$ [MΩ/m]	1.03	9.77
R_{th} [MΩ/m] @ inj.	5.17	29.6
R_{th} [MΩ/m] @ eq.	3.99	7.10

The transverse impedance exceeds the threshold for SPS at equilibrium state.

The transverse impedance is well lower than the threshold for alternative ring.

Coupled bunch instabilities

The growth time of the coupled bunch instabilities by the transverse resistive wall has been estimated:

$$\tau\,[s^{-1}] = \frac{CIc}{Z_0 b^3\gamma I_A\pi Q_\beta 2}\sqrt{\frac{Z_0 c}{\pi\sigma(1-\Delta_\beta)}}$$

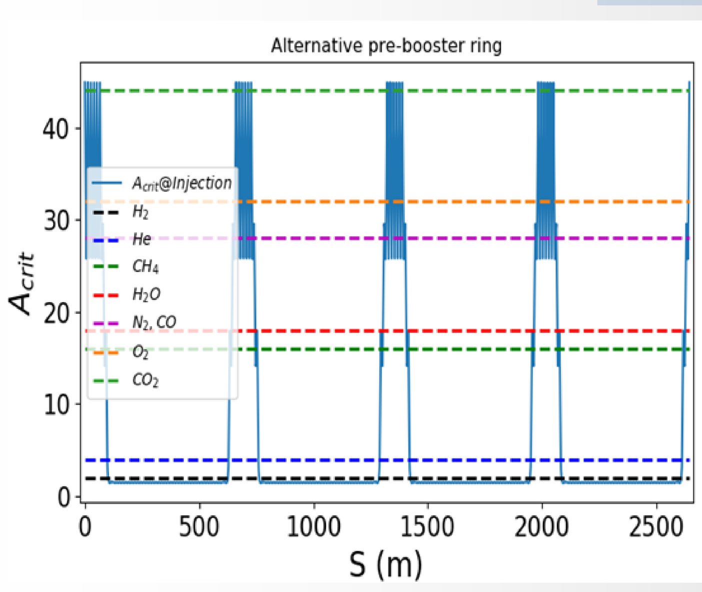
	Alternative PBR	SPS as PBR
τ [s^{-1}] @ inj./eq.	42.35	98.20
t_{growth}/t_{rev} @inj./eq.	2678	441

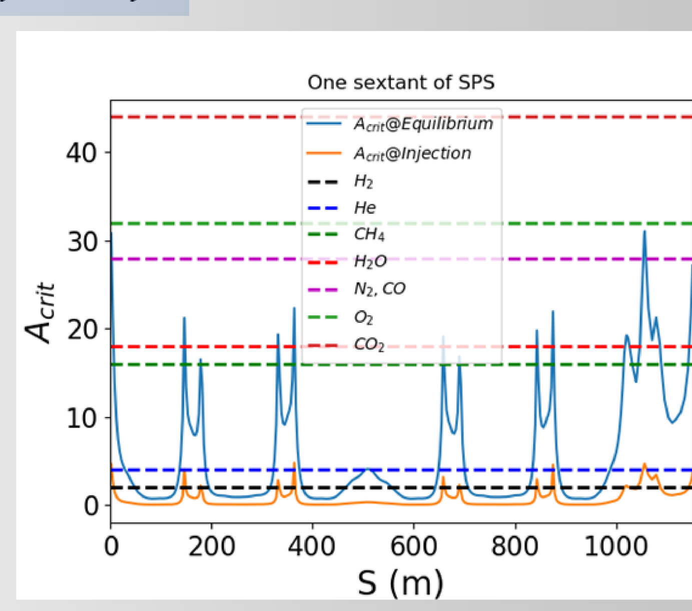
The growth times are **long enough** for damping with feedback system for both options.

Ion effects

The residual gas in the vacuum can be ionized and create positive ions by the electron beam in the accelerator. These **ions** may be trapped for if they exceed a **critical mass**. The field from the trapped ions affects the electron beam and causes **tune shift** and **emittance growth**.

$$A_{critx,y} \cong \frac{N_b\Delta T_b c r_p}{2\sigma_{x,y}(\sigma_x+\sigma_y)}$$





The tune shift and fast-ion rising time are given by:

$$\Delta Q_{ion} \cong \frac{N_b n_b r_e C}{\pi\gamma\sqrt{\varepsilon_x\varepsilon_y}}\left(\frac{\sigma_{ion}p}{k_B T}\right)$$

$$\tau_{inst} \cong \frac{0.1\gamma\sigma_x\sigma_y}{N_n n_b c r_e\beta_y\sigma_{ion}}\left(\frac{k_B T}{p}\right)\sqrt{\frac{8}{\pi}}$$

	Alternative PBR	SPS as PBR
ΔQ_{ion}	0.005	0.015 → @ eq. (0.004) → @ inj.
τ_{inst} [μs]	766	1623 (19689)
τ_{inst} [t_{rev}]	86	70 (854)

The rise time is around 86 t_{rev} for the alternative ring (with 10^{-10} mbarr) and around 70 t_{rev} (with 10^{-11} mbarr) for the SPS.

Small tune shifts and long enough rise times that can be compensated with a feedback system, provided that ultra-low vacuum pressure can be achieved.

e-cloud

'Ionization of the residual gas', 'emission of electrons from photoelectric due to CR' and 'electron desorption from the vacuum chamber' may generate e-cloud inside the vacuum pipe of the accelerator. e-cloud may affect the beam by causing instability.

The **e-cloud** build up stops at a density roughly equal to the **neutralization density**, where the attractive force from the beam is on average balanced by the space-charge field of the electron cloud.

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

$$\rho_{neutr} = \frac{N_b}{L_{sep}\pi h_x h_y}$$

$$\Delta Q_{x,y} = \frac{r_e}{2\gamma} < \beta_{x,y} > \rho_e C$$

	Alternative PBR	SPS as PBR
ρ_{neutr} [$10^{11}/m^3$]	15.6	7.06
ρ_{th} [$10^{11}/m^3$] @inj.	3.56	13.03
ρ_{th} [$10^{11}/m^3$] @eq.	1.34	1.62
ΔQ_x @neut. (Inj./Eq.)	0.006	0.035
ΔQ_y @neut. (Inj./Eq.)	0.01	0.035

For both options, the neutralization density exceeds the threshold. However, the tune shifts for both options are not big.

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