Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Coordination meeting
WP4 : Progress summary

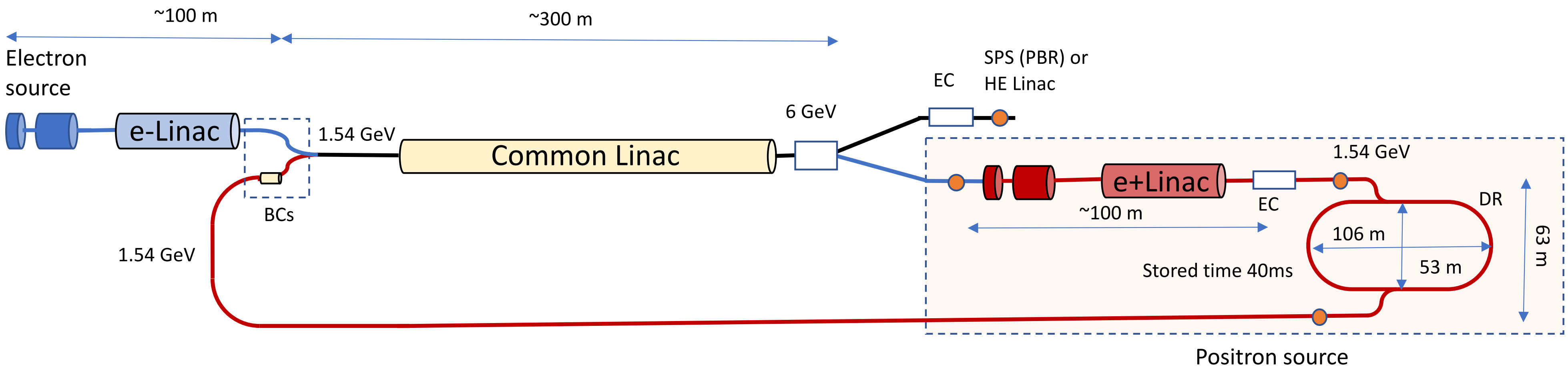
Milardi C.[1] *, De Santis A.*[1]*,*
Ramjiawan R. L.[2]*, Dutheil*[2]*,*

[1] *LNF-INFN, Frascati, Italy,*
[2] *CERN, Geneva, Switzerland.*

Outline

- DR Dynamical aperture
- Longitudinal Beam Dynamics and RF system
- Transfer Lines
- DR timing scheme
- WP4 manpower and management

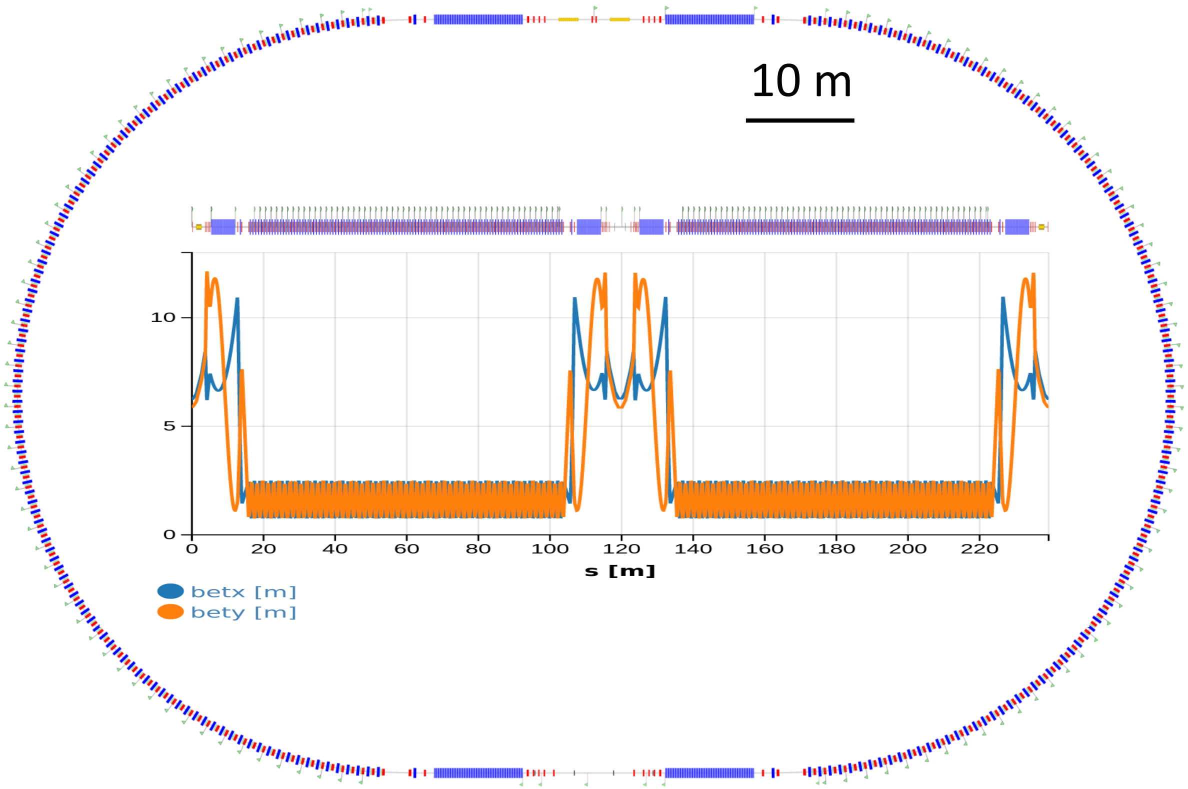
FCC-ee injector layout 6 GeV option



Damping Ring

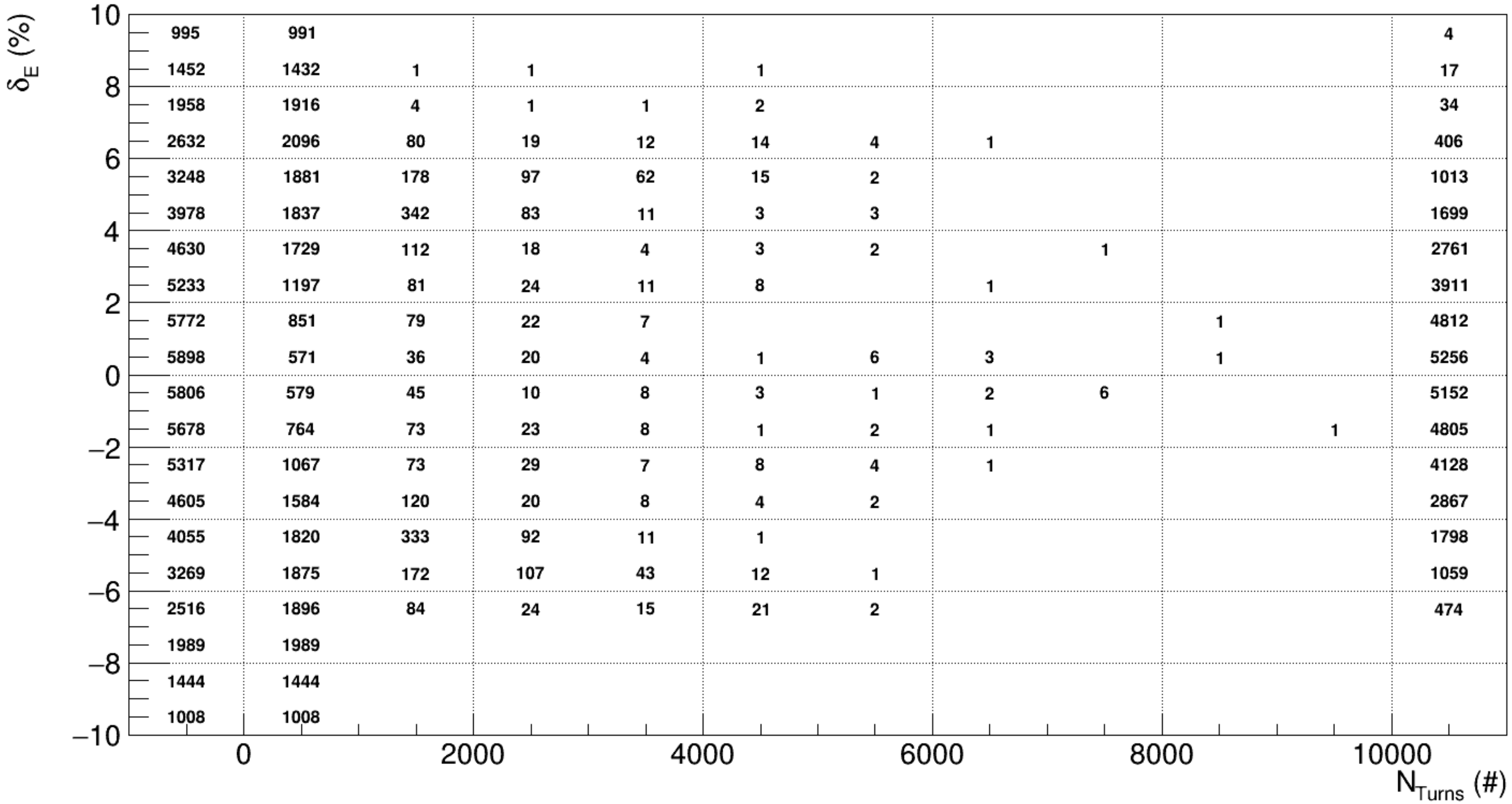
Following the FCC-ee injector review report reccomandations, the reference design for the DR is again the one initially provided by K. **Oide** and S. **Ogur** in 2020, which is more optimized and has less demanding parameters.

Parameter	FCC_ee DR
Circumference	241.8 m
Equilibrium emittance (x/y/z)	0.96 nm/ - /1.46 µm
Dipole length, Field	0.21 m / 0.66 T
Wiggler #, Length, Field	4, 6.64 m, 1.8 T
Cavity #, Length, Voltage	2, 1.5 m , 4 MV
Bunch # Stored, Charge	16, 3.5 nC
Damping Time $\tau_x/\tau_y/\tau_z$	10.5 / 10.9 / 5.5 ms
Store Time	40 ms
Kicker Rise Time @1.54 GeV	50 ns
Energy Loss per Turn	0.225 MV
SR Power Loss Wiggler	15.7 kW



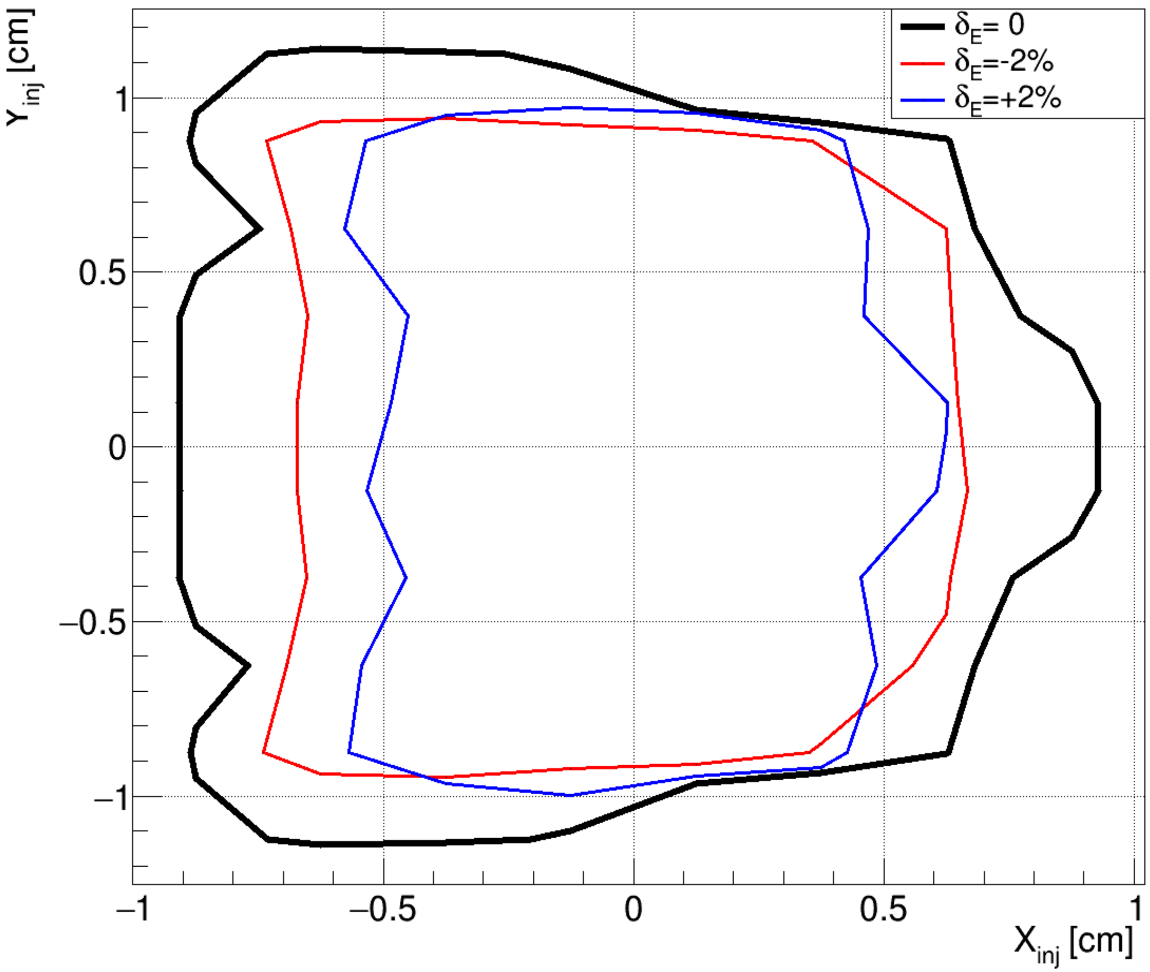
DR Dynamical Aperture

DR dynamical aperture: Tracking study



Tracking has been performed with **PTC (MAD-X** interface) for **10k turns**.
Initial distribution are Gaussian with **nominal emittance** (CDR ε_x:1.29 ε_y:1.22 10^{-6}m rad).
Tracking includes **radiation loss** and **RF effects**.
The numbers In the table refer to the particles lost at a given turn (1k bin width). The first column is the number of initial particles.
The range of energy considered is quite large in order to estimate the acceptance as a function of the energy deviation.

DR dynamical aperture



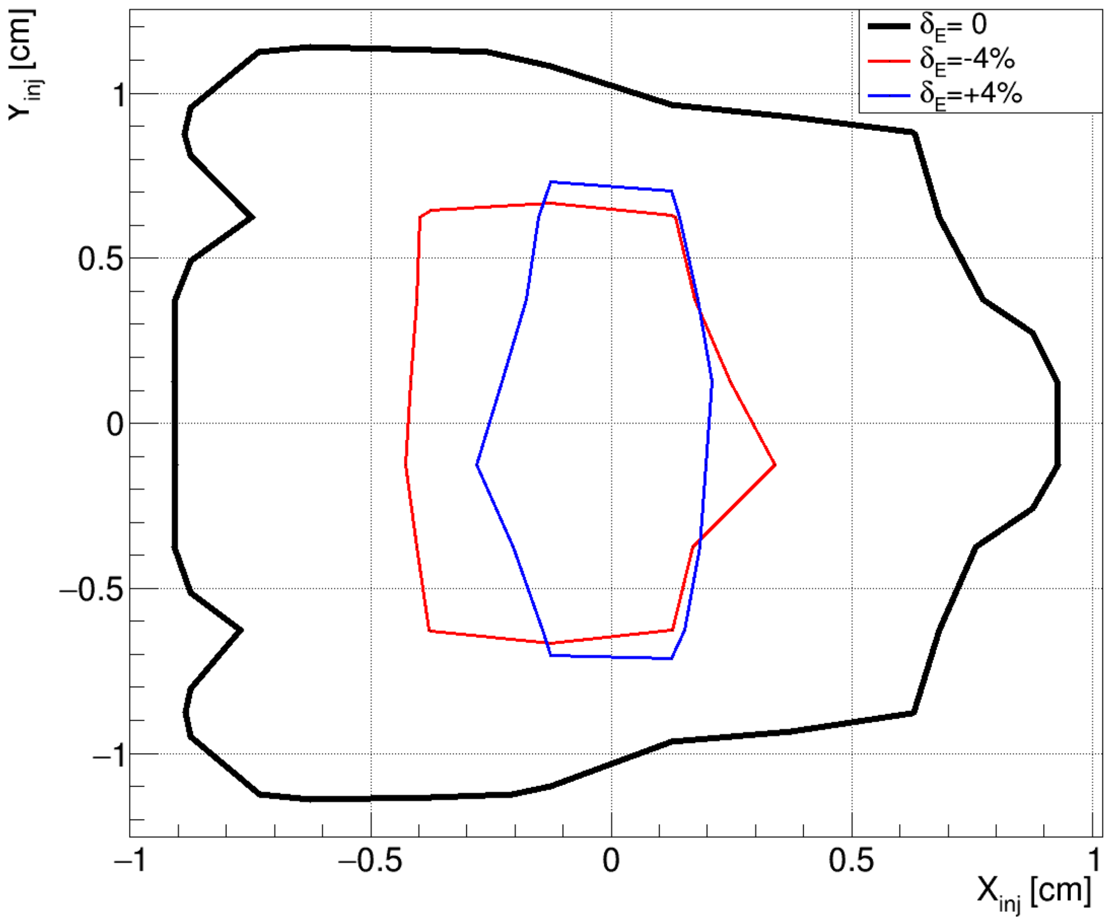
2000 turns have been tracked (~15% damping time). The estimated loss of accuracy is below 1% at the nominal energy.

The phase space have been sampled up to 3x3 cm^2 in the transverse plane. Only on-axis particles have been simulated (x'/y'=0).

Radiation damping has been neglected allowing a much faster tracking of the DR.

The stability region in the transverse plane have been evaluated for different energy deviation, in the range between ±2%.
Contours represents regions where at leas 90% of the initial conditions leads to a succesful tracking.
A probability definition is needed in order to take into account the average value over the surface.

DR dynamical aperture



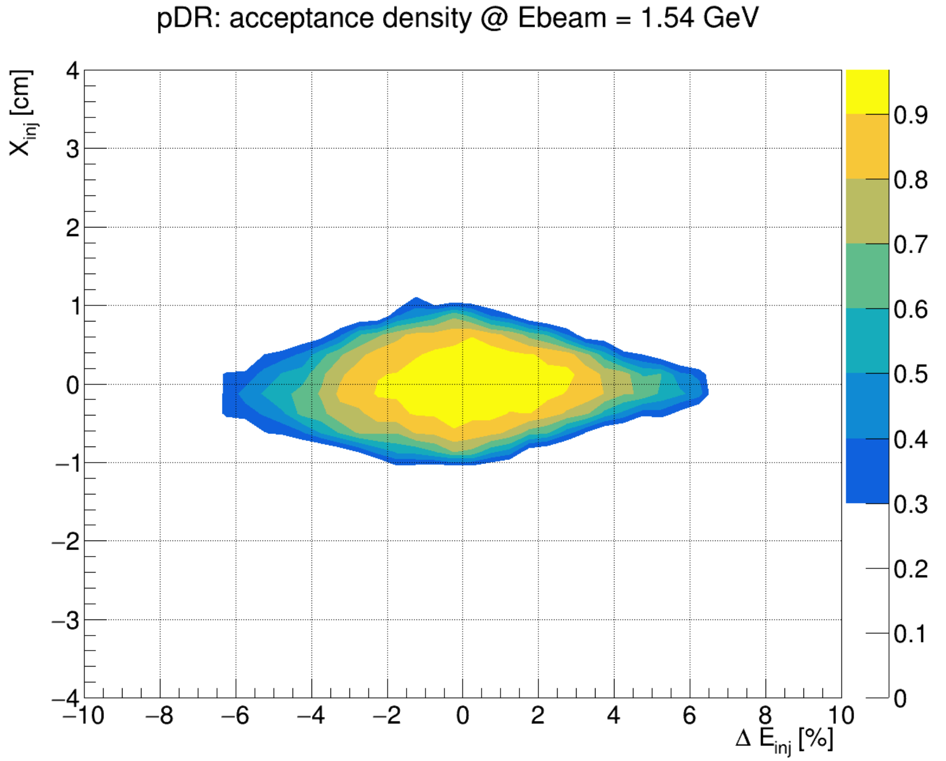
2000 turns have been tracked (~15% damping time).
The estimated loss of accuracy is below 1% at the nominal energy.

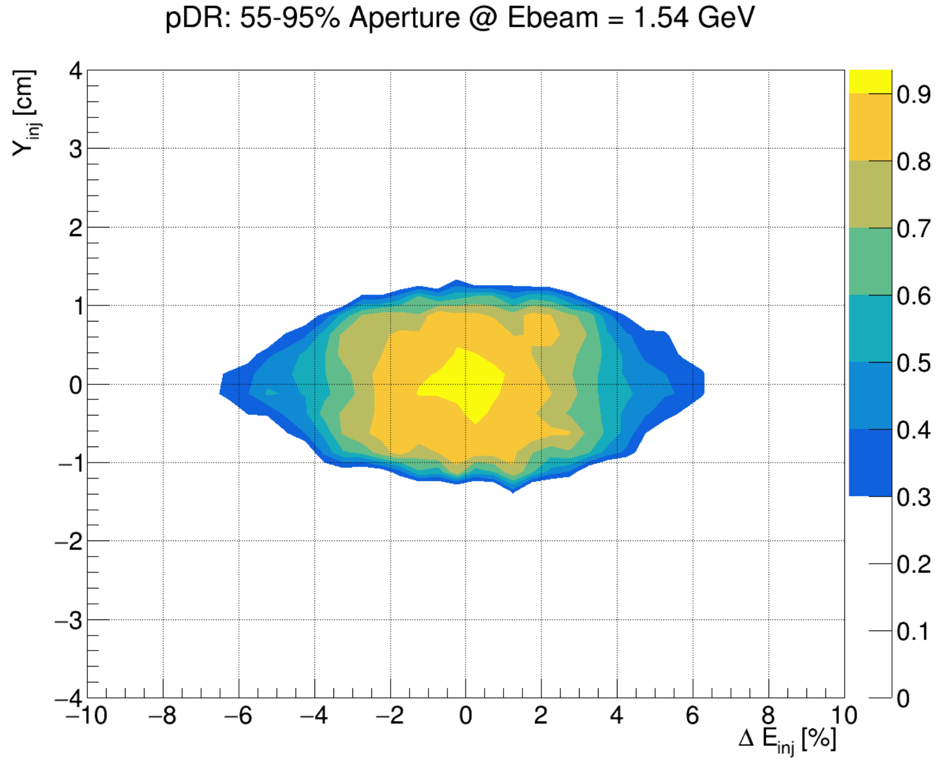
The phase space have been sampled up to 3x3 cm^2 in the transverse plane.
Only on-axis particles have been simulated (x'/y'=0).

Radiation damping has been neglected allowing a much faster tracking.

For larger energy variations (±4%) the stability region shrinks, and it is no longer symmetric w.r.t. the energy variation itself, in the transverse plane being considerably smaller at higher energy (blue) w.r.t. lower energies (red). The stability region at the nominal energy has been reported for reference.

DR acceptance probability



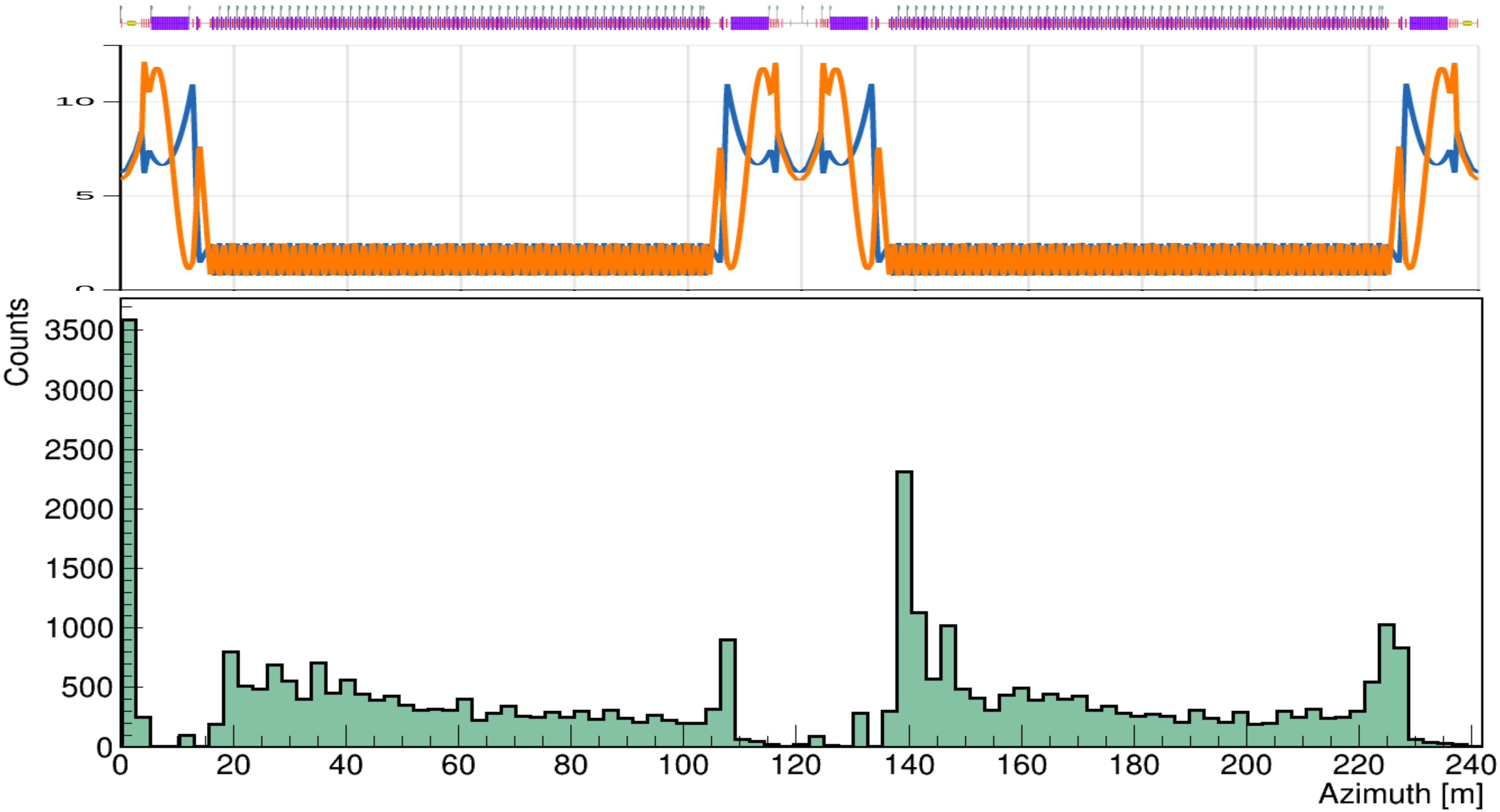


DR acceptance probability has been evaluated starting with nominal beam parameters at the injection: Gaussian profile with nominal width at the injections (σ ~ 2mm in both planes).
The energy distribution has been assumed Gaussian with 5% resolution.

The color map represent the *projection of the survival probability* associated to the different position in space: horizontal and vertical, respectively.

A full matrix in phase space will be delivered to reshape particle distribution at the positron source.

DR: particle loss distribution



Tracking has been performed starting with nominal beam parameters at the injection: Gaussian profile with nominal width (σ ~ 2mm in both planes). The energy distribution has been assumed Gaussian with 5% resolution.

The plot shows the distribution of losses along the ring.

Longitudinal Beam Dynamics and RF system

Longitudinal Beam Dynamics

RF system must:

- restore energy lost by Synchrotron Radiation emission U_0
- provide a suitable energy acceptance compliant with the large energy spread of the incoming positron beam
- Assure beam parameters compatible with stable beam dynamics conditions

Energy Acceptance at injection for e^+ beam

$$\left(\frac{\Delta E}{E_s}\right) = \pm\beta\sqrt{\frac{eV}{\pi h \alpha_c E_s}\mathcal{R}(\varphi_s)}$$

$$\mathcal{R}(\varphi_s) = \lfloor 2\cos\varphi_s + (2\varphi_s - \pi)\sin\varphi_s \rfloor$$

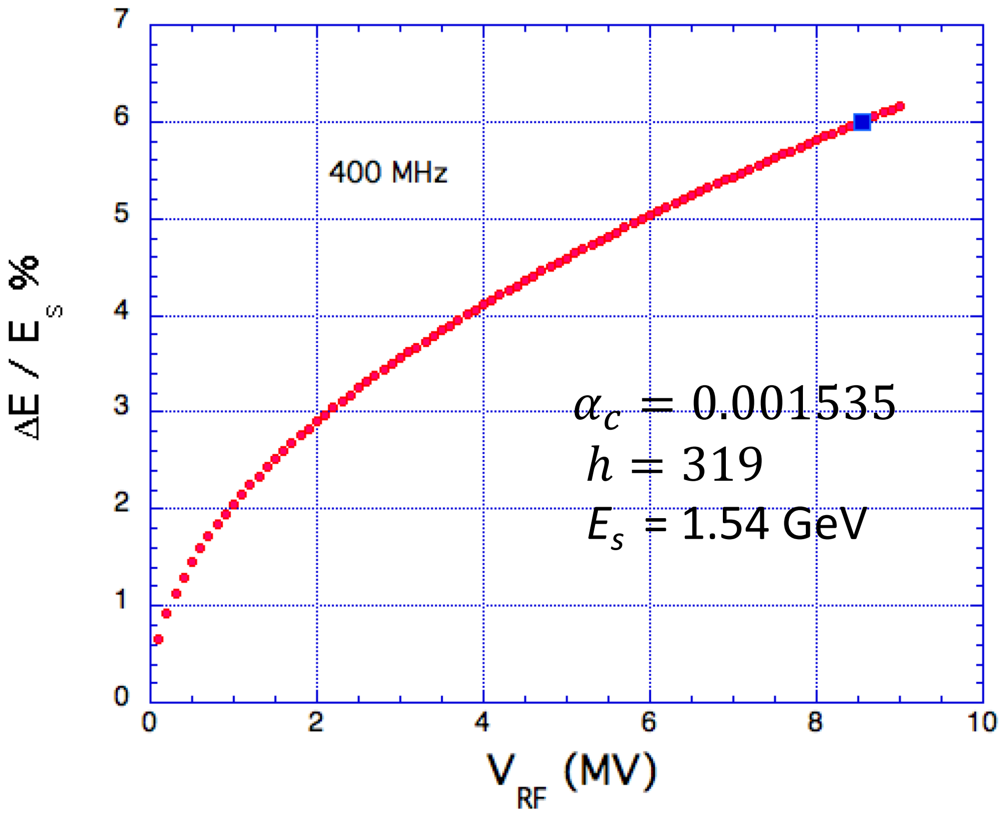
If an energy acceptance of the order of

$$\left(\frac{\Delta E}{E_s}\right) \sim 6\ \%$$

is requested in injection

V_{RF} = 8.53 MV

SC RF cavities working at 400 MHz and providing at last 4 MV are considered.



Minimum RF cavity voltage request to compensate the energy lost per turn is E_{LT} = 0.225 MV

DR Beam Dynamics Parameters

Relying on DR parameters:

E_s = 1.54 GeV

L = 239.2628817 m

$\alpha_c = 0.001535$

$\boldsymbol{h = 319}$

	V= 8MV	V= 6MV	V= 4MV	V= 2MV
U_0 [KeV]	227.1			
DE/E_s	$0.71 \bullet 10^{-3}$			
Ω_s [KHz]	25.313	21.918	17.888	12.618
T_0 [μsec]	0.79801			
ω_0 [s^{-1} rad]	$7.87\ 10^6$			
ν_s	0.003215	0.00278	0.002272	0.0016
L_{bunch}[m]	**0.00207**	0.00239	0.00293	0.00415
φ_s [rad]	0.0283967	0.0378663	0.0568164	0.113817
$(E - E_s)$ [GeV]	0.124	0.107	0.0862	0.058
$\Delta\varphi$ [unit of π]	1.8	1.7769	1.7269	1.6016
L_{bucket}[m]	0.6788	0.6664	0.6476	0.6006

Short bunch length can be an issue for:

lifetime,
injection must be carefully tuned,
impedance and bunch lengthening must be evaluated,
beam coupling with RF system
CSR,
IBS,
beam instability impact.

Separatrix

W - Φ representation, canonical coordinates

$$\frac{1}{\Omega_s}\frac{d\varphi}{dt} = \frac{2\pi c}{L}\sqrt{\frac{2\pi h^3 \eta_{tr}}{E_s eV \cos\varphi_s}}\,W$$

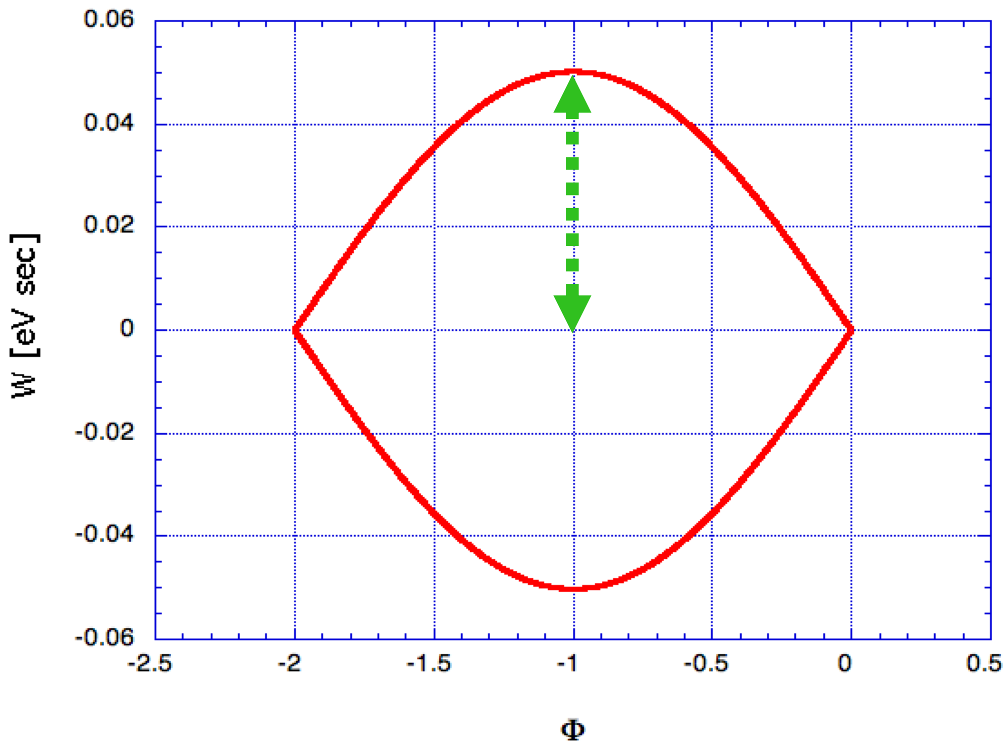
$$W_{bh} = \frac{L}{\pi h c}\sqrt{\frac{eV E_s}{2\pi h \eta_{tr}}}$$

$$\boldsymbol{A_{bk} = 2\int_0^{2\pi} W\, d\varphi = 8\, W_{bh}}$$

The area of the bucket is an adiabatic invariant, ***longitudinal acceptance***

Bunch area is ***longitudinal emittance***

$\varepsilon_t = 4\pi\, \sigma_E\, \sigma_t$ ***[eV sec]***



Assuming:

$\alpha_c = 0.001535$

$h = 319$

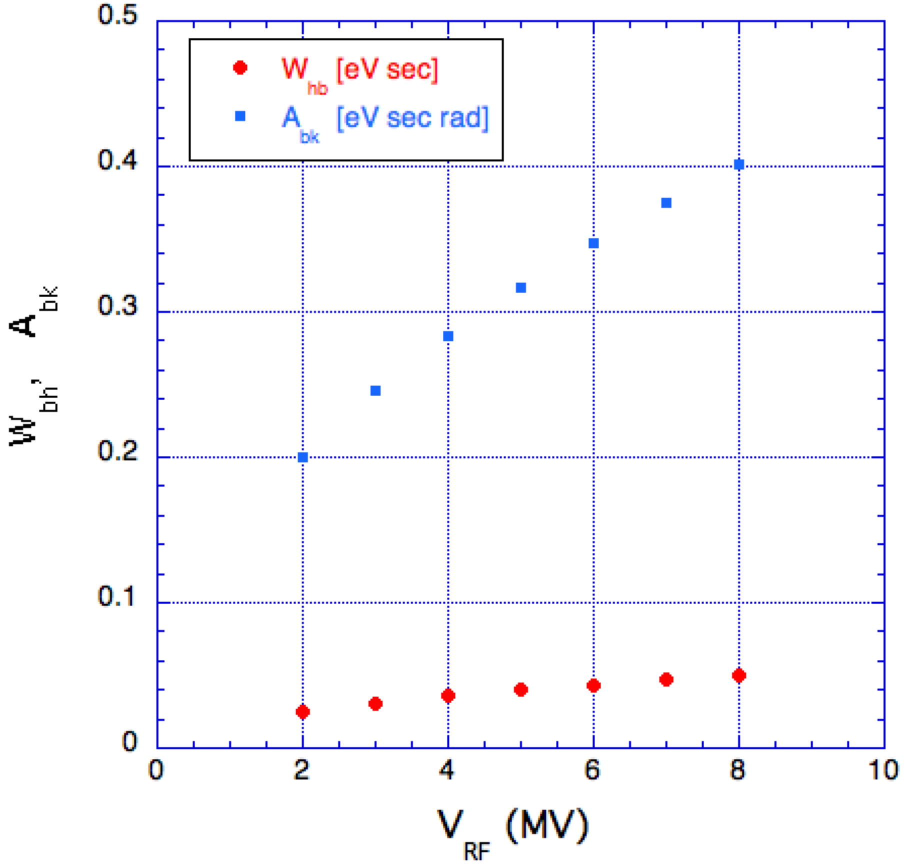
V = 8 MV

E_s = 1.54 GeV

W_{bh} = 0.0501813 (eV sec)

A_{bk} = 0.401451 (eV sec rad)

Separatrix vs. V_{RF}



DR acceptance

DR energy acceptance of the DR may be reduced to 3.5% by lowering the voltage in order to increase the bunch length so that emittance dilution due to coherent synchrotron radiation (CSR) is avoided.
For this reason, the incoming e+ beam may be collimated at the end of the LINAC at 3.5% or an energy compressor could be installed.

There is a clear limit on the DR acceptance coming from transverse beam dynamics.

RF System

RF as in the CDR

LHC type 400 MHz,
SC cavities.
two RF modules providing 4 MV each,
1.5 m long (3.5 with cryostat).

Total RF Power Requirement

$$P_b = I_b \frac{\Delta U_0}{e} \qquad P_l = \frac{V_{RF}^2}{2 n_{RF} R_{shunt}}$$

$$P_{RF} = P_b + P_l$$

Positron charge from LINAC	I_b [mA]	I [mA] $n_b = 2 \div 18$	P_b [KW]
4.5 [nC]	5.638	11.3 ÷ 101.5	2.6 ÷ 23
0.5 [nC]	0.6	1.3 ÷ 11.3	0.285 ÷ 2.56

General considerations about RF System

DR RF system must have rather high voltage in order to provide the required energy acceptance necessary to accommodate the positron beam coming from the LINAC which has a large energy spread, of the order of 6%.

If a *NC RF cavities* are considered, assuming to maintain the same operating frequency 400 MHz, in order to not change the harmonic number, it would be necessary to use many more cavities to achieve the same voltage.
Generally at most about 0.5 MV per module can be achieved using NC technology.
A lower RF frequency should be considered in order to reduce the voltage requirement.

As far as the total RF power requirement is concerned, wall dissipation for a NC cavity is considerably higher than for SC cavity.

SC cavities provide higher gradient

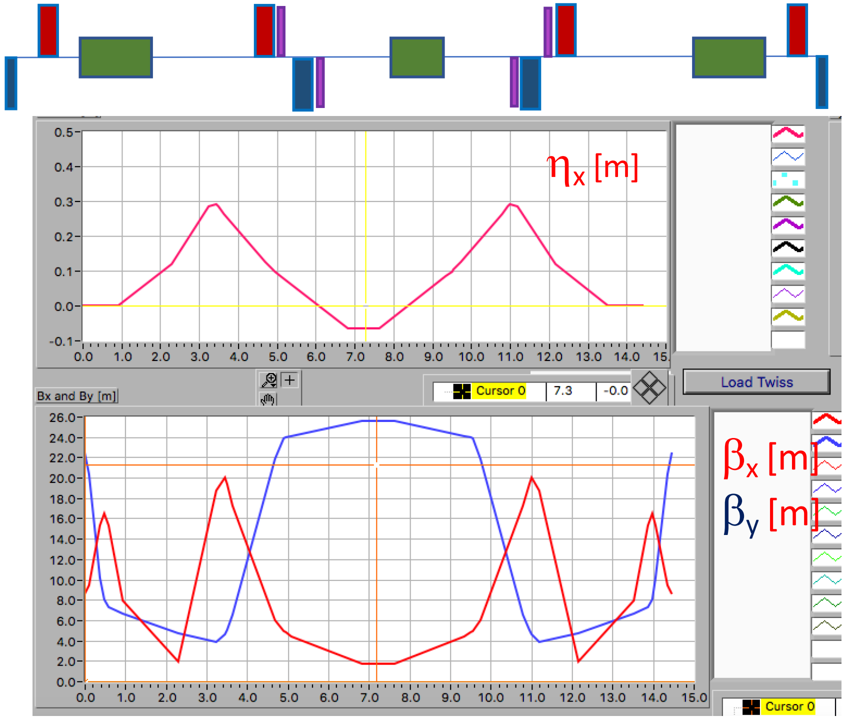
HOM are less harmful for SC cavities

It's convenient to use the same RF cavity for the different accelerator in the FCC ee project, in order to contain the R&D efforts.

Transfer Lines

Triple Bend Achromat Cell for Arcs

The TL design developed for the previous injector layout is still valid



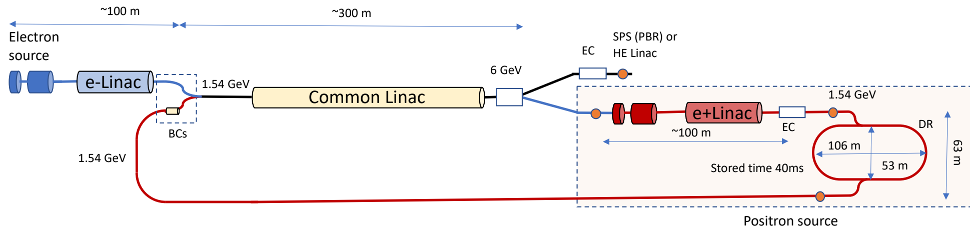
θ_b[rad]	0.174532925
L_b[m]	1.506/0.865
ρ[m]	8.633/4.959
B[T]	0.595/1.035
nQUADS	8
LQUA	0.2
Lcell	16.2573

Quadrupole gradient m^{-2}

$K_{D01} = K_{D04} = -9.840$
$K_{D02} = K_{D03} = -1.905$
$K_{F01} = K_{F04} = 7.281$
$K_{F02} = K_{F03} = 4.623$

Sextupole gradient m^{-3}

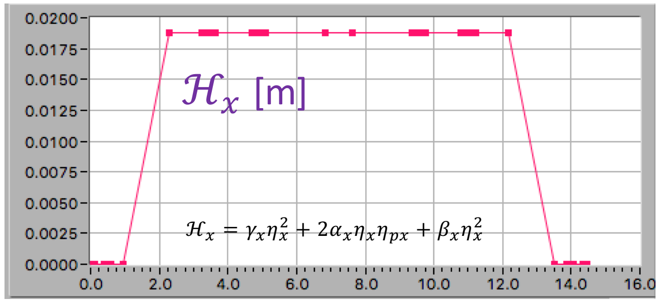
$K^s_{D01} = K^s_{D02} = -58.738$
$K^s_{F01} = K^s_{F02} = 44.294$

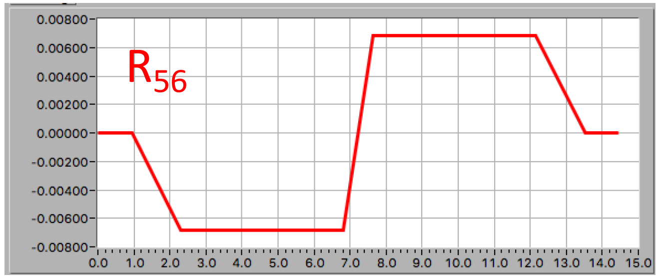


- $\beta_{x,y} < 30$ m
- low η_x
- $\alpha_{x,y} = 0$ both ends
- achromatic
- isochronous
- low invariant

$mu_x = 1.32$
$mu_y = 0.31$

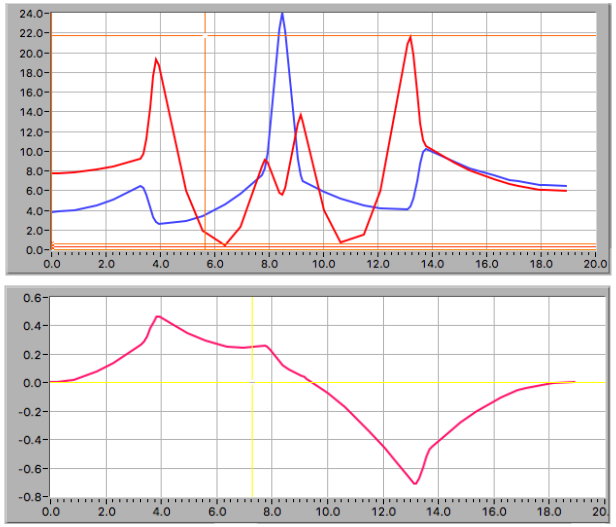
$\xi_x = -4.27$
$\xi_y = -2.06$

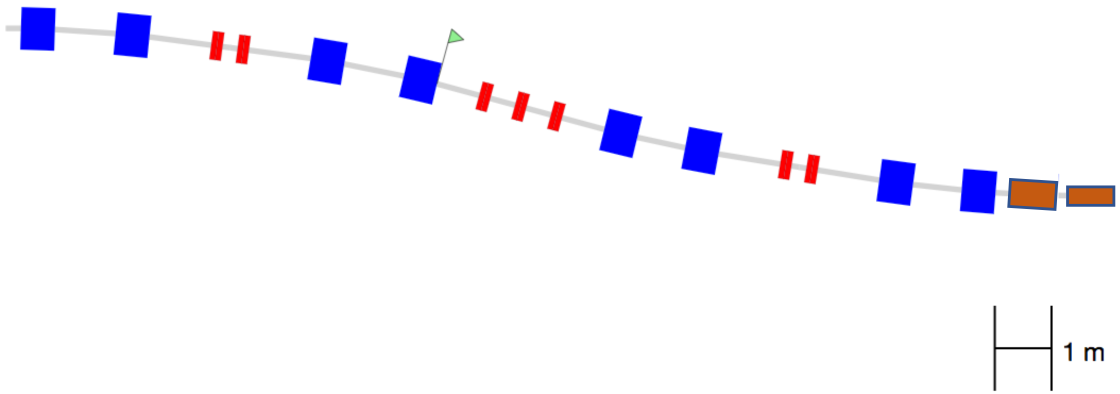




Injection-Extraction dogleg

Preliminary design

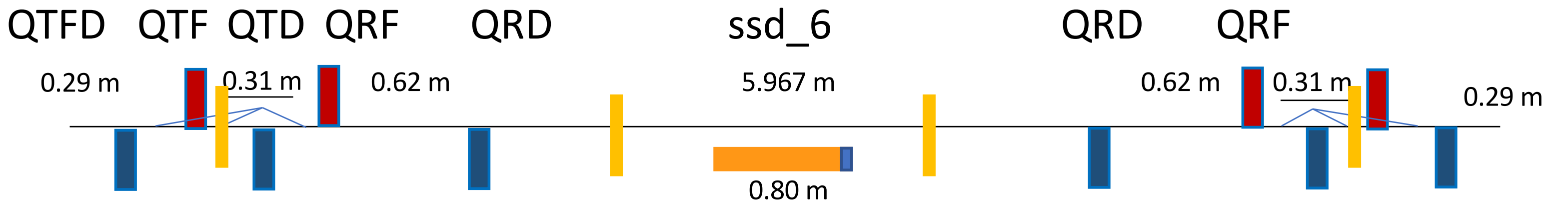




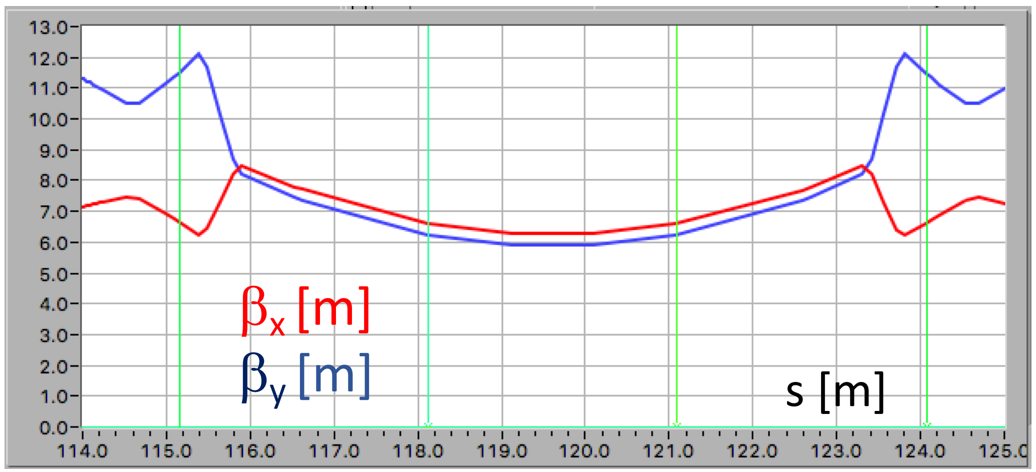
- flexible
- achromatic
- R_{56} ~ - 7 cm

	Angle [degree]	Length [m]	Field [T]	Thickness [mm]
B1	3.8	0.8	0.567	
B2	3	0.8	-0.448	
SPT1	2	0.8	-0.2238	7
SPT2	1.2	0.8	-0.1343	2 - 4

DR Injection Section



Twiss Functions at injection septum

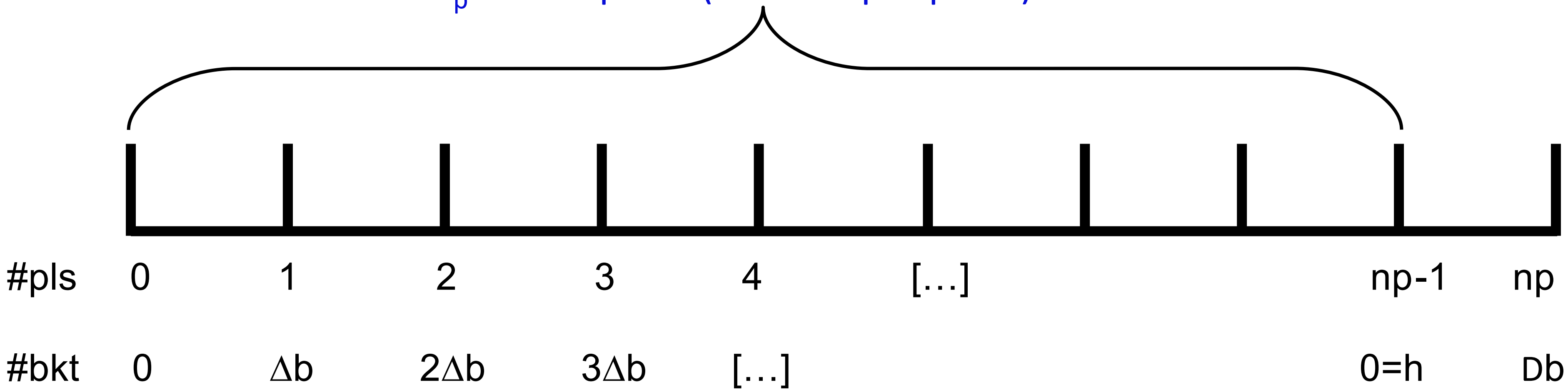


Ideal section no SXT
Injection Kickers position optimized
Twiss function are not optimal for injection

Timing considerations

DR Injection timing

N_p LINAC pulse (2 bunch per pulse) stored in DR



$$\Delta_b = INT[h/N_p]$$

$$\mathrm{T}_{gun} = iT_1 + \Delta_b T_{RF}(1\%np)$$

$$\Delta T_{DR} = (N_p - 1)T_1 \geq \alpha\tau_D$$

Gun is phased with DR RF so that the "first" gun pulse fills #bkt=0

To store for at least 4 damping times

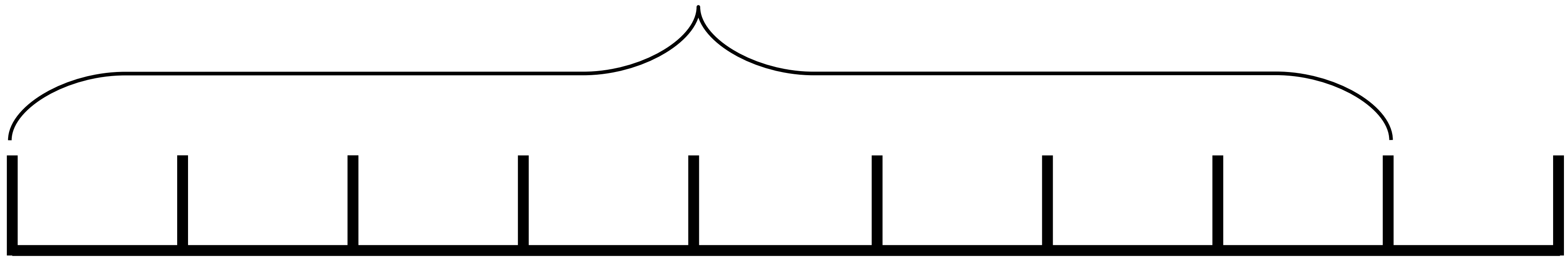
$$\mathrm{N}_p \geq 9 \quad \Rightarrow \quad \Delta_b \leq 35$$

$$\mathrm{h}\%\mathrm{N}_p \neq 0 \Rightarrow \Delta_b \equiv \Delta_b(i)$$

If D_b = 35 the last filled bucket is the 281st 38 bucket before the 319th

(A. De Santis 11/04/22)

Timing: DR Extraction



#pls	0	1	2	3	4	[…]	np-1	np
#bkt	0	Δb	2Δb	3Δb	[…]		0=h	Δb
#ext		-	-	-	[…]		0	1

$$\mathrm{T}_{EXT} = \boxed{T_{gun} + \Delta T_{DR}} + \boxed{T_S/2} + \boxed{T_2 - \Delta T_{12}}$$

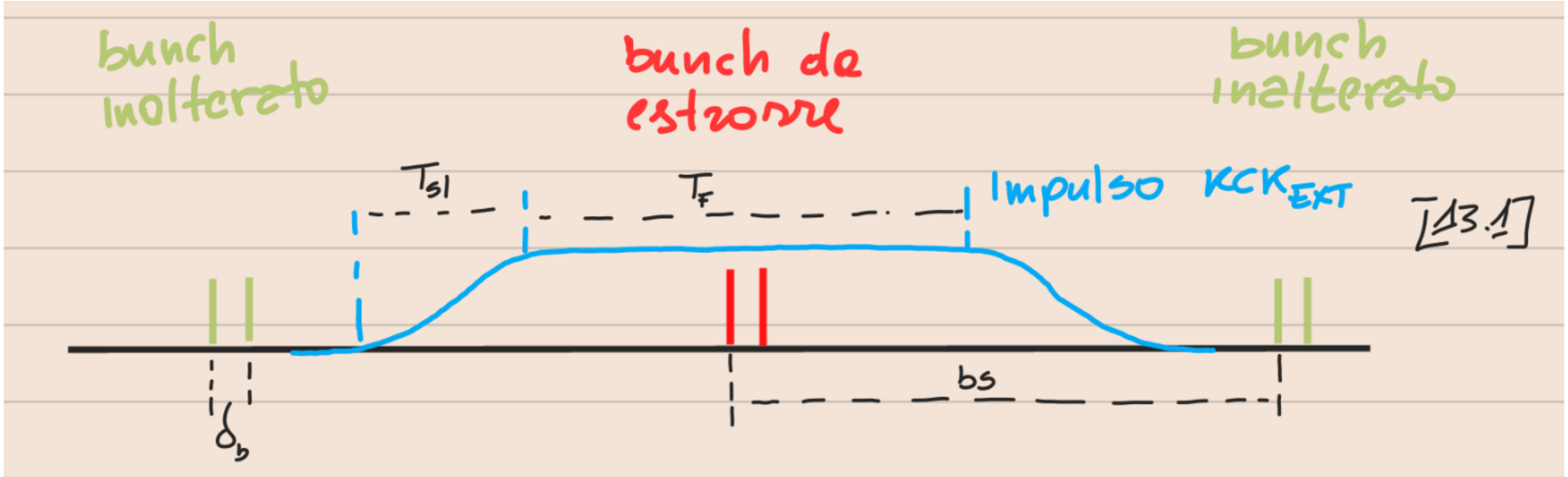
Arrival + Storage time

Half turn to reach the extraction section

Phasing with “empty” Common LINAC pulses.
Δ_{12} accounts for propagation time from DR to Common LINAC
Time is measured in T_S units

A. De Santis 11/04/22

Extraction kickers timing



$$\delta_b \sim 4 \div 7T_{RF} \qquad\qquad \Delta_b = 35T_{RF}$$

Time differences between the two bunches of the same pulse (10-15 ns) and between different pulses stored (87.5 ns) has the following implications on kickers pulses:

$$\mathrm{T}_{sl} \geq 70 \text{ ns} \qquad T_F > 17.5 \text{ ns}$$

(A. De Santis 11/04/22)

Working Package Management

WP4 Manpower and Present Organization

WP4 structure, coordinator C. Milardi

4.1 Damping Ring coordinator C. Milardi:

- **C. Milardi**,
- A.De Santis,
- R. L. Ramjiawan,
- Y. Dutheil,
- *CERN collaboration on RF systems*,
- O. Etisken (by end 2022 for 1 year).

4.2 Transfer Lines to/from Damping Ring, coordinator A. De Santis:

- C. Milardi,
- **A.De Santis**,
- R. L. Ramjiawan,
- Y. Dutheil,
- O. Etisken,
- S. Spampinati (temporary position he will start on Dec 5^{th} 2022).

4.3 Energy pre-compression before injection into DR:

- C. Milardi,
- A.De Santis,
- S. Spampinati ,
- *CERN collaboration*

4.4 Bunch compression scheme before reinjection in the high energy LINAC:

- C. Milardi,
- A.De Santis,
- S. Spampinati.

SPARES

Timing: Some definitions

$R_1(T_1)$: Repetition rate (Period) L1: 200 Hz

$R_2(T_2)$: Repetition rate (Period) L2: 400 Hz

$RF(T_{RF})$: DR Radio Frequency (RF Period): 400 Hz

ΔT_{ep} : Delay between Electron Gun an DR injection

T_S : DR Revolution period: $\sim 0.8\ \mu s$

h: DR harmonic number: 319

N_p : Number of LINAC pulses stored (2 bunch each)

τ_D : Damping time: $\sim$10 ms

The number of stored pulses depends on the time needed to damp the incoming positron beam.