FCC_ee Injector Complex

WP04: Transfer lines and Damping Ring

Damping Ring status

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Outline as it should be

- DR optics
- Longitudinal acceptance
- Dynamical aperture
- Damping ring acceptance
- Collective effects preliminary evaluation
- IBS impact evaluation
- Injetion/extraction timing scheme
- Conclusions

Real Outline that we want to discuss

- DR optics
- Longitudinal acceptance
- Dynamical aperture
- Damping Ring acceptance
- Collective effects preliminary evaluation
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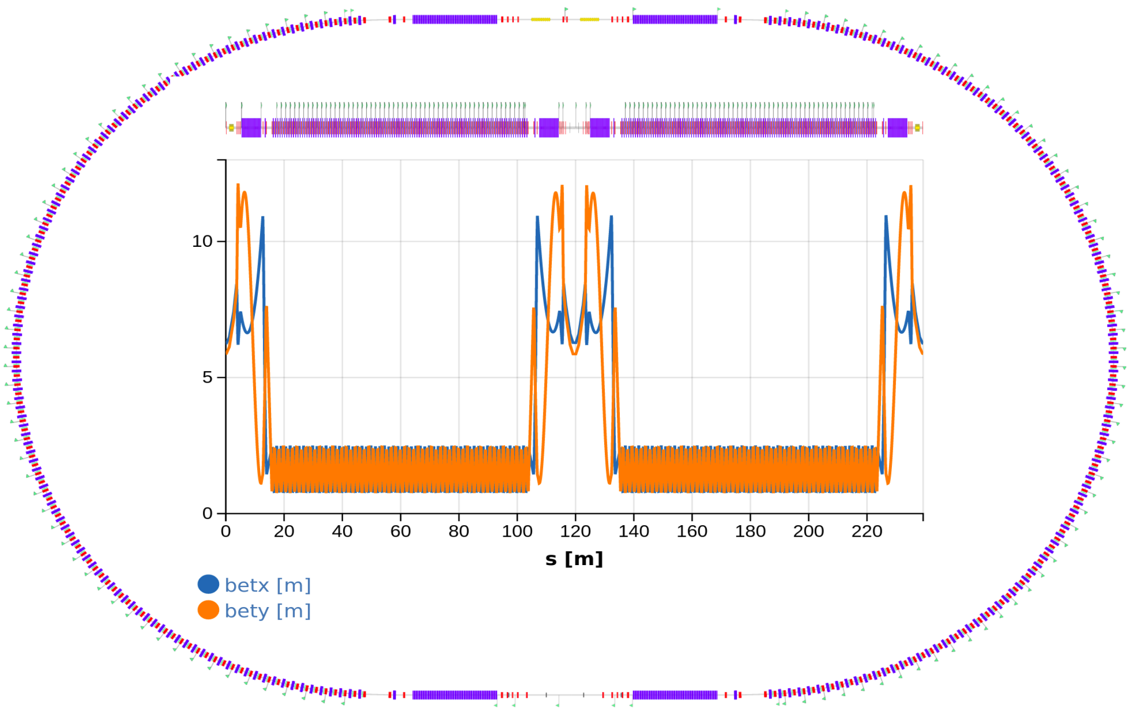
- Conclusions

Damping ring layout



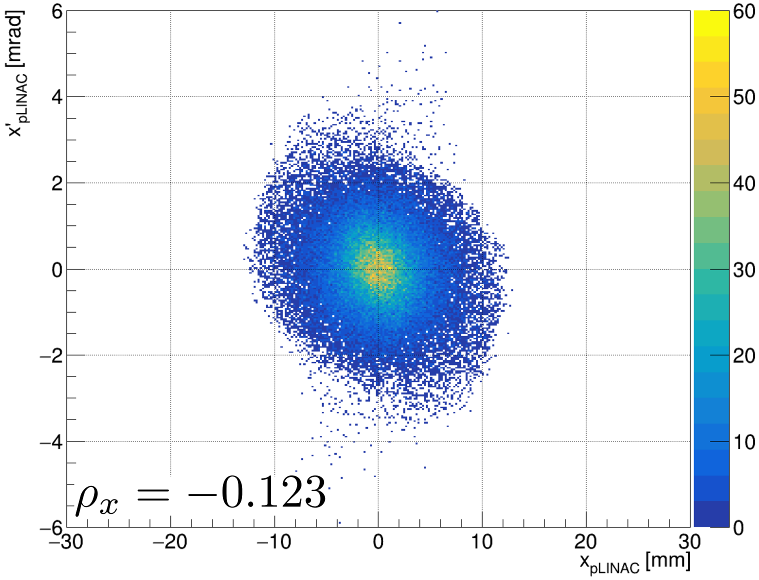
Parameter	FCC_ee DR
Circumference	**239.2 m**
Harmonic number	**319**
Eq. Emittance (x/y/z)	**1.01 nm/ - / 1.46 μm**
Dipole length, Field	**0.21 m, 0.66 T**
Wiggler #,Lenght, Field	**4, 6.64 m, 1.8 T**
Cavity #, Lenght, Voltage	**2, 1.5 m, 4 MV**
Bunch stored #, charge	**18 , 4.0 nC**
Damping Time (x/y/z)	**10.8 / 10.8 / 5.4 ms**
Store Time	**42.5 ms**
Energy loss per turn	**0.227 MV**
SR Power Loss (WGL)	**15.7 kW**

Current DR shopping list:

- 232 BEND (21 cm each) in the arcs
- 258 QUADRUPOLE (20 cm each mostly in the arcs)
- 232 SEXTUPOLE (8 cm each mostly in the arcs)
- 4 WIGGLER (6.7 m each: 44 poles of 5 cm each)
- 2 Straight section hosting RF Cavity and Injection/Extraction equipments

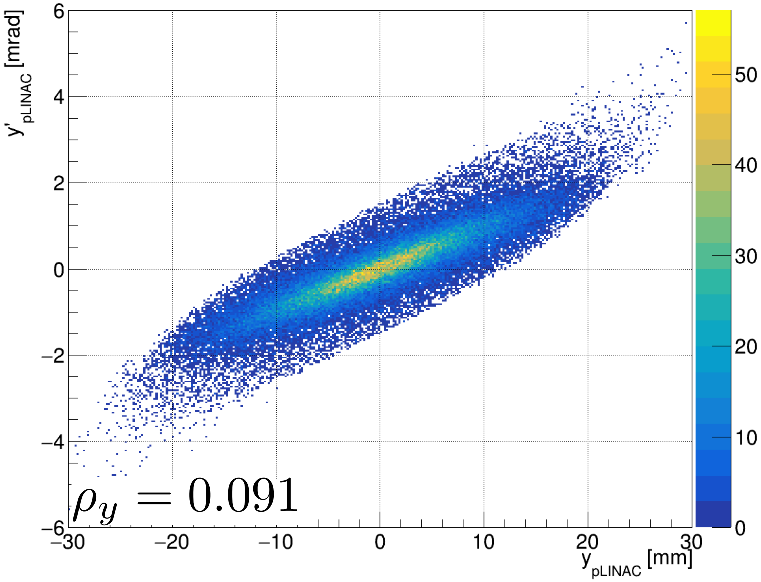
Damping Ring acceptance

Transverse emittance @ pLINAC (Jan23)



$$\Sigma_x = \begin{pmatrix} 3.26^2 & -0.35 \\ -0.35 & 0.88^2 \end{pmatrix}$$

$$\epsilon_x = \sqrt{det\Sigma} = 2.83 \text{ mm mrad}$$



$$\Sigma_y = \begin{pmatrix} 8.06^2 & 0.60 \\ 0.60 & 0.82^2 \end{pmatrix}$$

$$\epsilon_y = \sqrt{det\Sigma_y} = 2.69 \text{ mm mrad}$$

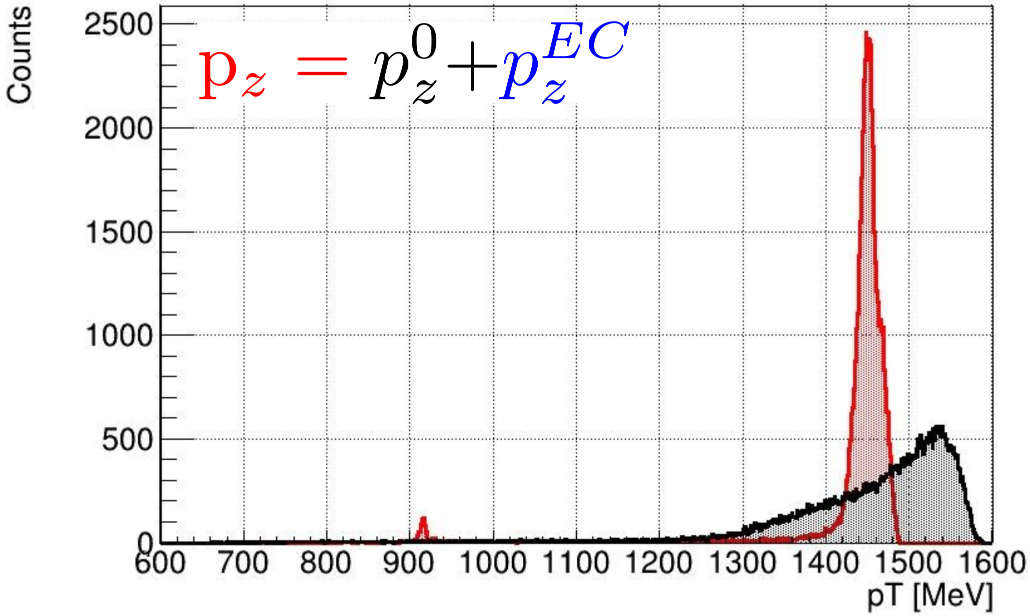
Simplified Energy Compressor optimization

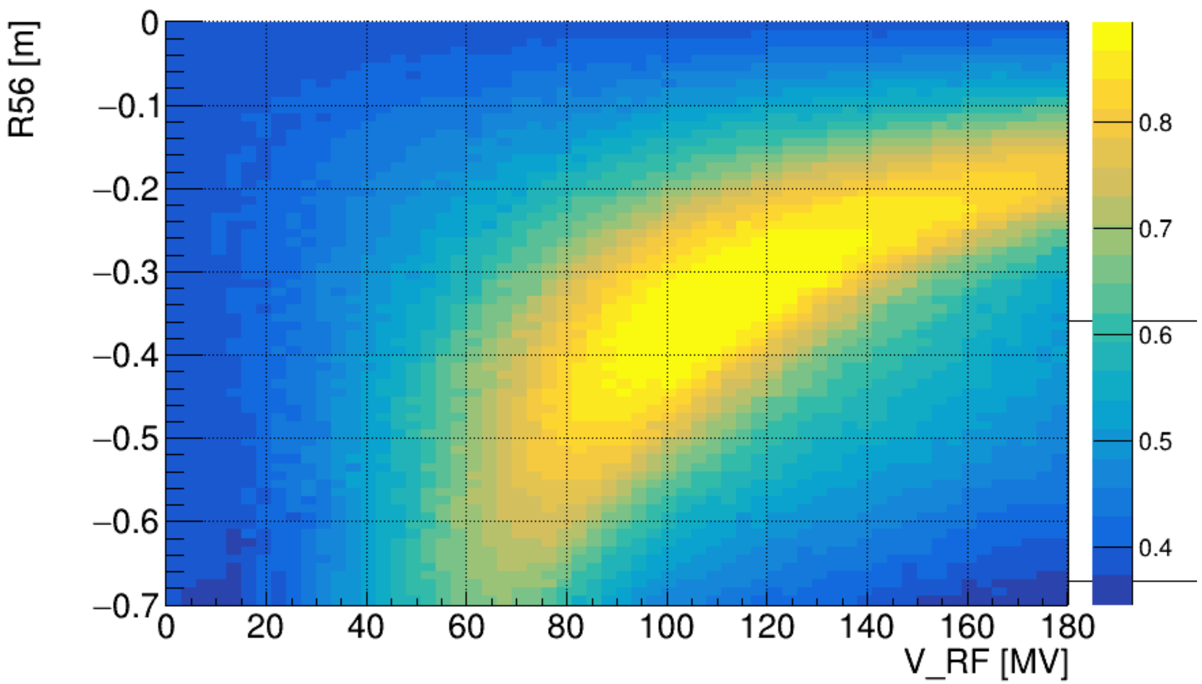
$$\delta t = t_0 - t_{ref}$$
$$\delta p_z = p_z^0 - p_z^{ref}$$

R_{56} + zero-crossing cavity transform:

$$t_{56} = \delta t + R_{56}\frac{\delta p_z}{p_T}$$

$$p_z^{EC} = V_{RF}\sin(2\pi f_{RF} t_{56})$$





V_{RF} and R_{56} parameter scan:

Maximize the fraction of particle within 2% of the central energy.

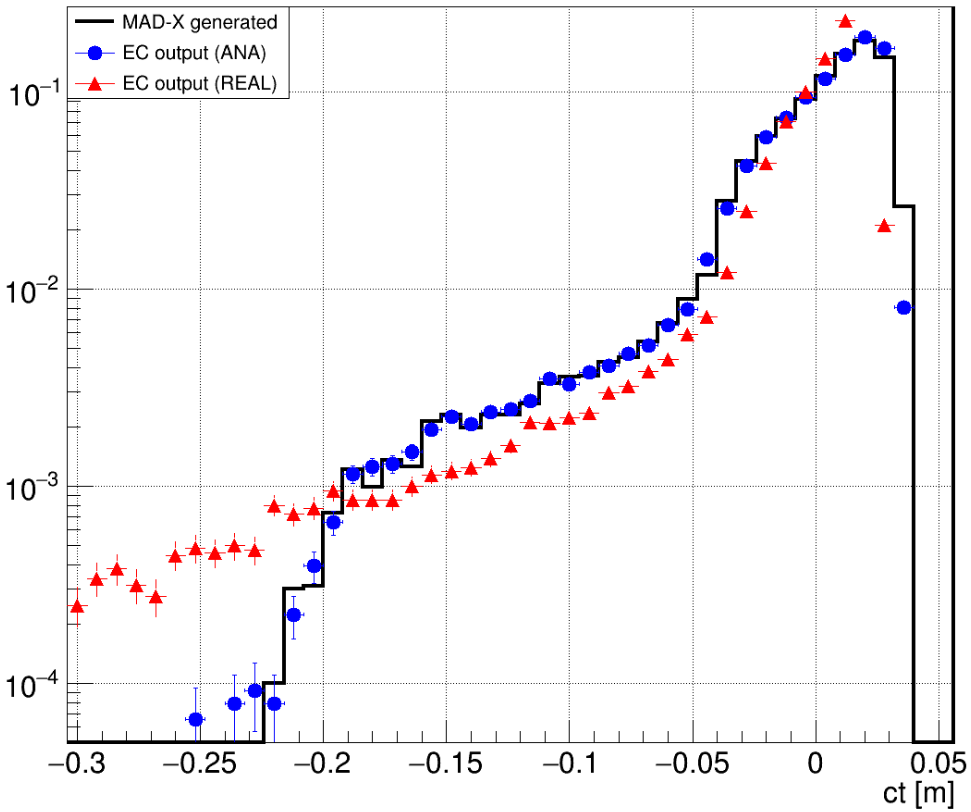
Result (only analytical):

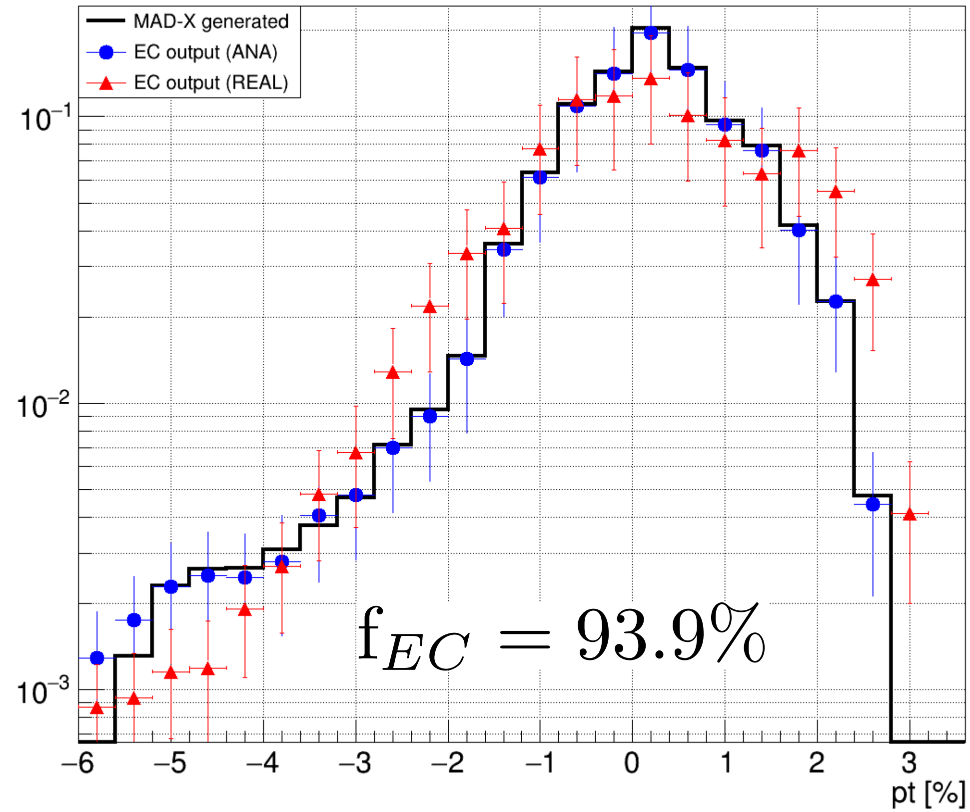
V_{RF} = 100 MV

R_{56} = -0.35 m

Results with Elegant simulation slightly different.

Tracking input distribution





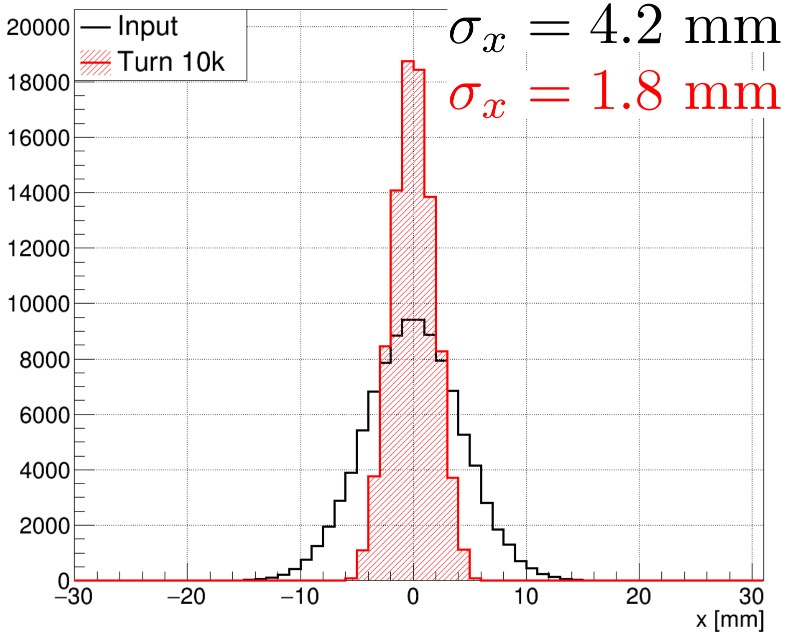
To increase the statistics EC distruibutions have been resampled. The central energy and time are assumed to be “free to be adjusted”.

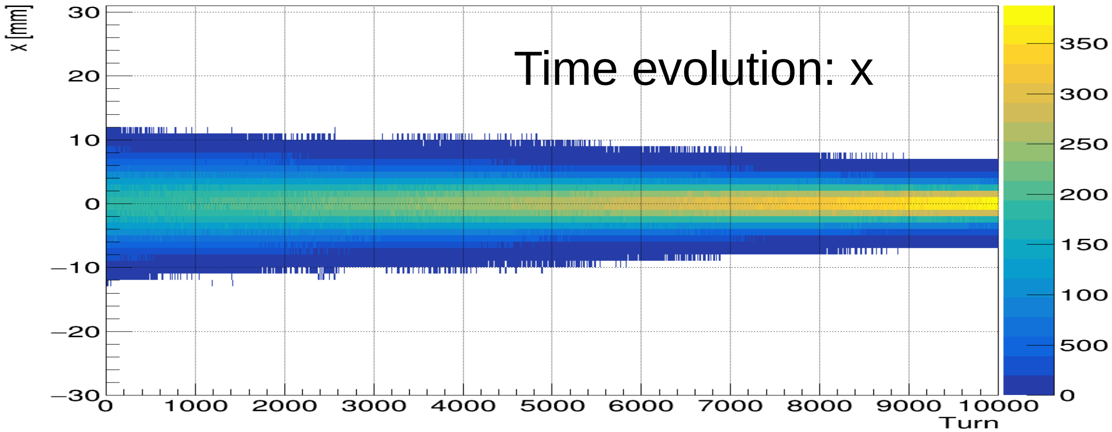
Cut on the tails have been applied (8% loss)

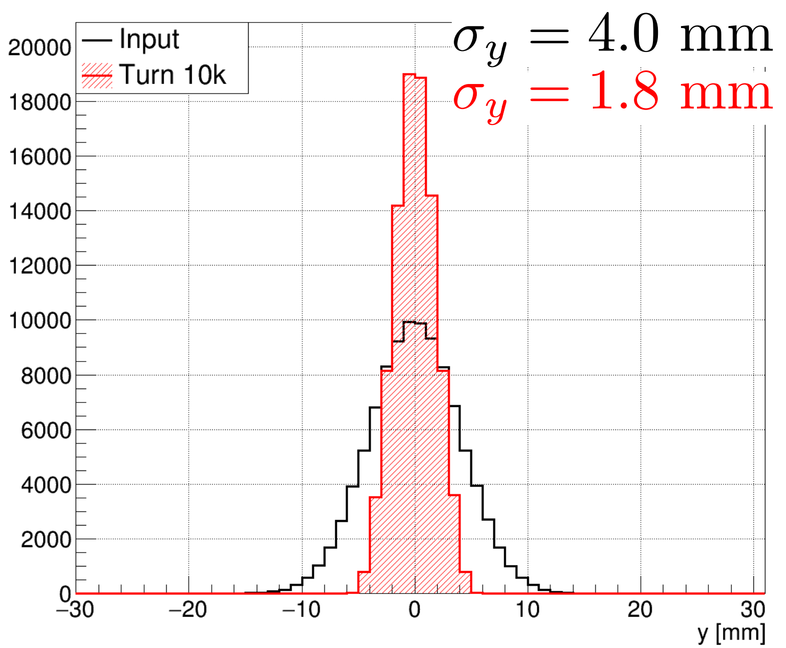
Comparison between EC(analytical) and EC(Elegant) shows some difference

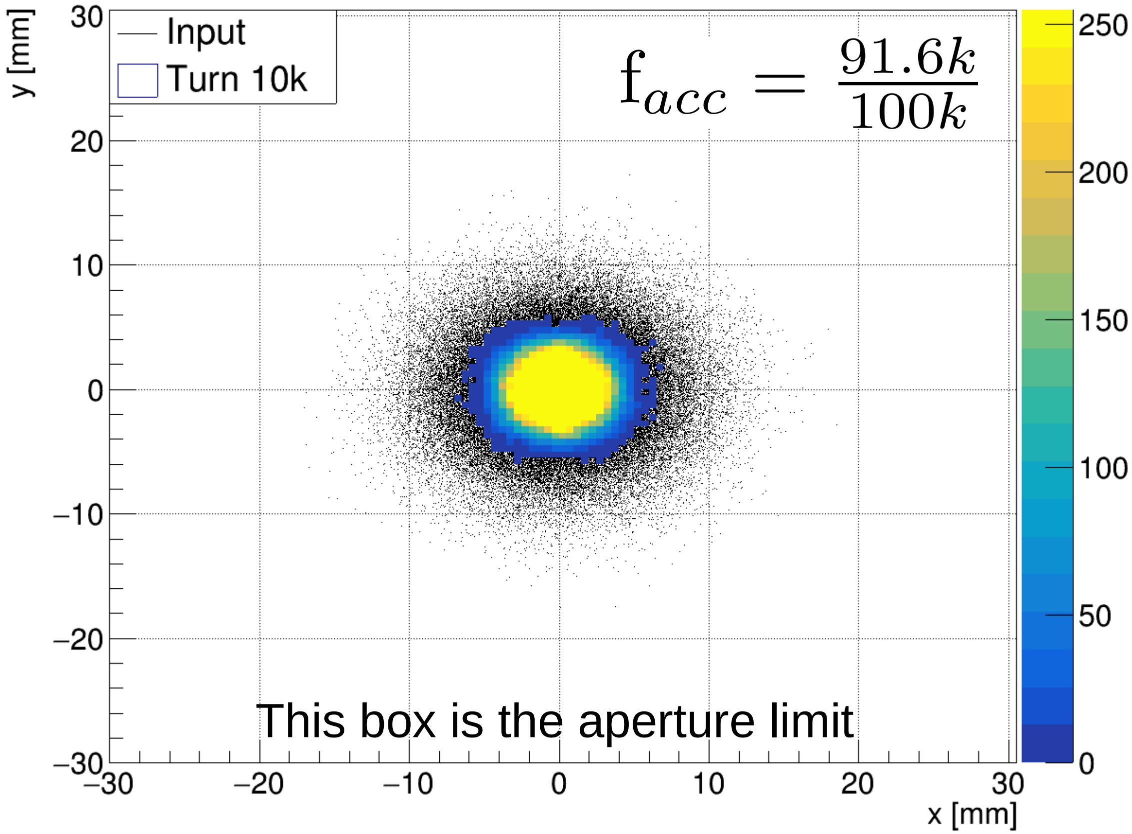
Simulations with EC(Elegant) distributions are on-going (no major difference expected)

Damping Ring acceptance



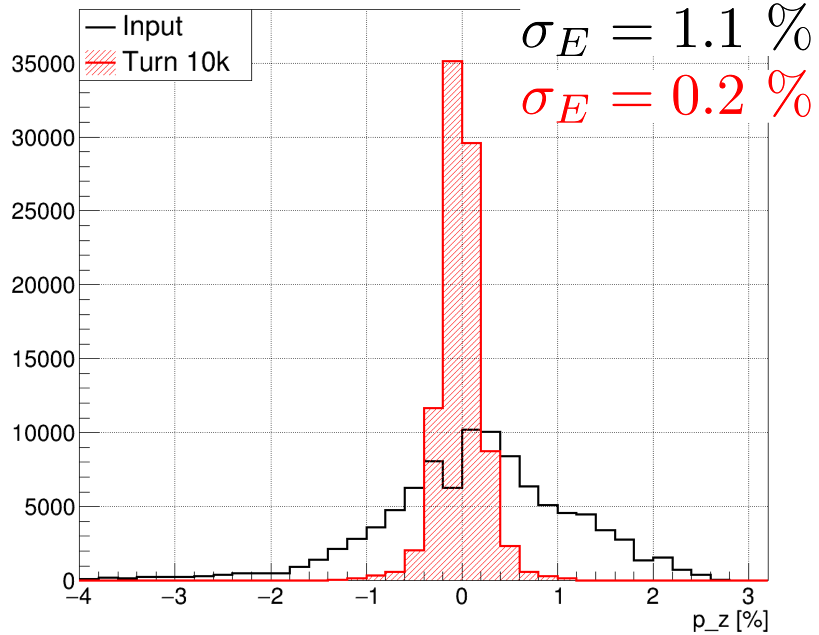


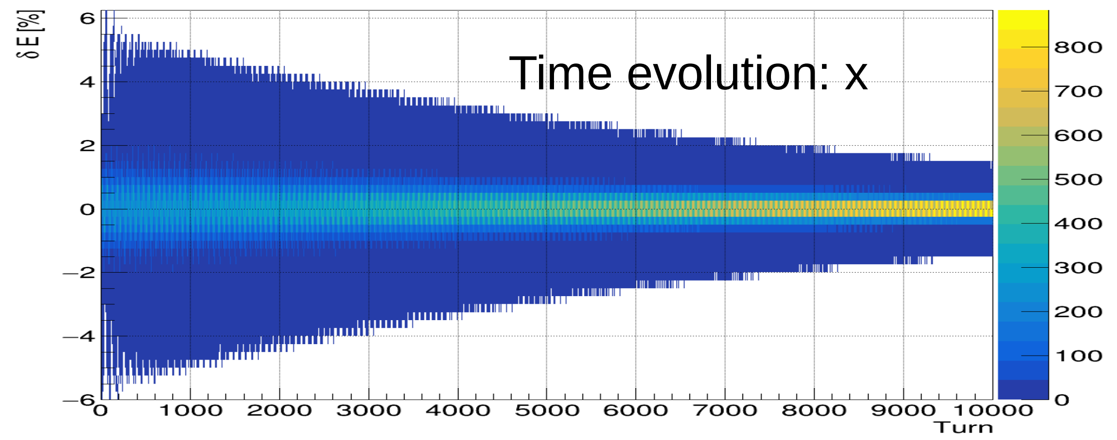


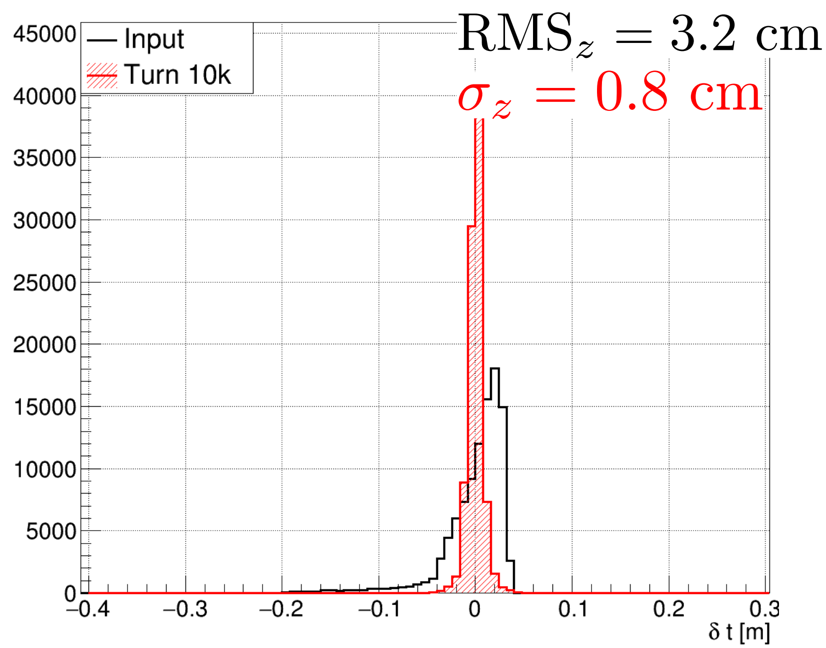


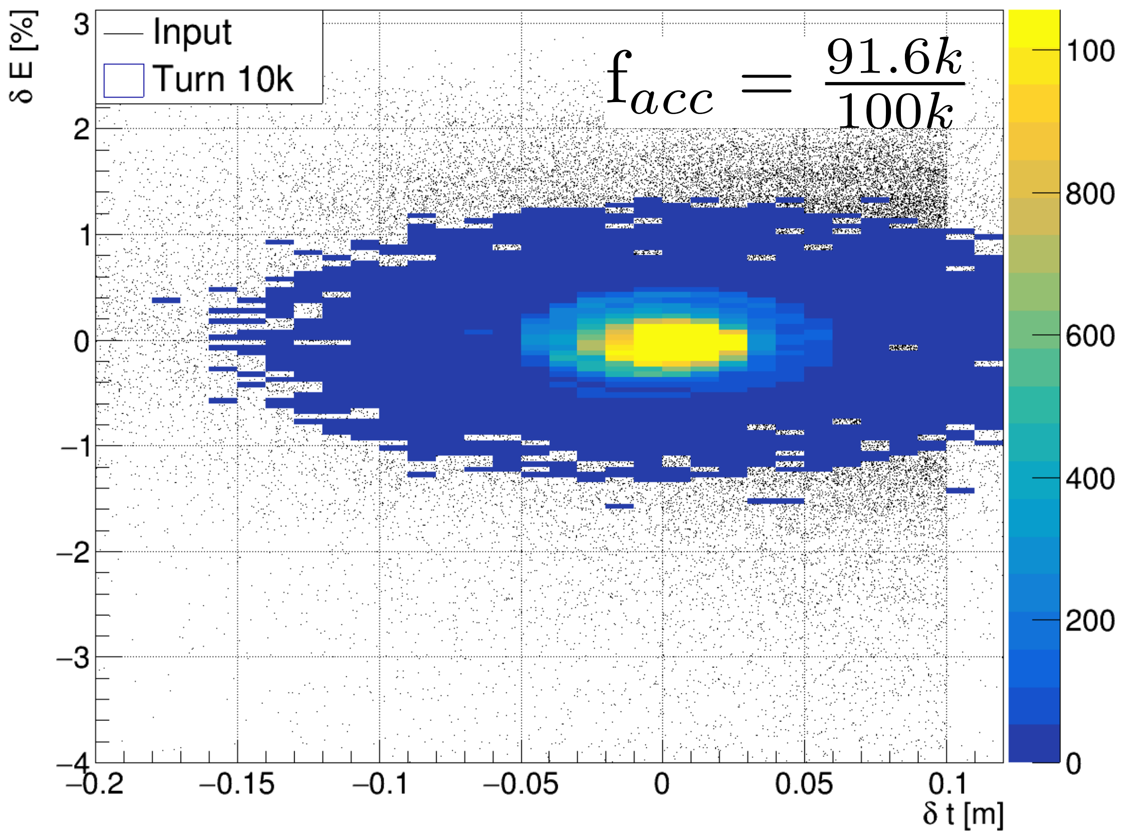
Initial distributions are strongly asymmetric

Damping Ring acceptance

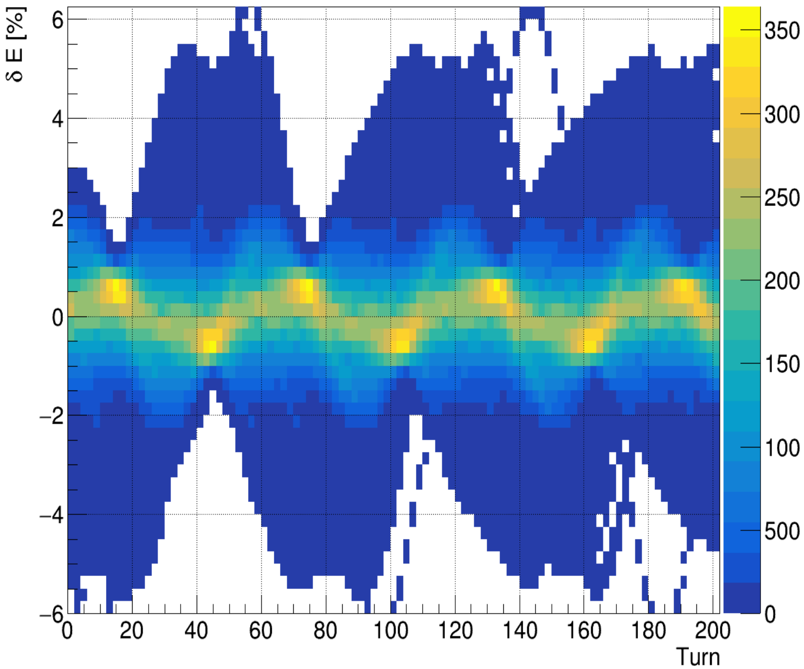






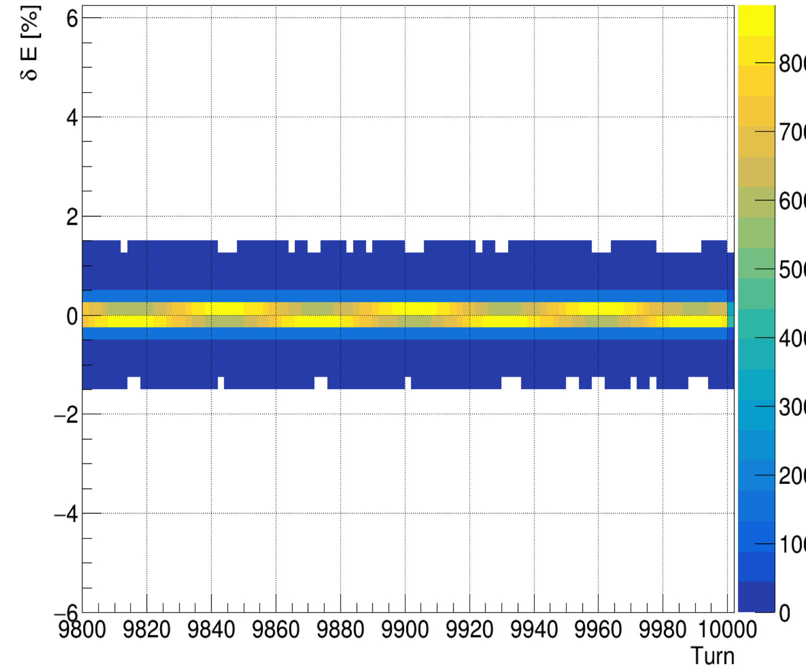


Energy distribution evolution



After 8 ms

10k turns



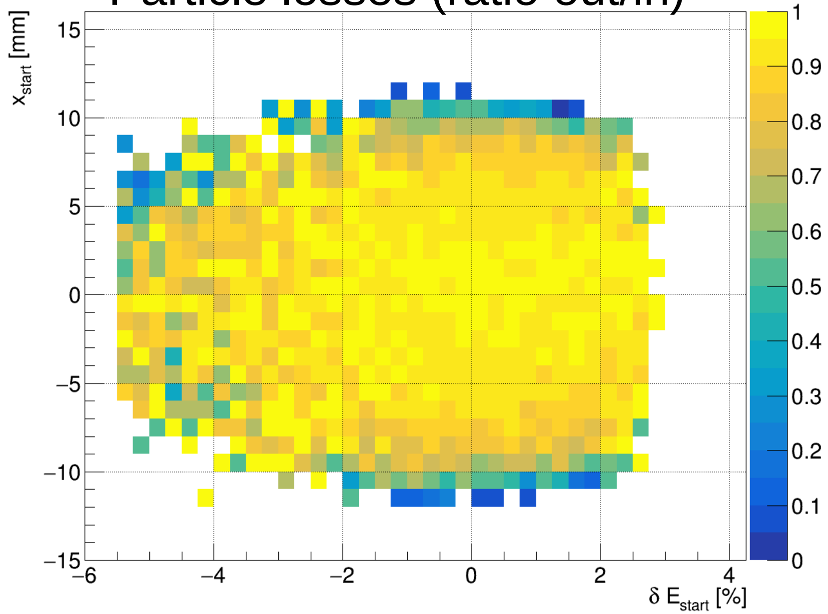
The larger is the deviation of the energy

Most of the losses are concentrated in the tail of the distribution as expected (see plot).

Global acceptance:

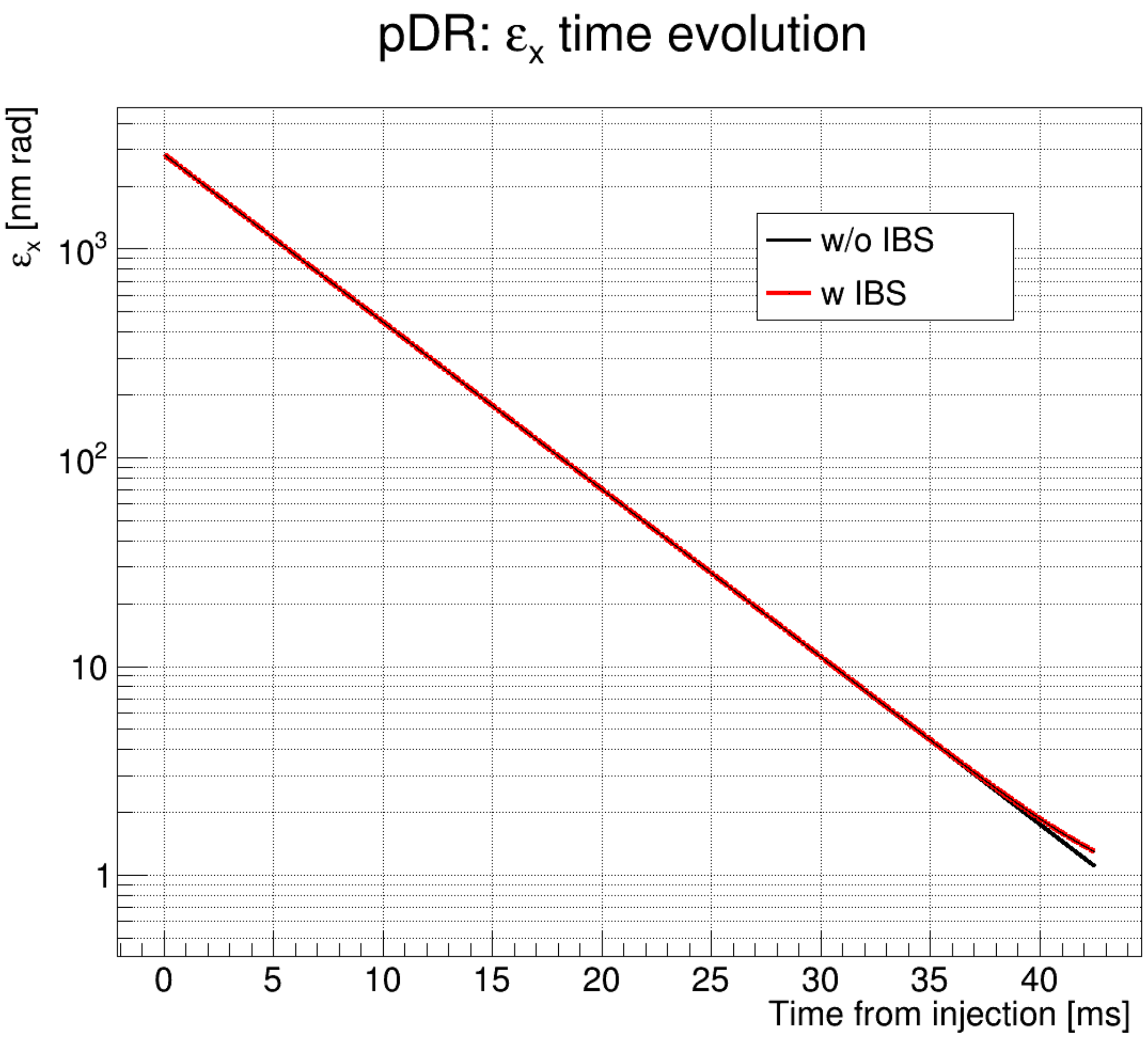
$$f_{ACC}(TOT) = 0.939 \times 0.917 = 86.1\%$$

Particle losses (ratio out/in)



IBS impact evaluation

Emittance evolution with IBS



The IBS has been evaluated using MAD-X module.

The initial emittance is 3 mm mrad

The bunch charge is 4 nC

ε_x(ext) = 1.29 nm rad

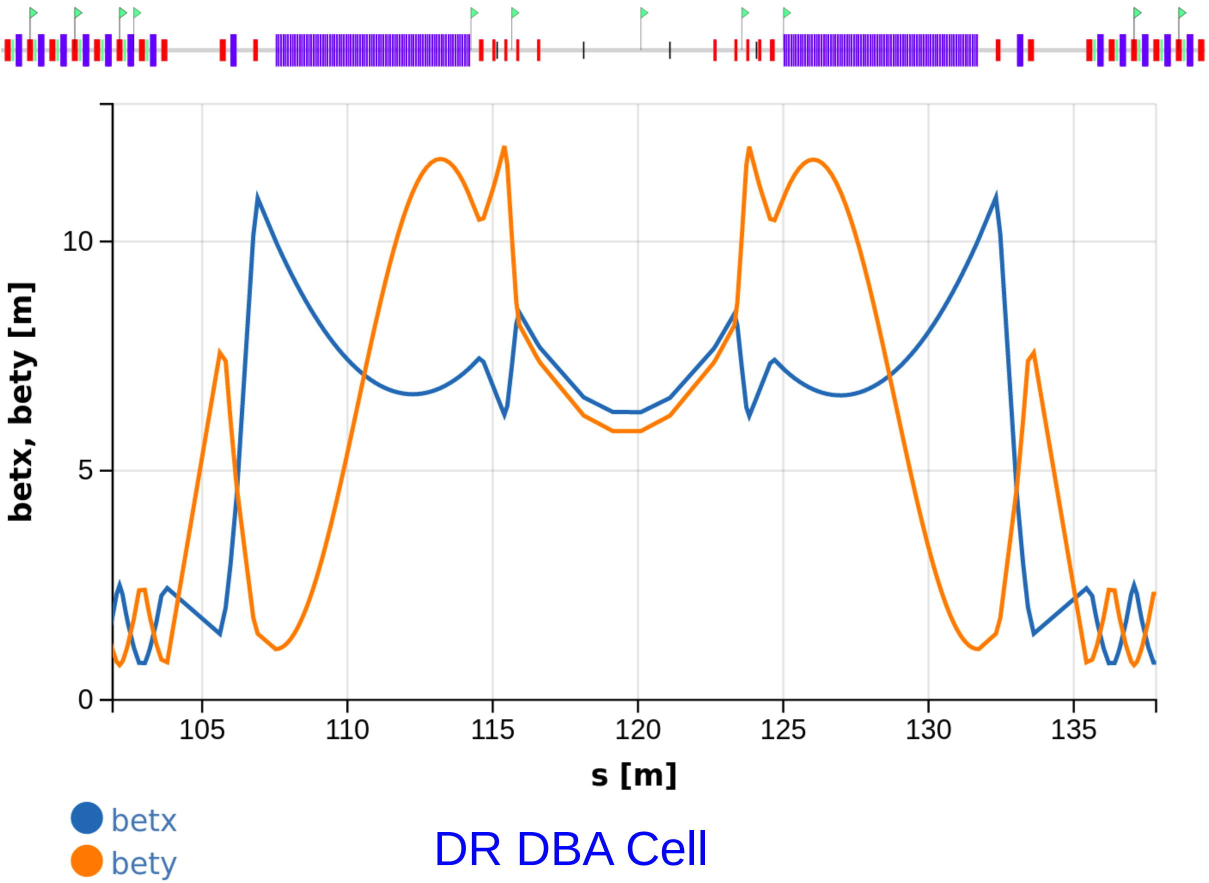
ε_y(ext) = 1.03 nm rad

Conclusions @ LNF Injector Meeting

- Transverse emittance of the pLINAC beam is confirmed to be very large (~3 mm mrad)
- Energy Compressor allows for reasonable energy spread at injection (~2%)
- **Damping Ring acceptance for EC beam is larger (~92%)**
- IBS does not limit the extraction emittance

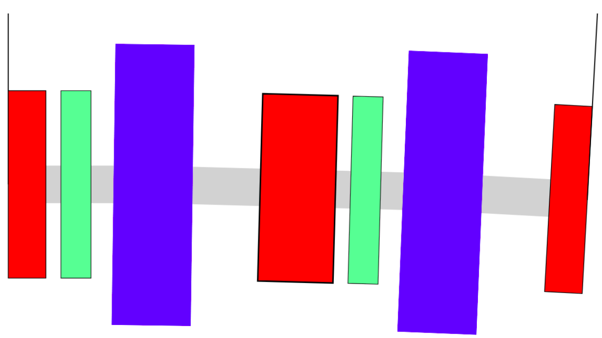
DR optics

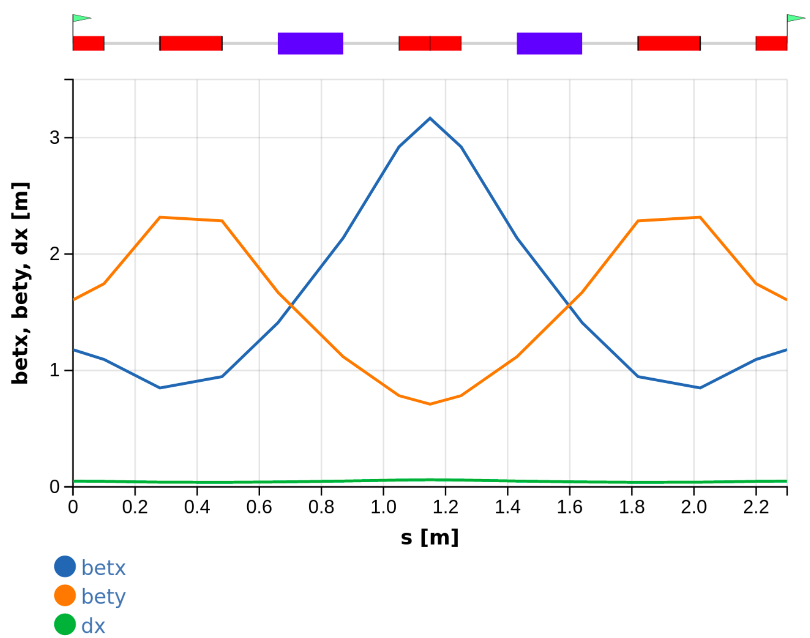
DR optics details



Straight section details.
Two of the four wigglers are shown.
Straight sections are designed to host RF cavities and Injection/Extraction equipments.

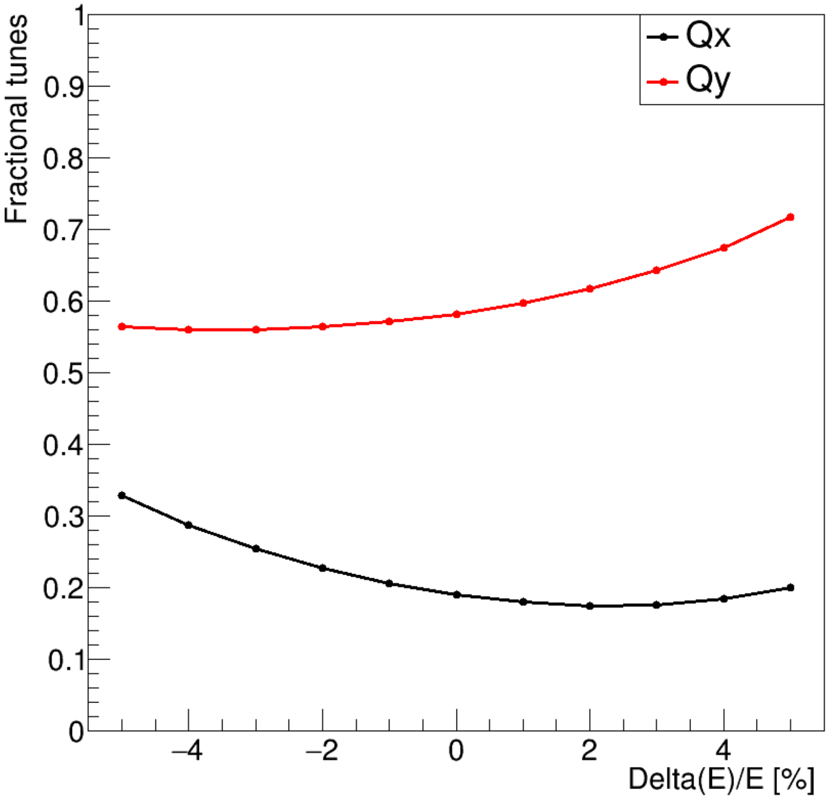
DR DBA Cell

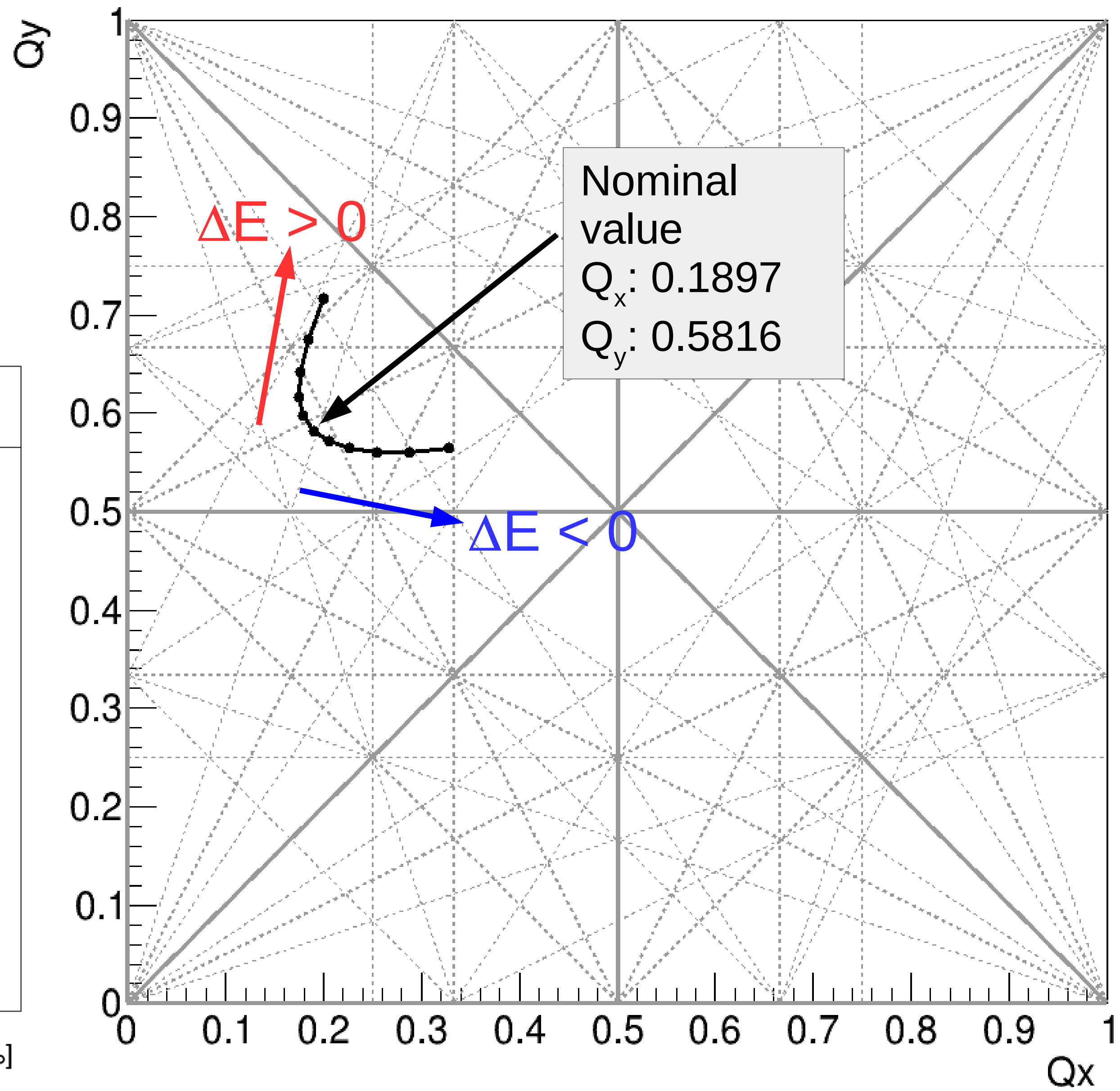




Tune diagram

Tune variation as a function of energy for the nominal lattice





DR longitudinal acceptance

Energy Acceptance at injection for e+ beam

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

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

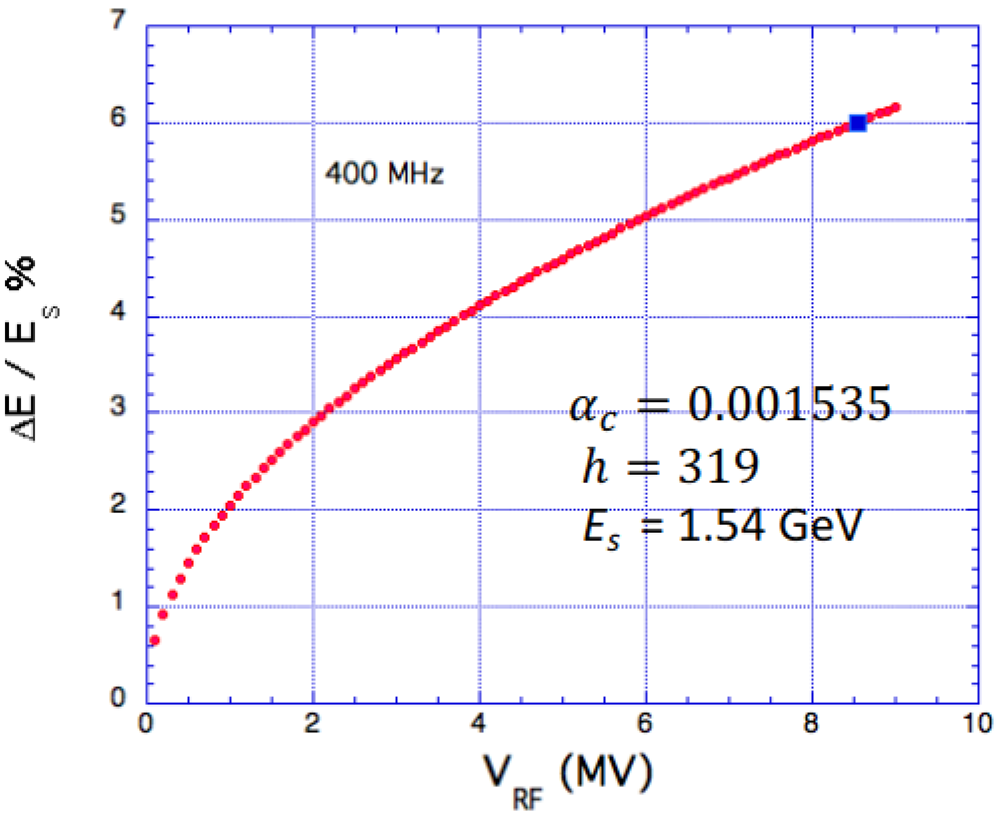
If an energy acceptance of the order of

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

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

α_c = 0.001535

$\boldsymbol{h = 319}$

	V= 8MV	V= 6MV	V= 4MV	V= 2MV
U_0 [KeV]	227.1			
DE/E_s	0. 71 • 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

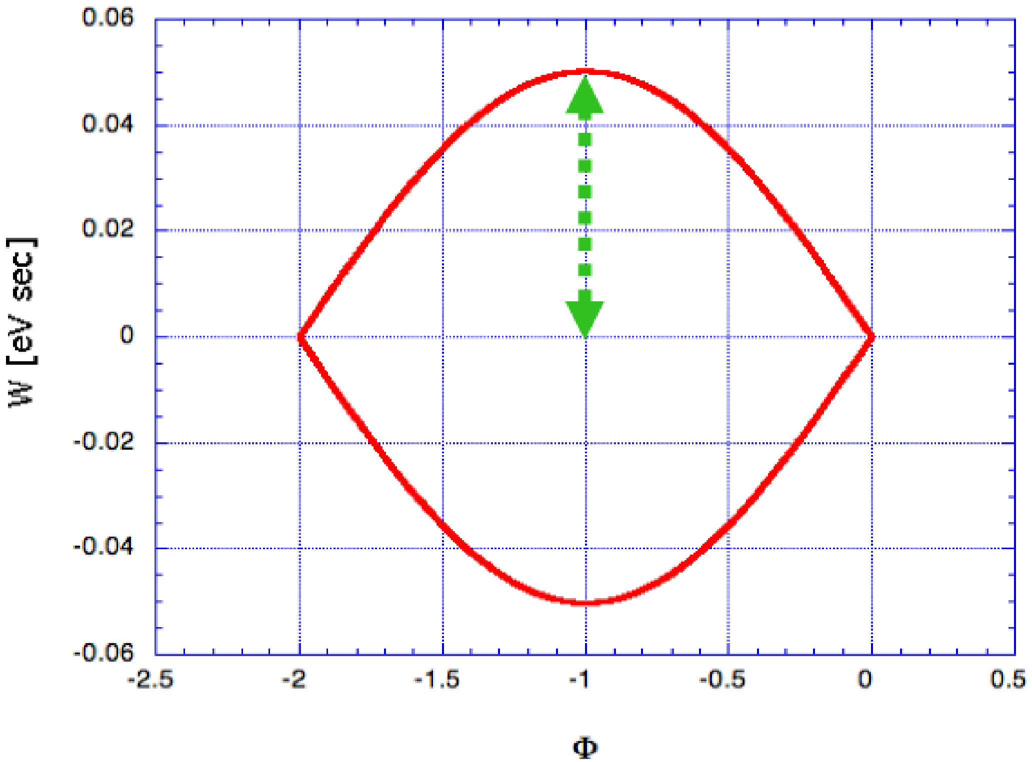
$$\frac{1}{\Omega_s}\frac{d\varphi}{dt} = \frac{2\pi c}{L}\sqrt{\frac{2\pi h^3 \eta_{tr}}{E_s eV \cos\varphi_s}}\, W$$

$$W_{bh} = \frac{L}{\pi hc}\sqrt{\frac{eVE_s}{2\pi h\eta_{tr}}}$$

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

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]***



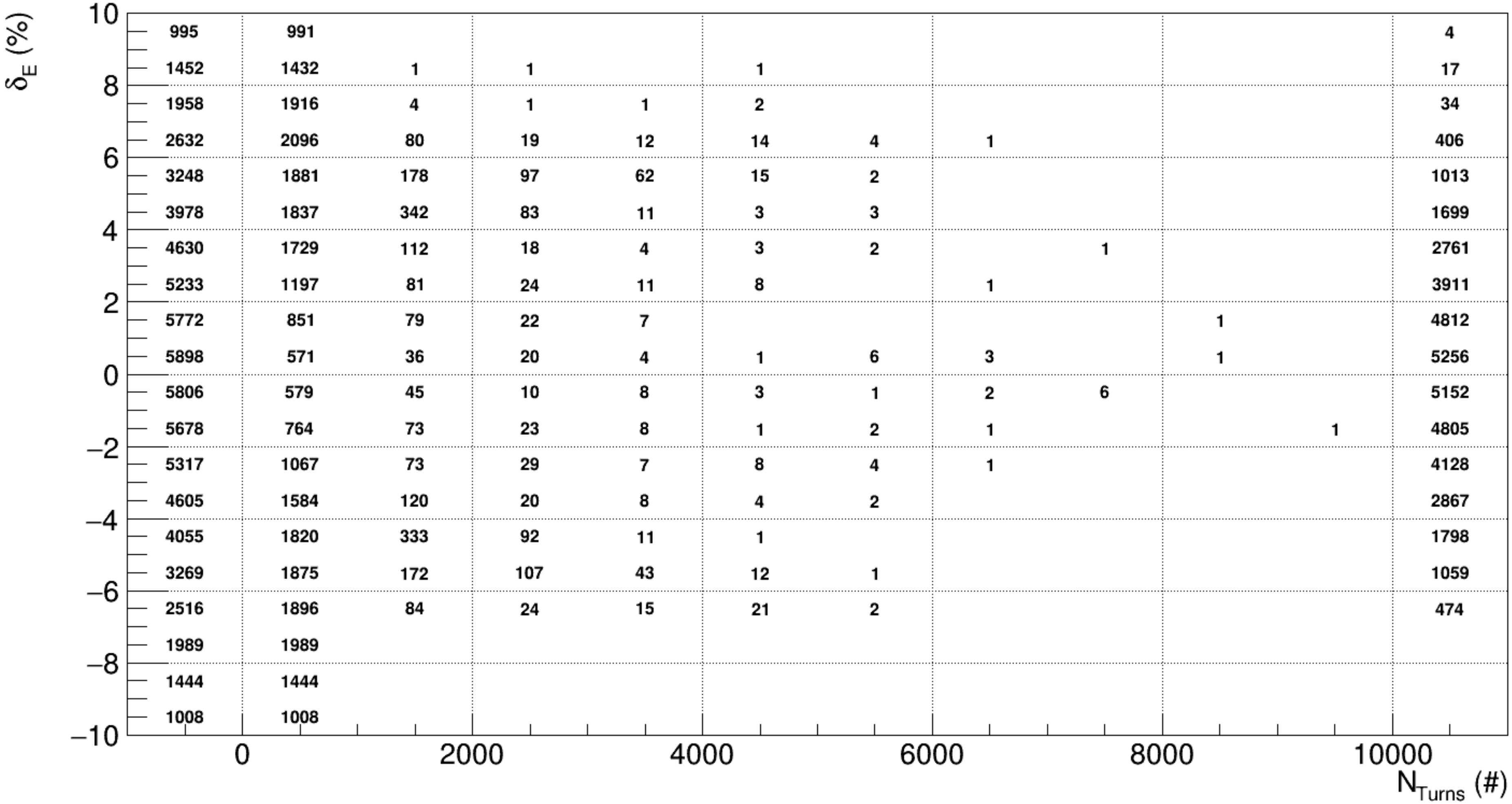
Assuming:

$\alpha_c = 0.001535$
$h = 319$
V = 8 MV
E_s = 1.54 GeV

W_{bh} = 0.0501813 (eV sec)
A_{bk} = 0.401451 (eV sec rad)

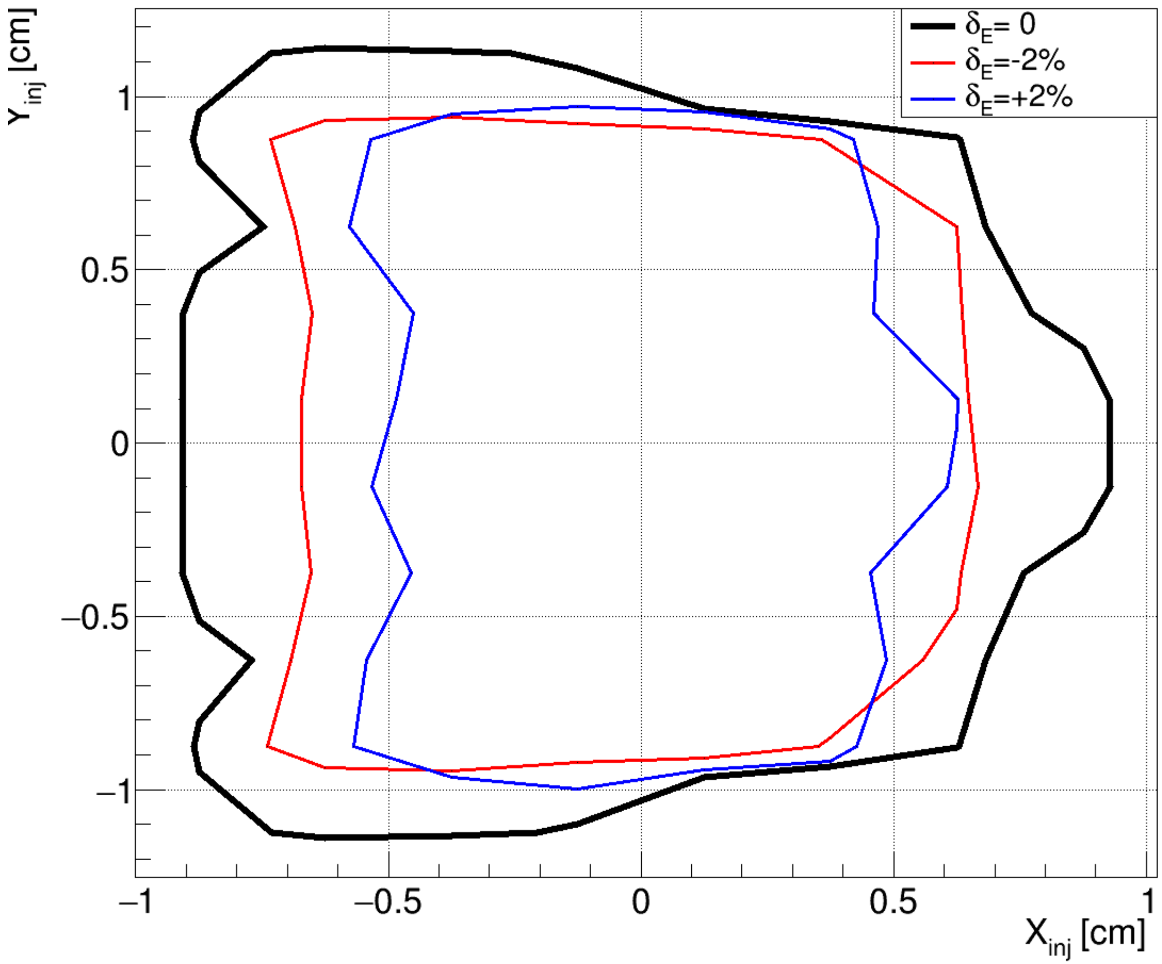
DR dynamical aperture

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).
Complete tracking has been performed, including radiation loss and RF effects.
In the table the numbers refers to the particles lost at a given turn (1k 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



Tracking has been performed with PTC (MAD-X interface).
2000 turns has been tracked (~15% damping time). The estimated loss of accuracy is below 1% at the nominal energy.

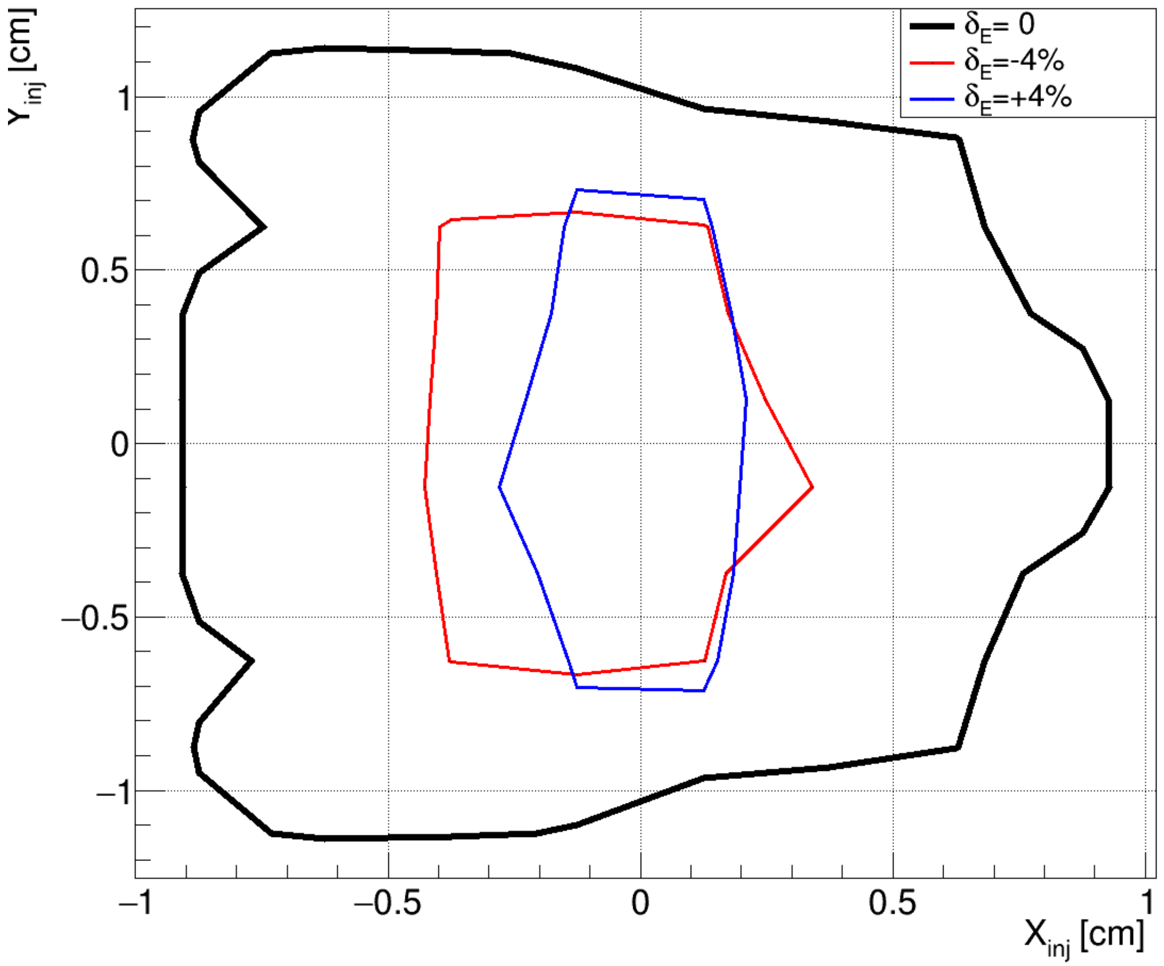
The phase space have been sampled up to 3x3 cm^2 in the transverse plane. Only on-axis particles have been simulated (x'/y'=0).

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 succesfull tracking. A probability definition is needed in order to take into account the average value over the surface.

DR dynamical aperture



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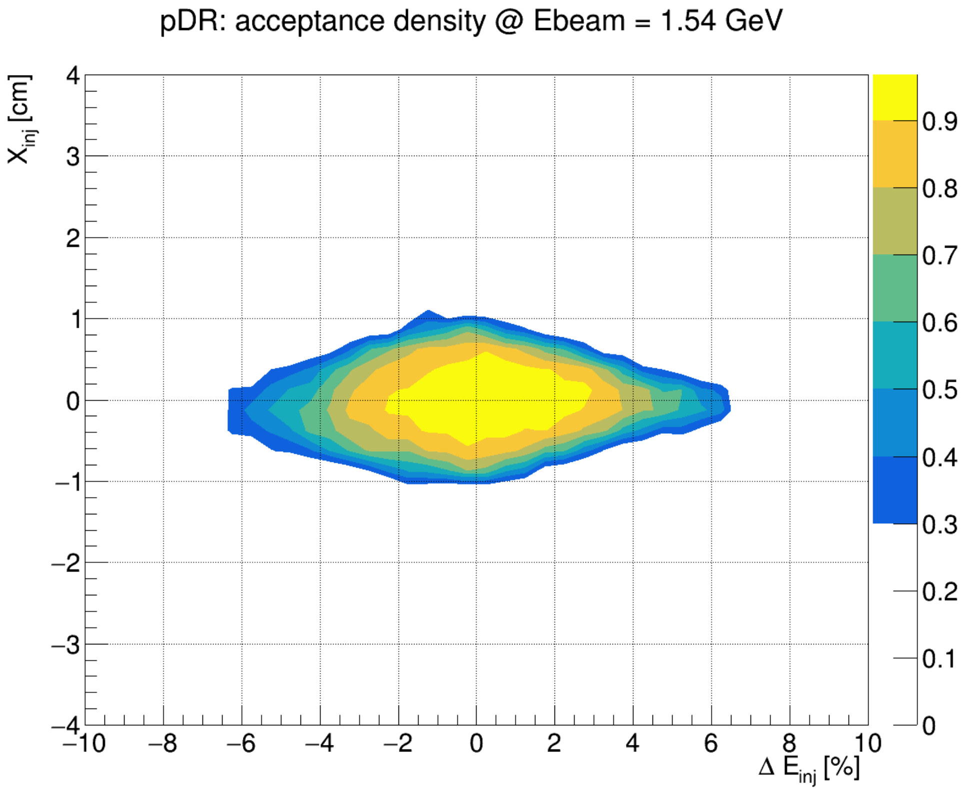
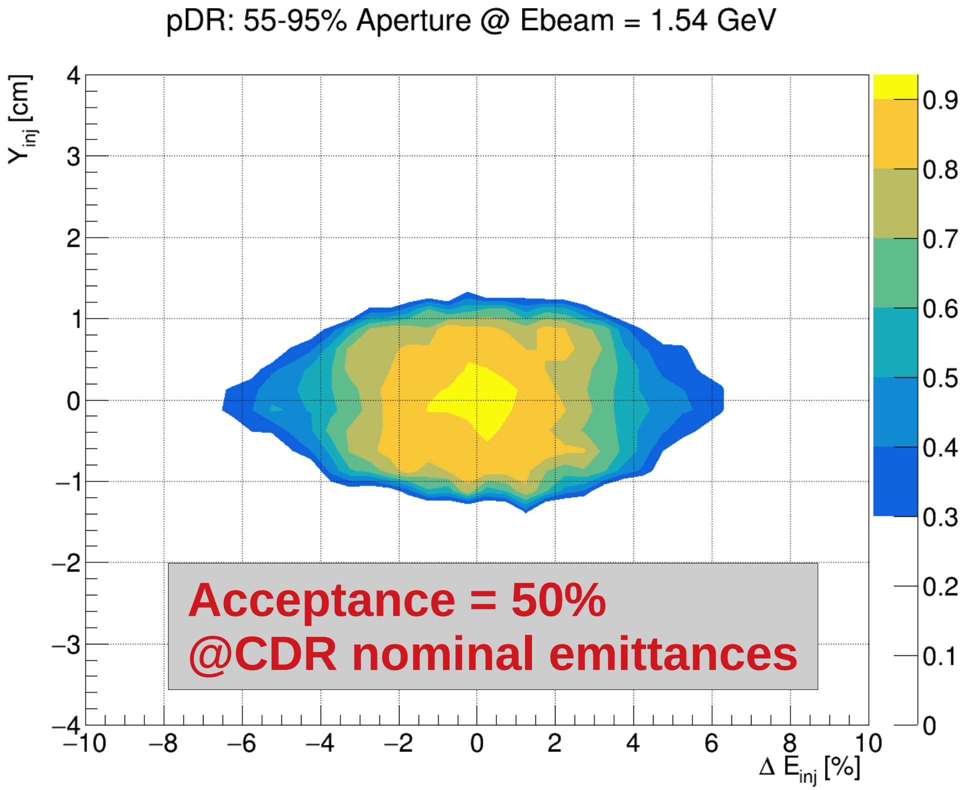
Radiation damping has been neglected allowing a much faster tracking of the DR.

For larger energy variations (±4%) the stability region shrinks considerably and it is clearly not 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). For reference the stability region at the nominal energy has been reported.

DR acceptance probability



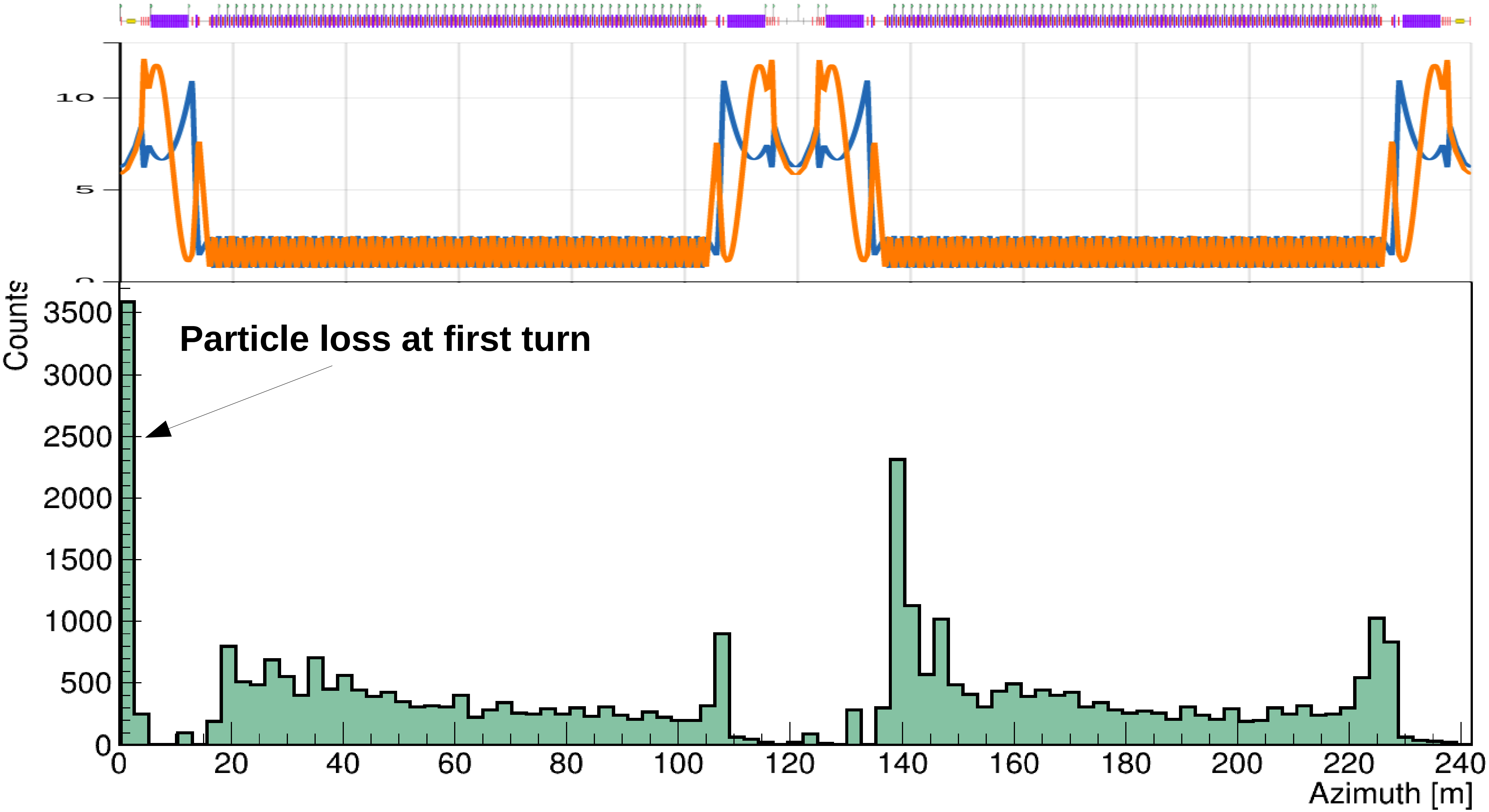


DR acceptance probability has been evaluated starting with nominal CDR beam at the injection: Gaussian profile with nominal width at the injections (σ ~ 2mm in both planes). The energy distribution has been assumed Gaussian with 5% resolution.

The color map represent the projection of the survival probability associated to the different position in space: horizontal and vertical, respectively as a function of energy deviation.

A full matrix in phase space is available to reshape particle distribution at the positron source.

DR: particle loss distribution



Tracking has been performed starting with nominal CDR beam 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 around the ring (lattice on top)

Collective effects

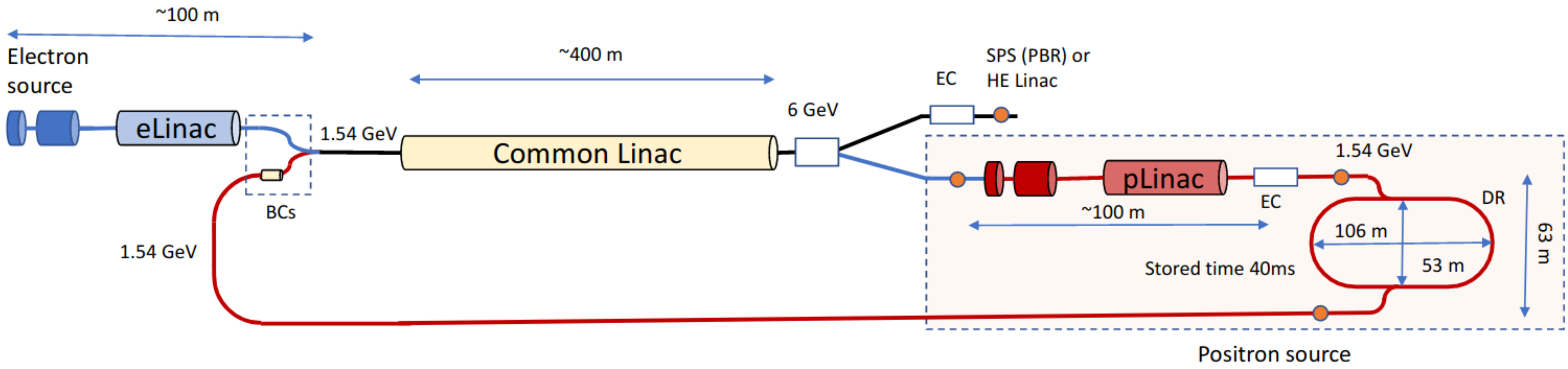
Collective Effect estimates for the “after CDR” Design

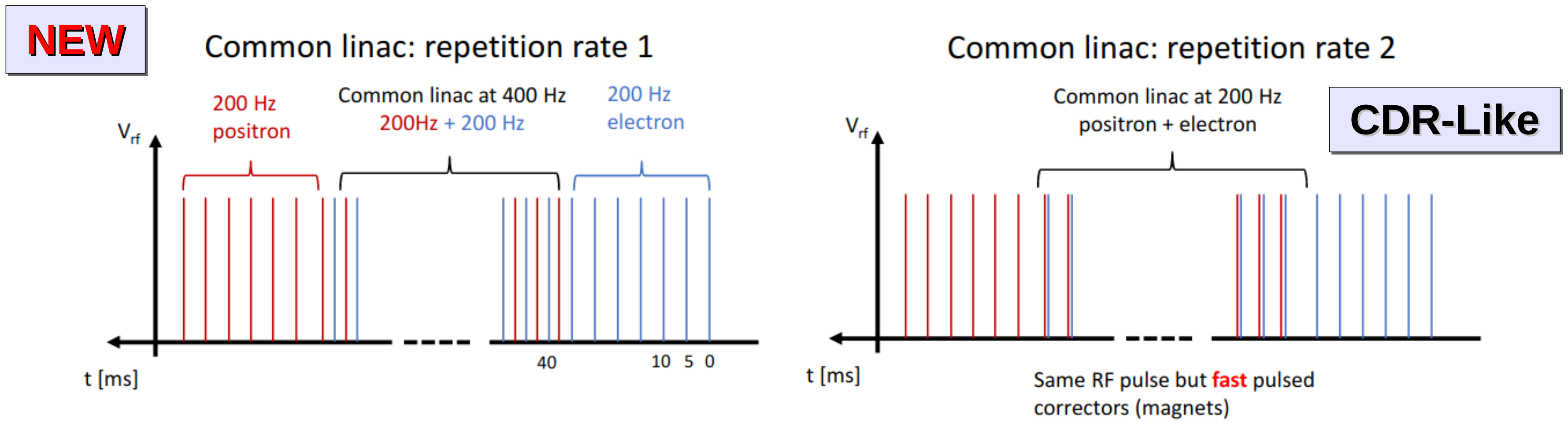
- *Collective effects can limit the ultimate performance of any accelerator. In this respect, an analytical estimation of intensity thresholds and impedance budgets have been performed for the current DR design.*
- Based on the analytical estimations, **No major limitations** are expected due to **IBS, 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 (need discussion with expert).
- It was shown that the **neutralization density exceeds** the ***e-cloud* instability threshold** for the equilibrium state. **This should be investigated with comprehensive simulations.**
- 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**.

Parameters	Parameters accounting for Collective Effects
$\delta Q_{x/y}$ - @inj. (e^-)	0.004/0.003
$\delta Q_{x/y}$ - @inj. (e^+)	$1.8\times10^{-4}/1.04\times10^{-5}$
$\delta Q_{x,y}$ - @eq. (e^- and e^+)	0.01/**0.09**
Emit. growth by IBS @inj. (e^-) [%]	78
Emit. growth by IBS @inj. (e^+) [%]	6
$Z_0^{//}$ [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
$Z_t^{\perp}$ [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
δQ_{ion} @inj./@eq.	0.003/<<
τ_{inst} [t_{rev}] @inj./eq.	770/14
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
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

Injection/Extraction timing scheme

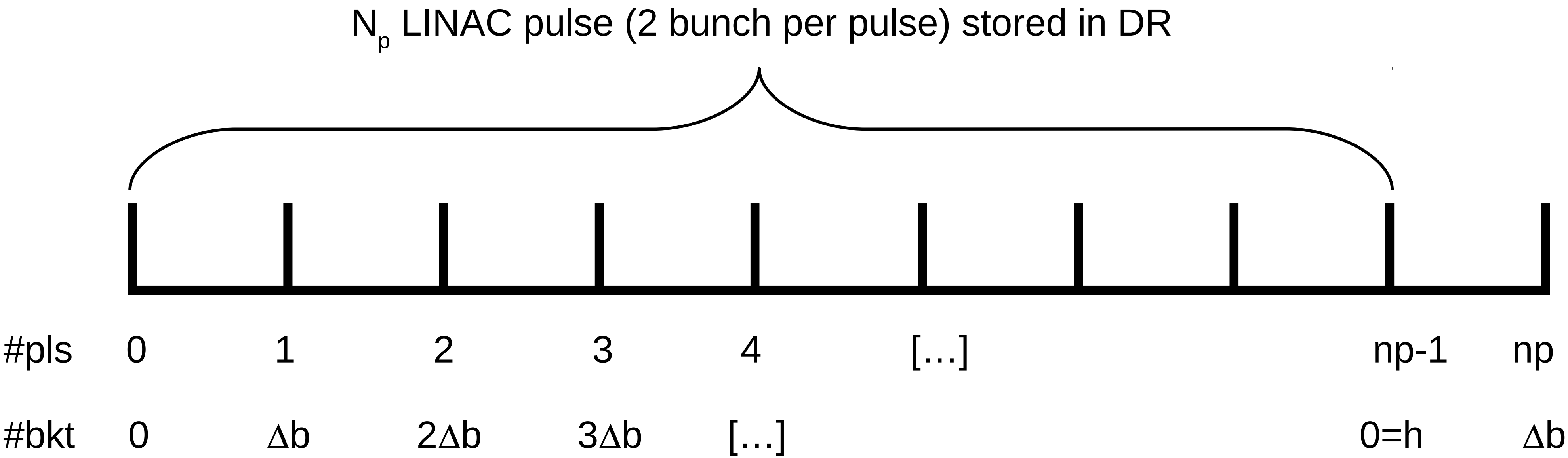
Injector current general layout





New baseline for FCC_ee Injector complex is under evaluation.
In the current scheme two low energy linac's are used for electron and positron and only the high energy linac is common.
DR should allow to damp the beam and delay extraction to allow single species operations for the coommon linac.

Timing: DR Injection



$$\Delta_b = INT[h/N_p] \quad \text{Space between first bunch for each pulse}$$

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

Gun has been phased with DR RF so that the "first" gun pulse arrives at the DR in the #bkt=0

$$\Delta T_{DR} = (N_p - 1)T_1 \geq m\tau_{x/y} \qquad \text{Store time}$$

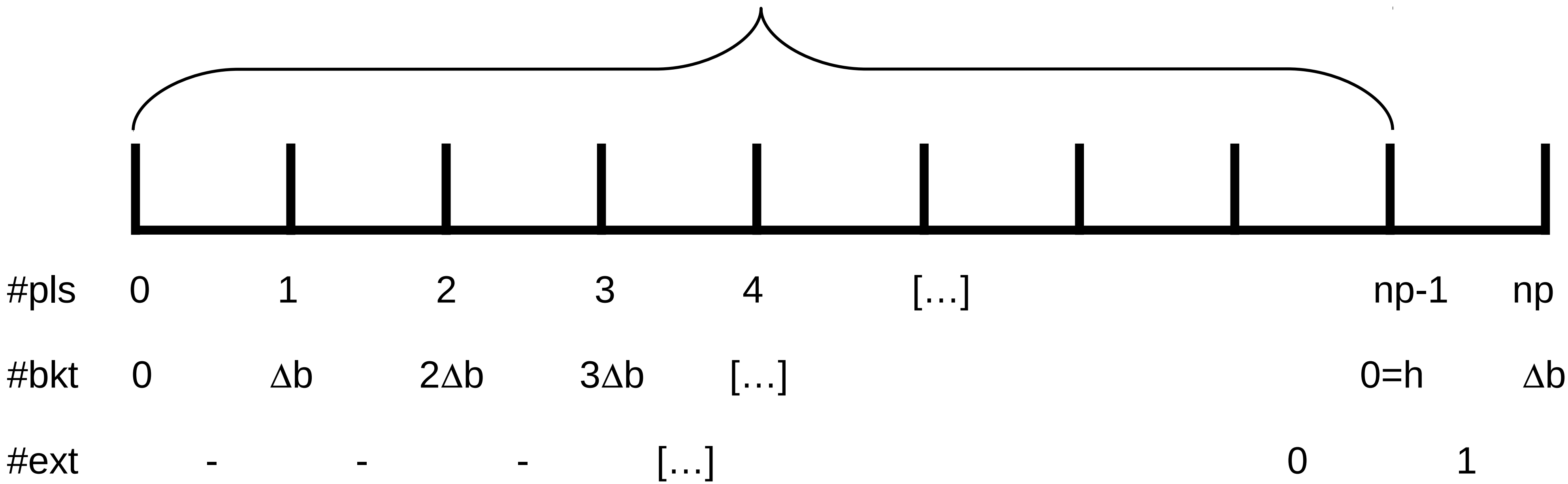
To store for at least 4 damping times

$$N_p \geq 9 \quad \Rightarrow \quad \Delta_b \leq 35$$

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

With Δ_b = 35 the last filled bucket is the 281st 38 bucket before the 319th

Timing: DR Extraction



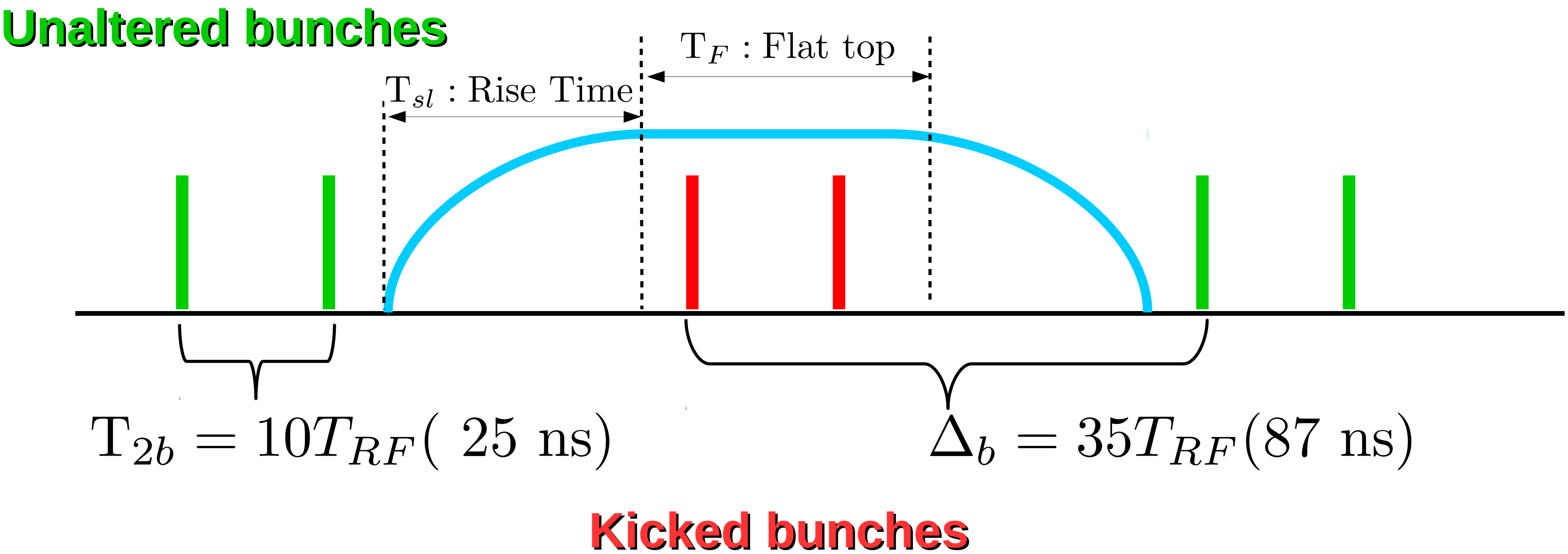
$$T_{EXT} = \boxed{T_{gun} + \Delta T_{DR}} + \boxed{T_S/2} + \boxed{T_2 - \Delta T_{12}}$$

Arrival + Storage time

Half turn to reach the extraction section

Phasing with “empty” L2 pulses.
Δ_{12} accounts for propagation time from DR to L2
Time is measured in T_S units

Timing: Extraction kickers details



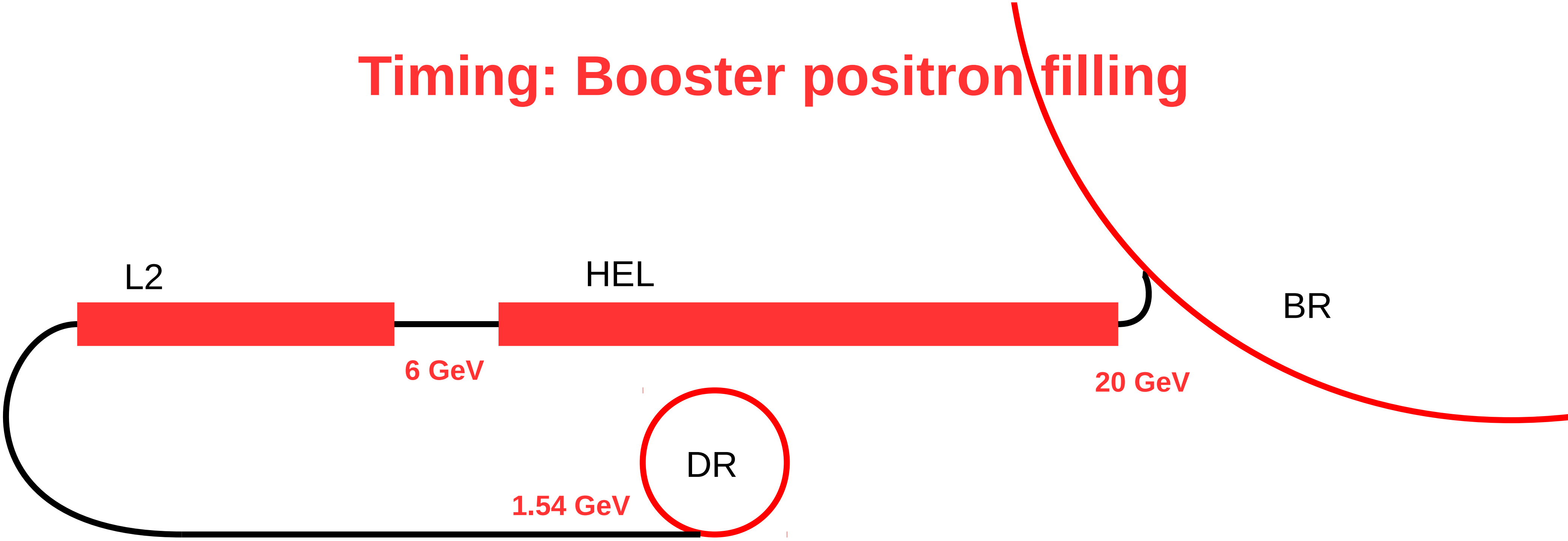
Time differences between the two bunches of the same pulse (25 ns) and betwen different pulses stored (87.5 ns) has the following implications on kickers pulses:

$$T_{sl} + T_F \leq 35T_{RF} \ \wedge \ T_F \geq T_{2b}$$

$$T_{sl} \leq 62\ \text{ns} \qquad T_F \geq T_{2b} = 25\ \text{ns}$$

Reasonable values could be: T_{sl} = 50 ns and T_F = 30 ns

Timing: Booster positron filling



$$\Delta T_{DB} : \text{ Time from DR to BR}$$

$$\mathrm{T}_S^D : \text{DR Revolution period: } \sim 1\ \mu\text{s}$$
$$\mathrm{T}_S^B : \text{BR Revolution period: } \sim 300\ \mu\text{s}$$

Extracting from the DR at the “nominal” delay time of 42.5 ms will fill, conventionally, the bunch “0” (actually the first pair of buckets).
Varying the turn of extraction allows to fill other buckets.
The homogeneous filling of the BR with all the 10k bunch at Z pole could require large time difference in extraction.

The impact on the common LINAC have to be considered.

Conclusions @ IJCLab Meeting

DR Longitudinal acceptance

- RF requirements to allow largest energy acceptance have been evaluated. Assuming SC RF cavity, two cells are needed.
- Large energy acceptance imply short bunch length. Potential issue

DR Dynamical aperture:

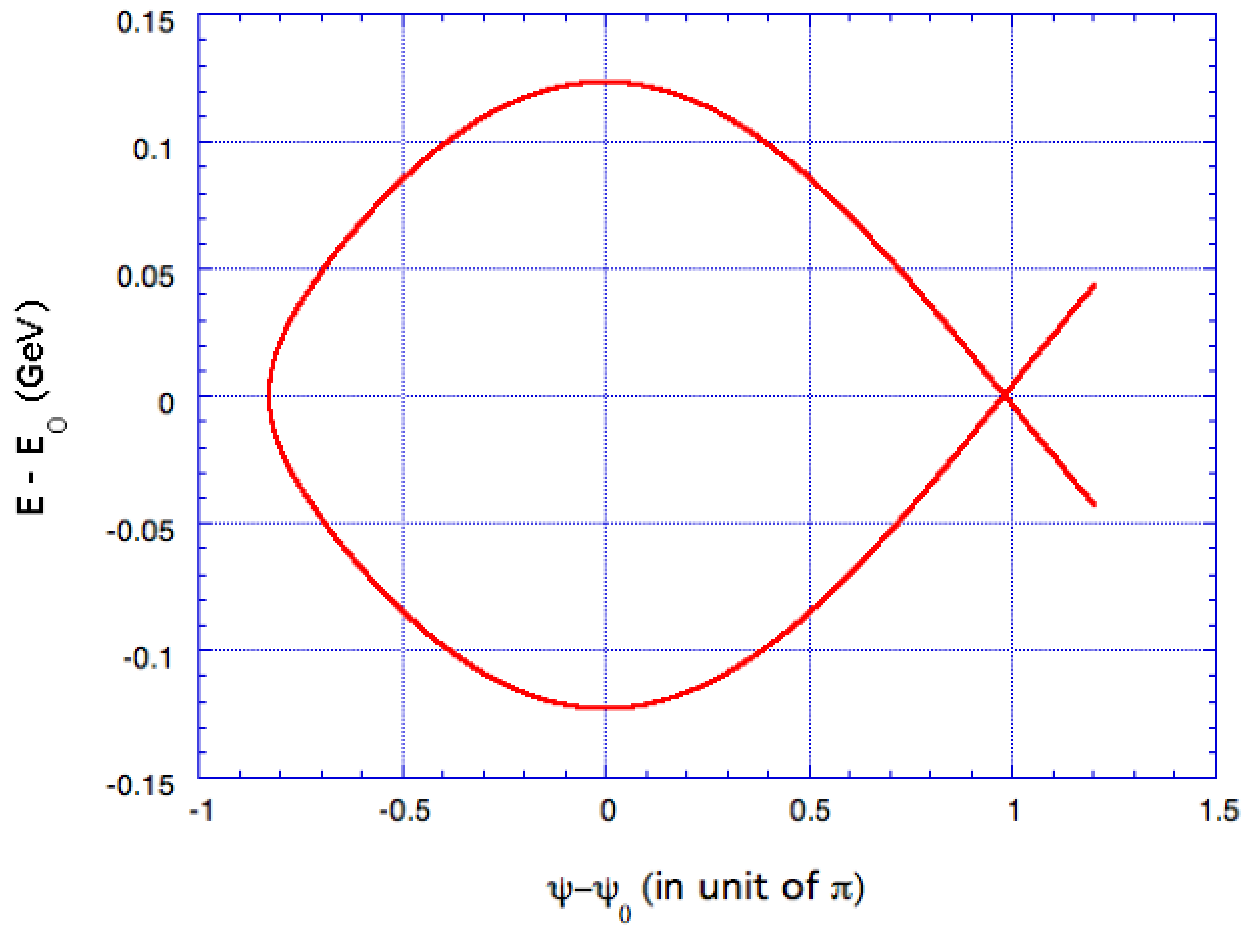
- Tracking has been performed with PTC
- **The maximal aperture is 3.5 sigma of the injected beam**
- **At the nominal injected beam emittance (CDR) a reduction of 50% is expected**

Timing:

- DR filling scheme allows to have extracted pulses after 42.5 ns.
- The scheme of L2 at 400 Hz Rep Rate is feasible
- Tunability of L1 effective repetition rate is requested to be within 0.8 μs O(10^{-4})
- Tunability of L2 effective repetition rate is requested to be at least 150 μs
- DR KCK’s time requirement have been defined and seems not prohibitive

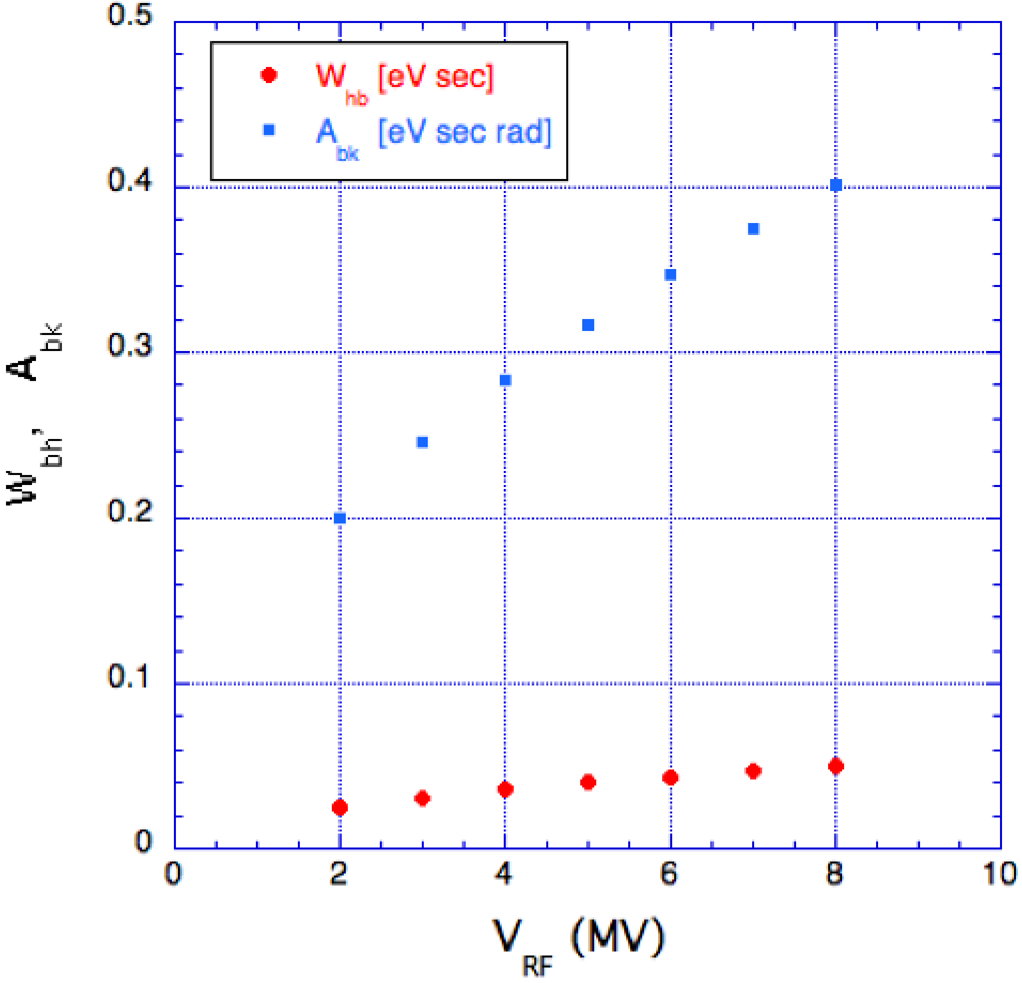
Separatrix

ΔE - ΔΨ representation



$\alpha_c = 0.001535$
$h = 319$
V = 8 MV
E_s = 1.54 GeV
φ_s = 0.028 rad

Separatrix vs. VRF



Timing: Some definitions

$\mathrm{R}_1(T_1)$: Repetition rate (Period) L1: 200 Hz

$\mathrm{R}_2(T_2)$: Repetition rate (Period) L2: 400 Hz

$\mathrm{RF}(\mathrm{T}_{RF})$: DR Radio Frequency (RF Period): 400 MHz

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)

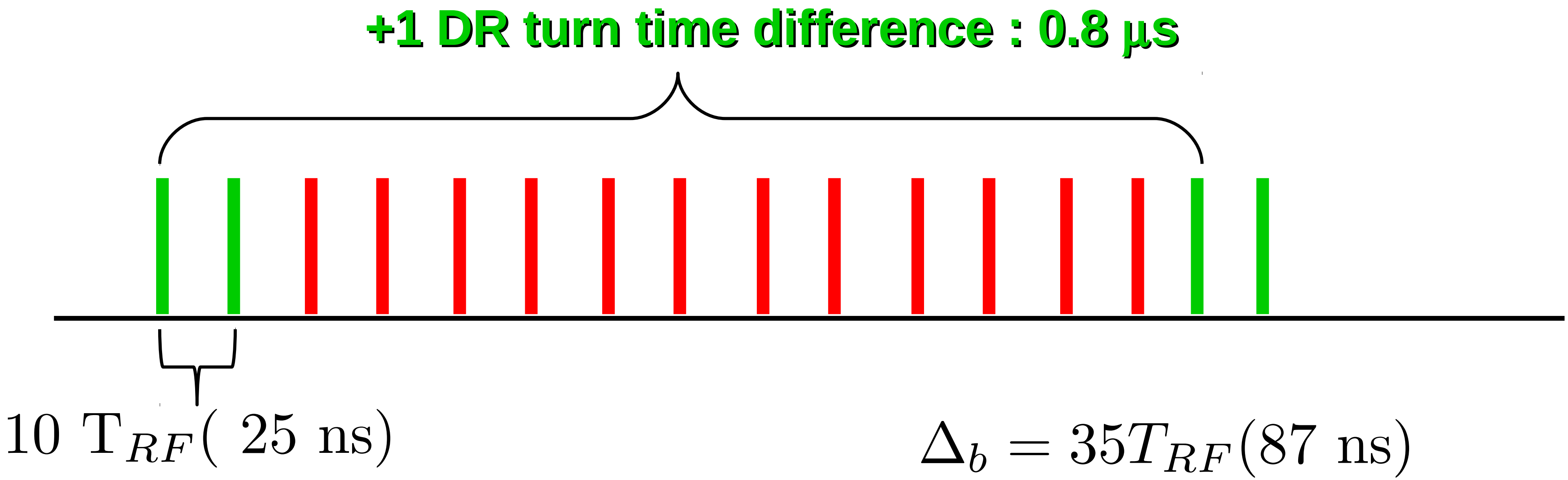
$\tau_{x/y}$: Damping time: $\sim$10.8 ms

Δ_b : Number of bucket delay between first bunch for each pulse

T_{2b} : Time differece between two bunch in the same pulse

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

Timing: Booster ring filling



Intermediate bunches

To fill the intermediate bunch more than 1 turn of BR (~300us) is needed
How many depends effectively in the ratios between DR and BR revolution period