FCC_ee Injector Complex

WP04: Transfer lines and Damping Ring

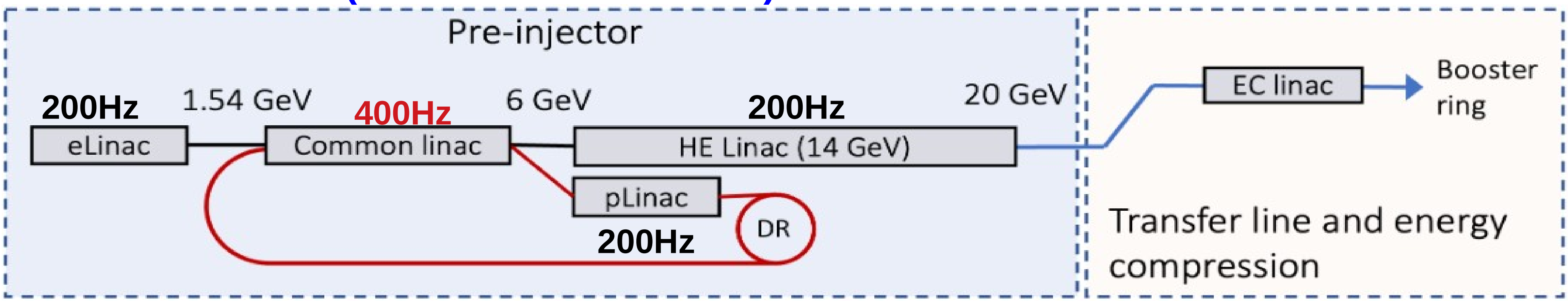
FCC_ee injector: Damping Ring status

A. De Santis [(a)], ***C. Milardi*** [(a)], ***S. Spampinati*** [(a)], ***O. Etisken*** [(a/b)], ***S. Ozdemir*** [(c)]

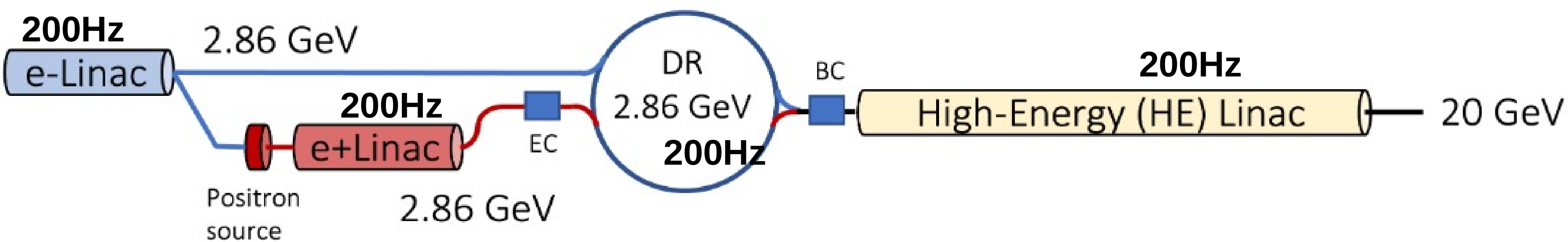
[(a)] **INFN – Laboratori Nazionali di Frascati**
[(b)] **Kirikalle University, Turkey**
[(c)] **Ege University, Izmir, Turkiye and Nisantasi University, Istanbul, Turkiye**

Outline

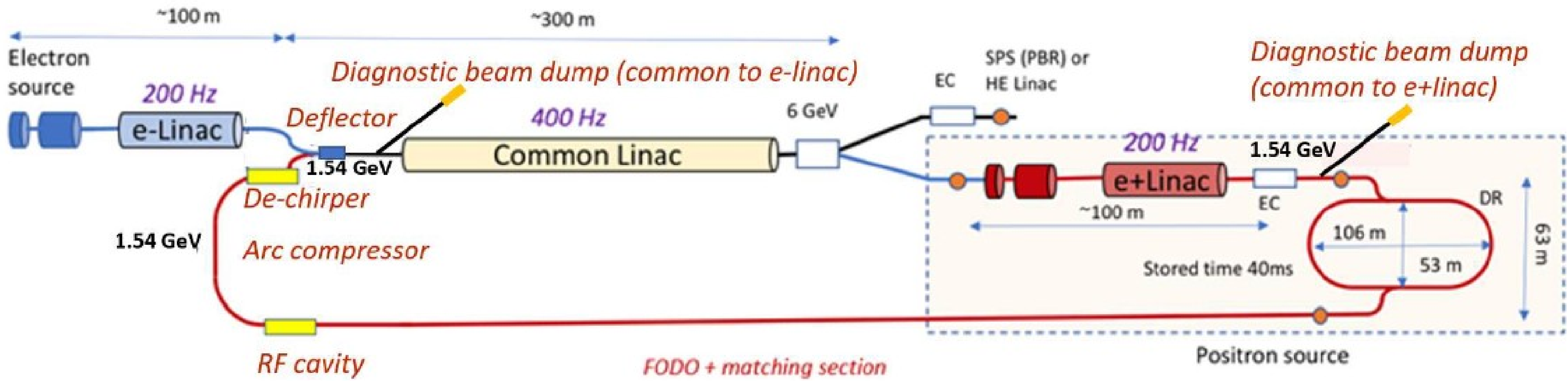
1) **Current Baseline (Mid-Term Cost Review)**



2) **High-Energy DR option**



FCC_ee Injector complex: general layout



Project structure:

- **WP1/2**: Electron Source, Electron and Positron Linacs
- **WP3:** Positron Source: Target and Capture System
- **WP4: Damping Ring and Transfer Lines**
- **WP6:** PSI Positron Production (P3) Project

FCC_ee Injector: WP4 task list

1) Damping Ring design (*coord. C. Milardi*)

- A. De Santis,
- O. Etisken,
- Y. Dutheil (Injection equipment: septa & kickers)
- CERN collaboration on RF systems.

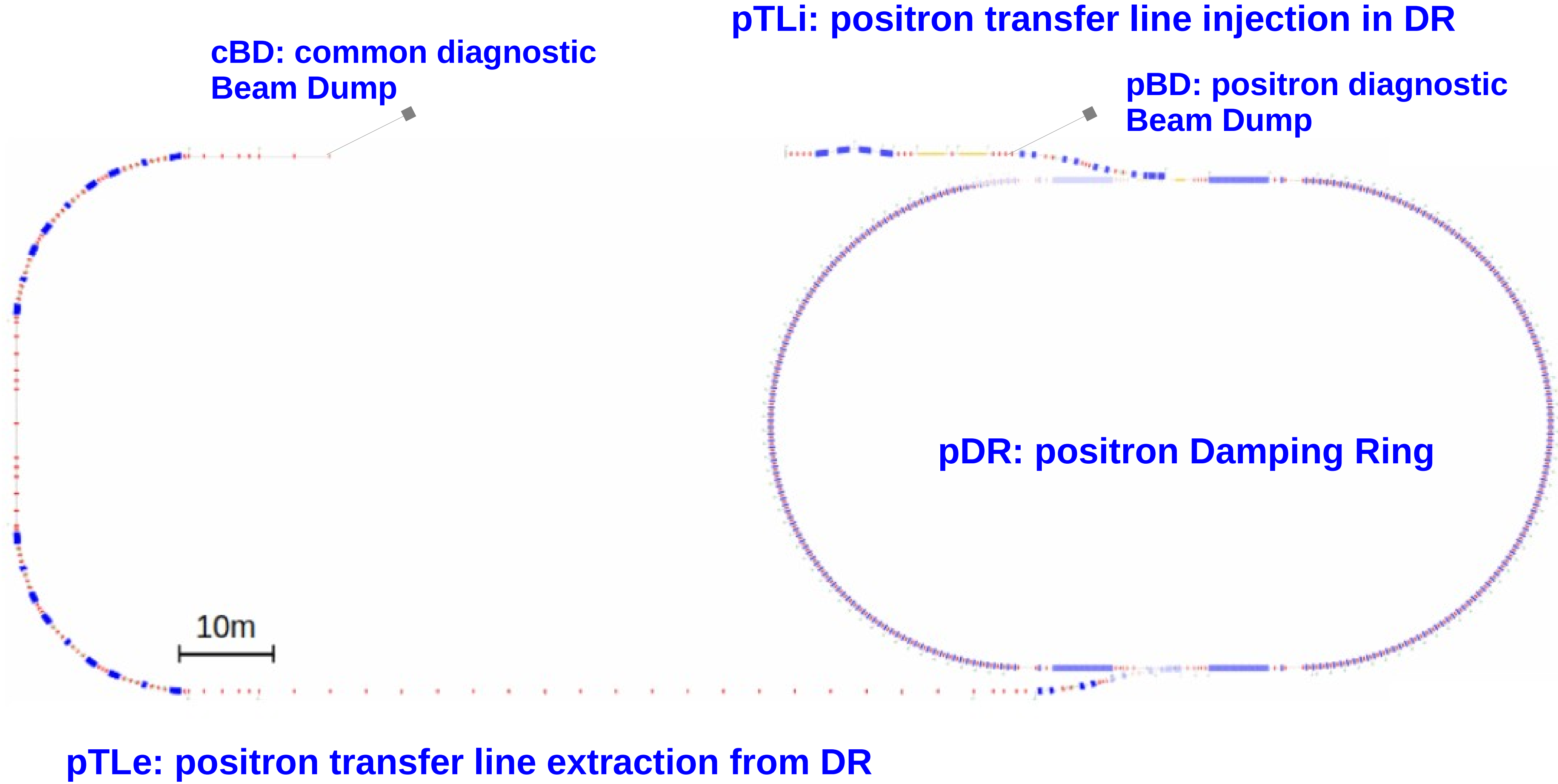
2) Transfer Lines design (*coord. A. De Santis*):

- C. Milardi,
- S. Spampinati.

3) Energy/Bunch Compression design (*coord. S. Spampinati*):

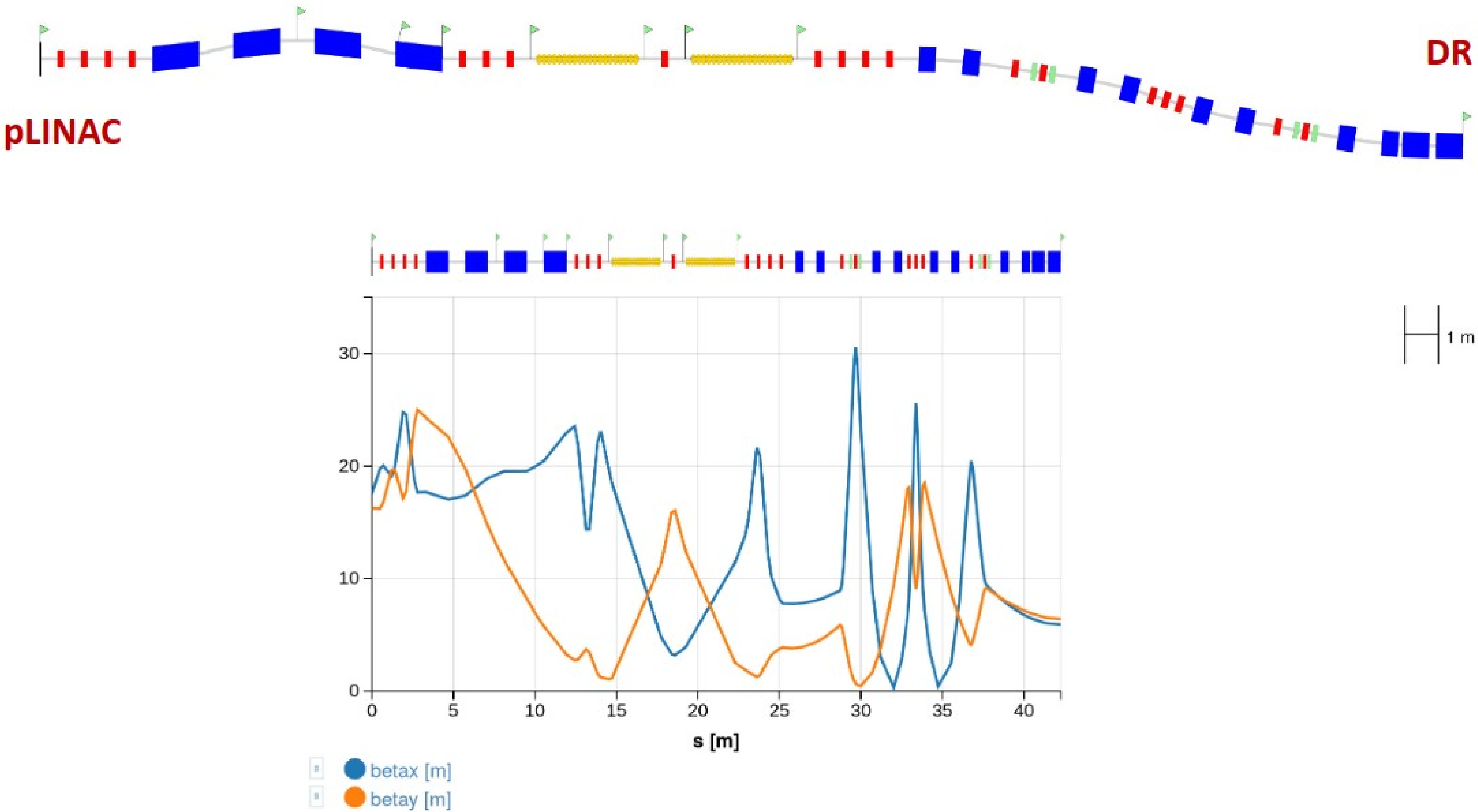
- C. Milardi,
- A. De Santis,
- CERN collaboration (e^+ LINAC group)

WP4: design status



pTLi/e will be covered by S. Spampinati

Transfer lines pLINAC - pDR



Topic covered in the S. Spampinati talk

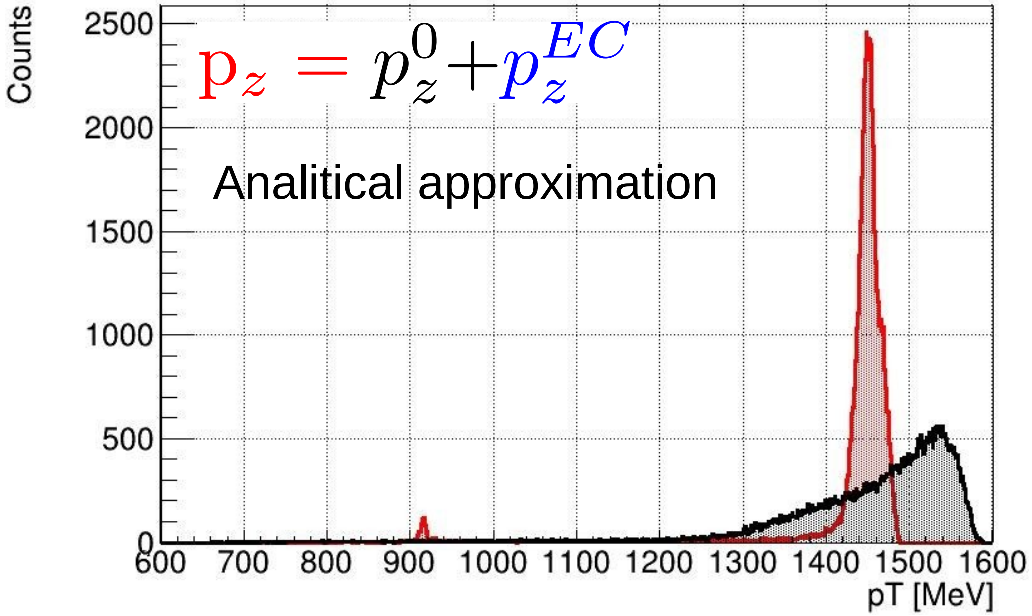
Energy Compressor optimization

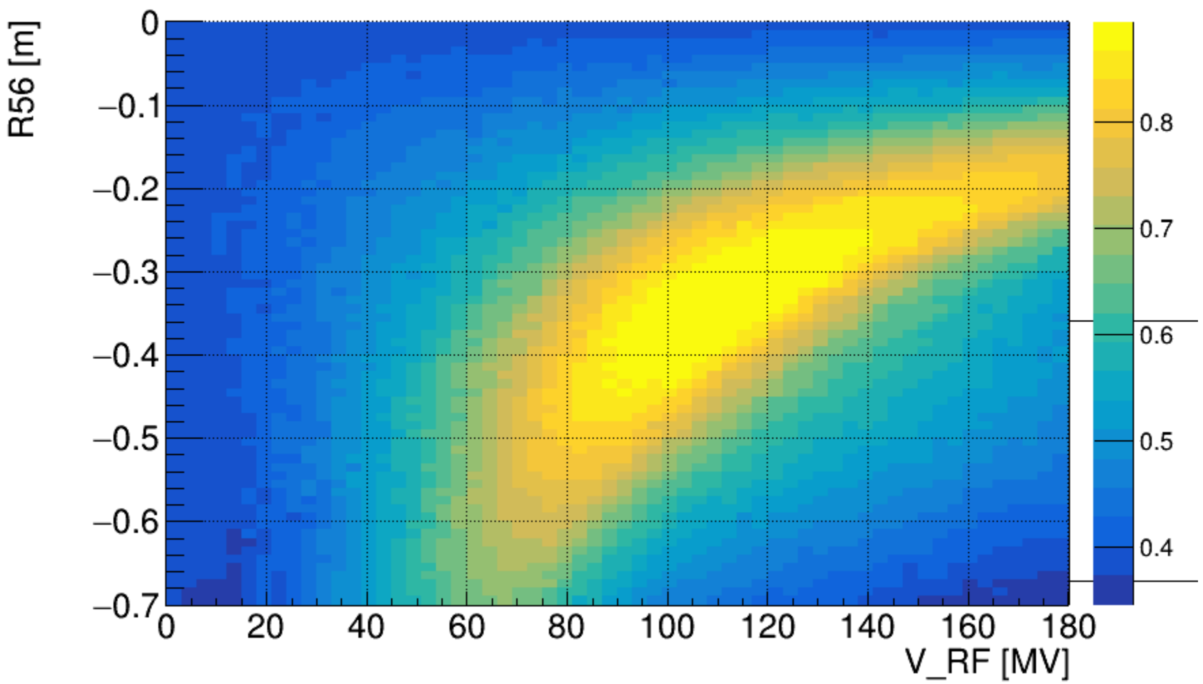
$$\delta t = t_0 - t_{ref}$$
$$\delta p_z = p_z^0 - p_z^{ref}$$

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):

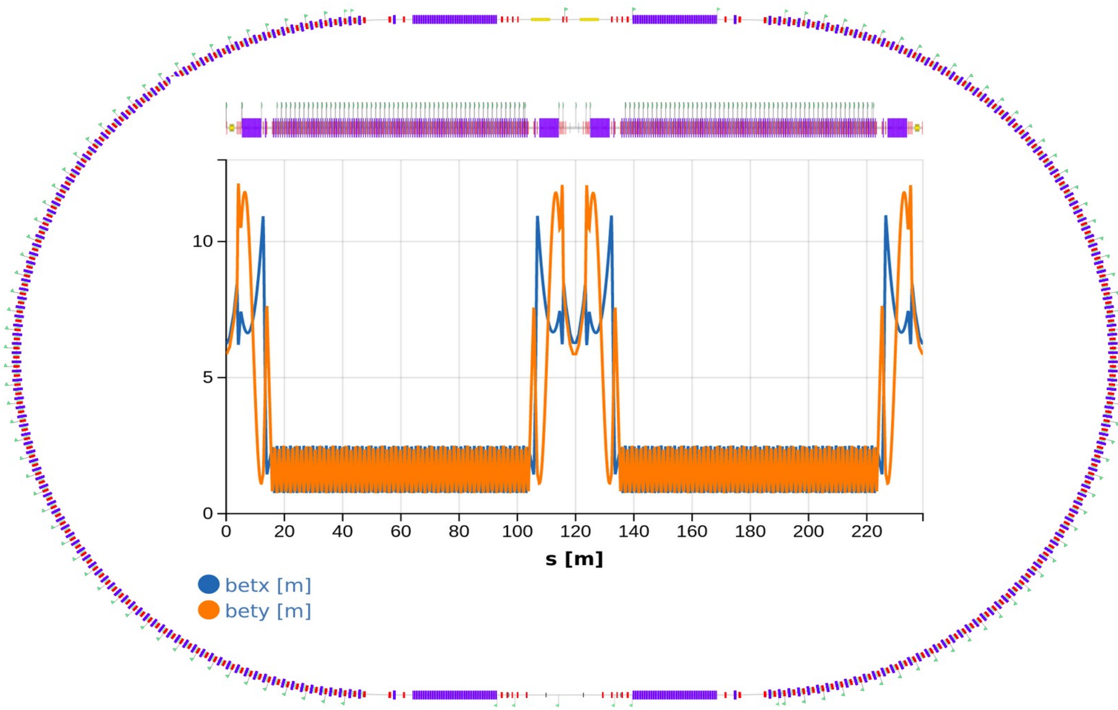
V_{RF} = 100 MV

R_{56} = -0.35 m

Results with Elegant simulation slightly different.

Positron Damping Ring Baseline @1.54 GeV

Damping ring layout

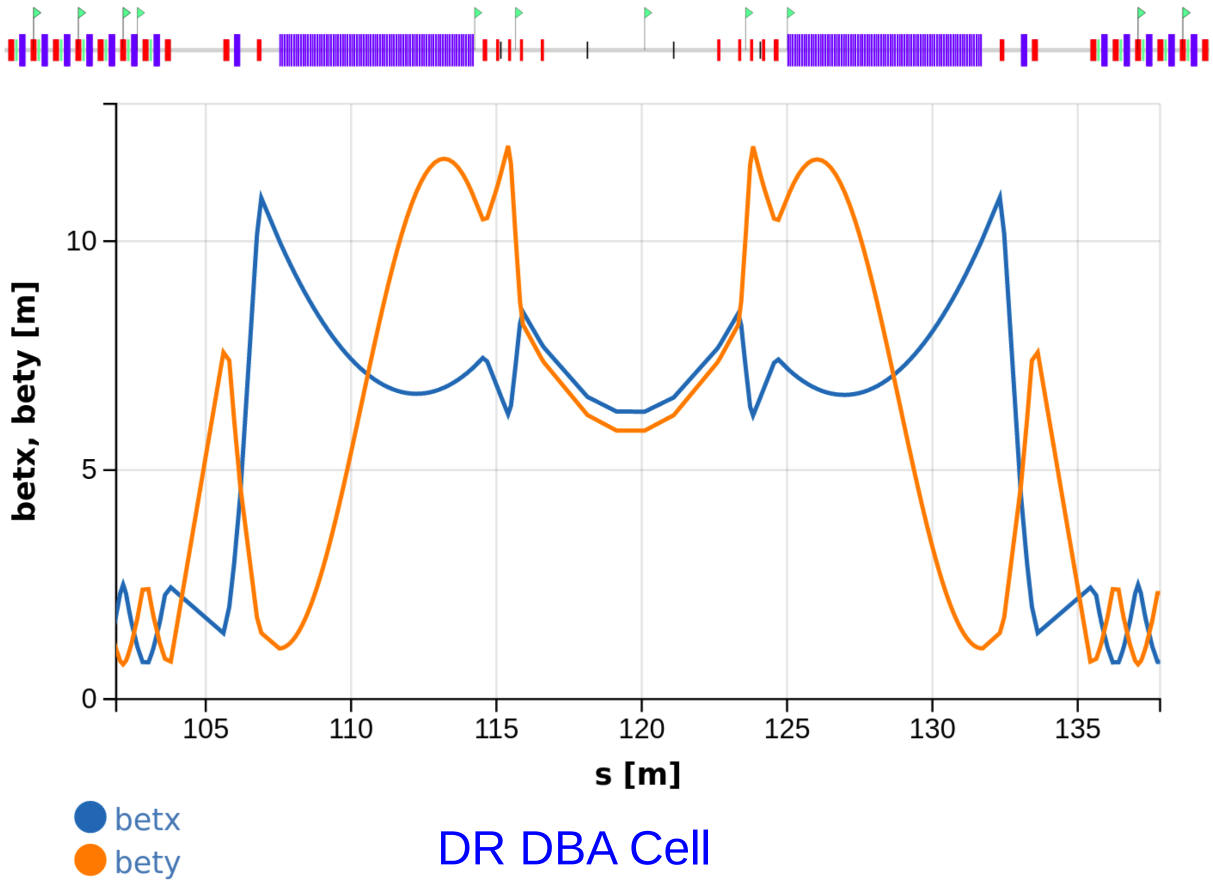


Parameter	FCC_ee DR
Circumference	239.2 m
Harmonic number	319
Eq. Emittance (x/y/z)	1.01 nm/ - / 1.46 mm
Dipole length, Field	0.21 m, 0.66 T
Wiggler #,Lenght, Field	4, 6.64 m, 1.8 T
Cavity #, Lenght, Voltage	2, 1.5 m, 4 MV
Bunch stored #, charge	18 , 4.0 nC
Damping Time (x/y/z)	10.8 / 10.8 / 5.4 ms
Store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

Current DR shopping list:

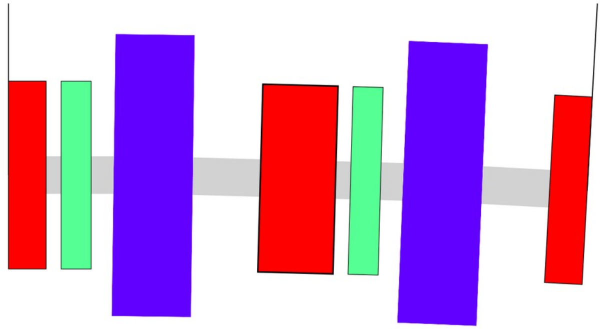
- 232 BEND (21 cm each) in the arcs
- 258 QUADRUPOLE (20 cm each mostly in the arcs)
- 232 SEXTUPOLE (8 cm each mostly in the arcs)
- 4 WIGGLER (6.7 m each: 44 poles of 5 cm each)
- 2 Straight section hosting RF Cavity and Injection/Extraction equipments

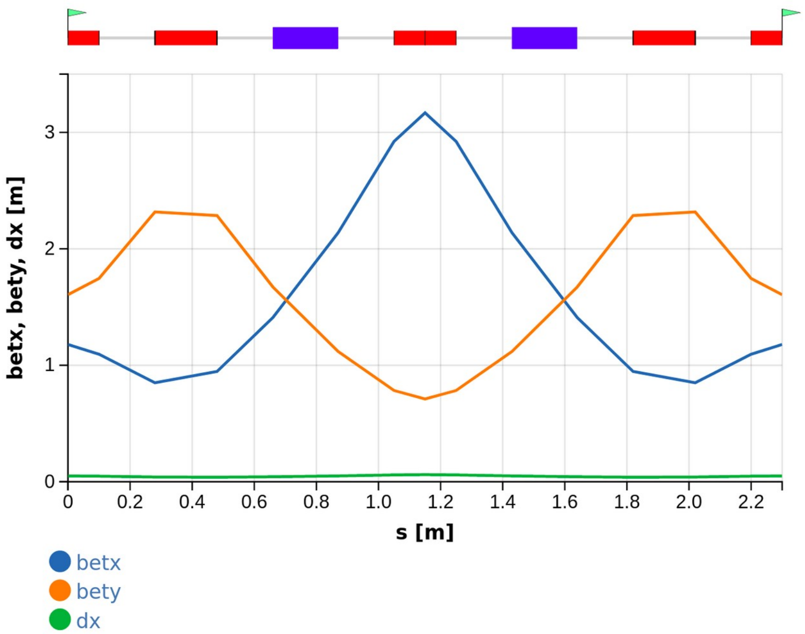
DR optics details



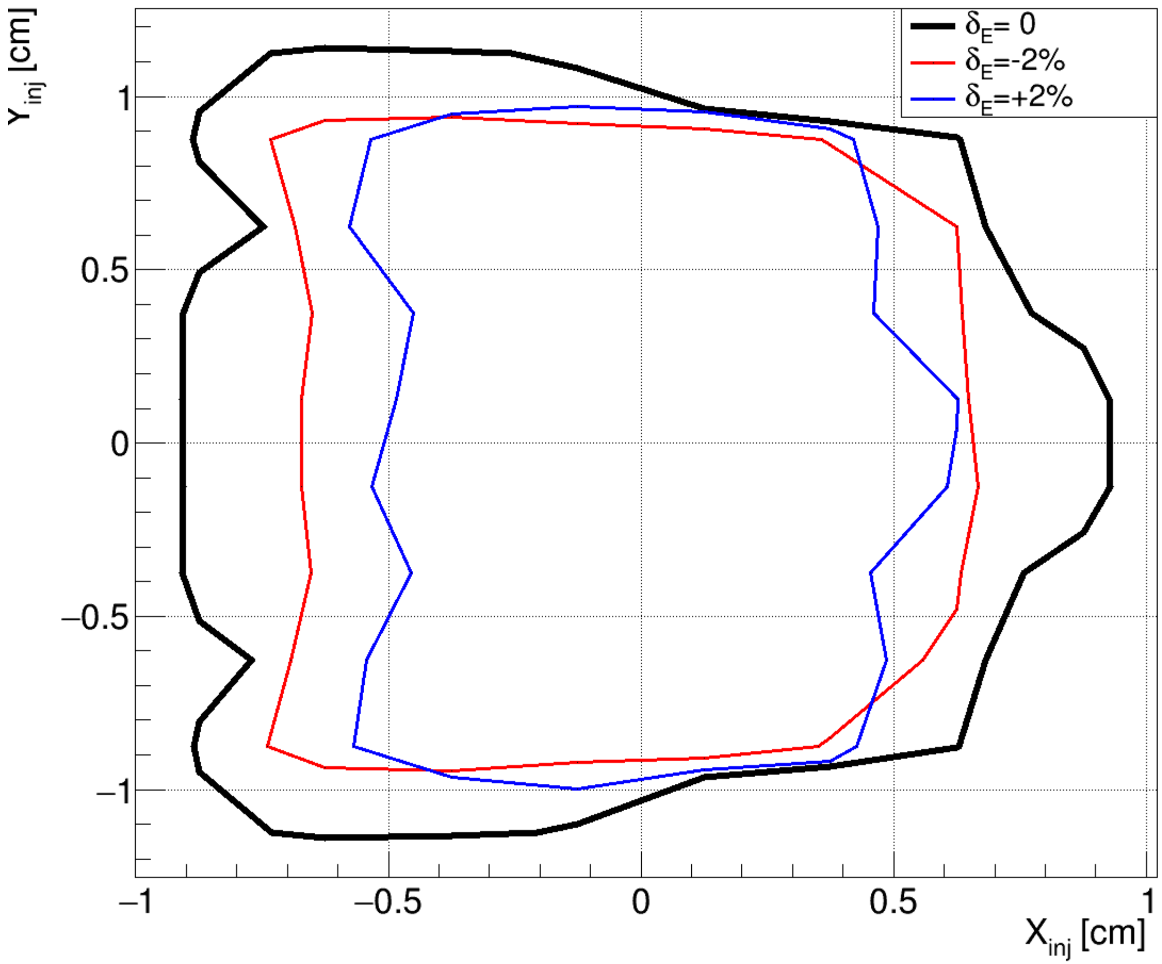
Straight section details.
Two of the four wigglers are shown.
Straight sections are designed to host RF cavities and Injection/Extraction equipments.

DR DBA Cell





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.

Radiation damping not enabled

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 Beam Dynamics Parameters

Relying on DR parameters:

E_s = 1.54 GeV

L = 239.2628817 m

α_c = 0.001535

$h = 319$

	V= 8MV	V= 6MV	V= 4MV	V= 2MV
U_0 [KeV]	227.1			
DE/E_s	$0.71 \cdot 10^{-3}$			
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

DR collective effects estimate

Parametric estimate of DR collective effects has been done using the current ring optics.

Theese studies almost confirm the results achieved for the old configuration:

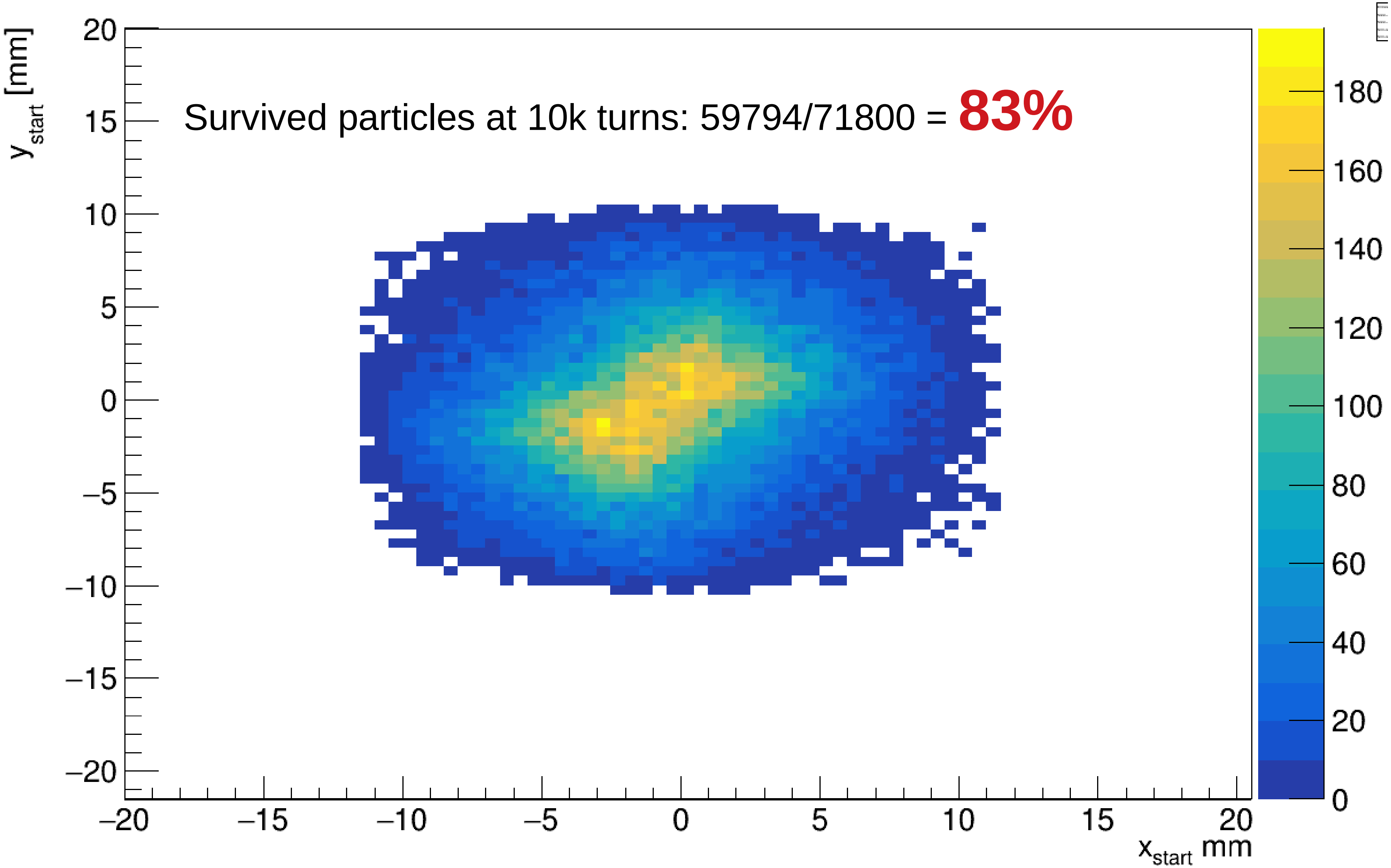
- SC induced tune shift might be an issue;
- no major limitations are expected from longitudinal micro-wave inst. (LMI), transverse mode coupling instability (TMCI), and coherent synchrotron radiation (CSR);
- e-cloud build-up, and instability requires extensive simulations;
- FII must be further investigated.

Preliminary e-cloud build-up simulations.

Analytical estimate of the power emitted by SR in the DR.

A special effort is on the go aimed at increasing our skills in the field of e-cloud simulations, exploiting also the DAFNE accelerator complex, which presently is the only facility in Europe to provide a stored positron beam.

pDR: Acceptance of the pLINAC particles



Start2End simulation: from positron source to Damping Ring stored beam

Further developments for Damping Ring

Motivations to review the DR design:

- Minimize cell number in the arcs,
- Reduce or even eliminate the use of wigglers magnets to achieve the required parameters (ε and τ_d),
- Improve Dynamic Aperture and ring acceptance,
- Optimize injection extraction sections.

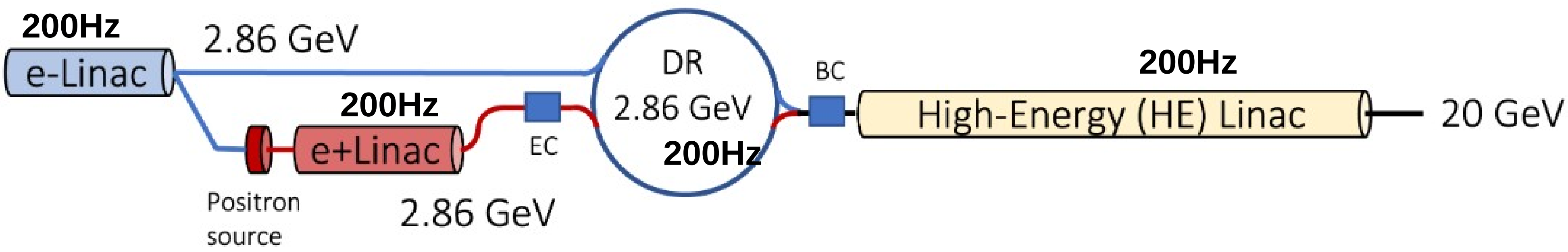
Parameters	CDR	Option - 1	Option - 2	Option-3
Energy [GeV]	1.54	1.54	1.54	**2.86**
Lattice type	FQDO	FODO	FODO with DQ	FODO
Layout	Racetrack	3 arcs and 3 SS	Racetrack	3 arcs and 3 SS
Bending magnet quantity	232	78	30 DQ / 12 D	144
Dipole magnet length [m]	0.21	0.4	0.55 / 0.4	0.65
Bending angle [degree]	1.55	4.61	10 / 5	2.5
Dipole magnetic field [T]	0.66	1.03	1.62 / 0.81	0.94
Filling factor	0.2	0.15	0.11	0.24
Damping wiggler magnet	26.5 m / 1.8 T	36.45 m / 2 T	- / -	36.45 m / 2 T
Robinson wiggler magnet	- / -	- / -	- / -	- / -
Circumference	242 m	248.19 m	181.74 m	384.87 m
Emittance	2 nm.rad	**2.1 nm.rad**	**2.25 nm.rad**	**1.20 nm.rad**
Damping time	10.5 ms	**8.1 s**	**9.1**	**6.4 ms**
Energy loss per turn	0.255 MeV	0.31 MeV	0.14 MeV	1.13 MeV

Abandoned for High Energy option

Positron Damping Ring
2.86 GeV

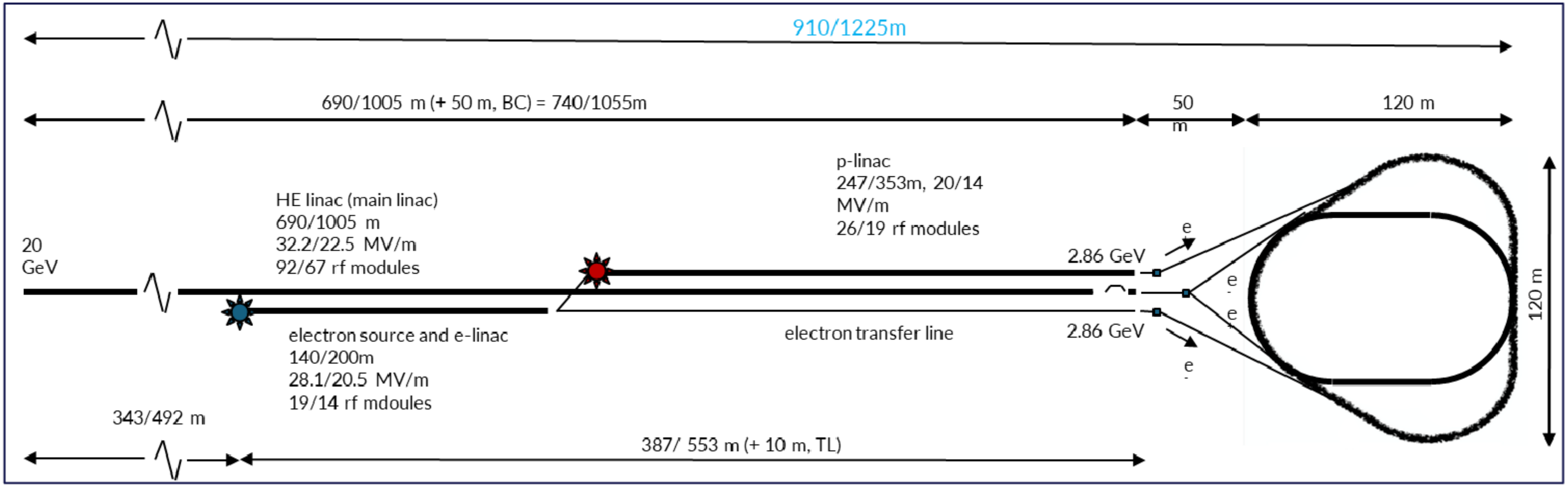
High-Energy DR option

High-Energy DR option



Sketched layout
becomes

P. Craievich / M. Benedikt



CLICK PDR

CLIC PDR

Table 3.6: Design parameters for the PDRs

Parameter, Symbol [Unit]	2 GHz	1 GHz	FCCee specs
			400 MHz
Energy, E [GeV]	2.86		
Circumference, C [m]	389.15		DR at 1.54 GeV: 242 m
Bunch population, N [10^9]	4.3		~0.7 nC, FCCee 5 nC
Basic cell type in the arc/LSS	TME/FODO		
Number of dipoles, N_d	38		
Dipole Field, B_0 [T]	1.2		
Horizontal and vertical tune, (Q_x,Q_y)	(16.39,12.26)		
Horizontal and vertical chromaticity, (ξ_x,ξ_y)	(-19.0,-22.9)		
Number of wigglers, N_w	36		
Wiggler peak field, B_w [T]	1.9		
Wiggler length, L_w [m]	3		
Wiggler period, λ_w [cm]	30		
Norm. equil. horizontal emittance, $\gamma\varepsilon_{x0}[\mu m]$	54		**FCCee < 10 mm mrad**
Hor., vert. and long. damping time, (τ_x, τ_y, τ_l) [ms]	(2.7,2.7,1.35)		
Momentum compaction factor, α_c [10^{-3}]	3.7		
Energy loss/turn, U [MeV]	2.8		
Equil. energy spread (r.m.s.), σ_δ [%]	0.1		
RF Voltage, V_{RF} [MV]	10		4 MV
Synchrotron tune, Q_s	0.071	0.051	
Bunches per train, n_b	312	156	
Bunch spacing, τ_b [ns]	0.5	1	
RF acceptance, ε_{RF} [%]	1.2	1.7	
Harmonic number, h	2596	1298	
Equil. bunch length (r.m.s.), σ_s [mm]	3.2	4.6	

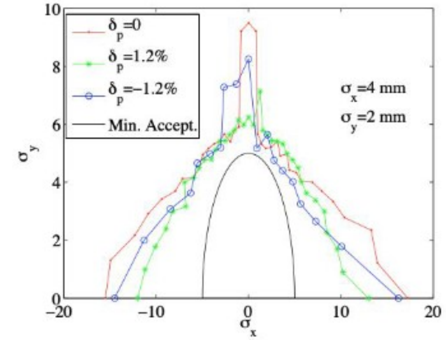


Fig. 3.13: The 5D, 1000-turns, Dynamic Aperture of the PDR, for particles with momentum deviations of zero (red), +1.2% (green) and −1.2% (blue), as compared to the physical ring acceptance (black)

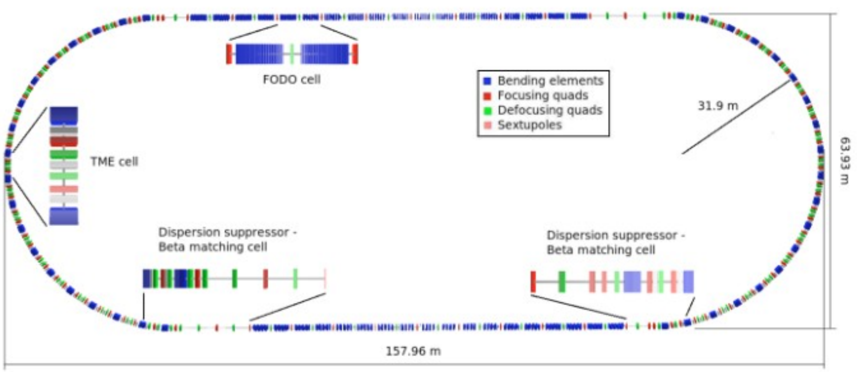
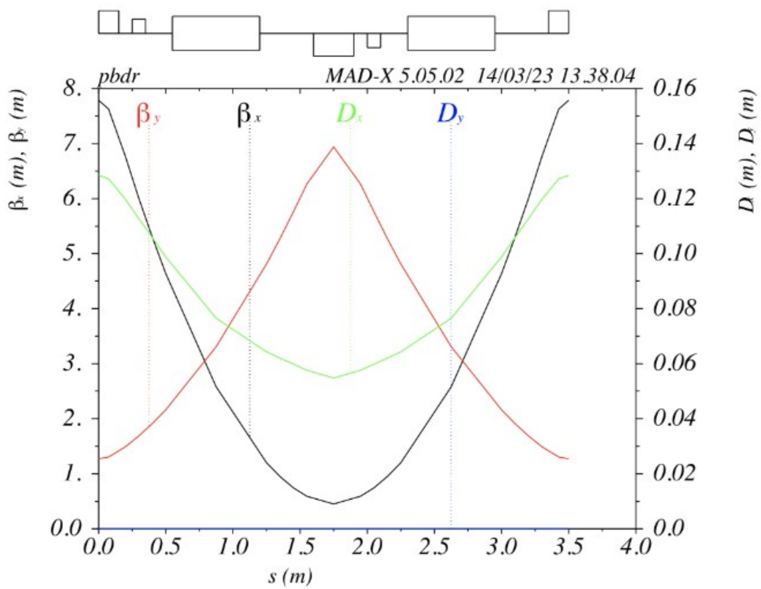


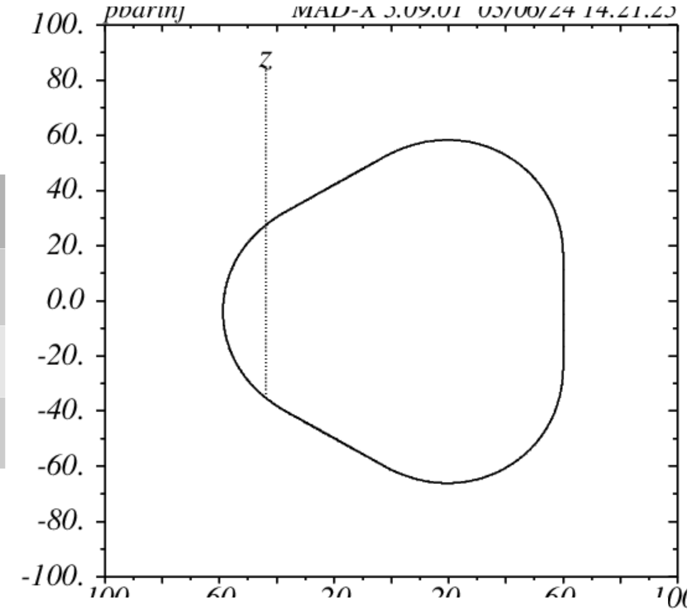
Fig. 3.7: Schematic layout of the CLIC Pre-damping rings.

Y. Papaphilippou:
"Shortened with SC WGL. Proper emitance with retuning TME. Impact on DA"

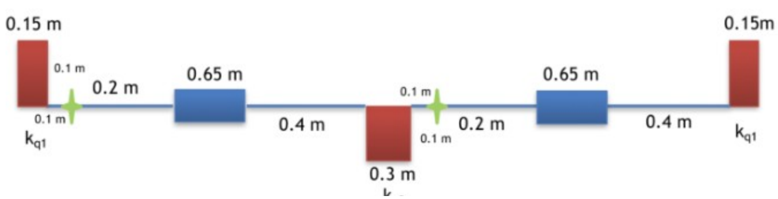
pDR(@2.86 GeV): alternative design



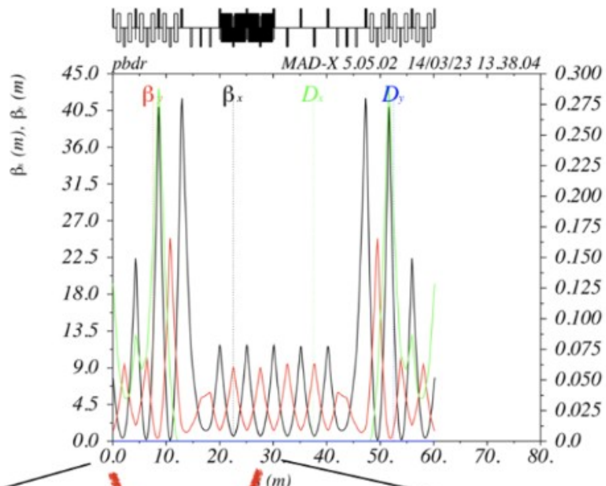
Length [m]	385
Emittance [nm rad]	1.20
Damping time [ms]	6.4
Energy loss [MeV]	1.13

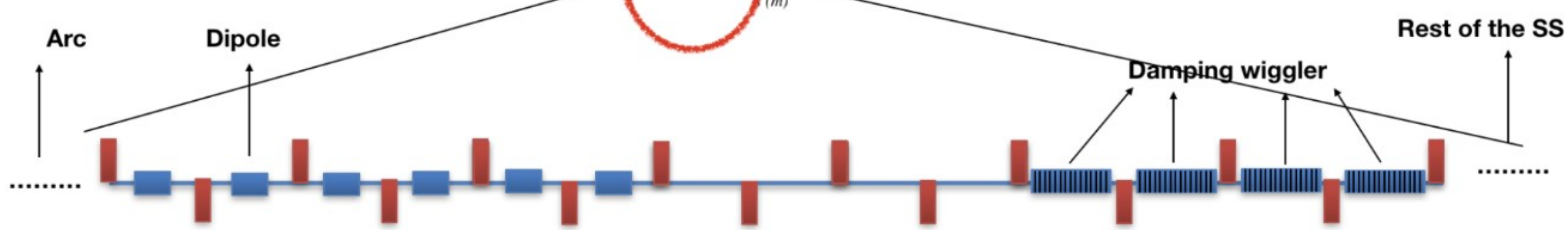


Arc: 18 FODO Cell



Here FODO optimized for the Minimum emittance



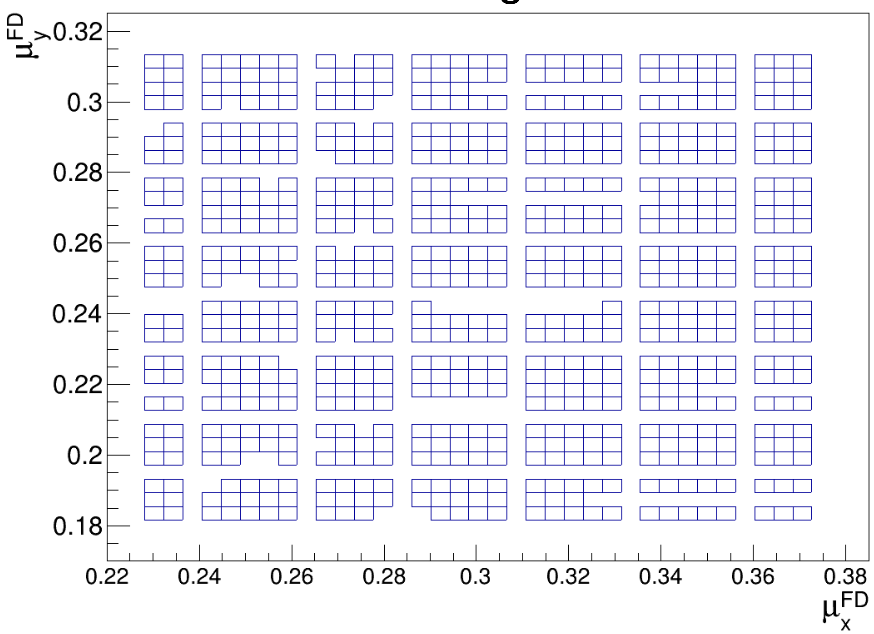


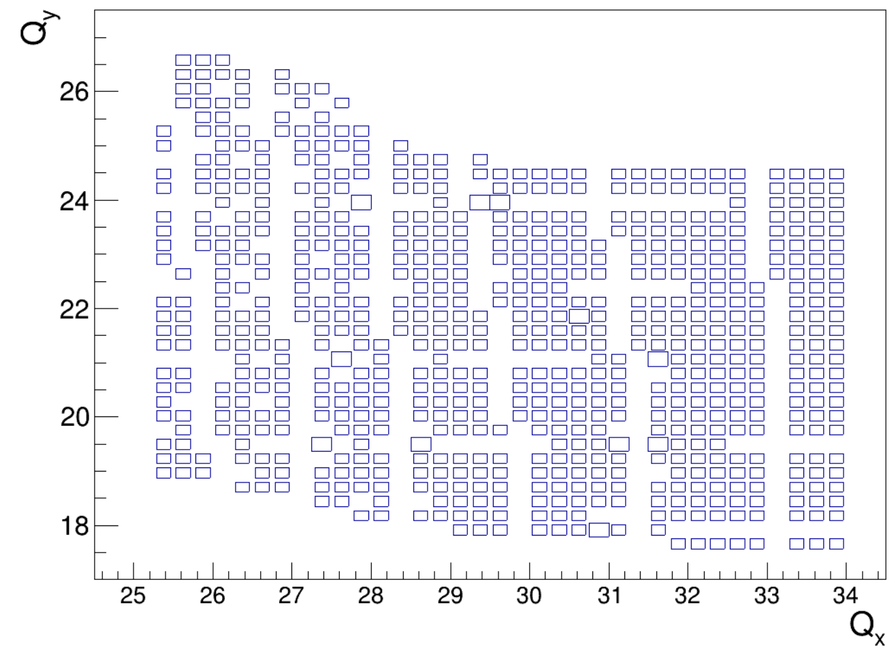
Some preliminary comparison

Parameters	CLICK PDR	TPDR (v3)
Energy [GeV]	2.86	2.86
Shape	Racetrack	Triangle
Lattice	TME	FODO
# Bending	38	144
Dipole length [m]	1.31	0.65
Dipole field [T]	1.2	0.94
Bending angle	9.47	2.5
# Quadrupole	196	186
# Sextupole	110	96
Filling factor	0.4 (inc. WGL)	0.24
Damping WGL	108 m/ 1.9 T	36.5 m / 2 T
Length [m]	**389.15**	**384.87**
Emittance [nm rad]	**9.6**	**1.2**
Damping time [ms]	**2.68**	**6.4**
Energy loss (SR) [MeV]	2.75	1.13

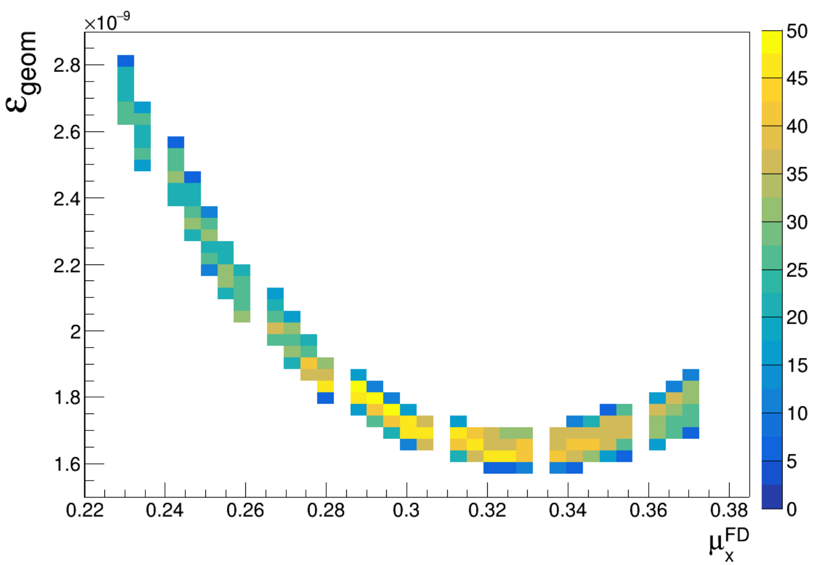
FODO scan

26x27 = 702 configuration





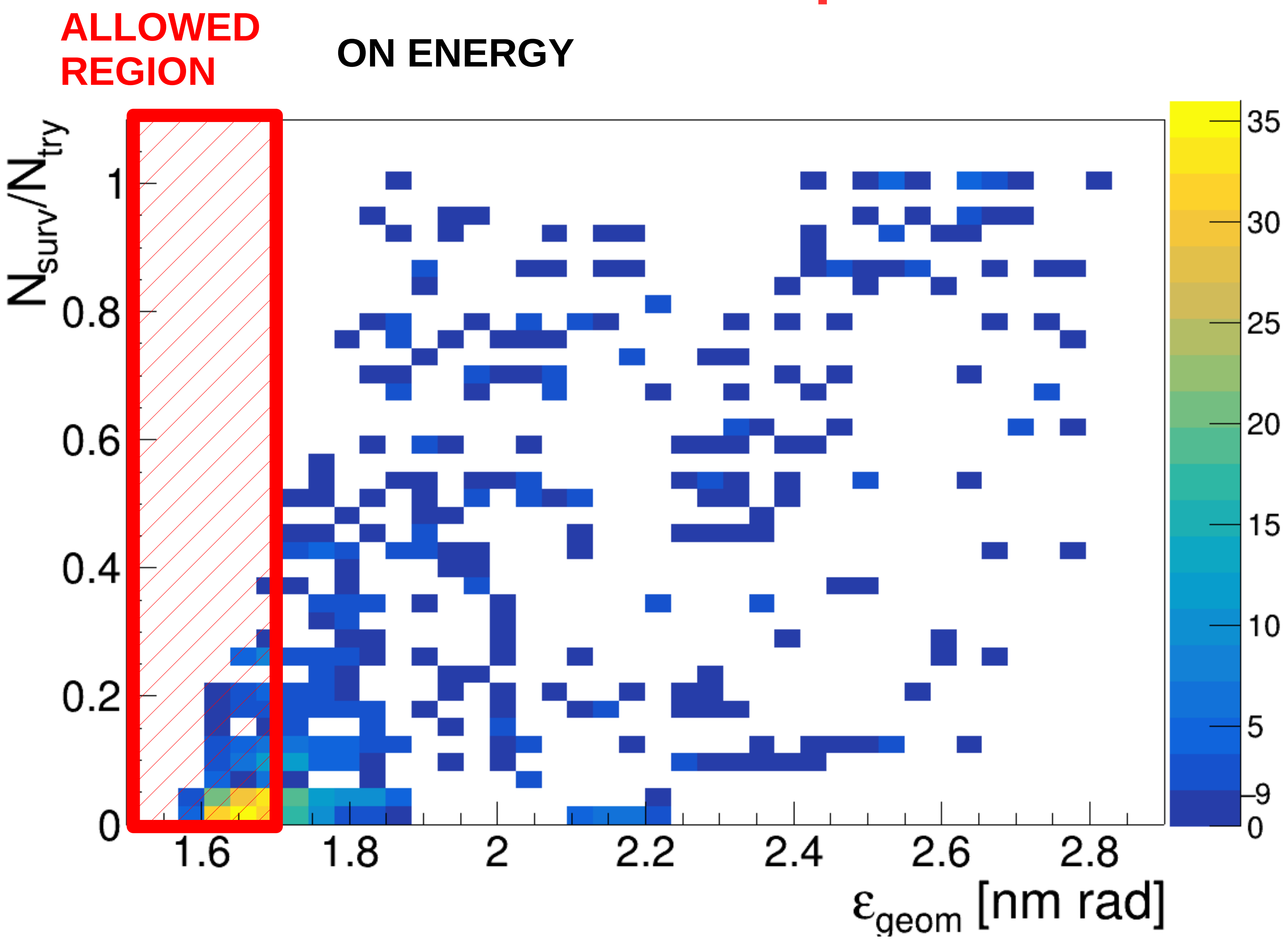
Tunes of the ring have been varied to find the best solution for resonances and aperture.
The scan has been performed by varying the FODO phase advance.



Equilibrium emittance varies as expected as a function of the FODO phase advance (round beam)

The requirement of 10 μm normalized emittance imply **$\varepsilon_{geom} \leq 1.7$ nm rad**

Acceptance

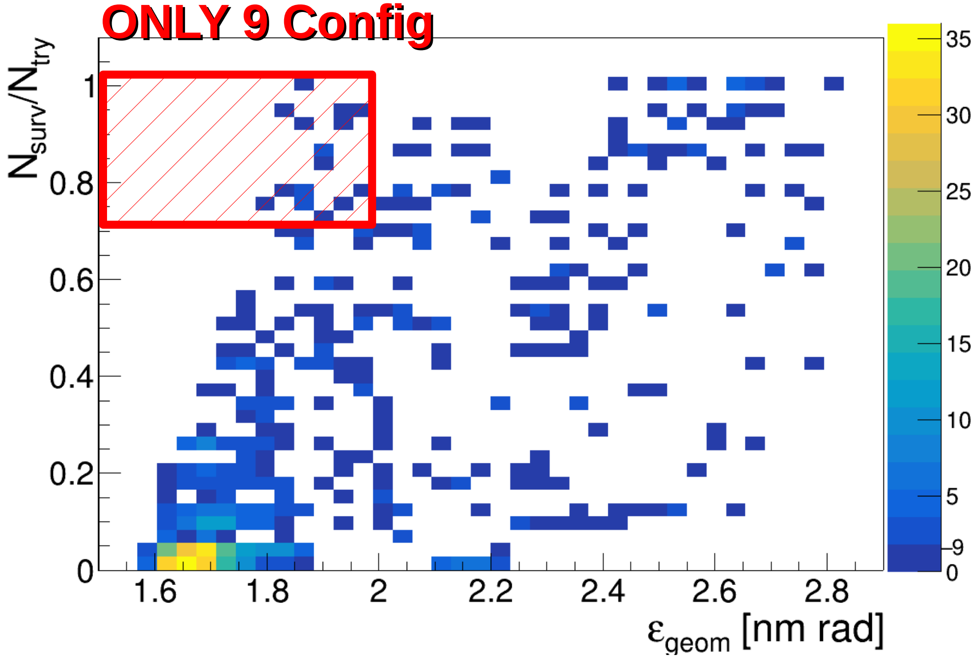


Color Map Represent the number of config in the bin

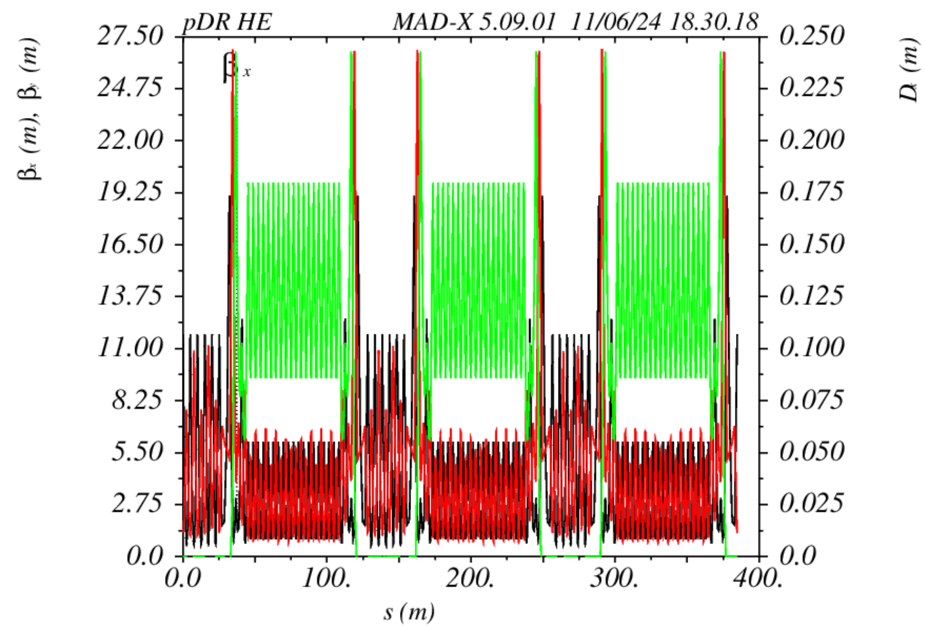
For each configuration tracking has been performed using a matrix of ~50 point in the Transverse plane (7x7 point spanning between +/- 3σ in the transverse plane)
Raw definition of acceptance: N_{surv}/N_{try}

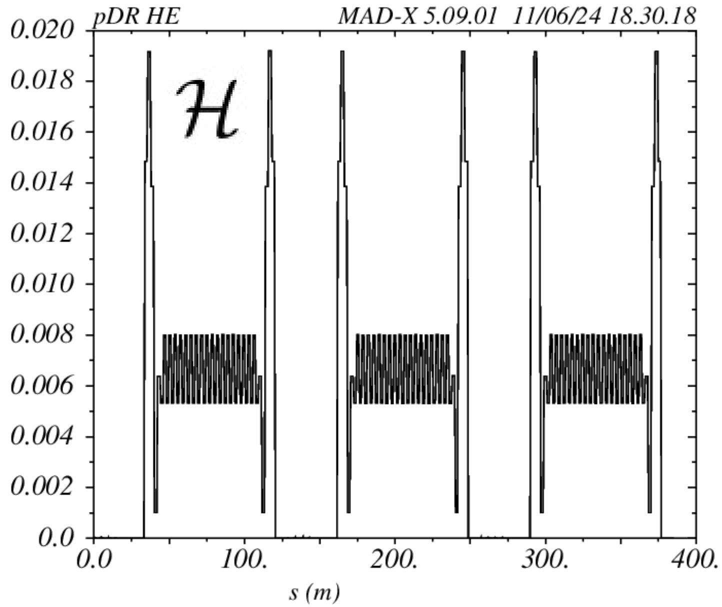
Best configuration

ONLY 9 Config

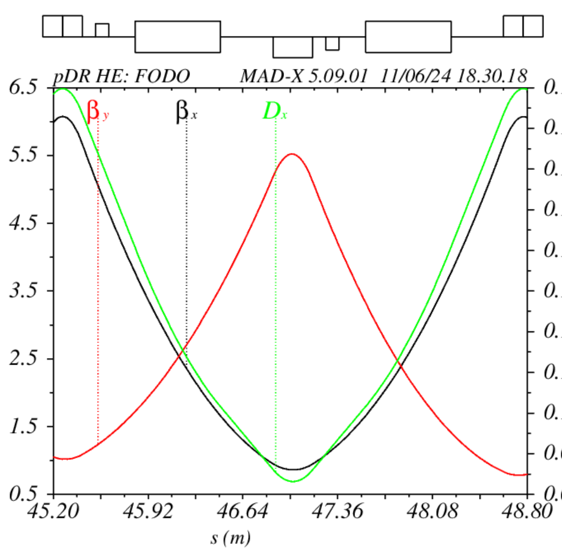


ε_{geom} = 1.9 nm rad

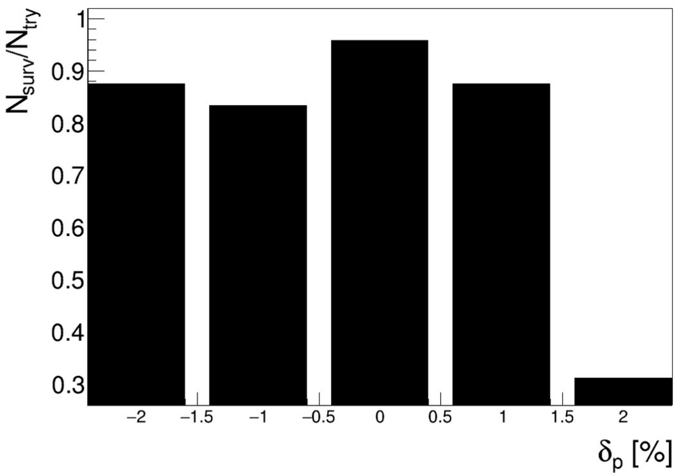




ARC FODO CELL



Energy acceptance: 185/240 total



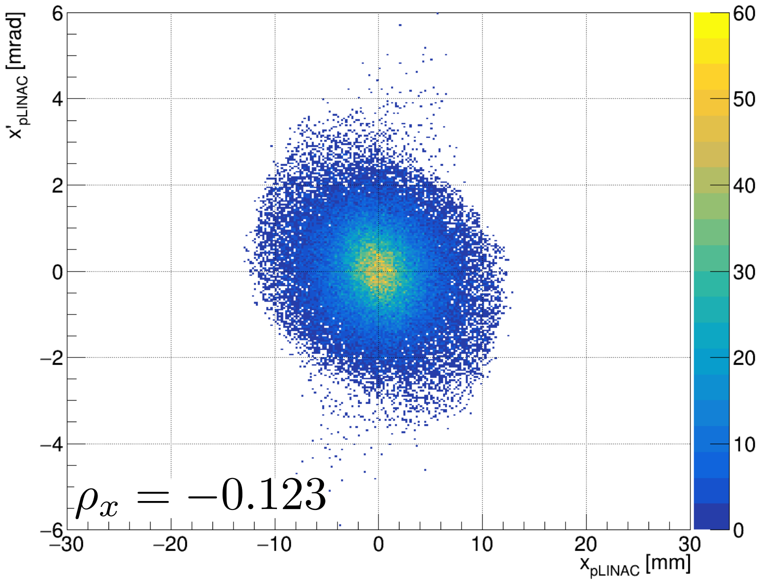
Conclusions

- **Damping Ring and Transfer Lines design has been completed (Baseline@1.54).**
- DR acceptance of the order of 83% including **Energy Compressor** before the pDR injection.
- A **Bunch Compressor has been included** between the pDR and the Common LINAC.
- **A preliminary costs estimate has been delivered**.
- Higher Energy pDR design work just started.

Spare slides

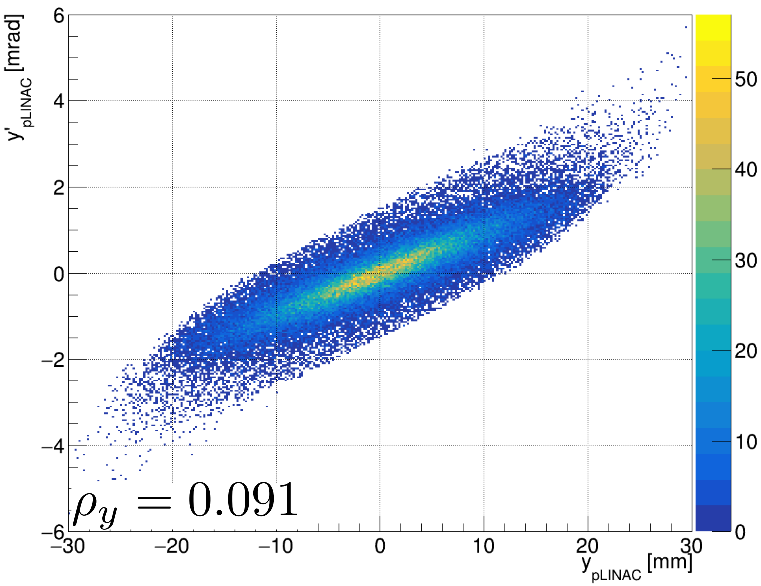
pTLi: Injection Transfer Line from pLINAC to DR

Transverse emittance @ pLINAC



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

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

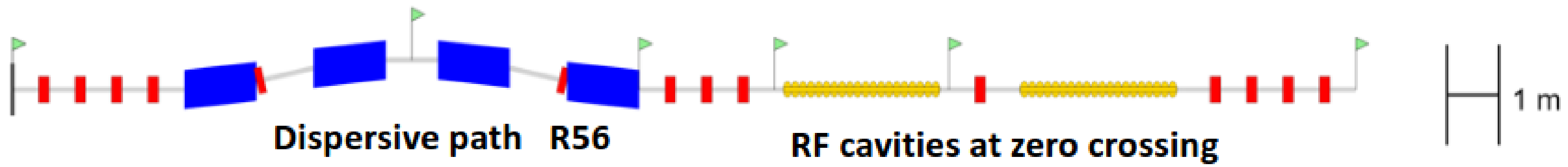


$$\Sigma_y = \begin{pmatrix} 8.06^2 & 0.60 \\ 0.60 & 0.82^2 \end{pmatrix}$$

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

Data from M. Schaer @ Jan23

Energy compressor layout

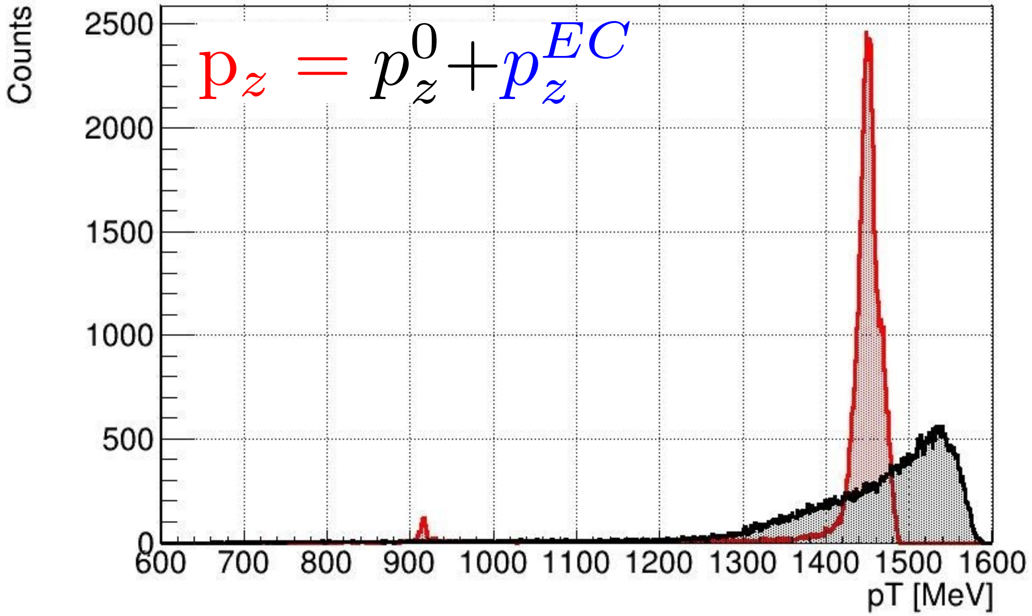


- In a four bending C-shape chicane dispersion and second order dispersion are intrinsically closed.
- Two cavities of the type used for the positron LINAC **(PSI design. LINAC THPOJO08 LINAC 2022)**
- The beam exit ECS on the same LINAC axis, thus same diagnostics can be used for LINAC and ECS tuning.

Parameters	Value	Unit
Dipole Bending angle	0.2256 (12.9)	rad (deg)
Dipole Magnetic length	1.395	m
Distance between dipoles	1	m
R56	0.205	m
Max dispersion	0.56	m
Number of Cavities	2	
RF frequency	2	GHz
Accelerating Gradient	20	MV/m
Accelerating Voltage	99	MV

Simplified Energy Compressor optimization

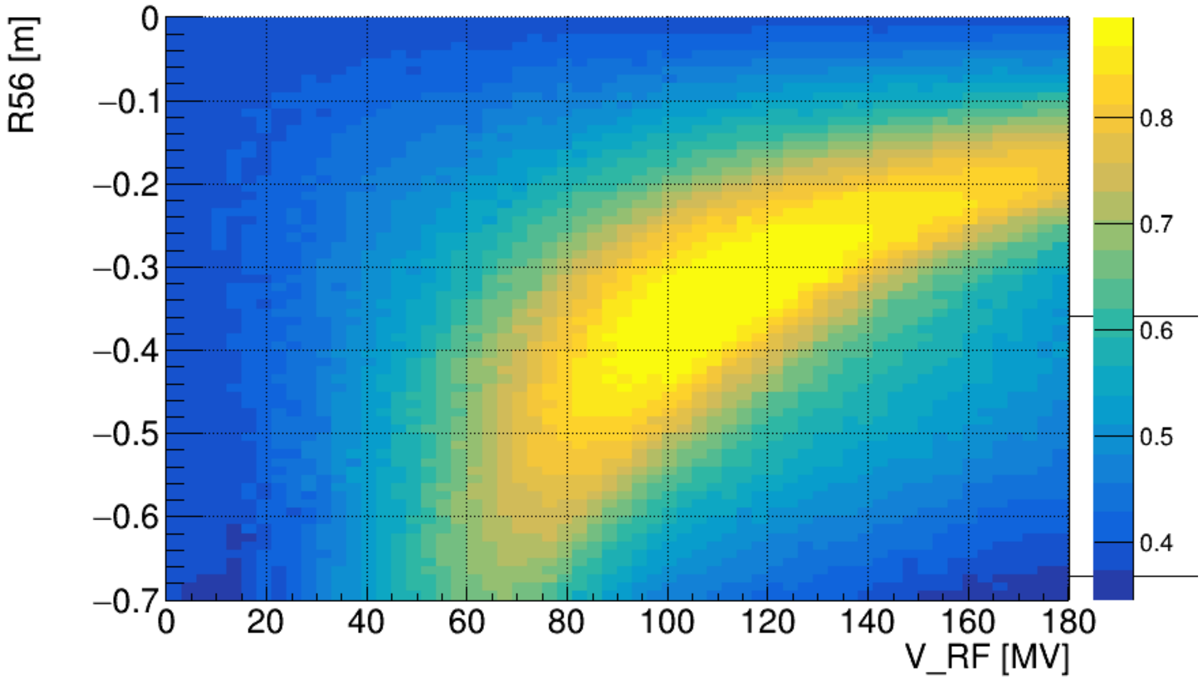
$$\delta t = t_0 - t_{ref}$$
$$\delta p_z = p_z^0 - p_z^{ref}$$



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.

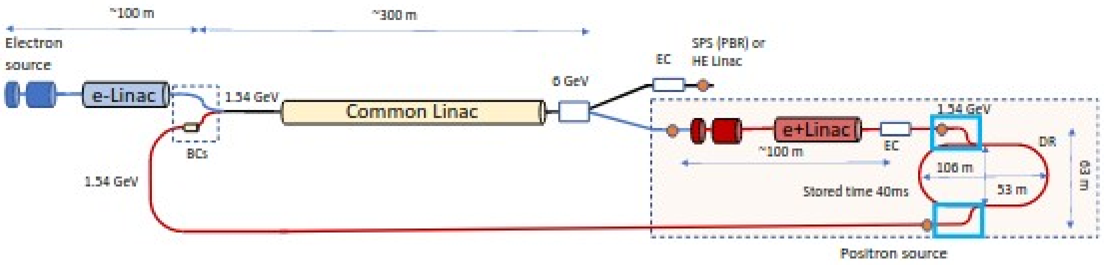
Result (only analytical):

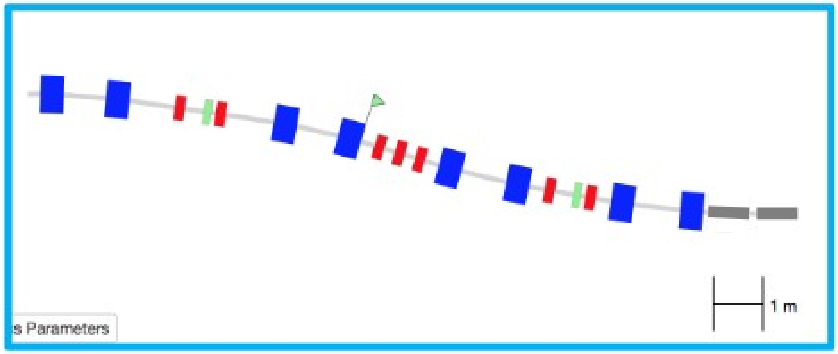
V_{RF} = 100 MV

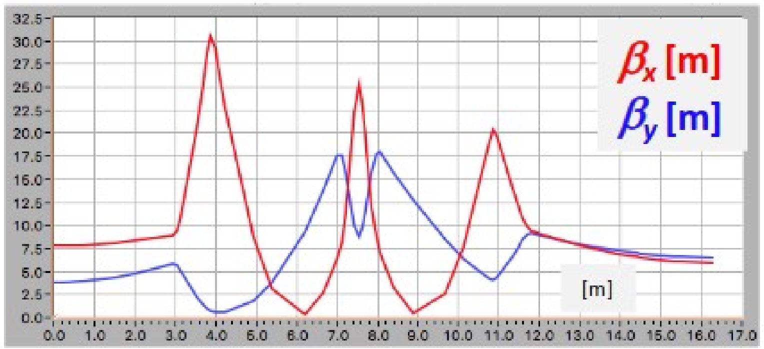
R_{56} = -0.35 m

Results with Elegant simulation slightly different.

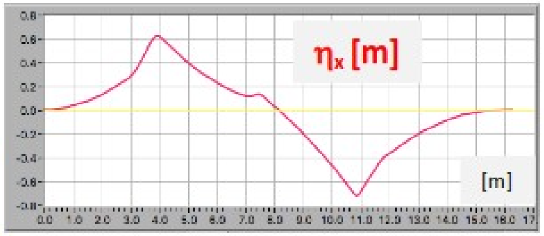
TL Injection/Extraction Section

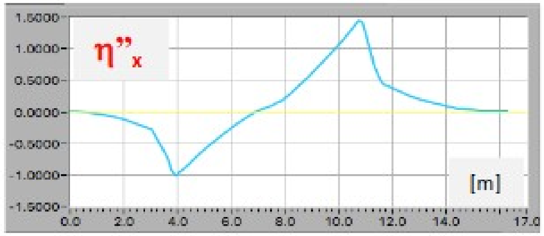






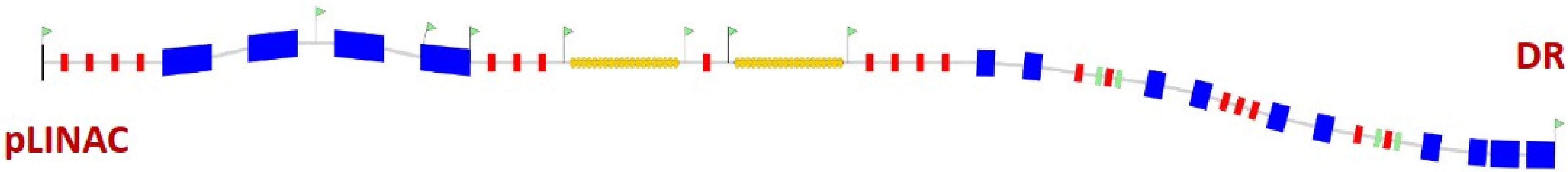
- *flexible*
- *achromatic*

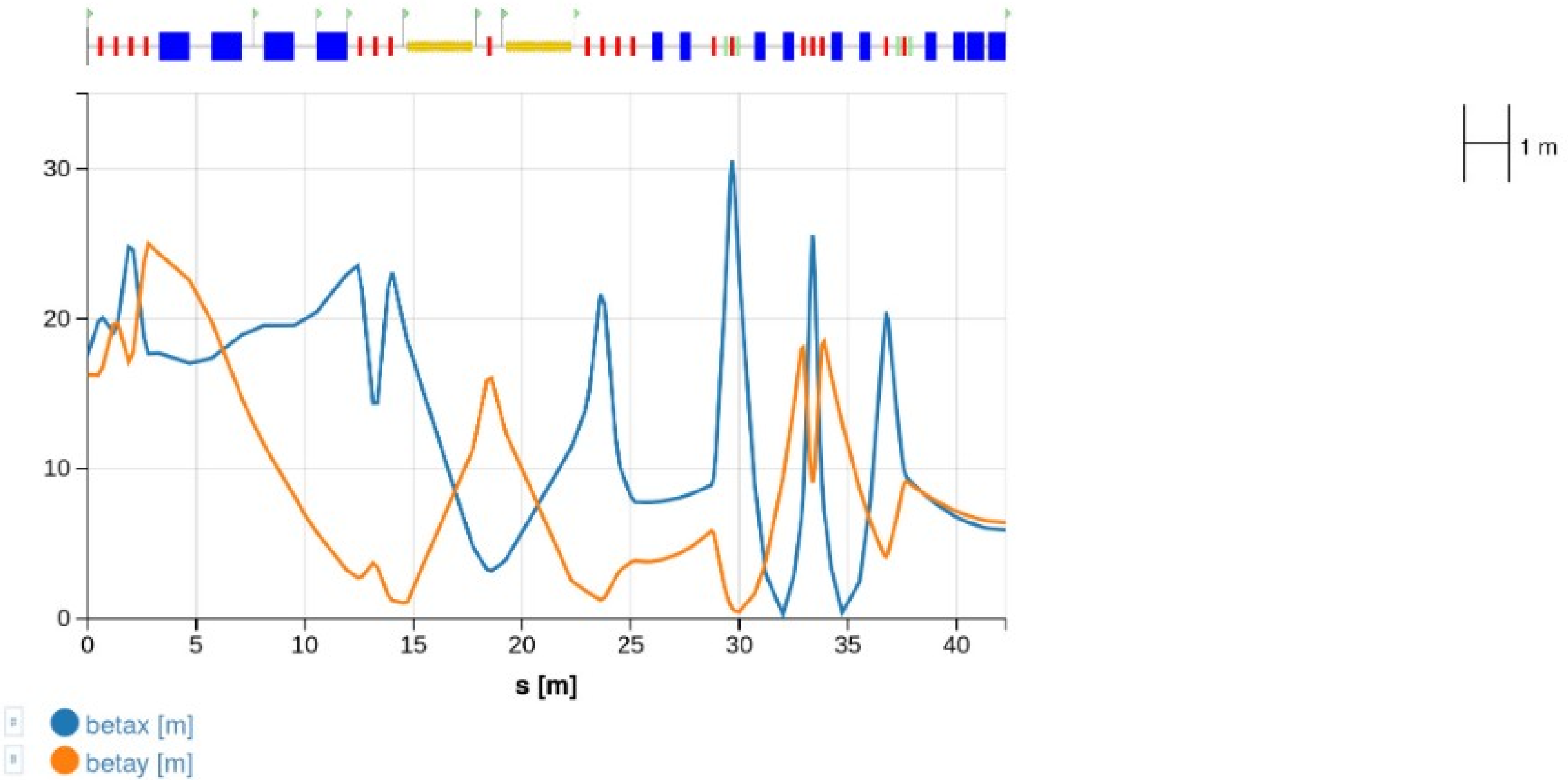




	Angle [degree]	Length [m]	Field [T]	Thickness [mm]
B1	4.2	0.47	0.8	
B2	-3.4	0.47	-0.65	
SPT1	-2	0.8	-0.044	7
SPT2	-1.2	0.8	-0.026	2 - 4

Transfer lines pLINAC - DR

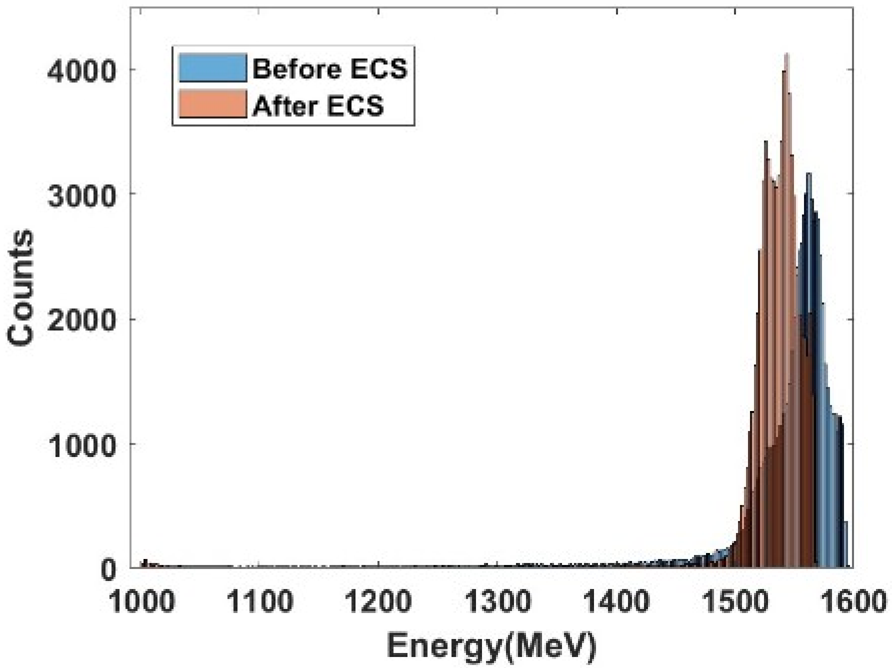


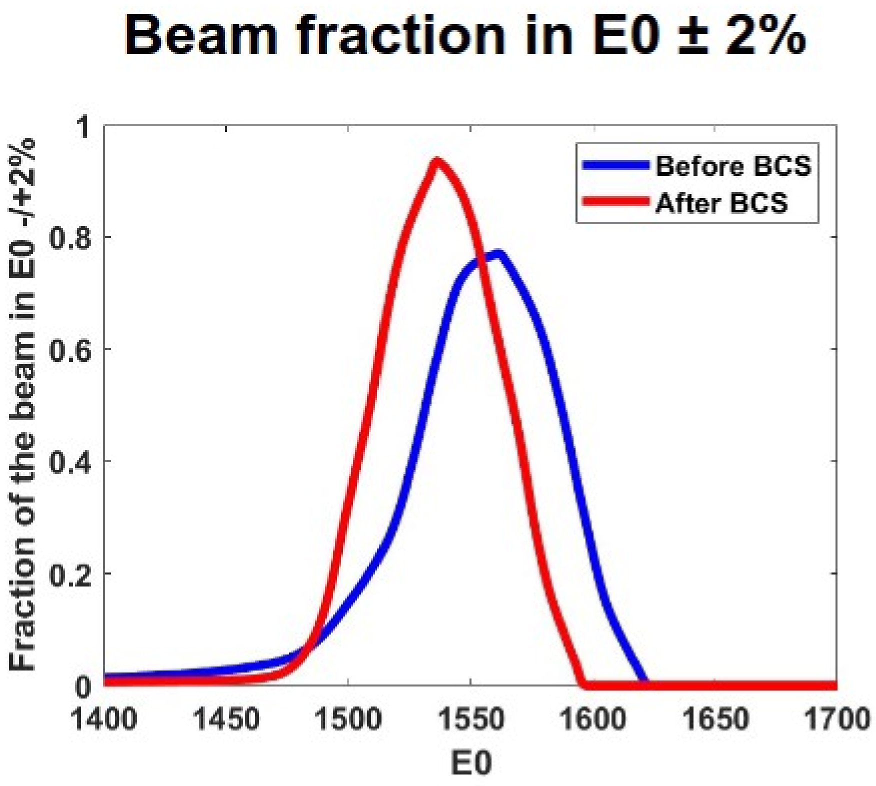


Topic covered in the S. Spampinati talk

EC Tracking with Elegant

- Energy Compressor (ECS) reduces the width of the energy distribution and increases the number of particle accepted by the DR.
- Elegant tracking of the distribution from pLINAC.
- Tracking includes 1D CSR model.

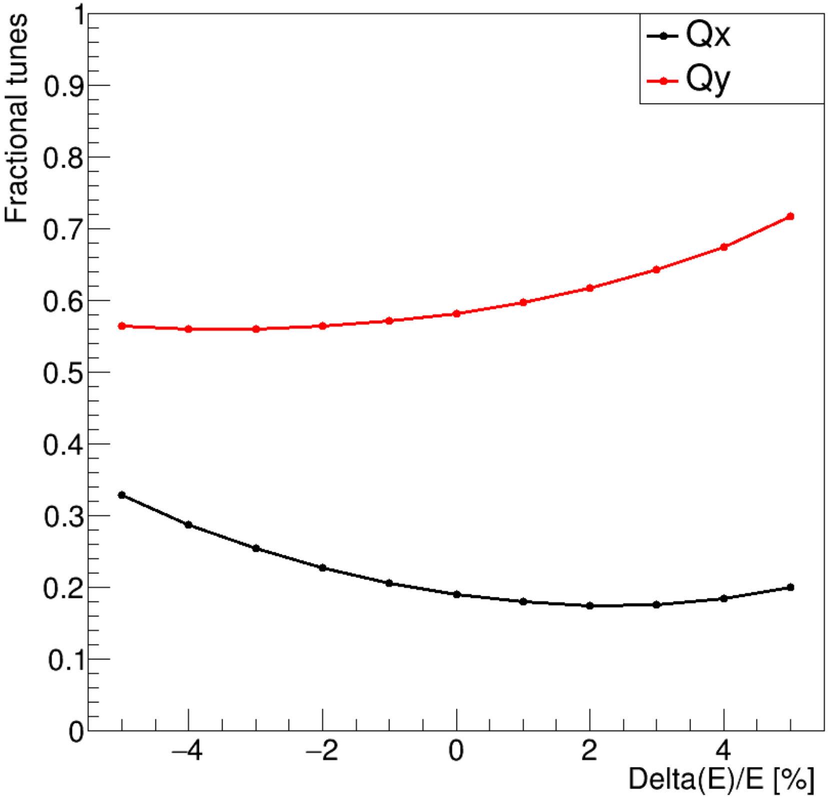


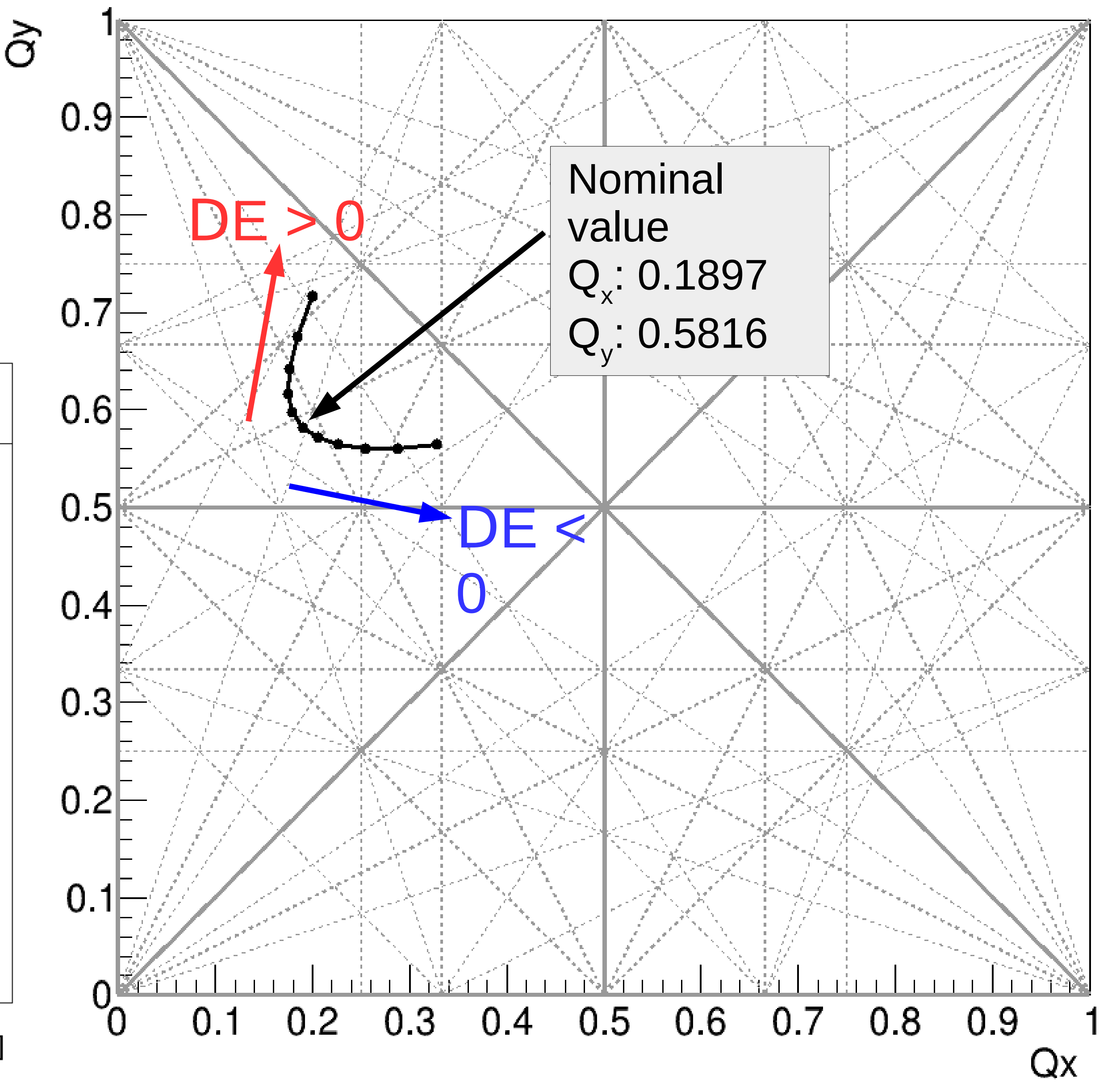


pDR: positron DR
1.54 GeV

Tune diagram

Tune variation as a function of energy deviation for the nominal lattice





Energy Acceptance at injection for e^+ beam

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

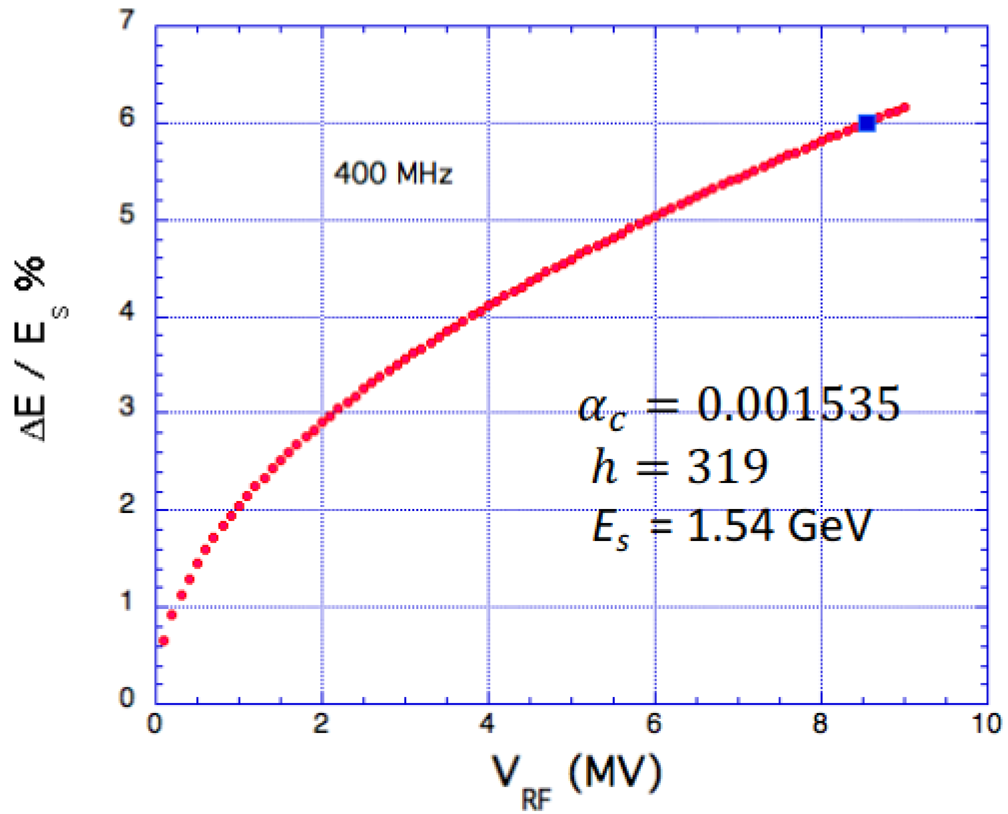
$$\mathcal{R}(\varphi_s) = \lfloor 2\cos\varphi_s + (2\varphi_s - \pi)\sin\varphi_s \rfloor$$

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

Separatrix

W* - *Φ representation, canonical coordinates

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

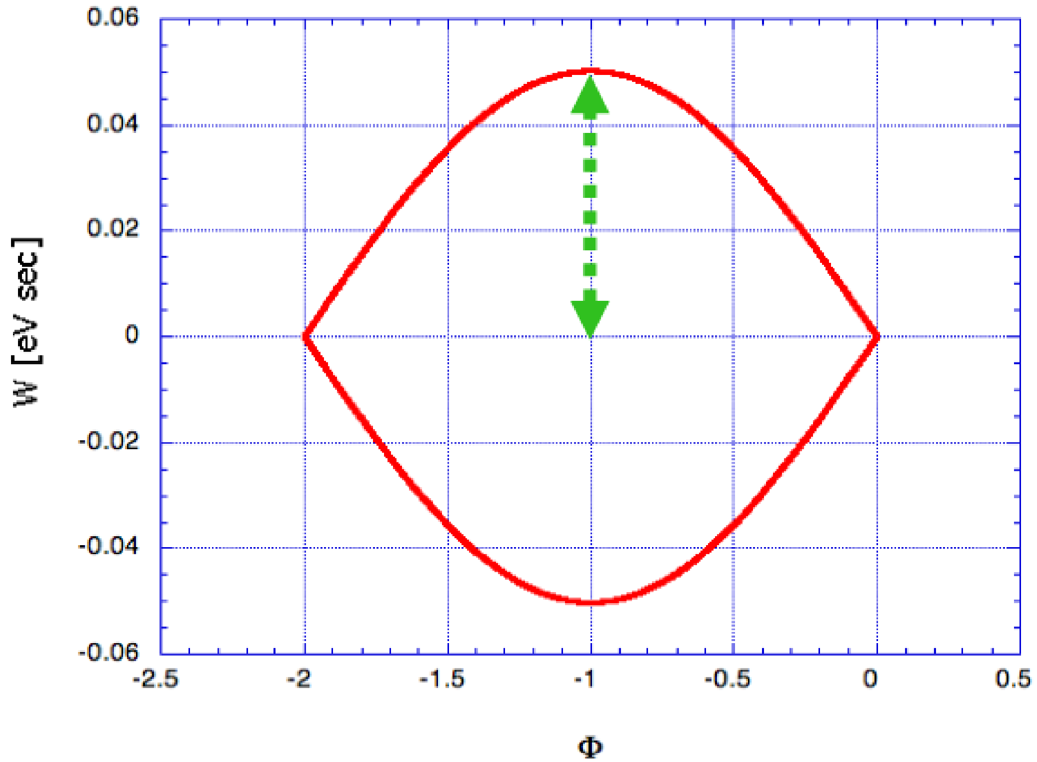
$$W_{bh} = \frac{L}{\pi hc}\sqrt{\frac{eV E_s}{2\pi h\eta_{tr}}}$$

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

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)

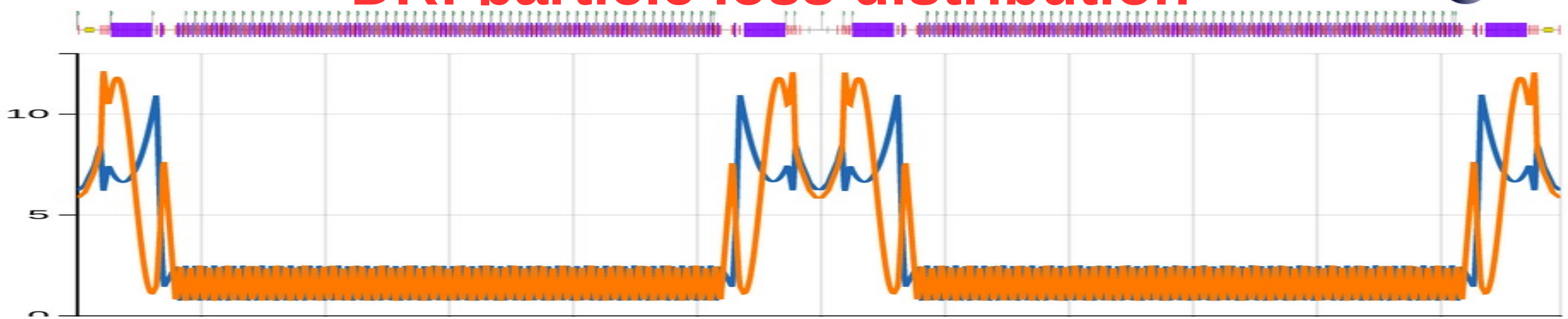
DR dynamical aperture: Tracking study

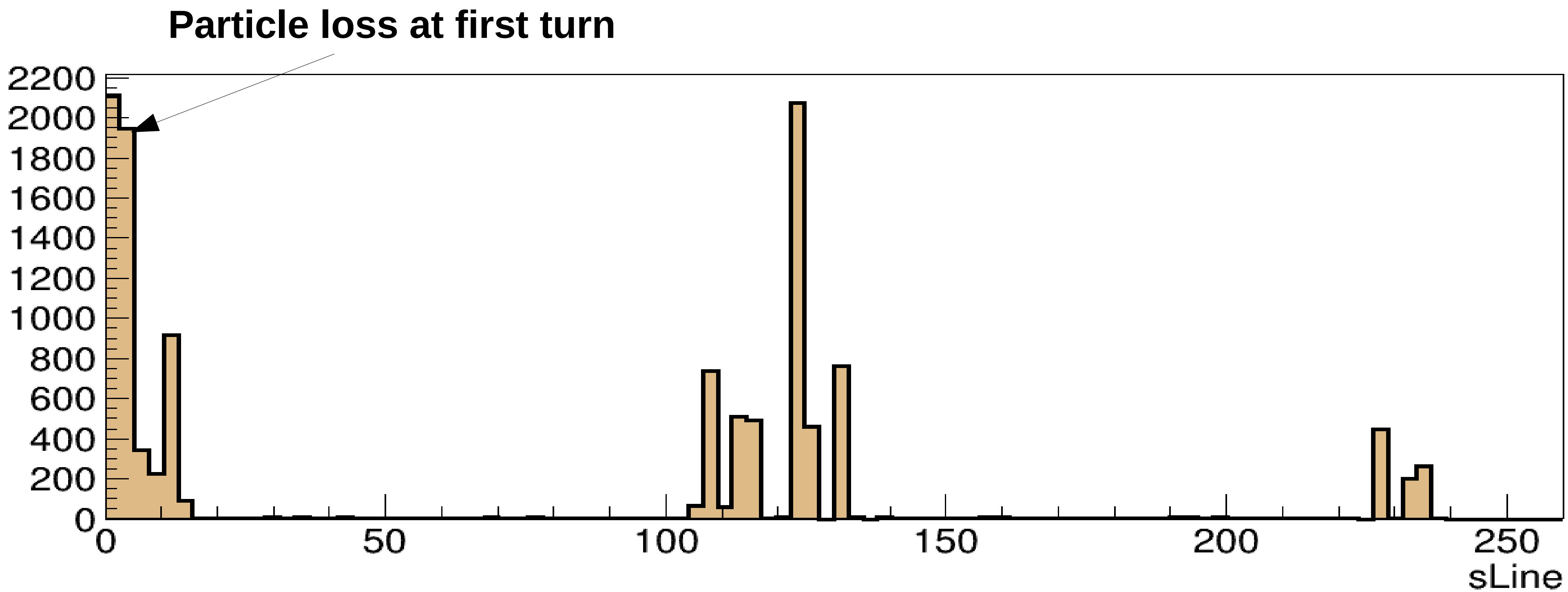
Rows: δ_E (%) from 10 (top) to −10 (bottom); columns: N_{Turns} (#), axis ticks 0, 2000, 4000, 6000, 8000, 10000.

995	991										4
1452	1432	1	1		1						17
1958	1916	4	1	1	2						34
2632	2096	80	19	12	14	4	1				406
3248	1881	178	97	62	15	2					1013
3978	1837	342	83	11	3	3					1699
4630	1729	112	18	4	3	2		1			2761
5233	1197	81	24	11	8		1				3911
5772	851	79	22	7					1		4812
5898	571	36	20	4	1	6	3		1		5256
5806	579	45	10	8	3	1	2	6			5152
5678	764	73	23	8	1	2	1			1	4805
5317	1067	73	29	7	8	4	1				4128
4605	1584	120	20	8	4	2					2867
4055	1820	333	92	11	1						1798
3269	1875	172	107	43	12	1					1059
2516	1896	84	24	15	21	2					474
1989	1989										
1444	1444										
1008	1008										

Tracking has been performed with PTC (MAD-X interface) for 10k turns.
Initial distribution are Gaussian with nominal emittance (CDR e_x:1.29 e_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: particle loss distribution

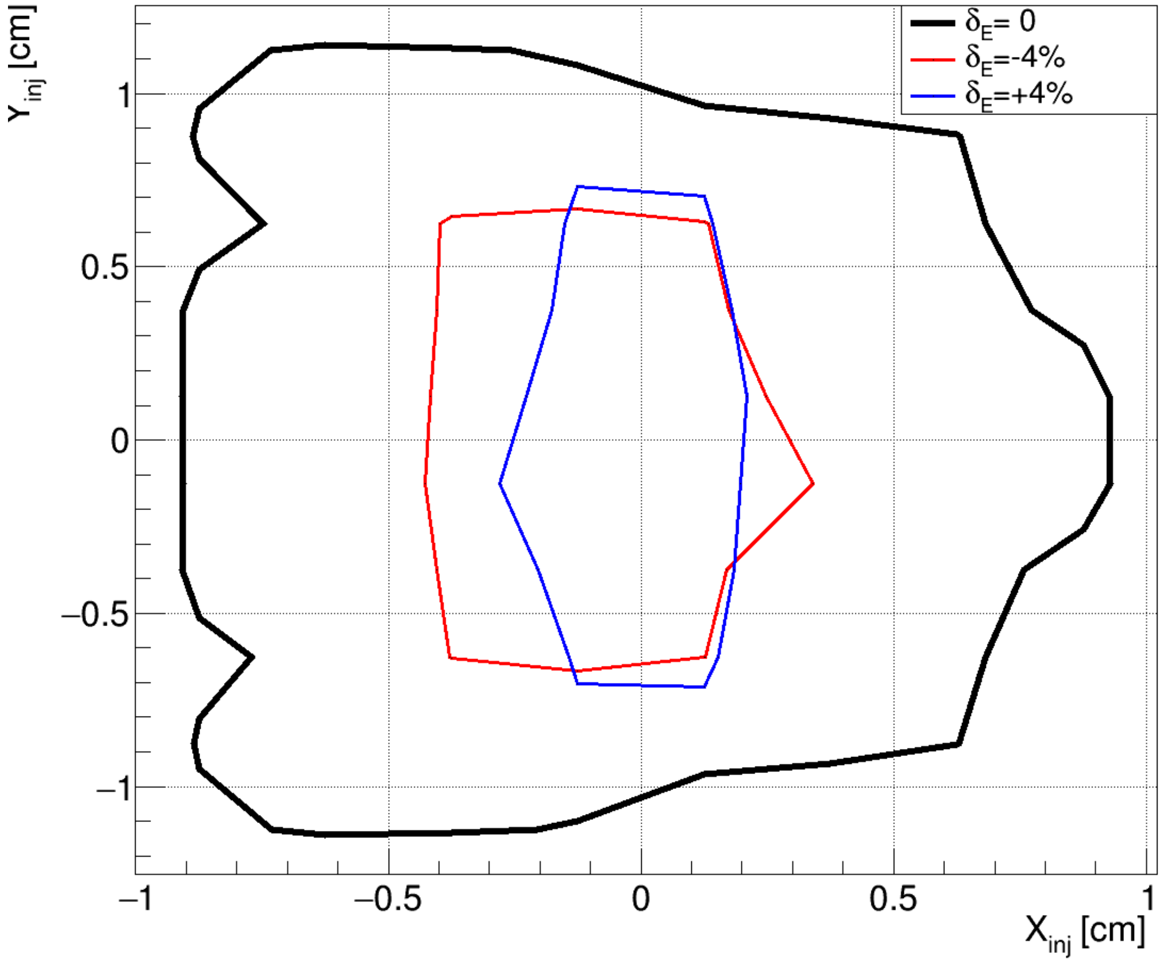




Tracking has been performed starting with nominal ECS + Injection DogLeg pLINAC transformation

The plot shows the distribution of losses around the ring (lattice on top)

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.

Radiation damping neglected

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.

Preliminary evaluation of collective effects

- *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

PDR eCloud: DAFNE benchmark

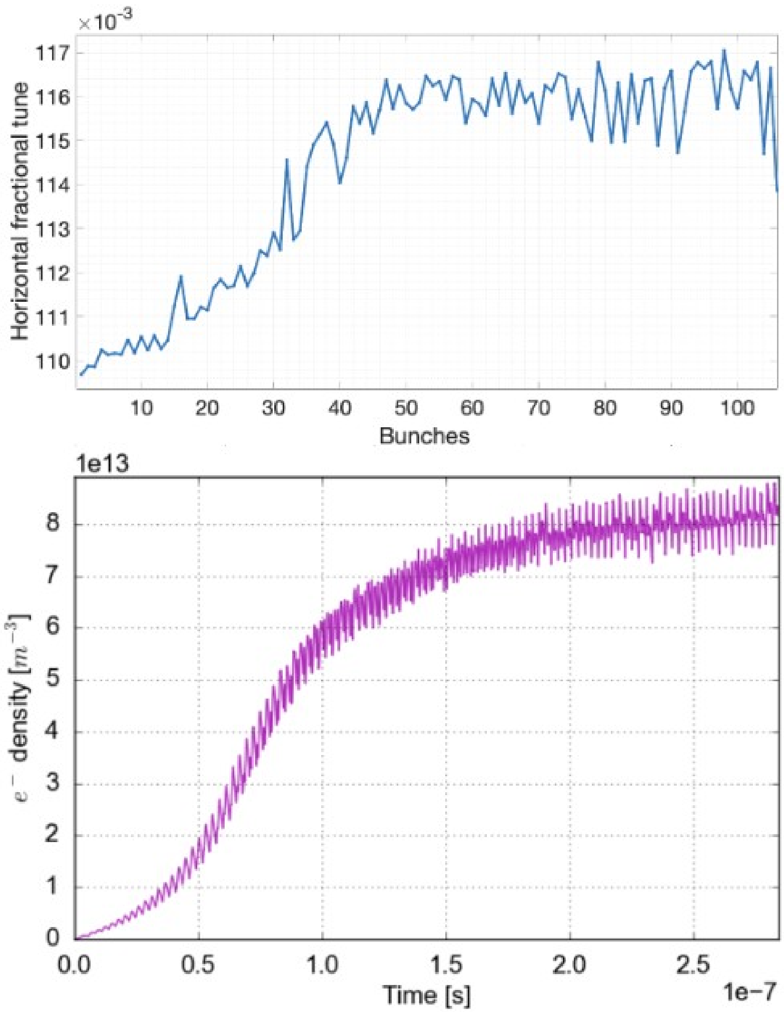


Figure 2: Horizontal tune shift measurement for 105 filled bunches (800 mA) (top) and e-cloud build-up simulation by PyECLOUD (bottom).

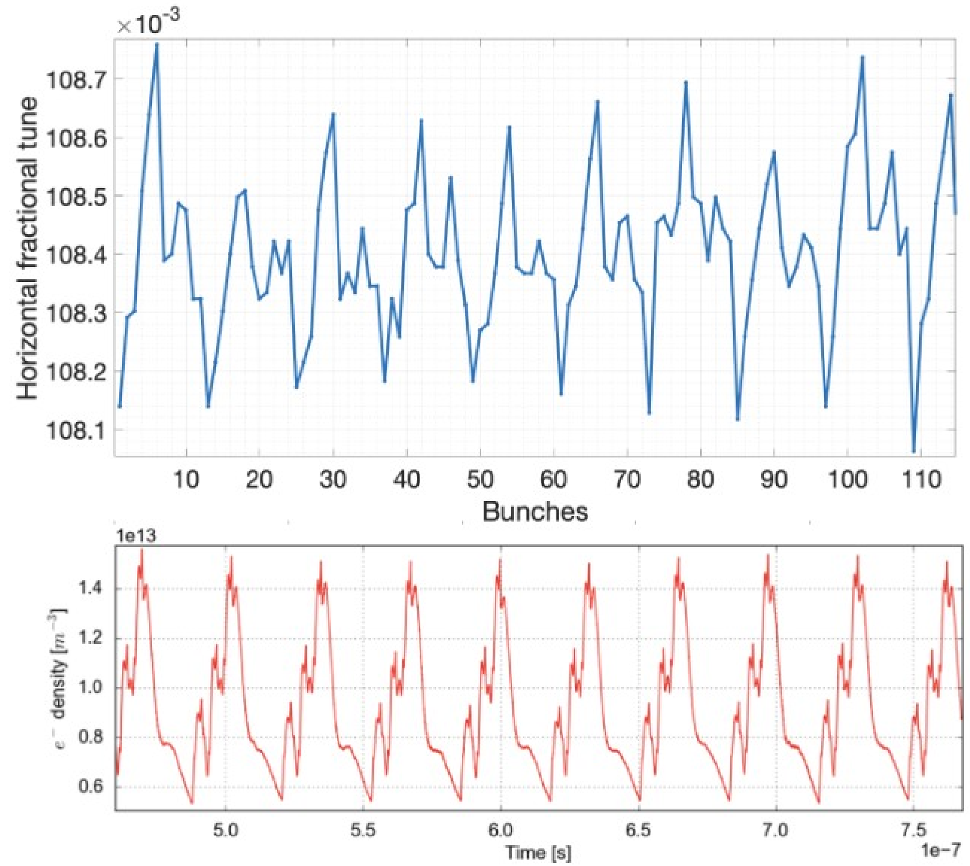


Figure 3: Horizontal tune shift measurement for 60 bunches (each train has 6 filled 6 empty buckets) which correspond to 290 mA beam current (top) and e-cloud build-up simulation by PyECLOUD (bottom).

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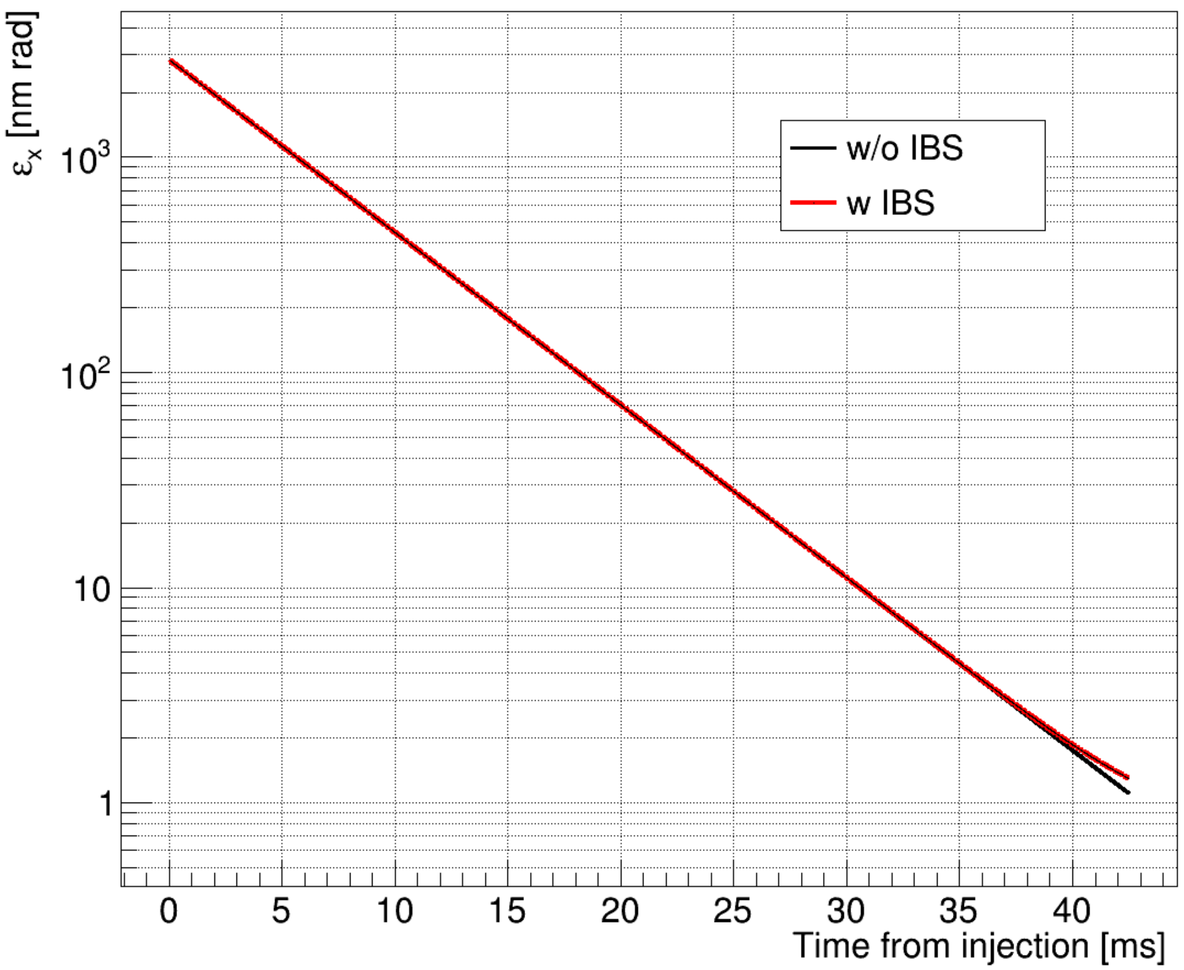
Emittance evolution with IBS

pDR: ε_x time evolution



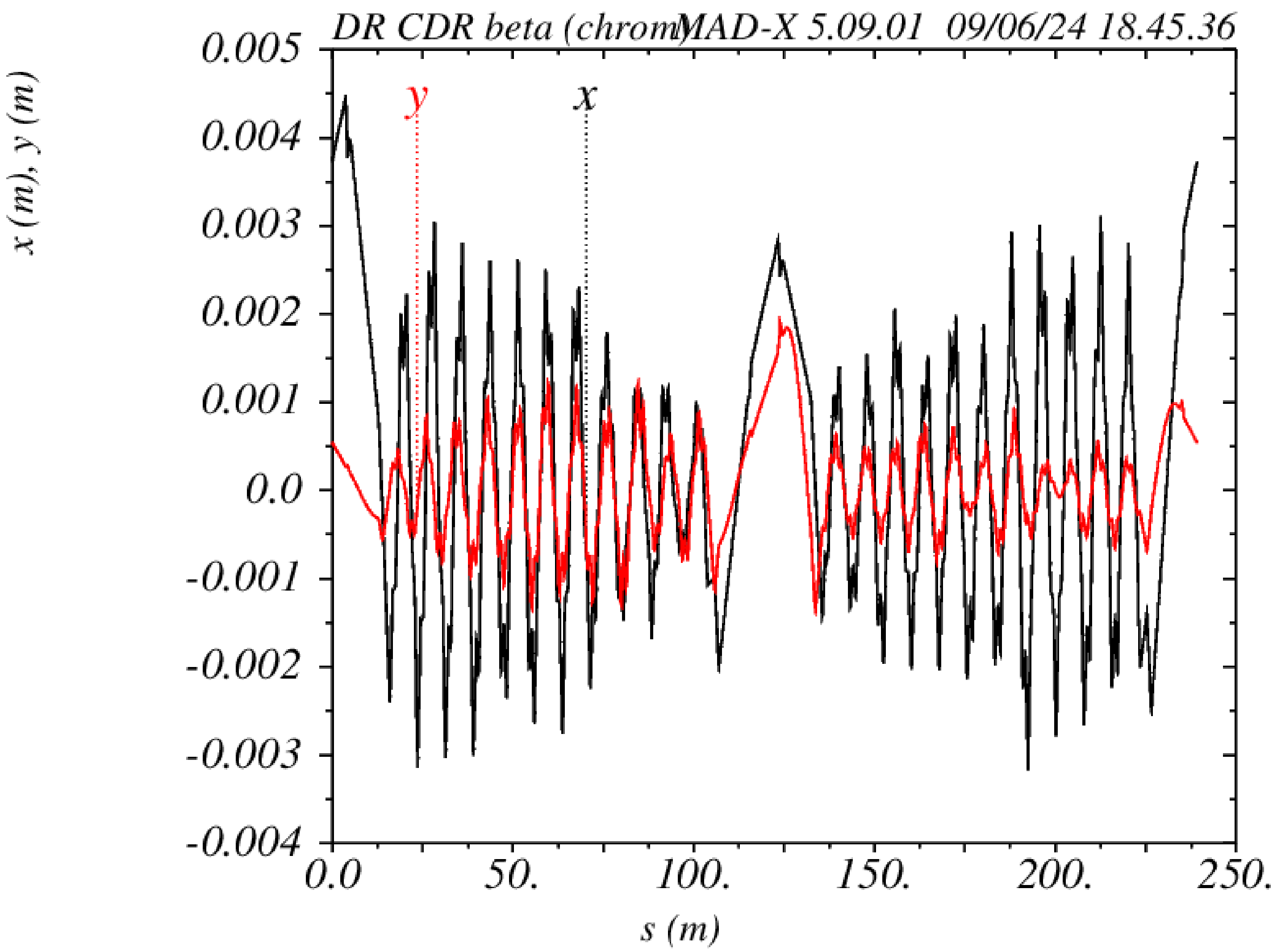
The IBS has been evaluated using MAD-X module.

The initial emittance is 3 mm mrad

The bunch charge is 4 nC

e_x(ext) = 1.29 nm rad
e_y(ext) = 1.03 nm rad

Alignment errors



Orbit variation for 100 μm average alignment error on quadrupoles (H/V).

Positron Damping Ring
2.86 GeV

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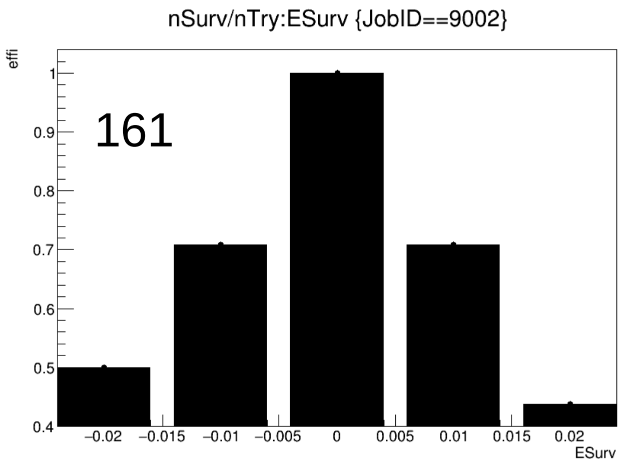
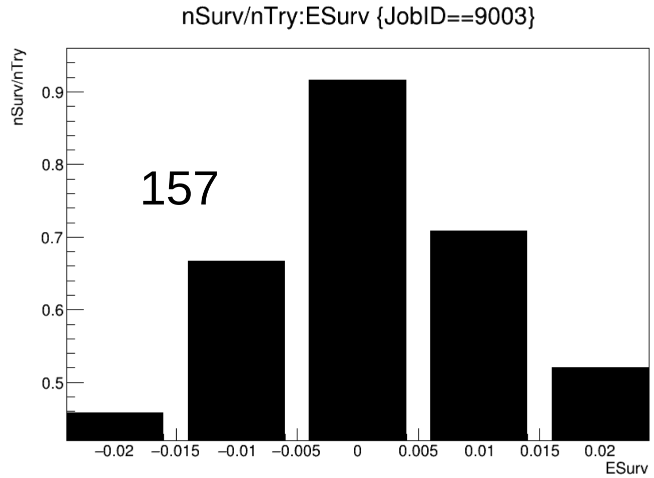
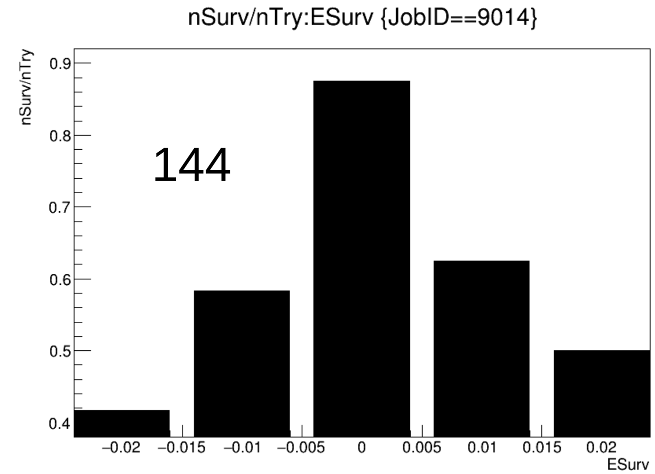
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Best configurations

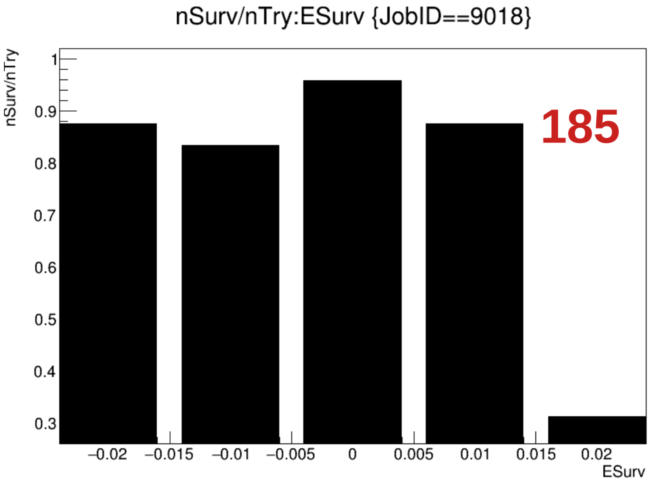
FUTURE CIRCULAR COLLIDER

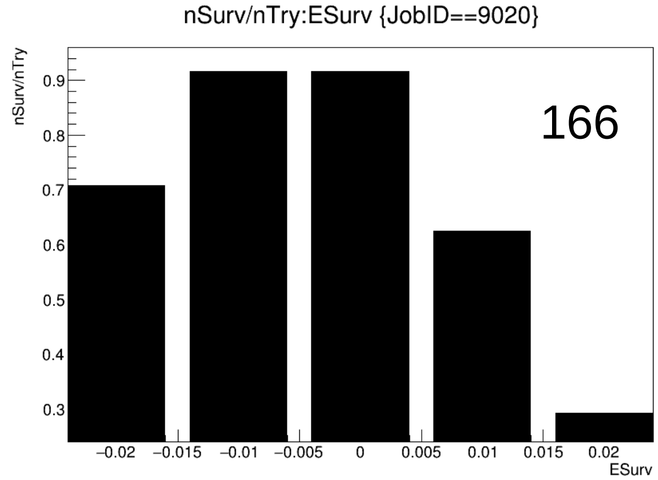


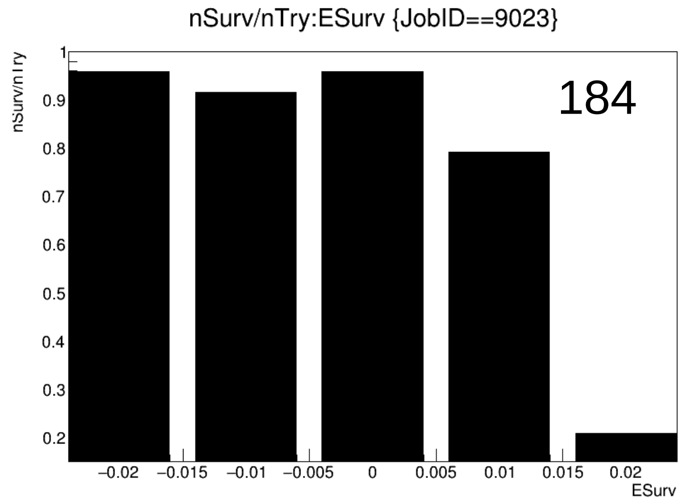




Emit= 1.932e-09







Best config Twiss output

+++++ table: summ

length	orbit5	alfa	gammatr
384.87	-0	0.001811136839	23.4976466
q1	dq1	betxmax	dxmax
28.27498137	-0.3008201949	19.1358592	0.2430111226
dxrms	xcomax	xcorms	q2
0.06267458497	9.623131305e-05	1.663028276e-05	22.98718137
dq2	betymax	dymax	dyrms
0.2525076544	26.95418562	0	0
ycomax	ycorms	deltap	synch_1
0	0	0	0.6972830838
synch_2	synch_3	synch_4	synch_5
1.207992067	0.1573632608	0.003141562579	0.0001940253416
synch_6	synch_8	nflips	dqmin
1739.469667	6.682676076	0	0

Potential configs