Damping Ring and Transfer Lines for the FCC-ee pre-Injector Complex

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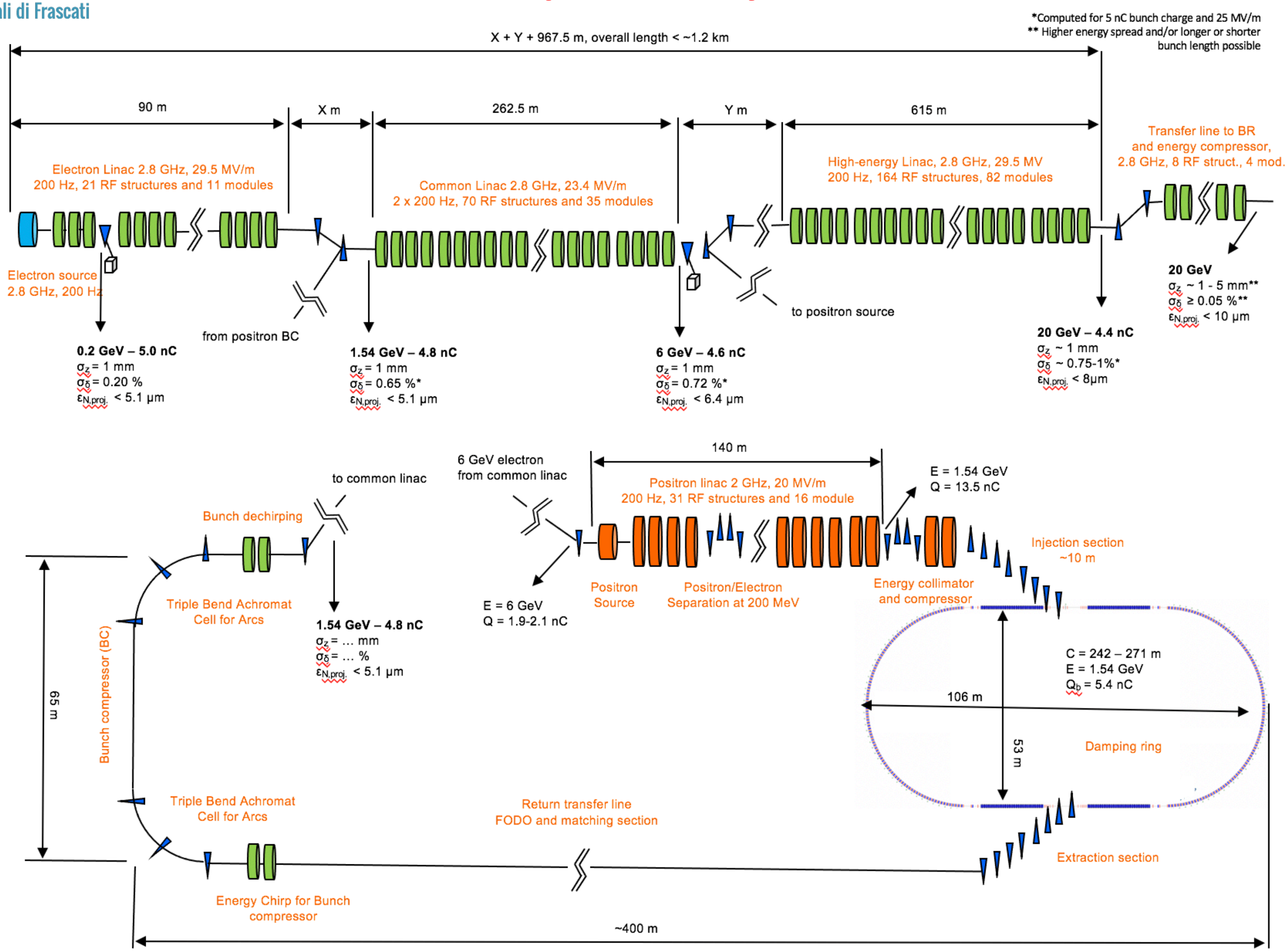
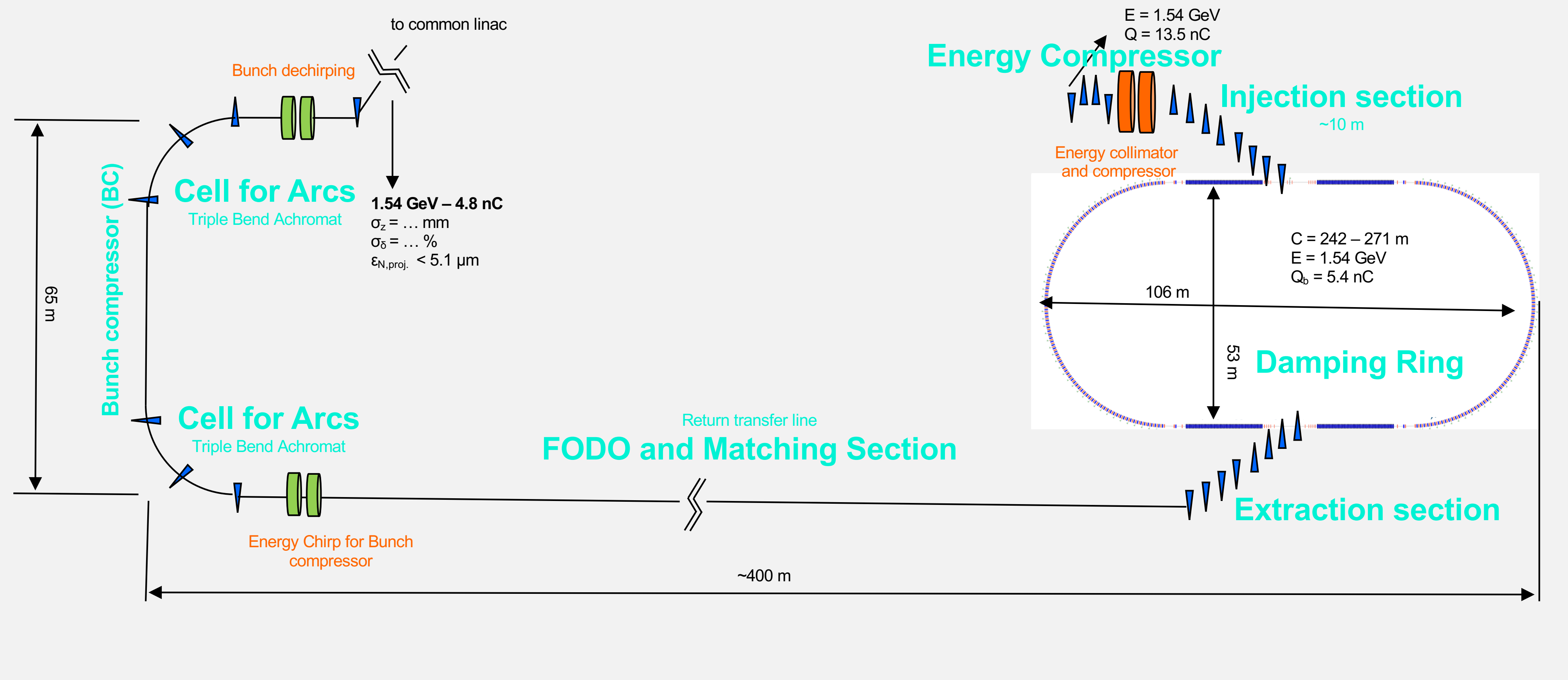
FCC-ee pre-Injector Complex Layout



(P. Craievich, CO84, version 8, 02.06.23)

Damping Ring and Transfer Lines

(WP4)



Injector Parameters (Z-mode)

FCC Accelerator Pillar meeting #07, 01.11.22

	SPS	HE Linac	Unit
Injection energy	6	20	GeV
Bunch charge both species	4.4	4.4	nC
Repetition rate	200	200	Hz
Number of bunches	2	2	
Bunch spacing	25	25	ns
Normalized emittance (x, y) (rms)	10,10	10,10	mm mrad
Bunch length (rms)	~1	~1	mm
Energy spread (rms)	~0.1	~0.1	%

← Specification for the charge at the linac end. Charge to be injected into the collider rings is 3.84 nC (bunch population 2.4×10^{10} particles).

← Target bunch length and energy spread at the LINAC end, TL from HE LINAC to booster will include energy and bunch length compression.

Other important requests:

- The bunch by bunch intensity will arbitrarily vary in the range 0 - 100%, depending on the beam intensity balance in the the collider rings
- Bunch-by-bunch injection intensity fluctuation: 3%
- Bucket selection/filling pattern

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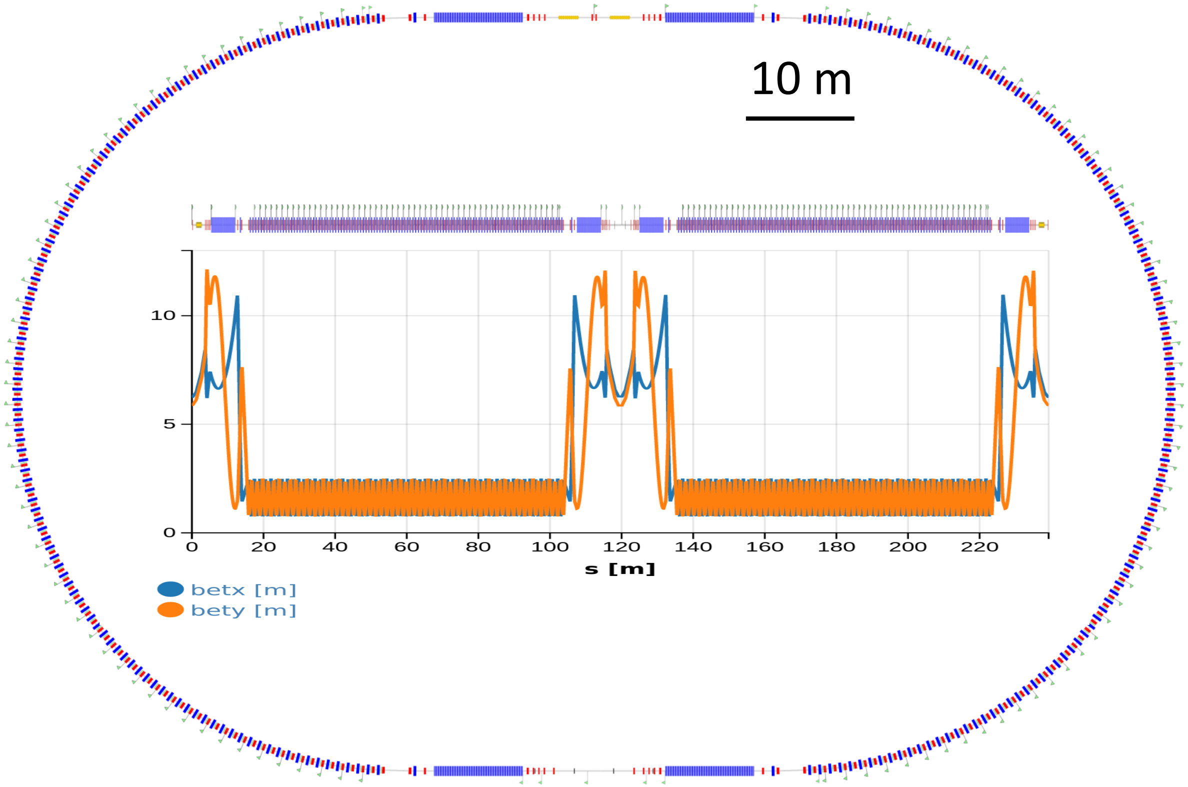
Damping Ring

Damping Ring

Damping Ring optics has been optimized starting from the CDR version, with special attention to: dynamic aperture evaluation, beam acceptance and injection section design.

Parameter	FCC_ee DR (CDR)
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



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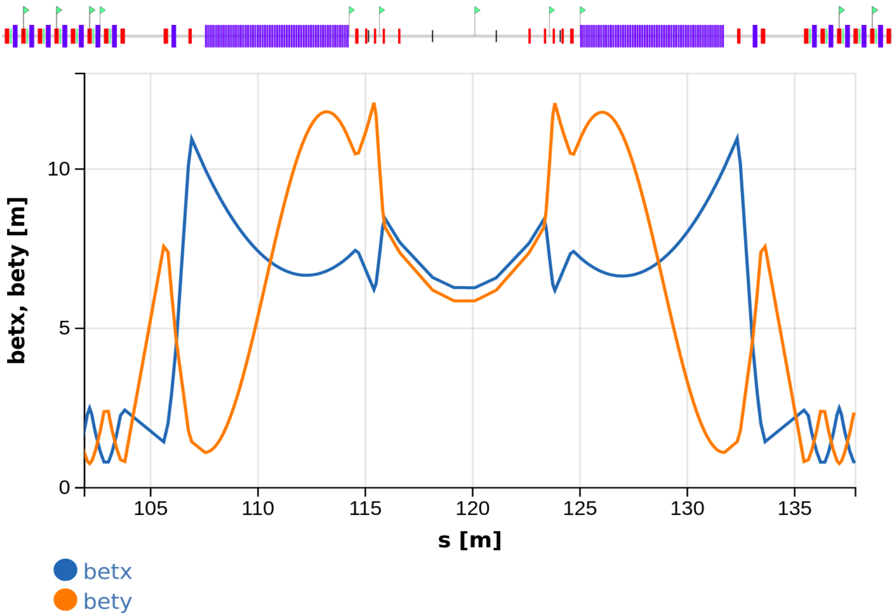
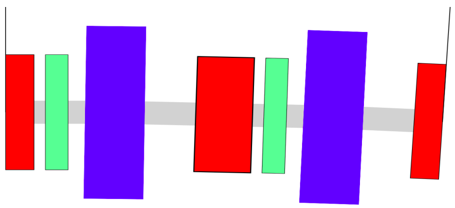
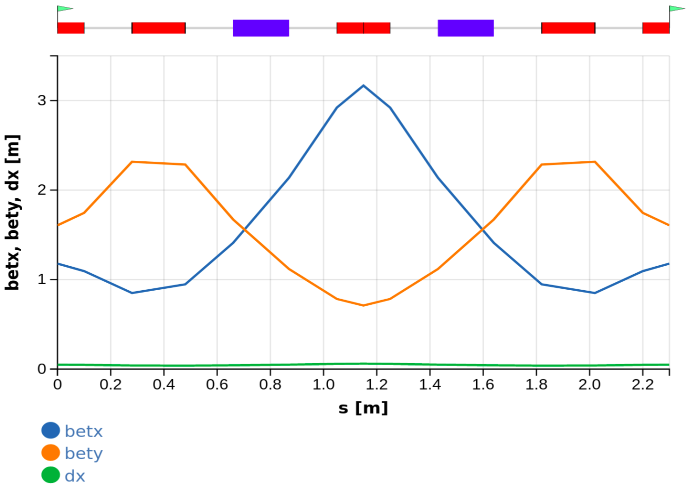
Damping Ring Optics



Straight section including two of the four wigglers.
Straight sections are designed to host RF cavities, and Injection/Extraction equipment.

DR FODO Cell





Beam Dynamics Parameters

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Computed by using the following 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 • 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

SC RF cavity working at 400 MHz and providing at last 4 MV is considered.
Minimum RF cavity voltage request to compensate the energy lost per turn is
E_{LT} = 0.225 MV

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.

RF System

RF as in the CDR

LHC type 400 MHz,
SC cavities.
two RF modules providing 2 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

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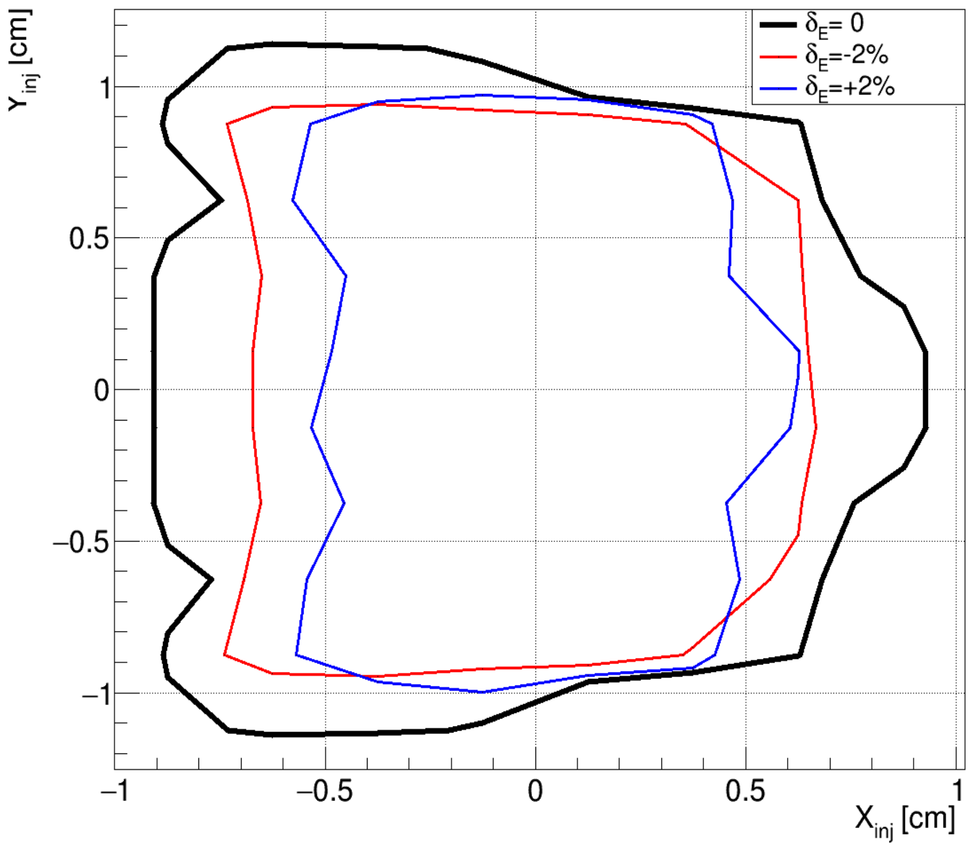
DR dynamic aperture



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 successful tracking.
A probability definition is needed in order to get the average value over the surface.

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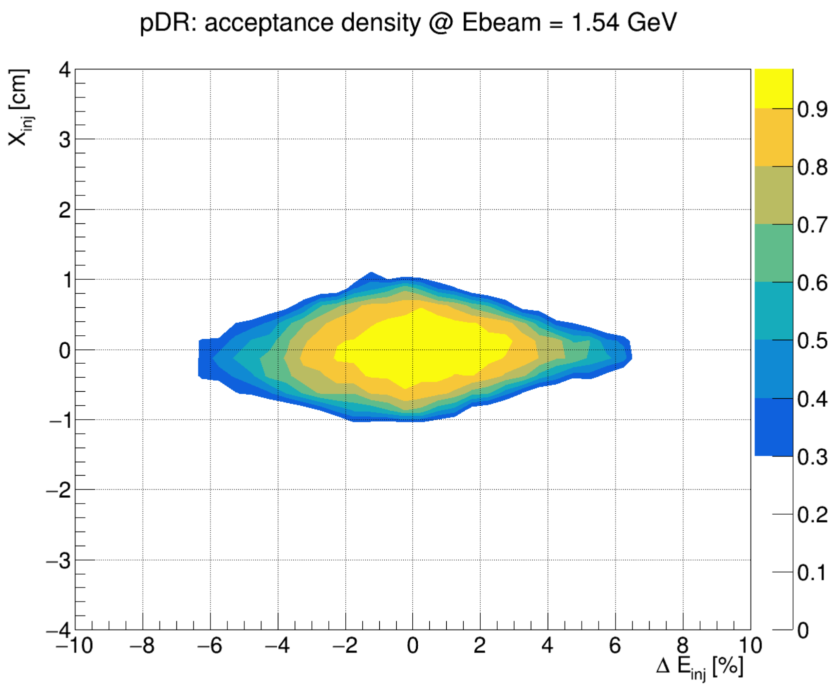
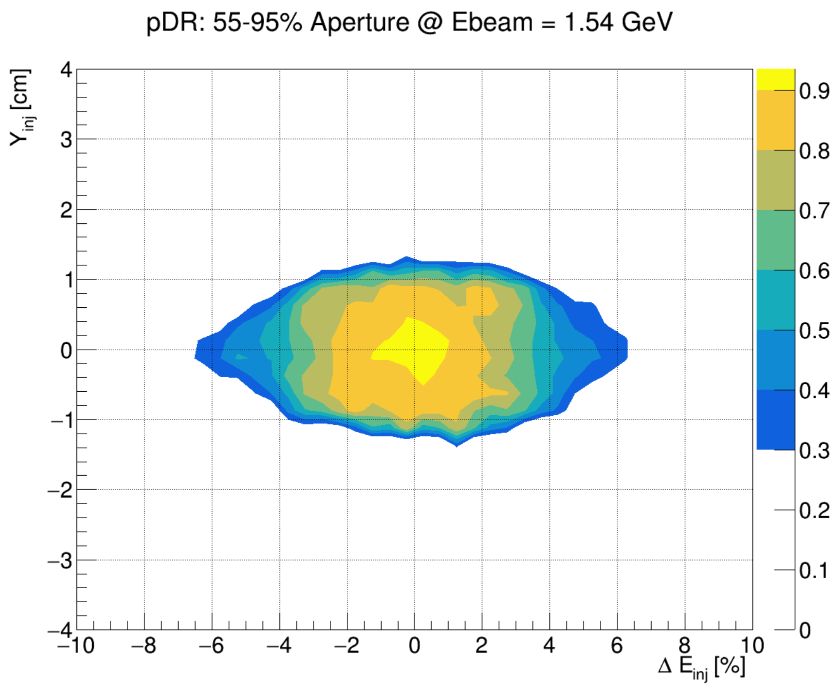
DR Acceptance Probability





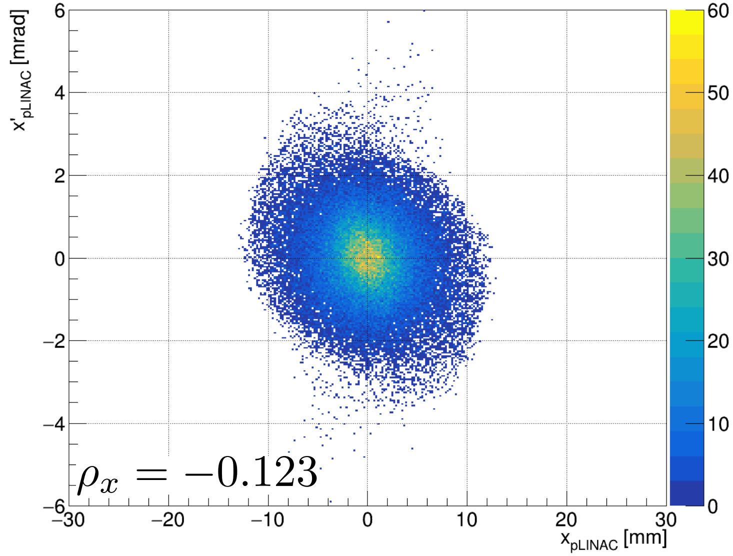
DR acceptance probability has been evaluated starting with nominal beam parameters at the injection: Gaussian profile with nominal width at the injections (σ ~ 2mm in both planes).
The energy distribution has been assumed Gaussian with 5% resolution.
10 kTurn and radiation ON.

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.

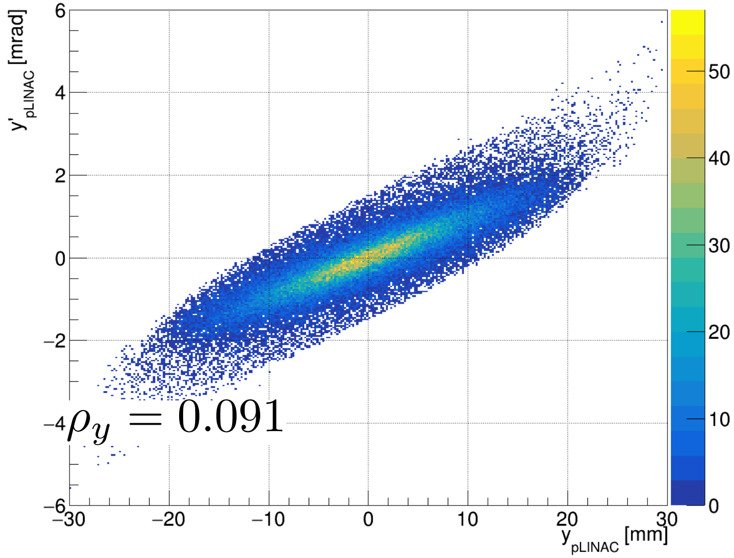
Damping Ring Acceptance, and Energy bunch compressor

Transverse emittance @ pLINAC (Jan23)



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

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



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

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

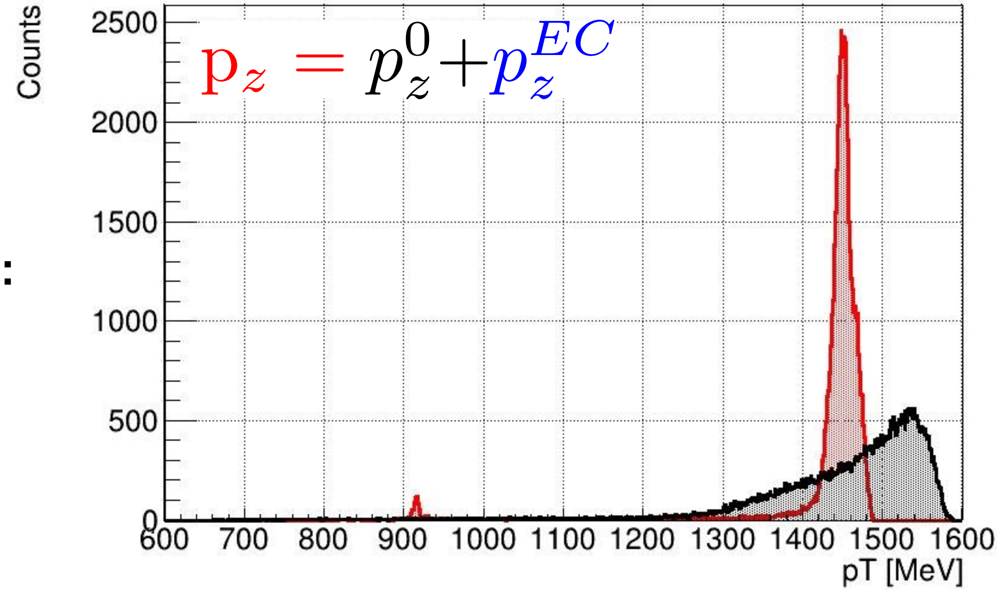
Analytical Energy Compressor optimization

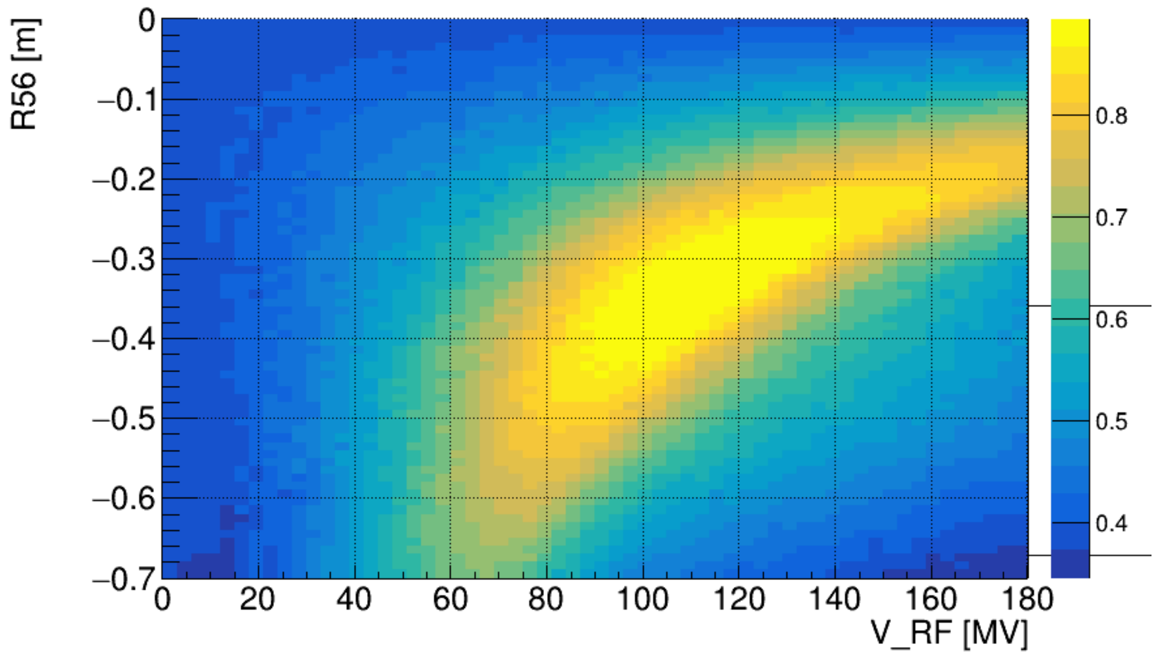
$$\delta t = t_0 - t_{ref}$$
$$\delta p_z = p_z^0 - p_z^{ref}$$

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 to *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.

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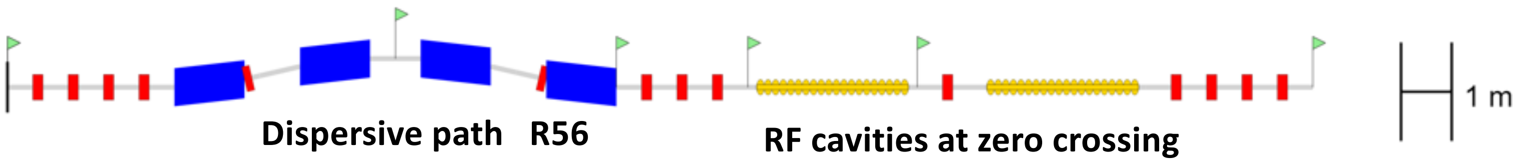
Energy Compressor Design



- 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

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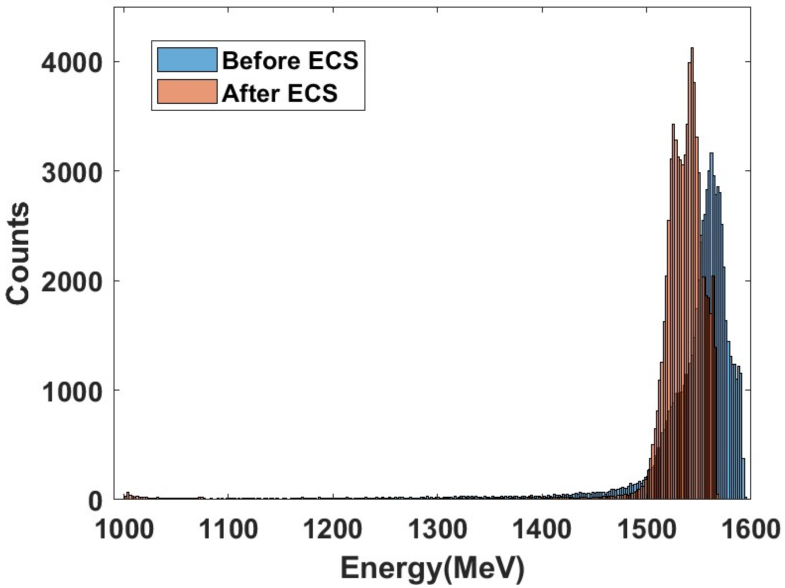
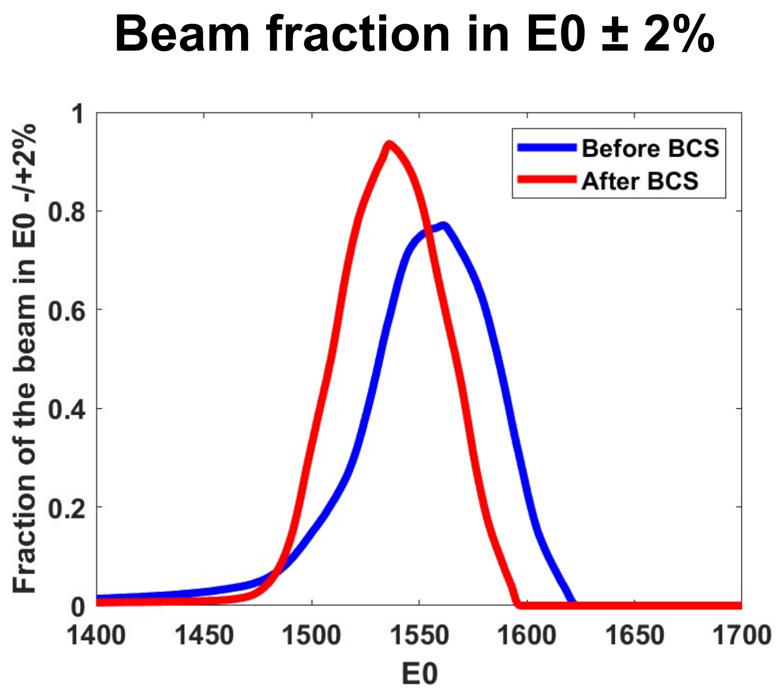
Results of tracking by Elegant

- 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.





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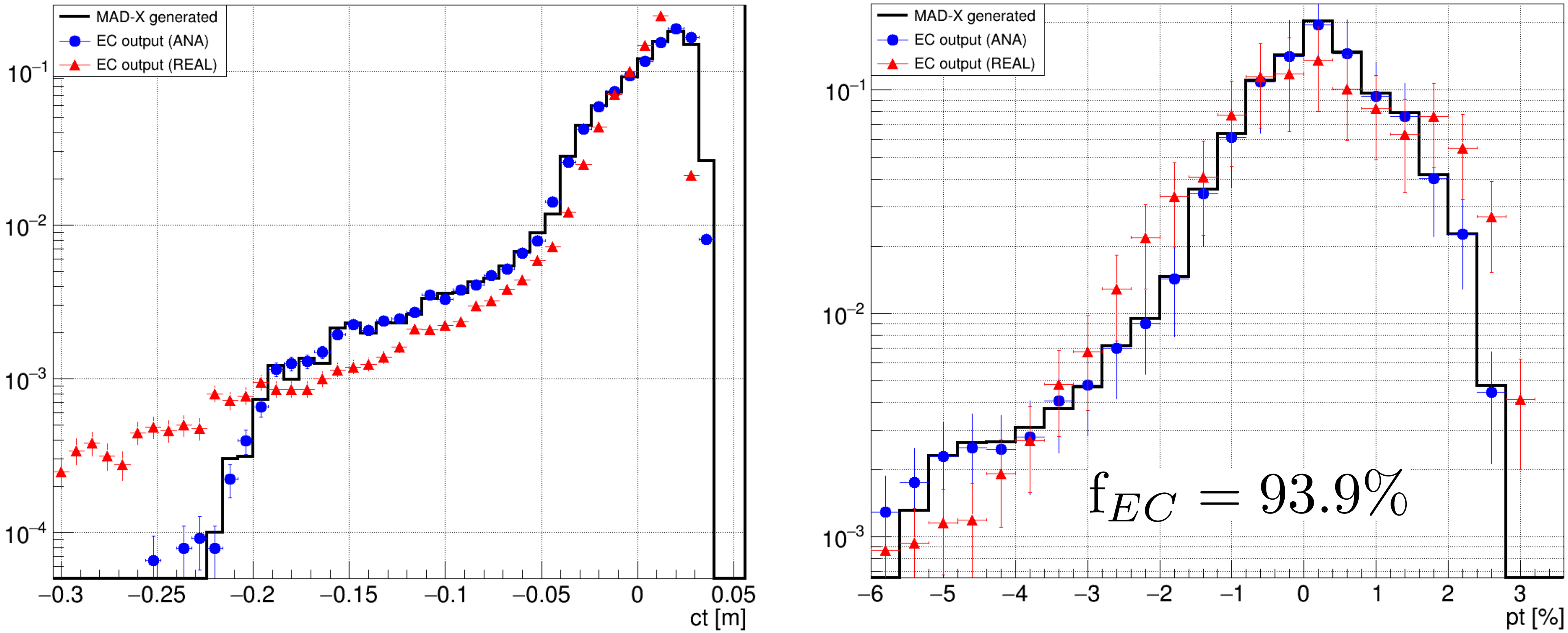
Tracking DR input distribution



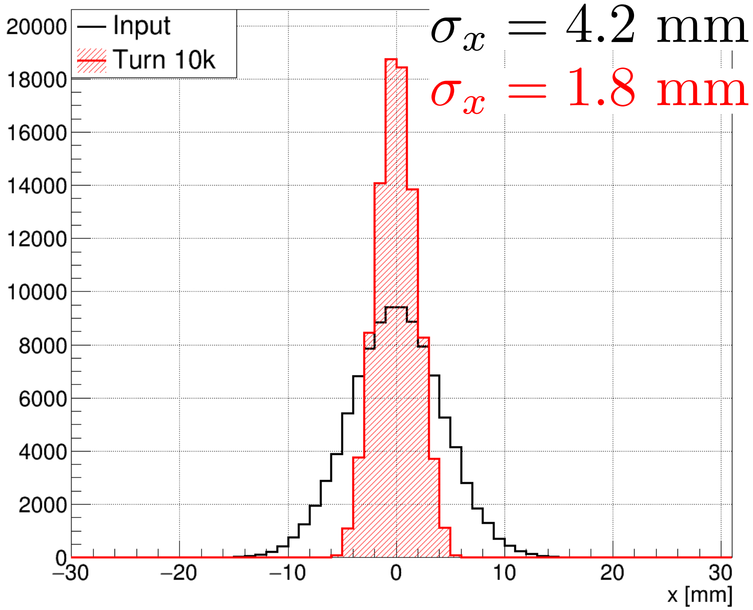
To increase statistics distributions from ECS have been resampled.
The central energy and time are assumed to be “free to be adjusted”.

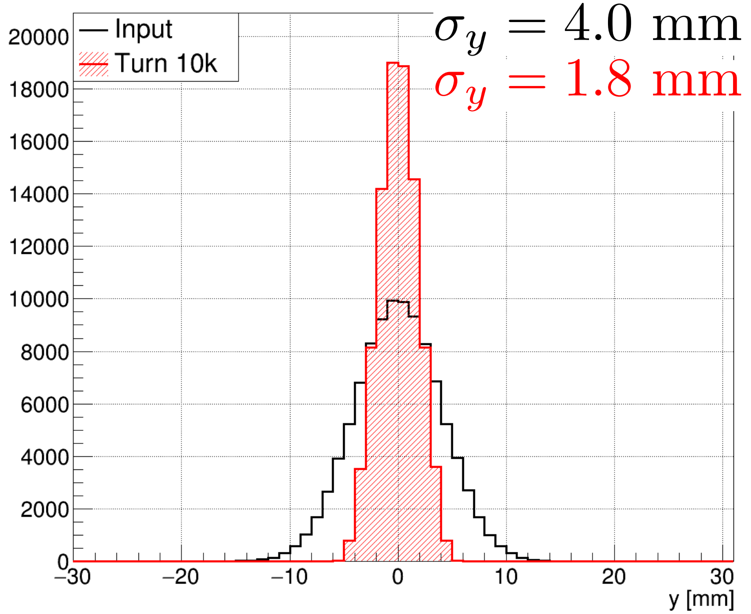
Cut on the tails have been applied (8% loss)

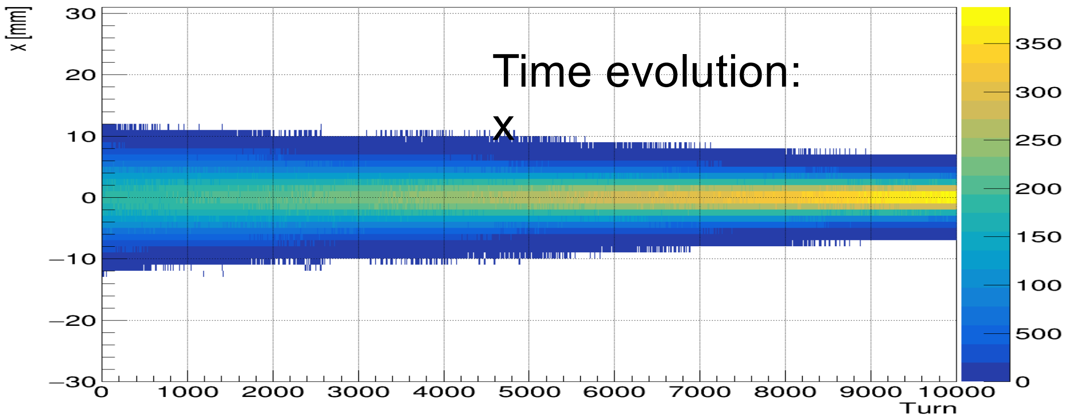
Comparison between ECS (analytical) and ECS (Elegant) shows some difference

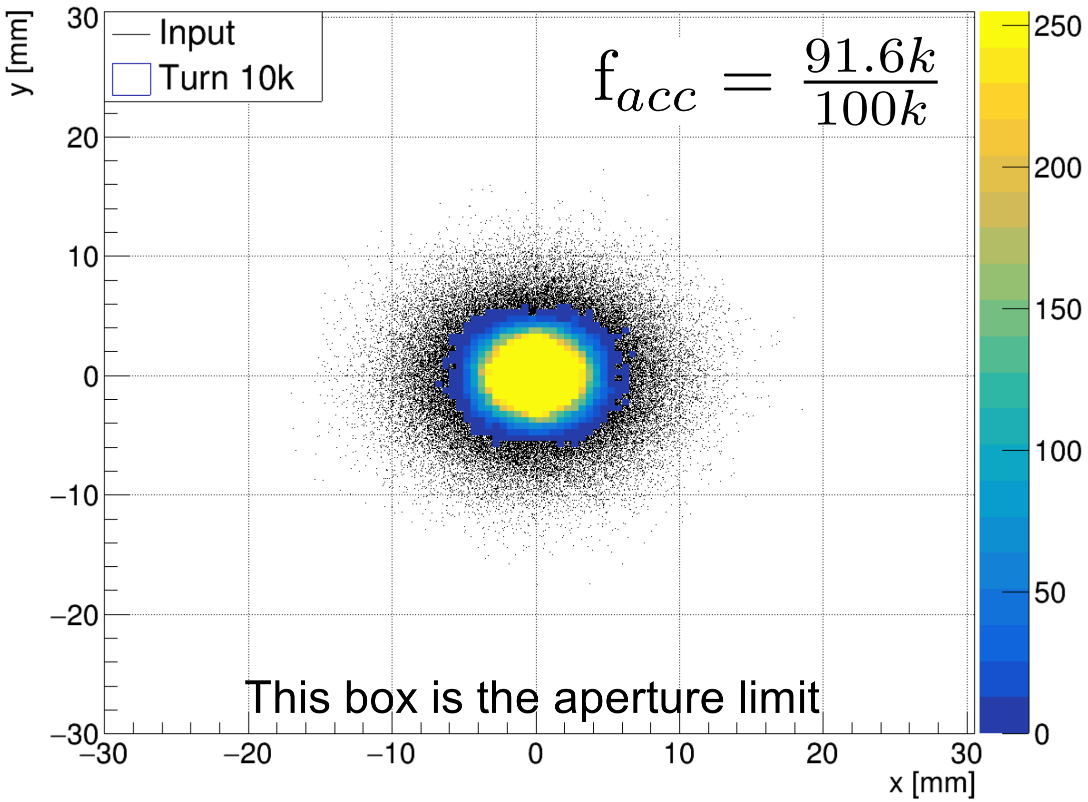
Simulations with EC(Elegant) distributions are on-going (no major difference expected)

DR Acceptance



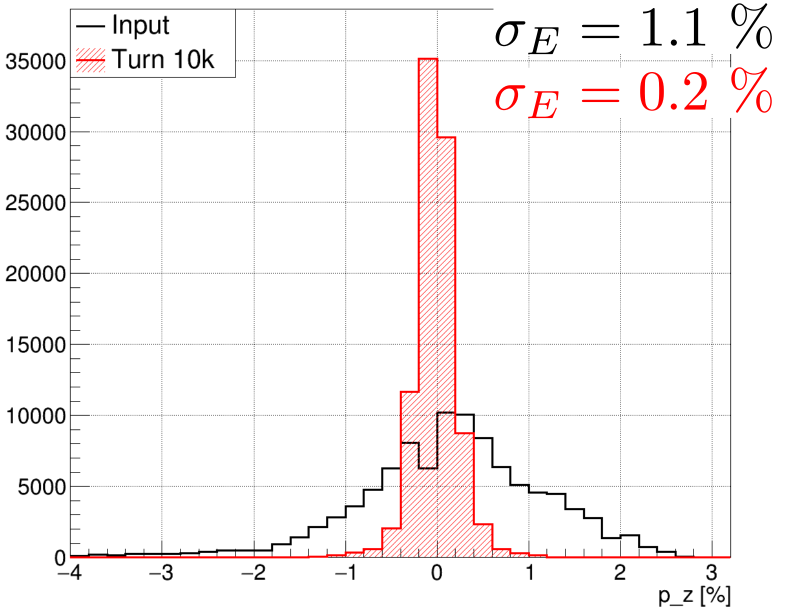


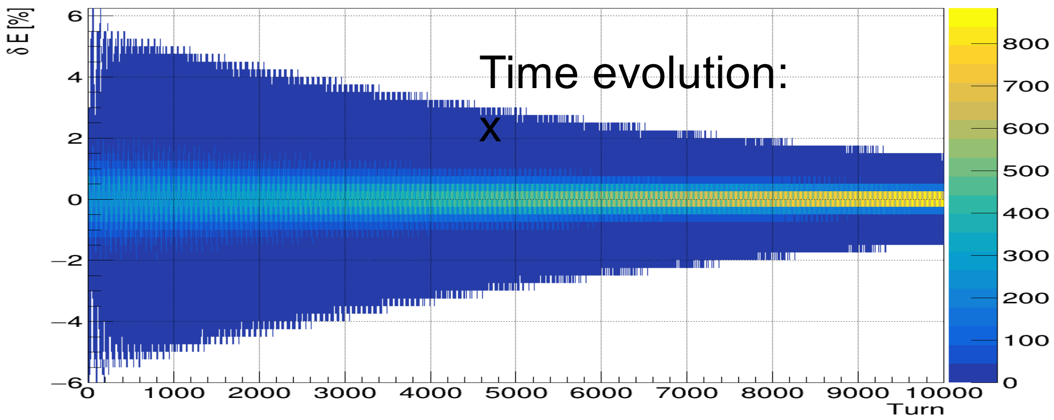


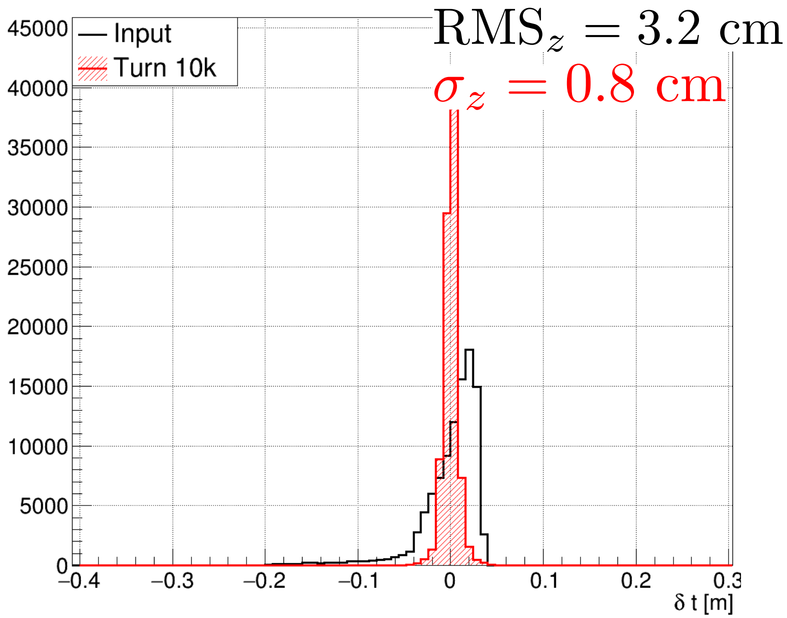


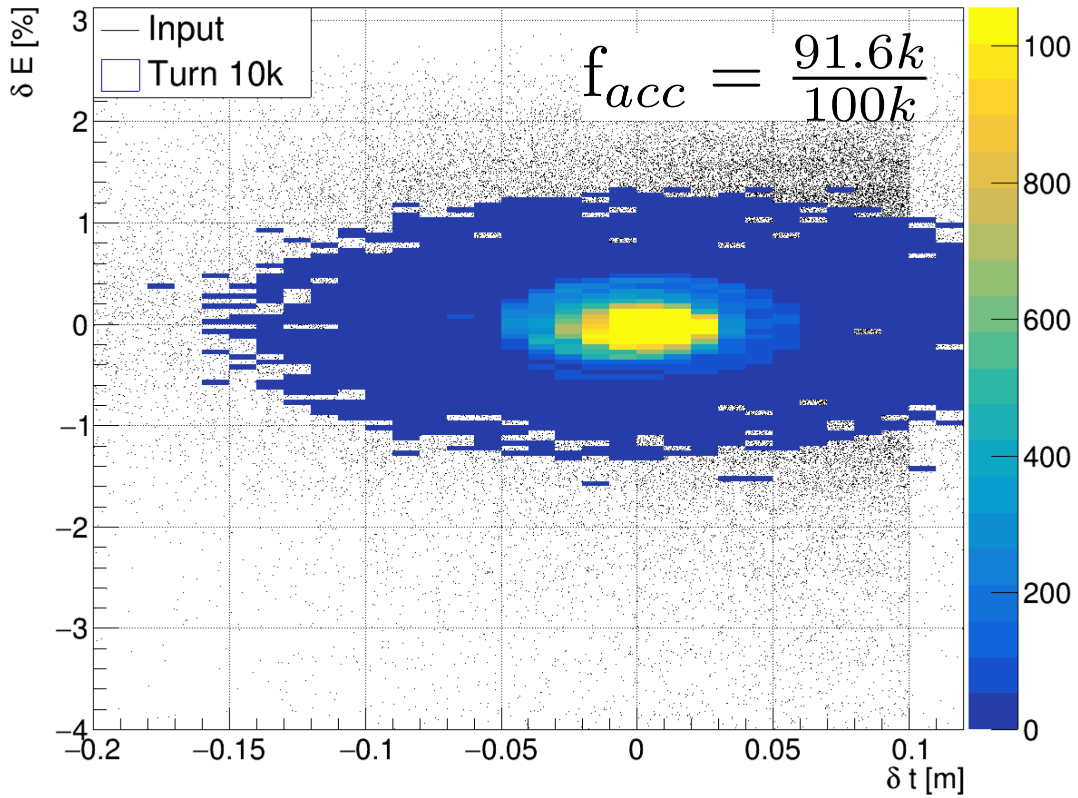
Damping Ring acceptance

Initial distributions are strongly asymmetric

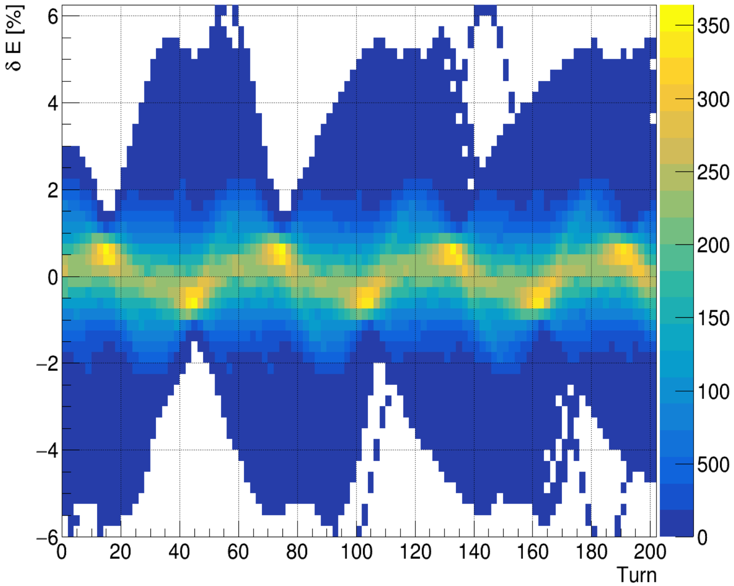






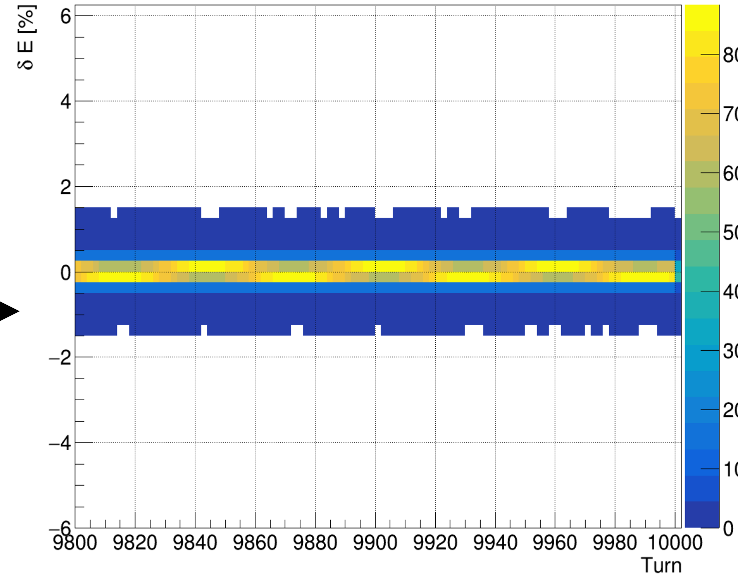


Energy Distribution Evolution



After 8 ms

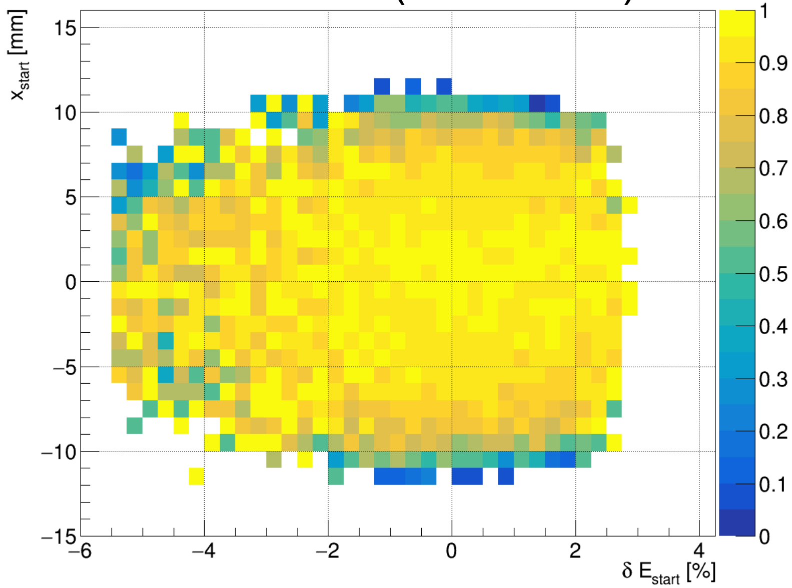
10k turns



At large energy deviation most of the losses are concentrated in the tail of the distribution as expected. Global DR acceptance:

$$f_{ACC} = 0.939 \text{x} 0.917 = 86.1\%$$

Particle losses (ratio out/in)



Recently the emittance of the beam provided by the pLINAC has been optimized -> an even larger DR acceptance is expected.

New DR acceptance is being evaluated.

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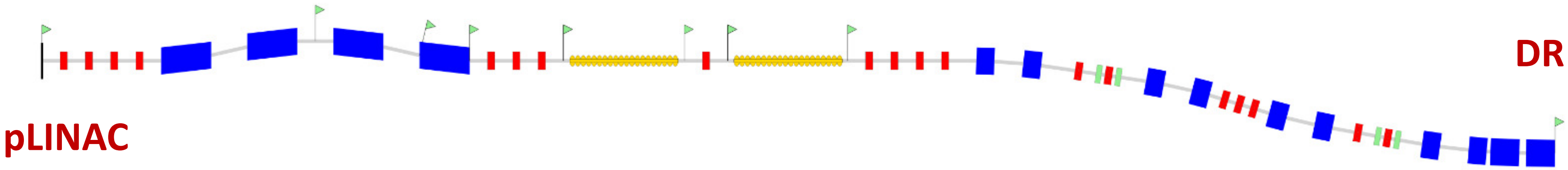
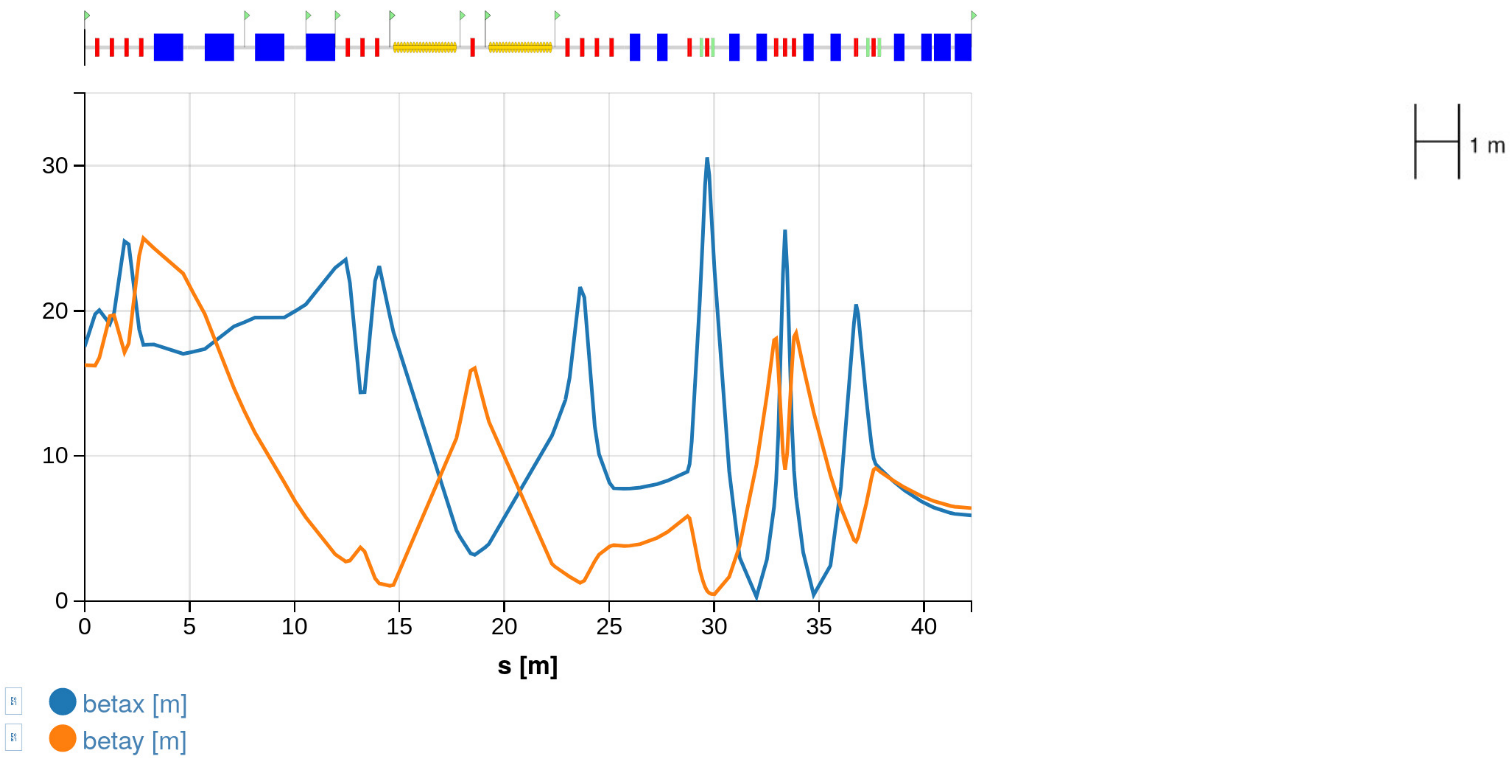
Transfer Lines, and Bunch Length Compressor

pLINAC to DR TL





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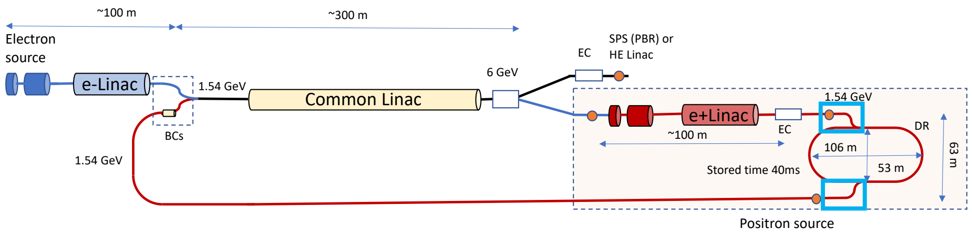
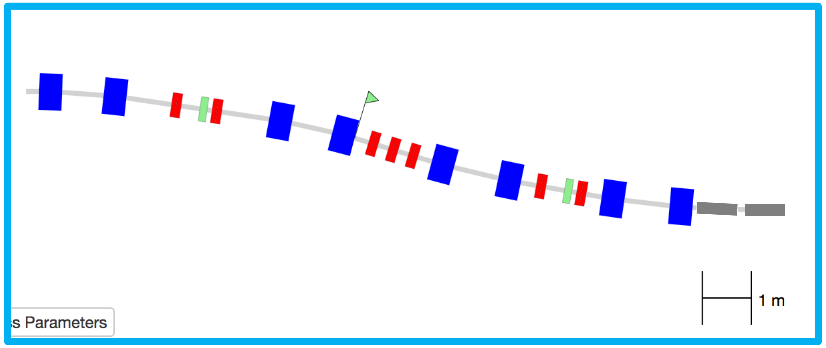
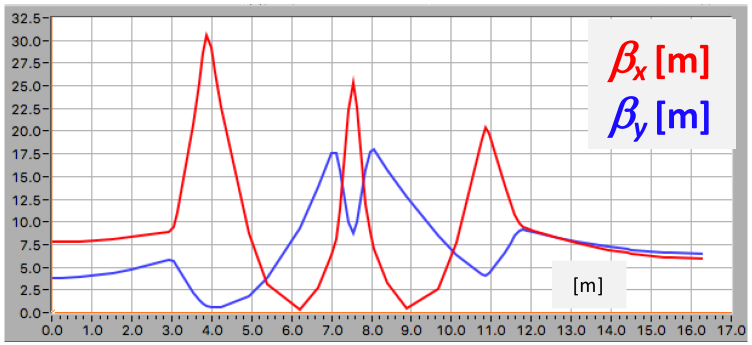
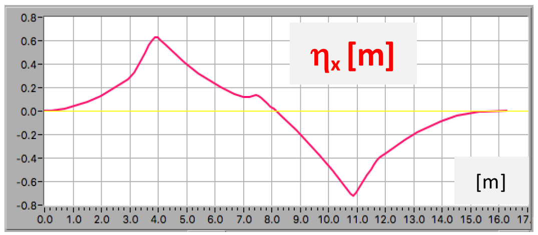
TL Injection Section

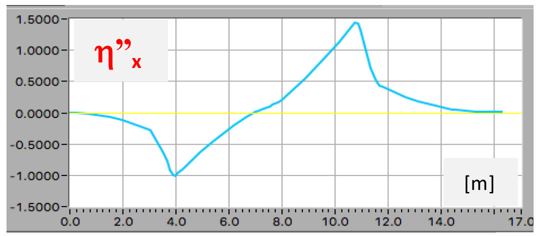






- *flexible*
- *achromatic*





	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

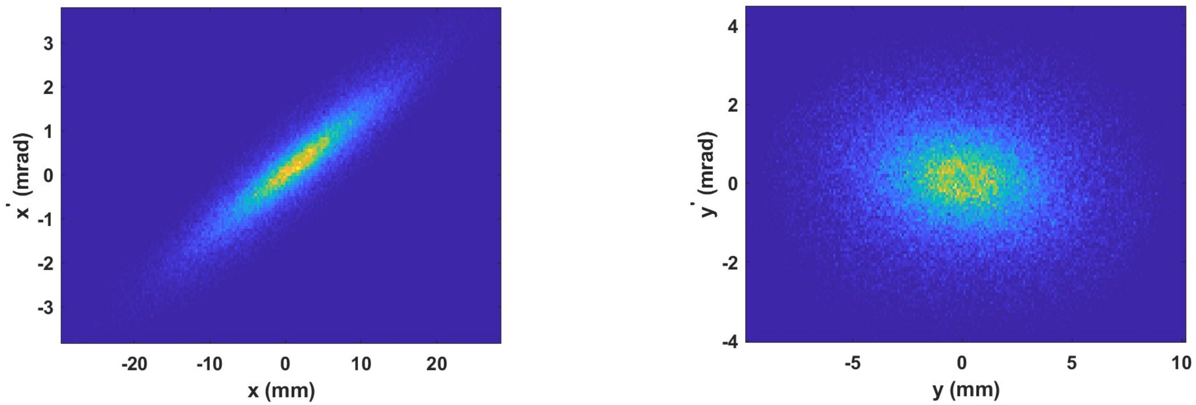
Transvers Distribution Evolution from pLINAC to DR

Transvers emittance is preserved

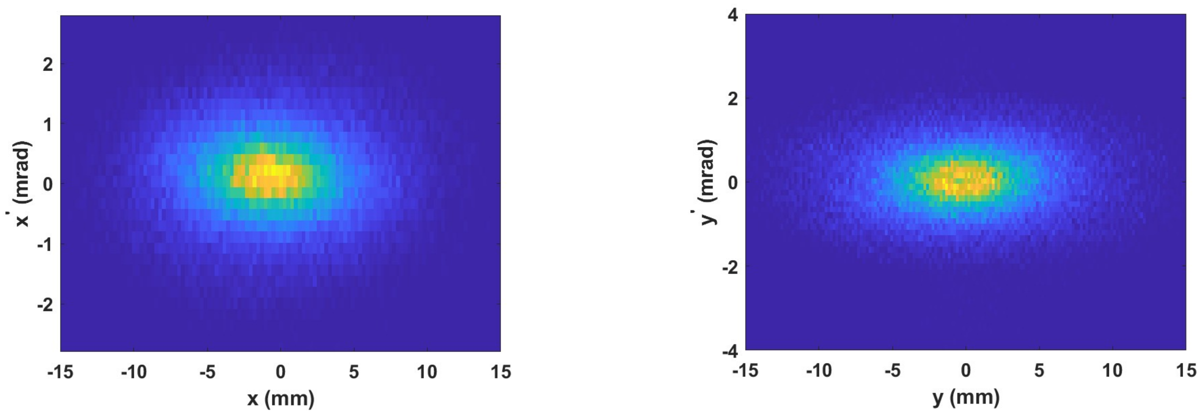
ε_x = 2.86 mm-mrad

ε_y = 3 mm-mrad

End of pLINAC



End of the injection transfer line



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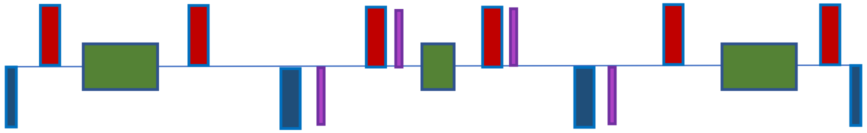
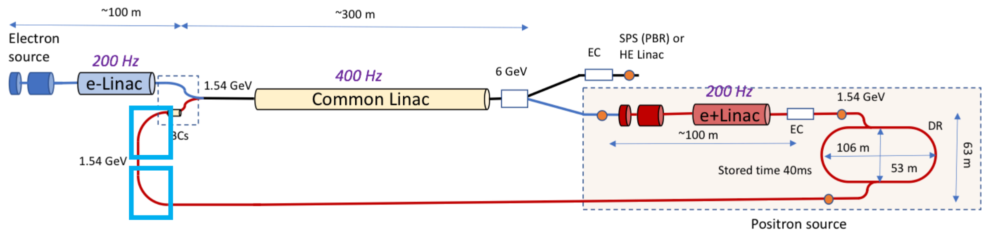
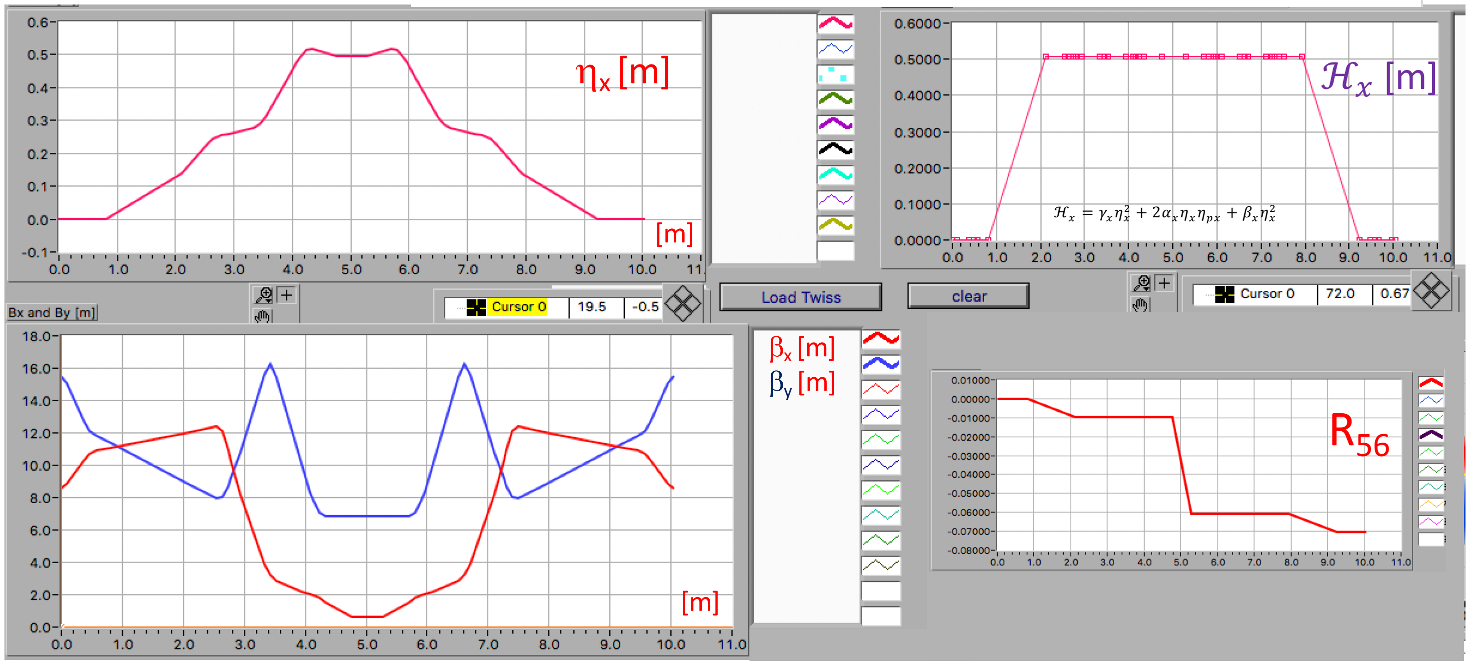
TBA Cell with R56 for Arcs





θ_b total [rad]	$\pi/2$
L_b [m]	1.0/0.5767
ρ [m]	5.736/3.304
B [T]	0.5366/0.9315
nQUADS	10
L_{QUA} [m]	0.2
L_{cell} [m]	10.0



Quadrupole gradient m^{-2}

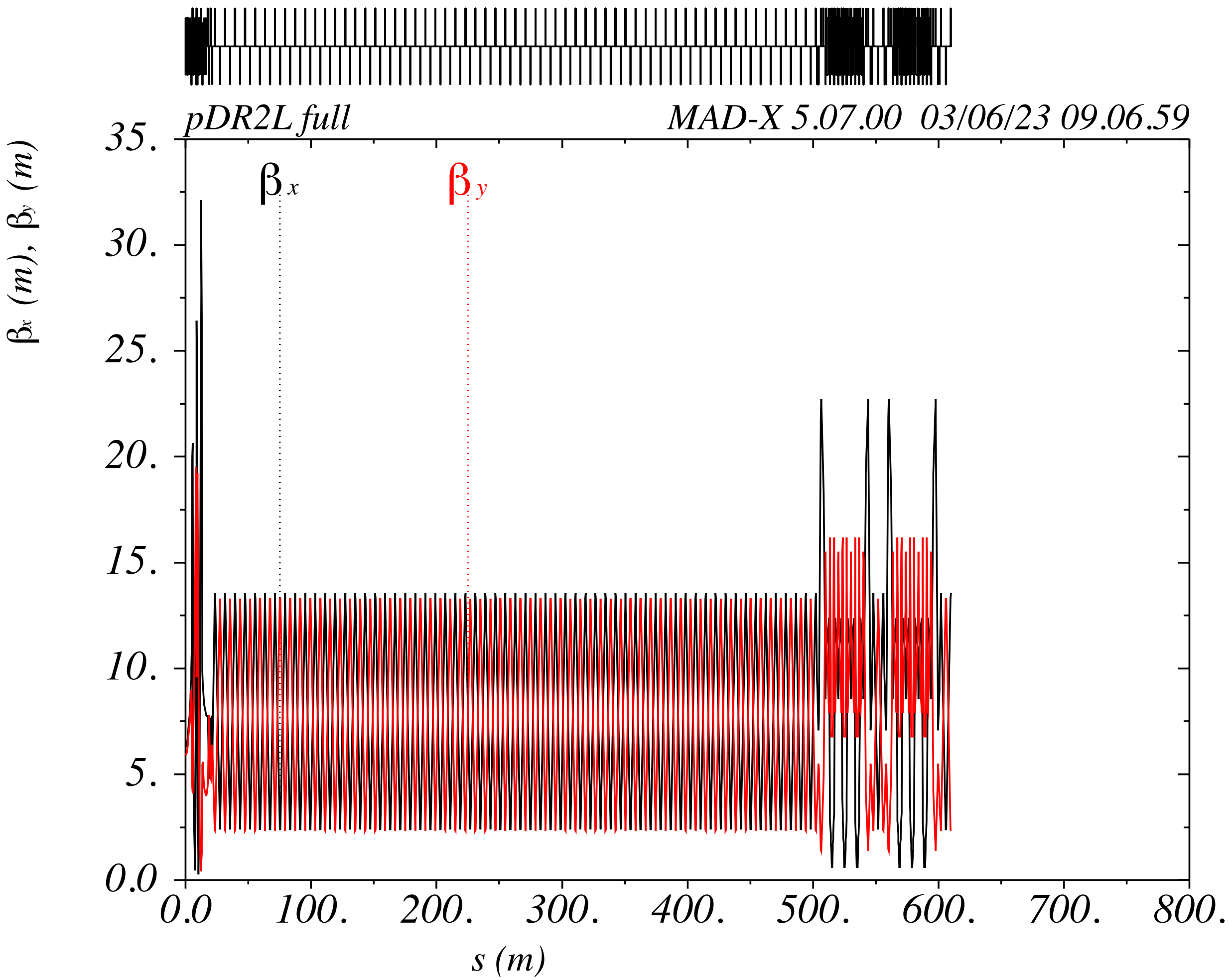
K1qf	3.47714
K1qd	-4.47514
K1qfe	1.1759
K1qde	-2.84811

Sextupole gradient m^{-3}

K2sf	1.7
K2sd	-2.8

- $\beta_{x,y} < 16$ m
- low η_x
- $\alpha_{x,y} = 0$ both ends
- achromatic
- low invariant
- R56 ~ 0.07 m

DR to common LINAC TL



Bunch Compressor Design

Beam parameters after Damping Ring

- Equilibrium (zero current) bunch length 2.9mm assuming V_{RF} = 4MV
- **Expected bunch length < 5mm**
- Equilibrium zero current bunch energy spread 0.07%
- **Expected Bunch energy spread ≈ 0.1%**
- Equilibrium emittance 0.96 nm (normalized emittance 2.9 mm*mrad)

Beam parameters at the common LINAC entrance

- **Bunch length ≈1mm**
- Relative bunch energy spread σ_γ < 0.65% at 1.54 GeV
- Normalized transverse emittance 3.4 mm*mrad

Bunch Compressor requirements

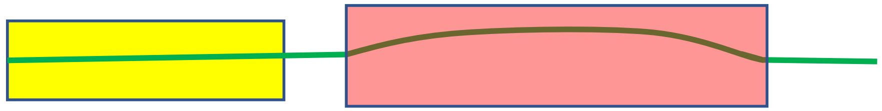
- Compressor factor 1-5 variable
- Final relative energy spread after BCS σ_γ < 0.65%
- **Preserve transverse emittance.**

BCS Design

- In order to achieve $\sigma_\gamma < 0.65\%$ after BCS

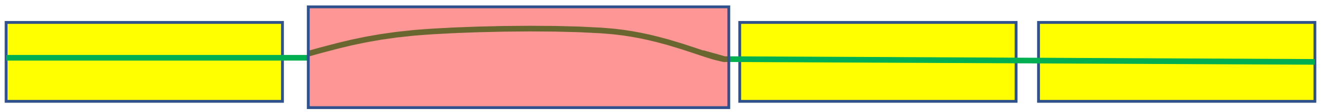
$$h = \frac{\sigma_\gamma}{\sigma_z} < 1.3\ \mathrm{m}^{-1} \qquad \text{Max } C = \frac{1}{1 - R56 * h} = 5 \qquad |R56| > 0.62\mathrm{m}$$

- R56 high for a single chicane



A de-chirper after the dispersive section can reduce |R56|

$$h = \frac{\sigma_\gamma}{\sigma_z} < 2.2\ \mathrm{m}^{-1} \qquad \text{Max } C = \frac{1}{1 - R56 * h} = 5 \qquad |R56| > 0.4\mathrm{m}$$

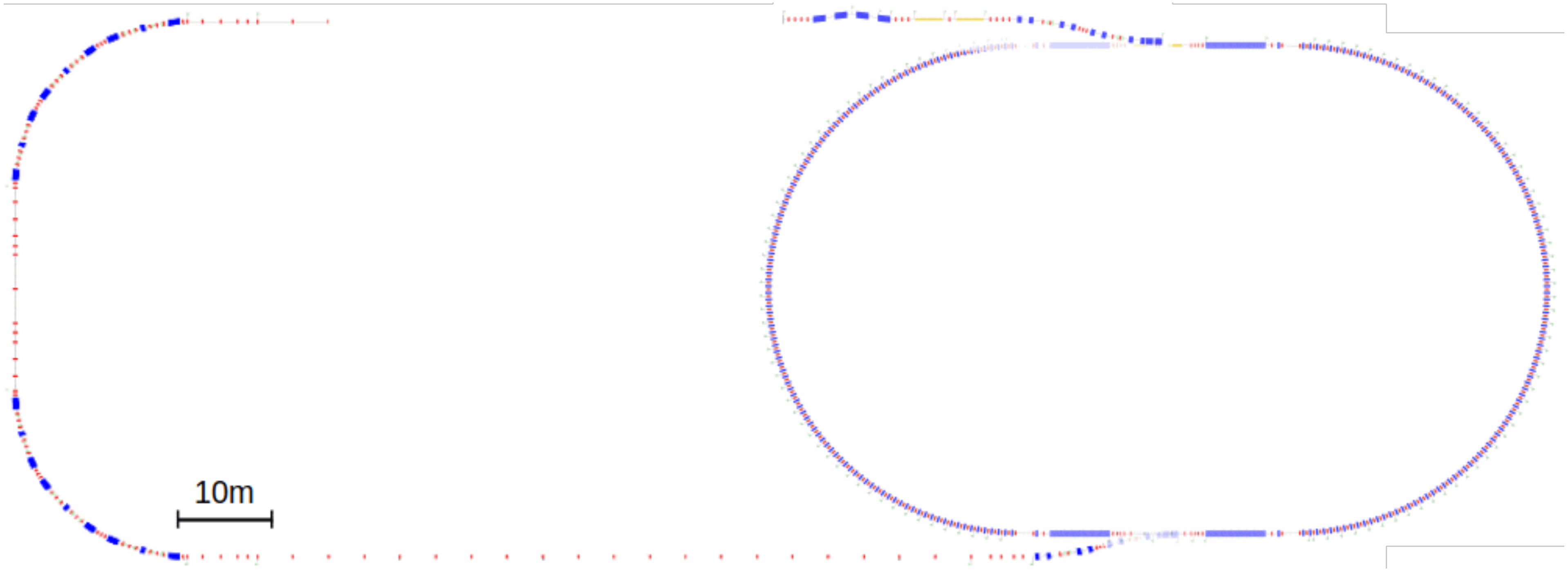


Cavity parameters (PSI design of the common LINAC THPOJO08 LINAC 2022**)**

- frequency 2.80 GhZ
- 84 cells for 3m structure
- One structures operating at a gradient of 20MV/m (60MV total) to chirp the beam
- Two structures operating at a gradient of 25MV/m (75MV total) to de-chirp the beam

Tunable |R56| > 0.42 m is provided by the arc cells of the TL connecting DR to common LINAC

DR and TLs Layout



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New DR Layout

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.

Present DR design:

- **The CDR DR includes a very large number of elements**
- **232 short dipole magnets** were used: which requires high number of components such as: quadrupoles, sextupoles, octupoles, steering magnets, and beam diagnostics high realization costs, complicate installation and alignment procedures.
- **Magnetic field in the dipoles are rather** low 0.66 T
- **Long damping wiggler** (26.56 m) are necessary to achieve required parameters
- Only 2 straight sections to host injection/extraction, Rf cavity and damping wigglers. This is not the best as far as NLD is concerned
- **Not optimum phase advance** were chosen for the beam emittance damping.

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Some of the new DR Layout

Parameters	**CDR**	**Option - 1**	**Option - 2**	**Option-3**
Energy [GeV]	1.54	1.54	1.54	**2.86**
Lattice type	FODO	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

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New DR Layout studies

- Different options are being evaluated including different type of cell and magnet
- In all the options, the number of elements was considerably reduced
- In a preliminary configuration (Option-2) beam parameters were achieved even without damping wiggler insertions which helps in simplifying vacuum chamber design impedance budget and realization costs.
  Option-2 also minimize curly H function which is important to avoid emittance dilution effects due to CSR

Conclusions

DR and TLs design has been completed

A DR acceptance larger than 86% can be achieved with the help of an ECS installed between the pLINAC and the DR injection line.
ECS reduces energy spread to ~ 2%.

A BCS has been included in the return line from the DR to Common LINAC.
BCS can provide maximum compression factor C ~ 5.

A breakdown schedule of the the components used for the different parts has been prepared costs are being evaluated.

Alternative DR designs are being considered.

Acknowledgment

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Spare Slides

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WP4 WBS

ECS

- 232 DIPOLEs (21 cm each) in the arcs
- 258 QUADRUPOLEs (L = 0.20 m each mostly in the arcs)
- 232 SEXTUPOLEs (L = 0.08 m each mostly in the arcs)
- 4 WIGGLERs (L= 6.7 m each: 44 poles 5 cm long)
- 258 BPMs
- 258 CHVs
- 1 SLM
- 1 DCCT
- 4 Strip line at injection extraction septa
- 2 Fluorescent screen + trigger camera
- Streak camera
- White noise generator and spectrum analyzer
- 2 Straight section hosting RF Cavity and Injection/Extraction equipment
- 4 injection/extraction kickers (Yann)
- RF (need info from CERN expert)

EBS

WP4 WBS

Damping Ring

- 232 DIPOLEs (21 cm each) in the arcs
- 258 QUADRUPOLEs (L = 0.20 m each mostly in the arcs)
- 232 SEXTUPOLEs (L = 0.08 m each mostly in the arcs)
- 4 WIGGLERs (L= 6.7 m each: 44 poles 5 cm long)
- 258 BPMs
- 258 CHVs
- 1 SLM
- 1 DCCT
- 4 Strip line at injection extraction septa
- 2 Fluorescent screen + trigger camera
- Streak camera
- White noise generator and spectrum analyzer
- 2 Straight section hosting RF Cavity and Injection/Extraction equipment
- 4 injection/extraction kickers (Yann)
- RF (cost evaluated by CERN expert)