Istituto Nazionale di Fisica Nucleare
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FCC-ee Injector
WP4
General status, and Transfer Line Overview

Milardi C., De Santis A., (LNF-INFN, Italy)
Etisken O., (Kirikalle University, Turkey)
Ramjiawan R. L., Y. Dutheil , (CERN, Geneva, Switzerland)

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FCC-ee Injector
project organization

- WP0 - Coordination
- WP1 – e+/e- 6 GeV Injector LINACs
- WP2 - e+/e- LINAC extension studies
- WP3 – Positron source: target and capture system
- WP4 – Damping Ring and Transfer Lines
- WP5 – CDR +
- WP6 – PoP e+ source at SwissFEL

Coordinators:
Alexej Grudiev (CERN)
Paolo Craievich (PSI)

Laboratories involved:
PSI
CERN
IJCLab - CNRS
LNF -INFN

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WP4 Structure and Organization

4.1 Damping Ring coordinator C. Milardi:

- **C. Milardi**,
- A.De Santis,
- R. L. Ramjiawan (CERN),
- Y. Dutheil (CERN),
- O. Etisken *,
- *CERN collaboration on RF systems.*

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 #

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 #.

* 1 year postDoc position since Mar 2023
\# 2 years temporary position starting on Dec 5th 2022.

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Damping Ring

Comprehensive ***tools for tracking studies*** have been set up.

Dynamic aperture has been evaluated over a wide δ_E range (± 4%).

DR ***longitudinal beam dynamics*** parameters have been evaluated in the approximations:

- stationary bunches
- equilibrium conditions
- assuming to install on the ring the 400 MHz LHC type SC RF cavity

A preliminary estimated of the ***RF power*** necessary to restore the incoherent synchrotron radiation emission has been done considering the bunch filling scheme of the DR.

A preliminary parametric analysis aimed at evaluate the impact of **collective effects** has been done for an intermediate DR layout version, it must be repeated for the latest DR optics.
Collaboration with other LNF expert and with La Sapienza have been established in order to address more systematic studies.

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Injection/Extraction timing

A general scheme to implement injection/extraction process in/from the DR has been proposed, it aims at:

- making the DR filling with bunches as uniform as possible,
- assuring the proper storing time suitable for e^+ beam damping,
- providing the necessary delay time, 2.5 msec, required to guarantee single beam, species operations in the common LINAC,
- keeping timing properties of injection kickers pulse compatible with the state of the art in the field.

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Concerning:

- DR activities
- Injection extraction scheme

Details will be presented in the Antonio De Santis talk.

Rationale for a New DR Layout

Motivations to review the DR design:

- The latest DR optics uses a quite large number of elements (232 dipoles) which determine:
  high number of components such as: quadrupoles, sextupoles, octupoles, steering magnets, and beam diagnostics
  high realization costs,
  complicate installation and alignment procedures.
- Injection section has not optimal Twiss functions
- Long damping WIGGLER magnets (the CDR includes 4, 6.64 m long magnets)
- Magnetic field intensity in the dipole is rather low and can be safely pushed toward values higher than 0.66 T,
- Having 3 Straight sections, instead of 2, might be better in terms of NLD and to avoid interferences among: damping wiggler magnets, RF and injection/extraction.
- Arc cells phase advance for the beam emittance damping can be optimized.

Preliminary design approach:

- ❖ Higher magnetic field which makes damping time shorter,
- ❖ Less magnets leding to larger emittance,
- ❖ Optimum phase advance for the FODO lattice,
- ❖ Three straight sections,
- ❖ Robinson WIGGLER has been added for emittance cooling.

New DR Layout

On going studies steaming from discussion within the FCC-ee collaboration aim to:

- meet some new parameter requirements:
  - emittance ~ 2 nm.rad,
  - damping time ~ 7.5 ms.
- eliminate Robinson WIGGLER magnet
- reduce dipole magnetic field intensity below 1.5 T.

As a possible approach we are considering to adopt dipole with field index for the arc cell bending magnets, in order to reduce emittance and have a more compact layout.

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Concerning:

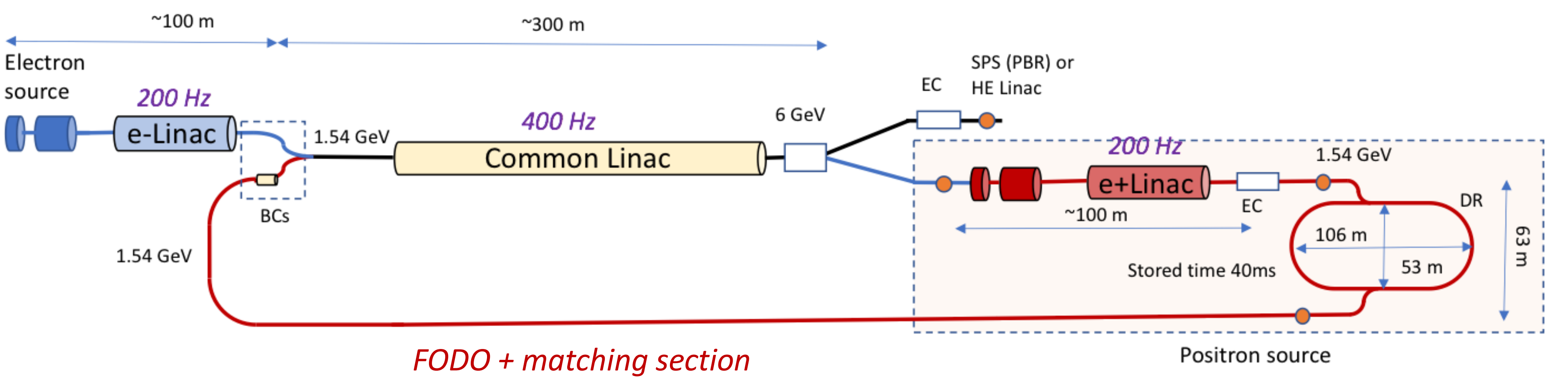
DR new optics layout study

Details will be presented in the Ozgur Etiksen talk.

Transfer Lines

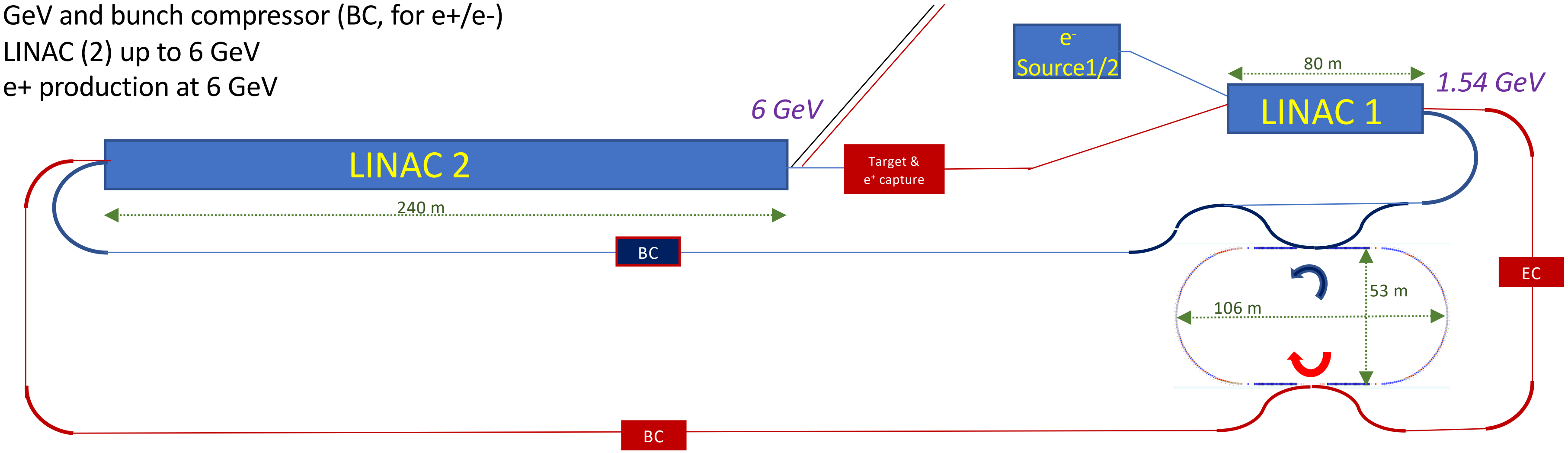
Several injector layout have considered with different TL arrangements

Latest FCC-ee injector layout 6 GeV option (since April 2022)



Injector Layout

- e- source
- Linac (1) up to 1.54 GeV
- Energy compressor (EC, for e+), damping ring (DR, for e+/e-) at 1.54 GeV and bunch compressor (BC, for e+/e-)
- LINAC (2) up to 6 GeV
- e+ production at 6 GeV



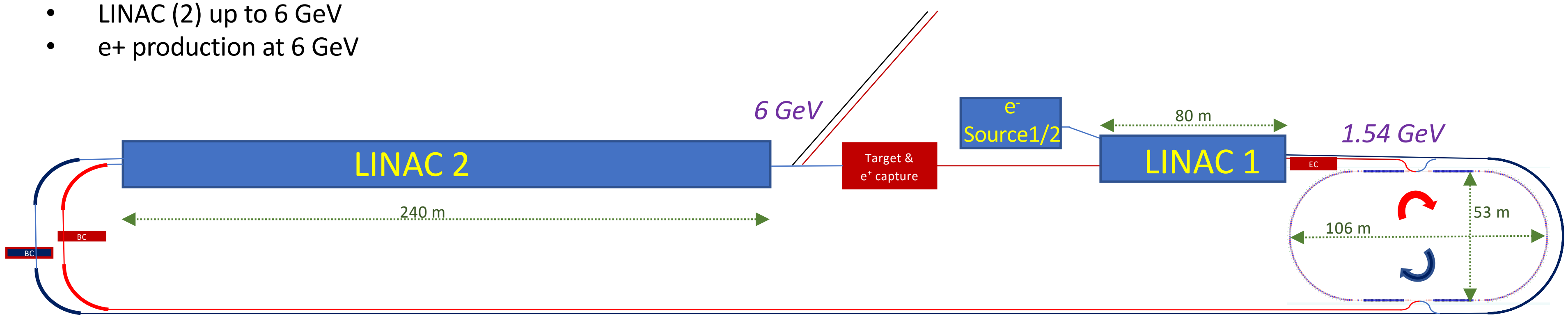
- Injection system is designed to damp positron and electron either
- **Simplified** and **modular design** based on:
  - 90 degree arc
  - 180 degree arc
  - dogleg
  - straight sections based on FODO cell
- Transfer lines are independent for the two beams beams and for injection/extraction
- Damping ring can store electron and positron without any modification
- Design flexible and compatible with requirements imposed by:
  - LINAC operation
  - Collider injection requirements

(28/10/21)

Injector Layout update

(27/01/22)

- e- source
- Linac (1) up to 1.54 GeV
- Energy compressor (EC, for e+), damping ring (DR, for e+/e-) at 1.54 GeV and bunch compressor (BC, for e+/e-)
- LINAC (2) up to 6 GeV
- e+ production at 6 GeV

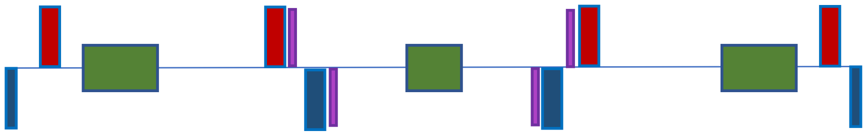


- Injection system is designed to damp positron and electron either
- **Simplified** and **modular design** based on:
  - 90 degree arc
  - 180 degree arc
  - asymmetric dogleg in the two injection sections
  - straight sections based on FODO cell
- Transfer lines are independent for the two beams beams and for injection/extraction
- Damping ring can store electron and positron without any modification
- Design flexible and compatible with requirements imposed by:
  - LINAC operation
  - Collider injection requirements

(presented at the meeting on Nov. 30th 2021)

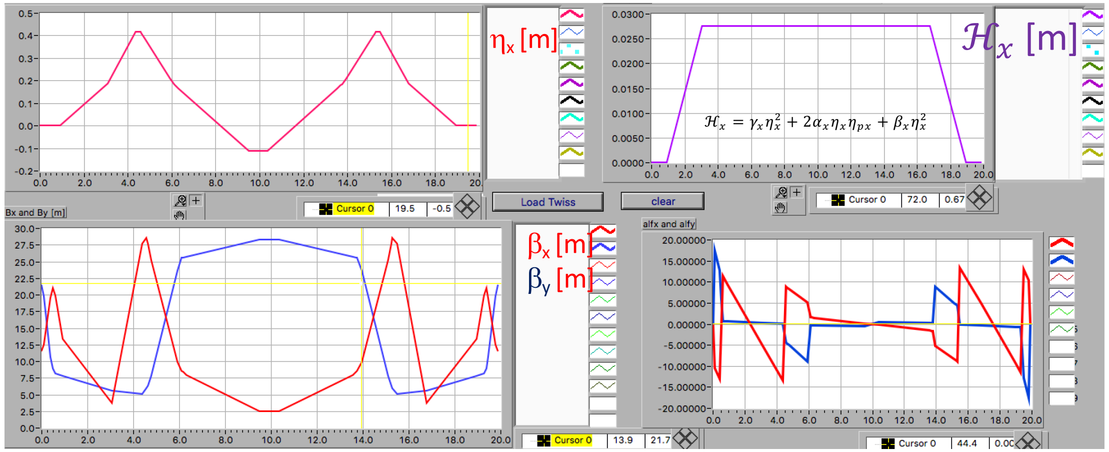
https://indico.cern.ch/event/1100972/

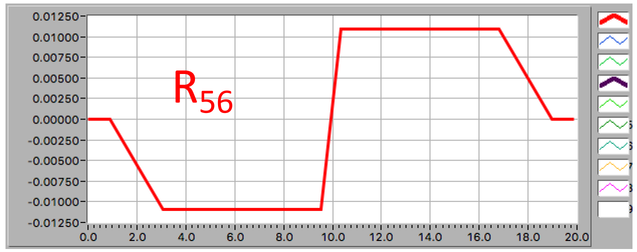
Triple Bend Achromat Cell for Arcs



For $\pi/2$ arc

θ_b [rad]	0.17453
L_b [m]	2.163/0.853
ρ [m]	2.864789
B [T]	0.415/1.05
nQUADS	8
L_{QUA} [m]	0.2
L_{cell} [m]	19.88





Quadrupole gradient m^{-2}

K1qf	3.92436
K1qd	-1.76910
K1qfe	6.07971
K1qde	-8.56306

Sextupole gradient m^{-3}

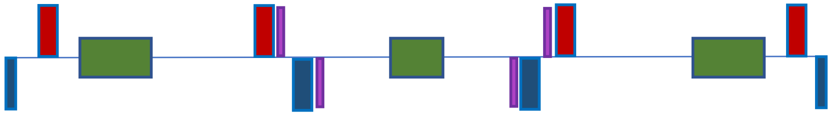
K2sf	2.64432e+01
K2sd	-3.58626e+01

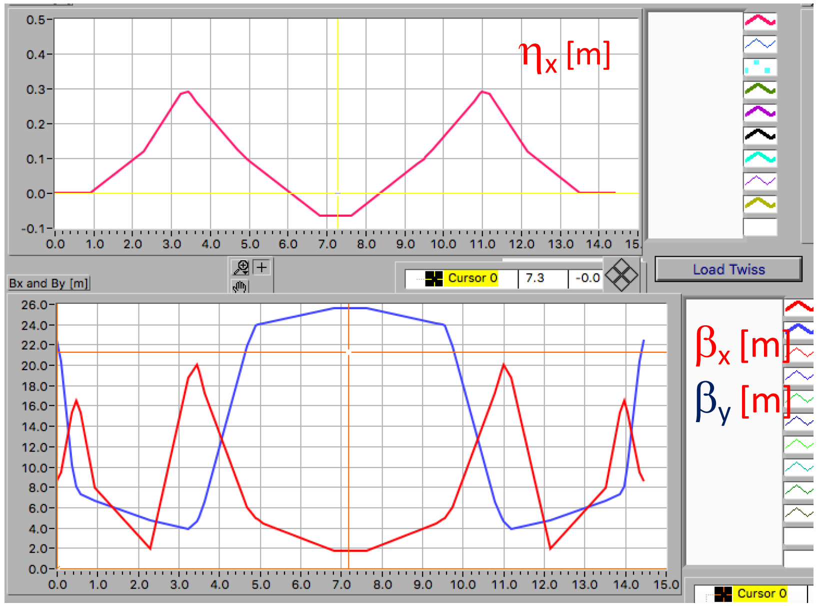
- $\beta_{x,y}$ < 30 m
- low η_x
- $\alpha_{x,y}$ = 0 both ends
- achromatic
- isochronous
- low invariant

$q_x = 1.32$
$q_y = 0.31$

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

Triple Bend Achromat Cell for π Arc

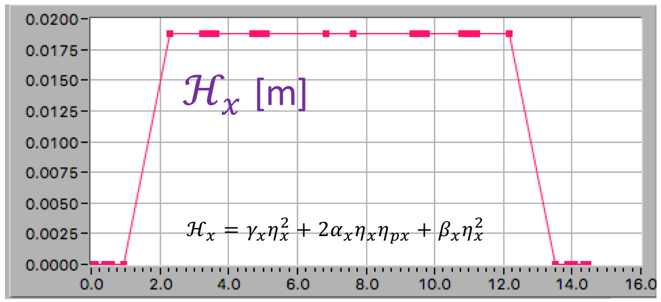


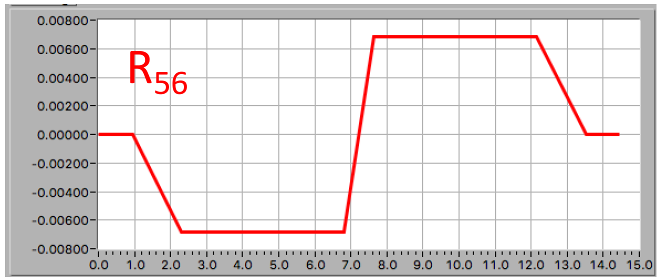


- $\beta_{x,y}$ < 30 m
- low η_x
- $\alpha_{x,y}$ = 0 both ends
- achromatic
- isochronous
- low invariant

$mu_x = 1.32$
$mu_y = 0.31$

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





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}

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

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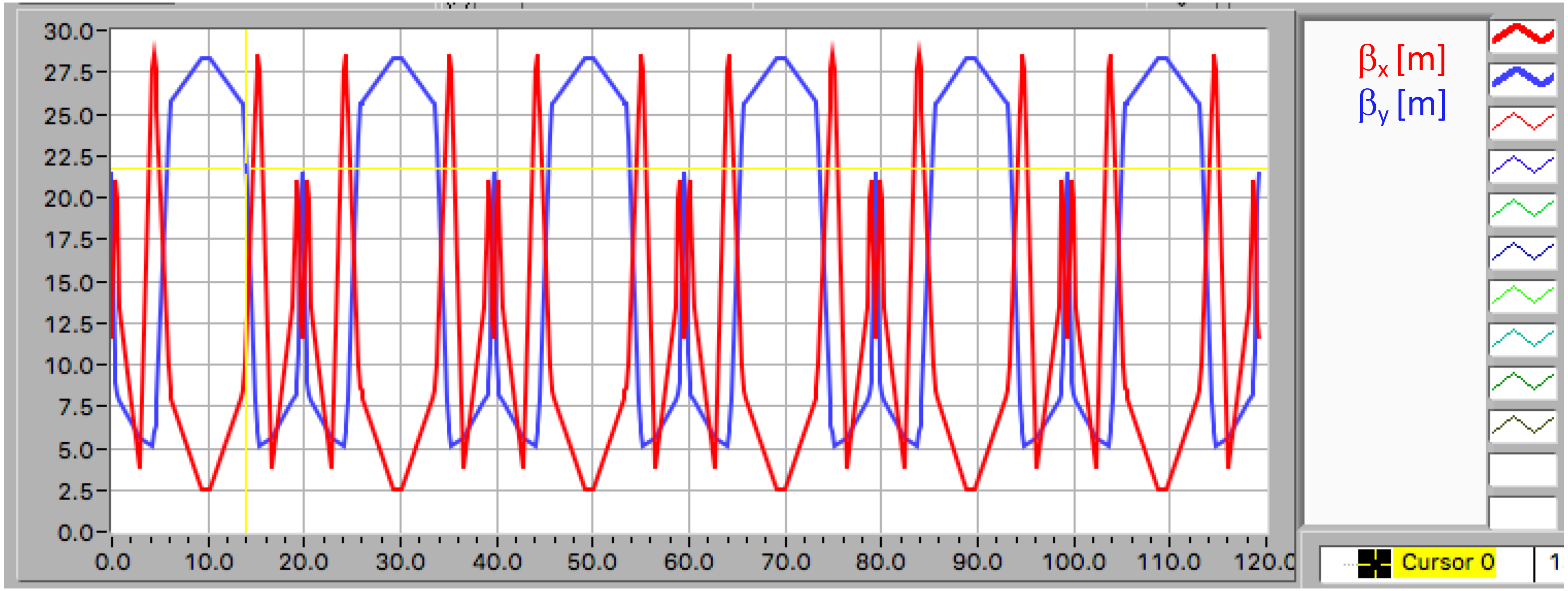
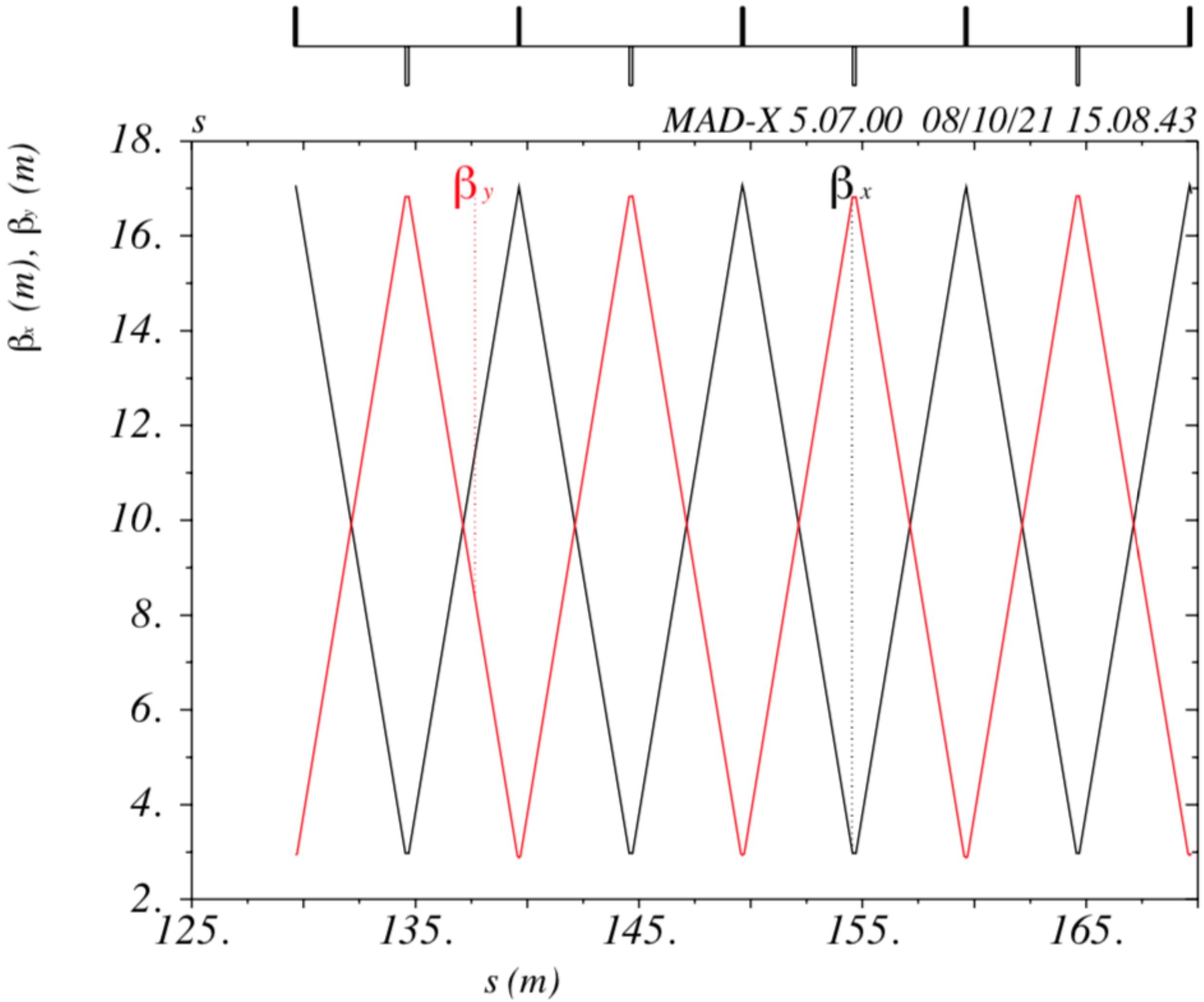
Twiss functions in the Turn around Loop

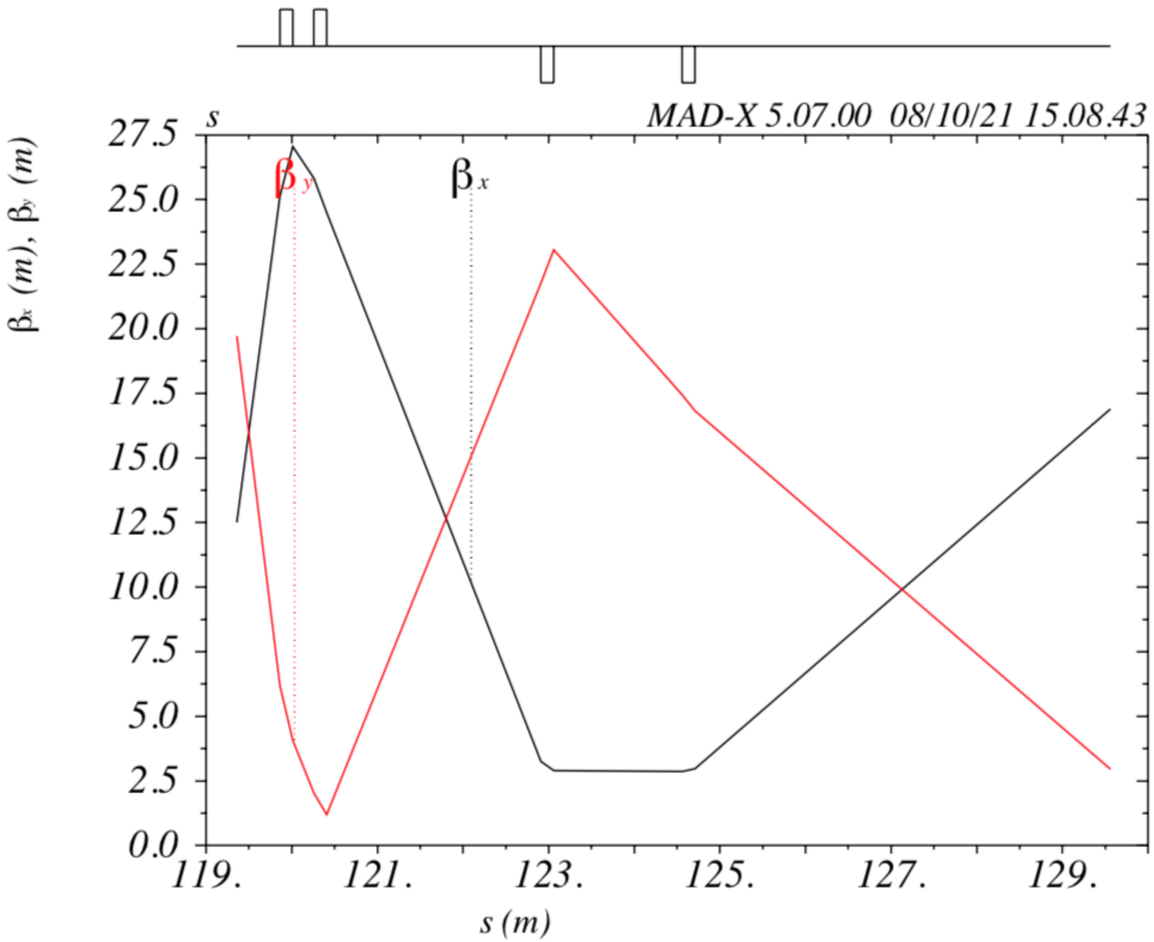


FODO Section

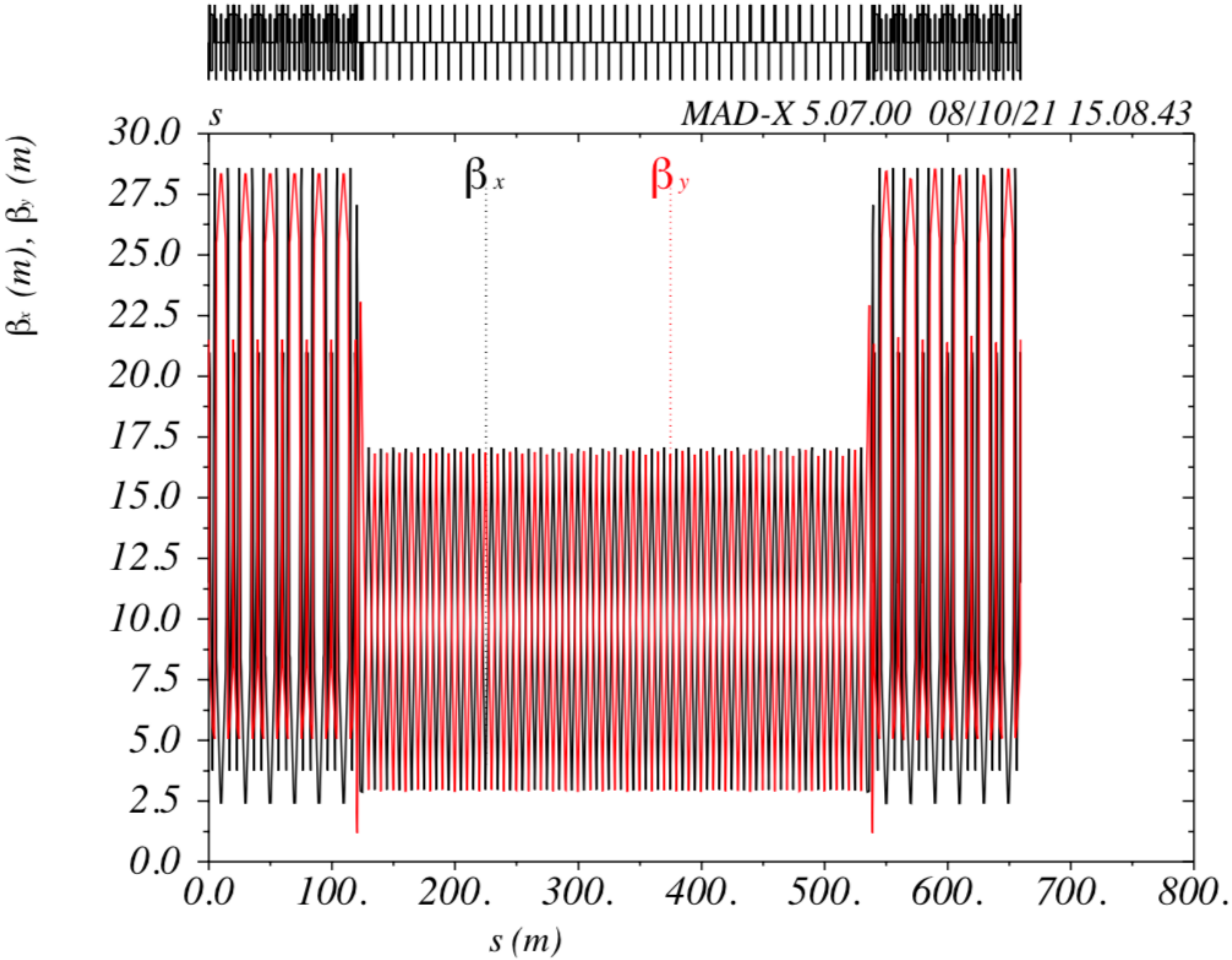


Matching Section

(between TBA and FODO)

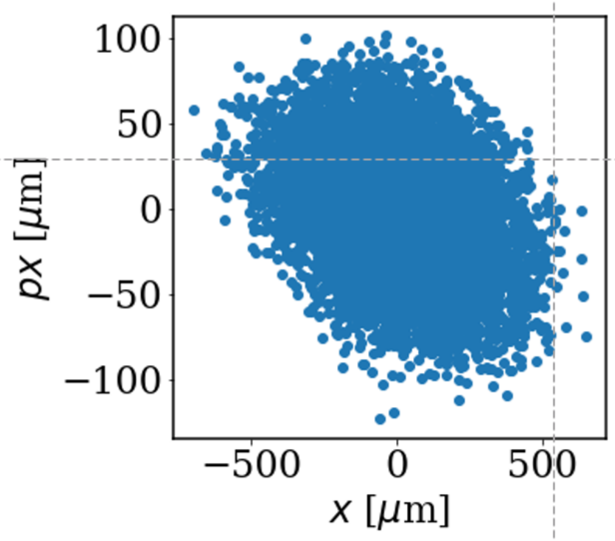


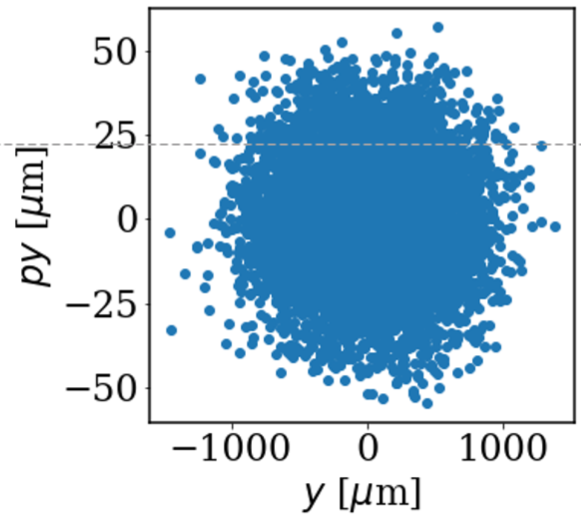
TL Twiss functions



Tracking (Elegant)

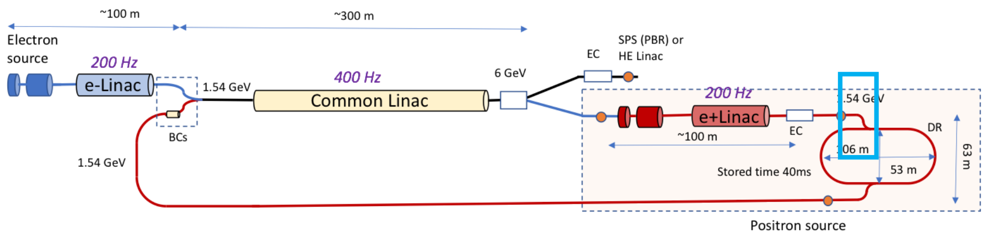
- Statistical emittance at end $\epsilon_x = 5.9$ nm rad, $\epsilon_y = 6.1$ nm rad.
- Statistically from tracking $\beta_x = 6.14, \beta_y = 22.44, \alpha_x = 0.34, \alpha_y = 0.02$.

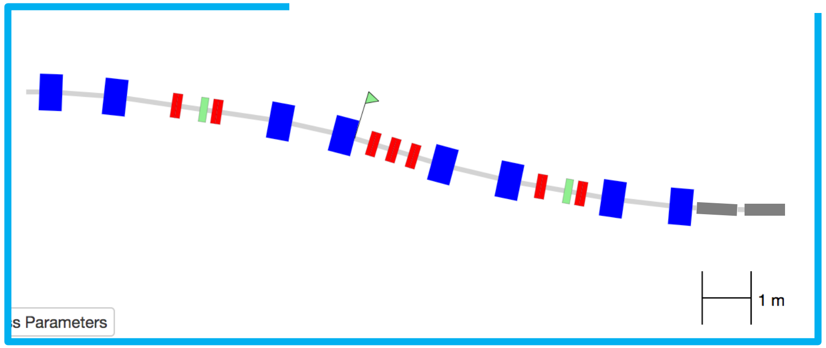


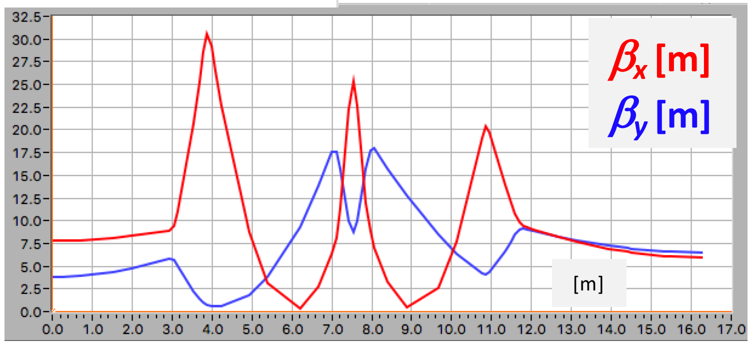


The exercise will be repeated with a different code as ***CSRtrack***

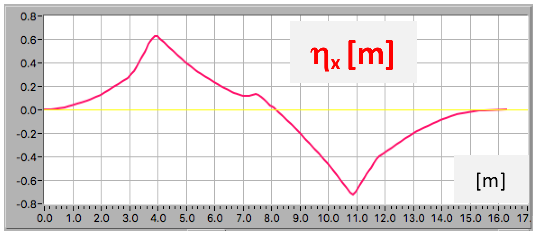
TL Injection Section

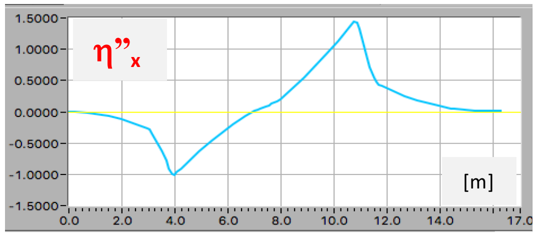




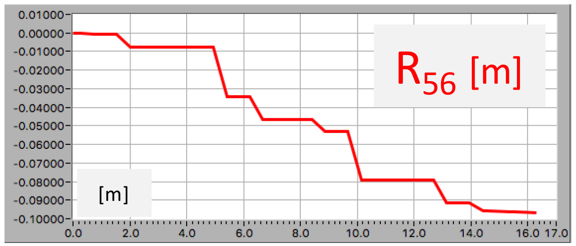


- *flexible*
- *achromatic*
- R_{56} *~ - 9.5 cm*





	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



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Injection in the Damping Ring

On - Axis injection in the horizontal plane

Incoming particles are injected on the ring nominal orbit at the end of the injection kicker.

Septum and kicker field must not perturb the stored beam

In order to minimize injection kicker strength septum must be as close as possible to the ring nominal orbit

Septum stray field must be very well shielded

On-Axis Injection

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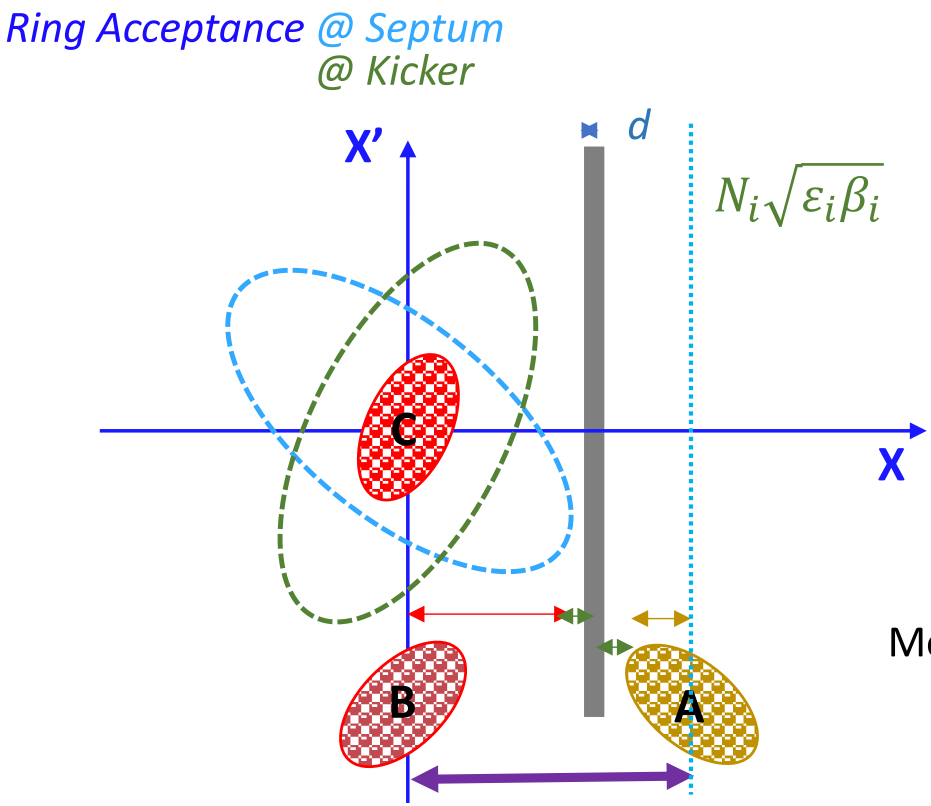
Horizontal transverse phase space



N_i *number of standard deviation of the incoming beam*
ε_i emittance of the incoming beam
d *septum thickness*
*Incoming beam matched with the ring at the entrance **A***
*Beam injected on axis in **C***

$$x_{inj} = HW_{inj} + 2*trj + d + HW_{acc}$$

Moving to normalized phase space coordinates ***X, X'***

$$\boldsymbol{X} = \frac{x}{\sqrt{\beta}} \qquad \boldsymbol{X}' = \frac{(\alpha x + \beta x')}{\sqrt{\beta}}$$

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Kicker Strength

$$\begin{pmatrix} X_{kck} \\ X'_{kck} \end{pmatrix} = \begin{pmatrix} \cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x \end{pmatrix} \begin{pmatrix} X_{spt} \\ X'_{spt} \end{pmatrix}$$

$X_{spt} = x_{inj}$
$X_{kck} = 0$
X'_{kck} determined so to minimize kicker strength

With some algebra

$$\boldsymbol{X'_{spt}} = -\frac{\cos\mu_x}{\sin\mu_x} X_{inj}$$

$$\boldsymbol{X'_{kck}} = -\frac{X_{inj}}{\sin\mu_x}$$

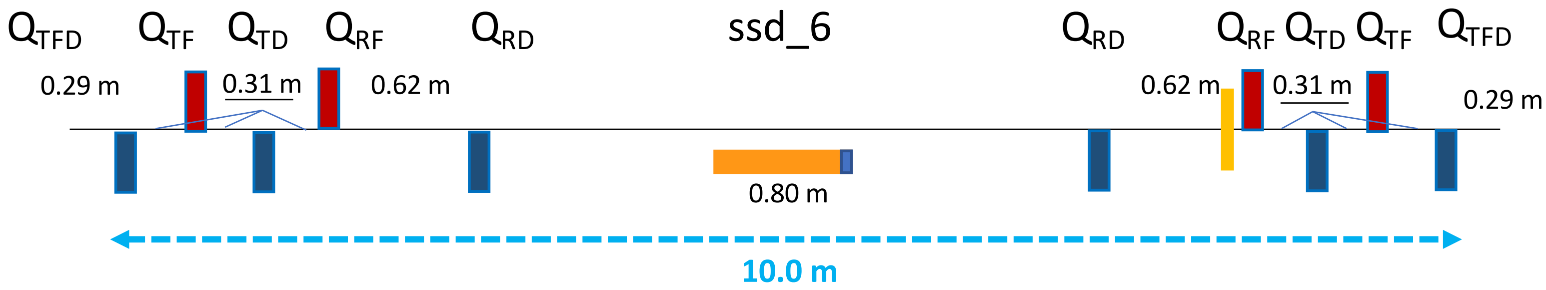
Going back to the initial coordinates

$$x'_{spt} = -\frac{x_s}{\beta_{spt}}\left(\frac{\cos\mu_x}{\sin\mu_x} - \alpha_{spt}\right)$$

$$x'_{kck} = -\frac{x_s}{\sin\mu_x\sqrt{\beta_{spt}\beta_{kck}}}$$

$$\theta_{kck} = \frac{x_{inj}}{\sin\mu_x\sqrt{\beta_{spt}\beta_{kck}}}$$

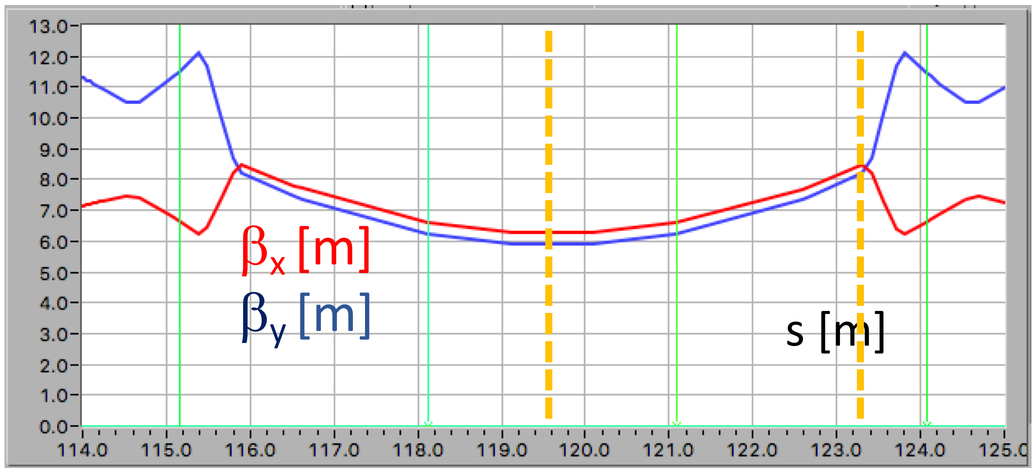
DR Injection Section



Twiss functions at injection septum:

- $\beta^{spt}{}_x = 6.3$ m
- $\alpha_{x,y} = 0$
- $\eta_{x,y} = 0$

$\beta^{kck}{}_x = 8.4$ m
Δmux(spt-kck) = 0.0728721
rather far from optimal

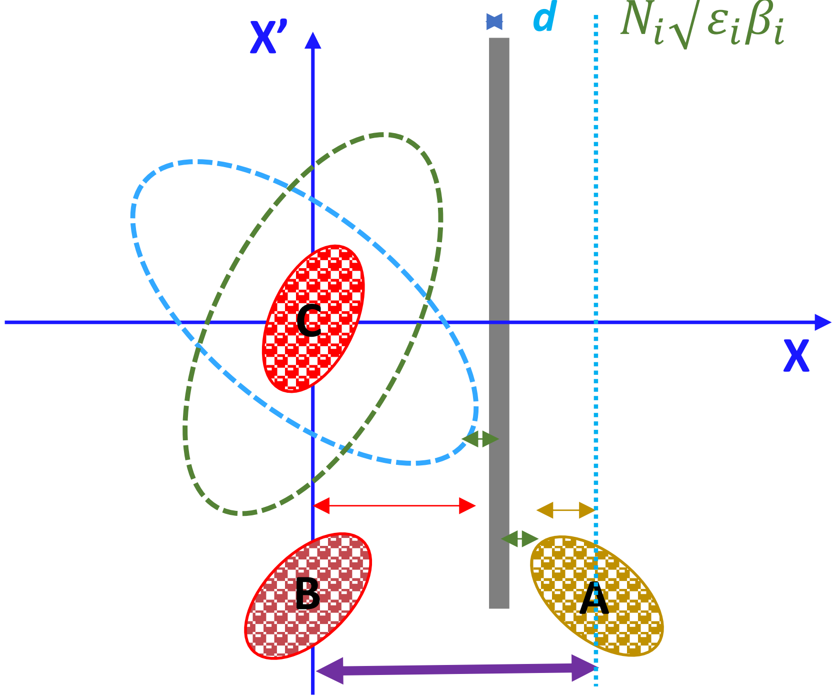


Ideal section no SXT
Injection Kicker position could be optimized
Twiss functions are not optimal for injection

On-Axis Injection

$$\theta_{kck} = \frac{x_{inj}}{\sin \mu_x \sqrt{\beta_{spt}\beta_{kck}}}$$

Horizontal phase space



x_{inj} = HW_{inj} + 2*trj + d + HW_{acc}

HW_{inj} = 0.0055 m
2*trj = 0.002 m
d = 0.002 m
HW_{acc} = 0.006 m

x_{inj} = 0.0155 m

θ_{kck} [rad] too high

Injection sections of TL and/or DR should be revised

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Conclusions

The WP4 project activities /tasks are both clear and fully planned

New people joining the group soon will give new strength to the work

Systematic **tracking studies** have been set up in order to to characterize in detail transverse beam dynamics and evaluate DR acceptance at injection.
Dynamical Aperture has been evaluated for the latest DR optics and the latest positron beam parameters at the injection.

Longitudinal beam dynamics parameter have been computed for the beam equilibrium configuration assuming to install on the DR the 400 MHz LHC type SC RF cavity.

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Conclusions

FCC hh ee he

Transfer Line design has been organized following high modularity criteria in order to cope with the unavoidable modifications.
Preliminary studies aimed at outlining possible CSR effect in the TL arcs have been done by using Elegant simulation code, no emittance dilution has been observed, however the exercise will be repeated with different codes.
A preliminary version of the DR injection/extraction section has been designed it’s parameters can be exploited, in combination with a chirped bunch, for bunch compression.

A preliminary parametric analysis aimed at evaluate the impact of **collective effects** has been done for the ‘After CDR’ DR layout version, it must be repeated for the latest DR optics.
Collaboration with other LNF expert and with La Sapienza have been established.

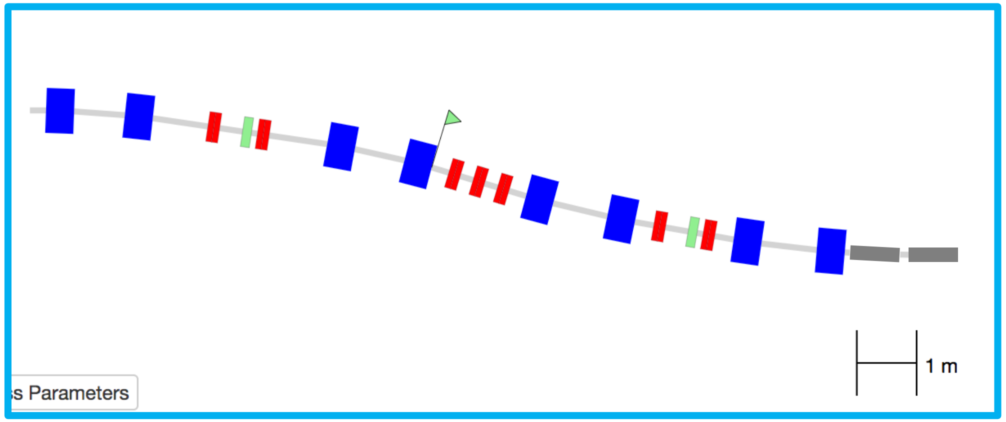
An injection/extraction timing scheme has been proposed it is compliant with the new injector layout.

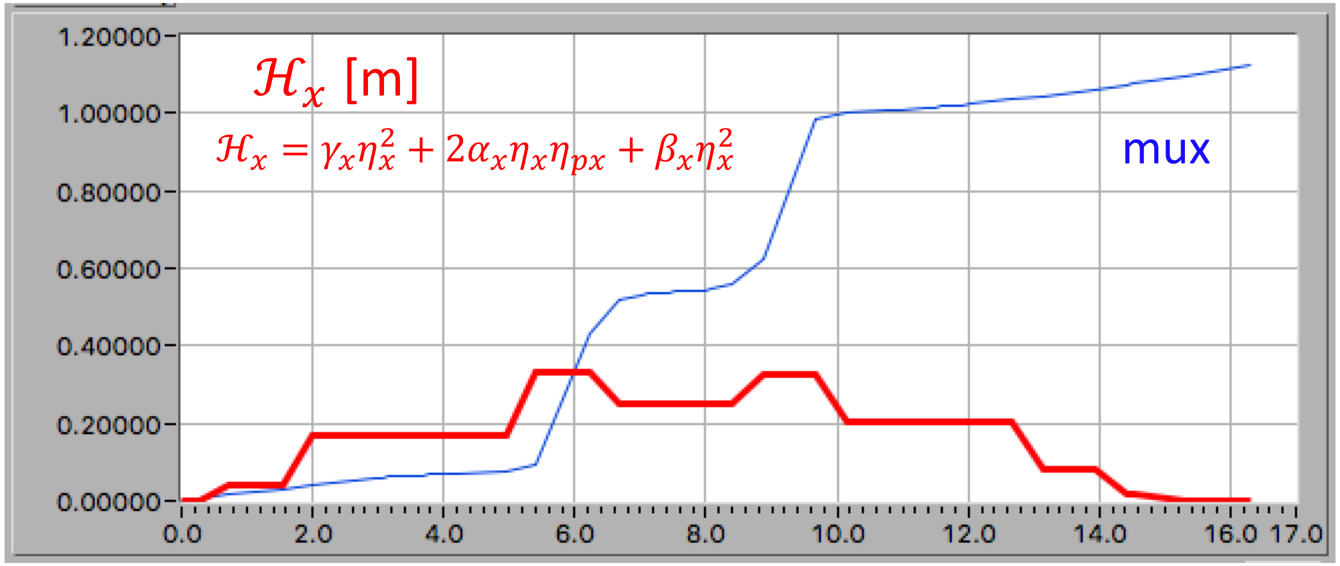
A new optimized DR layout is under study

Thank you

SPARES

TL Injection Section





General Consideration about Injection

On – Axis Injection

- the phase space accepting the incoming beam must be empty, staking is not possible,
- Injected pulse or train of pulse is shorter than revolution time,
- Septa and kickers must not act on the stored beam:

  stray fields of the septum very well optimized,

  fast kickers providing quite short pulse.

Off – Axis Betatron Injection

- Suitable for lepton rings which are dominated by radiation damping
- useful when it's necessary accumulate current
- It is implemented by using septum magnets and injection kickers
- A first pulse is injected, then radiation damping damps oscillation amplitude of the incoming particles, after that a second pulse can be stored.

WP4 Manpower

	FTEY
C. Milardi	**0.3**
A.De Santis	**0.3**
O. Etisken	0.5
S. Spampinati	0.5

O. Etisken (postDoc position 1+1 year since next Mar 23),
S. Spampinati (temporary position 1+1 year, starting on Dec 5th 22).

Since WP4 activities are co-funded by INFN and CERN S. Spampinati as well as O. Etisken, who is going to take a postdoc temporary position, will work for 50% of their time on DAΦNE.

Recruiting manpower with a minimum experience in beam optics has been definitely quite difficoult.