EUROPEAN SPALLATION SOURCE

ESS neutrino Super Beam plus

Liouvillian Proton Injection

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Accelerator Physics in Sweden
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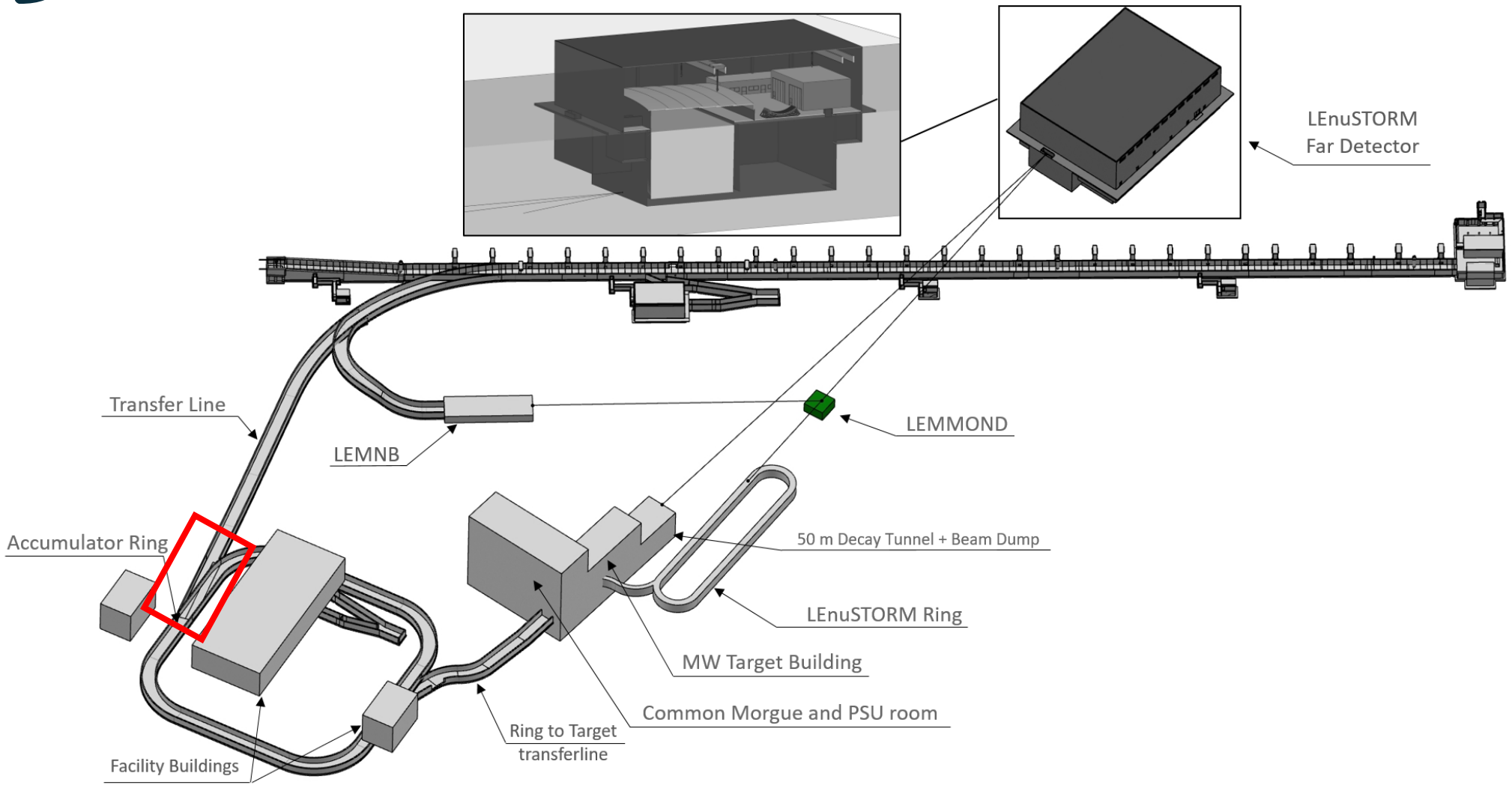
ESSnuSB

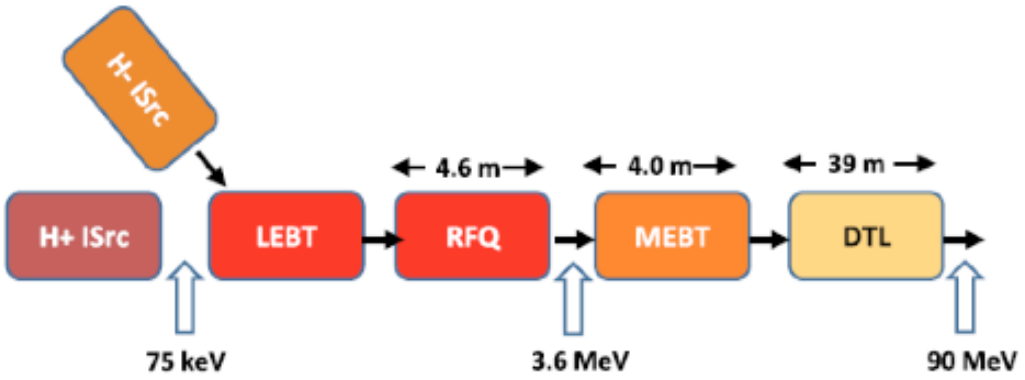

LEnuSTORM
Far Detector
Transfer Line
LEMNB
LEMMOND
Accumulator Ring
50 m Decay Tunnel + Beam Dump
LEnuSTORM Ring
MW Target Building
Common Morgue and PSU room
Ring to Target
transferline
Facility Buildings

Why LIO?

The main goal of this study is to develop the the Liouvillian Injection Optimization (LIO) method for injecting protons from the linac directly into the accumulator using a 4D Liouvillian multi-turn accumulation process without stripping. This approach avoids the drawbacks of the H^- stripping injection, which is considered a "dirty process" due to several issues

- High activation caused by the unstripped H^- and H0.
- Complex management of stripped electrons.
- Limited foil lifetime and the foil replacement system is complicated.
- H^- source has constraint for current and lifetime compared to proton sources.
- A transfer line for protons is simpler.

In addition, if the choice is done to use H^- for ESSnuSB, the linac operation for both proton and H^- beams will require a substantial increase in complexity of the linac control system, low-level RF systems and safety systems.

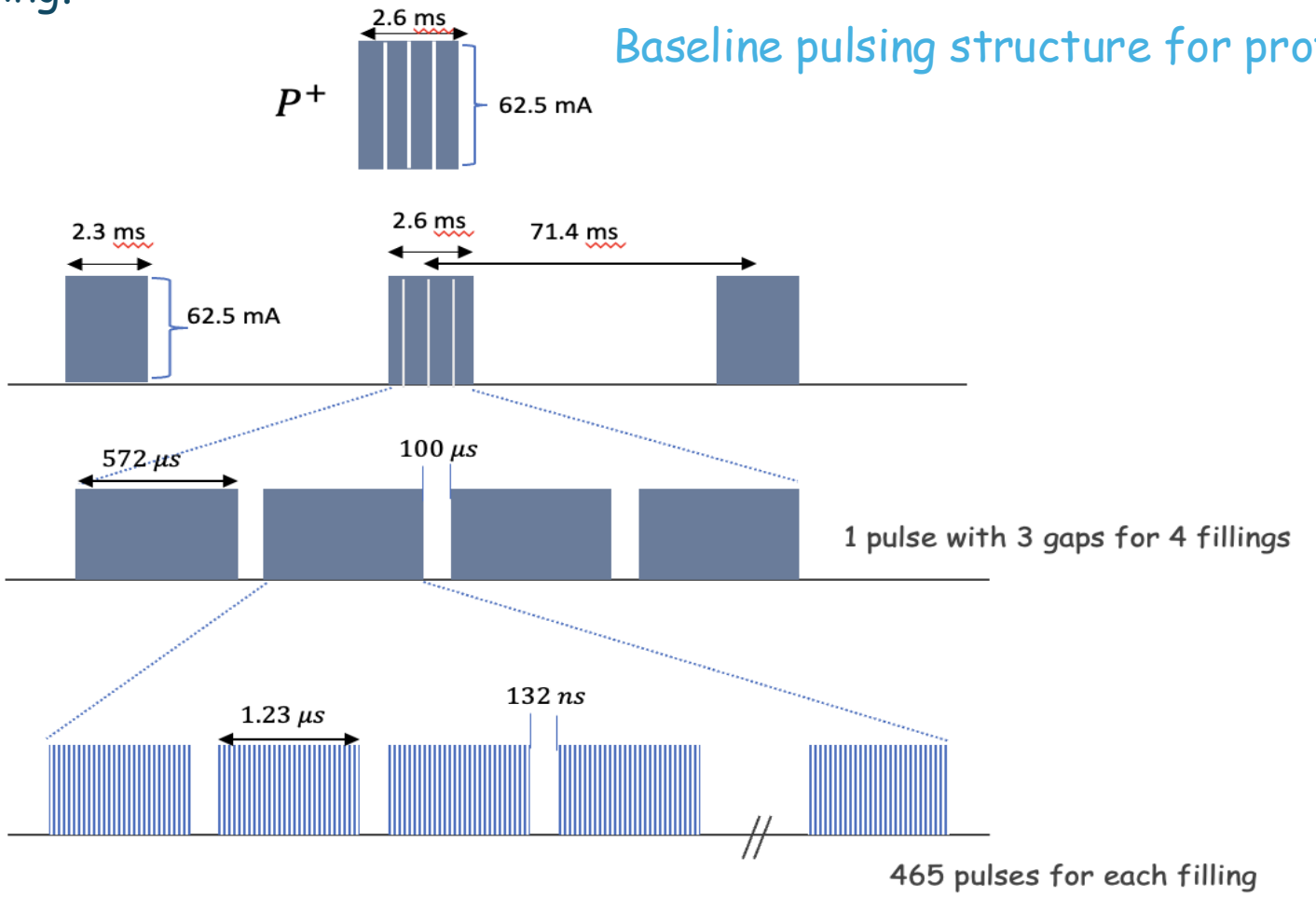


Multi-turn injection

The main goal of this study is to develop the the Liouvillian Injection Optimization (LIO) method for injecting protons from the linac directly into the accumulator using a 4D Liouvillian multi-turn accumulation process without stripping.

Multi-turn injection is the process of stacking >1 bunch during multiple turns of stored beam.

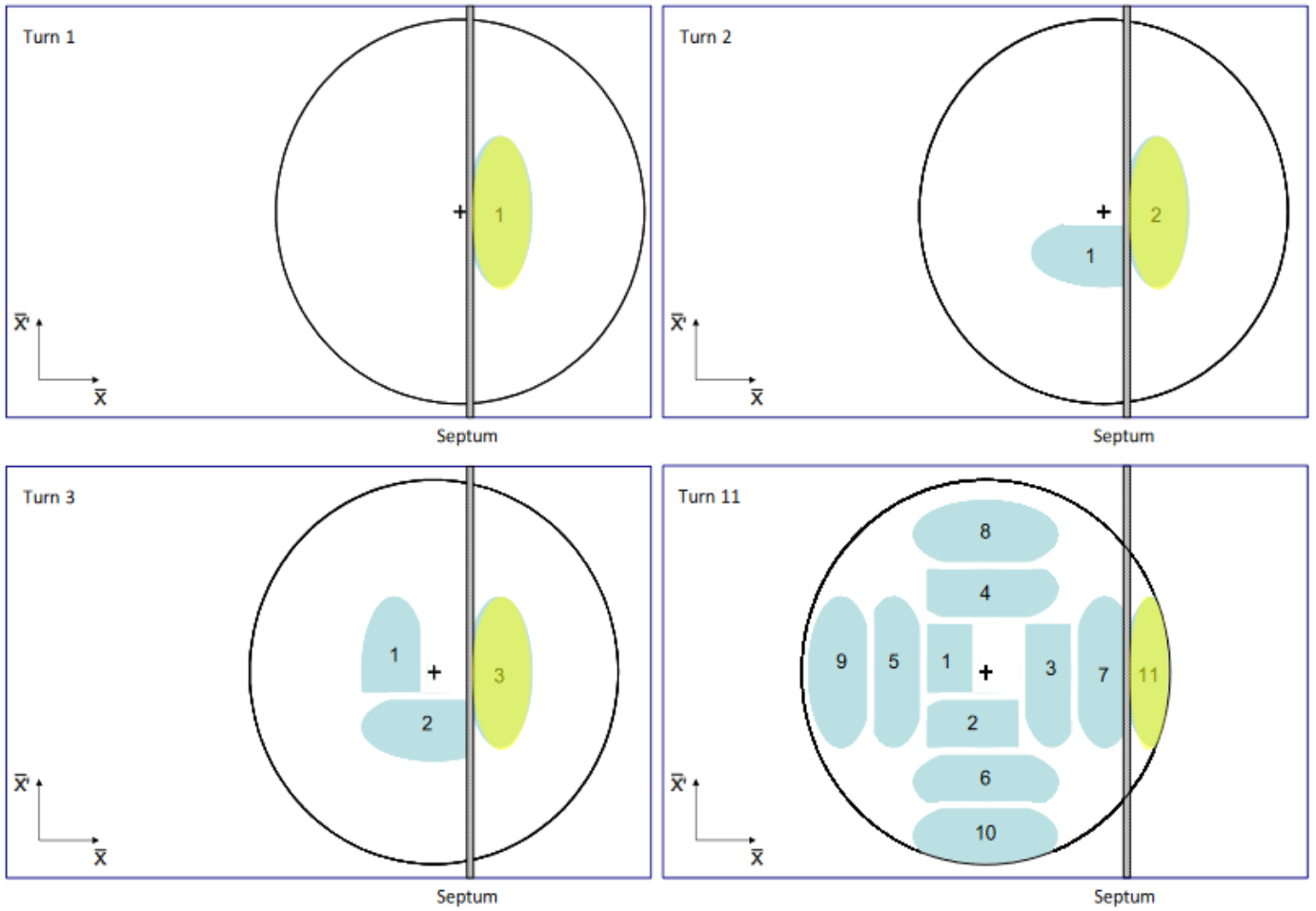
Baseline pulsing structure for proton



Multi-turn injection (2D)

Multi-turn injection is the process of stacking >1 bunch during multiple turns of stored beam.

The circulating beam position changes during injection. Cannot inject a new bunch directly on top of existing bunch due to conservation of emittance (Liouville's Theorem)



Multi-turn injection(4D)

Multi-turn injection is the process of stacking >1 bunch during multiple turns of stored beam.

The circulating beam position changes during injection. Cannot inject a new bunch directly on top of existing bunch due to conservation of emittance (Liouville's Theorem)

With multi-turn injection, we can paint the transverse phase space, (x, x') (y, y') in the receiving ring to obtain as low as possible stored emittances using a tilted septum. ("two plane painting injection")

2D accumulation in the horizontal phase-plane:

$$E_{acc\_x} = Nb_{turns}\, Ei_x\, DF_{2D\_x}$$

$$E_{acc\_y} = Ei_y$$

ESSnuSB Accumulator Ring:

$Nb_{turns} = 600,$

$Ei_x = 2.8\,\pi\,mm\,mrad \quad \rightarrow \quad E^*_{acc\_x} = 1680\,\pi\,mm\,mrad$

in the ideal case $DF_{2D\_x} = 1$, even worst in the real life!!!

4D accumulation in transverse phase-planes:

$$E_{acc\_x}\, E_{acc\_y} = Nb_{turns}\, DF_{4D\_x}\, Ei_x\, DF_{4D\_y}\, Ei_y$$

ESSnuSB AR in the ideal case ($DF_{4D} = 1$) :

$$E^*_{acc\_x}\, E^*_{acc\_y} = 600\ 2.8\ 2.8 = 4704$$

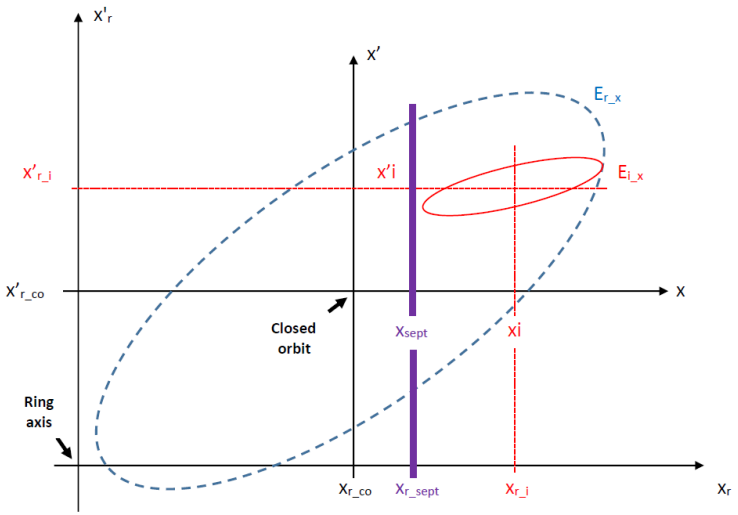
When the 4D painting is done the same way in H and V,

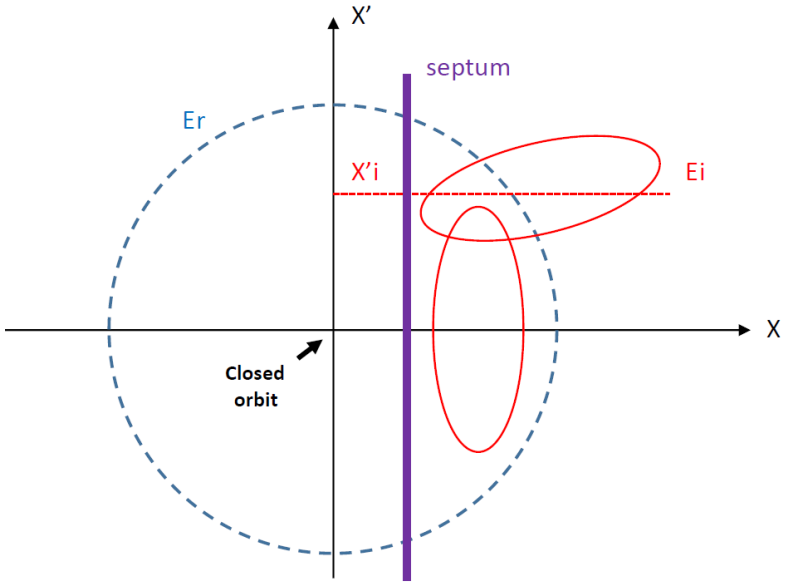
$$E^*_{acc\_x} = E^*_{acc\_y} = \sqrt{600\ 2.8\ 2.8} = 68.6\,\pi\,mm\,mrad$$

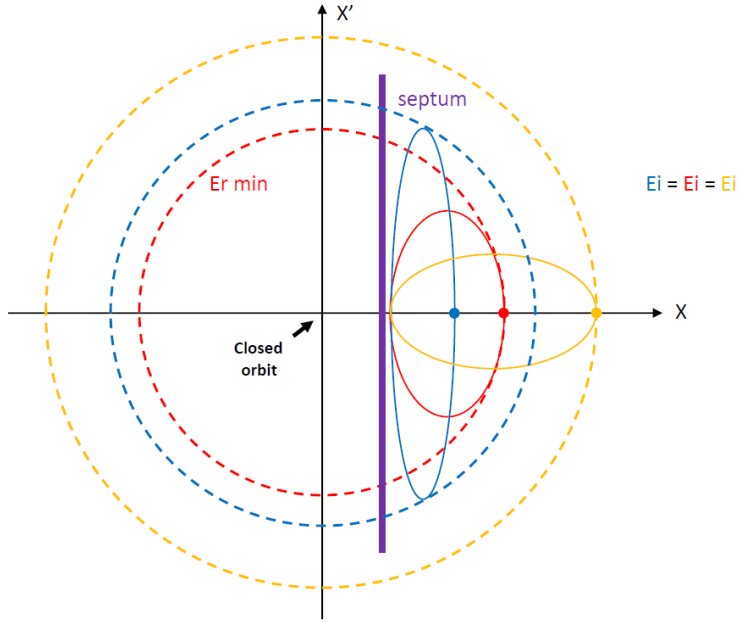
The horizontal accumulated emittance reduced by a factor 24.5

Normalized phase-space

The LIO method has been developed by optimizing the injection parameters to accumulate the beam with no loss and as low as possible stored emittance.







To optimize the injection, we develop LIO simulation

Step-1- Choice of best potential working point (μ_x, μ_y),

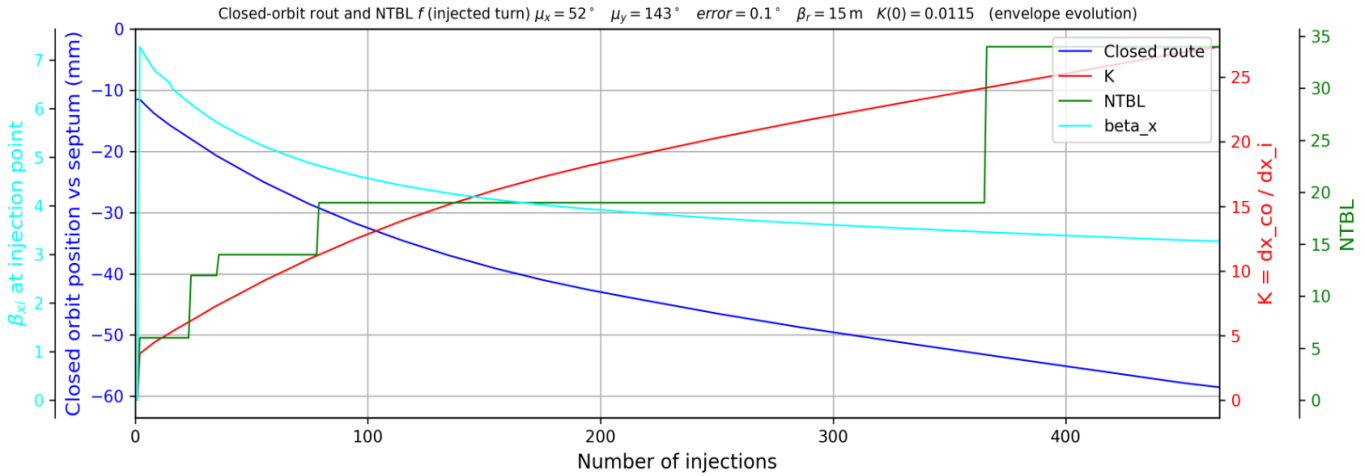
Step-2- Choice of K(0) = dx_{co} (first injected turn) / dx_i, corresponding to the initial closed-orbit,

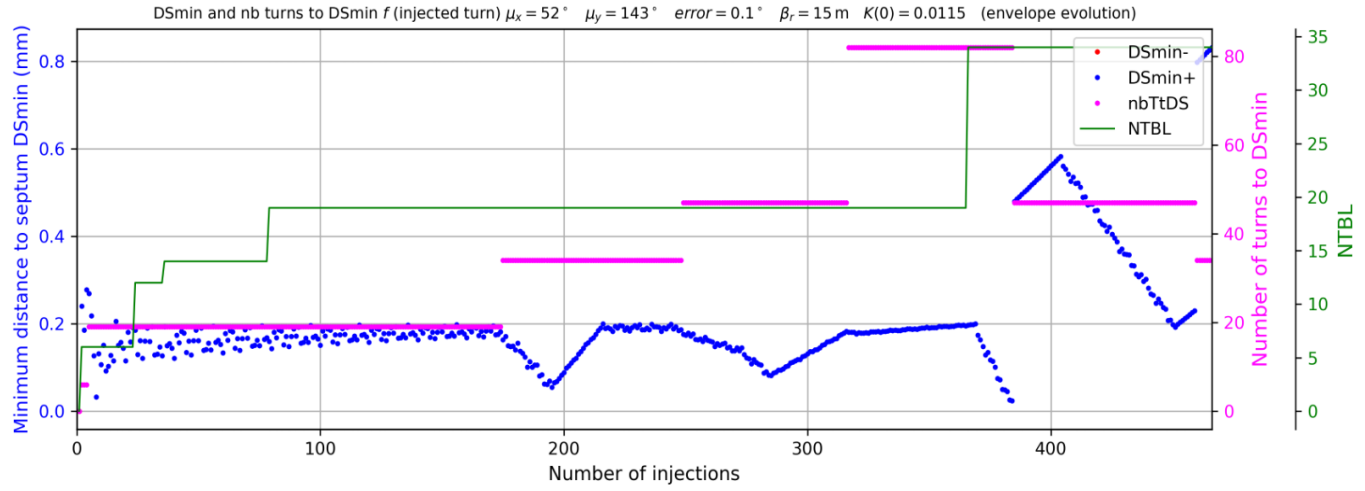
Step-3- Choice of a closed orbit route for no loss beam and a minimum stored emittance for N injected turns.

Linear calculation of LIO

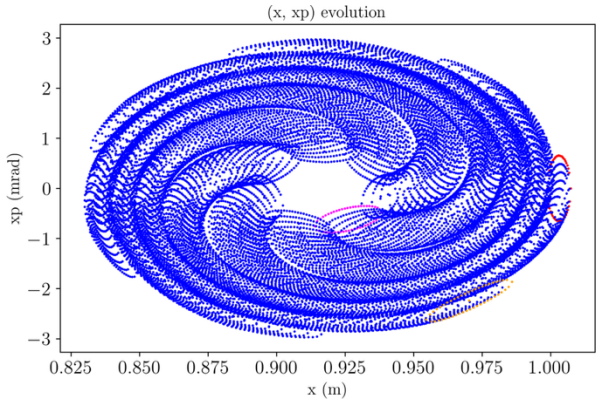
Closed-orbit rout and Ds_{min} along the 465 injection of 100% emittance for working point $(8.144, 8.397)$

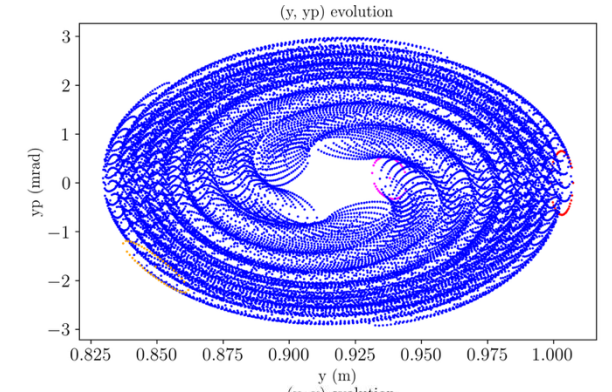
$$\frac{\varepsilon_r}{\varepsilon_i} = 95.8$$

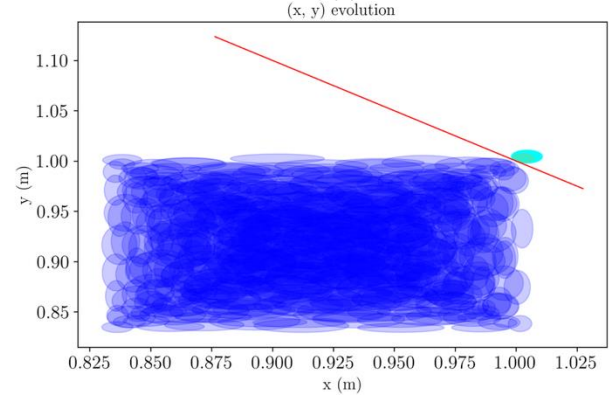




Particles at real & phase-space after 465 injections







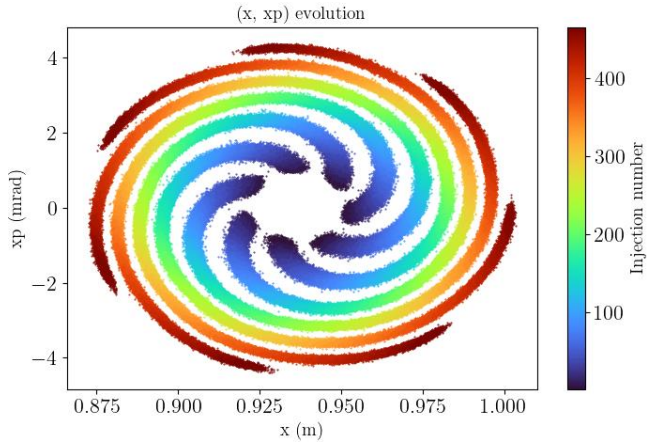
PyOrbit simulation of LIO

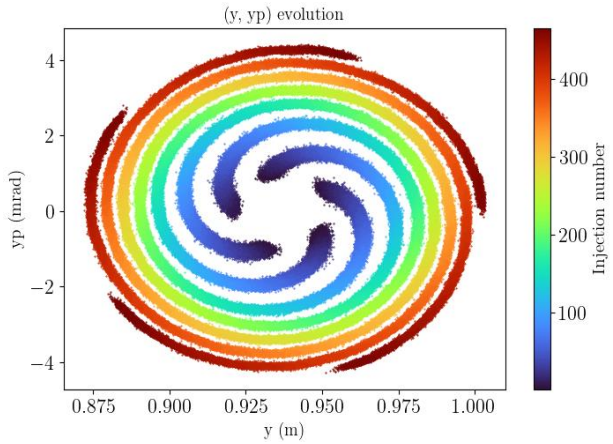
Tracking 3D distributed injected particles through accumulator ring using PyOrbit simulation code for working point $(8.144, 8.397)$: No energy spread

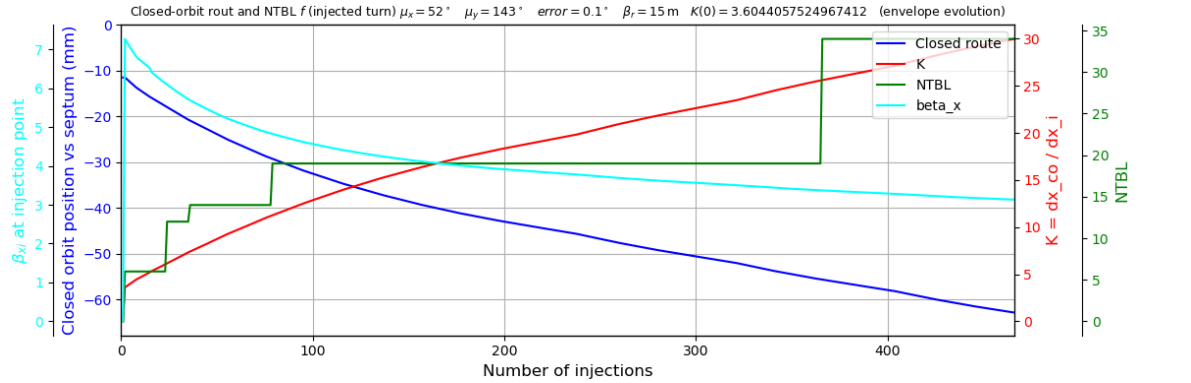
$$\frac{\varepsilon_r}{\varepsilon_i} = 109$$

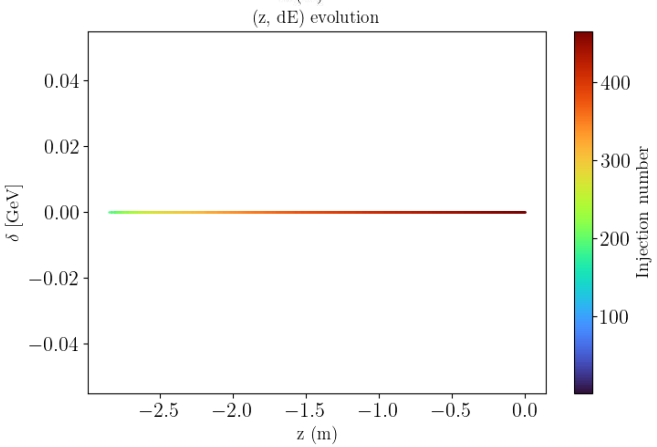
Number of particles at each injection = 1000

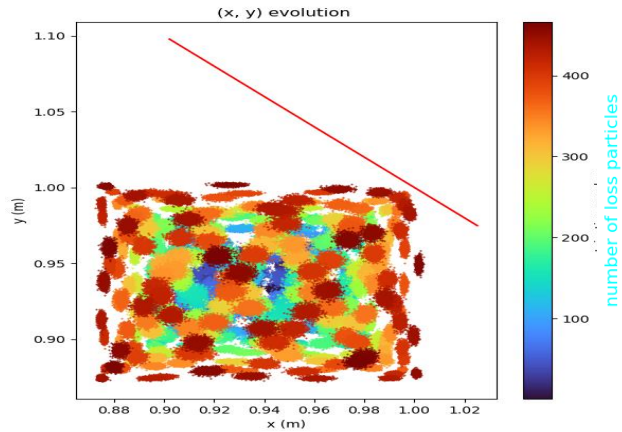
Closed-orbit rout and Ds_{min} along the 465 injection of rms emittance

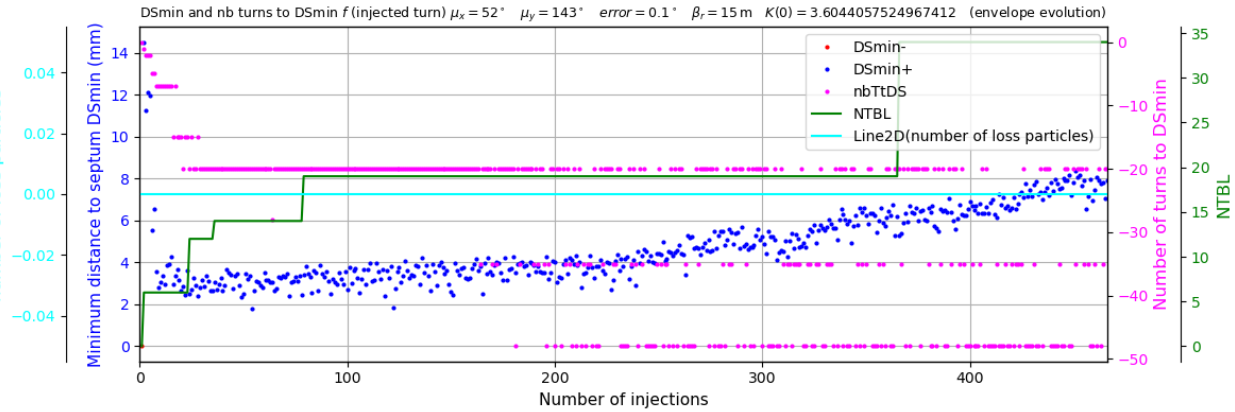










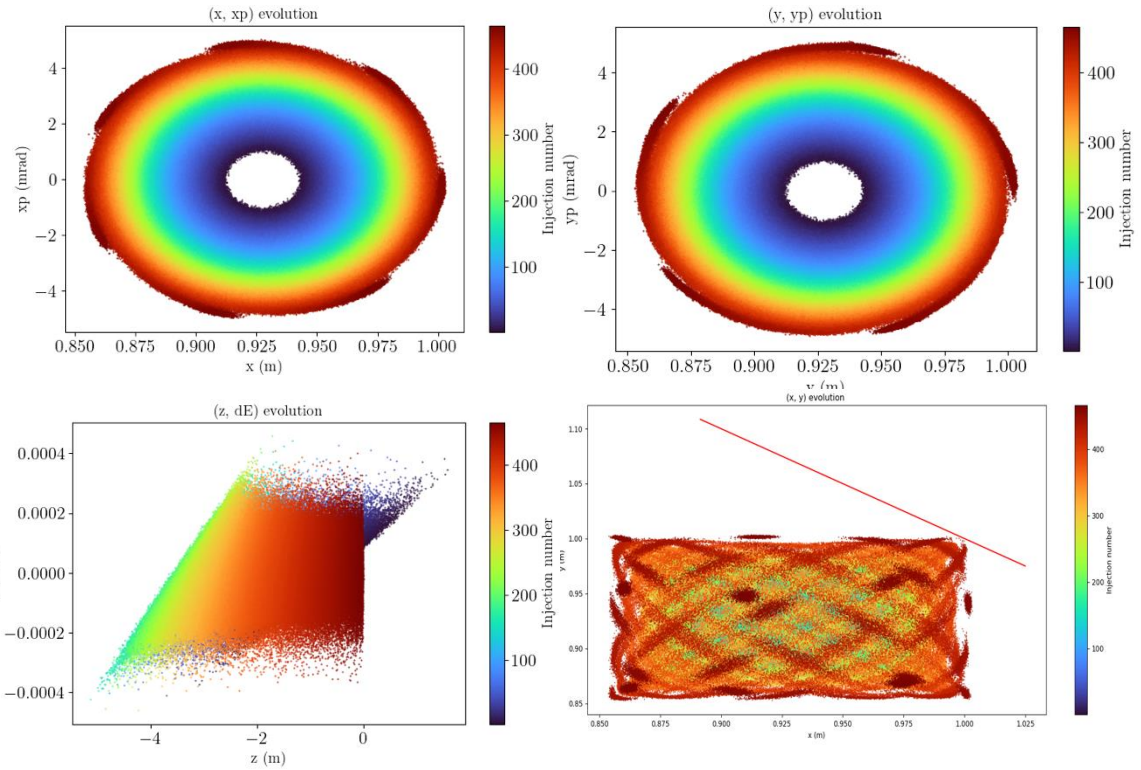


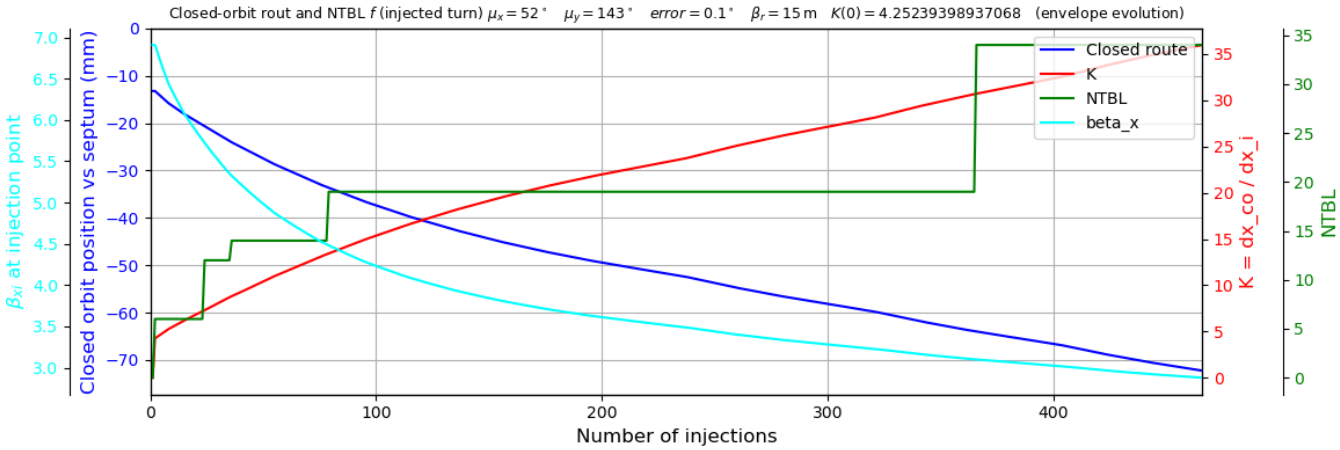
PyOrbit simulation of LIO

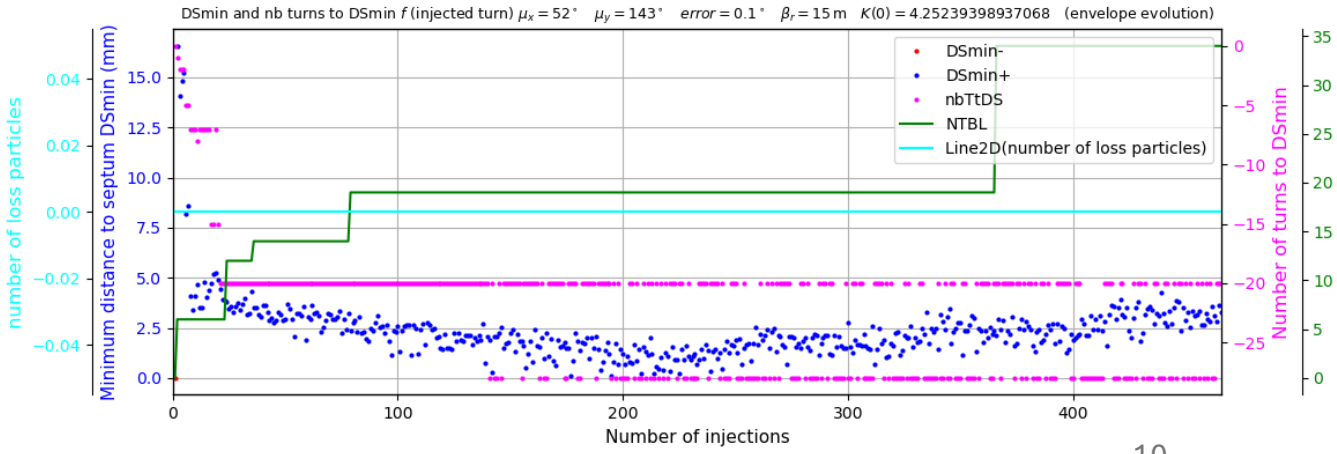
Tracking 3D distributed injected particles through accumulator ring using PyOrbit simulation code for working point $(8.144, 8.397)$. With energy spread & No space-charge

Number of particles at each injection = 1000

$$\frac{\varepsilon_r}{\varepsilon_i} = 141$$



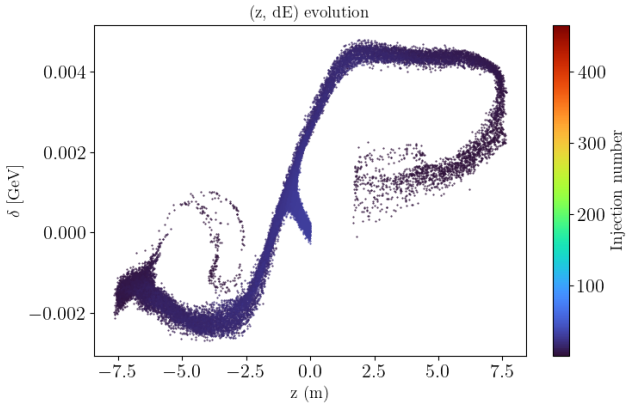


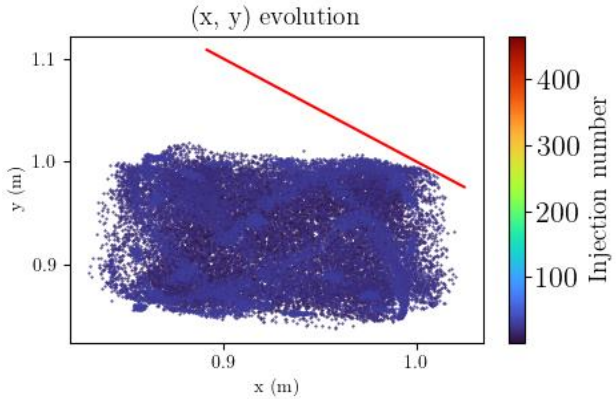


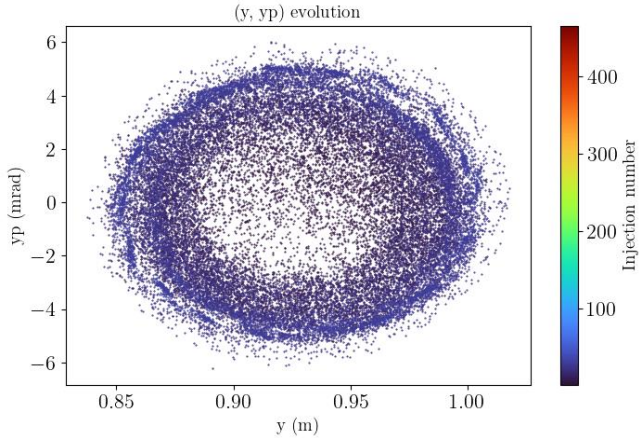
PyOrbit simulation of LIO

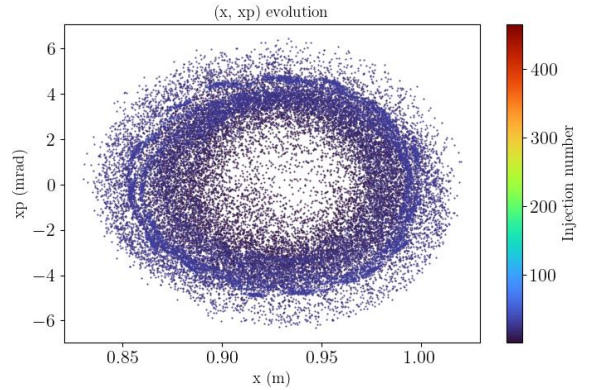
Tracking 3D distributed injected particles through accumulator ring using PyOrbit simulation code for working point $(8.144, 8.397)$. With space-charge & energy spread

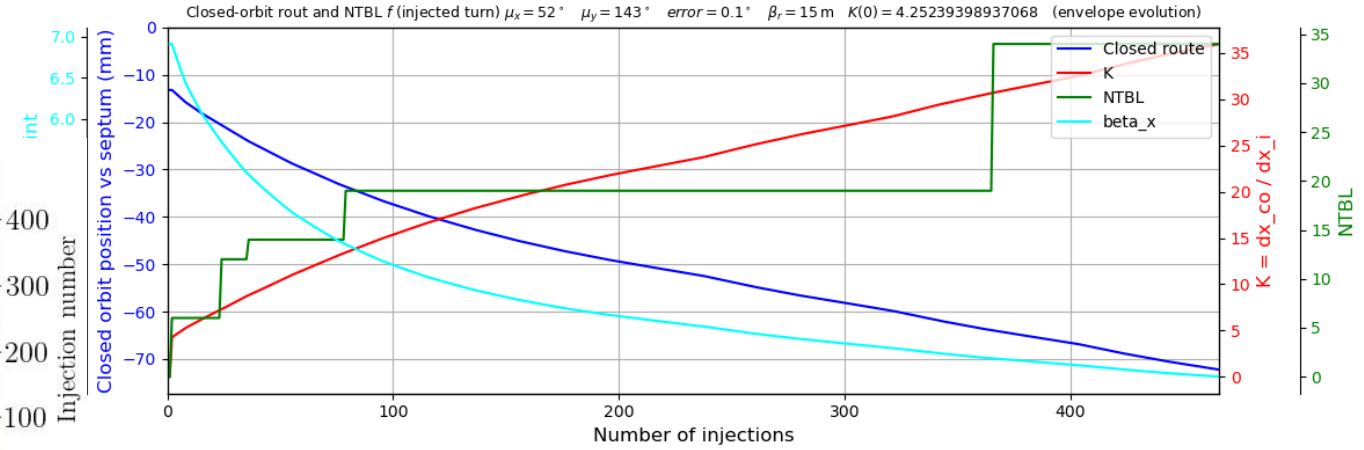
Number of particles at each injection = 100

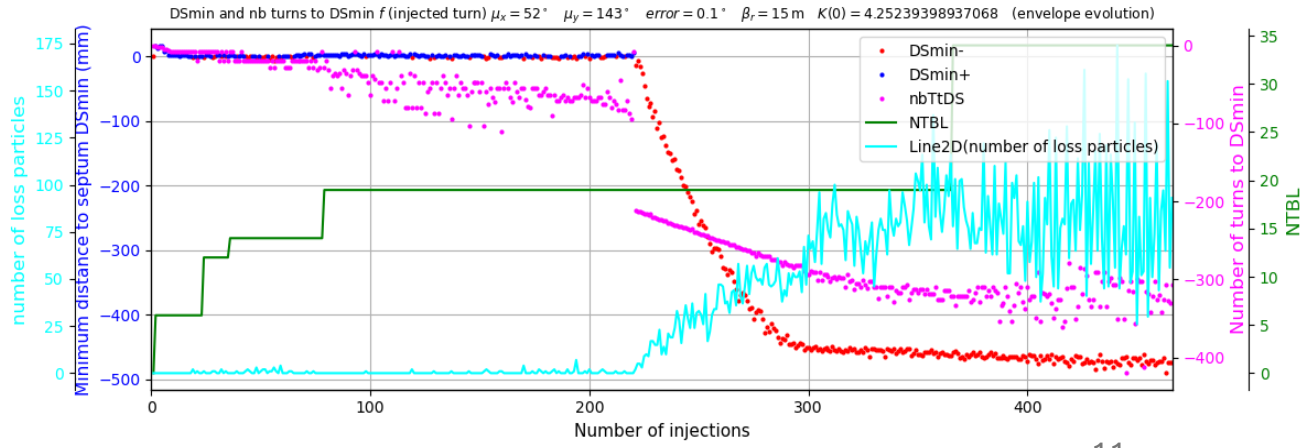












Summary

- ✓ The optimizations has been performed by selecting the best tree parameters for $\mu_x, \mu_y, and\ K(0)$, with optimized closed-orbit shift as DS/NTBL.
- ✓ We have done the LIO method for constant ring beta function of 15 m. We can optimize the ring beta function to 50m for improving the ring final emittance.(next step)
- ✓ The LIO method has been carried out using the PyOrbit simulation code. Some nonlinear effects has been observed in the results which comes from energy spread, and injected orbit deviation at the injection point. In the next step, we aim to compensate for these nonlinear effects using sextupoles.

A comparison of unnormalized ring emittance between LIO method which is $\varepsilon_r = 268\ \pi mm\ mrad$ and H^- stripping method at 100% emittance $\varepsilon_r = 70\ \pi mm\ mrad$.

Thank you!