STAR facility: Genetic Algorithm code for beam dynamics optimization in Thomson back-scattering

Antonietta Olivieri

Supervisors:

Enrico Tassi (INFN-CS and University of Calabria)
Alberto Bacci (INFN-MI and University of Milan)

Introduction and motivation

Beam dynamics simulations and optimization in particle accelerators face several significant challenges

- Complexity and nonlinearity
- High dimensionality of the parameters involved
- The need to simulate the behaviour of a high number of particles to achieve statistically significant results also demands substantial computational resources
- The need to adapt to changing conditions necessitating real-time optimization and control approaches

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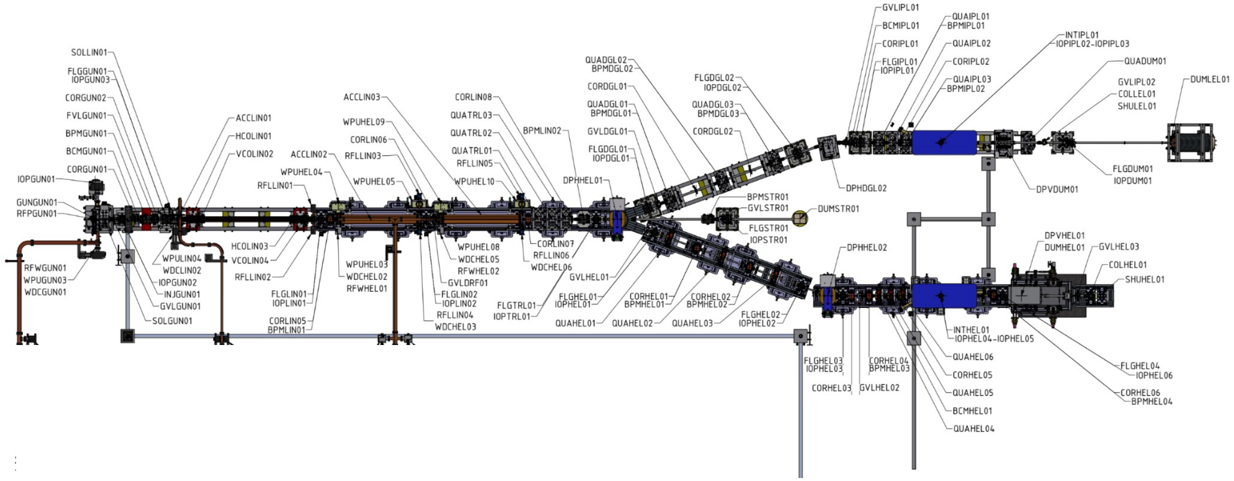
The optimization process might be challenging and time-consuming.

A genetic algorithm (GA) proves to be a powerful tool capable of improving the beam performance in both radiation production and time efficiency.

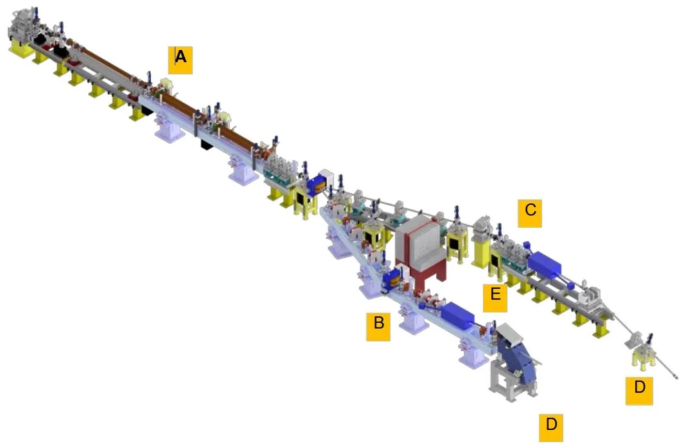


STAR *(**S**outhern Europe **T**homson Back-Scattering Source for **A**pplied **R**esearch)*

The STAR (Southern European Thomson Source for Applied Research) facility, located at the University of Calabria campus in Italy, is designed to construct an advanced Thomson source for X-ray beams ranging from 20 to 350 keV.
INFN was awarded the project for installing, testing, and commissioning the electron beamline.

LE-Line: 20 – 65 MeV
HE-Line: 40 – 150 MeV

Layout



A. Cavities: 1 S-band (2856 MHz RF frequency), 2 C-band (5712 MHz RF frequency)
B. STAR HE-Line
C. STAR LE-Line
D. Beam dump
E. IP

ASTRA (*A Space Charge Tracking Algorithm*)

ASTRA, written in Fortran 90, is an open source code developed at DESY

The ASTRA program package consists of:

- The program ***generator*** which may be used to generate an initial particle distribution
- The program ***Astra*** which tracks the particles under the influence of external and internal fields
- The graphic program ***fieldplot*** which is used to display electromagnetic fields of beam line elements and space charge fields of particle distributions
- The graphic program ***postpro*** which is used to display phase space plots of particle distributions
- The graphic program ***lineplot***, which is used to display the beam size, emittance, bunch length etc. versus the longitudinal beam line position

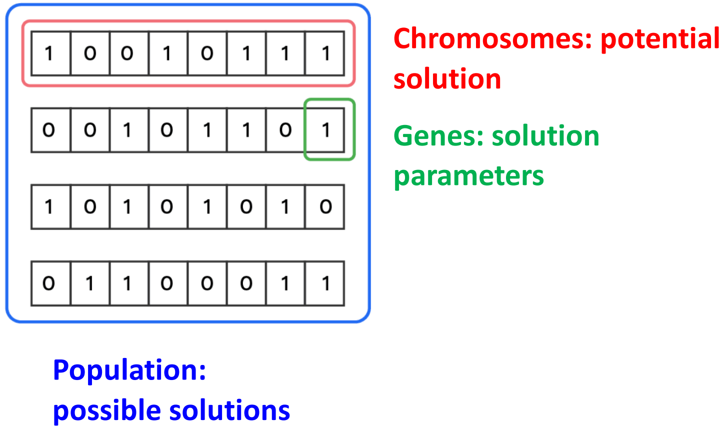
GIOTTO (*Genetic Interface for OpTimising Tracking with Optics*)

Giotto is a software based on a **Genetic Algorithm** (GA) developed by A.Bacci and M.R.Conti (INFN-MI). GAs are a class of artificial intelligence particularly well-suited to handle complex problems in which variables are strongly correlated in a nonlinear way, by iteratively improving a population of candidate solutions.

A **genetic algorithm** is an optimization and search technique based on the principles of natural selection and genetics, where the best solutions are selected, recombined, and mutated to produce new generations of potentially better solutions

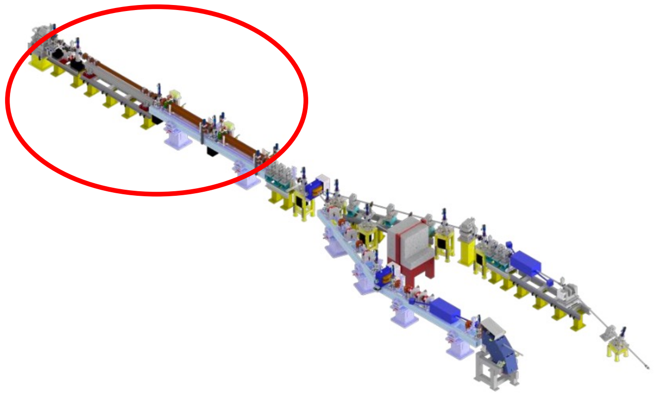
GIOTTO starts by driving the tracking code Astra and by using all its parameters as possible knobs for optimizations

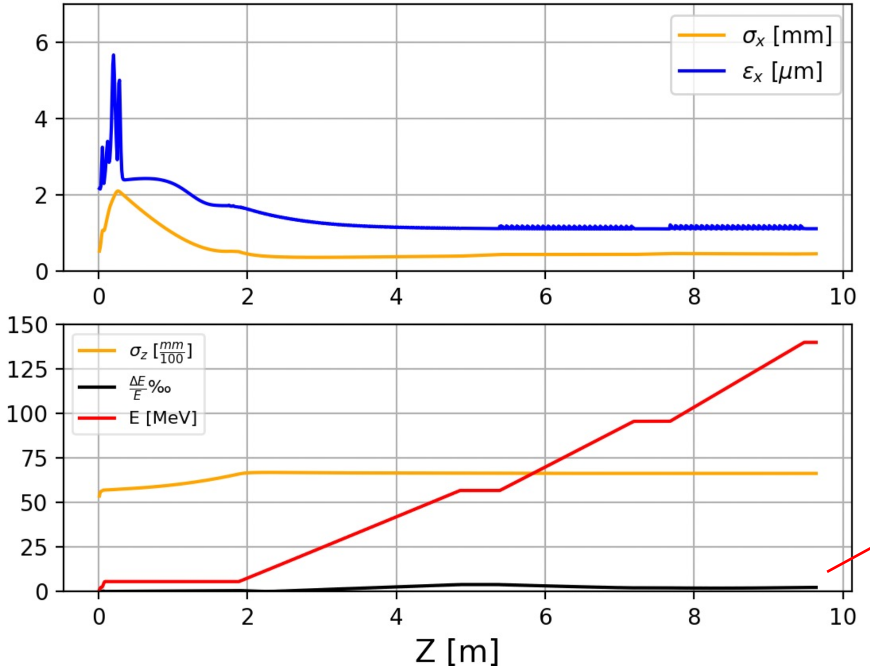
- It starts with a population of candidate solutions (chromosomes)
- Each individual in the population has a Fitness Function that measures how well it solves the problem
- The best individuals are selected to create a new generation
- The process repeats until an optimal solution is found



HE-Line beam dynamics for 140 MeV

BD optimizations conducted at different WPs (100-150 MeV)





Emittance and **spot size** minimized

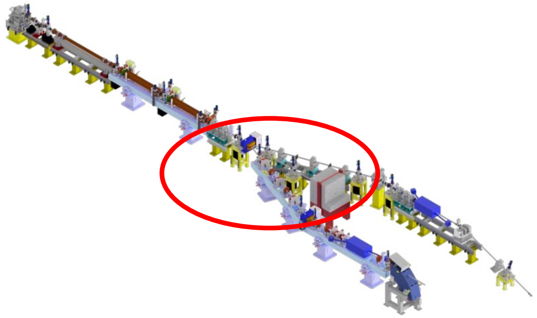
The optimal electron beam energy spread compensation is visible: using ad hoc injection phases, in all the 3 acceleration cavities, it is possible to keep the energy spread to minimum values

Beamline parameters (genes of the GA): amplitude and phase of the RF fields (in all the 3 cavities)

Beam parameters to optimize: x,y emittances, $\sigma_{x,y}$, energy spread

x,y envelopes [mm]	0.450
Normalized x,y emittances [mm-mrad]	1.0
Bunch length [mm]	0.670
Energy spread [%]	0.023

HE-Line beam dynamics for 140 MeV - Dogleg

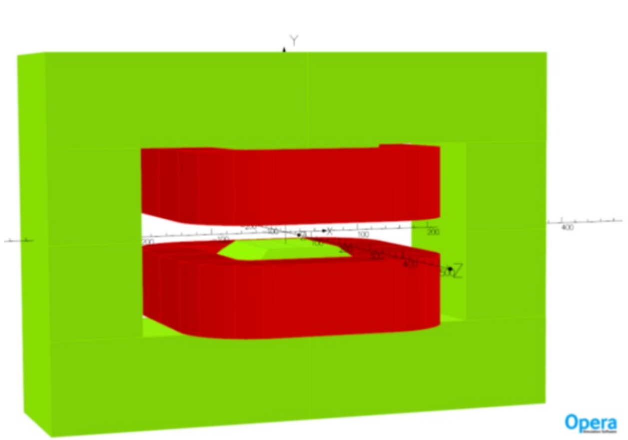


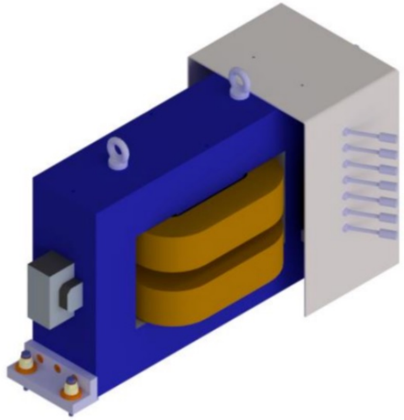
Dipole simulation in Astra

Analytical:

The namelist DIPOLE allows to include dipole fields based on analytical expressions.
Dipoles are defined by two edge lines, defining the entrance and the exit face of the dipole. Each line is defined by two points in the input deck. The connecting lines of these points define the area in which the actual field calculation takes place.

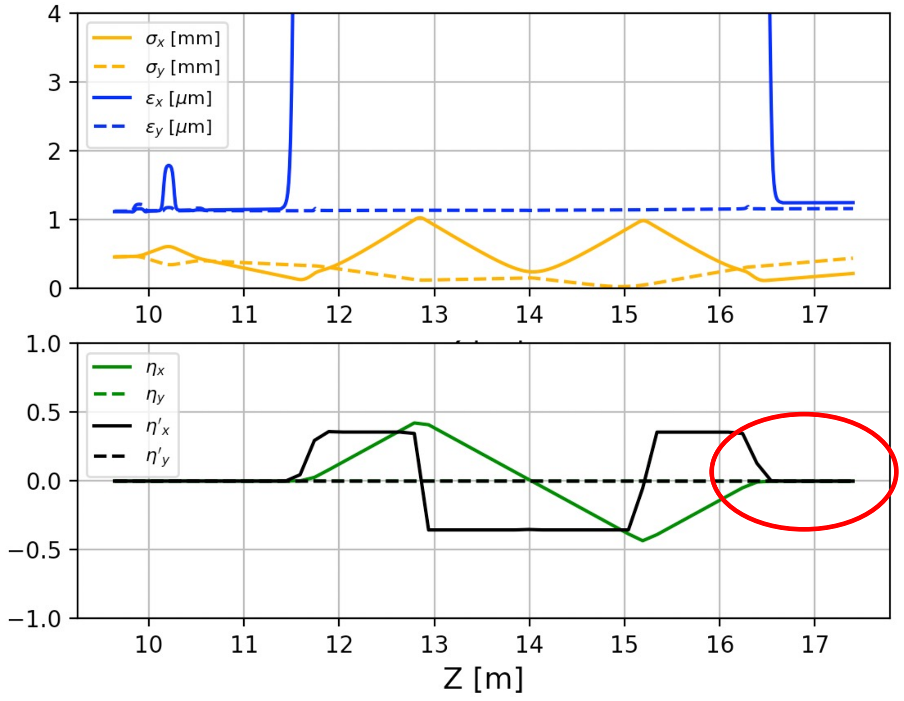
3D field maps:





The 3D field map is a file which contains the value of the B in each point
X [mm], Y [mm], Z [mm]
Bx [T], By [T], Bz [T]

HE-Line beam dynamics for 140 MeV - Dogleg



x,y envelopes [mm]	0.20, 0.43
Normalized x,y emittances [mm-mrad]	1.2, 1.1

Beamline parameters (genes of the GA): quadrupole/dipole gradients
Beam parameters to optimize: x,y emittances, $\sigma_{x,y}$, $\eta_{x,y}$, $\eta'_{x,y}$

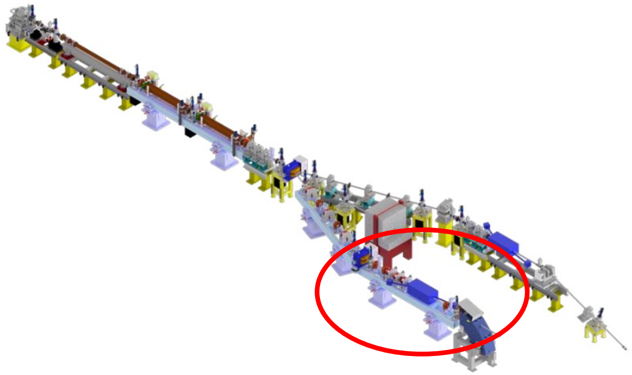
- In a dispersion region, η quantifies the horizontal displacement caused by momentum deviations. For instance, a higher momentum particle will deviate further from the reference trajectory, and this displacement is proportional to η. It it can lead to **beam size growth** in the transverse plane
- η' represents the **angular dispersion** of particles with different momenta as they pass through the dogleg. It affects how the beam focuses or diverges after passing through the dispersion region

Space charge effects can be perfectly compensated by an appropriate beamline setting using a code like GIOTTO, both closing the dispersion and compensating the emittance in the dispersive region

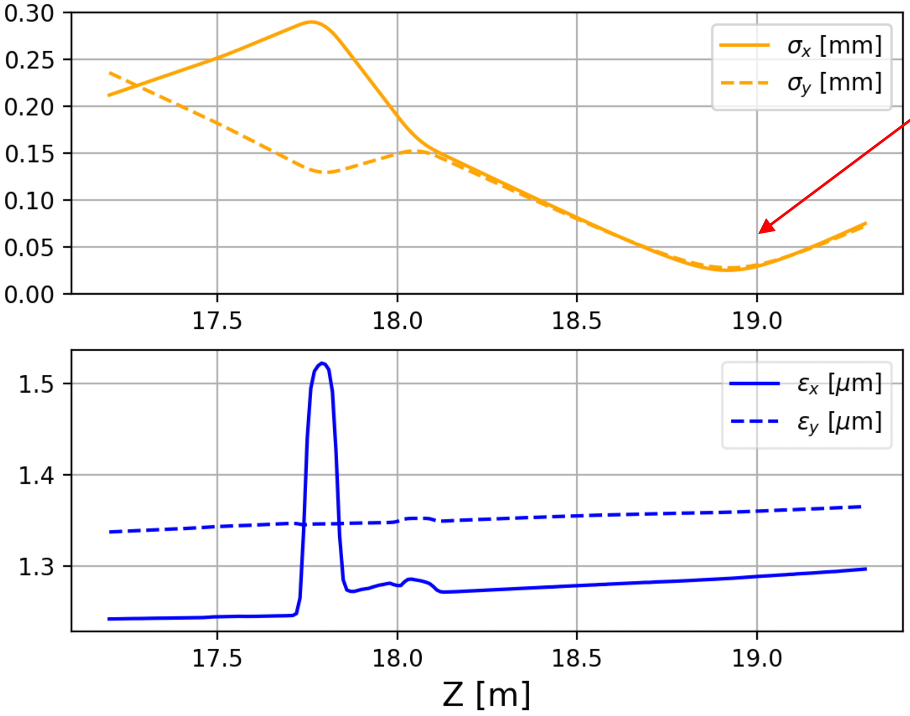
HE-Line beam dynamics for 140 MeV – Interaction Point

Minimizing the **electron beam spot size** at the IP is essential:

- By reducing the electron beam spot size at the IP, the density of electrons increases, which in turn increases the probability of interaction between electrons and photons. This leads to a greater production of X-rays
- A tightly focused electron beam at the interaction point reduces the **emittance:** this is important because an electron beam with a larger emittance can introduce **undesirable scattering effects**, leading to an increase in the divergence of the generated photon beam
- Enhancing conversion efficiency



IP at 18.9 m

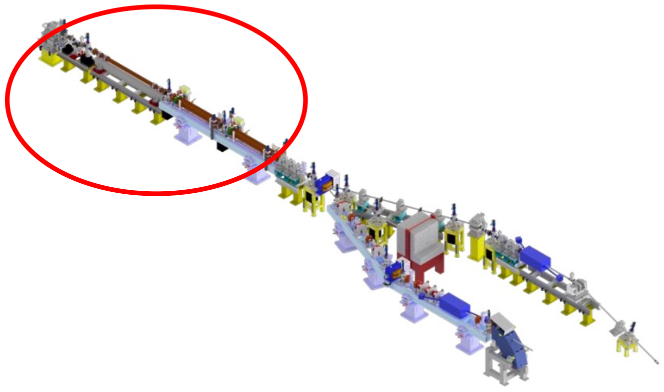


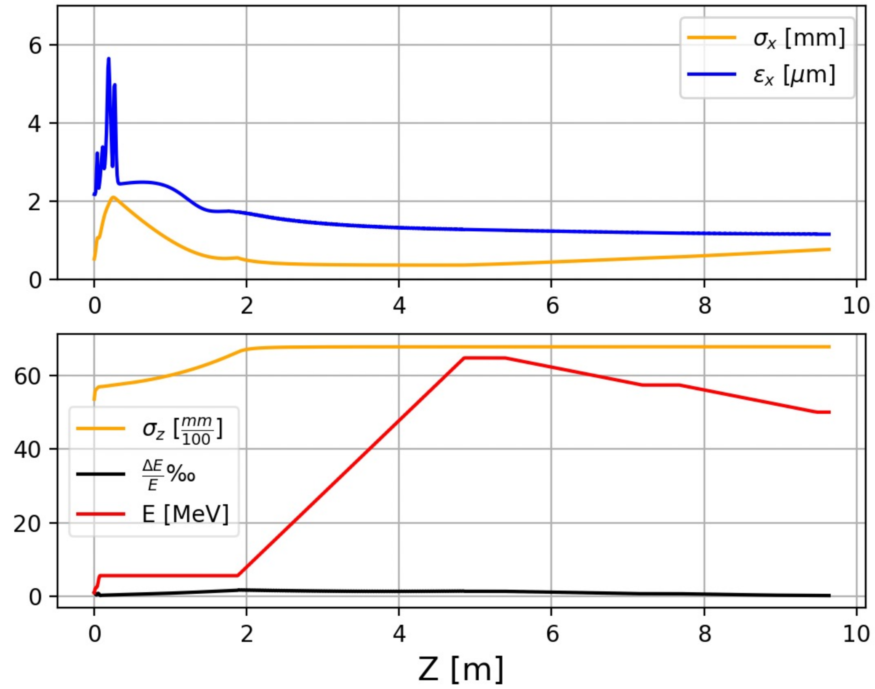
x,y envelopes [μm]	25, 26
Normalized x,y emittances [mm-mrad]	1.29, 1.37

Beamline parameters (genes of the GA): quadrupole gradients
Beam parameters to optimize: x,y emittances, $\sigma_{x,y}$

LE-Line beam dynamics for 50 MeV

BD optimizations conducted at different WPs (20-60 MeV)





Emittance, spot size and energy spread minimized

Beamline parameters (genes of the GA): amplitude and phase of the RF fields (in all the 3 cavities)

Beam parameters to optimize: x,y emittances, $\sigma_{x,y}$, energy spread

x,y envelopes [mm]	0.76
Normalized x,y emittances [mm-mrad]	1.16
Bunch length [mm]	0.677
Energy spread [%]	0.025

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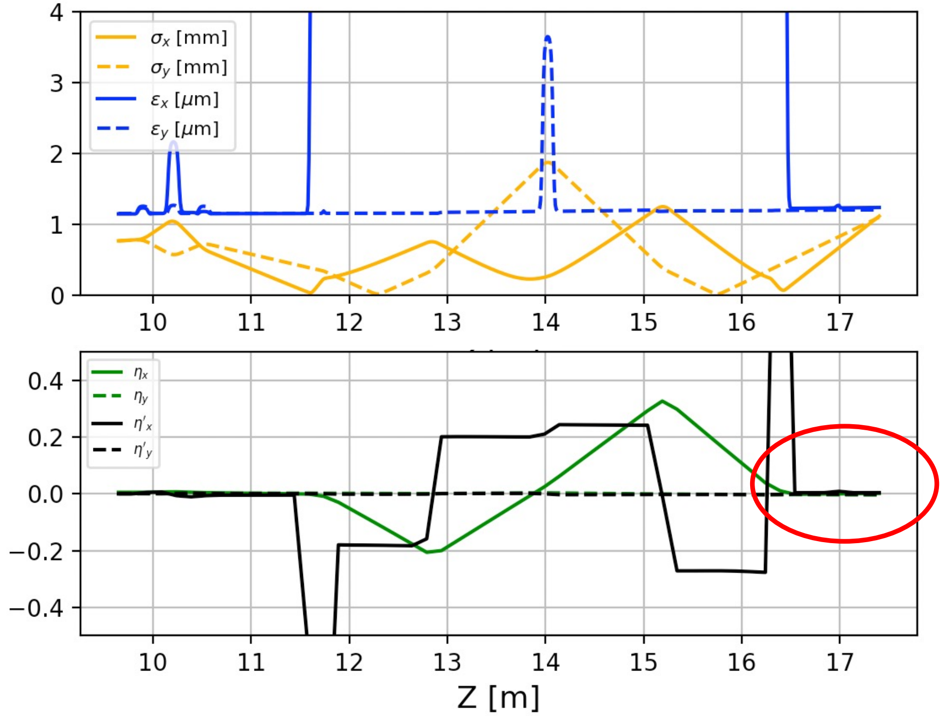
LE-Line beam dynamics for 50 MeV - Dogleg



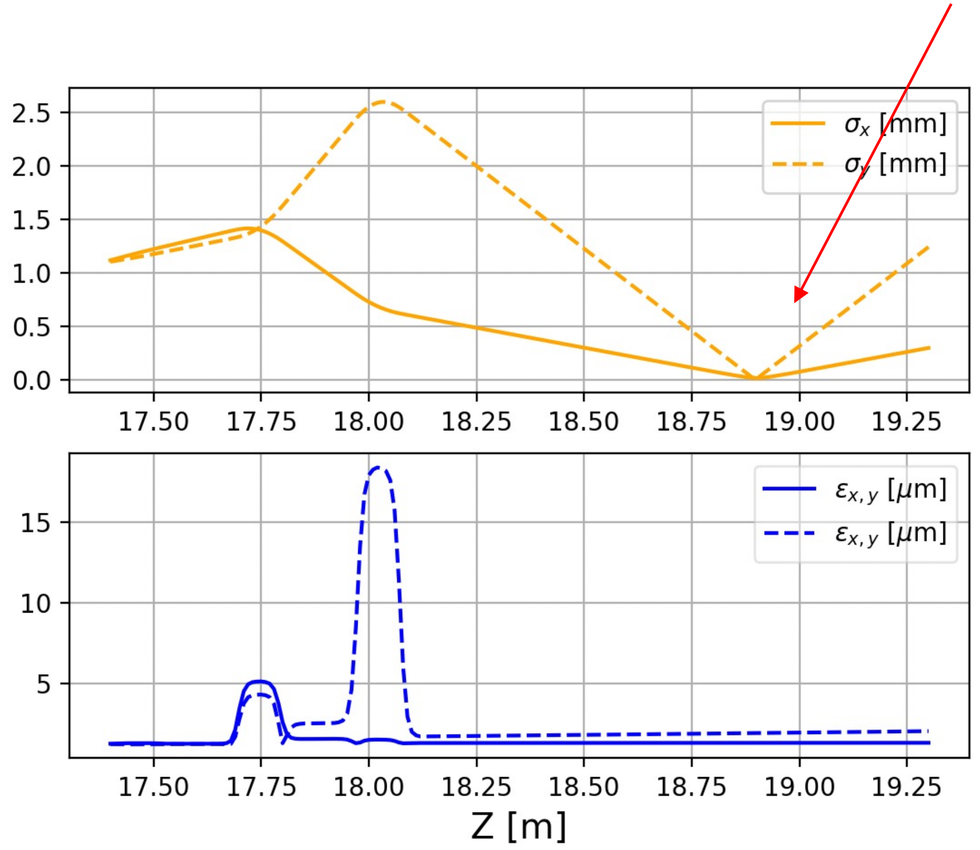
Space charge effects are stronger $\propto 1/\beta\gamma^2$

Any dispersion present will have a more pronounced effect on the trajectory and focus of the beam

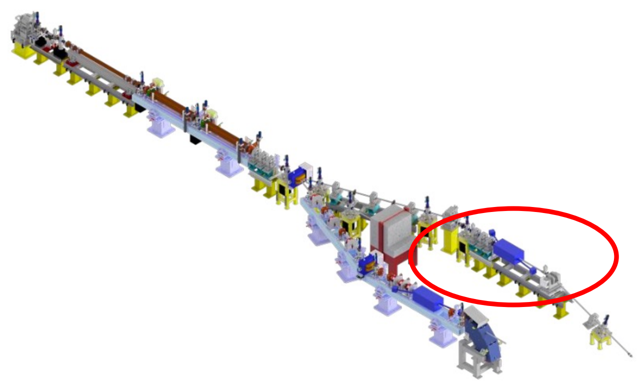
η and η' are critical for controlling the beam's transverse spread at lower energies

x,y envelopes [mm]	1.1, 1.0
Normalized x,y emittances [mm-mrad]	1.23, 1.2

LE-Line beam dynamics for 50 MeV - IP



Minimizing the spot size of a low-energy electron beam is more challenging due to **space charge effects**, **greater divergence**, **higher sensitivity to magnetic fields**, and **dispersion**.
These factors make controlling and focusing the beam more difficult.

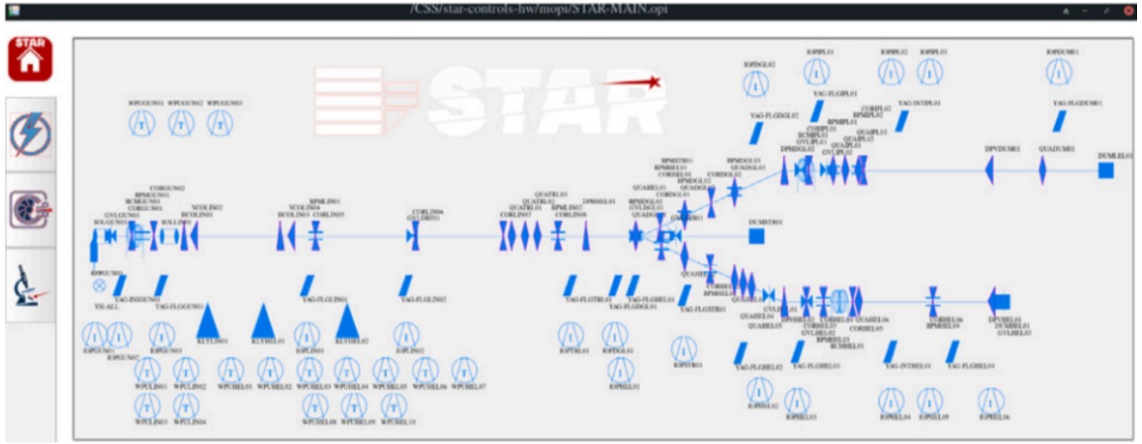


x,y envelopes [μm]	17.4, 9.2
Normalized x,y emittances [mm-mrad]	1.29, 1.9

Control system: EPICS (*E*xperimental *P*hysics and *I*ndustrial *C*ontrol *S*ystem)

EPICS is a set of Open-Source software tools, libraries, and applications developed collaboratively and with an international user-base. The EPICS framework is widely used as the control system infrastructure to create distributed soft real-time control systems for large scientific installations.

The STAR control system relies on the EPICS framework, which enables control of devices and organizes data into Process Variables (PVs) that are distributed across the LAN. Control System Studio (CSS) was chosen as the graphical user interface for operators. The transition to the latest version of the GUI software, *Phoebus*, is an active part of the project.



CS are tasked with continuously monitoring and adjusting critical parameters. Each time the system is put into a new operating condition, extensive tuning is required.

The integration of the software GIOTTO is planned: it offers the prospect of optimizing the generated radiation by dynamically controlling beam parameters in real-time directly on the STAR control system and to refine them as a function of the different operating energies or set-up changes

Thank you for the attention!