RF-Track Modeling of FCC-ee Injector Linacs and Optimization of Linac-to-Ring Transmission

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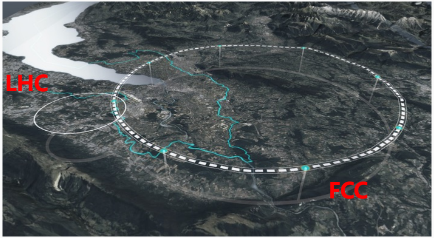
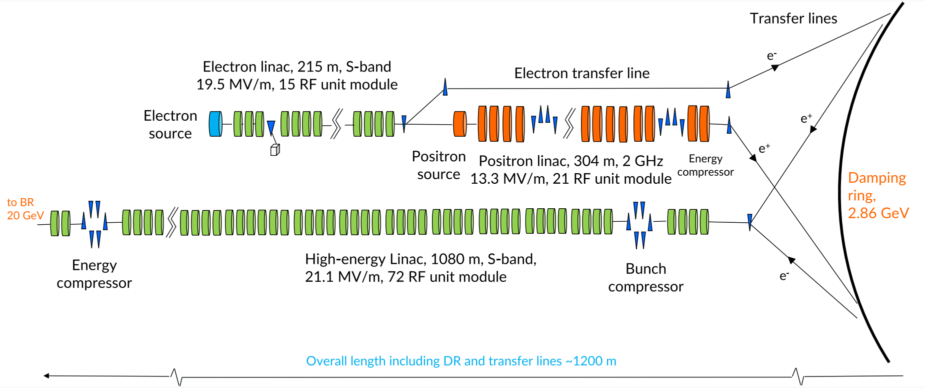


Running mode	Z	W	ZH	$t\bar{t}$	Unit
Number bunches in collider	11200	1856	300	64	
Nominal bunch charge in collider	34.40	22.08	27.04	23.68	nC
Allowable charge imbalance	5	3	3	3	%
Beam lifetime, lumi 4 IPs (q, BS, lattice)/4	916	517	428	497	s
Trains/Bunches per booster cycle	40×280	8×232	2×150	2×32	
Max injected bunch charge	3.43	3.43	1.60	1.60	nC
Number of bunches	4	4	2	2	
Linac rep. rate	100	100	50	50	Hz
Bunch spacing	25				ns
Beam energy at BR	20				GeV
Norm. emittance (x, y) (rms) (BR)	<20,2				mm mrad
Bunch length (rms) (BR)	∼4				mm
Energy spread (rms) (BR)	∼0.1				%

- **Continuous operation** due to the short beam lifetime.
- The **charge imbalance between** the **electron** and **positron beams** in the collider remain **within 3-5%**. This constraint requires a **precise** and **uninterrupted injection** process to maintain beam-beam stability.
- The **top-up operation** for each operating mode requires **the charge of the individual bunch** in the train to vary from a **few tens of pC to about 4 nC** per injection.
- The **reliability** and **availability** of the injector is of critical importance, as any downtime could compromise the overall efficiency of the collider.

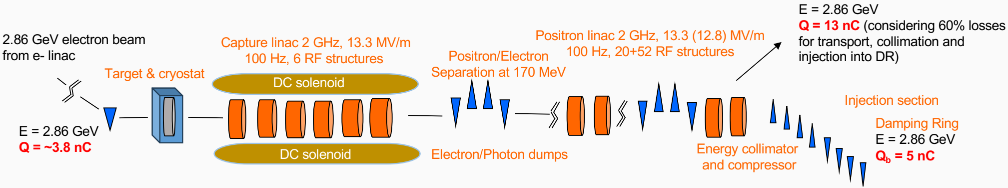
FCC-ee Injector Baseline Layout

Outcome of the **Feasibility Study**



- Beam: **train of 4 bunches** (25-ns spacing), **5 nC** bunch charge
- e^- linacs: **S-band**, **100 Hz ;** e^+ linacs: **L-band**
- **Damping ring** at higher energy: **2.86 GeV**

FCC-ee Positron Source



Capture system (~ 20 meters)

Positron production : conventional scheme (e- beam size on target = 1 mm rms). Target exit located at 40 mm w.r.t. HTS solenoid peak field.

Matching device is based on the SC solenoid (5 HTS coils, 72 mm bore, ∅ 60 mm including shielding)

Capture linac is based on the 6 L-band TW RF structures (2 GHz, ∅ 60 mm, 3-m long)

NC solenoid B = 0.5 T (realistic conventional design based on the short coils B = 0.31 T) + short "tuning" solenoid B = 0.25 T before the 1st RF structure

Positron linac (~ 280 meters)

Separator chicane : Rectangular beampipe and hor./vert. collimators, Dipole peak field: ~0.2 T

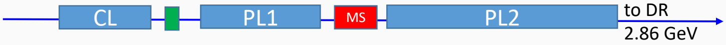
Section 1 : up to ~ 930 MeV. Same RF structure as that of the Capture Linac (CL). 20 structures. G = 13.3 MV/m

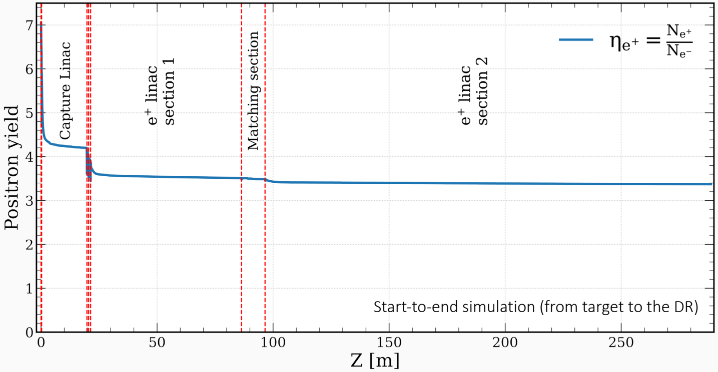
Matching section : 5 quadrupoles (0.4 m long)

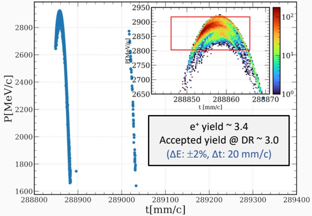
Section 2 : up to 2.86 GeV. Same RF structure as that of the CL. 52 structures. Quadrupole (0.4 m long), 2 structures per FODO cell. G = 12.8 MV/m

Slide courtesy of **I. Chaikovska**, IJCLab

FCC-ee Positron Source







*Simulations include collective effects (space charge and short-range wakefield)

e+ @ linac end

Average energy [GeV]	2.87
Positron yield [N_{e+}/N_{e-}]	3.4
Accepted positron yield @DR [N_{e+}/N_{e-}]	3
Bunch length [mm]	2.8
Energy spread	0.9
Spots size [mm]	5.3/2.8
Normalized emittance [mm·rad]	~13

Ensures reliable e+ production and meets the requirements set by FCC-ee (Z-pole) with the safety margins

Slide courtesy of **I. Chaikovska**, IJCLab

Ring layout

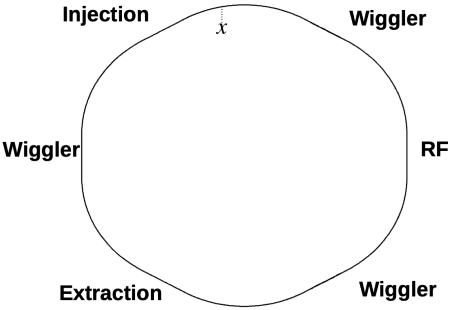
Hexagonal shape: 6 Arcs + 6 Straight

Arcs based on Multi-Bend cells

Straight sections used for specialized purpose: Injection or extraction, wigglers, RF cavity

Playing with optical functions possible to have super-periodicity of three (as for the triangle shaped DR)

Different options considered:
- Same basic layout
- Similar arc cell philosophy



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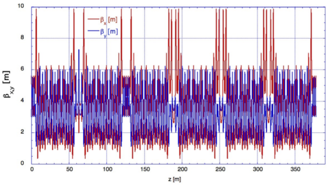
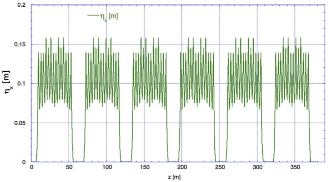
FCC-ee Damping Ring

Ring parameters (FS)

Parameters	Value
Energy [GeV]	2.86
Circumference [m]	373.46
Arc Cell	multi-bend
Lattice shape	six-fold symmetry
Nat. emittance [nm rad] (WGL on/off)	1.3 / 2.3
Bunch Lenght [mm]	5.1
Damping time $\tau_{x,y}$ (WGL on/off) [ms]	16.9 / 29.4
Nat. Cromaticity (x/y)	-38.2/-28.3
Nat. energy spread (WGL on/off) [10^{-4}]	7.1 / 5.2
Betatron amplitude max (x/y) [m]	9.66 / 6.49
Betatron amplitude min (x/y) [m]	0.5 / 1.1
Tune (Q_x,Q_y)	27.8707 / 22.3728
Momentum compaction (WGL on/off) [10^{-3}]	1.55 / 1.57
Revolution period [μs]	1.2457
Dipole #, length [m], field [T]	180 , 0.7 1.13, 0.34 0.39
Wiggler #, length [m], field [T]	3, 3.5 , 1.8
Cavity #, length, voltage [MV]	1.5, 4
Max. # Bunch stored, Bunch Curr. [mA]	40 / 4
Store time	5 τ_y
Energy loss per turn (WGL on/off) [keV]	422.2 / 246.7
SR power loss wiggler [kW]	27.83
Kicker rise time [ns]	50





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FCC-ee Damping Ring

Full ring parameters (6BA)

$L = 403.08$ m
$T_{per} = 1.343$ μs ;
$\alpha_c = 0.000758$
Ncel = 24

$Q_x = 39.566$
$Q_y = 21.867$

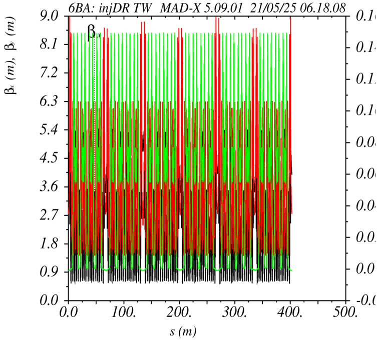
$\xi_x =$ 7.1e-9 (corr) / -50.48 (nat)
$\xi_y =$ 1.4e-8 (corr) / -36.87 (nat)

$\beta_x(\max) = 6.09$ m
$\beta_y(\max) = 8.32$ m

$U_0 = 571$ keV
$\Delta E =$ 7.3e-4

ε = 1.82 nm rad

$\tau_{x/y}$ = 13.5 ms



Synchrotron integrals:
I_1 = 0.30527316
I_2 = 0.6063789197
I_3 = 0.0541043725
I_4 = 0.001614382676
I_5 = 9.174328584e-05

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Damping time ≅ 10'000 turns.

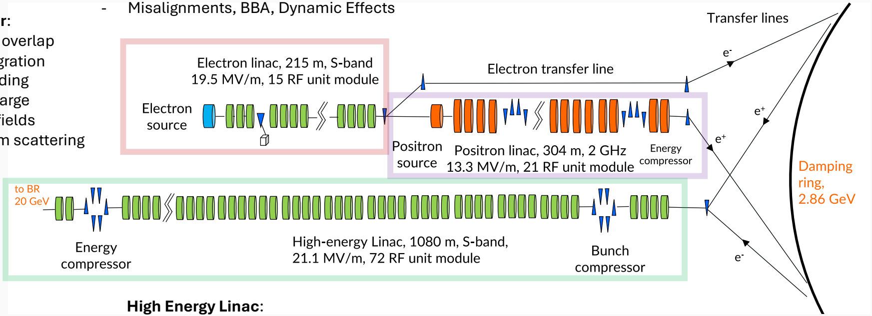
FCC-ee Injector Simulation

FCC-ee Injector Simulation Requirements

Positron source and Positron Linac:
- Elements overlap
- Time integration
- Realistic fields
- Coherent Synchrotron Radiation (EC)
- Beam loading from electrons and positrons
- Misalignments, BBA, Dynamic Effects

Electron Linac:
- Multi-bunch beam loading
- Short- and Long-range wakefields
- Misalignments, BBA, Dynamic Effects

Photoinjector:
- Elements overlap
- Time integration
- Beam loading
- Space-charge
- Realistic fields
- Intra-beam scattering



High Energy Linac:
- Short- and Long-range wakefields
- Multi-bunch beam loading
- Coherent Synchrotron Radiation (BC, EC)
- Misalignments, BBA, Dynamic Effects

Damping Ring: DA studies
- Dynamic aperture
- Synchrotron Radiation
- (Space-charge)
- (Intra-beam scattering)

RF-Track!

What is RF-Track?

RF-Track Characteristics

- **RF-Track** is a CERN-developed particle tracking code
- Simulates **generation**, **acceleration**, and **transport** of **any** particle species
- Works with both **realistic 3D field maps**, **special** and **conventional beamline elements**

Specific Applications

- **Photo-injectors** and **electron guns**
- **Positron sources**
- High-intensity **electron linacs**
- **RFQs** and high-intensity **proton and ion linacs**
- **Ion-electron cooling**
- **Inverse Compton scattering** X-ray sources
- **Ionization cooling channel** of the **Muon Collider**

RF-Track Architecture

High-performance, Multi-Threaded C++ Core

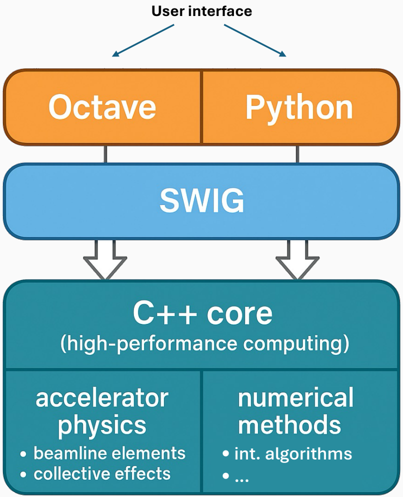
- Relativistic transformations
- Three- / Four-vectors
- 1D / 2D / 3D meshes
- Robust interpolators
- Quaternions
- Truncated Power Series Algebra (TPSA)

Accelerator Simulation Core

- Beamline elements
- Electromagnetic fields
- Collective effects

User Interface: Python / Octave

- Beamlines & beams
- Imperfections
- Orbit correction schemes

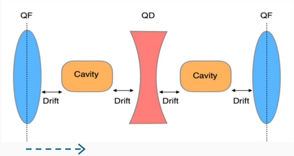


In-Time and In-Space Tracking

Lattice: “in-space” beam evolution

- A list of elements
- Tracks the particles element by element, along the longitudinal direction
- Elements can be arbitrarily misaligned

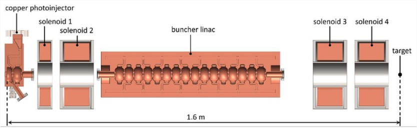
Example of Lattice: FODO cell



Volume: “in-time” beam evolution

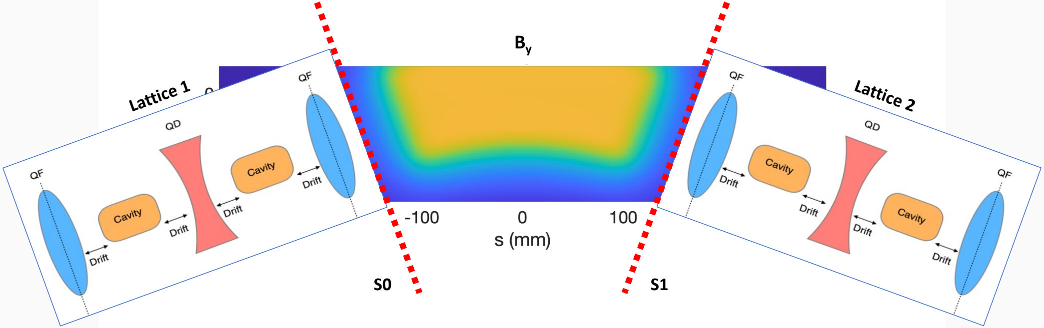
- A portion of 3D space
- Elements can be placed anywhere
- Element misalignment via Euler angles (pitch, yaw, roll)
- Allows element overlap
- Allows creation of particles
- Can simulate cathodes and field emission
- Suitable for space-charge-dominated regimes

Example of Volume: Photoinjector



Volume as a Lattice element

The boundaries of a Volume can have arbitrary orientation in space:



⇒ A Volume can be **sandwiched** between two Lattices.

RF-Track Highlights

Key Capabilities

- Tracking in **time** and **space** of **any particle** at **any energy**, including **spin**
- **Realistic fields** and **arbitrary field maps**
- **Overlapping** elements
- **Space-charge effects**
- **Beam-beam effects**
- **Intra-beam scattering**
- **Wakefields** (short- and long-range)
- **Synchrotron radiation emission**
- **Multi-bunch Beam loading** in **SW** and **TW structures**
- **Particle-matter interaction**
- Arbitrary **element misalignments**
- **Beam-based alignment** algorithms
- **Back-tracking** also in the presence of collective effects

RF-Track Community

Those I am aware of:

RFQs, hadron linacs: Peking University (**China**), Dongguan (China), Institute of Modern Physics, Lanzhou (China), CIEMAT (**Spain**), IFIC Valencia (Spain)

Photo-injectors: CLEAR (CERN), CTF2 (CERN), **SwissFEL** (**PSI**), **ESRF**

Positron sources: FCC-ee (**IJClab**, CERN), CLIC (CERN)

Optics in field maps: ThomX (IJClab), Synchrotron Soleil (**France**)

Inverse-Compton Scattering: X-band applications (CERN), ThomX (IJClab), **Arizona State University** (USA), **LASA** (Milan, Italy), **INFN Ferrara**, **Korea University**

Medical accelerators: **PMB** (France), **THERYQ** (France), **Thales** (France)

High-intensity electron linacs: Injector upgrade at **ESRF**, Thales (France), IFIC Valencia (Spain), C^3 electron-positron collider (**SLAC**), EuSPARC (**LNF-INFN**), Shanghai Advanced Research Institute (China)

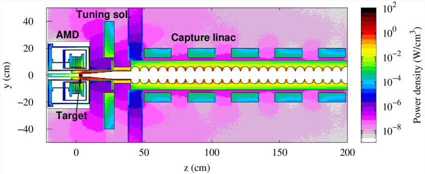
Klystron design: **Thales** (France)

Exotic scenarios: GaToroid (CERN, **Oxford**, Groningen), Muon Cooling Channel (CERN, Muon Collider Collaboration)

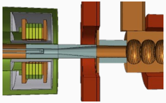
RF-Track Simulations of the FCC-ee Injector

FCC-ee Positron Source

Capture Linac



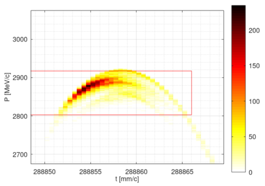
Y. Zhao, A. Lechner, B. Humann (CERN)



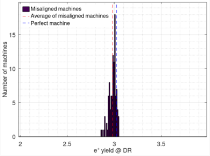
M. Daugaard (CERN)

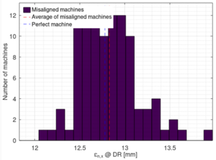
Total yield: 3.37

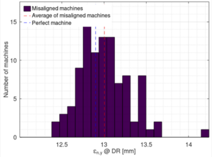
Yield within window: 2.97



Misalignment studies







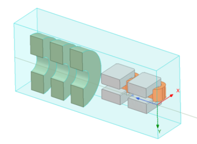
Accurate beam tracking in the target and capture area is crucial

Particle losses and energy deposition maps

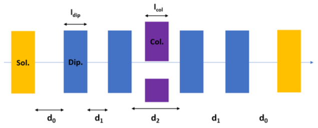
Geant4: Tungsten target for e^+ production

RF-Track: tracking in 250 meters of field maps

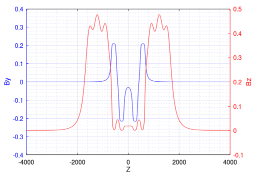
Chicane



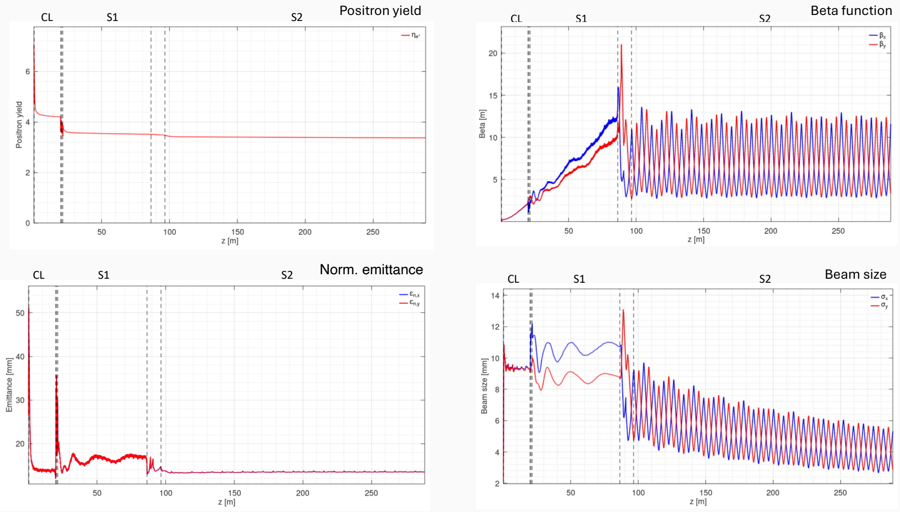
¼ view



Y. Zhao (CERN), R. Zennaro (PSI)



FCC-ee Positron Source



Y. Zhao, CERN

Damping Ring

Using the MAD-X lattice in RF-Track:

Added the beam pipe physical aperture:

- $R_x = 3$ **cm, horizontal radius**
- $R_y = 1.5$ **cm, vertical radius**

to all elements except for the RF structures, where the aperture is fixed by the frequency

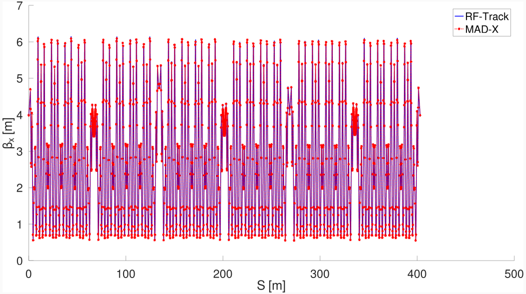
Mechanism for losing particles:

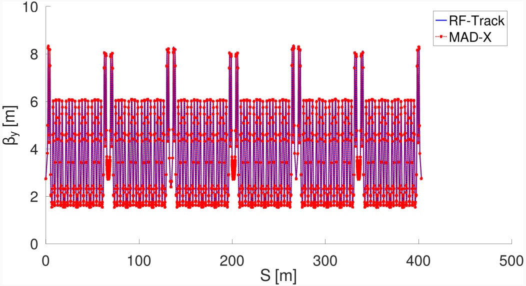
1. **Particles hit the aperture**
2. **Particles slip off the synchronous RF bucket**

```
RF_Track;

% Load Lattice
L = Lattice('full_twiss_file.tws');

% Define a bunch
T = Bunch6d_twiss();
T.beta_x = 3.9851;                  % m
T.beta_y = 2.7454;                  % m
T.alpha_x = 0.0060;
T.alpha_y = -0.0016;
T.emitt_x = 13e3;                   % mm.mrad
T.emitt_y = 13e3;                   % mm.mrad

mass = RF_Track.electronmass;       % MeV/c^2
Q = +1;                             % positron charge
Nparticles = 10000;                 % nb of macroparticles
Pref = 2859.999954;                 % MeV/c, reference momentum

% Create a bunch
B0 = Bunch6d_QR (mass, 0.0, Q, Pref, T, N);

% Perform tracking
B1 = L.track(B0);
```

FCC-ee Damping Ring Simulation

Validation of the **optics functions:**

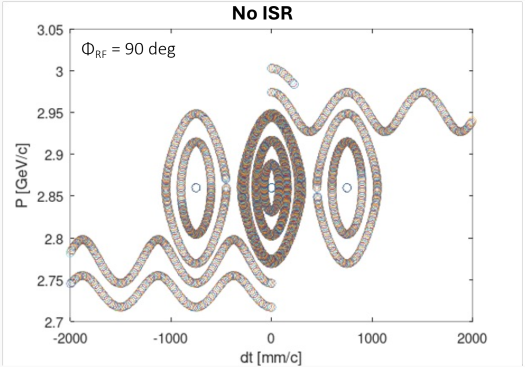


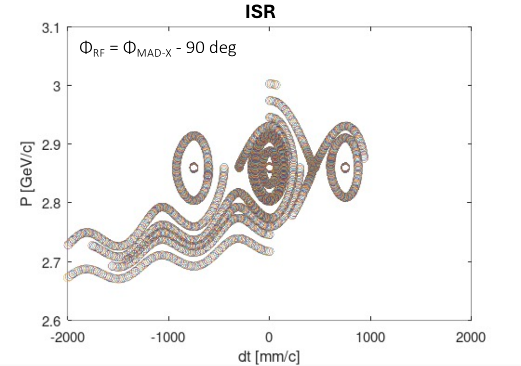


Horizontal Plane **Vertical Plane**

Setting the RF Phase

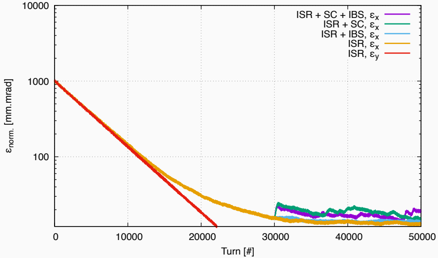
The lattice has **one SW structure** - implemented as a **pillbox cavity** in RF-Track

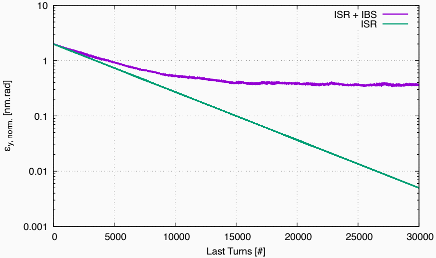


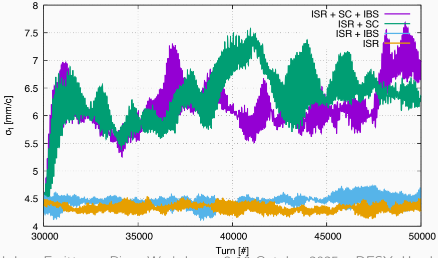


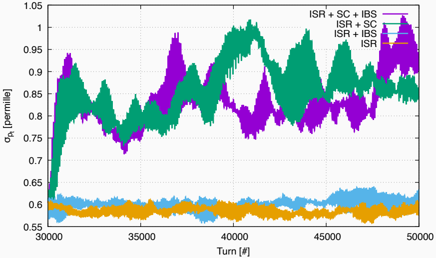
Multi-turn Tracking

50'000 turns tracking. **10'000 macro particles**. **5 nC** bunch charge. **ISR + quantum-excitation**. **SC** and **IBS** from turn 30'000.









6D Dynamic Aperture

6D Dynamic Aperture

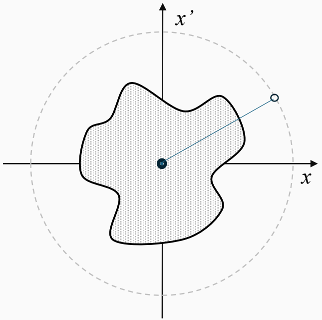
There exist two clearly-defined regions in the phase-space:
(1) where particles survive 1000 turns
(2) where particles are lost

Given a radial direction in the $x - x'$ plane and an initial radius $R = 1$

Algorithm:

1. Identify the two regions:
   If $R = 1$ is inside the inclusion region, increase R until it enters the exclusion region.
2. Find the separation between the two regions:
   Use a binary search to find the separation:
   - Stop when $R_{\text{out}} - R_{\text{in}} < \epsilon$
     (I used $\epsilon = 0.001$ mm/mrad.)
   - Store $R_{\text{surface}} = R_{\text{in}}$.

2D Representation



6D Dynamic Aperture (II)

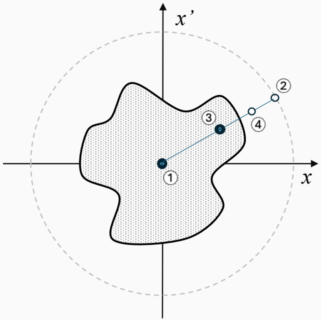
There exist two clearly-defined regions in the phase-space:
(1) where particles survive 1000 turns
(2) where particles are lost

Given a radial direction in the $x - x'$ plane and an initial radius $R = 1$

Algorithm:

1. Identify the two regions:
   If $R = 1$ is inside the inclusion region, increase R until it enters the exclusion region.
2. Find the separation between the two regions:
   Use a binary search to find the separation:
   - Stop when $R_{\text{out}} - R_{\text{in}} < \epsilon$
     (I used $\epsilon = 0.001$ mm/mrad.)
   - Store $R_{\text{surface}} = R_{\text{in}}$.

2D Representation



6D Dynamic Aperture (III)

Step 1. For all points uniformly distributed on a 6D sphere:

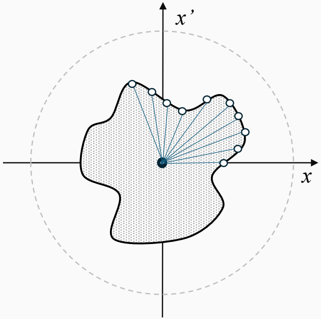
1. Find its radius $R_{\text{surface},i}$
2. Store all $R_{\text{surface},\ i}$ points, so that any arbitrary angle can be associated with its R_{surface}

The resulting surface (manifold) is the dynamic aperture.

Step 2. Acceptance algorithm:

For each particle in an arbitrary distribution:

1. Compute its 5D coordinates on the manifold (i.e., its corresponding index i)
2. Compute the distance of the 6D point from the origin, R
3. Verify: $\begin{cases} R < R_{\text{surface},\ i} & \text{the particle is within the acceptance} \\ \text{otherwise} & \text{the particle is outside the acceptance} \end{cases}$



Calculation in 6D

Challenge:

- Given a **6D phase space vector**

$$\left(x, \quad x', \quad y, \quad y,' \quad \delta t, \quad \delta\right)$$

with

$$\delta t = t - t_{\text{ref}}$$
$$\delta = \frac{P - P_{\text{ref}}}{P_{\text{ref}}}$$

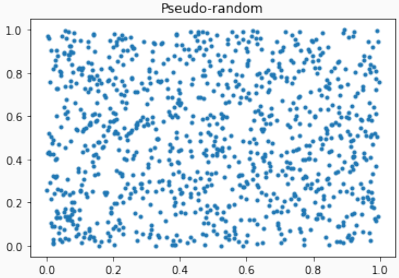
We need to define a criterion for uniformly filling a 5D surface

How to Fill a 6D Surface Uniformly

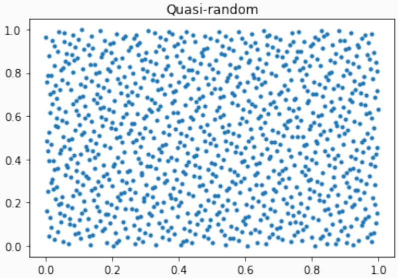
The solution:

Quasi-Random numbers, a.k.a. **Low-discrepancy sequences**.

Example in 2D:



⇒

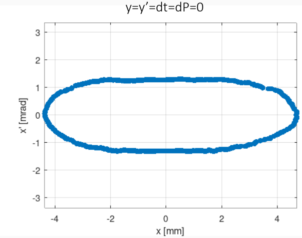


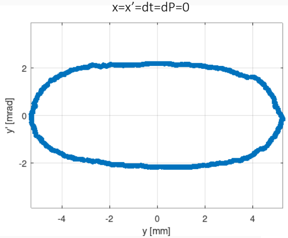
Low-discrepancy sequences are deterministic ⇒ **we can index each point** on the 5D surface.

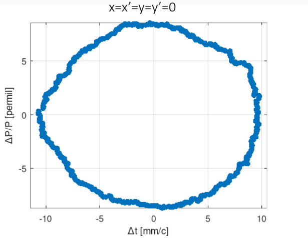
RF-Track allows to create such distributions, in any dimensions.

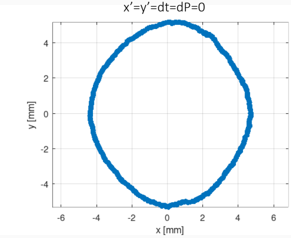
FCC-ee DR's 6D Dynamic Aperture

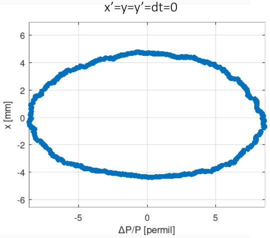
At the DR entrance:

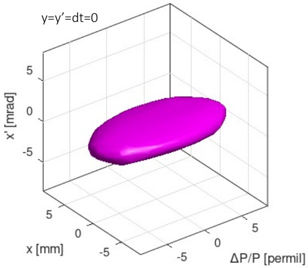






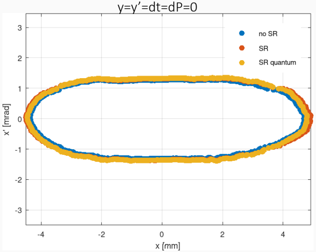


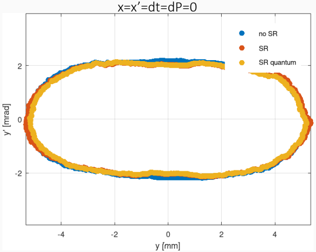


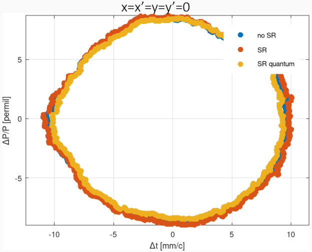


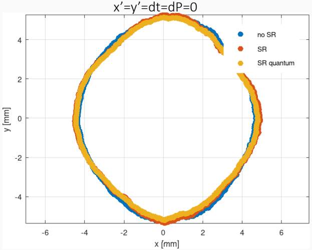
FCC-ee DR's 6D Dynamic Aperture - SR ON

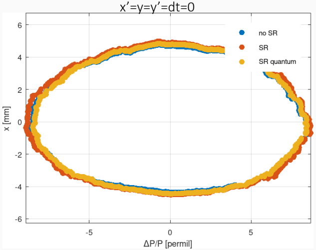
At the DR entrance:









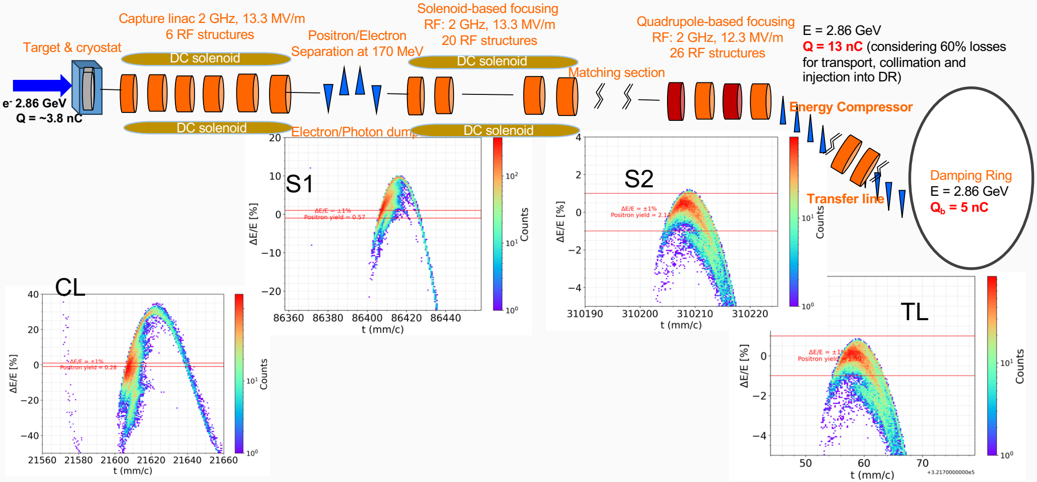


These graphs show cross-sectional views of a multidimensional surface.

This is a 5D surface embedded in the 6D phase space.

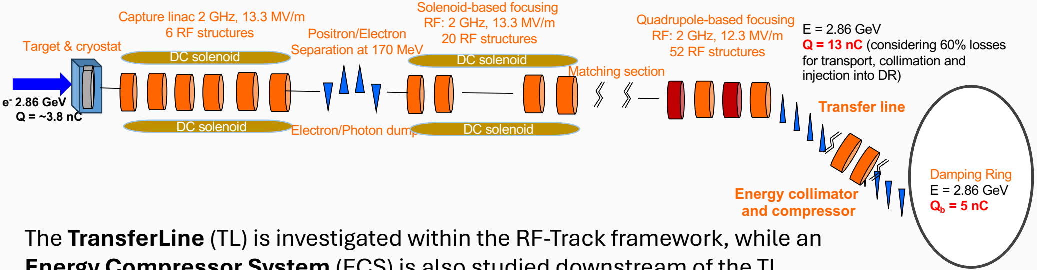
Particles inside the surface survive for at least 1,000 turns. Particles outside are lost.

Acceptance in DR



Slide courtesy of **Y. Wang**, IJCLab

Maximizing Transmission



The **TransferLine** (TL) is investigated within the RF-Track framework, while an **Energy Compressor System** (ECS) is also studied downstream of the TL.

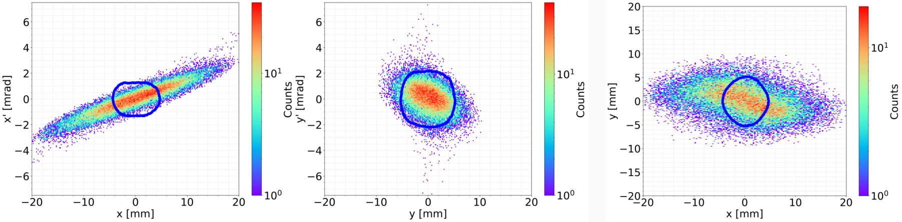
The **TransferLine** is a **special RF-Track element**, whereas the ECS is modelled **using analytical formulae.**

Xopt optimization of the Transfer Line and of the ECS: $[Length,\ \beta_x,\ \alpha_x,\ \mu_x,\ \beta_y,\ \alpha_y,\ \mu_y,\ R_{56},\ R_{65}]$

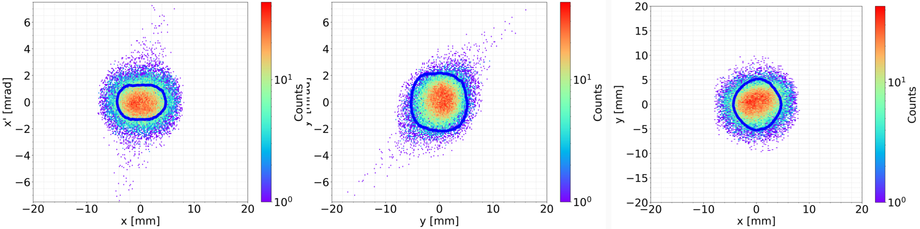
Slide courtesy of **Y. Wang**, IJCLab

Optimization - Transverse Plane

Xopt-optimized matching using the element **TransferLine:**



@S2

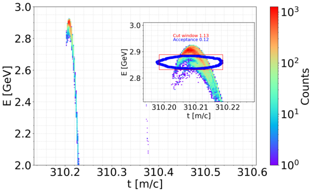


@TL

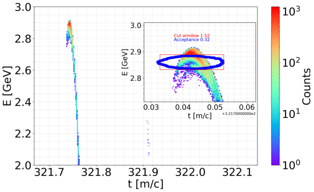
Slide courtesy of **Y. Wang**, IJCLab

Optimization - Longitudinal Plane

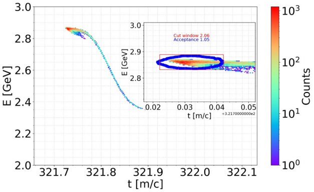
Xopt-optimized Energy Compressor using **an analytic formula:**



@S2



@TL



@ECS

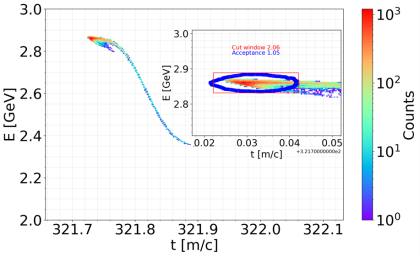
Slide courtesy of **Y. Wang**, IJCLab

Damping Ring Conclusions

- Start-to-end simulation including the DR (using the FS layout + TL + ECS).
- The DR acceptance is based on the linear tracking without errors. The realistic acceptance will probably be even smaller.

	Main Bucket (95 %)
e^+ yield @ Linac end [N_{e+}/N_{e-}]	3.3 (3.4 FULL)
e^+ yield @DR [N_{e+}/N_{e-}] 6D acceptance	1.05/ (≲ 2.6*)
Norm. emittance @ECS [mm*rad] Within 6D acceptance	14.1/13.2 5.0/6.1
Geom. emittance @ECS [mm*mrad] Within 6D acceptance	2.54/2.40 0.89/1.09
Energy spread @ECS (RMS) [%] Within 6D acceptance	2.5 % 0.18 %
Bunch length @ECS (RMS) [mm] Within 6D acceptance	24.2 mm 3.3 mm
Beam size @ECS Within 6D acceptance	2.6/2.2 1.6/1.2

*Minimum required e^+ yield for an e^- bunch charge of 5 nC



Work in progress to quantify the losses in transverse and longitudinal planes

Slide courtesy of **Y. Wang** and **I. Chaikovska**, JCLab

Conclusions

- The **FCC-ee Injector design and optimization is in progress, using RF-Track** from the photo-cathode to the booster ring (20 GeV)
- A method to **compute the 6D Dynamic Aperture** was proposed
- A method to **fast match the positron beam** to the DR has been tested

- **RF-Track** is a **particle tracking code** designed to track particle sin **3D field maps**, **conventional** and **non-conventional beamline elements**.
  - `https://gitlab.cern.ch/rf-track`
  - `https://pypi.org/project/RF-Track`

Outlook

- Positron acceptance of the FCC-ee Damping Ring must be improved