RF-Track Development for the FCCee Injectors

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Introduction and Highlights

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** and **conventional beamline elements**

Applications

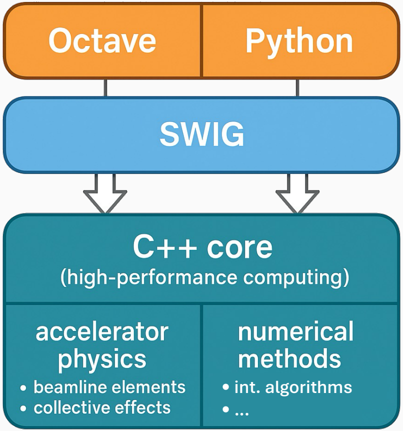
- **Photoinjectors** and **electron guns**
- **Positron sources**
- High-intensity **electron linacs**
- **RFQs** and high-intensity **proton and ion linacs**
- **Ion-electron cooling**
- **Inverse Compton scattering** X-ray sources
- **Ionisation cooling channel** of the **Muon Collider**

RF-Track Structure

High-performance, Multi-Threaded C++ Core
- Relativistic transformations
- Three- / Four-vectors
- 1D / 2D / 3D meshes
- Robust interpolators
- Quaternions
- Truncated Power Series Algebra

Accelerator Simulation Core
- Beamline elements
- Electromagnetic fields
- Collective effects

User Interface: Python / Octave
- Beamlines & beams
- Imperfections
- Correction schemes



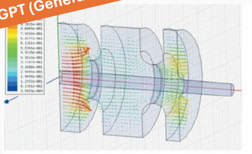
RF-Track Key Capabilities

Key Capabilities

- Tracking in **time** and **space** of **any particle** at **any energy**
- **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** in the presence of collective effects

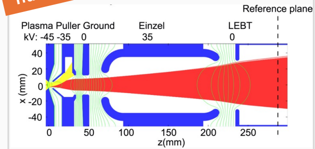
RF-Track Use Cases

ASTRA, Parmela, GPT (General Particle Tracer)



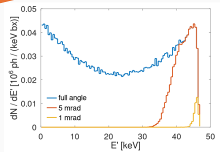
Photoinjectors and electron guns (space-charge, IBS)

PATH, Parmila, TraceWin, IBSimu



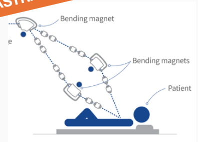
Positron, proton, and ion sources & linacs

Guinea-Pig. CAIN



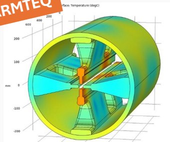
Inverse-Compton Scattering Compact X-ray sources

GPT + PLACET ? ASTRA + ELEGANT ?



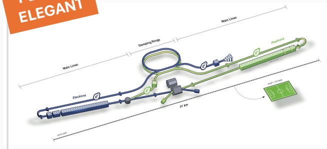
Medical e⁻ linacs for Flash therapy

Tuotatis, PARMTEQ



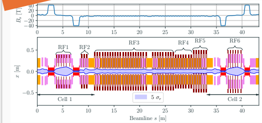
Radio-Frequency Quadrupoles (RFQ)

PLACET, ELEGANT



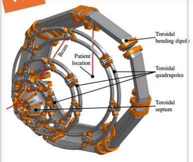
Linear Colliders, Free-Electron Lasers (Wakefields, beam loading, …)

ICOOL, G4Beamline



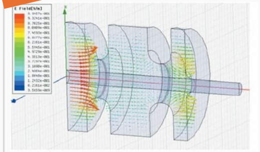
Muon Cooling (Particle-matter interaction)

???

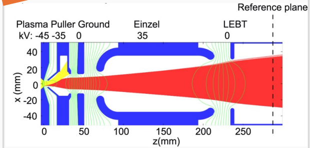


GaToroid (Optics in complex fields)

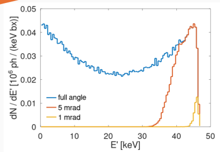
RF-Track Use Cases



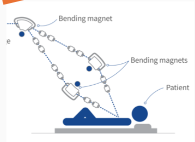
Photoinjectors and electron guns (space-charge, IBS)



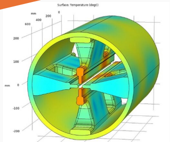
Positron, proton, and ion sources & linacs



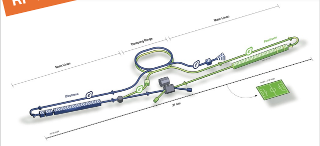
Inverse-Compton Scattering Compact X-ray sources



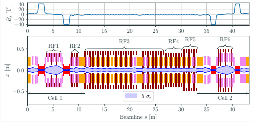
Medical e^- linacs for Flash therapy



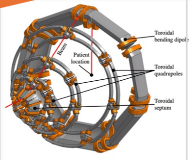
Radio-Frequency Quadrupoles (RFQ)



Linear Colliders, Free-Electron Lasers (Wakefields, beam loading, ...)



Muon Cooling (Particle-matter interaction)



GaToroid (Optics in complex fields)

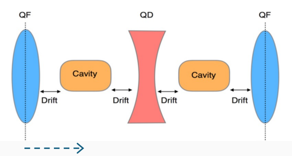
Feature Showcase

Tracking Environments

Lattice: in-space integration

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

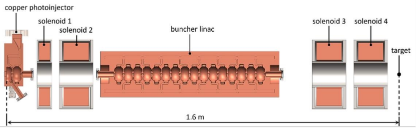
Example of Lattice: FODO cell



Volume: s integration

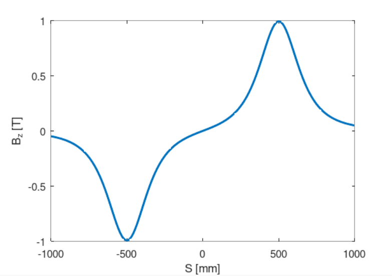
- A portion of 3D space
- Elements can be placed anywhere
- Element misalignment via Euler angles (pitch, yaw, roll)
- Allows element overlap
- Allows creation of particles
- Can simulate cathodes and field emission
- Includes cathode mirror charges

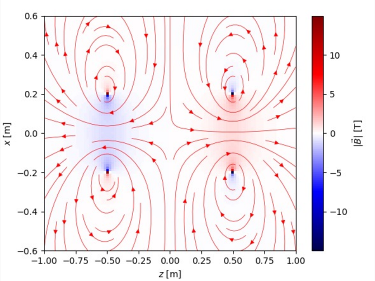
Example of Volume: Photoinjector



Example of Volume: Overlapping Fields

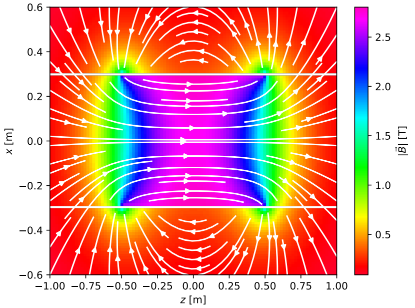
```
RF_Track;

L = 0;   % length [m]
B = 1;   % field at the center of the coil [T]
R = 0.2; % coil radius [m]

Cm = Coil(L, -B, R);
Cp = Coil(L, +B, R);

V = Volume();
V.add(Cm, 0, 0, -0.5, 'center');
V.add(Cp, 0, 0,  0.5, 'center');

figure(1)
Za = linspace(-1e3, +1e3, 1000); % mm
[E,B] = V.get_field(0, 0, Za, 0);

plot(Za, B(:,3));
xlabel('S [mm]');
ylabel('B_z [T]');
```





The element Solenoid

In Lattice, a Solenoid is a standard **symplectic transfer matrix**. In Volume, a Solenoid is the three-dimensional field generated by an **arbitrary number of thin sheets of current**:



Solenoid field computed by RF-Track.

[Plot courtesy of Bernd Michael Stechauner (CERN, TU Vienna)]

Overview of the Beamline Elements

1. **Standard set** of **symplectic** elements:
   - **Sector bend, Quadrupole, Solenoid, Multipole**
   - **Drift** (embedded in an optional constant electric and magnetic fields)

2. **Field maps**
   - **1D / 2D / 3D RF field maps**, **standing-** and **traveling-wave** – with **symplectic interpolators**

3. **Special elements**:
   - 3D analytic fields**:** **Coil** and **Solenoid**, **Undulator**, **Standing-wave** and **Traveling-wave** structures, **Adiabatic matching devices**, **Toroidal Harmonics**
   - **Screens** to capture the phase space at any point with any orientation in space
   - **Absorber** (predefined materials: air, water, beryllium, lithium, tungsten, ...)
   - **LaserBeam** for Inverse Compton Scattering simulation
   - **Electron Cooler** for electron cooling in ion storage rings
   - **Transfer Line** to track through an arbitrary lattice given in form of Twiss table (phase advances, momentum compaction, 1^{st} and 2^{nd} order chromaticity are considered)

Collective and single-particle effects

Collective effects

- **Space-charge**, full electromagnetic interaction, 3D Particle-in-Cell (FFT) or P2P
  - Full computation of electric and magnetic effects – includes beam-beam
  - Optionally considers mirror charges at cathode
- **Wakefields**
  - **Short-range:** Karl Bane's model
  - **Long-range:** Damped resonators from frequency, amplitude, and Q factor
  - **User-defined spline**, longitudinal monopole or transverse dipole
- **Beam loading** in TW and SW structures
  - Given: R/Q, group velocity, and Q factors along the structure, computes the beam loaded fields
- **Intra-beam scattering [NEW!]**
  - Hybrid-Kinetic Monte Carlo model

Single-particle effects

- **Incoherent Synchrotron Radiation** (from *any* fields)
- **Magnetic multipole kicks** for imperfection studies
- **Particle-matter interaction**

All effects can be attached to **any element** and **overlapped**

RF-Track for the FCCee Injectors

RF-Track for the FCCee Injectors

Positron source and Positron Linac:

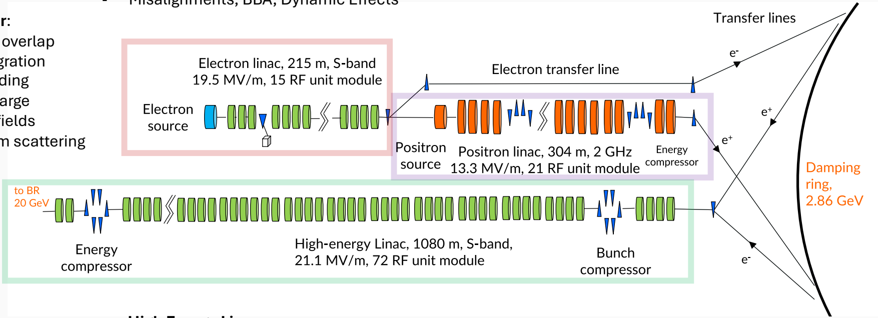
- Elements overlap
- Time integration
- Realistic fields
- Coherent Synchrotron Radiation (EC)
- Beam loading from electrons and positrons
- Misalignments, BBA, Dynamic Effects

Electron Linac:

- Beam loading
- 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:

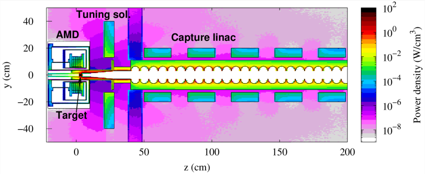
- Short- and Long-range wakefields
- Multi-bunch beam loading
- Coherent Synchrotron Radiation (BC, EC)
- Misalignments, BBA, Dynamic Effects

Damping Ring: DA studies

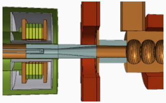
- Dynamic aperture
- Intra-beam scattering

FCCee Positron Source

Capture Linac



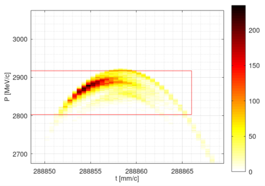
Y. Zhao, A. Lechner, B. Humann (CERN)



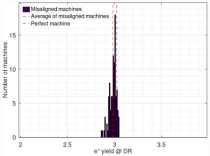
M. Daugaard (CERN)

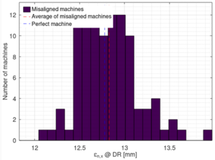
Total yield: 3.37

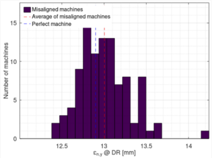
Yield within window: 2.97



Misalignment studies





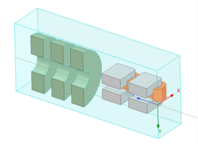


Accurate beam tracking in the target and capture area is crucial

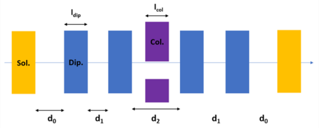
Particle losses and energy deposition maps

250 meters of beam tracking in field maps

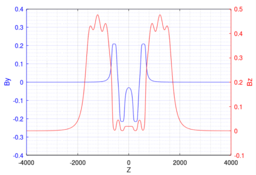
Chicane



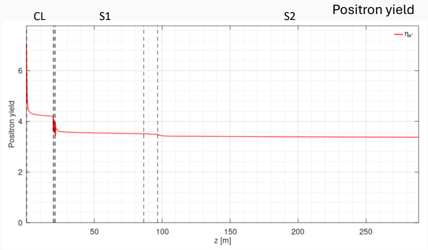
¼ view

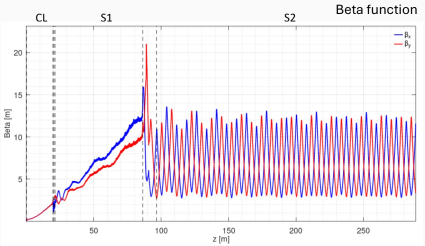


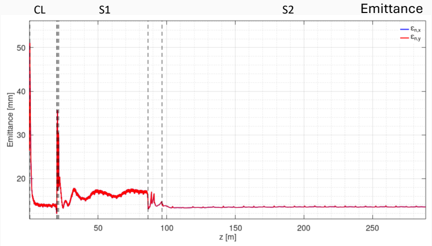
Y. Zhao (CERN), R. Zennaro (PSI)

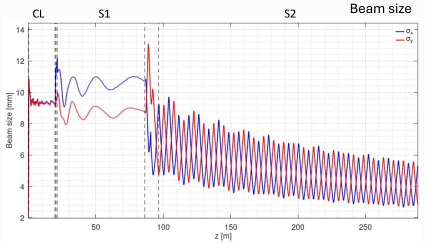


FCCee Positron Source









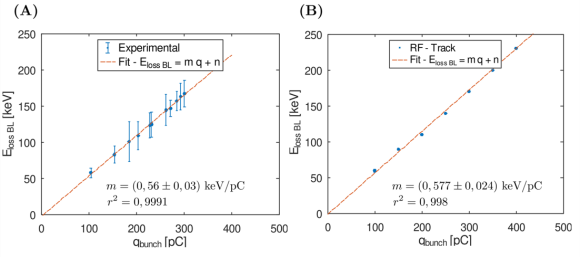
[Y. Zhao (CERN)]

Beam Loading in Standing-Wave Structures

Beam-loading effects have also been computed in standing-wave structures.

Follow the example of the photoinjector of the CLEAR test facility at CERN. The plots show the beam-induced energy loss of a train of 150 bunches with 1.5 GHz bunch-spacing, as a function of the bunch charge.

Beam parameter (end of linac)	Value range
Energy	60 - 220 MeV
Bunch charge	0.01 - 1.5 nC
Normalized emittances	3 um for 0.05 nC per bunch 20 um for 0.4 nC per bunch (in both planes)
Bunch length	~100 um - 1.2 mm
Relative energy spread	< 0.2 % rms (< 1 MeV FWHM)
Repetition rate	0.8 - 10 Hz
Number of micro-bunches in train	1 - 150
Micro-bunch spacing	1.5 or 3.0 GHz

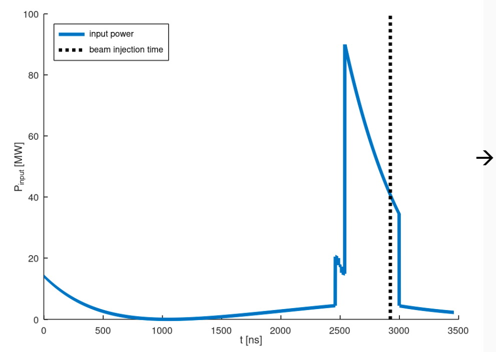


(A) Experimental measurements
(B) RF-Track simulation

J. H. Olivares et al., "Implementation of the beam-loading effect in the tracking code RF-track based on a power-diffusive model", Frontiers in Physics, 2024

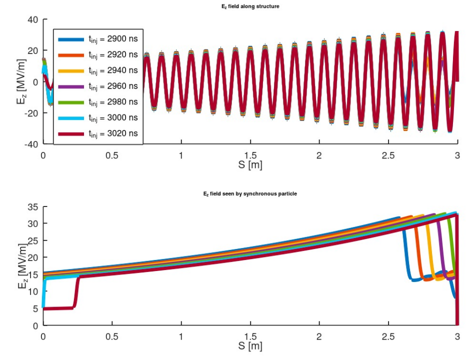
Beam Loading Compensation in the HE Linac

The element `TW_Field` was created to simulate **beam loading compensation** in the **High-Energy Linac** (to 20 GeV)



Modulated Input Power from the Klystron

→



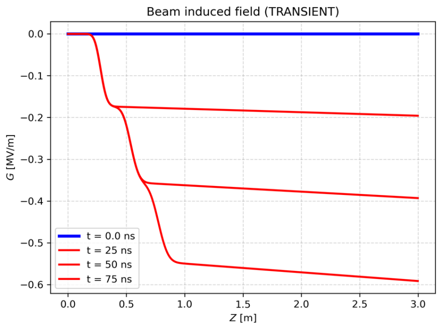
Field in the structure

[The modulated input power shown is the “Golden pulse”, A. Kurtulus, A. Grudiev (CERN)]

Beam Loading in the FCC-ee Injector Linacs' TW Structures

TW_Field

```
# Input power in watts
P = 60e6  # W

# Structure parameters
N_cells = 84
freq = 2.8e9 # Hz
ph = 2*np.pi/3 # phase advance

# Load Beam Loading parameters from text files
QQ  = np.loadtxt("Q_HE_linac.txt")                   # Quality factor
R_Q = np.loadtxt("r_Q_HE_linac.txt") * 1e3           # Ohm/m
VG  = np.loadtxt("Group_velocities_HE_linac.txt") / 100  # fraction of c

# Define the TW_Field object
TW = rft.TW_Field(P, QQ, R_Q, VG, freq, ph, N_cells)
TW = rft.TW_Field(P_vec, dt_power, t_injection, QQ, R_Q, VG, freq, ph, N_cells)
```



Beam loading initialization

```
BL = rft.BeamLoading (N_cells, freq, ph, QQ, R_Q, VG)

TW.add_collective_effect(BL) # Add transient BL to TW
TW.set_cfx_nsteps(10)        # 10 kicks per structure
```

TW_Field with **Golden Pulse** + **Beam Loading** for multi-bunch beam dynamics studies of **timing / energy errors**.

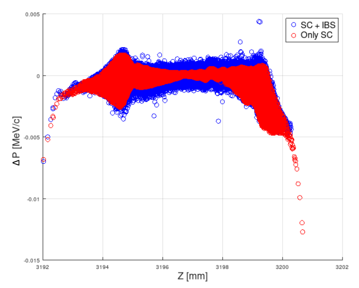
Intra-beam Scattering

Implemented using a Hybrid-Kinetic Monte Carlo Model.

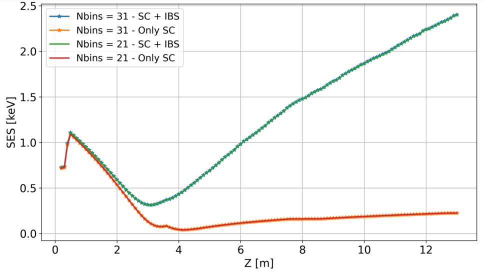
First tests: Slice-Energy Spread (SES) in the SwissFEL Photoinjector: 200 pC bunch, from 0 to 130 MeV

- Z < 3 m: Photocathode, 3 GHz electron gun, solenoid, up tp 7 MeV
- Z > 3 m: two 3 GHz Traveling-Wave structures, up to 130 MeV

SES at Z = 3 m



Slice-Energy Spread along the injector



Benchmark with measurements in progress.

[Work in progress for muon studies: Paula Desire Valdor (CERN, University of Groningen): SwissFEL studies: Thomas Lucas (PSI)]

Ongoing and Future Developments

Ongoing and Future Developments

Ongoing:

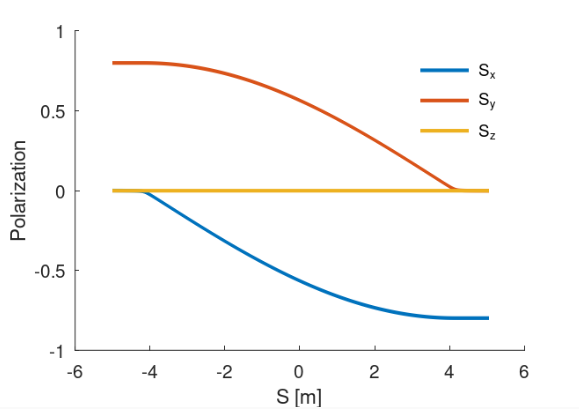
- **Spin polarisation** tracking: (under testing)
  - FCC-ee application: electron and positron sources

Coming Future:

- **3D Coherent Synchrotron Radiation** emission:
  - FCC-ee application: Injectors arcs, bunch and energy compressors
- **Interface to SuperFish**:
  - More powerful RF design $\longleftrightarrow$ beam dynamics optimisation
- **JSON lattice description**:
  - Ease **Octave** $\longleftrightarrow$ **Python** exchange
  - Ease **RF-Track** $\longleftrightarrow$ **Xsuite** exchange

Spin Tracking [Testing Phase]

A **5 GeV electron beam** with **vertical polarization = 0.8**, through a **8.32 m long solenoid** with a $B_z = 3.15$ **T field:**



[Solenoid of the ILC Spin Rotator]

RF-Track Community

Those I am aware of:

RFQs, hadron linacs: Linac4 (CERN), Peking University (China), Institute of Modern Physics, Lanzhou (China), CIEMAT (Spain), IFIC Valencia (Spain)

Photoinjectors: CLEAR (CERN), CTF2 (CERN), SwissFEL (PSI)

Positron sources: FCCee (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)

Medical accelerators: DEFT (CERN), PMB (France), THERYQ (France)

High-intensity electron linacs: CERN, Thales (France), IFIC Valencia (Spain), C^3 electron-positron collider (SLAC), EuSPARC (LNF-INFN)

Exotic scenarios: GaToroid (CERN, Oxford Univ.), Muon Cooling Channel (CERN)

RF-Track Resources

CERN website:

- Octave binaries, Documentation, Jupyter Notebooks Tutorials
  `https://gitlab.cern.ch/rf-track`

PyPi:

- Python version
  `https://pypi.org/project/RF-Track`

Reference Manual:

- `https://gitlab.cern.ch/rf-track/rf-track-reference-manual/-/raw/master/RF_Track_reference_manual.pdf?ref_type=heads`

Summary

- **RF-Track** is a **CERN-developed** particle tracking code designed to simulate the **generation**, **acceleration**, and **transport** of **any particle species** through an accelerator. It supports both realistic **3D field maps** and **conventional beamline elements**.
- RF-Track allows tracking **in both time and space** domains and includes a comprehensive set of **single-particle** and **collective effects**, including:
  - **Space-charge, Beam–beam interactions, Beam loading** in **standing- and traveling-wave structures, Short-** and **long-range wakefields, Synchrotron radiation emission, Multiple Coulomb scattering,** and **Intra-beam scattering**
- These capabilities make RF-Track ideally suited for the simulation of **high-intensity accelerator systems**. It has been successfully applied to:
  - **Electron linacs** including for medical applications and **FCCee Injectors**,
  - **Photoinjectors,**
  - **Positron sources, including the FCCee positron source**
  - **Proton linacs,**
  - **Ion–electron cooling**, and
  - **Inverse Compton scattering** X-ray sources,
  - **The ionisation cooling channel** of a future **muon collider**

Thank you for your attention

Gitlab

PyPi

Manual

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