The tracking code RF-TRACK and its applications

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Outline

- **PART I:** Introduction and RF-Track Highlights
- **PART II:** Tracking in space and time
- **PART III:** Beamline elements
- **PART IV:** Applications
  - Beam Loading Scenarios

PART I: Introduction and Highlights

RF-Track Highlights

- It handles **complex 3D fieldmaps** of oscillating RF electromagnetic fields
  - SW, backward and forward TW.
  - Static E, H fields
- It can simulate particles with **any mass and charge**
  - No approximations, like $\beta \simeq 1 \quad \gamma \gg 1$
  - **Mixed-species beams**: protons, ions, electrons, positons, photon, muons.
  - Photocathodes
- High-order adaptative integration algorithms
- **Collective effects**
- **Modular, flexible** and **fast**

RF-Track – Physics oriented

- RF-Track is written in parallel C++, focusing **only** on **accelerator simulation**:
  - Flexible accelerator description and beam models
  - Accurate integration of the equations of motion
  - Robust interpolation of fieldmaps
  - Collective effects
  - Easy implementation of imperfections and correction algorithms
- For *all the rest*:
  - GSL (Gnu Scientific Library): Mathematical routines
  - FFTW (Fastest Fourier Transform in the West)
- **2 user interfaces:** Octave and Python

PART II: Tracking in space and time

Tracking in space and time

RF Track implements **two beam models**:

- Beam moving in **space**: `Bunch6d()`
  - All particles have the same S position — Equations of motion integrated in dS: $\mathrm{S} \rightarrow \mathrm{S} + \mathrm{dS}$
- Beam moving in **time**: `Bunch6dT()`
  - All particles are considered at same time t — Equations of motion integrated in dt: $\mathrm{t} \rightarrow \mathrm{t} + \mathrm{dt}$

- For each particle, it also considers:

  Mass: **m** [MeV/c] — Charge: **Q** [e] — Nb of particles / macroparticle: **N**

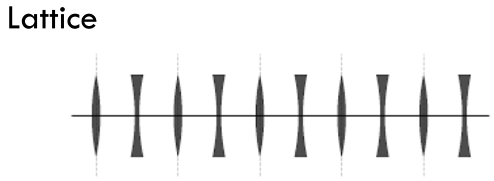
  Creation time: $\mathbf{t_0}$ [mm/c] * — Lifetime: $\boldsymbol{\tau}$ [mm/c] (new!)

- RF-Track can simulate **mixed-species beams** and the **creation** and **decay** of particles.

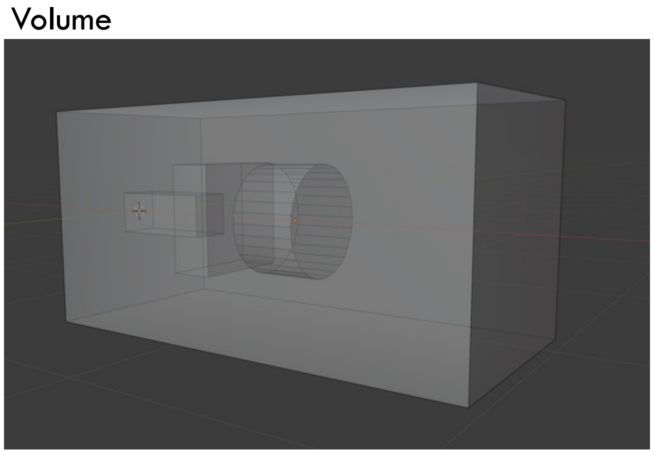
Tracking in space and time

RF Track implements **two tracking environments**:

- Integration in **space**: `Lattice()`
  - List of elements
  - Tracking along **longitudinal direction**, element by element

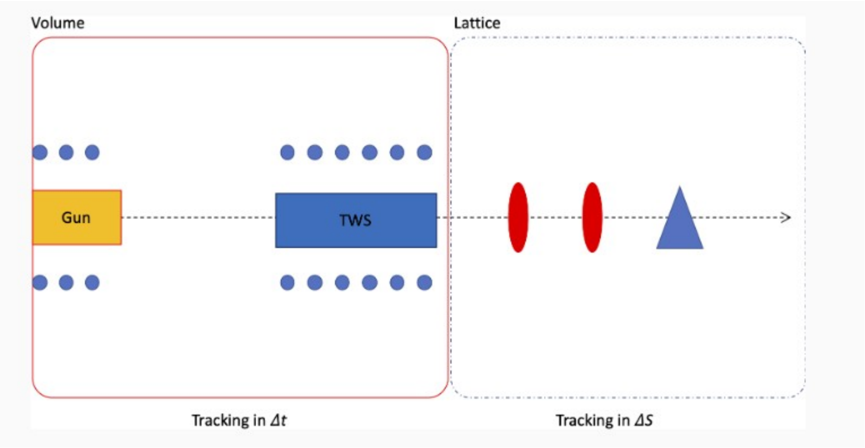


- Integration in **time**: `Volume()`
  - 3D space: Elements can be placed **everywhere**
    - Element misalignment via Euler angles
  - Allows: element **overlap**, **creation** of particles
  - **Cathodes** and **field emission**
    - Cathode **mirror charges**



Tracking in space and time

`Lattice` and `Volume` can be used together or separately



- `Volume` (**time** integration): Suitable for **space-charge** dominated regimes
- `Lattice` (**space** integration): Suitable for **ultra-relativistic** regions

PART III: Beamline elements

Beamline elements

- **Matrix-based symplectic** elements: Sbends, Quadrupoles, Drifts
- **Fieldmaps:**
  - **1D fieldmaps** (on axis): Maxwell Equations to reconstruct 3D field off axis (cylindrical symmetry)
  - **2D fieldmaps:** Given a field on a plane, applies cylindrical symmetry
  - **3D fieldmaps:**
    - 3D mesh of complex numbers
    - Accepts quarter field maps: Automatic mirroring with boundary conditions

- **Special elements**: Absorbers, 3D analytic fields, laser beam, e-cooler, toroidal harmonics.

Collective & single particle effects

- **Collective effects**:
  - **Space-Charge**: Full 3D, Particle-in-Cell (FFT) or P2P
    - Full computation of EM fields
    - Beam-beam effects automatically included
    - Mirror charges at cathode
  - **Short & Long-range wakefields**: K-Bane, damped oscillator or 1D user-defined spline
  - Self-consistent **Beam Loading** effect
- **Single particle effects**:
  - Incoherent Synchrotron Radiation
  - Magnetic multipole kicks
  - Multiple Coulomb Scattering

PART IV: Applications. Beam Loading scenarios

Applications

- RF-Track is currently used for the design, optimization and simulation of:
  - The CLIC and FCC-ee **positron sources**
  - **Linac4** @ CERN
  - Compact **Inverse-Compton Scattering** sources
  - The **Cooling** channel of a **Future Muon Collider**
  - The **DEFT** facility
  - VULCAN - Electron-driven **neutron source**
  - etc

Beam Loading with RF-Track

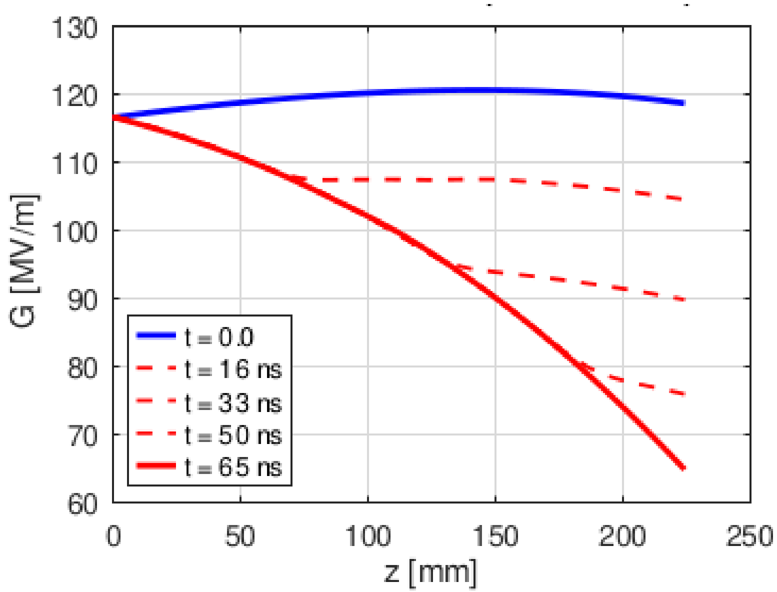
- Based on power-diffusive model:

$$-\frac{\partial G_{\text{eff}}}{\partial t} = v_g \frac{\partial G_{\text{eff}}}{\partial z} + \left(-\frac{v_g Q}{r_{\text{eff}}} \frac{\partial (r_{\text{eff}}/Q)}{\partial z} + \frac{\omega}{Q} + \frac{\partial v_g}{\partial z} \right) \frac{G_{\text{eff}}}{2} + \underbrace{\frac{\omega r_{\text{eff}} \tilde{I}}{2Q}}_{\text{Beam Loading term!}}$$

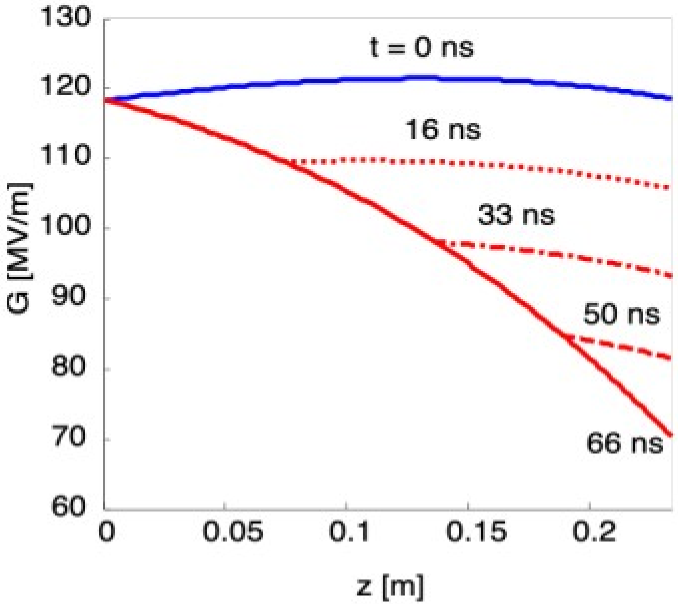
- Some assumptions
  - Obtained by averaging RF-period: Captures **long-range** effect
  - **Causality**
  - **Paraxial** & **quasi-static** approximation
  - Captures both **transient** and **steady** states.

BL – CLIC Accelerating Structures

- Reliable **gradient reduction** calculation



> CLIC main Accelerating structure gradient reduction for a train of I = 1.02A and length of 152 ns



> CLIC main Accelerating structure gradient reduction for a train of I = 1.02A and length of 152 ns. Theoretical calculation

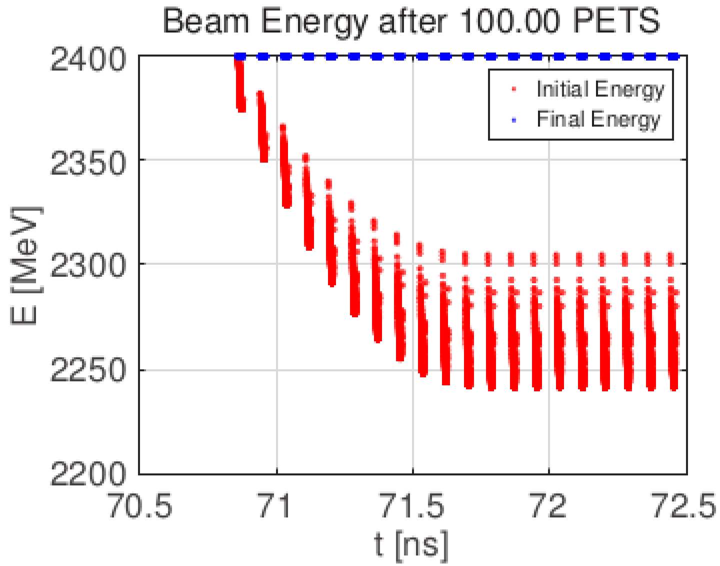
Magnitude	Units	Value
r/Q_{average}	Ω/m	16178
Q_{average}	-	5636
$v_{g\,\text{average}}$	$c/100$	1.21
f_0	GHz	12.00
f_0/f_b	-	6
N_{bunches}	-	312
σ	mm/c	0.3
$\langle I \rangle$	A	1.20
t_{train}	ns	152.0

> CLIC main Accelerating structure gradient details

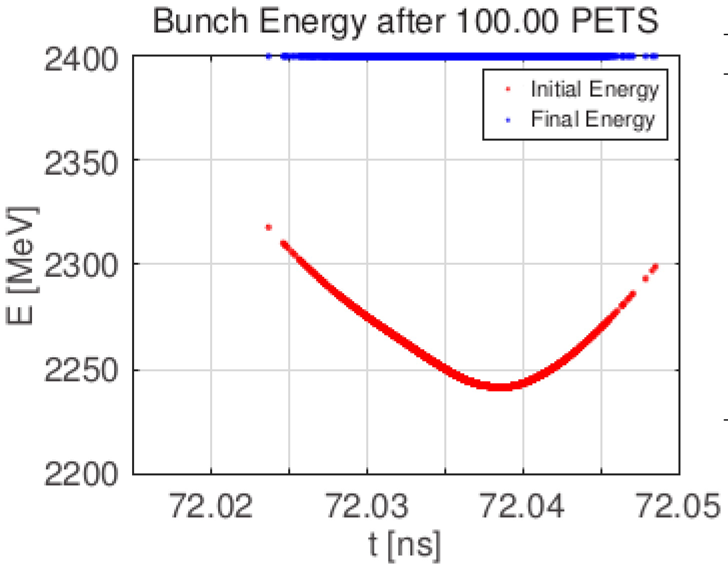
[1] A. Grudiev, A.Lunin, V. Yakovlev. *Analytical solutions for transient and stead state beam loading in arbitrary travelling wave accelerating structures.* Phys. Rev. Special topics **14**, 052001 (2011)

BL – CLIC PETS

- **Transient** tracking
  - **PETS**: Power Extraction and Transfer Structures. → **Deceleration** due to BL



> Beam Energy after going through 100 PETS.



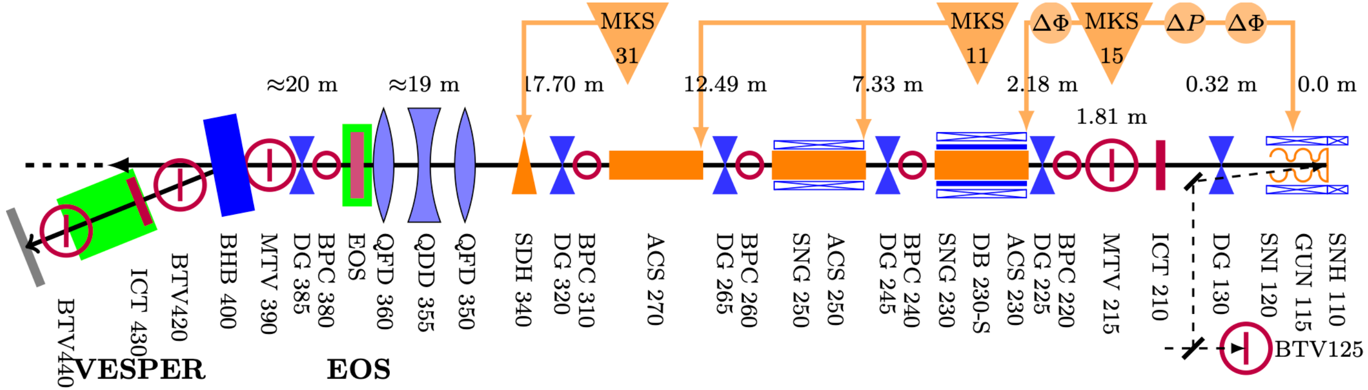
> 11th Bunch Energy after going through 100 PETS.

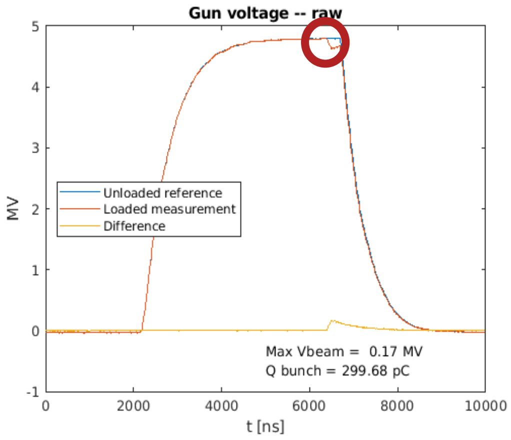
Magnitude	Units	Value
r/Q_{average}	Ω/m	2294
Q_{average}	-	7200
$v_{g\text{average}}$	$c/100$	45.3
f_0	GHz	12.00
f_0/f_b	-	1
N_{bunches}	-	2928
σ	mm/c	1.0
$\langle I \rangle$	A	101
E_0	MeV	2400

> PETS gradient details

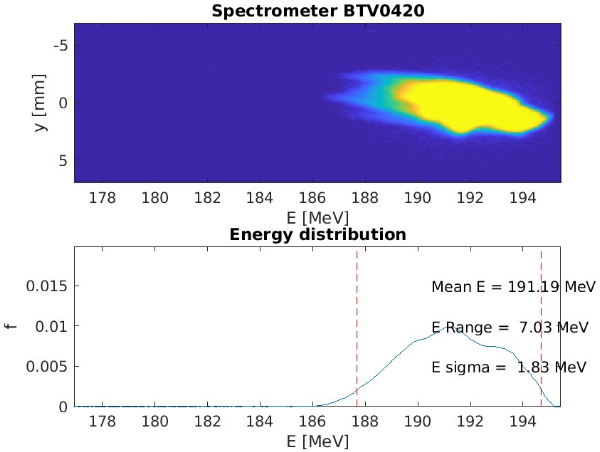
[2] Erik Adli (2009). *A Study of the Beam Physics in the CLIC Drive Beam Decelerator.* PhD Thesis

Comparison with measurements at CLEAR





> Voltage measurement at the gun loop in CLEAR photo-injector.

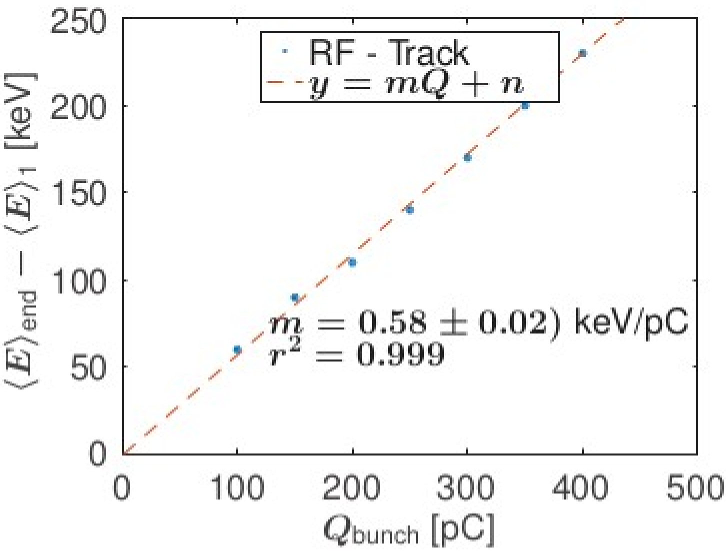


[3] CLEAR official site: https://clear.cern/content/beam-line-description

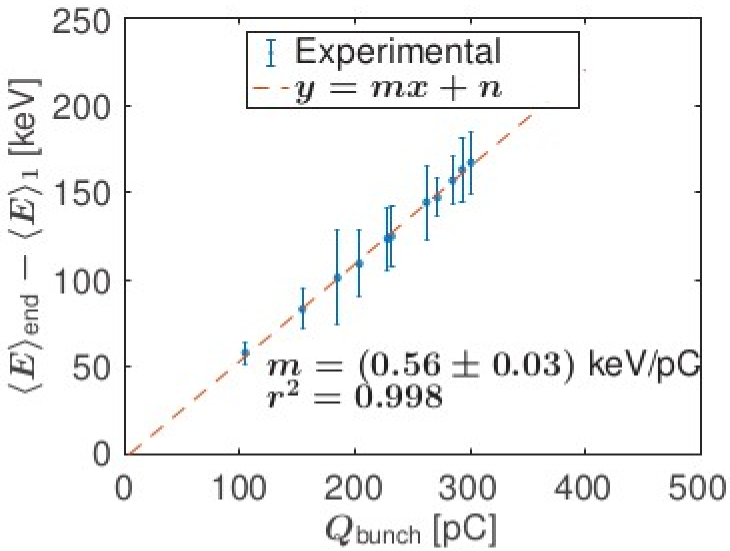
> Spectrometer image and associated energy distribution for a **train of 13 bunches** arriving to the screen after having traveled through all structures.

BL comparison with CLEAR photo-injector

- Train of **150 bunches** with **variable charge (Q_{bunch})** per bunch; $f_b = f_{RF}/2$



> Beam Loading Energy Spread induced in a train of 150 bunches as a function of charge (RF-Track)



> Beam Loading Energy Spread induced in a train of 150 bunches as a function of charge (measurement at CLEAR)

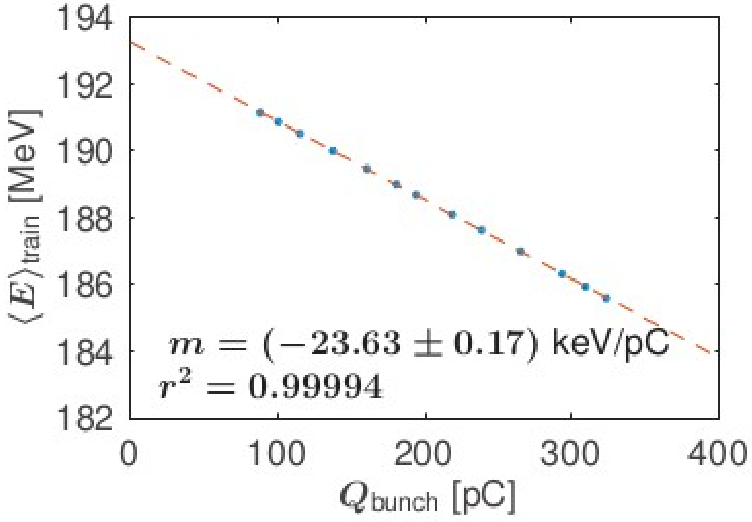
Magnitude	Units	Value
$r/Q_{average}$	Ω/m	3765
$Q_{average}$	-	5920
f_0	GHz	3.00
f_0/f_b	-	2
$N_{bunches}$	-	150
σ	mm/c	1.0

> CLEAR SW photoinjector information

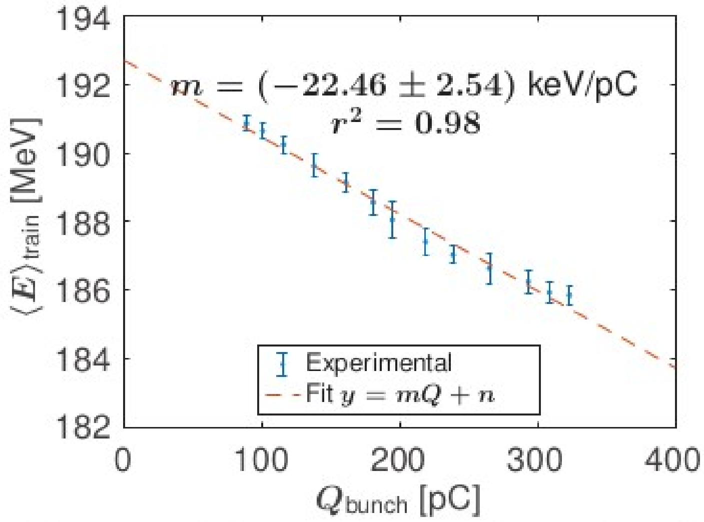
[3] CLEAR official site: https://clear.cern/content/beam-line-description

BL comparison with CLEAR Start-to-end

- Train of **150 bunches** with **variable charge (Q_{bunch})** per bunch; $f_b = f_{RF}/2$



> Beam Loading Energy Spread induced in a train of 150 bunches as a function of charge



> Beam Loading Energy Spread induced in a train of 150 bunches as a function of charge (RF-Track, corrected attempt)

Magnitude	Units	Value
$r/Q_{average}$	Ω/m	4400
$Q_{average}$	-	15000
f_0	GHz	3.00
f_0/f_b	-	2
$N_{bunches}$	-	150
σ	mm/c	1.0

>CLEAR TW structures information

[3] CLEAR official site: https://clear.cern/content/beam-line-description

Conclusions

- **RF-Track**:
  - Minimalistic, parallel, fast
  - High-order adaptative integration algorithms
  - Several collective effects
  - Optimization and design of DEFT, FCC-ee, positron sources, Muons Cooling, RFQ, ICS sources…
  - Reproduction of realistic scenarios: BL @ CLEAR

- Official **documentation**:
  - `https://zenodo.org/record/4580369`
- **Pre-compiled binaries** and more up-to-date **documentation** are availables here:
  - `https://gitlab.cern.ch/rf-track`

Thanks for your attention

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