The Tracking Code RF-Track and its Applications

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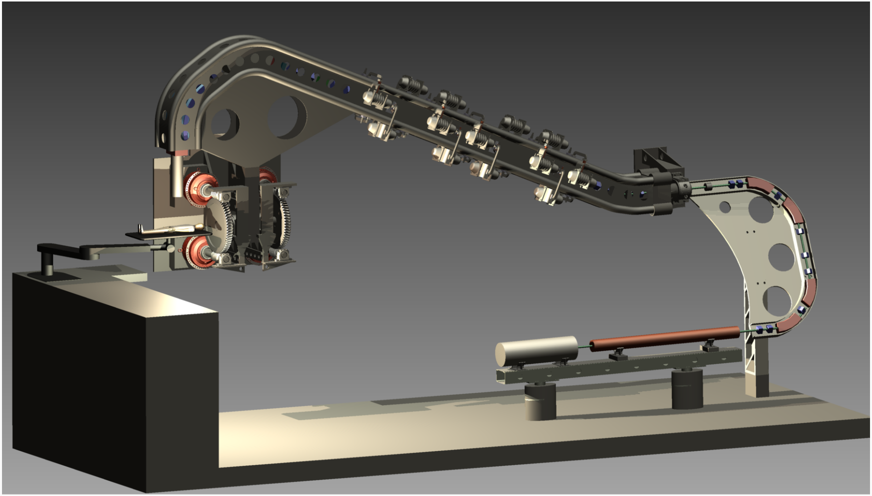
1. Introduction and RF-Track highlights
2. Beamline elements
3. Collective effects
4. Examples of applications
5. Conclusions and future developments

Introduction and highlights

Motivation for developing RF-Track: the TULIP project

A linac for hadron therapy featuring high-gradient S-band backward travelling-wave structures



S. Benedetti, A. Grudiev, and A. Latina, "High gradient linac for proton therapy", Phys. Rev. Accel. Beams 20, 040101 [2017]

RF-Track highlights

- It handles ℂ**omplex 3D field maps** of oscillating RF electromagnetic fields:
    - *Standing-wave*; *Backward* $\ll$ and *Forward* $\gg$ travelling-wave fields
    - *Static* electric and magnetic fields
    - Robust interpolation algorithms

- It can simulate particles with **any mass** and **charge**
    - No approximations, like $\beta \simeq 1$ or $\gamma \gg 1$, are made
    - It is used to simulate: *protons, ions, electrons, positrons, photons, muons, ...* from creation to ultra-relativistic
    - It implements **photocathodes**
    - It can simulate **mixed-species beams**

- Implements **high-order adaptive integration algorithms**
    - Can do **back-tracking**

- Implements several **collective effects**

- It's **modular, flexible,** and **fast**

RF-Track, minimalistic and physics-oriented

RF-Track is written in parallel and fast C++, focusing *only* on accelerator simulation:

- Flexible accelerator description and beam models
- Accurate integration of the equations of motion
- Robust interpolation of the field maps
- Collective effects
- Easy realisation of imperfections and correction algorithms

For *all the rest* (ODE solvers, random number generation, special functions, ...), it relies on two robust and well-known open-source libraries:

- **GSL**, "Gnu Scientific Library", provides a wide range of mathematical routines such as high-quality random number generators, ODE integrators, linear algebra, and much more
- **FFTW**, "Fastest Fourier Transform in the West", arguably the fastest open-source library to compute discrete Fourier transforms

RF-Track provides **two user interfaces**: one in Octave and one in Python.

Tracking, in space and in time

RF-Track implements two beam models:

1. **Beam moving in space**: `Bunch6d()`
   - All particles have the same S position
   - The equations of motion are integrated in dS: $S \rightarrow S + dS$ (moves the bunch element by element)

2. **Beam moving in time**: `Bunch6dT()`
   - All particles are considered at same time t
   - The equations of motion are integrated in dt: $t \rightarrow t + dt$
   - Particles can have $P_z < 0$ or even $P_z = 0$: particles can move backward

For each particle also considers

$\mathbf{m}$: mass [MeV/c^2], $\mathbf{Q}$: charge [e^+]

$\mathbf{N}$: nb of particles / macroparticle, $\mathbf{t_0}$: creation time$^{(\star)}$ $\boldsymbol{\tau}$: lifetime **[NEW!]**

$^{(\star)}$ only for beams moving in time.

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

Two tracking environments

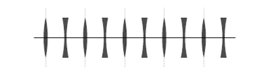
Lattice: for integration *in space*

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

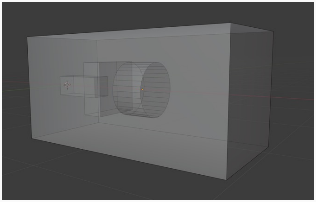
Volume: for integration *in time*

- 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**

Lattice

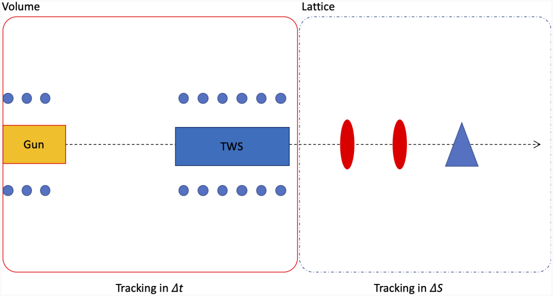


Volume



Lattice and Volume

Lattice and Volume can be used together or separately

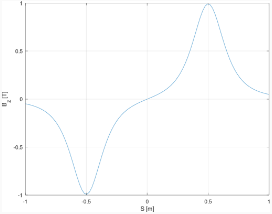


Typically, *Volume* (time integration) is suitable for space-charge dominated regimes, whereas *Lattice* (space integration) is suitable for ultra-relativistic regions of the machine.

*Volume*s can be inserted in a Lattice. And *Lattice*s can be placed in a Volume.

Example of Volume (Octave)

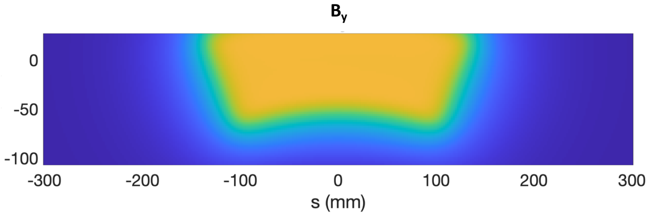
```
%% Load RF-Track
RF_Track;

%% Declare two coils
Cm = Coil(0.01, -1.0, 0.2);    % L length [m],
                               % B field at the center of the coil [T],
                               % R radius [m]
Cp = Coil(0.01, +1.0, 0.2);

%% Create a Volume
V = Volume();

% Add the two coils
V.add(Cm, 0, 0, -0.5);
V.add(Cp, 0, 0, 0.5);

% Set the boundaries
V.set_s0(-1.0); % -1 m
V.set_s1(+1.0); % +1 m
```



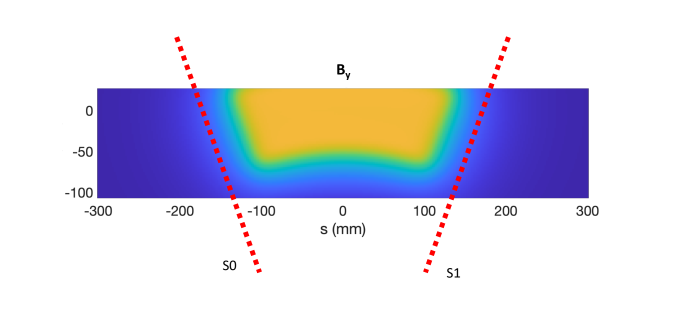
Example of Lattice (Octave)

```
% load RF-Track
RF_Track;

% create a bunch from phase-space matrix
B0 = Bunch6d(electronmass, 200 * pC, -1, phase_space_matrix);

% create a lattice (1 FODO cell)
Lq = 0.4; % m
Ld = 0.6; % m
G = 1.2; % T/m

FODO = Lattice();
FODO.append (Quadrupole (Lq, G));
FODO.append (Drift (Ld));
FODO.append (Quadrupole (Lq, -G));
FODO.append (Drift (Ld));

% track the beam
B1 = FODO.track(B0);

% plot the phase space
T1 = B1.get_phase_space("%x %xp %y %yp");
scatter (T1(:,1), T1(:,2), "*");
xlabel ("x [mm]");
ylabel ("x' [mrad]");
```

Complex simulation scenarios (new feature!)

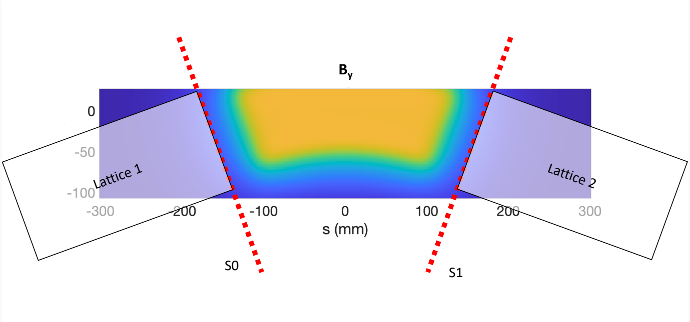


Complex simulation scenarios (new feature!)



The boundaries of a Volume can have any orientation in space.

Complex simulation scenarios (new feature!)



One can sandwich a Volume between two Lattices.

Beamline elements

Overview of the beamline elements

1. **Standard set** of **matrix-based symplectic** elements:
   - **Sector bend, Quadrupole**
   - **Multipoles**
   - **Drift** (with an optional constant electric and magnetic fields, can be used to simulate e.g., rbends, or solenoids)

Overview of the beamline elements

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2. **Field maps** (see next slide)

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2. **Field maps** (see next slide)

3. **Special elements**:
   - **Absorber** (predefined materials: air, water, beryllium, lithium, tungsten, ...)
   - 3D analytic fields**: Coil** and **Solenoid, Standing-wave** and **Traveling-wave** structures, **Adiabatic matching devices**, **Toroidal Harmonics**
   - **LaserBeam** for Inverse Compton Scattering simulations
   - **Electron Cooler**
   - **Twiss table**: tracks through an arbitrary lattice given as Twiss table (phase advances, momentum compaction, 1^{st} and 2^{nd} order chromaticity are considered)

Field maps

RF-Track can import several types of oscillating RF field maps, which are interpolated *linearly* or *cubically*

- **1D field maps** (on-axis field)
  - It uses Maxwell's equations to reconstruct the 3D fields off-axis, assuming cylindrical symmetry

- **2D field maps**: given a field on a plane, applies cylindrical symmetry

- **3D field maps** of oscillating electro-magnetic fields
  - It accepts 3D meshes of complex numbers
  - It accepts quarter field maps and performs mirroring automatically

It also provides elements dedicated to **StaticElectric** and **StaticMagnetic** field maps

- They ensure curl-free (electric) and divergence-free (magnetic) interpolation of the field

Integration algorithms

In field maps and analytic fields,

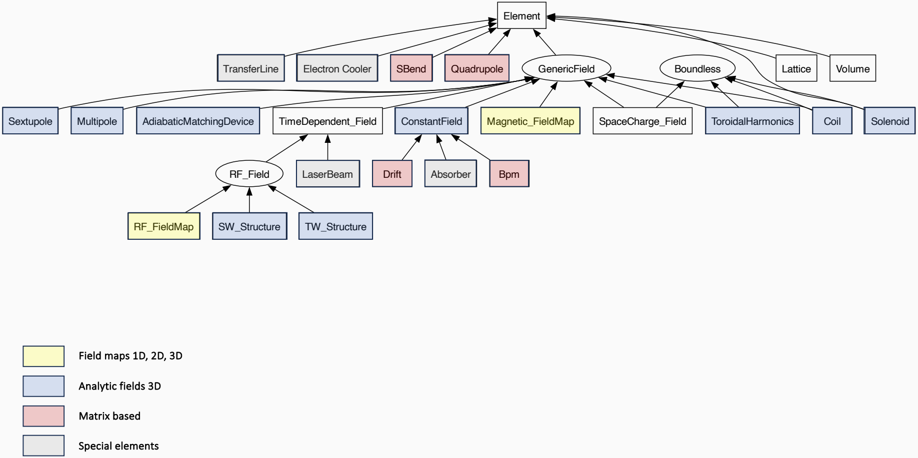
- The default is: "**leapfrog**":
  - ⋆ super fast, second-order accurate, symplectic

- "**analytic**" algorithm:
  - ⋆ integration assuming a locally-constant EM field, symplectic

- **Higher-order, adaptive algorithms** provided by GSL:
  - ⋆"**rk2**" Runge-Kutta (2, 3)
  - ⋆"**rk4**" 4th order Runge-Kutta
  - ⋆"**rkf45**" Runge-Kutta-Fehlberg (4, 5)
  - ⋆"**rkck**" Runge-Kutta Cash-Karp (4, 5)
  - ⋆"**rk8pd**" Runge-Kutta Prince-Dormand (8, 9)
  - ⋆"**msadams**" multistep Adams in Nordsieck form (order varies dynamically between 1 and 12)

(backtracking is possible)

Element hierarchy



Collective and Single-particle effects

Overview of the collective and single-particle effects

Collective effects:

- **Space-charge**, full 3D, Particle-in-Cell (FFT) or P2P
  - Full computation of electric and magnetic effects
  - Beam-beam effects are automatically included
  - Optionally considers mirror charges at cathode
- **Short-range wakefields**:
  - Karl Bane's approximation
  - 1D user-defined spline, longitudinal monopole or transverse dipole
- Two models of **Long-range wakefields:**
  1. Damped oscillator. Takes modes: frequency, amplitude, and Q factor
  2. 1D user-defined spline, longitudinal monopole or transverse dipole
- Self-consistent **Beam-loading** effect in TW and SW structures
  - Given: a field map, group velocity and Q factors along the structure, computes the beam loaded fields

Single-particle effects:

- **Incoherent Synchrotron Radiation** (from *any* fields)
- **Magnetic multipole kicks** for imperfection studies
- **Multiple Coulomb Scattering** (recently updated!)

Example applications

Example applications

RF-Track is currently used for the design, optimisation, and simulation of:

- the **DEFT facility** (CERN, PMB), the **CLIC** and **FCC-ee positron sources** (CERN, IJClab, PSI) and **FCC-ee pre-injector linacs** (CERN, PSI)

- **Linac4** (CERN), **Inverse-Compton Scattering sources** (CERN, IJClab, INFN Ferrara, Korea University), and the **Cooling channel** of a future **Muon Collider** (CERN), etc.

I'll show six examples:

1. ADAM's RFQ
2. ThomX and Inverse Compton Scattering
3. Electron Cooling at LEIR
4. Multiple Coulomb Scattering
5. Muon Cooling Channel
6. CERN's RFQ and Linac4

1. ADAM's RFQ

Credits: Veliko Dimov (CERN, ADAM)

«LIGHT is a normal conducting 230 MeV medical proton linear accelerator being constructed by ADAM.

For the commissioning, RFQ beam dynamics simulations were performed with RF-Track by simulating the particles through the 3D field map.»

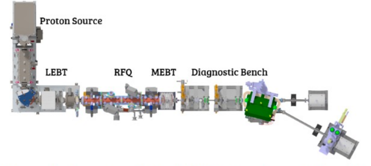


Figure 1: Layout of the LIGHT structures during the beam commissioning at 5 MeV.

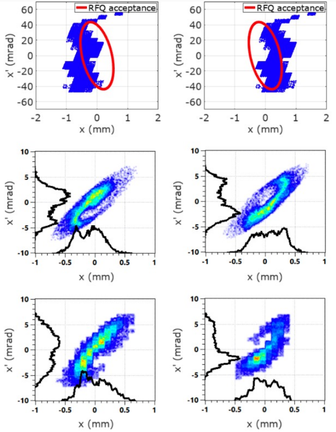
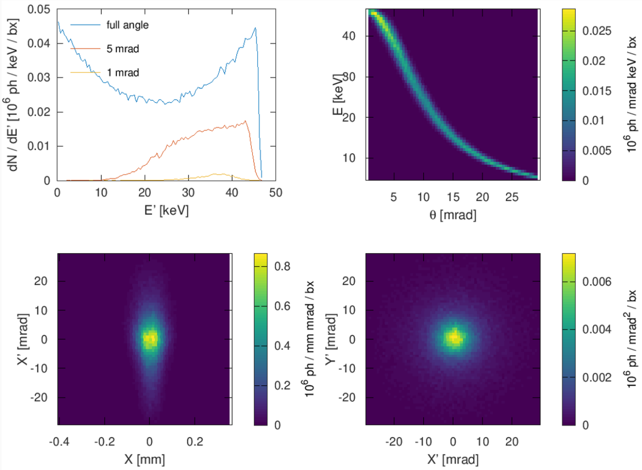


Figure 7: Horizontal phase space plots of the RFQ input beam when steered in the negative and positive x directions (first row), expected (second row) and the measured (third row) phase space plots after the RFQ for each case.

V. Dimov et al., "Beam commissioning of the 750 MHz proton RFQ for the LIGHT prototype", IPAC2018, Vancouver, BC, Canada, TUPAF002

2. LaserBeam element and Inverse Compton Scattering

Generation of hard X-rays via Inverse Compton Scattering at ThomX



2. ThomX simulation (1/4)

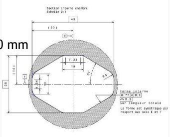
RF-Track helped to solve a serious design issue:

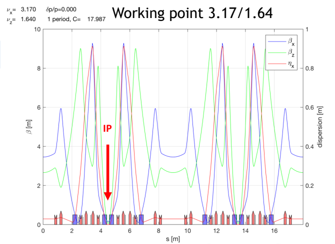
- 8 Dipoles
- 24 Quadrupoles
- 12 Sextupoles
- 2 Kickers
- 1 Septum
- 1 RF cavity
- 12 BPM
- 12 Correctors

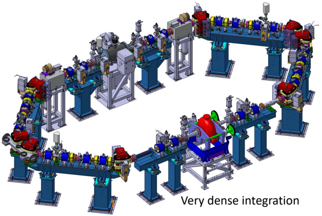
ThomX SR: L = 18 m, T = 60 ns, f_{rep} = 16.7 MHz

Parameter	Value/Units
Beam energy	50-70 MeV
Bunch Charge	1 nC
Bunch length (rms)	~30 ps
Circumference	18 m
Revolution frequency	**16.7 MHz**
Current	16.7 mA
RF frequency/Harmonics	**500/30 MHz**
Momentum compaction	0.0125 - 0.025
Betatron tunes	3.17/1.64
Natural chromaticity	-9/-13
Damping time trans./long.	1.2/0.6 s
Repetition frequency	50 Hz (20 ms)
Beam size at the IP	70 µm
Nominal RF Voltage/cavity	300 kV (500 kV max)
Energy loss per turn	1.57 eV

28x40 mm



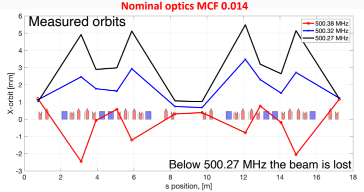




Courtesy of Viacheslav Kubytskyi (IJCLab)

An unexpected find: shorter circumference

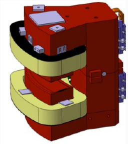
Nominal optics MCF 0.014

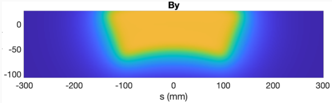


- **The RF frequency is found experimentally to be 0.3 - 0.4 MHz higher than the nominal. What is the reason?**
- **Need explicit simulation!**

Short and small-radius dipoles, long fringe fields

Features of dipoles	
Quantity	14 + 1 (pre-serie)
Radius of curvature	352 mm
Main field B_0	0.7 Tesla
Gap	42 mm
Good field region	+/- 20mm
Integral of field	184.59 mT.m
Current max.	275 Amp
Beam energy	from 50 to 70 MeV





Courtesy of Viacheslav Kubytskyi (IJCLab)

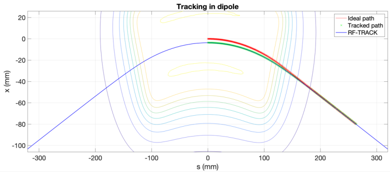
2. ThomX simulation (3/4)

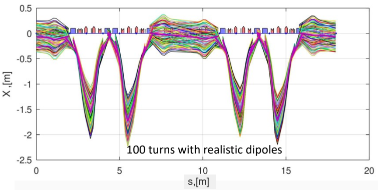
“Experiment on the table” with RF-track

First study to measure ring frequency :

- Lattice with dipoles represented by **SBEND** (usual way) : F = 500.02 MHz
- Lattice with dipoles represented by **VOLUME** with realistic magnetic field : F =500.38 MHz, dispersive orbit. The same effect as in the experiment!

It was found that the beam trajectory in the dipoles is shorter wrt. to the ideal path => shorter pathlength and so smaller total circumference





Big step in understanding of the problem

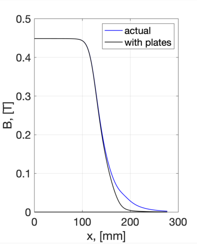
Courtesy of Viacheslav Kubytskyi (IJCLab)

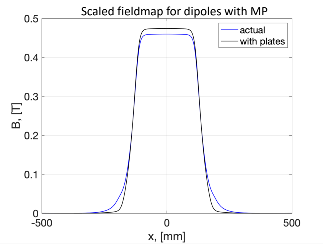
2. ThomX simulation (4/4)

"Experiment on the table" with RF-track

Studies to compensate dipole fringing fields and retrieve nominal frequency by:

- Displacement of dipole
- Adding metallic plates to reduce fringing field
- Mechanical extension of the ring by +12mm



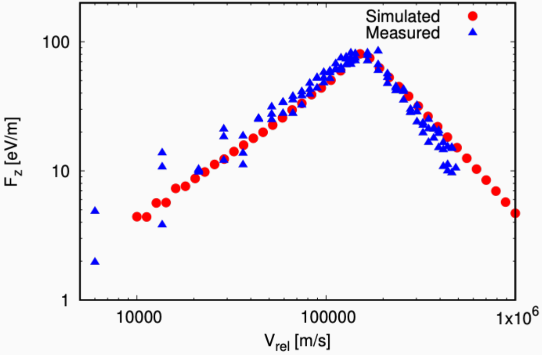


Correct scaling of magnetic field for the magnet with plates allows to recover the nominal frequency

Courtesy of Viacheslav Kubytskyi (IJCLab)

3. Electron Cooling at LEIR

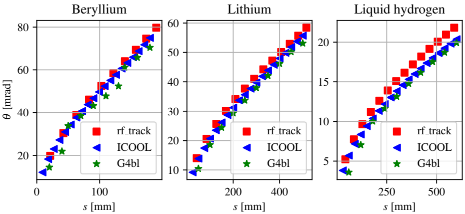
In 2019 we measured and benchmarked the cooling force as a function of ion-electron relative velocity measured at LEIR (blue) and simulated with RF-Track (red).



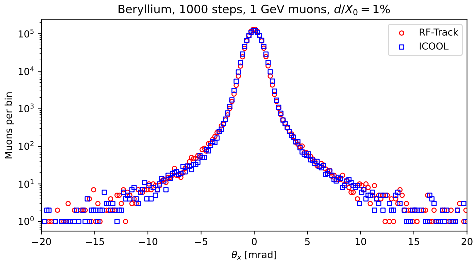
Very good agreement between measurements and simulations.

4. Absorber element and Multiple Coulomb Scattering

Credits: Bernd Stechauner (CERN)

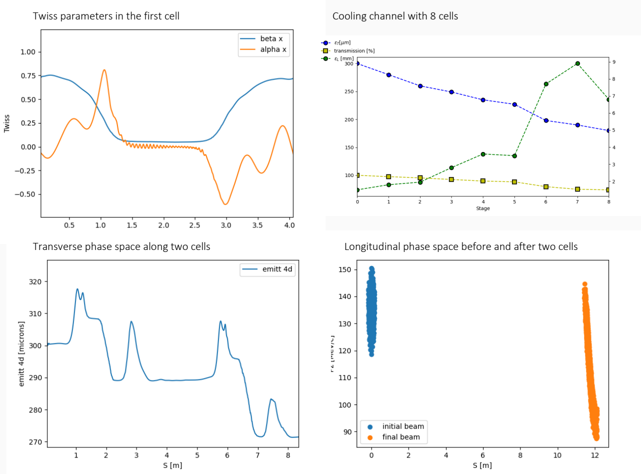


Large scattering angles



5. Muon cooling channel optimisation

Credits: Elena Fol (CERN)



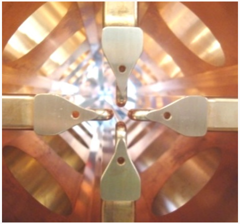
This simulation includes: a constant solenoid field, realistic 3D solenoid, several standing-wave structures, and the absorber, simultaneously together and overlapping.

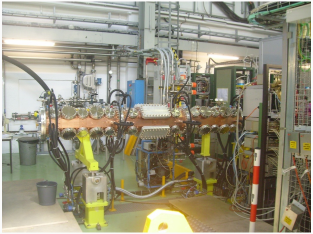
6. CERN's Linac4 RFQ (1/2)

352.2 MHz RFQ (45 keV → 3 MeV) injecting into Linac4

4 vanes, 3m length (3x1m modules)
Entire in-house fabrication (2009-2012)

Parameter	Value	Unit
Operating frequency	352.2	MHz
Inter-vane Voltage	78	kV
Kilpatrick factor	1.84	-
Unloaded Quality factor	6700	-
Cavity Coupling factor □□□without beam)	1.59	-
Total dissipated RF Power (without beam)	390	kW

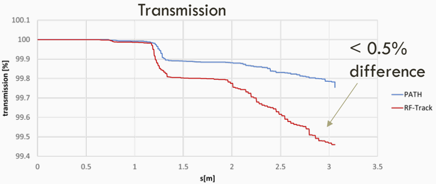




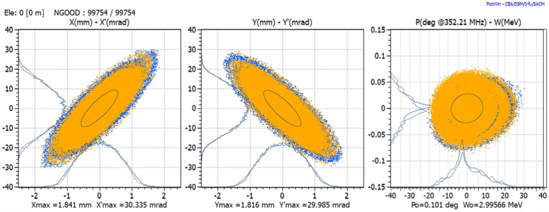
Credits: Giulia Bellodi (CERN)

6. CERN's Linac4 RFQ (2/2)

352.2 MHz RFQ injecting into Linac4. Benchmark against PATH



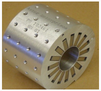
Output 3 MeV beam, **PATH** vs **RF-Track**



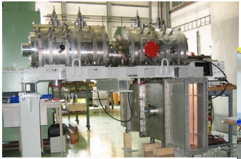
Credits: Giulia Bellodi (CERN)

6. CERN's Linac4 (1/3)

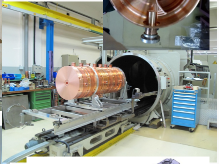
DTL: 3→ 50 MeV
3 tanks in Cu-plated StSt
120 drift tubes with PMQs
FFDD system
ESS-Bilbao collaboration

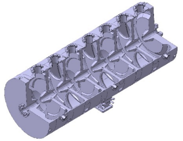


CCDTL: 50→100 MeV
7 modules of 3 tanks each
DTL-like tanks w/ coupling cells
PMQs+ EMQs (external cells)
VNIITF/BINP collaboration



PIMS: 100-160 MeV
12 tanks of 7 pi-mode cells each
External EMQs
Soltan Institute/FZ Juelich coll.





Credits: Giulia Bellodi (CERN)

6. CERN's Linac4 (2/3)

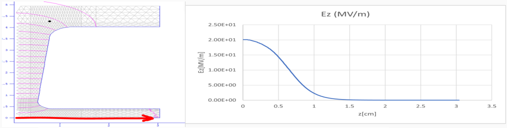
PATH: sequence of drifts and zero-length RF gaps giving acceleration kicks (thin gap model).

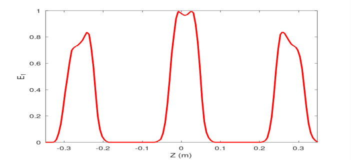
RF-Track: choice to use 1D field maps of on-axis longitudinal electric field obtained with Poisson-Superfish.

The longitudinal electric field is modelled with a generalized Gaussian function whose main parameters are fitted case by case to reproduce the different geometry and match the specified TTF (*ad-hoc* fitting procedure).

The same procedure is applied to all types of Linac4 cavities (DTL, CCDTL, PIMS): 77% of the Linac is simulated using field maps.

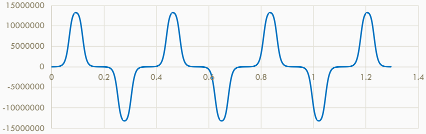
DTL-type gap





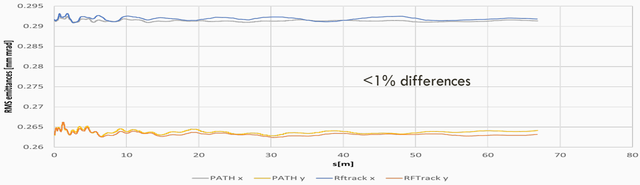
CCDTL tank

PIMS cavity

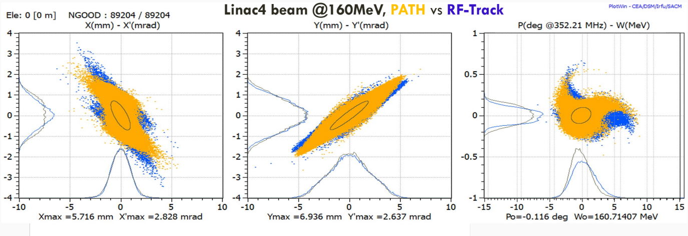


Credits: Giulia Bellodi (CERN)

6. CERN's Linac4 (3/3)



Linac4 with zero space charge



Credits: Giulia Bellodi (CERN)

Summary, future developments, and how to get it

RF-Track:

- Minimalistic, parallel, fast
- Friendly and flexible, it uses Octave and Python as user interfaces
- Ideal for nontrivial optimisation and numerical experimentations
- Several collective effects
- Currently used for: DEFT, FCC-ee, positron sources, Muons cooling, RFQ, Linac4, ICS sources ...

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- Implement Intra-beam Scattering
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"**Official**" documentation:

- `https://zenodo.org/record/4580369`

Pre-compiled binaries and **more up-to-date documentation** are available here:

- `https://gitlab.cern.ch/rf-track`

The end.

Thank you for your attention!

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