Single and multi-bunch tracking for PERLE

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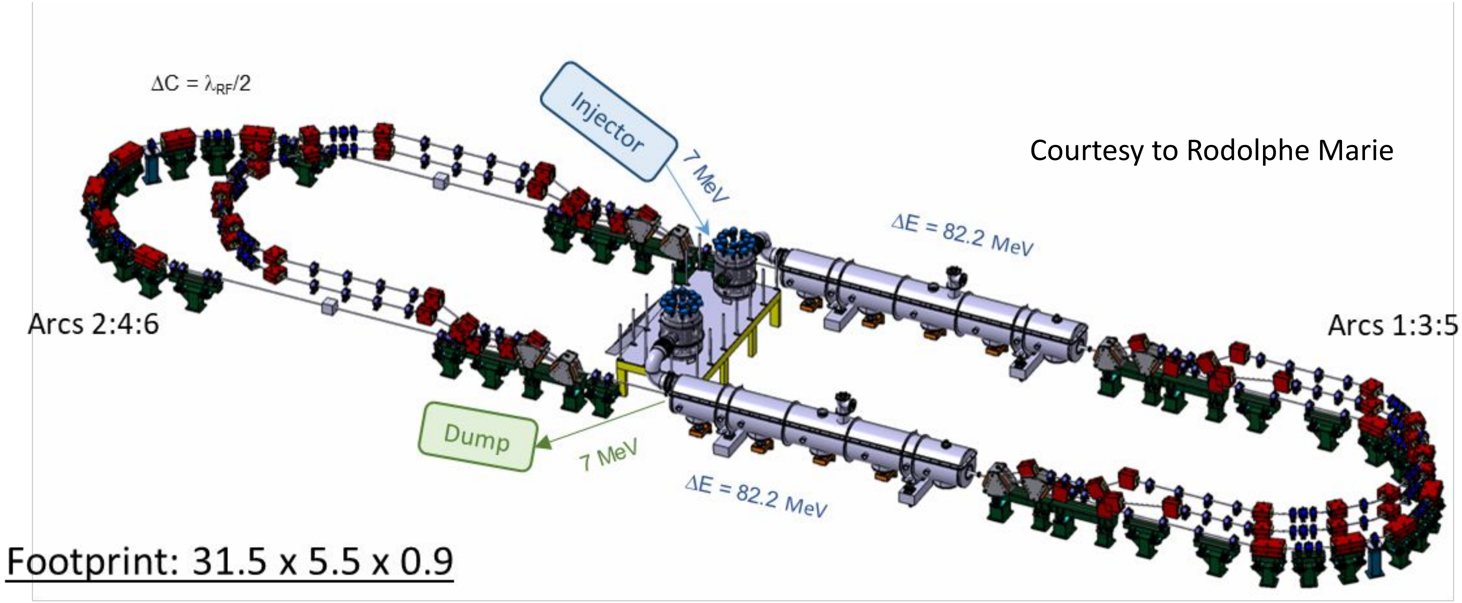
Outline :

- ERL lattice and optics design
- Effect of the RF curvature
- Single bunch tracking studies including CSR
- Multi-bunch tracking studies
    - Effect of LRW with bunch intensity
    - Effect of LRW with bunch recombination pattern

Parameter	Unit	Electron
Injection energy	MeV	7.0
Top energy	MeV	500.0
Beam current	mA	20.0
Bunch population	$10^9 e^-$	3.1
Bunch charge	pC	500
Bunch spacing	ns	25
Normalised emittance	mm.mrad	6.0
RMS bunch length	mm	3.0
Longitudinal emittance	keV.mm	25.0
RF frequency	MHz	801.6

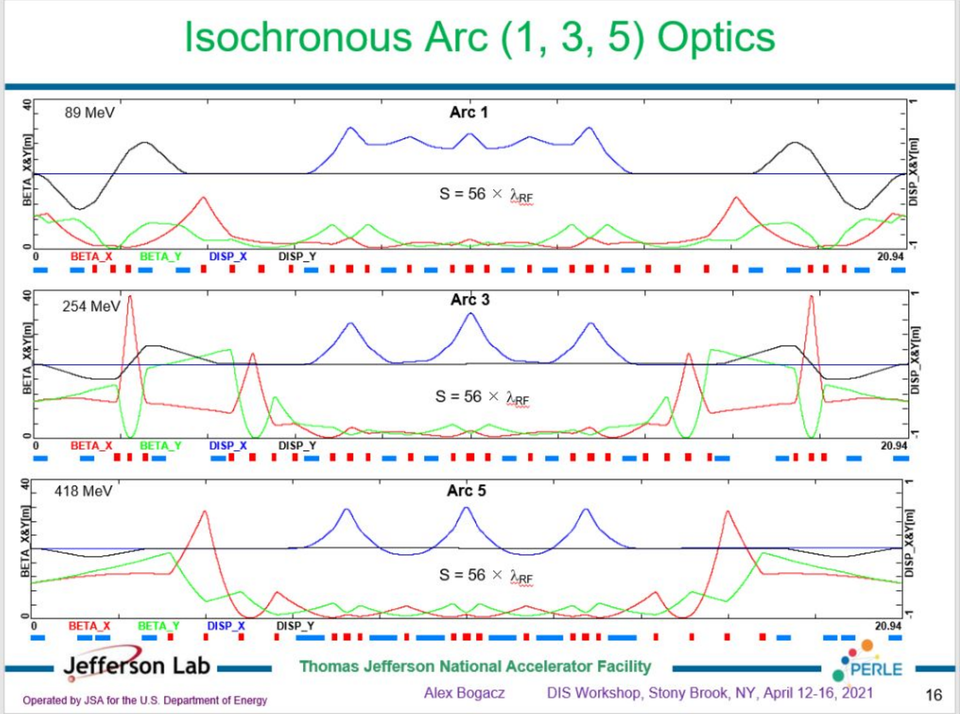
ERL construction - Lattice splitting for the timing in PLACET2

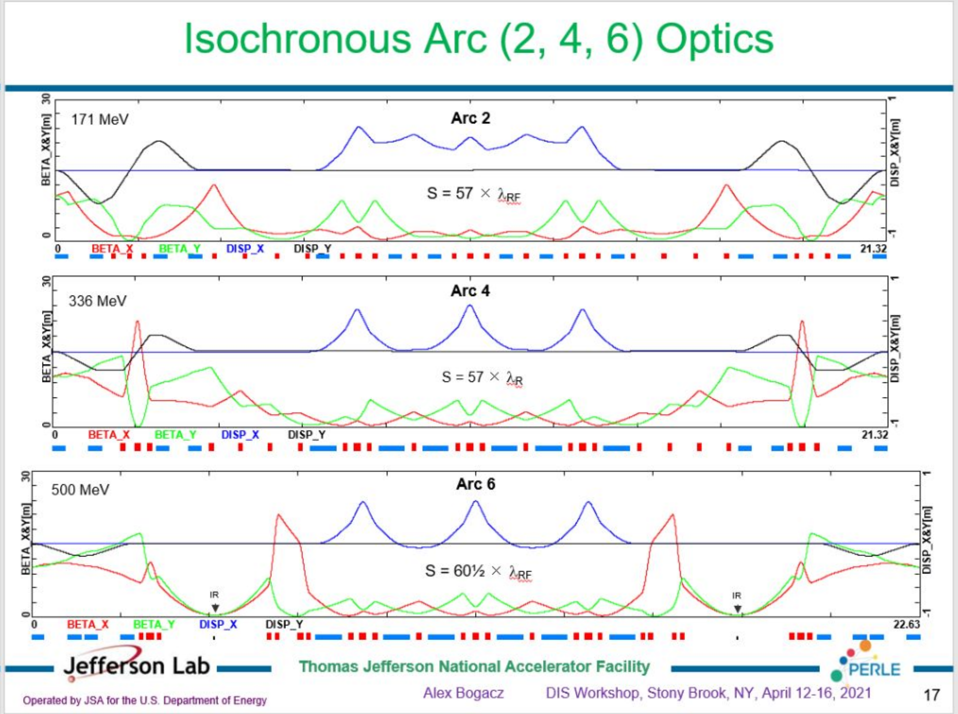


The linac is 27 λ_{RF} including the injection chicane, the injection chicane was included into arc 2, 4, 6 such that only the cryomodule and the doublet of quadrupole are in the "linac lattice".

The linac becomes 24 λ_{RF} long,
The chicane is 3 λ_{RF} (merged in the arcs)
The arcs 2, 4, 6 are respectively 63, 63, 66.5 λ_{RF} long while the arcs 1, 3 & 5 are all 56 λ_{RF} long.

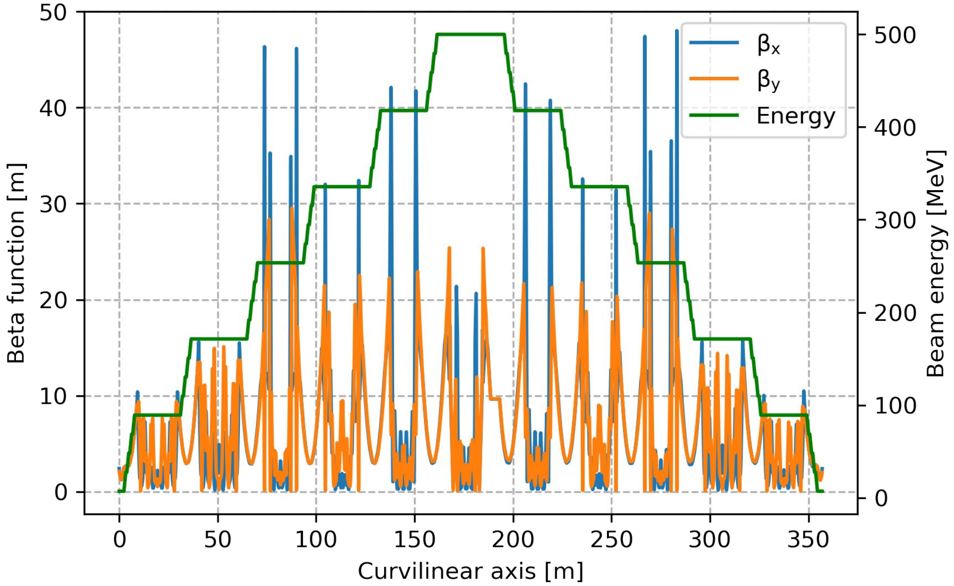
Individual arc optics





The momentum compaction factor is < 2e-5 for all arcs according to Optim.

Multi-turn optics



Magnets apertures

Quadrupoles : 40 mm diameter aperture

Cavities : 130 mm diameter aperture

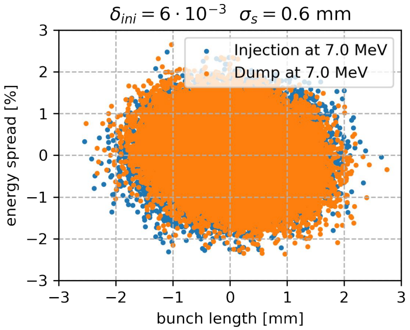
H/V dipoles : 40 mm aperture for the smallest transverse direction & 90 mm aperture in the other transverse direction.

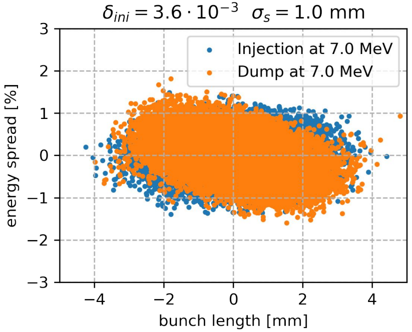
PLACET2 tracking code has been used because it features:

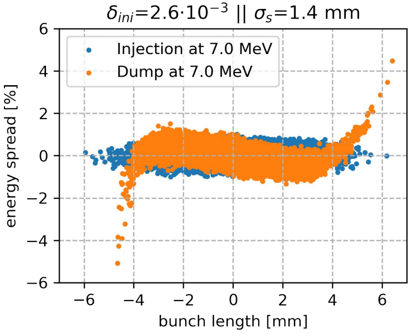
- Coherent Synchrotron Radiation (CSR) benchmarked with *M. Dohlus, T. Limberg Nucl. Inst. and Meth. in Phys. Rev. A (393) 1997*, see ref.
- and short and long-range wakefields based on SPL cavities scaled to 802 MHz.

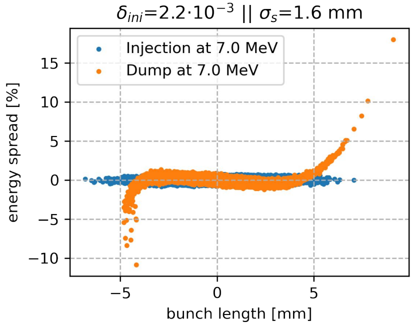
Longitudinal phase space curvature from the RF field

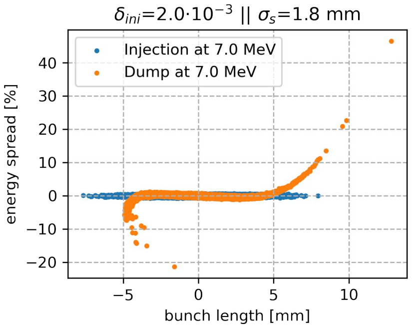
A hook shape forms and bunch elongation is visible as the initial bunch length increases. A longitudinal matching can mitigate the bunch elongation see **Gustavo's talk**. The nominal r.m.s bunch length of 3.0mm has been reduced to 1.4mm r.m.s bunch length to perform single and multi-bunch tracking studies.

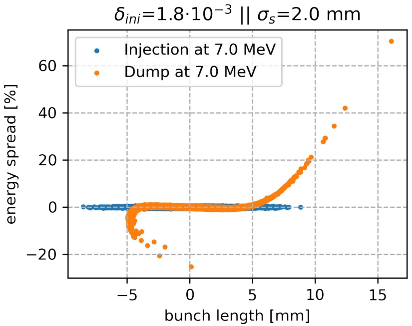


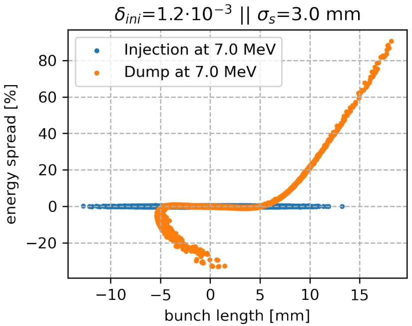










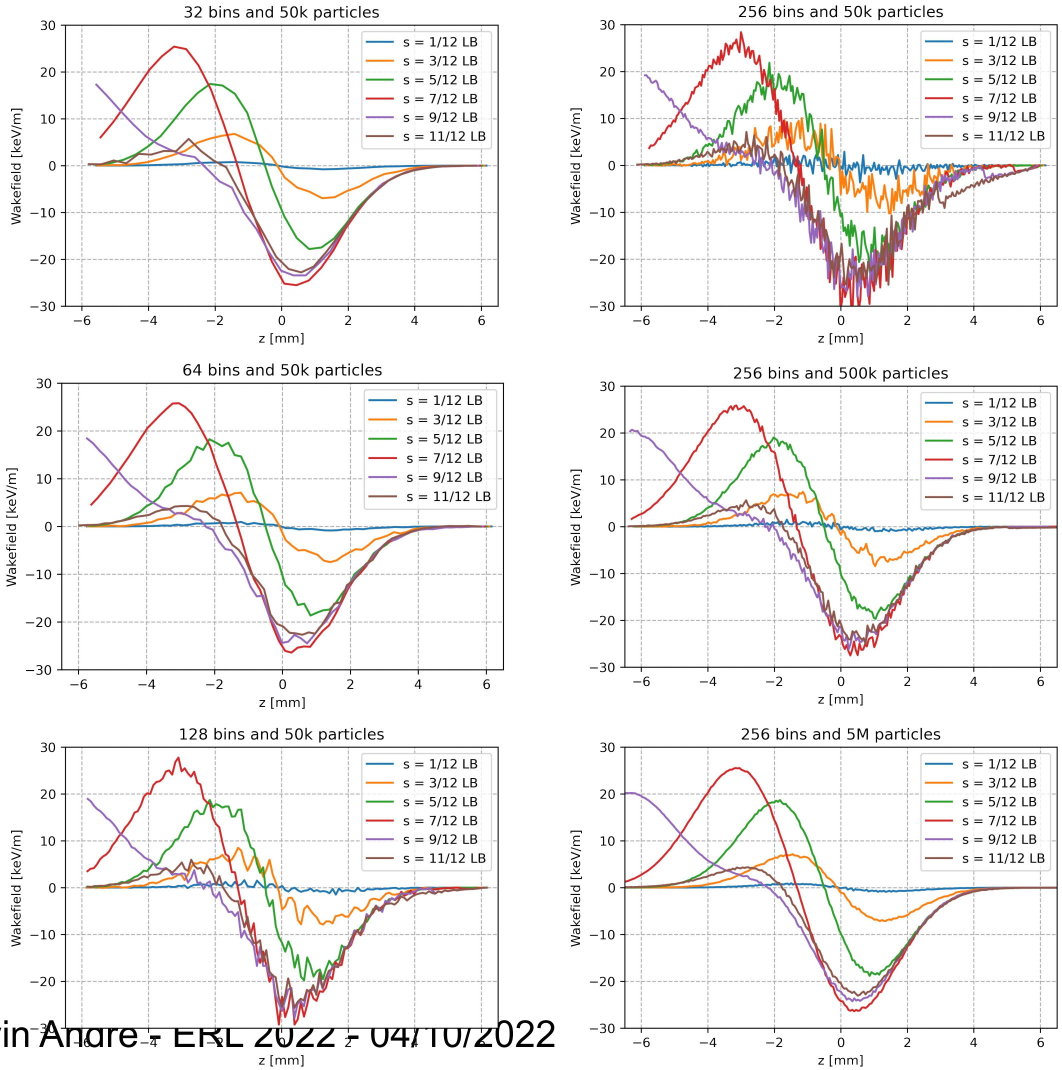


CSR and longitudinal binning

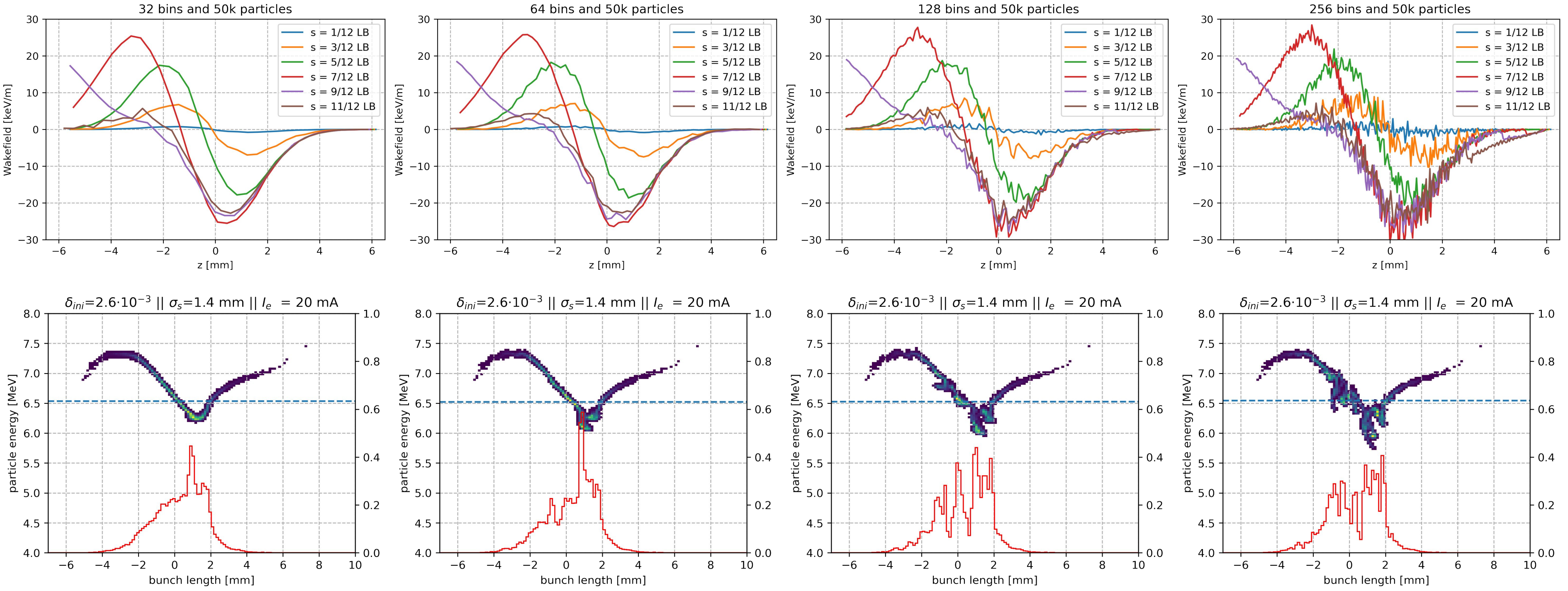
The number of nodes in the dipole doesn't change the behavior.

However the binning of the beam along the longitudinal axis does.

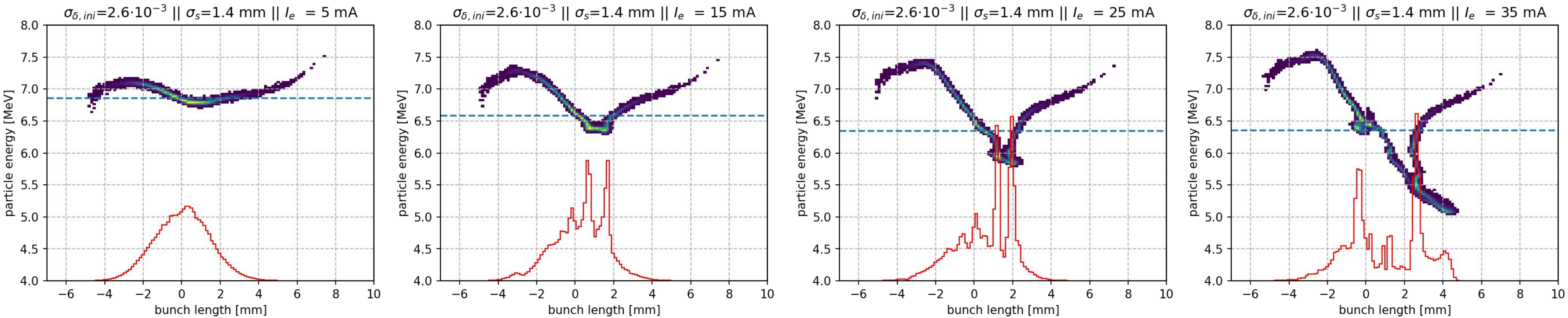
A minimum number of particles is required to mitigate the wakefield noise (no smoothing is applied).



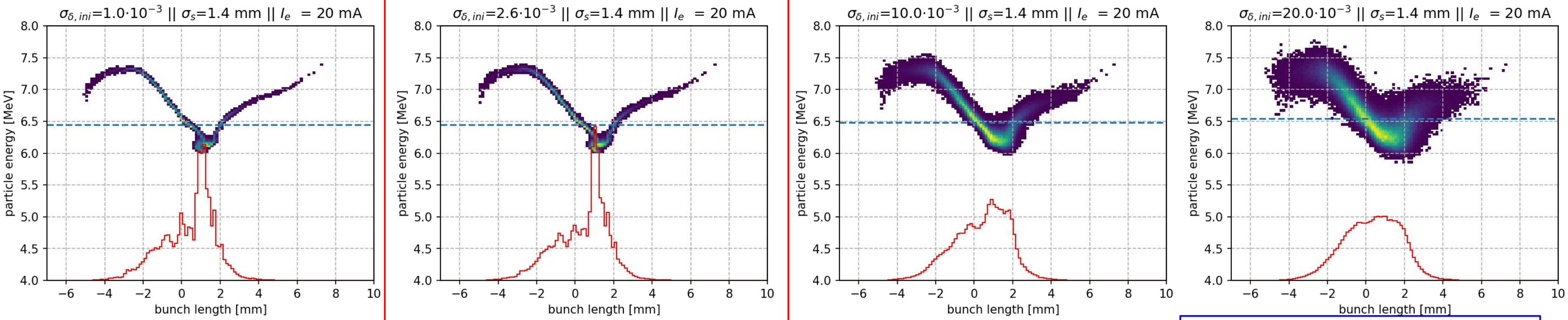
CSR and longitudinal binning



CSR with beam current increase



CSR with initial relative energy spread variation, I_e=20 mA



Similar to laser heating effect

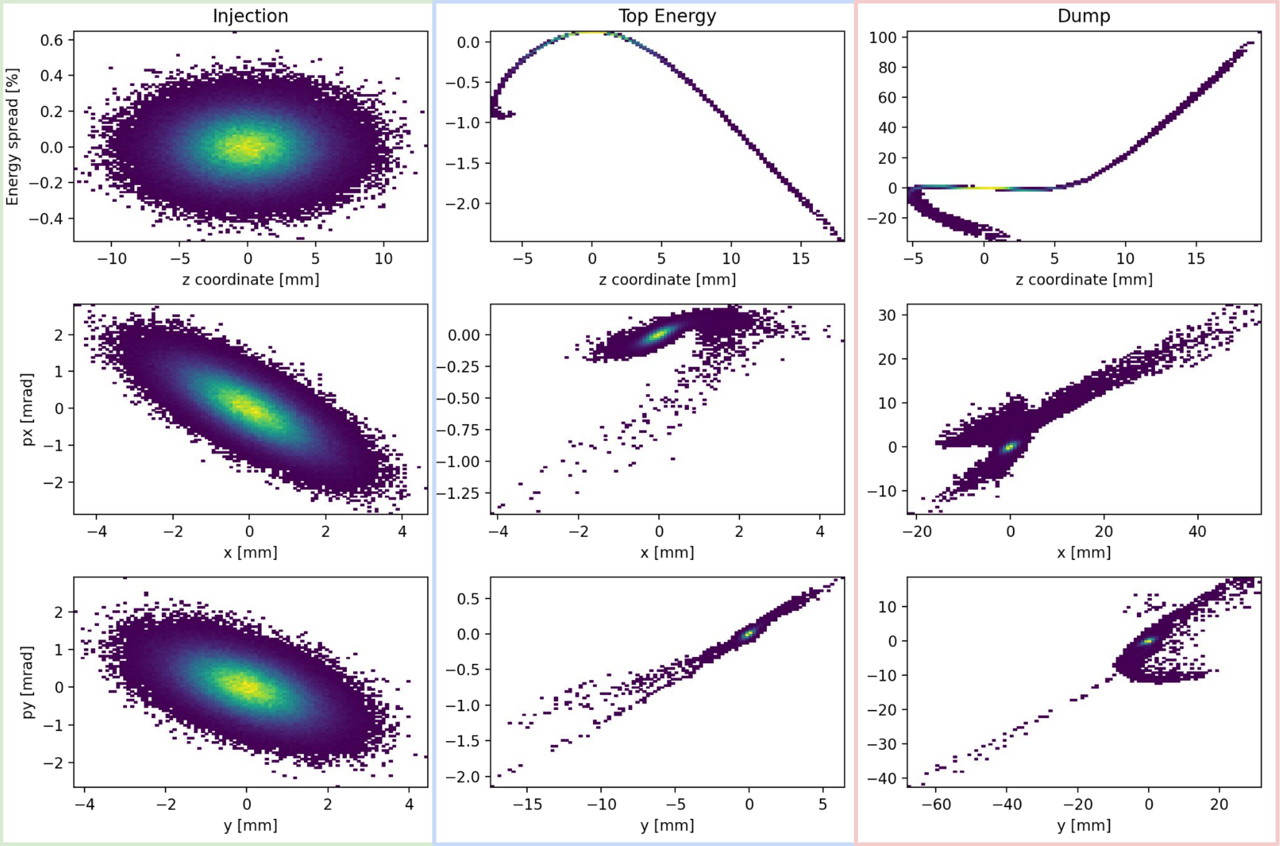
Plain tracking - bunch length of 3.0 mm - 20 mA

The normalised emittance at injection is **6 mm.mrad**

The longitudinal emittance at injection is **25 keV.mm**

$\sigma_{\delta,ini} = 1.2\ 10^{-3}$, $\sigma_s = 3.0$ mm

The tracking results in 99.5 % transmission without CSR.



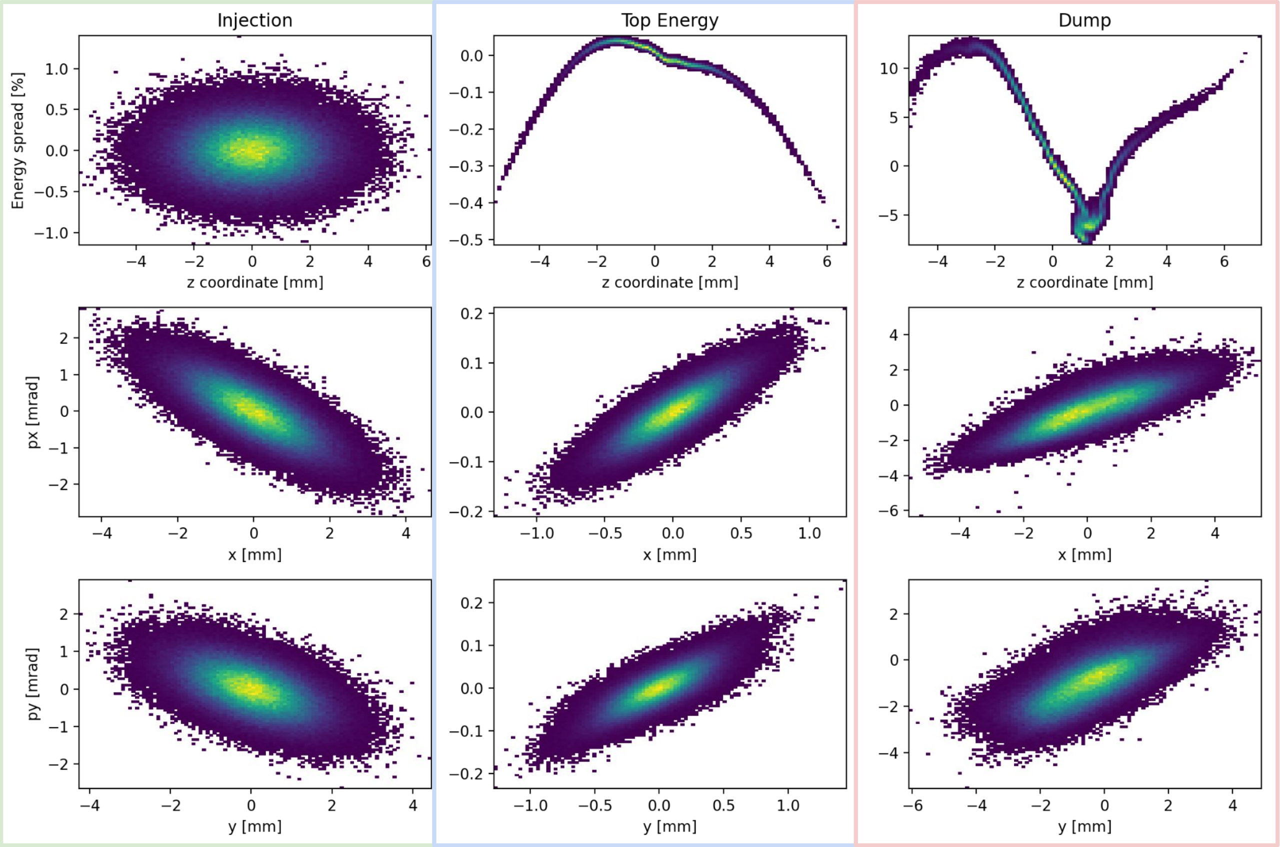
Tracking including CSR - bunch length of 1.4 mm - 20 mA

The normalised emittance at injection is **6 mm.mrad**

The longitudinal emittance at injection is **25 keV.mm**

$\sigma_{\delta,ini} = 2.6\ 10^{-3}$, $\sigma_s = 1.4$ mm

64 bins - 250000 macro particles



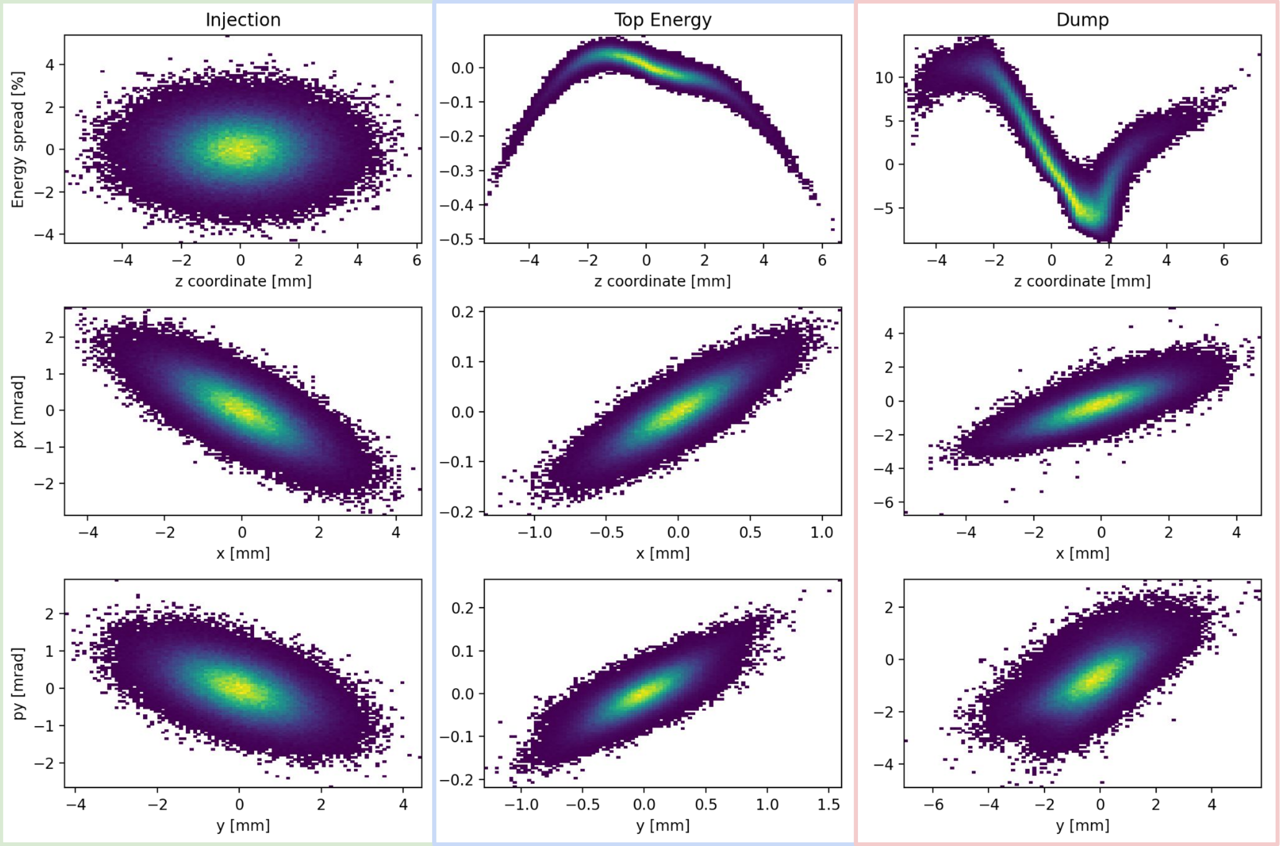
Tracking including CSR - bunch length of 1.4 mm - 20 mA

The normalised emittance at injection is **6 mm.mrad**

The longitudinal emittance at injection is **98 keV.mm**

$\sigma_{\delta,ini} = 10^{-2}$, $\sigma_s = 1.4$ mm

64 bins - 250000 macro particles



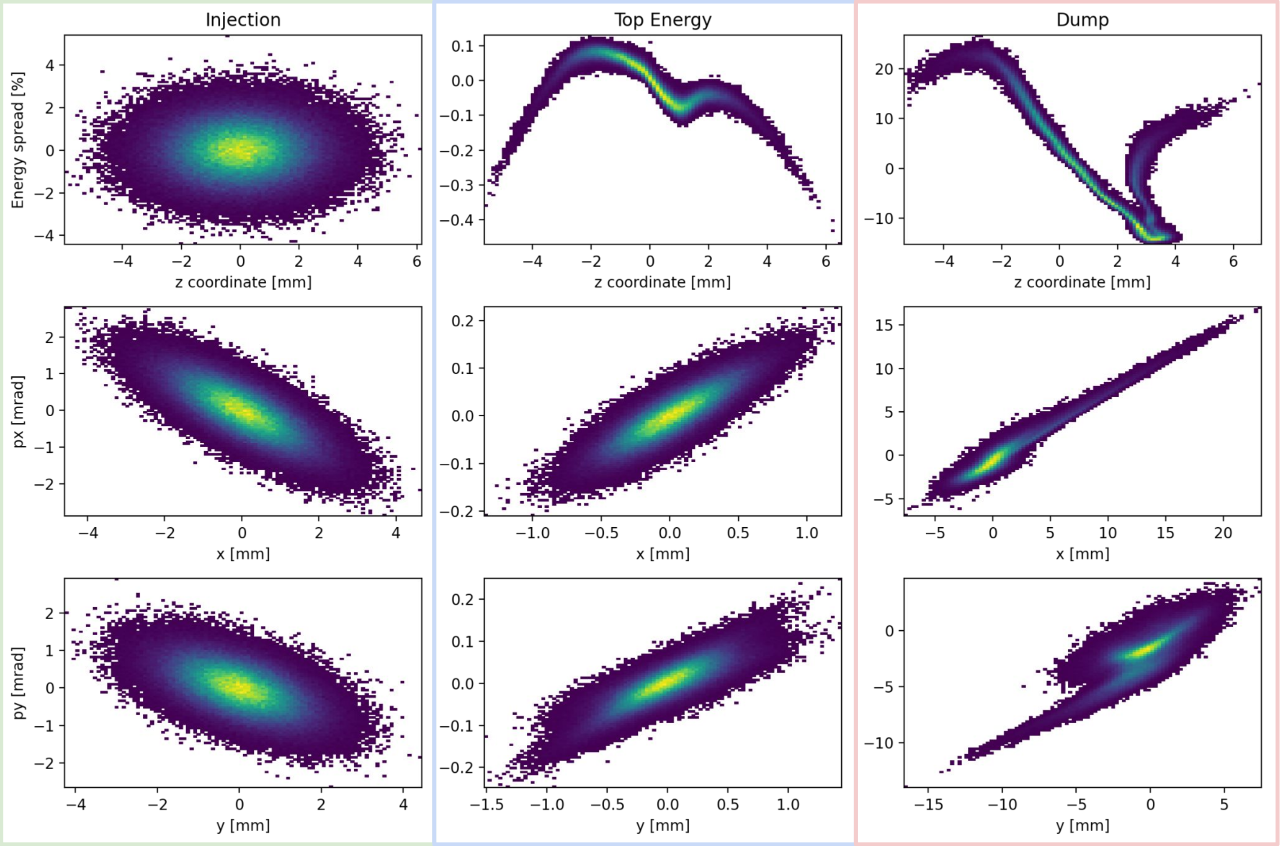
Tracking including CSR - bunch length of 1.4 mm - 40 mA

The normalised emittance at injection is **6 mm.mrad**

The longitudinal emittance at injection is **98 keV.mm**

$\sigma_{\delta,ini} = 10^{-2}$, $\sigma_s = 1.4$ mm

64 bins - 250000 macro particles



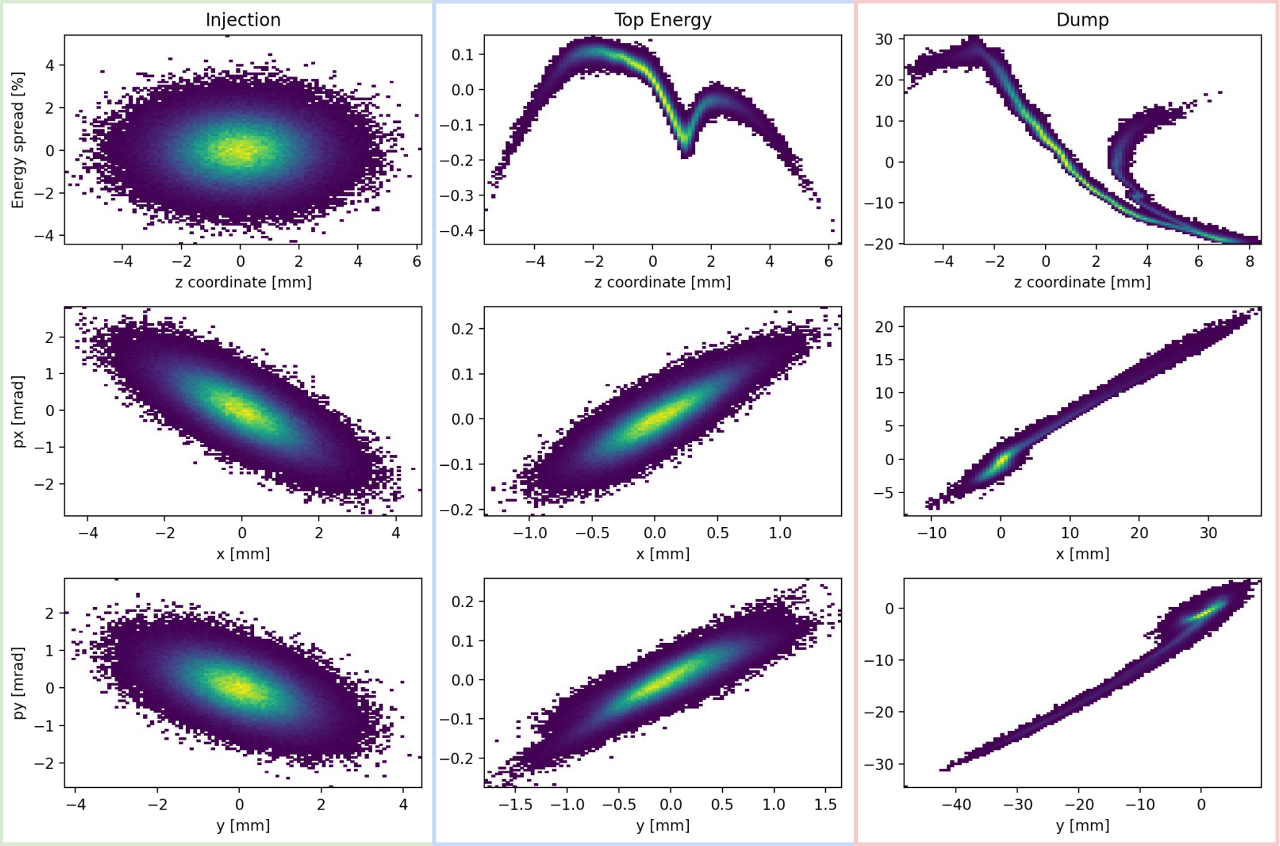
Tracking including CSR - bunch length of 1.4 mm - 45 mA

The normalised emittance at injection is **6 mm.mrad**

The longitudinal emittance at injection is **98 keV.mm**

$\sigma_{\delta,ini} = 10^{-2}$, $\sigma_s = 1.4$ mm

64 bins - 250000 macro particles



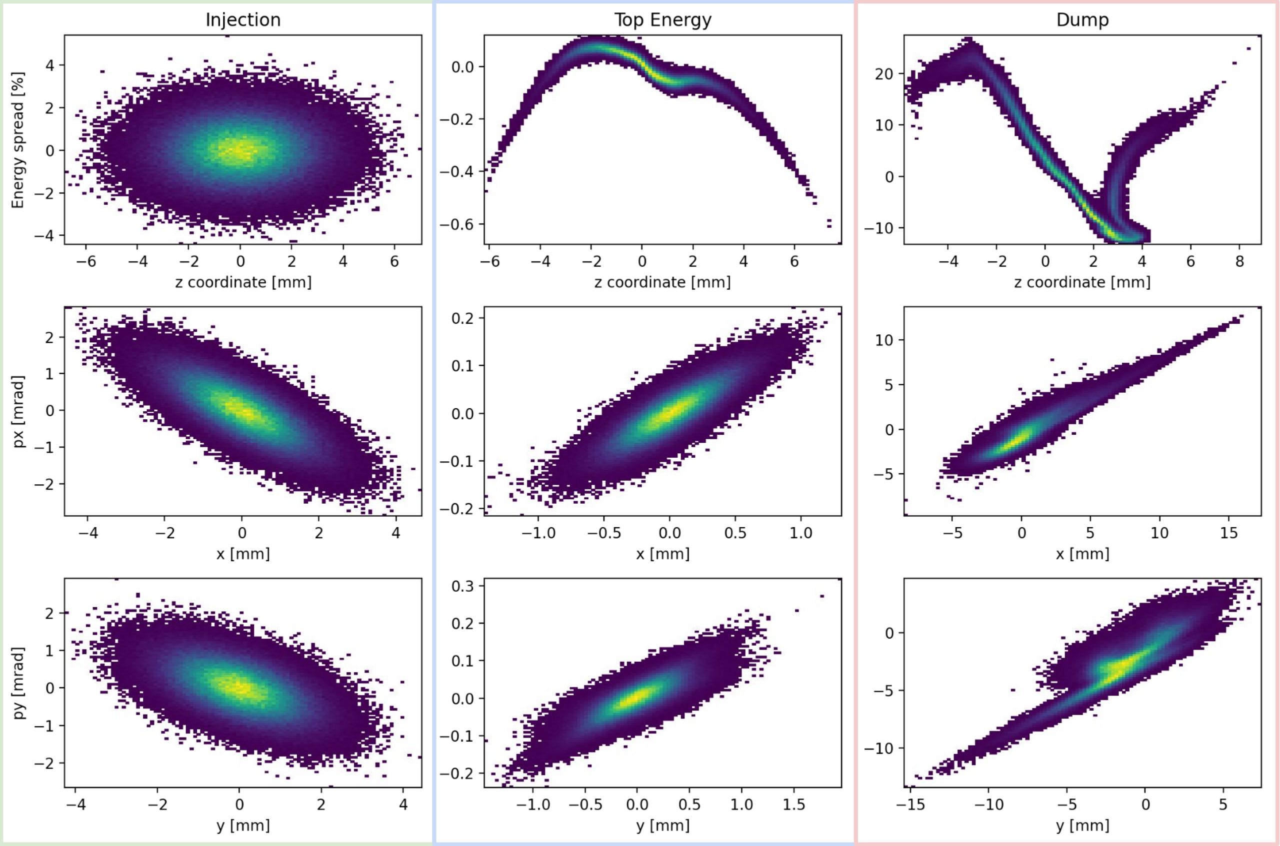
Tracking including CSR - bunch length of 1.6 mm - 45 mA

The normalised emittance at injection is **6 mm.mrad**

The longitudinal emittance at injection is **112 keV.mm**

$\sigma_{\delta,ini} = 10^{-2}$, $\sigma_s = 1.6$ mm

64 bins - 250000 macro particles



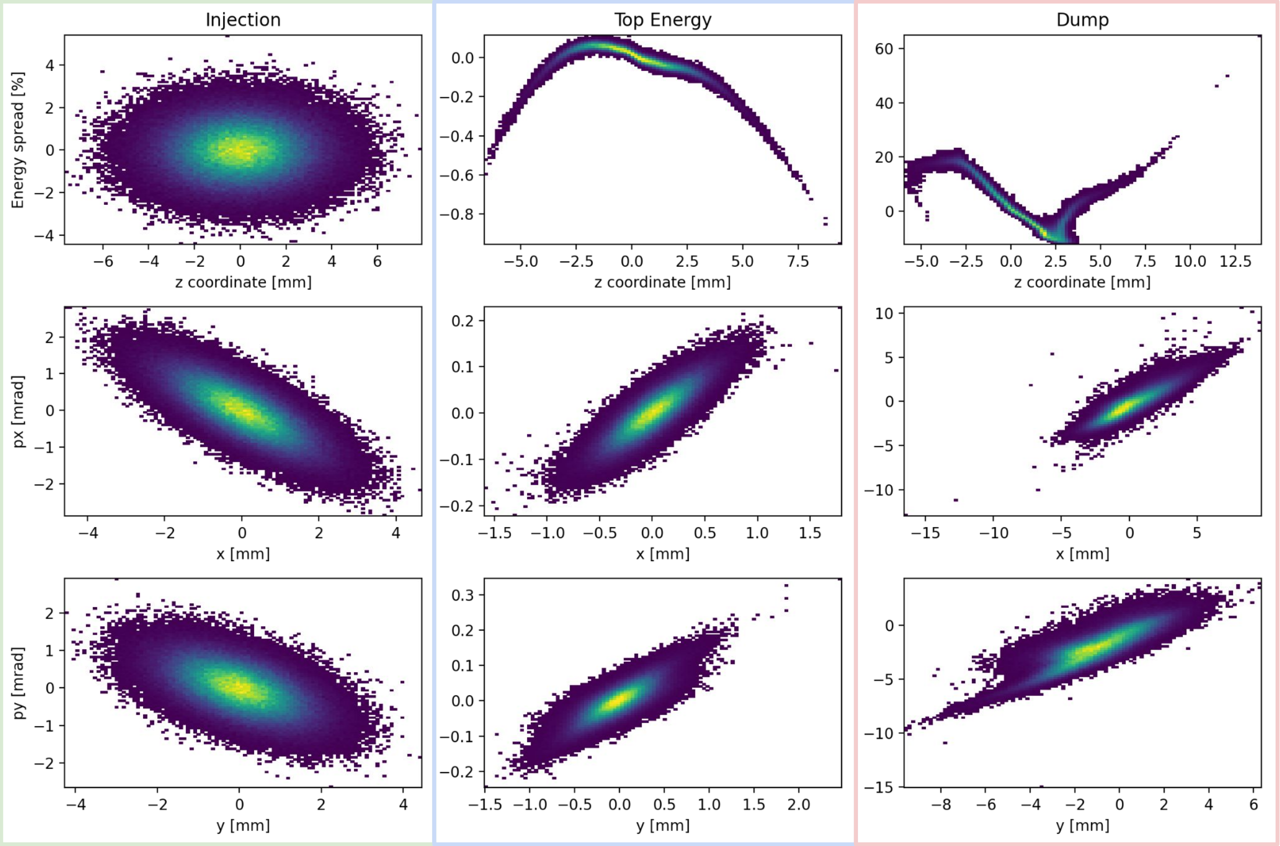
Tracking including CSR - bunch length of 1.8 mm - 45 mA

The normalised emittance at injection is **6 mm.mrad**

The longitudinal emittance at injection is **126 keV.mm**

$\sigma_{\delta,ini} = 10^{-2}$, $\sigma_s = 1.8$ mm

64 bins - 250000 macro particles



Multi-bunch tracking studies

The multi-bunch tracking studies consist of:

The tracking of 5000 macro particles per bunch, with the injection of 10000 bunches, one every 25 ns. Follow the evolution of the transverse HOM amplitudes while varying the number of particles per bunch and/or bunch filling pattern.

Three areas have been studied :

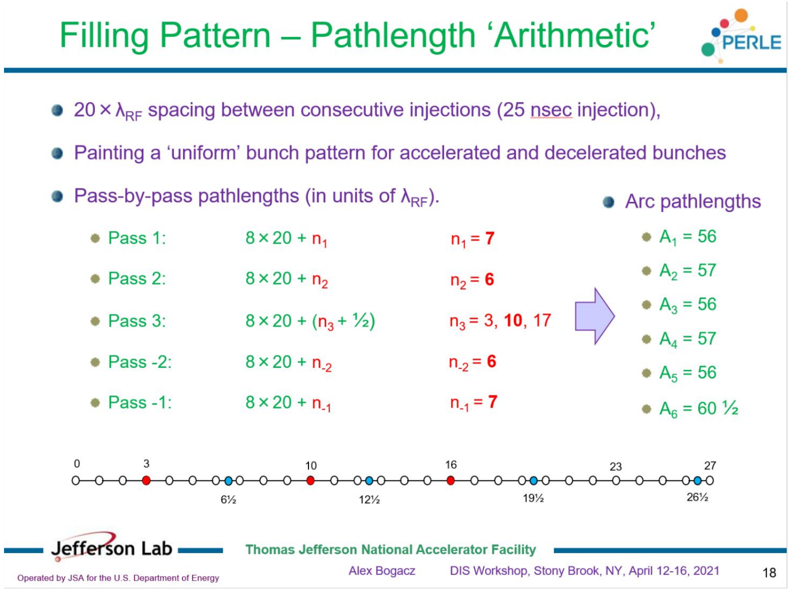
- Modification of the bunch filling pattern;
    - Such that the most disturbed bunch is as far as possible from the newly injected bunches,
    - Such that the injection is "regular".
- Implement the frequency detuning of the HOM from cavity to cavity that happens naturally due to the geometry imperfections.

Mode #	f [GHz]	A [V/C/m^2]	Q	Mode #	f [GHz]	A [V/C/m^2]	Q
1	0.9151	9.323	1e5	14	1.675	4.160	1e5
2	0.9398	19.095	1e5	15	2.101	1.447	1e5
3	0.9664	8.201	1e5	16	2.220	1.427	1e5
4	1.003	5.799	1e5	17	2.267	1.377	1e5
5	1.014	13.426	1e5	18	2.331	2.212	1e5
6	1.020	4.659	1e5	19	2.338	11.918	1e5
7	1.378	1.111	1e5	20	2.345	5.621	1e5
8	1.393	20.346	1e5	21	2.526	1.886	1e5
9	1.408	1.477	1e5	22	2.592	1.045	1e5
10	1.409	23.274	1e5	23	2.592	1.069	1e5
11	1.607	8.186	1e5	24	2.693	1.256	1e5
12	1.666	1.393	1e5	25	2.696	1.347	1e5
13	1.670	1.261	1e5	26	2.838	4.350	1e5

Frequency, Amplitude and Q-value of the transverse HOM modes. The HOM frequencies are based on the SPL cavity with amplitudes scaled to the PERLE RF frequency. The Q-value is the worst from the TESLA cavity.

Previous multi-bunch tracking studies with long-range wakefields from D. Pellegrini featuring the CDR version of the PERLE lattice showed a BBU threshold between 10e9 and 12e9 electrons per bunch ≡ 77mA.

Multi-bunch tracking studies and filling pattern



Filling Pattern – Pathlength 'Arithmetic'

PERLE

- 20 × λ_{RF} spacing between consecutive injections (25 nsec injection),
- Painting a 'uniform' bunch pattern for accelerated and decelerated bunches
- Pass-by-pass pathlengths (in units of λ_{RF}).
  - Pass 1: $8 \times 20 + n_1$ — $n_1 = \mathbf{7}$
  - Pass 2: $8 \times 20 + n_2$ — $n_2 = \mathbf{6}$
  - Pass 3: $8 \times 20 + (n_3 + ½)$ — $n_3 = 3, \mathbf{10}, 17$
  - Pass -2: $8 \times 20 + n_{-2}$ — $n_{-2} = \mathbf{6}$
  - Pass -1: $8 \times 20 + n_{-1}$ — $n_{-1} = \mathbf{7}$
- Arc pathlengths
  - $A_1 = 56$
  - $A_2 = 57$
  - $A_3 = 56$
  - $A_4 = 57$
  - $A_5 = 56$
  - $A_6 = 60$ ½

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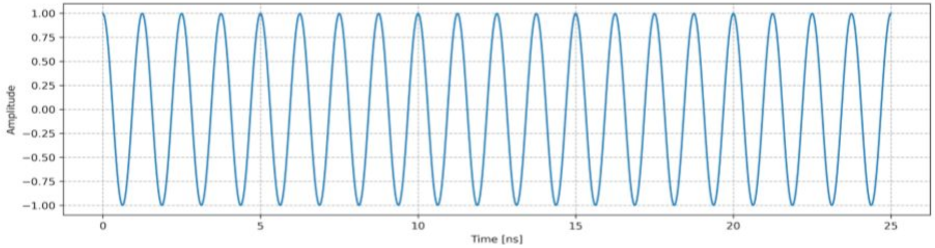
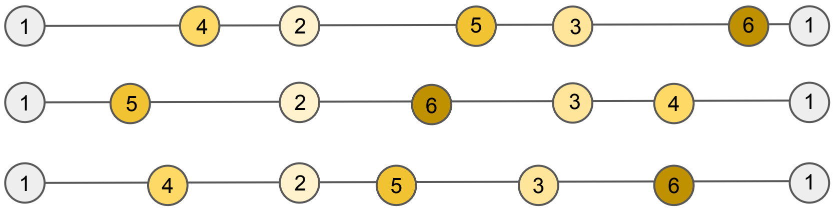


PERLE :
7-7-10.5

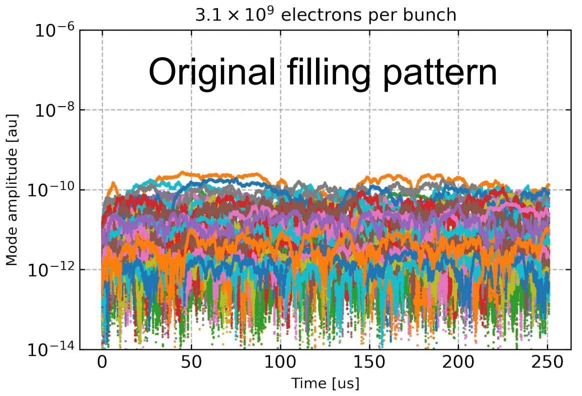
PERLE :
7-7-2.5

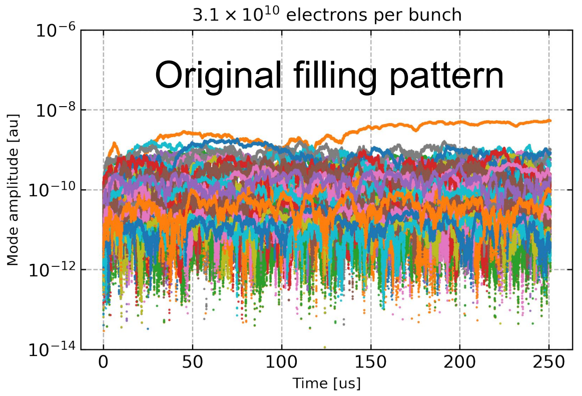
PERLE :
7-6-10.5

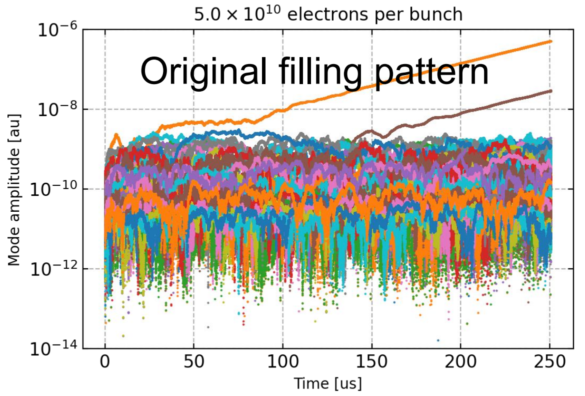


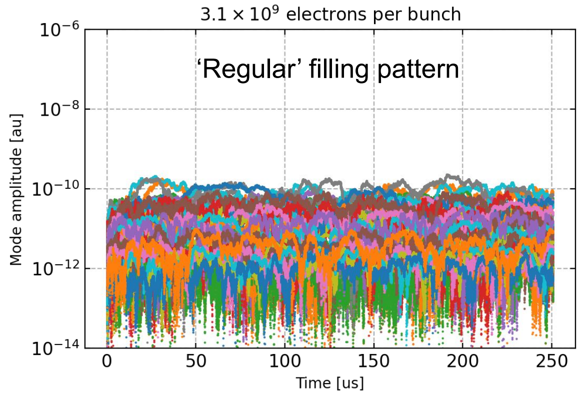
The lattice design is based on a 7-7-10.5 λ_{RF} path-length adjustment during the first, second and third turns to alternate accelerating (**1, 2 & 3**) and decelerating (**4, 5 & 6**) bunches.
7, 6, 10.5 λ_{RF} path-length adjustment combines regular injections and alternation of the bunches.
7, 7, 2.5 λ_{RF} path-length adjustment combines maximal distance between 6 1 and bunches alternation.

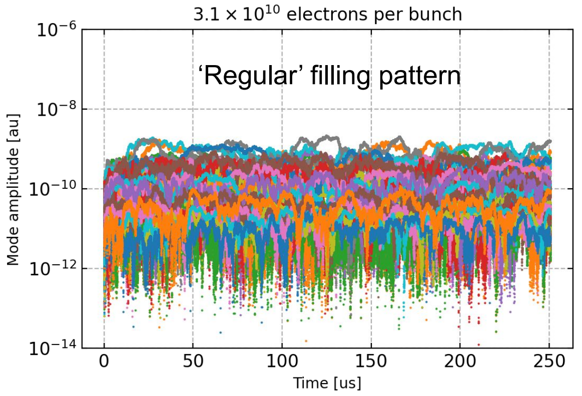
Multi-bunch tracking studies

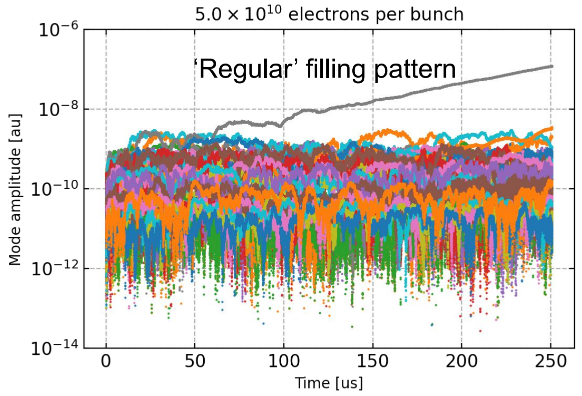




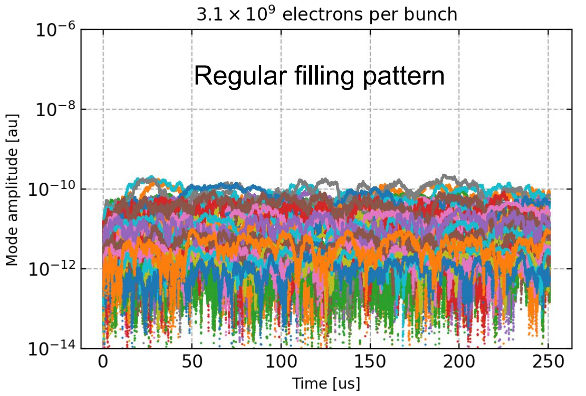


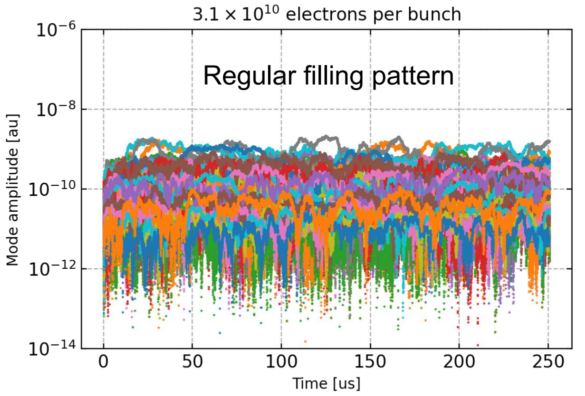


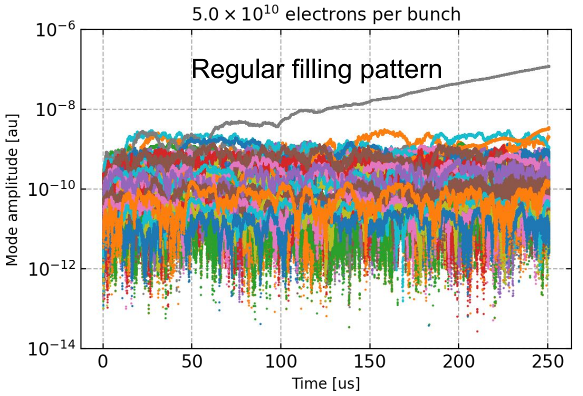


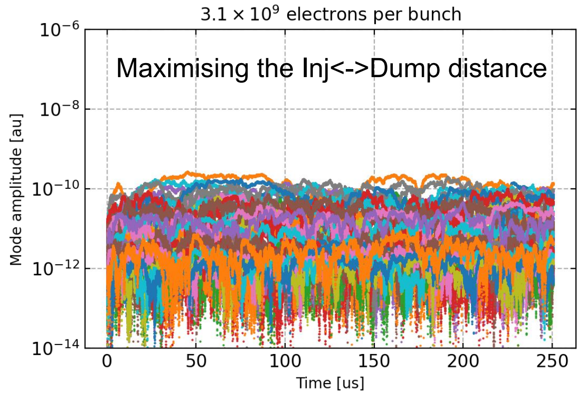


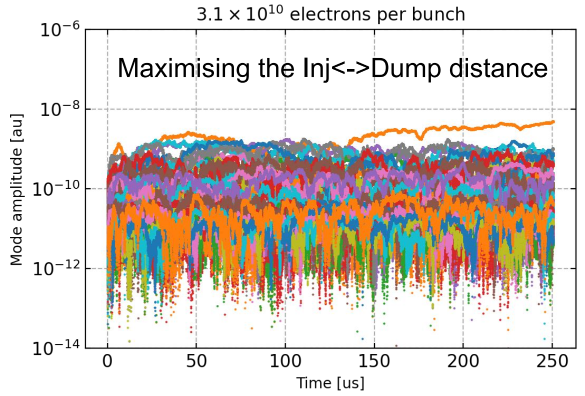
Multi-bunch tracking studies

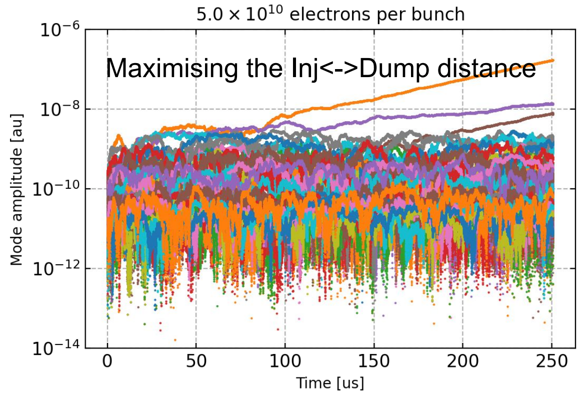




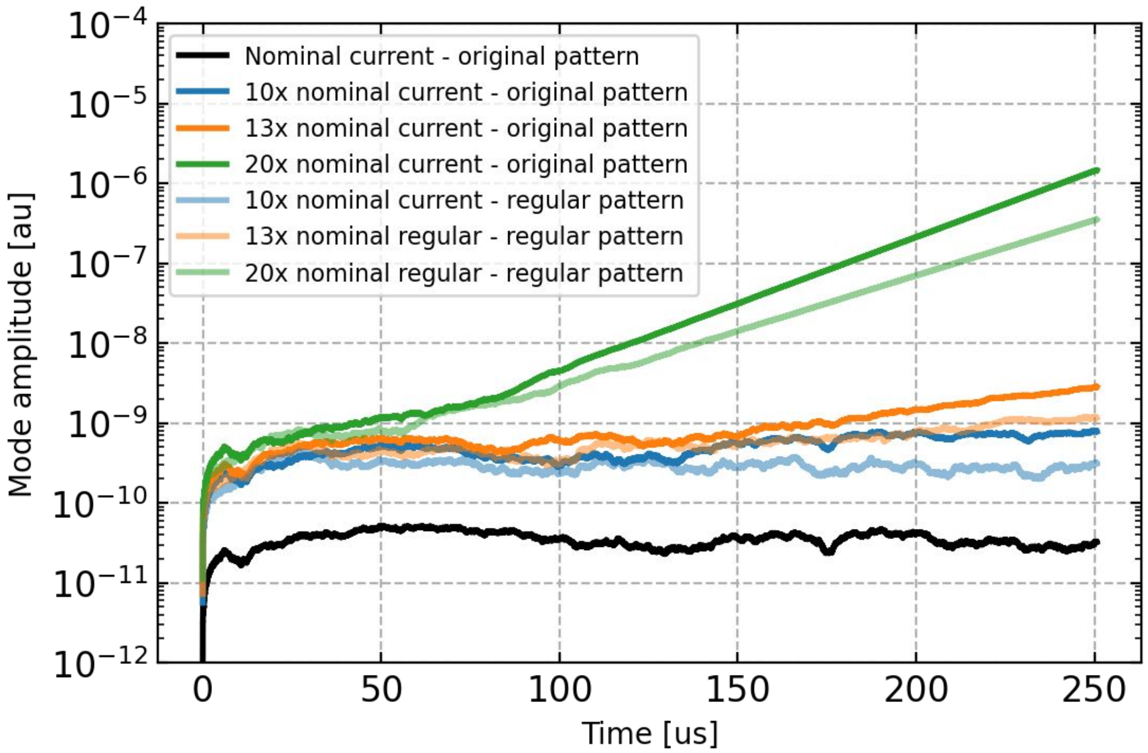








Multi-bunch tracking studies summary



Comparison of the HOM amplitude quadratic means for:

- The nominal **20mA** and path-length adjustment **7-7-10.5**
- **200mA** and path-length adjustment **7-7-10.5**
- **200mA** and path-length adjustment **7-6-10.5**
- **260mA** and path-length adjustment **7-7-10.5**
- **260mA** and path-length adjustment **7-6-10.5**
- **400mA** and path-length adjustment **7-7-10.5**
- **400mA** and path-length adjustment **7-6-10.5**

Summary

- PERLE lattice design includes **two experimental areas** with low beta insertions.
- Tracking simulations have been performed with a **reduced bunch length (1.4mm)** until the lattice providing a longitudinal matching is available.
- **Lossless particle tracking including CSR** and **short range wakefields** with a 1.4mm r.m.s bunch length **is achieved until 45mA** (2.25 times nominal)
- **Multi-bunch tracking is stable at nominal current**, the optimisation of the bunch filling pattern does not show unstable HOM up to 10 times the nominal current.