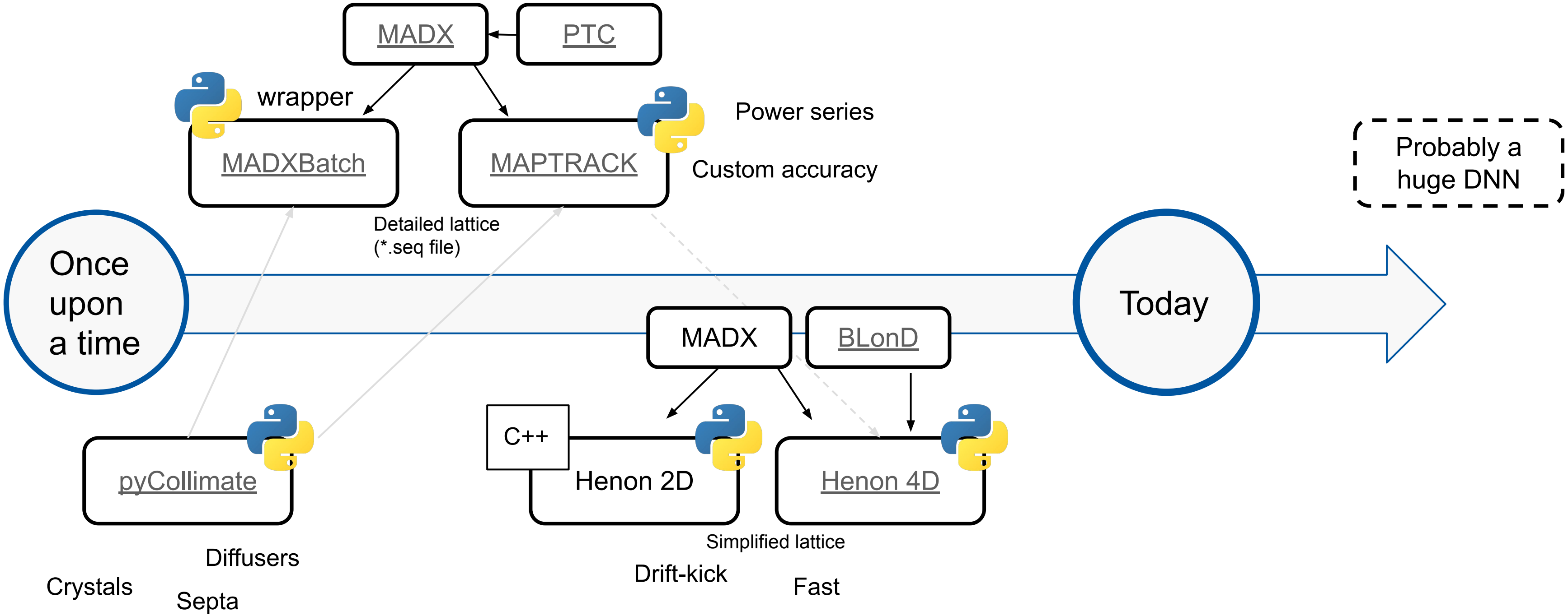
Slow extraction simulations at CERN

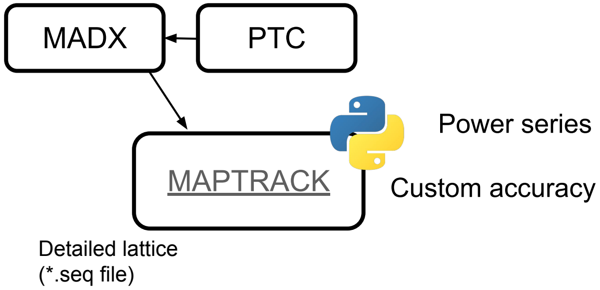
Advancements, benchmarking and next steps

Pablo A. Arrutia Sota, Michelangelo Pari

A (very rough) timeline of our codes



Maptrack

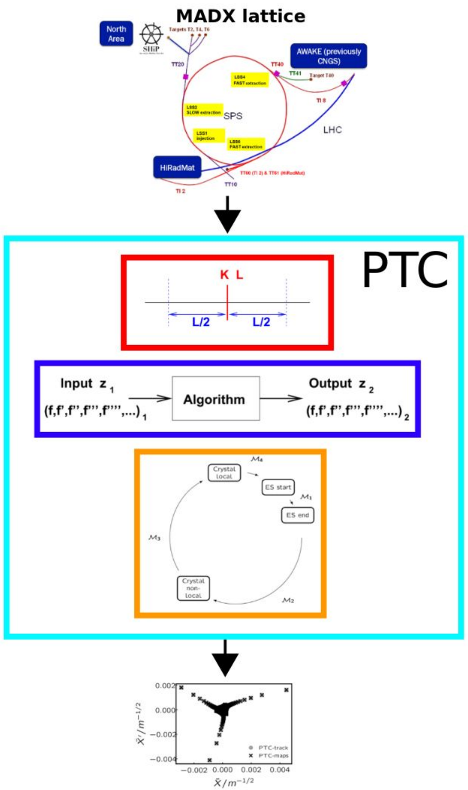

MADX
PTC
MAPTRACK
Power series
Custom accuracy
Detailed lattice
(*.seq file)

Great summary of the code by F. Velotti

Maptrack

Concept:

- MADX lattice as input
- PTC exploits fancy maths (TPSA) to ‘track’ (integrate) power series around ring
- We effectively obtain solution around the closed orbit for all particles in one go
- Order of power series and number of sectors chosen for accuracy/speed trade-off
- Power series used in python for tracking



Maptrack

Features:

- Trade off between accuracy and speed easily controlled
- Python implementation -> thread with anything!
- Couplings between coordinates easily readable

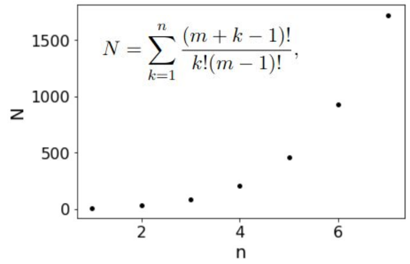


Figure 2.22: Number of terms in a power series map, m=6.

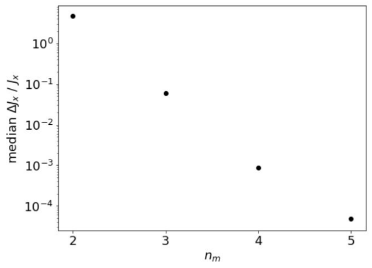


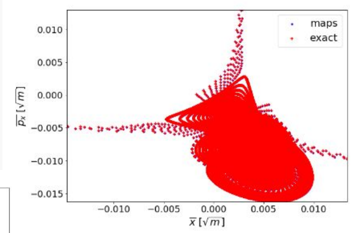
Figure 2.24: Relative action error.

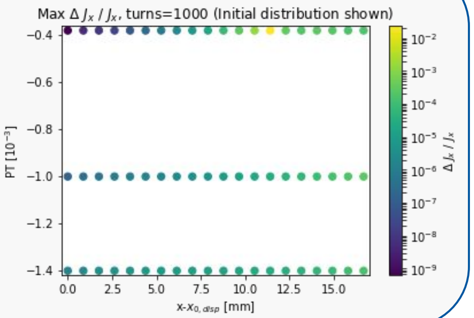
$$X_{new} = 1.963663472377548\delta^3 + 174.824549769672\delta^2 p_x + 3.474817355975599\delta^2 x - 1.069603593297128\delta^2 + 22638.1414959444\delta p_x^2 + 808.20317538044\delta p_x x - 33.9068469457053\delta p_x - 18699.0528122214\delta p_y^2 - 705.492954639224\delta p_y y$$
$$+ 5.21974610980863\delta x^2 - 0.233421922557007\delta x - 4.74462299315588\delta y^2 + 0.815810328943972\delta - 7484.26952506821 p_x^3 - 17.1658827400797 p_x^2 x - 5630.47845980583 p_x^2 - 153055.780871724 p_x p_y^2 - 6784.72769946376 p_x p_y y$$
$$+ 15.3078802076427 p_x x^2 - 304.819813150183 p_x x - 71.8640496922984 p_x y^2 + 21.6819845471695 p_x - 4698.57020527277 p_y^2 x + 4676.36213424362 p_y^2 - 213.664076715945 p_y x y + 267.714203895552 p_y y + 0.278120441761117 x^3$$
$$- 4.0687062324966 x^2 - 2.35079934845526 x y^2 - 0.513133144684428 x + 3.74705000782842 y^2$$

Advancements:

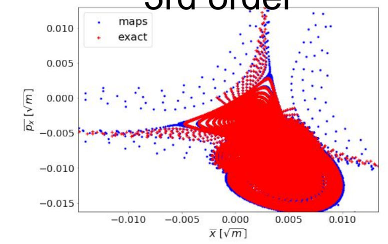
- Python interface for map generation
- Python benchmarking tool
- Symbolic representation of maps (sympy)
- ~10x speed-up with vector operations

4th order





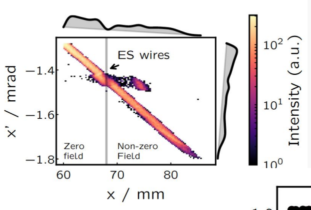
3rd order

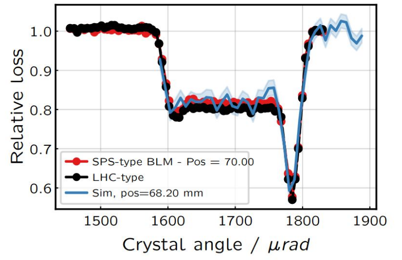


Maptrack, examples

Crystal shadowing SPS

- Combined python crystal model
- Fast multi-dimensional scans

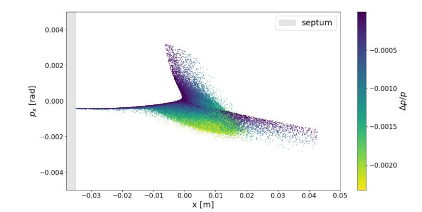




F. Velotti

MedAustron extraction

- Combined python RFKO model
- Small machine -> hard to speed-up!

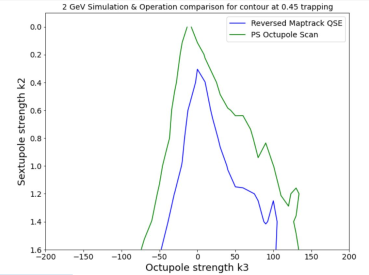


Method	Time [μs/particle/turn]	Comments
Maptrack	51	4th order, two sectors.
Maptrack	20	3rd order, two sectors.
MADX thin-lens track	13	4 slices per dipole, quad; 2 slices per sextupole.

Table 2.4: Time Benchmarking.

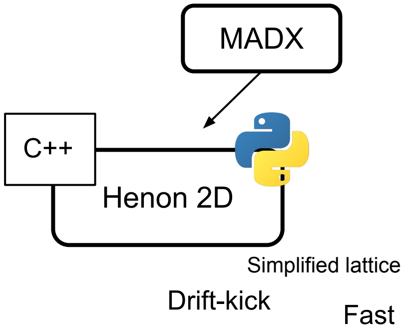
PS octupole trapping

- Combined python dynamic octupoles and sextupoles
- Fast multi-dimensional scans



R. Taylor

Henon 2D



Simulation for frequency response study

M. Pari, F.M. Velotti, M.A. Fraser, V. Kain, O. Michels

Michelangelo Pari
Phys. Dep. G. Galilei and INFN Padova, Padova, IT
CERN, Geneva, CH

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

Henon 2D

Concept

- Henon-map based 2D simulation model for frequency response of SPS spill* (link)

Using the SPS extraction parameters to configure the simulation, in particular:

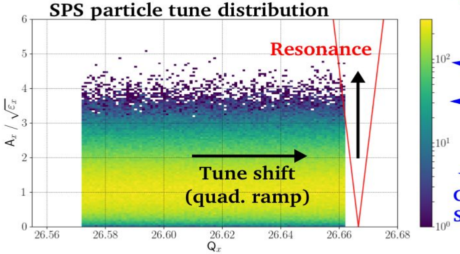
$$\begin{pmatrix} x \\ x' \end{pmatrix}_{n+1} = \mathbf{R}\left(2\pi Q_n\right) \begin{pmatrix} x \\ x' + V_{ss}\, x^2 \end{pmatrix}_n$$

Setting up henon map parameters

SPS QSWEEP 2018

Parameter	Value
Momentum	400 GeV/c
Emittance	1.9×10^{-8} m
One turn time	23 µs
Chromaticity	−26.67
Resonant tune	$26.6\bar{6}$
Start of tune ramp	26.62
End of tune ramp	26.72
Flat top duration	4.8 s
Momentum range (δ_p)	3×10^{-3}
Virtual sextupole strength	169.3 $m^{-1/2}$
Closed orbit bump (max)	48 mm
Electrostatic septum pos.	68 mm

Extraction condition



Generating SPS phase space & mom distr.

IFAST-REX, 17/02/2022, M.Pari

Features

- Very fast, up to 100x
- Batch jobs via HTCondor

(*) Phys. Rev. Accel. Beams 24, 083501 (2021)

M.Pari, PhD Thesis, University of Padova http://paduaresearch.cab.unipd.it/13202

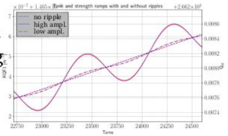
Henon 2D, examples

SPS

Matching the two models:

- Use same SPS parameters
- Strength-to-tune conversion
- Some mismatch can be expected due to high simplifications of Henon model, **BUT:**

Tune/kQ block: approximated with a linear law (more precise modeling can be used if needed)

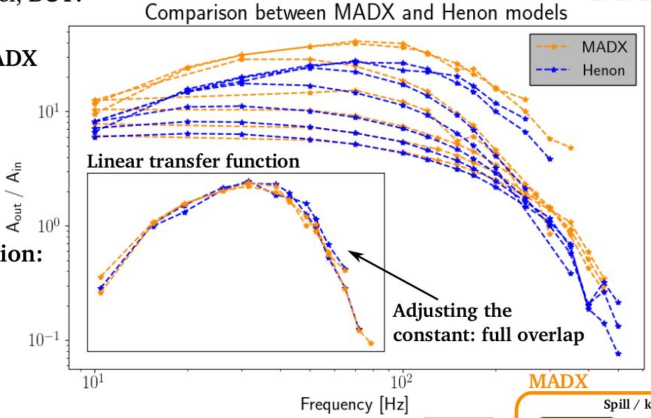


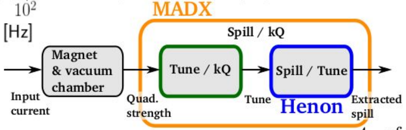
The transfer functions from the complete MADX model and the Henon one can be scaled to be fully compatible:

→ In particular, the **linear** transfer functions (generic & amplitude independent) show good agreement.
Univocal definition of lin. transfer function: solid result.

⇩

Henon-map model captures the essence of the process





IFAST-REX, 17/02/2022, M.Pari

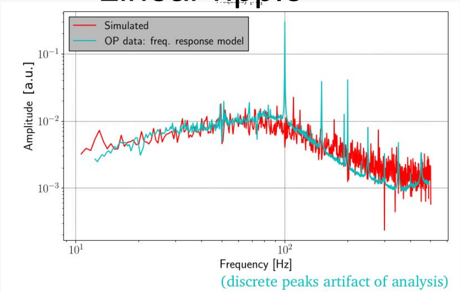
4 of 6

Henon 2D, examples

SPS (ii)

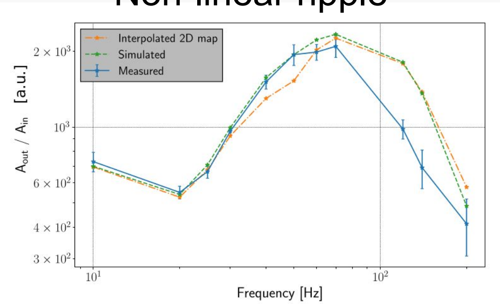
- MADX model validated with operational data
- Noise floor removed via theoretical transfer function before running simulation

Linear ripple



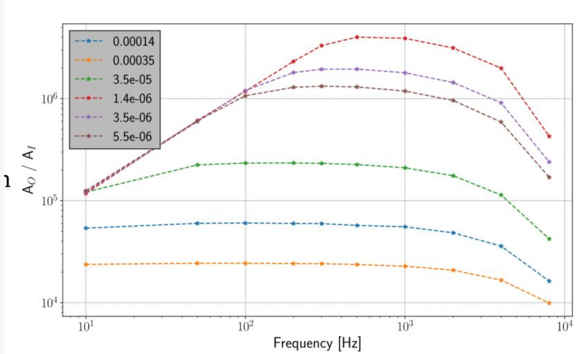
- High amplitude ripples (10s of ppm)
- Low intensity run due to technicalities (100x)
- Good agreement for most injected frequencies

Non-linear ripple

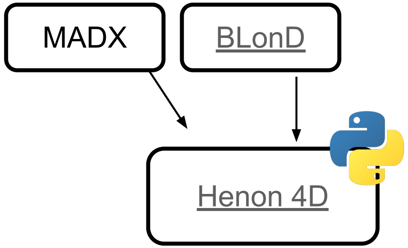


MedAustron

- Model easily ported to other machine
- Low-pass filter poles move by 50x (T_{SPS}/T_{MA} = 55)
- Lesson learnt: need high freq ripple injection and measurements



Henon 4D



Simplified lattice

Drift-kick

Fast

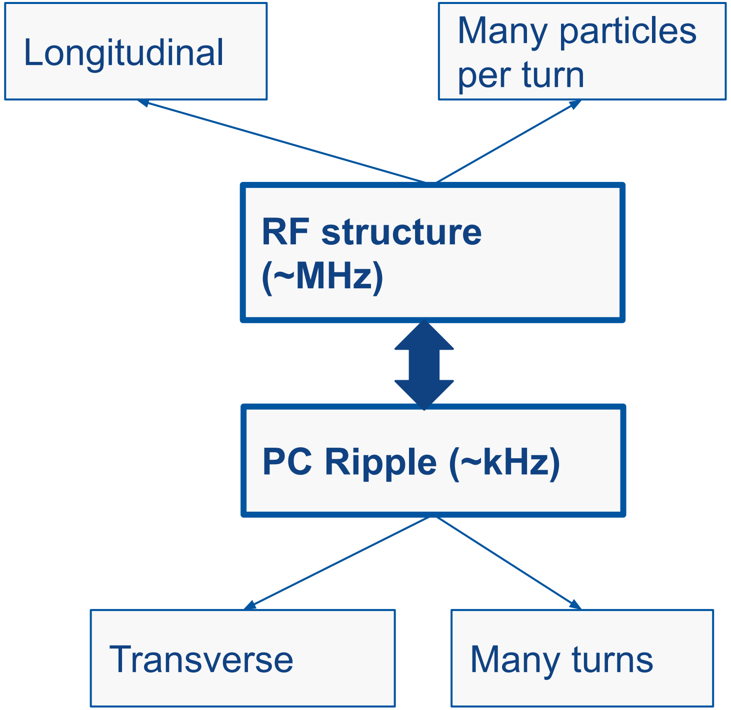
Henon 4D

Concept

- Goal: understand spill structure at vastly different timescales
- Normalised transverse (X, X') based on M. Pari's code (Henon 2D)
- Expanded to longitudinal (t, p) based on BLonD (Henon 4D)

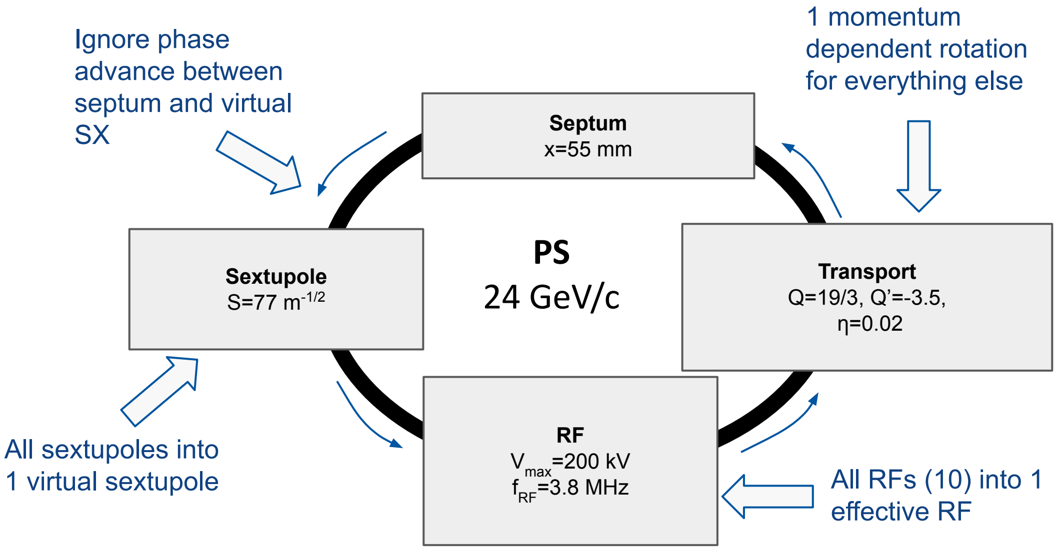
Features

- Keep it modular: favour speed and add complexity if needed
- Dynamic effects (ramping, rippling…) easily programmable turn by turn (or even more granular)
- Can run scans on HTcondor batch system



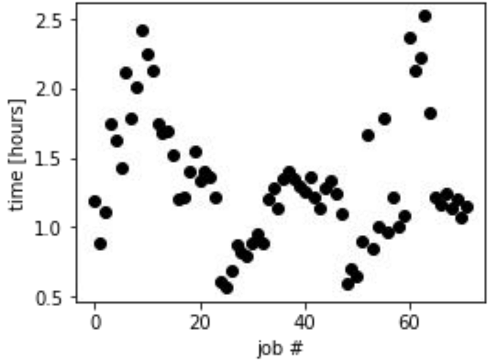
Henon 4D, example

- Study of bunch length with empty bucket channelling in PS



<u>Settings</u>

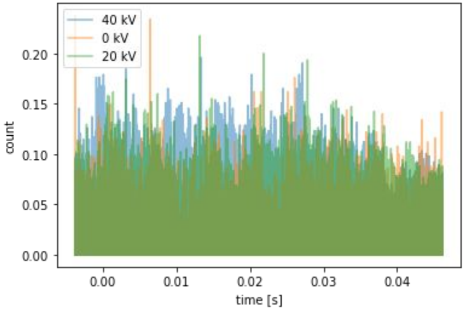
- 72 jobs in parallel (scanned RF voltage and frequency)
- 100 000 particles per job
- 100 000 turns per job



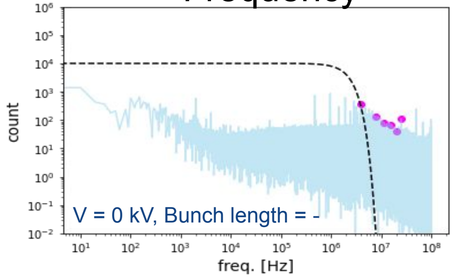
Henon 4D, example

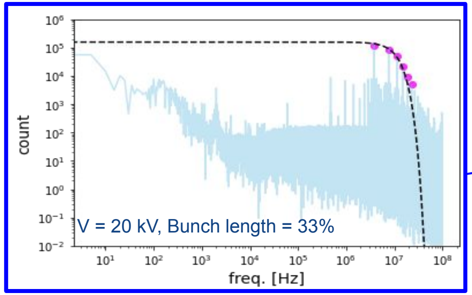
- Benchmarking with machine measurements:

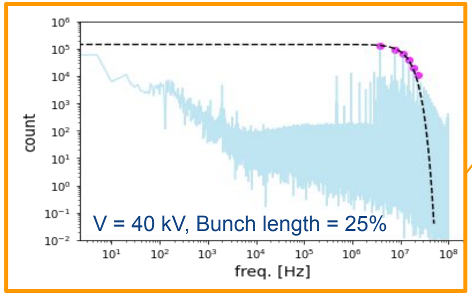
Time

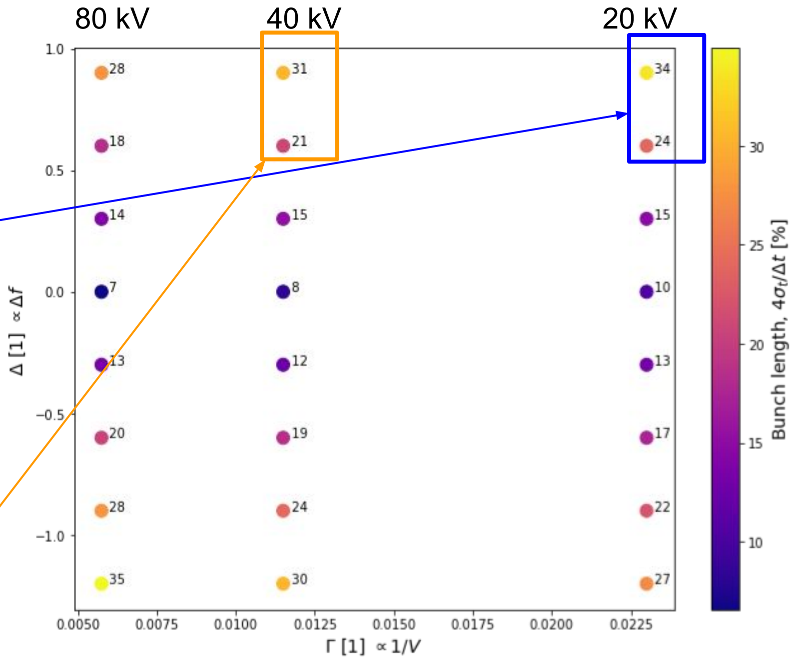


Frequency

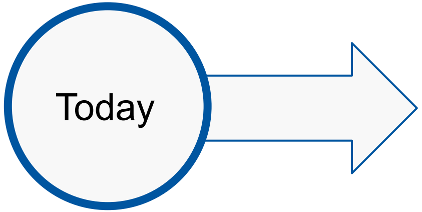








Next steps



Next steps

Maptrack (Power series based)

- Full exploitation of PTC capabilities to implement maps dependent on knobs (e.g. magnet strength)
- Add feature to run on HTCondor system

Henon (Kick-drift based)

- Continue communication with BLonD to add more longitudinal features
- Benchmark 4D dynamics vs. 6D dynamics from standard code
- Extend to other phenomena (e. g. Slow extraction with octupoles)

- GPU implementations for further speed-up
- Hybrid solutions using both codes for certain applications: e.g. understand impact on beam loss at septum from applying RF techniques such as empty bucket channelling

Thank you!

Extra slides