Short proton bunches for AWAKE: Simulation studies @ CERN

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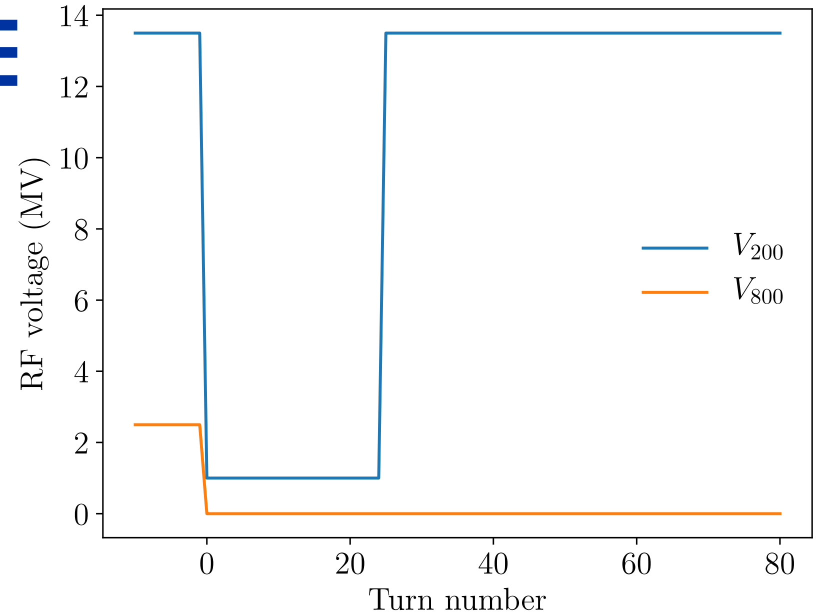
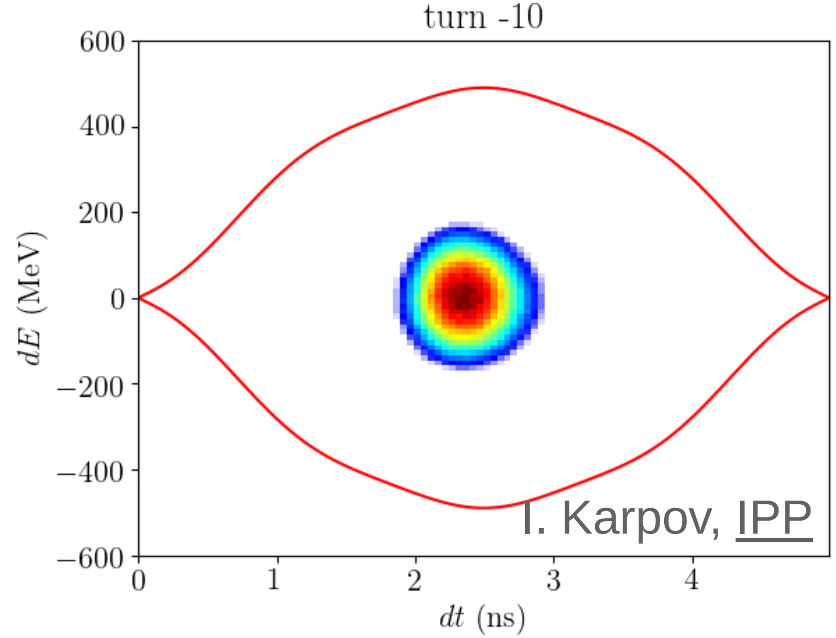
Outline

- **RF manipulations to shorten bunches**
- **Quadrupole pumping for short bunches**
- **EiC quadrupole pumping model (F. Willeke)**
    - Benchmarking zero intensity
    - Adding intensity effects
- **SPS quadrupole pumping model**
    - Short bunches for AWAKE
- **PS quadrupole pumping measurements**
- **Summary and Further work**

Context: Bunch rotation for AWAKE



- **Currently SPS uses a non-adiabatic double voltage jump to rotate bunches for AWAKE.**
- **This rotates a $\tau_b\ (4\sigma) = 1.3\ ns \rightarrow\ \sim 0.5\ ns$**
  - $\tau_b\ (1\sigma) = 325\ ps \rightarrow\ \sim 125\ ps$
- **Compression factor of 2.6 ($N_p = 3 \times 10^{11}$).**

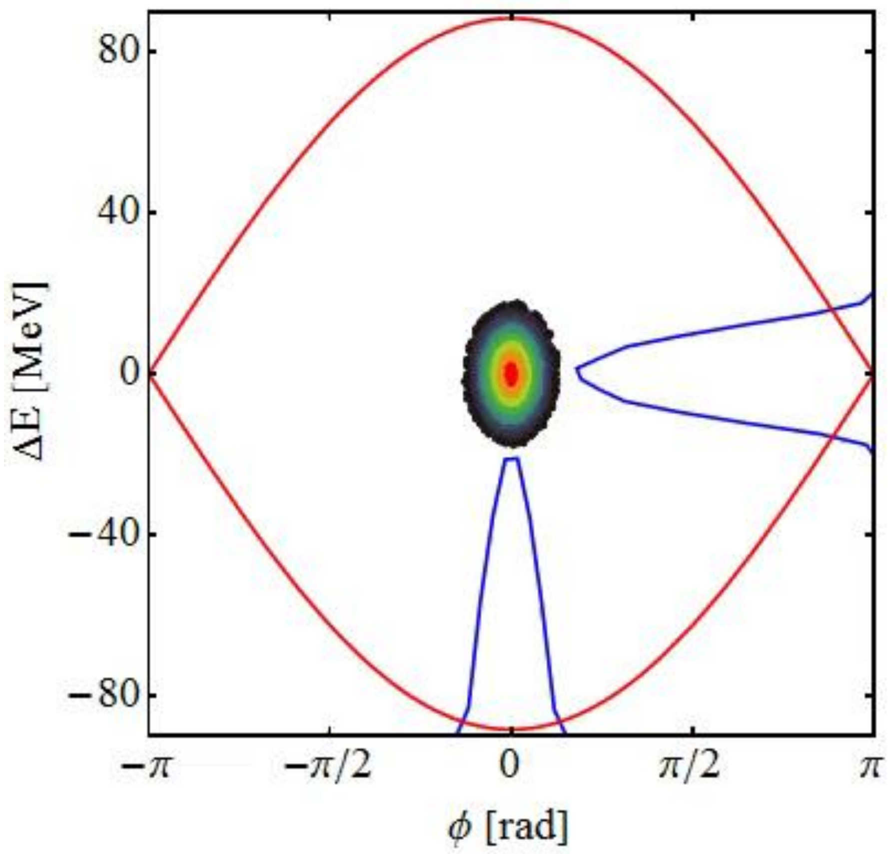


- **F. Willeke proposed an RF manipulation to create $\tau_b\ (1\sigma) = \sim 1\ ps$ with resonant quadrupole excitation.**
  - Compression factor of 10-15.

- **Goal of this study is to have a first, preliminary look at intensity effects.**

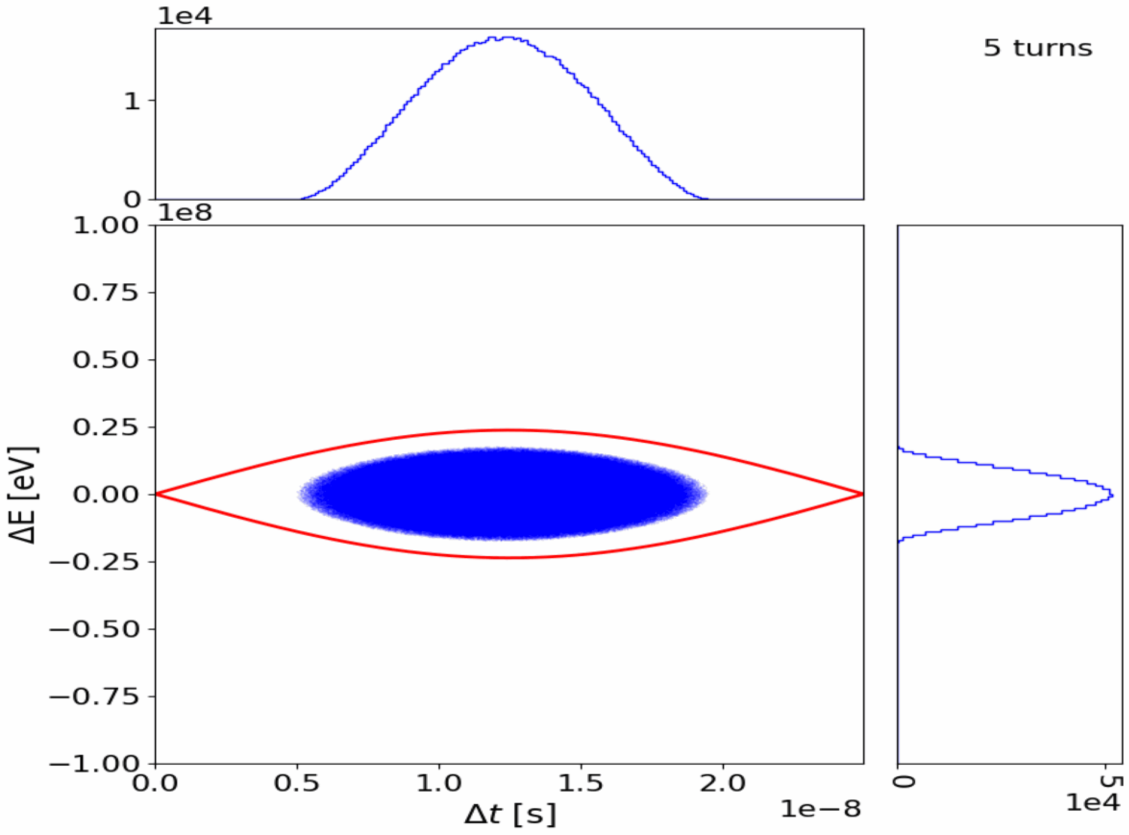
Two main types of bunch rotation @ CERN

- Phase jump to unstable fixed point



H. Damerau, CAS 2023

- Non-adiabatic voltage jump



Quadrupole Pumping @ BNL

- **RF voltage is modulated $(2f_s)$ to excite quadrupole oscillations.**
- **Performed in the Booster before transfer to Alternating Gradient Synchrotron (AGS) at BNL.**
  - Goal was to minimise momentum spread.
- **Not currently utilised at CERN.**
- **F. Willeke proposes this RF modulation, with the addition of linearisation, to create short bunches.**

PERFORMANCE OF THE AGS TRANSITION JUMP SYSTEM*

L.A. Ahrens, J.M. Brennan, J.W. Glenn, T. Roser, W.K. van Asselt[#], BNL, Upton, NY

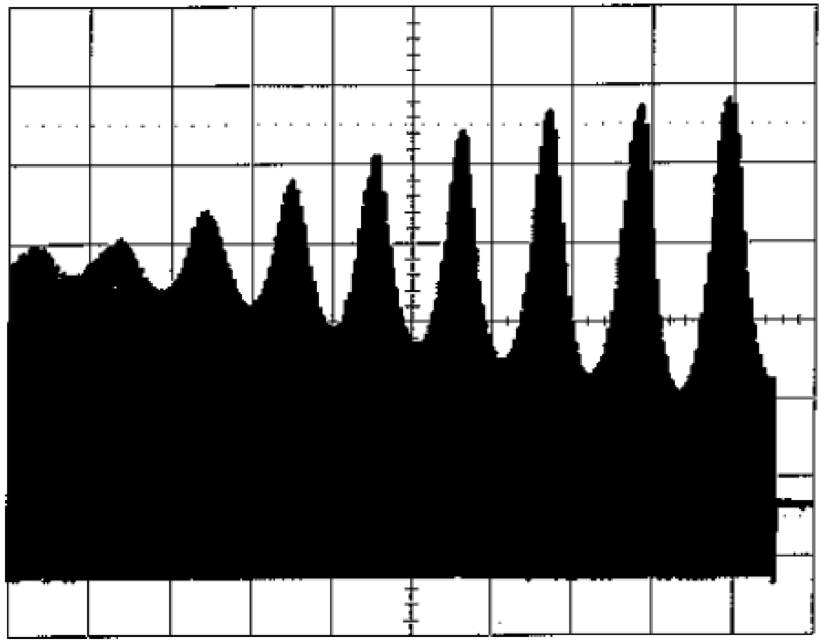
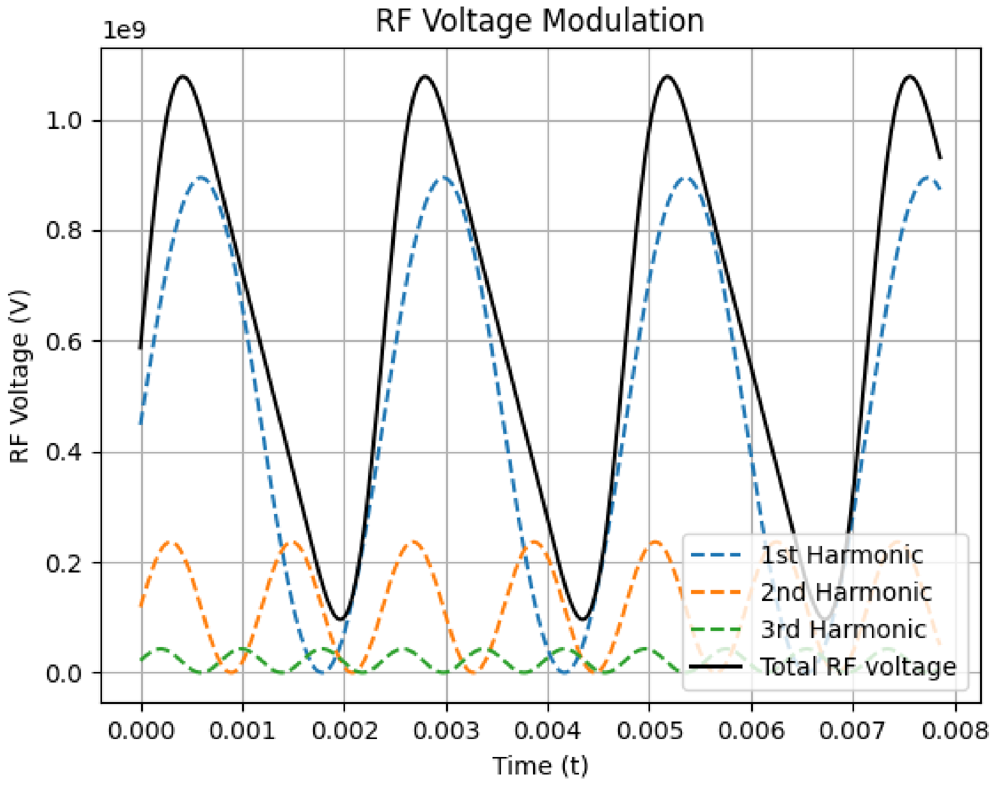
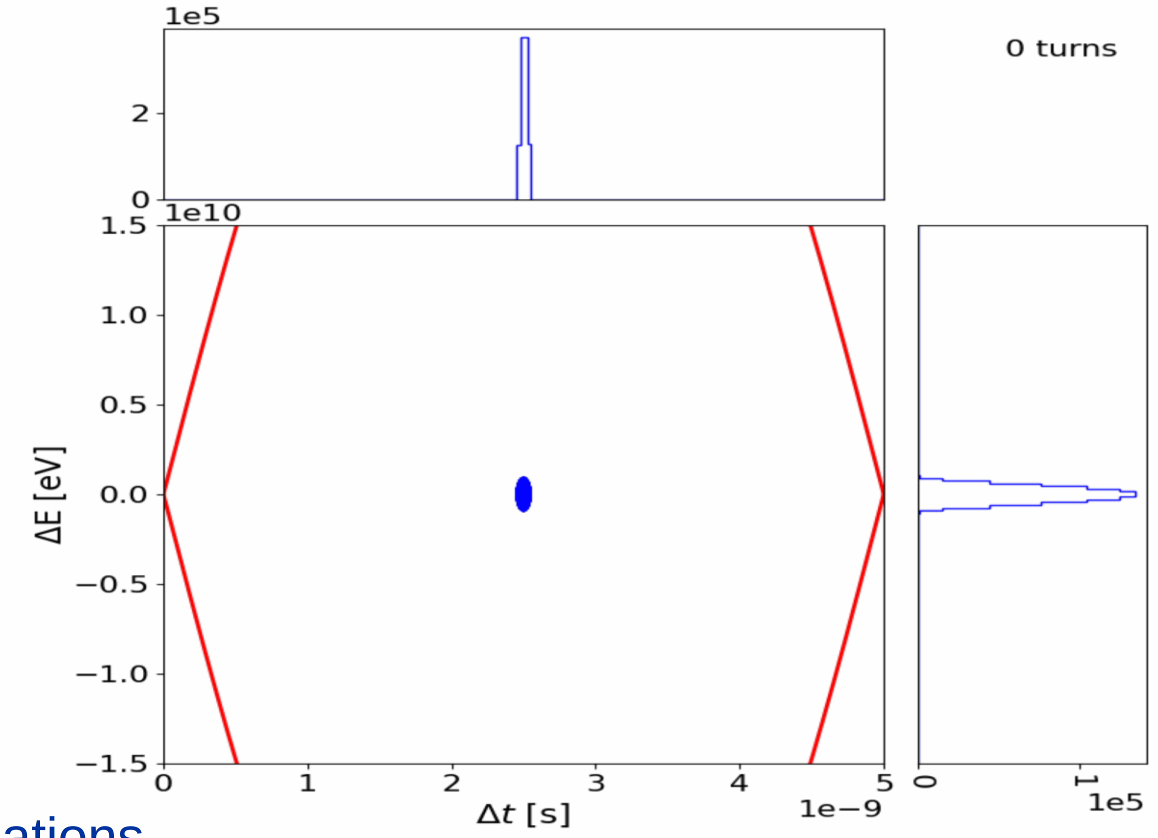


Figure 1: The wall current monitor signal showing the peak current density variations in the Booster before transfer to the AGS. Horizontal scale is 1 ms/s

L. A. Ahrens, J. M. Brennan, J. W. Glenn, T. Roser and W. K. van Asselt, "Performance of the AGS transition jump system," *Proceedings of the 1999 Particle Accelerator Conference*

Quadrupole pumping with linearisation: F. Willeke



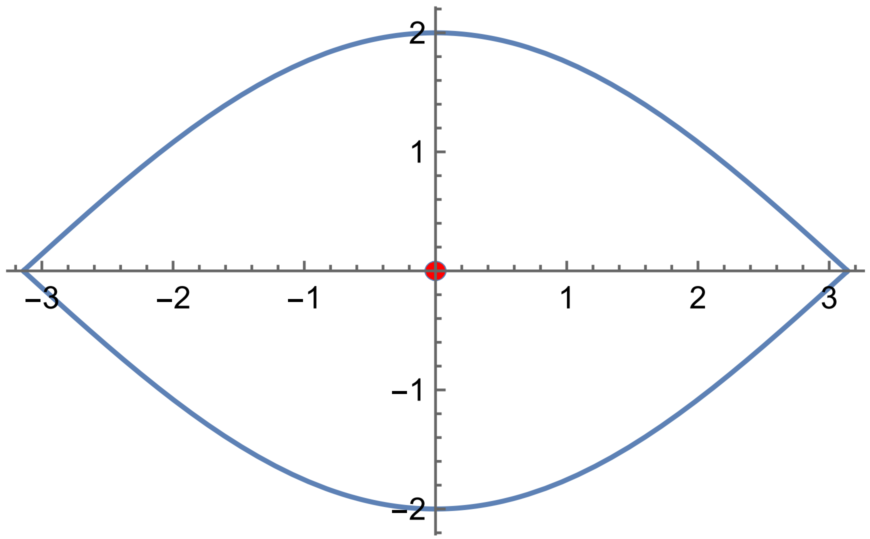


- ➢ RF voltage modulated to excite quadrupole oscillations.
- ➢ Additional harmonics to linearise rotation.
  - ➢ Smaller synchrotron frequency spread → less tails.
  - ➢ Greater bunch compression.

Creating short proton bunches by resonant quadrupole excitation - F. Willeke

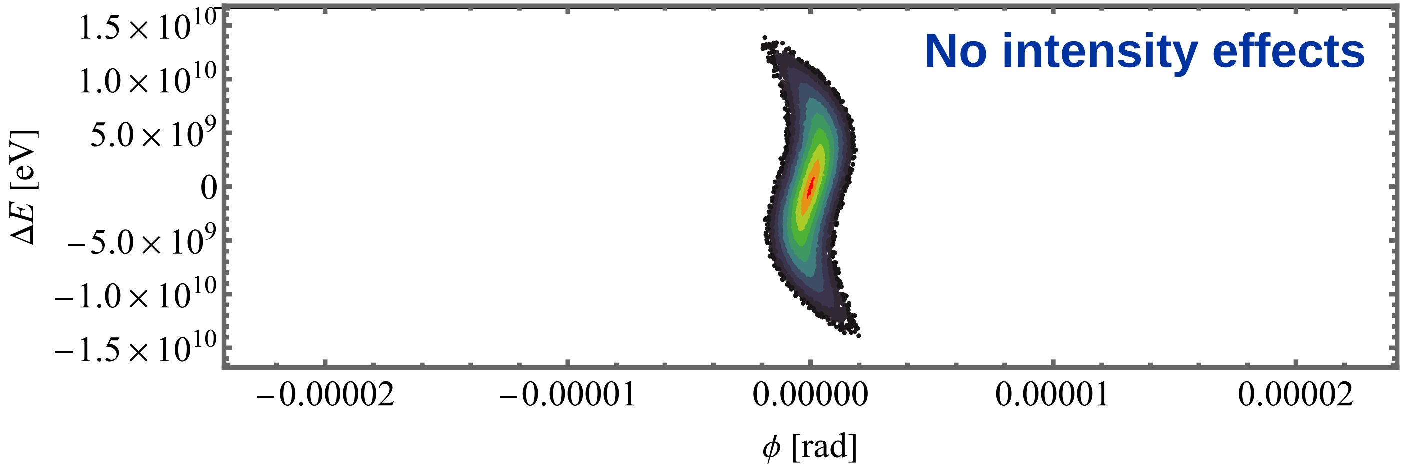
Toy model with RHIC/ EiC parameters

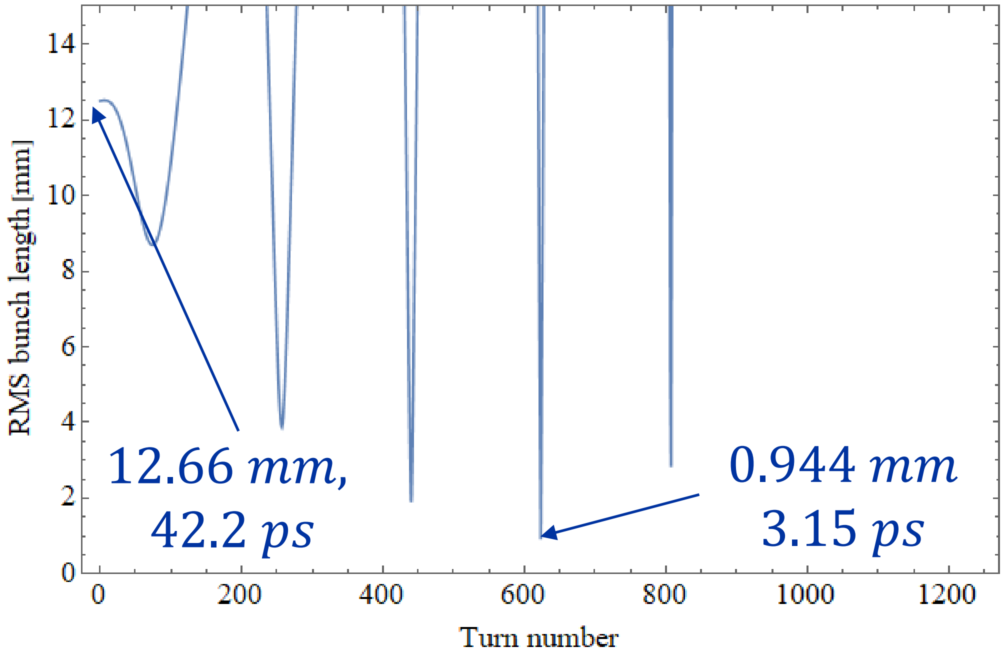
Beam Energy	$E = 600\ GeV$
Circumference	$C = 3887\ m$
Number of ppb	$\boldsymbol{N_p = 10^{11}}$
Revolution frequency	$f_{rev} = 7.713 \times 10^4\ \mathrm{Hz}$
Energy spread	$\delta_p = 0.001$
Bunch length (initial)	$\boldsymbol{\sigma_b = 12.685\ mm\ (42.3\ ps)}$
Momentum compaction	$\alpha_{mc} = 0.5 \times 10^{-4}$
RF voltage	$\boldsymbol{U_{RF} = 254\ MV}$ $\boldsymbol{(U_{Max} = 900\ MV)}$
RF frequency	$f_{RF} = 200\ \mathrm{MHz}$
RF harmonic	$h = 2593$



Initial bunch size in bucket

Creating short proton bunches by resonant quadrupole excitation - F. Willeke

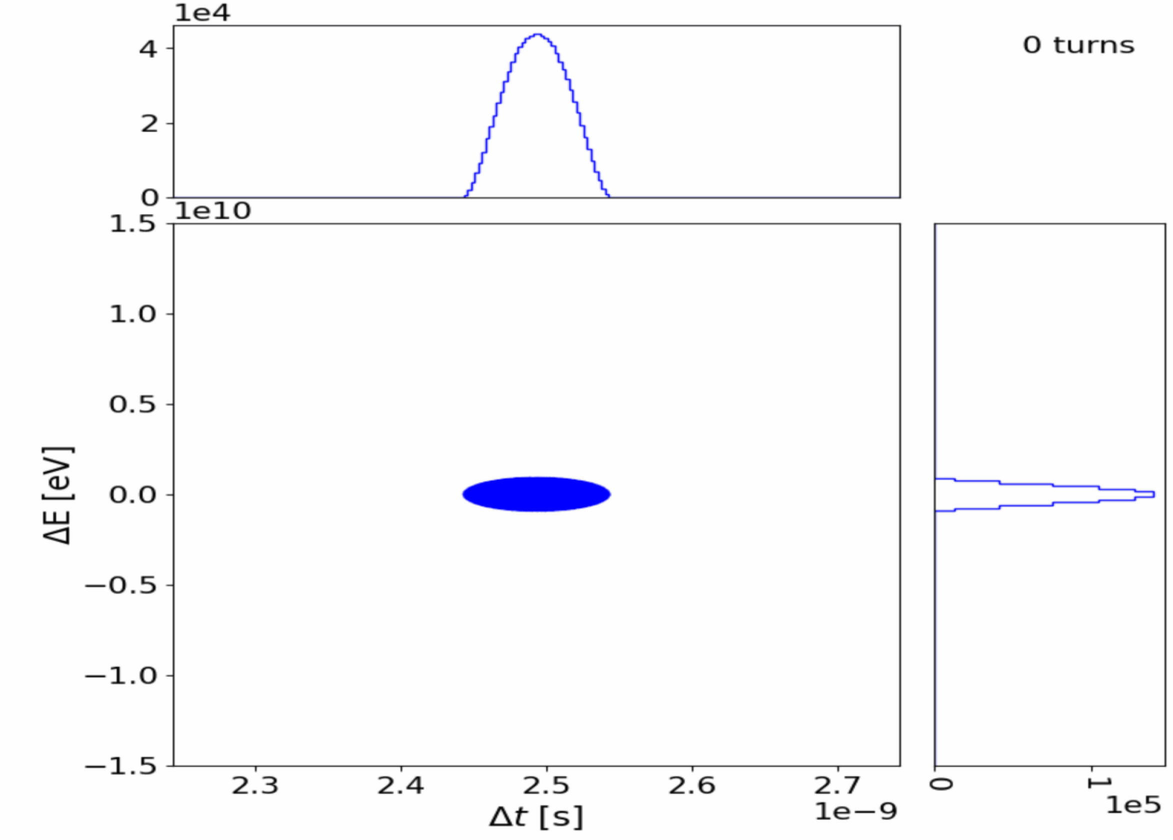


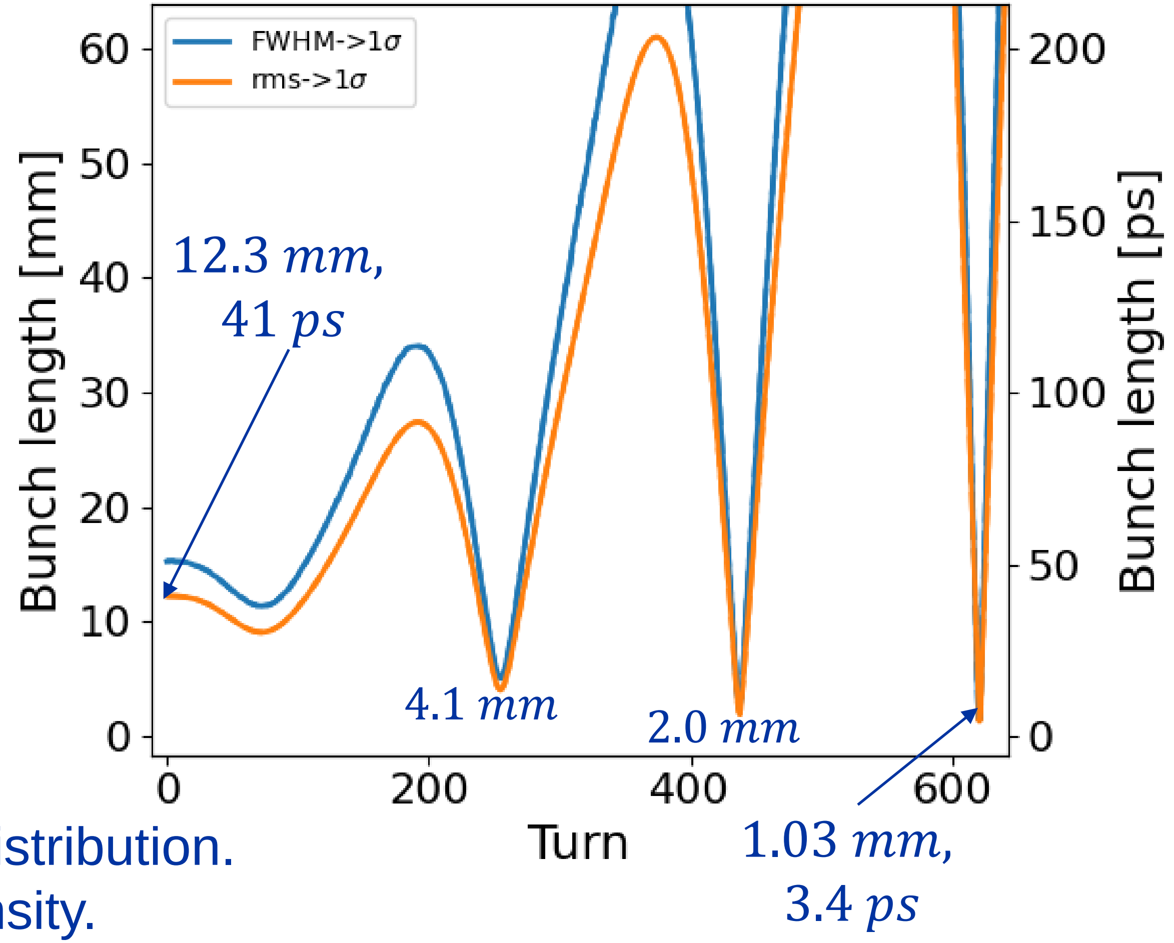


- Possible to get short bunches (excluding intensity effects).
- May require extreme RF parameters:
  - Large voltage (900 MV) + modulation.
  - Higher harmonics – linearization.
  - Low momentum compaction factor ($\alpha_{mc} = 0.5 \times 10^{-4}$).
- Benchmarked in Mathematica.

Compression factor of 13.4

Quadrupole pumping RHIC/ EiC BLonD model - No intensity effects





- Recreated simulation in BLonD.
- Compression factor of 11.9 – difference due to distribution.
- Two tracking tools essentially agree at zero intensity.

Adding Intensity Effects to RHIC/ EiC model

Disclaimer

- **Very preliminary study (~2 weeks).**
- **Needs further investigation and benchmarking.**
  - Bunch stability over longer time periods (~10k turns), acceleration etc.

Assumptions

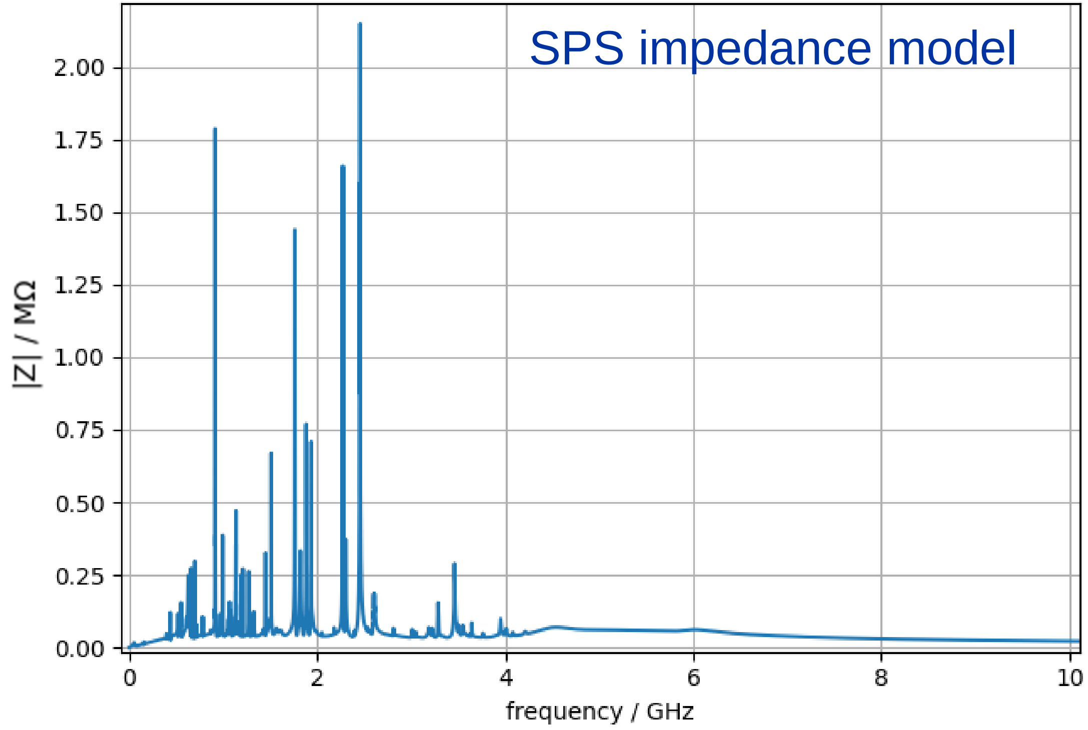
- **Single bunch.**
- **Assuming a similar impedance model to SPS.**
- **Not including impedance of higher harmonics RF systems (used for linearisation).**
- **Neglecting multi-turn wakes, IBS, e-cloud etc.**

Overestimating Impedance

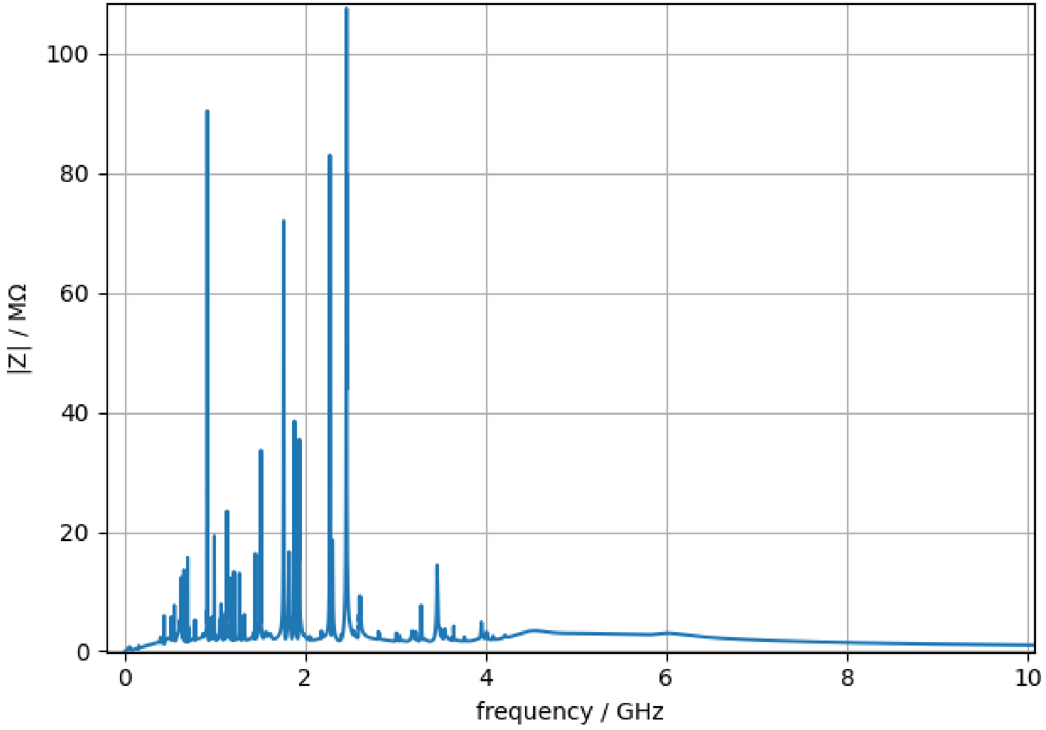
SPS peak voltage: 15 MV

~ × 50

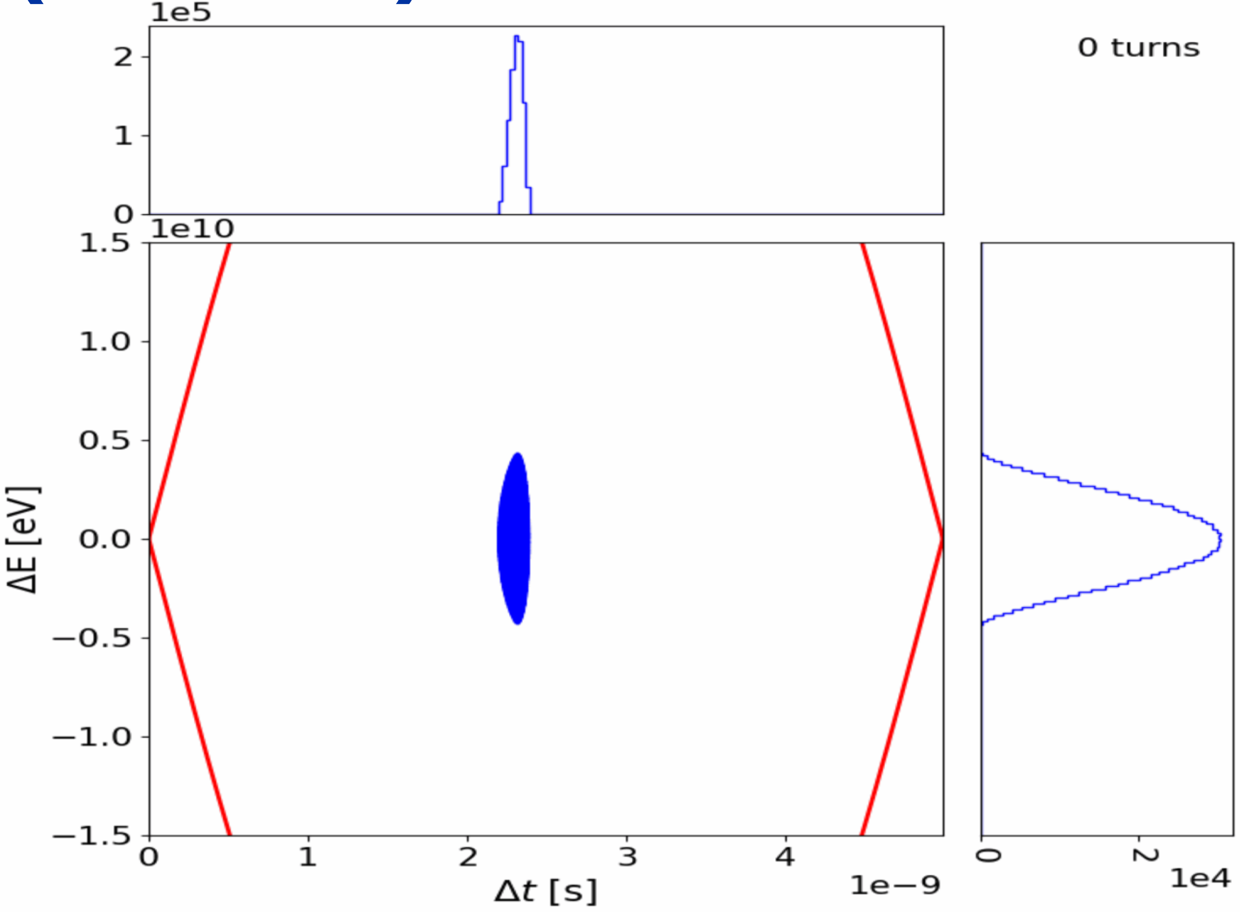
EiC peak voltage: ~800 MV

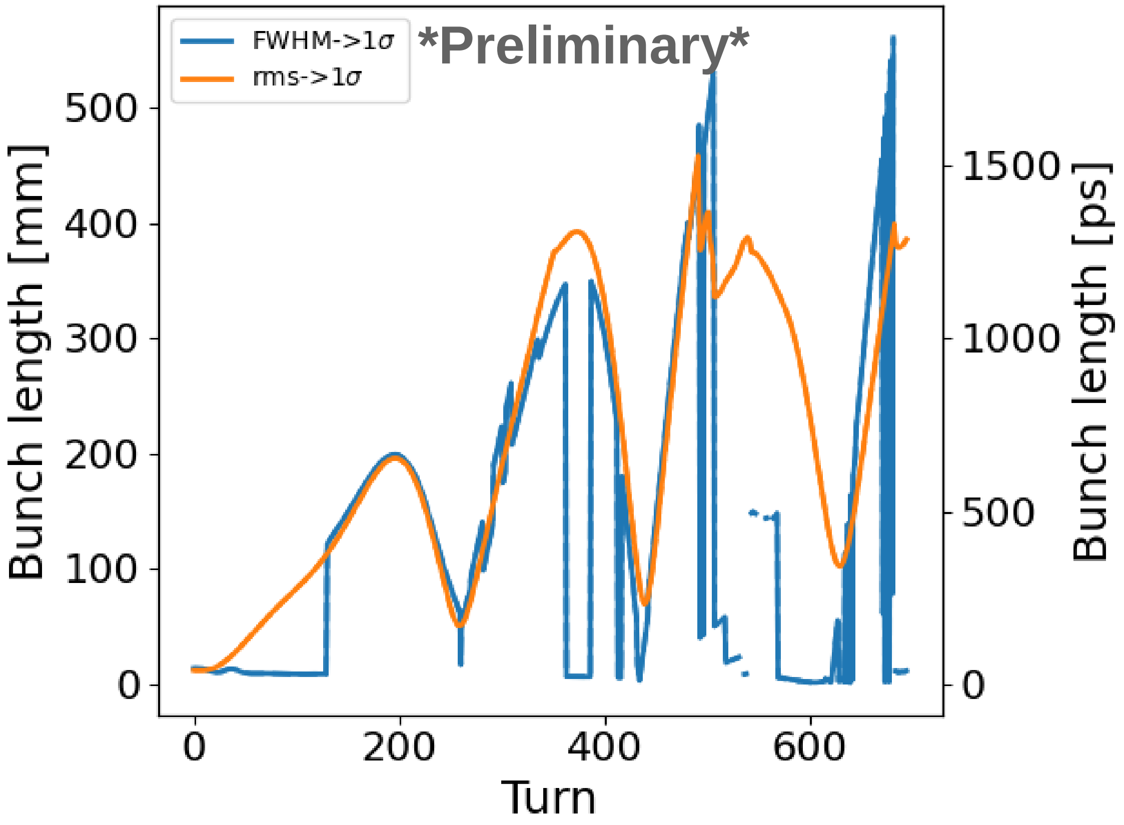


× 50



Quadrupole pumping RHIC/EiC + Impedance (SPSx50)





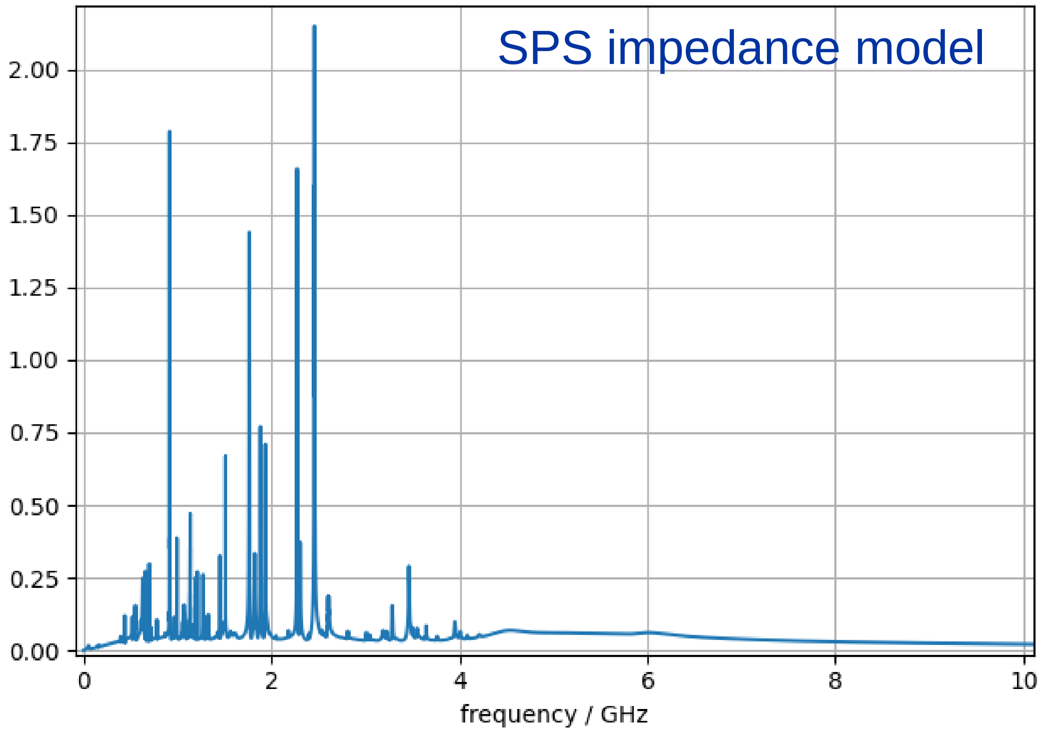
➢ Bunch unstable due to collective effects.

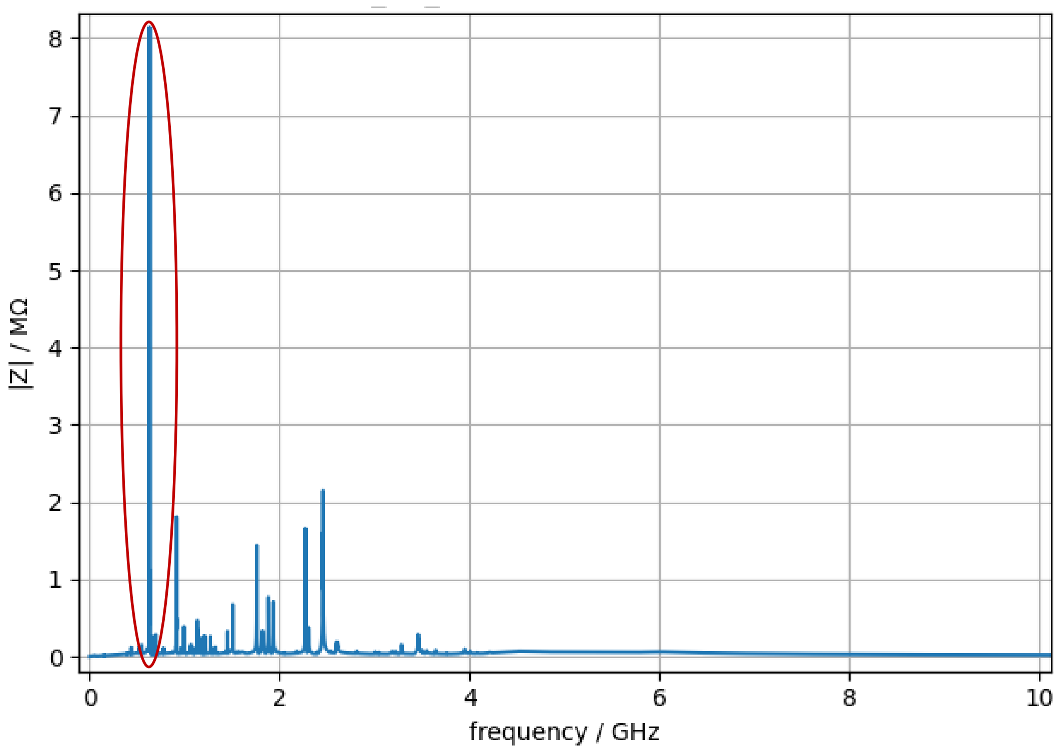
Scaling 200 MHz cavity impedance

SPS peak voltage: 15 MV

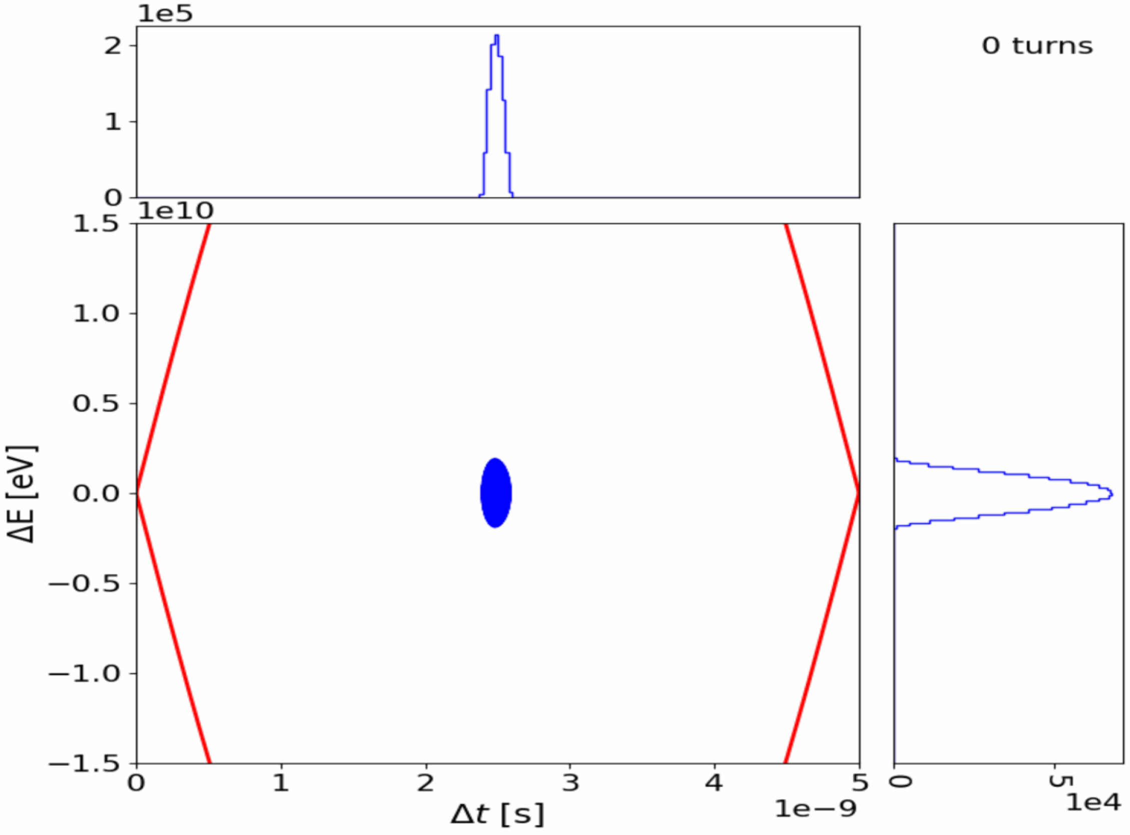
~ × 50

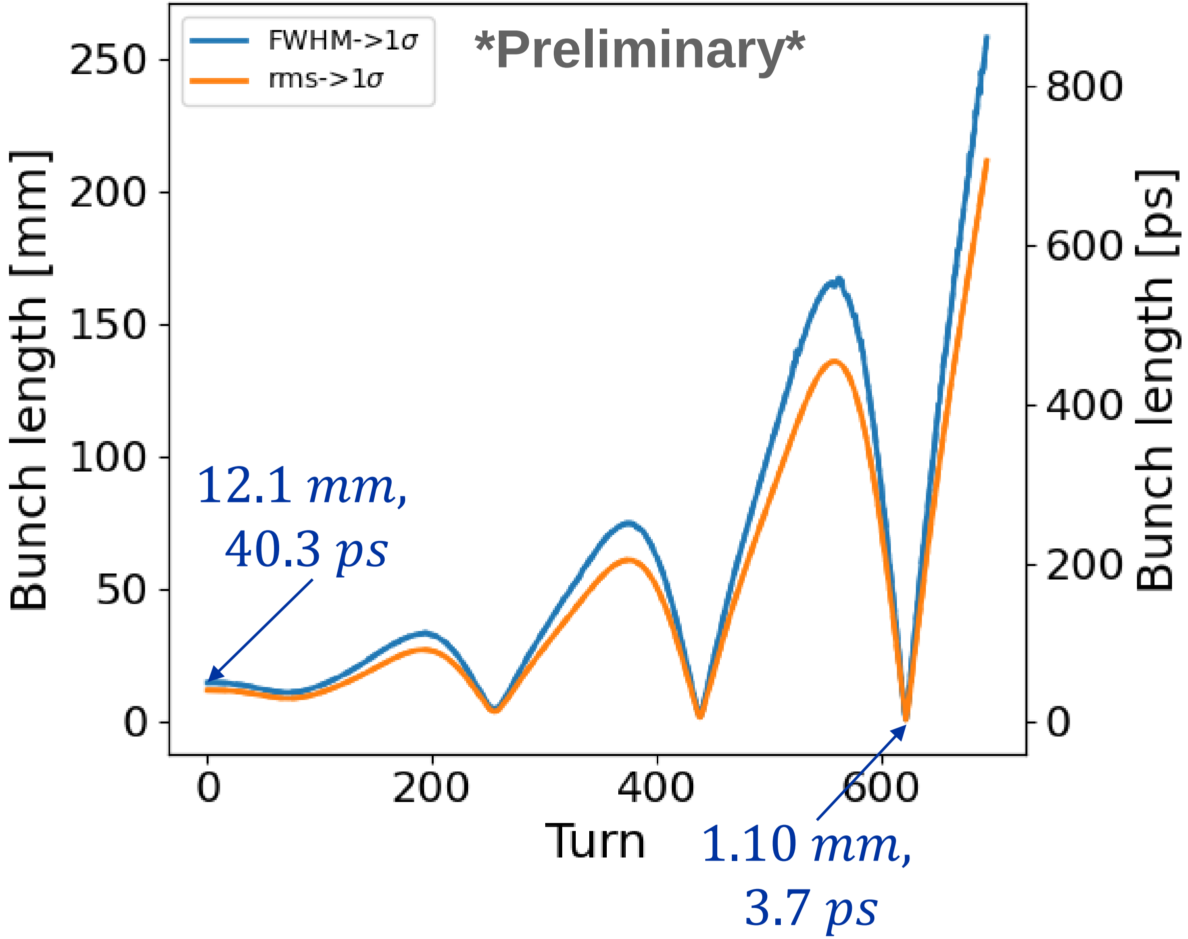
EiC peak voltage: ~800 MV





Quadrupole pumping RHIC/EiC + Impedance (200MHz x50)



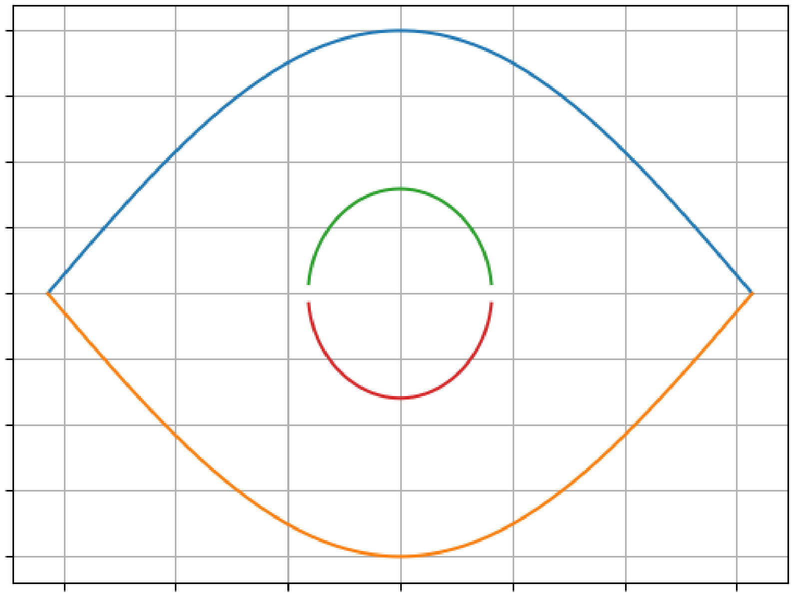


- ➢ **Interestingly, bunch seems stable.**
- ➢ **Compression factor of 11.0.**

SPS quadrupole pumping model

Toy model in SPS

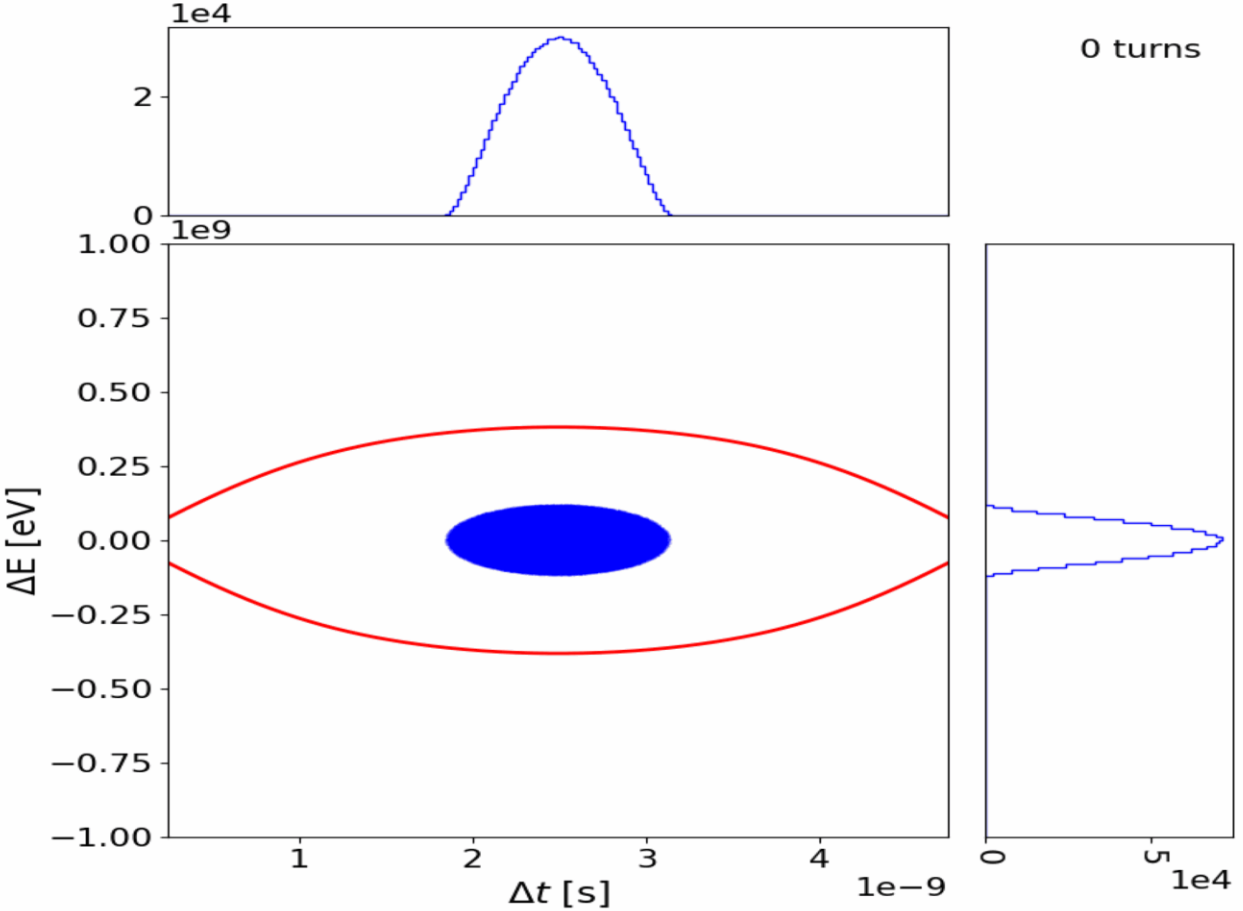
Beam Energy	$E = 400\ GeV$
Circumference	$C = 6911.5\ m$
Number of ppb	$N_p = 3 \times 10^{11}$
Revolution frequency	$f_{rev} = 43.4\ \mathrm{kHz}$
Energy spread	$\delta_p = 0.0009$
Bunch length (4σ)	$\tau_b = 1.3\ ns$
RF voltage	$U_{RF} = 15\ MV$
RF frequency	$f_{RF} = 200\ \mathrm{MHz}$
RF harmonic	$h = 4620$



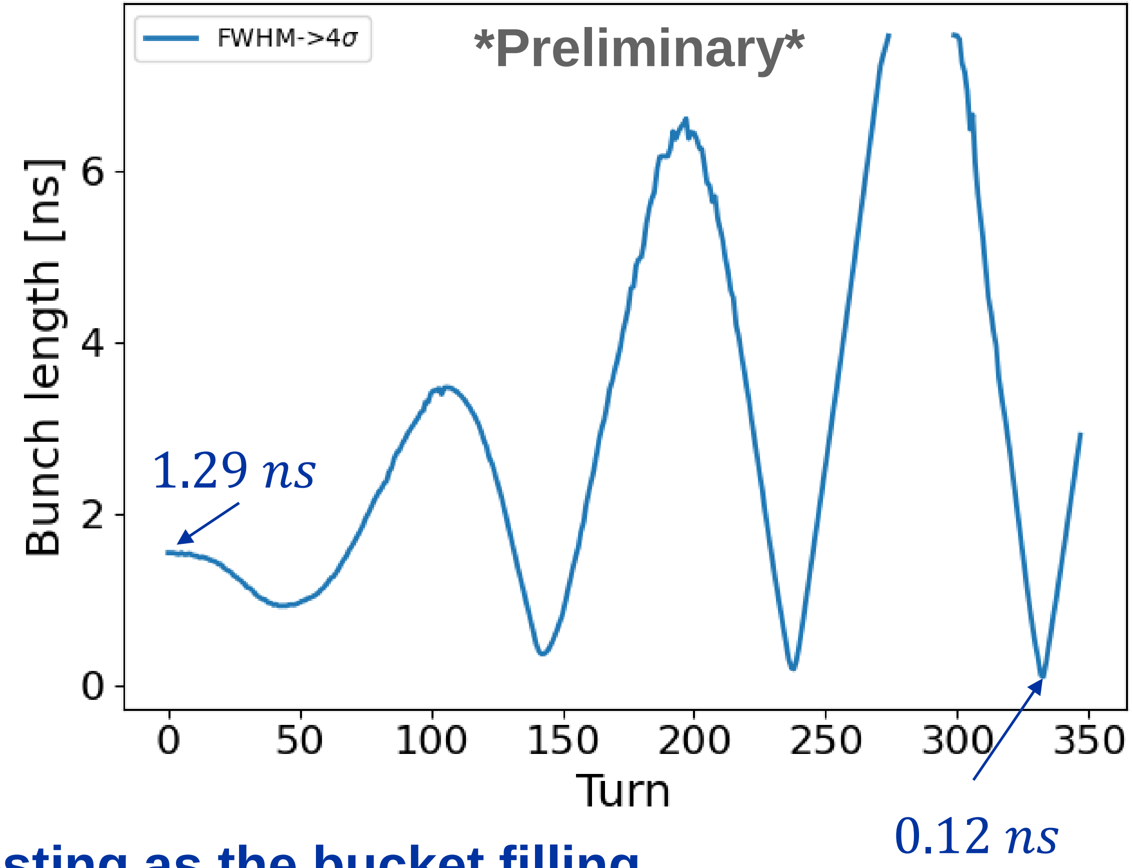
Initial bunch size in bucket

SPS – No intensity effects (linearised)

*Additional 400 MHz & 600 MHz system added for linearization



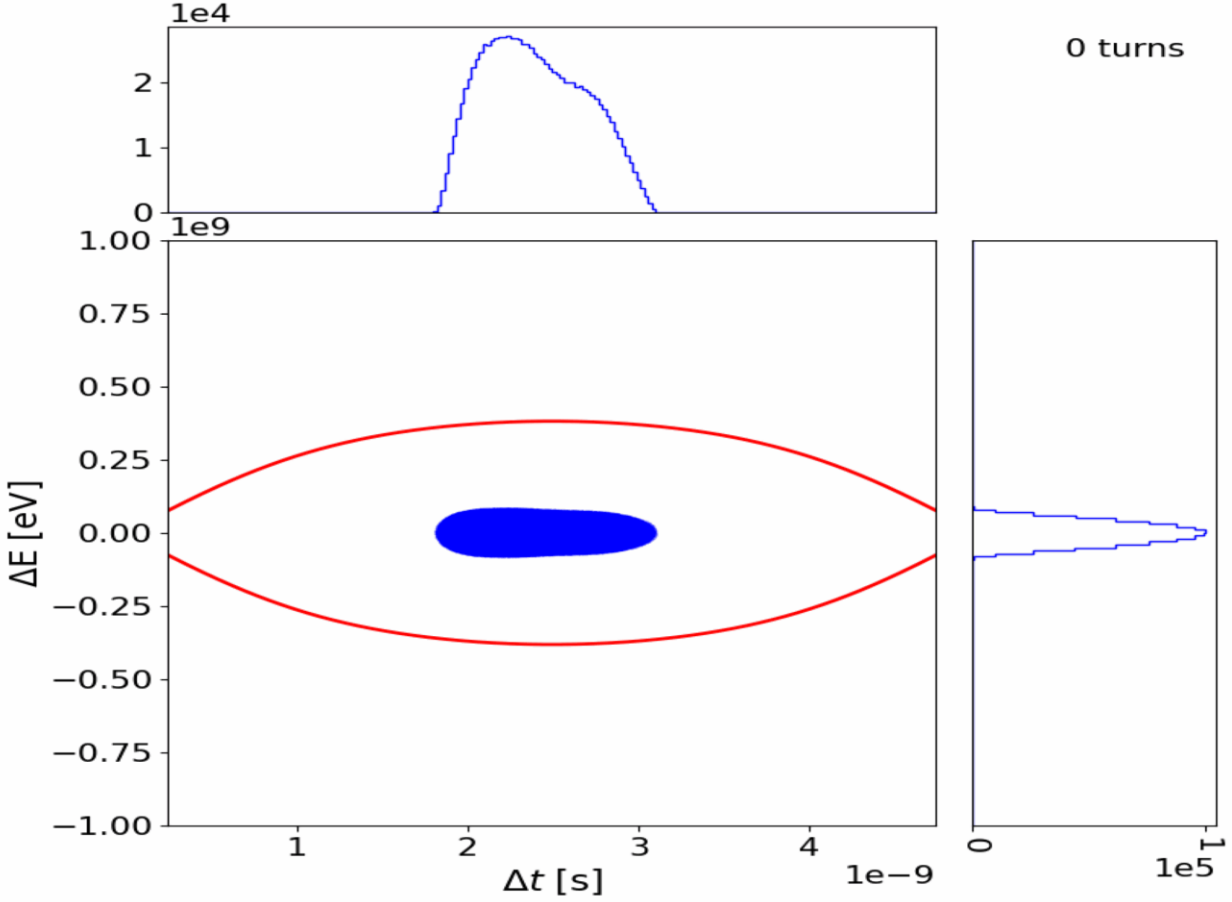
Current compression factor for AWAKE ~ 2.6

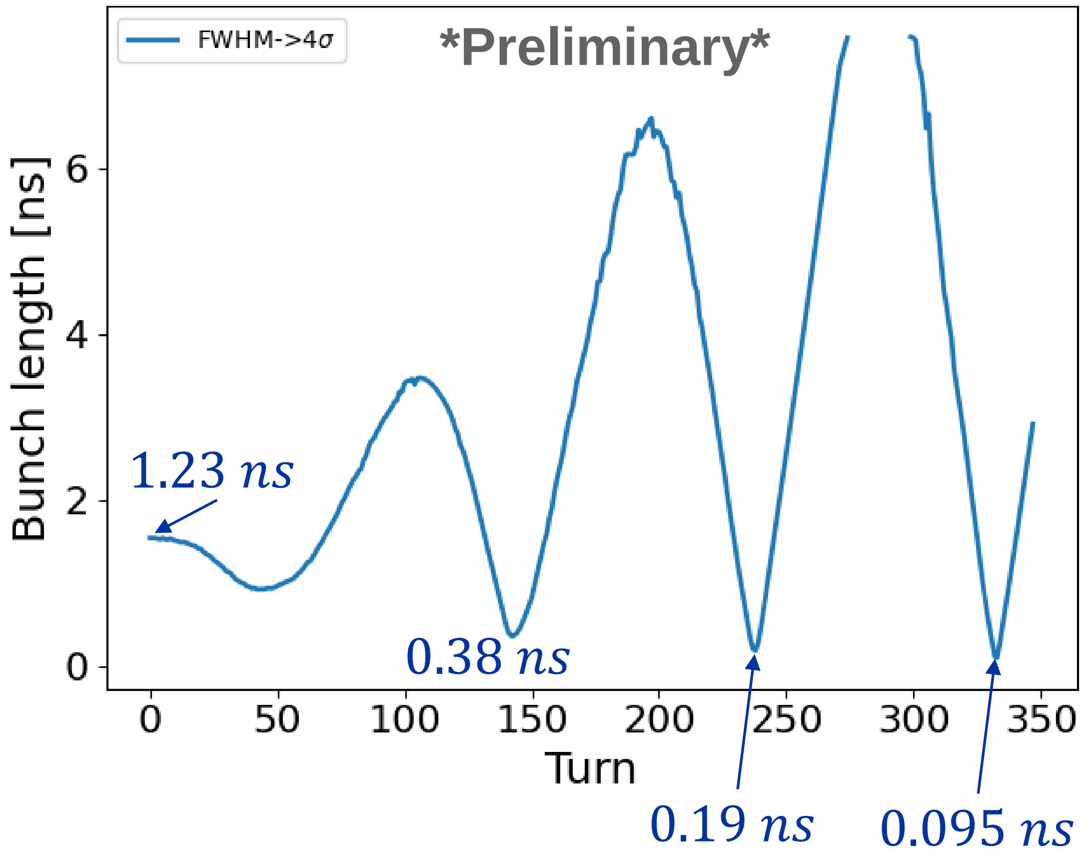


Compression factor of 10.4 → Interesting as the bucket filling factor is much bigger than before.

SPS + Impedance (linearised)

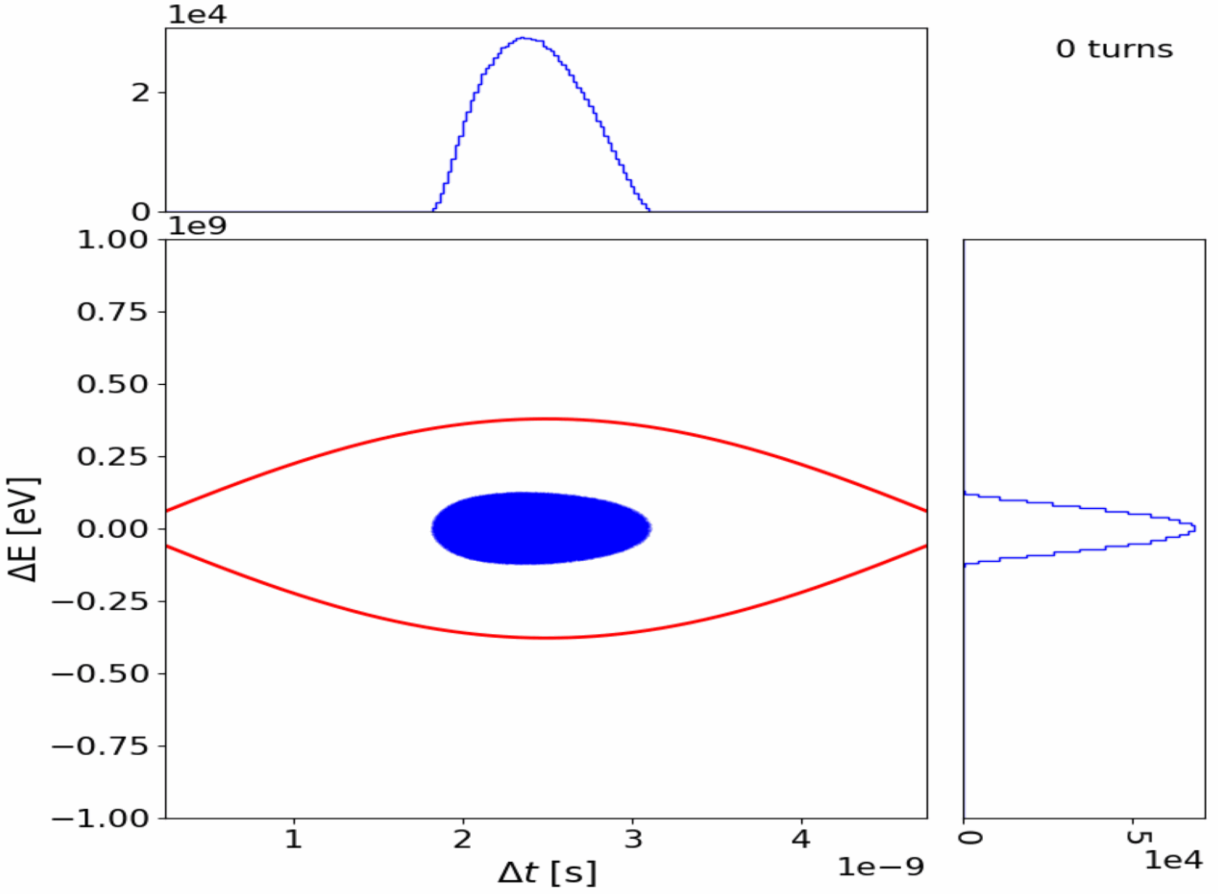
*Additional 400 MHz & 600 MHz system
added for linearization



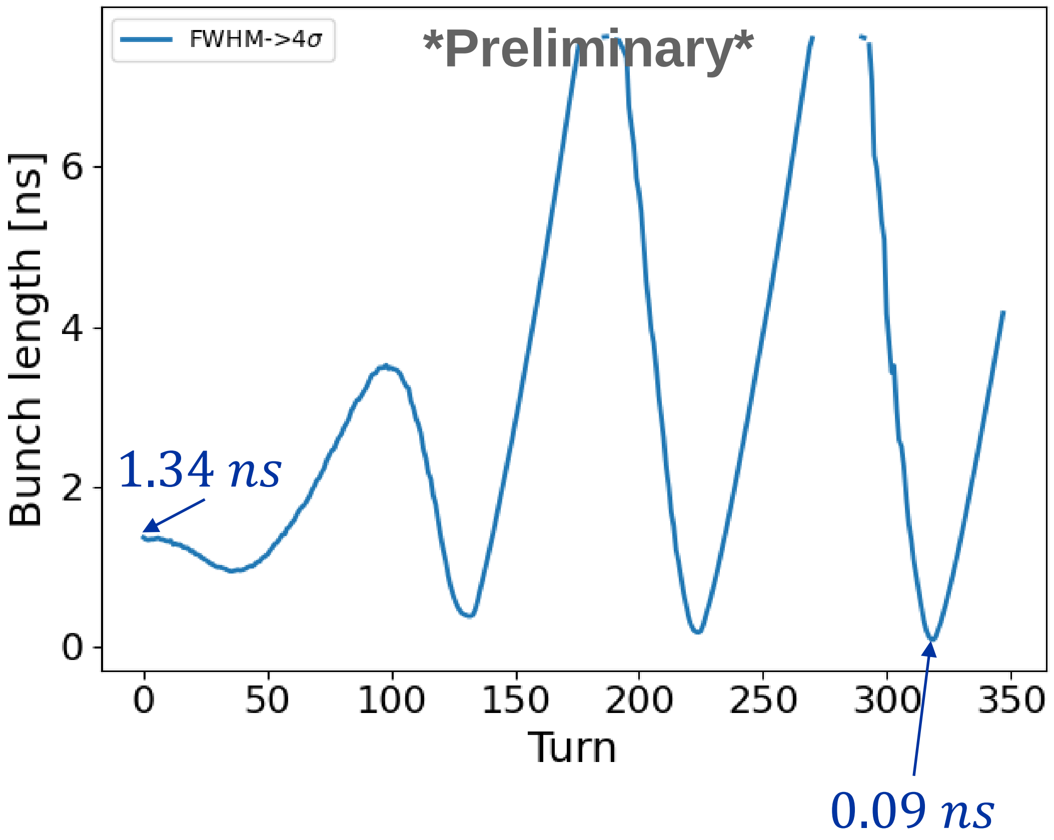


Compression factor of 12.9*.

SPS + Impedance (non-linearised)



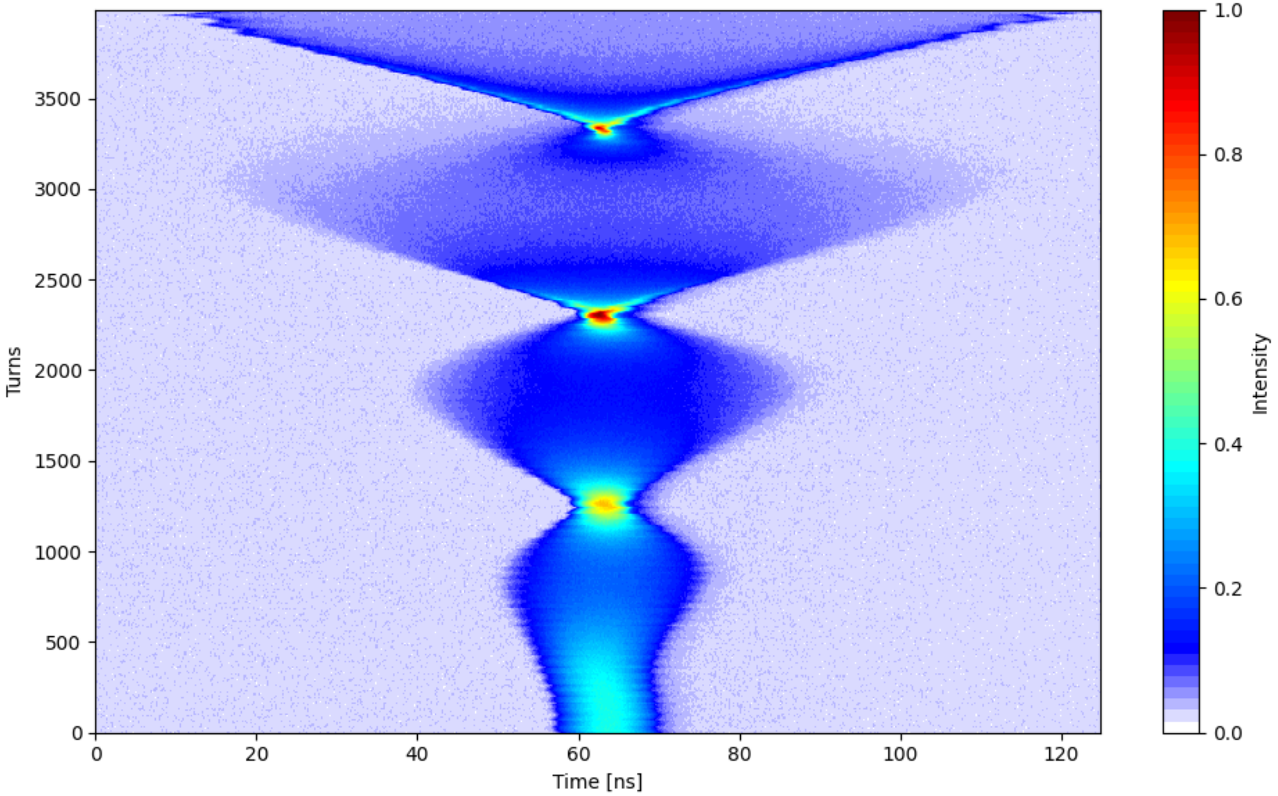
*Better definition of bunch length needed for analysis.

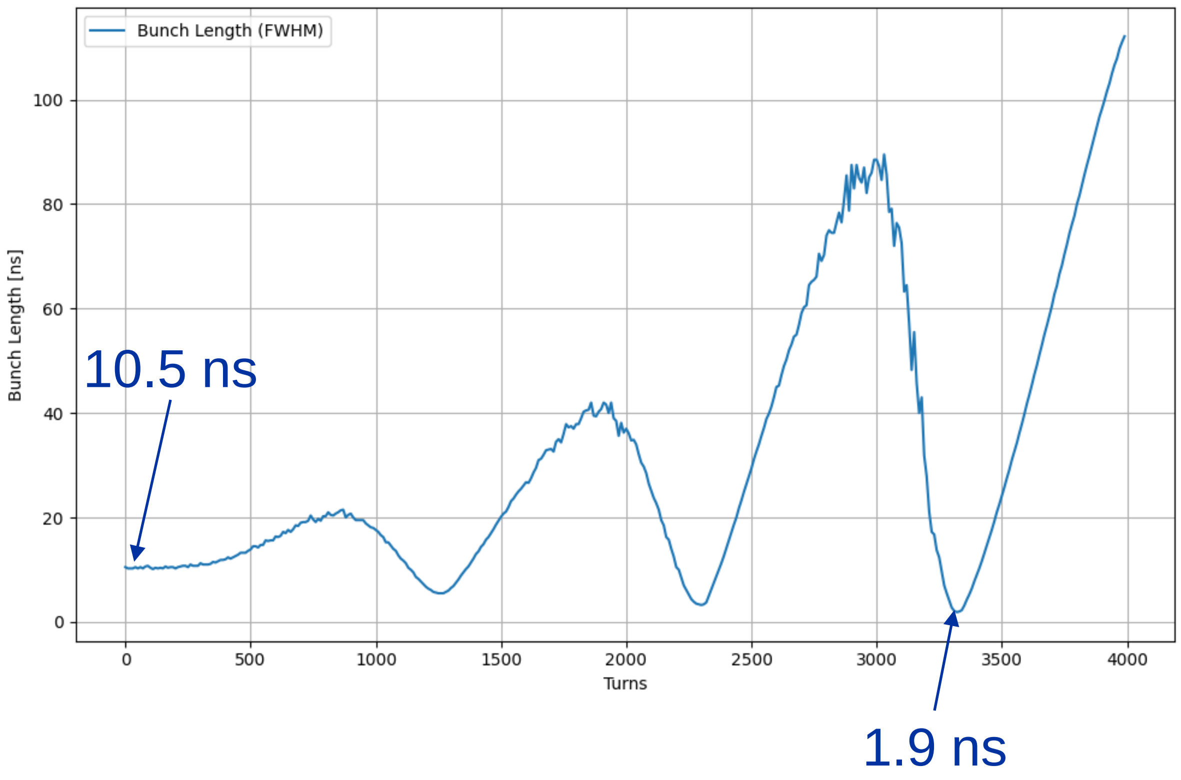


Compression factor of 14.9* → more populated tails.

Quadrupole pumping measurements in the PS

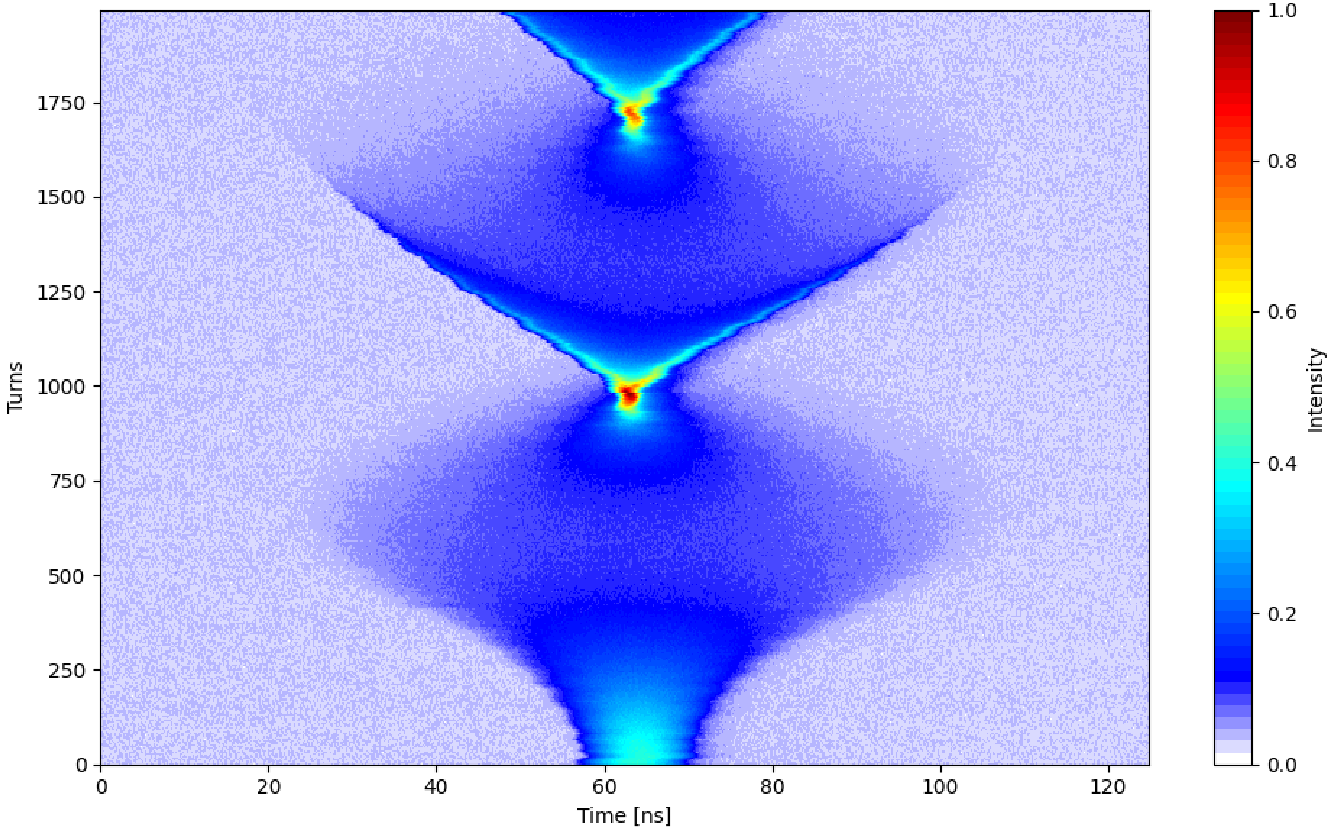
- Initial proof-of-principle tests were done with beam in the PS.
- Single bunch, moderate intensity, no RF linearisation.

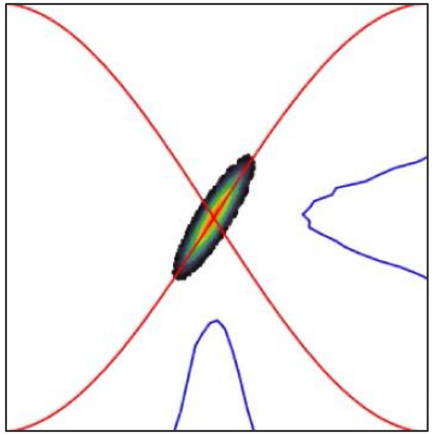


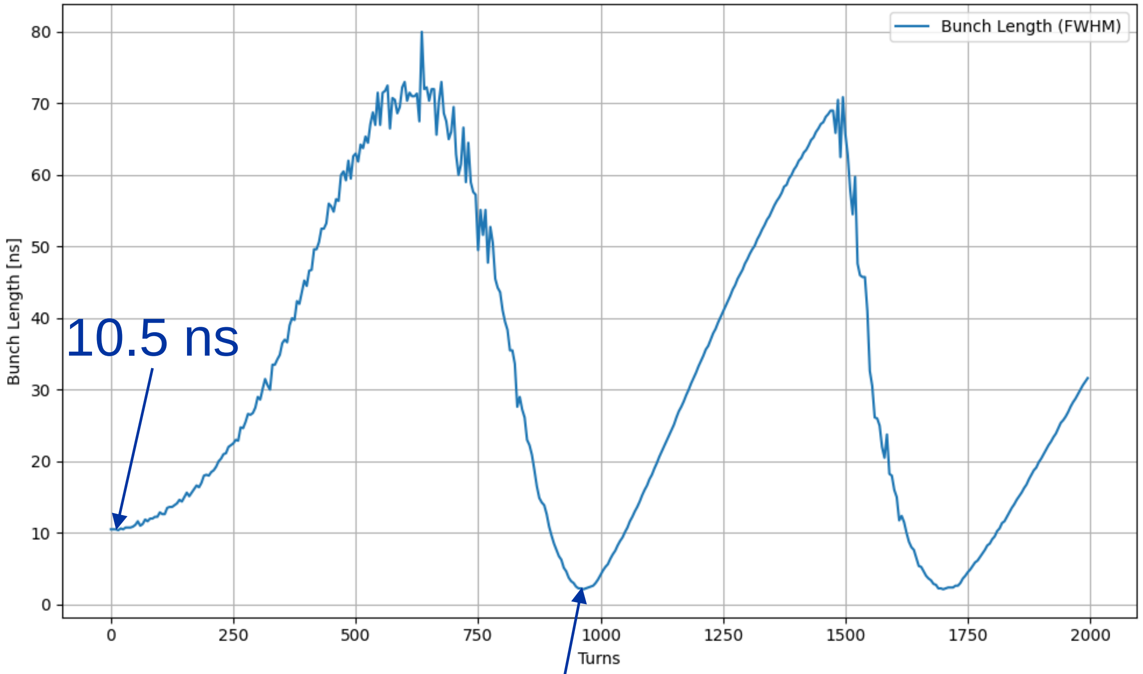


➢ **Compression factor of 5.5.**

Comparison to conventional phase-jump bunch rotation







- ➢ **Compression factor of 5.**

Summary

- **Linearised quadrupole pumping is an interesting scheme for creating short bunches in theory.**
- **However, extreme RF parameters may be needed:**
  - Large voltage (900 MV) + modulation.
  - Higher harmonics for linearization.
  - Low momentum compaction factor ($\alpha_{mc} = 0.5 \times 10^{-4}$).
- **Intensity effects play a crucial role in determining how short we can make bunches.**
- **Initial simulations show quadrupole pumping could be used in SPS for AWAKE bunches.**

Future Work

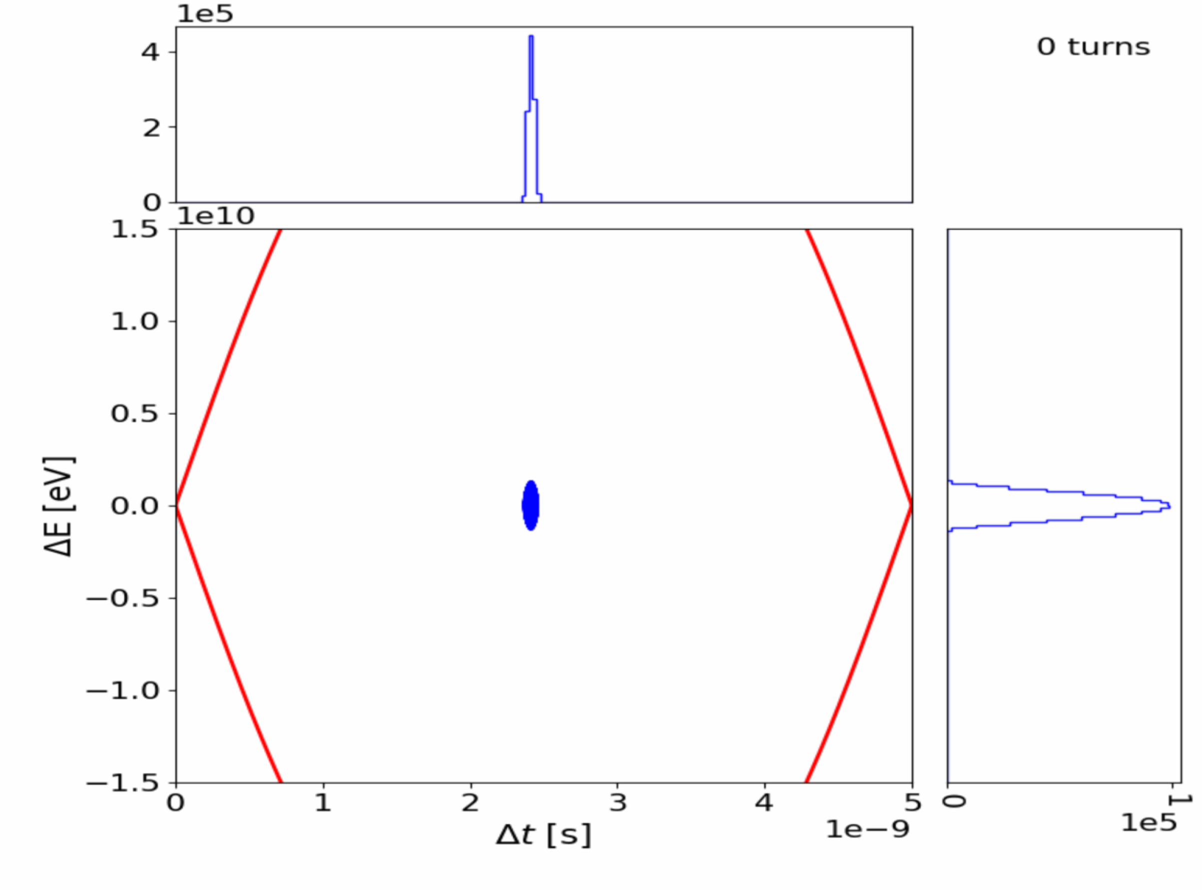
Lots of further work to be done…

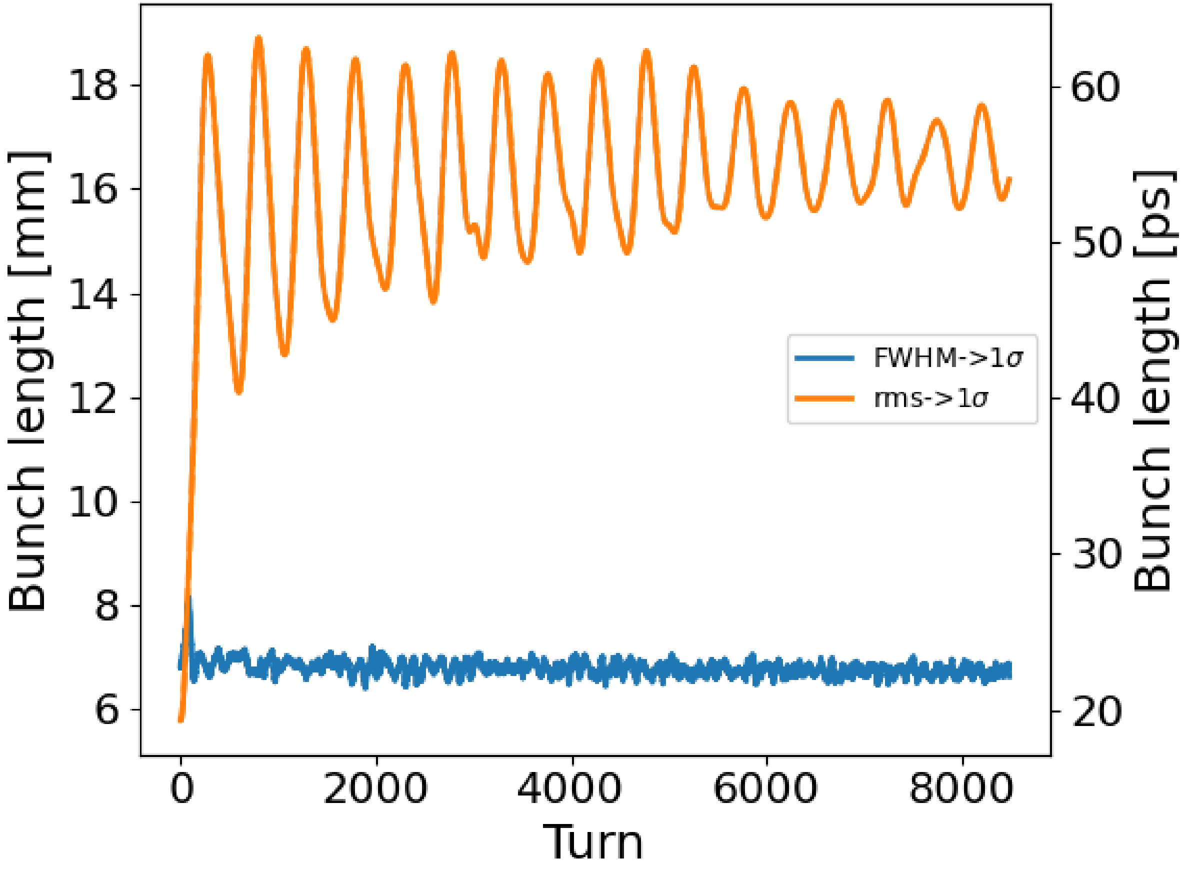
- **Further benchmarking and studies.**
- **Thorough study of the stability of the initial bunch with intensity effects.**
- **Additional intensity effects (multi-turn wake, IBS, e-cloud etc.).**
  - Transverse collective effects.
- **Delivery of small longitudinal emittance bunches from injector chain.**

Back up slides

Increasing intensity, halving bunch length

$$\sigma_b = 6\,mm, N_p = 3 \times 10^{11}$$

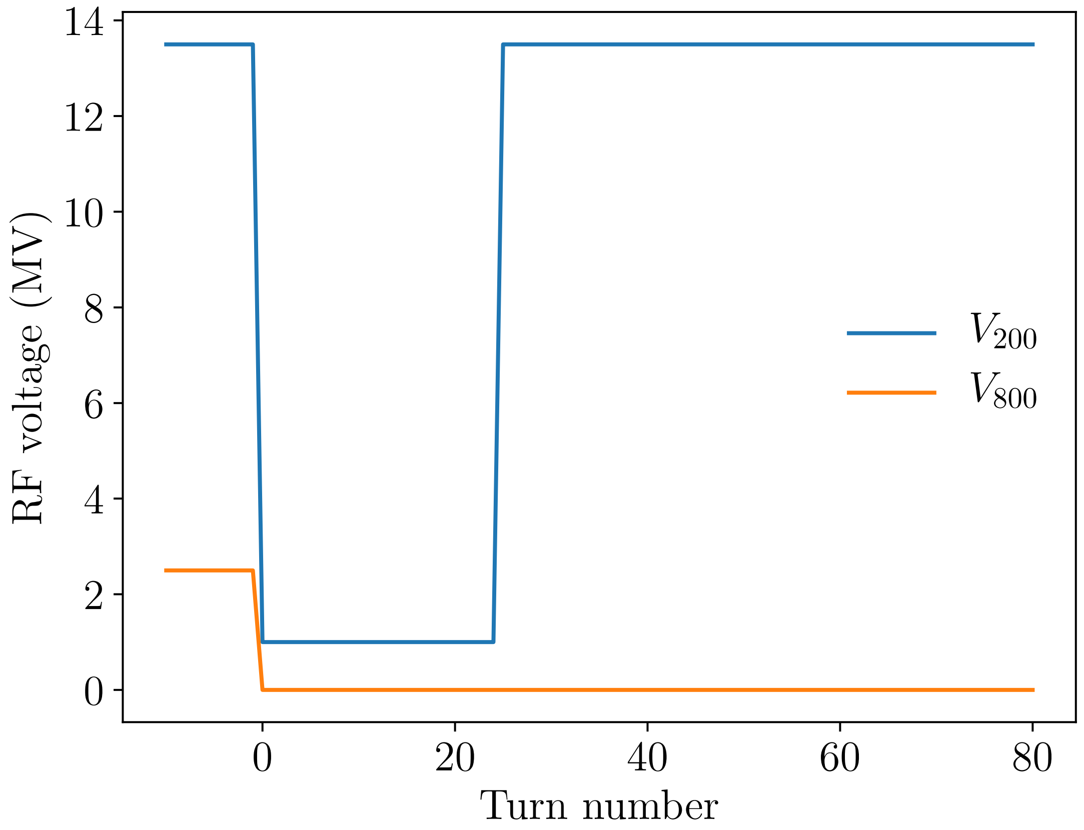




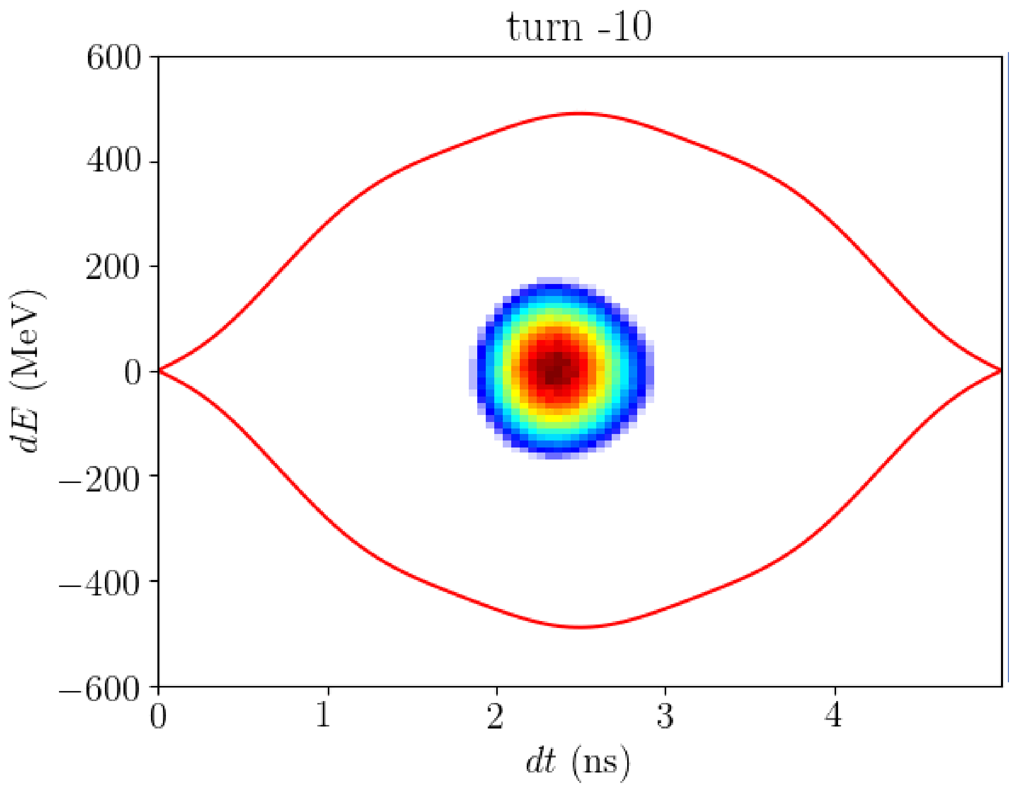
- ➢ Bunch unstable due to collective effects.

Bunch rotation using double jump scheme*

Voltage programs



BLonD simulations of bunch rotation



→ High V_{200} and V_{800} before jumps and short reproducible time with low RF voltages guarantee beam stability
→ This option requires modification 800 MHz LLRF system (synchronized RF OFF with extraction timing)