Which vacuum pressure is acceptable in the booster?

L. Mether, F. Sommerfelt Grønvold

Acknowledgements:
G. Rumolo, F. Zimmermann

FCCIS 2023 WP2 workshop
Rome, Italy
13-15 November 2023

Which vacuum pressure is acceptable in the booster?

Vacuum constraints from ion trapping and instability

L. Mether, F. Sommerfelt Grønvold

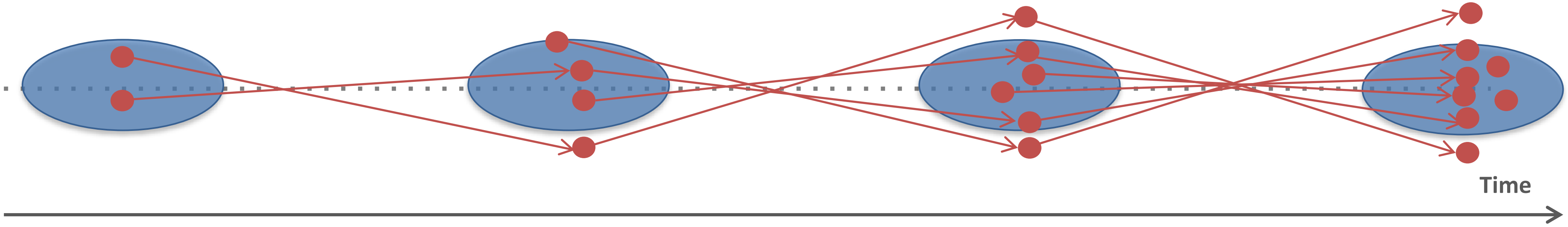
Acknowledgements:
G. Rumolo, F. Zimmermann

FCCIS 2023 WP2 workshop
Rome, Italy
13-15 November 2023

Ion trapping in electron machines

Beam-induced gas ionization gives rise to electrons and ions along the beam path

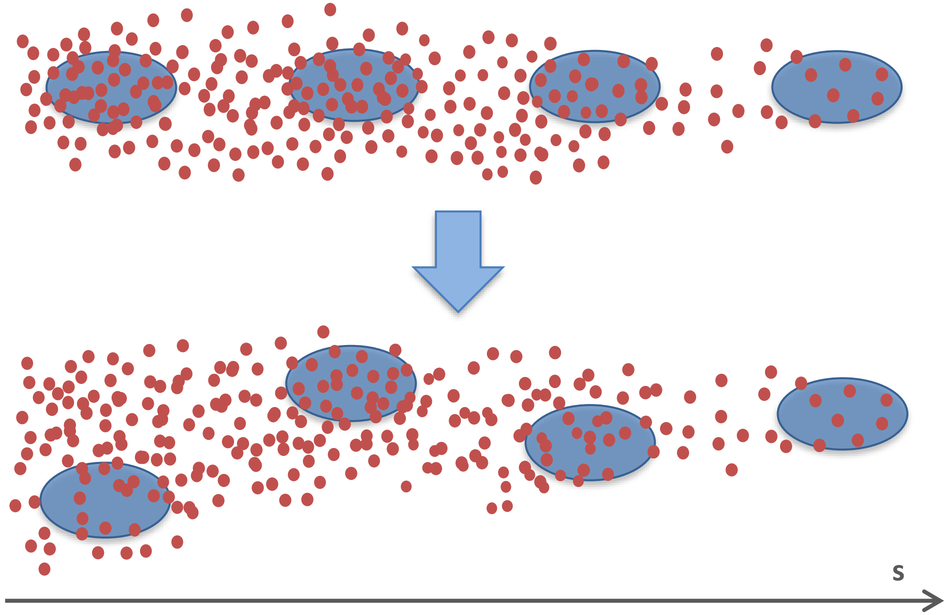
- The positive ions are attracted by the electron beam field and may be trapped in oscillation along the bunch train



- Trapped ions accumulate over the passage of a bunch train and can lead to a fast beam-ion instability (FBII)

  - Due to their large mass, the trapped ions barely move during the passage of a single bunch
  - However, they transfer information on the offset of one bunch to the next, seeding a coupled-bunch instability

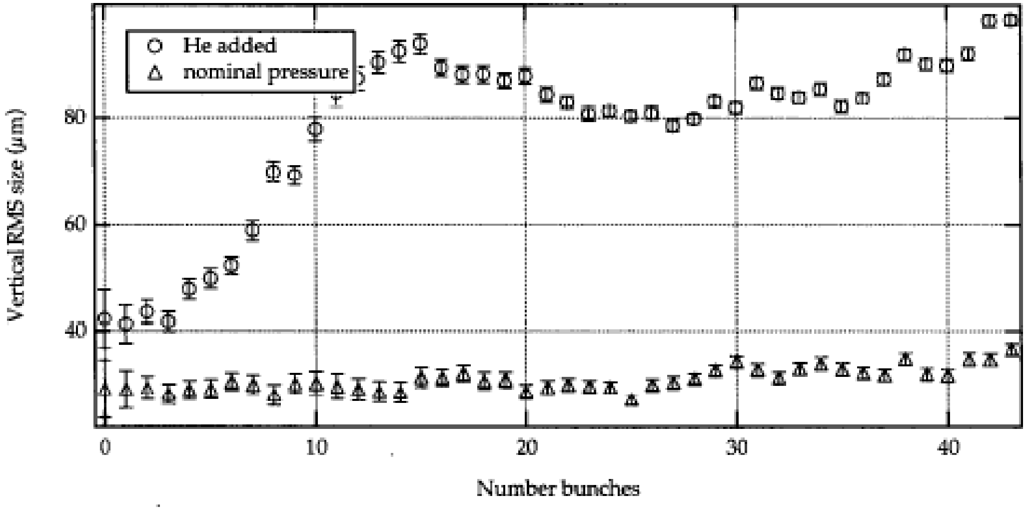
  - Ion trapping also gives rise e.g. to emittance growth and tune shifts



Machine observations

- Fast beam-ion instabilities have been observed since the 90’s in several machines
  - ALS
  - PLS
  - BESSY II
  - ELETTRA
  - ALBA
  - SOLEIL
  - Cesr-TA

Measurement at ALS



J. Byrd, A. Chao, S. Heifets, et al. Phys. Rev. Lett. 79 (1997), 79-82

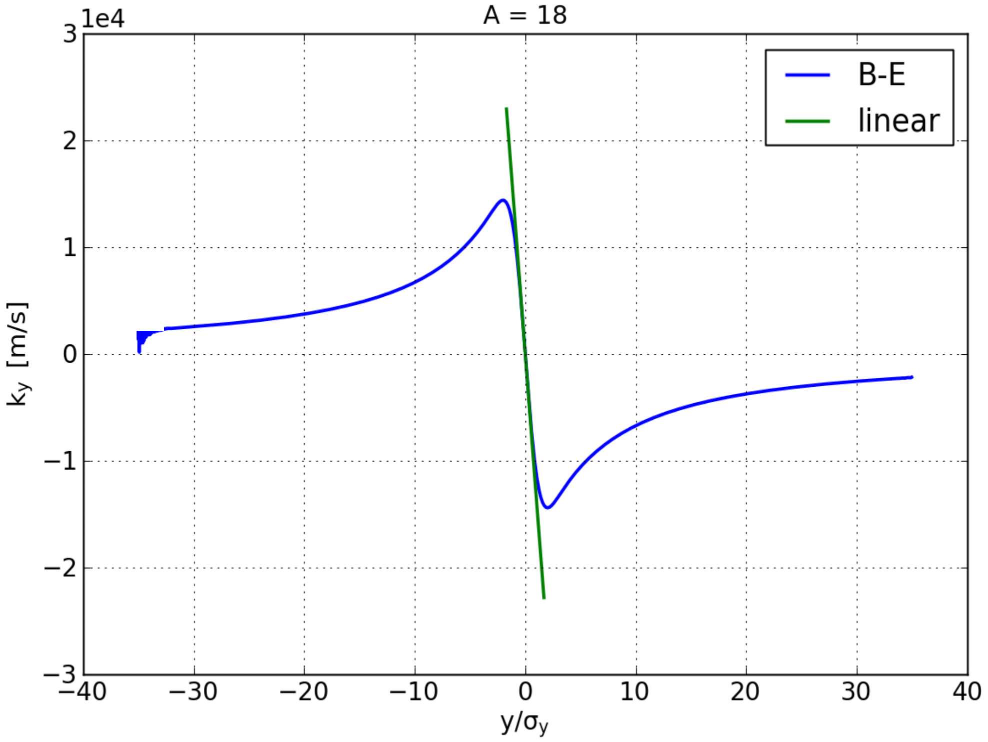
- In most cases the instability has been observed only in the presence of vacuum degradation
  - During commissioning
  - Due to a local pressure rise, e.g. due to impedance-induced heating
  - During experiments with additional injected gas

Analytical model: Ion trapping

Ion trapping can be modelled using the linear approximation of the Bassetti-Erskine formula for a Gaussian beam field

- An ion with mass number *A*, receives a velocity kick by the beam

$$\frac{2N_b r_p c}{A}\frac{x,y}{(\sigma_x+\sigma_y)\sigma_{x,y}} = k_{x,y} * x, y$$



N_b = bunch intensity
r_p = classical proton radius
$\sigma_{x,y}$ = transverse beam size

Raubenheimer et al., Phys. Rev. E 52, 5, 5487,
Stupakov et al., Phys. Rev. E 52, 5, 5499

Analytical model: Ion trapping

Ion trapping can be modelled using the linear approximation of the Bassetti-Erskine formula for a Gaussian beam field

- An ion with mass number *A*, receives a velocity kick by the beam

$$\frac{2N_b r_p c}{A}\frac{x,y}{(\sigma_x+\sigma_y)\sigma_{x,y}} = k_{x,y} * x, y$$

- During the bunch spacing T_b , the ions drift
  - The kick – drift – kick – drift… motion is stable if $k_{x,y}T_b < 4$
    → Trapping condition for the ion mass number

$$A > A_{\text{trap}} = \frac{N_b r_p T_b c}{2\left(\sigma_x+\sigma_y\right)\sigma_{x,y}}$$

- The instability rise time can also be estimated
  - Opposite dependence on bunch spacing, beam size and intensity w.r.t the trapping condition
  - Faster instability for large pressure, small mass (if trapped) and long trains

$$\tau_{\text{inst}}^2 \propto \frac{\gamma^2 A\omega_\beta}{n_b^4 N_b^3 P^2 T_b c}\left(\sigma_x+\sigma_y\right)^3 \sigma_{x,y}^3$$

N_b = bunch intensity
r_p = classical proton radius
$\sigma_{x,y}$ = transverse beam size

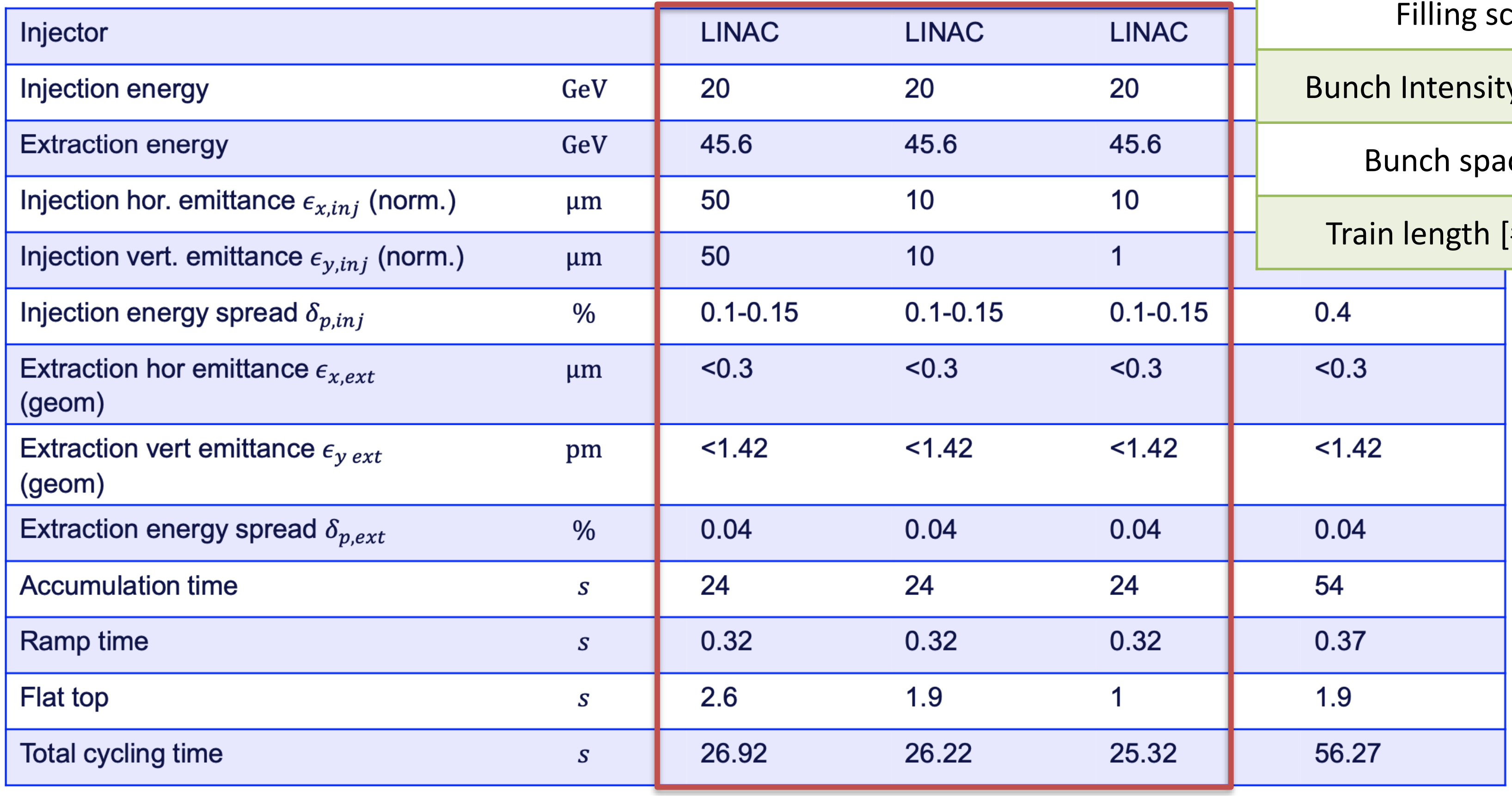
n_b = nr of bunches
P = pressure
ω_β = betatron frequency

Raubenheimer et al., Phys. Rev. E 52, 5, 5487,
Stupakov et al., Phys. Rev. E 52, 5, 5499

Ion trapping in the booster

- Since ion trapping is more likely for small bunch spacing, it is of concern mainly for *Z* mode operation
  - We consider the booster parameters as presented at the FCC Week 2023 by A. Chance
    - Assuming the “standard” booster optics and LINAC as injector
  - For the filling scheme, we assume ”case 4” from the MTR, with 10% of the collider bunch intensity

A. Chance et al, FCC Week 2023



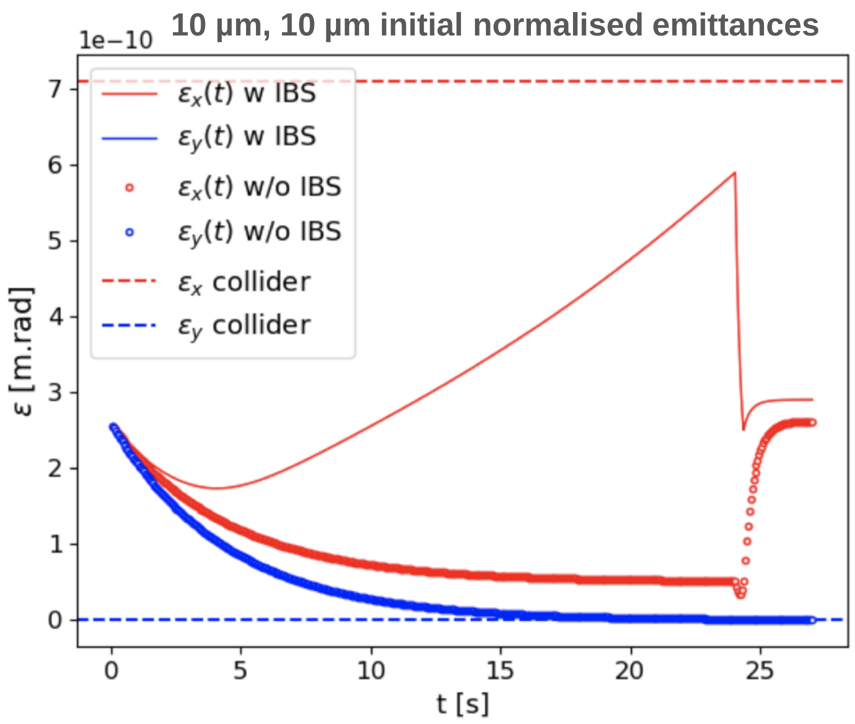
Injector		LINAC	LINAC	LINAC	
Injection energy	GeV	20	20	20	
Extraction energy	GeV	45.6	45.6	45.6	
Injection hor. emittance $\epsilon_{x,inj}$ (norm.)	µm	50	10	10	
Injection vert. emittance $\epsilon_{y,inj}$ (norm.)	µm	50	10	1	
Injection energy spread $\delta_{p,inj}$	%	0.1-0.15	0.1-0.15	0.1-0.15	0.4
Extraction hor emittance $\epsilon_{x,ext}$ (geom)	µm	<0.3	<0.3	<0.3	<0.3
Extraction vert emittance $\epsilon_{y\ ext}$ (geom)	pm	<1.42	<1.42	<1.42	<1.42
Extraction energy spread $\delta_{p,ext}$	%	0.04	0.04	0.04	0.04
Accumulation time	s	24	24	24	54
Ramp time	s	0.32	0.32	0.32	0.37
Flat top	s	2.6	1.9	1	1.9
Total cycling time	s	26.92	26.22	25.32	56.27

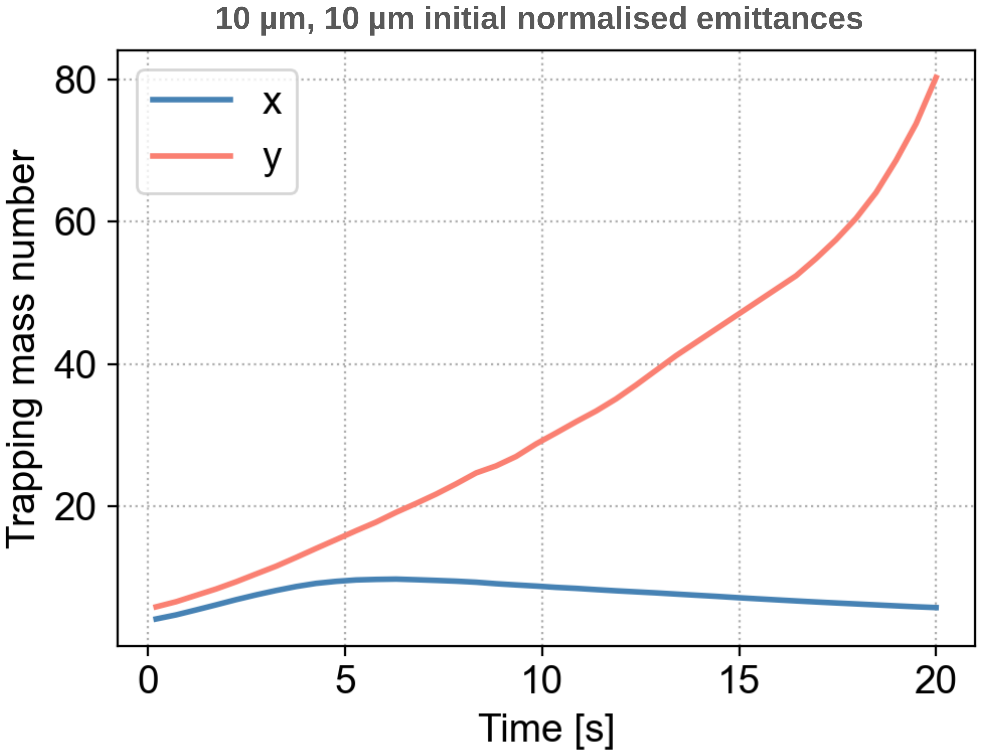
Filling scheme	1	2	3	4
Bunch Intensity [x10^{10} ppb]	1.51	2.15	2.15	2.43
Bunch spacing [ns]	15	20	25	25
Train length [# bunches]	2.15	280	560	255

Ion trapping in the booster

A. Chance et al, FCC Week 2023

- Based on the emittance evolution during the booster cycle, we can estimate the evolution of the trapping mass
  - The trapping condition is determined by the vertical plane
  - The trapping mass is lowest, i.e. most critical, right after injection and increases with the decrease in vertical emittance

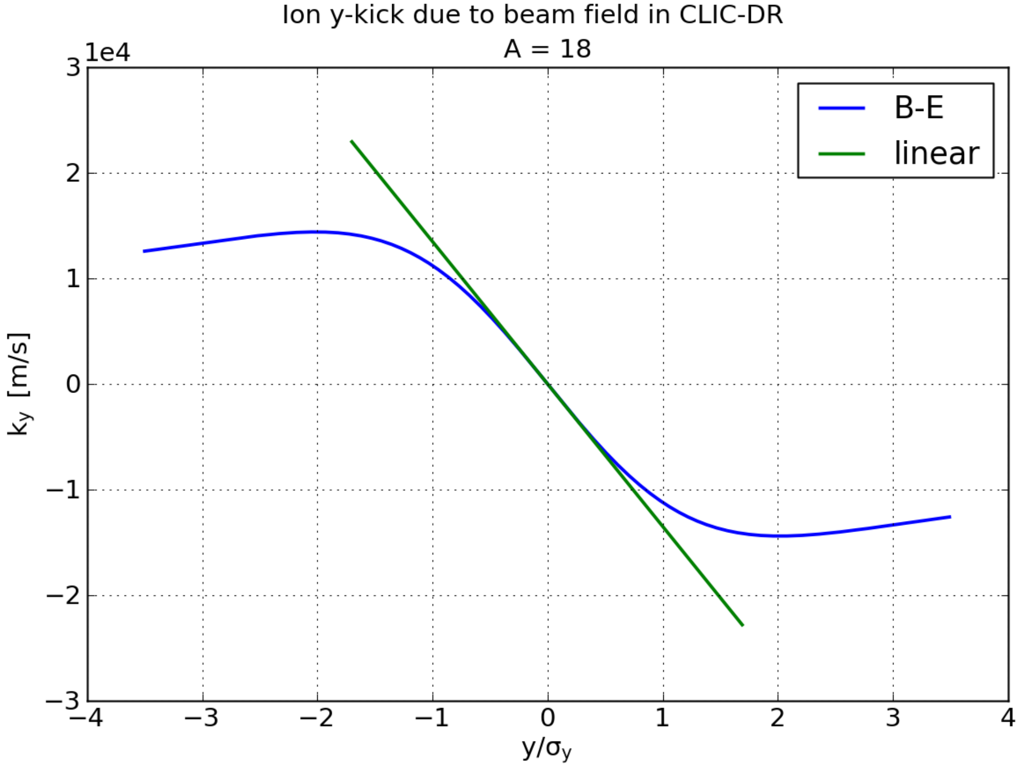




- In this case the initial trapping mass is around 5
  - Consequently, H_2 (A = 2) should not be trapped, while most heavier species would be trapped
  - However, in reality, the situation is more subtle

Analytical model: beyond the linear approximation

The linear approximation is good only in a small region around the centre of the beam: $x,y \leq 0.5\ \sigma_{x,y}$



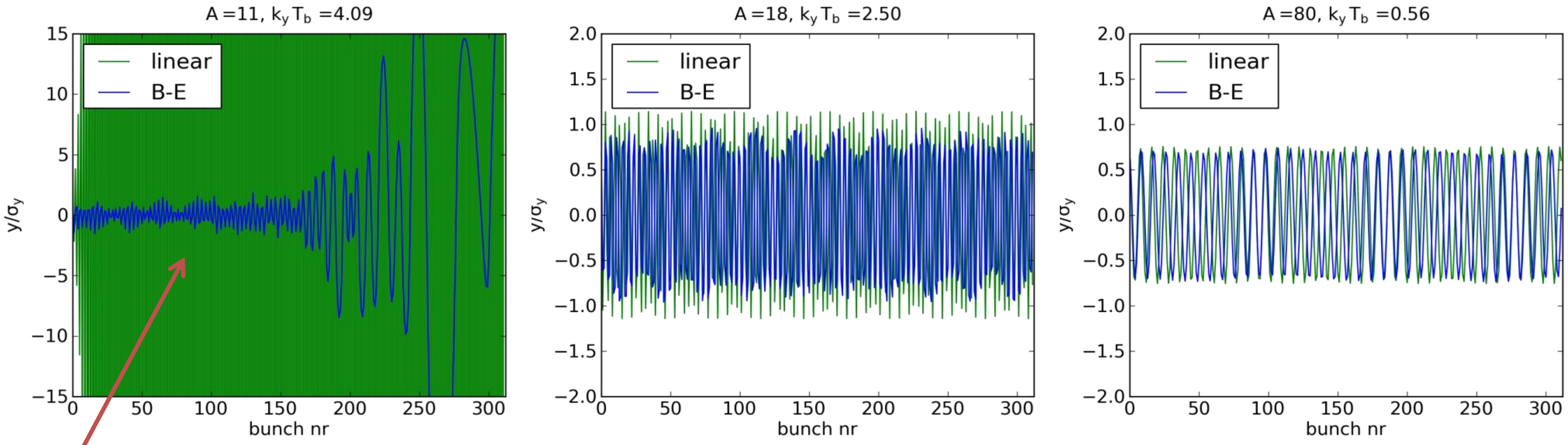
Analytical model: beyond the linear approximation

The linear approximation is good only in a small region around the centre of the beam: $x,y \leq 0.5\ \sigma_{x,y}$

- In the non-linear regime, ion trajectories are altered and ions below the trapping mass can oscillate around a bunch train for some time (“weak trapping”)

Trajectories for ion of mass A during the passage of a CLIC bunch train

$x_0 = 0.7\ \sigma_x$, $y_0 = 0.7\ \sigma_y$



Ion is trapped for several bunch passages

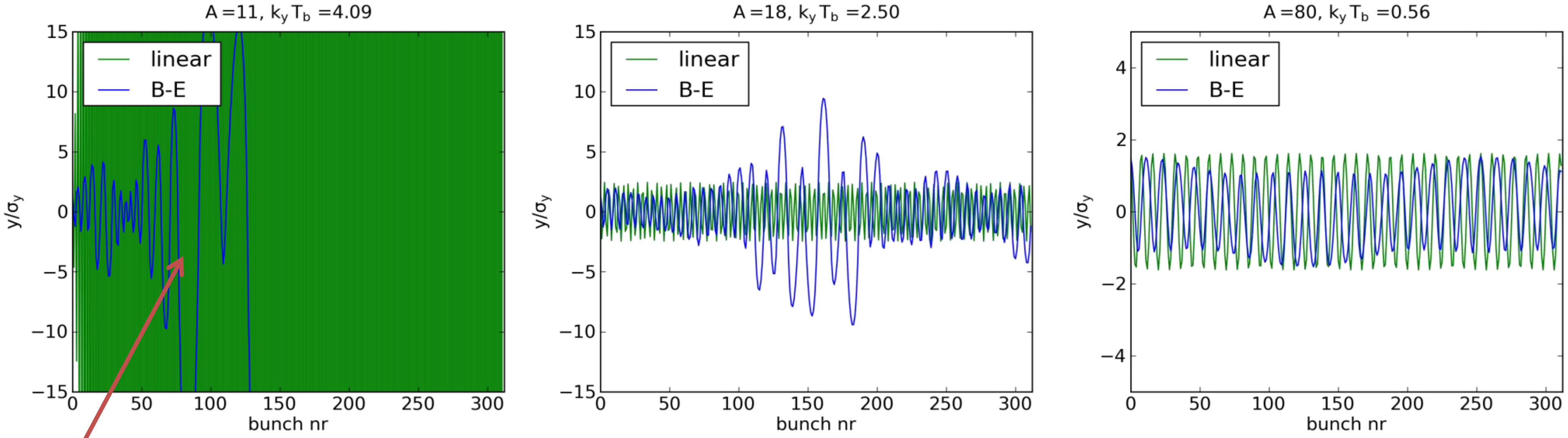
Analytical model: beyond the linear approximation

The linear approximation is good only in a small region around the centre of the beam: $x,y \leq 0.5\ \sigma_{x,y}$

- In the non-linear regime, ion trajectories are altered and ions below the trapping mass can oscillate around a bunch train for some time ("weak trapping")

Trajectories for ion of mass A during the passage of a CLIC bunch train

$x_0 = 1.5\ \sigma_x$, $y_0 = 1.5\ \sigma_y$



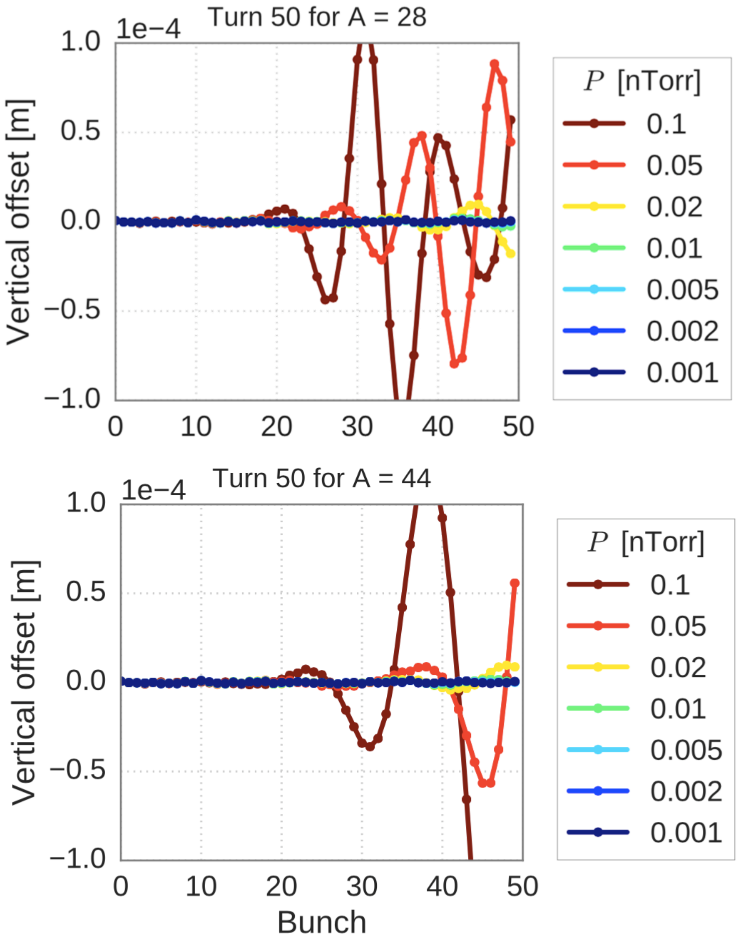
Ion is trapped for several bunch passages

Weak trapping in simulations

- This effect has been observed also in a past simulation study for the FCC-ee from 2017 (with obsolete parameters)
  - Weak trapping can also cause instability, but with different characteristics than for fully trapped ions

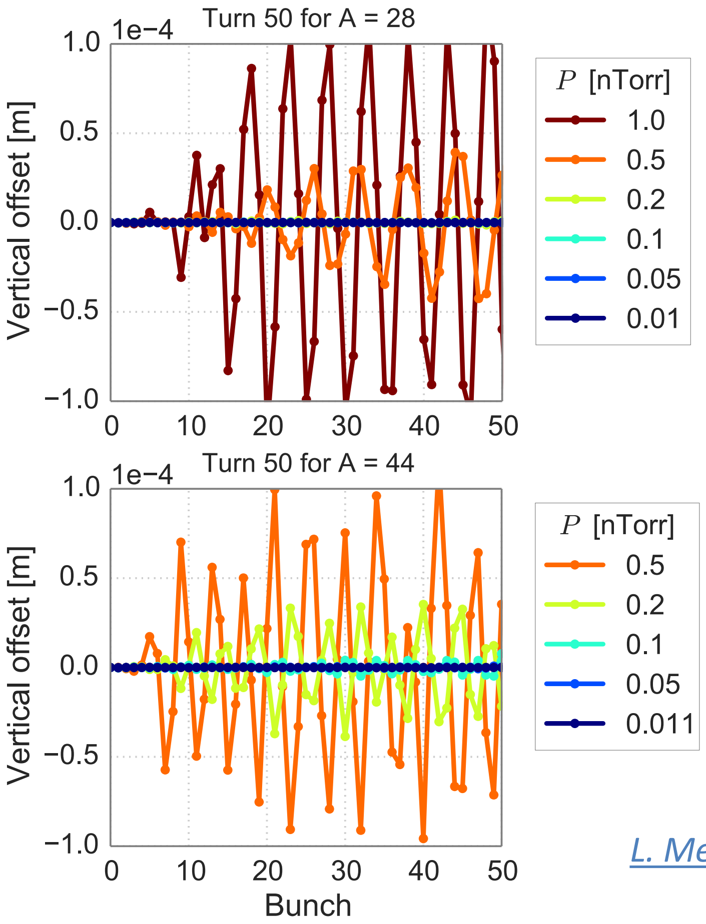
A_{trap}≈10, N_2 and CO_2 are fully trapped

The instability starts at the end of trains, moving towards the front with increasing pressure



The instability is stronger for **lower A**

A_{trap}≈80, N_2 and CO_2 are weakly trapped



The instability develops simultaneously over most of the train

The instability is stronger for **higher A**

L. Mether et al, FCC Week 2018

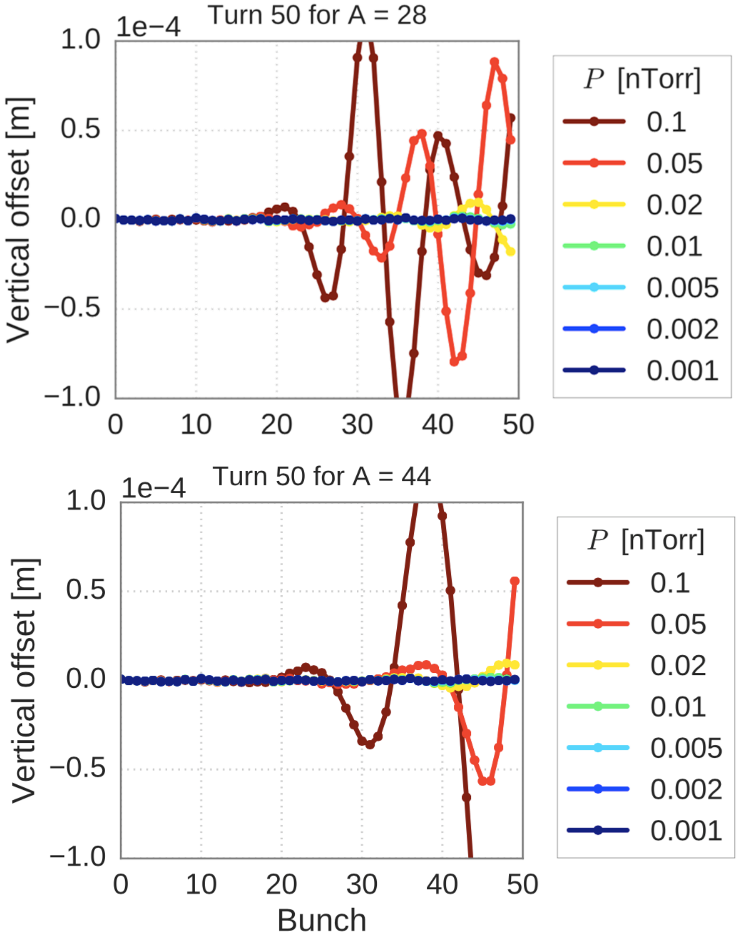
Weak trapping in simulations

- This effect has been observed also in a past simulation study for the FCC-ee from 2017 (with obsolete parameters)
  - Weak trapping can also cause instability, but with different characteristics than for fully trapped ions

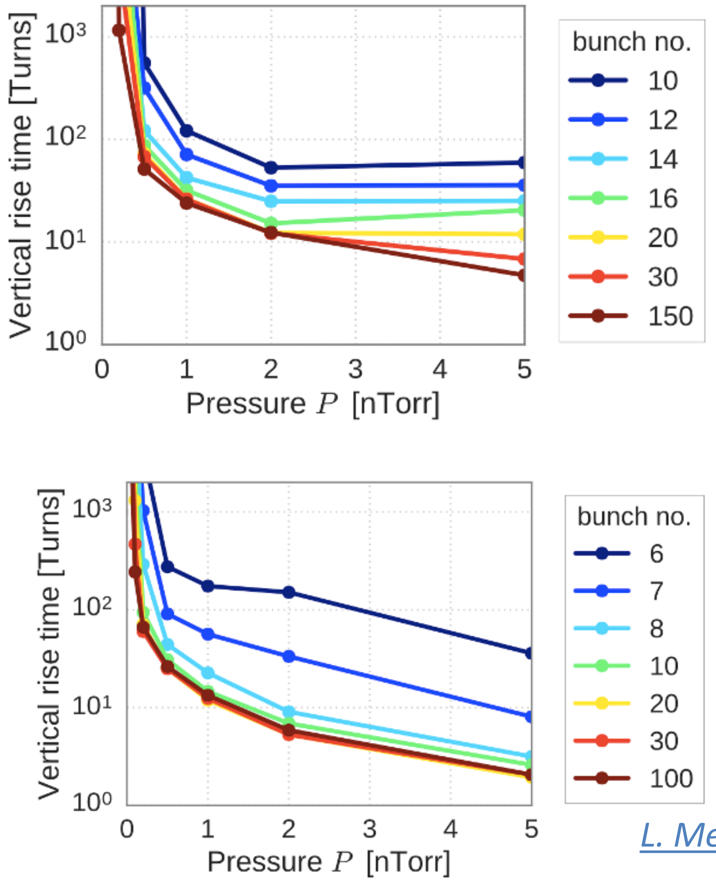
The instability starts at the end of trains, moving towards the front with increasing pressure

The instability is stronger for **lower A**

A_{trap}≈10, N_2 and CO_2 are fully trapped



A_{trap}≈80, N_2 and CO_2 are weakly trapped



Bunch-by-bunch rise times (based on emittance) saturate after a small part of the train

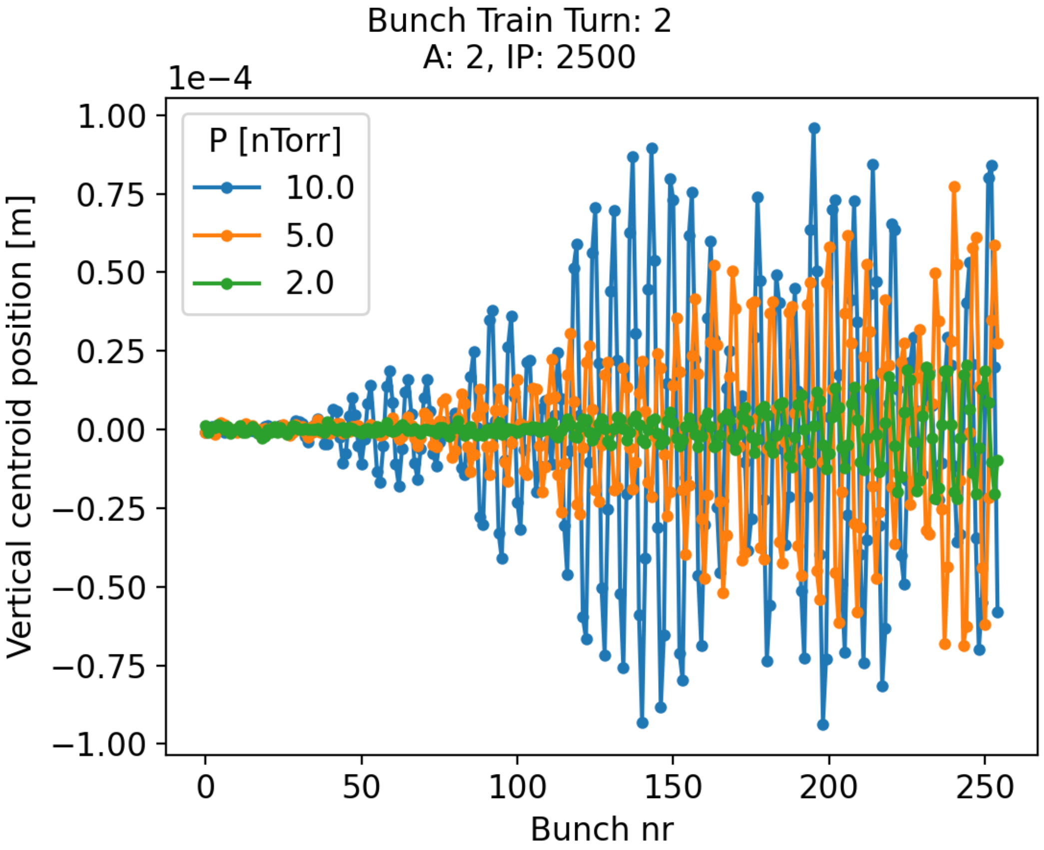
L. Mether et al, FCC Week 2018

First instability simulations for booster

- Ideally, we should simulate the FBII with a realistic composition of vacuum species for different total pressures over at least a damping time
    - FBII simulations are computationally very heavy → such a study takes months to perform

- First simulations cover only a few cases over a small number of turns
    - Focus on H_2, despite weaker trapping, since heavier species make up a much smaller fraction of the total pressure

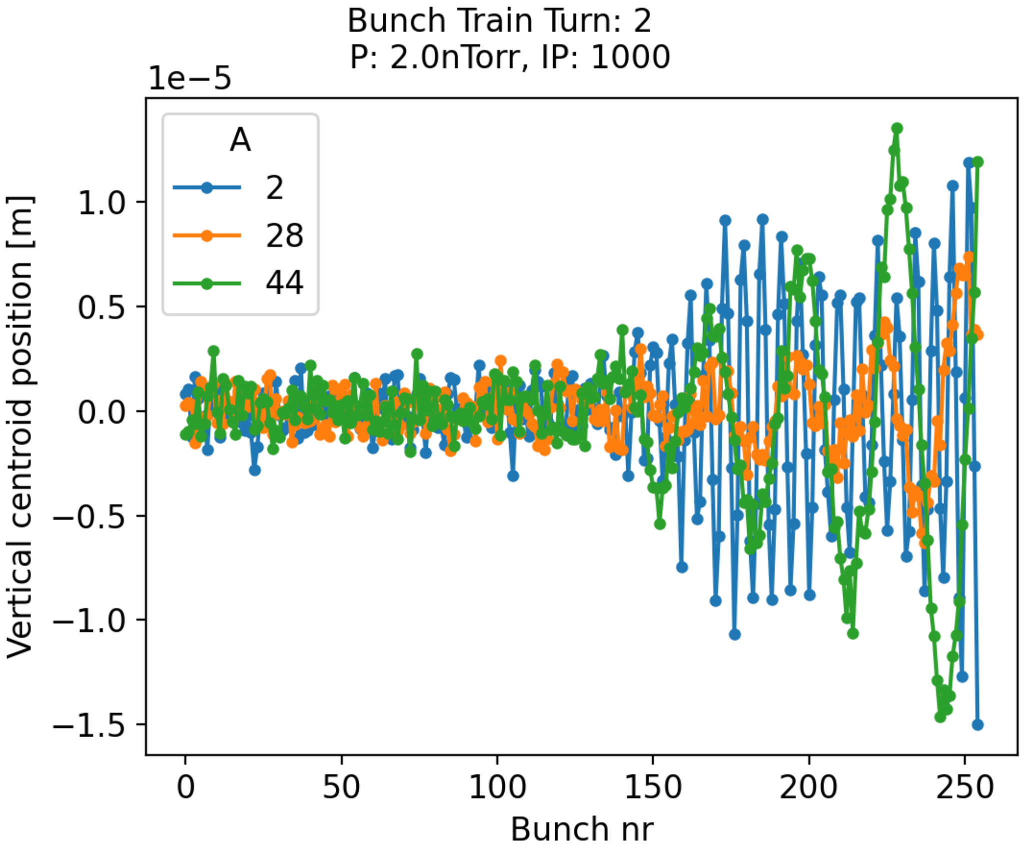
    - With initial emittances of 10 µm in both planes, an instability develops within 2 turns even for a pressure of 2 nTorr ≈ 2.7e-9 mbar



Trapping of heavier species

- Heavier species, such as CO, N2 and CO2, are strongly trapped with a round beam of 10 µm

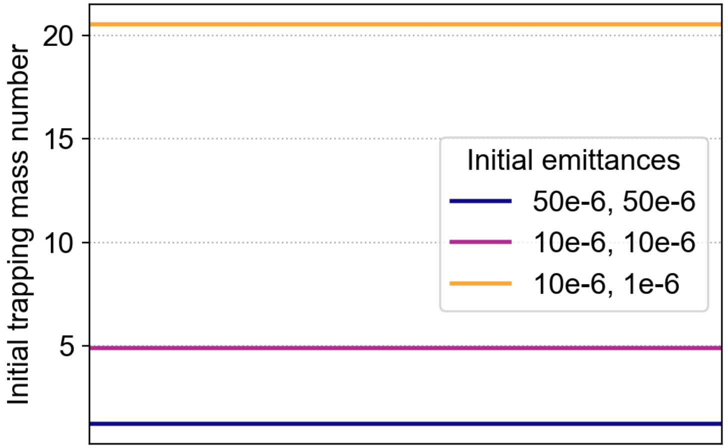
- Also for these species, an instability develops within 2 turns for a pressure of 2 nTorr ≈ 2.7e-9 mbar
  - However, this would correspond to larger total pressures, since the fraction of heavier species is typically much lower

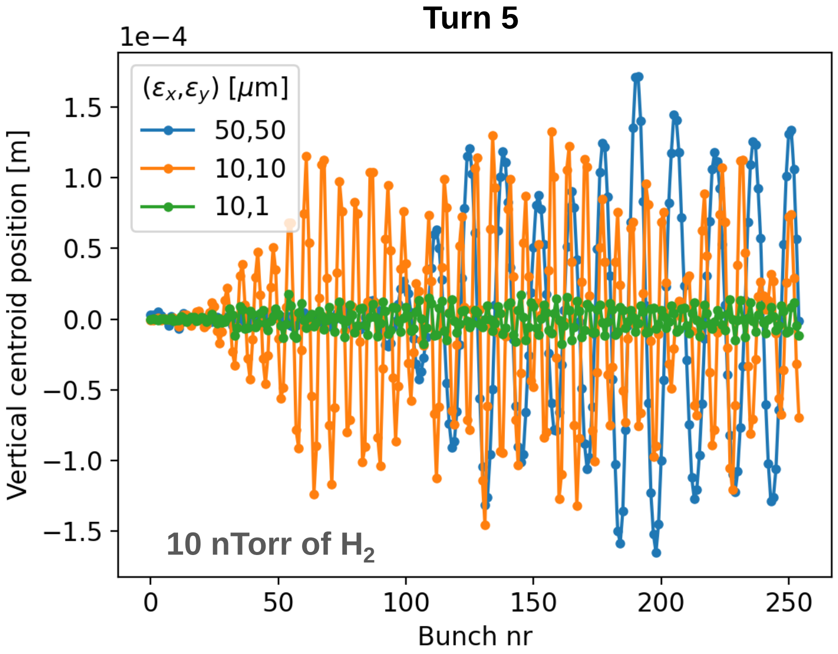


Impact of initial emittances

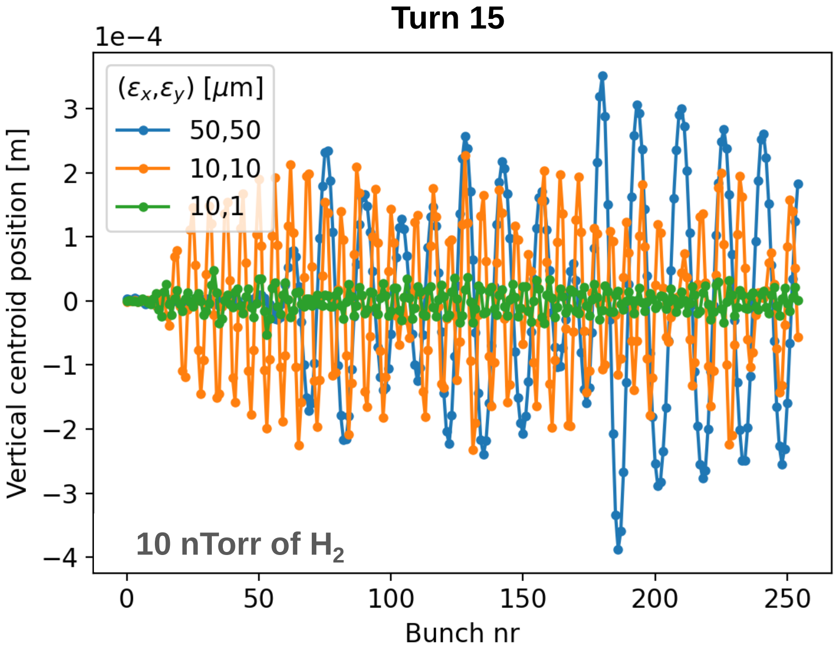
- Since the trapping mass number increases with decreasing emittance, a lower (vertical) emittance at injection should alleviate the instability, at least for H_2

- Simulations confirm that the option with 1 μm vertical emittance at injection is significantly less impacted by H_2 trapping, although smaller amplitude oscillations still occur



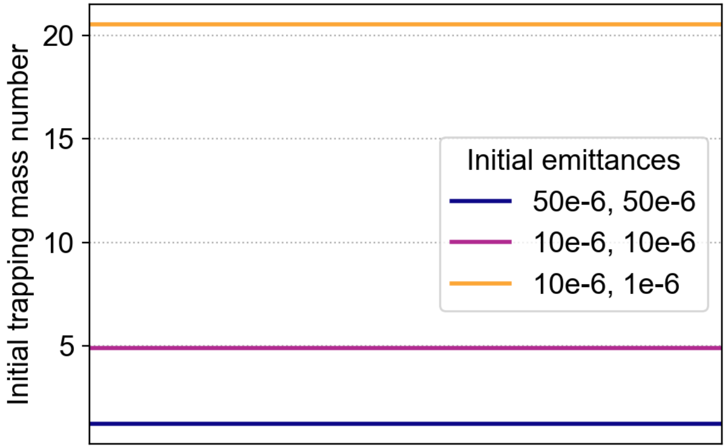


Note the change in scale

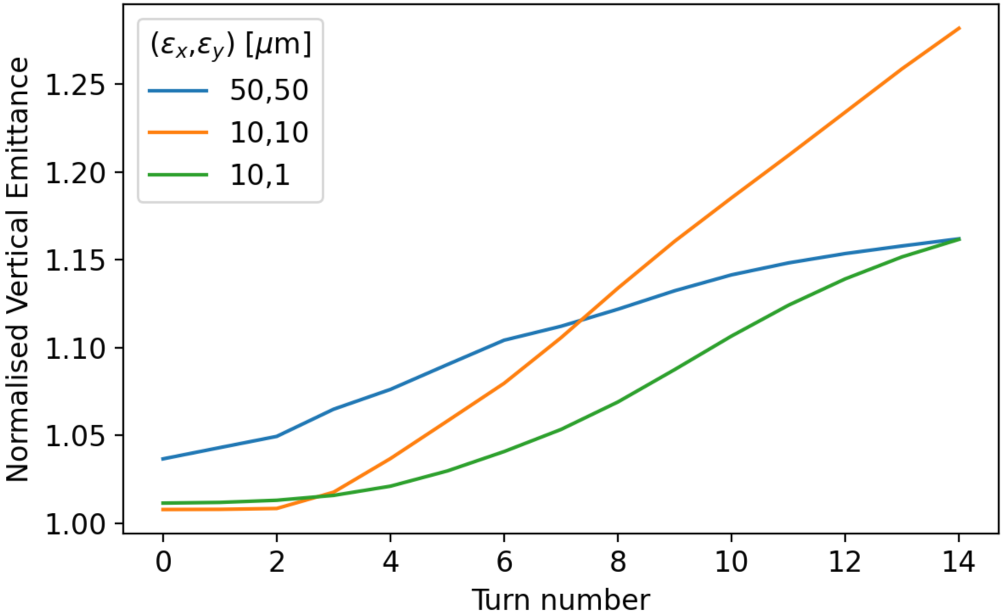


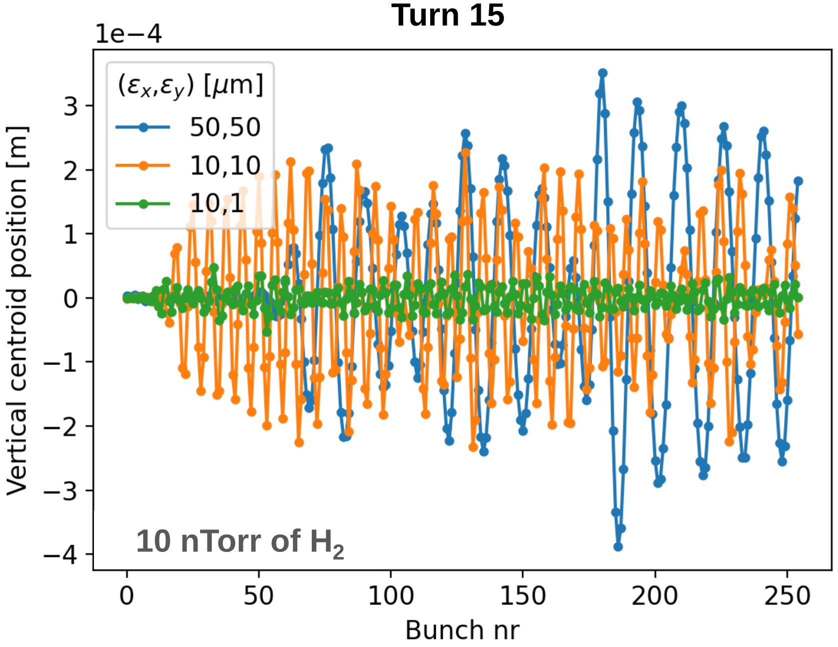
Impact of initial emittances

- Since the trapping mass number increases with decreasing emittance, a lower (vertical) emittance at injection should alleviate the instability, at least for H_2



- Simulations confirm that the option with 1 μm vertical emittance at injection is significantly less impacted by H_2 trapping, although smaller amplitude oscillations still occur
  - ○ Emittance growth occurs in all cases





Conclusion and outlook

- The fast beam-ion instability is likely to cause problems with the currently foreseen vacuum system
  - Ion trapping is strongest just after injection
    - Heavier ion species, e.g. CO, N_2, CO_2 are trapped for all considered emittances
    - Hydrogen is weakly trapped for emittance of ~30 µm or smaller, but can still cause instability
  - Opting for a smaller vertical emittance at injection reduces the impact, but it is probably not sufficient

- Mitigation measures that don't rely on low vacuum pressure can be considered
  - The instability can generally be mitigated with a transverse feedback, but ion trapping will still occur and may still lead to tune shift and emittance growth
  - Clearing electrodes could be another solution, but design and impact e.g. on impedance need to be considered

- A more extensive study (with the latest parameters) is needed for more accurate constraints
  - The need for mitigation measures should be assessed and their effectiveness evaluated
  - Mitigation strategy should be included in the overall design process, including in cost estimates