Impact of a 200MHz RF system

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Thanks to B. Salvant, R. Calaga, E. Jensen, N. Mounet and E. Shaposhnikova

Motivations and open questions

- Possible benefits:
  - Higher bunch intensity with longer bunches
  - Mitigate electron cloud and heating
  - Allows for bunch length leveling
- Disadvantages (?):
  - Reduced synchrotron tune: TMCI?
  - Are long bunches compatibles with 400MHz crab cavities?
  - Larger luminous region: consequences?
- Can we achieve similar or better luminosity performances with 200MHz system?

→ First estimates presented at RLIUP workshop (*R. Tomas "HL-LHC alternatives"*) rather encouraging

Beam parameters

	HL-LHC baseline	200MHz
N_p [10^{11} p/bunch]	2.2	2.56
ε [μm]	2.5	3.0
Minimum β^* [m]	0.15	0.15
LR Separation [σ]	12	12
σ_s [m]	0.0755	0.126 / 0.14 (double RF)
Q_s	2.0e-3	8.8e-4
Virtual L [10^{35} cm^{-2}.s^{-1}]	1.83	1.37 / 1.17

→ 200MHz longitudinal parameters based on calculations by E. Shaposhnikova with 6MV. Bunch lengths are for 200MHz only (Gaussian) or 200MHz+400MHz (flat)

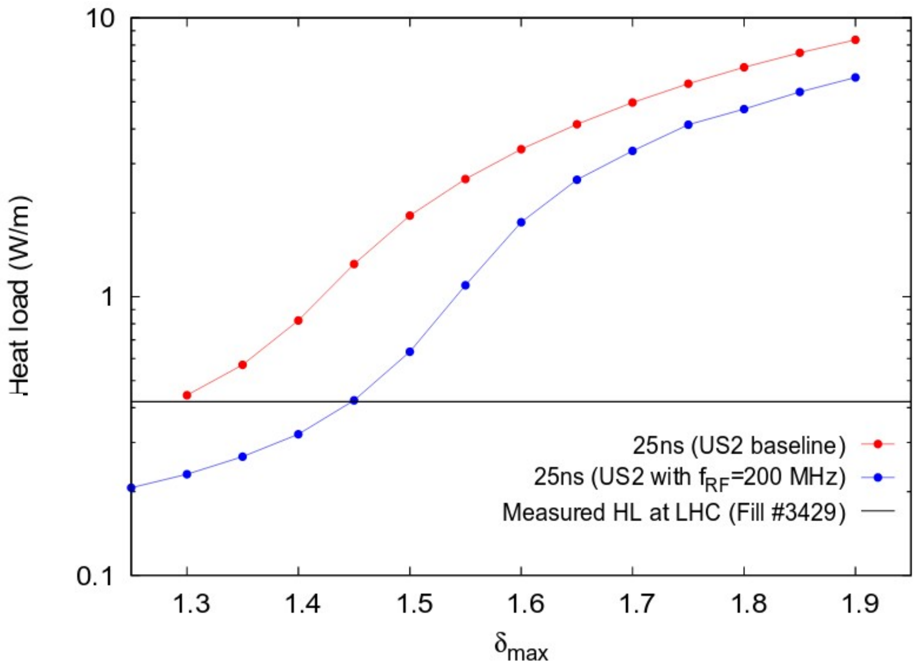
→ Both cases assume 400MHz crab cavities: **clear degradation of the virtual luminosity for longer bunches (RF curvature + hourglass) but more protons to “burn”: what are the consequence for integrated luminosity?**

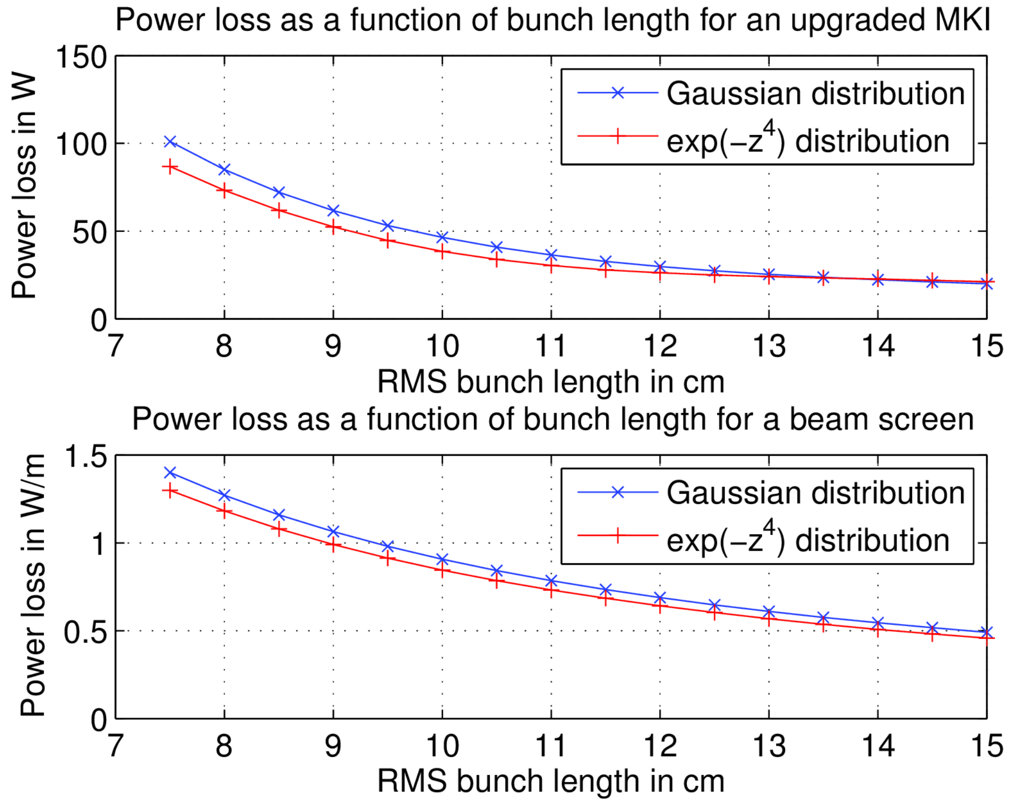
→ Beam-beam parameter scales with N_p/ε: no changes (assuming perfect CC)

Electron cloud and heating

→ Heat load from electron cloud as a function of maximum SEY

→ Clear benefits from longer bunches: may help in case of limitations at 25ns bunch spacing





- Beam induced heating:

→ factor ~5 gain in the MKI

→ factor ~2 gain in the beam screens

→ Very little difference between Gaussian and flat profile

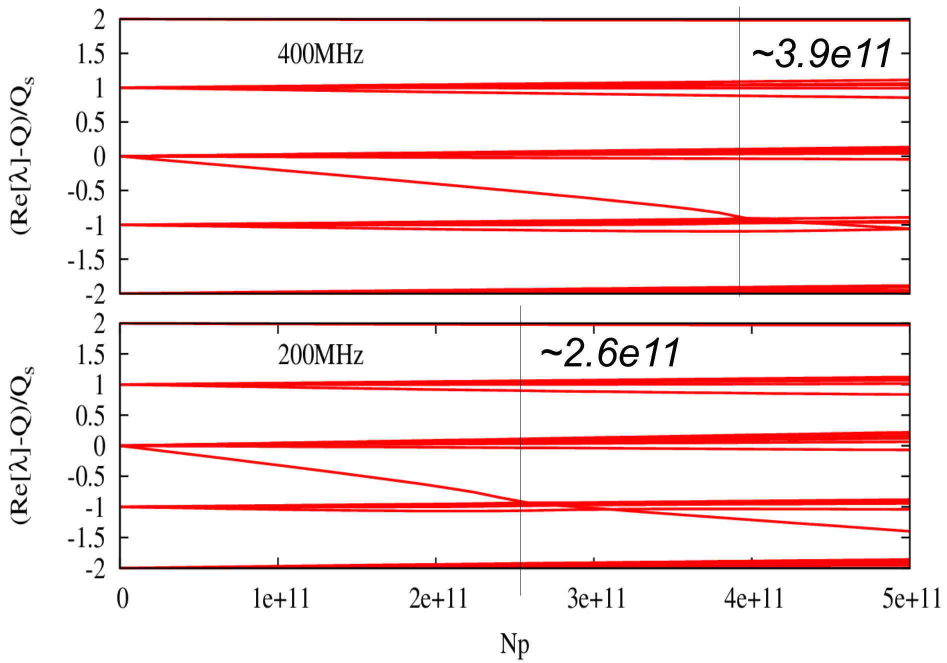
TMCI

- For the case of LHC the TMCI threshold is dominated by the tune shift of mode 0 (See *E. Metral et al. "Collimator-driven impedance"*):

$$\frac{\Delta Q_{0,0}^{y}}{Q_s} < -1 \quad \rightarrow \quad \Im\left(Z_y^{eff}\right)_{max} = \frac{4\pi\left(E_t/e\right)\tau_b Q_s}{N_b e \beta_y^{av}}$$

→ The threshold is proportional to Q_s and σ_s, for 200MHz we have:

$Q_s(400)$ / $Q_s(200)$ x $\sigma_s(400)$ / $\sigma_s(200)$ = 1.36



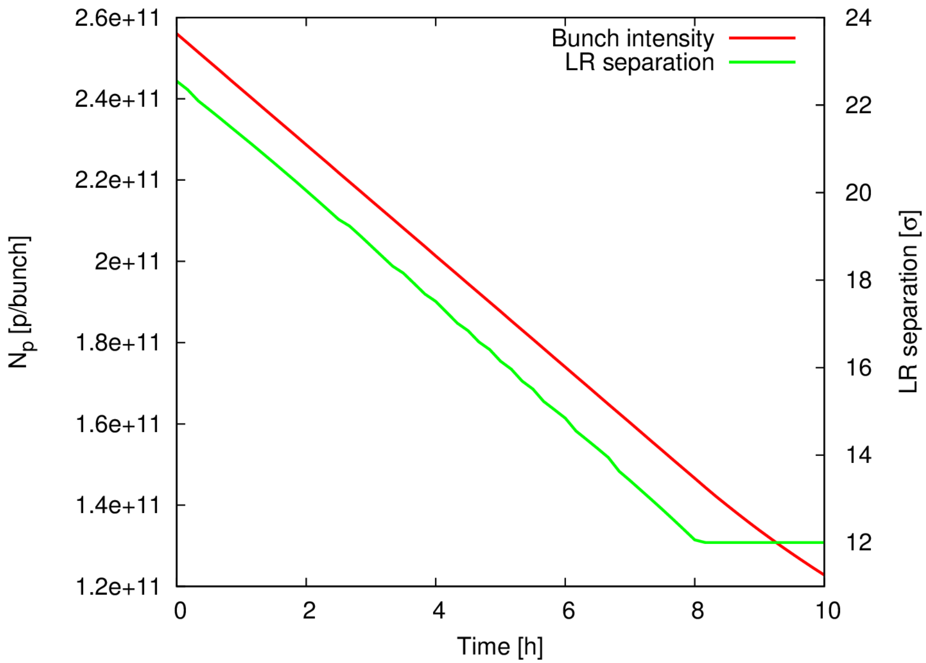
→ Calculations using the new HL-LHC impedance model (See *N. Mounet "Transverse impedance in the HL-LHC era", Daresbury*)

→ In reality the degradation is ~1.5: foreseen intensity barely below threshold

→ Chromaticity,damper and double RF should help, consider alternative material for collimators?

→ So far not a show stopper: more detailed studies required!

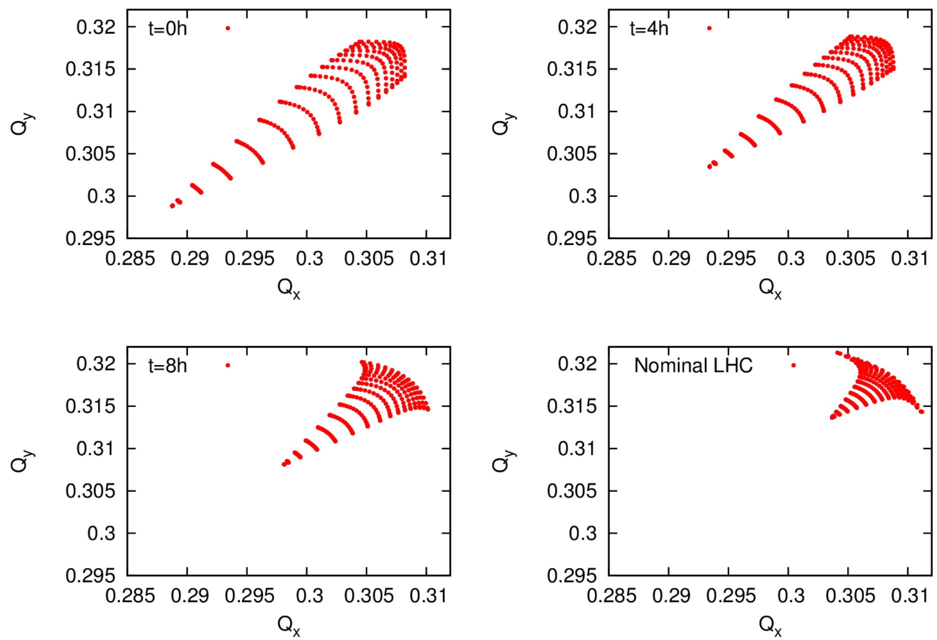
Do we "need" the BBLR wires?



→ The LR beam-beam tune shift scales with N/d^2 (d separation in σ)

→ The separation at the LR is set to 12σ using nominal parameters (not leveled)

→ With β* leveling the separation is much larger when the intensity is the highest



- **Very simple approach:**

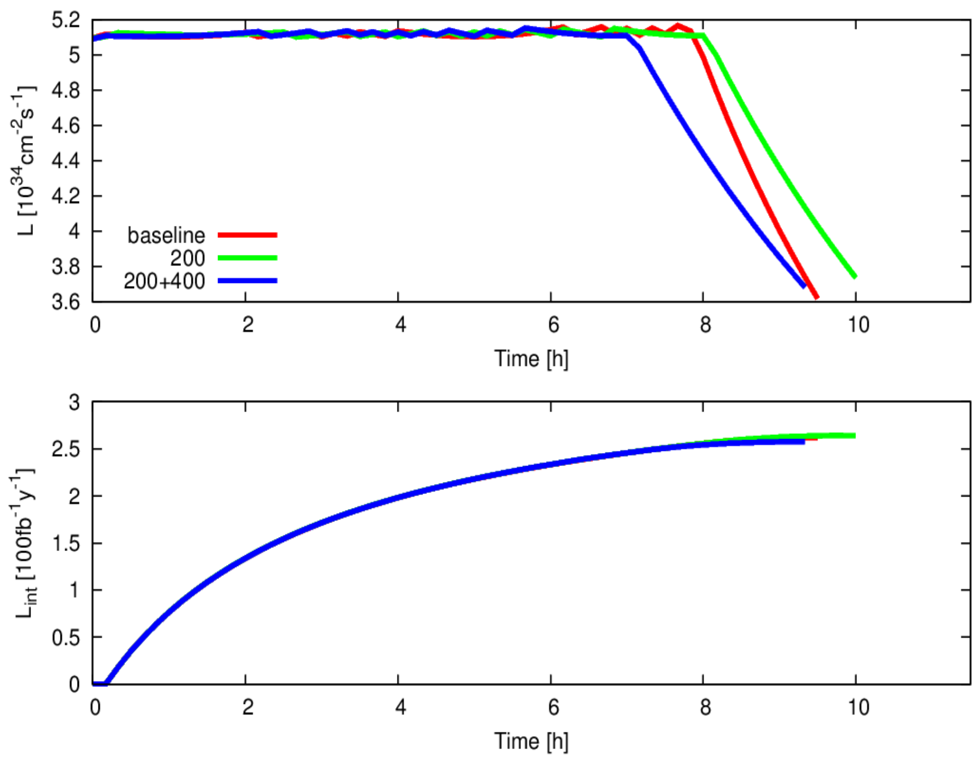
→ Lumped LR, same separation in all LR and perfect crab cavities

→ **Footprint is not the whole story…**

→ But it looks like we will be dominated by the head-on during the whole fill: **are LR really an issue if we level with β*?**

Luminosity performance with 400MHz CC

- For simplicity consider only β* leveling – bunch length could be used to increase the leveling time and performance

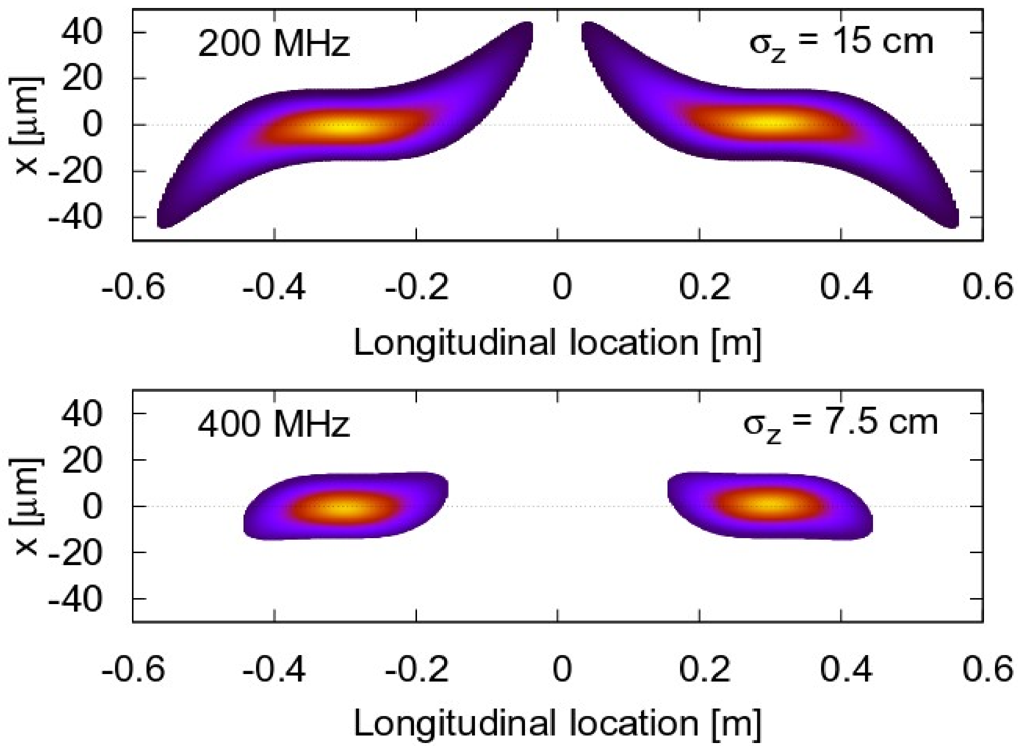


	Baseline	Gaussian	Flat
L/y [fb^{-1}]	**261.7**	**264.4**	**257.8**
Fill [h]	9.3	9.8	9.1
t_{level} [h]	8.0	8.1	7.1
β^*_{max}	0.62	0.53	0.48
σ_{Lumi} [m]	0.05	0.065	0.07

→ Luminosity leveled at 5.1e34 to get a pile-up of 140

→ 200MHz only performs better than the baseline (higher bunch intensity), small degradation for flat profile

Crab cavity frequency – what can we gain?

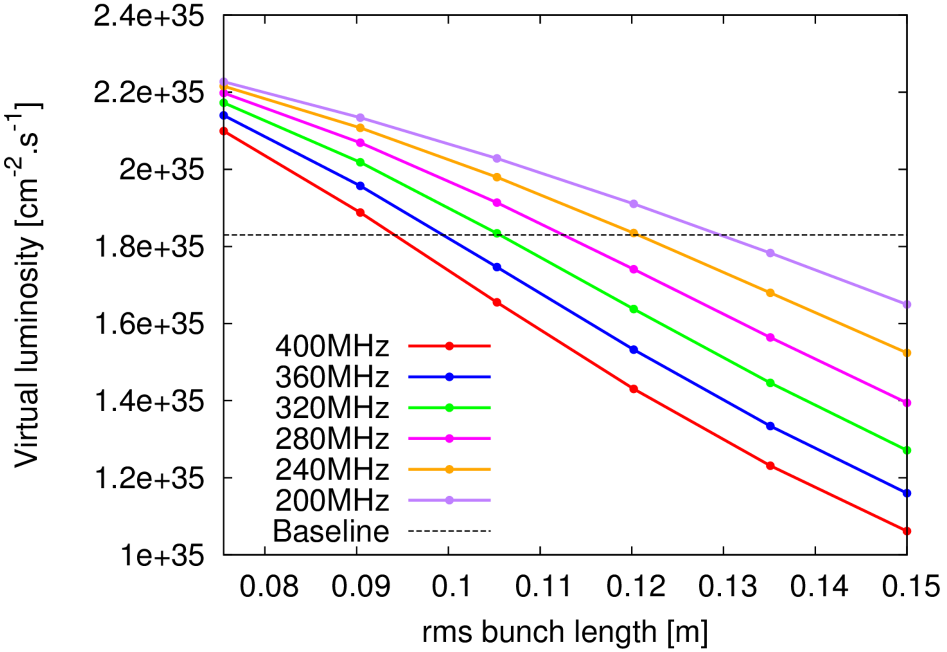


→ Substantial RF curvature with longer bunches

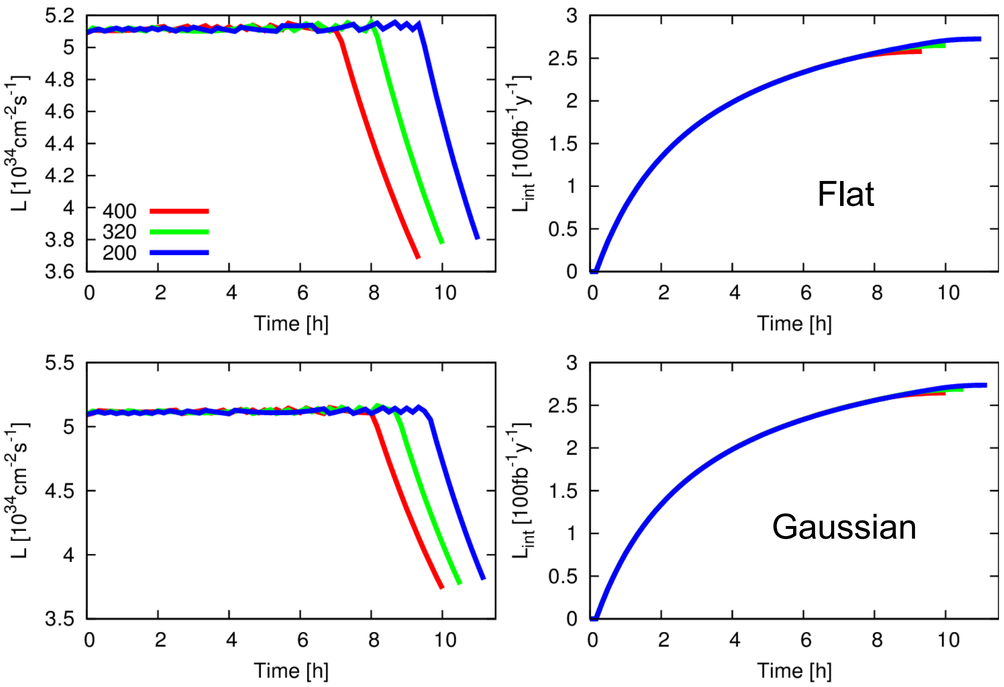
→ Reduces virtual luminosity and performance reach

→ Dependency of virtual luminosity on CC frequency for flat profile

→ Loss in performance due to longer bunches could be recovered by decreasing the frequency



Luminosity performance



→ **A reduction of the CC frequency by 80MHz would allow to achieve better than design performance**

→ Represents a gain of only ~3%

→ 200MHz CC represents a more significant gain but design looks difficult (size,voltage)

→ Bunch length leveling not considered

	Gaussian			Flat		
f_{CC} [MHz]	400	320	200	400	320	200
L/y [fb^{-1}]	**264.4**	**268.8**	**273.4**	**257.8**	**264.8**	**272.4**
Fill [h]	9.8	10.0	11.0	9.1	9.8	10.0
t_{level} [h]	8.1	8.8	9.6	7.1	8.1	9.5
β^*_{max}	0.53	0.59	0.68	0.48	0.57	0.68
σ_{Lumi} [m]	**0.065**	**0.072**	**0.083**	**0.07**	**0.08**	**0.092**

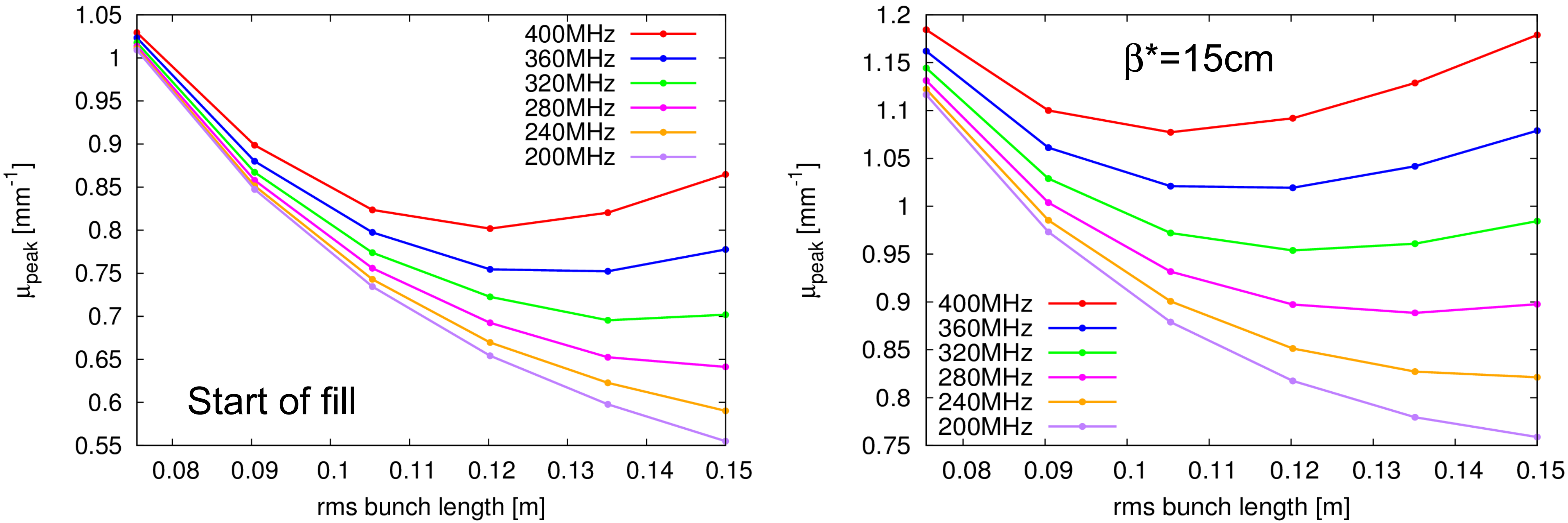
Pile-up density

- Recent interest to minimize pile-up density. A new scheme, “crab kissing”, has been developed to reduce this quantity (see S. Fartoukh and A. Valishev, this workshop)

$$\mu_{peak} = \frac{\mu_{tot}}{R(\sigma_s)\sqrt{\pi}\,\sigma_s}$$

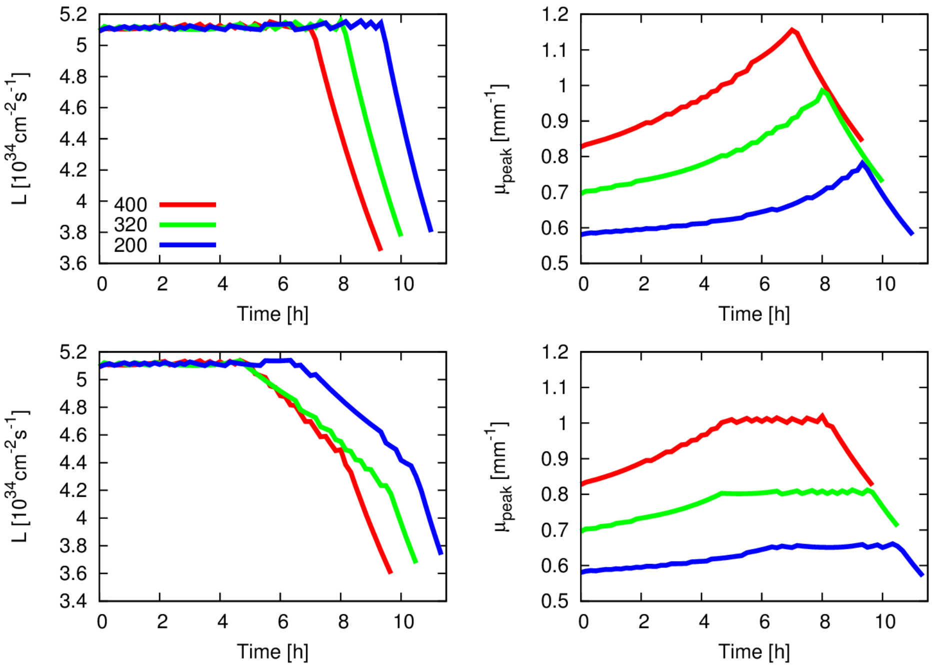
with μ_{tot}=140 and R the luminosity reduction factor

→ Can we profit from the increased bunch length by lowering the CC frequency?



→ With 320MHz CC and flat profile we could keep μ_{peak} below 1.0 during the whole fill

Fill evolution and pile-up leveling



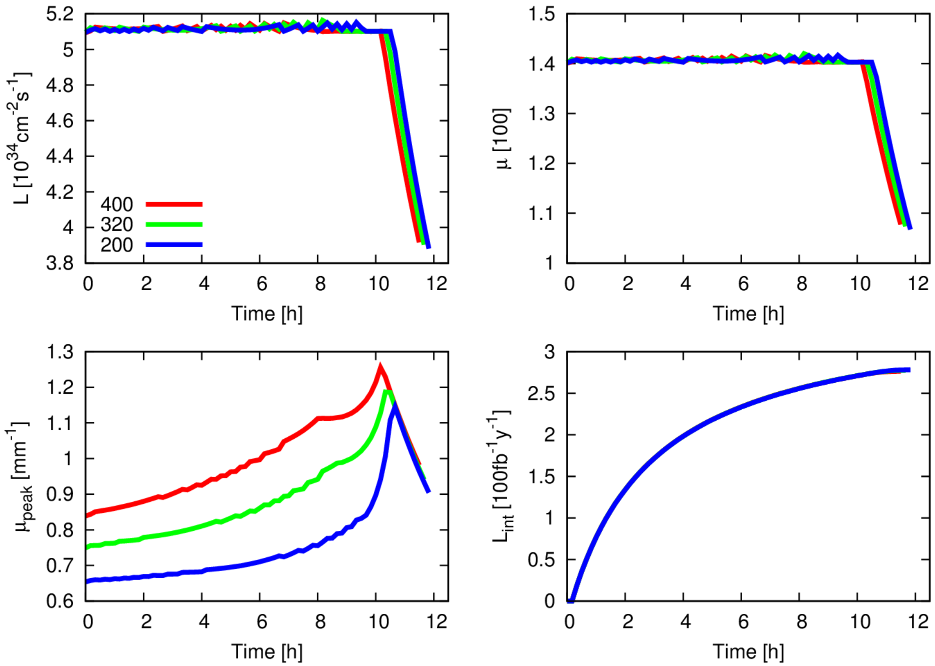
→ The pile-up density is maximum when β* reaches a minimum

→ Pile-up density leveling is possible without significant loss in integrated Luminosity

→ Leveling the pile-up density increases the fill length

	Flat			Flat + PU level		
f_{CC} [MHz]	400	320	200	400	320	200
L/y [fb^{-1}]	**257.8**	**264.8**	**272.4**	**254.7**	**258.9**	**268.2**
Fill [h]	9.1	9.8	10.0	9.5	10.0	11.0
μ_{peak} [mm^{-1}]	**1.15**	**1.0**	**0.8**	**1.0**	**0.8**	**0.65**
β^*_{max}	0.48	0.57	0.68	0.48	0.57	0.68
σ_{Lumi} [m]	0.07	0.08	0.092	0.07	0.08	0.092

Bunch length leveling



f_{CC} [MHz]	400	320	200
L/y [fb^{-1}]	**276.4**	**277.4**	**278.1**
Fill [h]	11.5	11.6	11.8
μ_{peak} [mm^{-1}]	**1.28**	**1.2**	**1.15**
β^*_{max}	0.53	0.59	0.68
σ_{Lumi} [m]	0.065	0.072	0.083

→ Use bunch length leveling once β* has reached a minimum (Gaussian approximation)

→ Reduction of luminous region at the end of fills → **increased pile-up density**

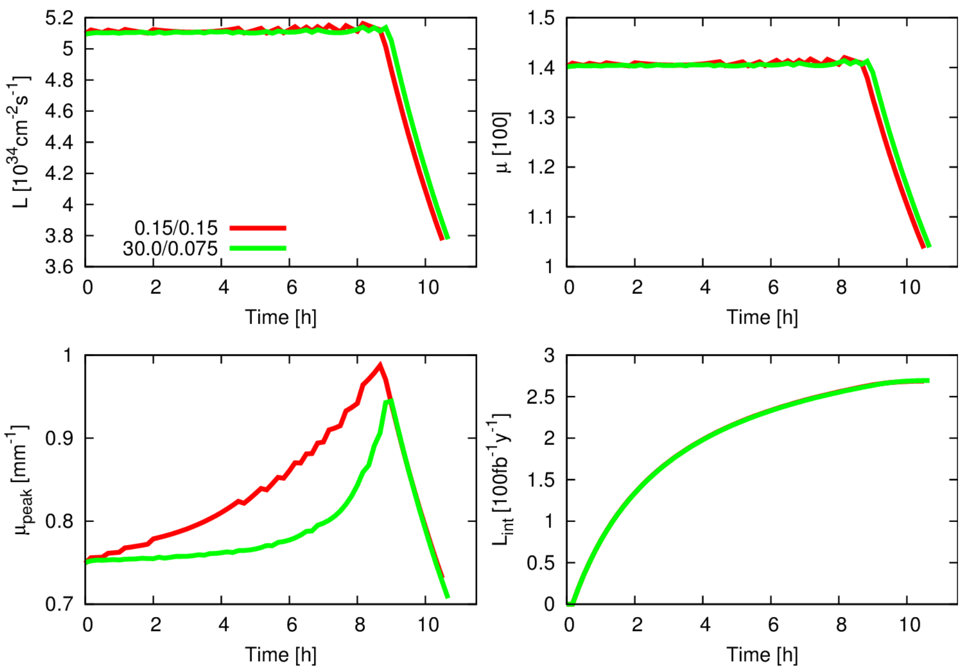
→ CC frequency has small impact on peak values due to the reduction of bunch length. The average pile-up density behavior is however significantly improved

→ **Better than the nominal 270fb^{-1} can be achieved in all cases**

Implication of lower CC frequency

- The voltage scales with 1/f to compensate for the same crossing angle. The size of the cavity will also increase due to to the reduced frequency unless compactness is improved **→ design more challenging, problems with integration?**

- The crossing angle scales with $1/\beta^{1/2}$ → for example the 30.0/7.5 cm optics would cover for the loss in compensation at constant voltage (larger β could be considered at the expense of some luminosity)



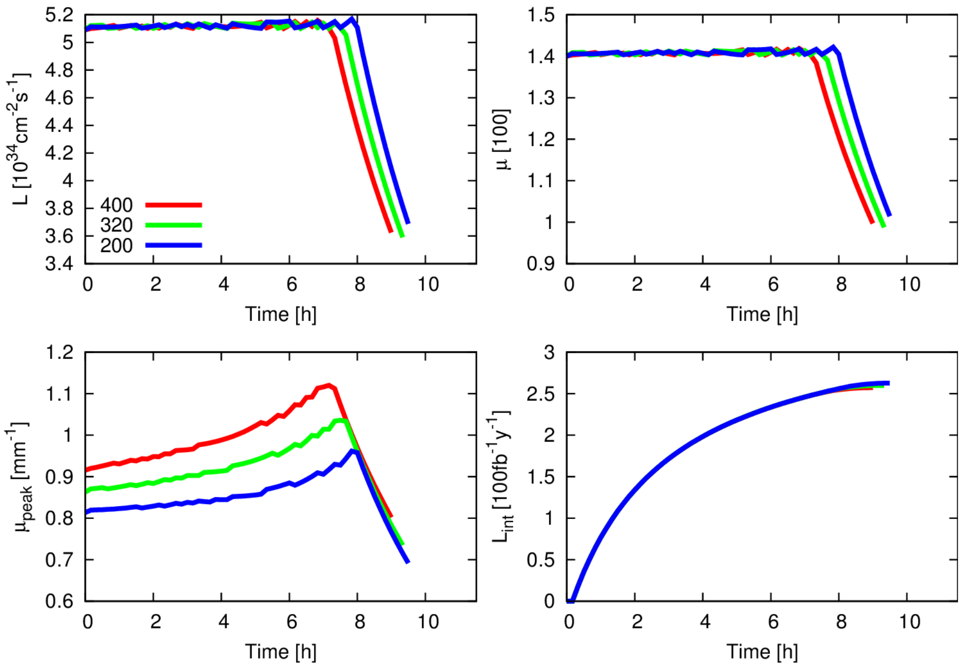
→ Example of the 320MHz CC with 200MHz only, no bunch length leveling

→ Slightly better performance with flat beams

→ Sharper peak in pile-up density: **Leveling will have smaller effect on overall performance**

→ In case integration and voltage are an issue this could be an option to reduce the required voltage (number of cavities?)

Can we gain with 400MHz main RF system?



→ Use “long” bunch length of 10cm

→ Very little gain in luminosity

→ Could gain ~10% in pile-up density with 320MHz

→ Maximum pile-up density similar to 200MHz (weaker hourglass) but average is higher: **difficult to level**

	12.6cm + Np = 2.56e11 (for comparison)			10cm		
f_{CC} [MHz]	400	320	200	400	320	200
L/y [fb^{-1}]	**264.4**	**268.8**	**273.4**	**257.2**	**259.8**	**262.6**
Fill [h]	9.8	10.0	11.0	8.8	9.1	9.3
μ_{peak} [mm^{-1}]	**1.11**	**0.99**	**0.82**	**1.12**	**1.04**	**0.96**
β^*_{max}	0.53	0.59	0.68	0.56	0.59	0.63
σ_{Lumi} [m]	0.065	0.072	0.083	0.06	0.063	0.068

Summary

- **Longer bunches would mitigate electron cloud and heating from impedance**

- **Luminosity performances are similar or better** than nominal depending on the scenario (flat or Gaussian)

- In order to fully profit from the increased bunch length one can **reduce the crab cavity frequency**:
  - Slightly better luminosity performance
  - **Reduction of pile-up density and efficient pile-up leveling with little loss in performance**
  - With 400MHz main RF very small gain

- **Performance can be further improved to the nominal 270fb^{-1}/year or better using bunch length leveling**: long fills and higher maximum pile-up density

- Open questions:
  - **Integration could be an issue**, larger cavities, higher voltage → flat beams required??
  - **The TMCI threshold is reduced by a factor 1.5** (smaller synchrotron tune). More detailed studies required
  - **To what extend do we need the BBLR compensation?** Simple calculations seem to indicate that with β^* leveling the LR tune shift is strongly mitigated: done for round beam, flat beams scenario needs to be checked