

# HL-LHC alternatives



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# Contents

- ★ Assumptions
- ★ Alternatives and merits
- ★ US1 performance
- ★ US2 performance
- ★ Exotic
- ★ Summary & Outlook

# Assumptions

- ★ Efficiency is 50% and it is defined as

$$N_{fills} \frac{T_{fill} + T_{turn-around}}{T_{run}}$$

- ★ Average fill length is either optimum or 6 hours.
- ★ Turn-around of 3 hours.
- ★ US1 and US2 crossing angles are  $10 \sigma$  and  $12 \sigma$ , respectively
- ★ US1 and US2 goals are  $170 \text{ fb}^{-1} \text{ y}^{-1}$  and  $270 \text{ fb}^{-1} \text{ y}^{-1}$ , respectively

# Alternative 1: 8b+4e

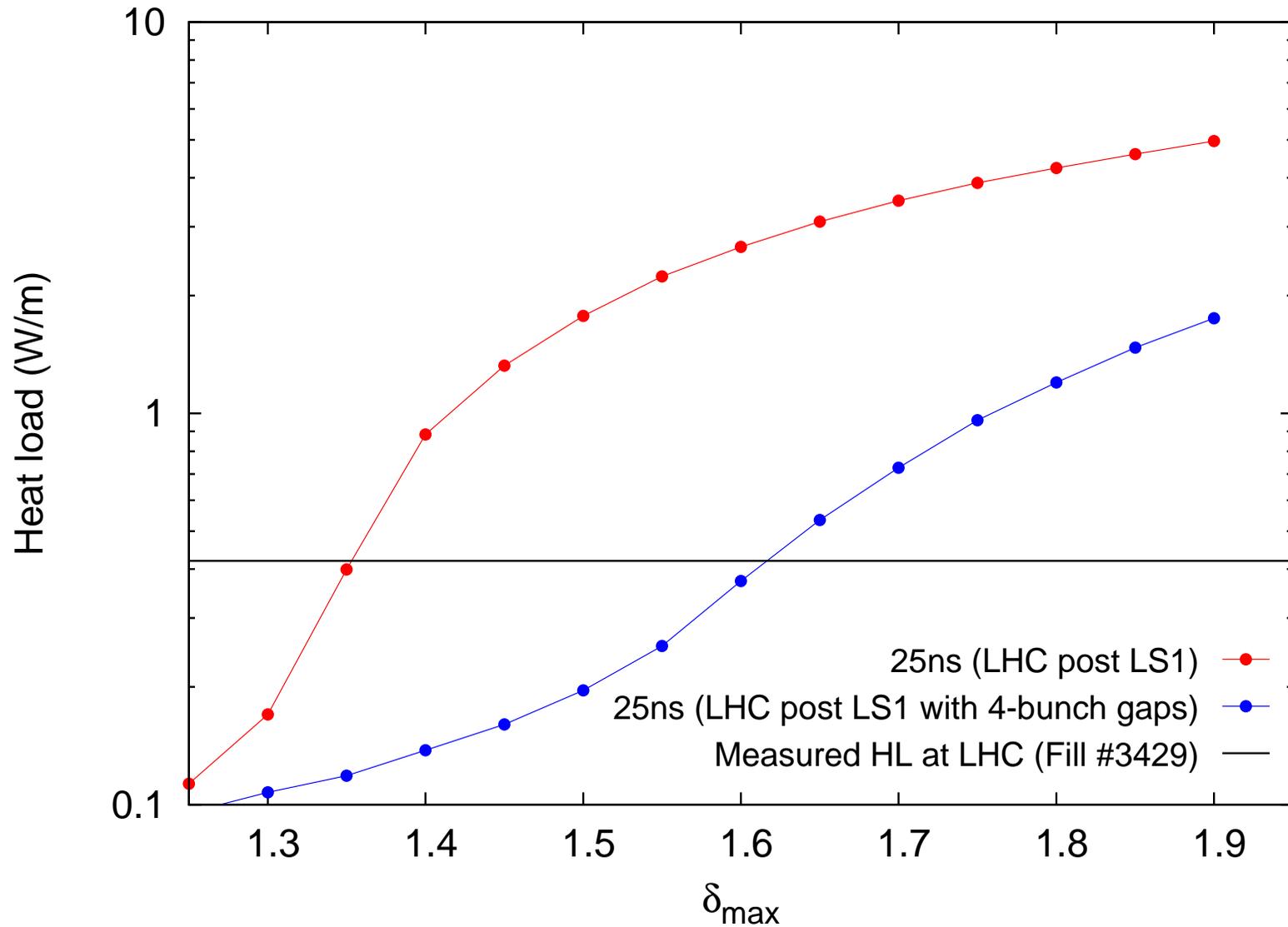
R. Garoby, H. Damerau

- ★ Double splitting instead of triple splitting in the PS for *more* bunch charge and 2/3 bunches. A PSB bunch becomes:



- ★ In the LHC: 1840 bunches with  $2.4 \times 10^{11}$  ppb
- ★ Details in Heiko's talk
- ★ First beam tests in injectors in 2014
- ★ Merits: Significantly lower e-cloud, no cost

# Alternative 1: 8b+4e, lower e-cloud



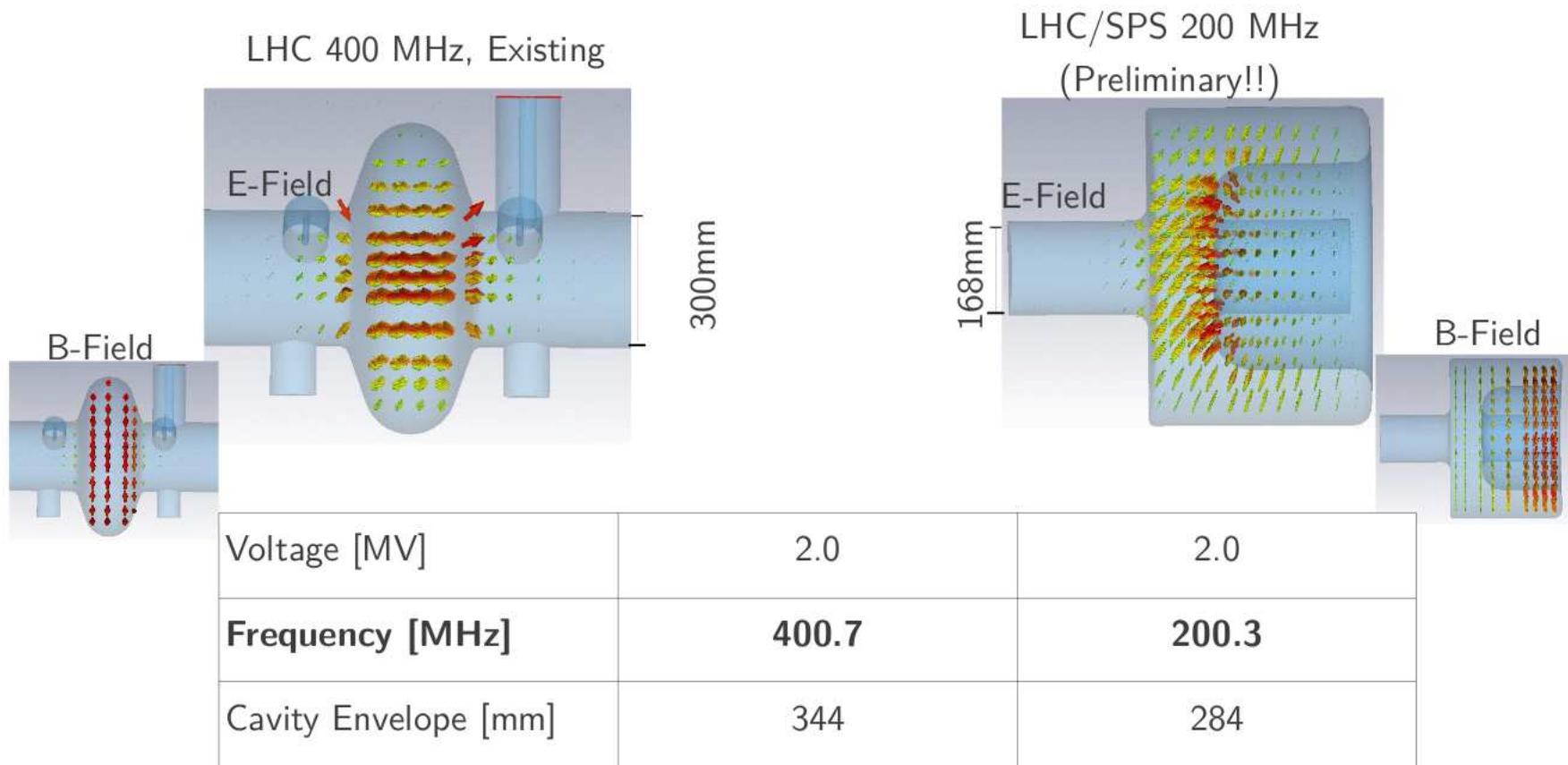
# Alternative 2: 200 MHz in LHC

R. Garoby,  
E. Shapochnikova,  
R. Calaga

- ★ 200 MHz (3 MV) allows to inject more intense longer bunches into the LHC and to have bunch length leveling
- ★ Potential first design of the 200 MHz SC cavities that would work from injection to store.  
<http://cern.ch/rcalaga/LHCRF/PrelimDraft.pdf>
- ★ Merits:  $2.5 \times 10^{11}$  ppb,  $\sigma_z = 15$  cm, lower e-cloud, bunch length leveling and significantly lower heating for most LHC devices.

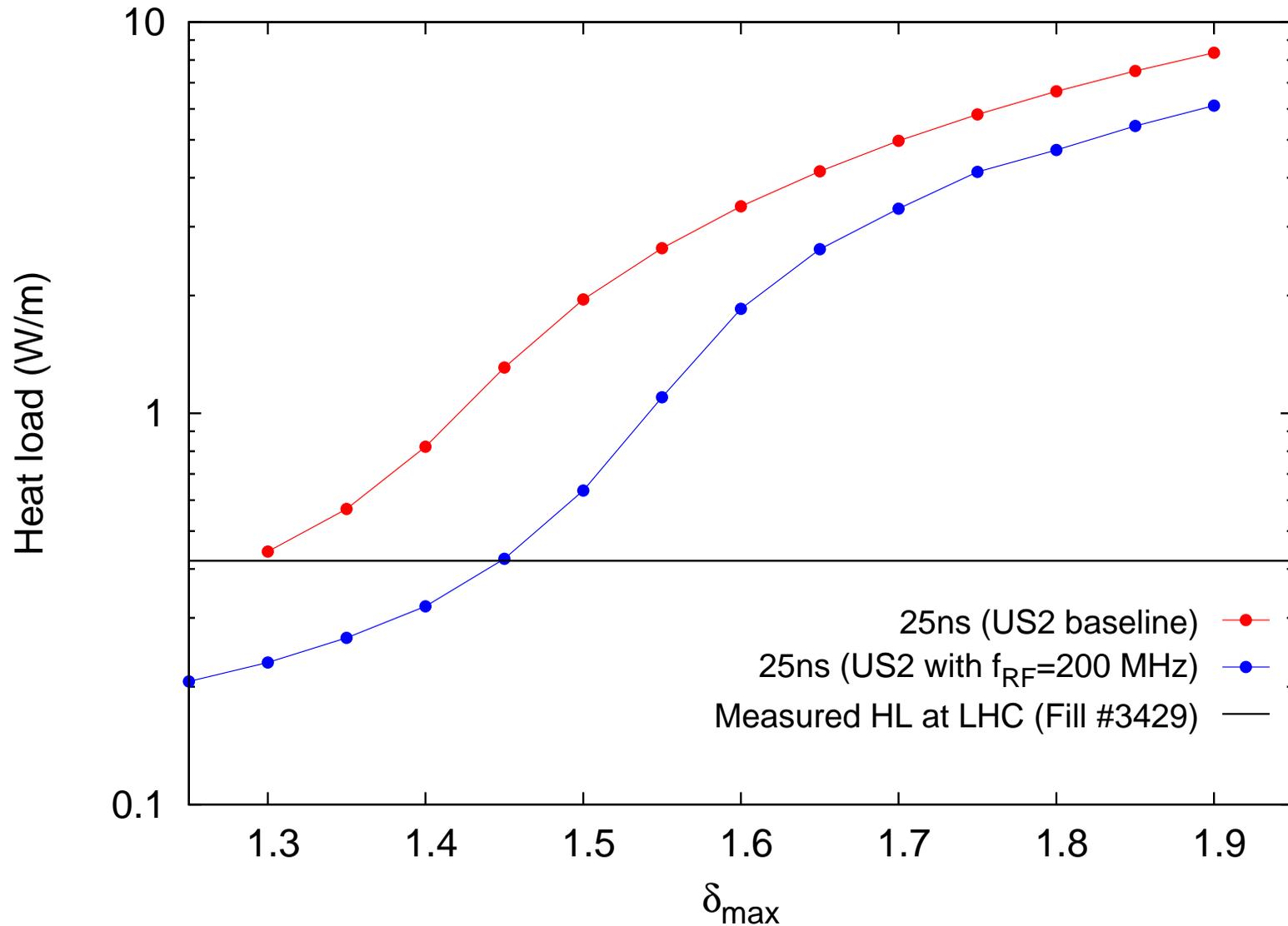
# Alternative 2: SC 200 MHz in LHC

R. Calaga



The 200 MHz SC quarter-wave cavity is even smaller than the current 400 MHz.

# 200 MHz ( $\sigma_z=15$ cm) has lower e-cloud

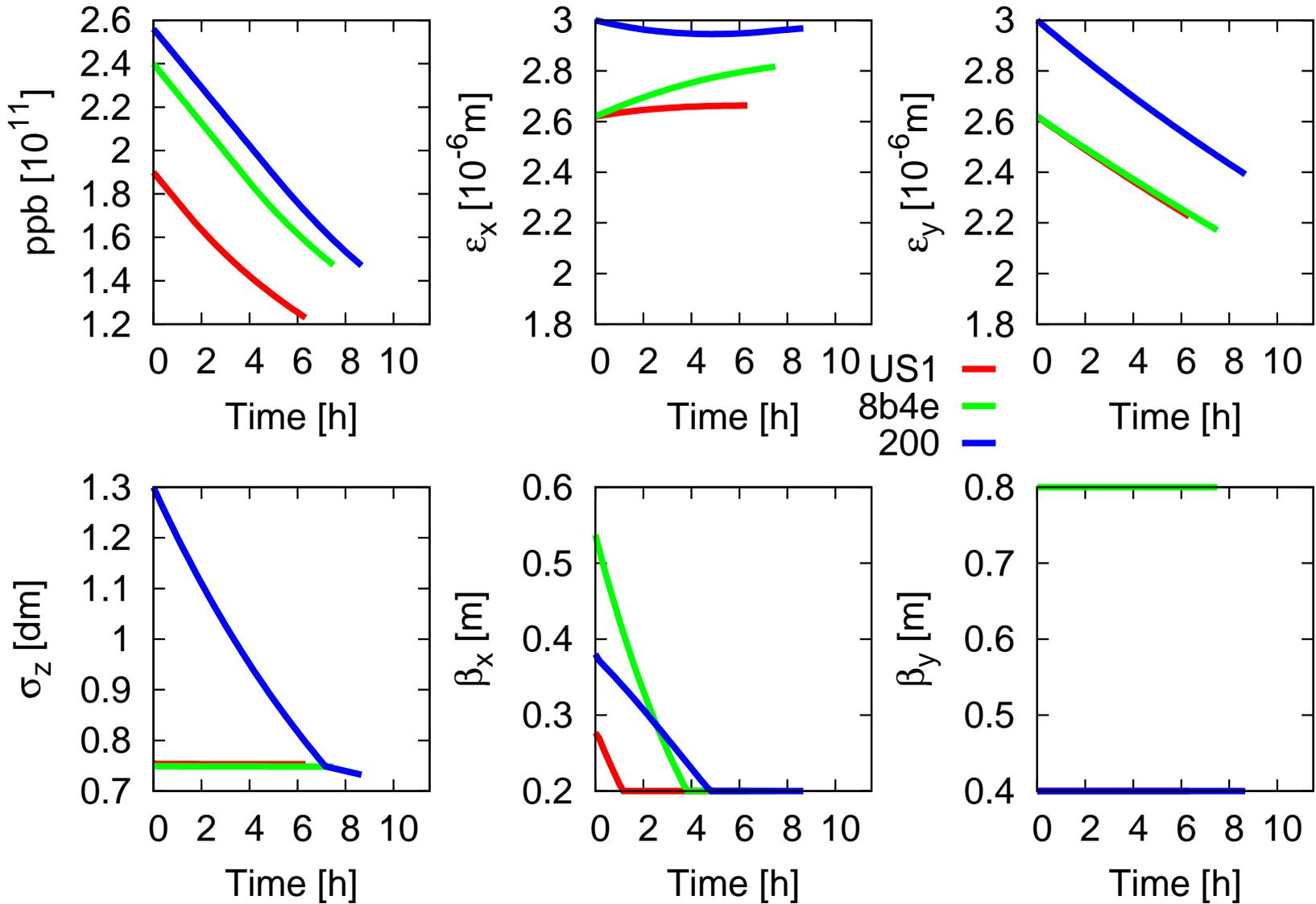


# US1 performance

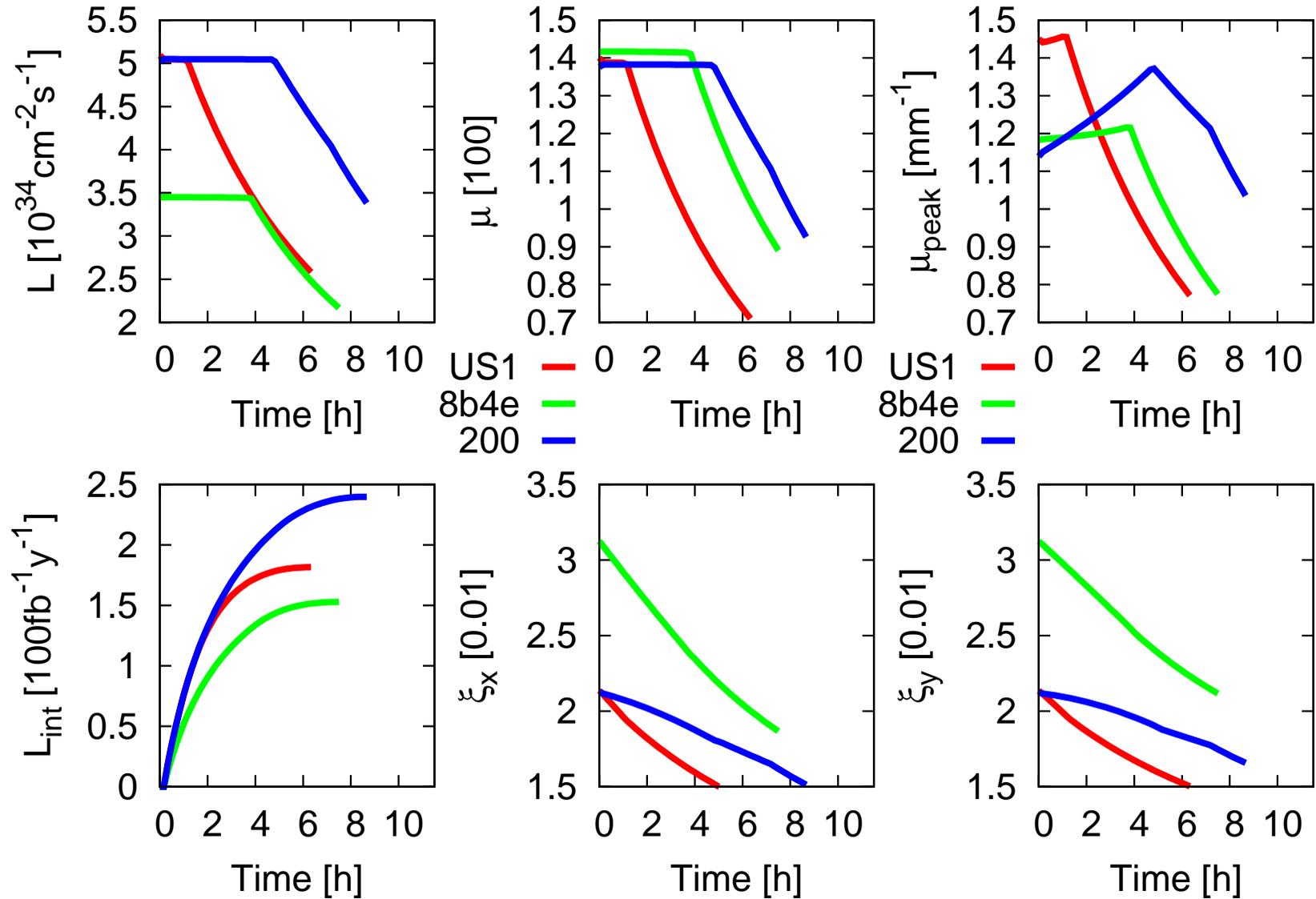
	N	$\epsilon$	$\beta_{x,y}^*$	$L_{year} [fb^{-1}]$		fill	Pile-up	
	$10^{11}$	$[\mu m]$	$[cm]$	Opt.	6h	$[h]$	$[\frac{1}{mm}]$	
US1	1.9	2.62	20,40	181	181	6.1	140	1.5
flatter	1.9	2.62	20,80	169	168	6.6	128	1.1
8b4e	2.4	2.62	20,80	153	150	7.3	141	1.2
50ns	3.5	3.0	20,80	142	118	12	143	1.1
200MHz	2.56	3.0	20,80	232	224	8.1	138	1.1
200MHz	2.56	3.0	20,40	<b>240</b>	228	8.5	138	1.4

8b4e still better than 50ns. 200 MHz has excellent performance also with lower e-cloud than nominal.

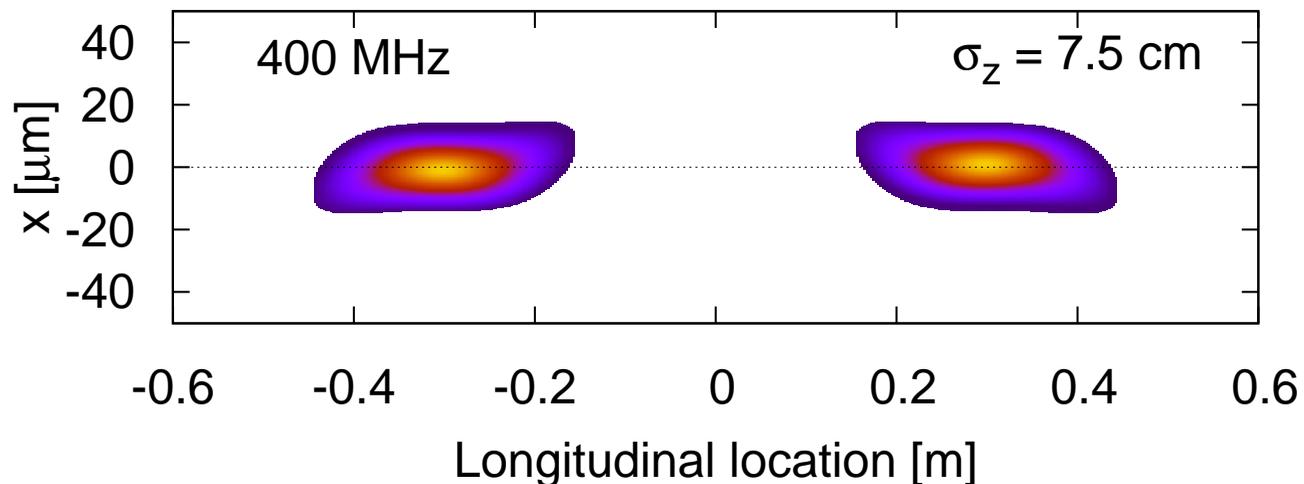
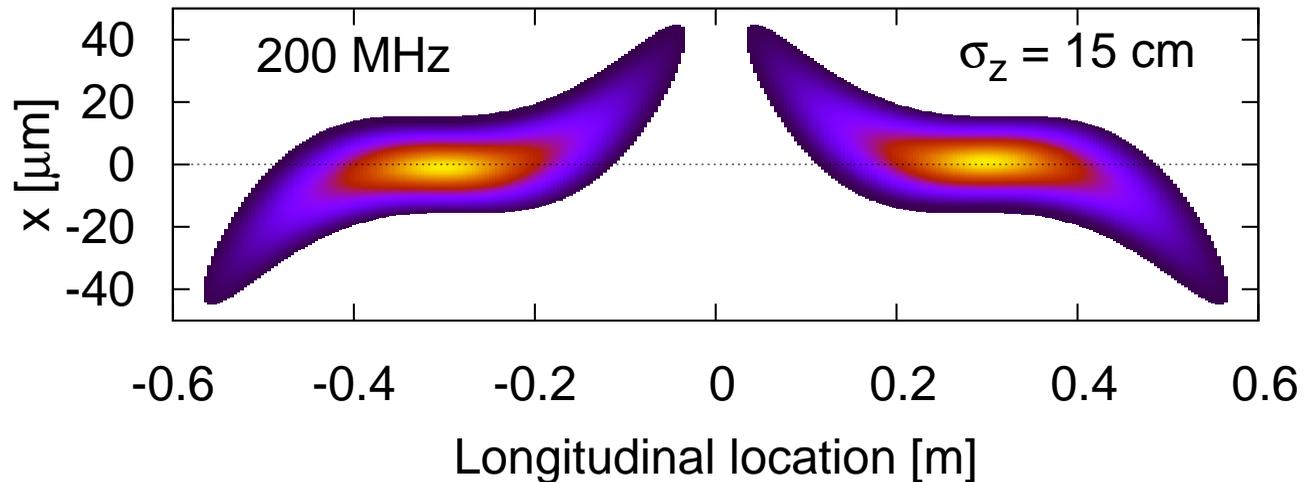
# US1 fill comparison I



# US1 fill comparison II



# US2: CC with 200 MHz?



$2\sigma$  envelopes with  $\beta^* = 15$  cm. CC RF curvature reduces overlap above  $1\sigma$  for 200 MHz.

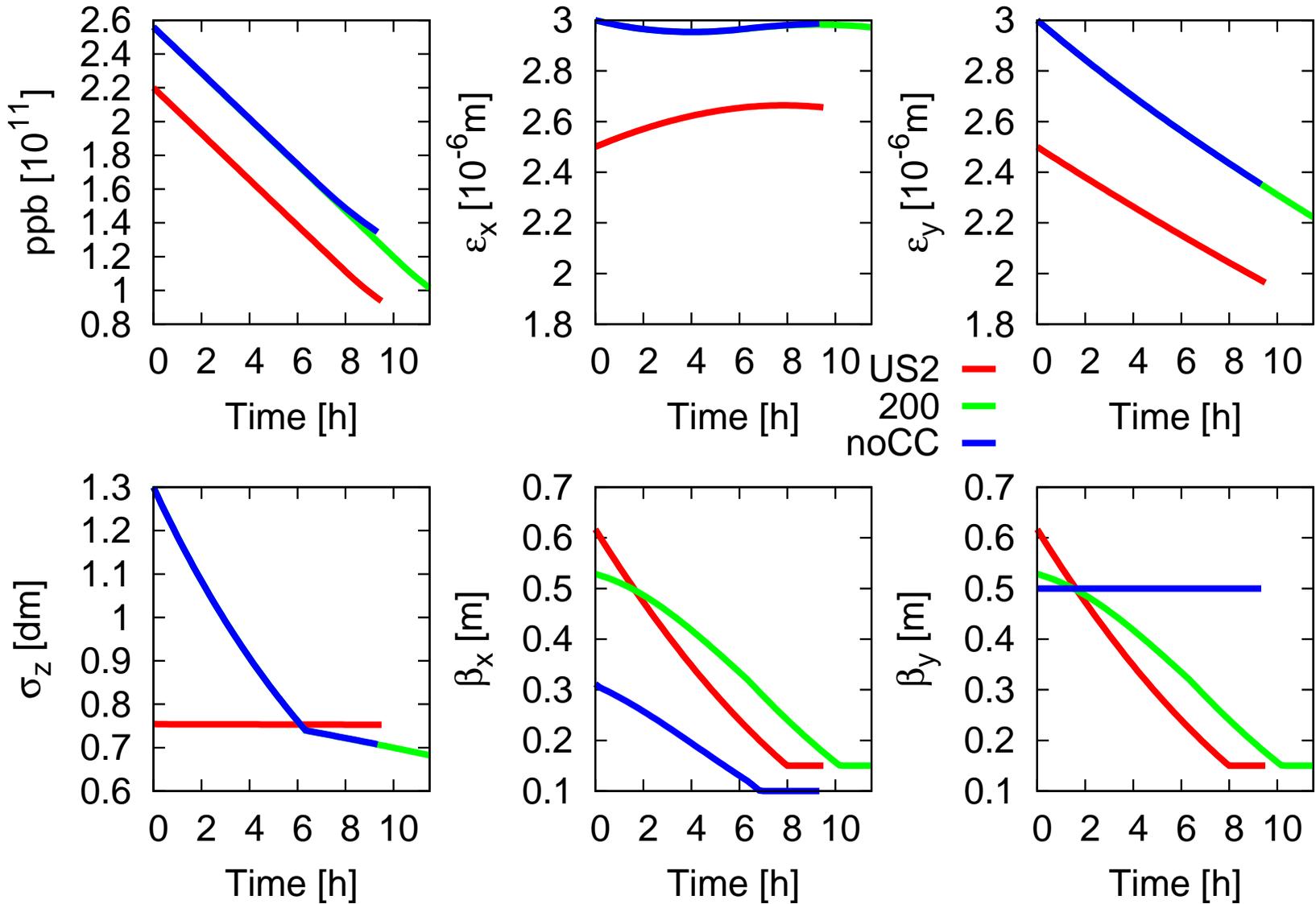
# US2 performance

	N	$\epsilon$	$\beta_{x,y}^*$	$L_{year} [fb^{-1}]$		fill	Pile-up	
	$10^{11}$	$[\mu m]$	$[cm]$	Opt.	6h	$[h]$	$[\frac{1}{mm}]$	
US2	2.2	2.5	15,15	261	232	9.3	140	1.2
200MHz	2.56	3.0	15,15	<b>276</b>	234	11	140	1.3
200MHz (no CC)	2.56	3.0	10,50	255	233	10	139	1.6

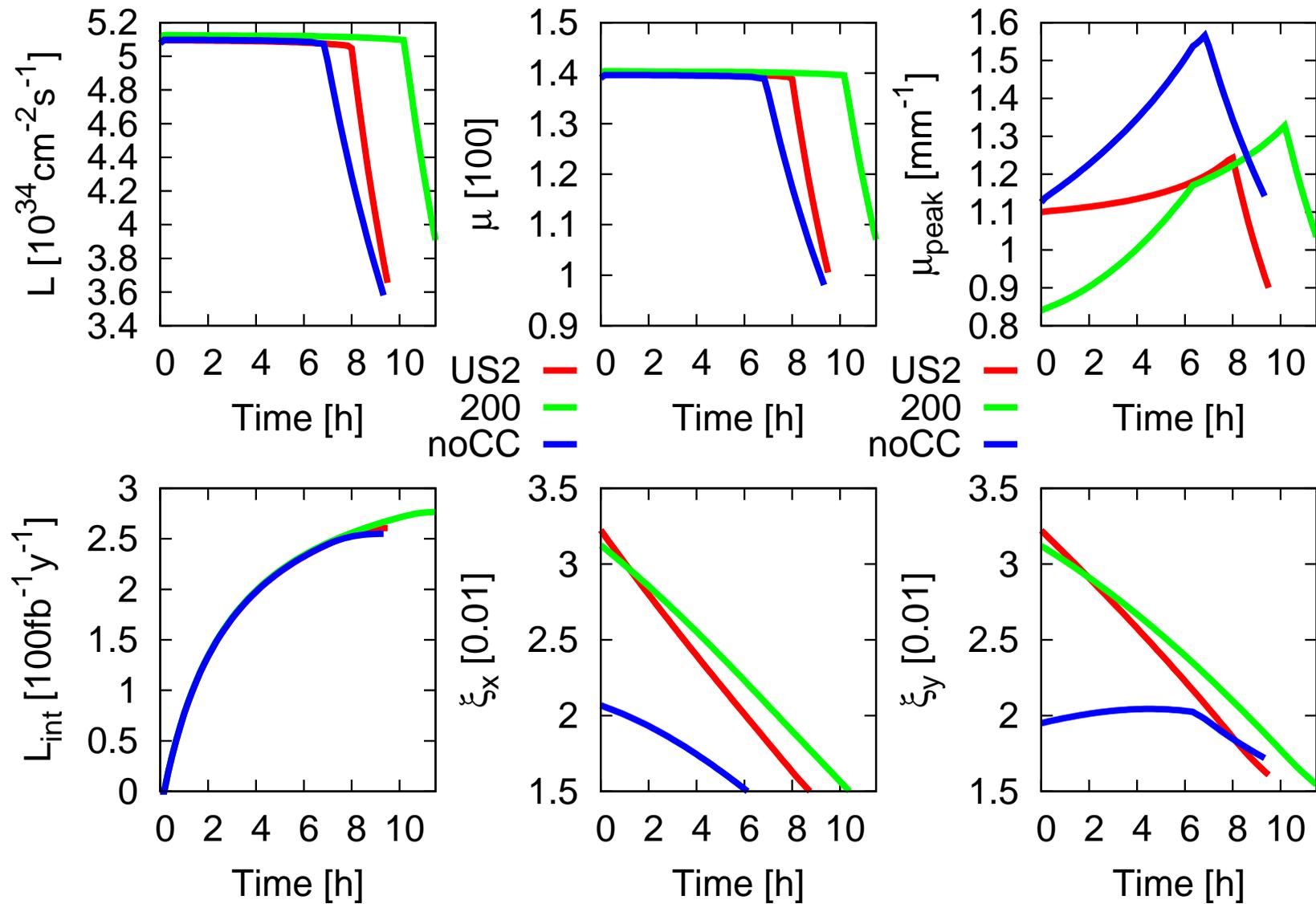
**200 MHz with CC gives the best performance** with lower e-cloud and it is robust against non-working CCs.

Can we improve the pile-up density?

# US2 fill comparison I



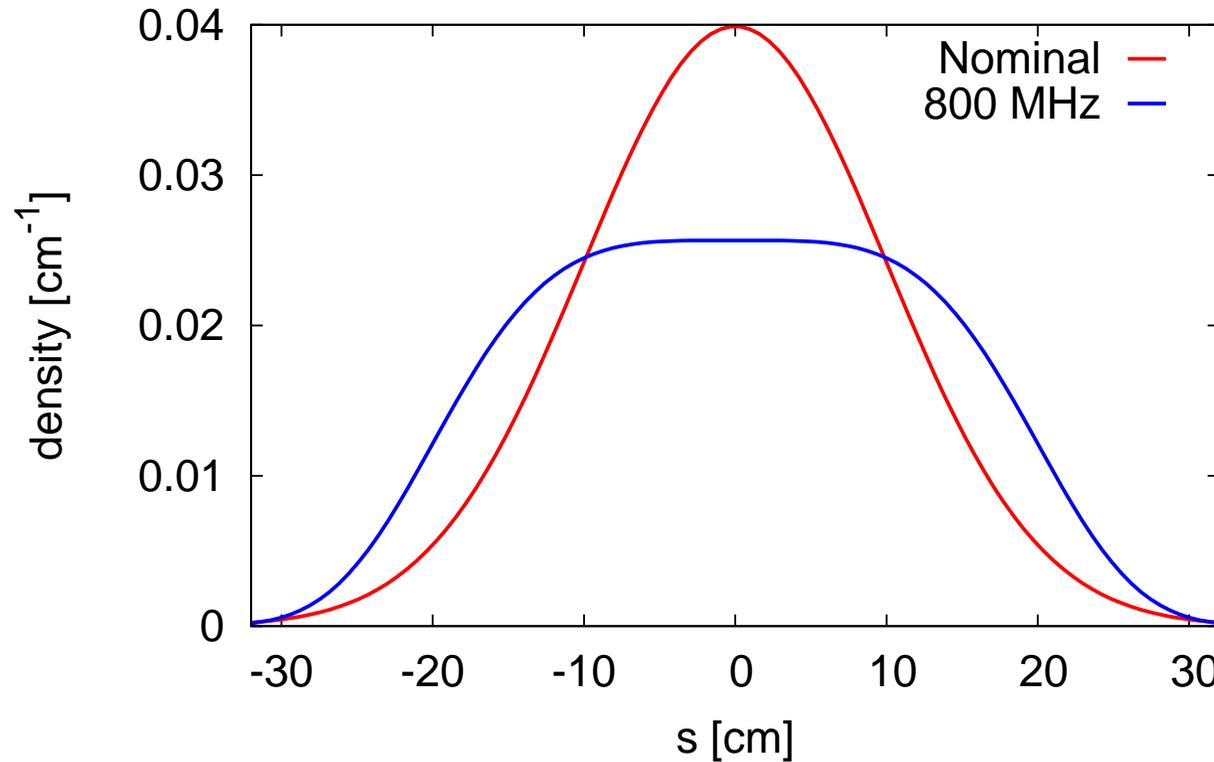
# US2 fill comparison II



# Pile-up density leveling?

- ★ The 1<sup>st</sup> proposal for pile-up density leveling was crab kissing (S. Fartoukh)
- ★ In general, we can level at constant pile-up density rather than at constant luminosity
- ★ This implies lower integrated luminosity
- ★ There are four options:
  - $\beta^*$  leveling with  $\sigma_z=10$  cm
  - 800MHz +  $\beta^*$  leveling
  - Crab kissing
  - 800MHz + Crab kissing

# 800 MHz - bunch profile



Assuming 8 MV 800 MHz system to provide 10-12.5 cm rms bunch length.

# Pile-up leveling in US2 nominal

	N	$\epsilon$	$\beta_{x,y}^*$	$L_{year} [fb^{-1}]$		fill	Pile-up	
	$10^{11}$	$[\mu m]$	[cm]	Opt.	6h	[h]		$[\frac{1}{mm}]$
US2	2.2	2.5	15,15	261	232	9.3	140	1.2
$\beta^*$ -level	2.2	2.5	15,15	250	232	9.5	142	1.0
800MHz	2.2	2.5	15,15	252	232	9.1	141	0.9

Peak pile-up density can be leveled to  $1.0 \text{ mm}^{-1}$  without any new hardware and with little loss in performance. A new 8 MV 800 MHz system can slightly help to reduce the pile-up density.

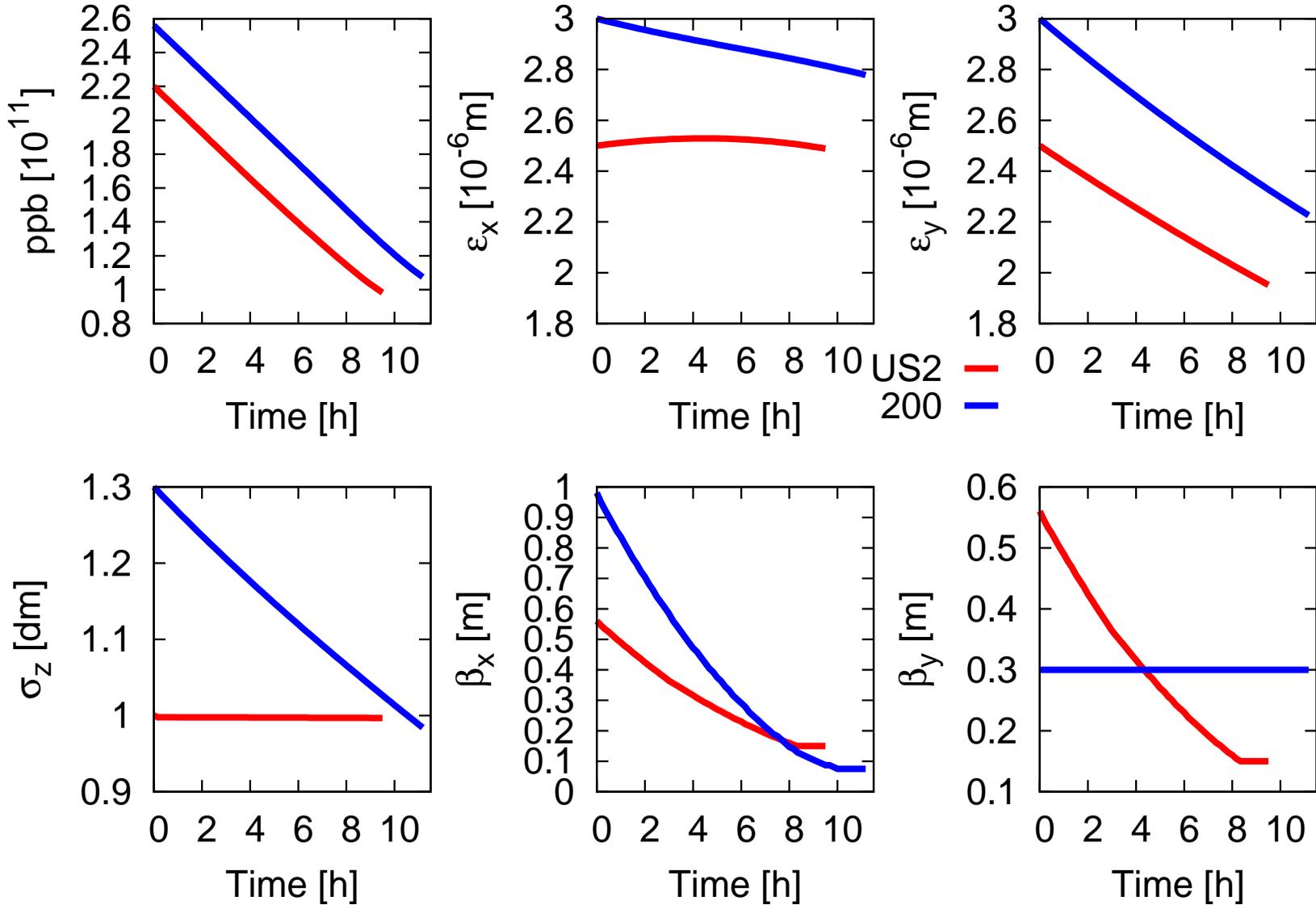
# Pile-up leveling in US2 with 200 MHz

The first step in 200 MHz is to have a minimum bunch length of 10 cm with flat  $\beta^*=7.5$ , 30 cm, then leveling pile-up density with  $\beta^*$  is also possible.

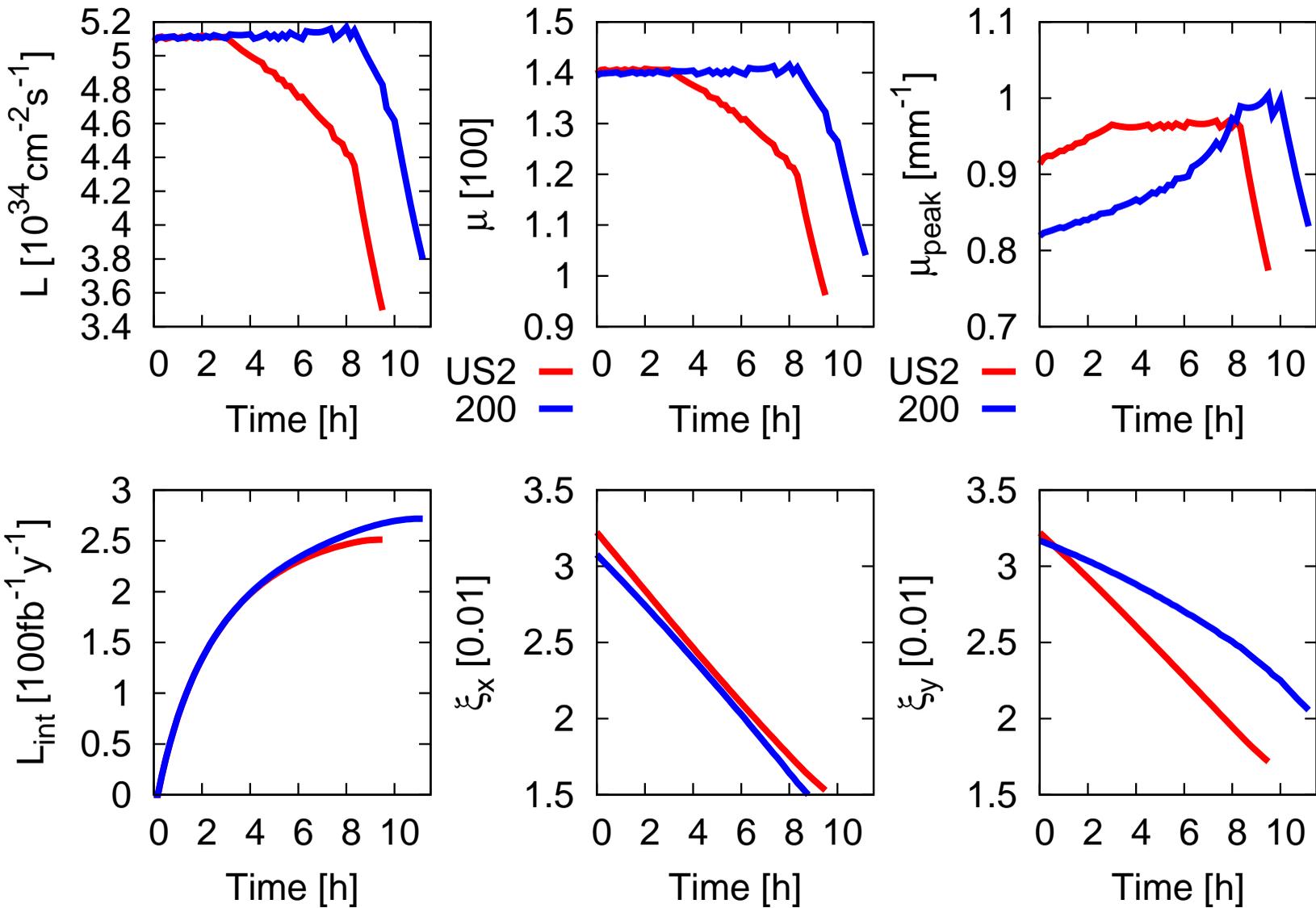
	N $10^{11}$	$\epsilon$ [ $\mu m$ ]	$\beta_{x,y}^*$ [cm]	$L_{year} [fb^{-1}]$		fill [h]	Pile-up	
				Opt.	6h			[ $\frac{1}{mm}$ ]
200MHz	2.56	3.0	15,15	276	234	11	140	1.3
$\sigma_z$ 10cm	2.56	3.0	7.5,30	272	233	11	140	1.1
$\beta^*$ -level	2.56	3.0	7.5,30	272	233	10	141	1.0

Pile-up density can also be leveled to  $1 \text{ mm}^{-1}$  with the 200 MHz.

# US2 $\beta^*$ Leveling comparison I



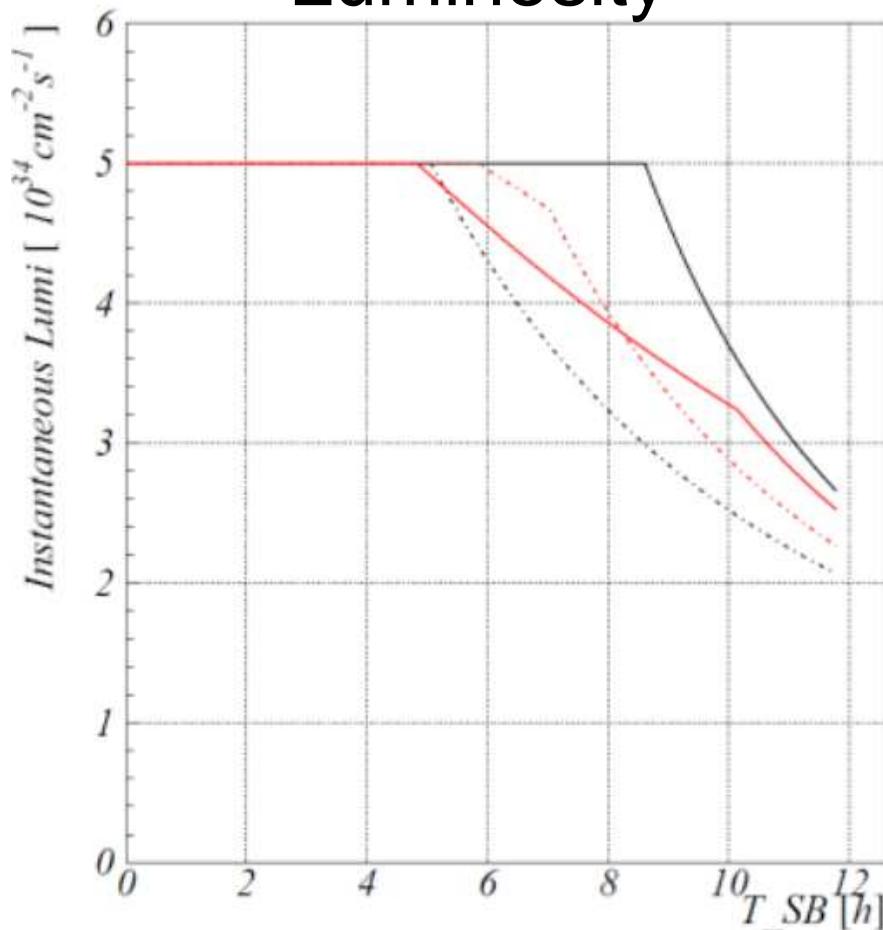
# US2 $\beta^*$ Leveling comparison II



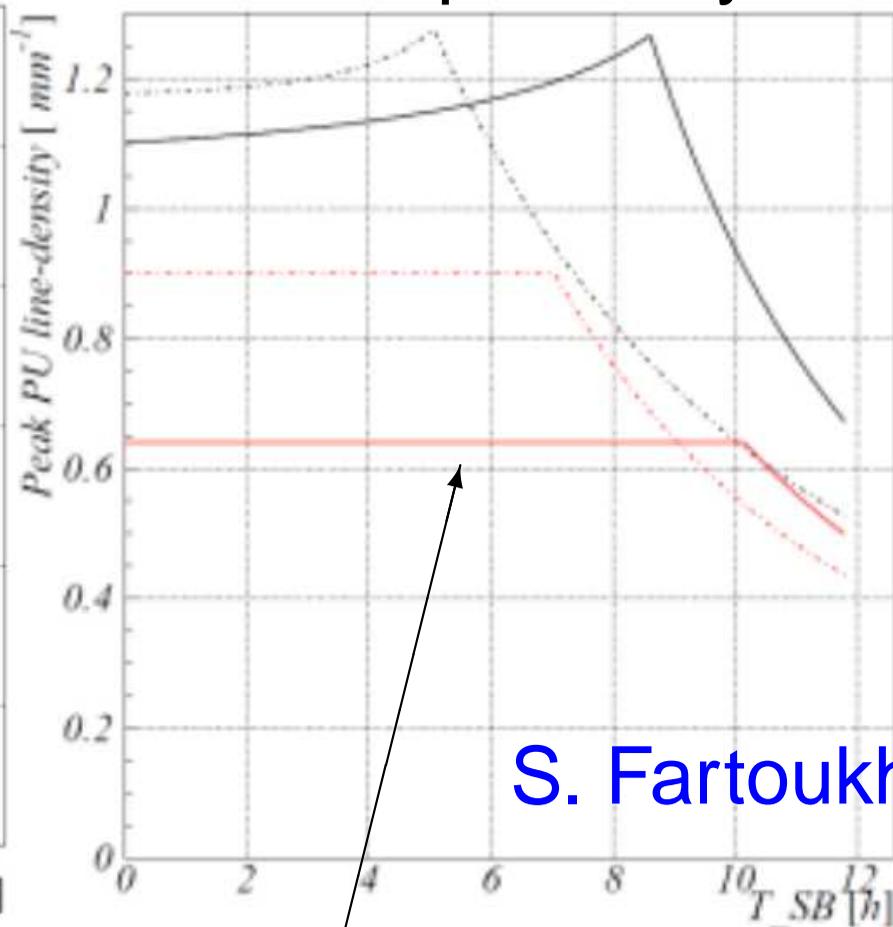
# Crab kissing



## Luminosity



## Pile-up density



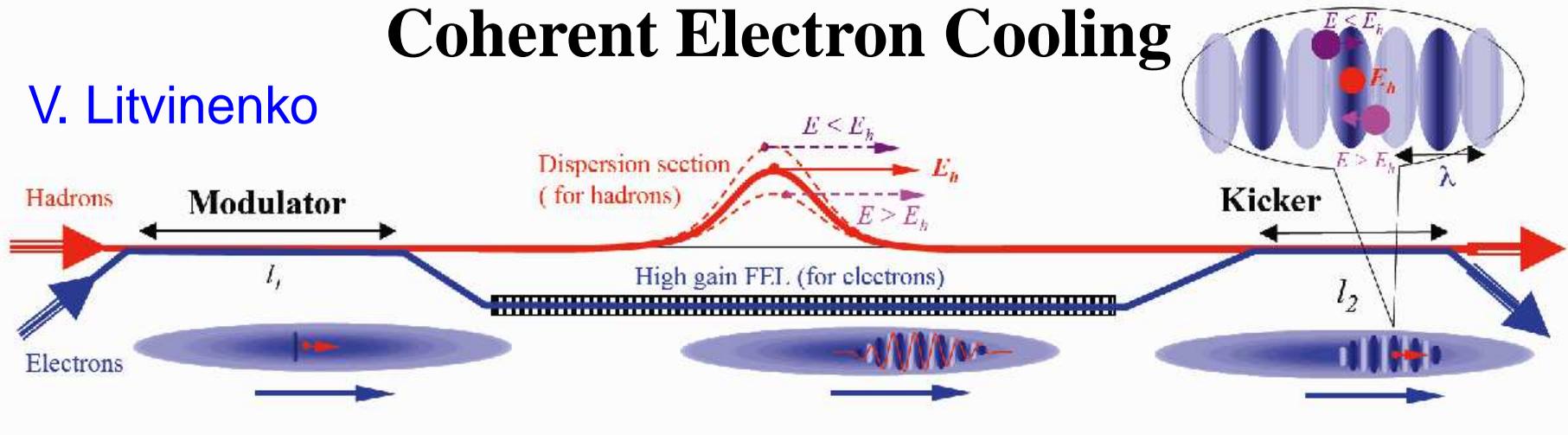
S. Fartoukh

Using CCs also in the separation plane + 800 MHz pile-up density can be leveled down to  $0.65 \text{ mm}^{-1}$ .

# Exotic alternatives for US2

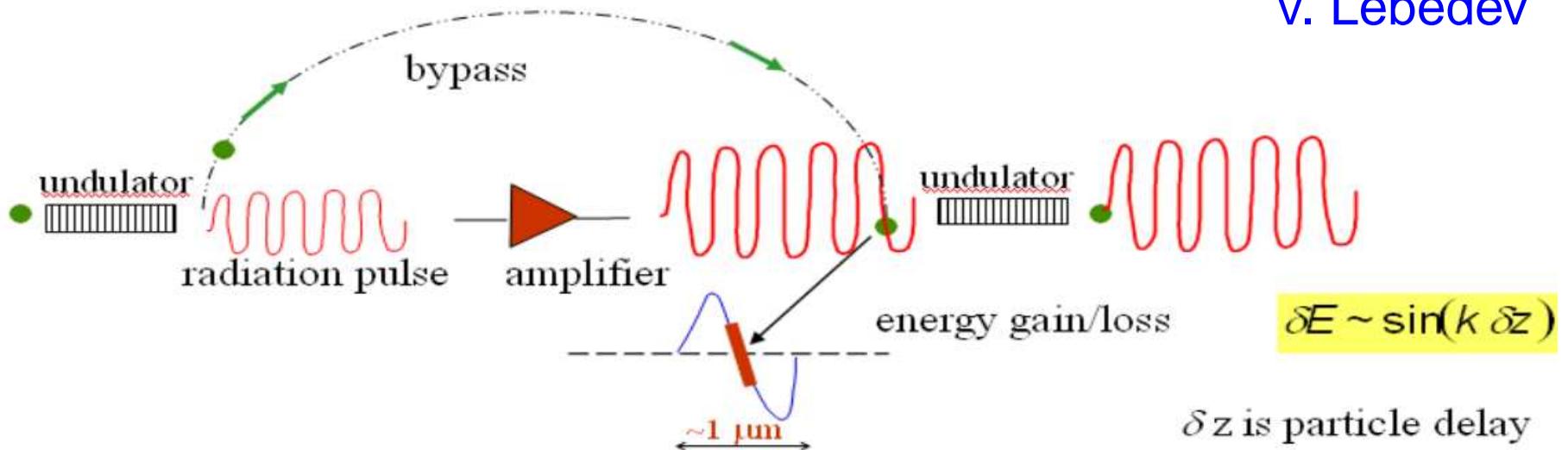
## Coherent Electron Cooling

V. Litvinenko



## Optical Stochastic Cooling

V. Lebedev



# Exotic alternatives for US2

- ★ CEC or OSC at store:
  - Promising performance
  - Challenging hardware, 3 GeV e- for CEC, 60 m undulators for both CEC and OSC
  - Never demonstrated
- ★ Coherent electron cooling at injection:
  - 1 hour cooling at injection to halve  $\epsilon$
  - LHeC ERL test facility as cooler
  - Never demonstrated, IBS still there
  - Performance improvement is marginal
- ★ Experimental tests planned in BNL and FNAL

# Summary & Outlook

- ★ 200 MHz gives the best performance and robustness with lower e-cloud than nominal.
- ★ 8b4e still better than 50ns.
- ★ Pile-up density leveling with  $\beta^*$  in US2  $\lesssim 1 \text{ mm}^{-1}$  possible without any extra hardware (similar for 200 MHz alternative)
- ★ 800 MHz system can slightly reduce pile-up to  $\approx 0.9 \text{ mm}^{-1}$
- ★ Crab kissing levels pile-up density to  $0.65 \text{ mm}^{-1}$  (uses CCs also in separation plane and 800 MHz system)