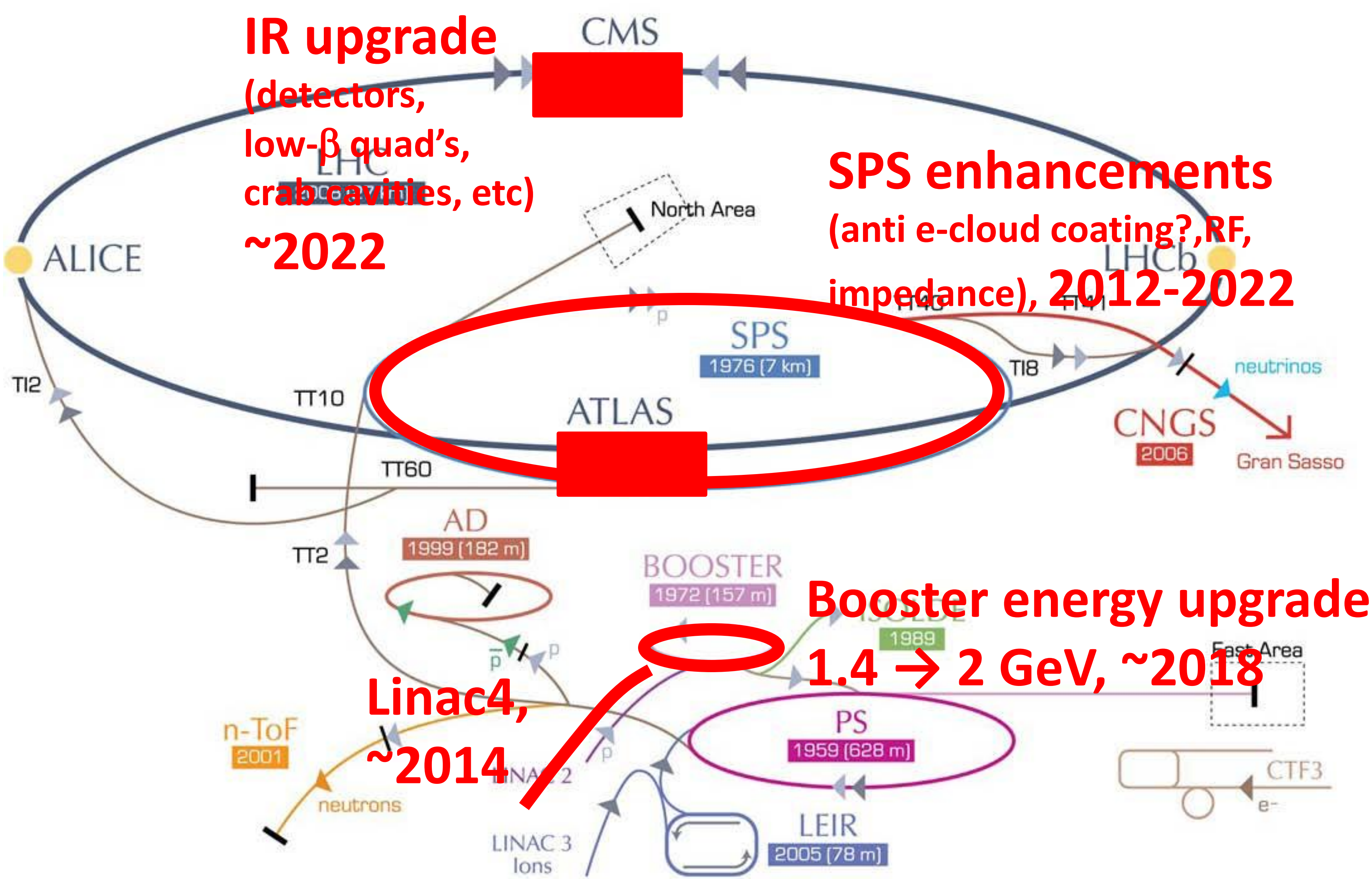
Upgrade Beam Parameter Space

Frank Zimmermann

LHC-CC11 - 5th LHC Crab-Cavity workshop

CERN, 15 November 2011

HL-LHC – LHC modifications



HL-LHC goals

- Leveled peak luminosity: $L = 5\ 10^{34}\ cm^{-2}\ s^{-1}$
- Virtual peak luminosity: $L = 10\ 10^{34}\ cm^{-2}\ s^{-1}$
- Integrated luminosity: 200 fb^{-1} to 300 fb^{-1} per year
- Total integrated luminosity: ca. 3000 fb^{-1} by 2030

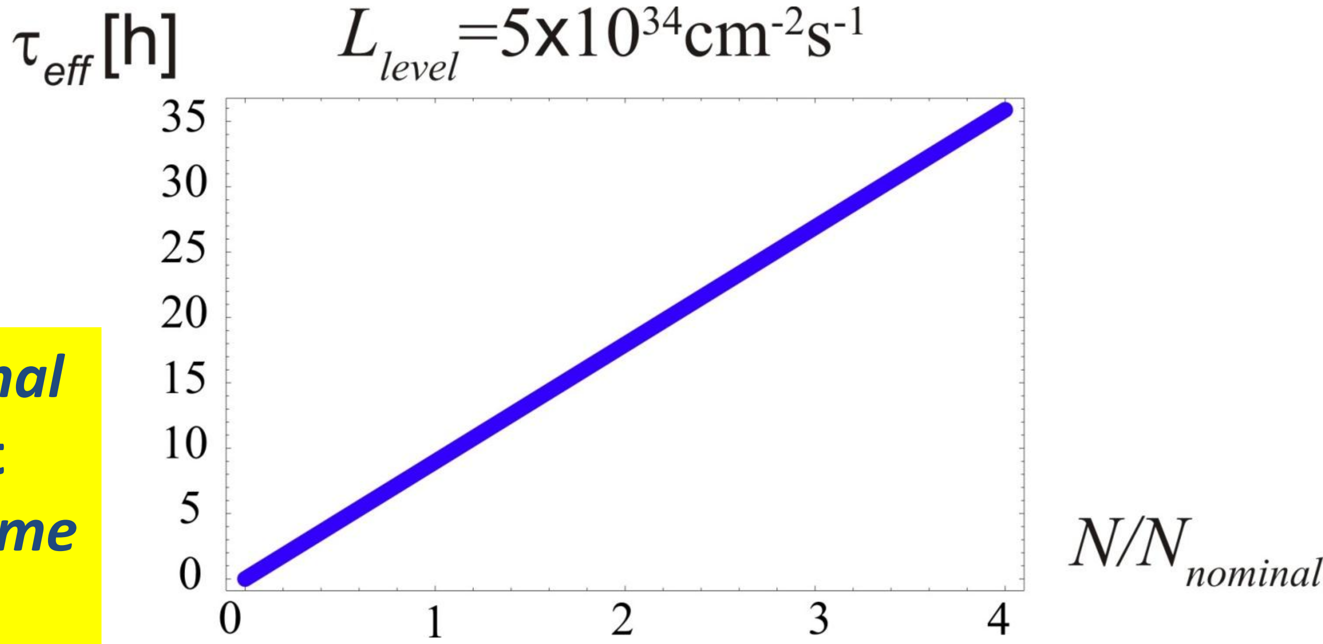
effective beam lifetime

for given luminosity

τ_{eff} scales with total beam current

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_{eff}} = -n_{IP}\sigma L_{lev}$$ (σ=100 mbarn)

$$\tau_{eff} = \frac{N_{tot}}{n_{IP}\sigma L_{lev}}$$

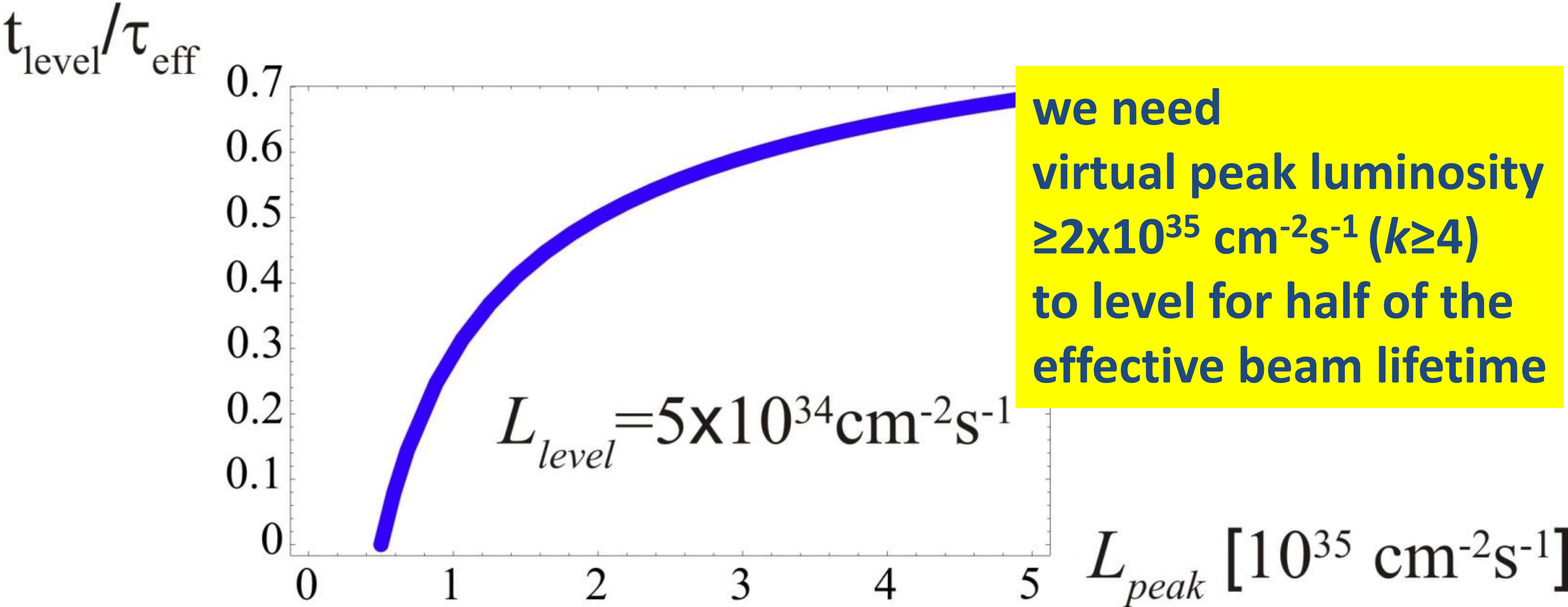


we need ≥ 2 x *nominal total intensity* to get *effective beam lifetime* ≥15 h

maximum leveling time

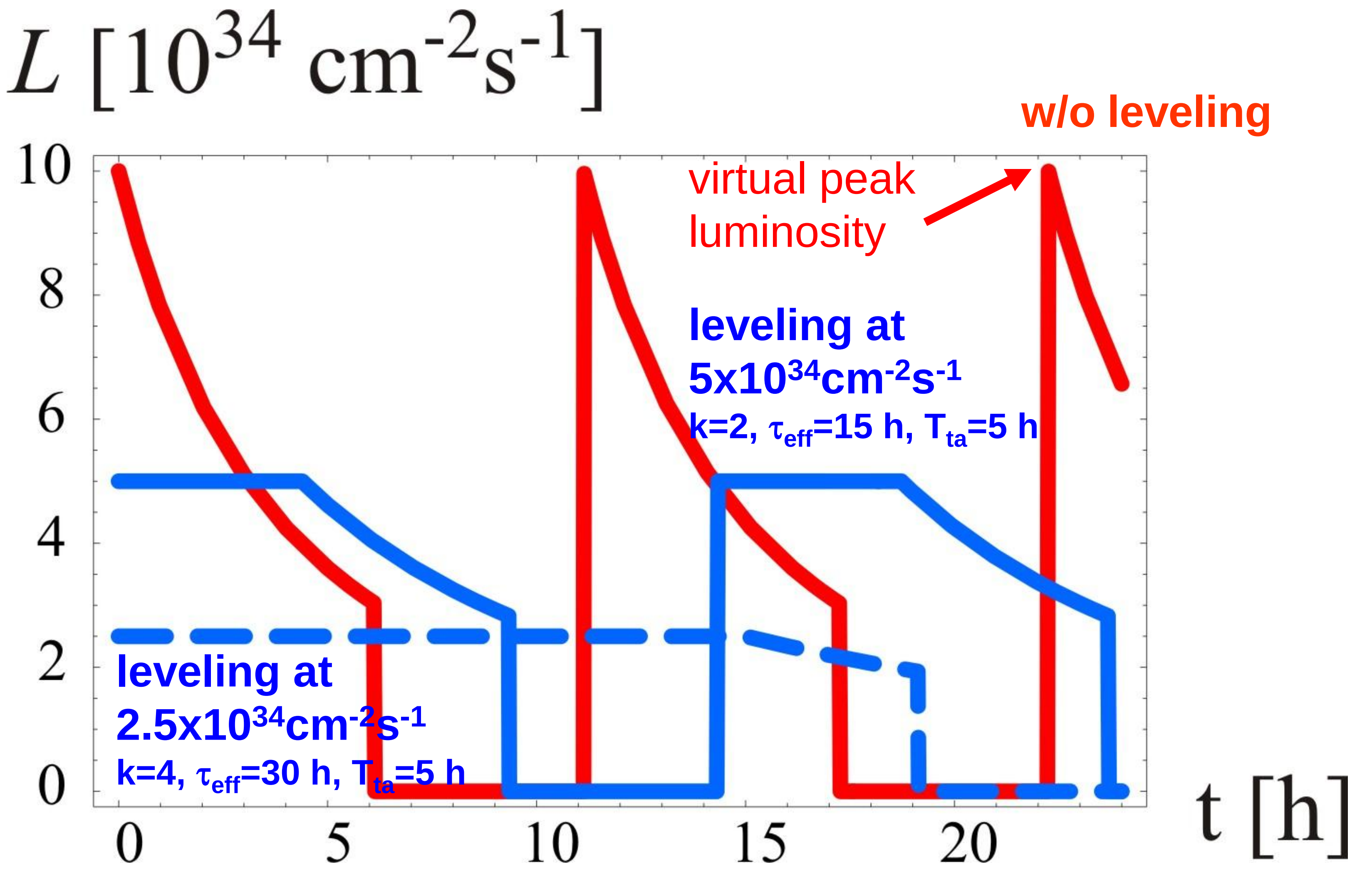
$\hat{L} = kL_{lev}$ virtual peak luminosity

$$t_{lev} = \tau_{eff}\left(1 - \frac{1}{\sqrt{k}}\right)$$

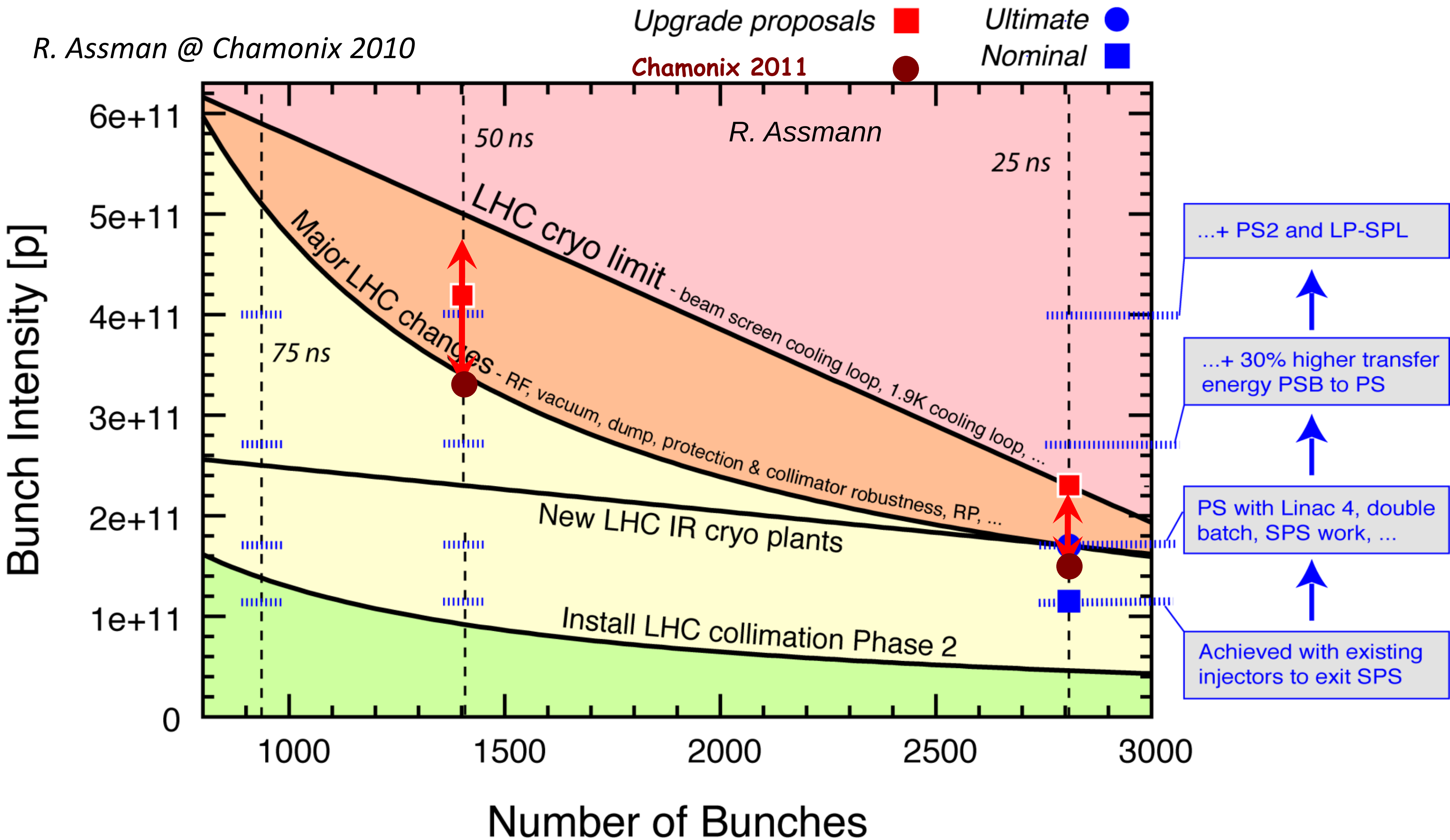


we need virtual peak luminosity ≥2x10^{35} cm^{-2}s^{-1} (*k*≥4) to level for half of the effective beam lifetime

luminosity leveling at the HL-LHC



LHC Intensity Limits (7 TeV)



Ideal scenario: no imperfections included!

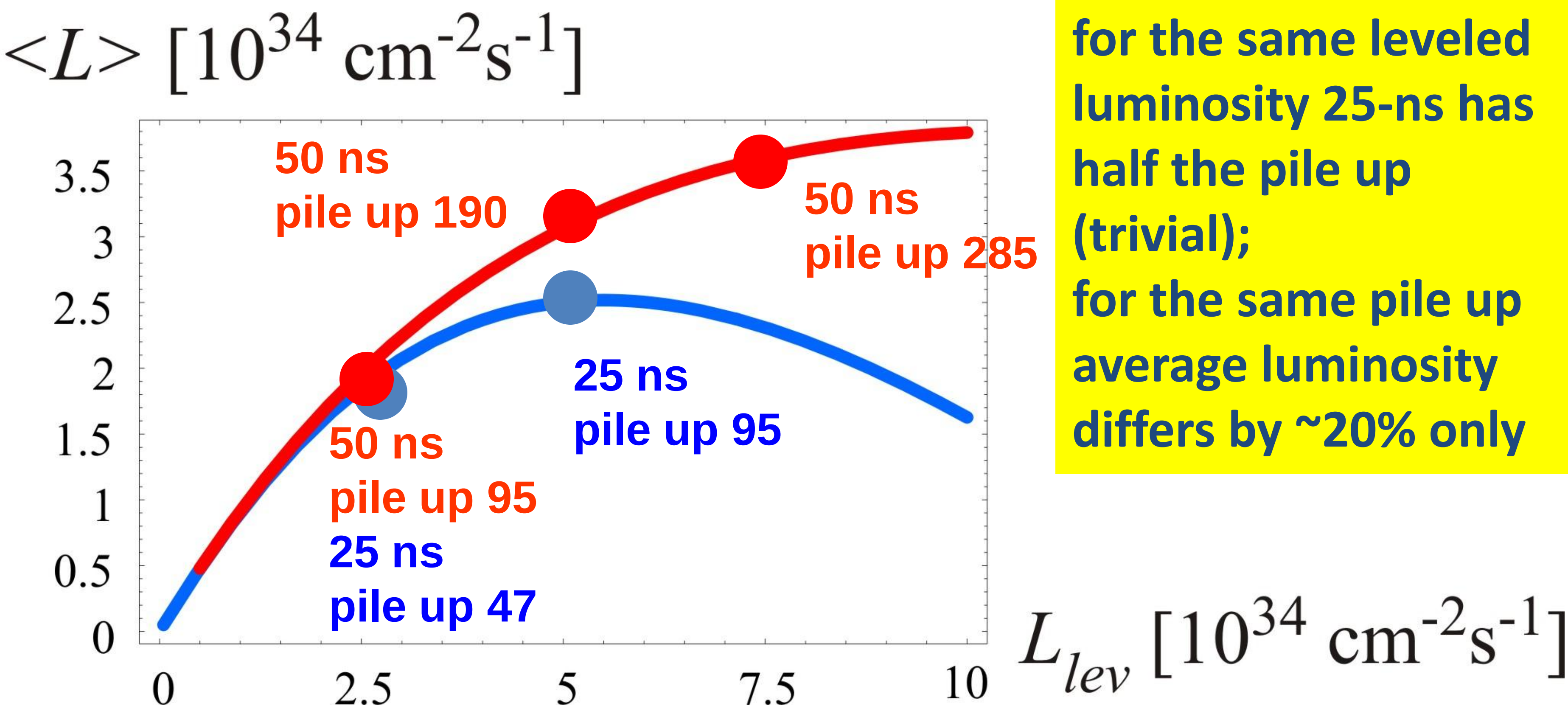
Note: Some assumptions and conditions apply…

example HL-LHC parameters

Chamonix ‘11

parameter	symbol	**nom.**	nom.*	**25 ns, crab, lrc**	**50 ns, crab, lrc**
protons per bunch	N_b [10^{11}]	**1.15**	1.7	**1.7**	**3.4**
bunch spacing	Δt [ns]	**25**	50	**25**	**50**
beam current	I [A]	**0.58**	0.43	**0.86**	**0.86**
rms bunch length	σ_z [cm]	**7.55**	7.55	**7.55**	**7.55**
beta* at IP1&5	β^* [m]	**0.55**	0.55	**0.15**	**0.15**
full crossing angle	θ_c [μrad]	**285**	285	**425**	**425**
normalized mittance	$\gamma\varepsilon$ [μm]	**3.75**	3.75	**2.8**	**2.8**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$	**0.65**	0.65	**2.13**	**2.13**
tune shift	ΔQ_{tot}	**0.009**	0.0136	**0.006-0.011**	**0.012-0.015**
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**9.6**	**19.3**
actual (leveled) pk luminosity	L_{lev} [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**5**	**5 (2.5)**
events per #ing		**19**	40	**95**	**190 (95)**
effective lifetime	τ_{eff} [h]	**44.9**	30	**13.3**	**13.3 (26.6)**
level time / run time	$t_{level,run}$ [h]	**15.2**	12.2	**3.7 / 8.6**	**6.5 / 10.1 (16.4)**
e-c heat SEY=1.2	P [W/m]	**0.2**	0.1	**0.4**	**0.3**
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	**0.32**	0.30	**0.58**	**0.91**
IBS ε rise time (*z*, *x*)	$\tau_{IBS,z/x}$ [h]	**58, 104**	39, 70	**71, 60**	**36, 30**
annual luminosity	L_{int}[fb^{-1}]	**57**	58	**259**	**317 (204)**

trade off: integrated lumi ↔ pile up



for the same leveled luminosity 25-ns has half the pile up (trivial);
for the same pile up average luminosity differs by ~20% only

roughly for 2 times more integrated luminosity 4 times the pile up

beam intensity & spacing

total intensity up 6×10^{14} per beam

corresponding to >1 A beam current

bunch spacing: 50 ns or 25 ns

- exotic options 12.5 ns or 15 ns

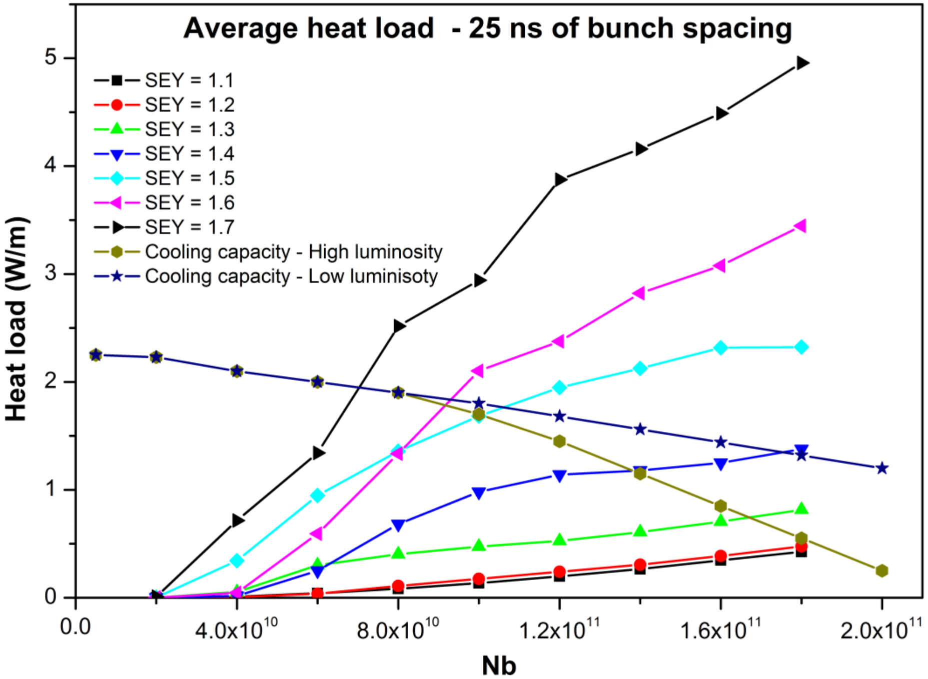
bunch population:

up to N_b=2×10^{11} at 25 ns

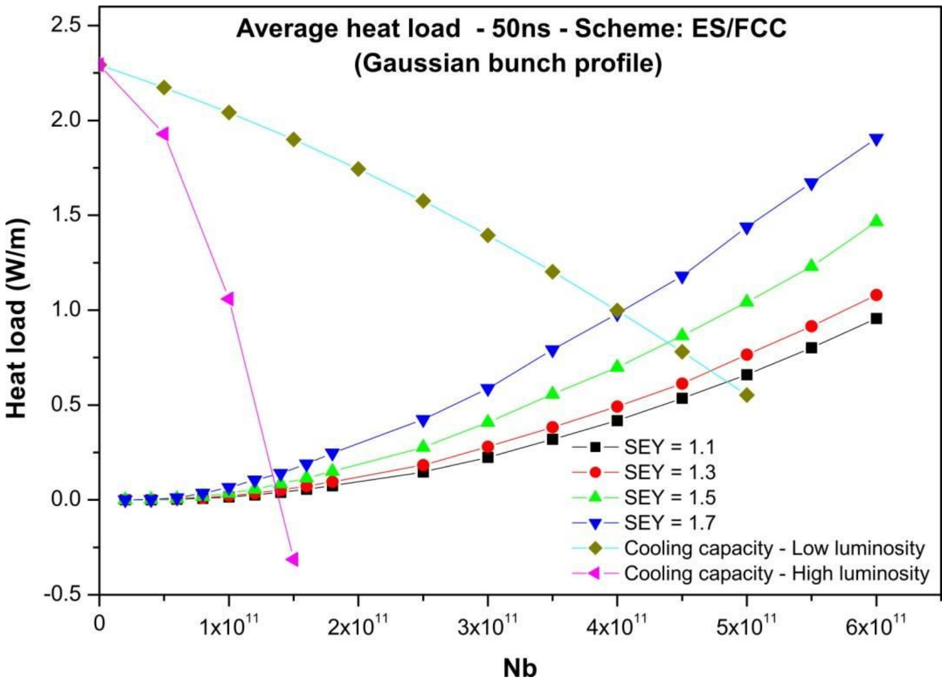
up to N_b=3.5×10^{11} at 50 ns

electron-cloud heat load (at 7 TeV)

25-ns bunch spacing



50-ns bunch spacing



H. Maury
L. Tavian

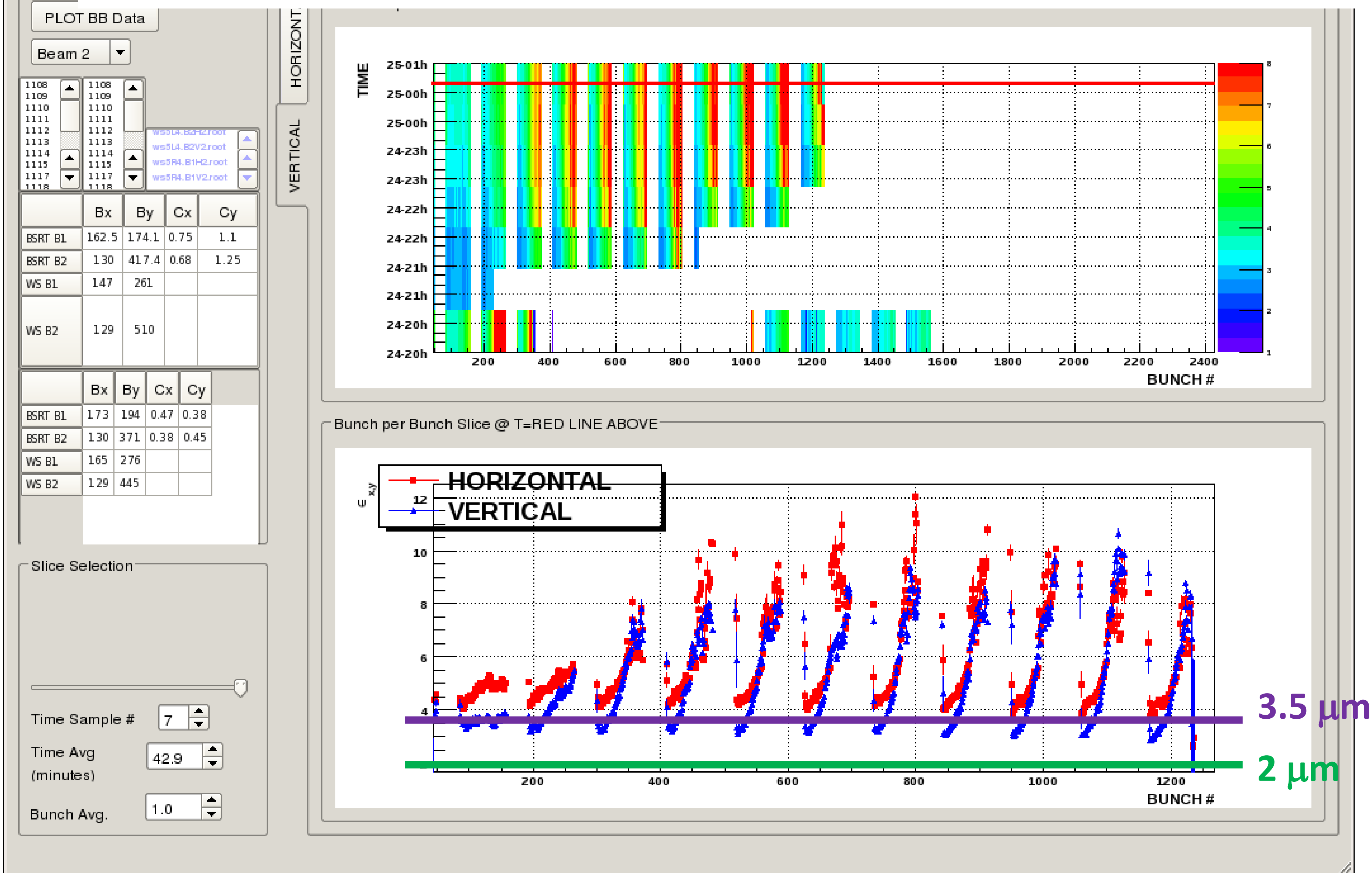
dedicated IR cryo plants needed;

50 ns much easier than 25 ns;

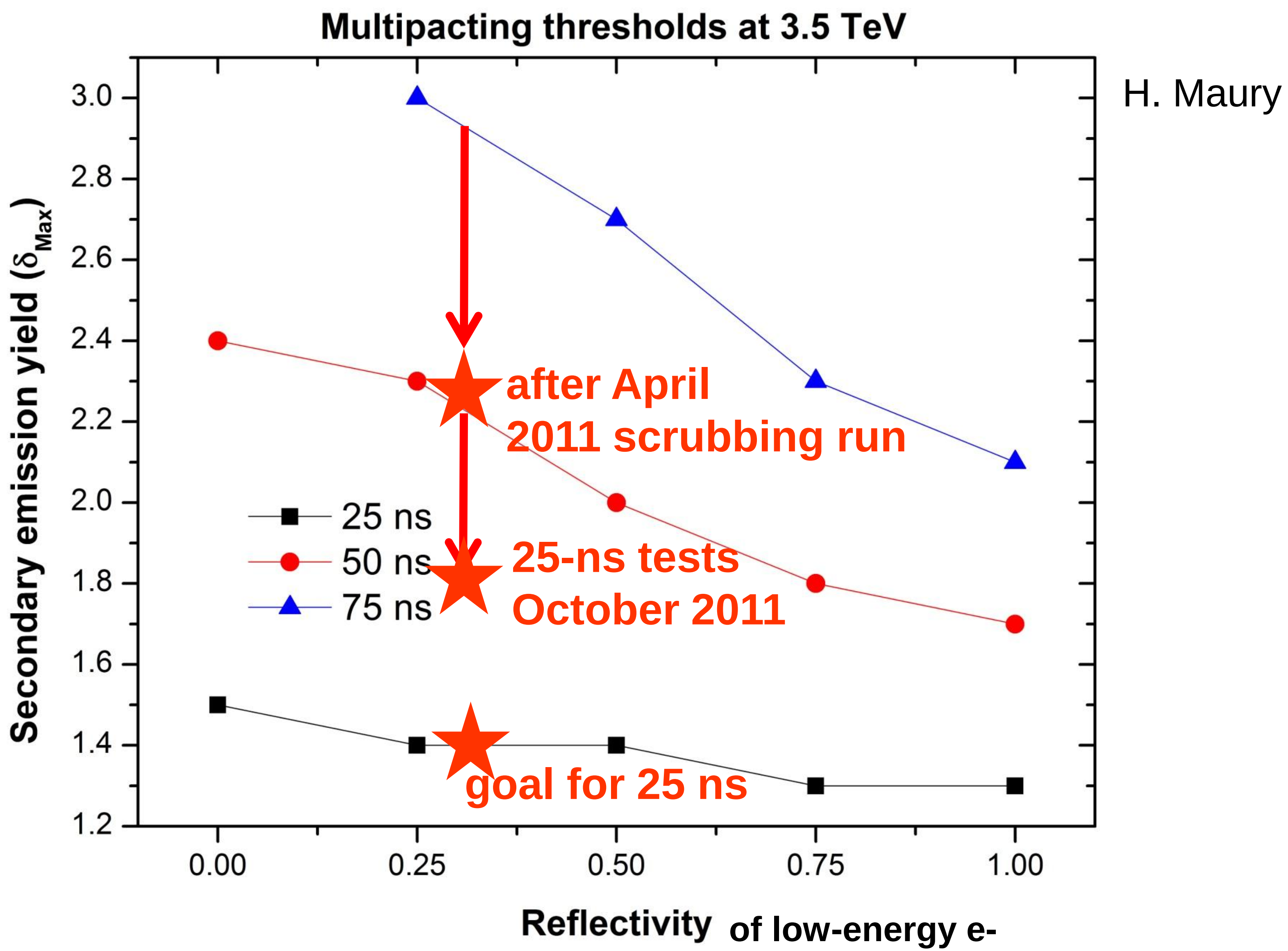
at 25 ns electron cloud contribution acceptable if $\delta_{max} \leq 1.2$

e-cloud emittance blow up with 25 ns

MD October 2011



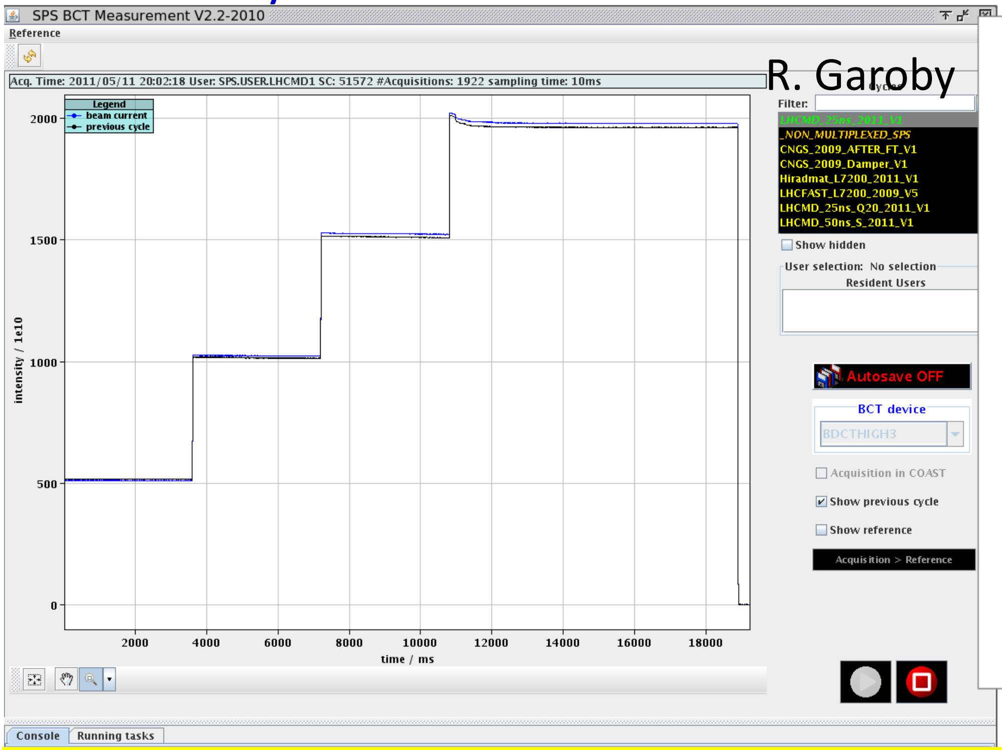
electron cloud scrubbing – LHC arcs



emittance

SPS: 50-ns bunch train – double PSB batch injection May 2011

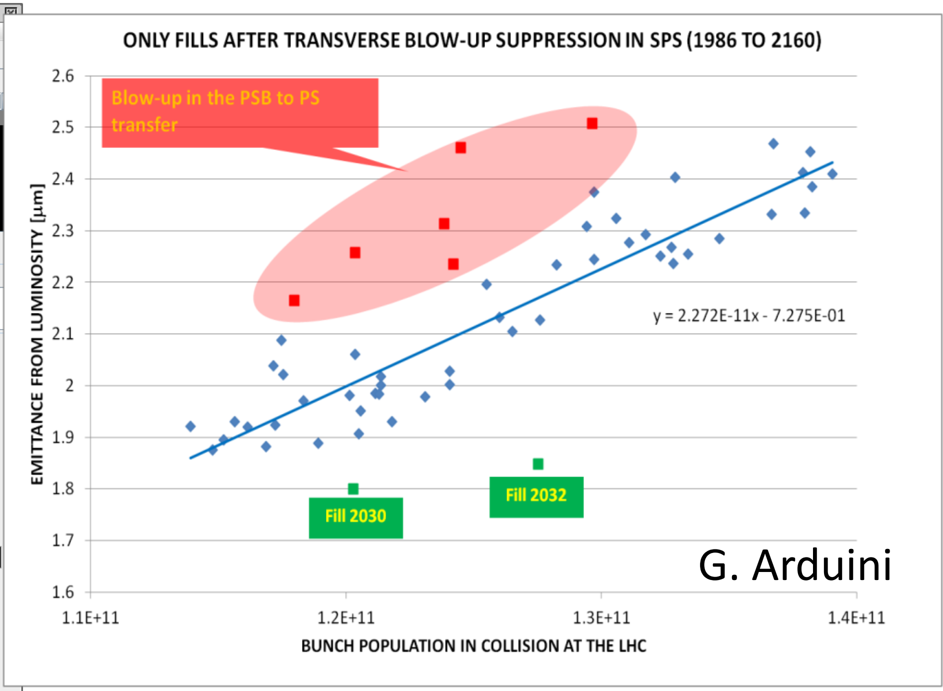
Intensity **1.65 10^{11} p/b reached !**
Up to 4 batches injected
Very low losses along the cycle ε_x=2.0 **μm and** ε_y**=1.9 μm** at flat top



R. Garoby

LHC: emittance vs bunch intensity with 50 ns spacing

at N_b**=1.5x10^{11} : ε~2.5 μm**



G. Arduini

including LIU, we may assume ε≤3.75 μm at maximum intensity;
LIU team is preparing 1 μm emittance scenario (no b-b limit in LHC)

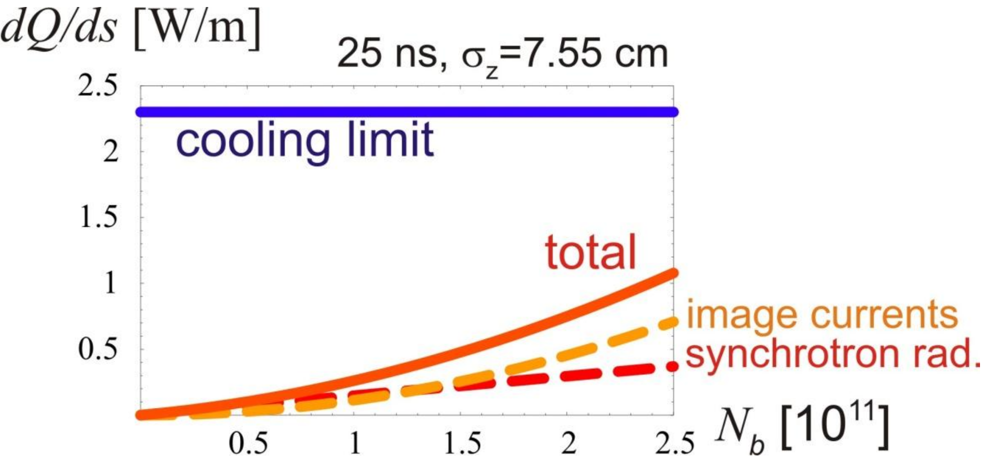
bunch length

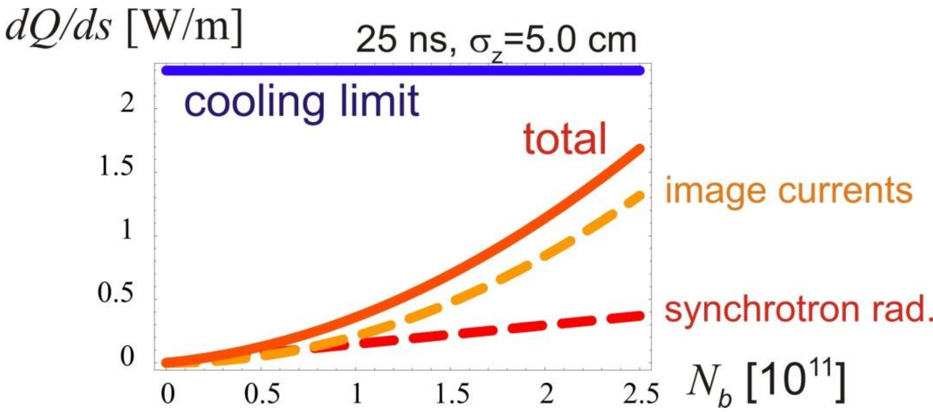
short bunch length would allow higher crab RF frequency

- **current rms design bunch length 7.55 cm**
  - **bunch shape approximately Gaussian**
  - **baseline for HL-LHC**
  - **heating concerns (presently 9 cm at 3.5 TeV)**
- **HL-LHC option: increase to 11.8 cm rms w flat shape**
  - **with 2nd or 3rd harmonic RF (C. Bhat)**
- **HL-LHC option: decrease to 5 cm rms, Gaussian**
  - **smaller emittance & 3rd harmonic RF (J. Gareyte)**
  - **IBS & heating concerns**

σ_z & intensity limit: heat load due to image currents & synchrotron radiation (w/o e-cloud & gas scattering)

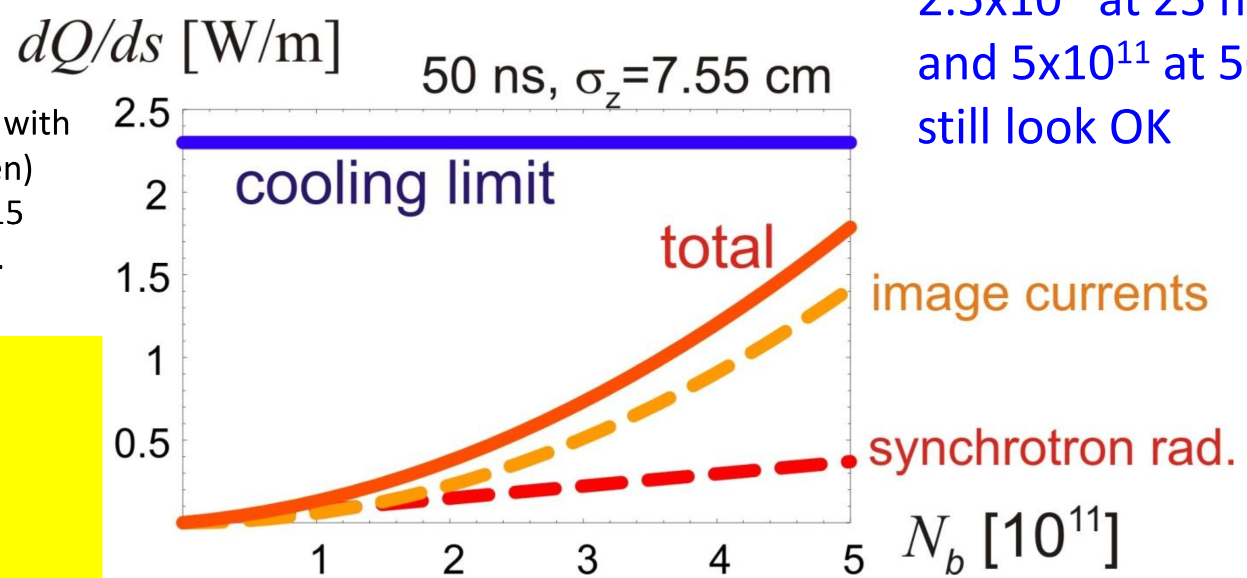
F.Z., Chamonix 2011





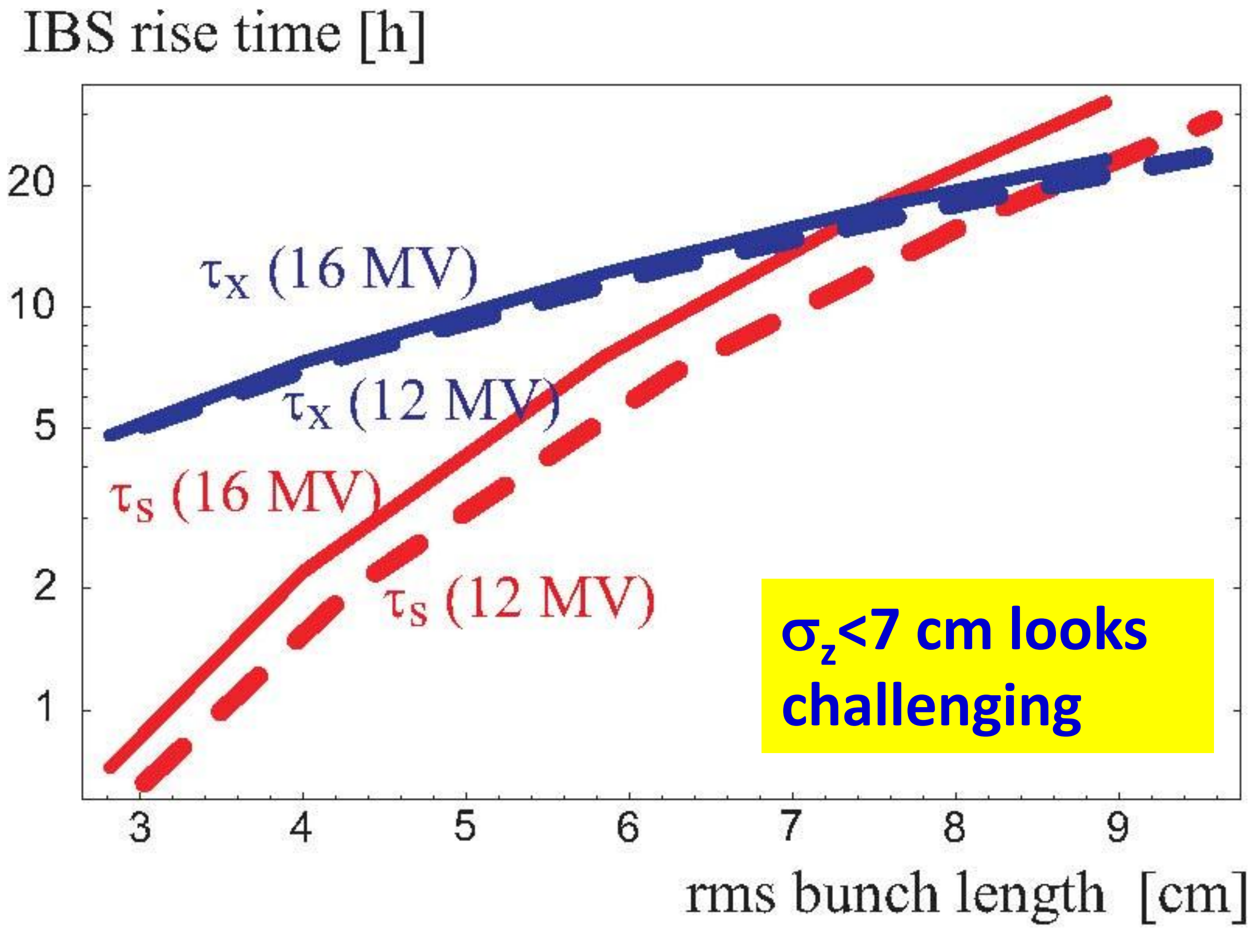
2.5x10^11 at 25 ns and 5x10^11 at 50 ns still look OK

also note:
nuclear beam-gas scattering with τ~100 h (32 ntorr RT hydrogen) contributes an equivalent 0.15 W/m at nominal current [e.g. HHH-2004]



σ_z<5 cm or spacing <25 ns look challenging

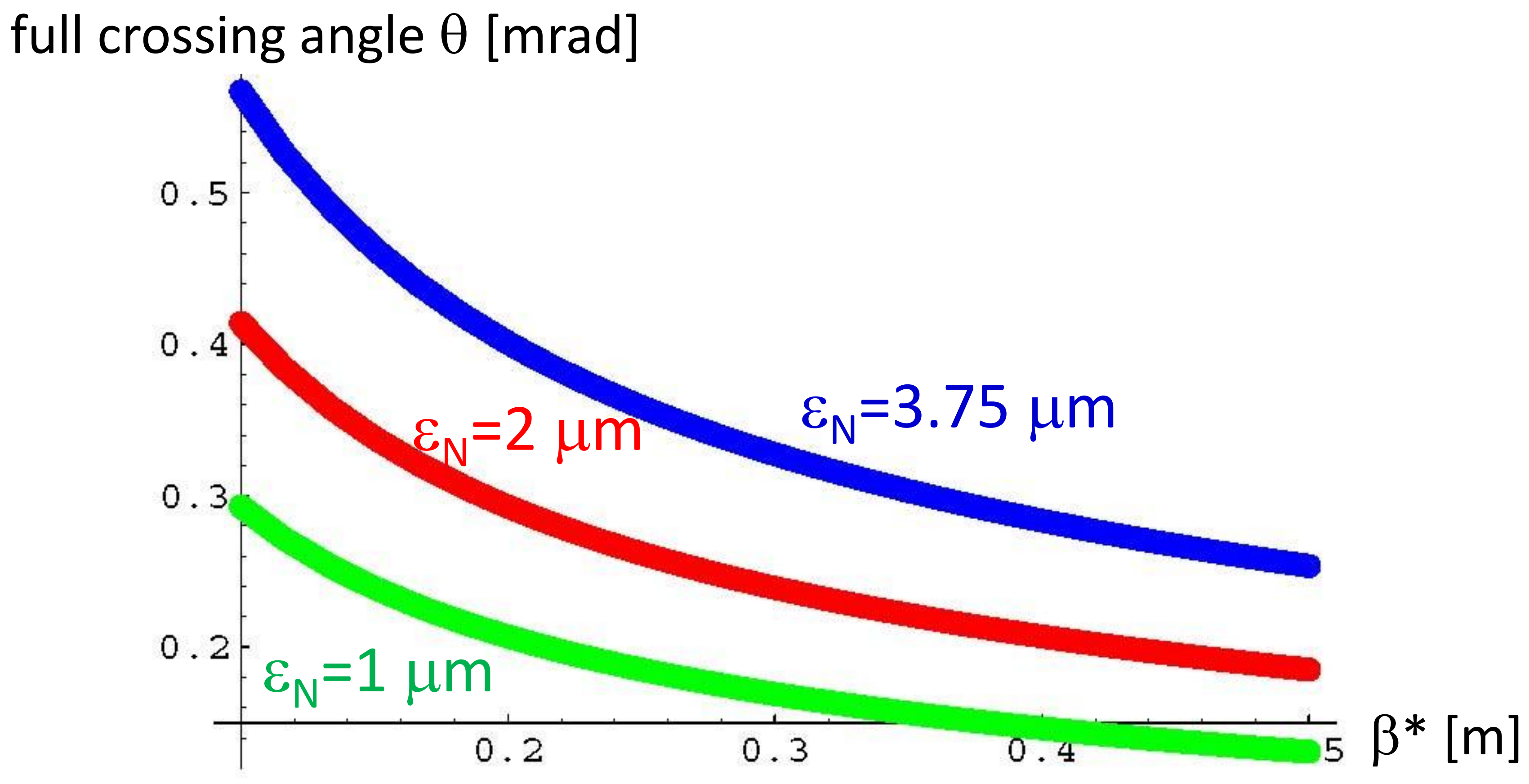
σ_z & intensity limit: intrabeam scattering



τ_{IBS} **vs** σ_z for $\gamma\varepsilon$**=2 μm**, N_b=**1.7x10**^{11}, V_{RF}=16 or 12 MV, ***E*****= 7 TeV**

crossing angle

with long-range beam-beam compensators need ~8 σ minimum separation at the near encounters

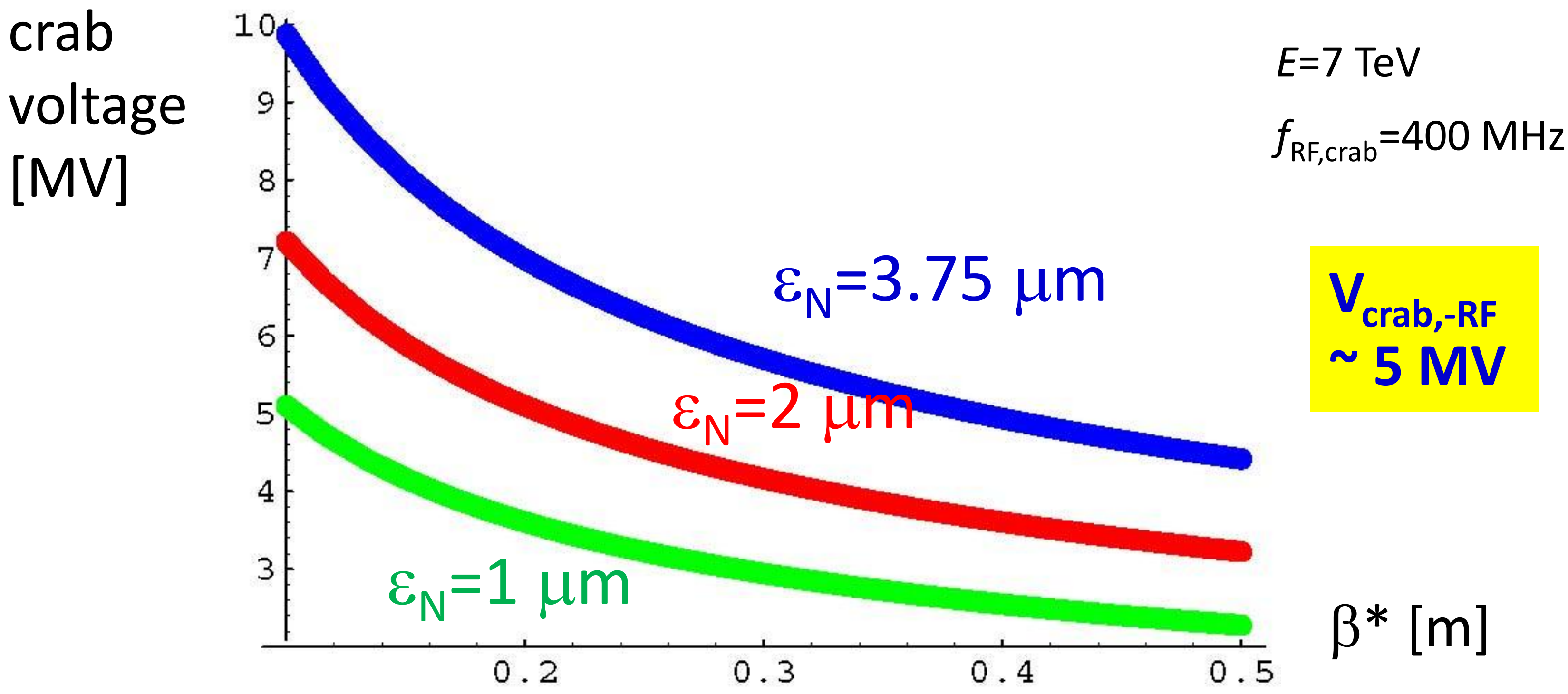


crab voltage

$$V_{crab} = \frac{cE_0 \tan(\theta_c / 2)}{e 2\pi f_{rf} R_{12}} \approx \frac{cE_0}{e 4\pi f_{rf} R_{12}} \theta_c$$

proportional to crossing angle & independent of IP beam size; scales with $1/R_{12}$; also inversely proportional to RF frequency

R_{12}~30-45 m for nominal optics (F.Z., CARE-HHH <Lumi'05)
R_{12} ~24 m for "ATS" upgrade optics (R. De Maria, LHC-CC10)



flat beam scenarios

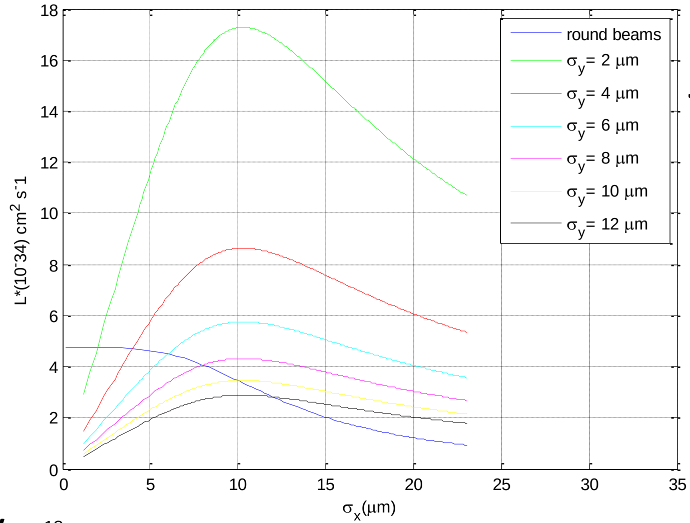
S. Fartoukh

$$V_{crab} \propto \frac{1}{r} \equiv \frac{\sigma_y^*}{\sigma_x^*}$$

up to r=2 possible at the present LHC (S. Fartoukh, LHC MAC #19, June 2006)

w/o crab cavity

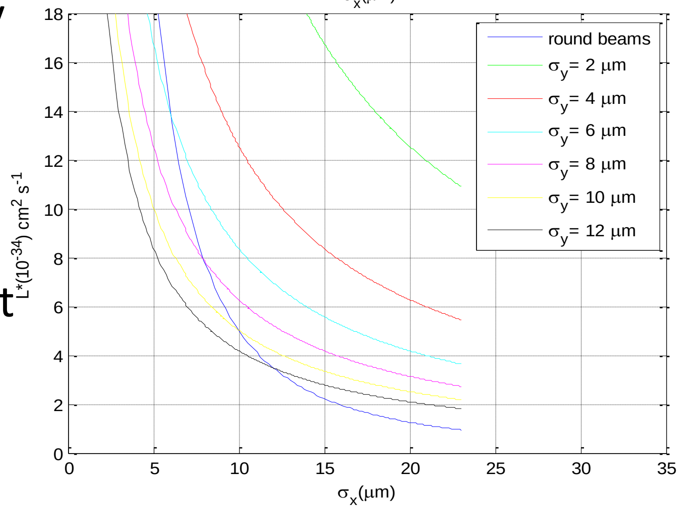
hourglass effect not included



J. Abelleira

with crab cavity

hourglass effect not included: results incorrect by > 5% for $\sigma_{x,y}$<6 μm



to be redone w hourglass

N_b= 2x10^{11}, σ_z=7.55 cm, γε= 2.2 μm, n_b = 1404, separation=9.5σ

a few conclusions

- HL-LHC **beam current up to 1 A** with 2808 or 1404 bunches, **25 or 50-ns bunch spacing**
- **rms bunch length larger than 7 cm** in view of heating & IBS, possibly 11.8 cm
- → $f_{crab,RF}$=800 MHz may be too high**, 400 MHz OK**
- **crab voltage of about 5 MV** required per beam and per side of IP
- crab-voltage requirement could be relaxed with **$\beta_x^* \neq \beta_y^*$ (quasi-flat beams)**

thank you for your attention