LHC beam parameters and luminosity upgrade options

Highlights from the CARE-HHH-APD workshop
LHC-LUMI-05, Arcidosso, 31 August-3 September 2005

- Scenarios for the LHC upgrade
- Effective luminosity
- High Intensity effects
- Upgrade of the LHC injector complex
- Final personal remarks

http://care-hhh.web.cern.ch/CARE-HHH/

A question of method...

- Minutes of the AB/ABMB, 5.09.2005, Arcidosso Meeting: It was reported that the conclusion from the Arcidosso meeting was that the focus should be on building a new PS in order to achieve higher performance in LHC. The proposed scheme would be based on a superconducting fast cycling machine with injection from the existing Booster and a final energy of 60 GeV. This proposal will be evaluated by the PAF.
- I disagree on the form and on the substance of such a statement:
  - The Arcidosso meeting was a CARE-HHH-APD workshop and the conclusions should be properly reported by the organizers and CARE-HHH coordinators
  - The proposal to shift the focus from a Super-SPS to a Super-PS was discussed in a parallel session of a working group in Arcidosso, but there was no clear consensus on the fact that this would allow to achieve a higher LHC performance
  - The agenda of the workshop was seriously perturbed and the final plenary discussion was made impossible

Highlights from the LHC-LUMI-05 workshop

Several LHC IR upgrade options were discussed, including:

- schemes with Crab cavities as an alternative to the baseline bunch shortening RF system at 1.2 GHz to avoid luminosity loss with large crossing angles
- quadrupole-first and dipole-first solutions based on NbTi or Ni_3Sn magnets, possibly with structured SC cable (P. McIntyre): in both cases an earlier beam separation may be obtained with a dipole located a few metres away from the IP (as suggested by JPK). It remains to understand whether such a "D0" dipole would allow us to reduce the crossing angle and be compatible with detector layout and heat deposition by the collision debris. The experimental solenoids should be included in the simulations.
- local chromaticity correction schemes (P. Raimondi)
- flat beams, i.e. a final doublet instead of a triplet

Expected factors for the LHC luminosity upgrade

The peak LHC luminosity can be multiplied by:

- **factor 2.3** from nominal to ultimate beam intensity (0.58 ⇒ 0.86 A)
- **factor 2** (or more?) from new low-beta insertions with $\beta^*=0.25$ m

$T_{turnaround}$~10 h ⇒ $\int Ldt$ ~ 3 x nominal ~ 200/(fb*year)

Major hardware upgrades (LHC main ring and injectors) are needed to exceed ultimate beam intensity. The peak luminosity can be increased by:

- **factor 2** if we can double the number of bunches (maybe impossible due to electron cloud effects) or increase bunch intensity and bunch length

$T_{turnaround}$~10 h ⇒ $\int Ldt$ ~ 6 x nominal ~ 400/(fb*year)

A new Super-SPS injecting into the LHC at 1 TeV would yield:

- **factor ~2** in peak luminosity (2 x bunch intensity and 2 x emittance)
- **factor 1.4** in integrated luminosity from shorter $T_{turnaround}$~5 h

thus ensuring L~10^{35} cm^{-2} s^{-1} and $\int Ldt$ ~ 9 x nominal ~ 600/(fb*year)

Scenarios for the luminosity upgrade

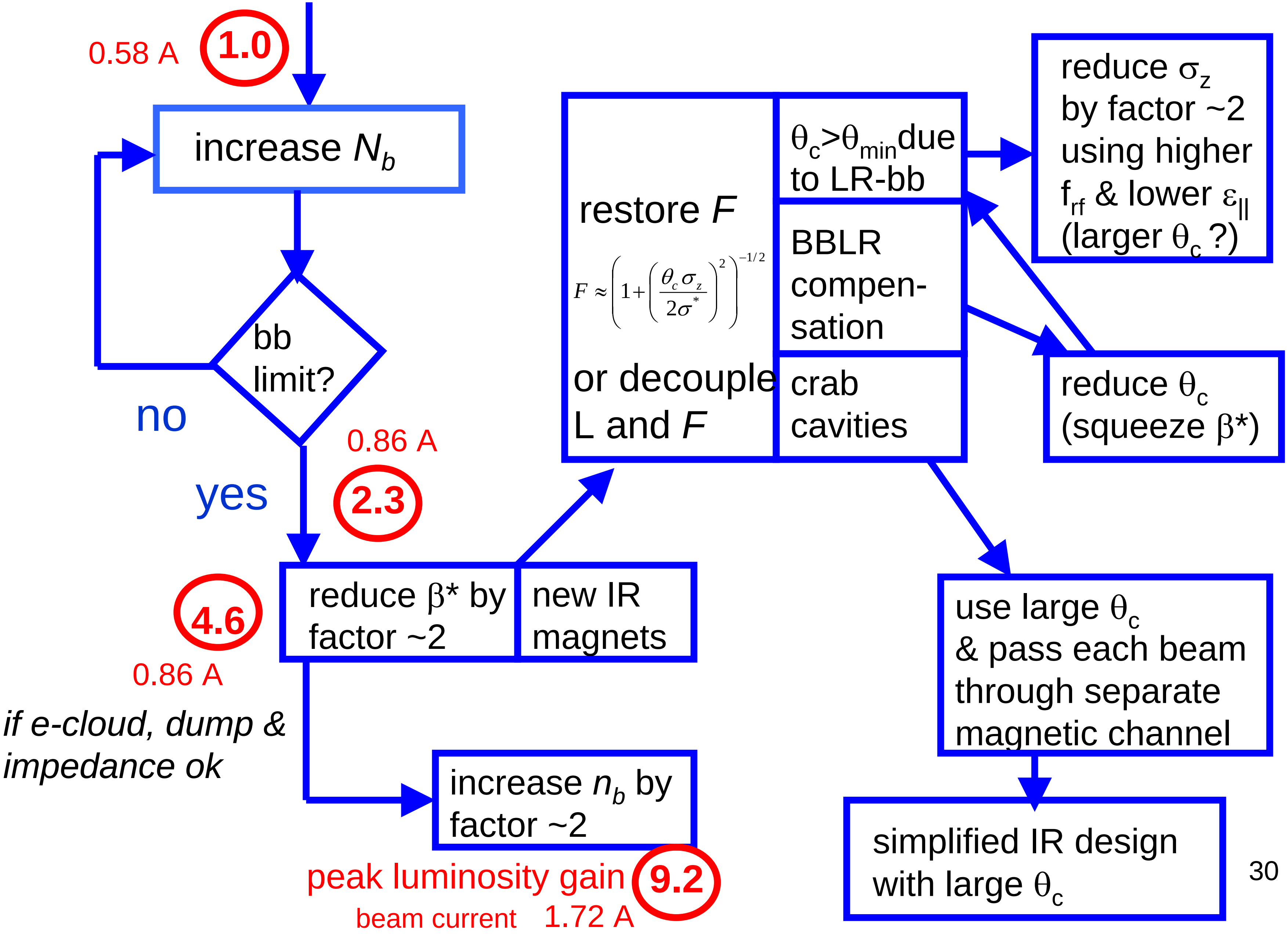
Phase 1: steps to reach maximum performance with only IR changes

1) Modify the insertion quadrupoles and/or layout $\Rightarrow$ $\beta^* = 0.25$ m
2) Increase crossing angle θ_c by √2 $\Rightarrow$ $\theta_c = 445$ μrad
3) Increase N_b up to ultimate intensity $\Rightarrow$ $L = 3.3 \times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
4) Halve σ_z with high harmonic RF system $\Rightarrow$ $L = 4.6 \times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
5) Double the no. of bunches n_b (and increase θ_c) $\Rightarrow$ $L = 9.2 \times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
   excluded by electron cloud? **Step 5 belongs to Phase 2**

☹ Step 4) is not cheap: it requires a new RF system providing
- ◆ an accelerating voltage of 43 MV at 1.2 GHz
- ◆ a power of about 11 MW/beam $\Rightarrow$ estimated cost 56 MCHF
- ◆ longitudinal beam emittance reduced to 1.78 eVs
- ◆ horizontal Intra-Beam Scattering (IBS) growth time decreases by ~ √2

☹ Operational consequences of step 5) $\Rightarrow$ exceeding ultimate beam intensity
- ◆ upgrade LHC cryogenics, collimation, and beam dump systems
- ◆ the electronics of all LHC beam position monitors should be upgraded
- ◆ possibly upgrade SPS RF system and other equipment in the injectors

luminosity upgrade: baseline scheme



0.58 A **1.0**

increase N_b

bb limit?

no

yes

0.86 A **2.3**

reduce β* by factor ~2

new IR magnets

4.6 0.86 A

if e-cloud, dump & impedance ok

increase n_b by factor ~2

peak luminosity gain **9.2**

beam current 1.72 A

restore *F*

$$F \approx \left(1+\left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2\right)^{-1/2}$$

or decouple L and *F*

$\theta_c > \theta_{min}$ due to LR-bb

BBLR compen- sation

crab cavities

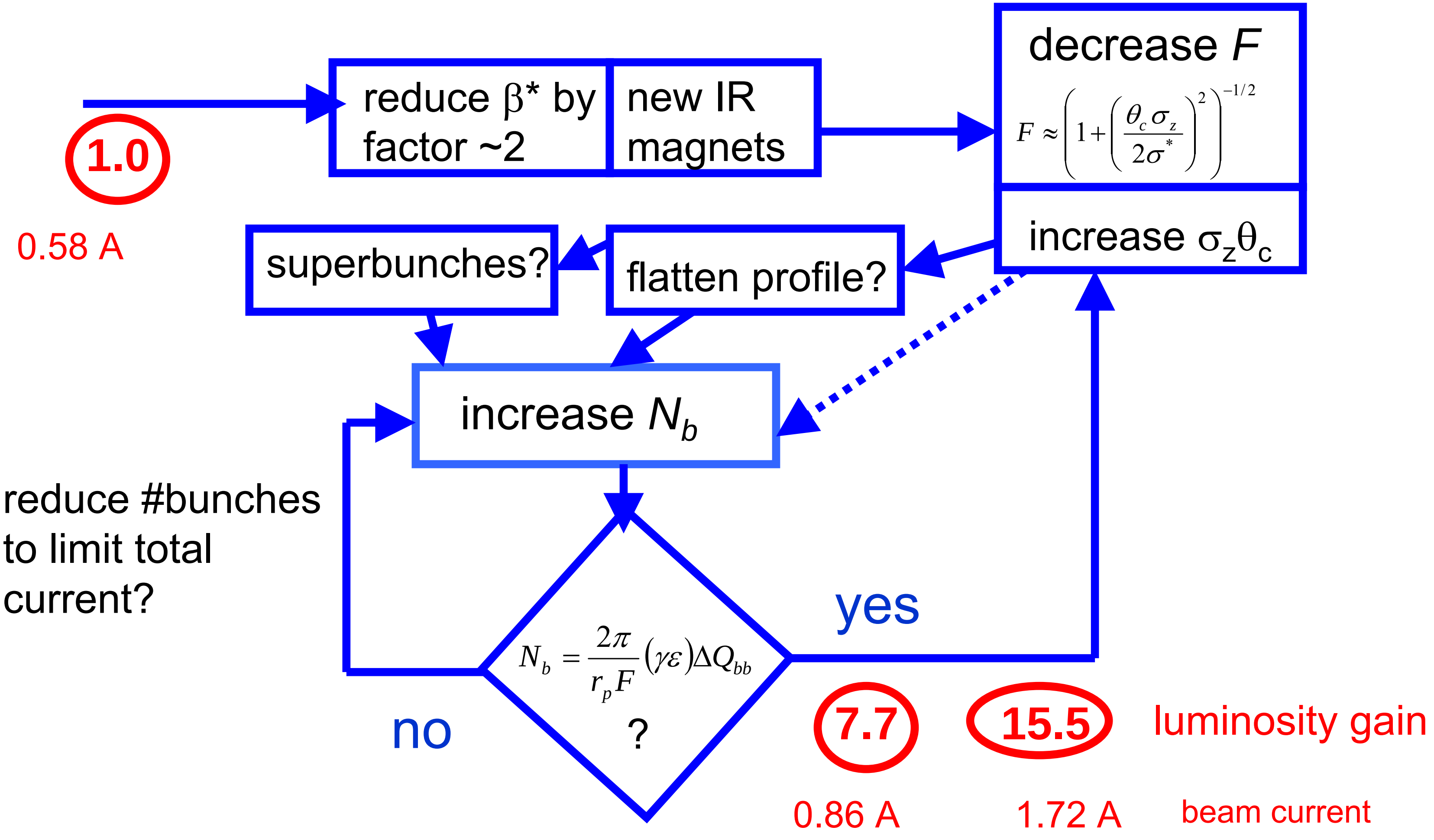
reduce σ_z by factor ~2 using higher f_{rf} & lower $\varepsilon_{||}$ (larger θ_c ?)

reduce θ_c (squeeze β*)

use large θ_c & pass each beam through separate magnetic channel

simplified IR design with large θ_c

luminosity upgrade: Piwinski scheme



1.0

0.58 A

reduce β* by factor ~2

new IR magnets

decrease *F*

$$F \approx \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2\right)^{-1/2}$$

increase $\sigma_z \theta_c$

superbunches?

flatten profile?

increase N_b

reduce #bunches to limit total current?

$$N_b = \frac{2\pi}{r_p F}(\gamma\varepsilon)\Delta Q_{bb}$$

?

yes

no

7.7

15.5

luminosity gain

0.86 A

1.72 A

beam current

Injector chain for 1 TeV proton beams

injecting in LHC more intense proton beams with constant brightness, within the same physical aperture

⇒ will increase the peak luminosity proportionally to the proton intensity

$$L \approx \gamma \Delta Q_{bb}^{2} \frac{\pi \varepsilon_n f_{rep}}{r_p^2 \beta^*} \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2}$$

$$\frac{d_{sep}}{\sigma} \approx \theta_c \sqrt{\frac{\gamma \beta^*}{\varepsilon_n}}$$

- at the beam-beam limit, the peak luminosity L is proportional to the normalized emittance $\varepsilon_n = \gamma\varepsilon$, unless limited by the triplet aperture
- an increased injection energy (Super-SPS) allows a larger normalized emittance ε_n in the same physical aperture, thus more intensity and more luminosity at the beam-beam limit.
- the transverse beam size at 7 TeV would be larger and the relative beam-beam separation correspondingly lower: long range beam-beam effects have to be compensated.

Events per bunch crossing and beam lifetime due to nuclear p-p collisions

$$\frac{\text{events}}{\text{X - ing}} = \frac{L}{n_b}\,\frac{\sigma_{bb}}{f_{rev}}$$

σ_{bb}=60 mb total inelastic cross section

$$\tau_N = \frac{N_b}{2\sigma_{TOT} L / n_b}$$

beam intensity halving time due to nuclear p-p collisions at two IP's with total cross section σ_{TOT}=110 mb

$$\frac{L}{N_b n_b} = \frac{\pi f_{rev}}{r_p^2}\,\frac{\gamma \Delta Q_{bb}^2}{\beta^* (F N_b / \varepsilon_n)} = \frac{f_{rev}}{2 r_p}\,\frac{\gamma \Delta Q_{bb}}{\beta^*}$$

nuclear scattering lifetime at the beam-beam limit depends only on β*!

$$\tau_L = \frac{1}{\frac{1}{2\tau_x^{IBS}} + \frac{2}{\tau_{gas}} + \frac{1.54}{\tau_N}}$$

luminosity lifetime: assumes radiation damping compensates diffusion

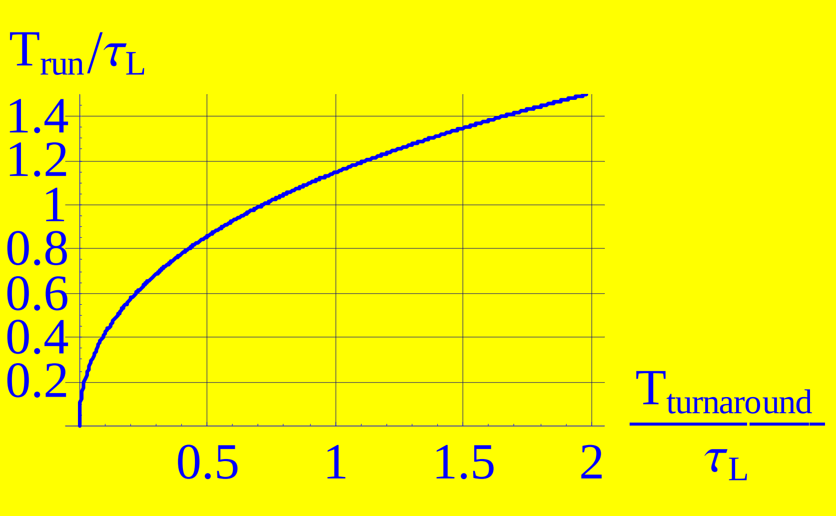
exponential luminosity lifetime due to nuclear p-p interactions

$$(\sqrt{e} - 1)\tau_N \cong \frac{\tau_N}{1.54}$$

Optimum run time and effective luminosity

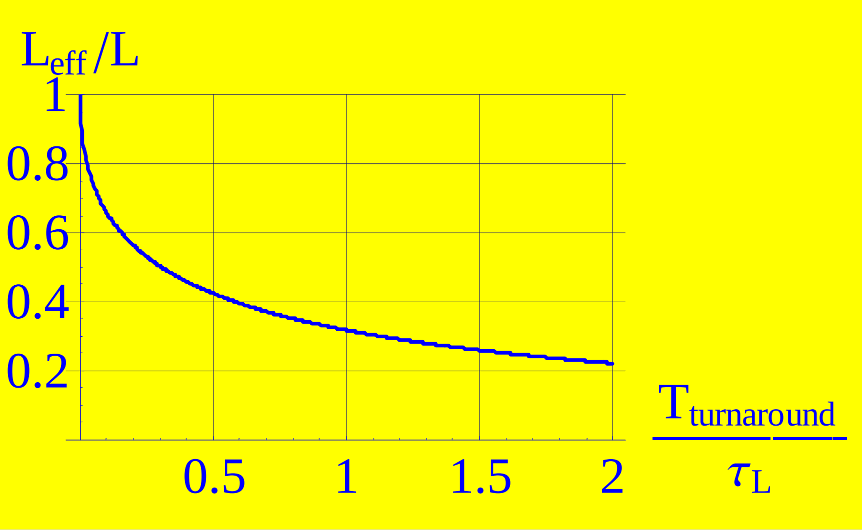
$$\frac{\tau_L + T_{run} + T_{turnaround}}{\tau_L} = e^{\frac{T_{run}}{\tau_L}}$$

The optimum run time and the effective luminosity are universal functions of $T_{turnaround}/\tau_L$



$$\frac{T_{run}}{\tau_L} = -1 - \frac{T_{turnaround}}{\tau_L} - \text{ProductLog}[-1,-e^{-1-\frac{T_{turnaround}}{\tau_L}}]$$

$$\frac{L_{eff}}{L} = \frac{\tau_L}{\tau_L + T_{run} + T_{turnaround}} = -\frac{1}{\text{ProductLog}[-1,-e^{-1-\frac{T_{turnaround}}{\tau_L}}]}$$



where $w = \text{ProductLog}[z] \Leftrightarrow z = we^{w}$

When the beam lifetime is dominated by nuclear proton-proton collisions, then $\tau_L \sim \tau_N/1.54$ and the effective luminosity is a universal functions of $T_{turnaround}/\beta^*$

Effective luminosity for various upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep}[ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
longitudinal profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	ß* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [µrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
IBS growth time	$\tau_{x,IBS}$ [h]	106	72	42	75
nuclear scatt. lumi lifetime	$\tau_N/1.54$ [h]	26.5	17	8.5	5.2
lumi lifetime (τ_{gas} =85 h)	τ_L [h]	15.5	11.2	6.5	4.5
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.4	0.8	2.4	1.9
($T_{turnaround}$=10 h)	T_{run} [h] optimum	14.6	12.3	8.9	7.0
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.5	1.0	3.3	2.7
(T_{turn}=5 h)	T_{run} [h] optimum	10.8	9.1	6.7	5.4

Summary of Session 2
High Intensity Effects

- *F. Zimmermann* – **Progress of beam-beam compensation schemes**
- *E. Shaposhnikova* – **High brilliance and closer bunches from the LHC injectors**
  - RF upgrades/cost for different LHC bunch spacings
- *J. Tuckmantel* – **New RF Systems for the Super-ISR and Super-SPS**
- *N. Catalan Lasheras* – **Beam collimation and control in the high energy injectors**

to boost LHC performance further various approaches have been proposed:

1) **increase crossing angle AND reduce bunch length**
(higher-frequency rf & reduced longitudinal emittance)
[J. Gareyte; J. Tuckmantel, HHH-20004]

2) **reduce crossing angle & apply “wire” compensation**
[J.-P. Koutchouk]

3) **crab cavities → large crossing angles w/o luminosity loss**
[R. Palmer, 1988; K.~Oide, K. Yokoya, 1989; KEKB 2006]

4) **collide long intense bunches with large crossing angle**
[F. Ruggiero, F. Zimmermann, ~2002]

F. Zimmermann: merits of wire compensation

- long-range compensation was demonstrated in SPS using 2 wires (lifetime recovery)
- simulations predict 1-2σ gain in dynamic aperture for nominal LHC
- allows keeping the same – or smaller – crossing angle for higher beam current →no geometric luminosity loss

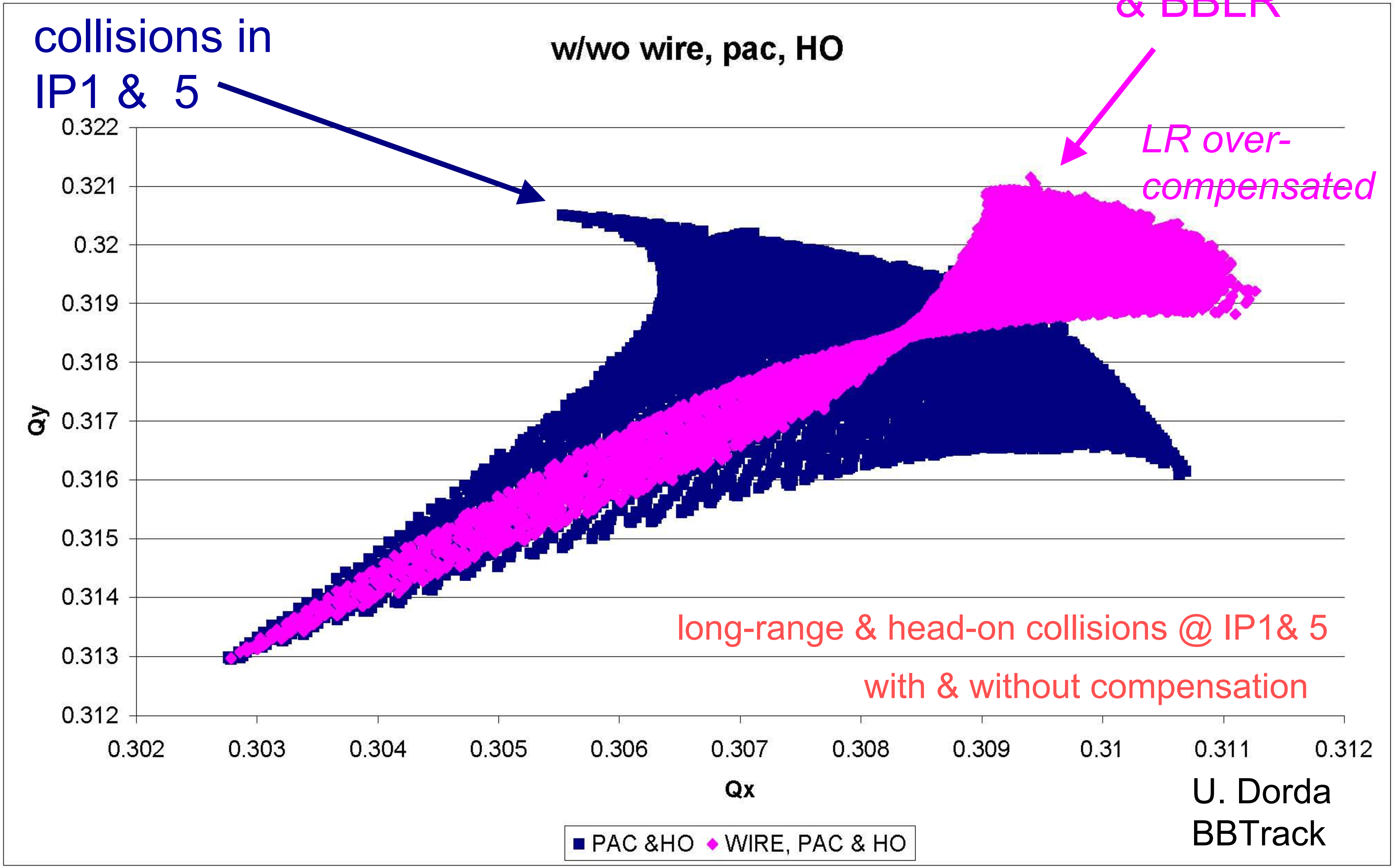
challenges & plans

- further SPS experiments (3rd wire in 2007)
- demonstrate effectiveness of compensation with real colliding beams (at RHIC)
- study options for a pulsed wire

LR beam-beam compensation: remarks and open issues

- Simulations of LR compensation with 2 wires indicate that lifetime is recovered over a wide tune range but not for all tunes.
- The measured SPS lifetime is 5 ms x $(d/\sigma)^5$. Extrapolation to LHC beam-beam distance (9.5 σ) would predict 6 minutes beam lifetime! Tevatron observations with electron lens show cubic dependence. Further SPS tests at different energy are needed.
- Lifetimes predicted by simulation codes are much larger than those observed, even though sensitivity to parameters seems correct. **Needs further understanding and beam tests, e.g. at RHIC.**
- For extreme PACMAN bunches there is overcompensation which causes the footprint to flip over or to increase instead of shrinking. **To avoid degraded lifetime for PACMAN bunches, the wire should be pulsed train by train.** It is rather challenging to make a pulsed wire for BB compensation: the required average pulse rate is 439 kHz and the turn-by-turn amplitude stability 10^{-4}.
- Experiments at RHIC (Fischer) **with a single LR encounter show that the BB effect is visible starting from a 5σ separation**, consistent with Tevatron and Daphne observations, but contrary to LHC simulations and possibly earlier observations at the SPS collider.

PACMAN bunch



head-on & LR collisions in IP1 & 5

head-on, LR & BBLR

LR over-compensated

long-range & head-on collisions @ IP1& 5

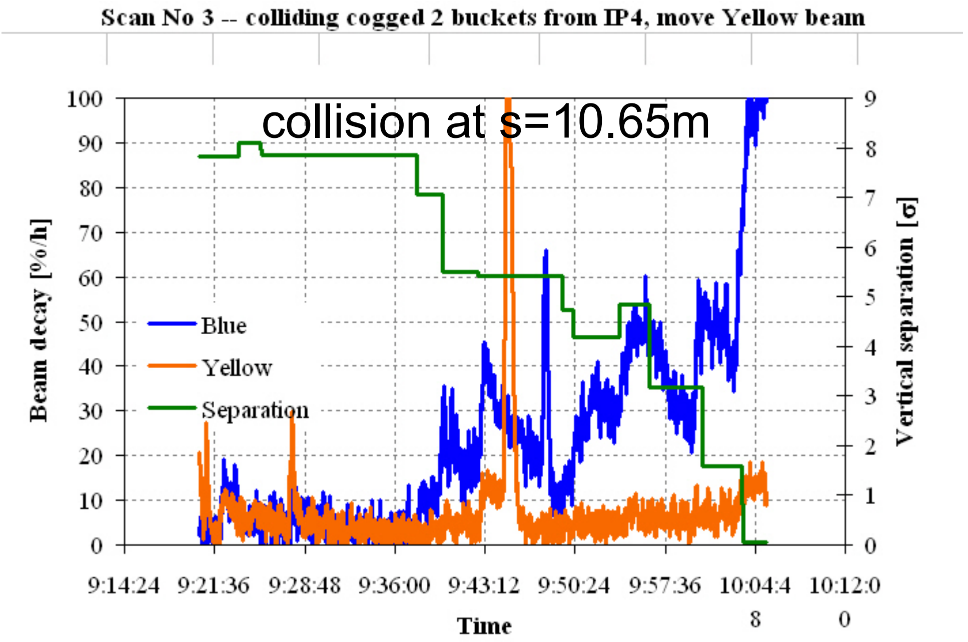
with & without compensation

U. Dorda
BBTrack

tune footprints for starting amplitudes up to 6σ in x and y

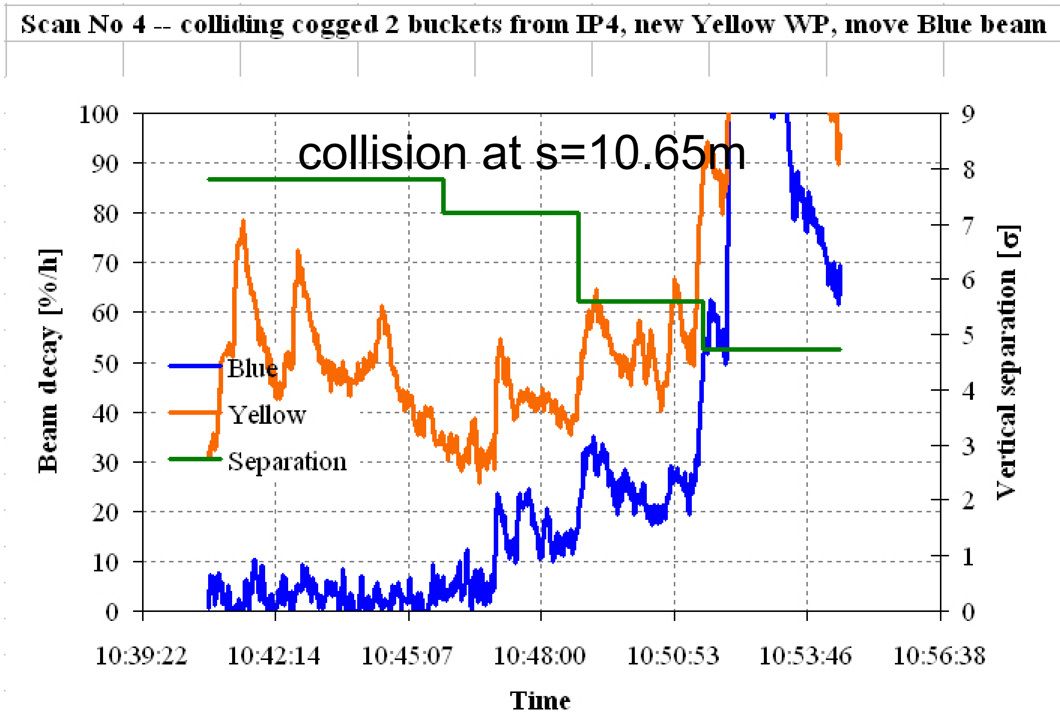
Long-Range BB Experiment in RHIC, 28 April 2005, Wolfram Fischer et al., 1 Bunch per Ring

… more data sets


Scan No 3 -- colliding cogged 2 buckets from IP4, move Yellow beam

collision at s=10.65m

Some time stamps have to be adjusted (used time of orbit measurement, not orbit change); parameters other than the orbit were changed - not shown. ***Scan 4 is the most relevant one.***


Scan No 4 -- colliding cogged 2 buckets from IP4, new Yellow WP, move Blue beam

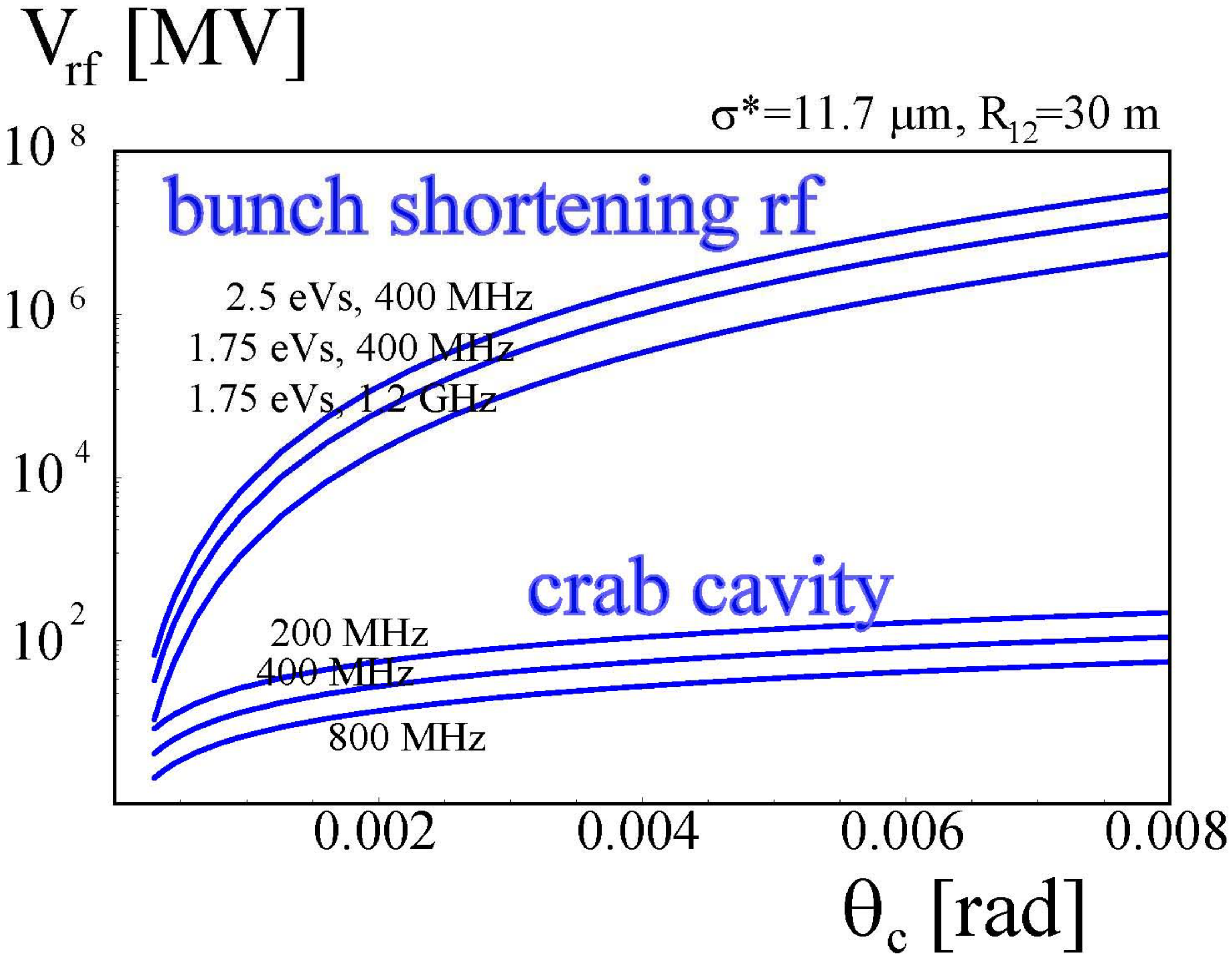
collision at s=10.65m

F. Zimmermann: merits of crab cavities

- practical demonstration at KEKB in early 2006
- avoids geometric luminosity loss, allowing for large crossing angles (no long-range beam-beam effect)
- potential of boosting the beam-beam tune shift (factor 2-3 predicted for KEKB)

challenges & proposed plans

- design & prototype of Super-LHC crab cavity (Cornell is interested)
- demonstration that noise-induced emittance growth is acceptable for hadron colliders (installation & experiment at RHIC?)


V_rf [MV]
σ*=11.7 µm, R_12=30 m
bunch shortening rf
2.5 eVs, 400 MHz
1.75 eVs, 400 MHz
1.75 eVs, 1.2 GHz
crab cavity
200 MHz
400 MHz
800 MHz
10^8
10^6
10^4
10^2
0.002
0.004
0.006
0.008
θ_c [rad]

comparison of timing tolerance with others

	KEKB	Super-KEKB	ILC	Super-LHC
σ_x^*	100 μm	70 μm	0.24 μm	11 μm
θ_c	+/- 11 mrad	+/-15 mrad	+/-5 mrad	+/- 0.5 mrad
Δt	6 ps	3 ps	**0.03 ps**	**0.08 ps**

IP offset of 0.2 σ_x^*

IP offset of 0.001 $\boldsymbol{\sigma_x^*}$

→ *not more difficult that ILC crab cavity*

E. Shaposhnikova – High brilliance and closer bunches from the LHC injectors

- **Existing injectors**
  - **The SPS is the bottle-neck to reach and exceed ultimate LHC intensity**
- **New LHC injectors**
  - **Target impedance for Super-SPS ~ 0.5 Ω, i.e. an order of magnitude less than present SPS.**

Summary for existing injectors (1/2)

Main limitations

- **Higher brilliance:** nominal emittance is not yet reached in the SPS in the vertical plane due to e-cloud.
- **Closer bunches:** new RF system needed either in the PS (10, 15 ns) or SPS and LHC (12.5 ns). In the SPS more problems with e-cloud (V-emittance blow-up) and coupled bunch instabilities.
- Intensity dependent **capture losses in the SPS**. Were reduced in 2004, but their exact cause and therefore scaling is not clear.
- **Coupled bunch instabilities in the SPS** can be cured by controlled emittance blow-up → 200 MHz capture system in the LHC.
- **Beam loading** in 200 MHz and 800 MHz RF systems - limit at ultimate intensity for known performance.
- **Fast transverse instability** for more MKE kickers or higher bunch intensities. Below the threshold - emittance blow-up. Cure by chromaticity at high voltage could increase losses.

Summary for existing injectors (2/2)

Possible improvements and machine studies in the SPS:

- Further SPS impedance reduction (MKE screens, improved passive damping of HOMs, search for transverse impedances...)
- Capture loss studies with shorter bunches from PS, the same or larger emittance (extra RF voltage in the PS)
- Increased voltage of 800 MHz RF system (1 more cavity in operation in 2006)
- Emittance blow-up up to 0.75 eVs for ultimate intensity - study effect of the synchrotron frequency shift along the batch
- Capture loss and beam lifetime studies (e-cloud, machine resonances, noise...) - analysis of 2004 data!
- High power RF tests in 2006 (pulsing mode)
- Ultimate intensity bunches injected into the SPS
- Scrubbing runs at higher intensities

Summary for new injector

- Reducing the top energy in the SPS to 150 GeV
  - allows the ramp length to be reduced to 2 s
  - does not improve longitudinal beam stability (coupled-bunch) on the flat top and controlled emittance blow-up may still be necessary
  - makes more difficult bunch-to-bucket transfer into 400 MHz RF system of the next ring
- HPS (Super-SPS):
  - with present SPS minimum ramp length can be 6 s
  - using a 400 MHz (SC) RF system requires extra capture RF system and twice more volts than for 200 MHz
  - using a 200 MHz (NC) RF system seems to be optimum, but requires tight impedance budget (probably achievable for a new machine)

Acceleration in the HPS: 150 GeV → 1 TeV (1/3)

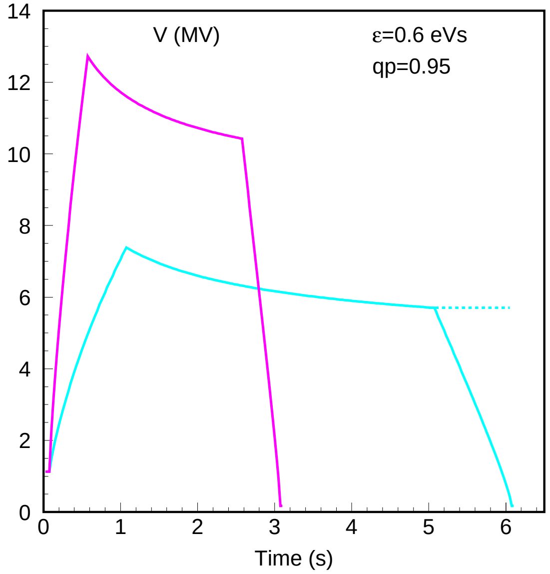
γ_t	ε eVs	ramp length s	V_{400} MV	V_{200} MV
23	0.6	3.0	23	13
30	0.6	3.0	19	12
23	0.5	3.0	20	12
23	0.6	6.0	16	7

- 400 MHz RF system (SC)
  - easy transfer to 400 MHz RF system in the LHC, but...
  - needs 200 MHz cavities in the SPS or HPS with voltage sufficient for acceleration in 6 s!
- 200 MHz RF system (NC)
  - cavities exist (8 MV) - "capture system" of LHC
  - for transfer to LHC @1 TeV for the same ε and V - 20% shorter bunches or $\sqrt{2}$ larger emittances (0.85 eVs)

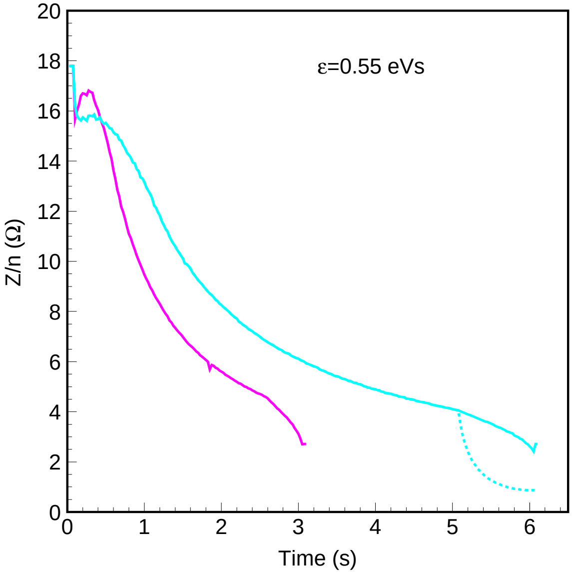
Acceleration in the HPS: 150 GeV → 1 TeV (2/3)

Beam stability at nominal intensity

The 200 MHz voltage programme

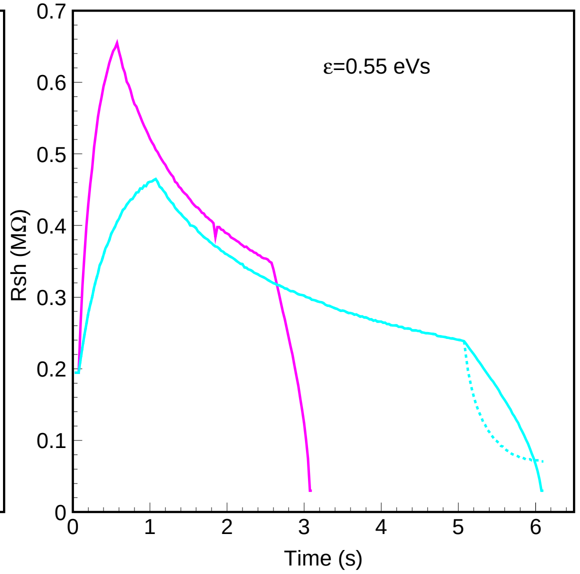


Broad-band impedance



$\Rightarrow \mathrm{Im}Z/n < 0.5\Omega$

Narrow-band impedance



$\Rightarrow R_{sh} < 70\ \mathrm{k}\Omega$

- **No 800 MHz RF system... but for $\varepsilon < 0.85$ eVs - still no 200 MHz RF system needed in LHC → emittance blow-up at high energy**

RF upgrades and tentative cost for different LHC bunch spacings

- **12.5 ns**
  - PS: double RF voltage at 80 MHz ~ 2 MSfr
  - SPS: more RF power and new RF cavities at 160 or 240 MHz ~ 75 MSfr
    new Faraday cage and infrastructure ~ ?
  - LHC: new capture cavities at 160 or 240 MHz (2x3 MV) ~ 5 MSfr
    new BPM electronics (MSfr + manpower + time)

TOTAL (12.5 ns) > 82 MSfr

- **10 or 15 ns**
  - PS: new RF system at 60 MHz ~ 5 MSfr
  - SPS: double RF power at 200 MHz + new couplers ~ 20 MSfr
  - LHC: no new capture cavities

TOTAL (10 or 15 ns) ~ 25 MSfr

Any bunch spacing shorter than 25 ns requires new electronics for the LHC BPM system, upgraded transverse feedback, collimation, cryogenics, beam dump, ...

J. Tuckmantel – New RF Systems for the Super-ISR and Super-SPS

Evident fact: Only **few cavities**, copper or superconducting, can easily supply the **desired voltage.**

Gradients have to be lowered voluntarily since the power coupler cannot transmit the corresponding RF power to accelerate high beam currents and compensate react. beaml.

- **Power coupler capabilities have to be increased considerably, Q_{ext} ??**
- **for sc. cav. couplers: RF losses into liquid He, “deconditioning”**

Conclusions (2)

For a 200 MHz system the existing ‘RF power factories’ for large power are very space consuming -> problem to house them close to cavities under ground (loop delay !!)

- **Study compact RF power transmitter at 200 MHz**

HPS acceleration 200 MHz

(ramp 6 s)

Keep bucket in HPS: need 7 MV during acceleration

-> **10** ACN cavities (0.75 MV) can de the **voltage-job**

150 GeV -> 1000 GeV in 6s, f_{rev}=43 kHz : 3.3 MeV/turn

-> for 10 cavities 330 kV/cav

-> **460 kW only beam power/cav** (2x nominal I_b)

Play numbers: 0.375 MV & 0.19 MV(acc) -> 300 kW/cav

18 cavities @200 MHz @300 kW RF power Q_{ext}=2000

(5.5 MW RF power under ground -> **10 MW wall plug, ‘pulsed’**)

Conclusions (3)

To keep the superconducting cavity option open - except copy the existing 400 MHz system as is –

- **Re-launch superconducting cavity research activity at CERN**

(The sputter activity Nb on Cu is not yet ‘dead’, possible study for LHC crab cavities)

Real Life: High Power RF (2)

- It is very difficult to find qualified staff
- -> Before throwing away 'old' hardware think twice **(not only $$):**
  - **New hardware needs manpower + time**
- **12.5 ns bunch distance in LHC ->**
- **Death of any 200 MHz (incl. capt. RF in LHC !!) + PS, booster, ...**
- **-> use 10 ns or 15 ns (check PS, …)**

New RF Systems for the Super-ISR and Super-SPS: remarks and open issues

- RF power generators should be located in the tunnel to reduce feedback delays.
- High power transmitters at or below 200 MHz are drastically different from higher frequency technology (klystrons). Also expertise in SC RF is very different from that in traveling or standing wave cavities. There are good reasons to adopt different technologies for different synchrotrons (e.g. SC cavities have very limited tunability and are not suited for lower energy injectors), but **there is a strong incentive to adopt similar technologies to reduce development and maintainance costs (P+M). This should guide the design of the future LHC injector complex.**

- Collimation is necessary for heat load, machine protection and activation concerns
- Enough aperture is essential for low losses and high cleaning efficiency. Do not forget it when defining the magnets
- Most losses are expected at injection energy.
- Collimation system very dependent on the energy
- Two stage collimation is necessary at all energies
- Collimation system needs to be integrated from the beginning but it is feasible
- More difficult to implement in an old machine
- A lot to learn from LHC specially for 1 TeV
- <u>Either the beam defines the collimation system or the collimation system will define the beam!!</u>

Beam collimation and control: remarks and open issues

- The position of collimators does not depend on the transverse size of the beam (shouldn’t be quantified in σ’s).
- Collimation at injection energy is critical, but **for large energy swings we may need an approach similar to the two-phase LHC collimators,** e.g. with light material primary collimators to be used at high energy initially located in the shadow of heavy material scrapers to be retracted during the acceleration cycle.
- The setting-up of the collimators will rely on BLM’s.
- Collimation efficiency depends on the number of particles at large amplitudes (population of the halo) and on the diffusion rate of particles towards the halo. **A realistic modelling of these mechanisms is challenging.**
- The worst case scenario are slow continuous losses that have to be intercepted by the collimation system.

Some personal views on the upgrade of the LHC injectors

- A new Super-PS injecting at 50-60 GeV would certainly improve the performance of the SPS (by how much?). For similar reasons, a new Super-SPS injecting at 1 TeV would certainly improve the performance of the LHC.
- It is difficult to quantify the advantages of a 1 TeV Super-SPS: the LHC turn-around time would be reduced, probably by a factor 1.5–2, and we may inject more beam intensity in the same physical aperture.
- The LHC luminosity gain will be limited by long-range beam-beam effects, therefore we need bb compensation wires, and by the triplet aperture, therefore we need large bore quadrupoles.
- A triplet with larger aperture would alternatively allow to increase luminosity by a further squeeze of β^* (S. Fartoukh), but we would hit chromatic correction limits sooner or later. Part of the triplet aperture is also needed to accommodate two beams, unless we go to very large crossing angles, and to let collision debris go through.
- Alternatively we could inject higher brightness beams with reduced emittance and blow them up before collision. However we may be limited by collimation and machine protection, since the beam energy density in the transverse plane would be increased and would not be optimal.

Personal views (continued)

- In conclusion, since the SPS is currently the bottle-neck in the LHC injectors chain, a Super-SPS remains the most logical option to increase the LHC luminosity. It has the additional advantage of preparing a possible LHC energy upgrade and to increase the overall energy of hadron beams available for physics at CERN (a high-energy physics lab, don't forget!)
- A superconducting PS may turn out to be the best choice for CERN if the PS magnet consolidation is not a long term solution: this can be used as an opportunity to develop new fast pulsing SC magnets. To be considered as the right move in the direction of the (high-priority) LHC performance upgrade:
  - a super-SPS should remain the strategic objective
  - the improvement of the SPS performance as LHC injector should be quantitatively assessed