LHC upgrade based on a high intensity high energy injector chain

Walter Scandale CERN AT department

PAF n. 6

CERN, 15 September 2005

luminosity and energy upgrade

Phase 2: steps to reach maximum performance with major hardware changes:

- equip the SPS with SC magnets, upgrade transfer lines to LHC and the injector chain, to inject into the LHC at 1 TeV (➔ super-SPS option)
  - ➔ beam luminosity should increase
  - ➔ first step in view of an LHC energy upgrade
  - for a given mechanic and dynamic apertures at injection, this option can double the beam intensity (at constant beam-beam parameter $\Delta Q_{bb} \propto N_b/\varepsilon_n$) increasing the LHC peak luminosity by nearly a factor two, in conjunction with long range beam-beam compensation schemes
  - LHC energy swing is reduced by a factor 2, hence the SC transient phenomena should be smaller and the turnaround time to fill LHC should decrease
  - interesting alternative ➔ cheap, compact low-field booster rings in the LHC tunnel
- install in LHC new dipoles with a operational field of 15 T considered a reasonable target for 2015 ÷ 2020 ➔ beam energy around 12.5 TeV
  - ➔ luminosity should increase with beam energy
  - ➔ major upgrade in several LHC hardware components

scenarios for upgrading the injector chain

CARE-HHH

- up to 160 MeV: LINAC 4
- up to 2.2 GeV: the SPL (or a super-BPS)

→ See CARE-HIPPI

- up to 25 GeV: a fully refurbished PS

The superconducting way:

- up to 150 GeV: a refurbished SPS
- up to 1 TeV: a SC super SPS
- SC transfer lines to LHC

The normal conducting way:

- Up to 450 GeV: a refurbished SPS

See CARE-HHH and CARE-NED

A 1 TeV booster ring in the LHC tunnel may also be considered

- Easy magnets (super-ferric technology?)
- Difficult to cross the experimental area (a bypass needed?)

basic assumptions

- PS extraction energy ≥ 25 GeV
- PS bunch population 2×10^{11} within 3.5 μm emittance, and 4×10^{11} within 7 μm,
- PS bunch separation 12.5 ns (or 10 ns, if the impact on RF system should be minimised)
- To evenly spread the energy swing from 25 to 1000 GeV, we need two rings: the first ring should reach 150 GeV and the second 1 TeV
- As an alternative the first ring can reach 100 GeV and the second 1000 GeV

luminosity upgrade should mostly come from:

- shorter turnaround time in filling the LHC
- increased circulating intensity and bunch population

shortening the turnaround time

CARE-HHH

- injecting in LHC 1 TeV protons reduces the dynamic effects of persistent currents i.e.:
  - persistent current decay during the injection flat bottom
  - snap-back at the beginning of the ramp
  - ➔ decrease the turn-around time and hence increases the integrated luminosity

$$T_{run}\ (\text{optimum}) \Rightarrow \begin{cases} 1+\dfrac{T_{run}+T_{turnaround}}{\tau_L} = e^{\frac{T_{run}}{\tau_L}} \\ \displaystyle\int_0^{T_{run}} L\,dt \approx \dfrac{L_0\tau_L}{T_{run}+T_{turnaround}+\tau_L} \end{cases}$$

$$L(t) = L_0 e^{-\frac{t}{\tau_L}}$$

with τ_{gas} = 85 h and

τ^{x}_{IBS}= 106 h (nom) ➔ 40 h (high-L)

halving T_turnaround

L_0 [$cm^{-2}s^{-1}$]	τ_L [h]	$T_{turnaround}$ [h]	T_{run} [h]	$\int_{200\ runs} L\,dt$ [fb^{-1}]	gain
10^{34}	15	10	14.6	66	×1.0
10^{34}	15	5	10.8	85	×1.3
10^{35}	6.1	10	8.5	434	×6.6
10^{35}	6.1	5	6.5	608	×9.2

increasing the circulating intensity

CARE-HHH

- 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

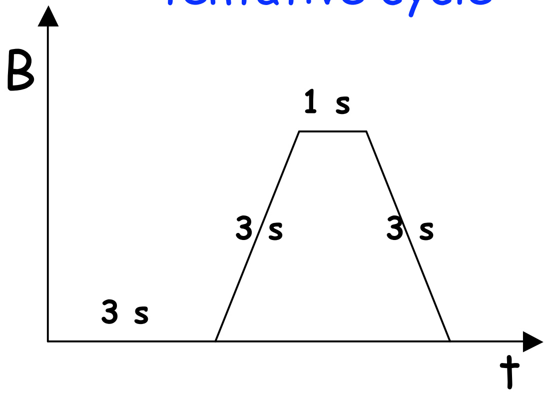
$$L \approx \gamma \Delta Q_{bb}^2 \frac{\pi \varepsilon_n f_{rep}}{r_p^2 \beta^*} \sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\sigma^*} \right)^2}$$

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

- at the beam-beam limit, peak luminosity L is proportional normalized emittance = $\gamma\varepsilon$ (we propose doubling N and ε_n, keeping constant ε_n/N).
- 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 b-b effects have to be compensated.

pulsed SC magnets for the super-SPS

tentative cycle



- with the present SPS dipole packing factor, at 1 TeV we need SC dipole with $B_{peak} \approx 4.5$ T
- to reduce dynamic effects of persistent current, the energy swing should not exceeds $\times 10$
- the optimal injection energy is of about 100÷150 GeV
- a repetition rate of 10 s should halve the LHC filling time

repetition rate 10s

SPS beam size:

- normalized emittance: $\varepsilon^* = 2\times 3.5\ \mu m$ (2 factor is related to the higher bunch intensity)
- peak-beta: $\beta_{max} \approx 100$ m (assuming the same focussing structure of the present SPS)
- rms beam size at injection: $\sigma_{150GeV} \approx 2.2$ mm $\sigma_{1000GeV} \approx 0.8$ mm

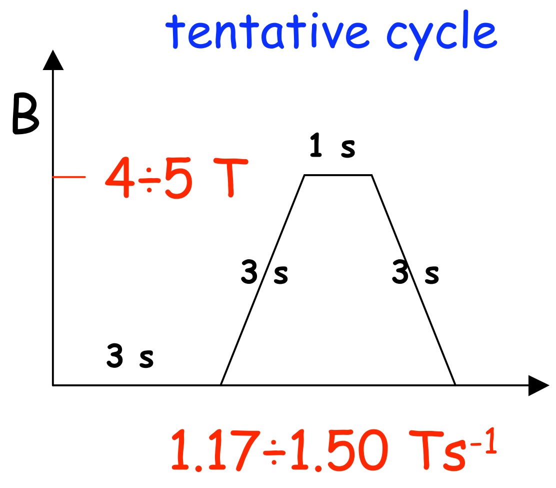
SPS aperture

- peak closed orbit: $CO_{max} = 5$ mm
- dispersive beam size $D\times\delta = 12$ mm (assuming D = 4 m, $\delta_{bucket} = 3\times 10^{-3}$)
- betatron beam size $6\times\sigma_{150GeV} = 12$ mm and $6\times\sigma_{1000GeV} = 5$ mm
- separatrix size for slow extraction 20 mm
- clearance of 6 mm

adding in quadrature the betatron and the dispersive beam size and linearly the closed orbit, the separatrix size, and the clearance one will need a radial aperture of at least 29 mm at injection and 44 mm at top energy.

inner coil aperture 70÷100 mm

pulsed SC magnets for the super-SPS

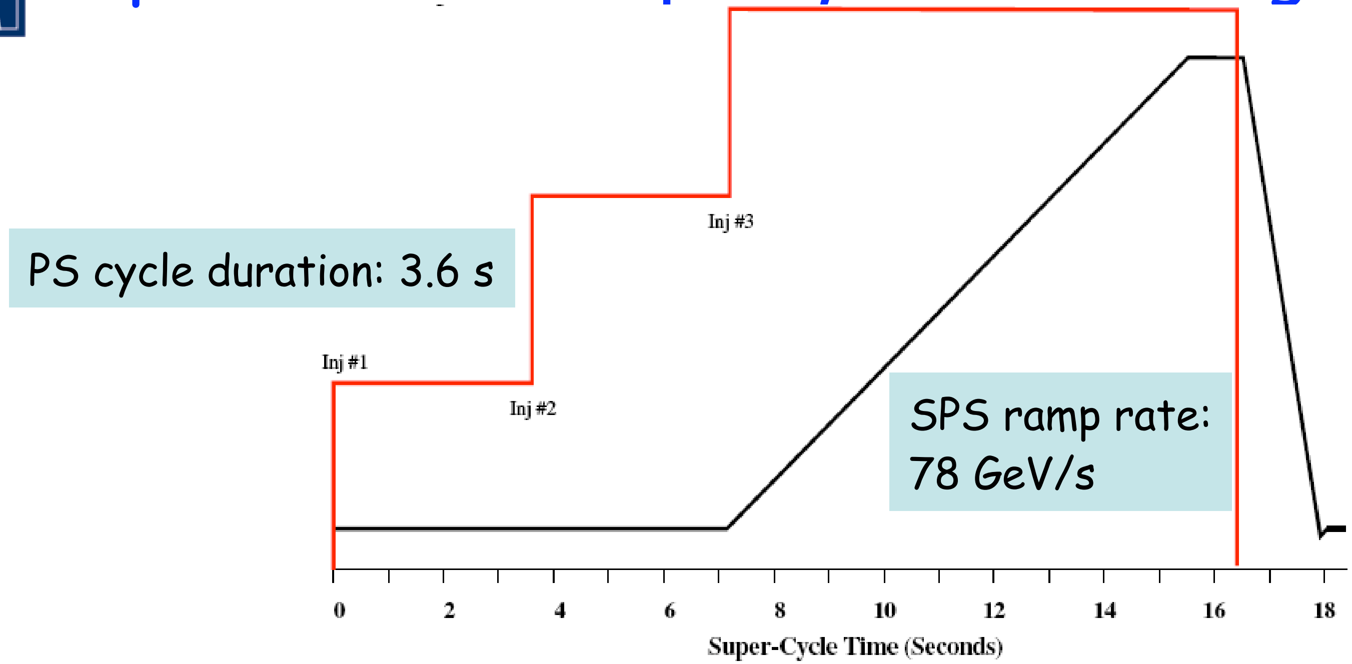


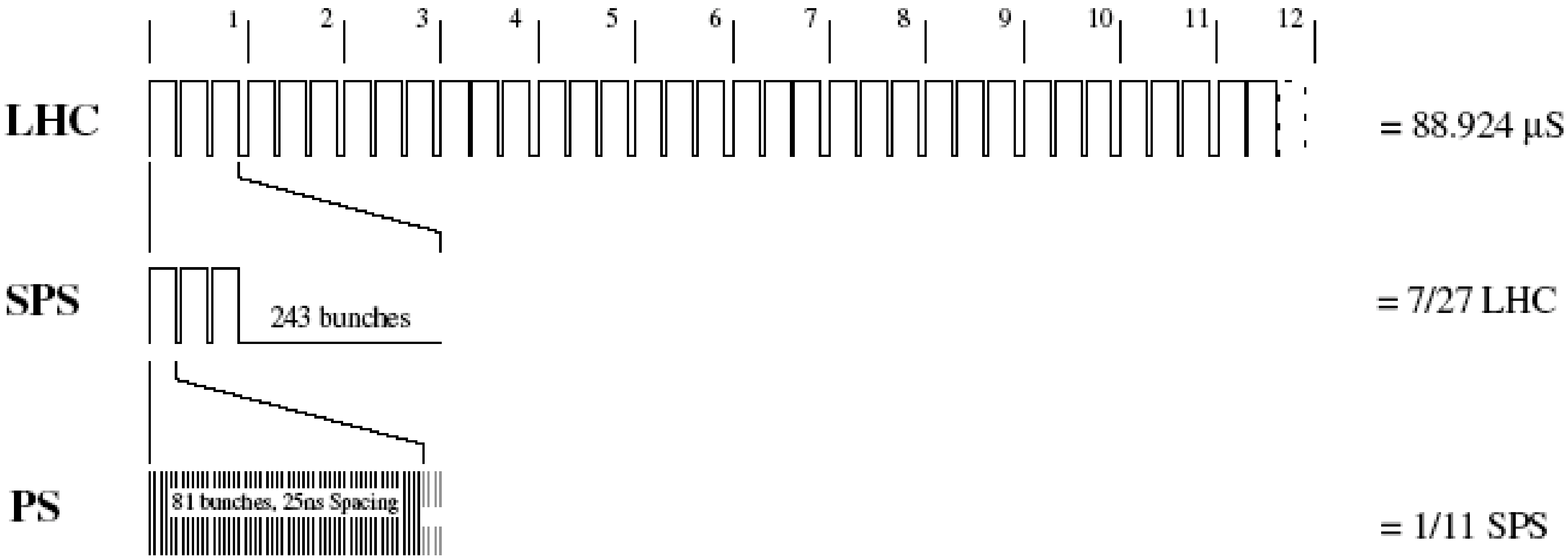
the technological challenge can be modulated:

- B_{max} = 4 T, dB/dt = 1.17 Ts^{-1} is rather easy, prototypes with close performance already exist, no major R & D required
- B_{max} = 5 T, dB/dt = 1.5 Ts^{-1} is rather difficult, no prototype exist, a major R & D is requested

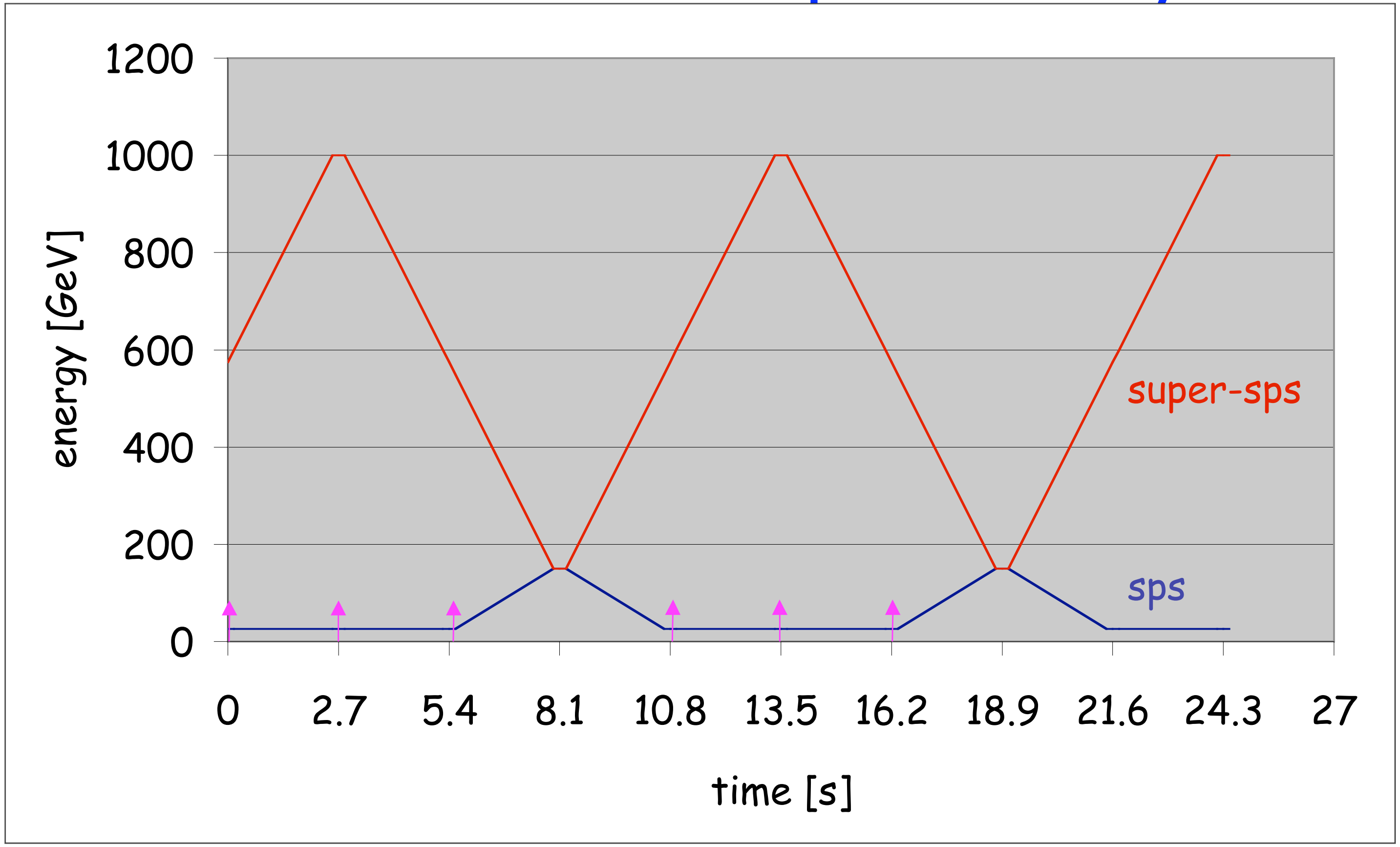
- a SC dipole for the SPS may produce 70 W/m peak (35 W/m effective ⇒ 140 kW for the SPS, equivalent to the cryogenic power of the LHC !)
- a rather arbitrary 'guess' for tolerable beam loss is of about 10^{12}px1000GeV/10s = 15 kW
- by dedicated R&D magnet losses should be lowered to 10 W/m peak (5 W/m effective ⇒ 20 kW), comparable to 'tolerable' beam loss power

present SPS supercycle for filling LHC





interleaved SPS & super-SPS cycles



PSB

0.9 s rep-rate

PS

2.7 s rep-rate

SPS

E_{inj} = 26 GeV

E_{ext} =150 GeV

10.8 s rep-rate

51.67 GeV/s ramp-rate

3 PS-batches/cycle

Super-SPS

E_{inj} = 150 GeV → B = 0.675 T

E_{ext} =1000 GeV → B = 4.5 T

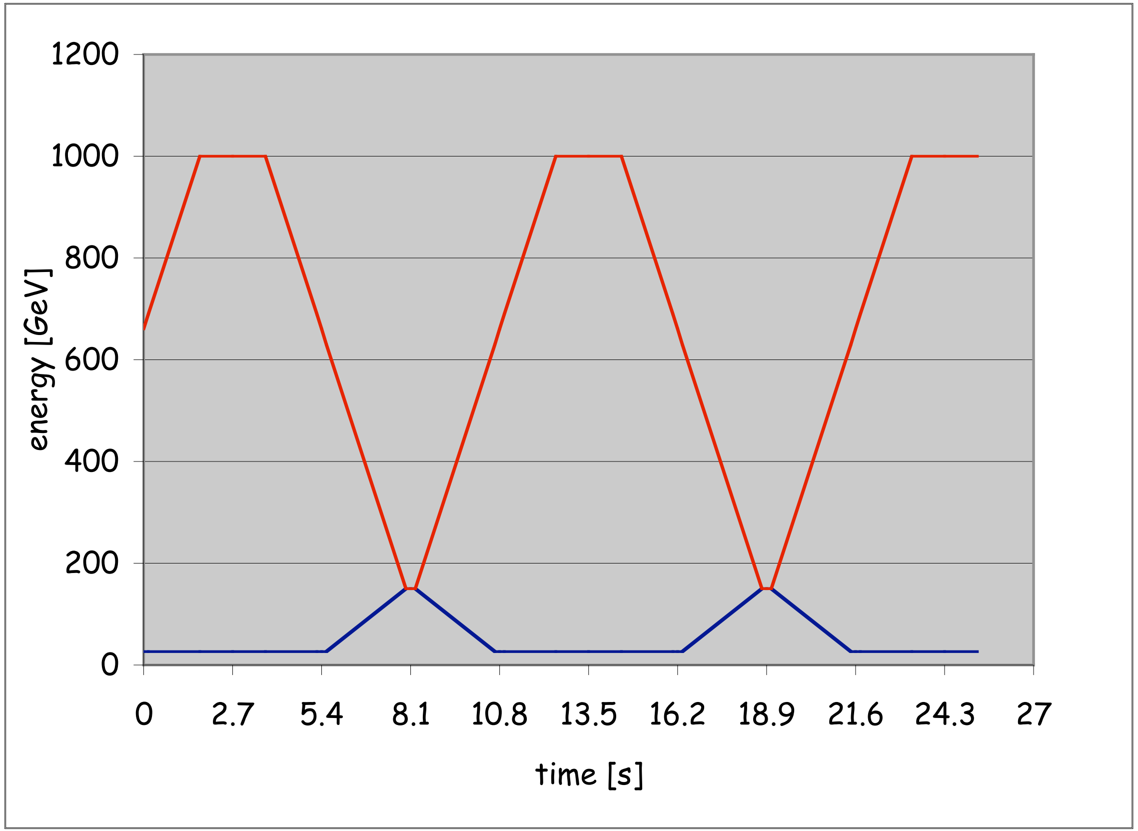
10.8 s rep-rate

166.67 GeV/s ramp-rate

dB/dt = 0.75 T/s

3 PS-batches/cycle

test beam cycle for the super-SPS



Super-SPS

E_{inj} = 150 GeV → B = 0.675 T

E_{ext} =1000 GeV → B = 4.5 T

10.8 s rep-rate

200 GeV/s ramp-rate

dB/dt = 0.9 T/s

3 PS-batches/cycle

flat-top 2 s

open items

1. evaluate all consequences of higher intensity operation
2. installation staging in the SPS tunnel, minimising the duration of the shutdown
3. lattice design also considering the partial use the present SPS ring
4. refined estimate of the magnet aperture
5. slow extraction design at 1 TeV within the space available
6. optimal extraction & injection channels (kickers and septa operating on more energetic particles within serious space occupancy constraints)
7. estimate of the expected loss
8. design of SC transfer lines to the LHC
9. optimal design for the SC magnets for the super-SPS: nominal parameters should be proposed and a road map for the requested R & D presented.
10. cryogenic system: solution should be investigated for the needs and the installation of cryogenics in the SPS tunnel.
11. RF systems: the optimal choice of the RF parameter is not yet available.

foreseeing other uses of the super-SPS

1. scenario to fill the whole super-SPS ring
2. upper value of the circulating intensity
3. optimal cycle duration
4. optimal bunch distance

concluding remarks

the expected factors for the LHC luminosity upgrade are

- factor 2 from new low-beta insertions with $\beta^*=0.25$ m
- factor 2.3 from nominal to ultimate bunch intensity (1.7×10^{11} p)

with an upgraded injector we expect a farther increase in luminosity of

- factor 2 if we can double the number of bunches
- factor 2 from a twice larger bunch intensity
- factor 1.4 from a shorter LHC turnaround time

ensuring $L=10^{35}$ cm^{-2} s^{-1} and a gain of about 9 in $\int L dt$

R & D is required on

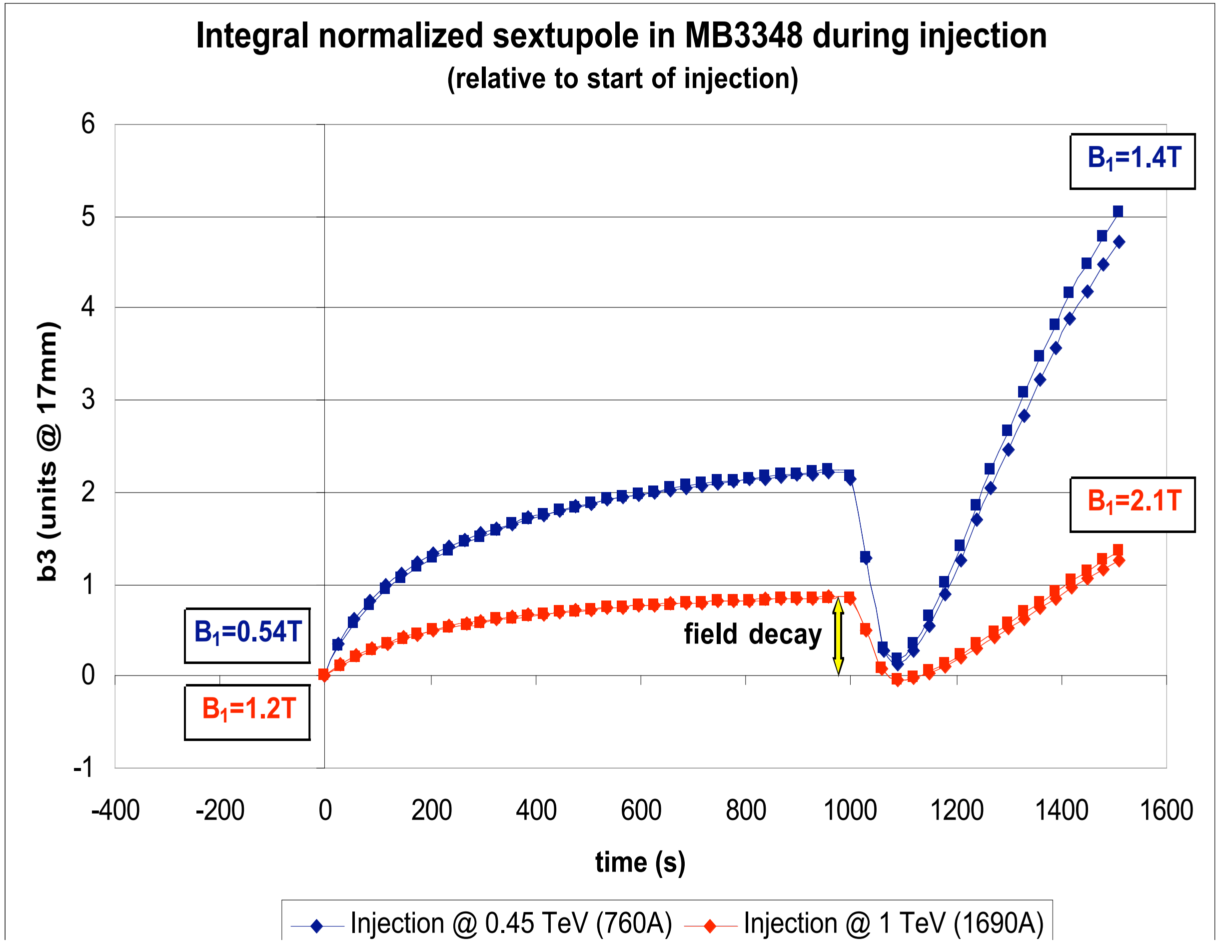
- optics, beam control, machine protection
- high gradient high aperture SC quadrupoles and RF
- SC fast ramping magnets

turnaround time

Status of Hera (Bieler), RHIC (Calaga), Tevatron (Sen)

- The definition of the turnaround time is not universal
  - Hera -> high weight to long duration faults
  - RHIC -> availability of the collider differs from filling/running time
  - Tevatron -> bias due to the long duration of pbar production
- With some caution the can infer that doubling the injector energy on can reduce from 10 to 7 h the LHC turnaround time

Decay and snapback in main LHC dipoles vs. injection current



Normalized B3 decay: reduction of a factor **2.6** from 0.45 TeV to 1 TeV injection

Optimal timing of the upgrade

Open discussion

- For IR triplet
  - Ordinary maintenance may impose unexpected replacement
  - Replacing the triplet in a programmed manner may take up to 2 y (1 for the hardware replacement, one for the re-commissioning
  - New performance should be worth recovering quickly this time loss
- For the injector
  - Staging the change is mandatory
  - This may push for a solution not optimal (respect to a green field approach)
  - However approach a la FNAL is appealing (linac up to 8 GeV, super-PS up to 80 GeV, super-SPS up to 1 TeV)

High intensity

Talk of Elena S. + open discussion

- Linac, BPS and PS
  - Can sustain up to 2 10^{11} ppp and above (times 4 ?)
- SPS
  - Limited to 1.5 10^{11}
  - Studies of the limitations are crucial. They require appropriate resources

Block coil magnets for the super-SPS

Talk of Peter McI.

- Bocks are parallel to the field as much as possible
- Large reduction of the thermal loss
- Very interesting for a fast cycling super-sps and probably also for a super-ps

super PS

Brainstorming in common

- motivations
  - present PS in a bad shape: 20 MCHF investment required for new magnets and generatrix and other
  - Reliable operation in the LHC injector chain
- Tentative design based on the existence of LINAC 4 and on a 0.9 s BPS cycle
  - same size as the present PS (within 10 %)
  - E_{inj} = 1.4 Gev
  - $T_{cycle} \leq 2.7$ s
  - T_{ramp} = 1.2 s -> 3T/s
  - Swing = 30
  - Close to gamma_tr
  - E_{peak} = 60 GeV
  - Flavor physics has close requirements
  - Beam power 0.5 MW
- Critical issues to be ready in 2012 (if possible Linac 4 available in 2011)
  - low loss cable, (start early in 2006)
  - magnet, (start in 2007 aiming at a test model by 2008)
  - RF design, Lattice design (start to be decided on resouce availability)

RF studies

- High priority issue
  - Investigate SPS limitations
  - Establish scaling rules
  - Propose solution for ultinate intensity and beyond
- Additional resources for
  - Data analysis
  - Simulations
  - Experiments (PS should provide bunches with ultimate intensity and beyond)

High intensity

G. Franchetti

- Space charge detuning in a bunch
- Periodic crossing of a resonance
- Locking on a resonance and trapping (similar e.g. to island trapping)
- Expect bunch length reduction and triangular shape of the bunch
- Comparison bunched and coasting beam with the same space charge tune spread
- Lifetime of the coasting beam is larger than that of the bunched beam since there is no synchrotron movement providing periodic crossing of a resonance.
- Are the distribution similar?
- Possible solution is to flatten the bunch.
- Possibility of benchmarking with simulations.
- Preliminary simulations seem to show that if you stop the synchrotron motion you do not see any more an emittance blow-up

RHIC magnets

D. Tommasini

- RHIC type dipole GSI001. 4 T/s and max field 4 T.
- Might be not trivial to go to higher field.
- 3T/s ➔ 120 J/cycle ➔ 3 s cycle ~ 40 W AC losses
- Temperature margin due to losses is not large
- 2006 R&D goals could be:
  - Specify and procure one billet of filament size 3 microns, Cu matrix. this wire could be sufficient to build a magnet with performance close to those required for the Super PS.
  - Explore CuMn (more resistive) matrix
  - Explore high interstrand resistance vs. core (stability, long term behaviour).
  - Specifications on the field quality

RF cost estimate for different bunch spacing

12.5 ns – 1.7x10^11 p/bunch – double n of bunches

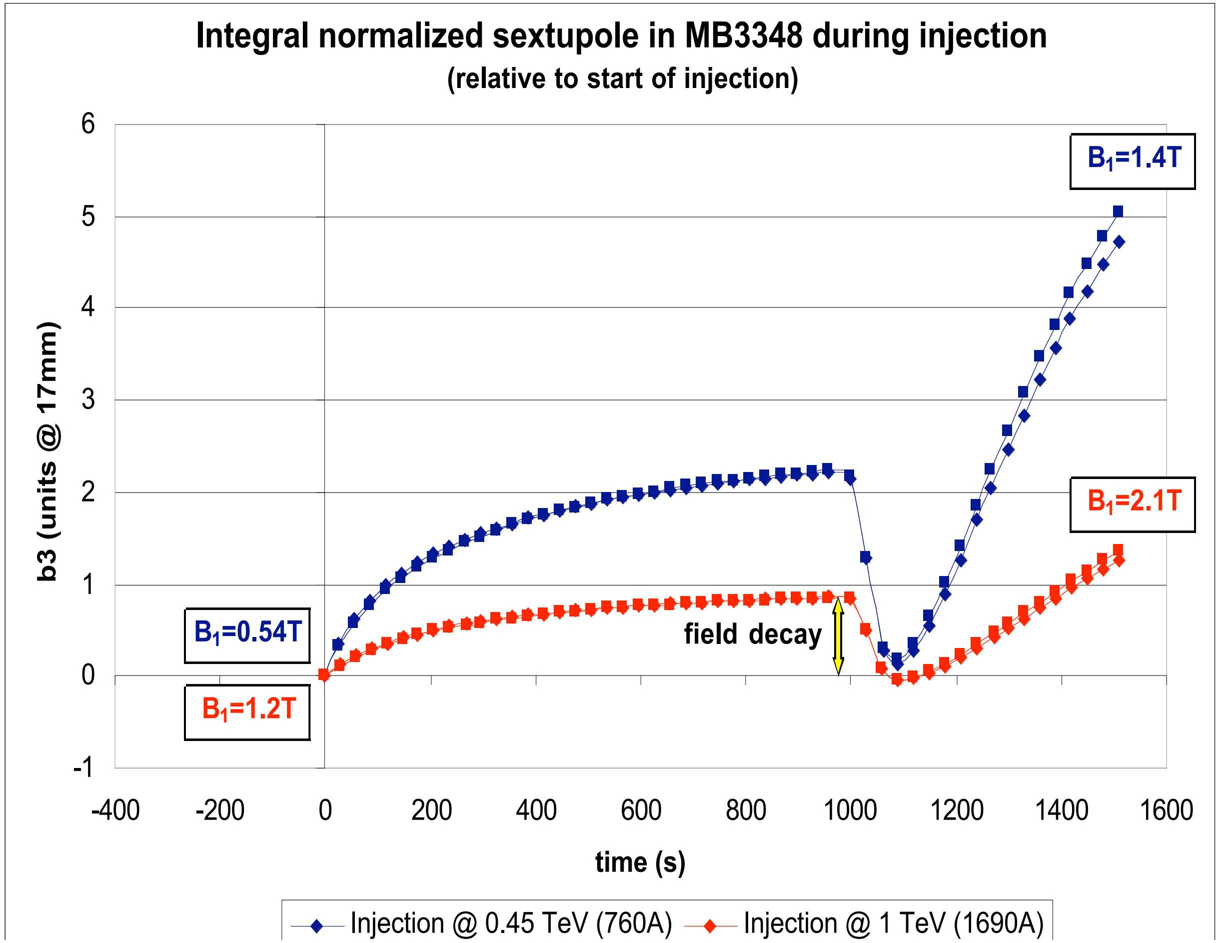
PS
More 80 MHz cavities – twice more volts – 2 MCHF
SPS
160-240 MHz system (power and cavities) – Ions would it be possible? – 75 MCHF
LHC
160-240 MHz cavities – 2 x 3 MV (power + cavities) – 10 MCHF

10 – 15 ns – 1.7x10^11 p/bunch – 2.5 n of bunches

PS
More 80 MHz cavities – twice more volts – 5 MCHF
SPS
More power for 200 MHz system 20 MCHF

For all the upgrades: need to upgrade transverse feedback in the SPS/LHC
Need new BPM electronics (5 MCHF) in the LHC

Decay and snapback in main LHC dipoles vs. injection current



Normalized B3 decay: reduction of a factor **2.6** from 0.45 TeV to 1 TeV injection