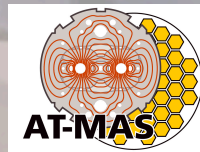


# Plans for the LHC Luminosity Upgrade Summary of the CARE-HHH- APD-LUMI-05 workshop

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LHC project seminar  
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# scenarios for the luminosity upgrade



- ◆ ultimate performance **without** hardware changes (**phase 0**)
- ◆ maximum performance with **IR** and **RF** changes (**phase 1**)
- ◆ maximum performance with '**major**' hardware upgrade (**phase 2**)

Nominal LHC performance → {

- ◆ beam-beam tune spread of 0.01
- ◆  $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  in Atlas and CMS
- ◆ Halo collisions in ALICE
- ◆ Low-luminosity in LHCb

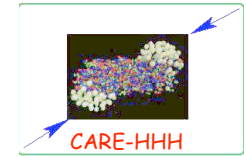
**Phase 0:** steps to reach **ultimate performance** **without** hardware changes:

- 1) collide beams only in **IP1** and **IP5** with alternating H-V crossing
- 2) increase  $N_b$  up to the beam-beam limit →  $L = 2.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- 3) increase the dipole field from 8.33 to 9 T →  $E_{\text{max}} = 7.54 \text{ TeV}$

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump/machine protection considerations.



# scenarios for the luminosity upgrade



**Phase 1:** steps to reach maximum performance with IR and RF changes:

- 1) modify the insertion quadrupoles and/or layout  $\rightarrow \beta^* = 0.25 \text{ m}$
- 2) increase crossing angle  $\theta_c$  by  $\sqrt{2} \rightarrow \theta_c = 445 \mu\text{rad}$
- 3) increase  $N_b$  up to ultimate luminosity  $\rightarrow L = 3.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- 4) halve  $\sigma_z$  with high harmonic RF system  $\rightarrow L = 4.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- 5) double the no. of bunches  $n_b$  (increasing  $\theta_c$ )  $\rightarrow L = 9.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

RF Upgrade

☹ step 4) is not cheap: it requires a new RF system in LHC providing

- ◆ an accelerating voltage of 43MV at 1.2GHz
- ◆ a power of about 11MW/beam  $\rightarrow$  estimated cost 56 MCHF
- ◆ a longitudinal beam emittance reduced to 1.78 eVs
- ◆ horizontal Intra-Beam Scattering (IBS) growth time will decrease by about  $\sqrt{2}$

☹ operational consequences of step 5) ( $\rightarrow$  exceeding ultimate beam intensity)

- ◆ upgrade LHC cryogenics, collimation and beam dump systems
- ◆ upgrade the electronics of beam position monitors
- ◆ possibly upgrade the SPS RF system and other equipments in the injector chain



# luminosity and energy upgrade



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

- ◆ **Injector chain:** install in the SPS and in the transfer lines SC magnets, to inject into the LHC at 1 TeV → **SPS+ option** (2015 ÷ 2017 )
  - beam luminosity should increase
  - first step in view of an LHC energy upgrade
  - this should allow doubling the **beam intensity** (at constant beam-beam parameter  $\Delta Q_{bb} \propto N_b/\epsilon_n$ ) and the LHC peak luminosity (long range beam-beam compensation schemes mandatory)
  - LHC energy swing is reduced by a factor of 2 → the SC transient phenomena should be smaller and the **turnaround time** to fill LHC should decrease  
(interesting alternative → compact low-field booster rings in the LHC tunnel)
- ◆ **LHC ring:** install in LHC new dipoles with a operational field of **15 T**  
considered a reasonable target for the 2020 decade → **beam energy around 12.5 TeV**
  - luminosity should increase with beam energy
  - major upgrade in several LHC hardware components



# basic options



We assume being able of handling in the PS:

- ◆ a bunch population  $2 \times 10^{11}$  within  $3.5 \mu\text{m}$  emittance, and  $4 \times 10^{11}$  within  $7 \mu\text{m}$ ,
- ◆ a bunch separation 12.5 ns (or 10 ns, if the impact on RF system should be minimised)

- ◆ **use the present PS and two new SC rings:**  
to evenly spread the energy swing from 25 to 1000 GeV, the first ring should reach 150 GeV and the second 1 TeV  
→ consider housing the first ring in the ISR tunnel and the second in the SPS tunnel
- ◆ **use two new SC rings**  
the first ring should replace the PS and reach up to 60 GeV, the second ring should replace the SPS and reach up to 1 TeV  
→ consider housing the new PS+ in a new tunnel and the second ring in the SPS tunnel



# upgrade of the entire injector chain



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

- Up to 60 GeV (PS+)
- Up to 1 TeV (SPS+) or the SPS
- SC transfer lines to LHC

- Up to 25 GeV a refurbished PS
- Up to 150 GeV (ISR+)
- Up to 1TeV (SPS+)
- SC transfer line to LHC

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?)





# shortening the turnaround time



♦ 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

$$T_{run} \text{ (optimum)} \Rightarrow \begin{cases} 1 + \frac{T_{run} + T_{turnaround}}{\tau_L} = e^{\frac{T_{run}}{\tau_L}} \\ \int_0^{T_{run}} L dt \approx \frac{L_0 \tau_L}{T_{run} + T_{turnaround} + \tau_L} \end{cases} \quad \begin{aligned} L(t) &= L_0 e^{-\frac{t}{\tau_L}} \\ \text{with } \tau_{gas} &= 85 \text{ h and} \\ \tau_{IBS}^x &= 106 \text{ h (nom)} \rightarrow 40 \text{ h (high-L)} \end{aligned}$$

- ♦ The turnaround time is a loose concept
- ♦ Its definition vary from lab to lab
- ♦ The operational experience reduces it
- ♦ Any hardware upgrade increases it
- ♦ Difficult to quantify the effect of doubling the LHC injection energy  
→ factor of 1.5 to 2 reduction ??

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

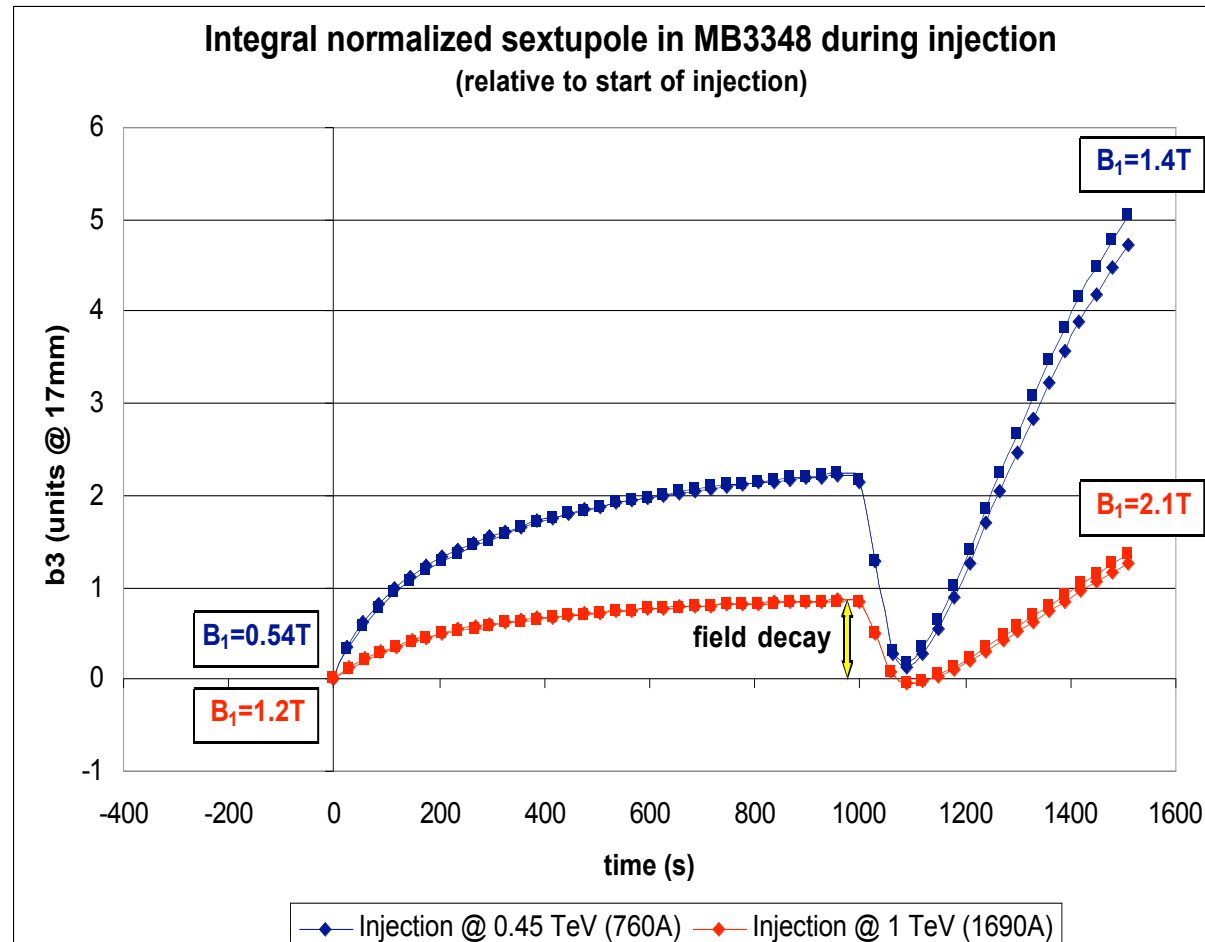


# reducing the dynamic effects of persistent current



Courtesy of Marco Buzio

## 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





# increasing the circulating intensity

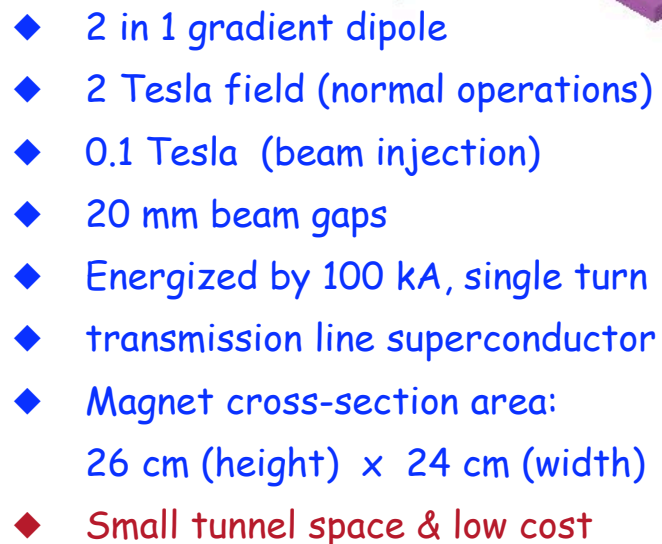


- ◆ injecting in LHC more intense proton beams with constant brightness, within the same physical aperture  
→ will increase the peak luminosity proportionally to the proton intensity

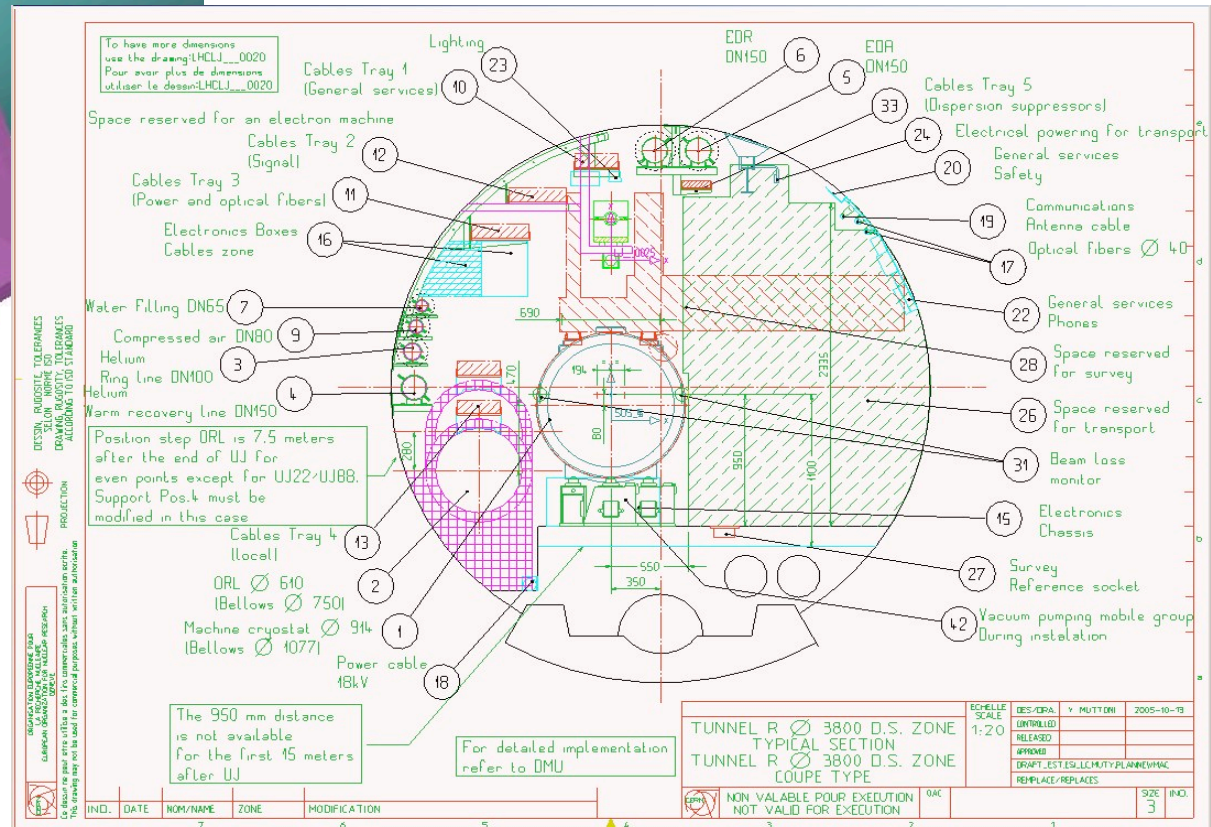
$$L \approx \gamma \Delta Q_{bb}^2 \frac{\pi \varepsilon_n f_{rep}}{r_p^2 \beta^*} \sqrt{1 + \left( \frac{\theta_c \sigma_s}{2\sigma^*} \right)^2}$$

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

- at the beam-beam limit, peak luminosity  $L$  is proportional normalized emittance =  $\gamma \varepsilon$  (we propose doubling  $N$  and  $\varepsilon_n$ , keeping constant  $\varepsilon_n/N$ ).
- an increased injection energy (SPS+) allows a larger normalized emittance  $\varepsilon_n$  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.



- ◆ Coolant - supercritical helium (4.2 K, 4 bar, 60 g/s)
- ◆ Warm beam pipe vacuum system (ante-chambers required)
- ◆ Alternating gradient at 64 m (half dipole length)





# why not LHCI or a superferric ring in the LHC tunnel ?



## 😊 positive aspects:

- 1) no need to upgrade the injection lines TI2 and TI8
- 2) relaxed magnets in the injector ring
- 3) higher injection energy (if needed we can reach 1.5 TeV)

## 😞 drawbacks

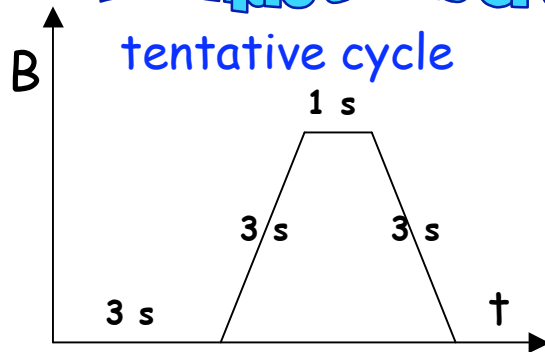
- 1) unchanged limitations in the SPS and in the transfer lines
- 2) by-pass needed for ATLAS and CMS (especially to avoid loss of test beams)
- 3) difficult optics for injection extraction with limited space in a dedicated long straight section of LHC tunnel
- 4) impedance budget considerably higher due to the small pipe



# pulsed SC magnets for the PS/SPS



## Example of the SPS



SPS beam size:

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

## SPS aperture

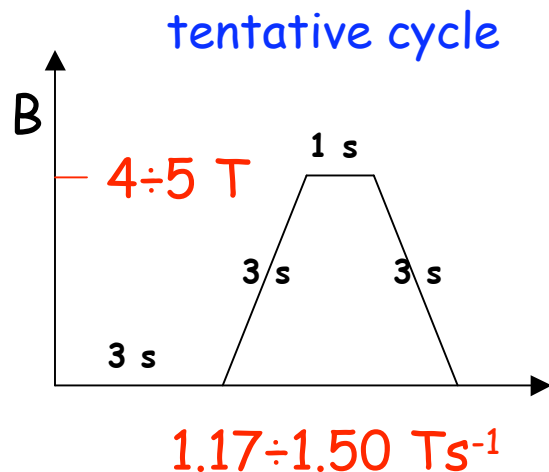
- peak closed orbit:  $CO_{\text{max}} = 5 \text{ mm}$
- dispersive beam size  $D \times \delta = 12 \text{ mm}$  (assuming  $D = 4 \text{ m}$ ,  $\delta_{\text{bucket}} = 3 \times 10^{-3}$ )
- betatron beam size  $6 \times \sigma_{150\text{GeV}} = 12 \text{ mm}$  and  $6 \times \sigma_{1000\text{GeV}}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

inner coil aperture 100 mm

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

repetition rate 10s

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.



the technological challenge can be modulated:

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

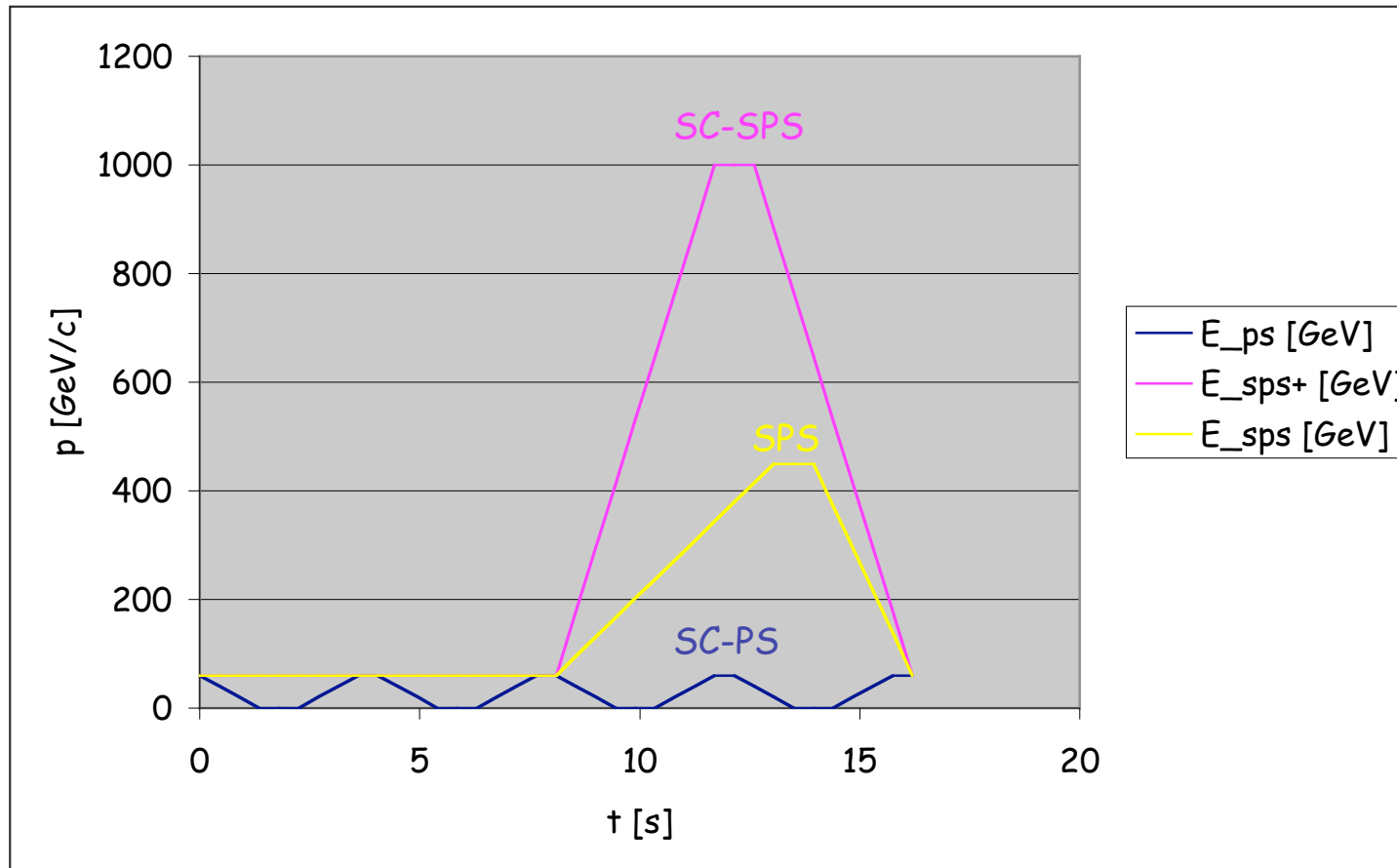
- ◆ a SC dipole for the SPS may produce 70 W/m peak (**35 W/m effective** ⇒ 140 kW for the SPS, equivalent to the cryogenic power of the LHC !)
- ◆ a rather arbitrary 'guess' for tolerable beam loss is of about  $10^{12} \text{ px} 1000 \text{ GeV} / 10 \text{ s} = 15 \text{ kW}$
- ◆ **by dedicated R&D** magnet losses should be lowered to 10 W/m peak (5 W/m effective ⇒ 20 kW ), comparable to 'tolerable' beam loss power



# tentative PS - SPS interleaved cycle



PS cycle duration: 4.5 s



SC-PS

$B_{MAX}=4$  T

Ramp=3 T/s

SC-SPS

$B_{MAX}=4.5$  T

Ramp=1.5 T/s

SPS

$B_{MAX}=2$  T

Ramp=0.35 T/s





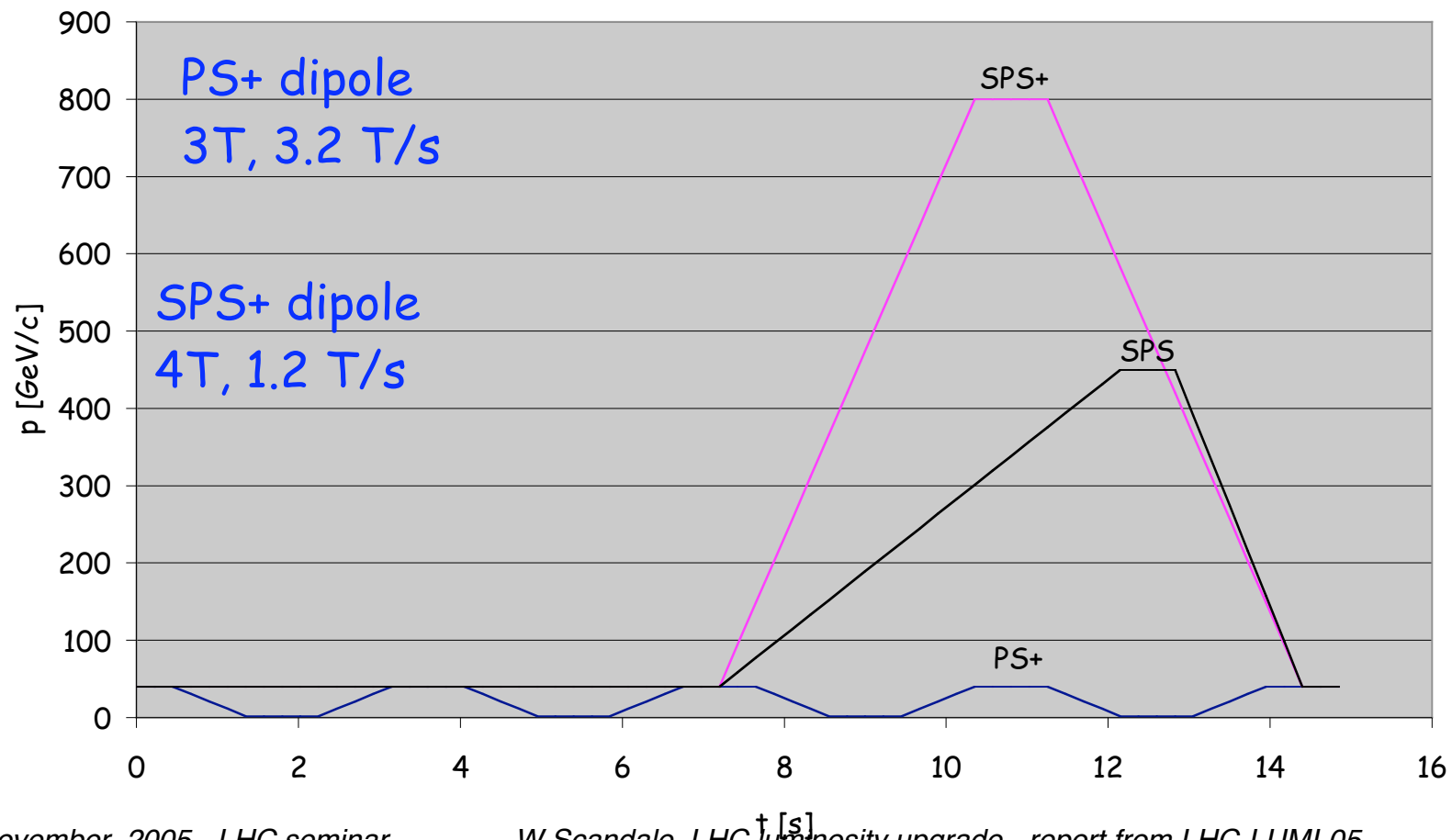
# tentative PS - SPS interleaved cycle



PS cycle duration: 3.6 s

SPS ramp rate:  
83 GeV/s

PS SPS interleaved cycles





# R&D on SC wire



Courtesy of Davide Tommasini

For 3T, 3T/s pulsed dipole

we aim at the following distribution of losses in the SC wire

- ◆ Filament hysteresis : 50%
- ◆ Interstrand resistance : 15 %
- ◆ Matrix coupling : 15 %
- ◆ Structure : 20 %

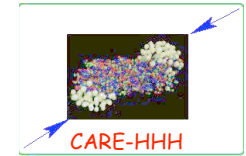
A possible way to proceed

- ◆ Specify and procure billets with filament size < 3 microns in Cu matrix
- ◆ Explore benefits Cu-Mn matrix
- ◆ Explore high interstrand resistance versus core (stability, long term behavior)
- ◆ About 10 billets required to explore alternatives of interest



# R&D on RF cavities

Courtesy of Joachim Tuckmantel



Only **few cavities**, copper or superconducting, can easily supply the **desired voltage** (at least for the upgrade of the SPS)

**Gradients** have to be **lowered** voluntarily since the **power coupler cannot transmit** the corresponding **RF power** to accelerate high beam currents and to compensate reactive beam loading

- ◆ Power coupler capabilities have to be increased considerably
- ◆ for sc. cav. couplers: RF losses into liquid He, "deconditioning"

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

- ◆ Study compact RF power transmitter at 200 MHz

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



# collimation for the injector chain



Courtesy of Nuria Catalan Lasheras

- ◆ 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 it in an old machine.
- ◆ A lot to learn from LHC specially for 1 TeV.
- ◆ Either the beam defines the collimation system or the collimation system will define the beam!!



# present views on injector upgrade



- ◆ Present bottle-neck of the injector complex
  - The SPS (capture loss, longitudinal stability)
  - The BPS (space charge)
- ◆ Best possible choice for upgrade
  - The linac (synergy with neutrino-physics needs)
  - The SPS (synergy with neutrino and flavour physics need ? - prerequisite for LHC energy upgrade)

however a SC PS turns out to be the best choice for CERN especially if the PS magnet consolidation program is not a reliable long term solution

- the right move towards the (high-priority) LHC performance upgrade
- an opportunity to develop new fast pulsing SC magnets

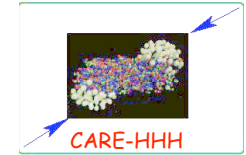
- ◆ The 1TeV SC SPS should remain the strategic objective
- ◆ The real benefit of any proposed upgrade should be fully quantified

discussions ongoing in PAF



# advantages of the PS+

Courtesy of Elena Shaposhnikova



- ◆ No transition crossing in the SPS for proton beam and probably for light ions
- ◆ Easier acceleration of lead ions in the SPS (less frequency swing)
- ◆ Smaller sensitivity on space charge tune spread and IBS growth time
  - critical for the ultimate proton intensity and for the nominal lead ions intensity
  - useful to mitigate capture loss
- ◆ Increase of the threshold of the coupled bunch instability induced by e-cloud in H-plane
- ◆ Increase of the threshold of the TMCI (without requesting more space charge)
- ◆ Shorter duration of the acceleration in the SPS

...but

- ◆ No obvious beneficial effect on known 'bottle necks'
  - Vertical e-cloud instability
  - Longitudinal coupled bunch instability
  - Beam loading

Increasing the PS energy will make much easier to operate the SPS





# factorization of the expected luminosity upgrade



◆ factor of 2.3 on  $L_0$  at the ultimate beam intensity ( $I = 0.58 \rightarrow 0.86 A$ )

◆ factor of 2 (or more ?) on  $L_0$  from new low- $\beta$  ( $\beta^* = 0.5 \rightarrow 0.25 m$ )

☹  $T_{turnaround} = 10h \rightarrow \int L dt = 3 \times \text{nominal} = 200 \text{ fb}^{-1} \text{ per year}$

◆ factor of 2 on  $L_0$  doubling the number of bunches (may be impossible due to e-cloud) or increasing bunch intensity and bunch length

☹  $T_{turnaround} = 10h \rightarrow \int L dt = 6 \times \text{nominal} = 400 \text{ fb}^{-1} \text{ per year}$

A new SPS injecting in LHC at 1 TeV/c would yield

◆ factor of 1.4 in integrated luminosity for shorter  $T_{turnaround} = 5 h$

◆ factor of 2 on  $L_0$  ( $2 \times$  bunch intensity,  $2 \times$  emittance)

☺  $L_0 = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$  AND  $\int L dt = 9 \times \text{nominal} = 600 \text{ fb}^{-1} \text{ per year}$



## Concluding remarks



- A vigorous R & D programme is required on
- optics, beam control, machine protection, collimation
  - high gradient high aperture SC quadrupoles
    - $\text{Nb}_3\text{Sn}$  SC wire and cable
    - radiation-hard design
  - RF & crab-cavities
  - SC fast ramping magnets

Time-scale required 10-12 years

→ START as soon as possible !