The CNGS Beam Challenge

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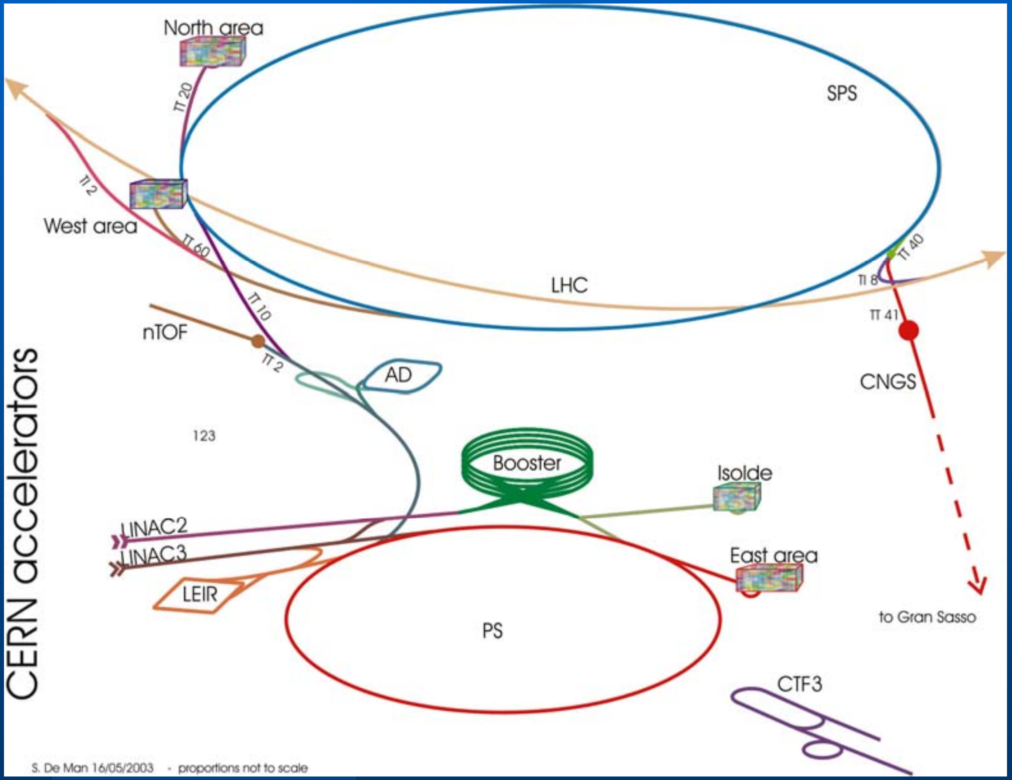
Acknowledgements: M. Benedikt, D. Forkel-Wirth, M. Giovannozzi, B. Goddard, C. Hill, E. Métral, T. Otto, E. Shaposhnikova, H. Vincke

Outline

- The CERN accelerator complex
- The CNGS beam
- The “cost” of high energy protons
  - Losses at extraction in the PS
  - Low energy losses in the SPS
  - SPS extraction losses
- The proton shortfall
- Summary and Conclusions

CERN Accelerator Complex



- CERN Proton accelerators for CNGS:
  - Linac 2
  - Proton Synchrotron Booster – PSB
  - Proton Synchrotron – PS
  - Super Proton Synchrotron – SPS

CERN Accelerator Complex

Accelerator	Inj. Kinetic Energy [GeV]	Ext. Kinetic Energy [GeV]	Commissioning year
Linac 2	0.00075	0.05	1979
PSB	0.05	1.4	1972
PS	1.4	13.1	1959
SPS	13.1	399.1	1976

Almost all machines will be more than 30 YEARS OLD for the CNGS commissioning!!!....and will have to serve RELIABLY for MANY YEARS as LHC INJECTORS

CNGS beam

- 4.5×10^{19} protons on target/year at a momentum of 400 GeV/c
  - ➔requires operating the machine at, or close to, the record intensity achieved in 1997 (4.8×10^{13} p/pulse)
  - ➔…and maintain it day after day with very low losses and high operational efficiency all through the accelerator complex
  - ➔very dangerous beam: ~3 MJ @ 400 GeV/c every 6 s ➔ ~0.5 MW average beam power

The "cost" of high energy protons

Based on 1997 performance (after 2-3 years of efforts to reduce losses) and 2004 tests

Process	Int. at the beginning of the process [10^{13} p/cycle]	Loss [10^{13} p/cycle]	Loss energy range [GeV]
Protons at 399.1 GeV	4.8		
Extraction from SPS	4.83	~0.03	399.1
Inj. and acc. in the SPS	5.2	~0.4	13.1-22
Ext. from PS-transfer to SPS	5.8=2x2.9	0.6	13.1
Inj. and acc. in the PS	6.1=2x3.1	0.3	1.4-5.0
Ext. from PSB-transfer to PS	6.4=2x3.2	0.3	1.4
Inj. and acc. in the PSB	15=2x7.5	8.6	0.05-0.15
Acceleration in Linac 2	16.4=2x8.2	1.4	0.001-0.05

The "cost" of high energy protons

- **Losses are the most critical issue for the whole complex:**
  - **Need to start with a factor 3 more beam at low energy**
  - **Most of the losses occur in the energy range 1-150 MeV:**
    - **Space charge effects in Linac 2 and PSB**
    - **Injection process in the PSB: painting in the transverse phase space to fill-up the available physical aperture with the maximum amount of beam**

The “cost” of high energy protons

- …but the radiological impact of losses increases with energy.

- when the energy “weighting” factor is taken into account:
  - Losses at extraction in the PS
  - Low energy losses in the SPS
  - SPS extraction losses

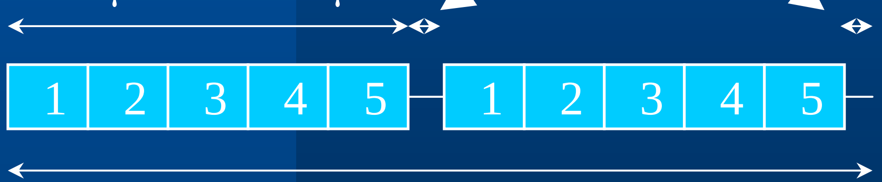
  have the largest radiological impact

Losses at extraction in the PS

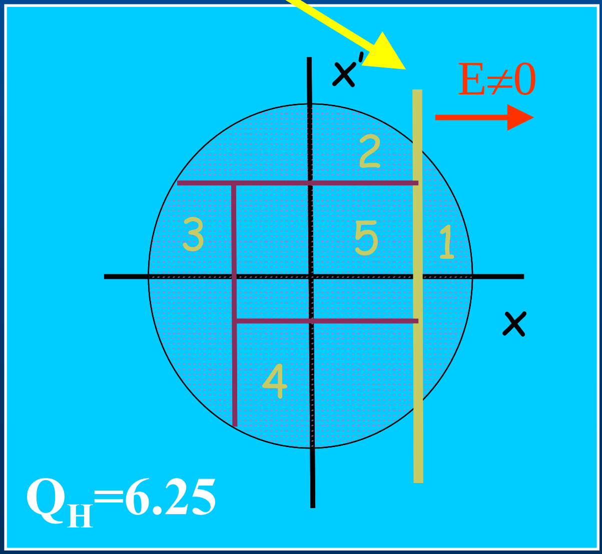
- **Present multi-turn extraction:**
  - **SPS Circumference = 11 × PS Circumference**
  - **2 consecutive injections (1.2 s) each filling 5/11 of the SPS circumference by transverse slicing of the PS beam in the H-plane by means of a thin electrostatic septum**

5 PS turns ~ 5 x 2.1 μs = 10.5 μs

1.05 μs gap for CNGS extraction or beam dump



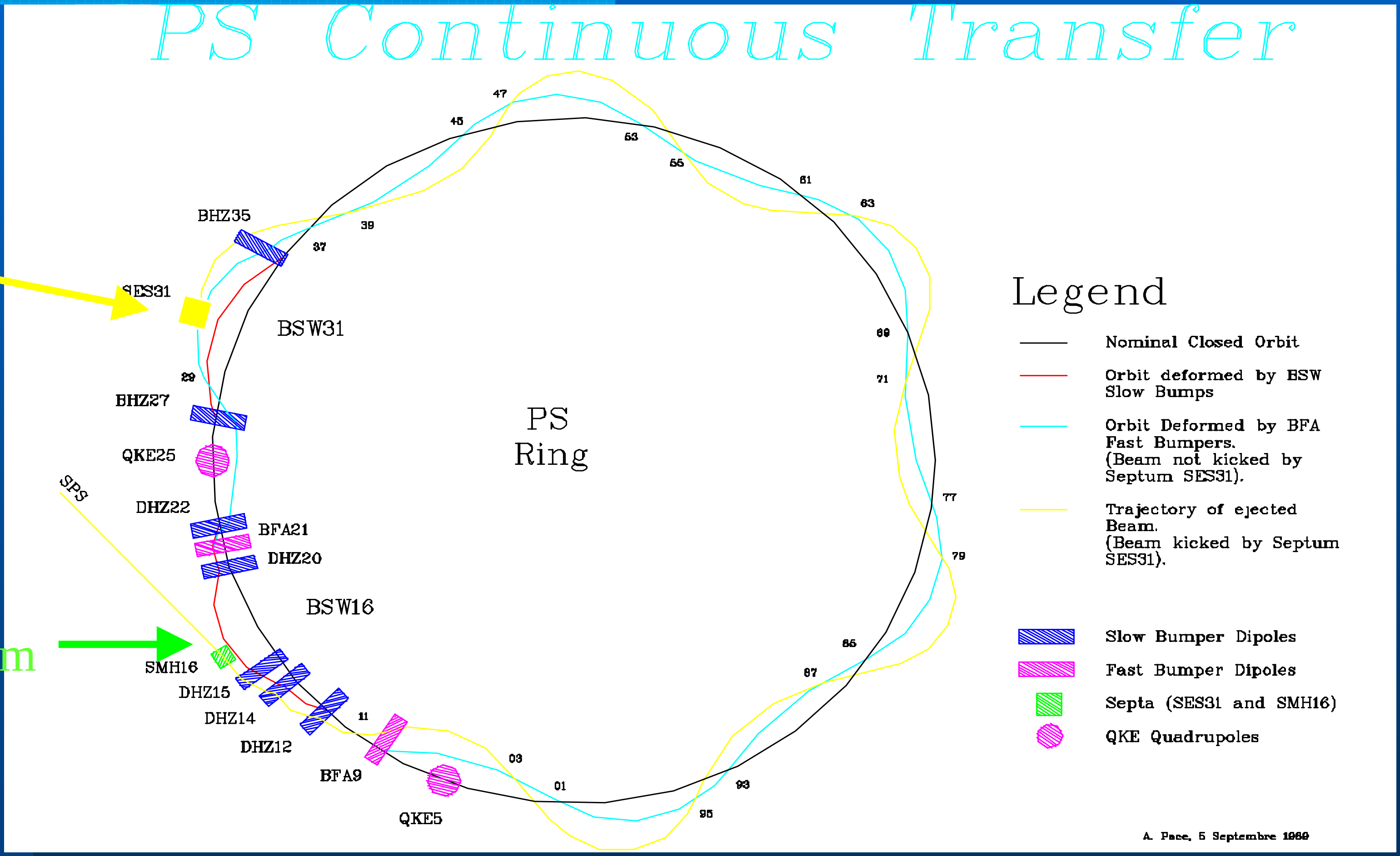
1 SPS Turn = 11 PS turns ~ 23.1 μs



Losses at extraction in the PS

Electrostatic Septum

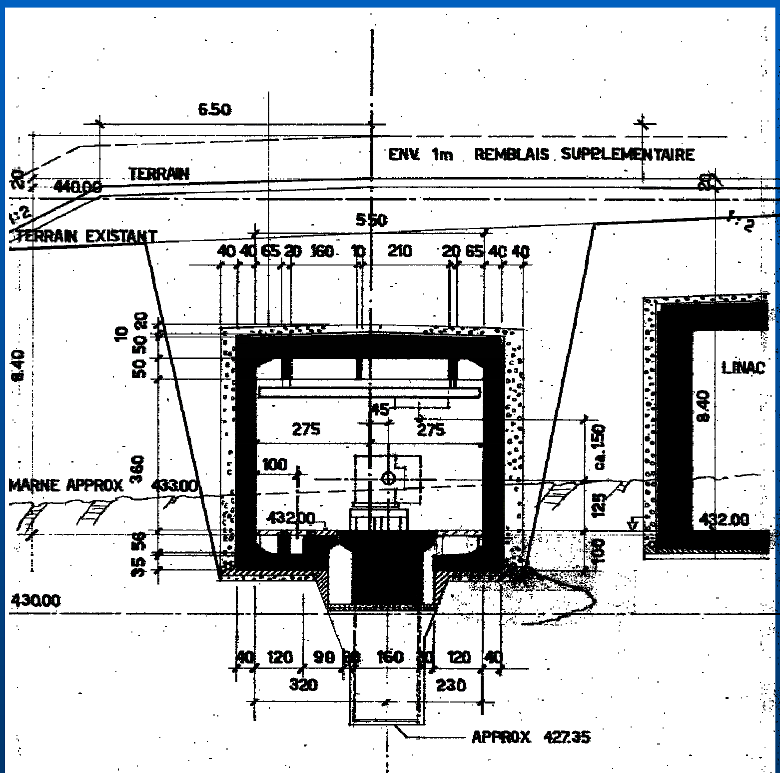
Magnetic septum



Losses at extraction in the PS

- **Most of the losses (~10 %) at the ES result from the beam-septum interaction (septum thickness ~300 μm)**
  - **Radiation & maintenance issues**
- **Losses observed also in other locations because of the large excursions of the "circulating" and "extracted" beam trajectories (over a large fraction of the machine circumference).**

Losses at extraction in the PS



Courtesy of T. Otto

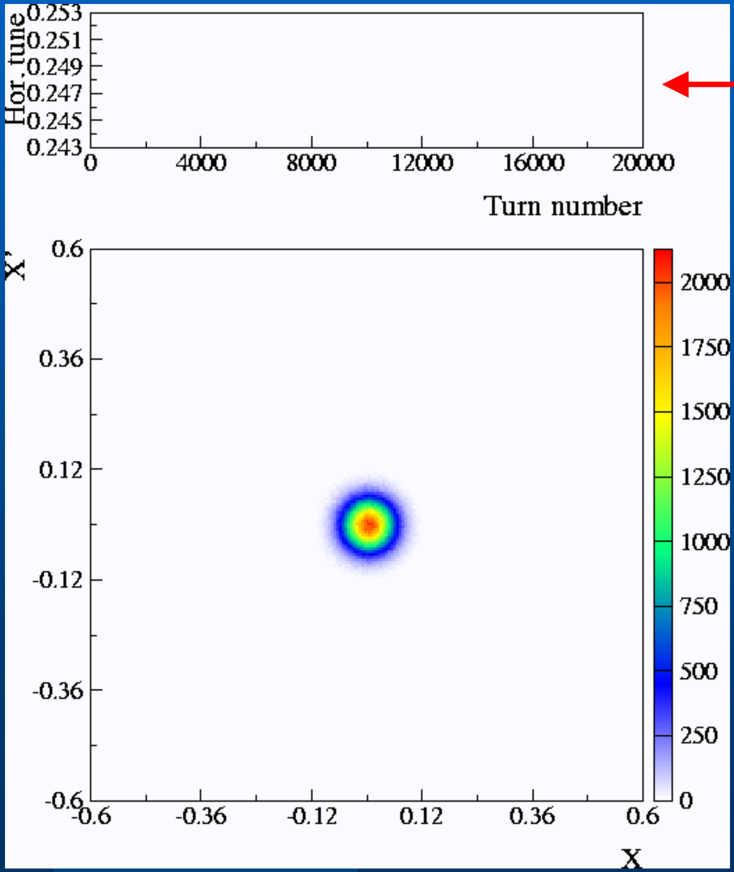
- **Losses lead to the activation of accelerator components:**
  - ➔ **Dose to the maintenance personnel**
  - ➔ **Lifetime issues**
- **PS Shielding and ventilation designed ~50 years ago for lower intensities**
  - ➔ **Stray radiation – "skyshine"**
  - ➔ **Activation of air**
- **Dose at the fence might be a hard limitation even for the nominal intensity**

New multi-turn extraction

- **Reduction of the losses** can be achieved by “splitting” the beam in 5 “beamlets” in transverse phase space by using:
  - Nonlinear magnetic elements (sextupoles and octupoles) to create stable islands.
  - Slow (adiabatic) tune-variation to cross an appropriate resonance.

- **Adiabatic capture in stable islands** (M. Giovannozzi et al.)

New multi-turn extraction



Machine working point vs. time

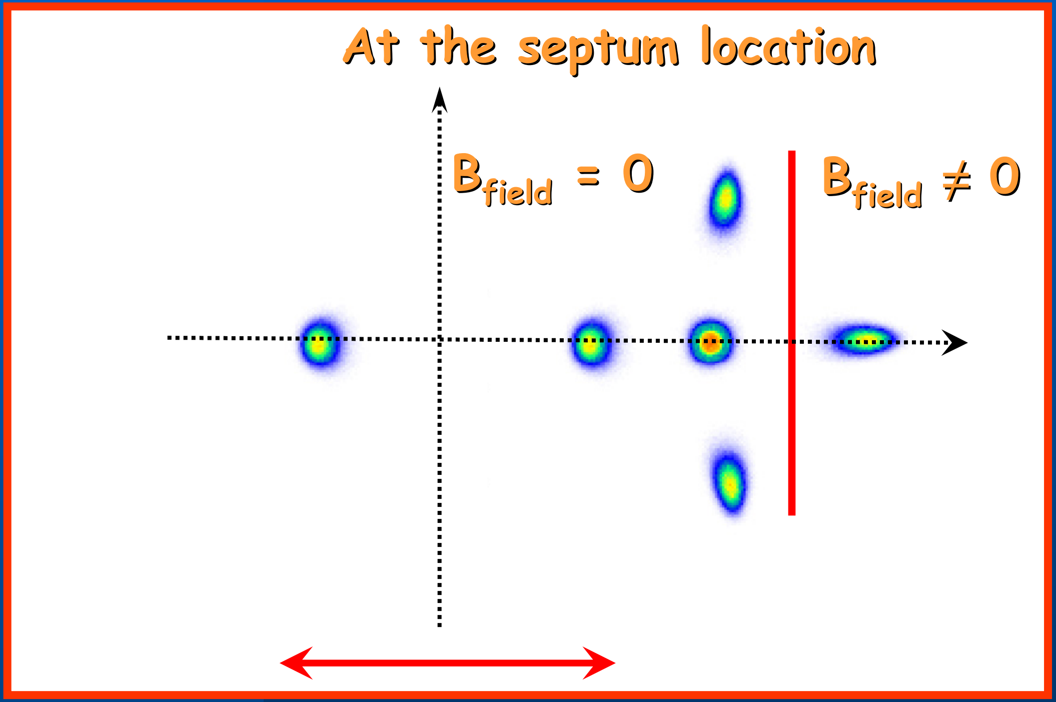
Phase-space portrait

- **The creation of a depleted area between the 4 islands and the core allows reducing the losses virtually to zero**

Courtesy of M. Giovannozzi

New multi-turn extraction

Courtesy of M. Giovannozzi



About 6 cm in physical space

Slow (few thousand turns) bump (closed distortion of the periodic orbit)

Fast (less than one turn) bump (closed distortion of periodic orbit)

New multi-turn extraction

Courtesy of M. Giovannozzi

- **Experimental tests since 2002:**
  - **Capture efficiency ~18% obtained with a high intensity beam. The core contains 28% of the beam. Required 20% ± 1%.**
- **Studies in 2006 will focus on further increasing the capture efficiency in the islands and in reducing the losses (2-3 % observed) during the capture.**

Measurements with beam

New multi-turn extraction

- **The present extraction hardware does not allow beam extraction of the "beamlets".**
- **Ongoing:**
  - **Finalization of an extraction scheme compatible with the present one.**
  - **Finalization of the scheme for the correction of the 5 extracted beamlets.**
  - **Analysis of the aperture requirements .**
- **At the earliest the hardware could be available for the start-up 2008.**
- **Losses are expected to be reduced from ~10% to about 2-3%.**

Low energy losses in the SPS

- Although amount of losses and energy range are similar to the extraction losses in the PS the radiological impact is mitigated because of:
  - Underground construction (> 22 m depth)
  - Distributed nature of the losses occurring for energies larger than the injection one.

Low energy losses in the SPS

- High intensity studies performed in 2004 have allowed to determine two main contributions:
  - @ 13.1 GeV: injection and during the 1.2s-long injection plateau
  - at transition* (~21 GeV)

* energy at which all the particles (even off-momentum ones) have the same revolution period ➔ for a given accelerating voltage bunches are getting shorter and the beam acquires a larger momentum spread

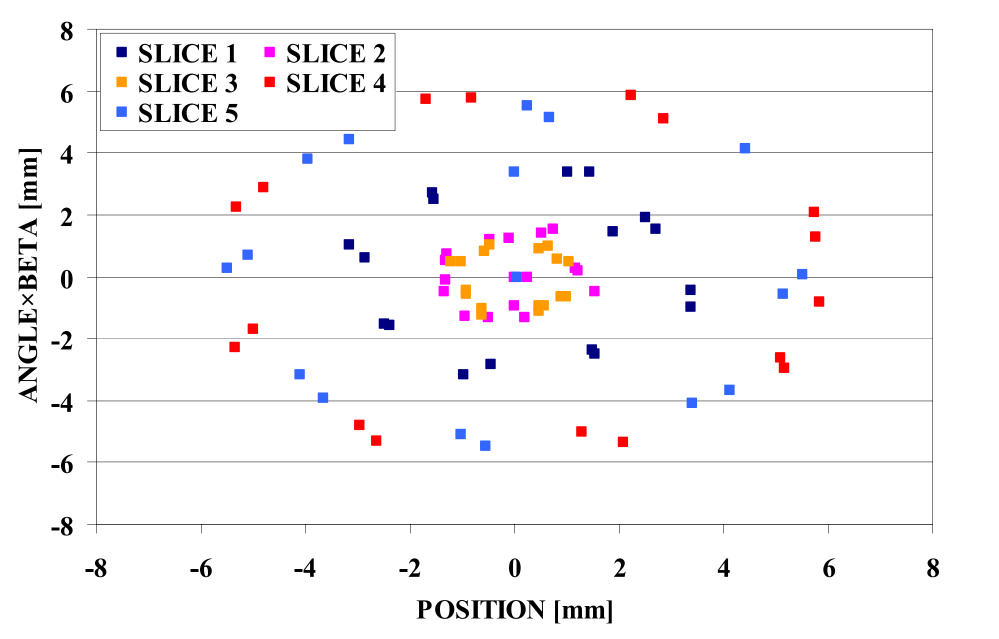
Low energy losses in the SPS

- @ 13.1 GeV/c: related to the physical vertical aperture of the SPS → 2004 studies confirmed the presence of an unwanted restriction at the high energy beam dump absorber resulting from a deformation of a Ti foil covering the graphite core

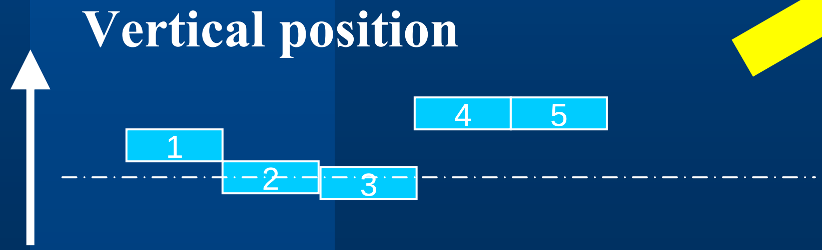
- Upgrade of the spare in progress for installation by the end of 2005

Low energy losses in the SPS

- **Different trajectories of the 5 PS beam "slices" reduce the available aperture margins.**
- **Means to correct the different trajectories with the available HW being studied profiting from the tools required for the new multi-turn extraction study.**



Measured in the vertical plane at injection in the SPS during the high intensity studies in 2004

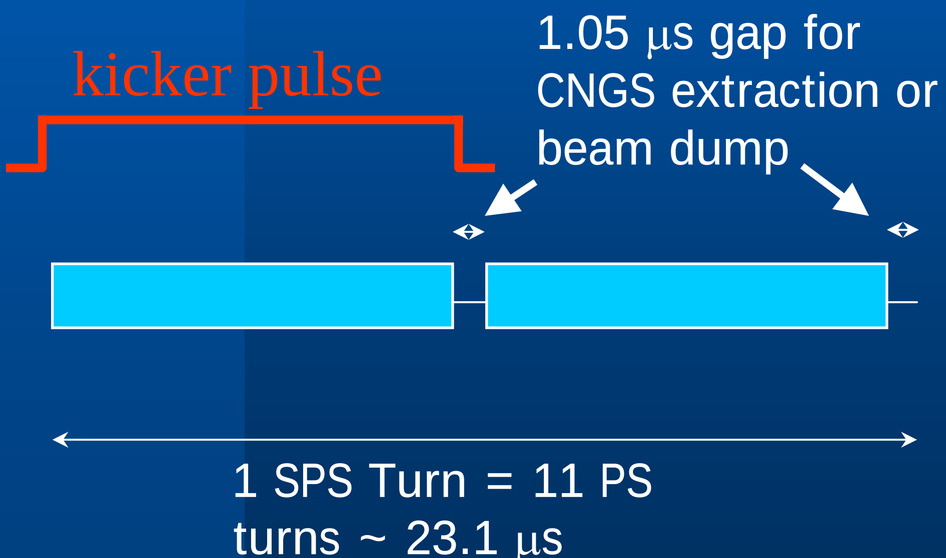


Low energy losses in the SPS

- **Transition crossing is another critical area:**
  - **Transient effects (beam loading) at the head of each of the two batches have been observed, leading to losses.**
  - **Reduction of these losses might require modification of the RF beam control.**

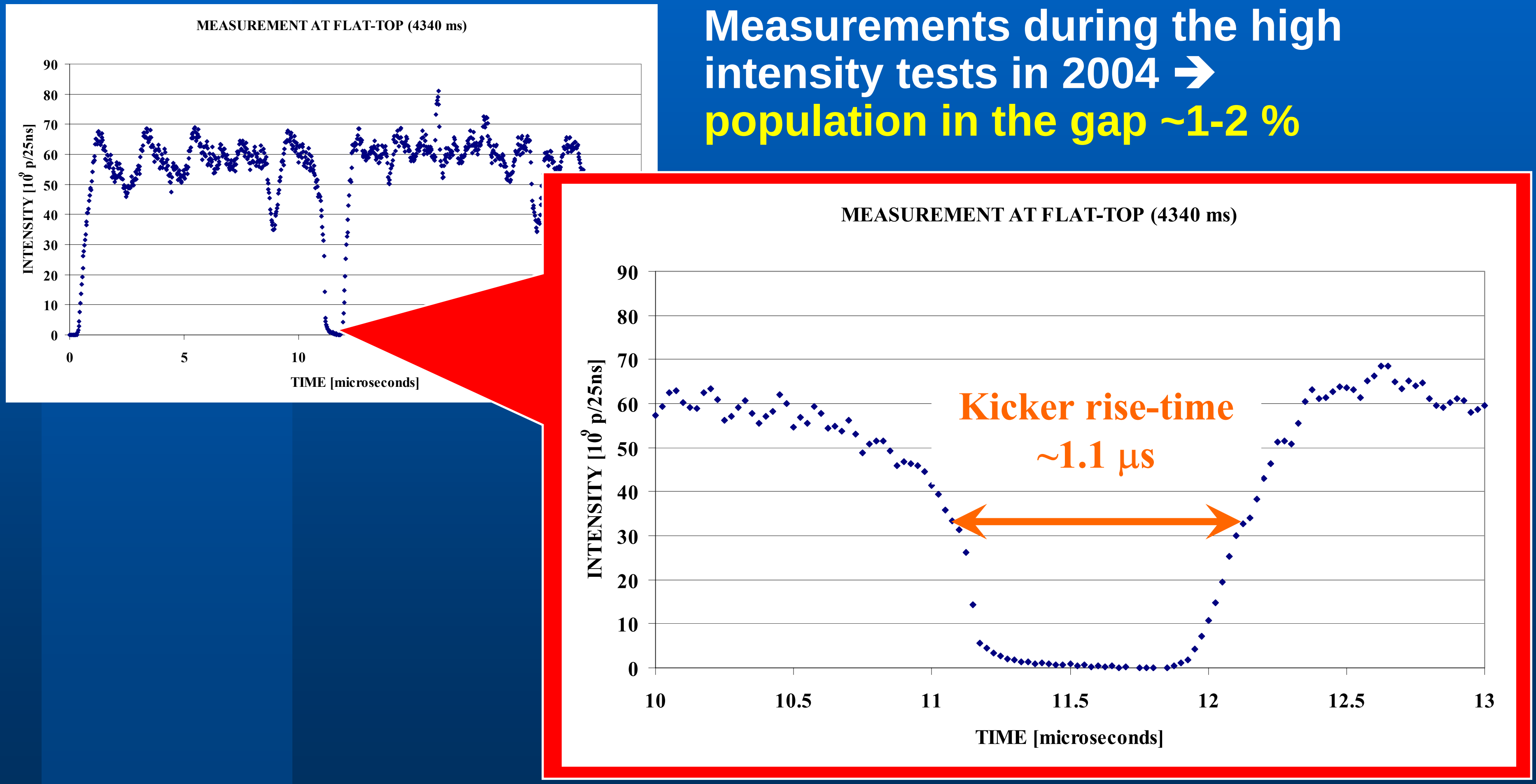
SPS Extraction losses

- **Consecutive (spaced by 50 ms) extractions of the two circulating batches by means of a fast kicker magnet whose pulse length is tailored to extract only one batch at a time.**



Loss-free if no beam in the gaps among the batches.

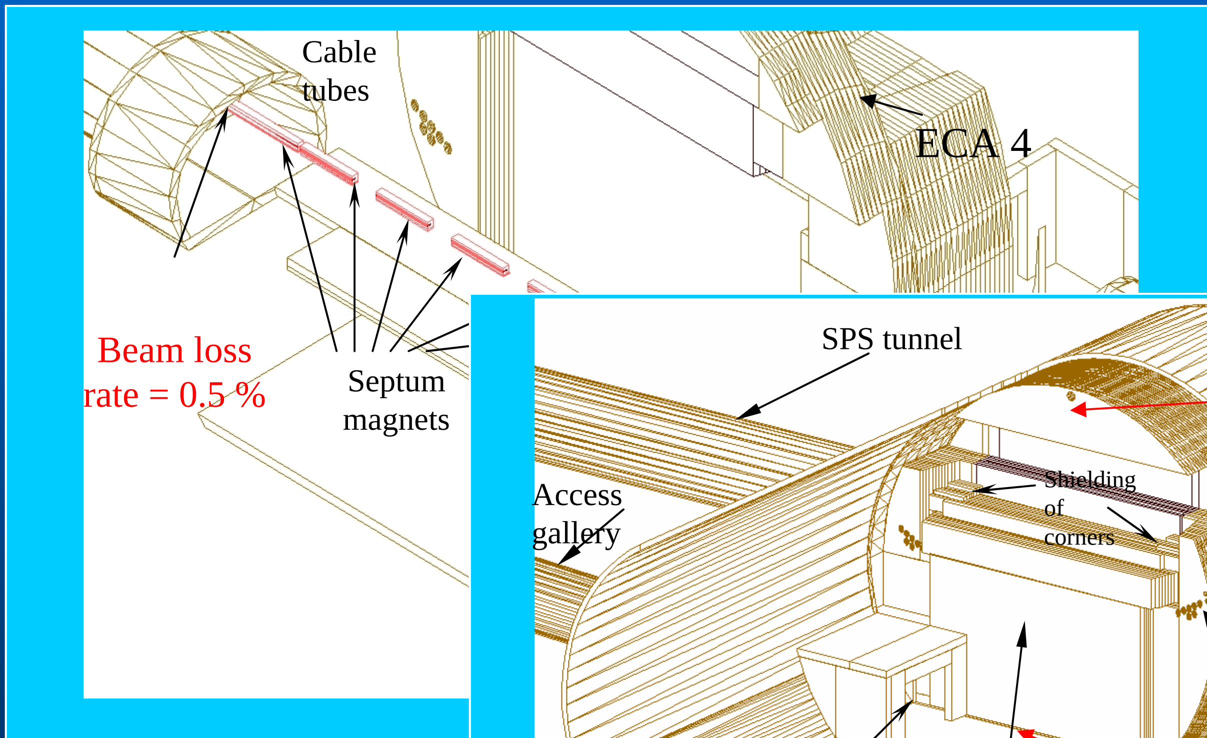
SPS Extraction losses

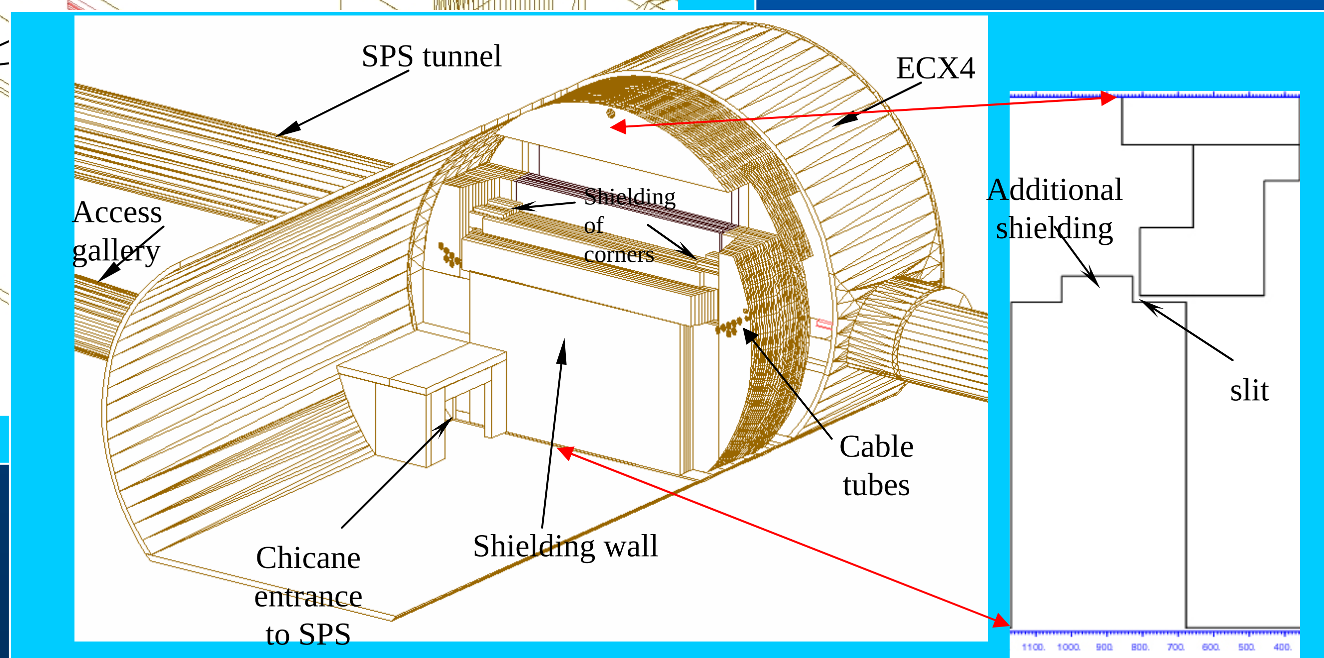


Measurements during the high intensity tests in 2004 ➔ **population in the gap ~1-2 %**

SPS extraction losses

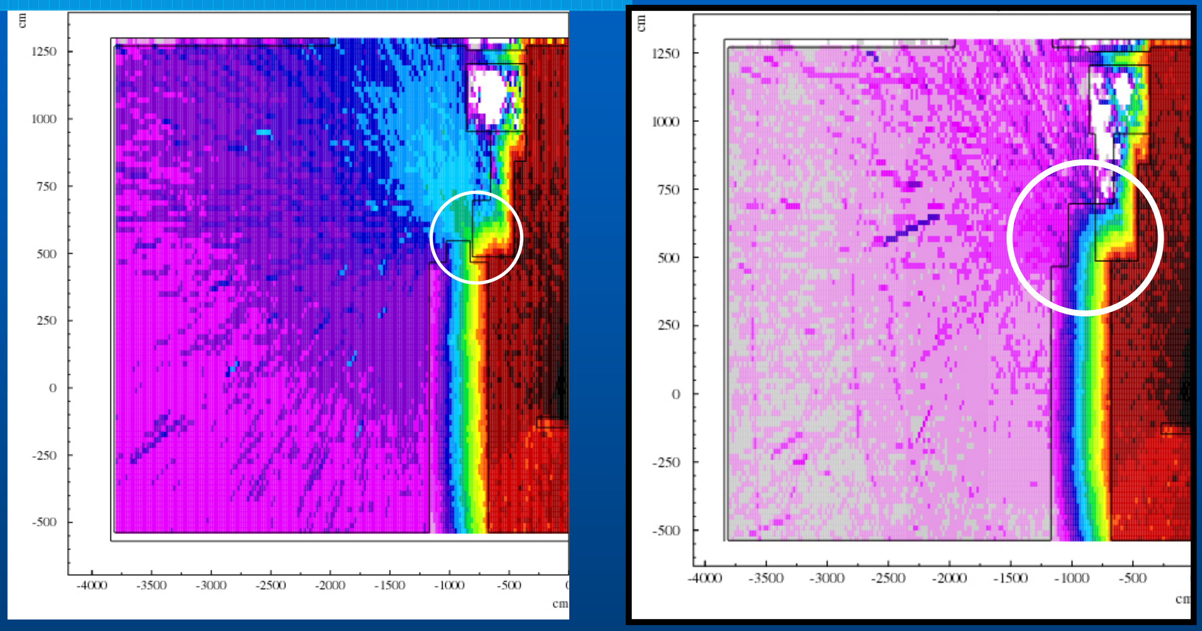
Courtesy of D. Forkel-Wirth

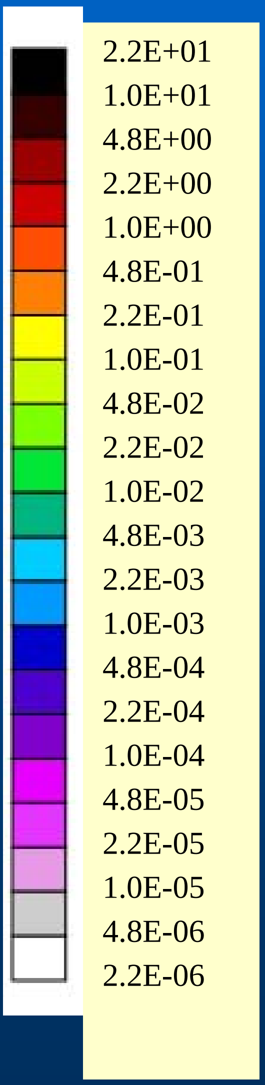




Losses located at the absorber protecting the extraction septa

SPS extraction losses





Dose rates after minor upgrade (ongoing) of the shielding:

ECA4 floor level: 10……30 uSv/h

upper levels: 50 …200 uSv/h

} Limited Stay Area ➔ Controlled access to the HV and synchronization equipment of the extr. kicker.

Courtesy of H. Vincke

SPS Extraction losses

- Origin of beam in the gap:
  - Finite rise-time of the fast extraction bump in the PS (400 ns)
  - Poor capture of the injected batches and recapture of the particles at the start of the ramp
- Possible solutions:
  - New beam control for the separate capture of each batch
  - Cleaning of the beam gap with the transverse feedback at low energy

The proton shortfall

- During the period 2006-2010 other users will be CNGS “competitors”, namely:
  – LHC from 2007
  – COMPASS
- Furthermore:
  – In 2006 PS & SPS will start after 18 month shut-down from a new control room and after a major consolidation campaign for the PS main magnets → more cold check-out and setting-up time required
  – LHC sector test in 2006
  – PS & SPS commissioning with the LHC ion beam will take place in 2006-2007

The proton shortfall

- Estimated distribution of SPS operation modes from LEP experience:
  - **2007: 50% of overall SPS time with 15% LHC filling and 35% LHC set-up mode.**
  - **LHC request should fall ~linearly to 15% of overall SPS time by 2010.**

SPS operation mode		2006	2007	2010
Physics operation	[h]	4000	4500	4700
LHC filling mode	[%]	0	15	5
LHC setup mode	[%]	0	35	10
CNGS – FT mode	[%]	100	50	85

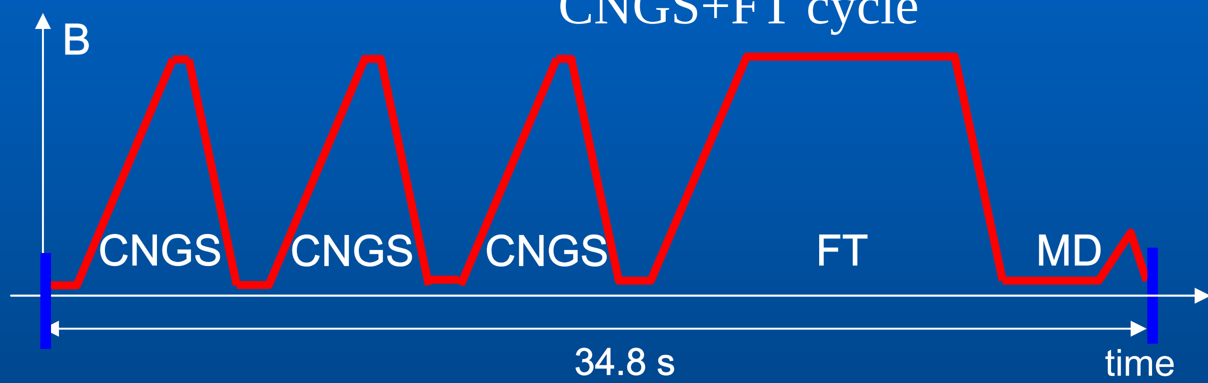
  - **The switching time between different SPS operation modes (supercycles) should be below 10 min, work in progress.**

The proton shortfall

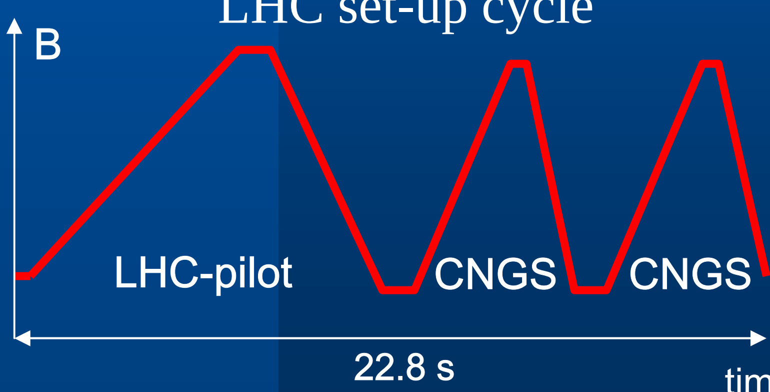
With the CNGS-FT cycle, an average of 4.4×10^{13}ppp and 80% efficiency ➔ 4120 hours of physics are required

Planned SPS cycles

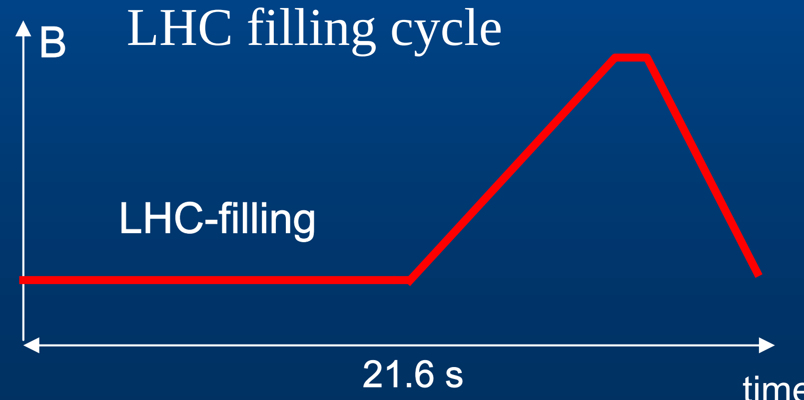
CNGS+FT cycle



LHC set-up cycle

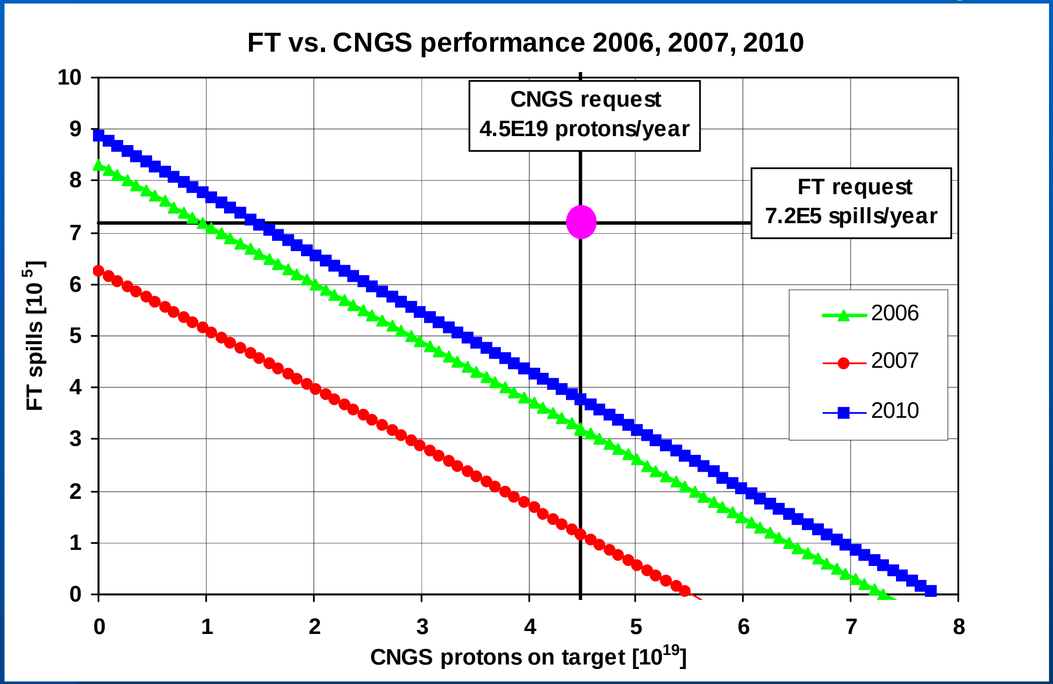


LHC filling cycle



The proton shortfall

Courtesy of M. Benedikt



- **Significant shortfall of protons on SPS for CNGS and FT physics together.**

The proton shortfall

"….CERN is committed to delivering $5\times4.5\times10^{19}$ p.o.t. to CNGS for the purpose of demonstrating ν_τ appearance in a ν_μ beam. The physics case remains valid. Therefore CERN should make every reasonable effort to fulfill this p.o.t. commitment. However, no compelling scientific case has yet been made to justify going beyond this commitment…."

(CERN-SPSC-2005-010 – Feb 2005)

Summary & Conclusions of the Villars meeting

Summary & Conclusions

- Beam losses and induced radiation are the main issues for the NOMINAL CNGS beam
- Possible means to reduce them have been identified
- Losses at extraction form PS have the largest radiological impact and a new multi-turn extraction might be required to supply the nominal beam and satisfy the radiation constraints.
- There is a clear lack of protons over the next years
- No strong recommendation (from SPSC at Villars) for providing more protons than previously committed to CNGS.
- Reduction of the beam losses is our goal in order to deliver the COMMITTED number of protons in a RELIABLE and SUSTAINABLE way.