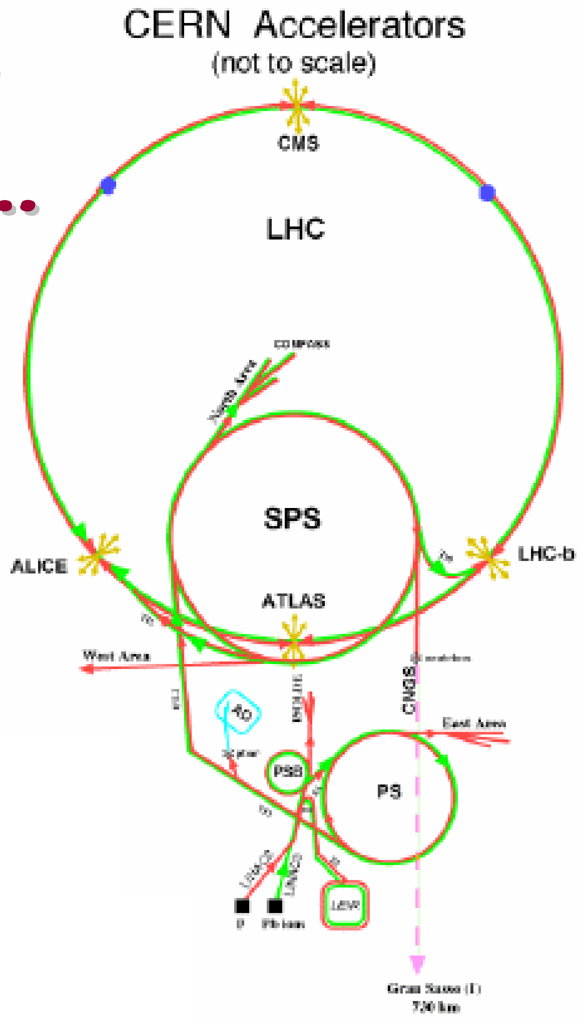
A Walk through the LHC Injector Chain …

Part 2

The SPS

Paul Collier AB/OP



Contents

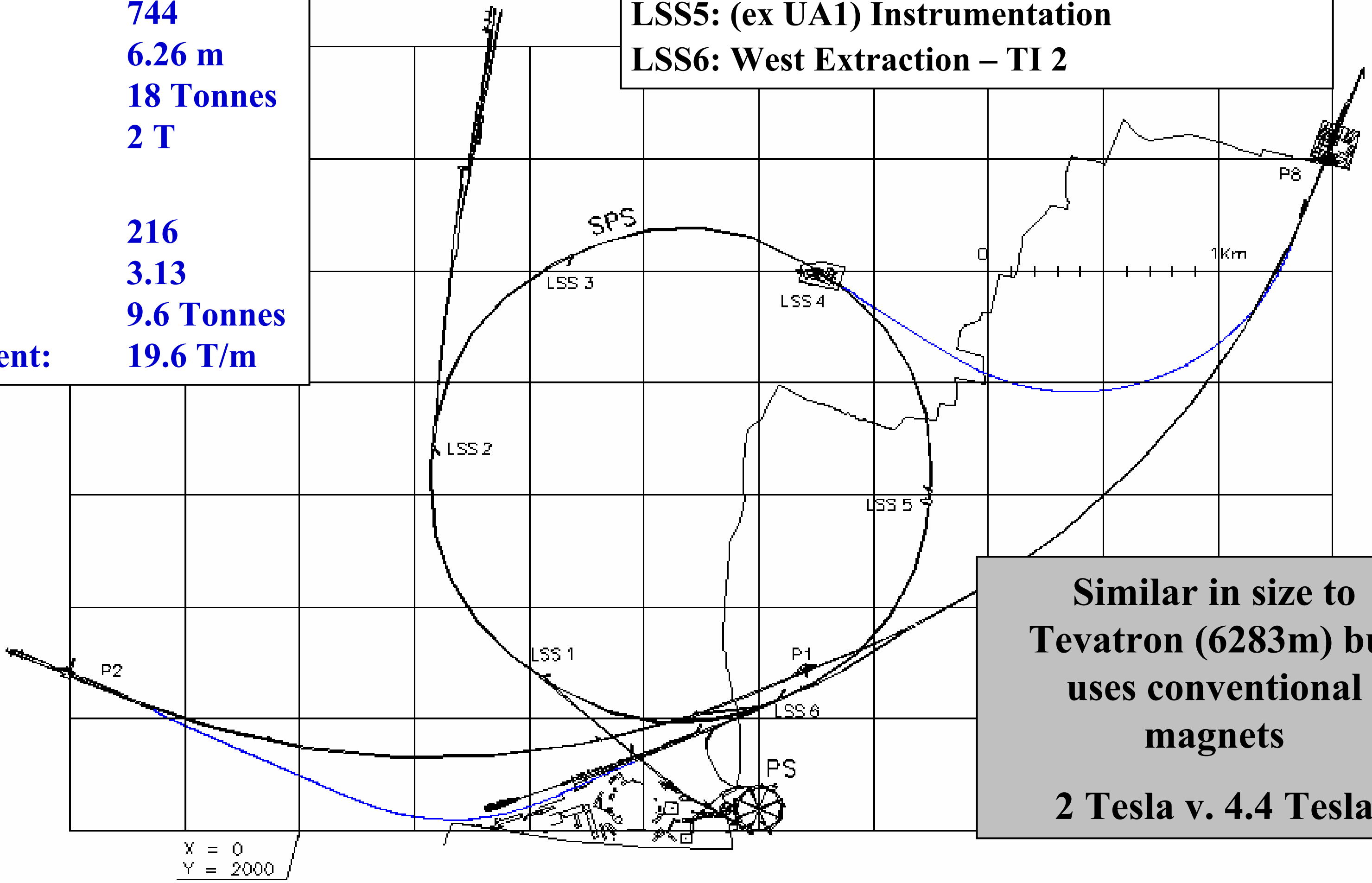
- A Brief History of the SPS …
- The LHC Requirements
  - Consequences for the SPS
- Coping with what we Expected …
  - Major System Upgrades for the SPS
  - Impedance reduction Campaign
- …And what we didn't Expect
  - Electron Cloud
- The LHC Transfer Lines
  - TI 8 installation, commissioning and beam tests
  - Status of TI 2
- Summary

The SPS

Circumference: 6911.55 m

Ratio SPS:PS	**11:1**
Main Dipoles	
Number:	**744**
Length:	**6.26 m**
Weight:	**18 Tonnes**
Max Field:	**2 T**
Main Quads:	
Number:	**216**
Length:	**3.13**
Weight:	**9.6 Tonnes**
Nominal Gradient:	**19.6 T/m**

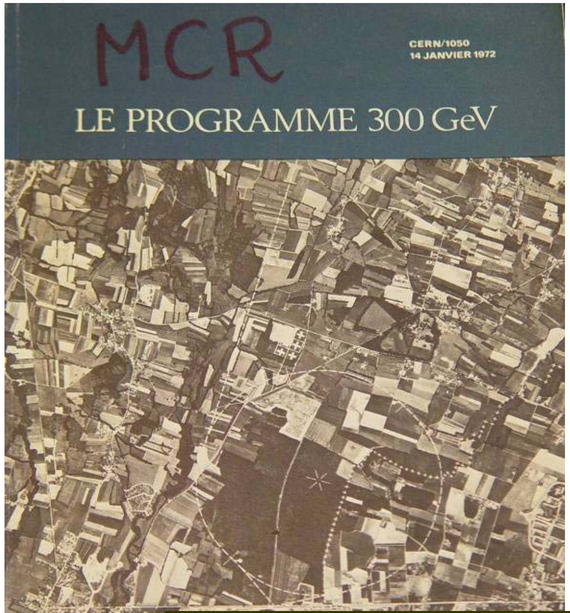
LSS1: Injection Region. Internal Dump
LSS2: North Extraction
LSS3: RF
LSS4: (ex UA2) East Extraction -TI8&CNGS
LSS5: (ex UA1) Instrumentation
LSS6: West Extraction – TI 2

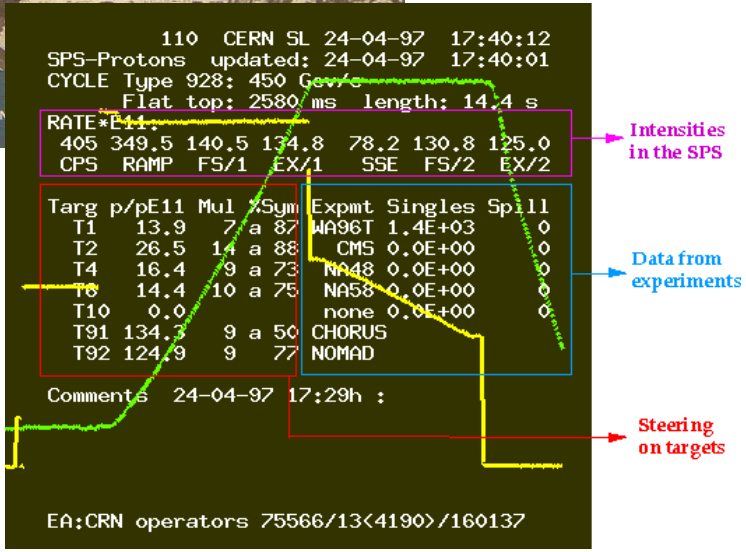


Similar in size to Tevatron (6283m) but uses conventional magnets

2 Tesla v. 4.4 Tesla

SPS Fixed Target





```
          110  CERN SL 24-04-97  17:40:12
SPS-Protons  updated: 24-04-97  17:40:01
CYCLE Type 928: 450 GeV/c
      Flat top: 2580 ms  length: 14.4 s
RATE*E11:
 405 349.5 140.5 134.8  78.2 130.8 125.0
 CPS  RAMP  FS/1  EX/1   SSE  FS/2  EX/2

Targ p/pE11 Mul %Sym Expmt Singles Spill
  T1   13.9   7 a 87 WA96T 1.4E+03     0
  T2   26.5  14 a 88   CMS 0.0E+00     0
  T4   16.4   9 a 73  NA48 0.0E+00     0
  T6   14.4  10 a 75  NA58 0.0E+00     0
  T10   0.0           none 0.0E+00     0
  T91 134.3   9 a 50 CHORUS
  T92 124.9   9   77 NOMAD

Comments  24-04-97 17:29h :


EA:CRN operators 75566/13<4190>/160137
```

1st Beam April 1976 – running ever since

(12 month shutdown 1980/1981)

(8 month shutdown 2000/2001)

Extraction: slow (s), fast-slow (ms) & fast (μs)

Extracted Beam Energy:

300 → 400 → 450 GeV

Intensity:

$1x10^{+13} \rightarrow \sim 5x10^{+13}$ p^+ per cycle

Experimental Areas:

North (3 Primary Targets)

West , WANF …   Now Closed

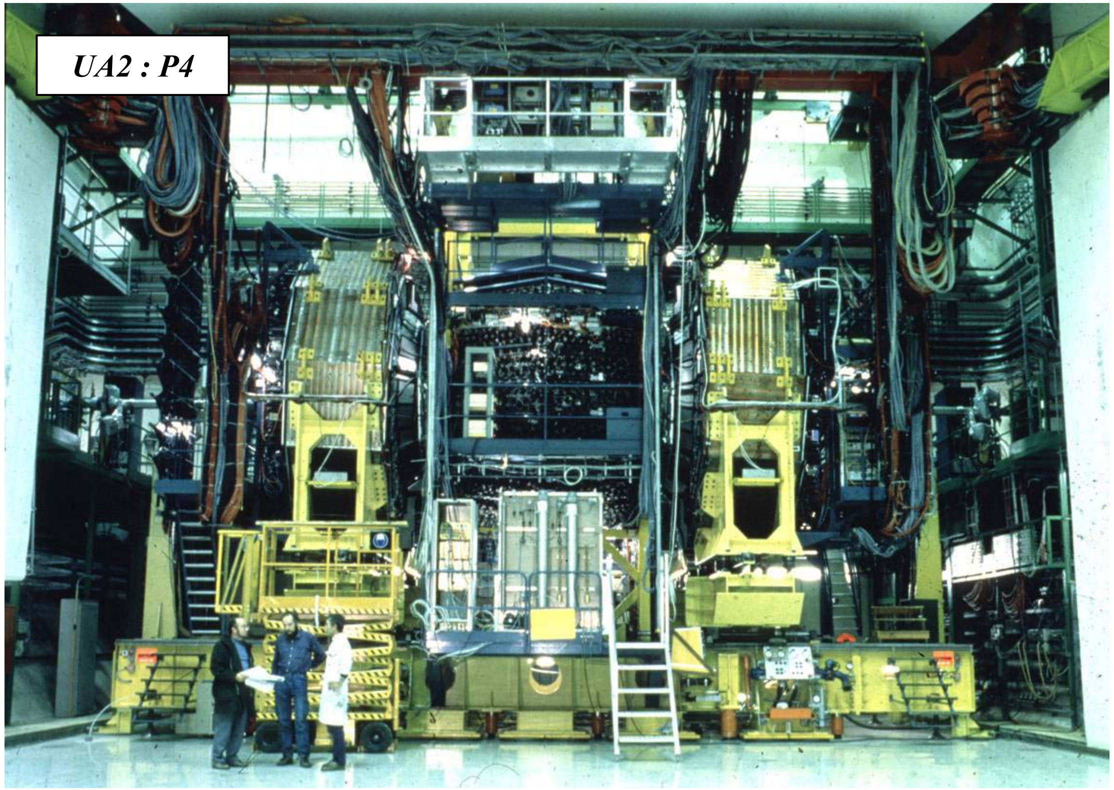
CNGS → Commissioning in 2006

Ion Species (Last ion run in 2003):

Deuterium, Oxygen, Sulphur,

Lead, Indium

SPS Collider



Ran from 1981 to 1991

2 Experimental Caverns

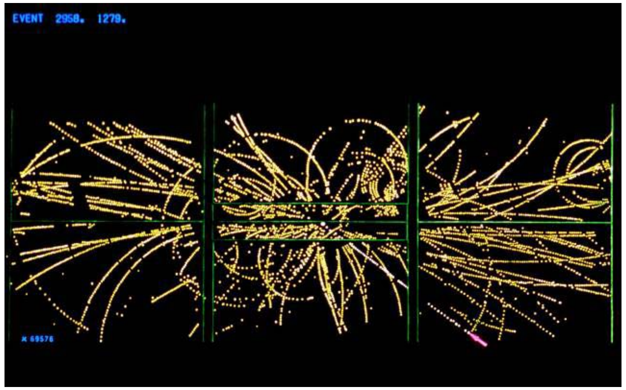
Quadrupole Magnets added to focus more strongly the beams at the experiments

6 proton bunches $\sim1.5x10^{+11}$

6 p-bar bunches $\sim1.5x10^{+10}$

Energy: 270 → 315 GeV

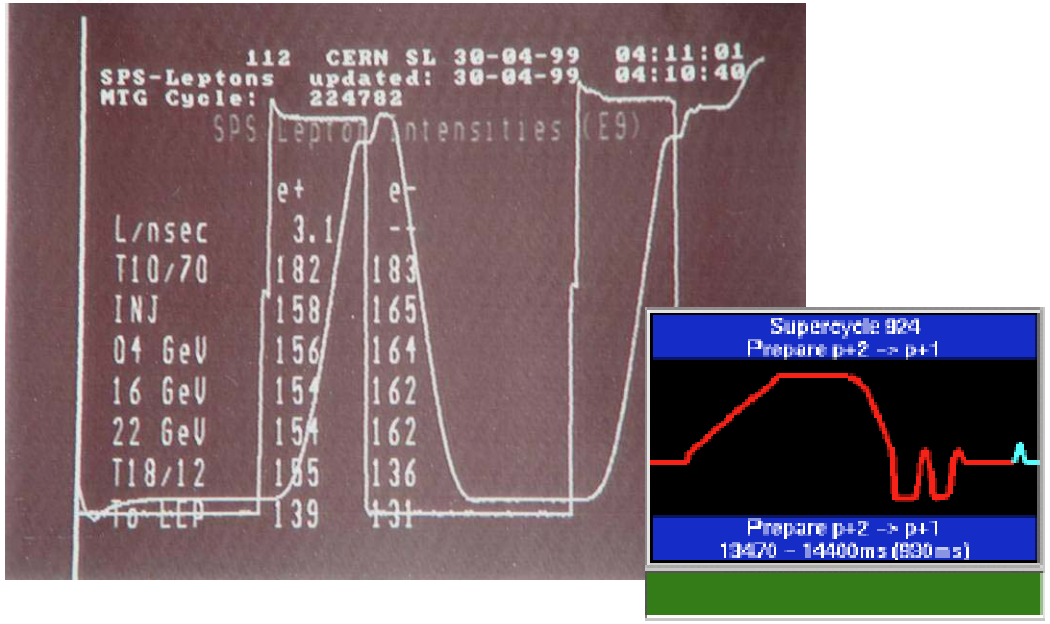
Luminosity $\sim10^{+30}$



Provided a lot of information used to determine the parameters of SPS as LHC injector – and the LHC itself!

Caverns re-used for new equipment

SPS as LEP Injector



112 CERN SL 30-04-99 04:11:01
SPS-Leptons updated: 30-04-99 04:10:40
MTG Cycle: 224782

SPS Lepton Intensities (E9)

	e+	e-
L/nsec	3.1	--
T10/70	182	183
INJ	158	165
04 GeV	156	164
16 GeV	154	162
22 GeV	154	162
T18/12	155	136
To LEP	139	131

Supercycle 924
Prepare p+2 -> p+1

Prepare p+2 -> p+1
13470 - 14400ms (930ms)

LEP Filling interleaved with FT proton operation.

4 cycles with 4 bunches ($2e^+$, $2e^-$) evolved to 2 cycles with 8 bunches *(~2x10^{+10} pb)*

Energy to LEP: 18 → 20 → 22 GeV

e^- used the antiproton injection line

2 Extractions in Point 6 towards LEP

Learned about synchrotron radiation

Installed lots of RF to accelerate Leptons:

200Mhz SWC, 100 MHz SWC, 352 MHz SC

SPS as LEP Injector Worked well …

But Leptons Have no memory therefore LEP could work in spite of its injectors

Not True for LHC

The Nominal LHC p^+ Beam in the SPS

High Intensity bunches –

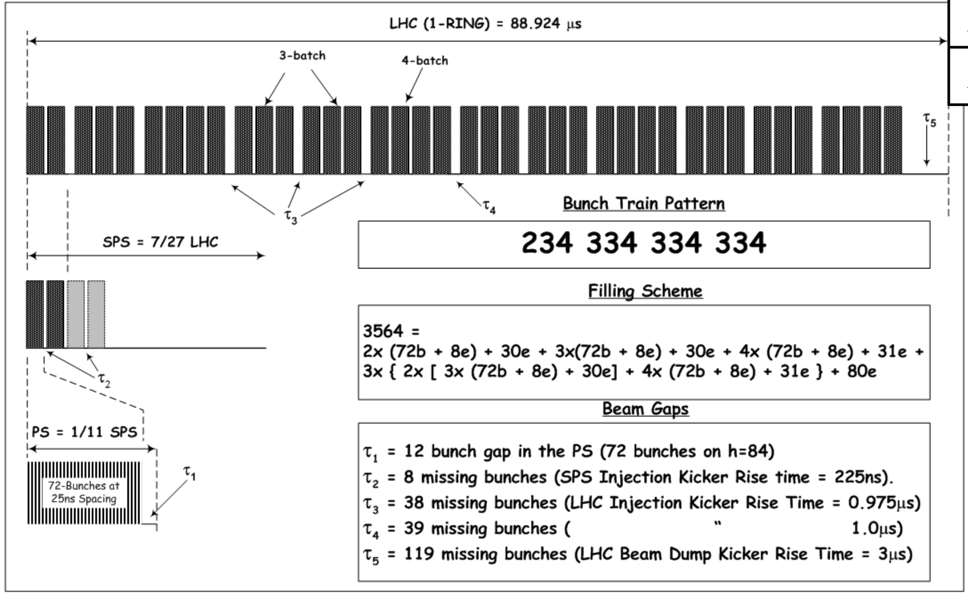
Similar intensity to p-pbar BUT

- ⇘**Many more bunches (288 vs. 6)**

Small beam size (smaller than p-pbar)

- ⇘**Very small blow up budget ~15%**

Momentum [GeV/c]	*26*	*450*
Revolution Period [μs]	*23.07*	*23.05*
Betatron Tune (H/V)	*26.19*	*23.05*
Gamma Transition	*22.81*	
Max. Number of Bunches	*288*	
Nominal Intensity per bunch [10^{+11} p]	*1.15*	
Peak Current [A]	*1.4*	
Bunch Spacing [ns]	*24.97*	*24.95*
Full Bunch Length [ns]	*4*	*1.74*
Rms. Normalised Transverse Emittance [μm]	*3*	*3.5*
Longitudinal Emittance [eV s]	*0.35*	*0.1-1.0*



Bunch Train Pattern

234 334 334 334

Filling Scheme

3564 =
2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) + 31e +
3x { 2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e } + 80e

Beam Gaps

τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975μs)
τ_4 = 39 missing bunches (" 1.0μs)
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3μs)

The LHC Filling scheme requires the beam to be compressed into a section of the SPS

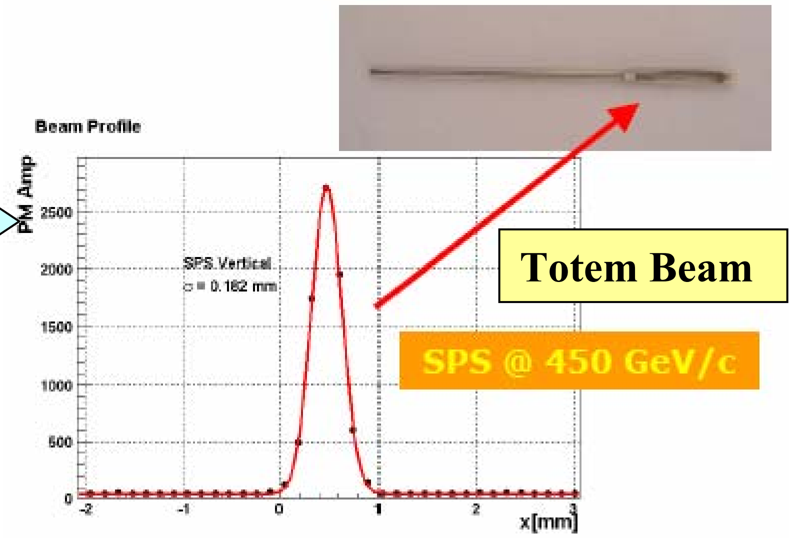
~1/3 SPS filled with beam…

- ⇘**very high peak current**

(2x FT record)

LHC p^+ Beam(s) in the SPS

	Intensity per bunch /10^{+11}	No. of Bunches /PS Batch	No. of Bunches in the SPS	Total Intensity /Ampere
Pilot	*0.05*	*1*	*1*	*3.50×10^{-5}*
Totem	*0.1-1.0*	*4*	*16*	*1.29×10^{-2}*
75ns	*0.1-1.0*	*24*	*96*	*0.077*
25ns Nominal	*1.15*	*72*	*288*	*0.232*
25ns Ultimate	*1.7*	*72*	*288*	*0.343*



Totem Beam

SPS @ 450 GeV/c

Pilots will be used to check the LHC Systematically before every fill

The others are different types of Physics beams

The normalised emittance should be kept constant ie no increase!

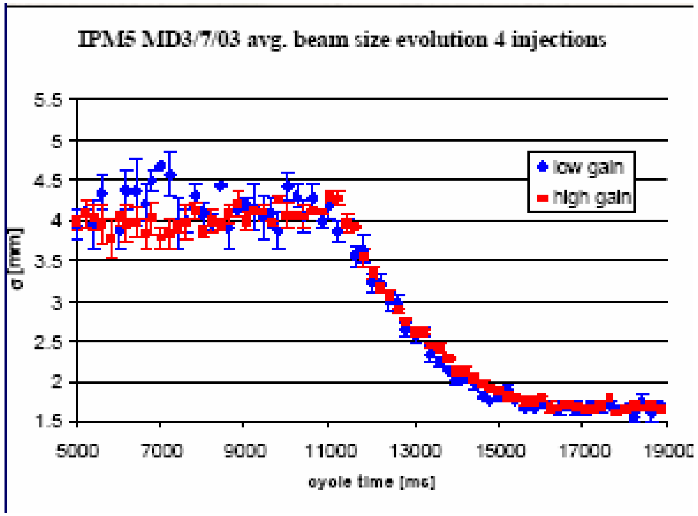
- but the real beam size shrinks with energy…

$$\sigma^2 = \beta \frac{\varepsilon_n}{(\gamma_r \beta_r)}$$

Normalized Emittance

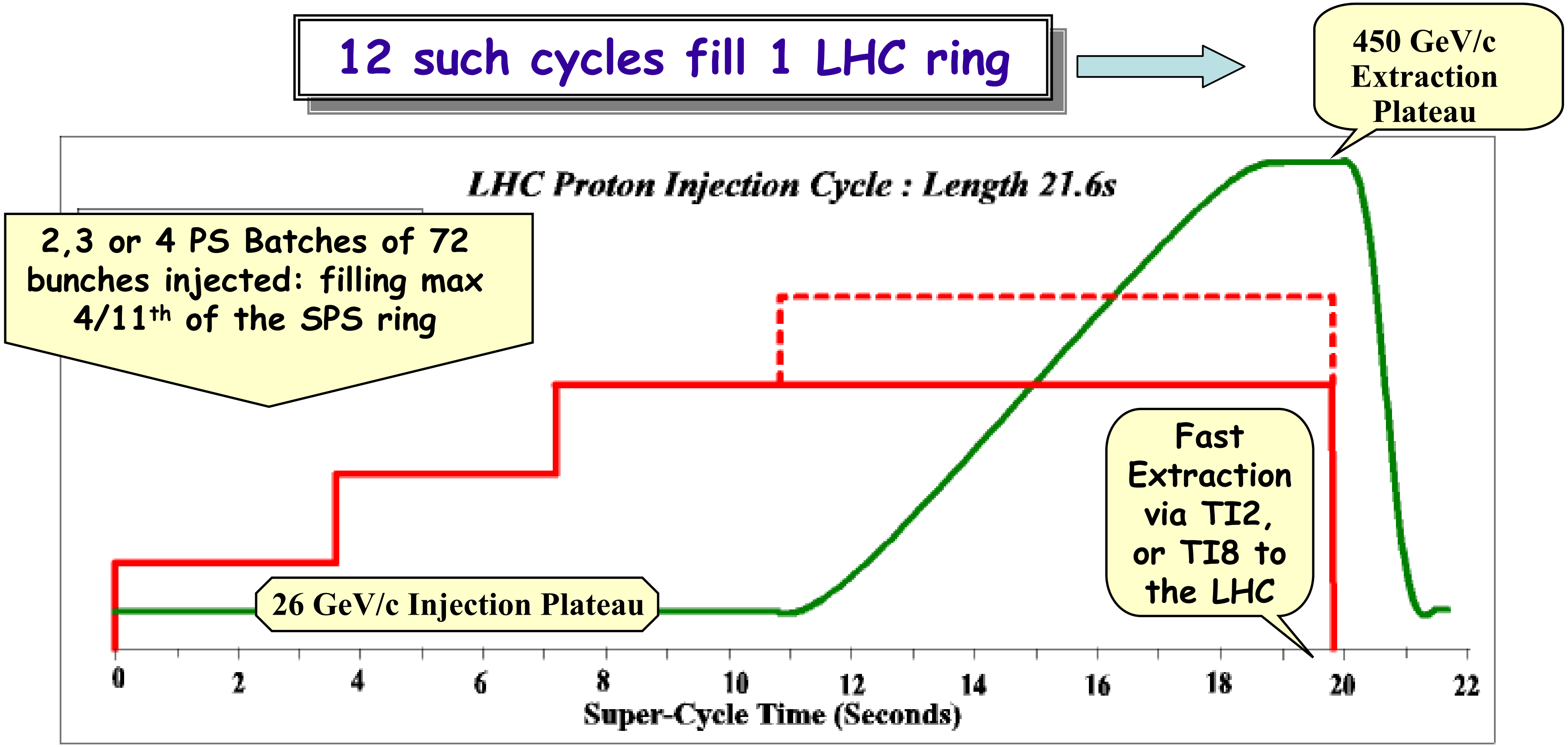
Relativistic factors

Optical β-function



The LHC Filling Cycle

12 such cycles fill 1 LHC ring



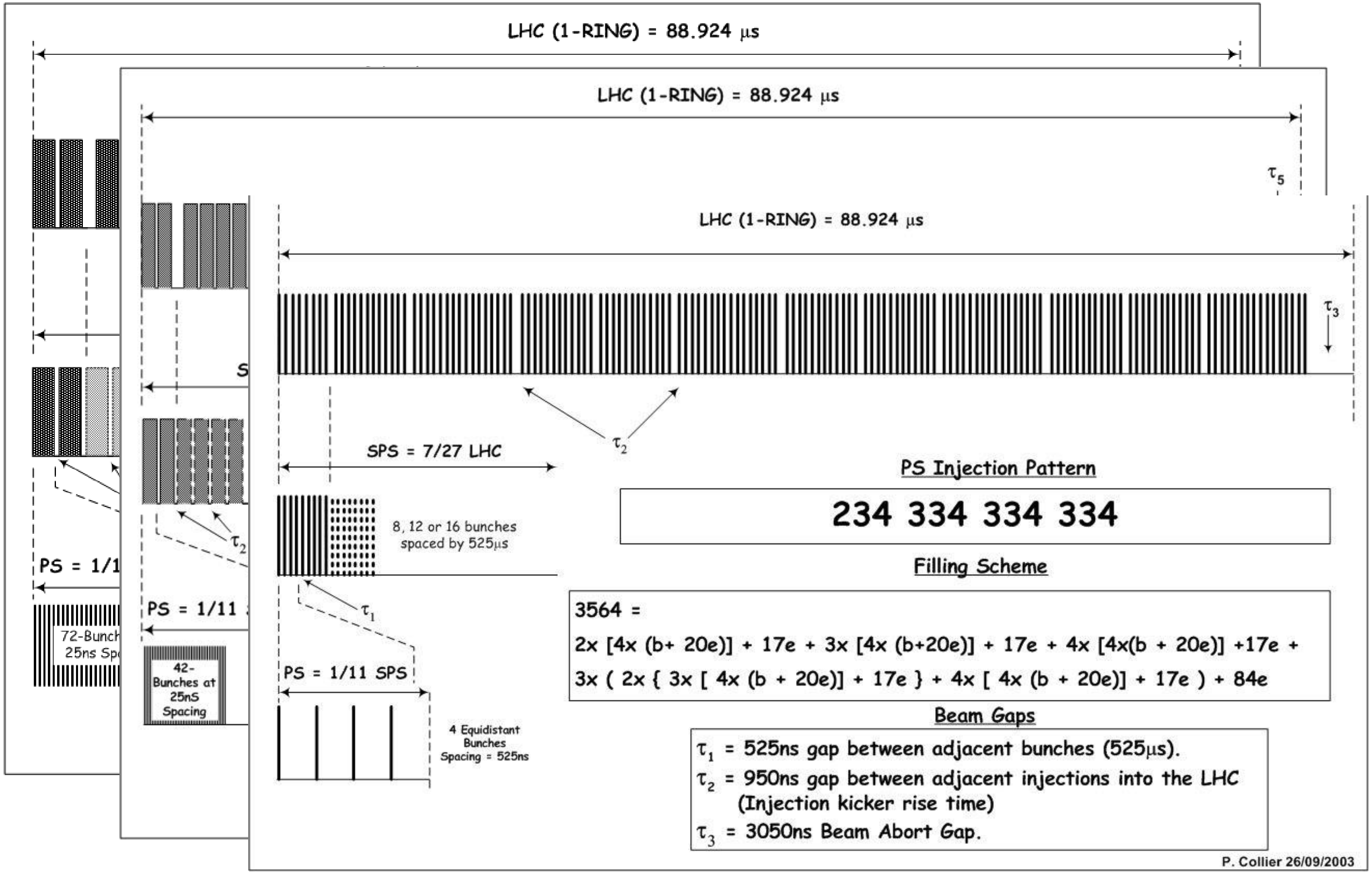
2,3 or 4 PS Batches of 72 bunches injected: filling max 4/11th of the SPS ring

Fast Extraction via TI2, or TI8 to the LHC

1 Batch of 72 bunches each 3.6 seconds from the PS

When actually filling the LHC, SPS Will do nothing else

LHC Filling Cycle



PS Injection Pattern

234 334 334 334

Filling Scheme

3564 =

2x [4x (b+ 20e)] + 17e + 3x [4x (b+20e)] + 17e + 4x [4x(b + 20e)] +17e +

3x (2x { 3x [4x (b + 20e)] + 17e } + 4x [4x (b + 20e)] + 17e) + 84e

Beam Gaps

τ_1 = 525ns gap between adjacent bunches (525μs).

τ_2 = 950ns gap between adjacent injections into the LHC (Injection kicker rise time)

τ_3 = 3050ns Beam Abort Gap.

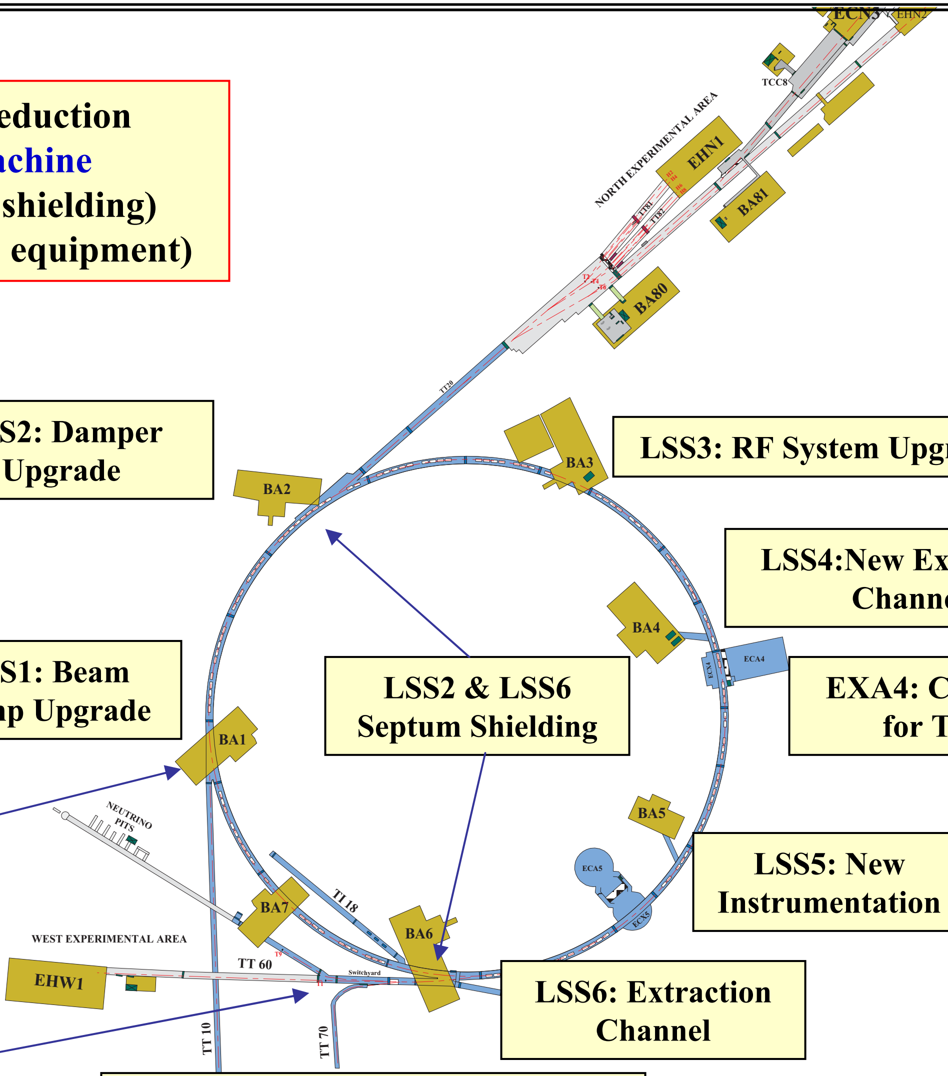
P. Collier 26/09/2003

The SPS Upgrade for LHC

- Reduce/Cure instabilities observed on the high intensity LHC beams
  - Remove obsolete equipment
  - Reduce the impedance of the machine
- Upgrade Hardware to cope with high beam loading
  - RF System
- Minimize transverse emittance growth
  - New Injection system and Damper
- Additional Hardware for Extractions
  - One completely new extraction channel (for TI8)
  - One re-designed and re-built extraction channel (for TI2)
- Miscellaneous
  - New instrumentation
  - New beam dump
  - Test-bed installations for LHC

Detailed Study Started in 1996, Project Launched in 1997

Location of Major Upgrades



Impedance Reduction
All SPS Machine
(Pumping port shielding)
(Remove obsolete equipment)

LSS2: Damper Upgrade

LSS3: RF System Upgrades

LSS4:New Extraction Channel

EXA4: Civil Engineering for TI8 & CNGS

LSS1: Beam Dump Upgrade

LSS2 & LSS6 Septum Shielding

LSS1: Injection Kicker Upgrade

LSS5: New Instrumentation

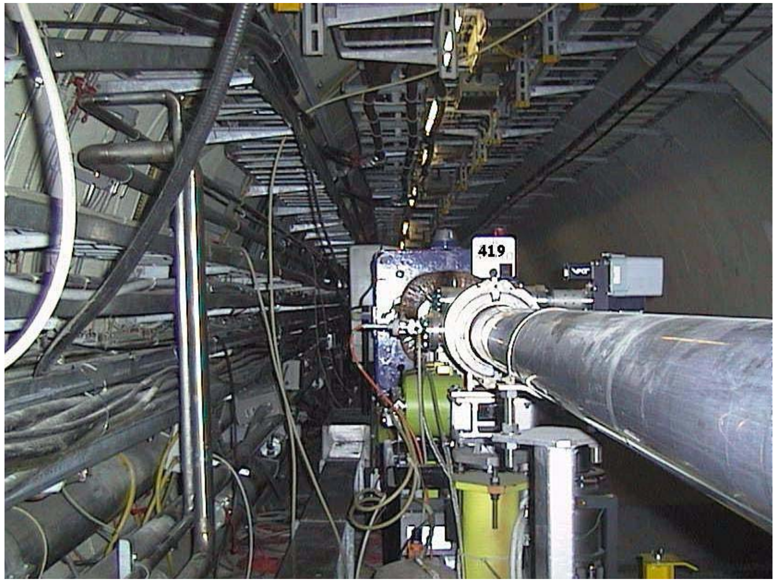
TCC6: Change Extraction Line, TI 2 Civil Engineering and Construction

LSS6: Extraction Channel

TT2/TT10 New Correctors, New Instrumentation

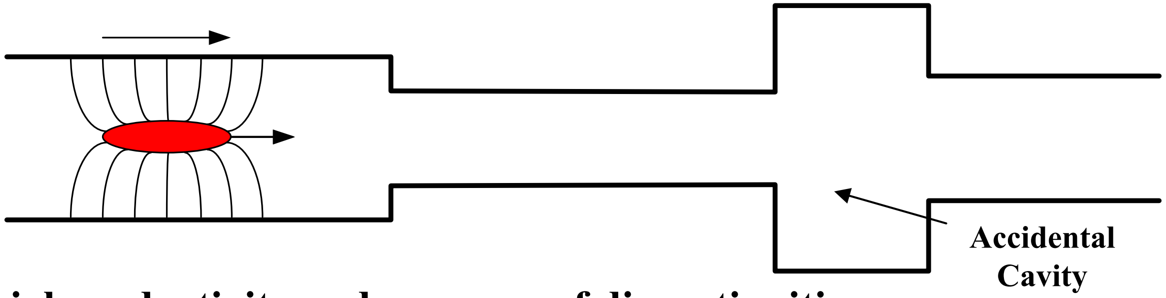
Removal of 'Obsolete' Systems

- 4 complete RF Systems removed
- 2 Lepton Extraction Channels in point 6
  - **Including high impedance kicker magnets , septum magnets and ~200 m of beamline in the SPS tunnel**
- Electron Injection Line (also p-bar injection line) from the PS
- Insertion Magnets for UA1 & UA2
  - **Together with lots of power switches and associated cabling**
  - **Strong correctors replaced by standard units**
- Cable clearing campaign and infrastructure modifications in the regions affected by civil engineering
- Harmonic Correctors – lots of small high order magnets



Why Impedance Reduction

Impedance: Electromagnetic Interaction of the beam with the surrounding vacuum chamber



Determined by:

Chamber dimensions, shape, material conductivity and presence of discontinuities

- Broadband impedance → space charge effects (*see yesterday*)

Where cavities exist resonant behaviour (narrowband resonant impedance)

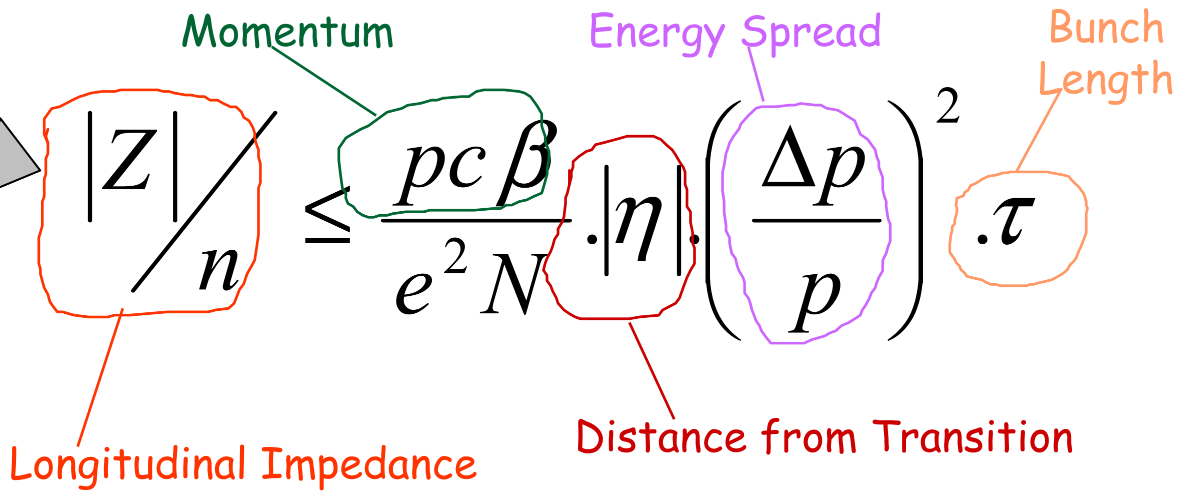
- High impedance at specific frequencies imposed on the bunch spectrum
- Single bunch microwave instability leading to increased longitudinal emittance (bunch length)

Many discontinuities in the vacuum chambers of the SPS – most in the form of accidental cavities

Why Impedance Reduction

During p-pbar Operation Longitudinal instability observed causing uncontrolled increase in the bunch length

...For Stability:-



$$|Z|\!\big/_{n} \le \frac{pc\beta}{e^2 N}.|\eta|.\left(\frac{\Delta p}{p}\right)^2.\tau$$

Threshold intensity (N) well below nominal LHC intensity

Non Starters:

- × **Increase the Injection Energy**
  - **Build a New PS!**
- × **Increase the Bunch Length**
  - **New RF System (80 MHz) in the SPS**
- × **Increase the Energy Spread**
  - **More RF Voltage in the PS and TL acceptance**

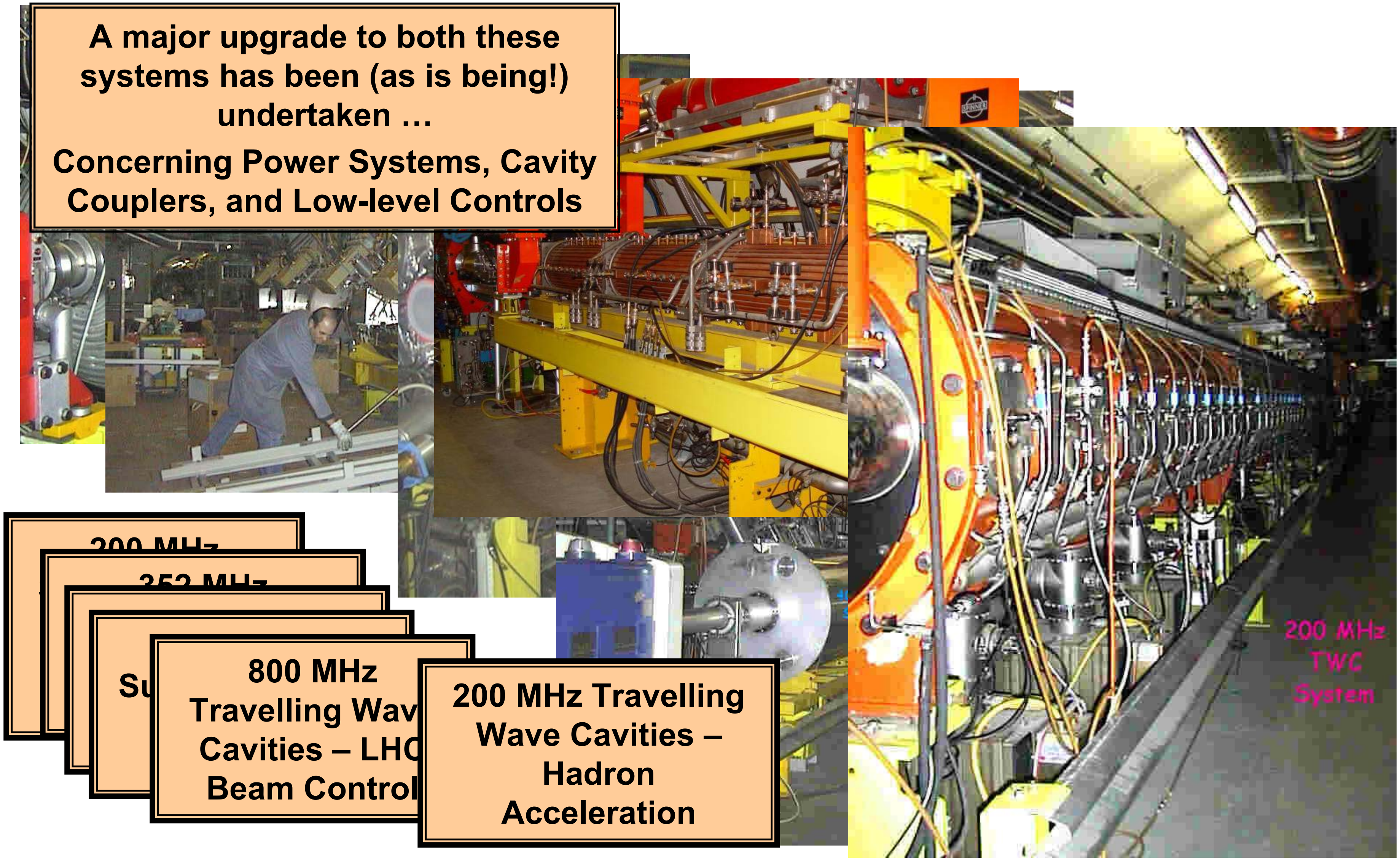
Better Bets:

- ✓ **Increase the distance from Transition**
  Not easy – additional quads
- ✓ **Reduce the impedance of the Machine:**
  - ⇘ **Shield Accidental Cavities**
  - ⇘ **Remove high Z equipment, where possible**

At The End of LEP – RF Systems in the SPS

A major upgrade to both these systems has been (as is being!) undertaken …

Concerning Power Systems, Cavity Couplers, and Low-level Controls



200 MHz

352 MHz

Su

800 MHz
Travelling Wav
Cavities – LHC
Beam Control

200 MHz Travelling Wave Cavities – Hadron Acceleration

RF System Upgrades

- **200 MHz Power**
  - New Power Couplers to reach 750 kW CW Power/cavity (was ~350kW)
  - Amplifier improvements to cope with beam loading and improve linearity
- **Cavity Controls**
  - 1-turn feedback to reduce effective cavity impedance seen by the beam
  - RF Feed-forward system – to fight beam loading (cancel beam induced voltage in the cavities).
- **Beam Control**
  - Phase & Accelerating Voltage loops
  - Frequency loop
  - Low Level loops for machine synchronization
- **Longitudinal Damping system using the 200 MHz cavities**
- **800 MHz System**
  - Beam Stabilisation system increasing the synchrotron frequency spread in the bunches.
  - Alternative use to increase longitudinal emittance in a controlled way.
  - Old power system to be upgraded …

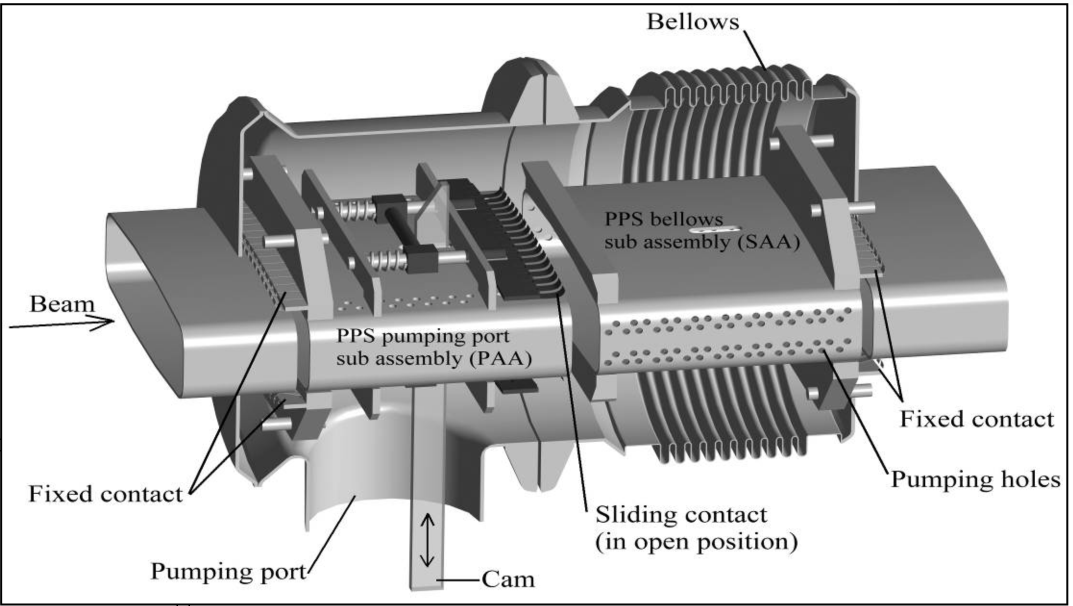
Pumping Port Shields

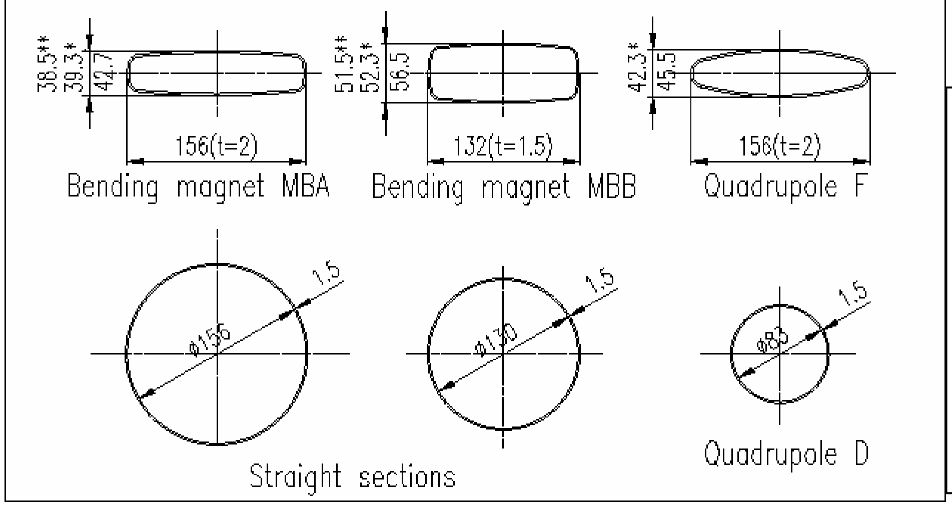
Vacuum Chamber Section Optimized to magnet gaps

Adjacent sections 'joined' using a cylindrical pumping port/bellows

Form a resonant cavity:

f_0 ~1.5 – 2.5 GHz





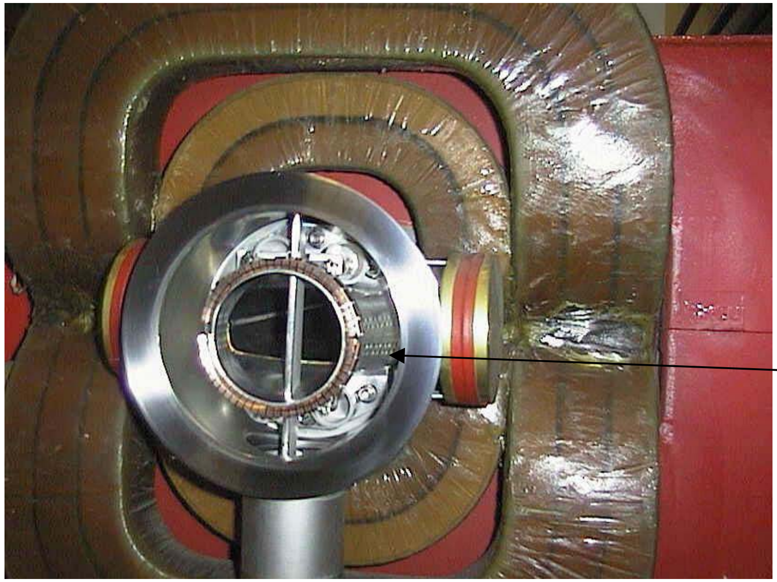
Shield using chamber extensions and sliding contacts.

~1000 PP around the complete SPS plus other special cases

Between each magnet and each chamber section change

Total of ~2500 manufactured pieces

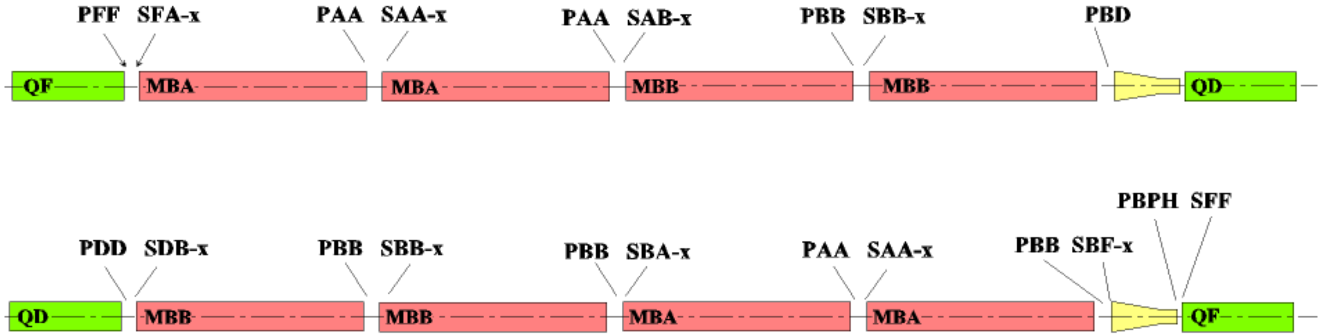
Pumping Port Shielding



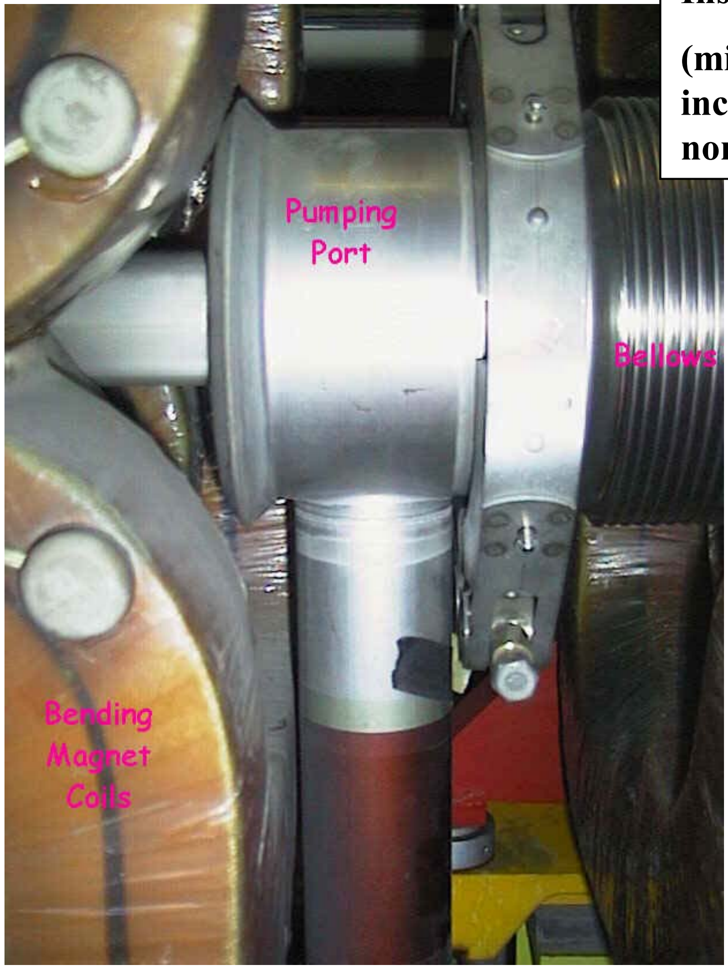
Special shields inserted into the pumping port cavity at each end

Remove every second dipole (18 Tonnes each): Total around 400 Dipoles

Also many of the SSS removed …

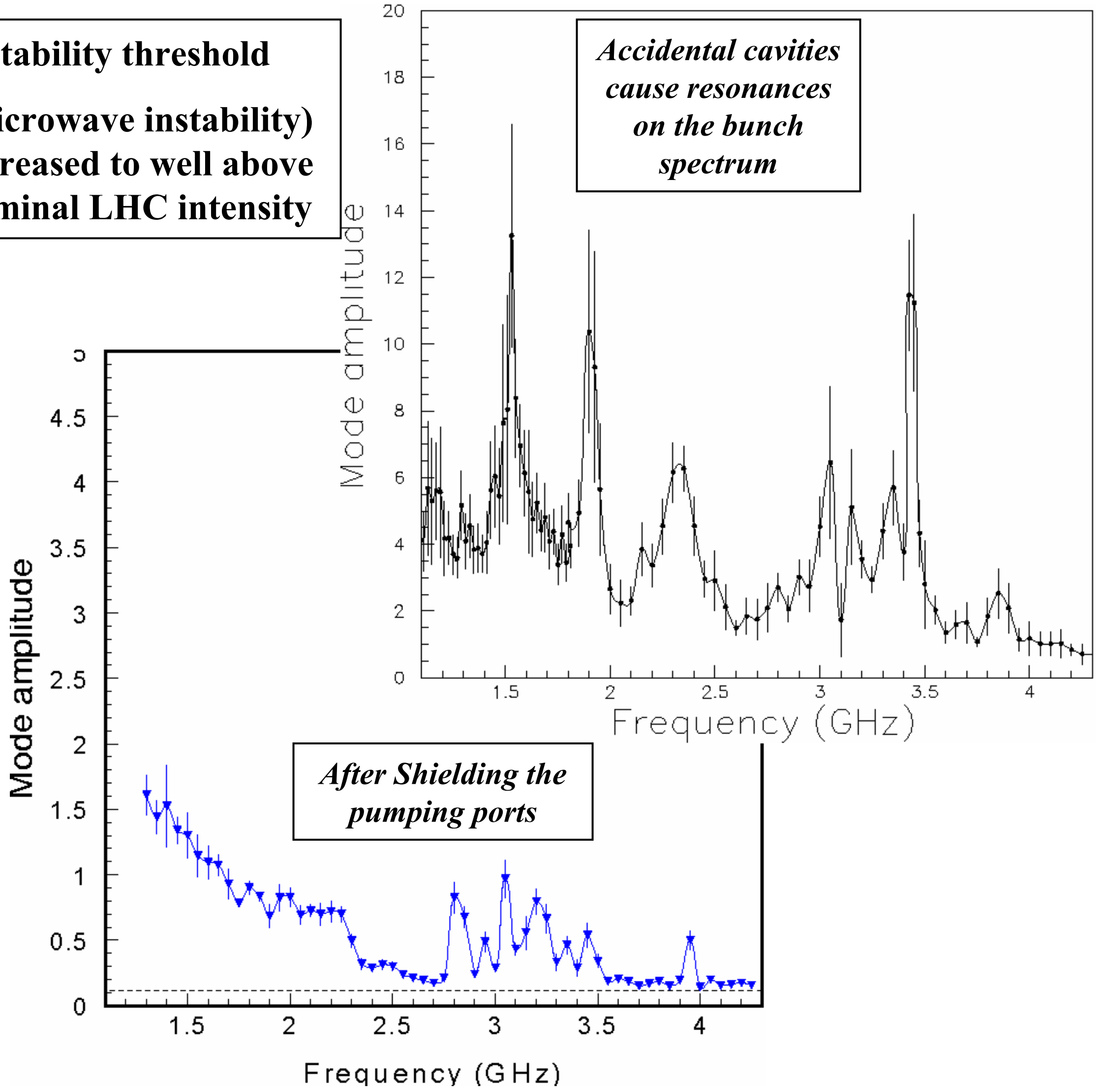


Impedance Reduction



Instability threshold

(microwave instability) increased to well above nominal LHC intensity

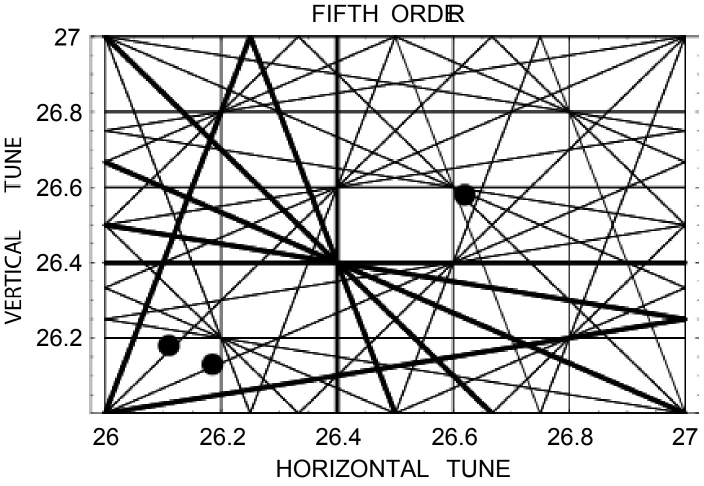


Accidental cavities cause resonances on the bunch spectrum

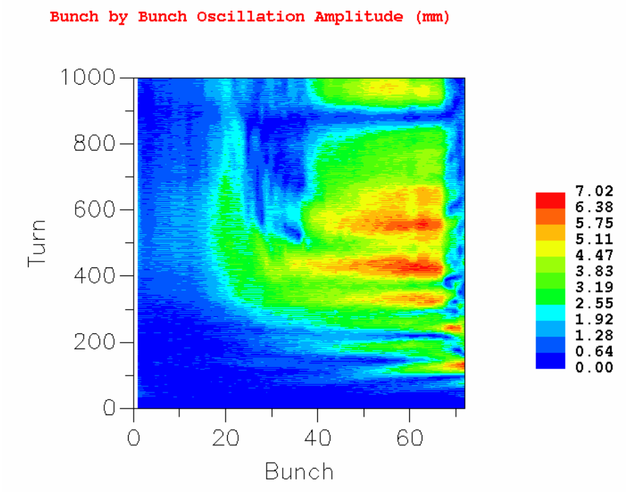
After Shielding the pumping ports

Other Things … (Briefly)

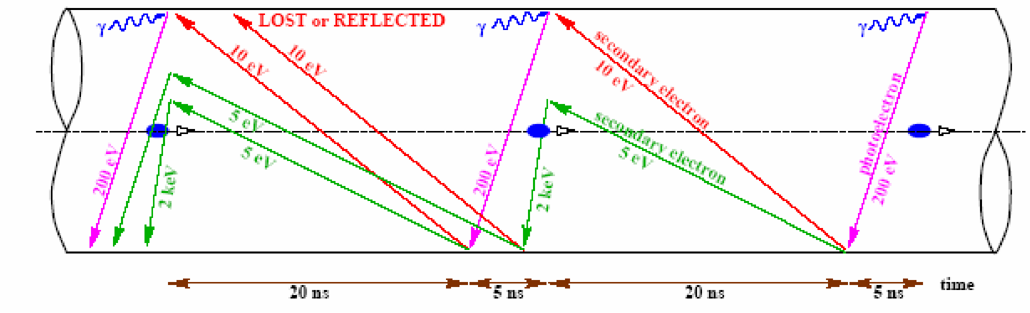
- Preservation of Transverse Emittance
    - More powerful damper (Transverse feedback)
        - Used to damp injection oscillations
    - Increased bandwidth to 20 MHz to fight coupled bunch instabilities
        - Fight instabilities throughout the cycle including e-cloud (later)
- Matching of PS and SPS to the transfer line
    - Avoid emittance blow-up during the extraction-transfer-injection process
- Optimization of the working point (tuning) in the SPS machine



Plus lots of instrumentation to make all this possible!



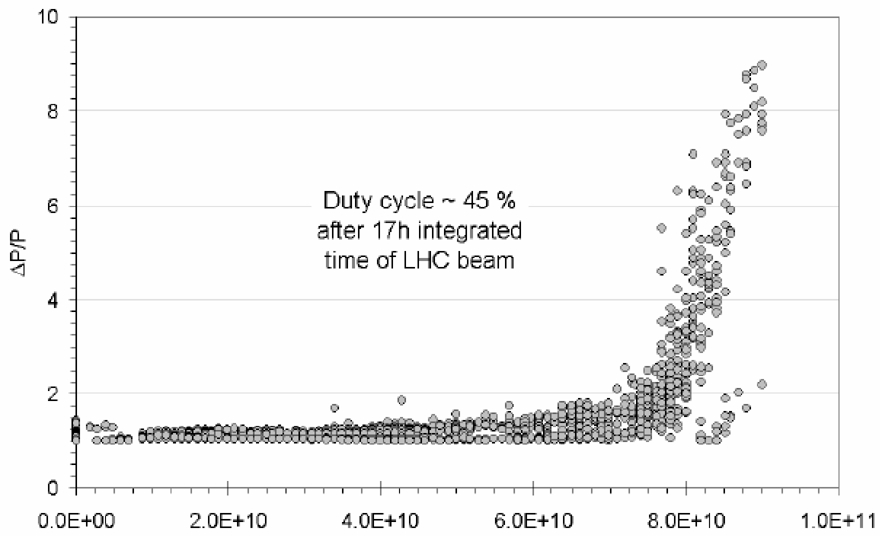
…and what we didn't Expect (in the SPS)

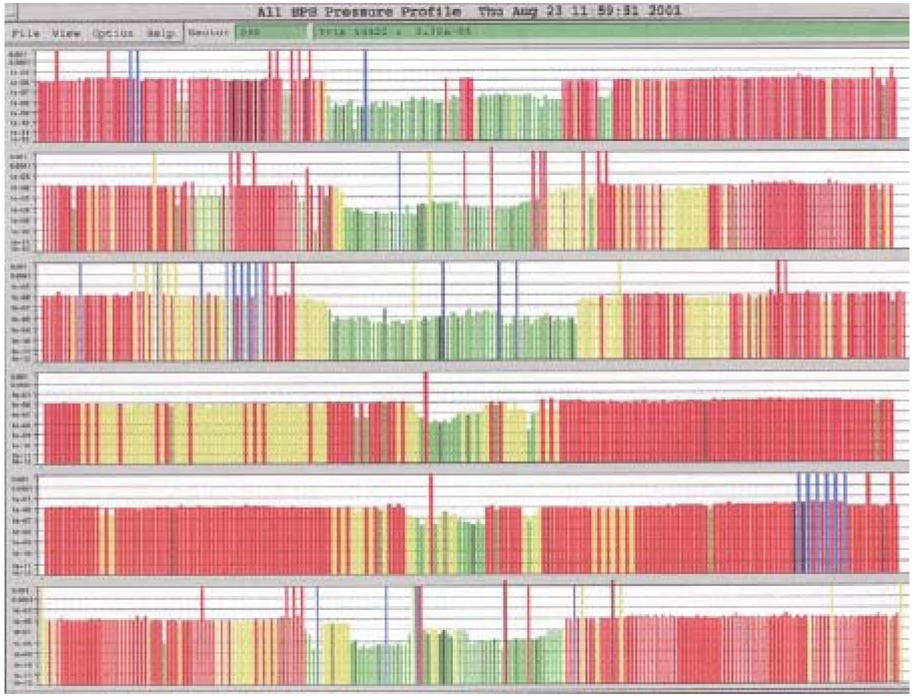


Electrons accelerated by the passing bunches produce additional electrons Build up of electrons in the vacuum chamber to form a cloud – provokes significant pressure rise in the SPS

Expected in the LHC – limitation due to heat load in Cryo system

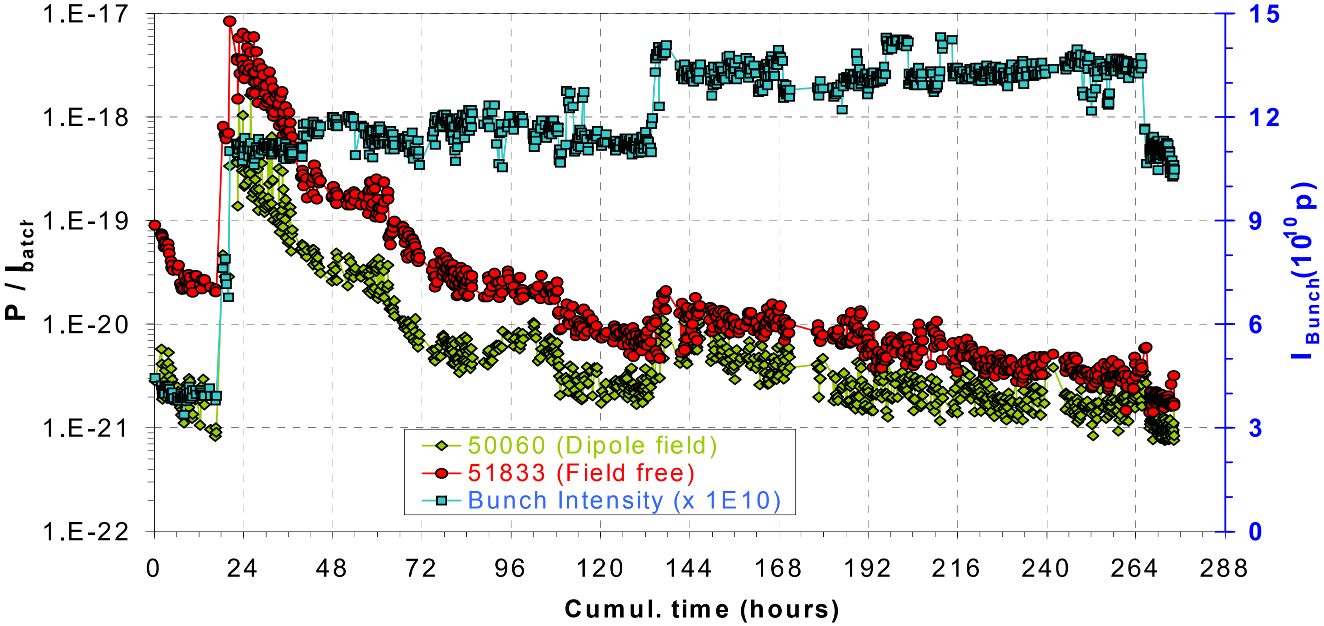
Depends on bunch spacing & characteristics, chamber dimensions, B-field, SEY of chamber material etc…





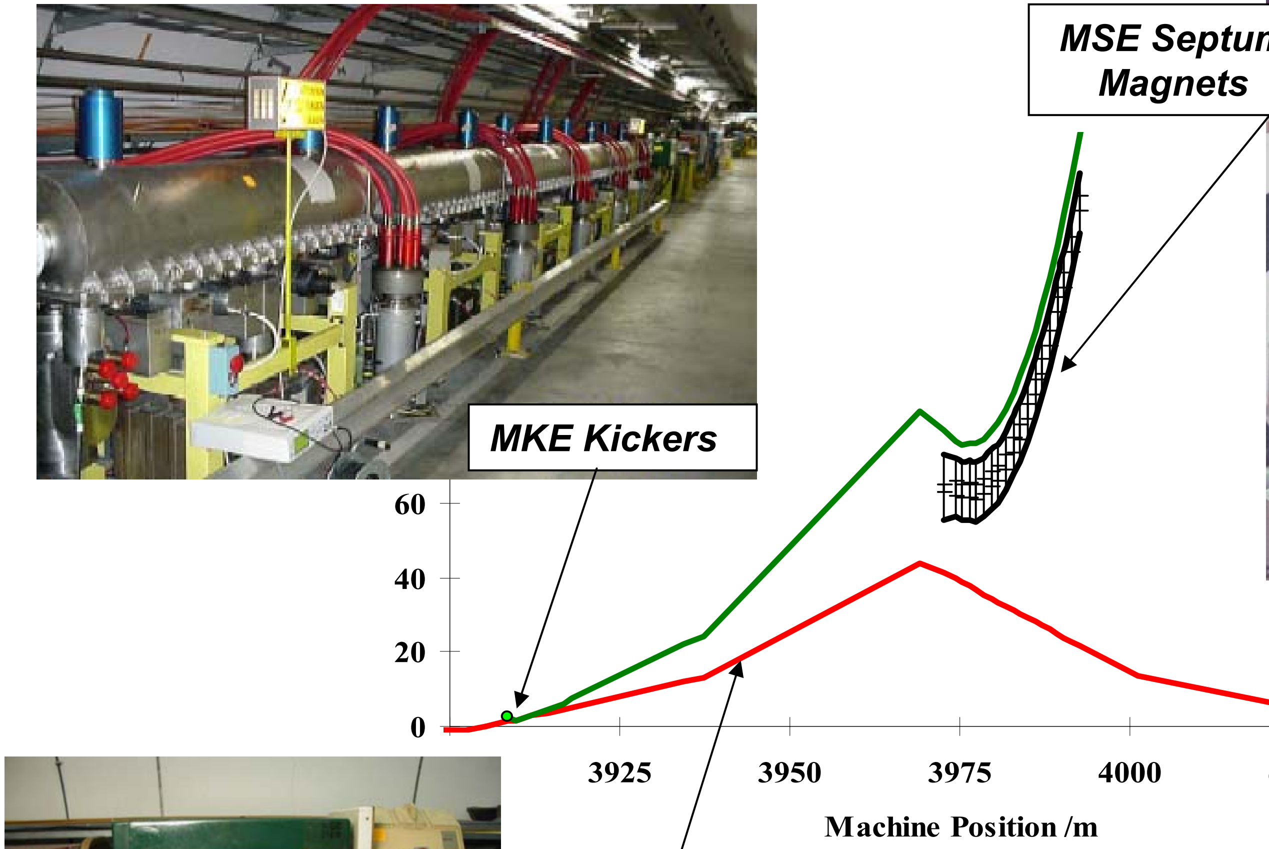
E-Cloud in the SPS

- Extensively studied in the SPS
  - As a test bench for LHC
  - For benchmarking simulation codes
  - For the SPS itself



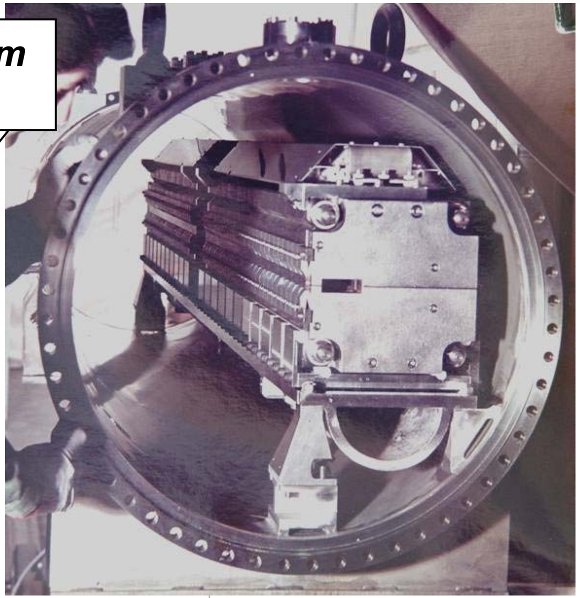
- In the SPS the electron cloud provokes instabilities in the beam
  - The surfaces condition with exposure to the electrons
  - The SEY of the chamber surface goes down.
  - Some de-conditioning with time or exposure to air
  - ‘Scrubbing runs’ now a normal part of the SPS schedule
  - Affects the 25ns LHC bunch structure – but has also been observed even with the normal fixed-target beam in the SPS.

Extraction Channels



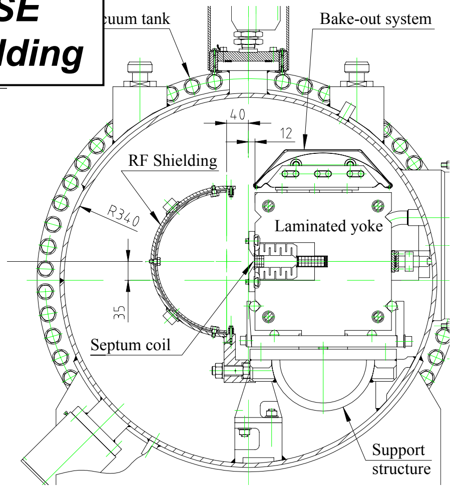
MKE Kickers

MSE Septum Magnets

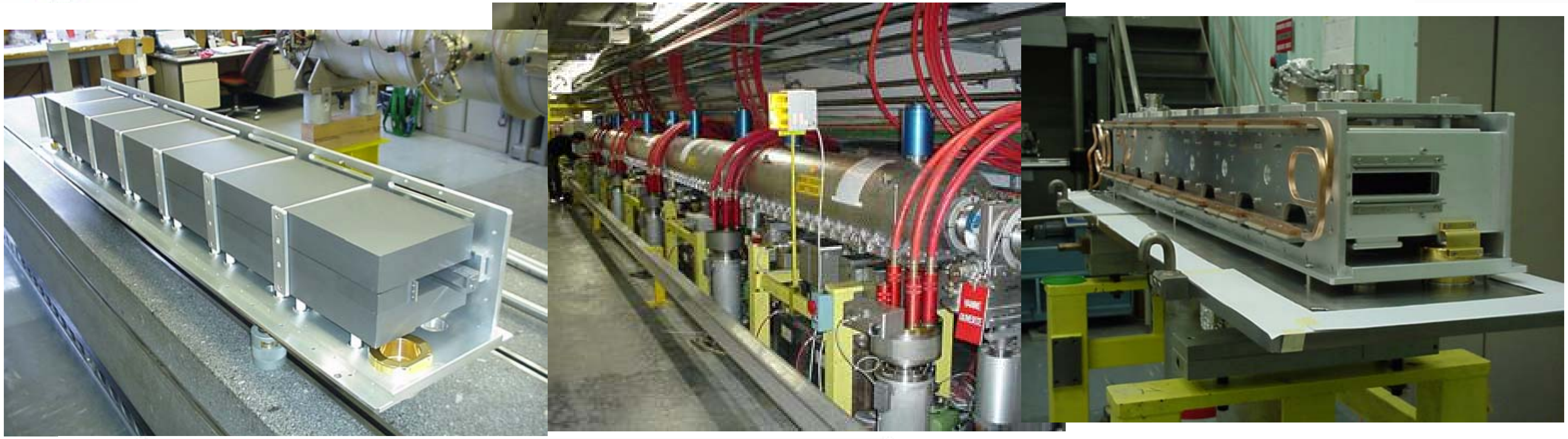


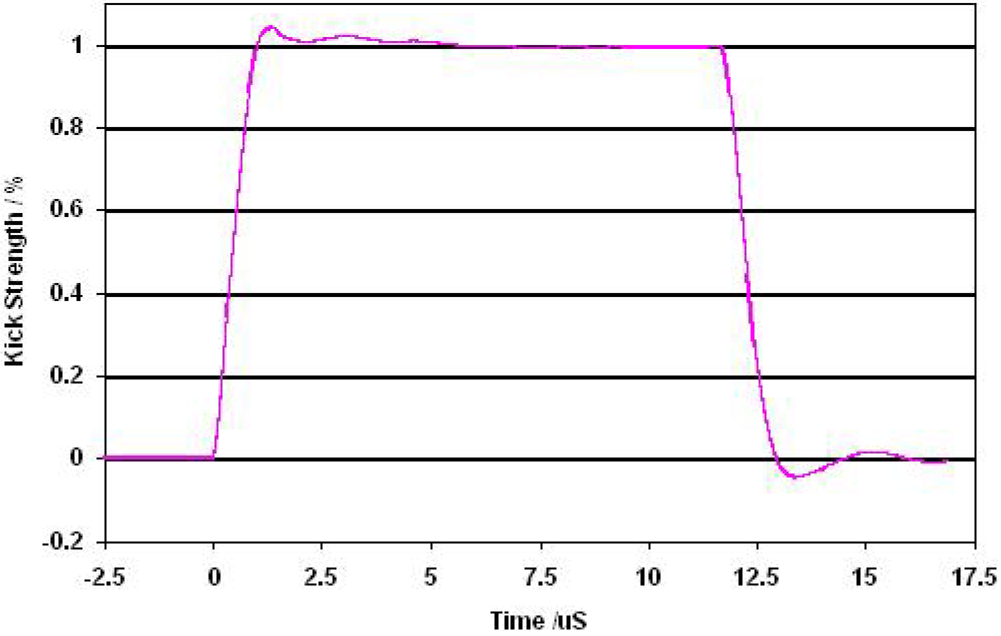
Bumped Circulating Beam

MSE Shielding



Kicker Magnets …





Resonant charging circuit – travelling wave discharge

Flat top duration tailored to beam structure

Injection ~2μS (MKP)

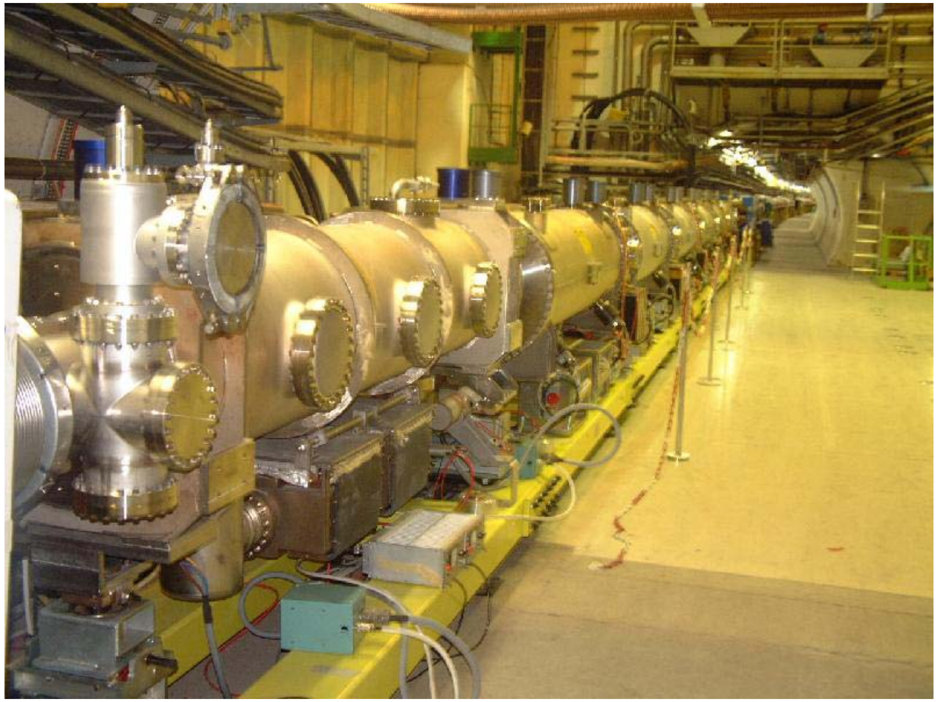
Extraction ~10.5 μS (MKE)

Minimize Ripple → bunch-bunch variations

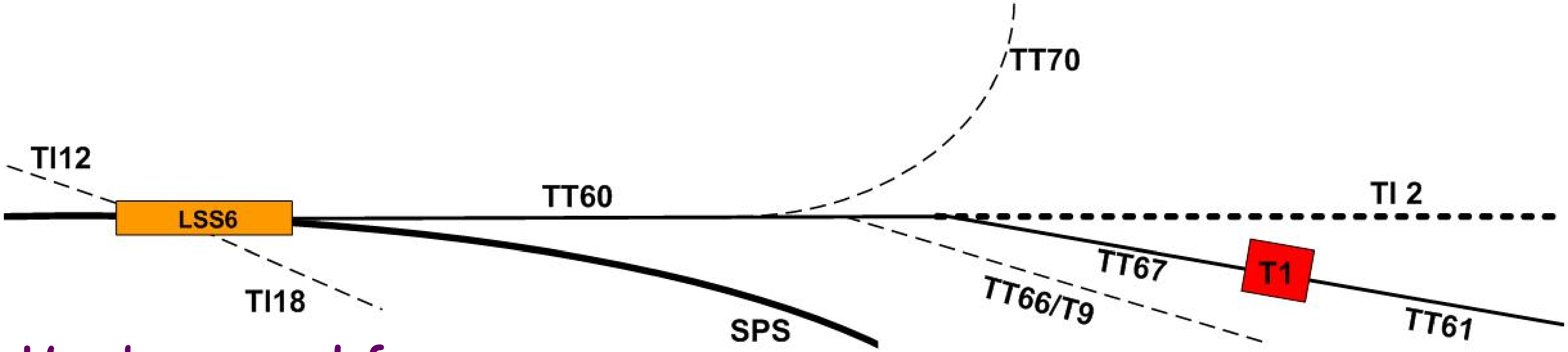
New Extraction in LSS4

- Built to Serve the LHC Via TI 8 and CNGS via TT41
- Fast Extraction only
  - Special conditions to allow 2 extractions ~100ms apart for CNGS
- Constrained by lack of space in some parts of the tunnel (no enlarged section)
- Extraction Septum built on a bridge across UA2 Cavern
- Generators, Power & Control Equipment installed in the old UA2 Garage Cavern

Tested with Beam during 2003 & 2004



From the West to the LHC …

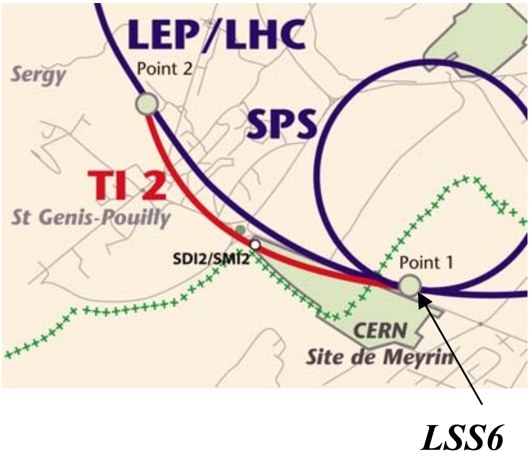


Has been used for

- Slow & Fast-Slow Resonant Extraction
- Fast Lepton Injection & Extraction

In the future will only need to provide

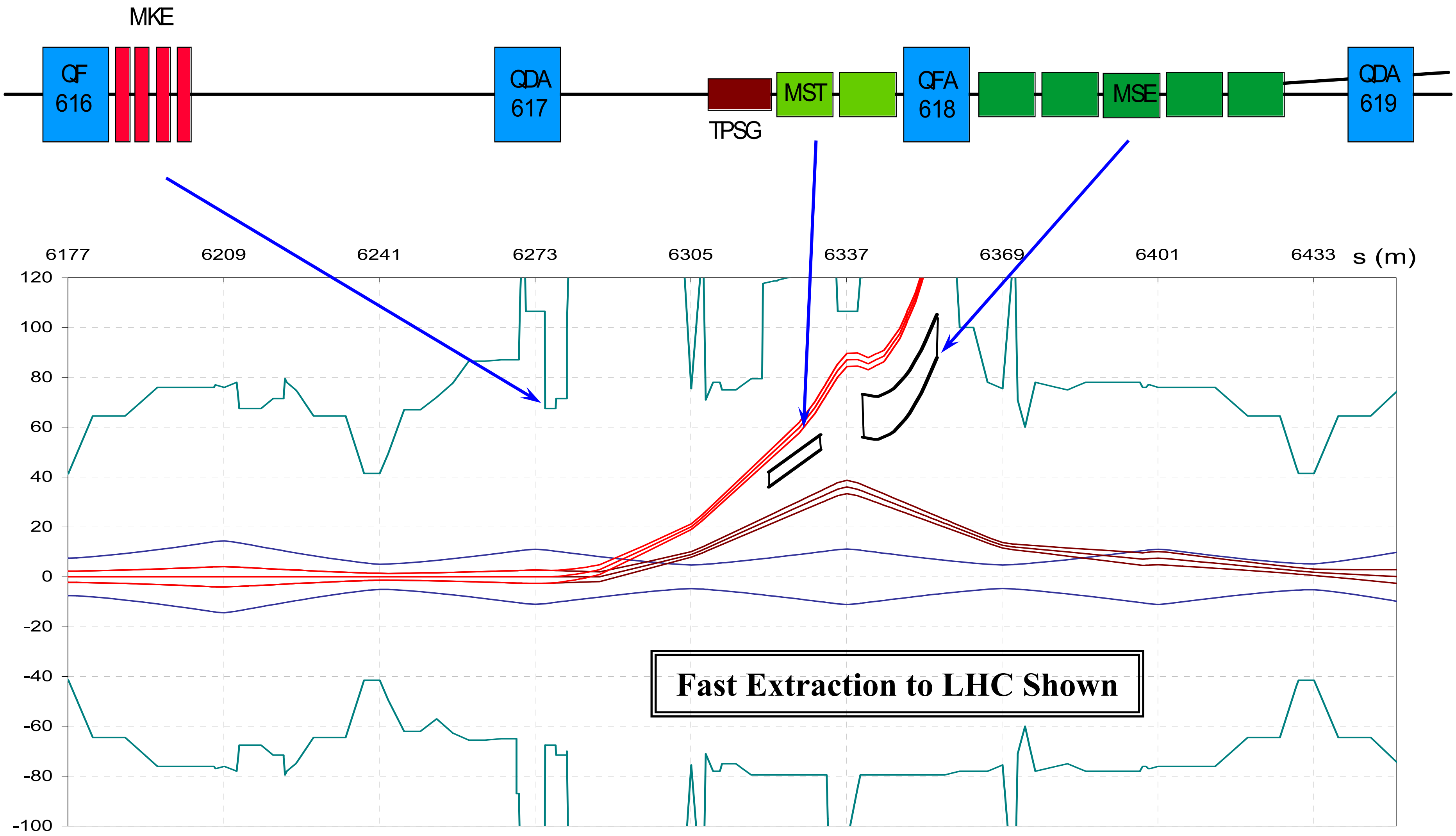
- Fast Extraction towards LHC via TI 2
- Slow Resonant extraction towards T1 and the west area no longer required (with closure of the West Area)



Installation in progress –

- Ready for startup 2006.

Baseline Layout for LHC: LSS6



Fast Extraction to LHC Shown

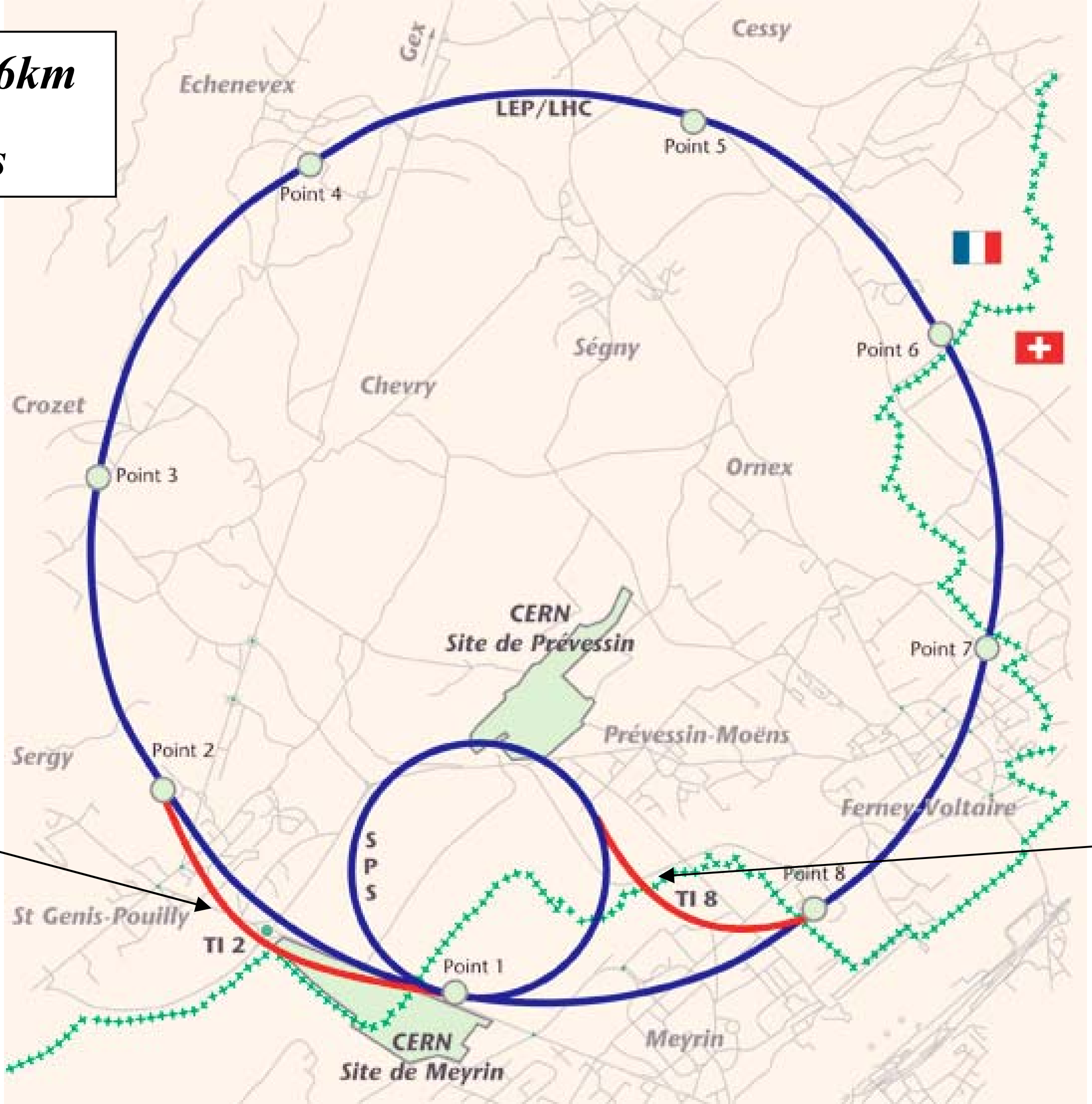
Status of the LHC Beam in the SPS

- During 2004 the required beam for Nominal LHC operation has been accelerated to 450GeV in the SPS – ready for transfer!
  - 288 bunches (4x72) with $1.2\text{x}10^{+11}$ ppb
  - Transverse emittance 3.0/3.6 um (3.5)
  - Longitudinal Emittance 0.6 eVs (0.5-1.0)
- Special Beams : 75ns, Pilot & Totem also prepared
  - Essentially Nominal Parameters as well
- Remaining challenges – Capture losses at SPS injection
  - ~5% for Nominal LHC beam – makes 'Ultimate' difficult
  - Beam induced heating of elements (Kickers)
  - Problem Understood – long term solutions under study.
- Extraction from one channel (LSS4) Commissioned with beam OK
- Otherwise need to consolidate performance and speed up changes to operational cycle.

Transfer Lines to the LHC

Total Length ~5.6km

~700 magnets



Very small physical aperture for the beam

Tails of the beam distribution to be scraped at ~3.5σ before transfer

Protection elements against mis-steering etc. to be installed

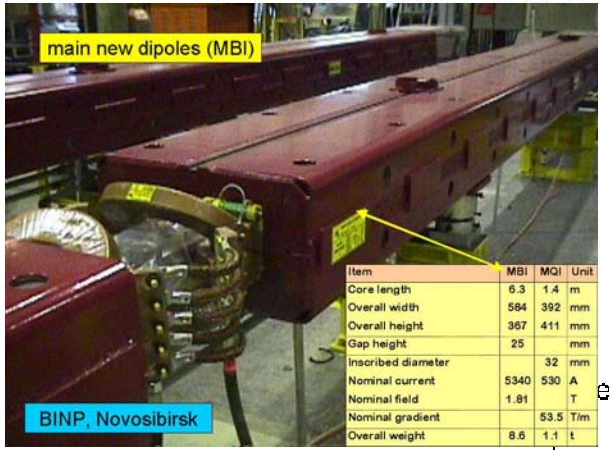
TI 2 From SPS LSS6

To LHC Point 2 (Alice)

TI 8 From SPS LSS4

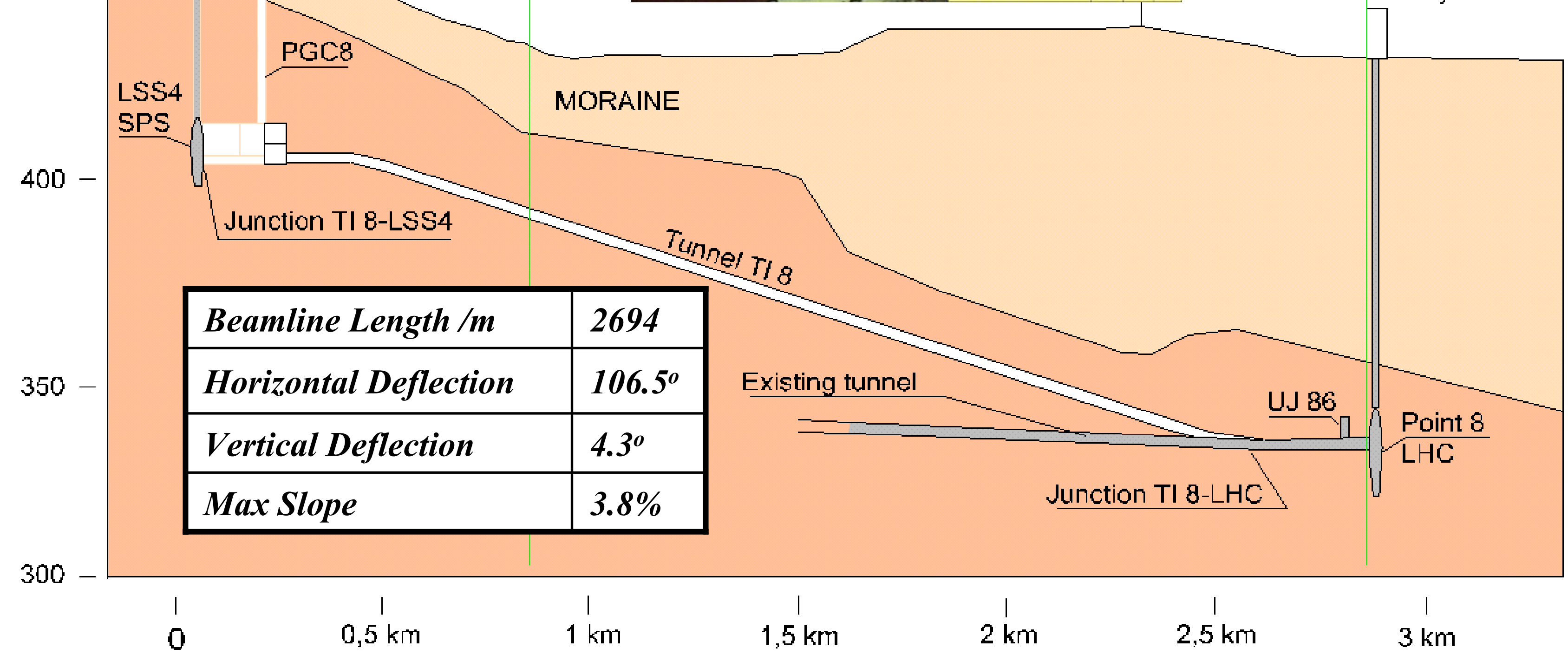
To LHC Point 8 LHCb

Transfer to LHC : TI 8



Item	MBI	MQI	Unit
Core length	6.3	1.4	m
Overall width	584	392	mm
Overall height	367	411	mm
Gap height	25		mm
Inscribed diameter		32	mm
Nominal current	5340	530	A
Nominal field	1.81		T
Nominal gradient		53.5	T/m
Overall weight	8.6	1.1	t

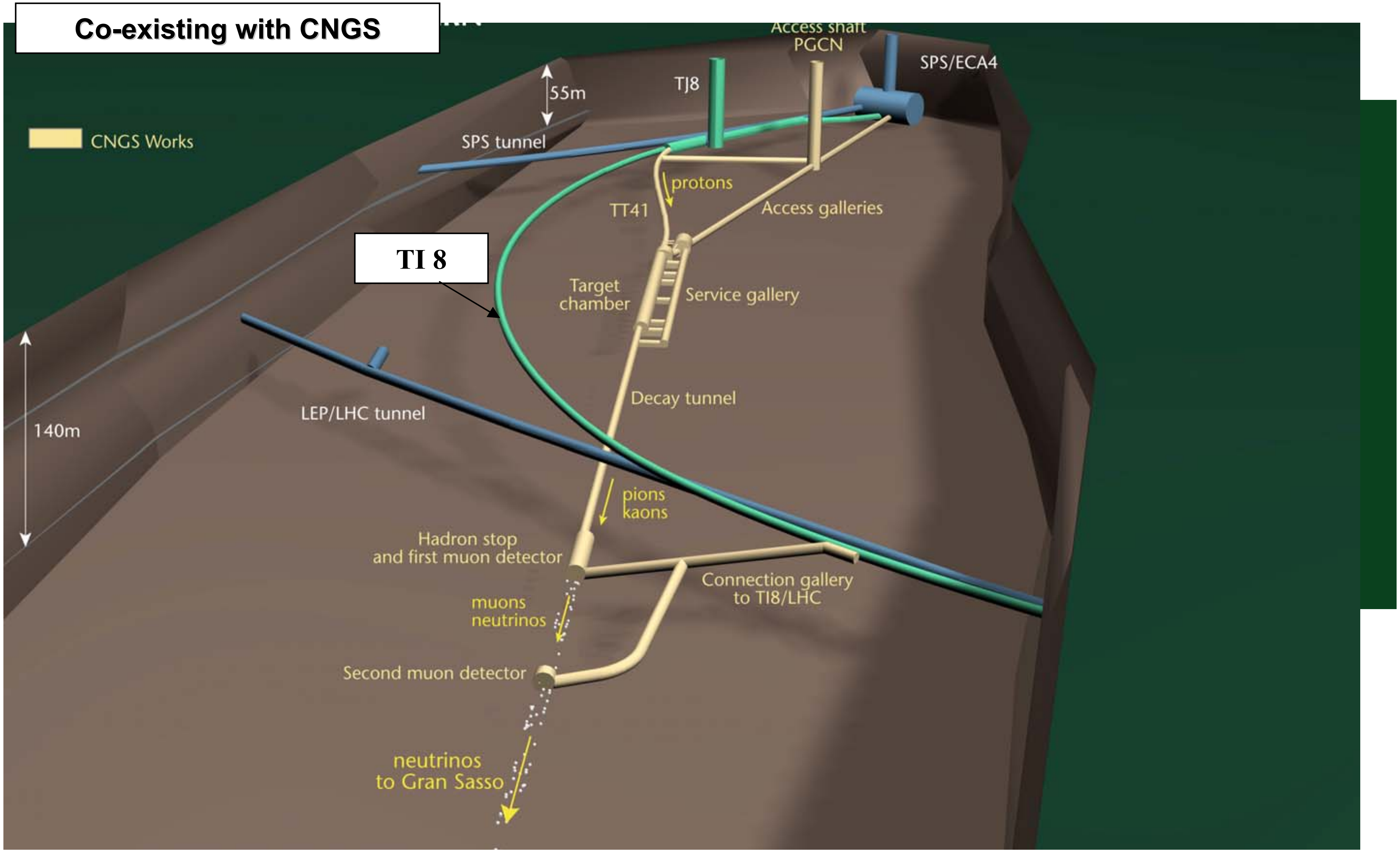
Magnet Count	
Dipoles	268
Quadrupoles	86
Correctors	42



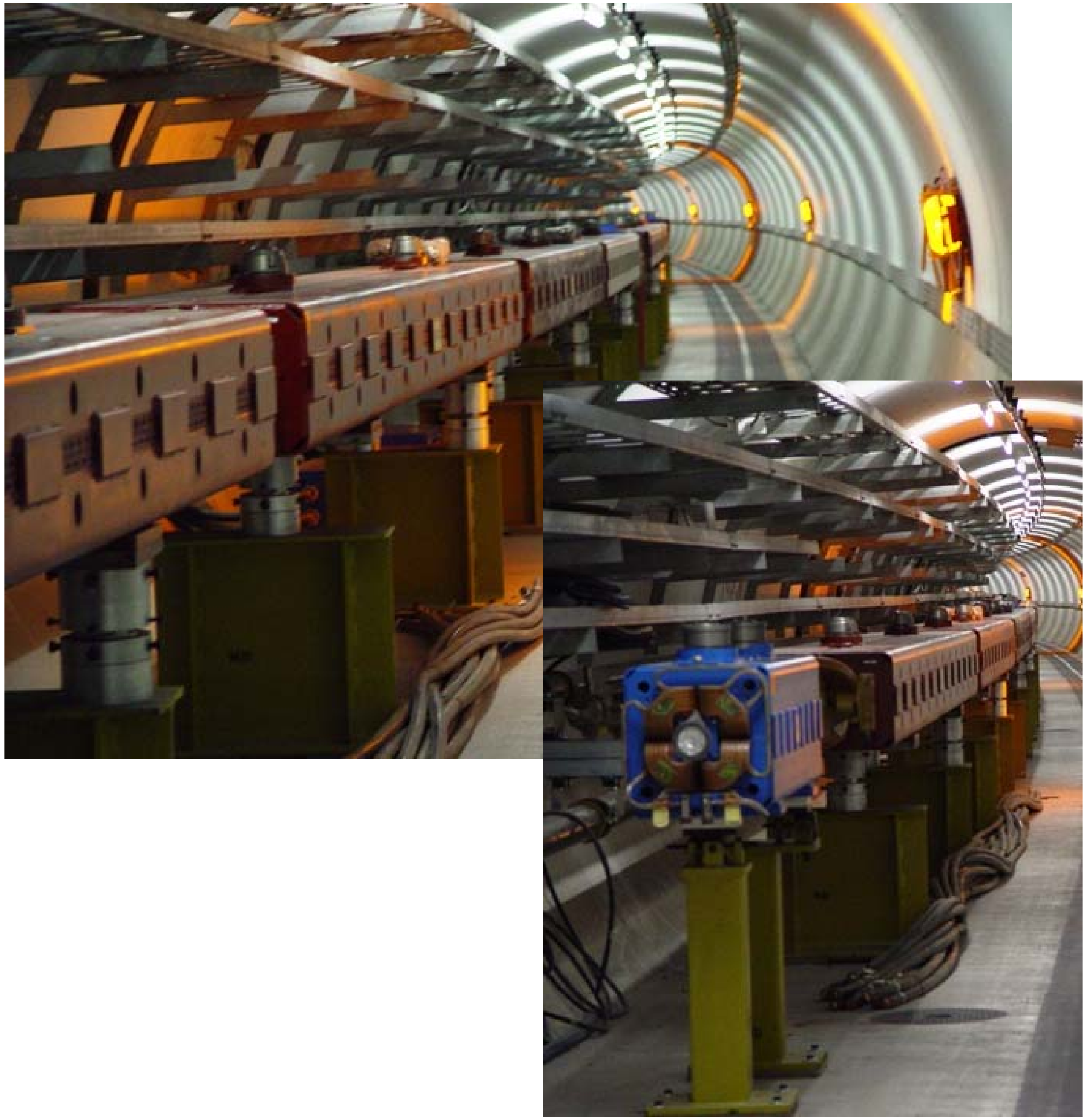
Beamline Length /m	*2694*
Horizontal Deflection	*106.5º*
Vertical Deflection	*4.3º*
Max Slope	*3.8%*

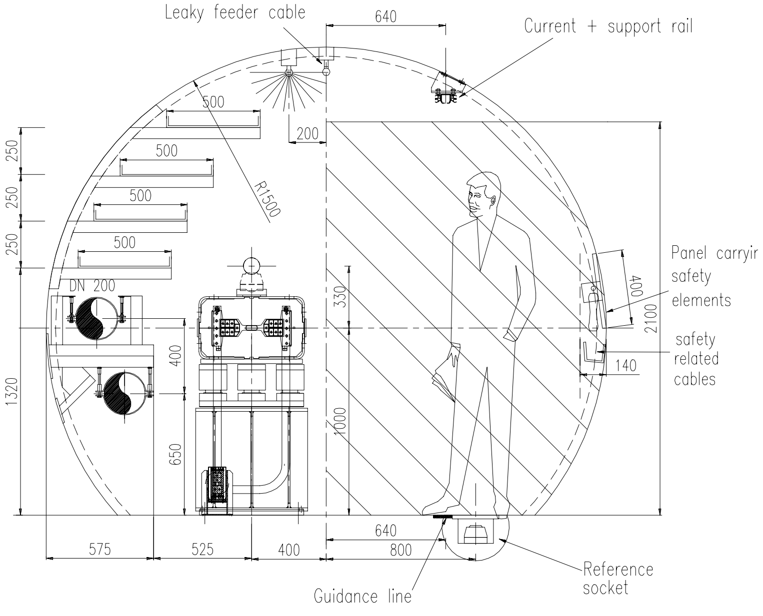
TI 8: Civil Engineering Layout

Co-existing with CNGS



TI 8 Installation

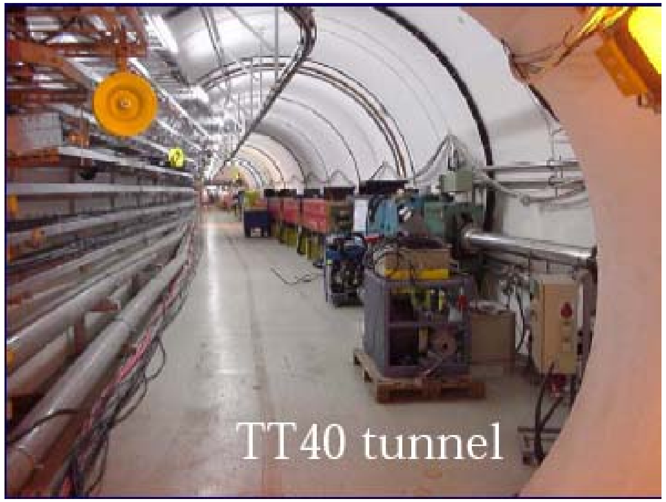


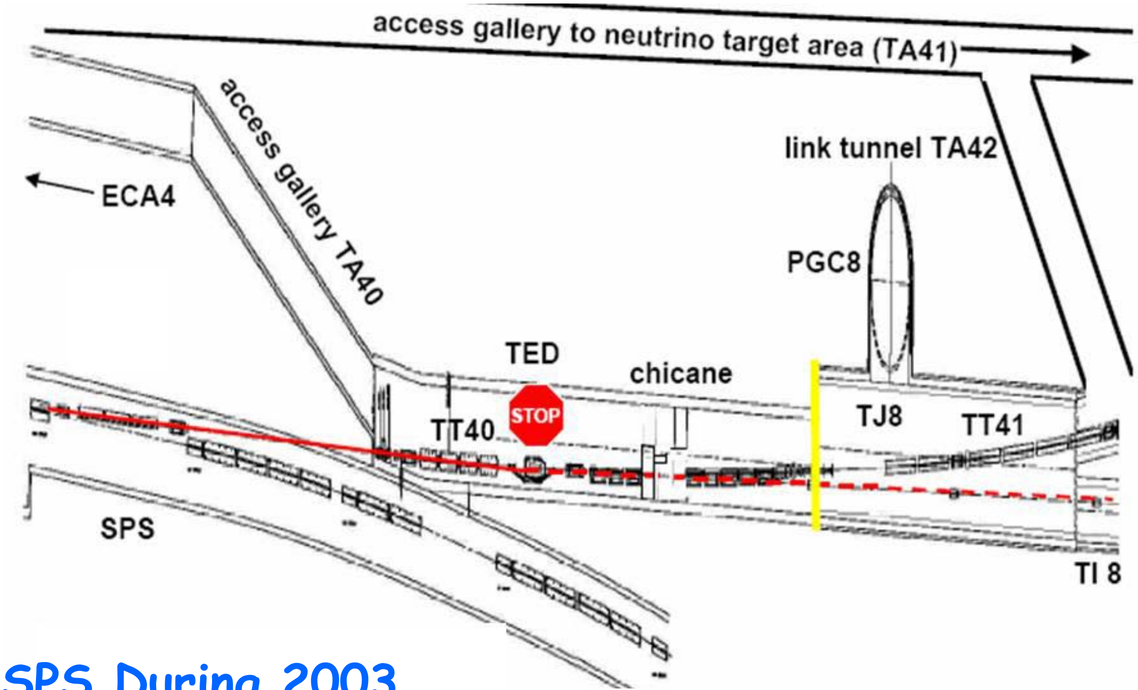


TYPICAL TI 8 CROSS SECTION

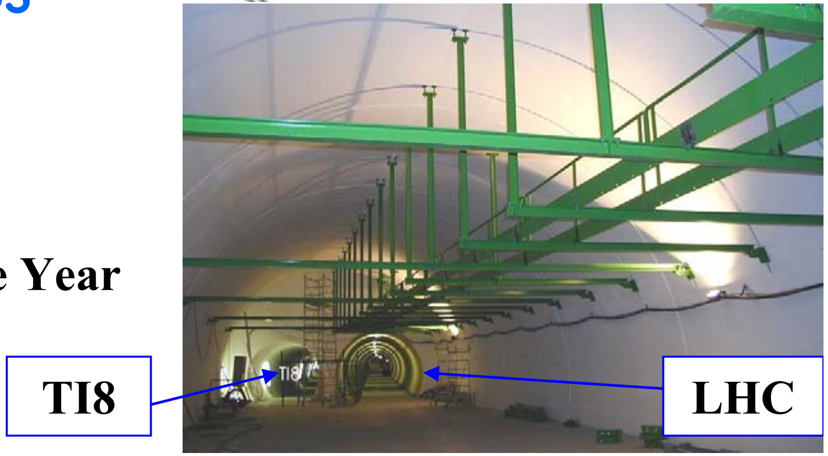
Magnets transported and placed in around 3 months.

TI 8 Continued



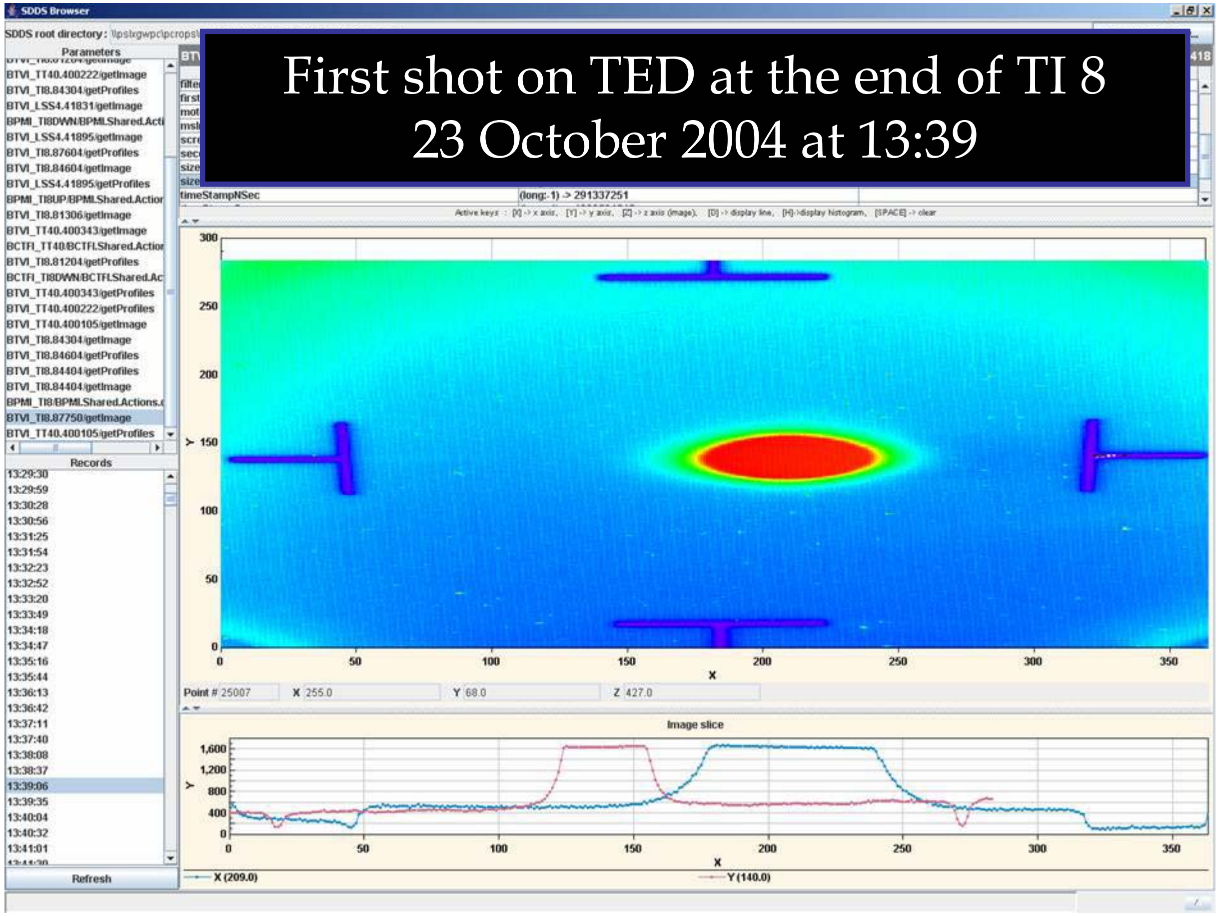


- **Extraction Tests from the SPS During 2003**
  - First 150m of line (TT40) installed for this
- **TI 8 Installation during Summer 2004**
  - Represents half an SPS Worth of beam line!
  - Extensive Beam Tests Towards the end of the Year
- **Installation of CNGS Continues**
  - Commissioning with beam in 2006



TI 8 Beam Tests

Settings of the line set to 449.1 GeV (Calibrated SPS Energy)



First shot on TED at the end of TI 8
23 October 2004 at 13:39

First shot went all the way down to the TI 8 Stopper at the entrance to the LHC tunnel

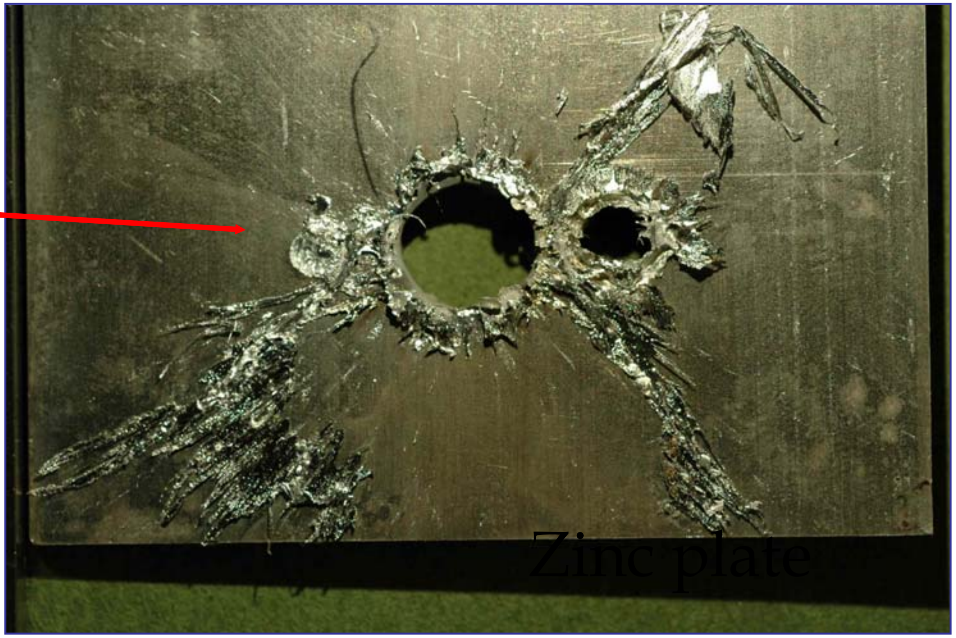
…. through 2.5 km of very small beam pipe

Quadrupole Vacuum chamber

Planned and Unplanned Impact Tests

During TI 8 Beam Tests

Planned material test: perpendicular impact of 72 nominal LHC bunches

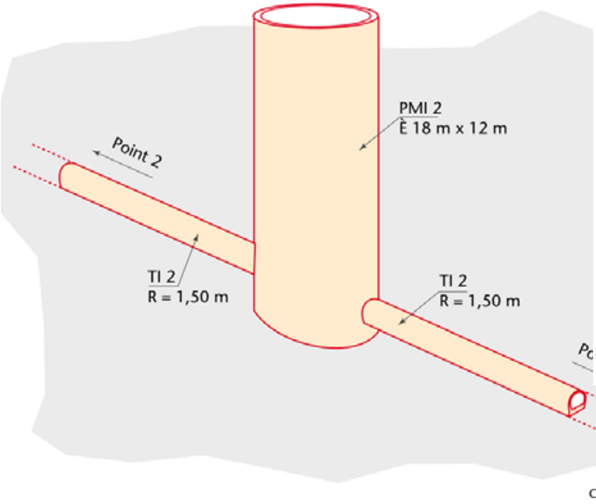


Non-planned material test: grazing incidence of 4 x 72 nominal bunches on QTRF 4002 vacuum chamber

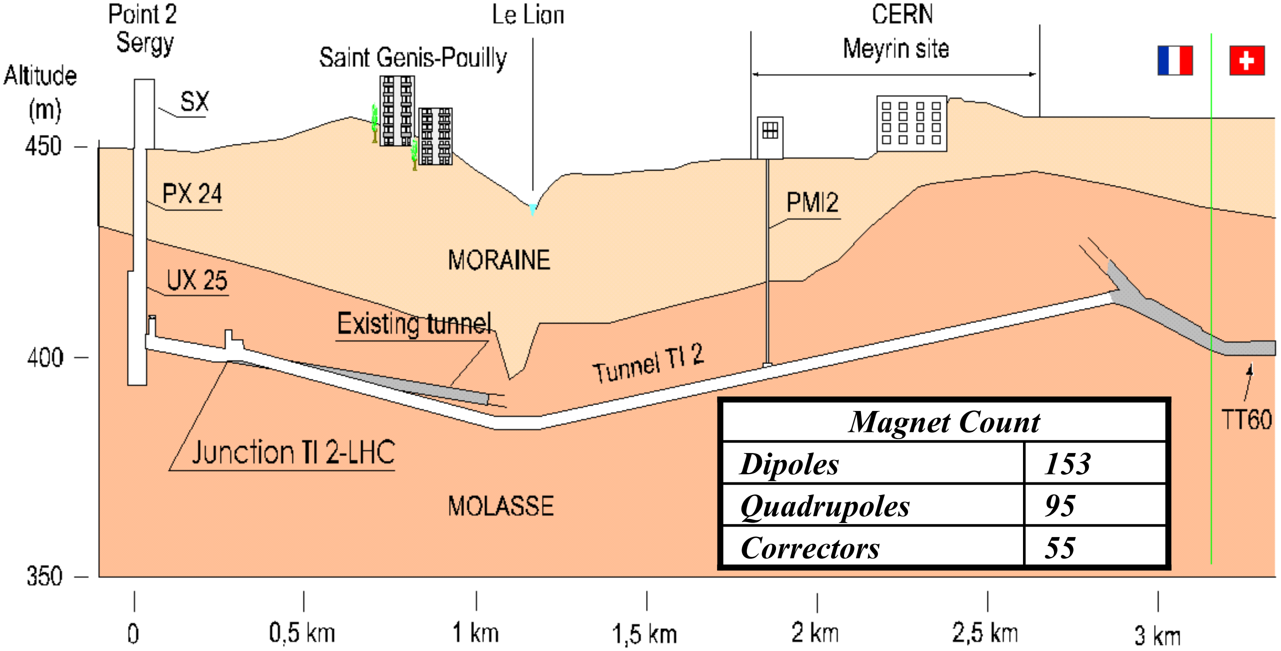
TI 2

Beamline Length /m	*2943*
Horizontal Deflection	*50.4^{o}*
Vertical Deflection	*6.2^{o}*
Max Slope	*4.2%*

Includes the only oval shaft at CERN

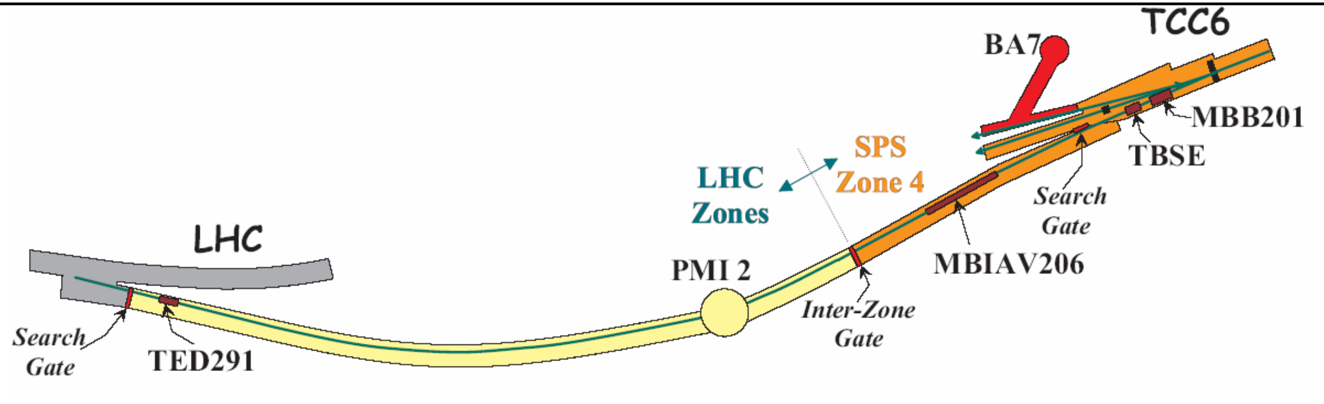


CERN AC - EI4-3 -



Magnet Count	
Dipoles	*153*
Quadrupoles	*95*
Correctors	*55*

TI 2



- Upstream Section being installed now
  - Roughly 1 km from the West area target cavern (TCC6) to PMI2
  - Requires partial dismantling of the old T1 target used for the West experimental area
- The Pit PMI2 is used to lower LHC cryo-magnets
  - Installation of downstream part of TI2 only when the last magnet is in the LHC – end 2006.
- Full Hardware and Beam commissioning of TI2 in 2007
  - Hopefully Just in time …
  - Extraction from SPS to be tested in 2006

Summary

- Preparing the SPS has been a long Project ~10 years.
- The LHC makes very stringent demands from it's injectors
  - **High brilliance** Beams (intensity/beam size)
  - **High reproducibility** from cycle to cycle
  - The LHC Beam is **dangerous** - already in the SPS
  - **Low error rate** – and interlock system to minimize danger to the LHC

- The LHC Transfer lines
  - Represent almost an 'SPS worth' of beamline
  - Civil engineering in parallel with SPS (and LEP) operation
  - Installation in Parallel with SPS Operation and CNGS activities
  - Successful series of **Beam Tests** in TI 8 during 2003 & 2004
  - TI 2 will be commissioned just before LHC commissioning begins

Summary (cont.)

- The LHC performance will depend on it's injectors …
  - Unlike Leptons, "Hadrons never forget"
- The nominal LHC proton beam
  - has already been produced in the injector chain
  - and accelerated to 450GeV, ready for LHC transfer
- The other beams requested by LHC are also pretty much ready
  - The 'ultimate' LHC beam has not yet been demonstrated
- The final hardware modifications in the SPS ring are in progress
  - Ready for the SPS start-up in 2006.
- Studies will continue to help make the p^+ LHC beams fully operational

Ions in the SPS Remain to be commissioned … See Tomorrow