
CERN

Pushing the performance

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Acknowledgments to all the colleagues who provided anecdotes, suggestions, material and corrections, and to the many who made the history of the PS

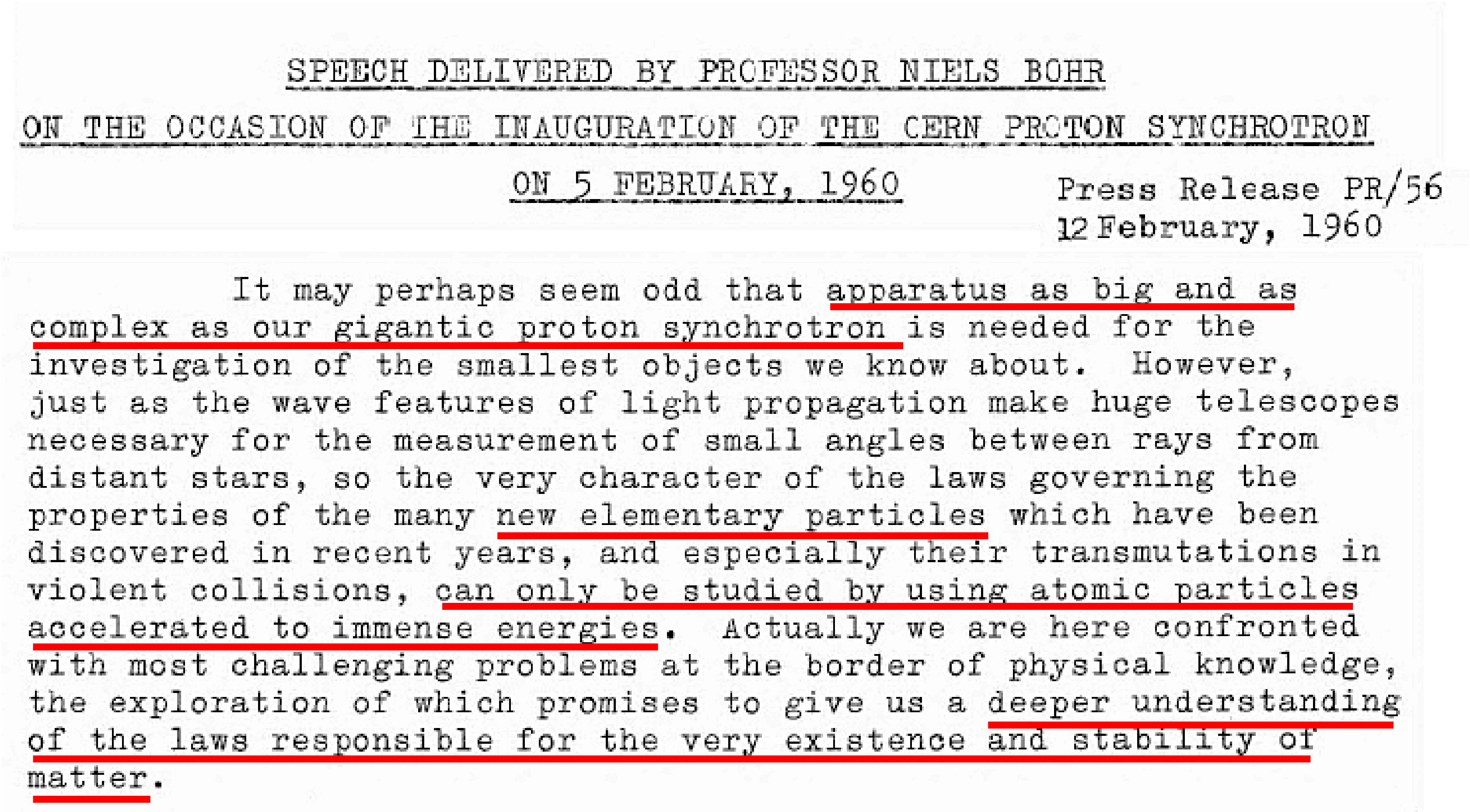
Pushing the performance

- "Performance" intended as:
  - Intensity and brightness increase
  - Orbit optimization
  - Losses control
  - Working point control, resonances
  - RF gymnastics (See Roland's talk)
  - Machine lifetime, availability…

- Many challenges to face:
  - Single bunch stability at injection and transition crossing
  - Space charge limit
  - Coupled bunch instabilities
  - Electron clouds
  - Conserving the brightness

The PS: an exceptionally versatile multiparticle machine, and a machine of many "firsts" that is still also an invaluable scientific tool for accelerator physics

- Unfortunately no time to talk about in details about :
  - Leptons and antiprotons
  - Beam instrumentation
  - Vacuum
  - Control system
  - Etc..



SPEECH DELIVERED BY PROFESSOR NIELS BOHR
ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON
ON 5 FEBRUARY, 1960

Press Release PR/56
12 February, 1960

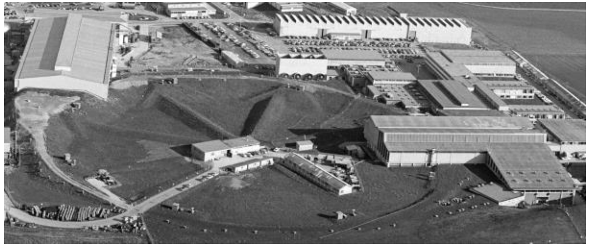
It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays from distant stars, so the very character of the laws governing the properties of the many new elementary particles which have been discovered in recent years, and especially their transmutations in violent collisions, can only be studied by using atomic particles accelerated to immense energies. Actually we are here confronted with most challenging problems at the border of physical knowledge, the exploration of which promises to give us a deeper understanding of the laws responsible for the very existence and stability of matter.

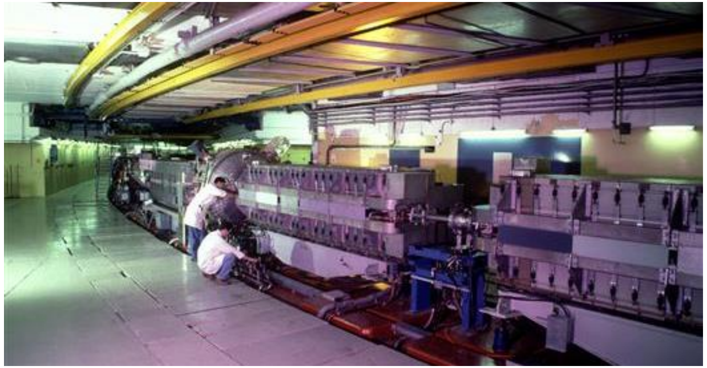
Make it simple ... But with Strong Focusing

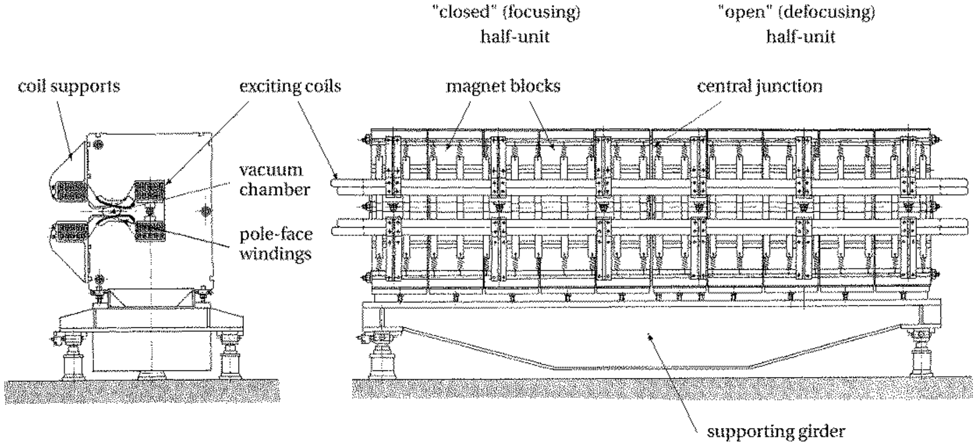
Circumference = 2 * π * 100 m

100 main combined function dipoles

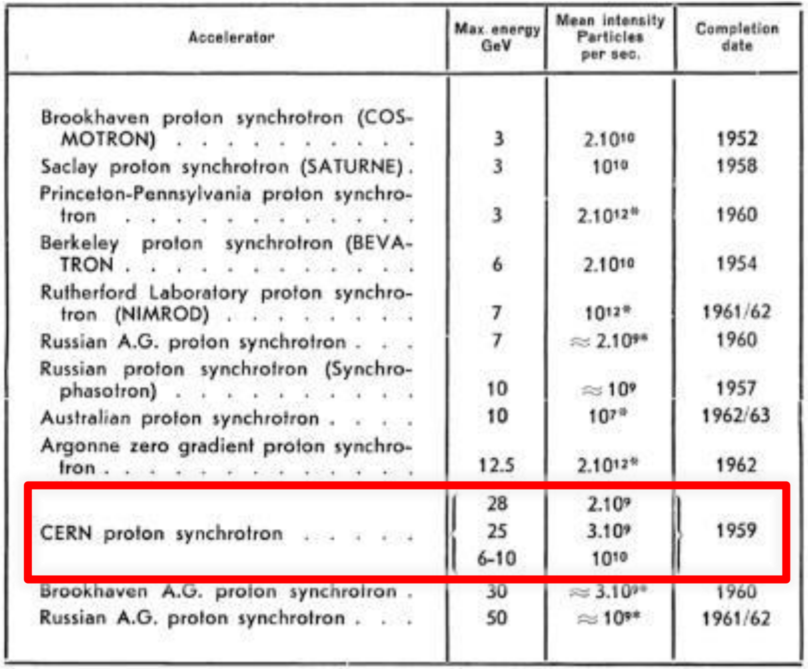
100 straight sections





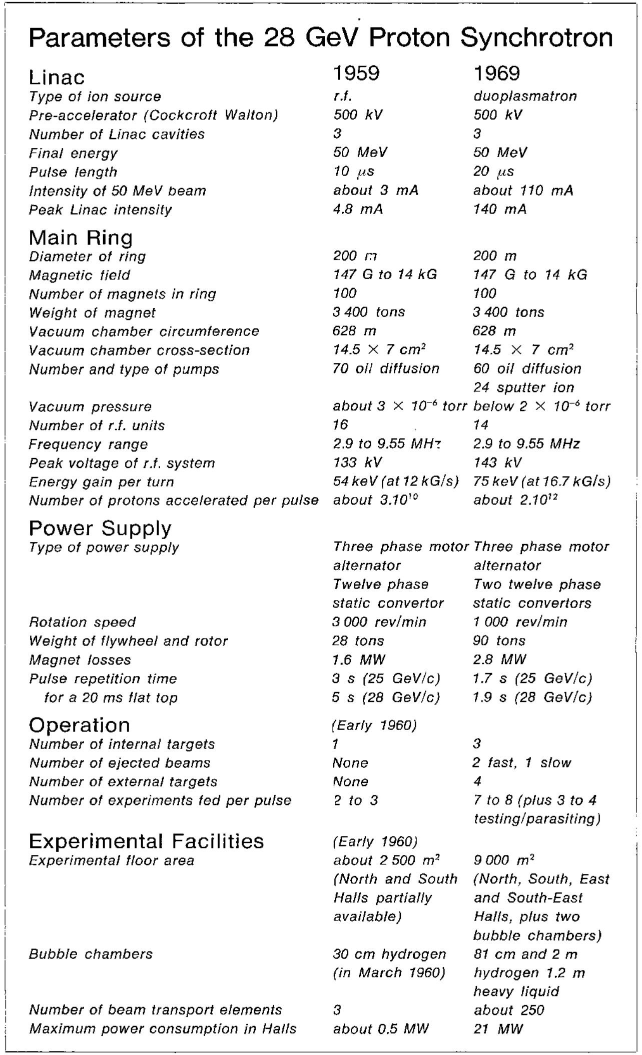


First parameter tables



Accelerator	Max energy GeV	Mean intensity Particles per sec.	Completion date
Brookhaven proton synchrotron (COSMOTRON)	3	2.10^{10}	1952
Saclay proton synchrotron (SATURNE) .	3	10^{10}	1958
Princeton-Pennsylvania proton synchrotron	3	2.10^{12*}	1960
Berkeley proton synchrotron (BEVATRON	6	2.10^{10}	1954
Rutherford Laboratory proton synchrotron (NIMROD)	7	10^{12*}	1961/62
Russian A.G. proton synchrotron . . .	7	$\approx 2.10^{9*}$	1960
Russian proton synchrotron (Synchrophasotron)	10	$\approx 10^{9}$	1957
Australian proton synchrotron	10	10^{7*}	1962/63
Argonne zero gradient proton synchrotron	12.5	2.10^{12*}	1962
CERN proton synchrotron	28 25 6-10	2.10^{9} 3.10^{9} 10^{10}	1959
Brookhaven A.G. proton synchrotron .	30	$\approx 3.10^{9*}$	1960
Russian A.G. proton synchrotron . . .	50	$\approx 10^{9*}$	1961/62

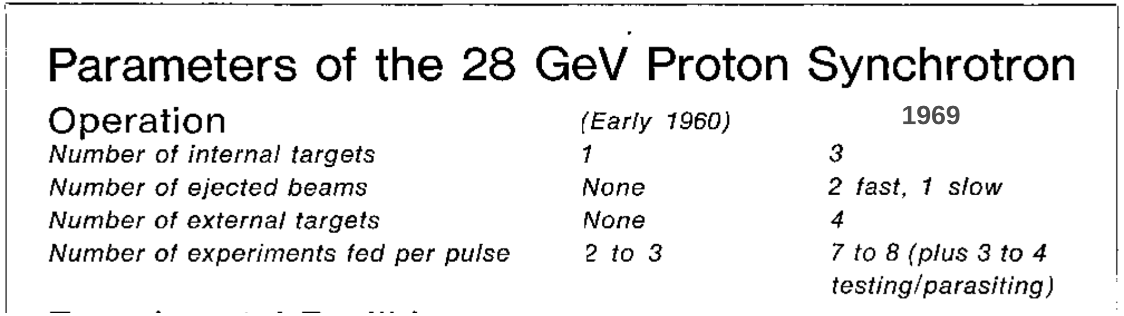
For reference (2018): 1 PS batch for LHC → 72 bunches, 1.2 10^{11} ppb



Parameters of the 28 GeV Proton Synchrotron

Linac	1959	1969
Type of ion source	*r.f.*	*duoplasmatron*
Pre-accelerator (Cockcroft Walton)	*500 kV*	*500 kV*
Number of Linac cavities	*3*	*3*
Final energy	*50 MeV*	*50 MeV*
Pulse length	*10 μs*	*20 μs*
Intensity of 50 MeV beam	*about 3 mA*	*about 110 mA*
Peak Linac intensity	*4.8 mA*	*140 mA*
Main Ring		
Diameter of ring	*200 m*	*200 m*
Magnetic field	*147 G to 14 kG*	*147 G to 14 kG*
Number of magnets in ring	*100*	*100*
Weight of magnet	*3 400 tons*	*3 400 tons*
Vacuum chamber circumference	*628 m*	*628 m*
Vacuum chamber cross-section	*14.5 × 7 cm*^{2}	*14.5 × 7 cm*^{2}
Number and type of pumps	*70 oil diffusion*	*60 oil diffusion* *24 sputter ion*
Vacuum pressure	*about 3 ×* 10^{-6} *torr*	*below 2 ×* 10^{-6} *torr*
Number of r.f. units	*16*	*14*
Frequency range	*2.9 to 9.55 MHz*	*2.9 to 9.55 MHz*
Peak voltage of r.f. system	*133 kV*	*143 kV*
Energy gain per turn	*54 keV (at 12 kG/s)*	*75 keV (at 16.7 kG/s)*
Number of protons accelerated per pulse	*about* 3.10^{10}	*about* 2.10^{12}
Power Supply		
Type of power supply	*Three phase motor alternator* *Twelve phase static convertor*	*Three phase motor alternator* *Two twelve phase static convertors*
Rotation speed	*3 000 rev/min*	*1 000 rev/min*
Weight of flywheel and rotor	*28 tons*	*90 tons*
Magnet losses	*1.6 MW*	*2.8 MW*
Pulse repetition time for a 20 ms flat top	*3 s (25 GeV/c)* *5 s (28 GeV/c)*	*1.7 s (25 GeV/c)* *1.9 s (28 GeV/c)*
Operation	*(Early 1960)*	
Number of internal targets	*1*	*3*
Number of ejected beams	*None*	*2 fast, 1 slow*
Number of external targets	*None*	*4*
Number of experiments fed per pulse	*2 to 3*	*7 to 8 (plus 3 to 4 testing/parasiting)*
Experimental Facilities	*(Early 1960)*	
Experimental floor area	*about 2 500 m*^{2} *(North and South Halls partially available)*	*9 000 m*^{2} *(North, South, East and South-East Halls, plus two bubble chambers)*
Bubble chambers	*30 cm hydrogen (in March 1960)*	*81 cm and 2 m hydrogen 1.2 m heavy liquid*
Number of beam transport elements	*3*	*about 250*
Maximum power consumption in Halls	*about 0.5 MW*	*21 MW*

What about extractions ?



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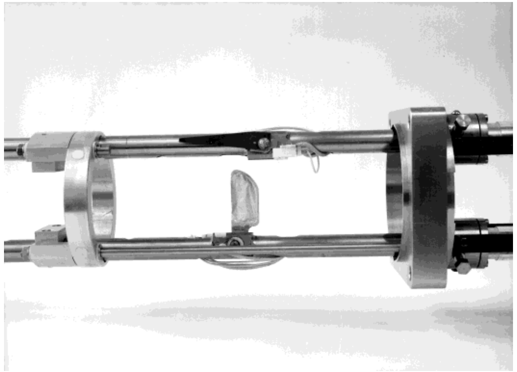
Internal target



At the beginning, no extractions at all

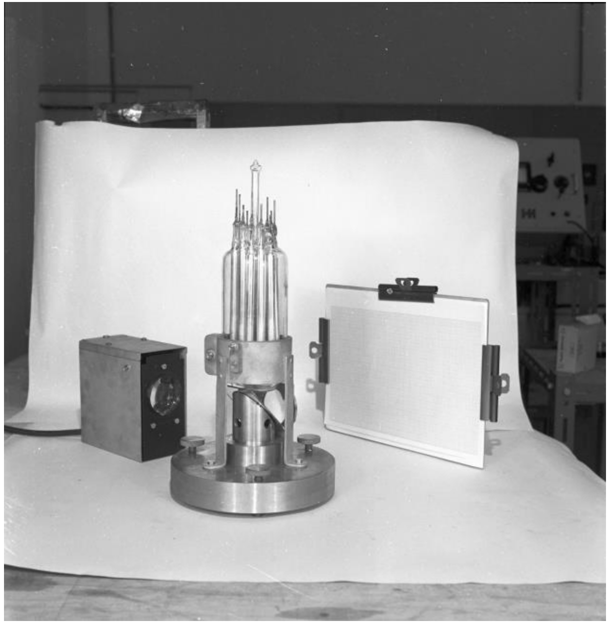
Up to today :

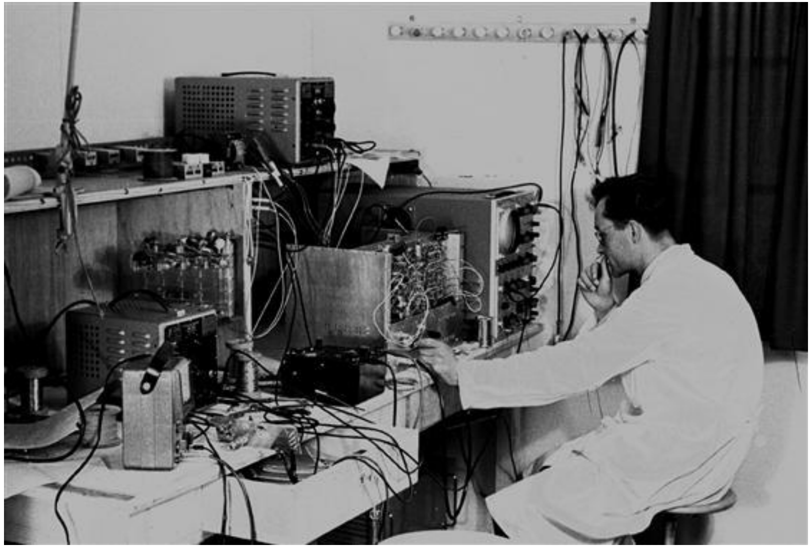
- Two fast extraction (particles and anti-particles)
- Two/three types of slow extractions
- Two 5-turns extractions (CT-continuous transfer and MTE-Multiturn extraction)

Early days…

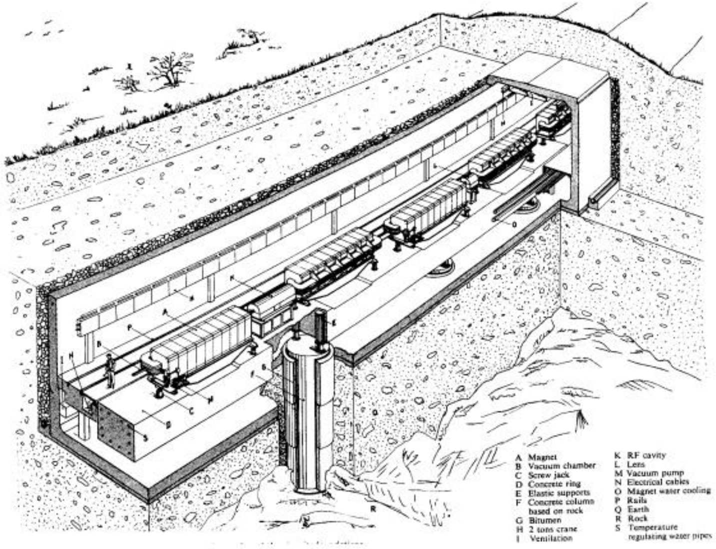
Starting from green fields

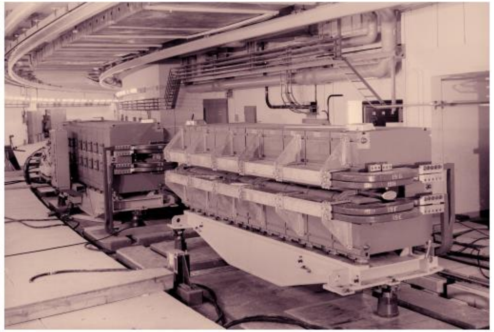
Simulating non-linear behaviour and betatronic resonances





Constructing everything on a floating concrete cooled ring



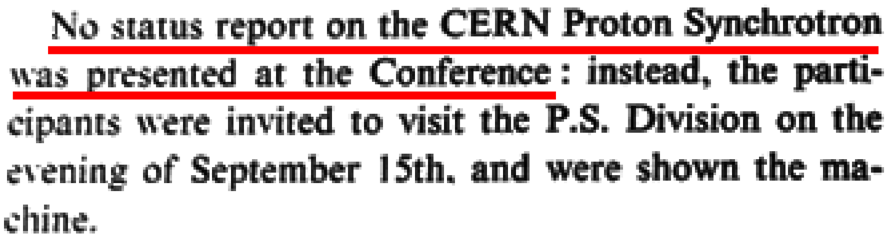


1979 : **explosives** used as part of the excavations for the new AA
Detonations timed to permit the effect of ground movement to be observed on the beam in the PS.
Nothing measurable was seen

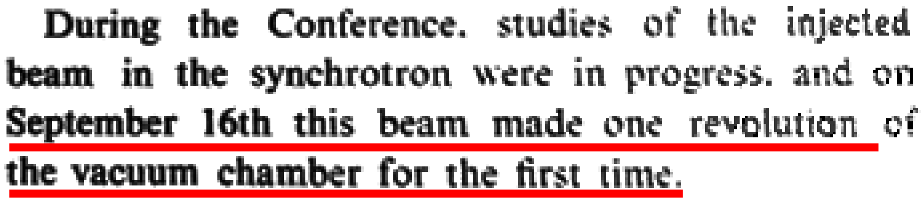
First circulating beam in September 1959

From : International conference on high-energy accelerators and instrumentation

14th – 19th September 1959 at CERN



No status report on the CERN Proton Synchrotron was presented at the Conference : instead, the participants were invited to visit the P.S. Division on the evening of September 15th, and were shown the machine.



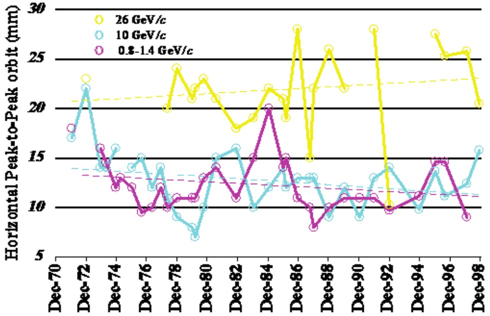
During the Conference, studies of the injected beam in the synchrotron were in progress, and on September 16th this beam made one revolution of the vacuum chamber for the first time.

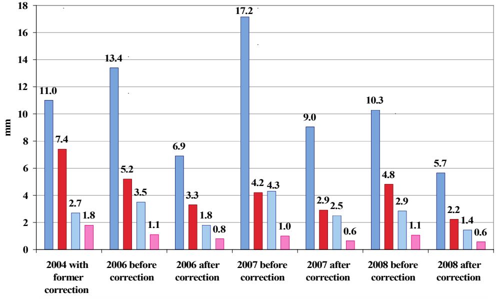
The first circulating beam in a strong-focusing proton synchrotron

And already the intensity was at some 10^{10}

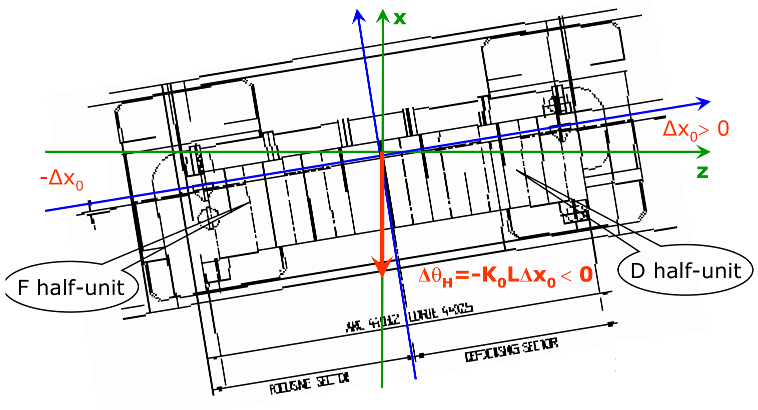
Closed orbit, a long-term concern

Orbit control/optimization always a must to maximize aperture
And reduce transverse emittance blow-up.

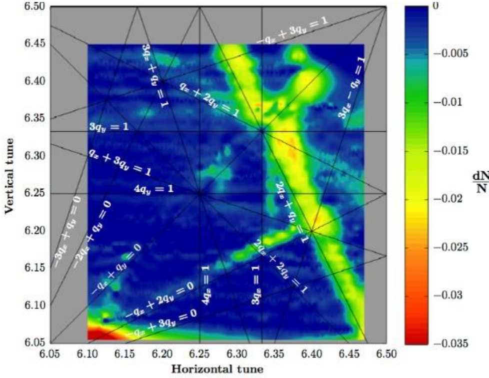


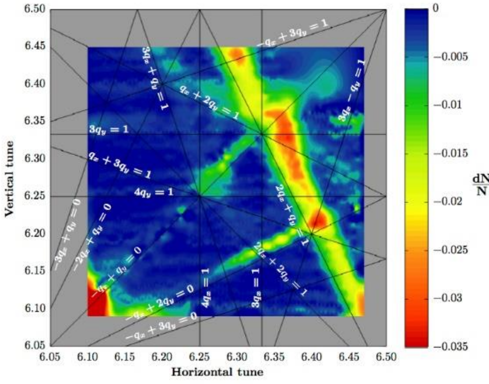


- Beam based orbit correction done by **rotating main combined function dipoles**
- Unfortunately some of the resonances are enhanced



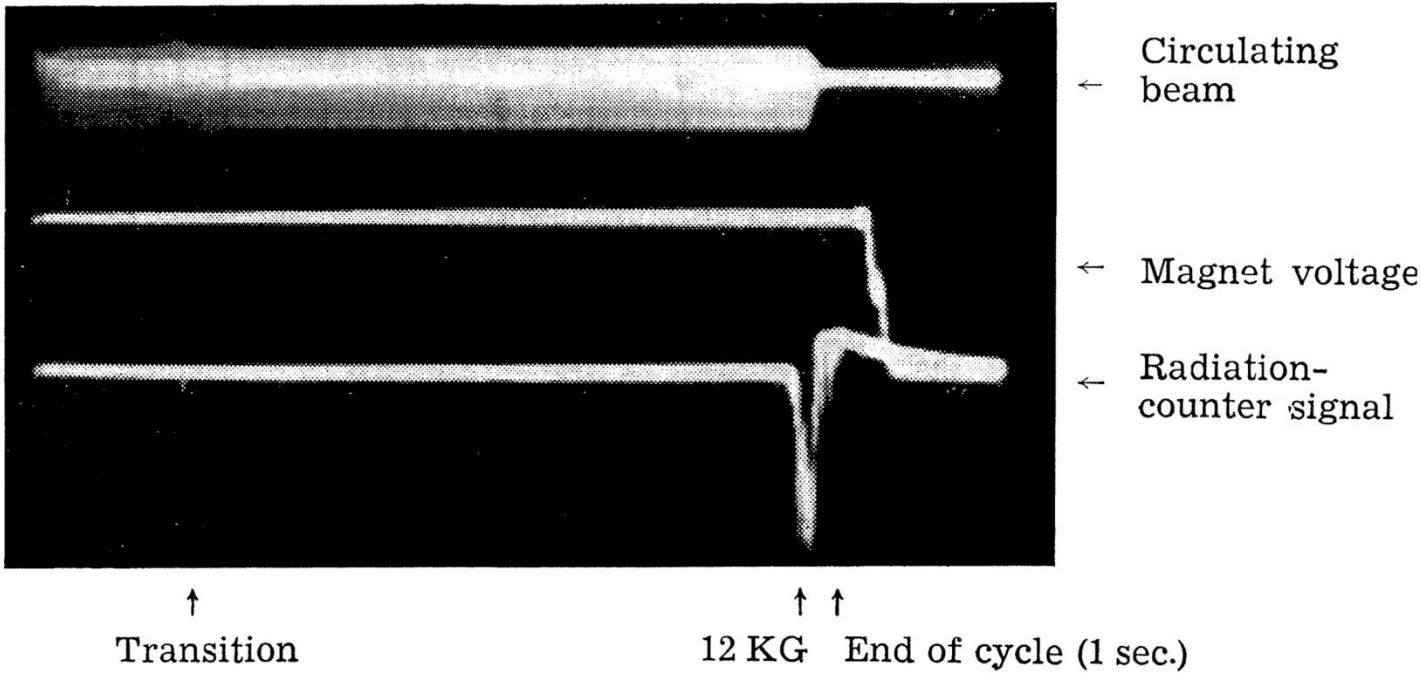
Before alignment





After alignment

The first accelerated beam to top energy: 24/11/59



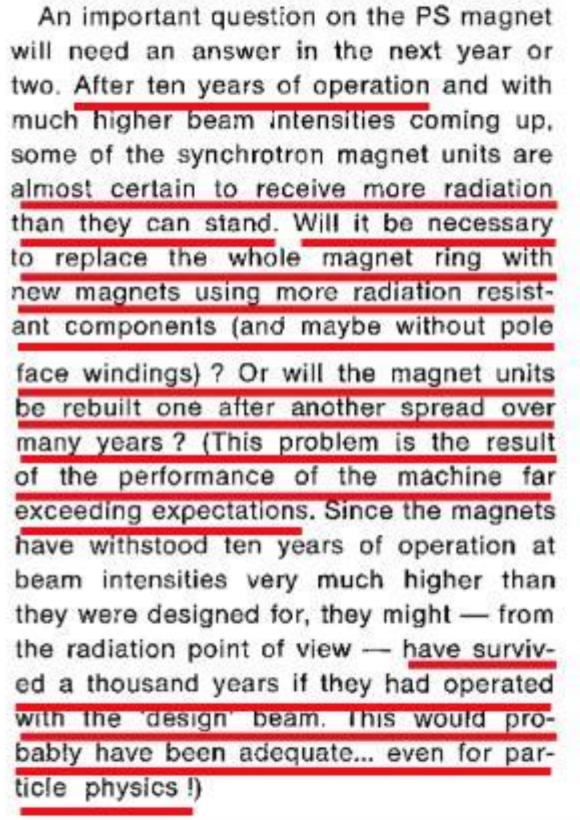
After 10 years

Open questions:

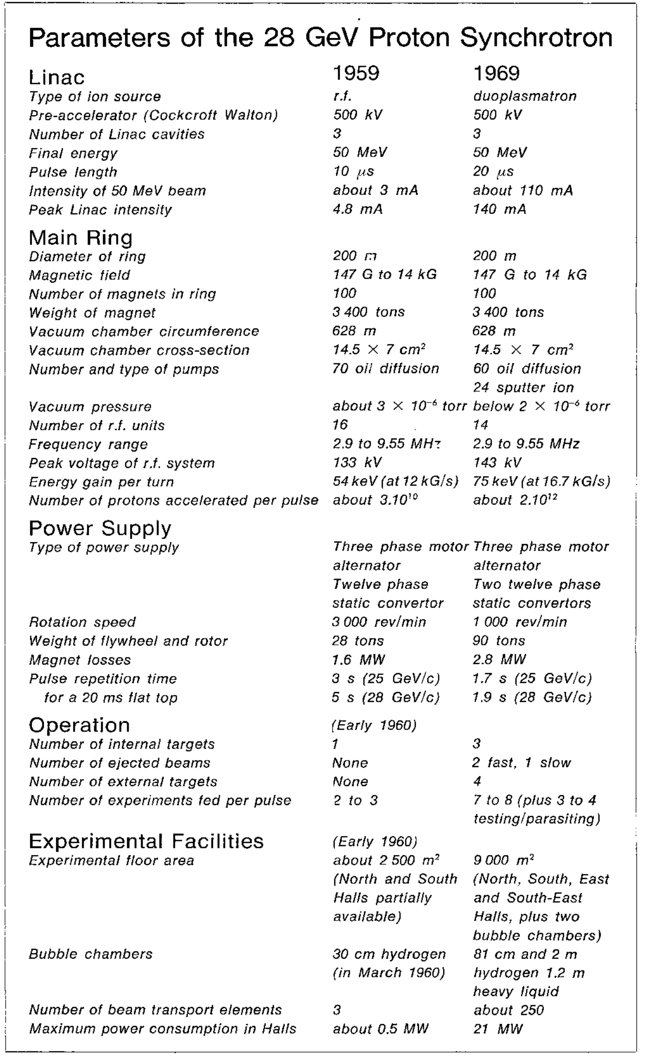
- How to preserve the machine from radiation damage while operating well beyond design parameters?
- Are pole face windings the future to control the working point?

CERN Courrier, n.11, Vol.9, 1969

10th PS anniversary



An important question on the PS magnet will need an answer in the next year or two. After ten years of operation and with much higher beam intensities coming up, some of the synchrotron magnet units are almost certain to receive more radiation than they can stand. Will it be necessary to replace the whole magnet ring with new magnets using more radiation resistant components (and maybe without pole face windings) ? Or will the magnet units be rebuilt one after another spread over many years ? (This problem is the result of the performance of the machine far exceeding expectations. Since the magnets have withstood ten years of operation at beam intensities very much higher than they were designed for, they might — from the radiation point of view — have survived a thousand years if they had operated with the 'design' beam. This would probably have been adequate... even for particle physics !)



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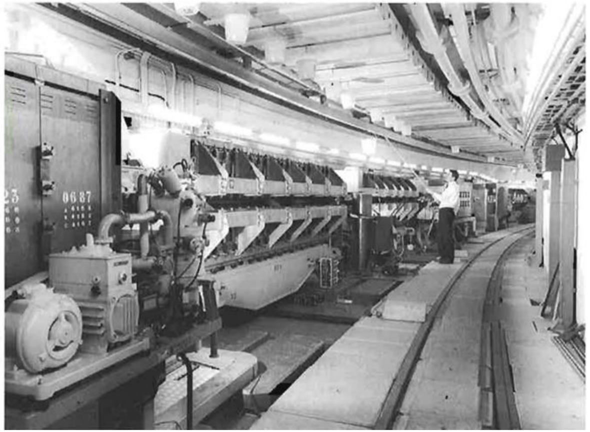
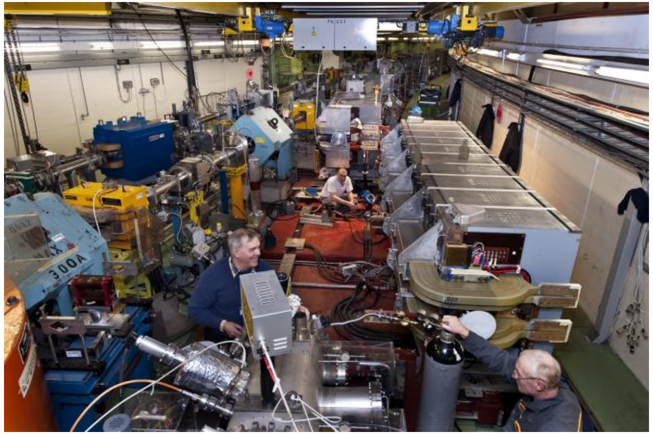
Magnet renovations

1960’s



2005-09 : First renovation campaign



2019 : Second renovation campaign

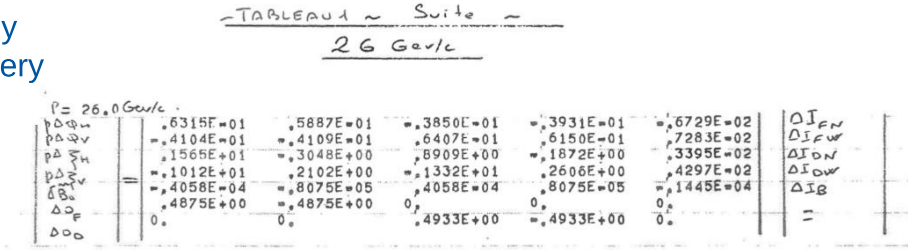
Few magnets changed during the years, **but only 1 failed during a run (July 2008)**

Pole-face windings (and Figure-of-eight loop)

Working point controlled (at first for saturation compensation) by auxiliary windings since the early days, and it will be still for a very long time.

Both for windings (and F8L) and power converters:

- First renovation in 1978
- Continuous improvement 1978 – 1981
- Second big campaign started in 2006 still ongoing



–TABLEAU 1 ~ Suite ~

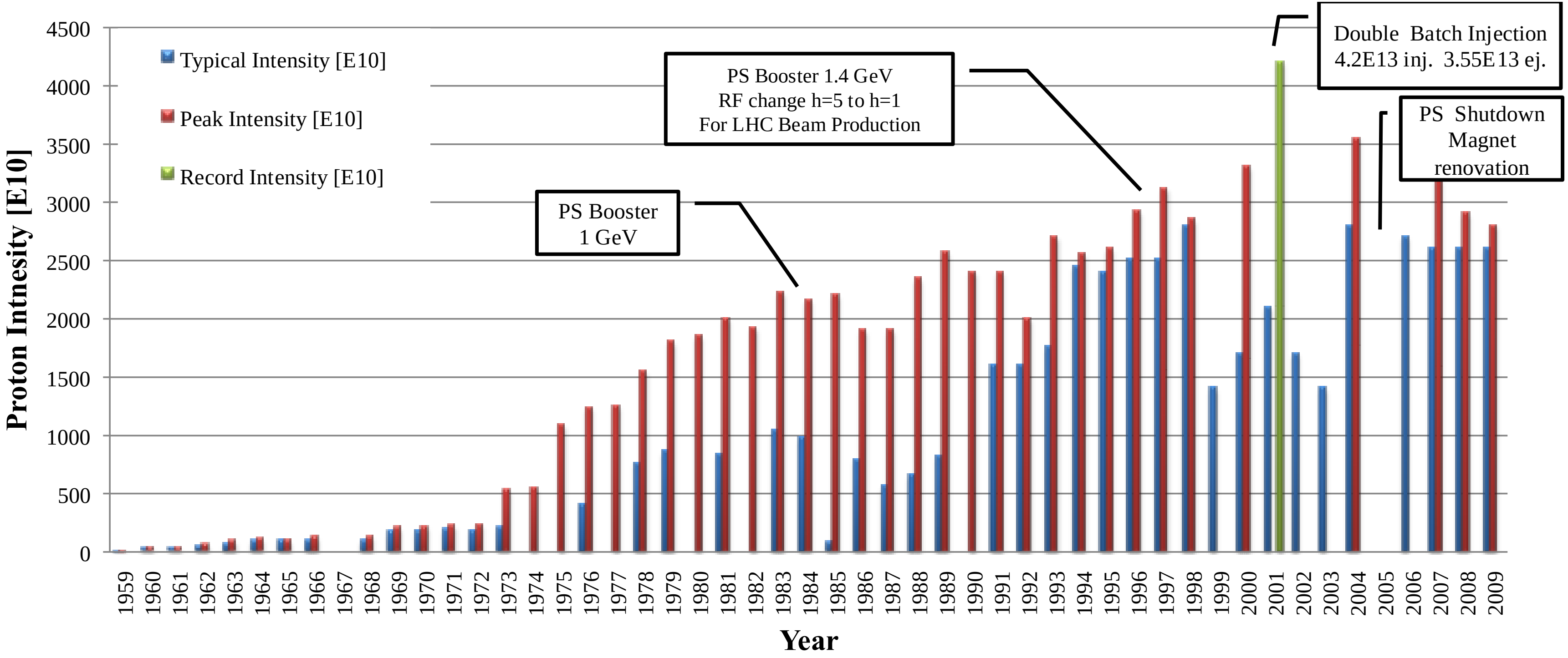
2 6 GeV/c

P= 26.0 GeV/c .

$$\begin{vmatrix} p\Delta\Phi_H \\ p\Delta\Phi_V \\ p\Delta\xi_H \\ p\Delta\xi_V \\ \delta\tilde{B}_0 \\ \Delta Q_F \\ \Delta Q_D \end{vmatrix} = \begin{vmatrix} .6315E-01 & .5887E-01 & -.3850E-01 & -.3931E-01 & -.6729E-02 \\ -.4104E-01 & -.4109E-01 & .6407E-01 & .6150E-01 & .7283E-02 \\ .1565E+01 & -.3048E+00 & .8909E+00 & -.1872E+00 & .3395E-02 \\ -.1012E+01 & .2102E+00 & -.1332E+01 & .2606E+00 & .4297E-02 \\ -.4058E-04 & -.8075E-05 & .4058E-04 & .8075E-05 & -.1445E-04 \\ .4875E+00 & -.4875E+00 & 0. & 0. & 0. \\ 0. & 0. & .4933E+00 & -.4933E+00 & 0. \end{vmatrix} \begin{vmatrix} \Delta I_{FN} \\ \Delta I_{FW} \\ \Delta I_{DN} \\ \Delta I_{DW} \\ \Delta I_B \\ = \end{vmatrix}$$

Combined degradation of organic material with high irradiation and **poor resistance against microbes**

Pushing the intensity, and brightness



PS Booster
1 GeV

PS Booster 1.4 GeV
RF change h=5 to h=1
For LHC Beam Production

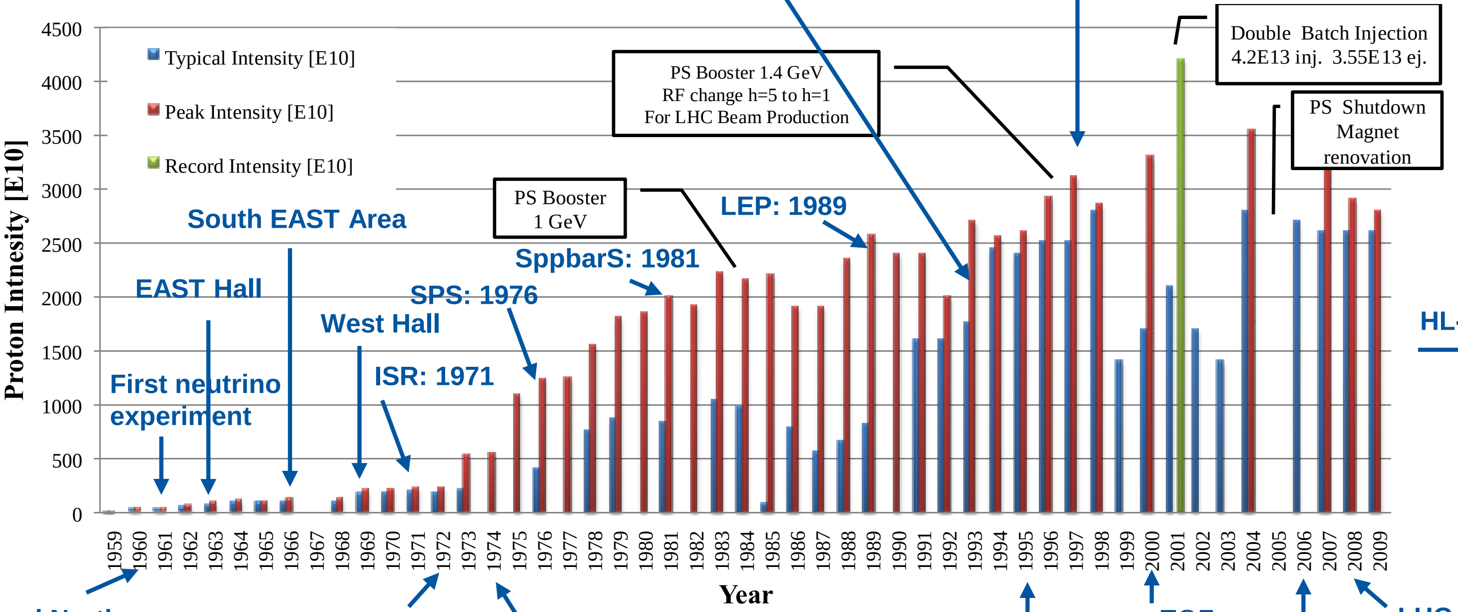
Double Batch Injection
4.2E13 inj. 3.55E13 ej.

PS Shutdown
Magnet
renovation

The first PS improvement program (the ’70s)

- Shortening the magnet cycle : stronger main magnet power supply
- High-power acceleration system
- Linac 2, 50 MeV in operation in 1978
- Improving limitation due to space-charge tune-shift at injection:
  PS injection energy increased to 800 MeV : the ‘Booster’ injector
- Improving the transition crossing by a rapid change of the beam focusing (‘transition jump’ by a set of pulsed quadrupole lenses)
- Improvement of the machine vacuum
- A general drastic reduction of beam losses during acceleration and the removal of delicate electronics from the tunnel.

Pushing the intensity, and brightness



Space-charge for LHC: 1993

Start of LHC beam preparation:
space charge, headtail, longitudinal gymnastics, electron clouds

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RF change h=5 to h=1
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renovation

PS Booster
1 GeV

LEP: 1989

South EAST Area

SppbarS: 1981

EAST Hall

SPS: 1976

West Hall

HL-LHC, LIU

ISR: 1971

First neutrino experiment

South and North halls

Headtail instabilities: 1972
PSB @ 800 MeV

Gamma Jump: 1974

Headtail instabilities: 1995

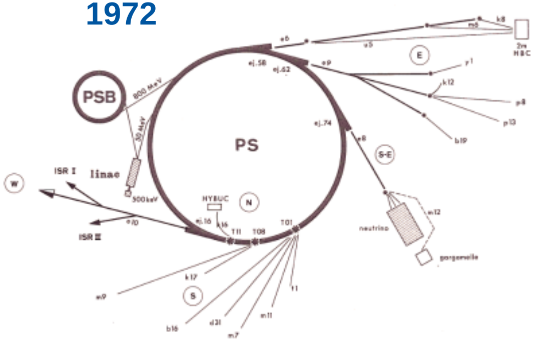
n_TOF

CNGS: 2006

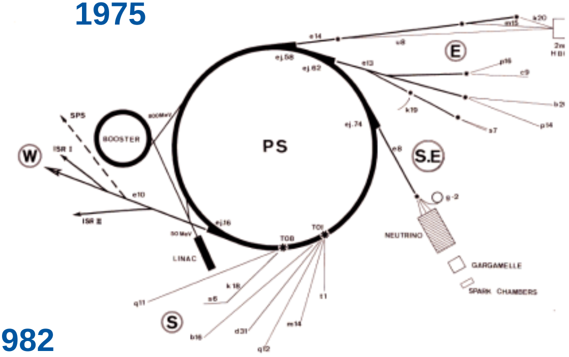
LHC: 2008

More and more users

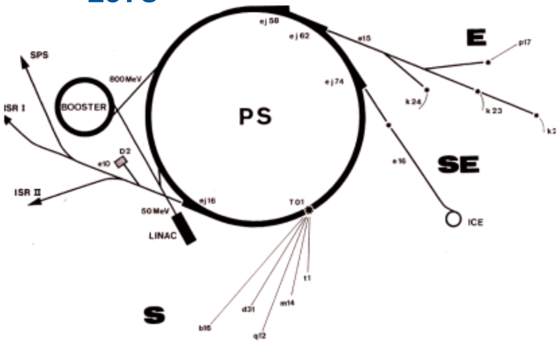
1972



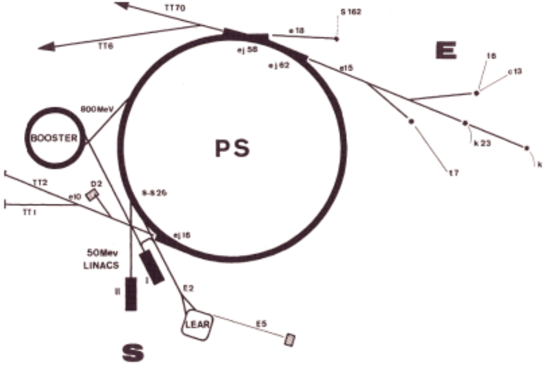
1975



1978



1982



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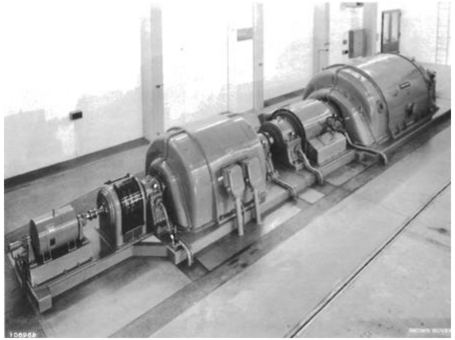
Powering the PS

First Service : 1968
Dismissed after > 200 10^6 cycles

POPS : 2011

First power supply into operation in 1959 changed after nine years.

First issue after
→ 40 924 500 pulses.



- Higher repetition rate
- “Flat tops”

- Potentially higher repetition rate
- Improved B field stability

The first PS improvement program (the ’70s)

- Shortening the magnet cycle : stronger main magnet power supply
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- **Improving limitation due to space-charge (Laslett) tune-shift at injection: PS injection energy increased to 800 MeV : the ‘Booster’ injector**
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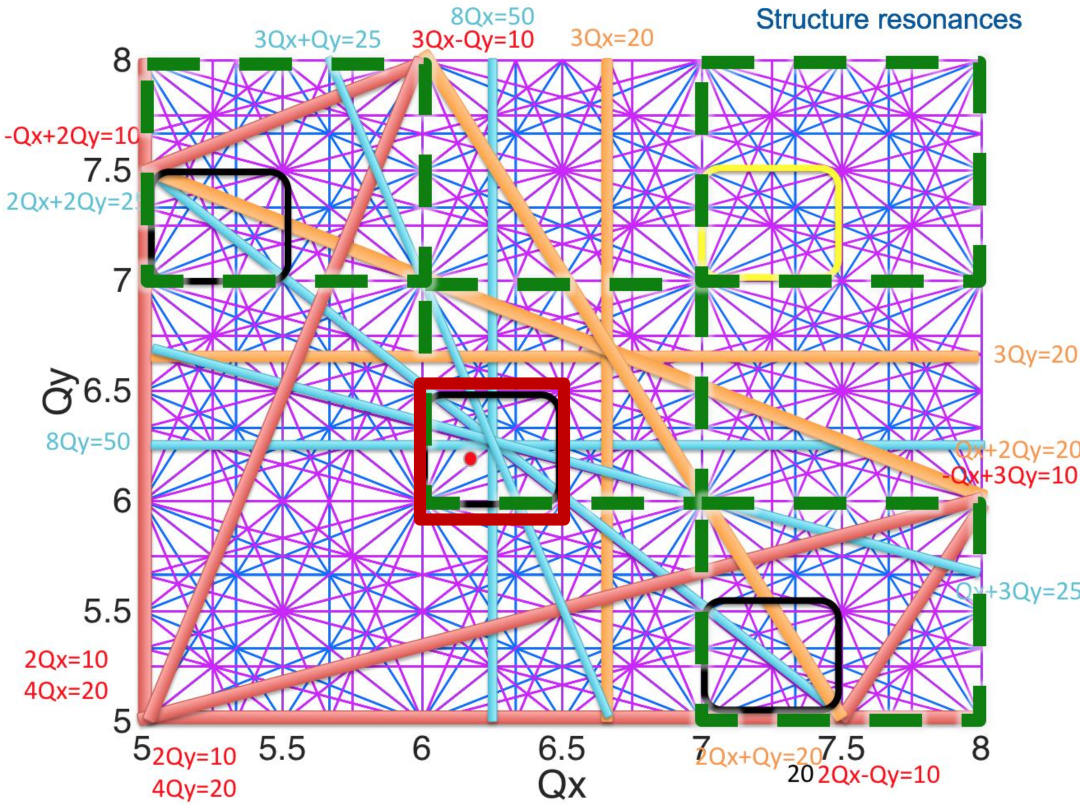
A forest of resonances

- Choice of the best working point for PS operation is a story as old as the PS

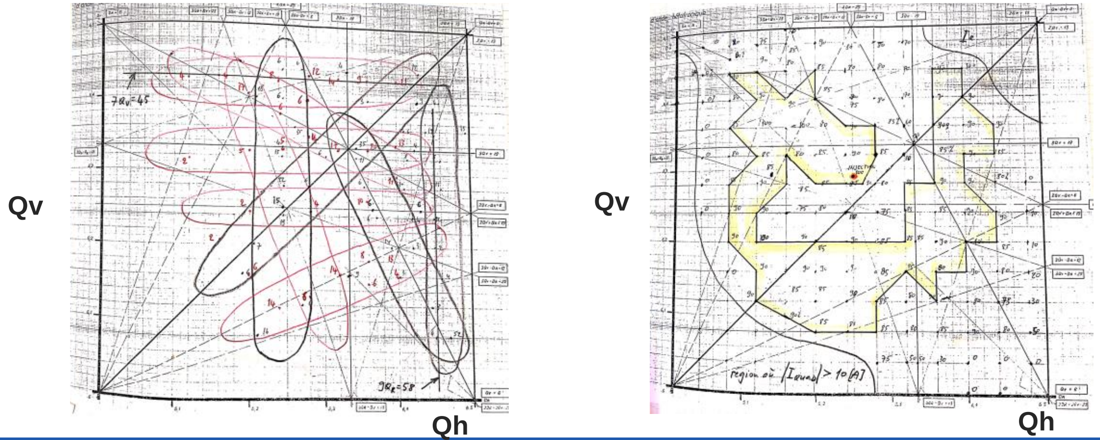
- PS integer chosen as (6,6) far away from main structure resonances



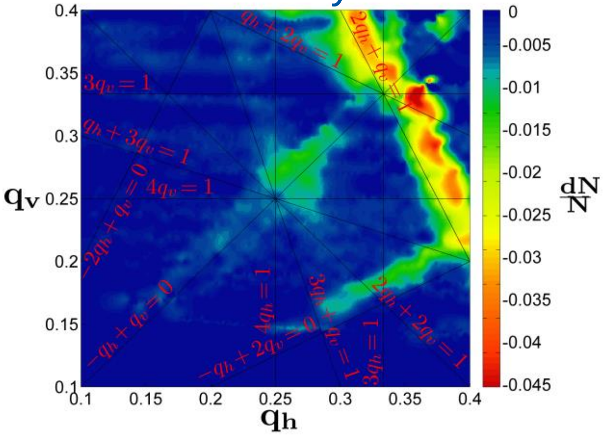
Which resonances are the worst ?

- Losses at low energy measured during tune scan typically with low energy quadrupoles to determine best operational working point
- Best working point to be found to avoid losses for high intensity operation and transverse emittance blow-up, in particular while preparing the PS to serve the LHC
- Some resonances could be compensated by dedicated auxiliary magnets

From MD Logbook, late '80

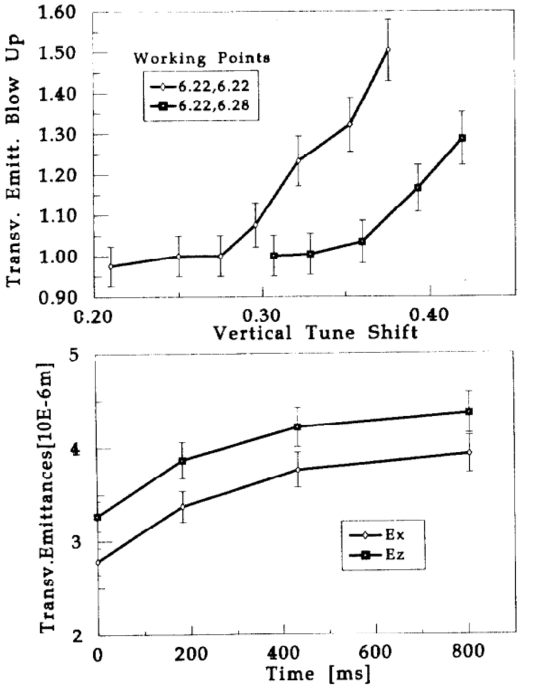


Today



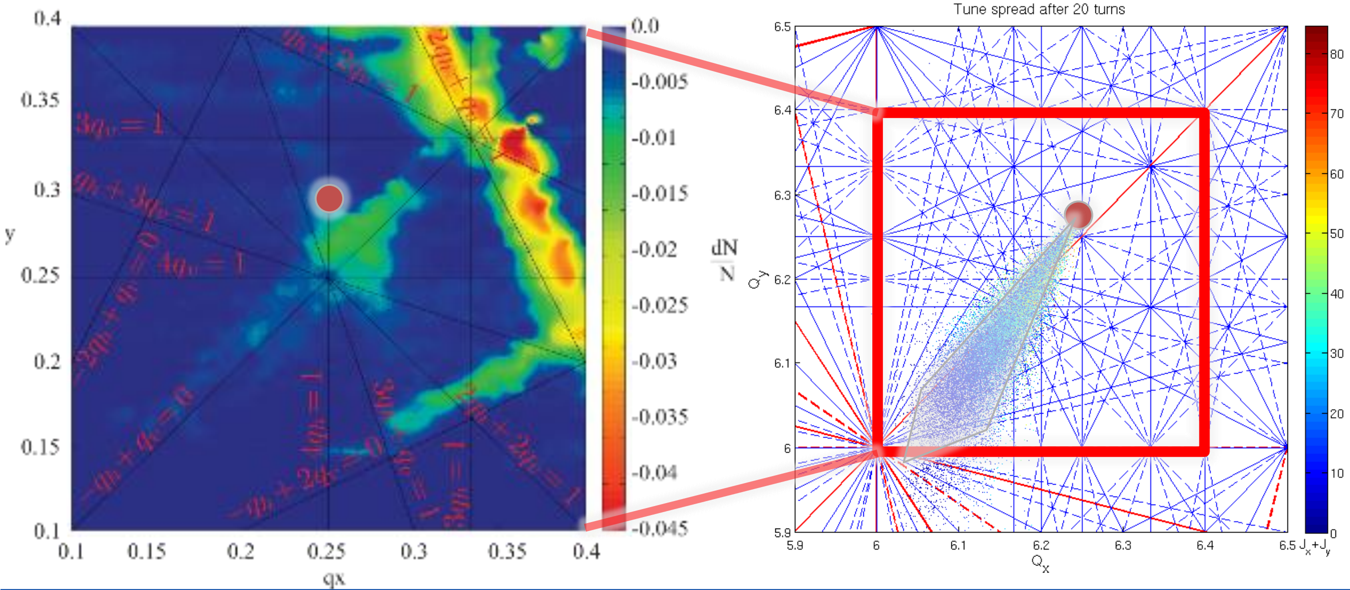
Direct space charge limit and resonances

R. Cappi et al., 1993



Max. Laslett Tune-spread

$$\Delta Q_{x,y} = \frac{r_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z}\oint \frac{\beta_{x,y}(s)ds}{\sigma_{x,y}(s)[\sigma_x(s)+\sigma_y(s)]}$$



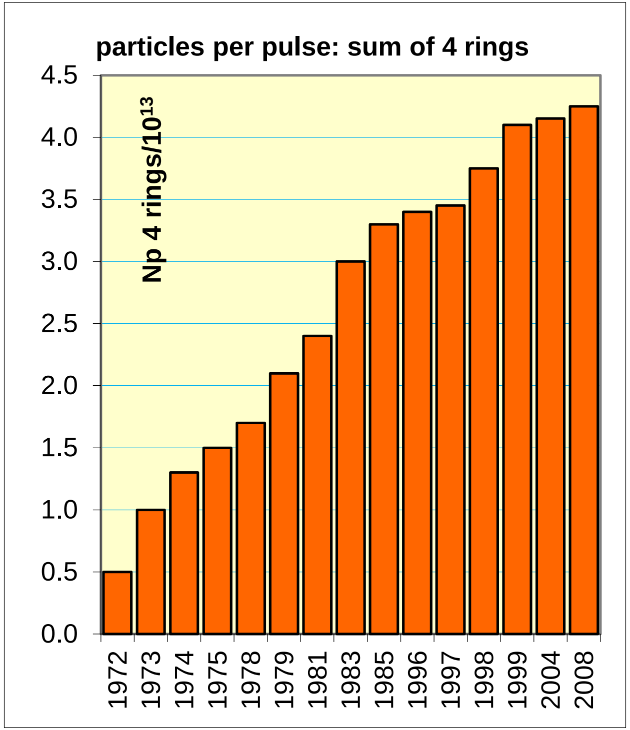
The PS long-term improvement program

Beating direct space-charge by increasing injection energy:

- Linac1 → Linac2 with PSB (50 MeV → 800 MeV, 1972)
- PSB at 1 GeV (1985)
- PSB at 1.4 GeV → PS as LHC injector (1998)
- PSB at 2 GeV → PS as HL-LHC injector Today*

*(see Klaus presentation)

PSB – an unbeatable companion



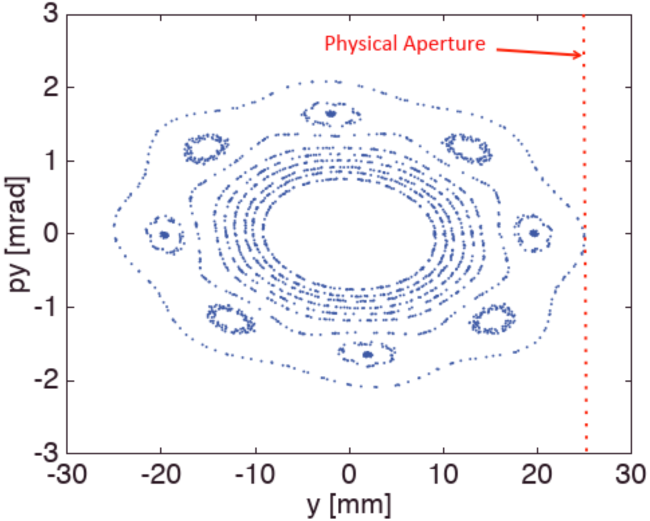
1972	**Running-in since May 1972. (Qx, Qy)~(4.8, 4.8).**
1973	Q-split by one integer: (Qx, Qy)~(4.2, 5.3) at injection, dynamic working point, first physics (neutral currents).
1974	Design intensity in PS: 1 10^{13} ppp.
1975	Feedback for longitudinal coupled modes between h=5 bunches.
1978	New Linac, Hereward damping of bunch shape oscillations.
1979	3rd order stopband compensation, enabling (Qx,Qy)~(4.25, 5.45).
1981	Increase of machine acceptance, transverse feedback system.
1983	2nd harmonic (h=10) cavities.
1985	Beam loading feedback, PSB=>1 GeV, Ring 2 champion.
1996	Preparation for ISOLDE.
1997	PS reaches >3E13.
1998	"Big Bang": PSB h=5 => h=1.
1999	PSB => 1.4 GeV; higher longitudinal acceptance with h=1, Linac2 => 180 mA, Ring 2 champion.
2004	Change of working point to (Qx, Qy)=(4.17,4.23). All rings equal.
2008	Better orbit correction increased acceptances.

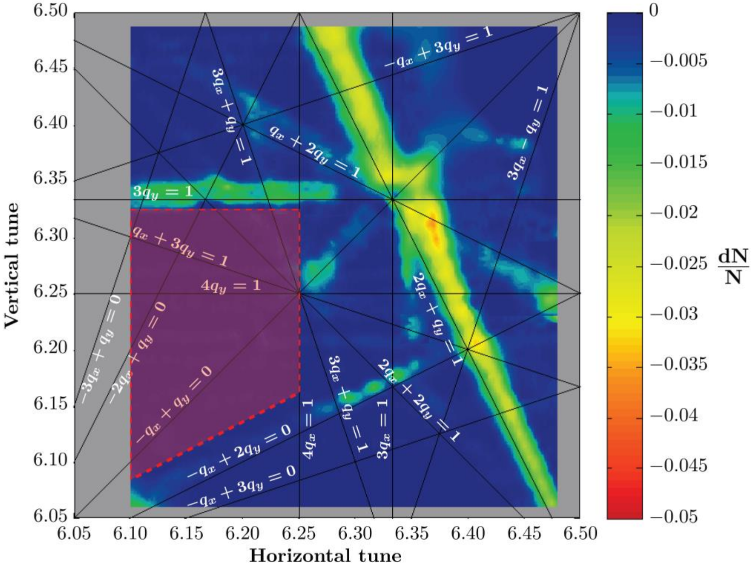
Latest result (2017): 8th order resonance excited by space-charge

Losses observed close to Qv=6.25 → structure resonance excited by space-charge
Loss mechanism from 8 Qv = 50 with *Qv=6.25*

Changing the working point integer, chosen more than 60 years ago, might help

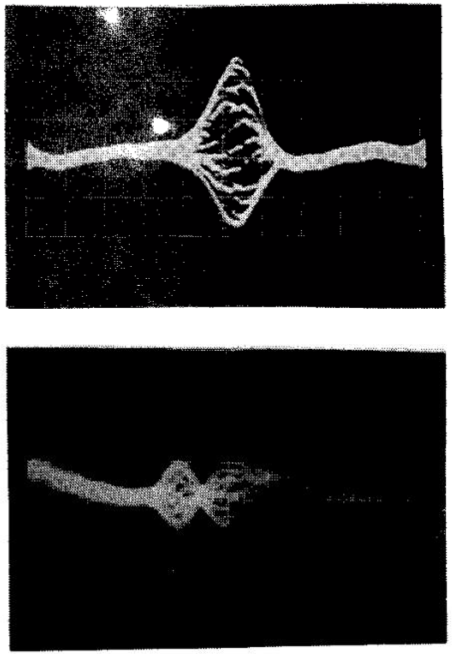
Simulations





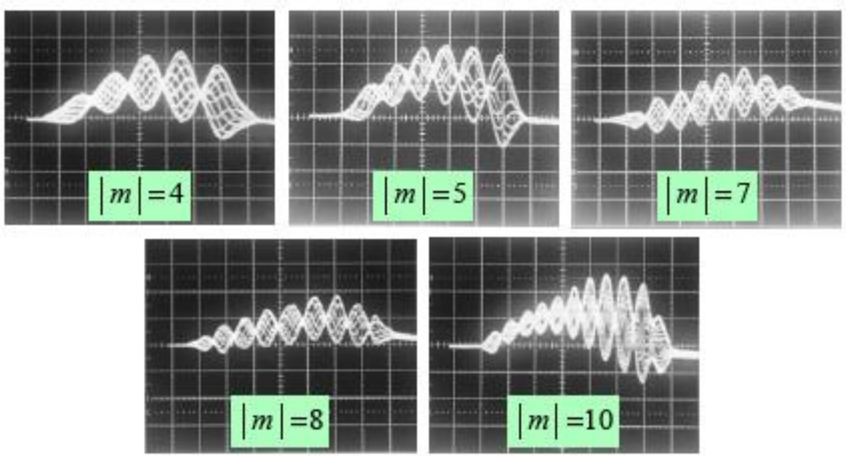
Headtail: injection single bunch instabilities

Headtail: 1978



Headtail instabilities limiting the PS intensity in the 1970 at 10^{12}

Then brightness limit for PS in the LHC era cure by:
- Linear coupling
- Transverse damper and chromaticity control



The first PS improvement program (the ’70s)

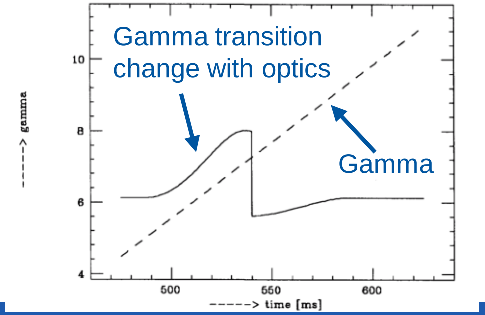
- Shortening the magnet cycle : stronger main magnet power supply
- High-power acceleration system
- Linac 2, 50 MeV in operation in 1978
- Improving limitation due to space-charge tune-shift at injection:
  PS injection energy increased to 800 MeV : the ‘Booster’ injector
- **Improving the transition crossing by a rapid change of the beam focusing (‘transition jump’ by a set of pulsed quadrupole lenses)**
- Improvement of the machine vacuum
- A general drastic reduction of beam losses during acceleration and the removal of delicate electronics from the tunnel.

Transition and instabilities

Losses at transition crossing
limiting maximum single bunch intensity from:

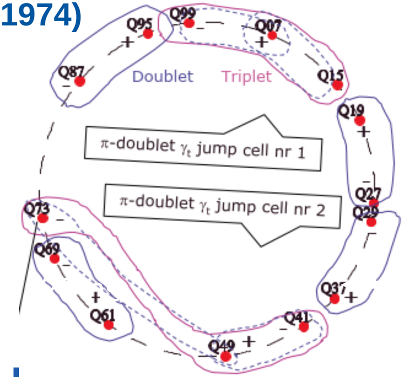
- Non-adiabatic and non-linear synchrotron motion
- Head–Tail instability : cured by octupoles and then by chromaticity sign change
- Negative mass and microwave instabilities
- Space-charge

Change dynamically the transverse optics to cross as fast as possible transition energy: Q-jump, later **Gamma Jump (1974)**



Gamma transition change with optics

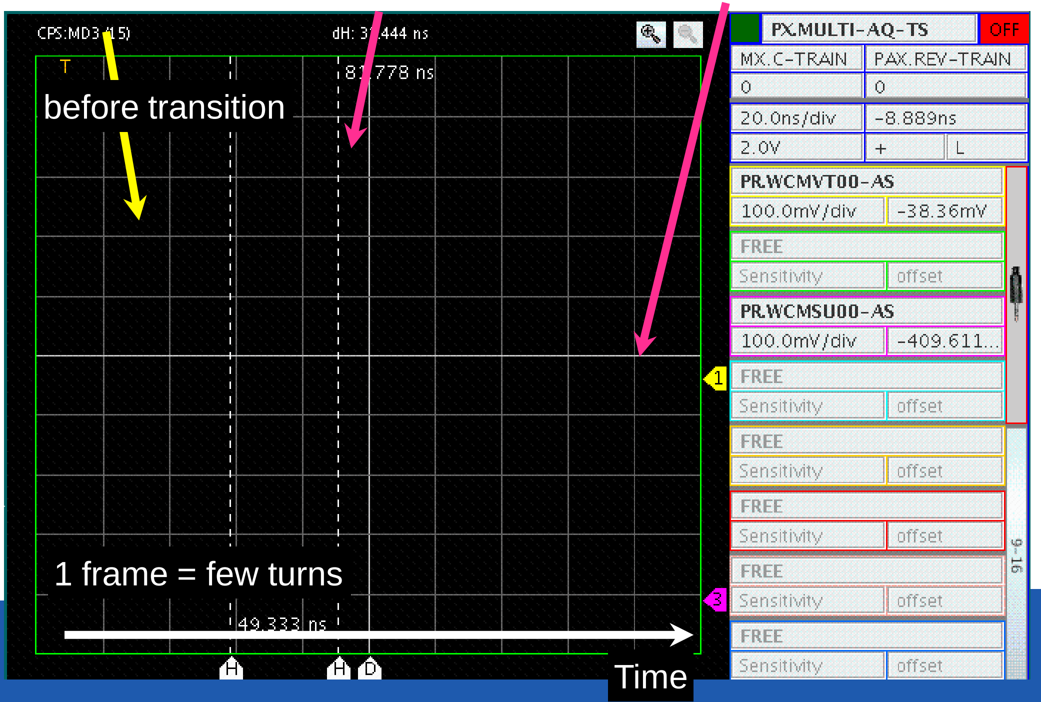
Gamma



Vertical position of the beam within a bunch

Bunch intensity

Beam losses
A fraction of the beam touched the vertical aperture

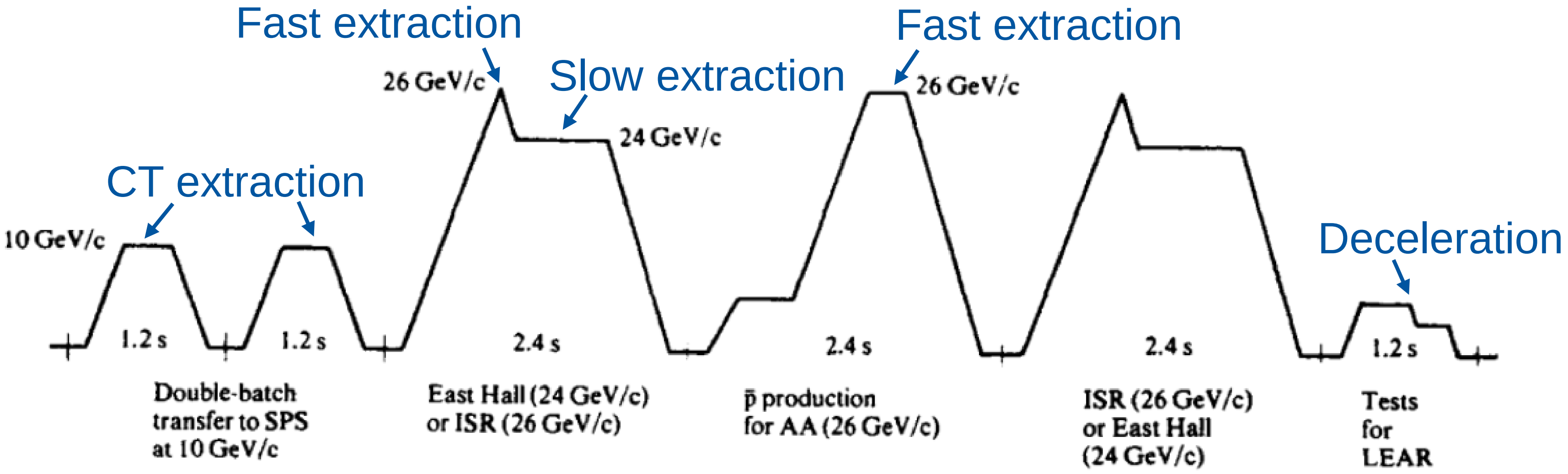


before transition

1 frame = few turns

Time

A versatile machine: the Supercycle


Fast extraction

Slow extraction

Fast extraction

CT extraction

Deceleration

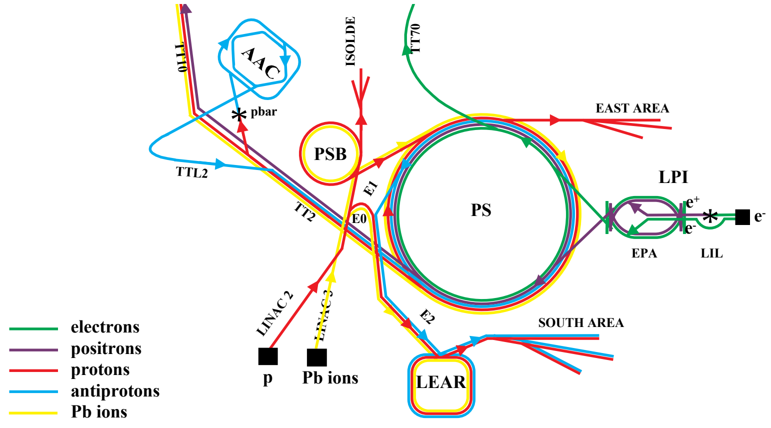
First machine capable of executing **a different cycle (user) every 1.2 s** with **different destination, extraction energy** and **extraction type**, and **different particles**, and even **two different extractions in the same cycle**.

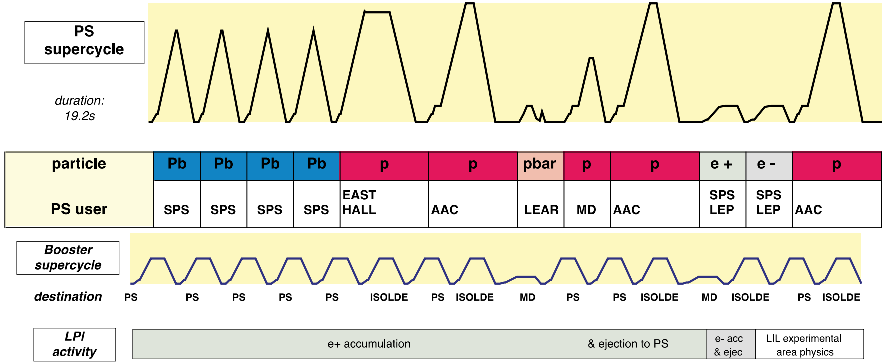
The 90's: the CERN hub

Different particle and antiparticle species <u>accelerated and decelerated</u> in the PS to serve all CERN users

Beam Label	User	Particle	Inj./ej momentum [GeV/c]	Inten-sity [ppp]	RF harm. Nr	No of bunches	ε_x , ε_y [µm] (1)	$\varepsilon_{//}$ [eVs]	Bunch length [ns]	Inj./ej. straight section	Peculiarities
SFT	SPS	p^+	1.69 / 14	2.5 10^{13}	20, 420	420x5	11 / 7	0.1	5	42 / 16	Highest intensity beam, 5 turn extraction
SPP	SPS-LEP	e^+	0.5 / 3.5	2 10^{11}	8 + 240	8	0.05 / 0.01$^{(2)}$	0.01	4	92 / 16	Robinson wiggler to change J_e & J_x
SPN	SPS-LEP	e^-	0.5 / 3.5	2 10^{11}	8 + 240	8	0.05 / 0.01$^{(2)}$	0.01	4	74 / 58	Robinson wiggler to change J_e & J_x
AA	AAC p^- production	p^+	1.69 / 26	1.6 10^{13}	10, 12, ..., 20	5	13 / 9	2	20	42 / 16	Transverse funneling, longitudinal merging and batch compression
TSTAAC	AAC p^- transfer simul.	p^+	1.69 / 3.5	2 10^{10}	20, 6	1	4 / 1.5	0.5	70	42 / 16	Test beam for steering adjustments of AA-PS transfer line
LEAR	LEAR p^- physics	p^-	3.5 / 0.6	10^{10}	10	1	2 / 2	0.2	160	16 / 26	Deceleration on a digital frequency program
PHYSE	East Hall	p^+	1.69 / 24	3 10^{11}	20	N/A	3 / 5	0.2	N/A	42 / 61	Slow extraction (400ms)
SFTION	SPS	Pb^{53+}	0.43 / 5.1$^{(3)}$	2 10^{8}	20	20	1.7 / 1.6	0.04 (4)	11	42 / 16	Stripped to 82+ in the transfer line to SPS
PHYFE	East Hall	p^+	1.69 / 3.5	10^{9}	20	1-5	2.0/1.5	0.5	30	42 / 61	Low but precise intensity

(1) $\varepsilon_{x,y} = \beta\gamma\,\sigma^2 / \beta_{x,y}$ (2) non normalized (3) [GeV/c/u] (4) [eVs/u]



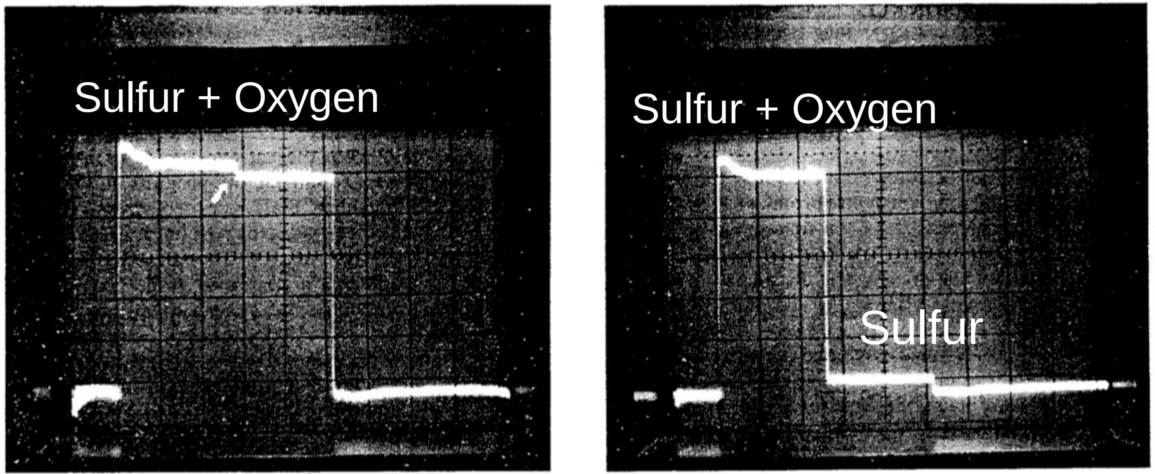


particle	Pb	Pb	Pb	Pb	p	p	pbar	p	p	e +	e -	p
PS user	SPS	SPS	SPS	SPS	EAST HALL	AAC	LEAR	MD	AAC	SPS LEP	SPS LEP	AAC

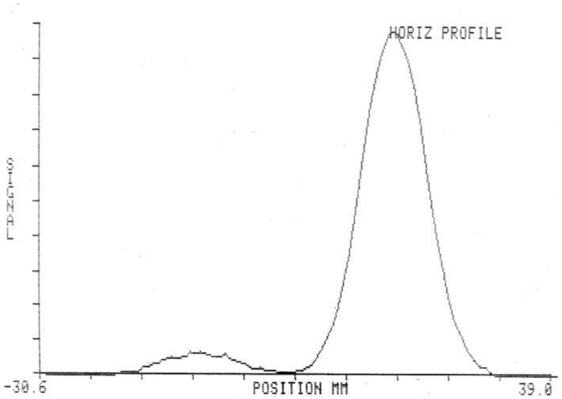
D. Simon,1995

Even two species in the same cycle

Separating Sulphur ions from oxygen at transition



Transverse profile of
oxygen and sulfur beams



Today: PS extracting Pb^{54+} at 1.22 TeV (total energy)

The PS accelerated a large variety of ions: D, He, S, O, In, Xe, Ne, ...

As injectors for many colliders

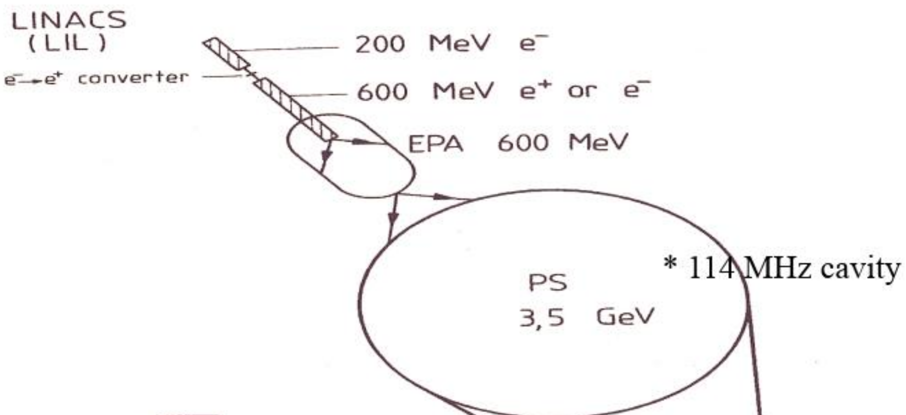
- ISR (p-p): proof of principle for future colliders

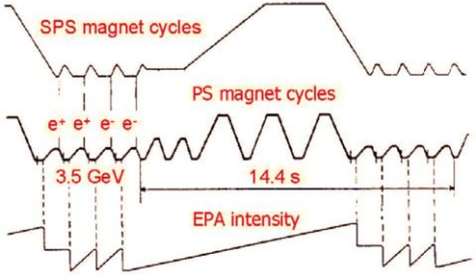
- p-pbar in the SPS

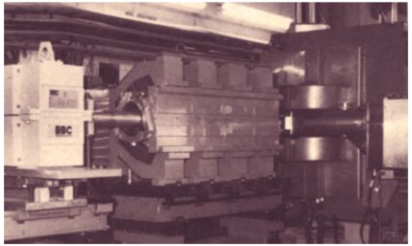
- LEP (e^+- e^-): the largest lepton synchrotron

- LHC (p-p, Pb-Pb, Pb-p, Xe-Xe)

As LEP injector



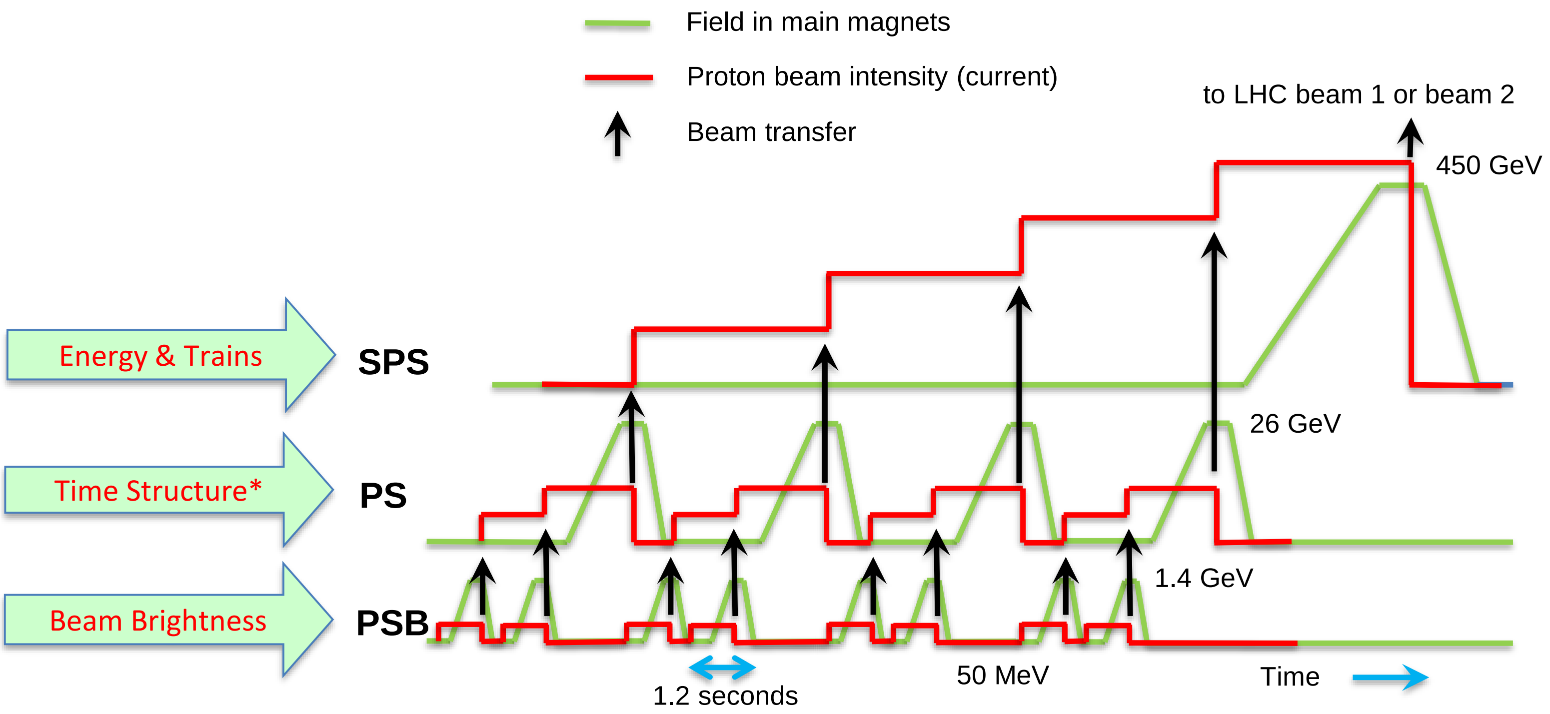




- Completely new twin injections from EPA
- Full vacuum chamber renovation to cope with vacuum requirement and synchrotron radiation
- Extraction to SPS at 3.5 GeV in common with p and pbar
- 114 MHz dedicated to leptons
- Robison wigglers

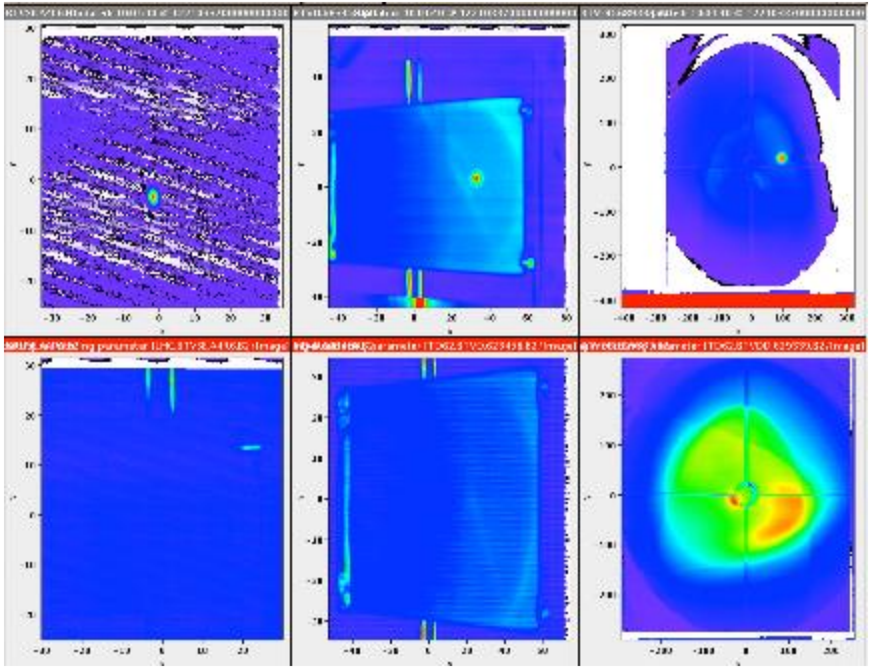
- Beams ready by 1987

The PS in the LHC era

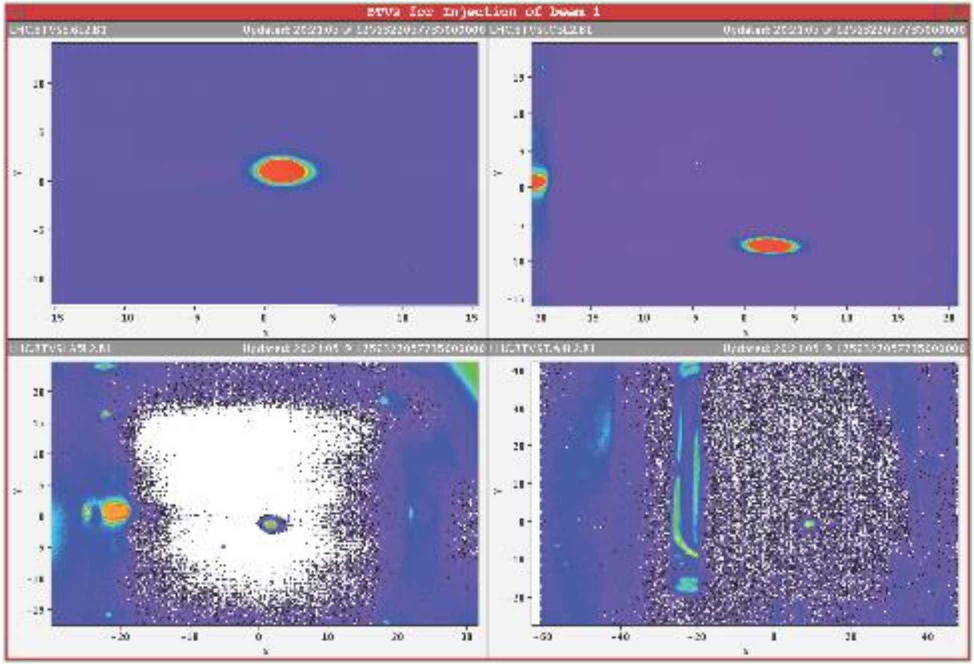


First protons and ions (Pb^{82+}) to the LHC

10 September 2008, first protons to LHC

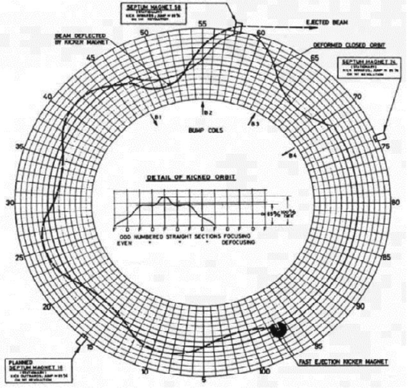


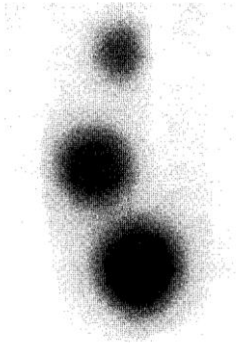
2010, Pb^{82+} to LHC



Fast Extraction

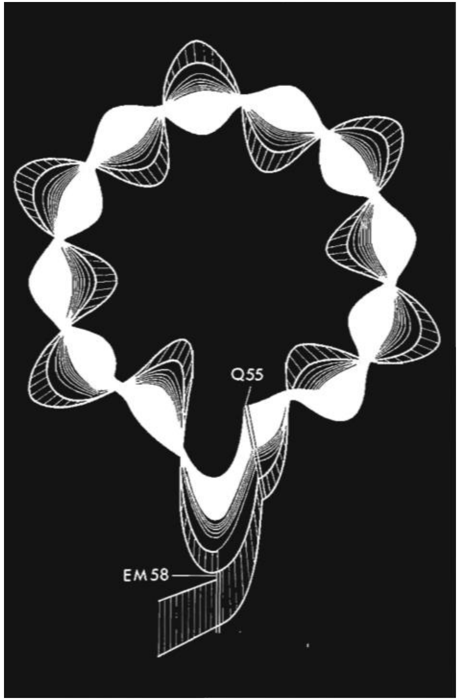
12 May 1963 : First 25 GeV fast extracted beam (in air)



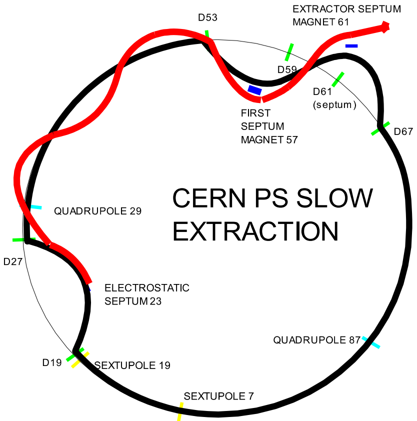


Slow Extraction

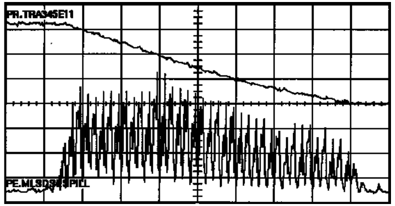
1965: integer resonant extraction

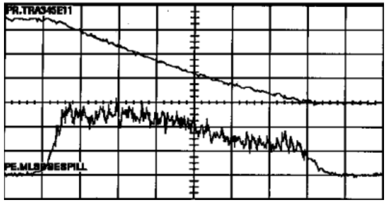


3rd order slow extraction serving the EAST area, 1992.
Preceded by ‘Squared extraction”



Spill noise reduction with air quadrupoles powered by an audio-frequency amplifier





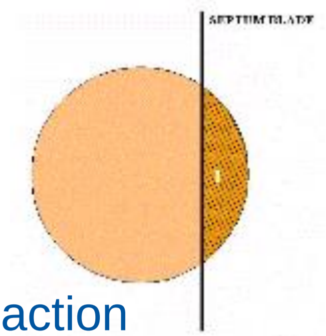
Some 10^{10} protons extracted over 400 - 500 ms

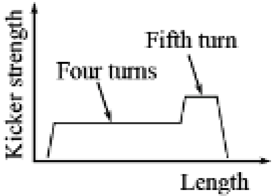
Not necessary anymore thanks to new PFW and auxiliary magnets power converters

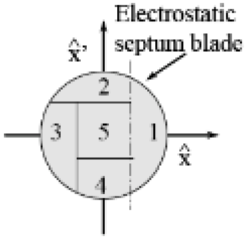
Filling the SPS: CT-extraction

Filling the maximum of the SPS (10/11 of the SPS circumference)
in the minimum amount of PS cycles ($C_{sps}=11C_{PS}$)

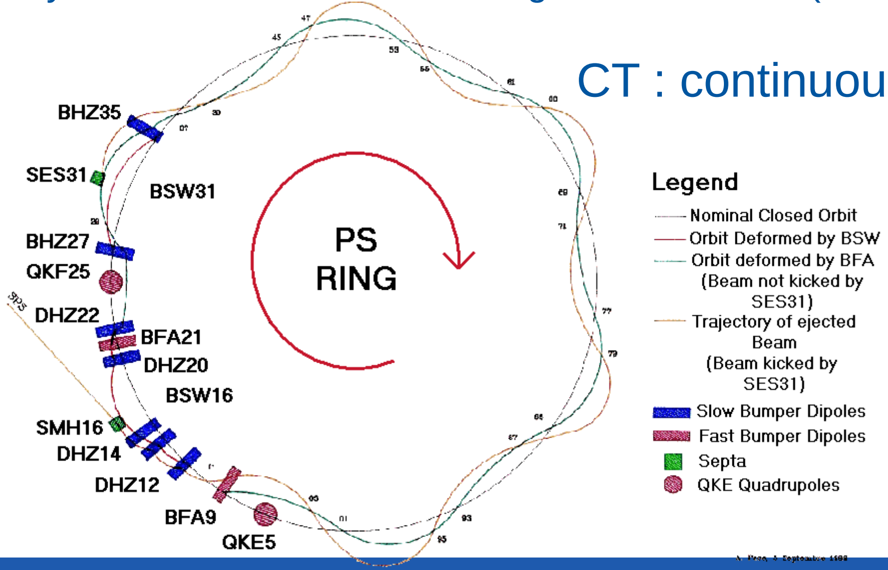
- By a single 10-turns long extraction (1973, 10 GeV/c)
- By two consecutive 5-turns long PS extractions (14 GeV/c)

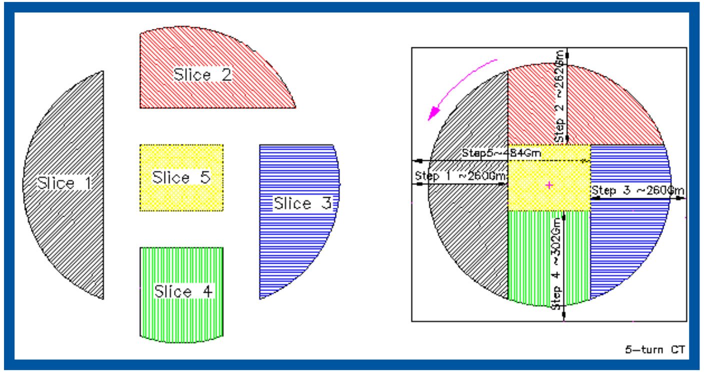






CT : continuous transfer extraction





Filling the SPS: CT-extraction

1973 : 10-turns

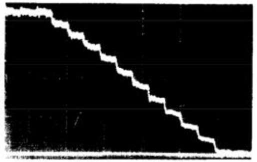


FIG. 4 a)
FALLING INTENSITY OF CPS BEAM OVER 11 TRUNS (5μs/cm; RF STRUCTURE FILTERED OUT)

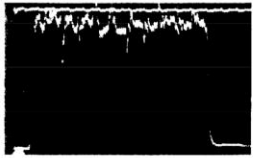


FIG. 4 b)
TYPICAL EJECTED BEAM INTENSITY (5μs/cm; RF STRUCTURE FILTERED OUT)

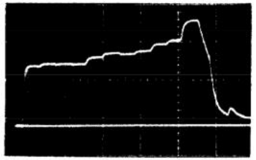


FIG. 4 c)
TYPICAL CURRENT OF FAST BUMPERS (5μs/cm)

1979 : 5-turns

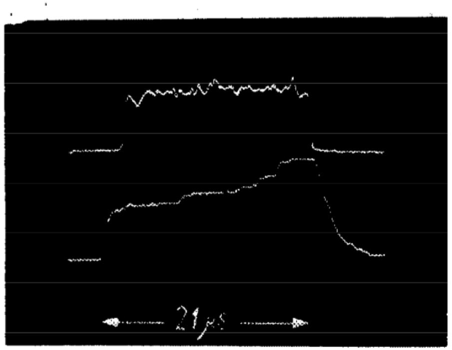
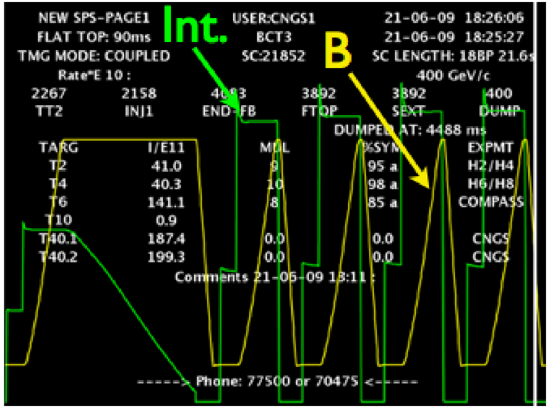


Fig. 3

a) Ejected beam (optimized) signal from beam current transformer.

b) Fast bump current signal.

2006 : start of CNGS run



```
NEW SPS-PAGE1                USER:CNGS1          21-06-09  18:26:06
FLAT TOP: 90ms                BCT3               21-06-09  18:25:27
TMG MODE: COUPLED            SC:21852        SC LENGTH: 18BP 21.6
     Rate*E 10 :                                   400 GeV/c
 2267        2158        4[illegible]3       3892        3892        400
 TT2         INJ1        END-FB      FTOP        SEXT        DUMP
                                          DUMPED AT: 4488 ms
 TARG          I/E11           MDL           %SYM          EXPMT
 T2            41.0            9             95 a          H2/H4
 T4            40.3            10            98 a          H6/H8
 T6            141.1           8             85 a          COMPASS
 T10           0.9
 T40.1         187.4           0.0           0.0           CNGS
 T40.2         199.3           0.0           0.0           CNGS
              Comments 21-06-09 18:11 :

          -----> Phone: 77500 or 70475 <-----
```

During 1973, CT extraction total losses in the PS corresponding to initial machine maxium design intensity, because of low intensity extracted. With 2.5 10^{13} extracted, losses up to 10% of the circulating beam, two order of magnitude more than machine maximum design intensity.

The Multi-Turn Extraction

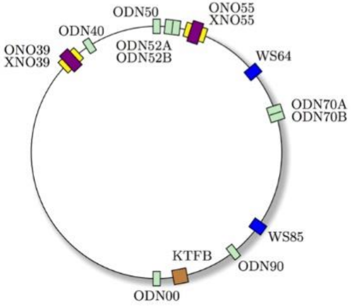
- Multi-Turn Extraction (MTE) put in operation in 2015 as replacement of the former Continuous Transfer (CT) extraction to serve SPS fixed-target physics programme
  - Significant **reduction of beam loss** at PS extraction and therefore reduced activation of ring elements
  - Indispensable step to allow production of future high-intensity beams
- MTE principle: resonant extraction process based on beam splitting in the horizontal phase space
  - **Non-linear elements** (sextupoles and octupoles) applied to excite fourth order resonance $4Q_x = 25$
  - Controlled **adiabatic crossing** of this resonance to **split the beam** into four islands and one core
  - Extraction of two consecutive **five-PS-turns long pulses** to uniformly fill the SPS circumference

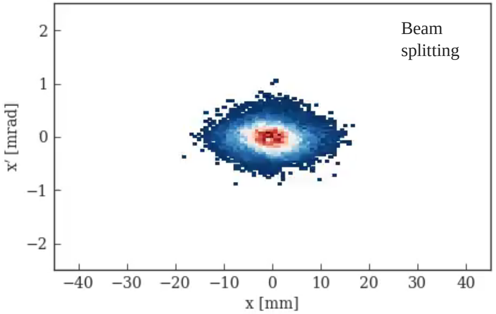
ONO**/XNO**: octupoles/sextupoles to control islands' geometry

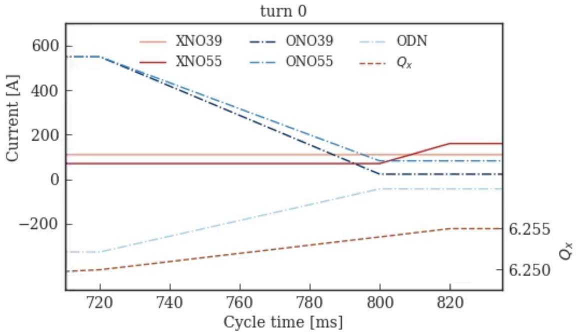
ODN**: octupoles to correct non-linear coupling between transverse planes

KTFB: kicker of the transverse feedback system for excitation during splitting

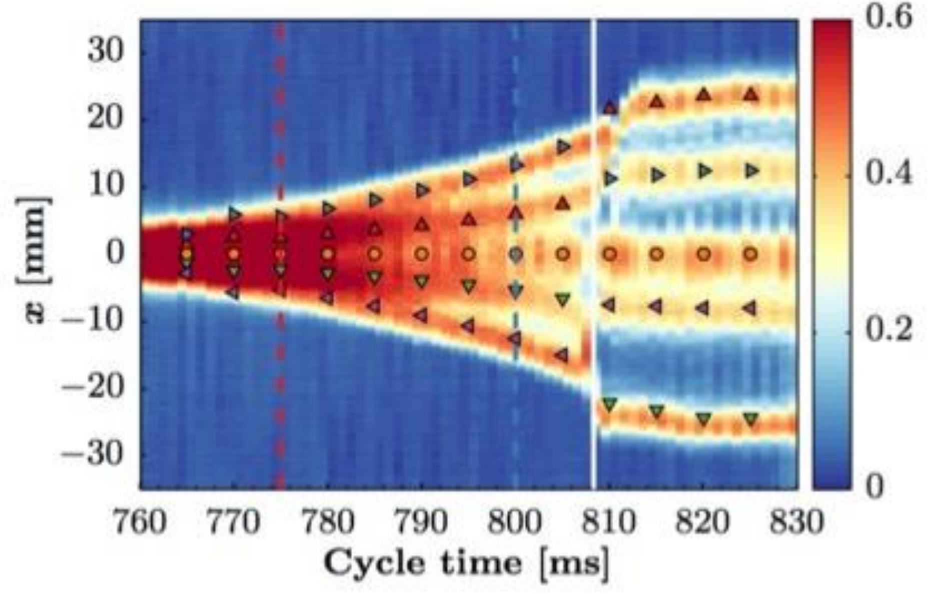
WS**: wire scanners

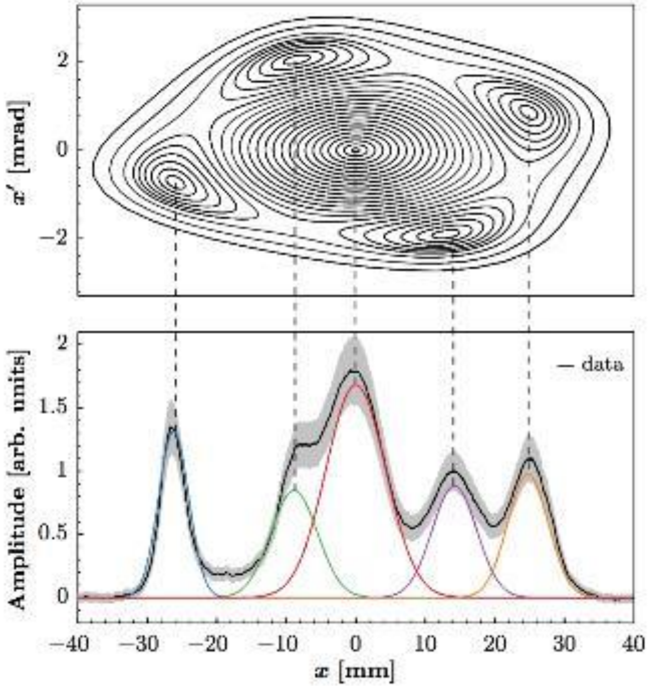






Filling the SPS: MTE-extraction

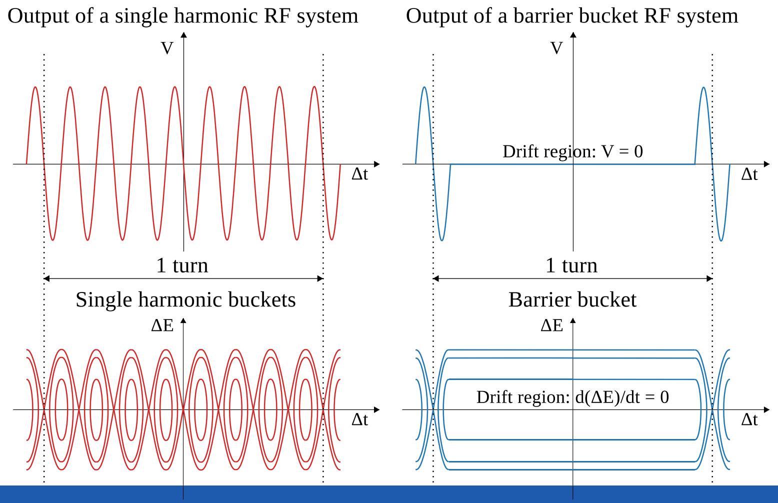


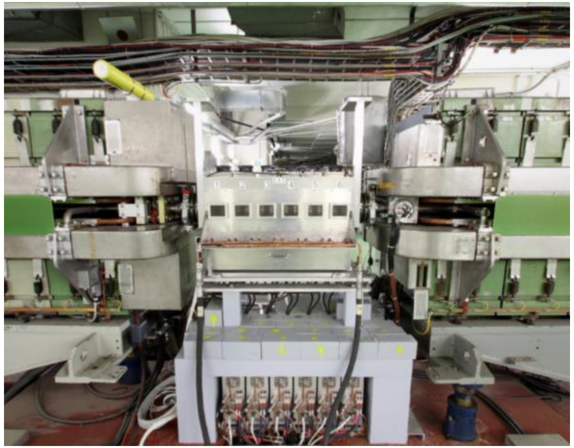


The newcomer: barrier bucket and MTE

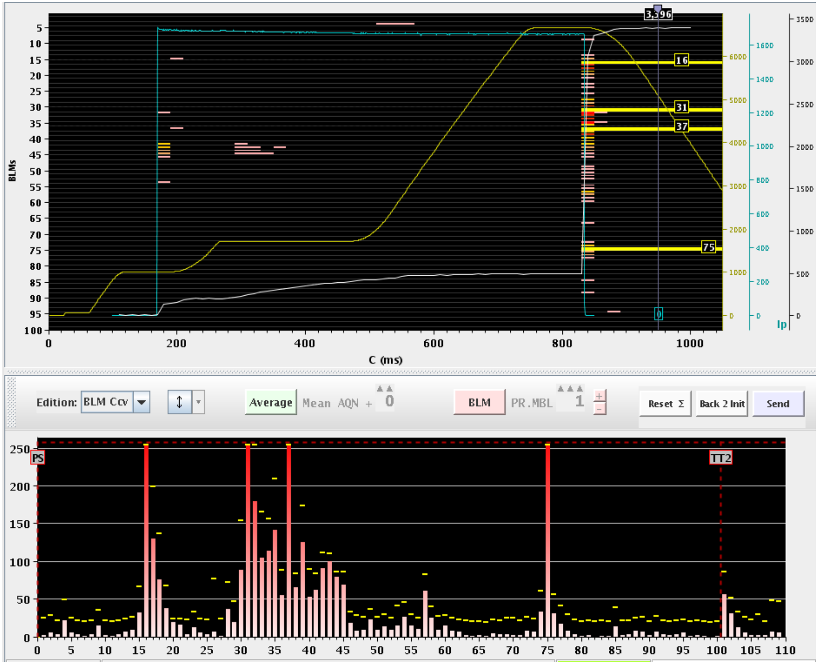
Barrier Bucket characteristics and technical implementation

- Long, flat RF bucket created by isolated RF pulses
- Particles are confined within **two potential barriers** and drift freely in-between, as in a coasting beam
- $d(\Delta E)/dt = 0$ within drift region as RF voltage is zero
- **Wide-band RF system** required for BB production: Prototype LLRF system for the PS Finemet® cavity

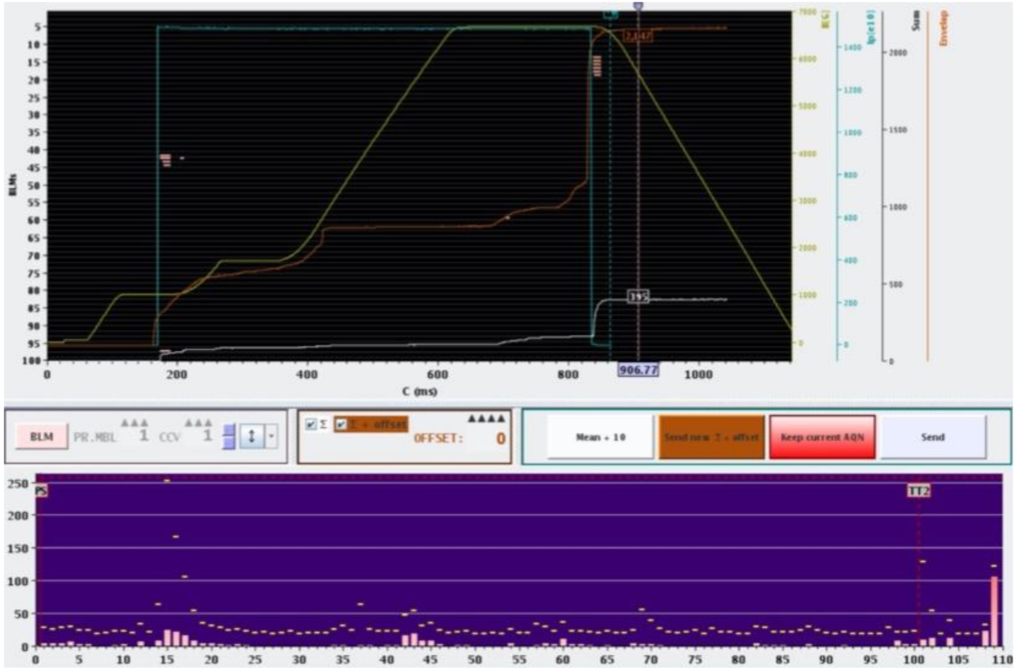




Losses, as low as possible (<1%) for high intensity

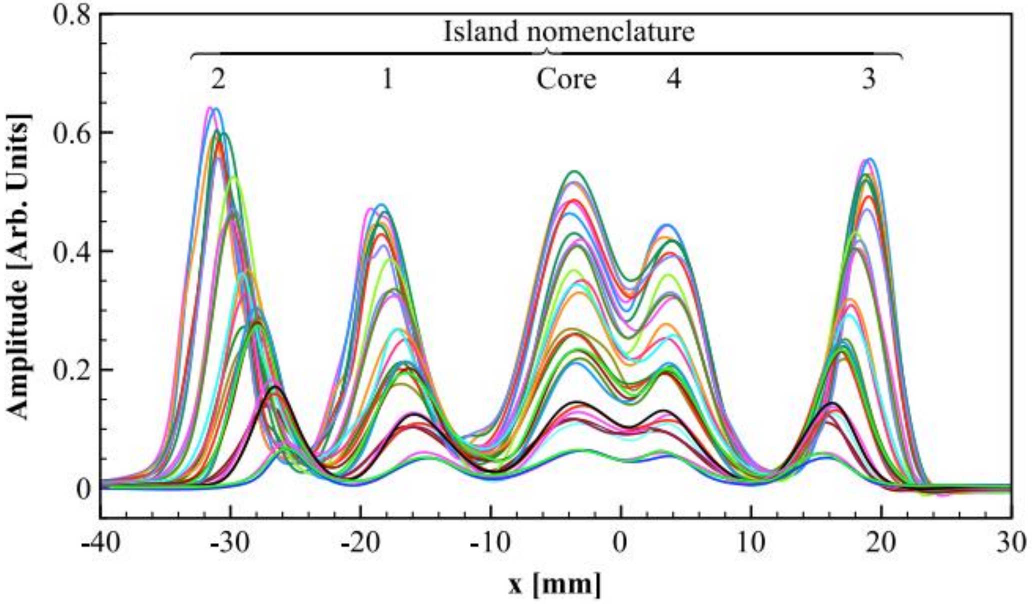


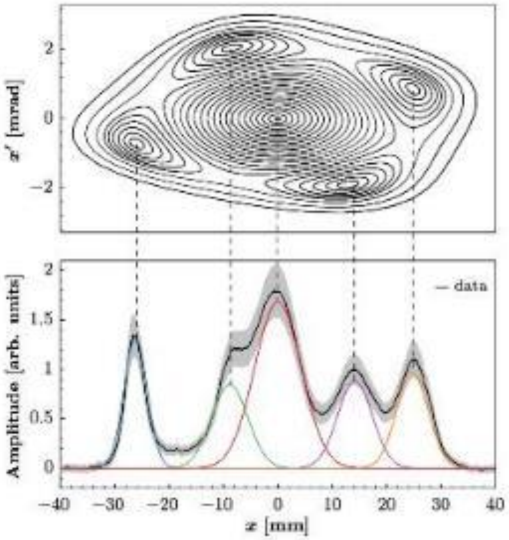
Edition: BLM Ccv



OFFSET: 0

Space charge and resonances





First observation of dependence of the beamlets’ parameters (position) on the total beam intensity due to space charge

Increasing the intensity: reducing the losses while improving the shielding

Original shielding not compatible
with increasing performances.
Two improvements: 1970‘ and 2000‘

Started from green field

and looking into the future

while always working together…

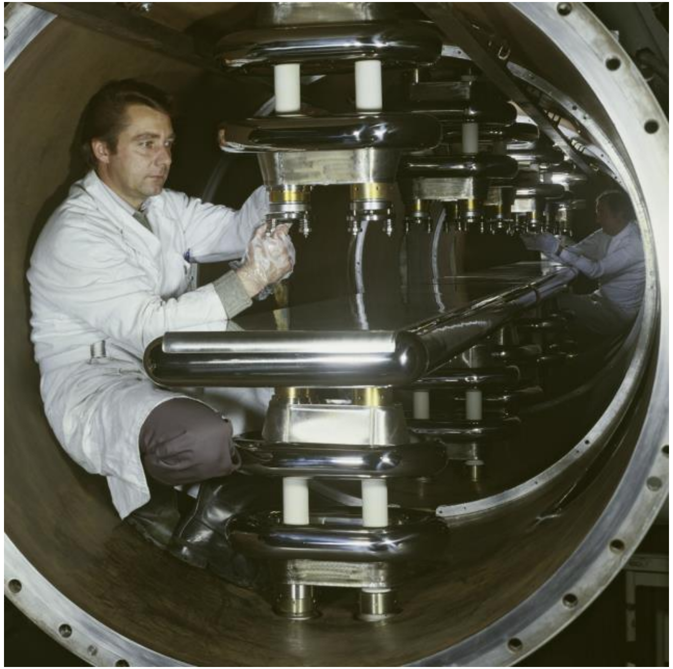
A quote to conclude …

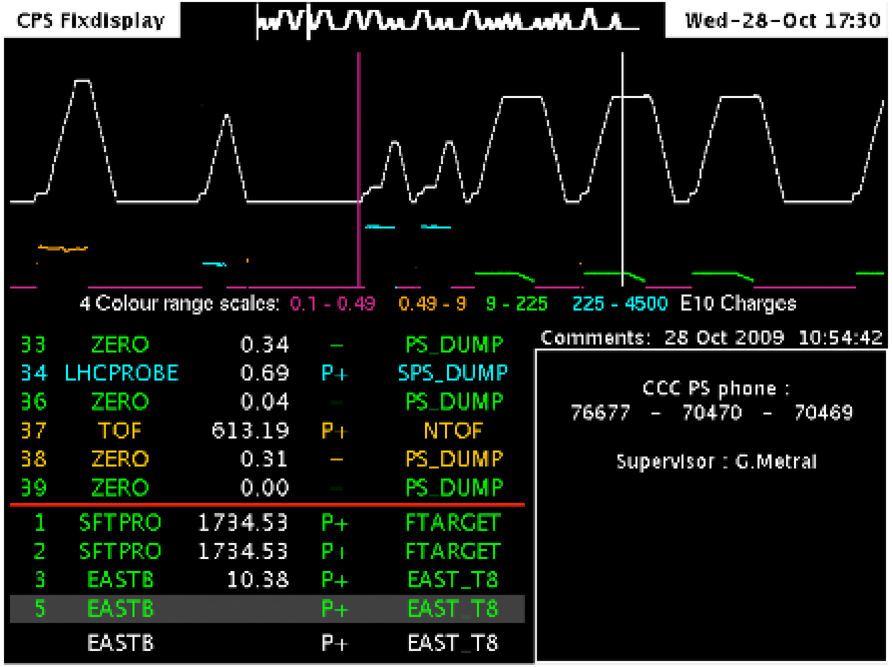
It was on 24 November 1959 that the proton beam in the CERN Proton Synchrotron was accelerated to a kinetic energy of 24 GeV. Thus the first strong-focusing proton synchrotron ever built has been faithfully serving the international physics community for 50 years. It has been the subject of a virtually continuous upgrade boosting its intensity per pulse from 10^{10} protons by more than three orders of magnitude to $3\ 10^{13}$.

Various injectors have been added and it has been modified such that, in addition to protons, light and heavy ions, positrons and electrons, as well as antiprotons could be accelerated or even decelerated often within the same supercycle.

This would not have been possible had the initial design not been solid and sound allowing for maintainability, flexibility, and versatility and whose intrinsic potential was brought to fruition by the efforts and the ingenuity of generations of accelerator physicists, engineers, operators, and technicians.


CERN





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CPS Fixdisplay                                        Wed-28-Oct 17:30

4 Colour range scales: 0.1 - 0.49   0.49 - 9   9 - 225   225 - 4500   E10 Charges

33     ZERO          0.34    –     PS_DUMP      Comments:  28 Oct 2009  10:54:42
34  LHCPROBE         0.69    P+    SPS_DUMP
36     ZERO          0.04    –     PS_DUMP              CCC PS phone :
37     TOF         613.19    P+     NTOF          76677  –  70470  –  70469
38     ZERO          0.31    –     PS_DUMP
39     ZERO          0.00    –     PS_DUMP           Supervisor : G.Metral
 1    SFTPRO      1734.53    P+    FTARGET
 2    SFTPRO      1734.53    P+    FTARGET
 3    EASTB         10.38    P+    EAST_T8
 5    EASTB                  P+    EAST_T8
      EASTB                  P+    EAST_T8
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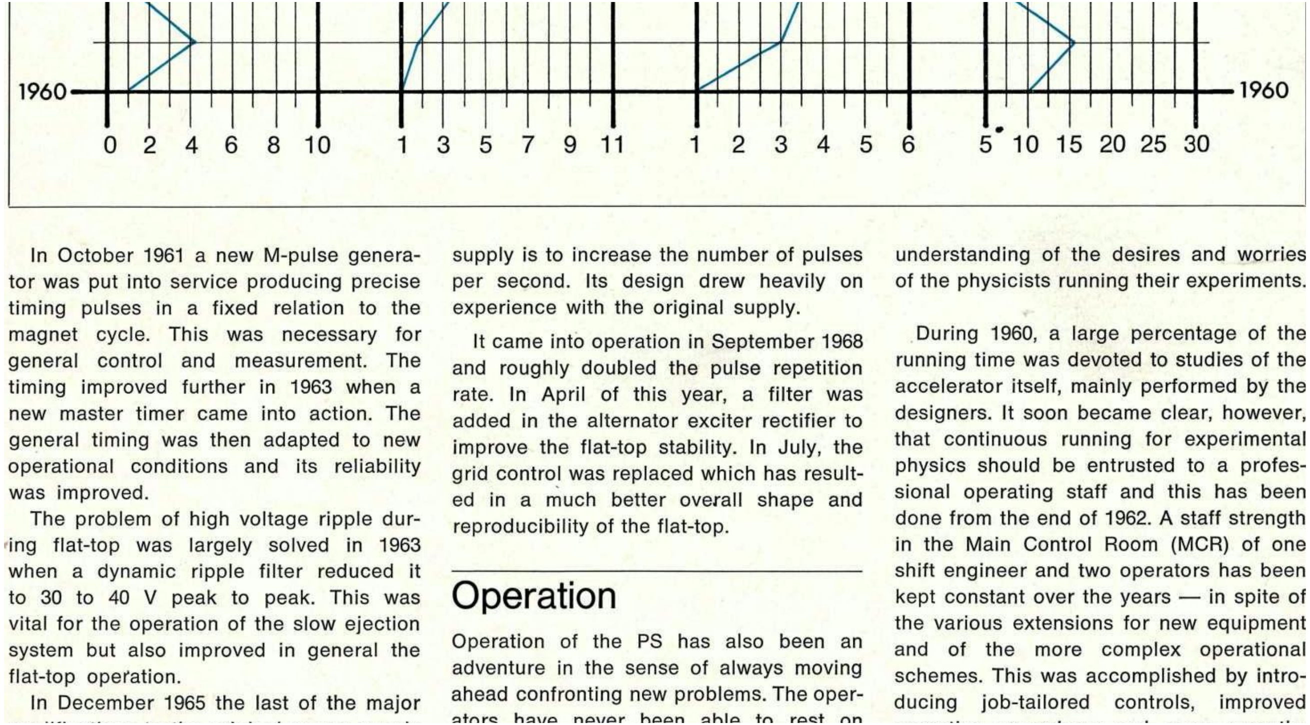


In October 1961 a new M-pulse generator was put into service producing precise timing pulses in a fixed relation to the magnet cycle. This was necessary for general control and measurement. The timing improved further in 1963 when a new master timer came into action. The general timing was then adapted to new operational conditions and its reliability was improved.

The problem of high voltage ripple during flat-top was largely solved in 1963 when a dynamic ripple filter reduced it to 30 to 40 V peak to peak. This was vital for the operation of the slow ejection system but also improved in general the flat-top operation.

In December 1965 the last of the major

supply is to increase the number of pulses per second. Its design drew heavily on experience with the original supply.

It came into operation in September 1968 and roughly doubled the pulse repetition rate. In April of this year, a filter was added in the alternator exciter rectifier to improve the flat-top stability. In July, the grid control was replaced which has resulted in a much better overall shape and reproducibility of the flat-top.

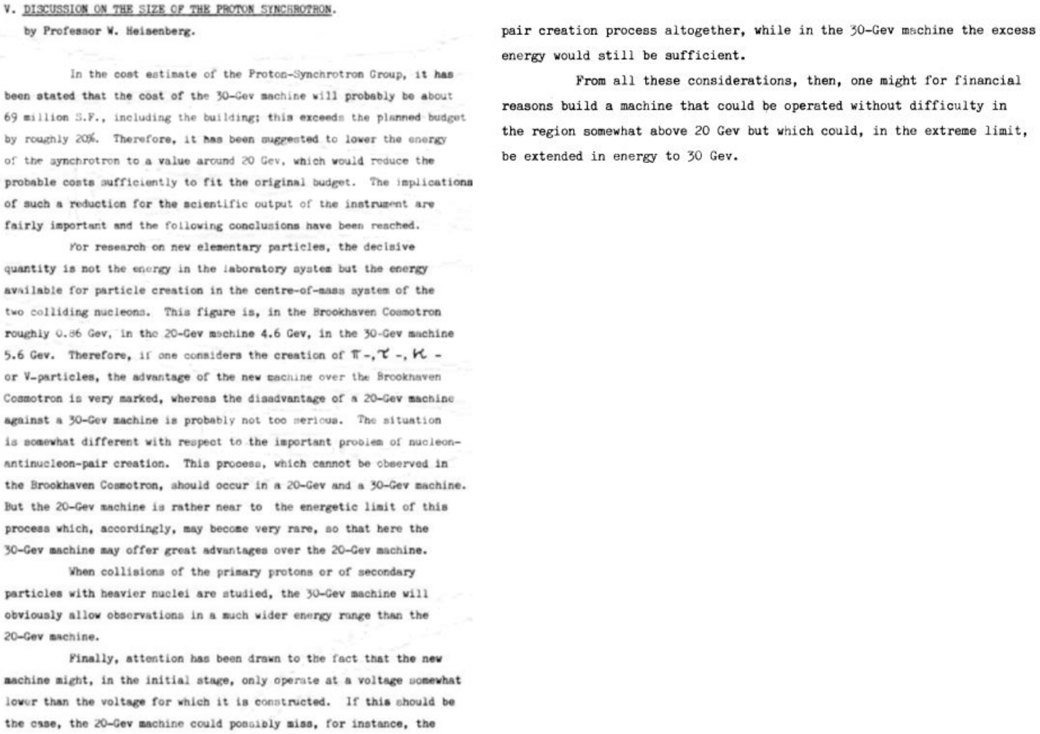
Operation

Operation of the PS has also been an adventure in the sense of always moving ahead confronting new problems. The operators have never been able to rest on

understanding of the desires and worries of the physicists running their experiments.

During 1960, a large percentage of the running time was devoted to studies of the accelerator itself, mainly performed by the designers. It soon became clear, however, that continuous running for experimental physics should be entrusted to a professional operating staff and this has been done from the end of 1962. A staff strength in the Main Control Room (MCR) of one shift engineer and two operators has been kept constant over the years — in spite of the various extensions for new equipment and of the more complex operational schemes. This was accomplished by introducing job-tailored controls, improved

Heisenberg & PS : 20 or 30 GeV (1953)



V. DISCUSSION ON THE SIZE OF THE PROTON SYNCHROTRON.

by Professor W. Heisenberg.

In the cost estimate of the Proton-Synchrotron Group, it has been stated that the cost of the 30-Gev machine will probably be about 69 million S.F., including the building; this exceeds the planned budget by roughly 20%. Therefore, it has been suggested to lower the energy of the synchrotron to a value around 20 Gev, which would reduce the probable costs sufficiently to fit the original budget. The implications of such a reduction for the scientific output of the instrument are fairly important and the following conclusions have been reached.

For research on new elementary particles, the decisive quantity is not the energy in the laboratory system but the energy available for particle creation in the centre-of-mass system of the two colliding nucleons. This figure is, in the Brookhaven Cosmotron roughly 0.86 Gev, in the 20-Gev machine 4.6 Gev, in the 30-Gev machine 5.6 Gev. Therefore, if one considers the creation of π-, τ-, κ- or V-particles, the advantage of the new machine over the Brookhaven Cosmotron is very marked, whereas the disadvantage of a 20-Gev machine against a 30-Gev machine is probably not too serious. The situation is somewhat different with respect to the important problem of nucleon-antinucleon-pair creation. This process, which cannot be observed in the Brookhaven Cosmotron, should occur in a 20-Gev and a 30-Gev machine. But the 20-Gev machine is rather near to the energetic limit of this process which, accordingly, may become very rare, so that here the 30-Gev machine may offer great advantages over the 20-Gev machine.

When collisions of the primary protons or of secondary particles with heavier nuclei are studied, the 30-Gev machine will obviously allow observations in a much wider energy range than the 20-Gev machine.

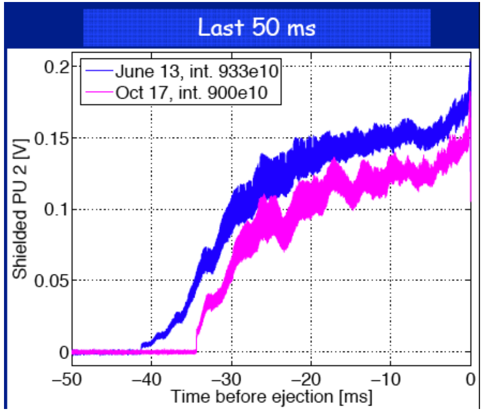
Finally, attention has been drawn to the fact that the new machine might, in the initial stage, only operate at a voltage somewhat lower than the voltage for which it is constructed. If this should be the case, the 20-Gev machine could possibly miss, for instance, the pair creation process altogether, while in the 30-Gev machine the excess energy would still be sufficient.

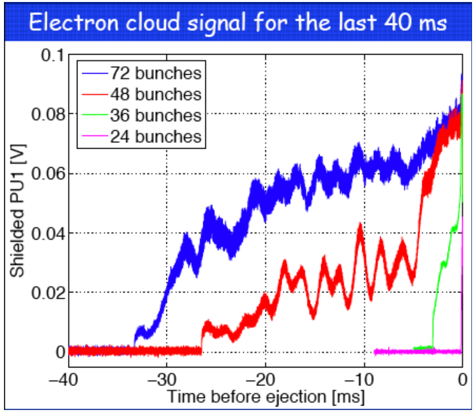
From all these considerations, then, one might for financial reasons build a machine that could be operated without difficulty in the region somewhat above 20 Gev but which could, in the extreme limit, be extended in energy to 30 Gev.

Electron cloud in the PS

- **Electron cloud was observed but not clear yet if any deleterious effect on the beam. Might become more critical with higher brilliance.**

(F. Caspers, T. Kroyer, E. Mahner)





New studies in 2011 since direct impact on time available for last RF manipulation

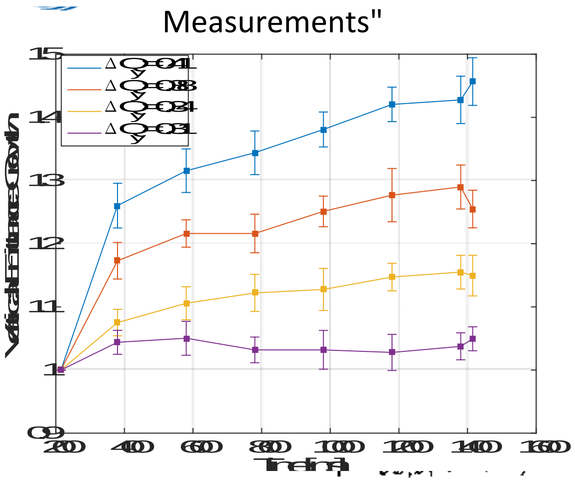
- *Transverse instabilities at flat top observed in 2001, 2004 and again 2006.*

- *Probably related to ecloud: why mainly horizontal and why not cured by chromaticity?*

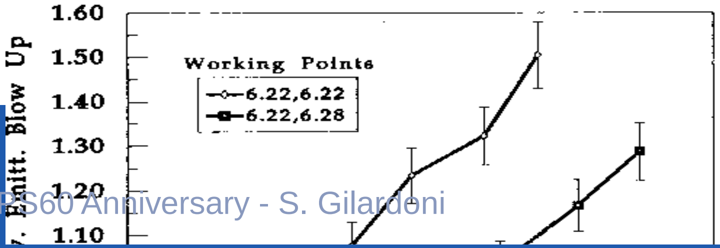
If solution like coating needed → MU removal → staging the intervention or LS2

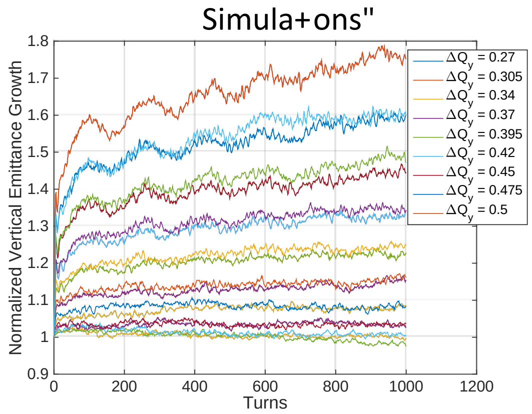
Emittance blow-up vs time

Fast emittance growth makes single batch injection less appealing for large space-charge tune shifts


Measurements"

an be used to estimate that the resultant transverse emit
ance blow-up would exceed 30%. An acceptable emittanc
ncrease requires $|\Delta Q_{x,z}| < 0.3$ which, from Eqn.1, implie
hat the PS injection energy must be raised to 1.4 GeV.




Simulations"