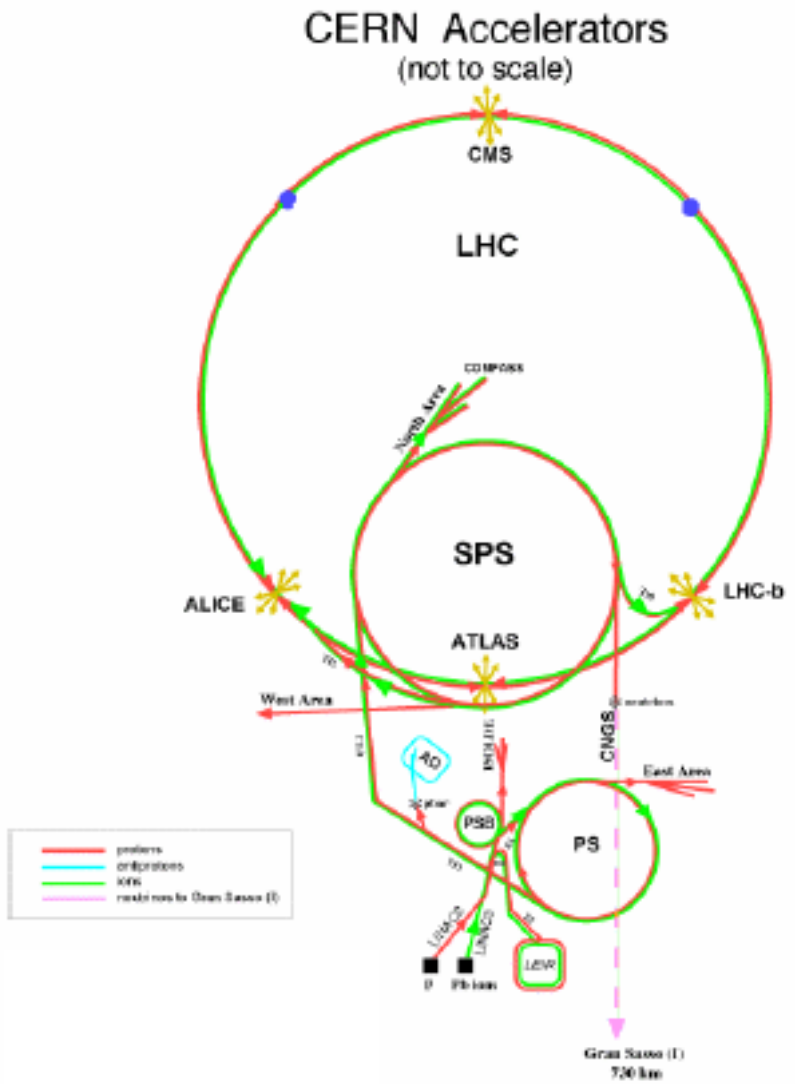
A Walk through the LHC Injector Chain

Part 1: The PS-Complex

Michael Benedikt, AB/OP



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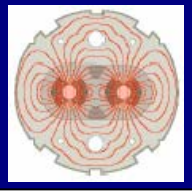
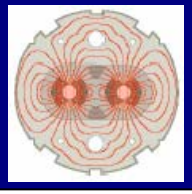


- **Introduction**
  - LHC requirements
  - Transverse phase space, emittance, adiabatic damping
  - What the PS Complex does for the LHC
- **Proton Source, RFQ and Linac2**
- **PS Booster**
  - Space charge tune spread
  - Double batch operation
  - Multi-turn injection
  - Energy increase
- **PS**
  - Production of the bunch train for LHC
  - Bunch shortening
  - Performance of nominal beam
- **Summary**

LHC Requirements (i)



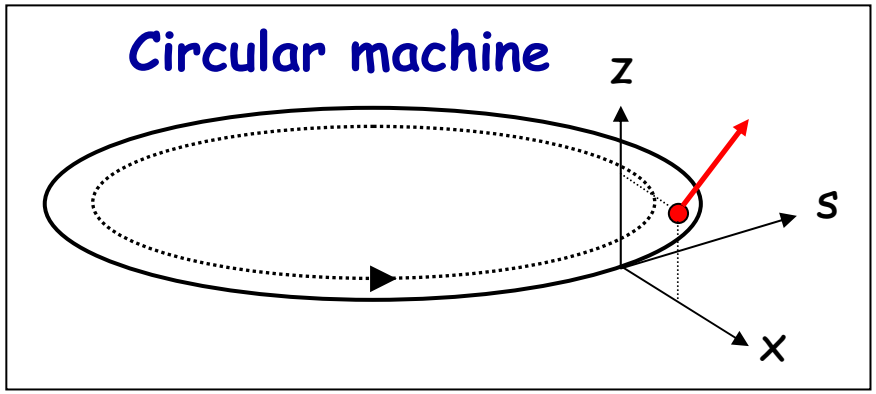
- **The luminosity is the figure of merit for a collider:**

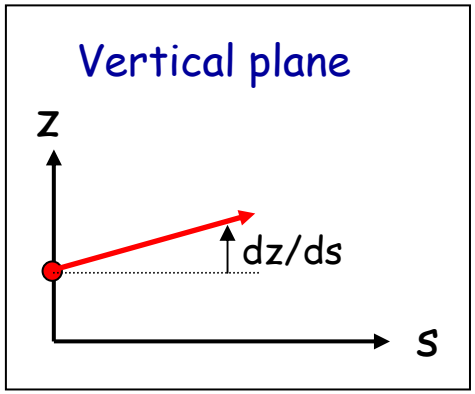
$$L \propto \frac{k_b N_b^2}{\varepsilon_n}$$

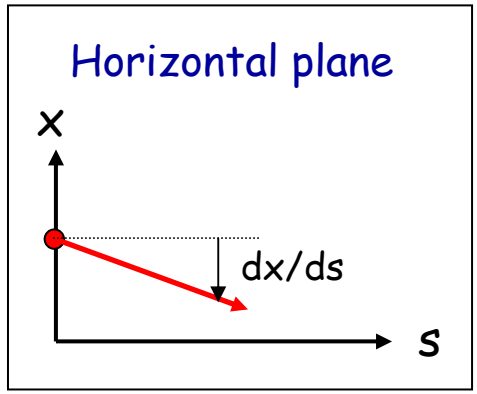
- k_b... number of bunches per ring.
- N_b.. Intensity per bunch.
- ε_n... normalized transverse beam emittance.

- **Some constraints when optimizing the luminosity:**
  - ε_n (beam emittance ~ size^2) has to be small to fit the LHC aperture.
  - N_b/ε_n (beam brightness) limited by the "beam-beam" effect in LHC.
  - N_b/ε_n (beam brightness) limited by "space charge" in injectors.
  - $k_b N_b$ (total intensity) limited by thermal energy (synchrotron radiation), has to be absorbed by cryogenic system.
  - Of course there are many other constraints...

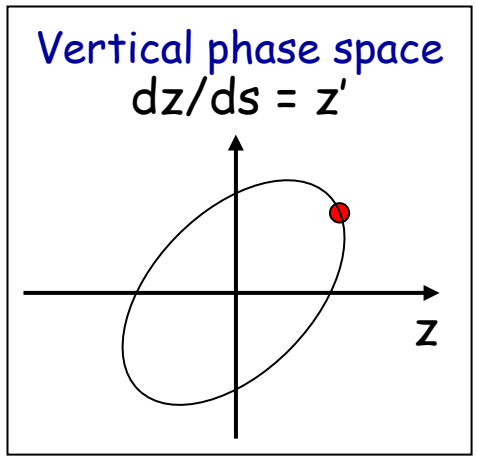
Transverse phase space

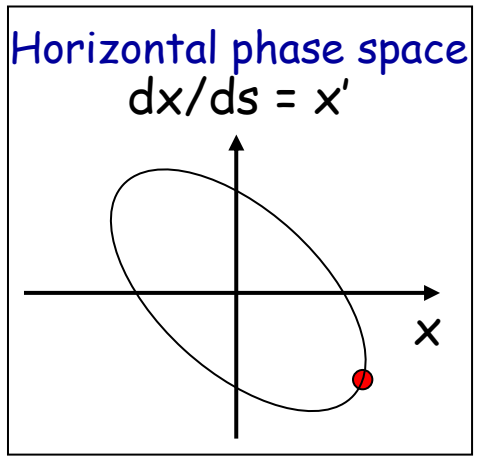






- **Description of single particles**
  - Start from projection onto horizontal and vertical planes.
  - Phase space coordinates (x,x'), (z,z').
- **Observing over many turns**
  - Describes an ellipse in phase space.
  - Imposed by boundary conditions of the circular machine.

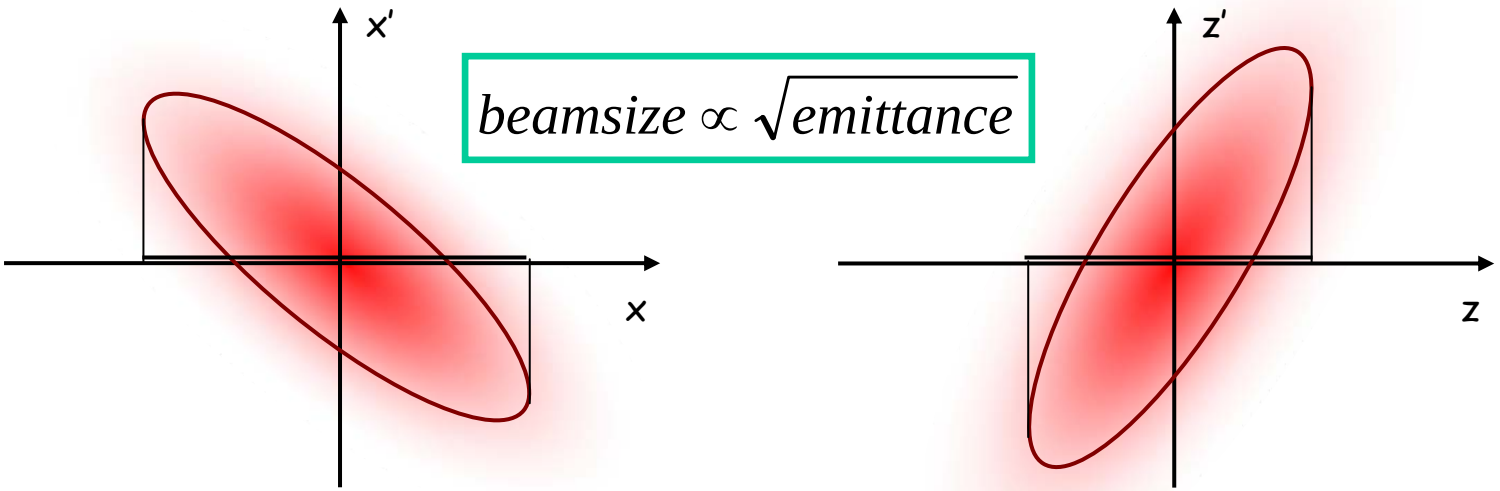




- Observing at a different position s along the machine, the ellipse changes shape but it contains the same phase space area!

Transverse emittance

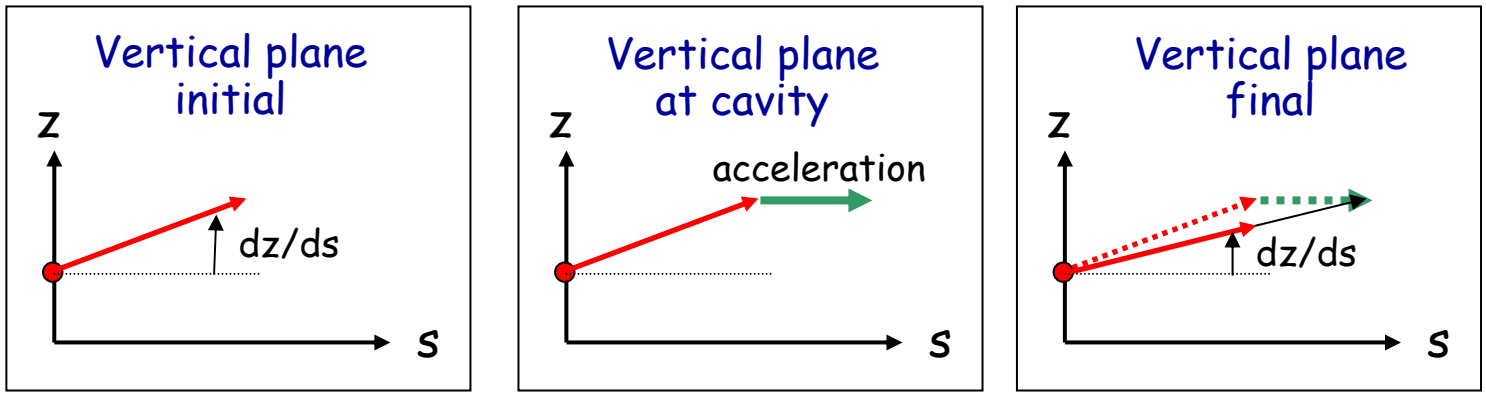
- **The beam consists of many particles…**
  - All particles describe similar ellipses in phase space.
- **The elliptical phase space area containing (a certain amount of) the beam is the Transverse Emittance, ε.**
  - The area is constant but the ellipse changes shape around the machine (determined by the magnet optics).
- **Beam size is the projection of the ellipse on horizontal/vertical axis.**



- **Therefore we must produce small emittance beams for the LHC beam but there is something that helps…**

Adiabatic damping of emittance

- Acceleration adds longitudinal momentum to the particles while leaving the transverse momentum unchanged (first order).
- As a result the "angular spread" reduces – and the emittance decreases.

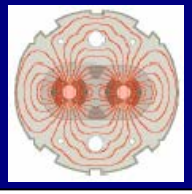


- This is adiabatic damping, inversely proportional to momentum increase.

$$p(\gamma) = m_0 c \cdot (\beta\gamma) \quad \Rightarrow \quad \varepsilon_{\text{geometrical}}(\gamma) = \frac{\varepsilon_{\text{normalized}}}{\beta\gamma}$$

- LHC beam emittance is defined at injection in the PS Booster (50 MeV). Emittance shrinks by a factor 1500 until injection into LHC (450 GeV).

LHC Requirements (i)



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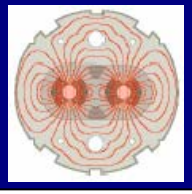
LHC Requirements (ii)



- **Outcome – the LHC would like to have:**
  - Many (ns-short) bunches (2808 per ring), i.e. small bunch spacing (25ns).
  - Small transverse emittance beams ($\varepsilon_{n,\sigma} \leq 3.6$ mm·mrad at injection).
  - Bunch intensities of ~ 10^{11} ppb (1.7×10^{11} ppb is ultimate LHC intensity).

- **But – that's not what the PS Complex normally provides…**

	East Hall	n-TOF	AD	SPS FT	LHC nominal
Intensity [ppb]	~0.3×10^{12}	8×10^{12}	8×10^{12}	$\leq 30 \cdot 10^{12}$	0.12×10^{12}
Bunch length [ns]	dc ~400 ms	20 ns	25 ns	dc-mod 10 μs	4 ns
Bunch spacing [ns]	-	-	100 ns	-	25 ns
Number of bunches	debunched	1	4	debunched	72
$\varepsilon_{n,rms\ h\ /\ v}$ [mm·mrad]	~ 4 / 1	~ 13 / 9	~ 12 / 9	~ 14 / 10	3 / 3
Energy [GeV]	23	19	25	13	25

The PS Proton Accelerator Complex

Proton Source

90 keV, pulsed every 1.2 s.

Radio Frequency Quadrupole

750 keV, pulsed every 1.2 s.

Linac2 (linear accelerator)

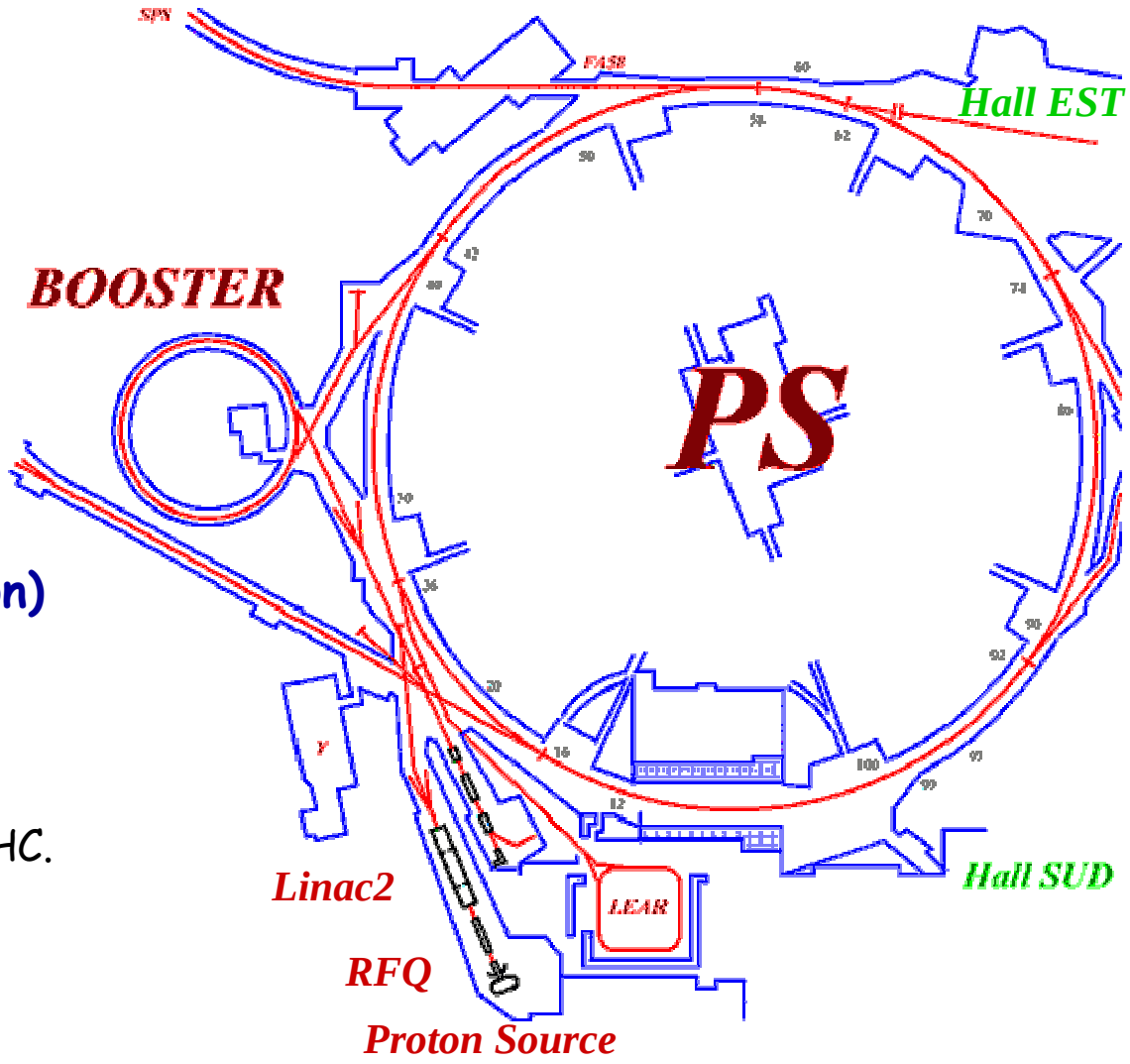
50 MeV, pulsed every 1.2 s.

PS Booster (4-ring synchrotron)

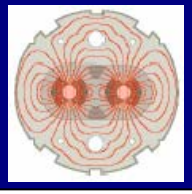
1.4 GeV, 1.2 s cycle time.

PS (Synchrotron)

25 GeV, 3.6 s cycle time for LHC.



What the PS Complex does for LHC



1. **The PS complex defines the transverse emittance**
   - The **multi-turn injection into the PSB** determines the beam size

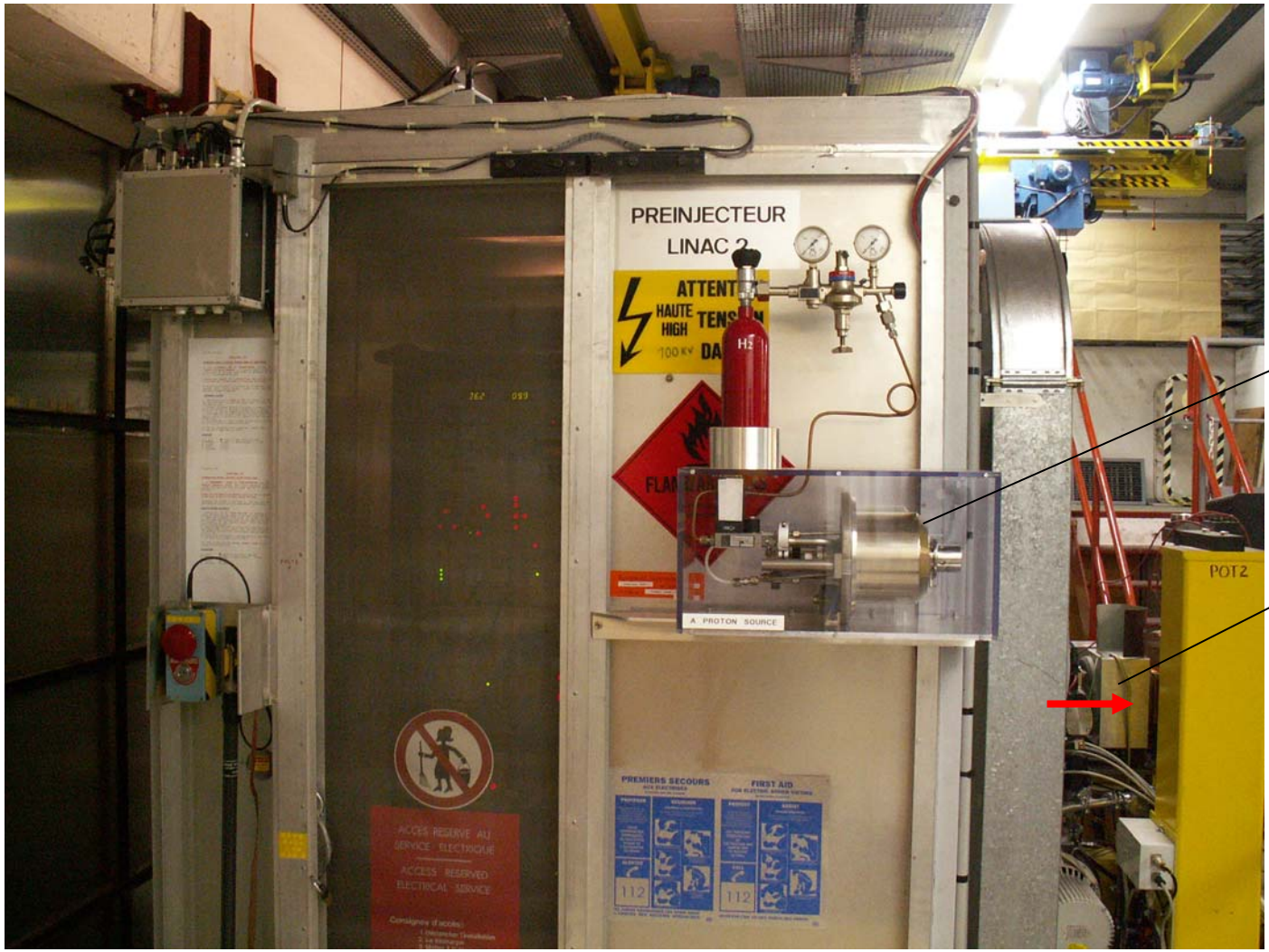
2. **The PS complex generates the bunch trains**
   - The **25 ns bunch spacing** is fully established at ejection from PS.

- **The main challenges are:**
  - The **beam brightness N_b/ε_n** is a factor 1.6 higher than achieved before.
    - How to overcome "space charge" limitations in PS Booster and PS.
  - The **"bunch train" production.**

- **Within the "PS conversion for LHC" project (1995 – 2000) the accelerators were upgraded to meet the LHC requirements.**

Here it starts…

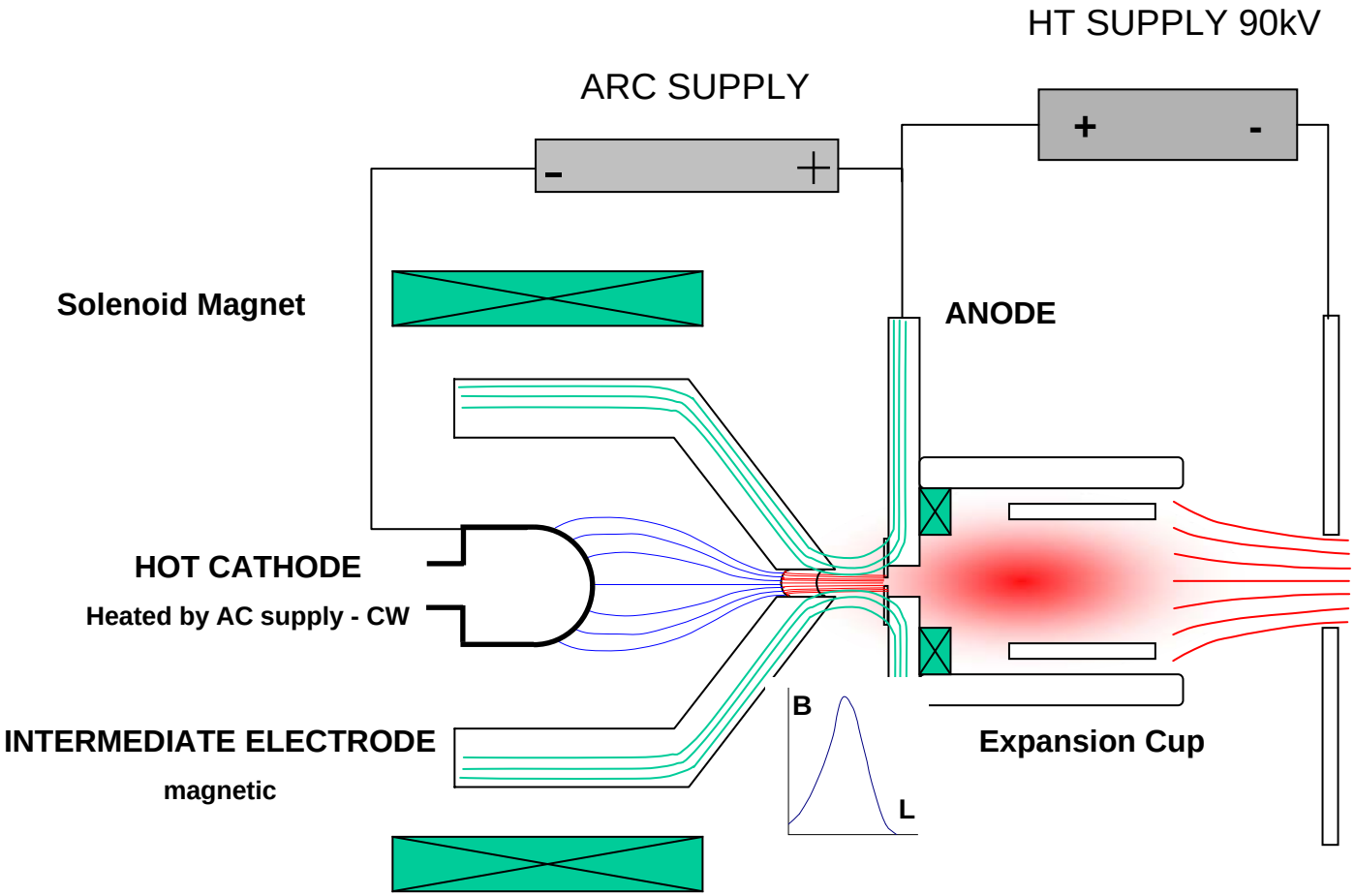
- The source cage houses the HV platform at 90 kV.



Source model (1 to 1)

Beam path to RFQ

Duoplasmotron Proton Source (i)



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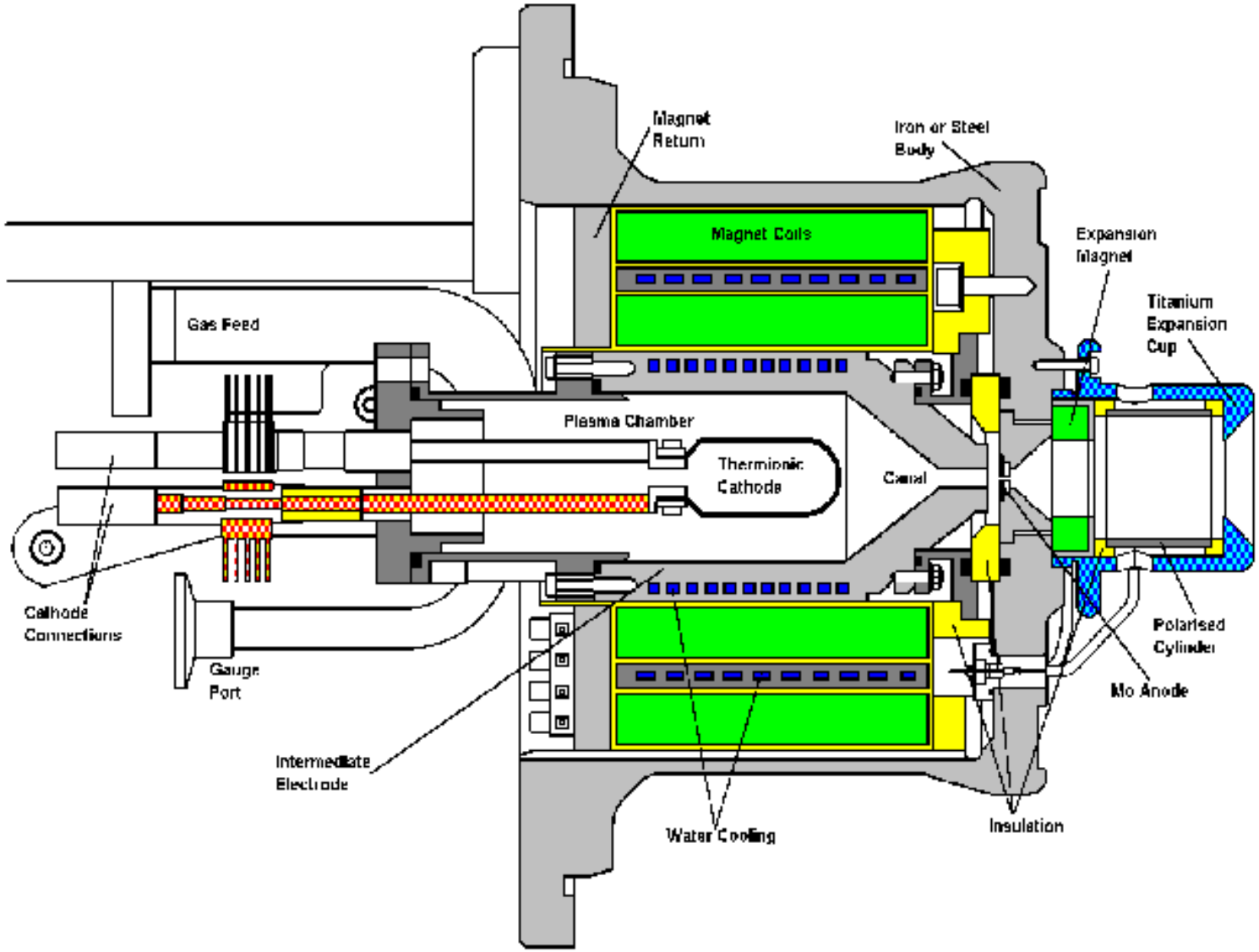
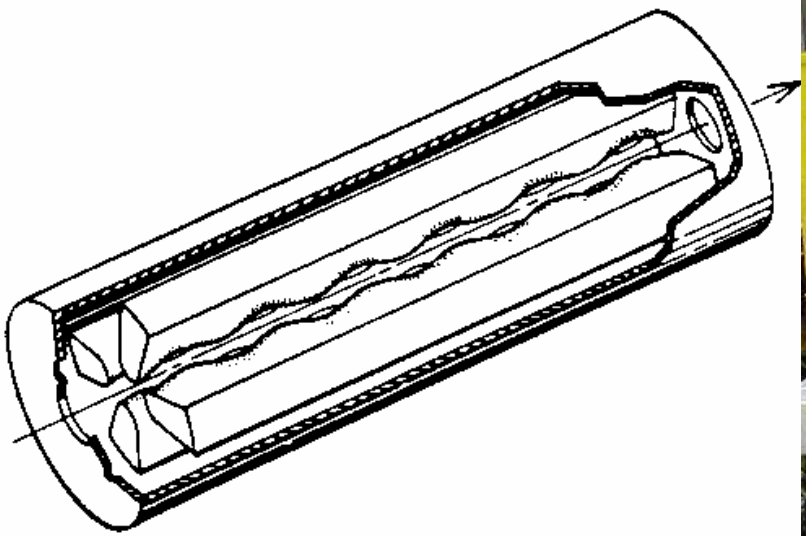
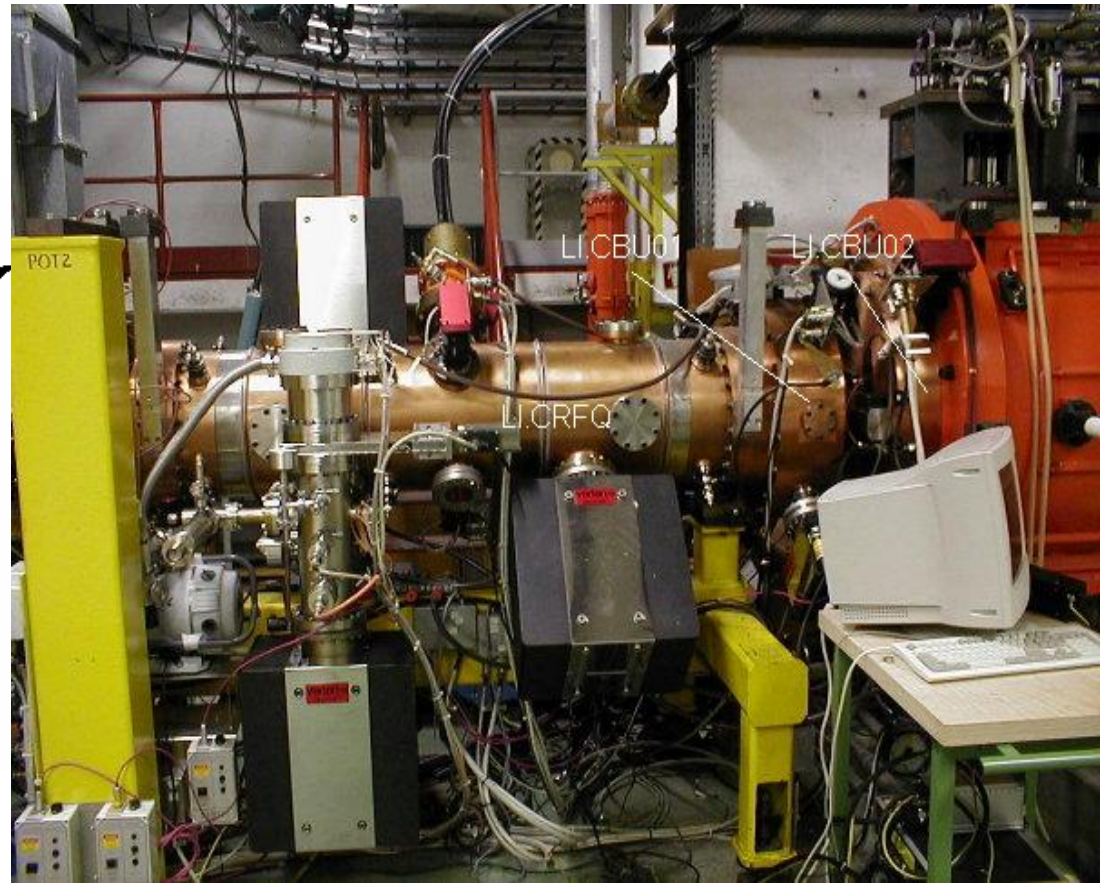
Duoplasmotron Proton Source



Radio Frequency Quadrupole (RFQ)

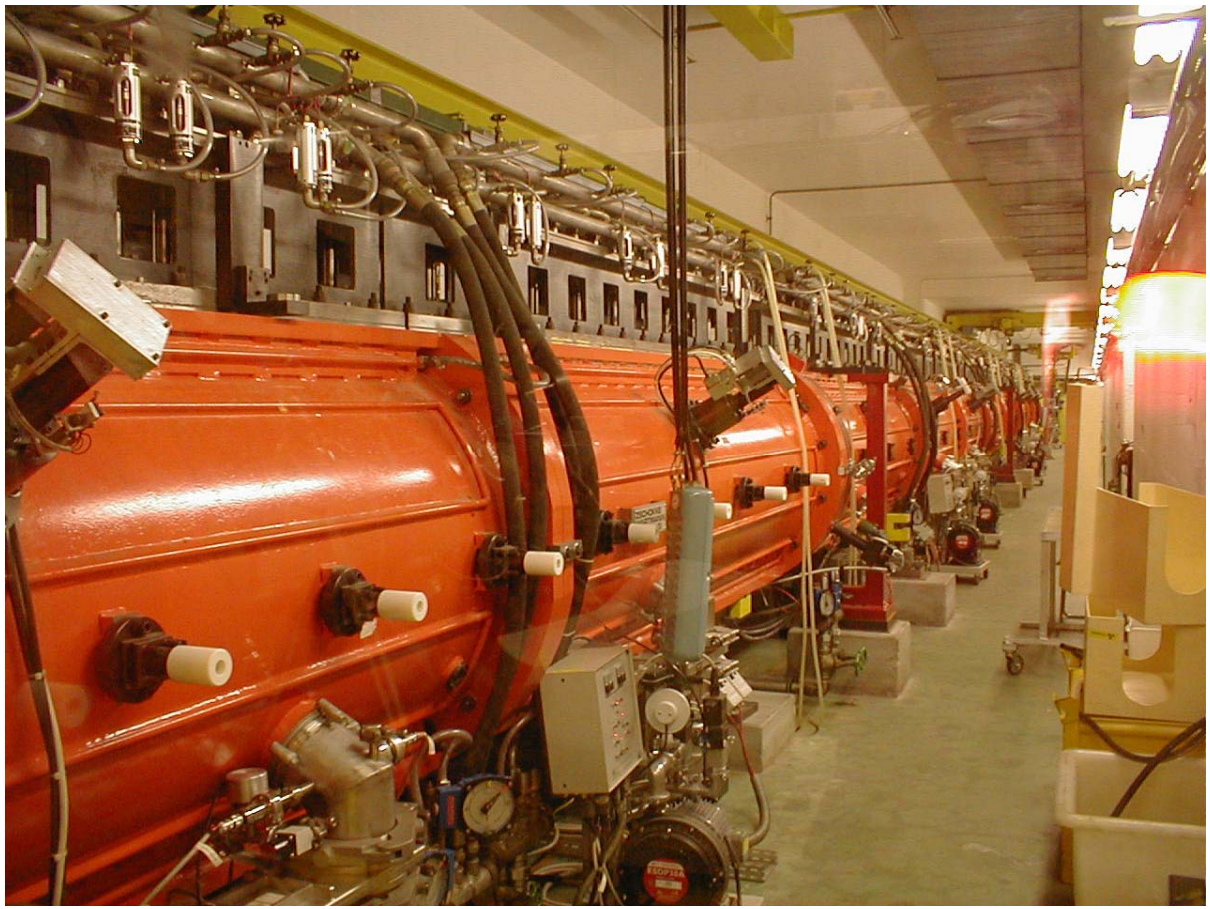
- Directly after the source, accelerates beam to 750 keV.
- Acceleration and focusing based on electrical fields.
- Special-shaped electrodes, structure length 1.75 m, 200 MHz.

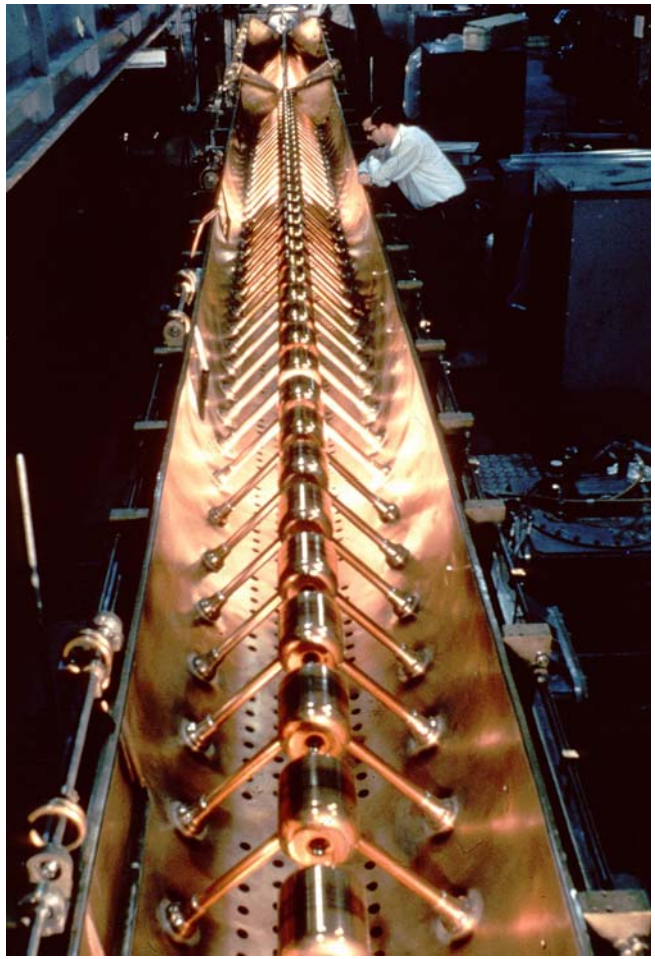




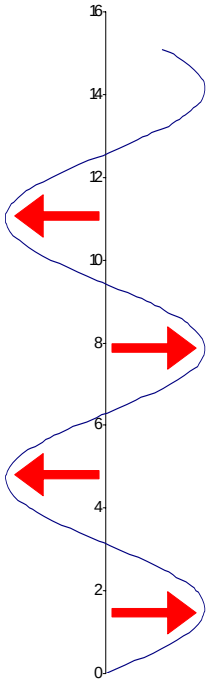
Linac2 (Alvarez structure)

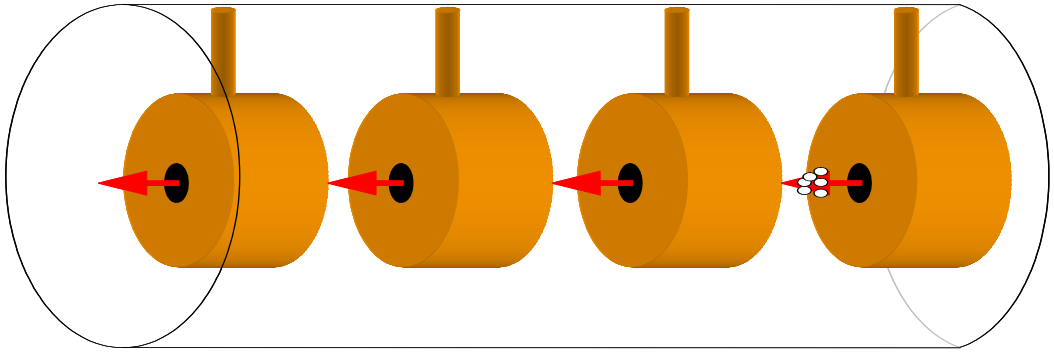
- Follows RFQ, accelerates the beam to 50 MeV.
- Acceleration with electrical field, focusing with quadrupole magnets.
- RF 200 MHz, length 30 m.

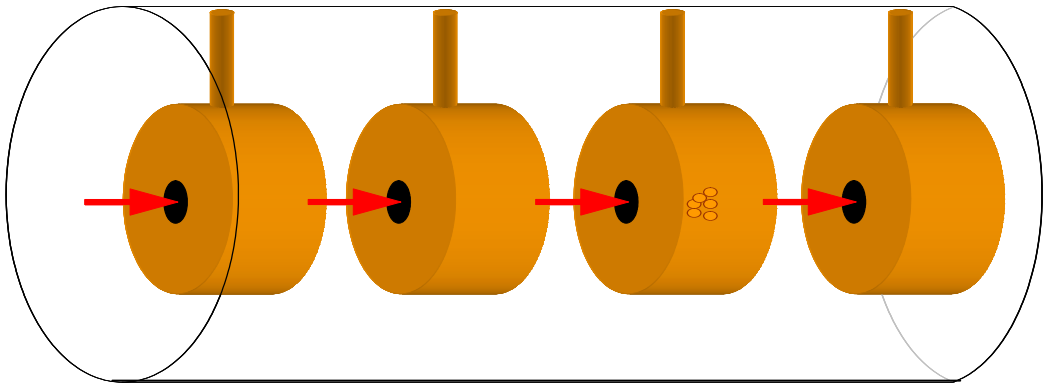




Alvarez operating principle







Beam is accelerated when particles travel between drift tubes.

Half a period later, protons would be decelerated but are shielded inside the drift tubes.

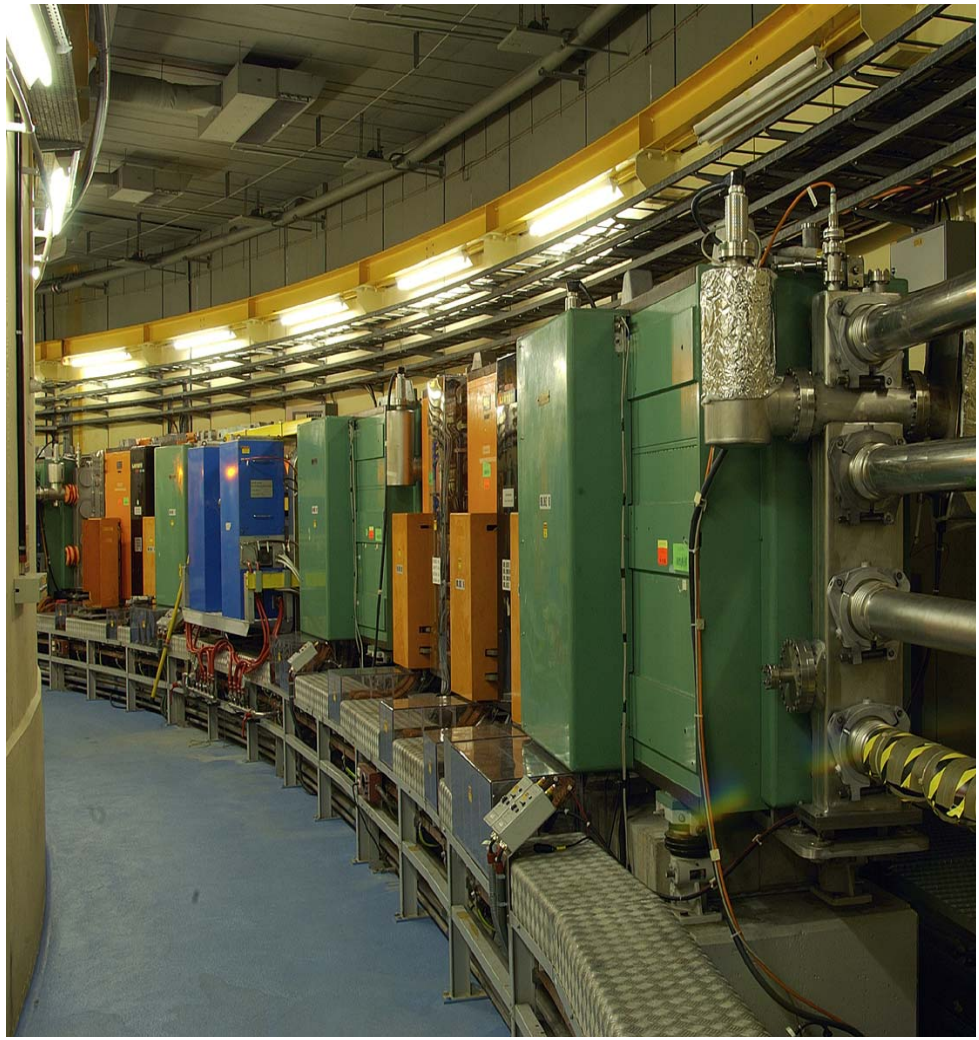
Accelerating field 200 MHz

R. Scrivens

Drift tubes and spacings become longer when energy increases (i.e. the beam is faster (travels longer distance per RF period).

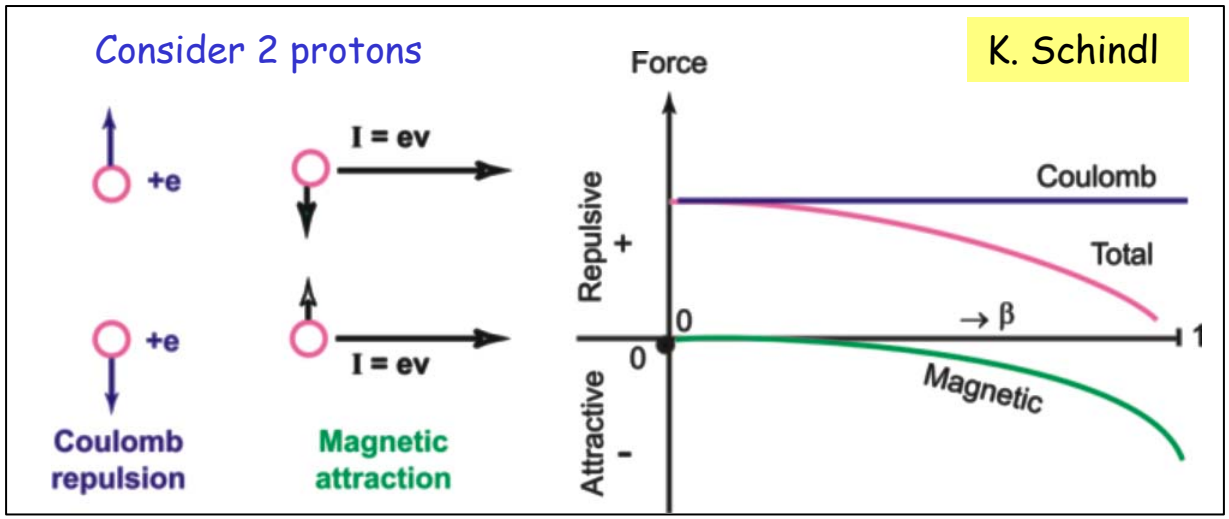
PS Booster

- Synchrotron with 4 vertically stacked rings (length $\frac{1}{4}$ of PS).
- Multi-turn injection of Linac beam defines LHC beam emittance
- Acceleration 50 MeV to 1.4 GeV.
- Cycling time 1.2 seconds
- Main problem (for the LHC beam) is the high beam brightness (1.6 times higher than achieved) which creates unmanageable space charge.



Space Charge

- **Space charge effect:**
  - Electrical force, Coulomb interaction, repulsive.
  - Magnetic force of parallel currents, attractive.

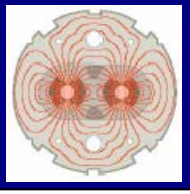


- **Overall force is repulsive but decreases with energy.**
- **Cancellation of forces for v = c**

$$F_{\text{rad}} \propto \frac{1}{\beta\gamma^2}$$

- **Space charge effects are problematic at low energy.**
- **Space charge force has a defocusing effect on the beam.**

Space Charge Tune Spread



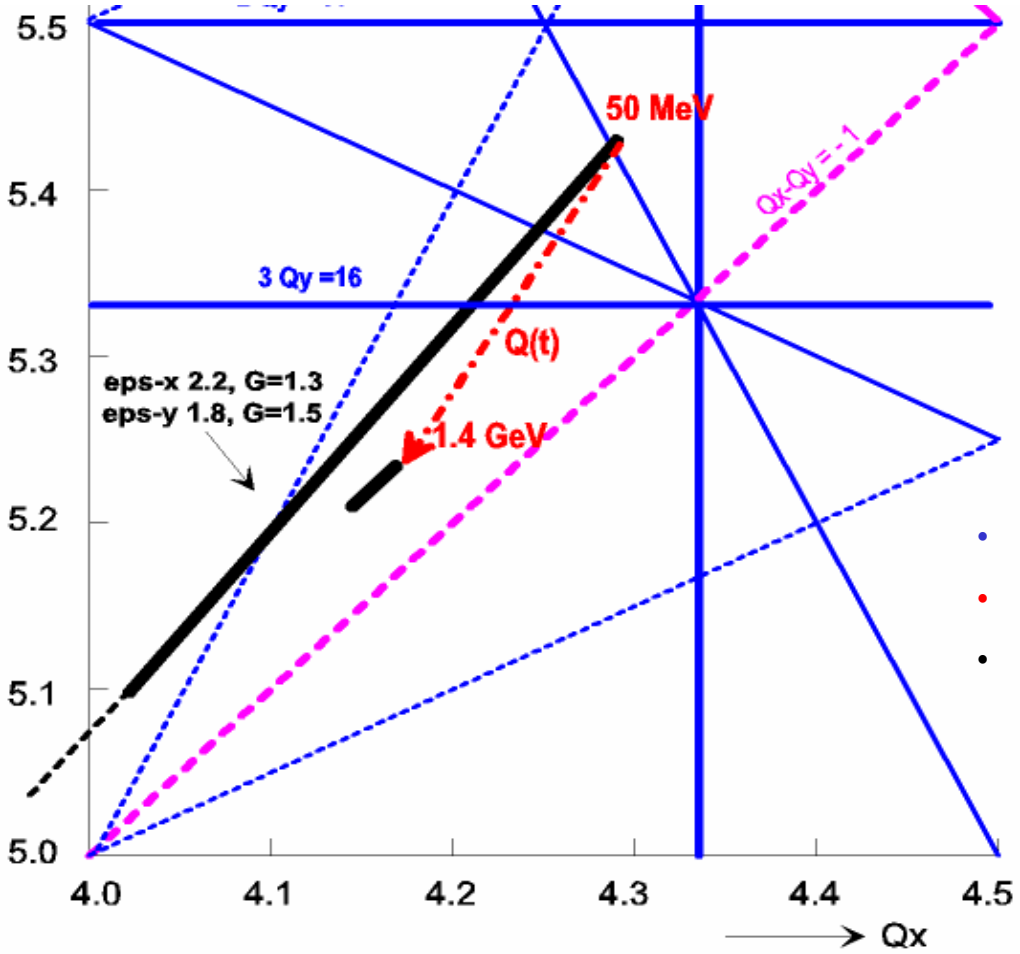
- **In circular machines the beam makes many turns (e.g PSB ~10^6 turns)**
  - Particles with small deviations from the design orbit oscillate around the orbit in phase space.
- **The Betatron Tune Q is the number of phase space oscillations per revolution in the machine.**
- **Integer tunes, ½ integer tunes, etc. must be avoided since they lead to resonances and beam loss.**
  - Particles will "sum-up" all machine/magnet imperfections, turn-by turn…
- **The defocusing effect of space charge reduces the tune and leads to a tune spread ΔQ in the beam:**

$$\Delta Q \propto -\frac{N_b}{\varepsilon_n}\frac{1}{\beta\gamma^2}$$

- **Once ΔQ becomes too big there will be always particles fulfilling a resonance condition and these will be lost.**
- **This is THE major problem at low energy in PSB and PS.**

Space Charge Tune Spread

- Tune diagram of PS Booster for nominal LHC beam



- stop-bands (some compensated)
- time-varying tune Q(t)
- space-charge ΔQ for LHC beam

How to beat space charge in the PSB

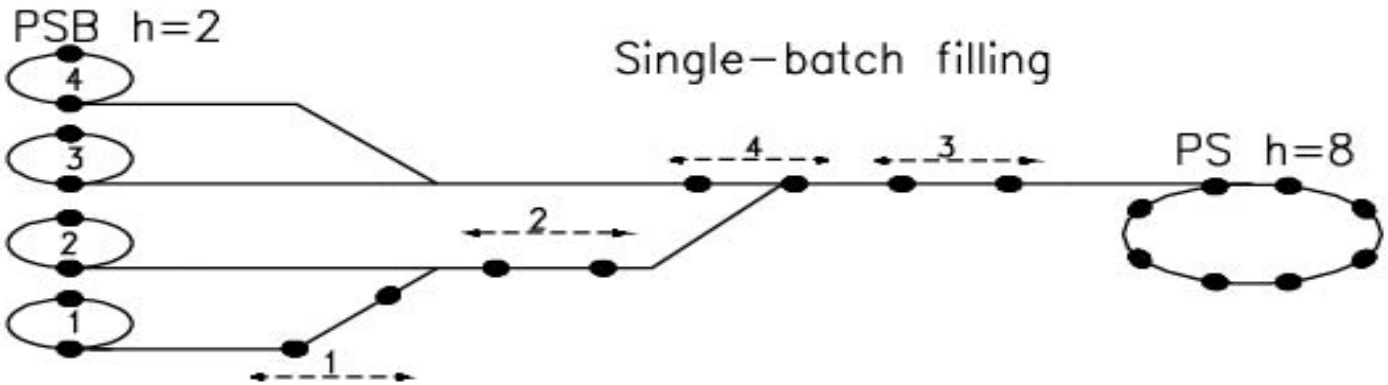
- Reduce the beam brightness required from the PS Booster.

$$\Delta Q \propto -\frac{N_b}{\varepsilon_n} \cdot \frac{1}{\beta\gamma^2}$$

- Fill the PS with two consecutive PS Booster cycles.
- This halves N_b per PSB batch and thus reduces the space charge tune shift by a factor 2 to $\Delta Q_y \approx 0.4$.
- Requirements:
  - PS Booster has to deliver 1 bunch per ring to PS (5 bunches before).
  - New RF system.
  - Modification of other RF systems.
  - New RF beam control.

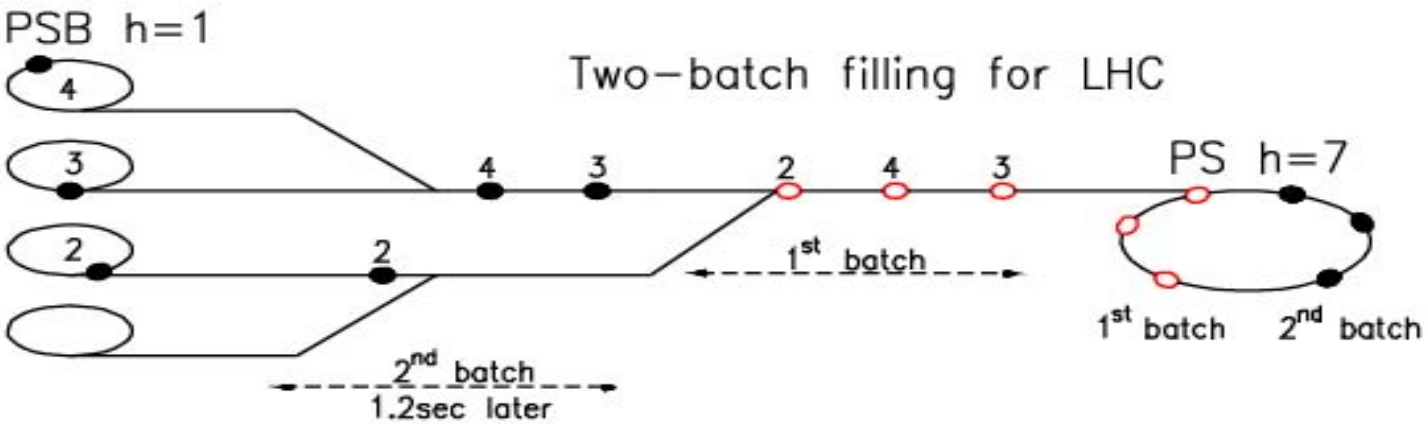
Double batch filling for PS

- Double batch filling requires h=1 operation (1 bunch per ring)



For SPS Fixed Target

Each PSB ring fills ¼ PS.



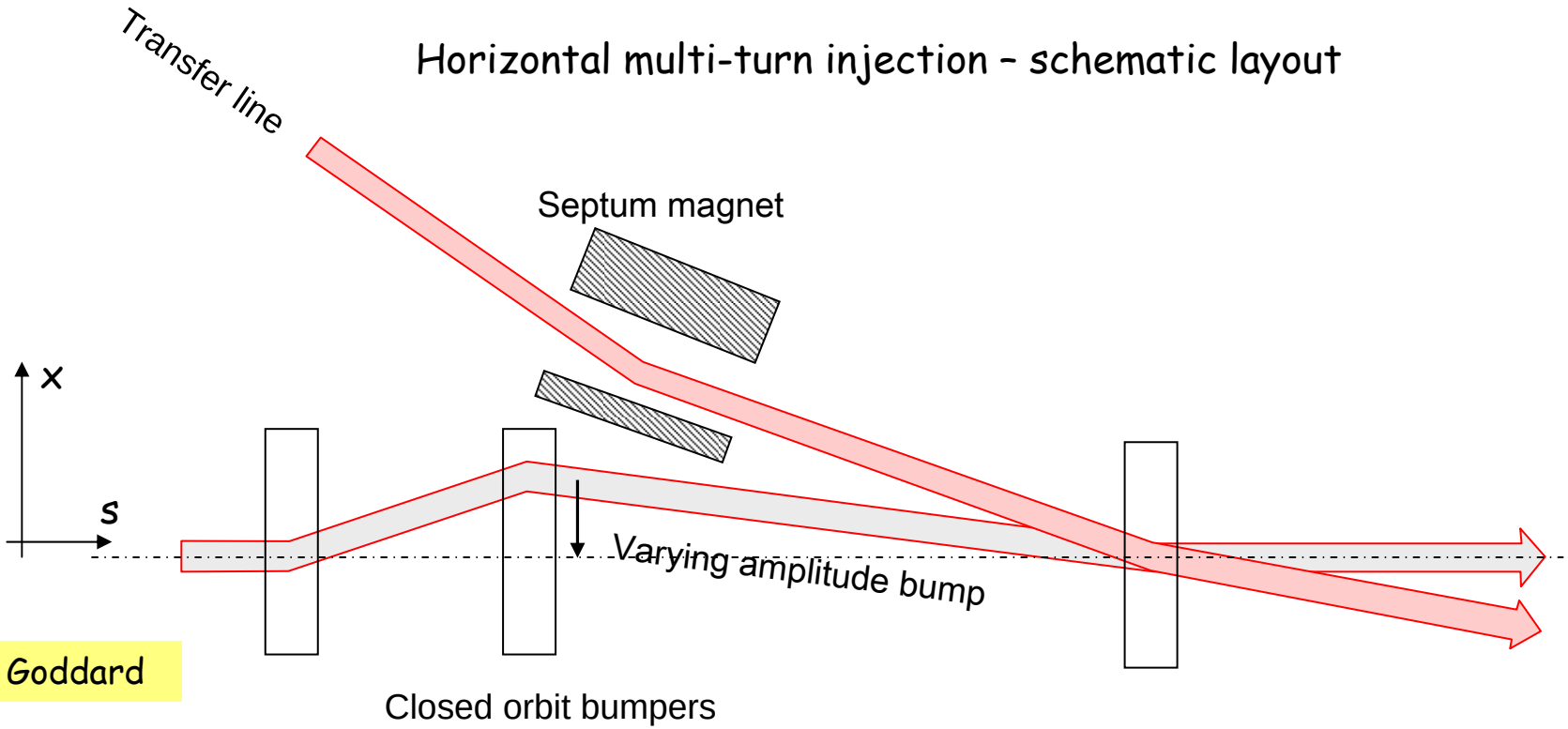
For LHC

PSB bunches concentrated in part of PS.

2nd PSB batch 1.2 s later

Multi turn injection - principle

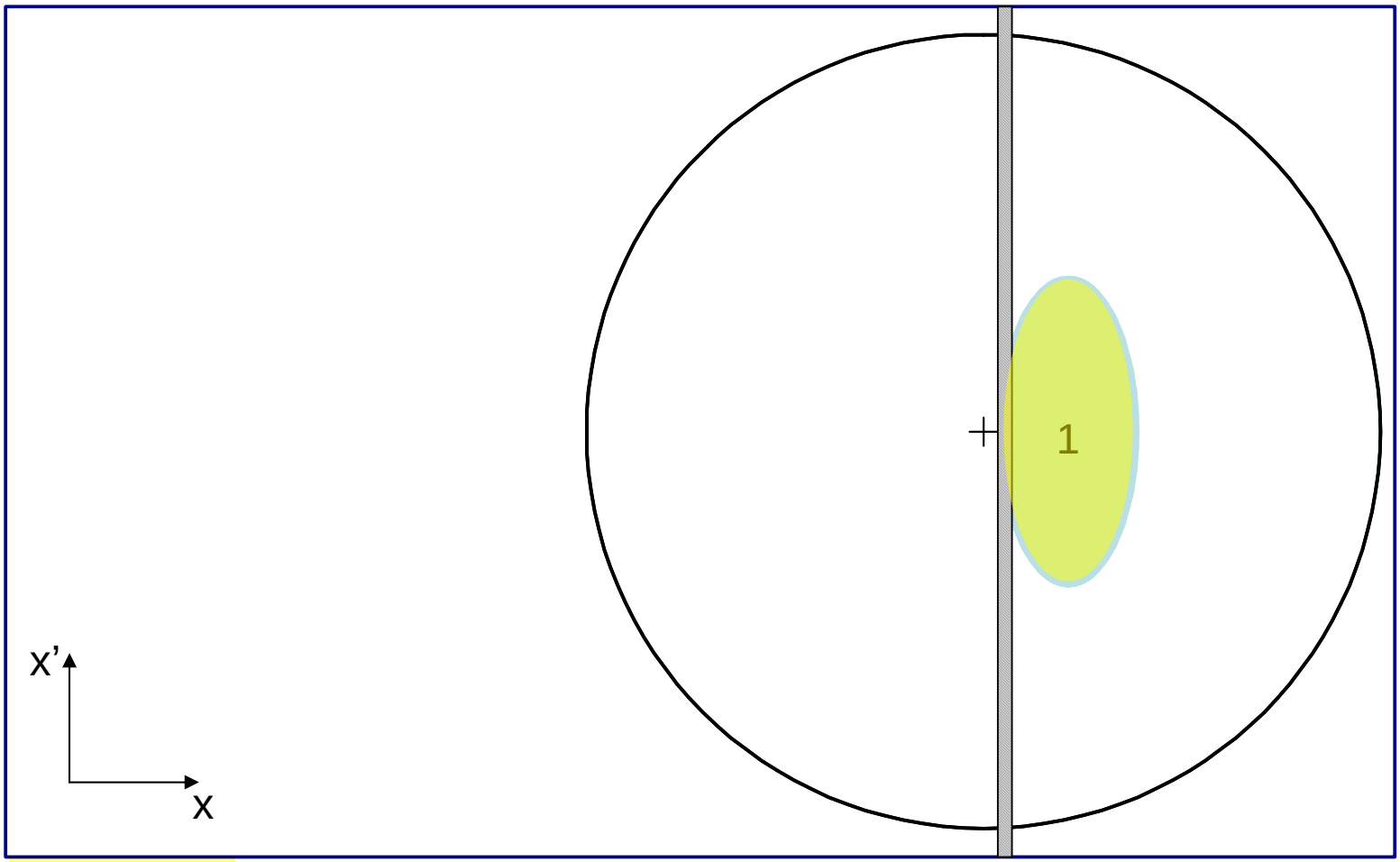
- Beam is injected during few "turns" (3 turns for LHC beam in PSB).
- Orbit bump amplitude at injection point varies with time.
- Injected beam oscillates (in phase space) around closed orbit, oscillation is controlled with the betatron tune.
- Process is called "phase space painting".



Multi turn injection

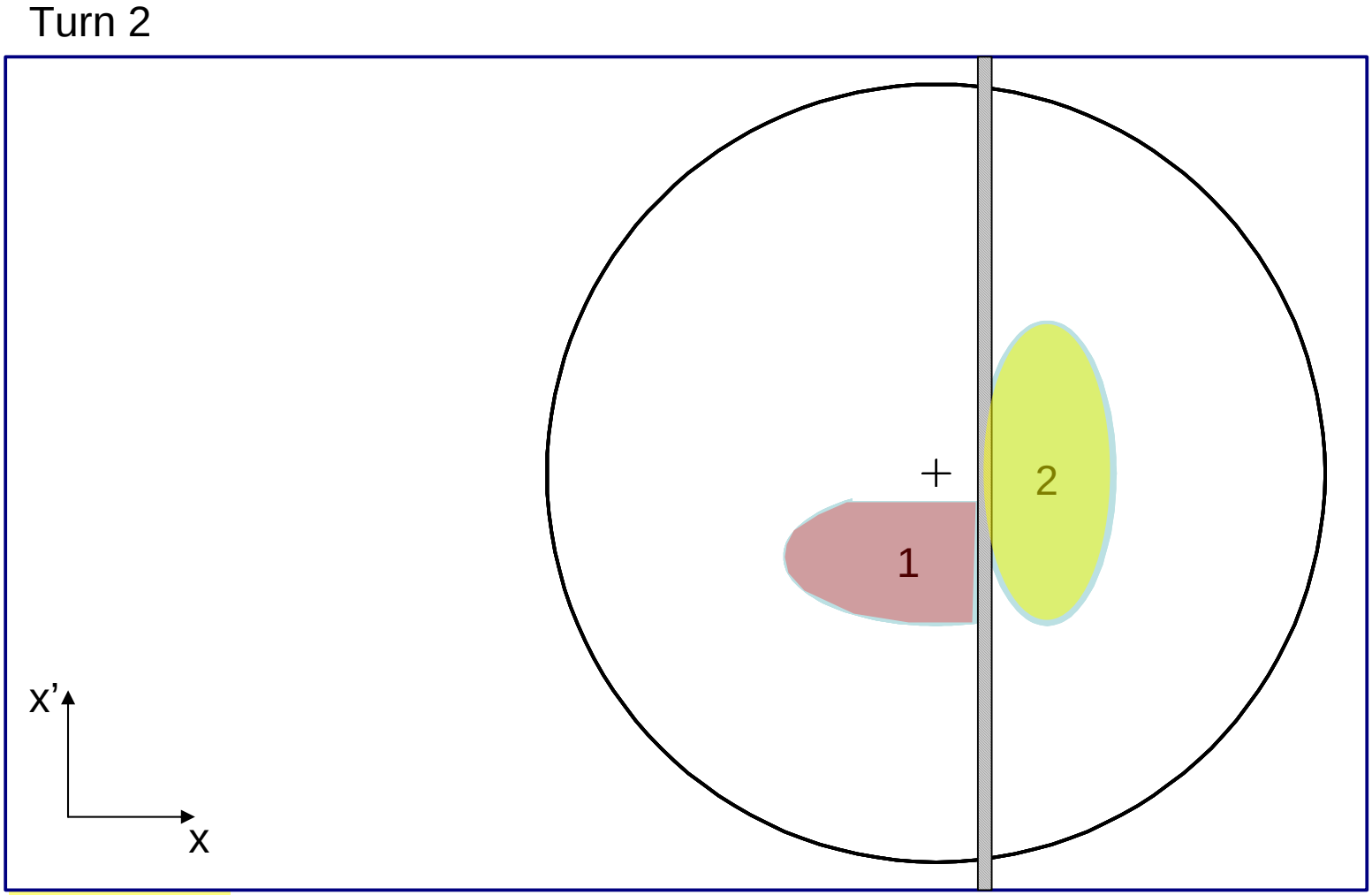
- Horizontal multi-turn injection with tune 4.25

Turn 1



B. Goddard

Multi turn injection



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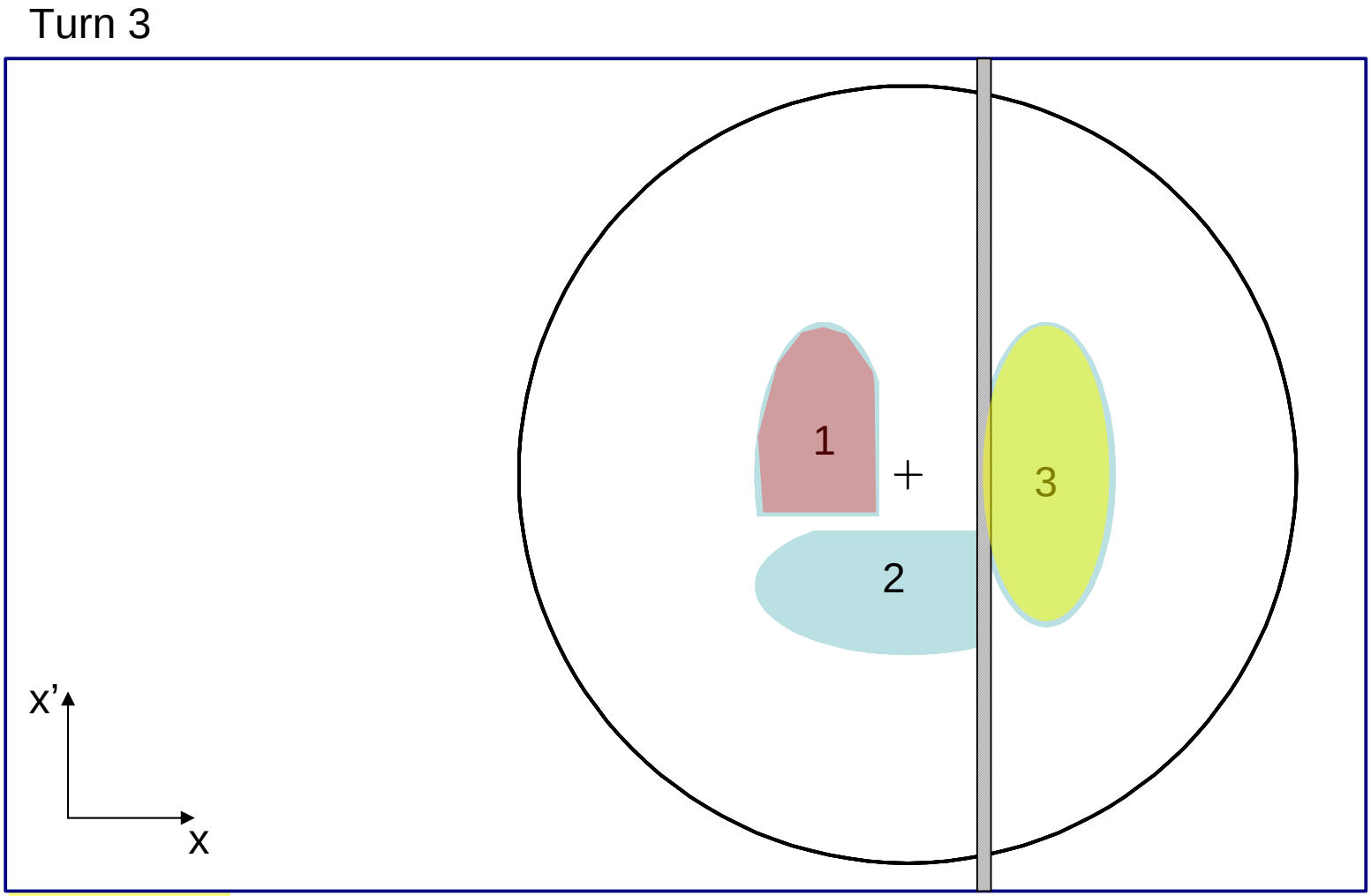

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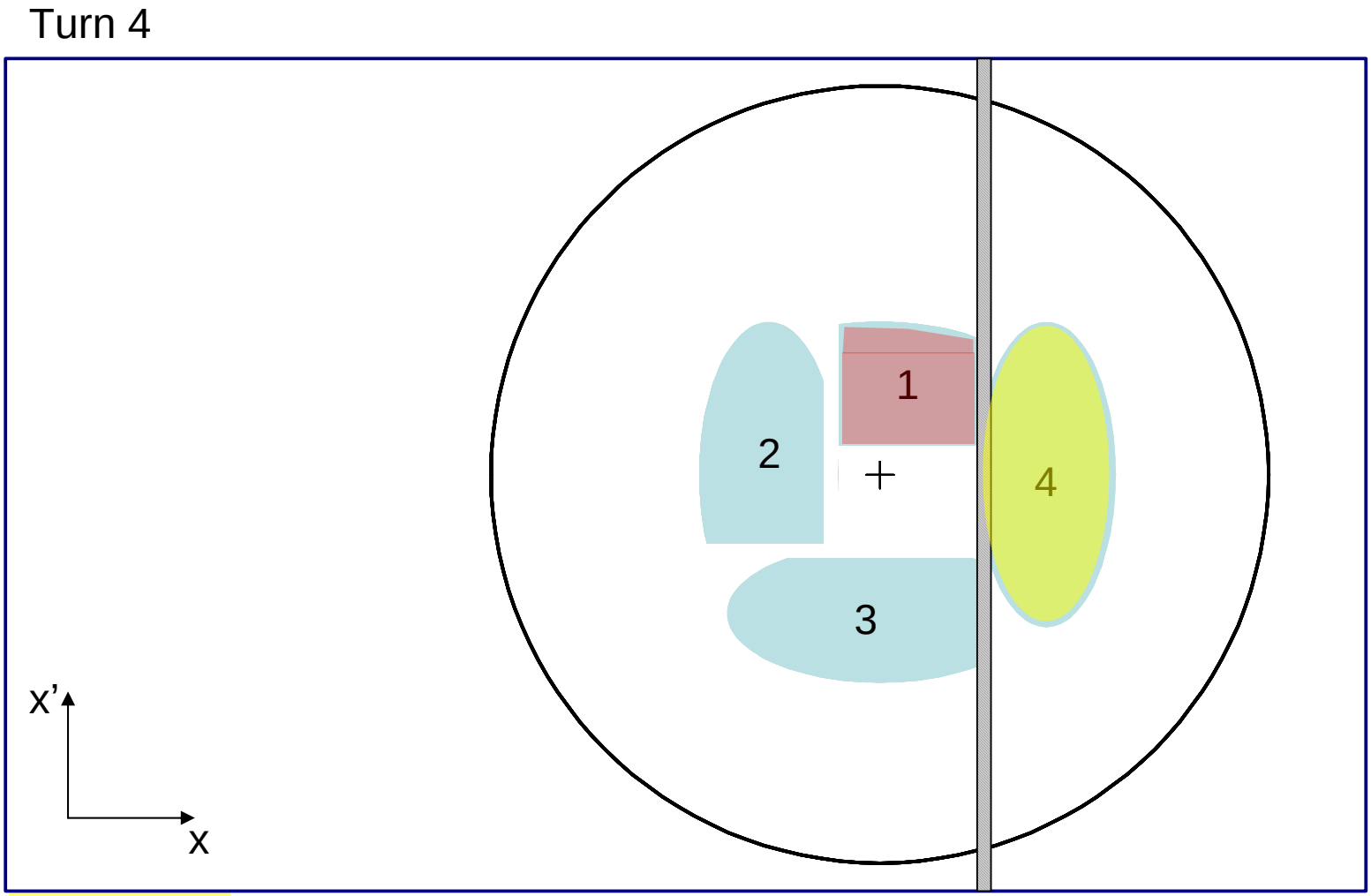
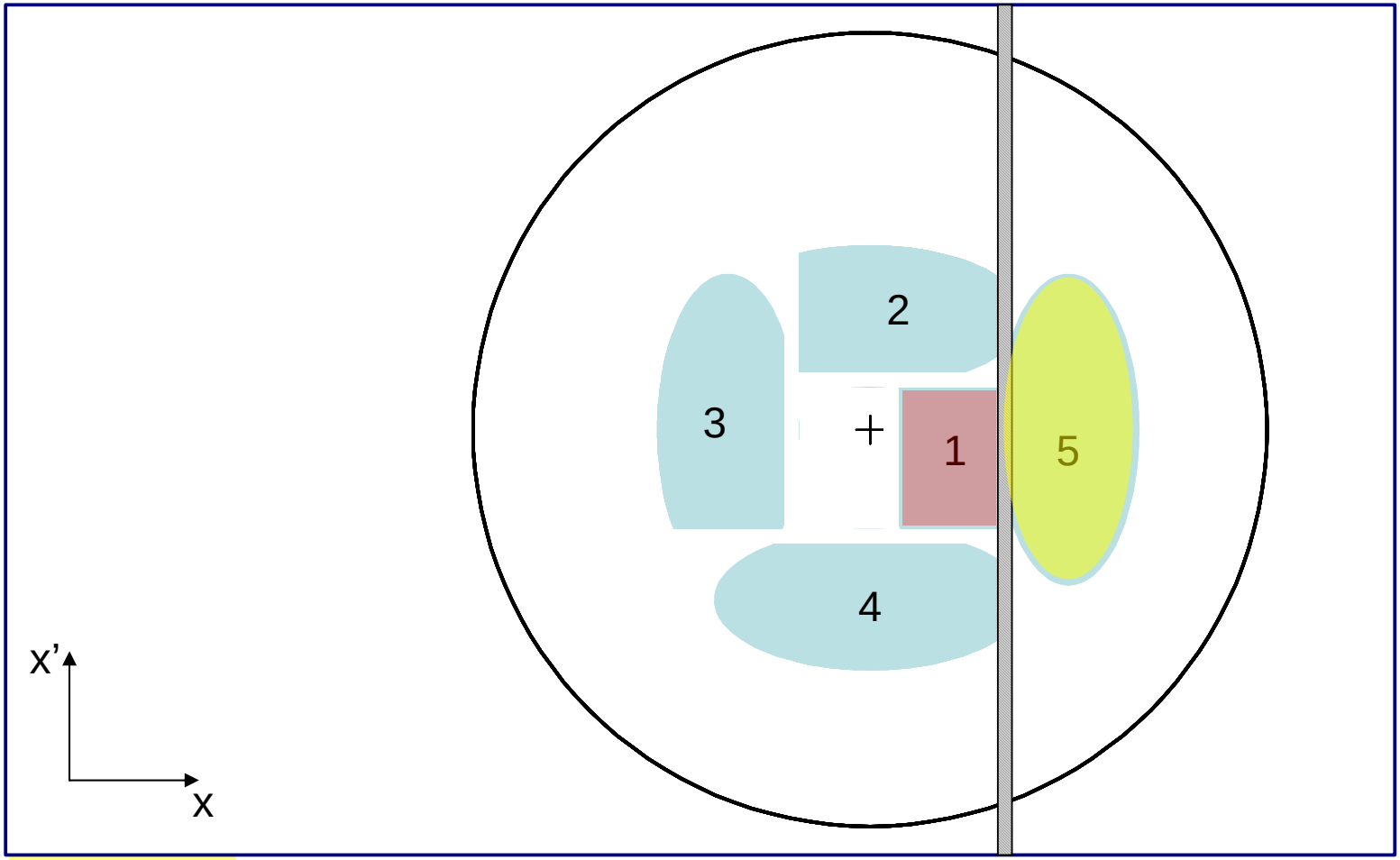


B. Goddard

Multi turn injection

Turn 5

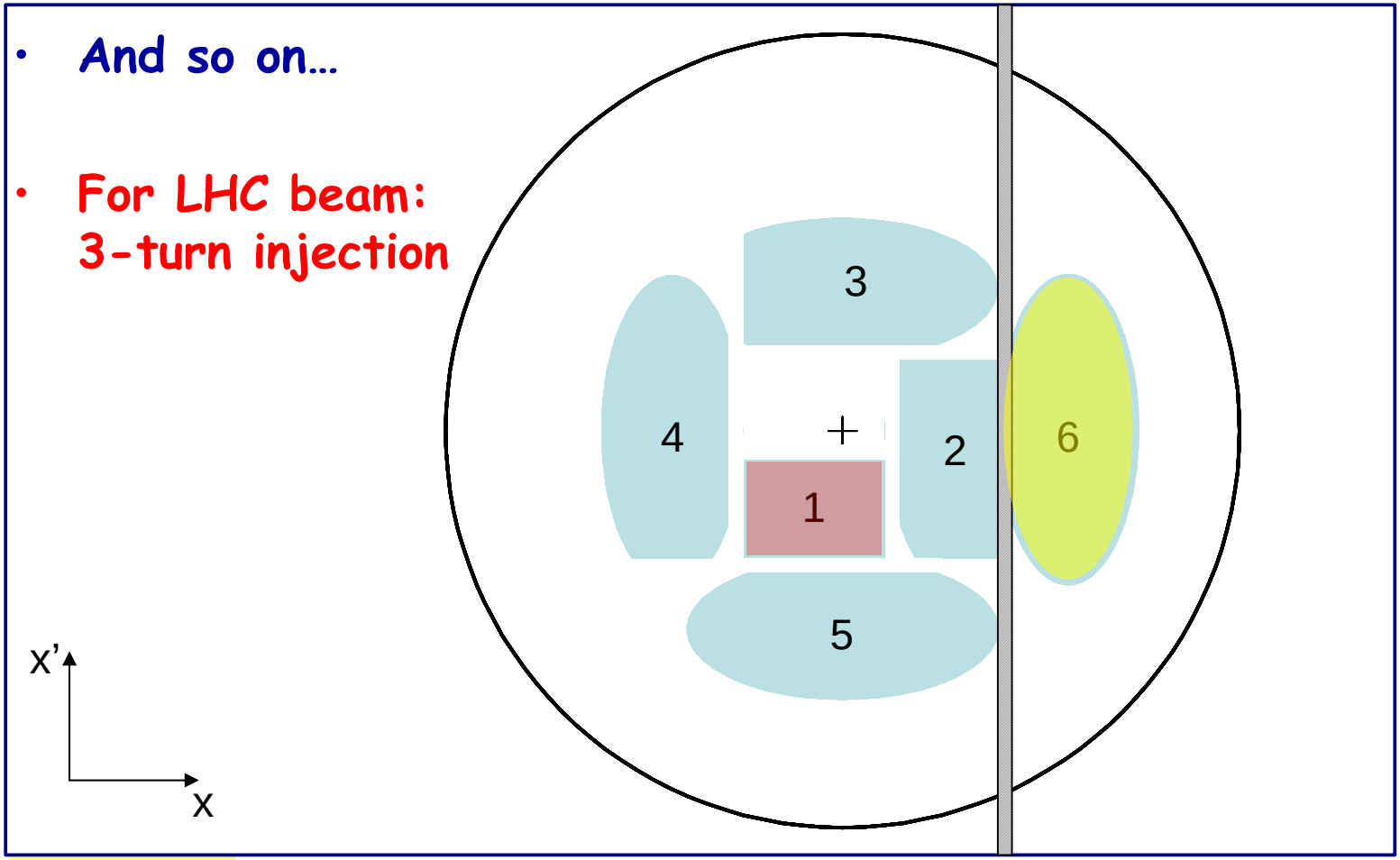


B. Goddard

Multi turn injection

Turn 6

- And so on…
- For LHC beam:
  3-turn injection



B. Goddard

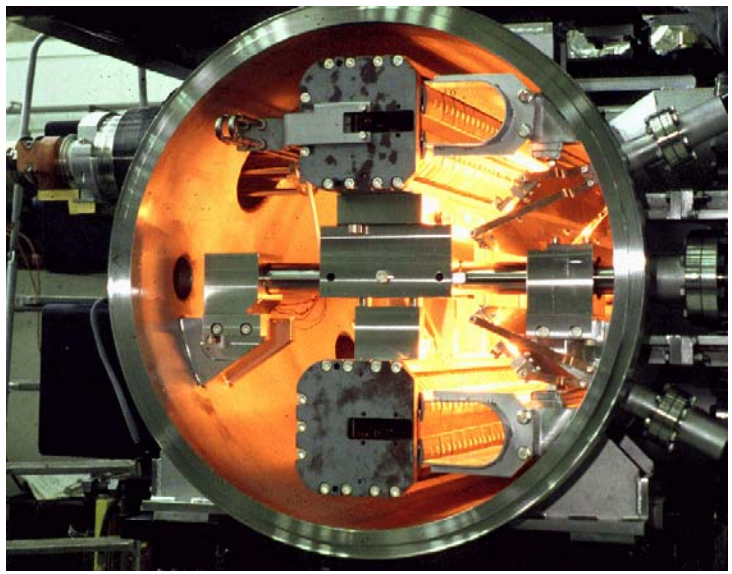
How to beat space charge in the PS

- Act on the relativistic parameters and not the beam brightness as for the PSB.

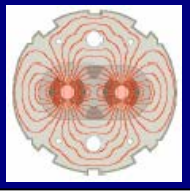
$$\Delta Q \propto -\frac{1}{\beta\gamma^2} \cdot \frac{N_b}{\varepsilon_n}$$

- Increase PS injection energy (PSB extraction energy) from 1 GeV to 1.4 GeV.
- Decreases space charge tune shift by factor 1.5 to $\Delta Q_y \approx 0.2$.
- Requirements:
  - Upgrade of PSB Main Power Supply.
  - New recombination septa & converters.
  - New generators and PFN for fast kickers.
  - New transfer line magnets & converters.
  - Upgrade of the PSB water cooling system.

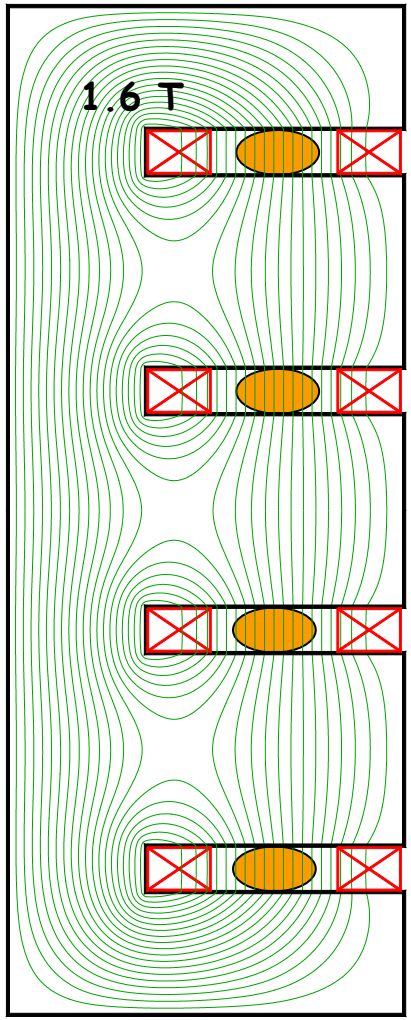
PSB ejection septa - double tank



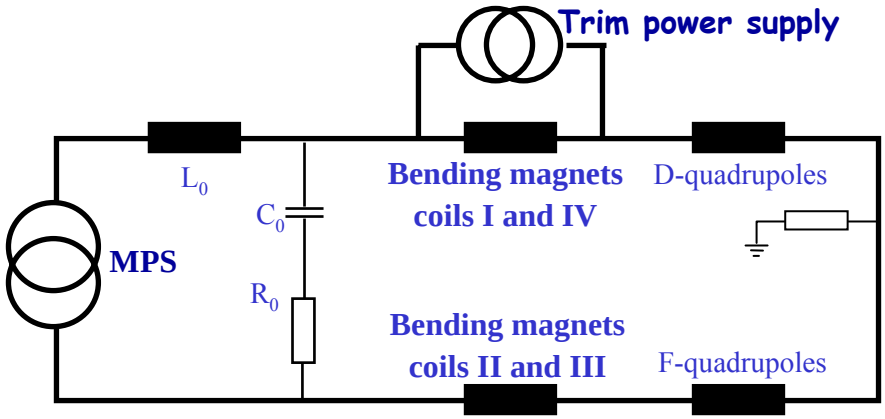
An "unforeseen" problem for PSB



Cross section
PSB main dipole magnet



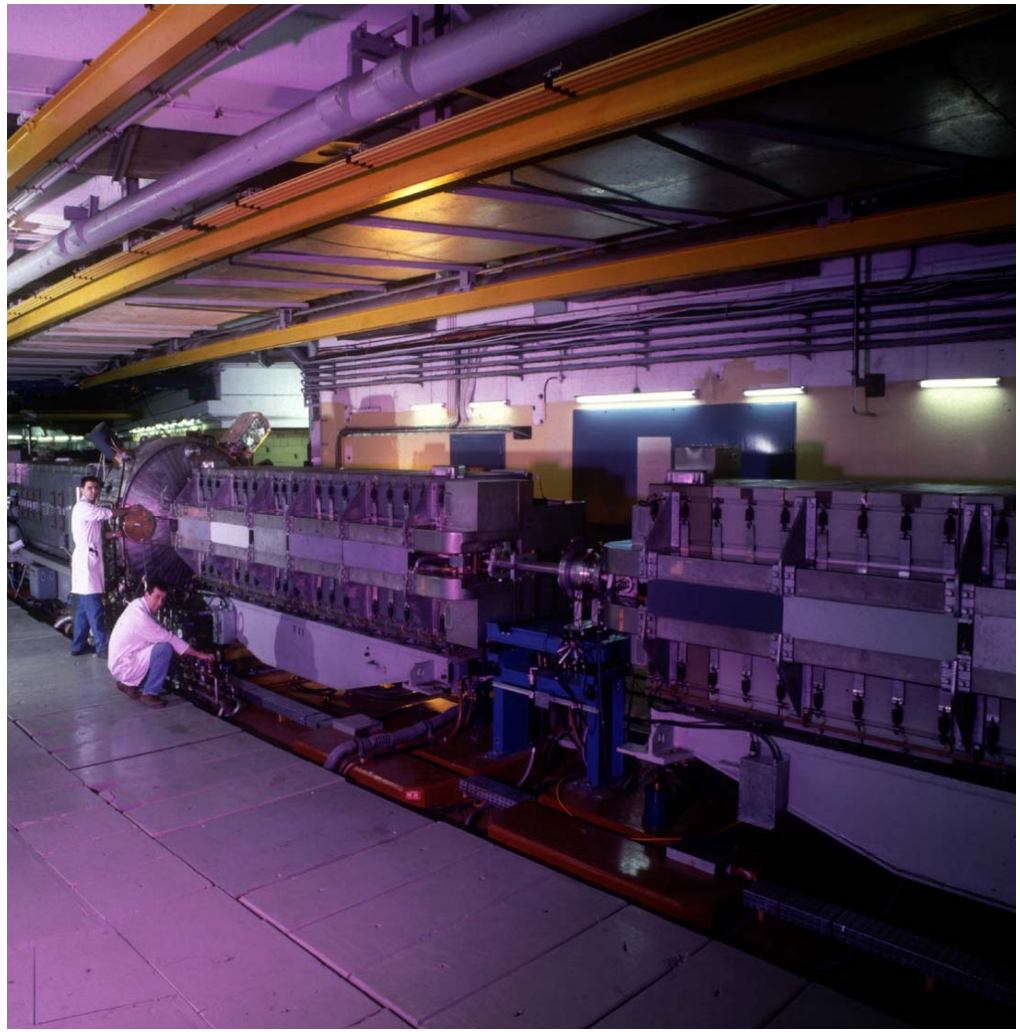
- **Main PSB bending magnets saturation**
  - Even though gap field is low (0.86 T @ 1.4 GeV), saturation in yoke corners due to special construction.
  - Higher magnetic resistance in outer circuits means lower field and gives different beam energies.
- **This problem was "easy" to resolve only because**
  - In 1970 potential problems with future energy upgrades were anticipated… and the cabling was done to allow for installation of a TRIM power supply.



Thanks to: A. Asner, G. Brianti, M. Giesch and K.D. Lohmann,
The PS Booster main bending magnets and quadrupole lenses, May 1970.

PS

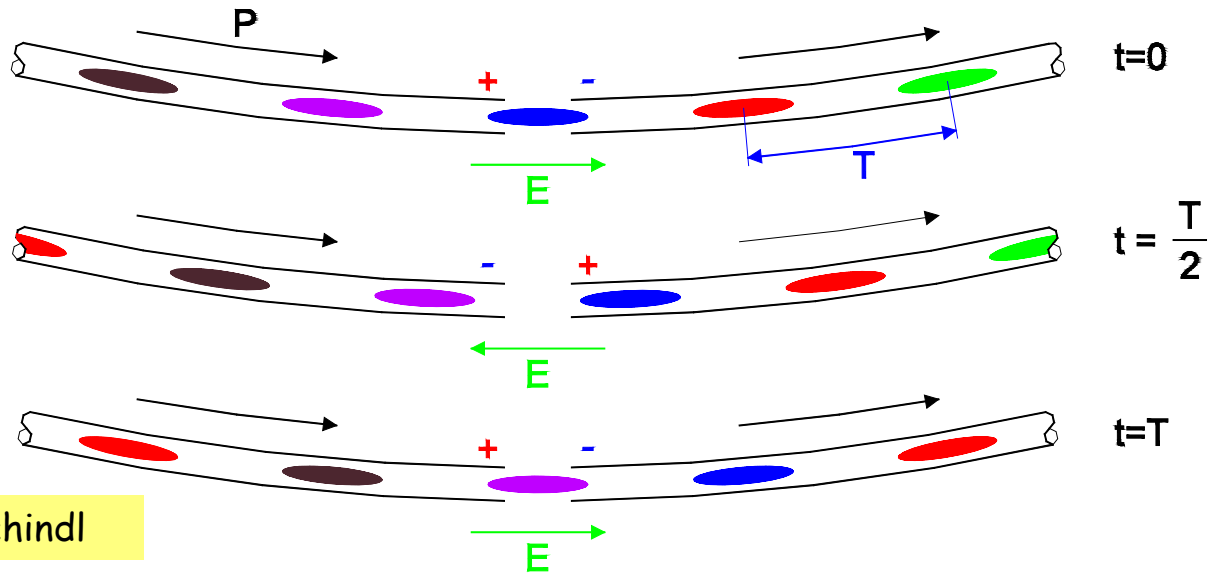
- Synchrotron (combined function magnets)
- Double batch injection from PSB (4 + 2 bunches 1.2 s later).
- Acceleration 1.4 to 25 GeV.
- Cycling time 3.6 seconds
- Creation of the 25 ns bunch train for LHC.
- Shortening bunches for SPS.



RF harmonics and bunches

- **Accelerating RF and the Beam revolution frequency are linked:**
  - With $f_{RF} = f_{rev}$ only one bunch can be formed and accelerated. The "correct" accelerating voltage is only established once per turn.
  - For **$f_{RF} = h \cdot f_{rev}$, h bunches ban be accelerated**, the synchronous condition is fulfilled h times per revolution period.

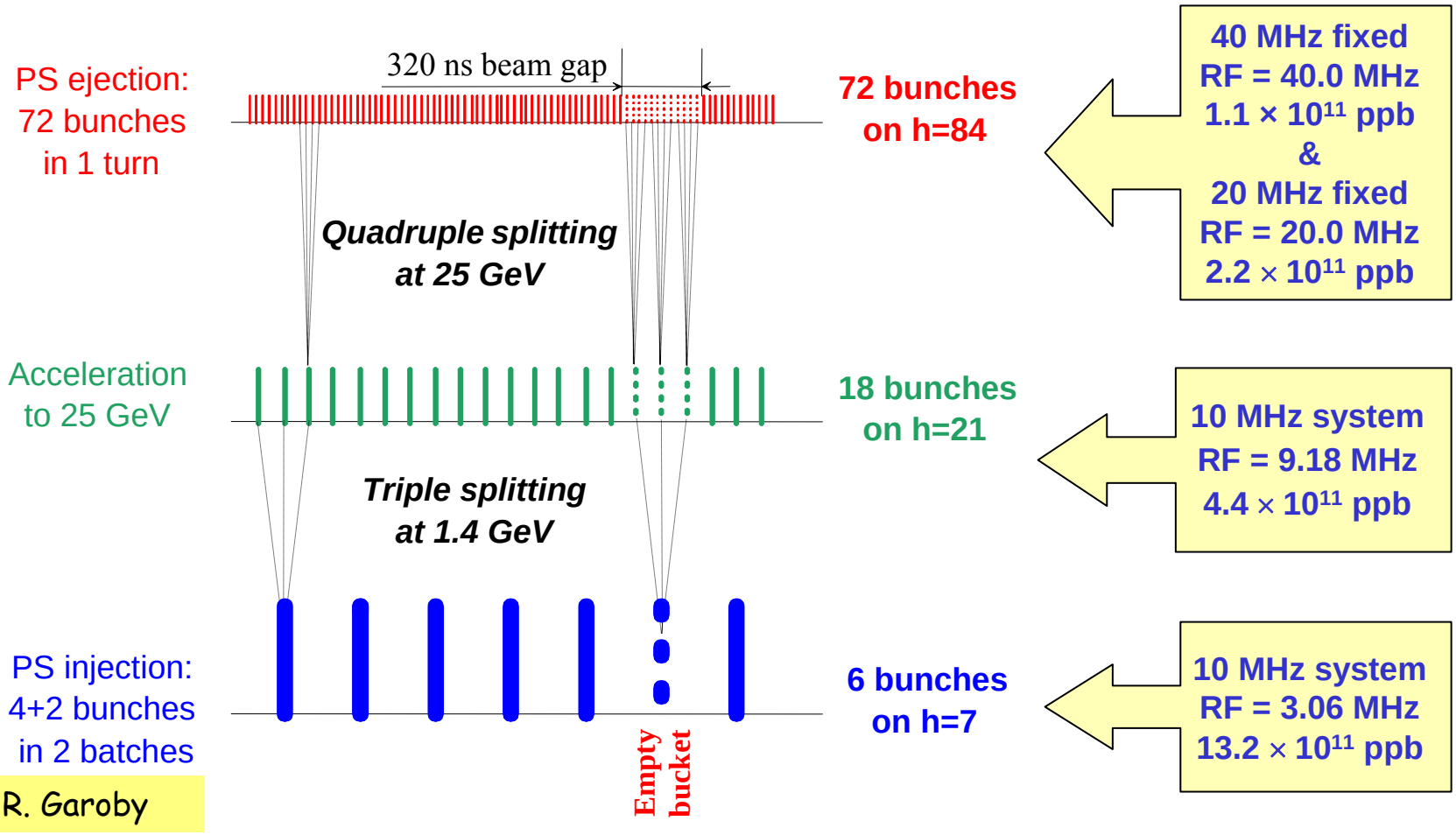
- **This integer h is called the harmonic number.**



K. Schindl

Generation of 25 ns bunch train in PS

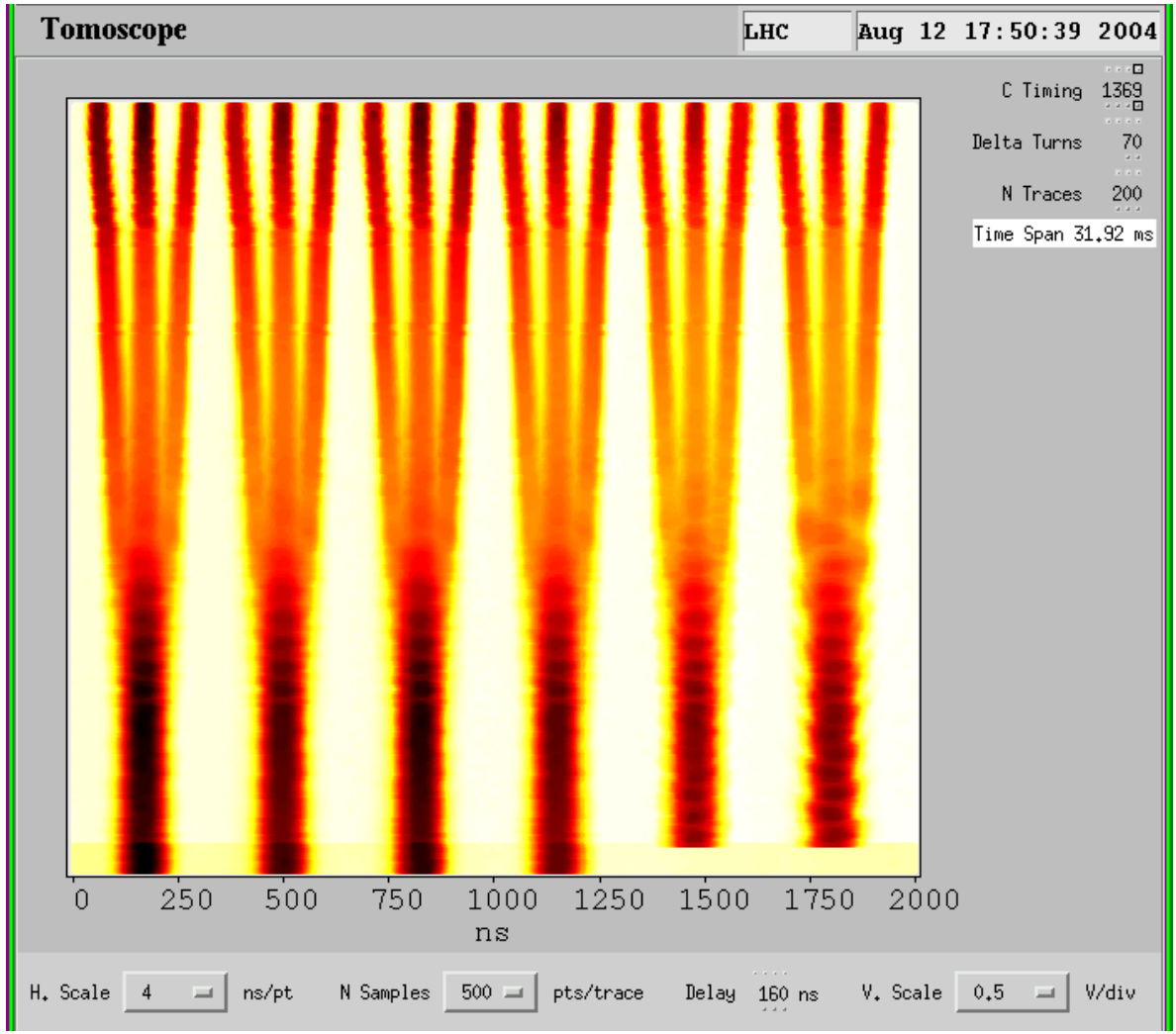
- **Longitudinal bunch splitting (basic principle)**
  - Reduce voltage on principal RF harmonic and simultaneously rise voltage on multiple harmonics (adiabatically with correct phase, etc.)



R. Garoby

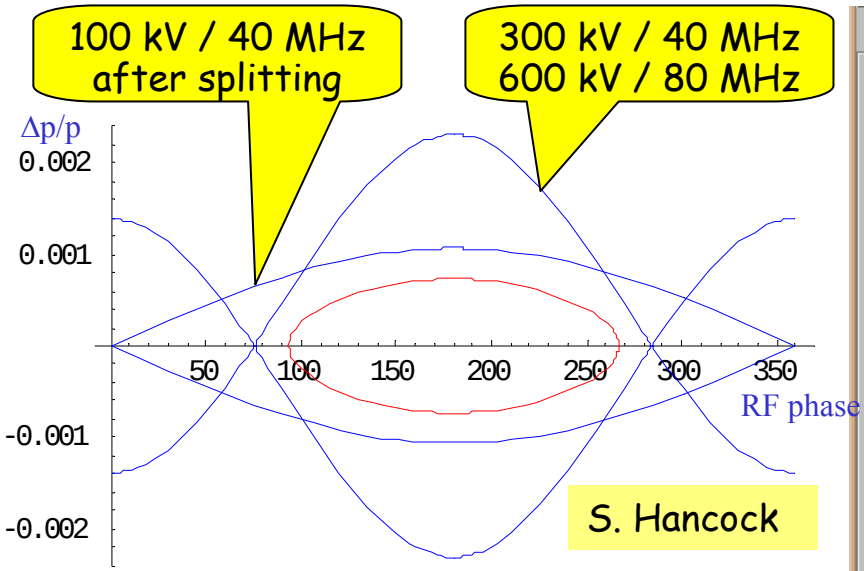
Triple splitting at 1.4 GeV

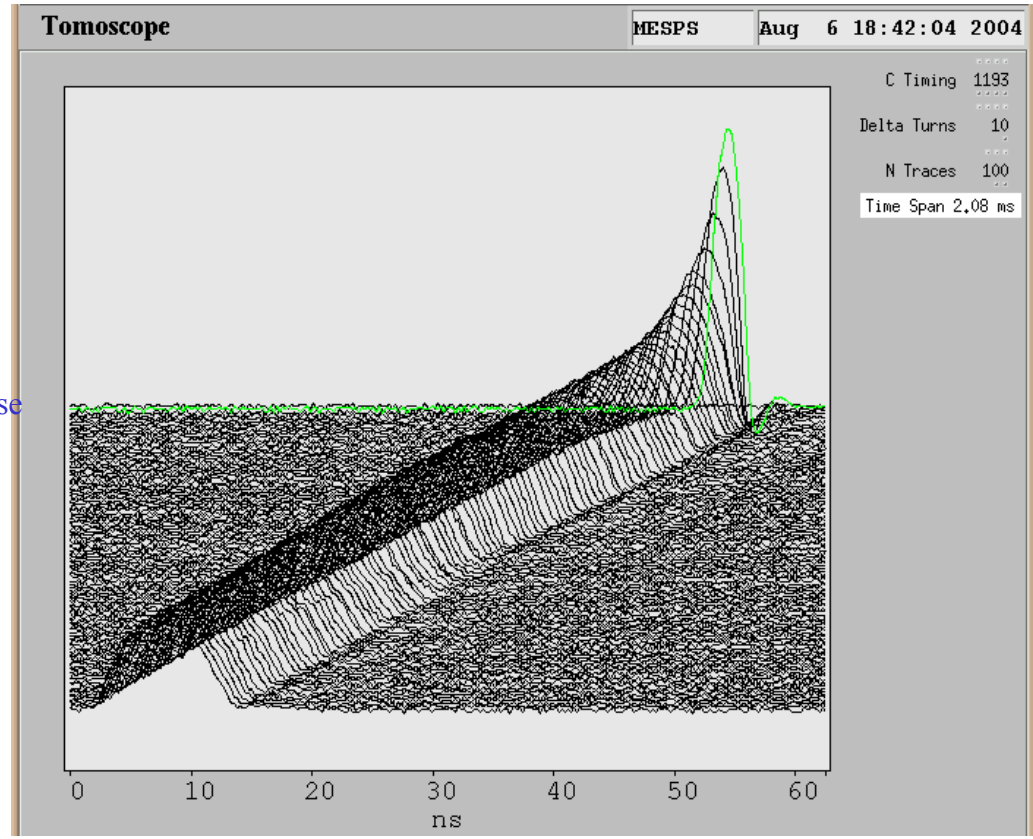
- Waterfall view of longitudinal gymnastics
- Injection of 2nd PSB batch (bunches 5 & 6)
- Triple splitting with different cavities of 10 MHz system.
  - h=7 to h=21
  - Horizontal scale 2μs (~1 turn)
  - Vertical scale 32 ms
  - Z-direction intensity



Shortening the bunches for the SPS

- The 72 bunches in the 40 MHz buckets are 12 ns long and have to be shortened to < 5 ns to fit the SPS 200 MHz system.
  - Increasing the voltage shortens the bunch.
  - High voltage is cheaper at higher frequency – therefore 40 & 80 MHz



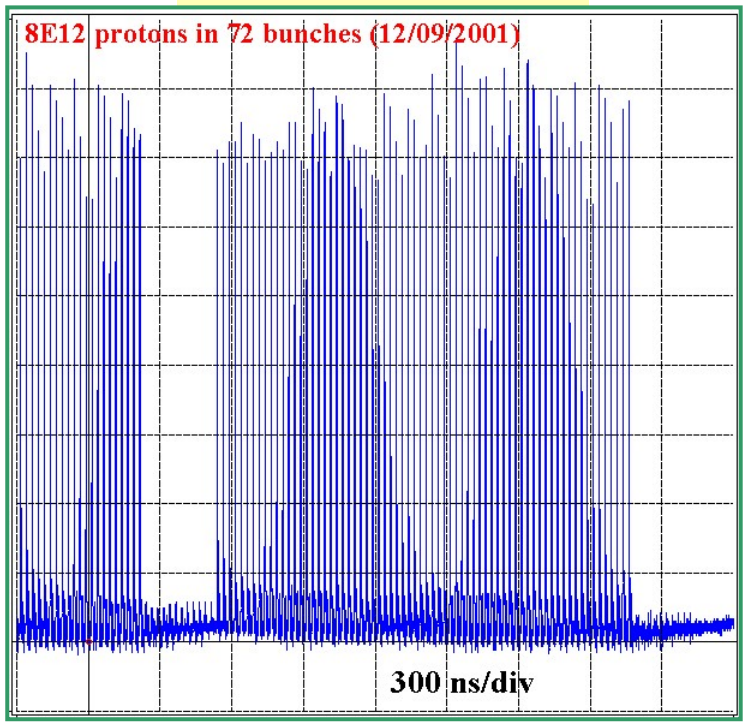


- Requirements for RF gymnastics in PS:
  - New 40/80 MHz RF systems.
  - New RF beam control.

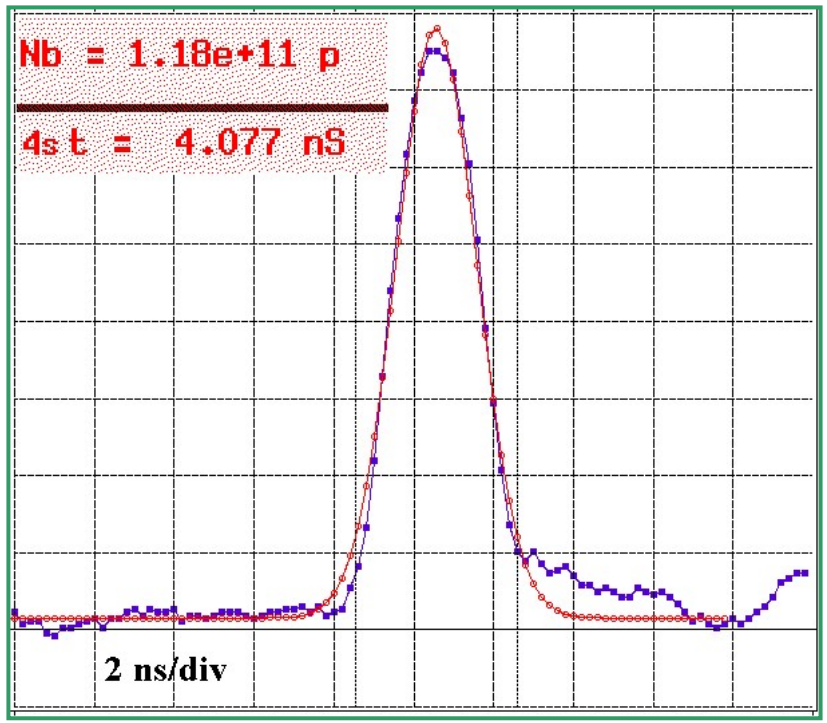
Performance of nominal LHC beam

- Required performance is achieved in routine operation.
- 72 bunches of 1.15×10^{11} ppb every 3.6 s for SPS.
- Bunch length ~4 ns, spacing 25 ns, $\varepsilon_{n,rms} < 3$ μm.

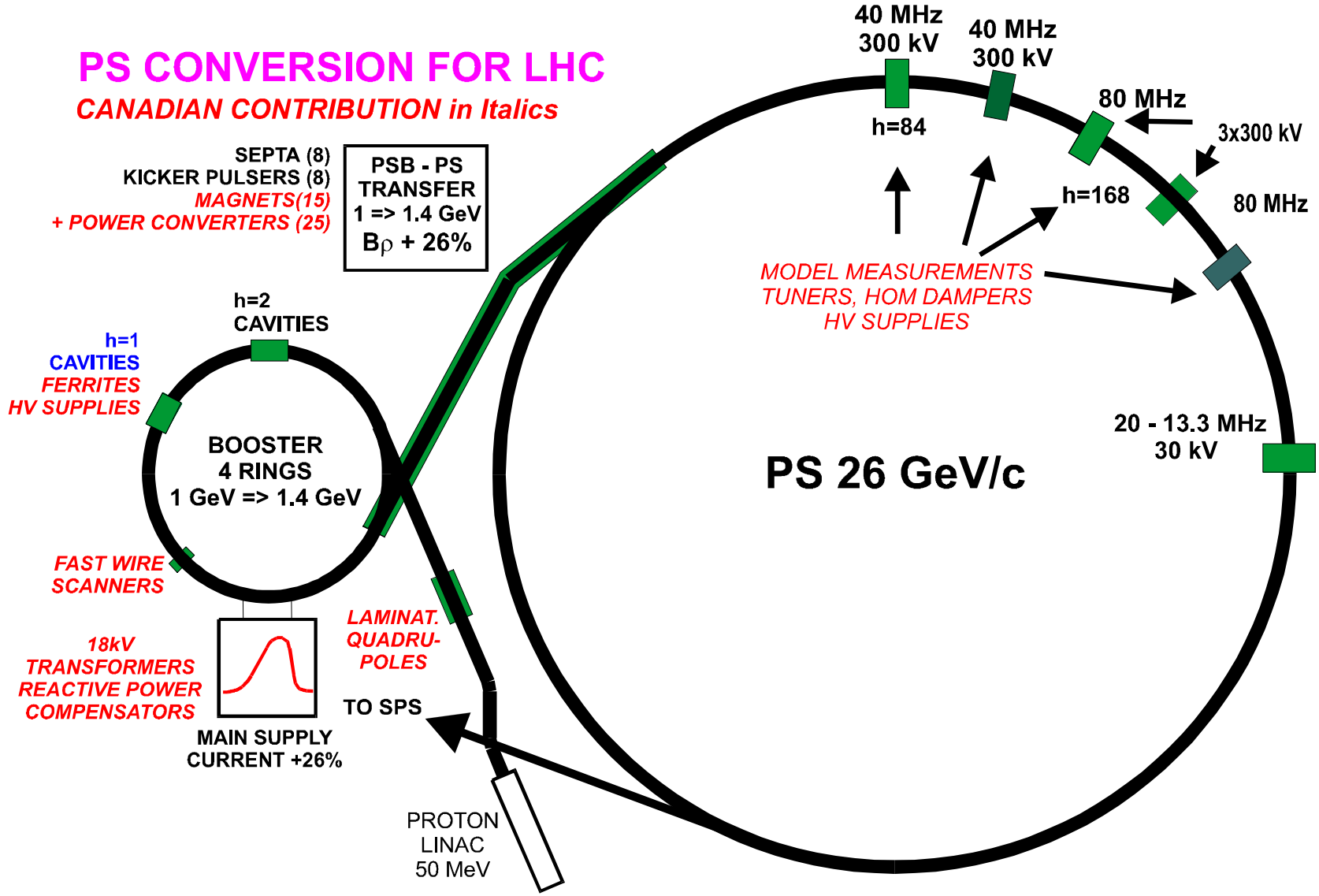
Bunch train
1.1×10^{11} p/bunch
Modulation ± 10 %



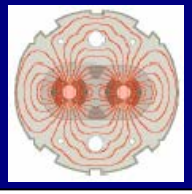
Bunch length
4.0 ns ± 0.2 ns



Summary: "PS for LHC" Conversion



Summary



- The PS Complex delivers the nominal beam for the LHC in standard operation.
- Efforts are now focusing on special beams, e.g. single bunch beams and ultimate intensities.
- Tomorrow's lecture will cover the proton aspects of SPS and LHC injection lines.