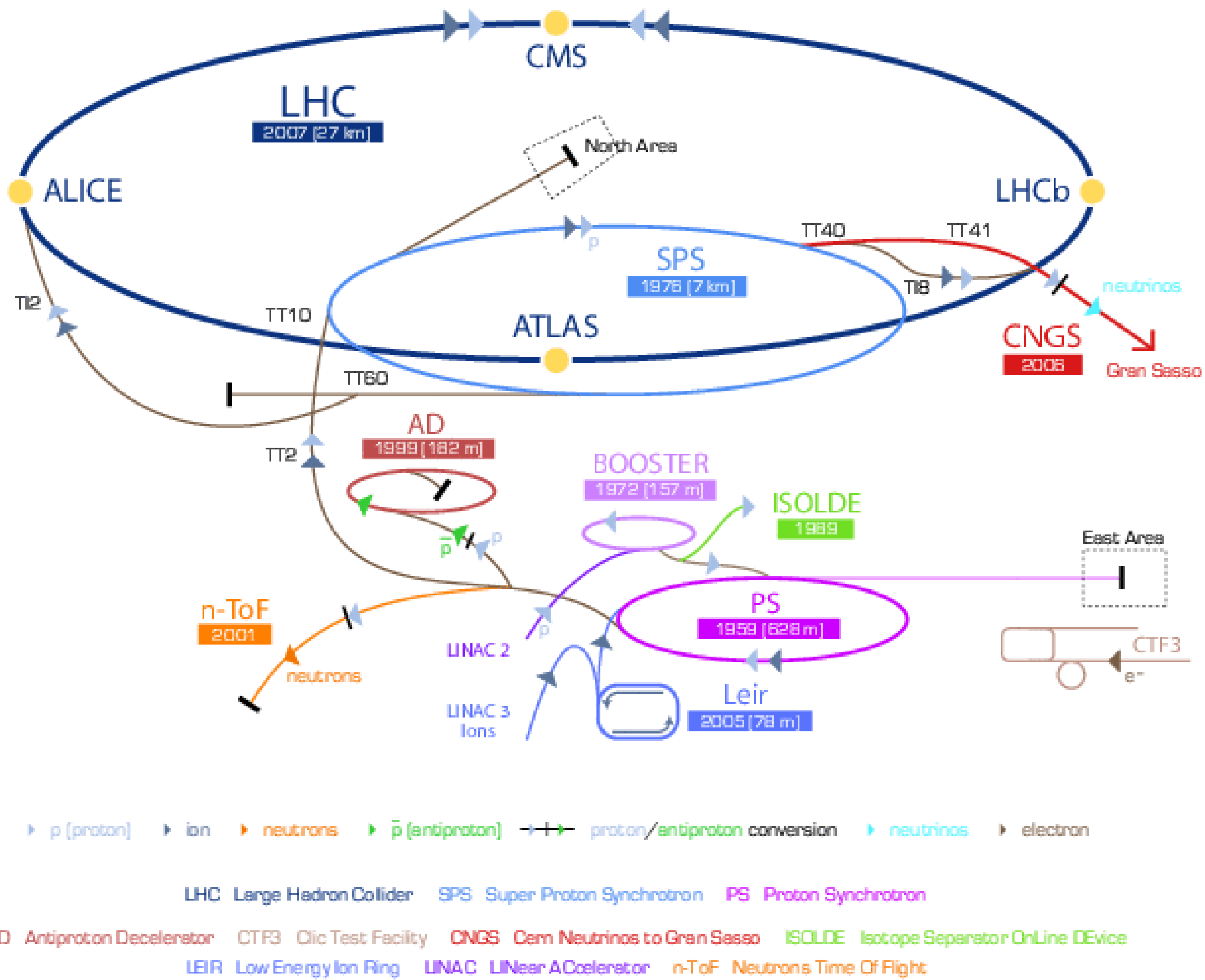
CERN System of Accelerators

Lecture 2

Frank Zimmermann, Pisa, 21 May 2007

Thanks to Franco Cervelli & Walter Scandale

CERN Accelerator Complex



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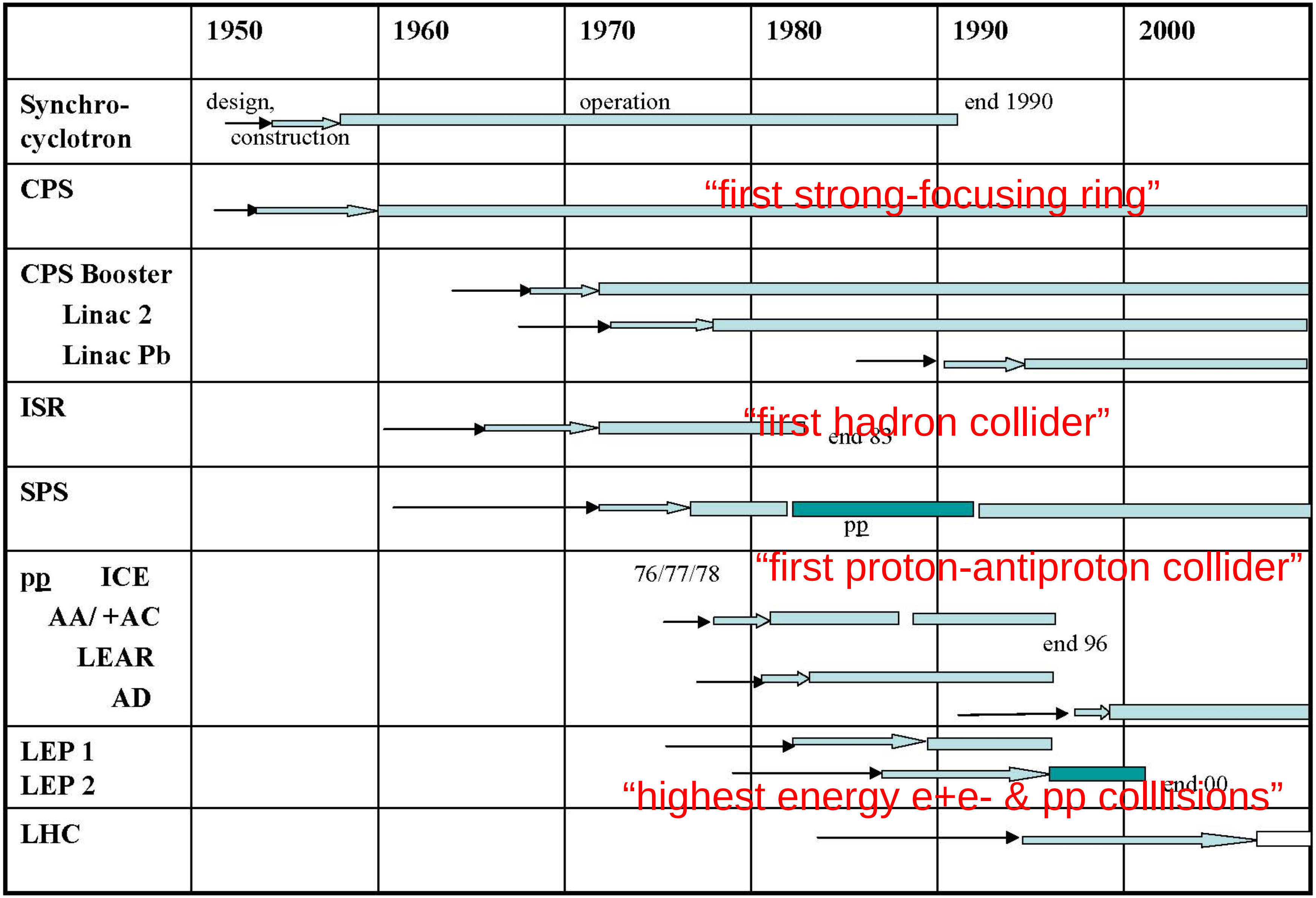
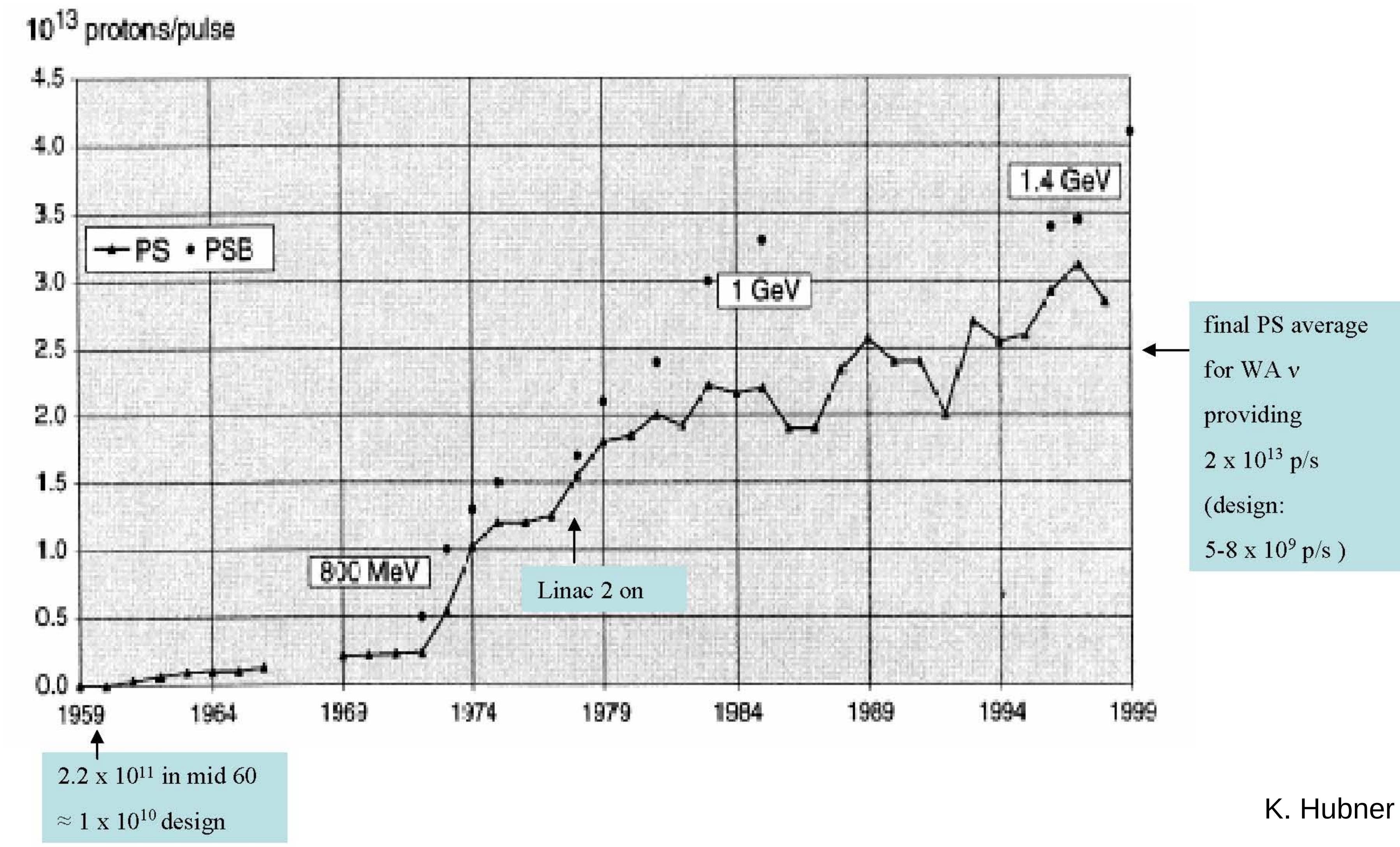
Evolution of Accelerator Park



Evolution of CPS and PSB Intensity



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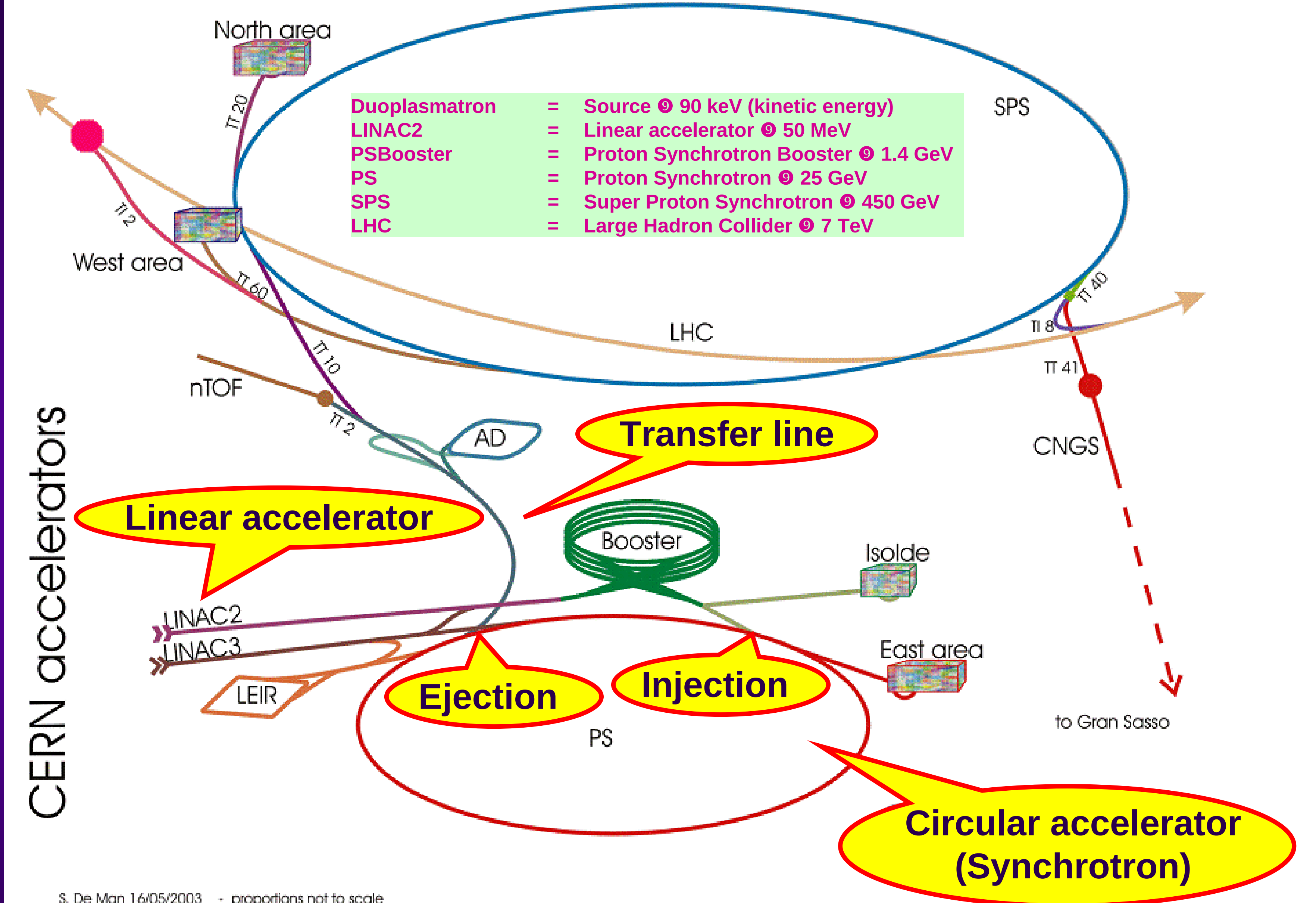


LHC and its injector chain

LHC requirements

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

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

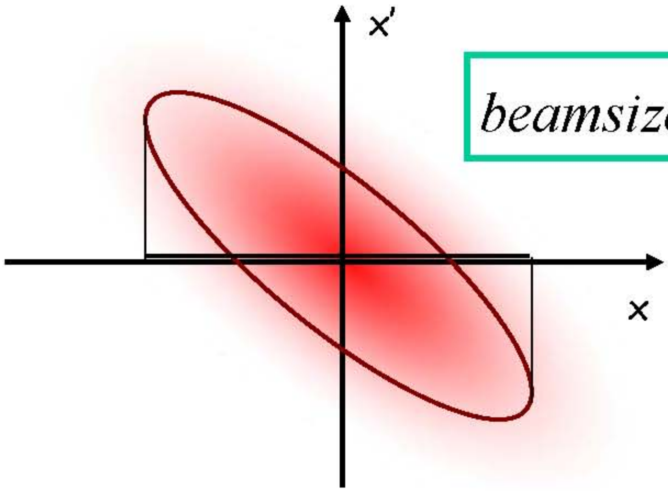
- k_b... number of bunches per ring.
- N_b.. Intensity per bunch.
- ε_n... normalized transverse beam emittance.

- **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...

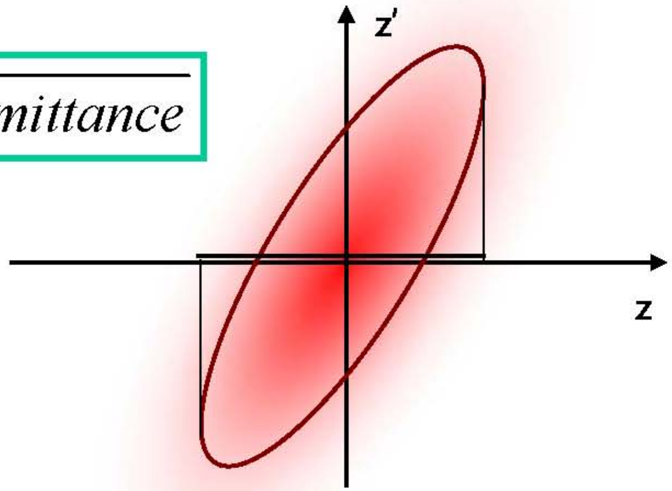
M. Benedikt

beam 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.



$$beamsize \propto \sqrt{emittance}$$



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

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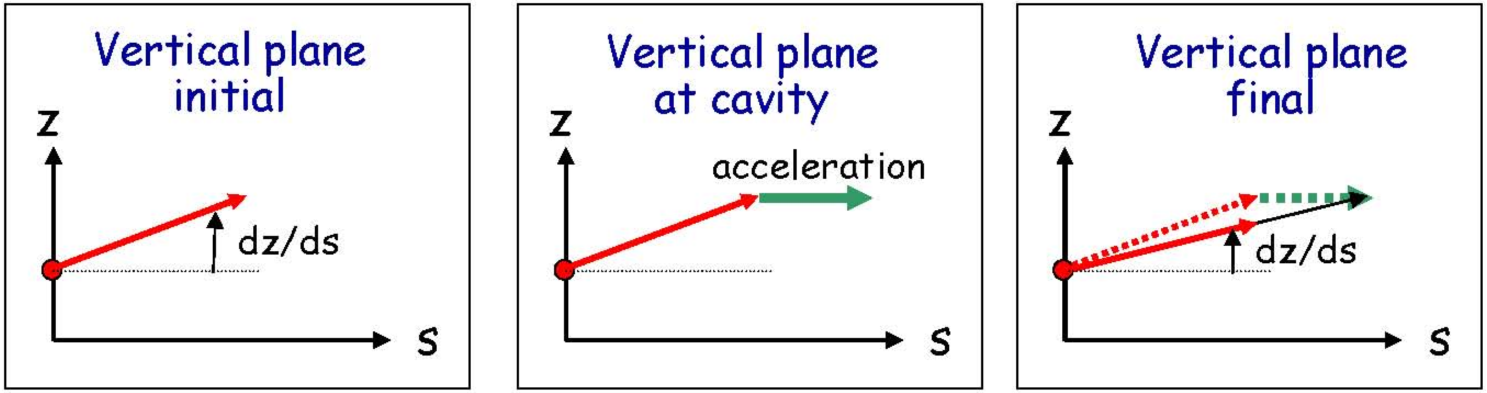
adiabatic damping of emittance

- 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).

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LHC requirements – optimization result

- **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]	$\sim 0.3 \times 10^{12}$	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

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PS proton accelerator complex

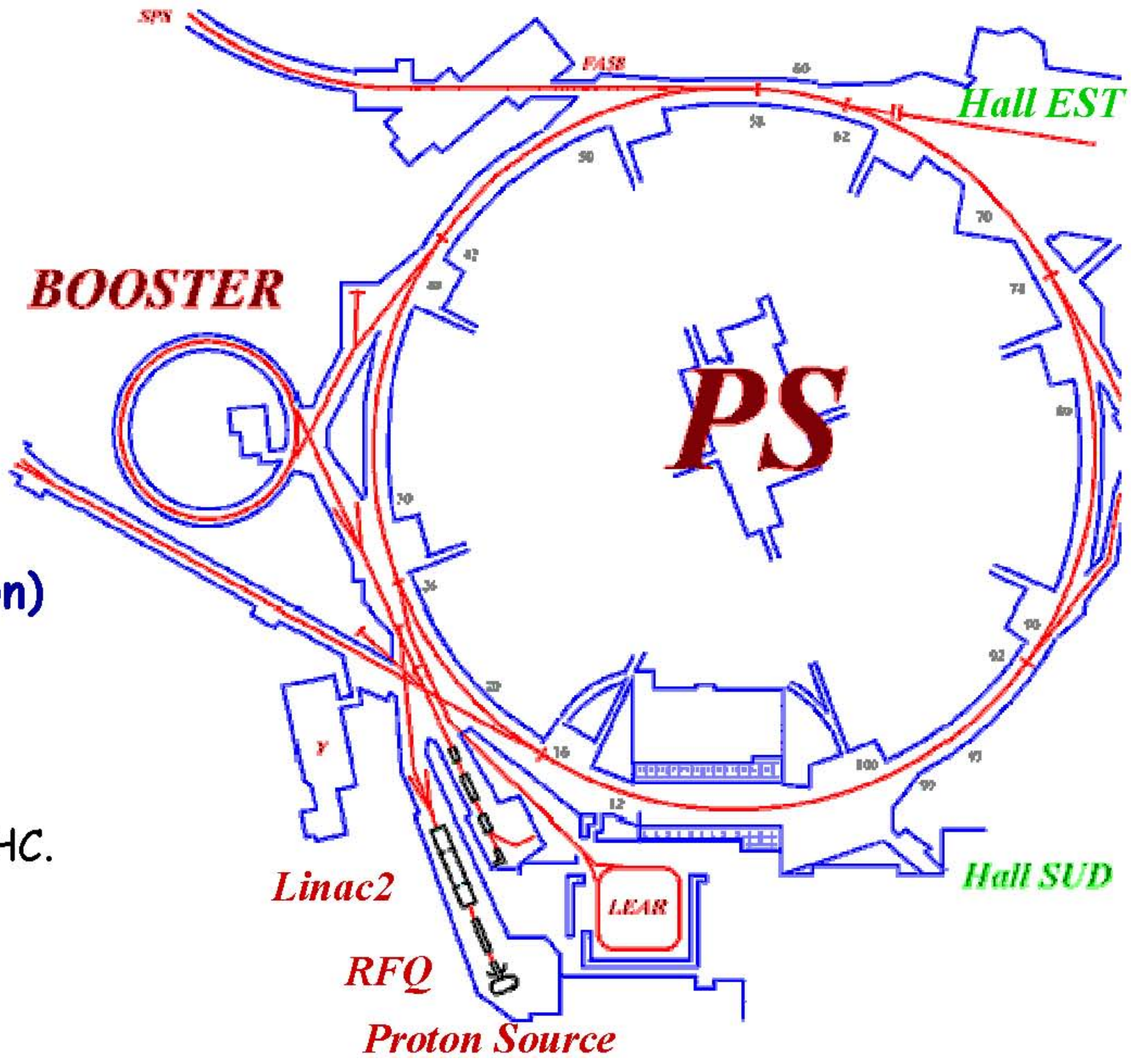
Proton Source
90 keV, pulsed every 1.2 s.

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.



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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.**

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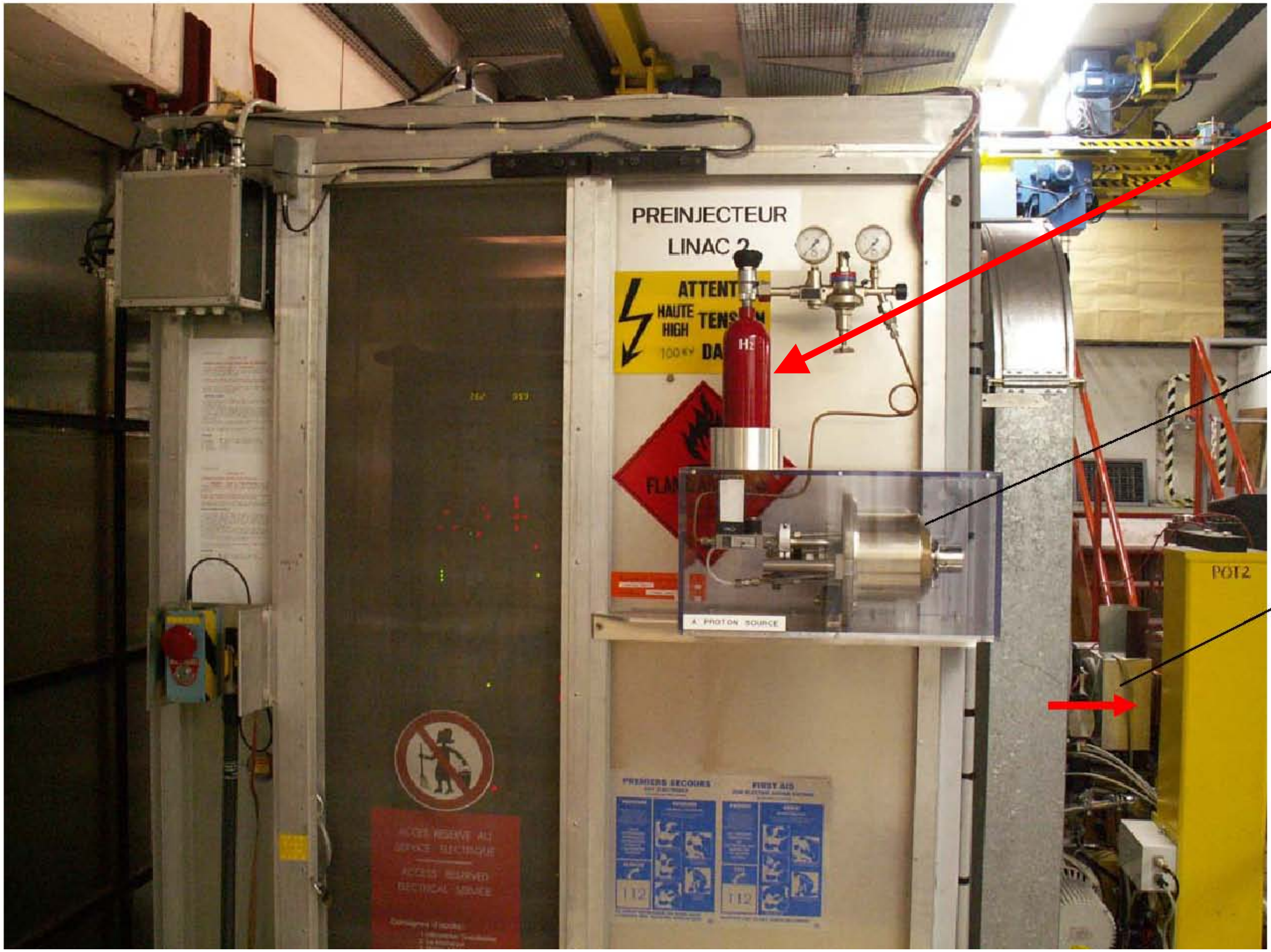
the beam starts from here…

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



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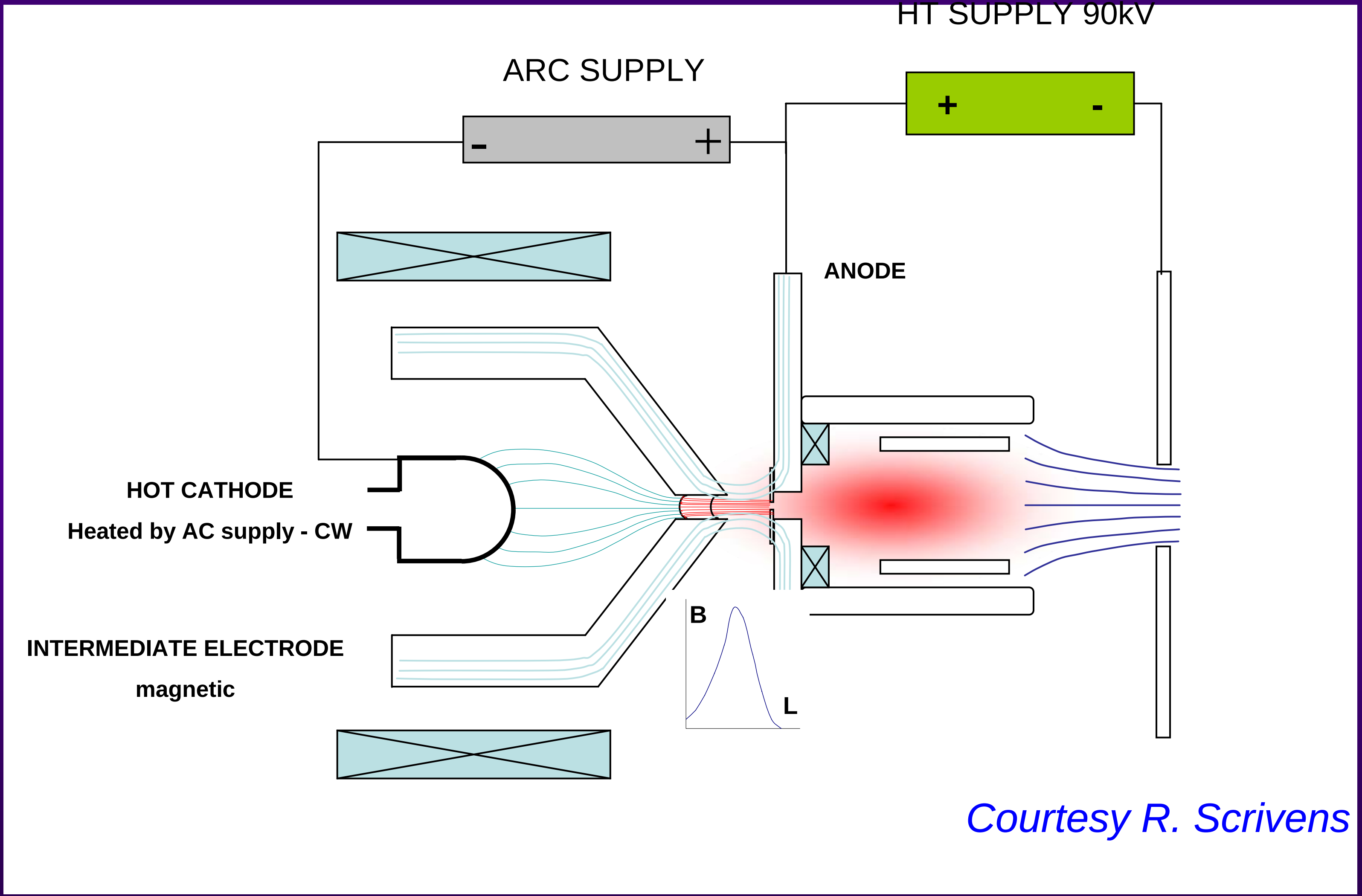
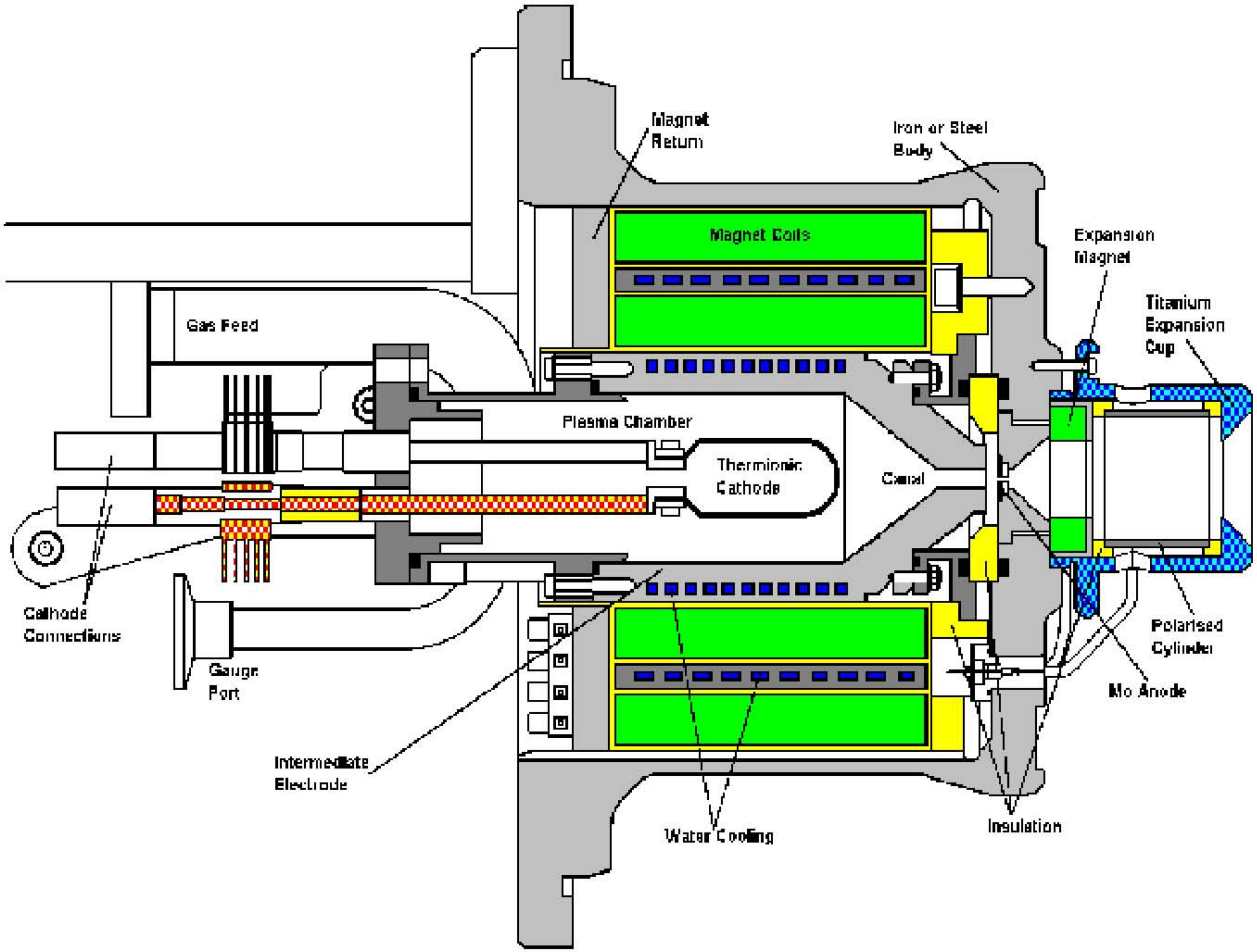
Duoplasmatron proton source

Protons (at 90 keV) are produced by the charging of a H_2 plasma due to interaction with free electrons from the cathode, forming a plasma; the plasma is then accelerated and becomes an ion beam



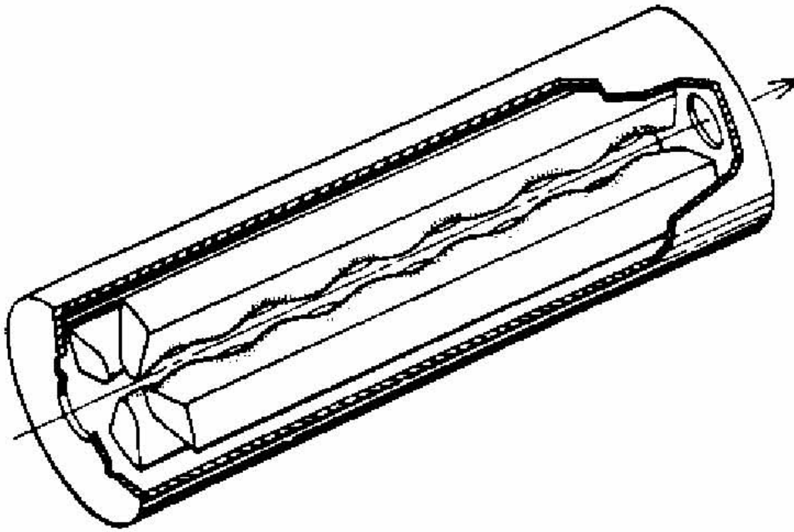
Invented by M. von Ardenne

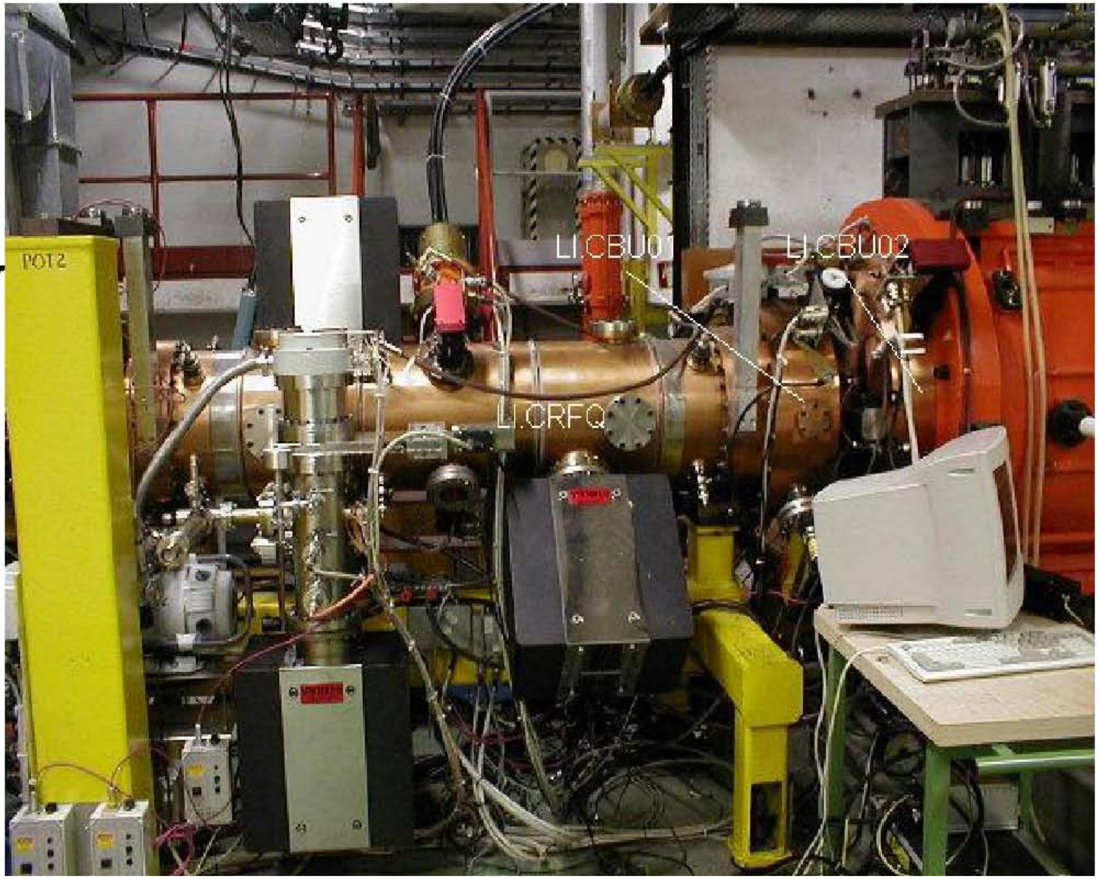
duoplasmatron proton source – 2



radiofrequency 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.





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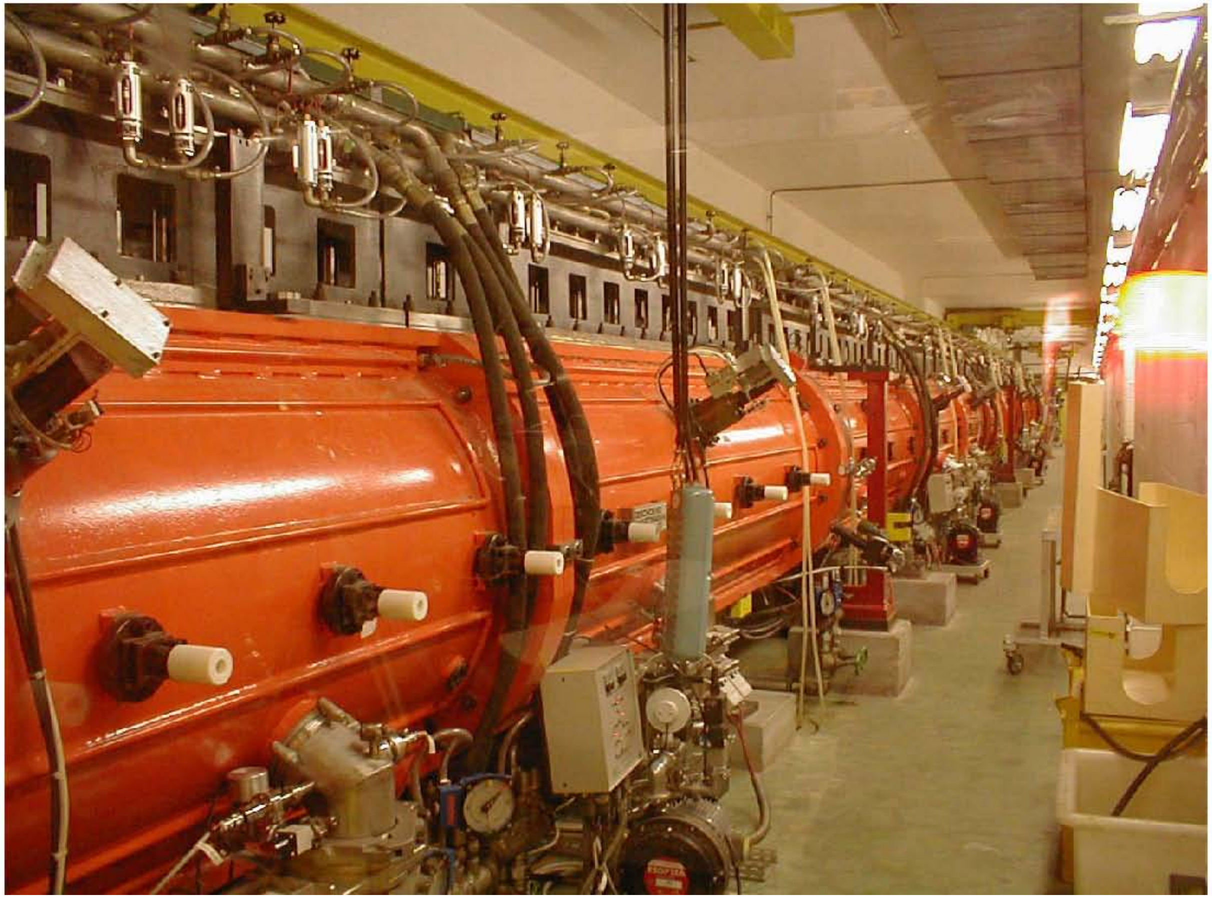
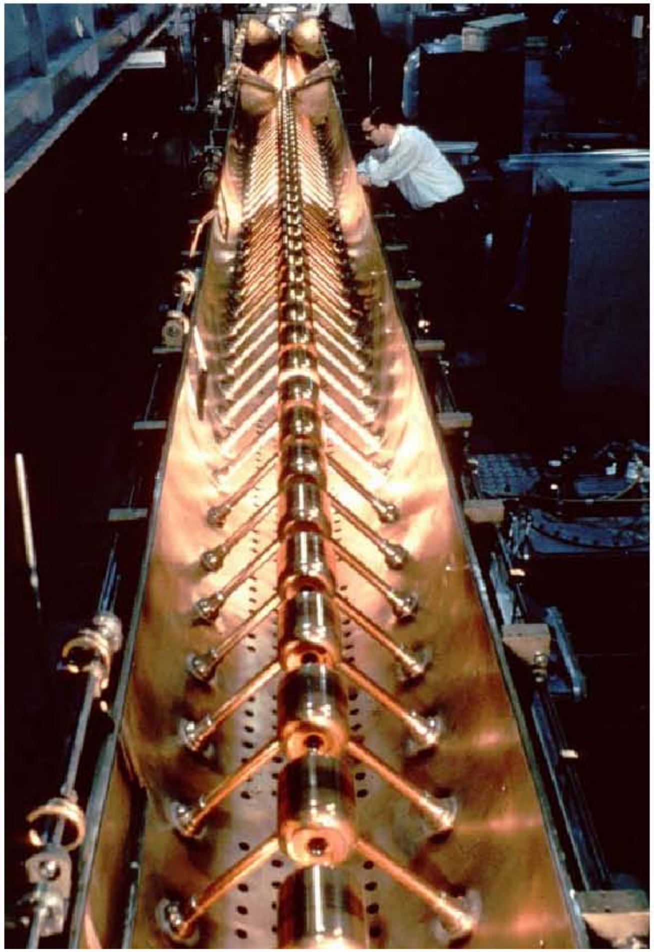
Linac2 (Alvarez structure or DTL)

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





1946 L. Alvarez et al / LBL

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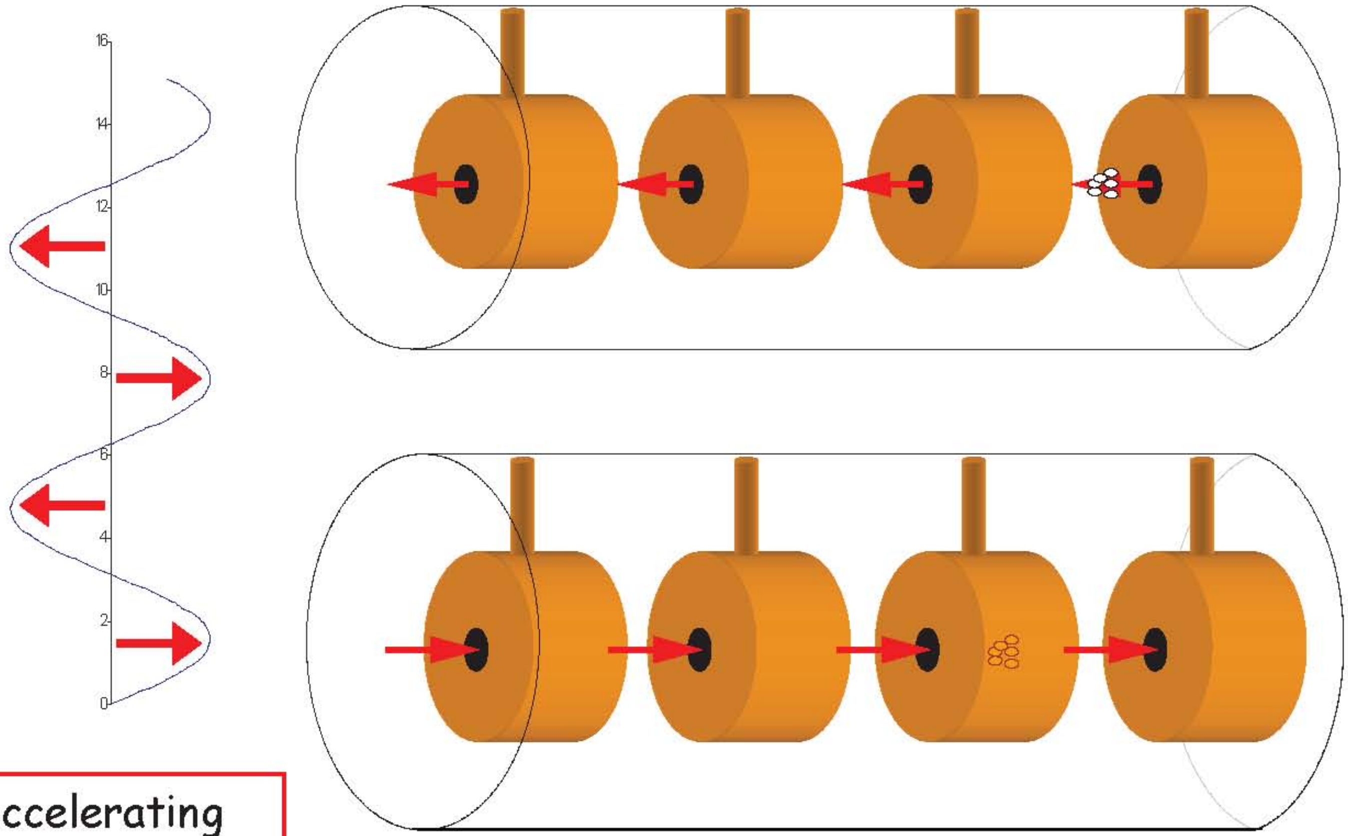
Alvarez operating principle



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).

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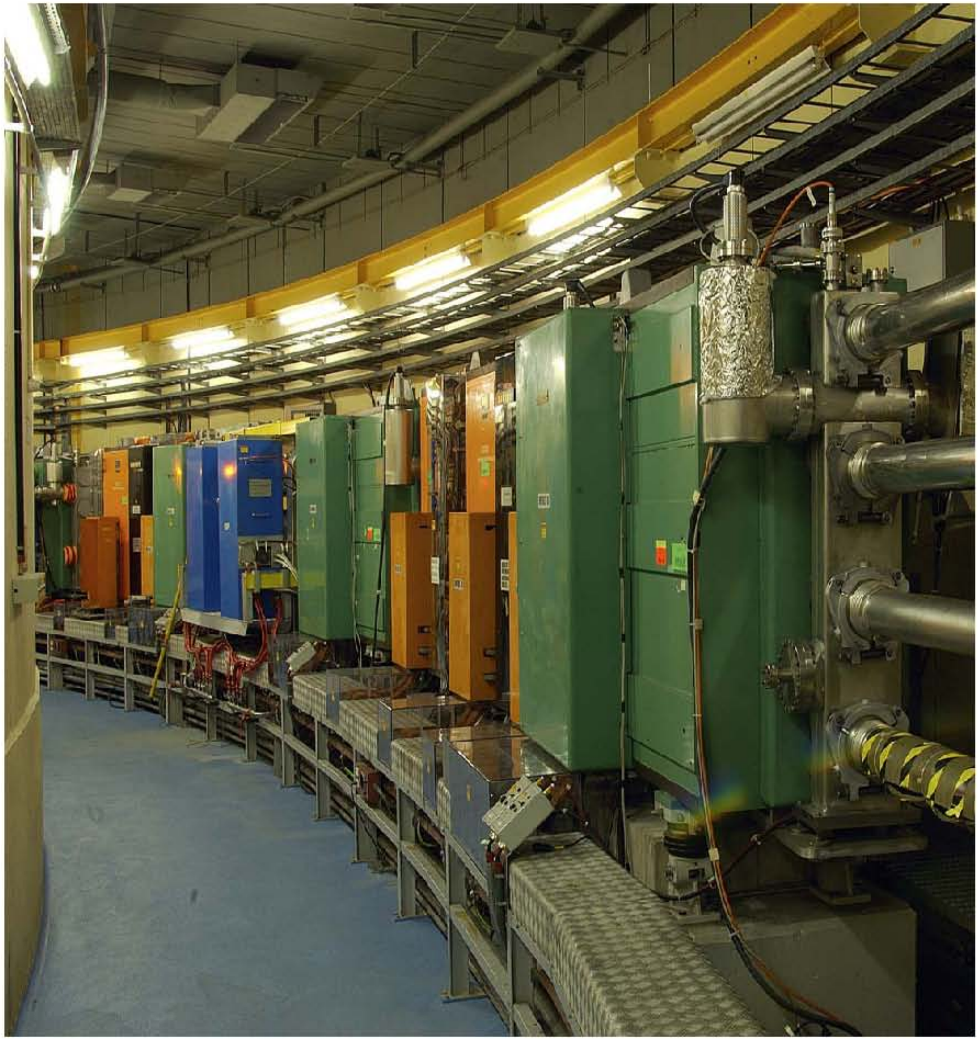
PS Booster

- 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.



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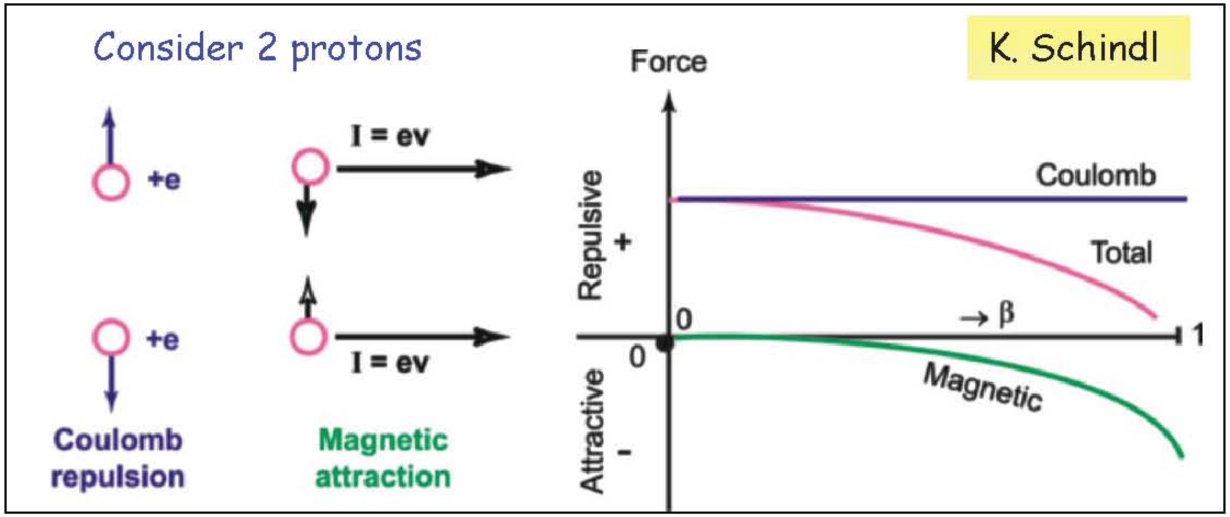
Space Charge

- **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.**

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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.

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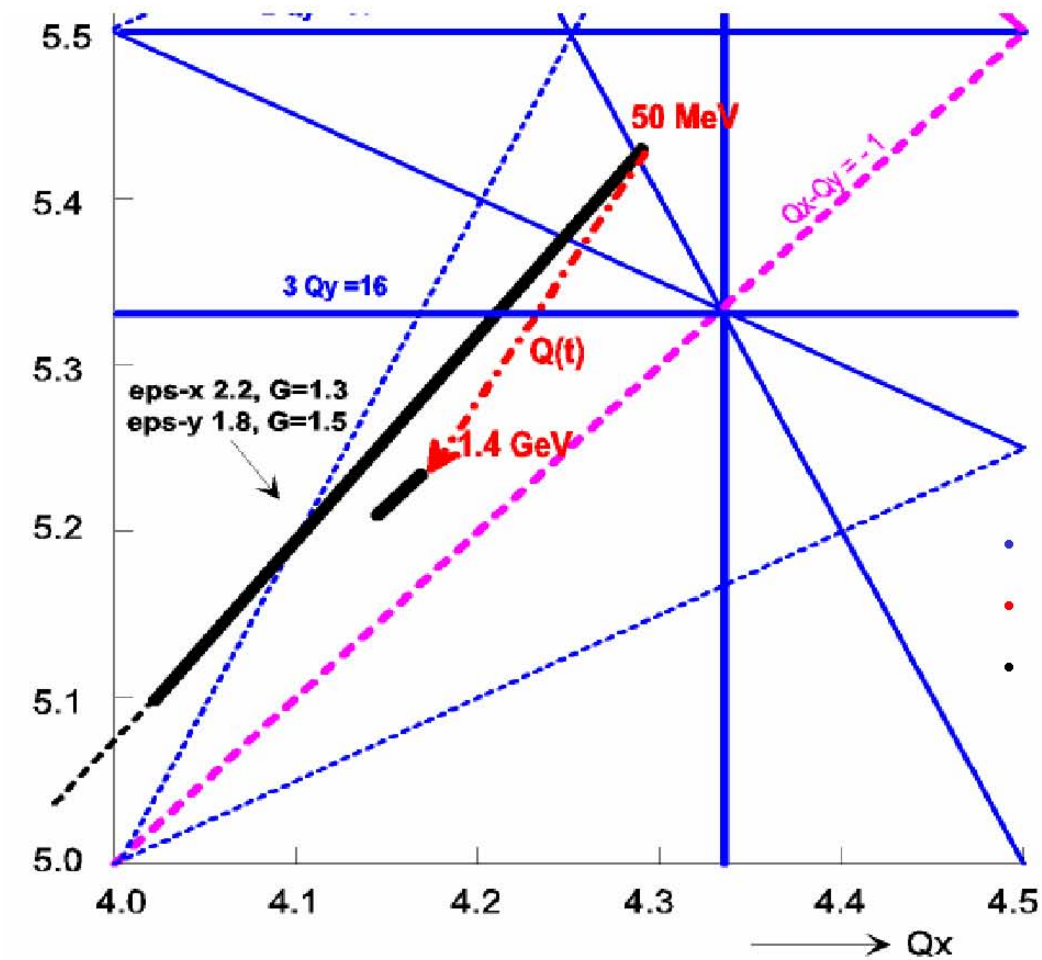
Space Charge Tune Spread

- Tune diagram of PS Booster for nominal LHC beam



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

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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 $\Delta Q_v \approx 0.4$.**
- **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.

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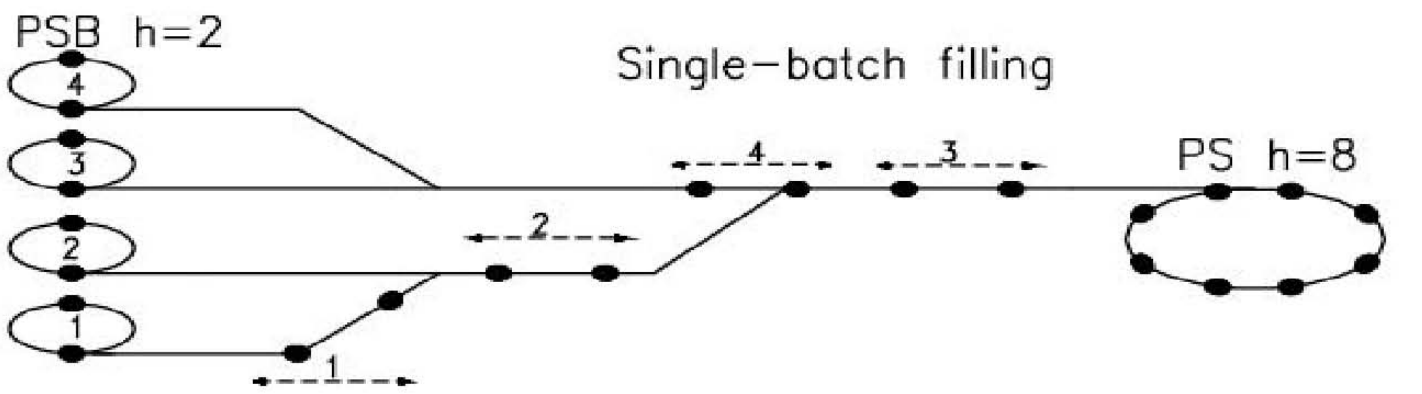
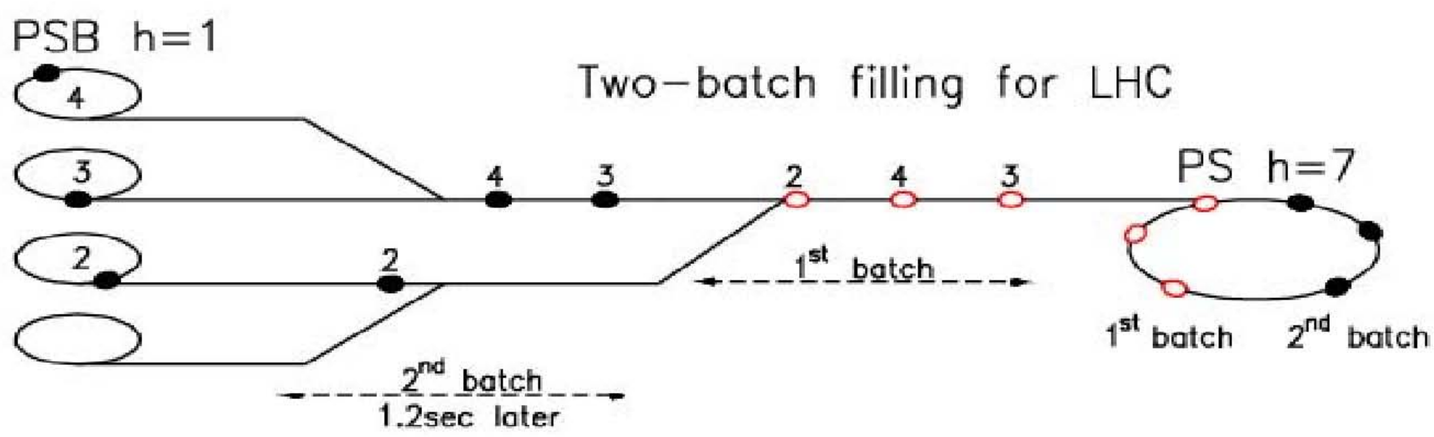
Double batch filling for PS

- 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

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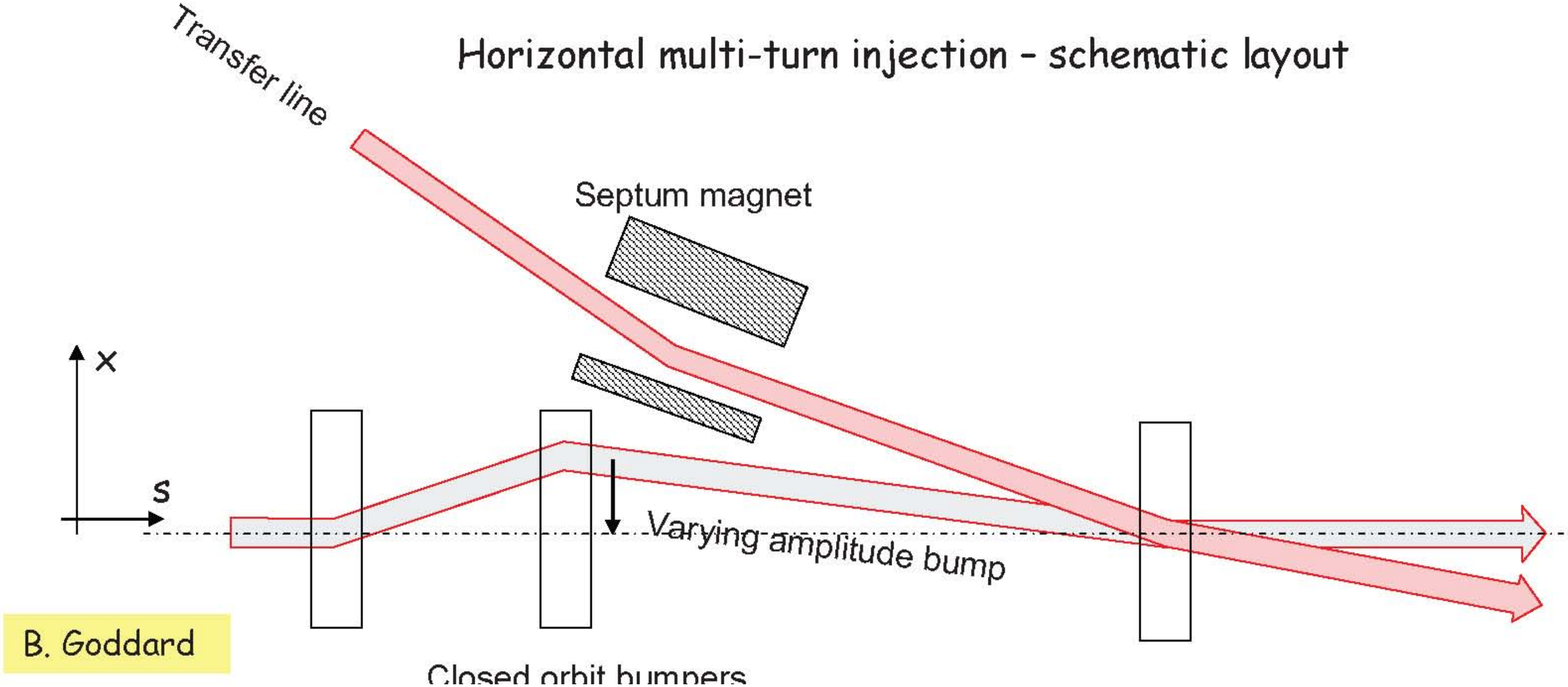
Multiturn injection - principle

- 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"**.



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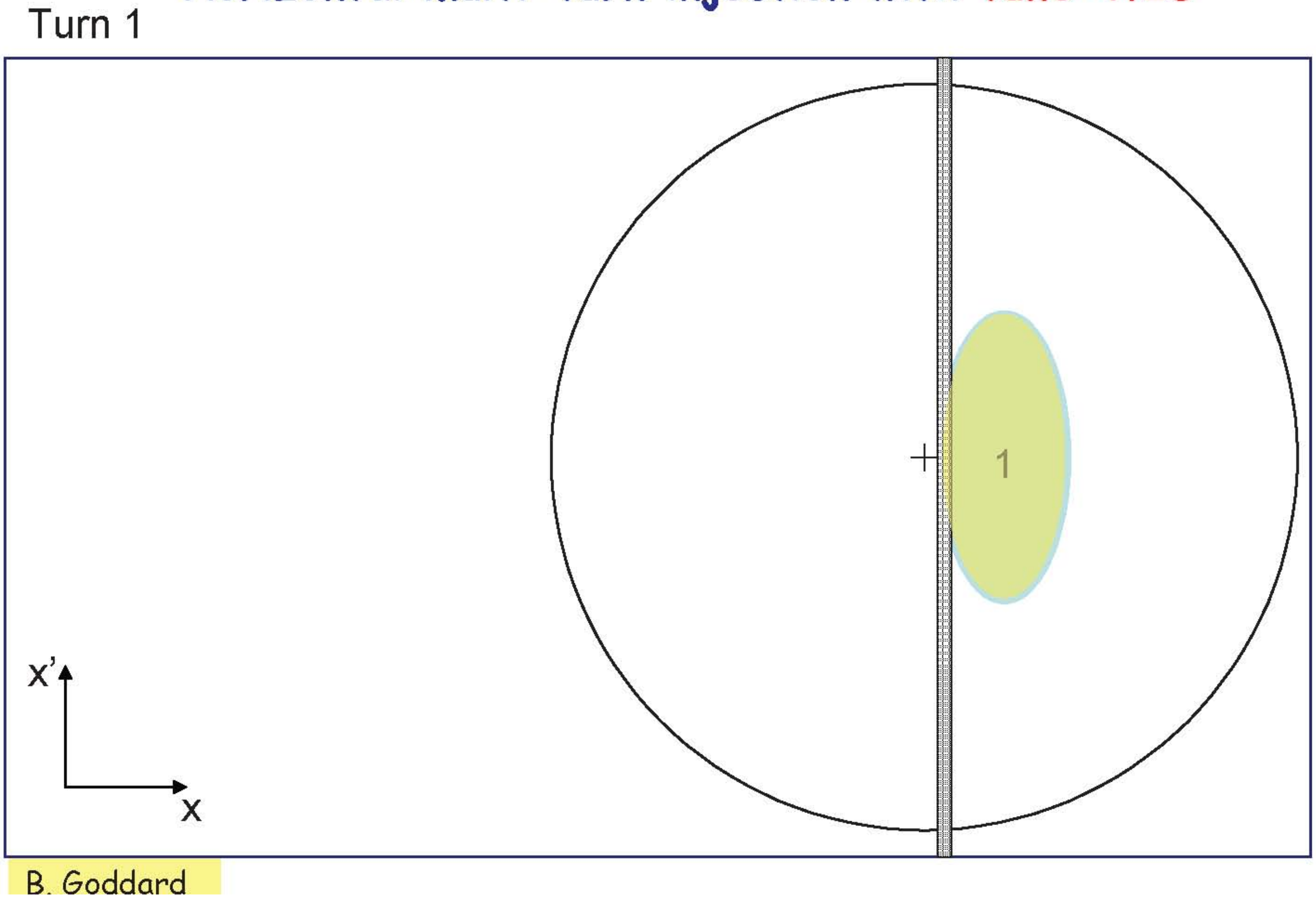
Multiturn injection

- Horizontal multi-turn injection with tune 4.25



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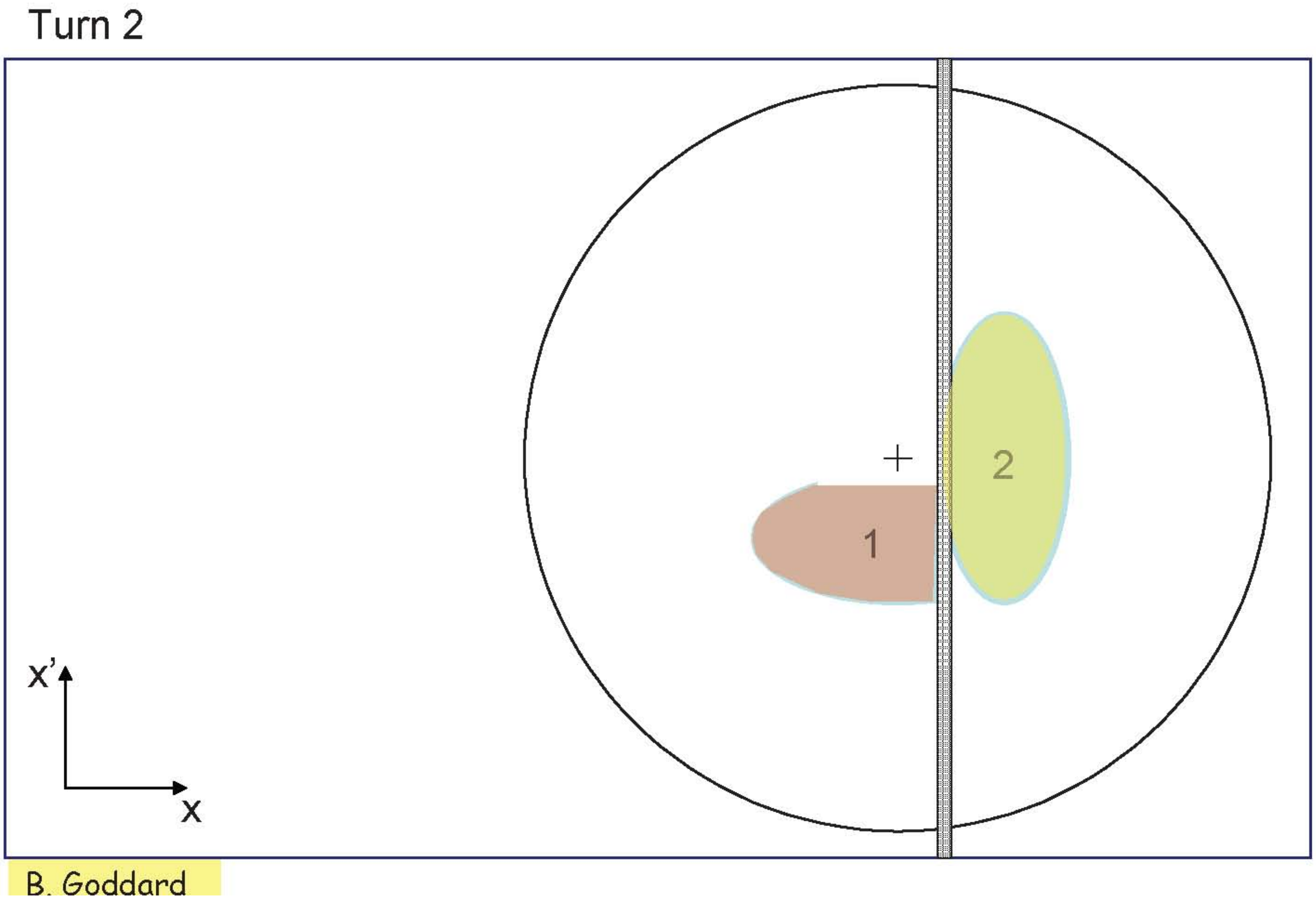
Multiturn injection



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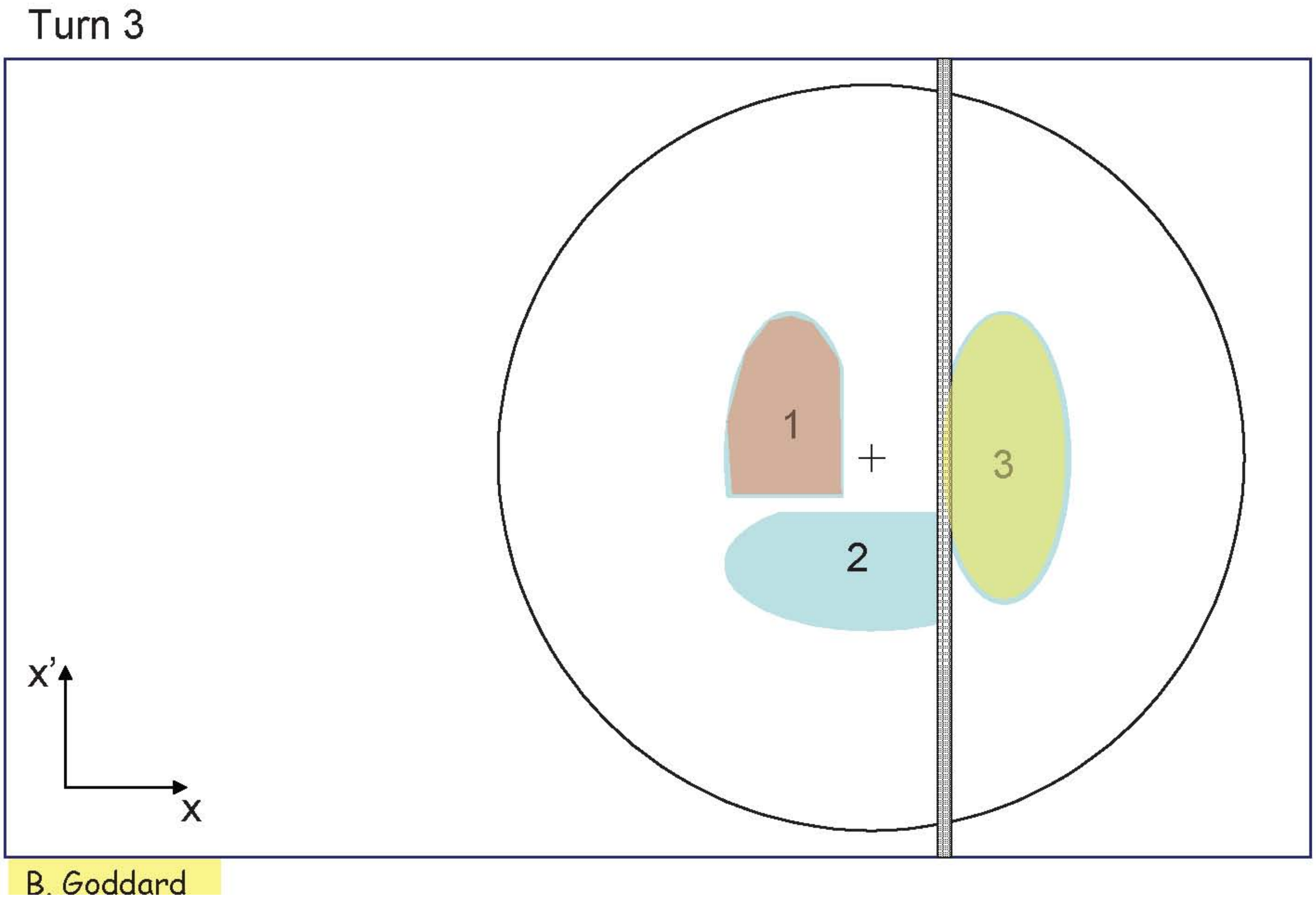
Multiturn injection



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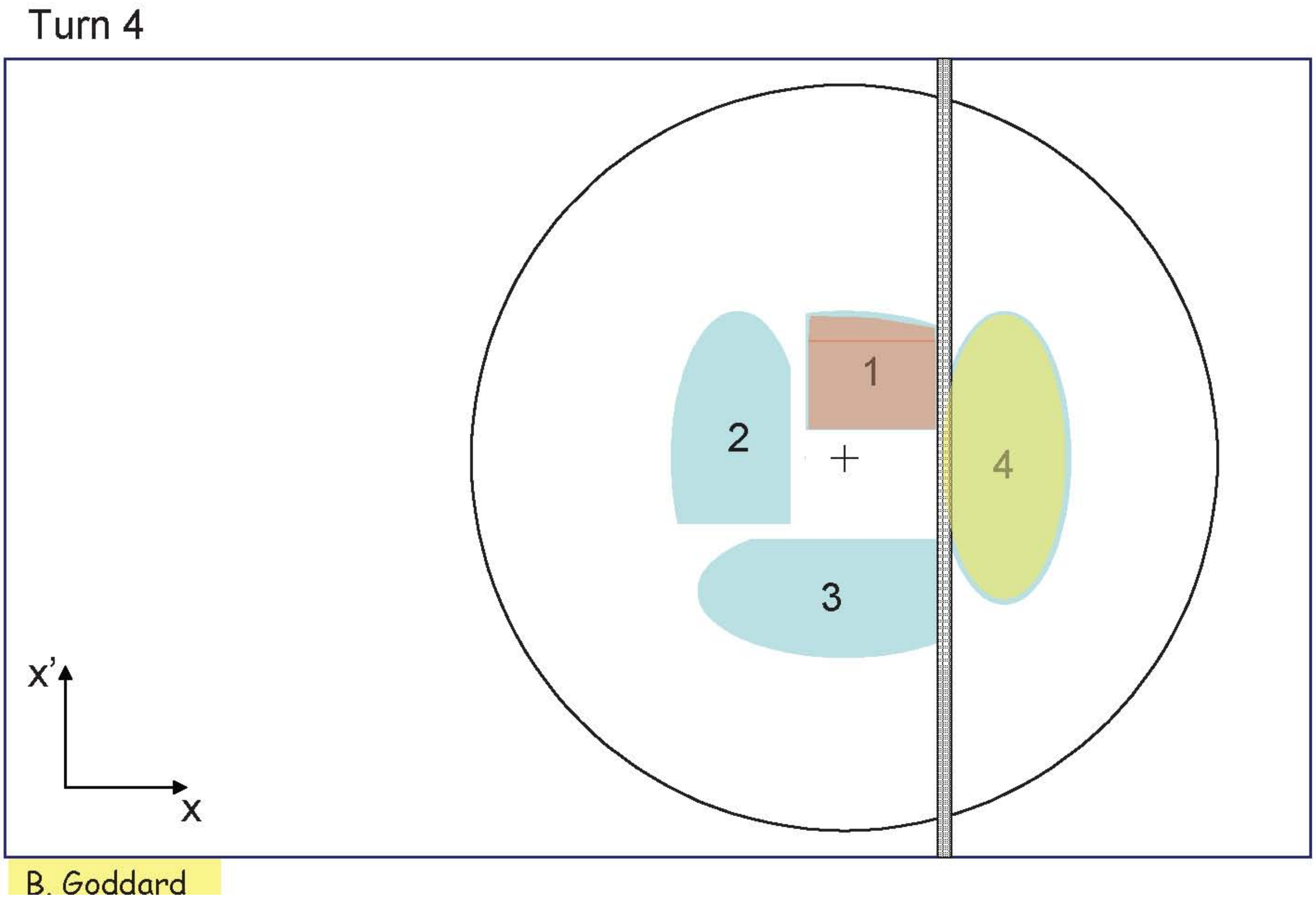
Multiturn injection



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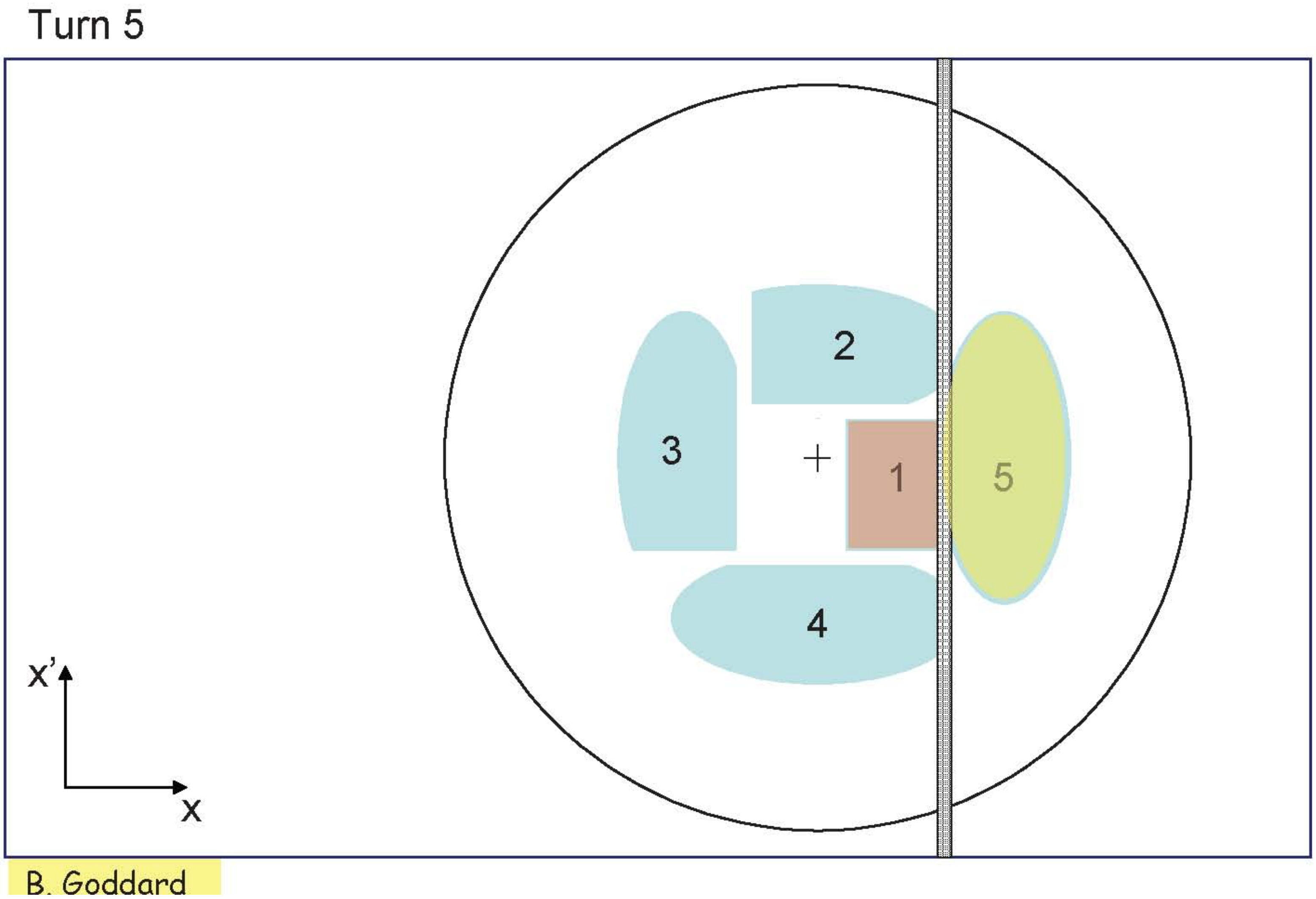
Multiturn injection



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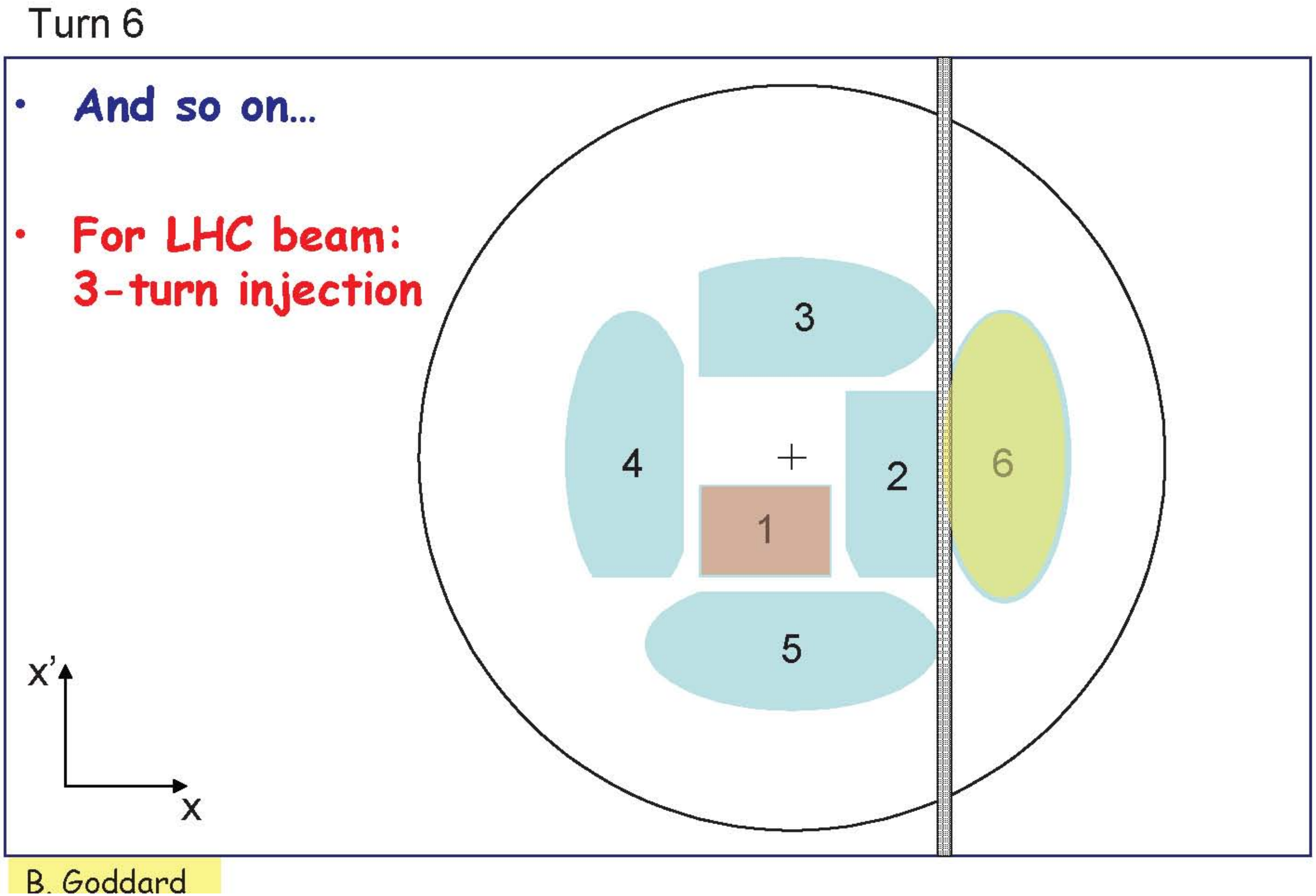
Multiturn injection



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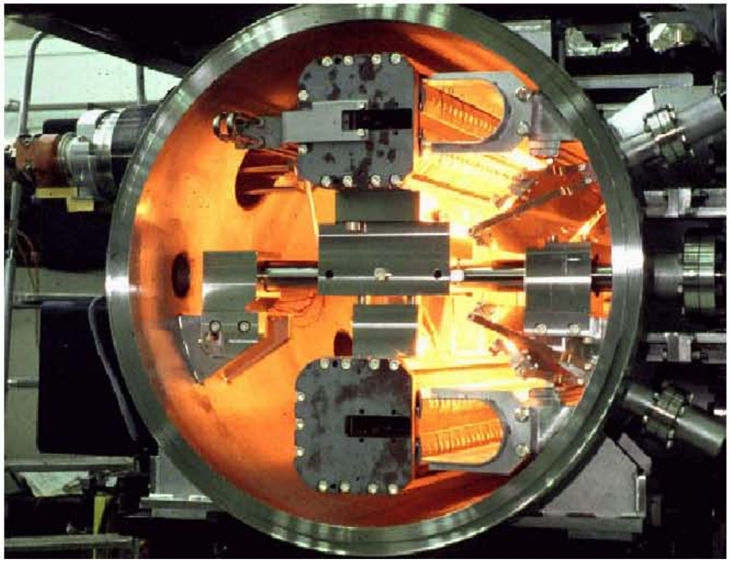
How to beat space charge in the PS

- **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 $\Delta Q_v \approx 0.2$.**
- **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



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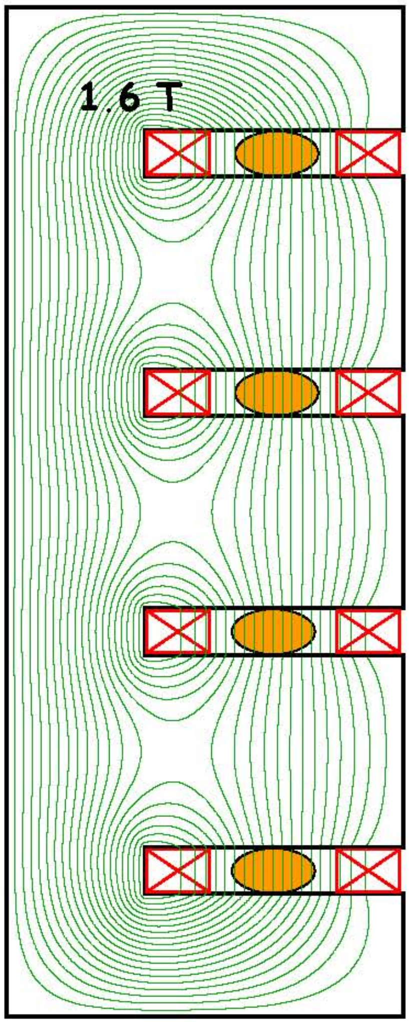
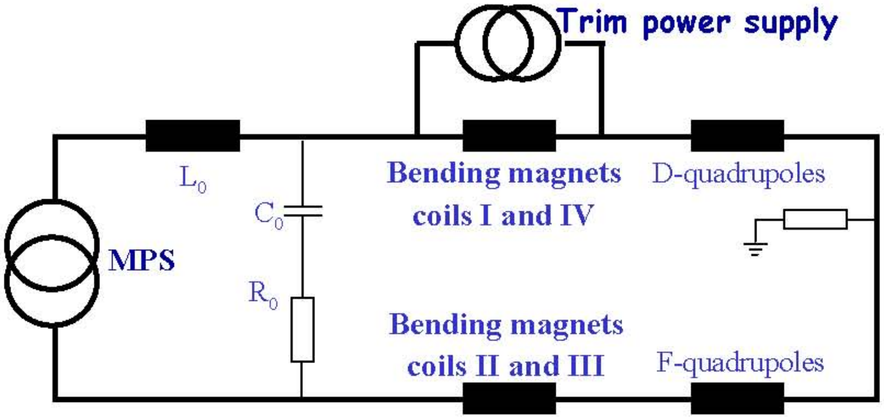
An “unforeseen” problem for PSB



- **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.

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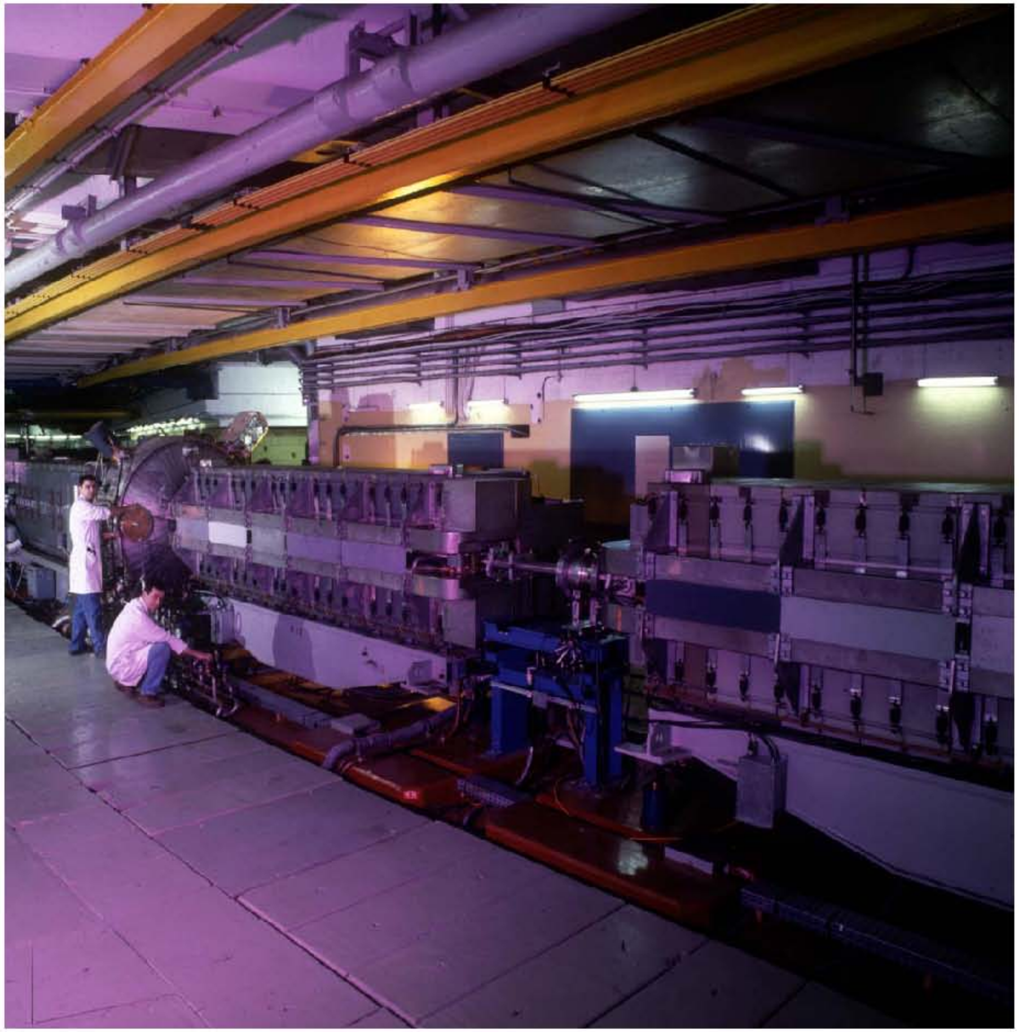
PS

- 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.



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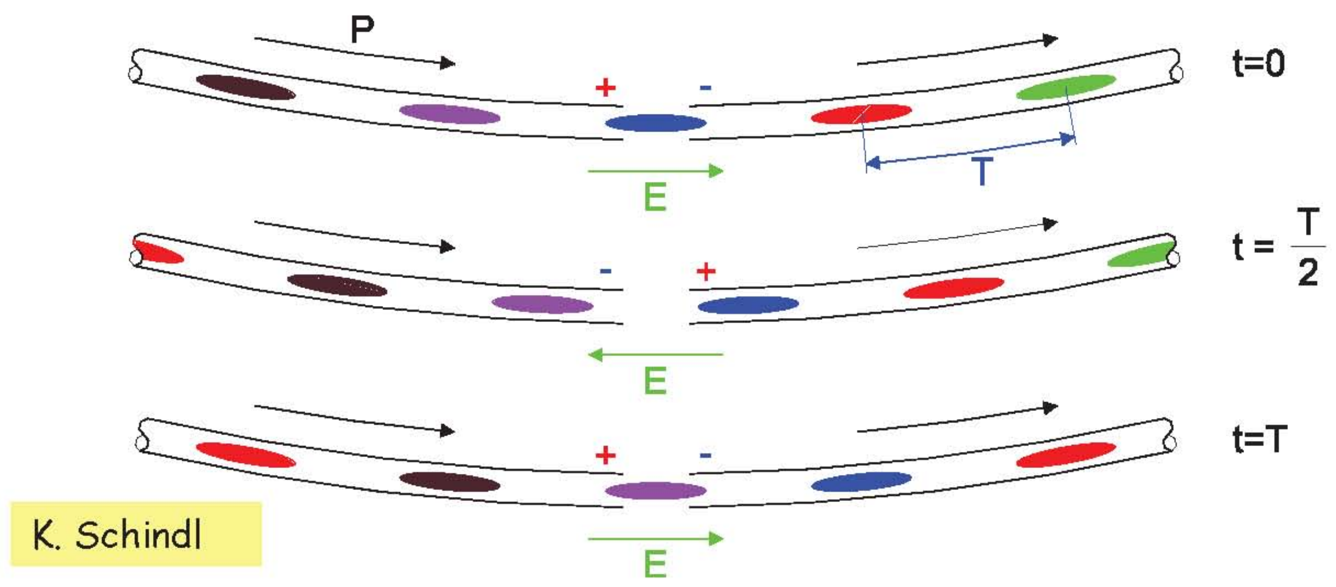
RF harmonics and bunches

- **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.**



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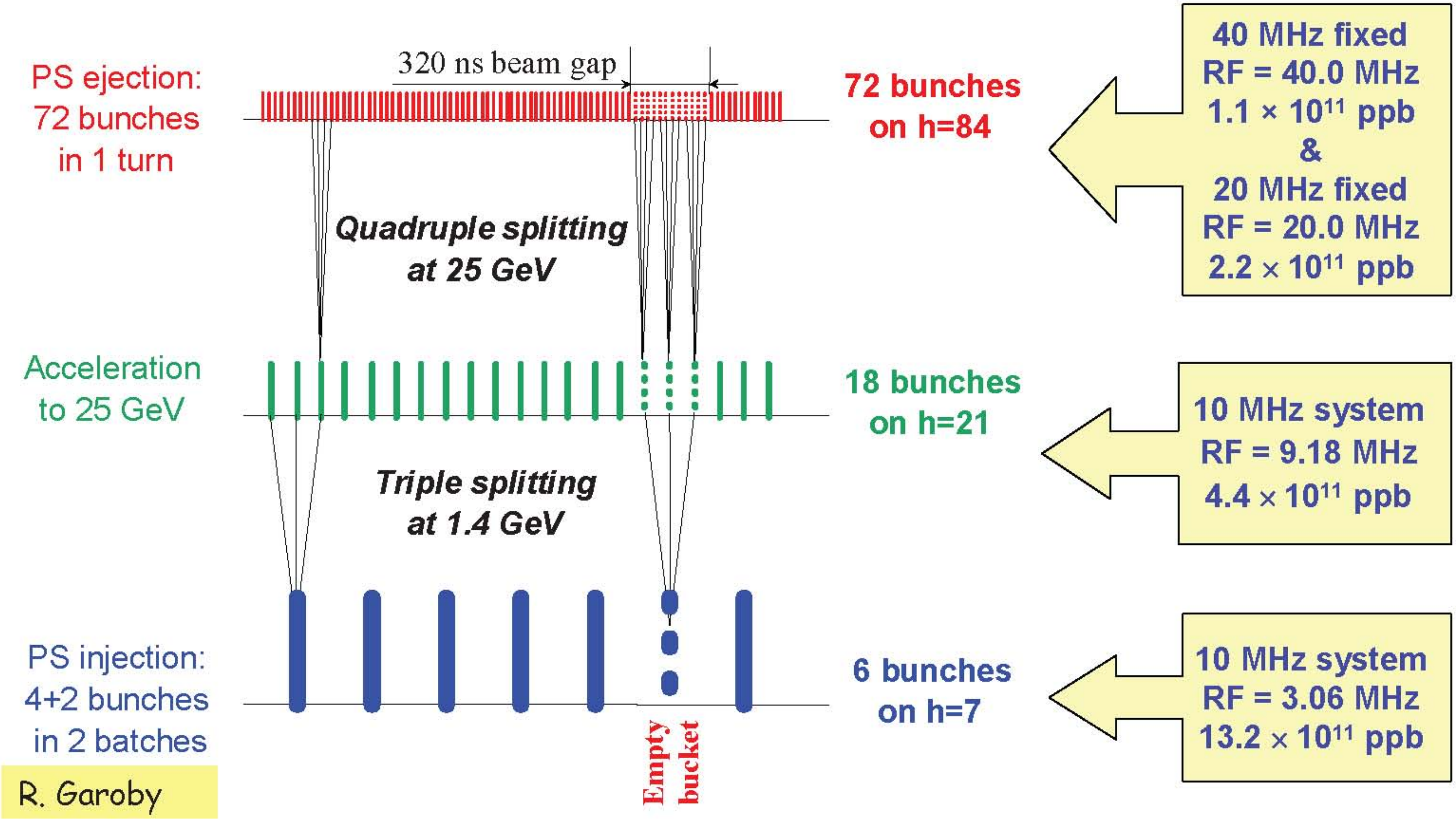
Generation of 25-ns bunch train in PS

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



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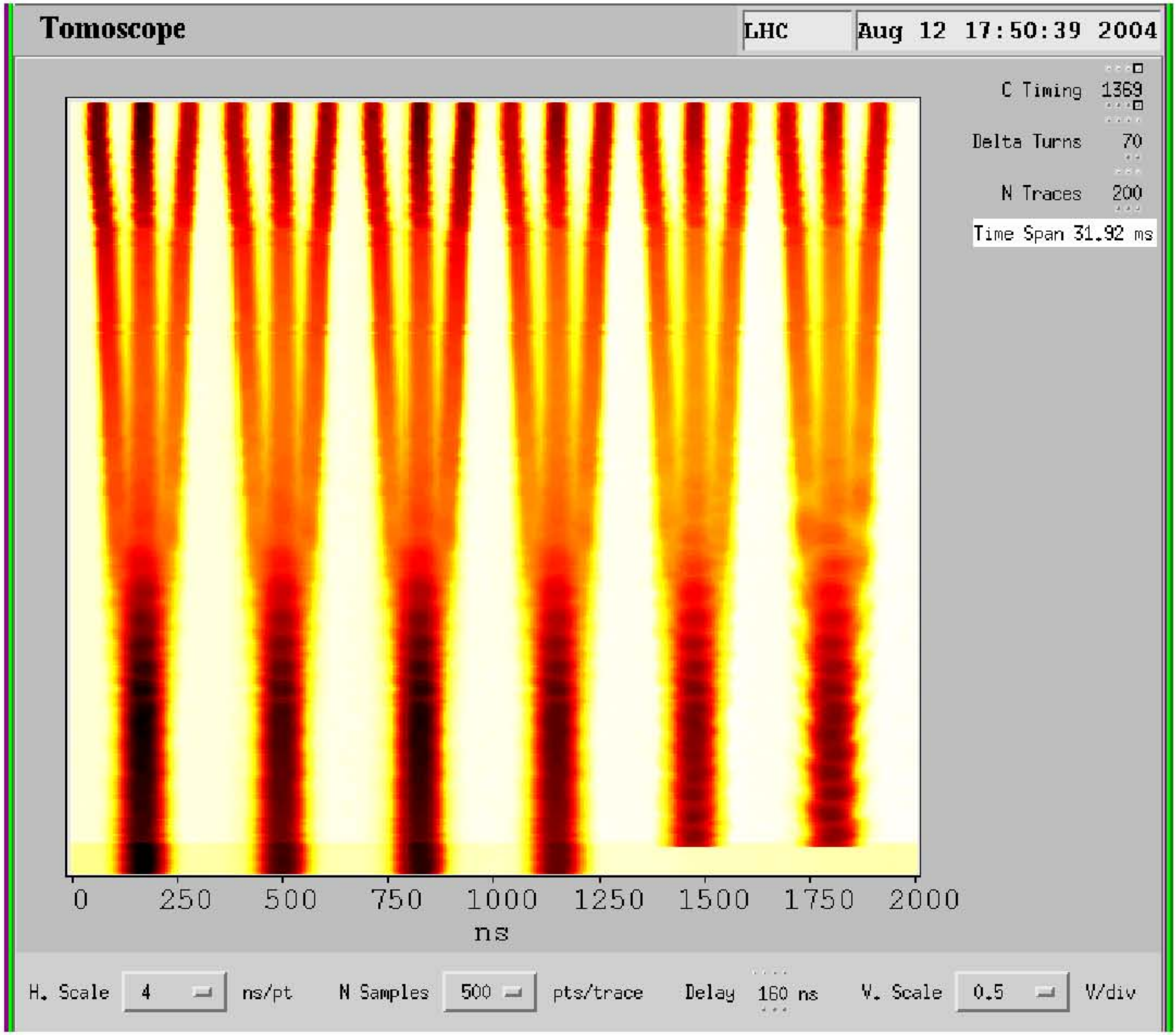
Triple splitting at 1.4 GeV

- **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



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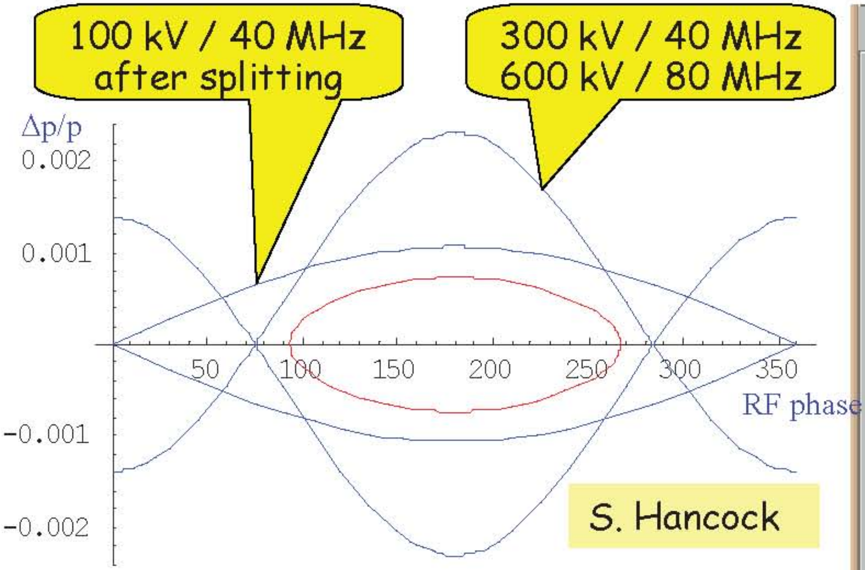
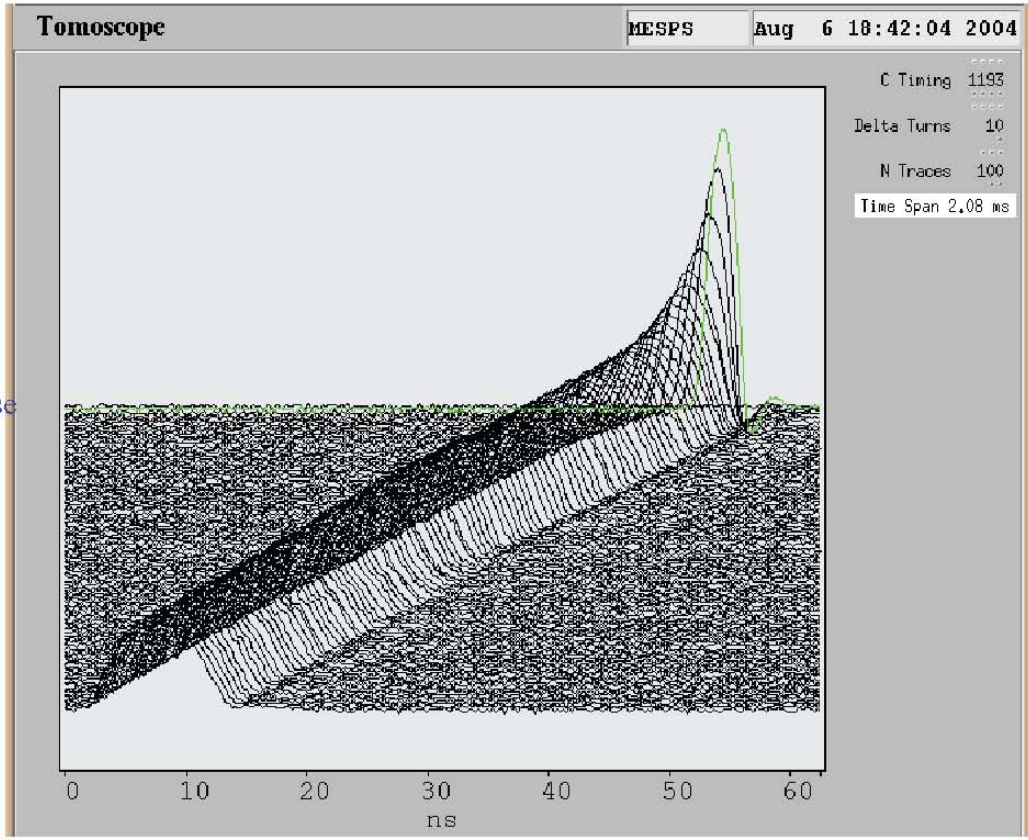
Shortening the bunches for the SPS

- 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.

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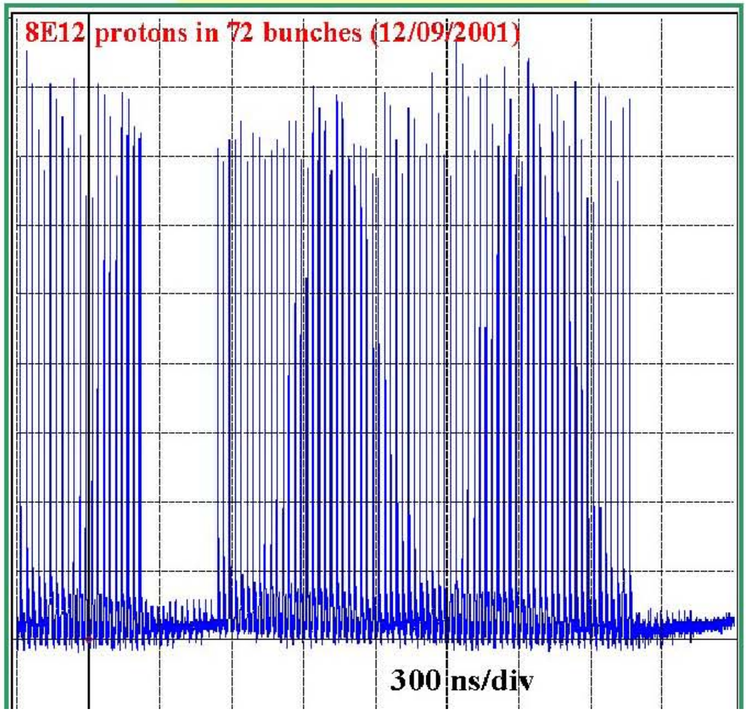
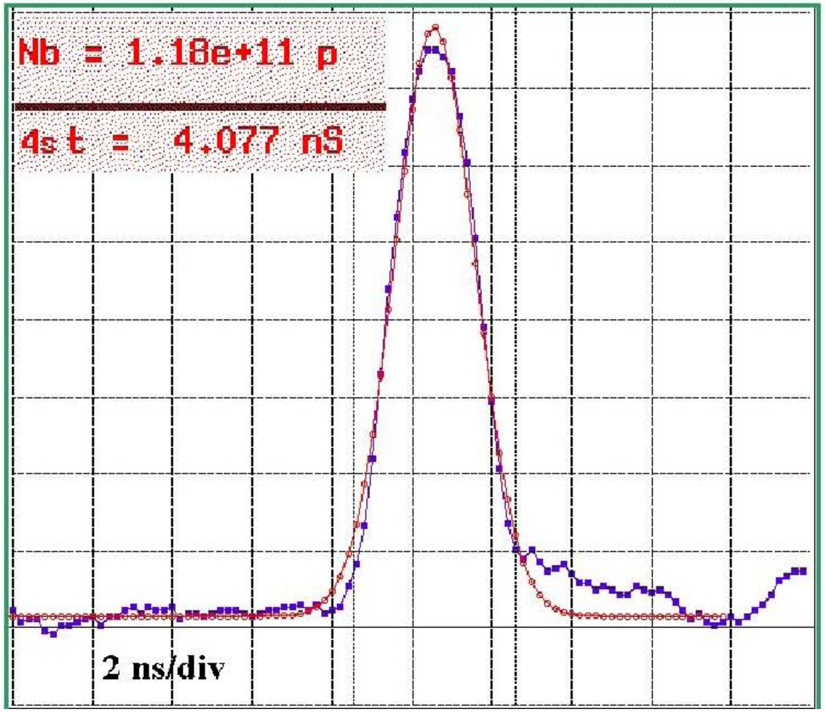
PS performance for nominal LHC beam

- 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



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Super Proton Synchrotron (SPS)

11 x PS circumference

Conventional magnets
(2 T vs. 4.4 T for Tevatron)

450 GeV energy

Up to ~5×10^{13} protons/cycle

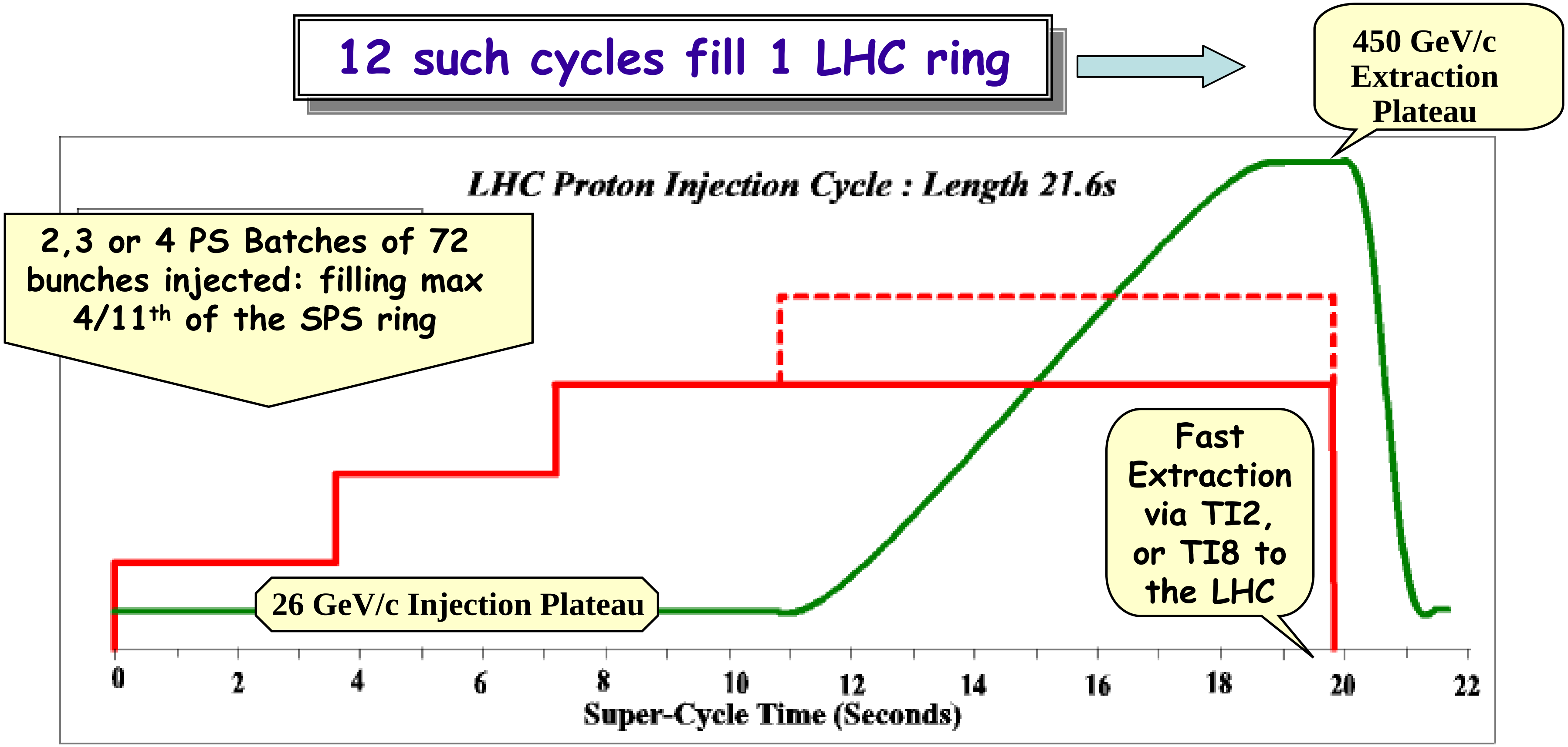
Extraction modes:
slow (s), fast-slow (ms), fast (μs)

CNGS ν beam to Gran Sasso commissioned in 2006

In addition to protons, SPS has also accelerated deuterium, sulphur, oxygen, lead, indium

The LHC Filling Cycle

12 such cycles fill 1 LHC ring

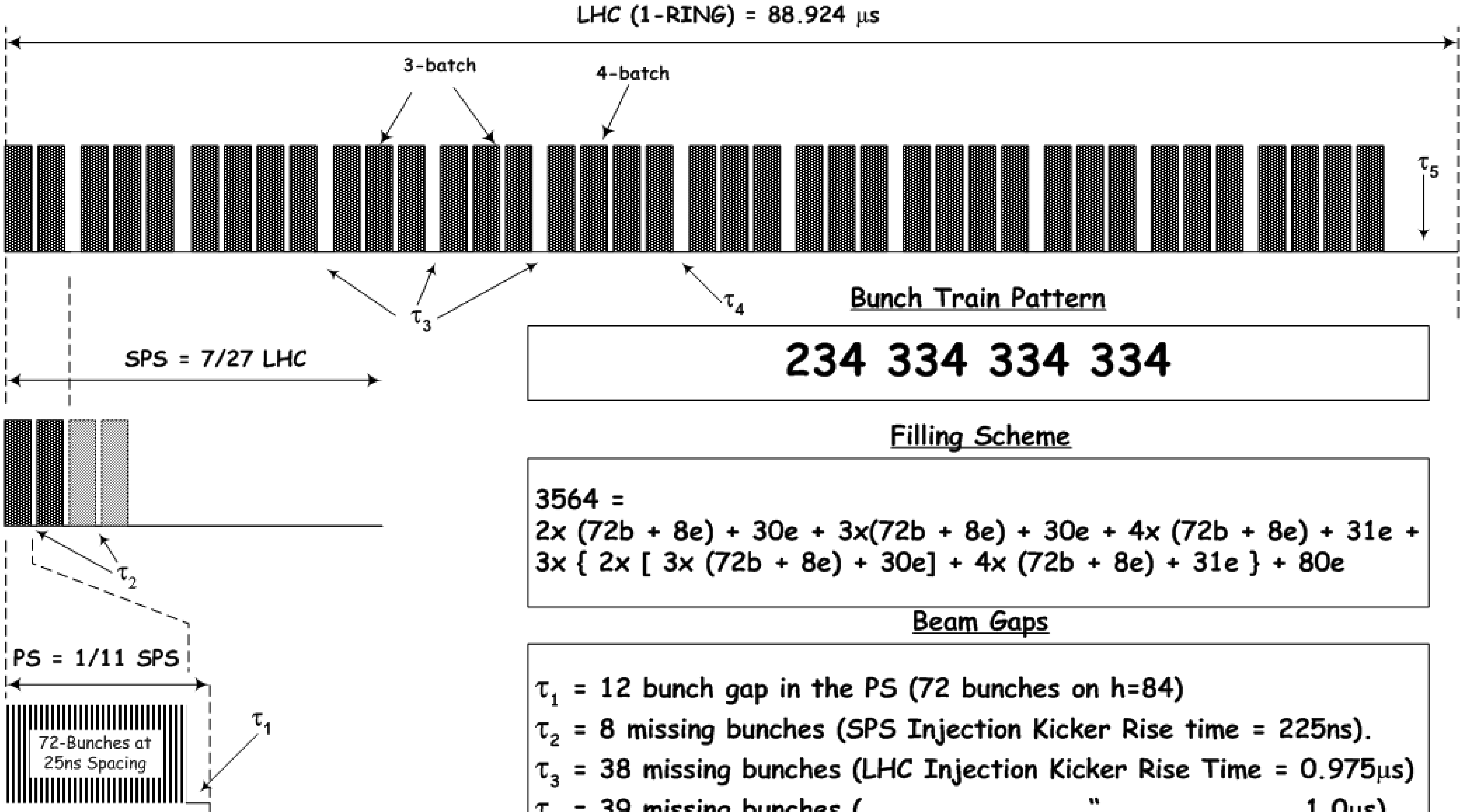


1 Batch of 72 bunches each 3.6 seconds from the PS

When actually filling the LHC, SPS Will do nothing else

P. Collier

LHC Filling Cycle



Bunch Train Pattern

234 334 334 334

Filling Scheme

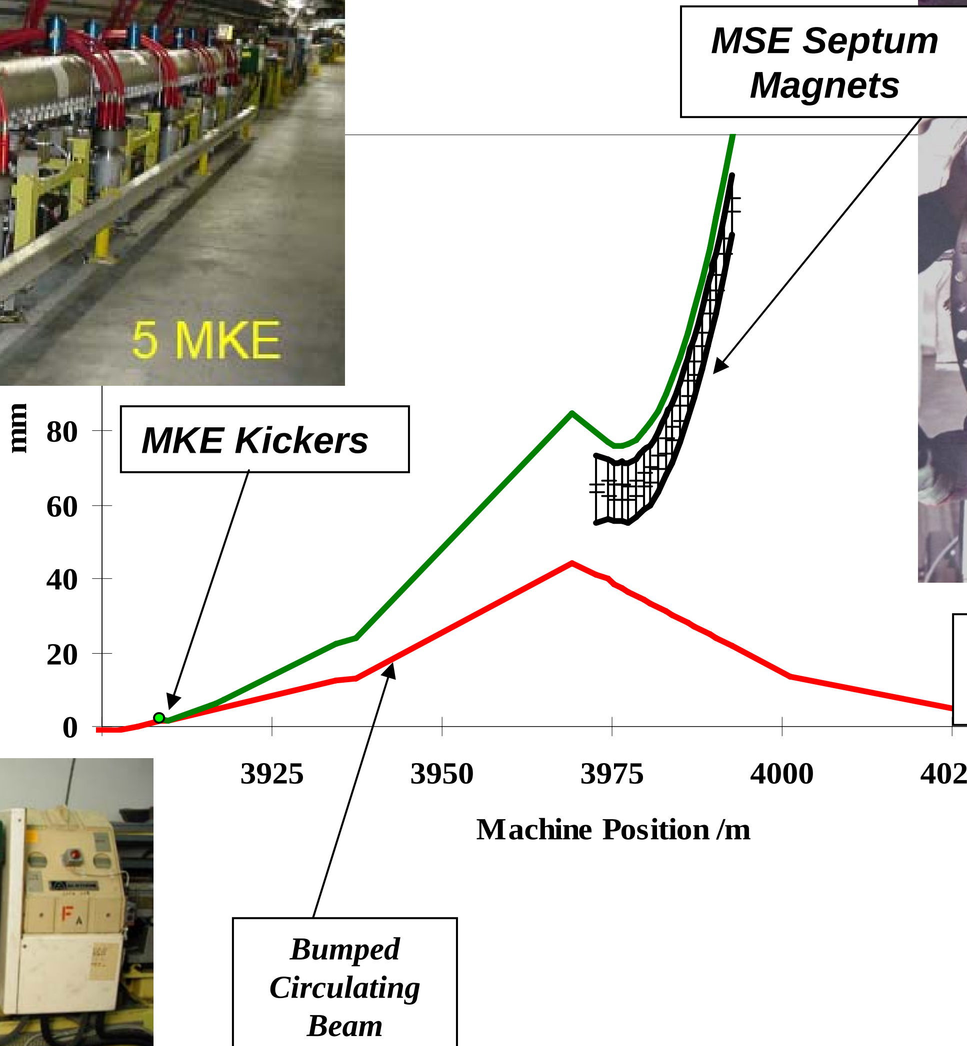
3564 =
2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) + 31e +
3x { 2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e } + 80e

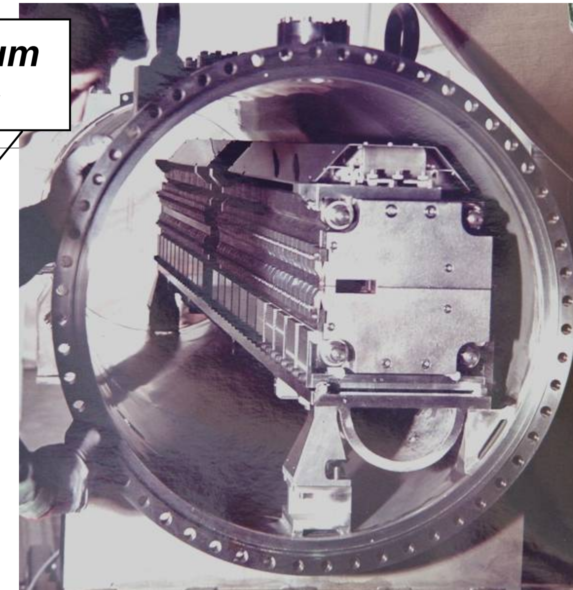
Beam Gaps

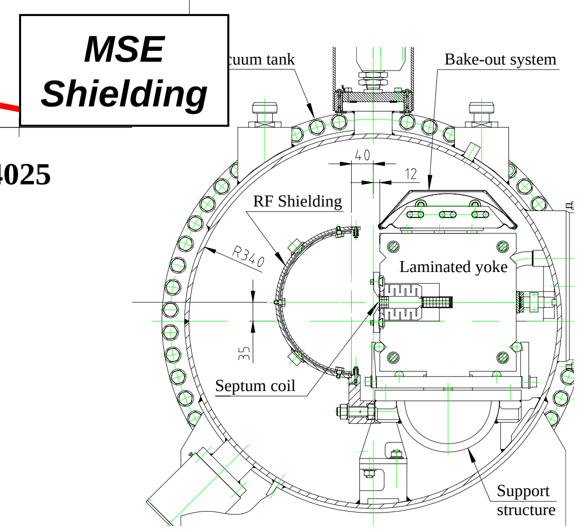
τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975μs)
τ_4 = 39 missing bunches (" 1.0μs)
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3μs)

P. Collier

SPS Extraction Channels







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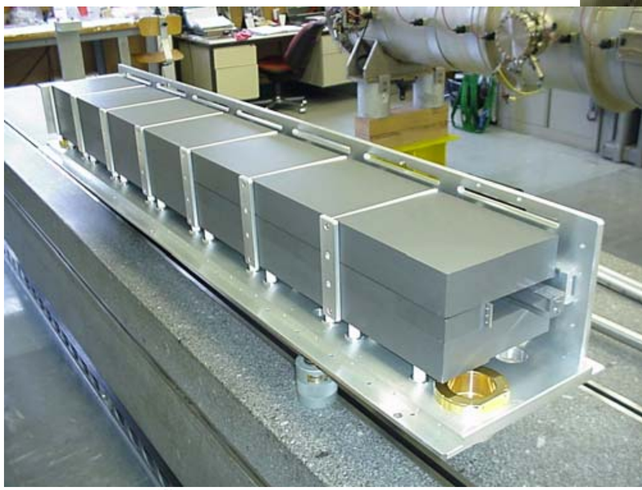
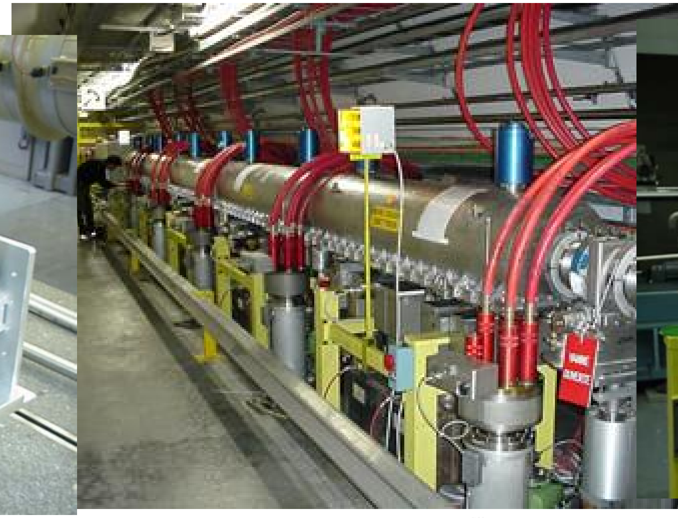
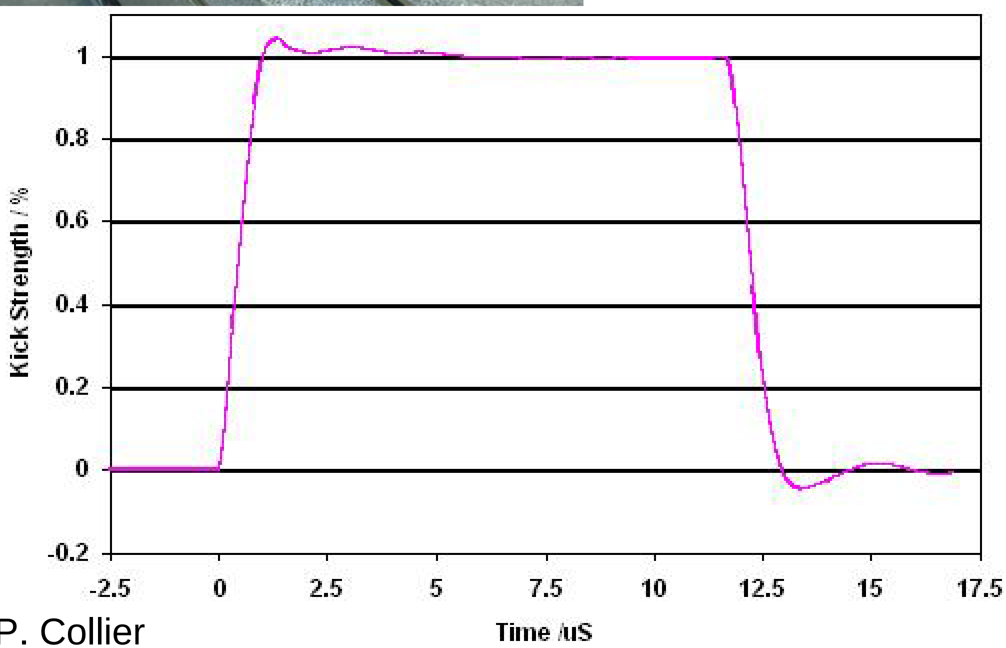
SPS Kicker Magnets …







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Resonant charging circuit – travelling wave discharge

Flat top duration tailored to beam structure

Injection ~2μS (MKP)

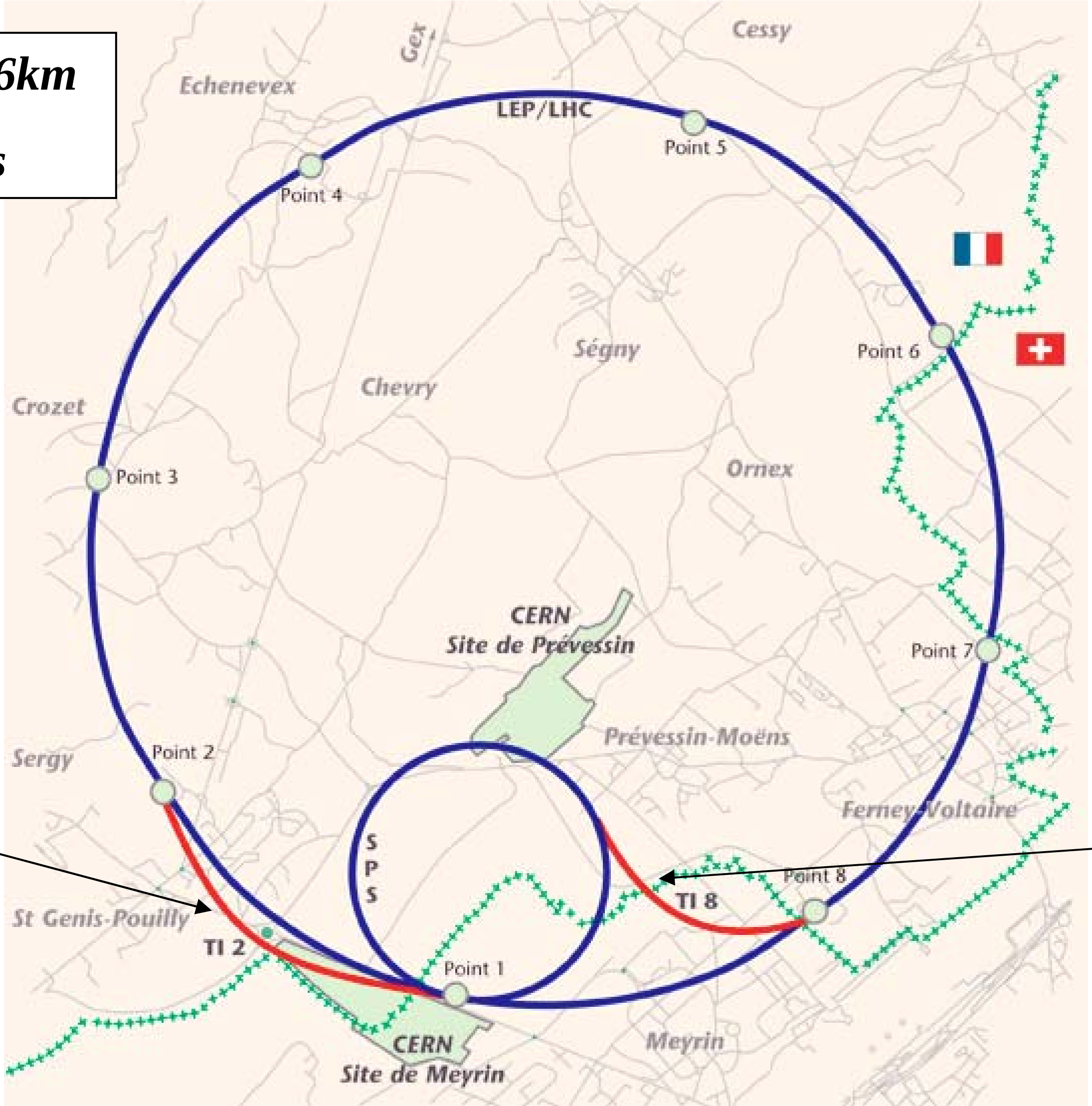
Extraction ~10.5 μS (MKE)

Minimize Ripple → bunch-bunch variations

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

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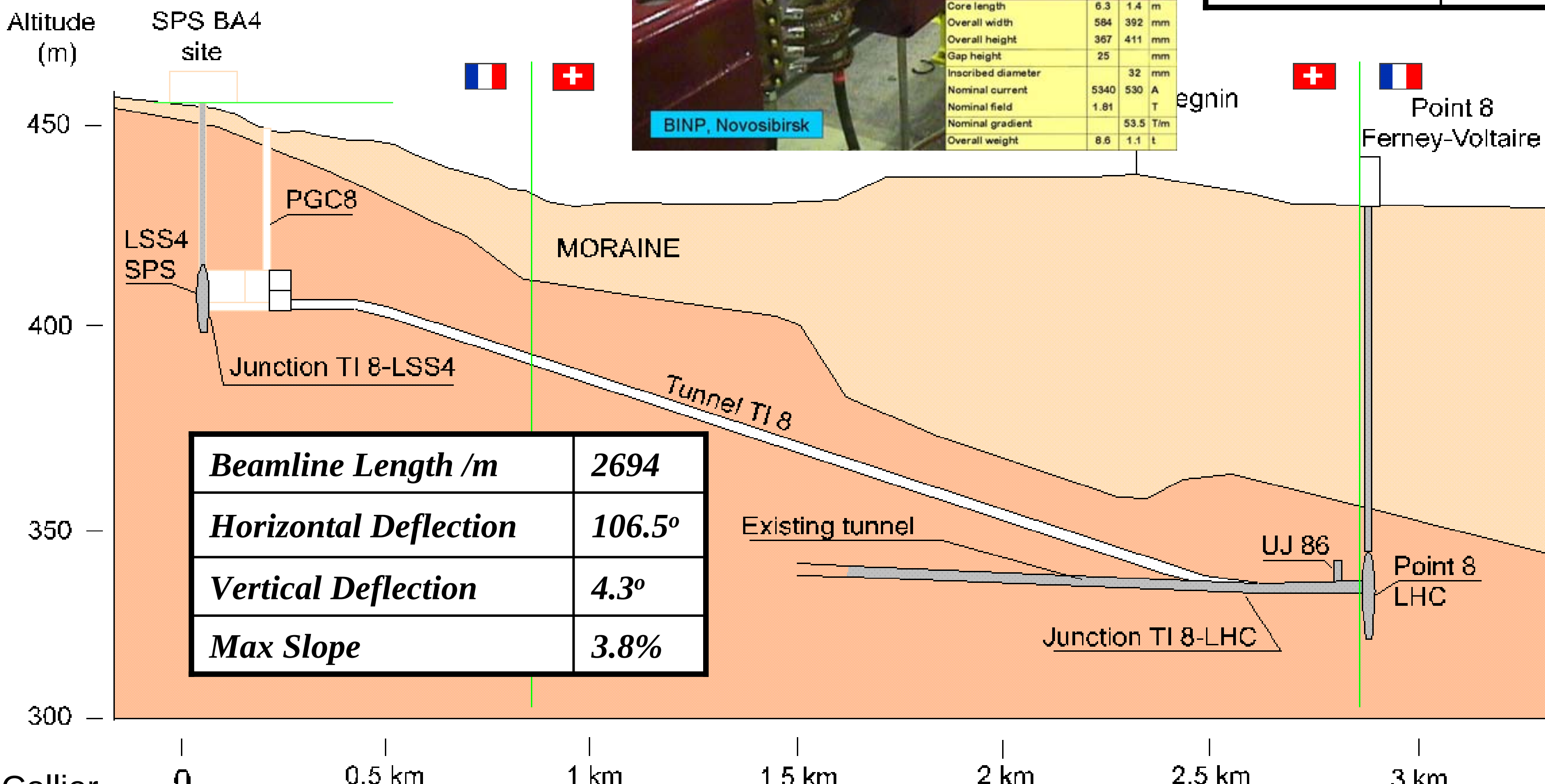
Transfer to LHC : TI 8

Magnet Count	
Dipoles	268
Quadrupoles	86
Correctors	42



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

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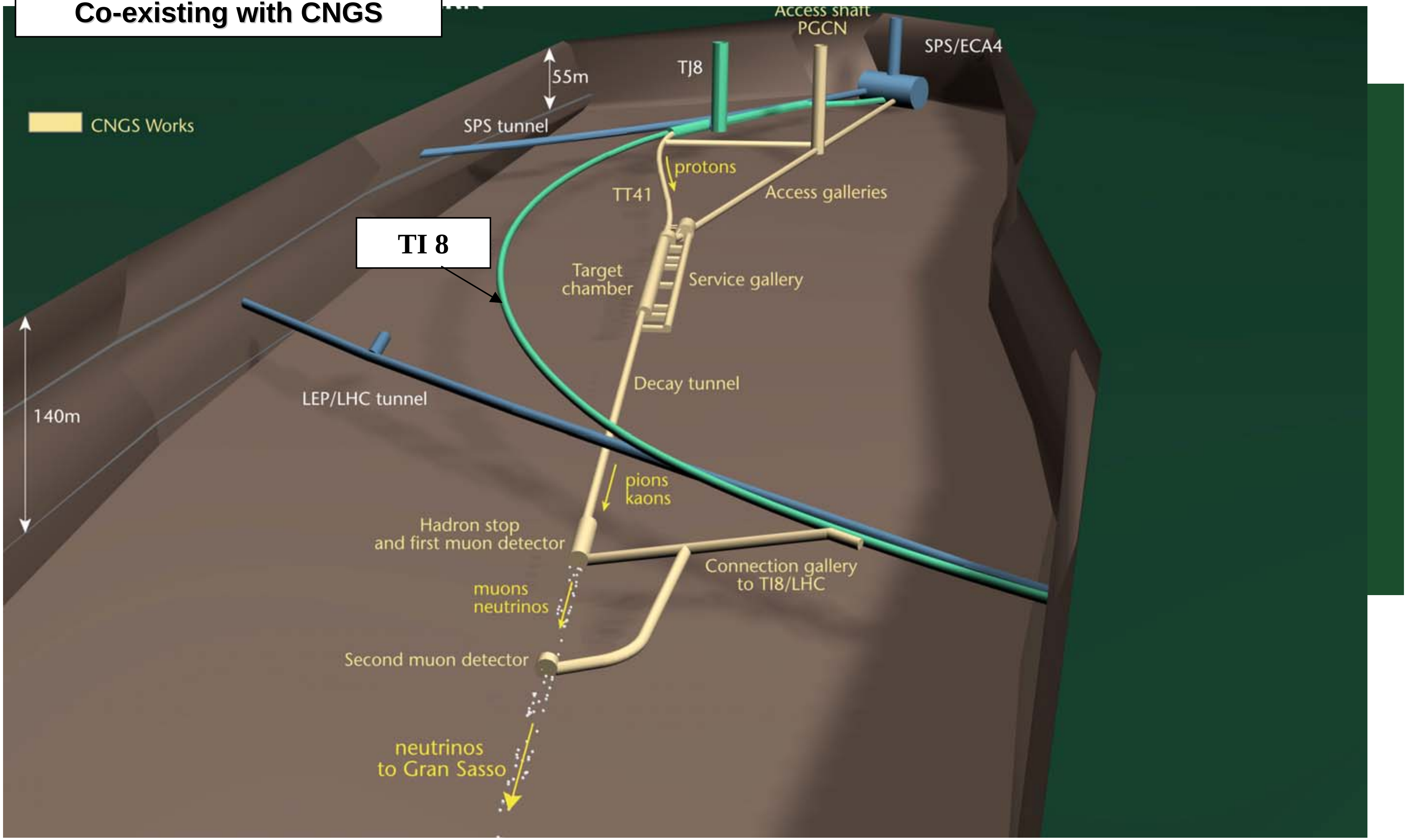
TI 8: Civil Engineering Layout

Co-existing with CNGS



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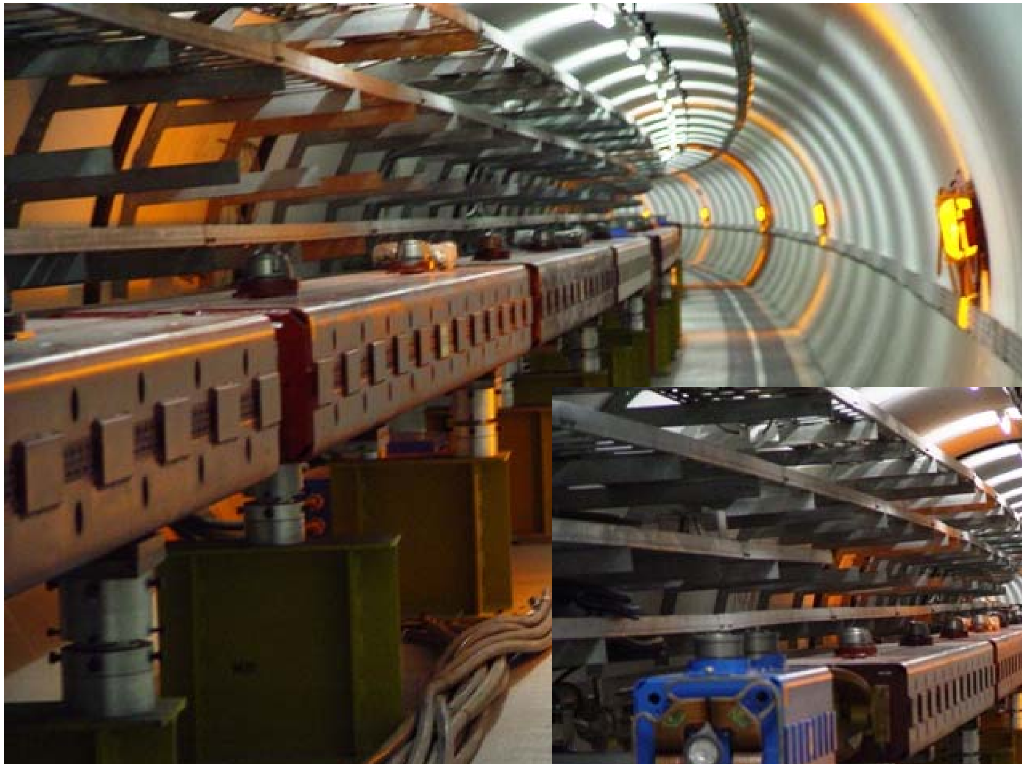
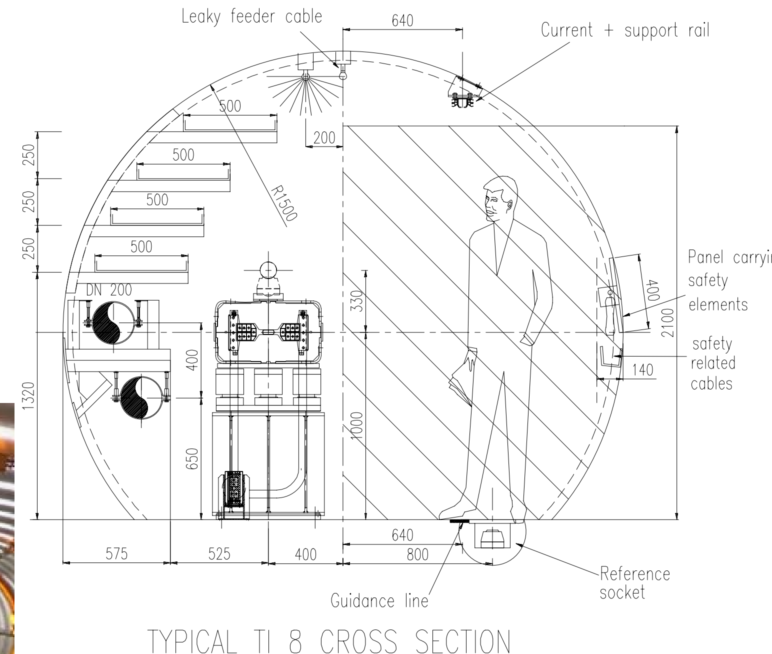
TI 8 Installation





Magnets transported and placed in around 3 months.

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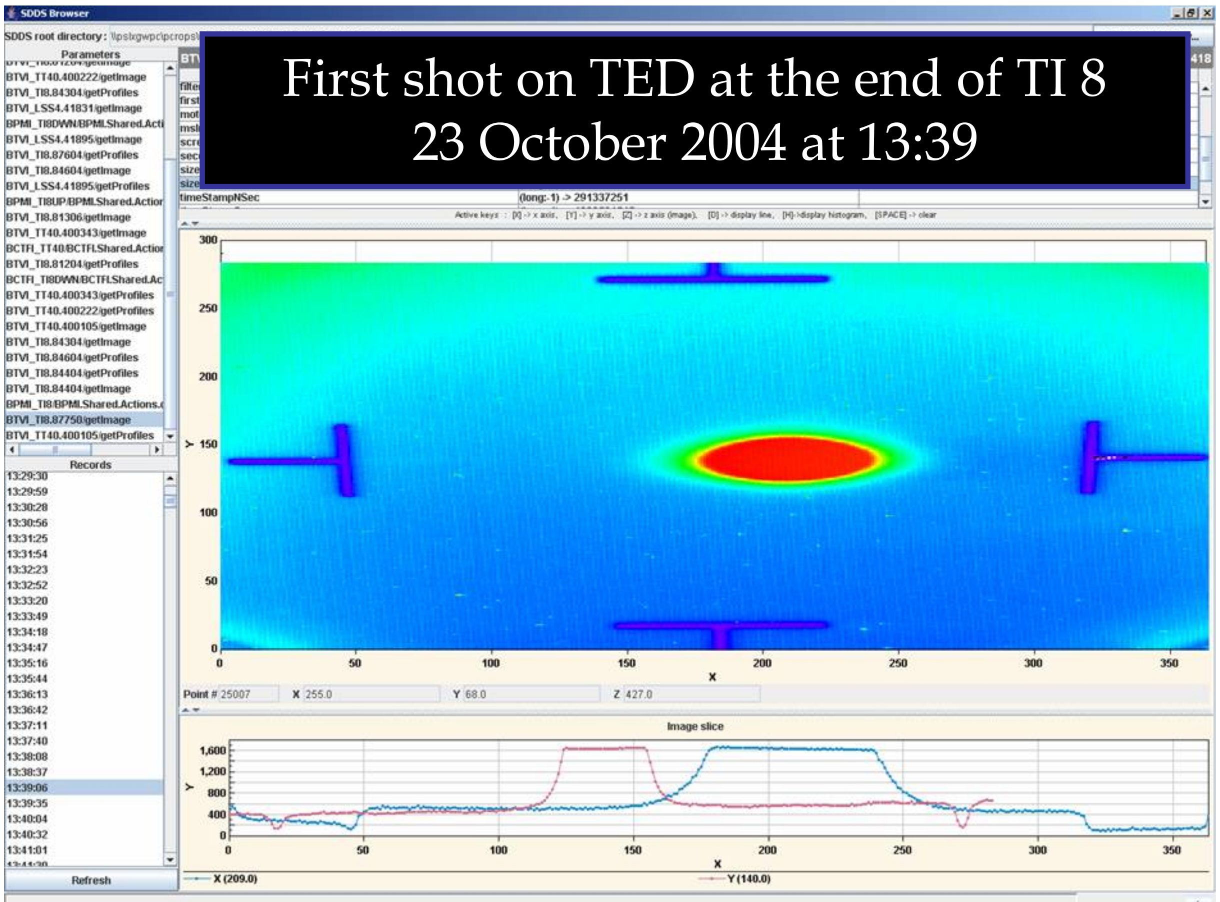
TI 8 Beam Tests

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



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

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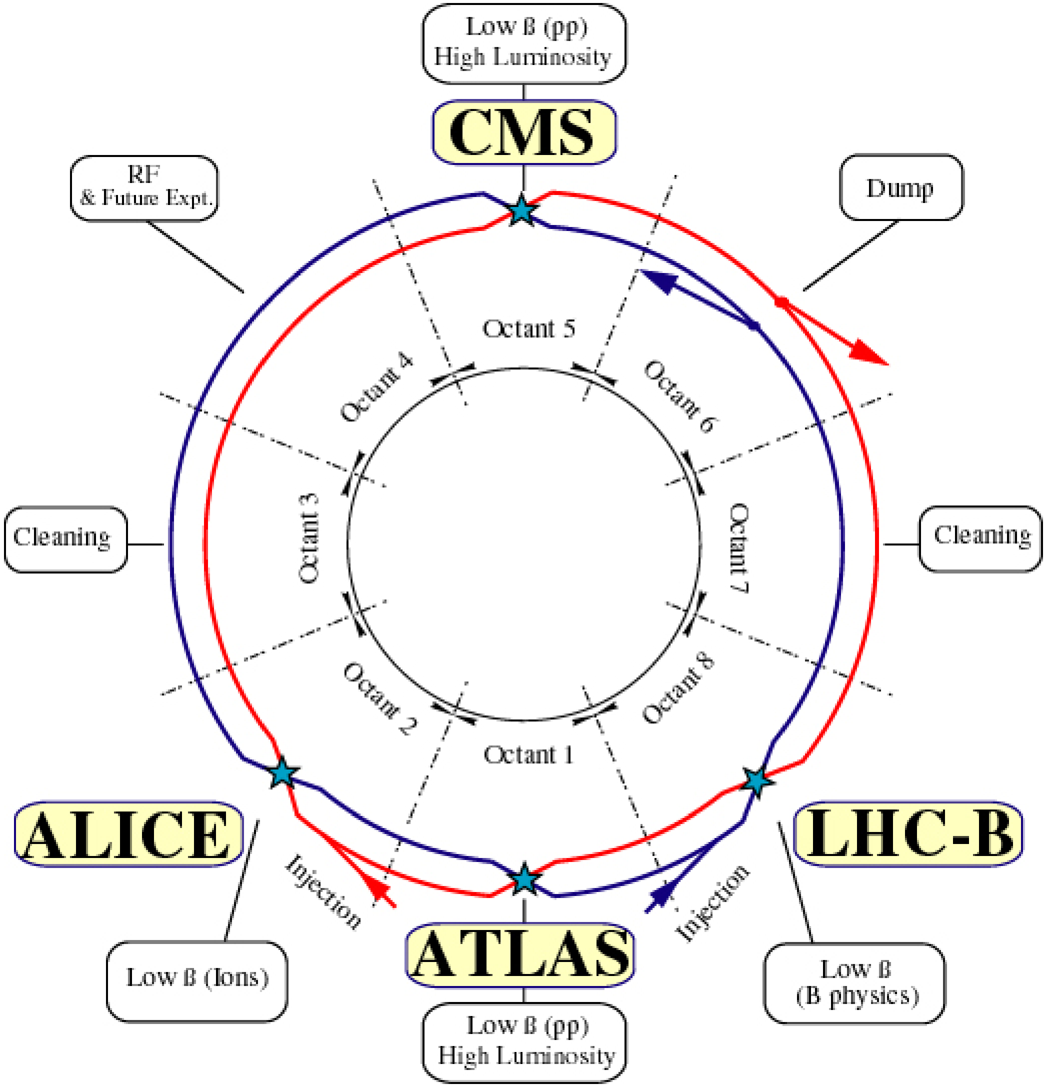
Large Hadron Collider (LHC)



proton-proton collider

next energy-frontier discovery machine

c.m. energy 14 TeV (7x Tevatron)

design luminosity 10^{34} $cm^{-2}s^{-1}$ (~100x Tevatron)

450-GeV engineering run in fall 2007; first 7-TeV physics run In 2008

nominal LHC is a very challenging machine!

BEAM RIGIDITY

$$B\,\rho\,[\mathrm{T\,m}] = 3.3356\; p_0\,[\mathrm{GeV/c}]$$

magnetic field

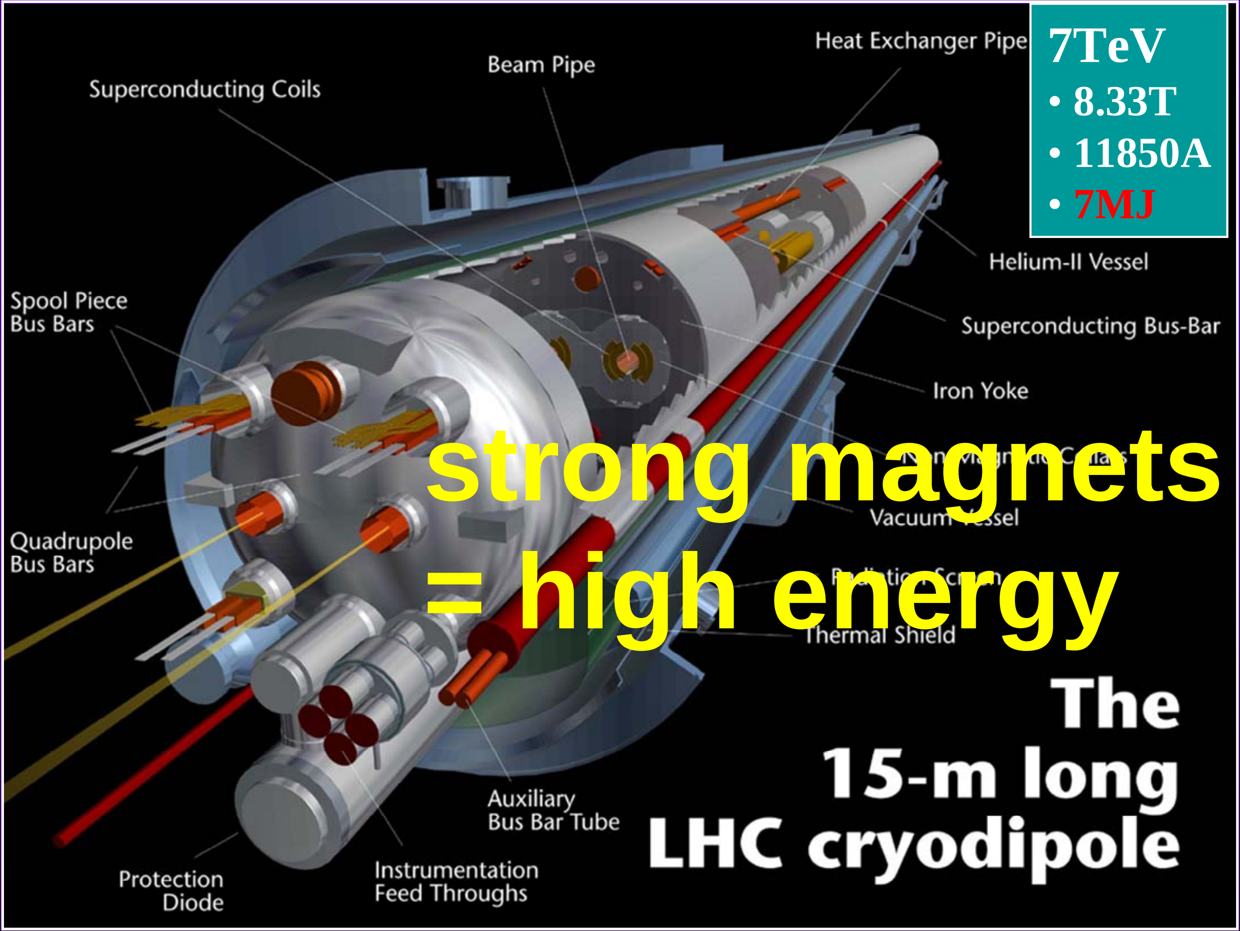
particle bending radius

beam momentum

~ 0.5 MCHF each

weight 37 tons

1232 dipole magnets



7TeV
- 8.33T
- 11850A
- 7MJ

strong magnets = high energy

E. Metral

luminosity & beam-beam

$$L = \frac{f_{rev} n_b N_b^2 \gamma}{4\pi\varepsilon_n \beta^*} F_{geom}$$

luminosity formula

$$\xi = \frac{r_p N_b}{4\pi\varepsilon_n} F_{geom}$$

head-on beam-beam tune shift / IP,
~N_b/ξ (brightness)
like space charge;
ξ_{tot}<0.01:
constraint from SPS experience

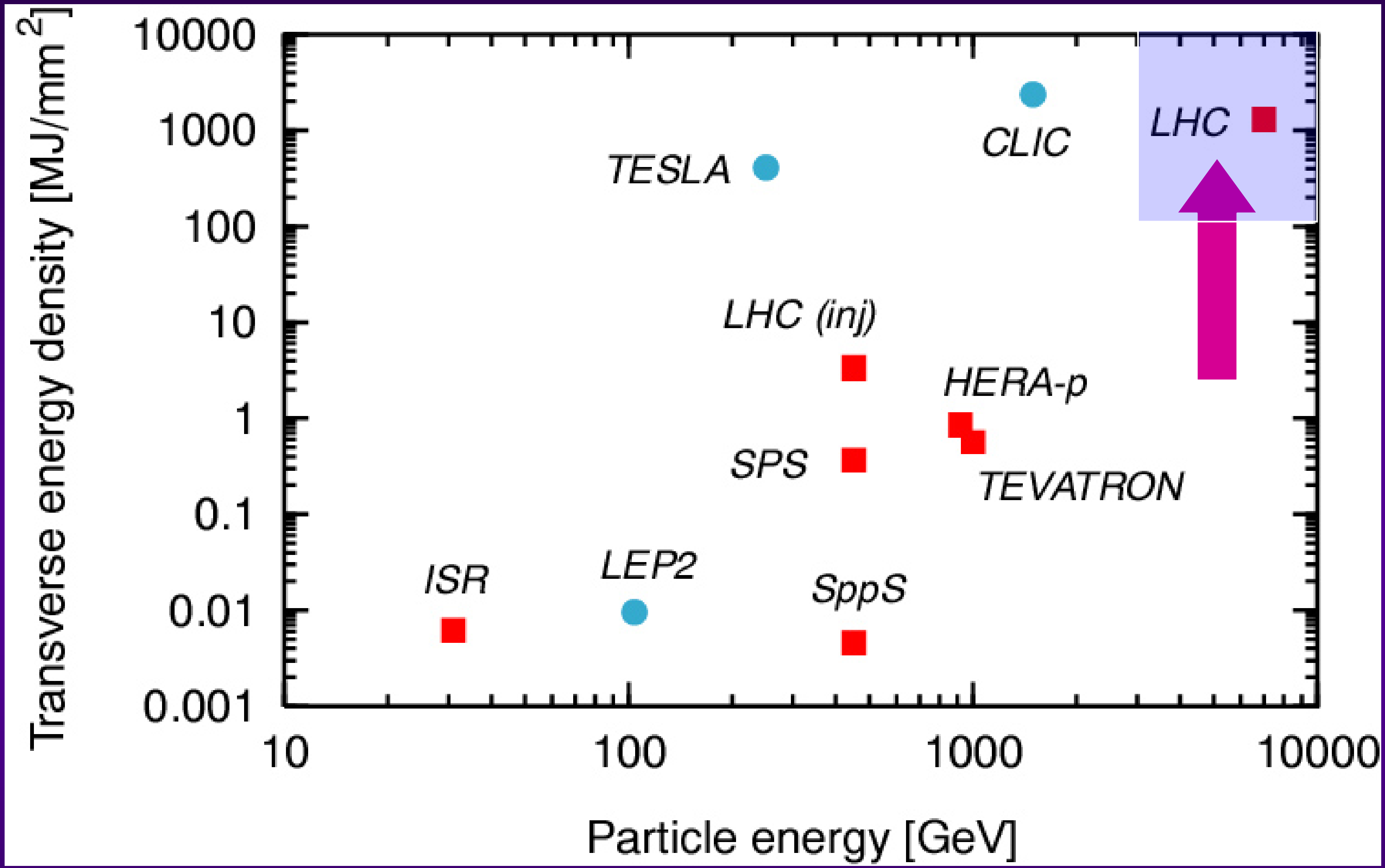
$$L = \frac{f_{rev} n_b N_b \xi \gamma}{\beta^* r_p}$$

alternative
luminosity formula
at beam-beam limit

f_{rev}: revolution frequency, n_b: #bunches, N_b: particles/bunch;
ε_n: normalized emittance; β^*: beta function at IP; r_p: classical proton radius;
F_{geom}: geometric reduction factor (crossing angle and hour glass)

three LHC challenges

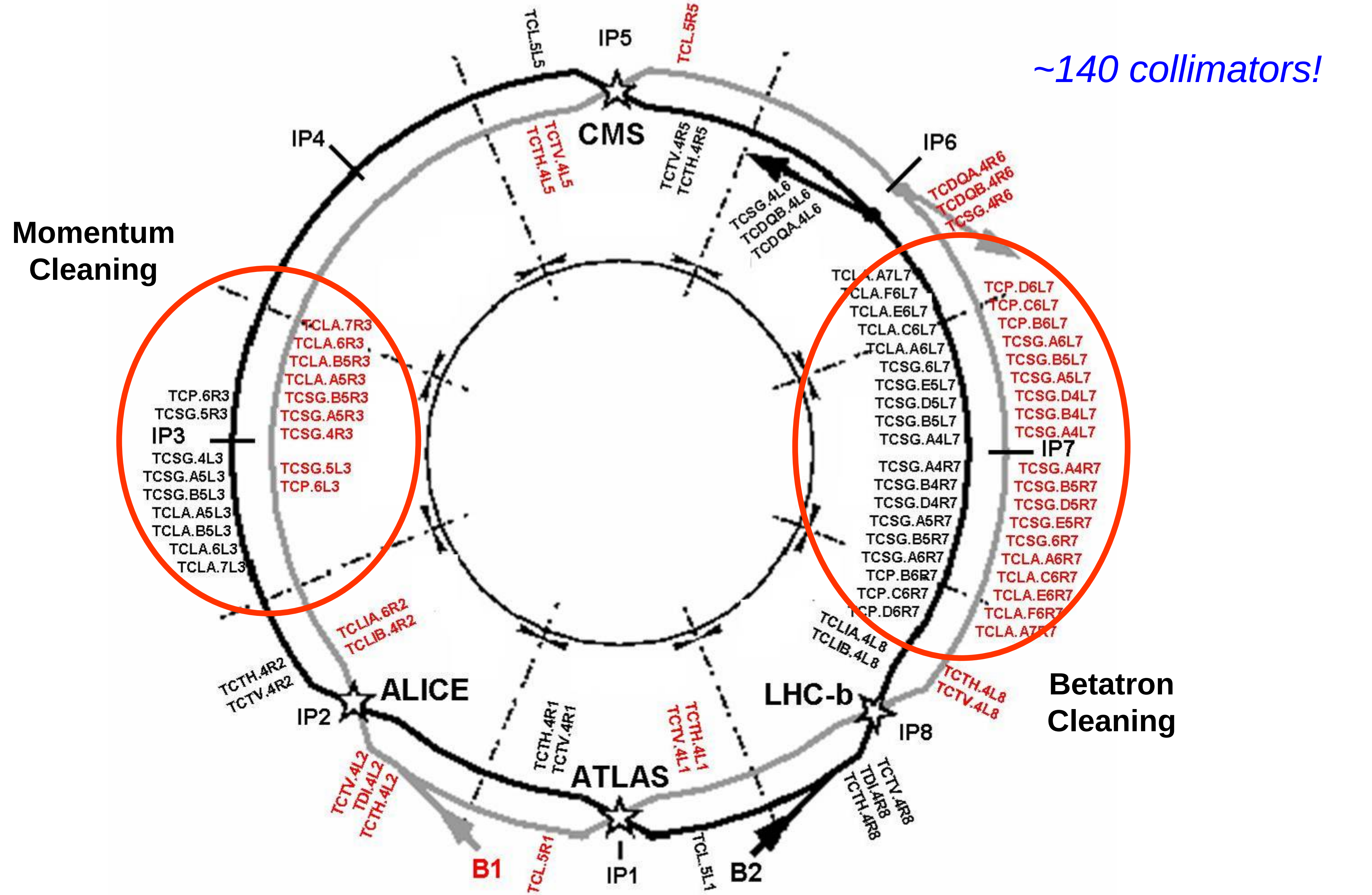
- collimation & machine protection
  - quenches, cleaning efficiency, impedance
- beam-beam interaction
  - head-on, long-range, weak-strong, strong-strong
- electron cloud
  - heat load, instabilities, emittance growth



At <1% of nominal intensity LHC enters new territory

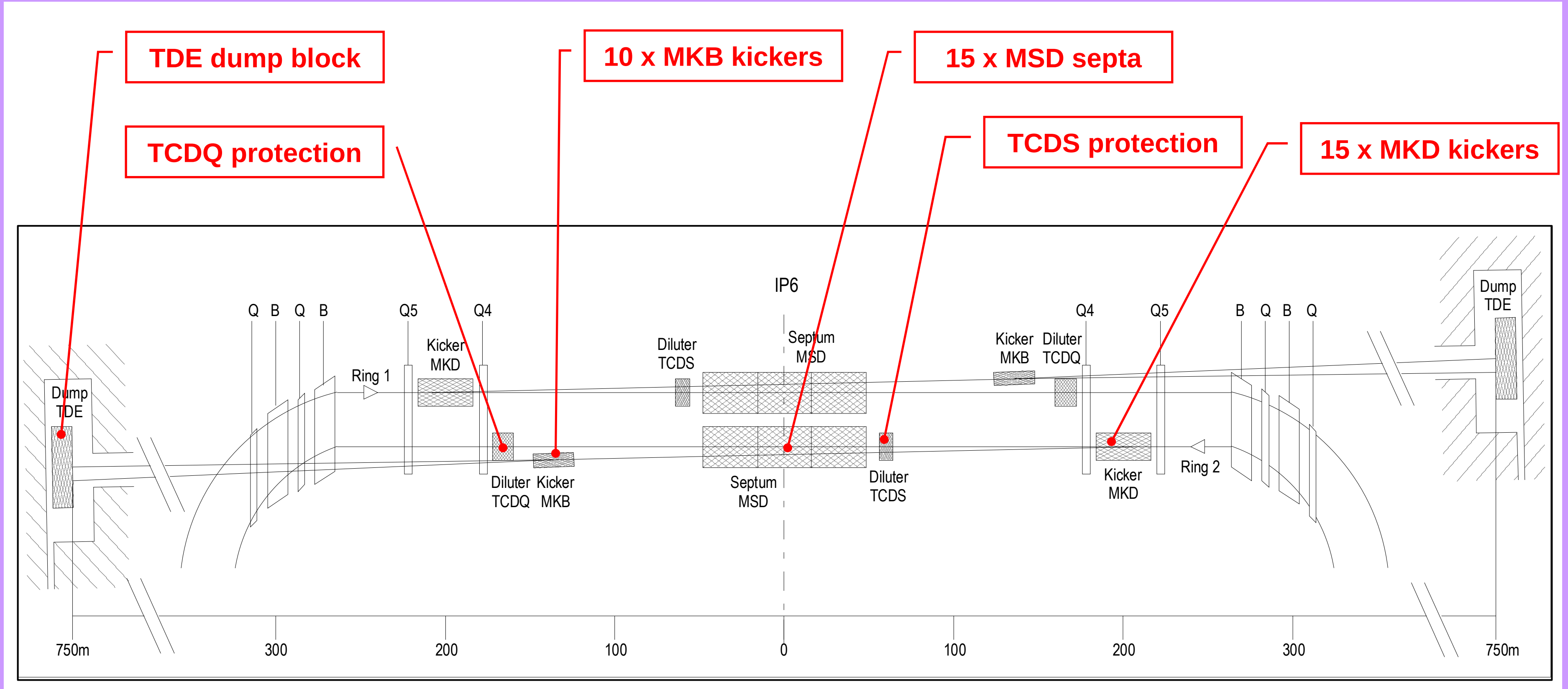
R. Assmann

LHC "phase-I" Collimation System



R. Assmann

LHC beam dumping system

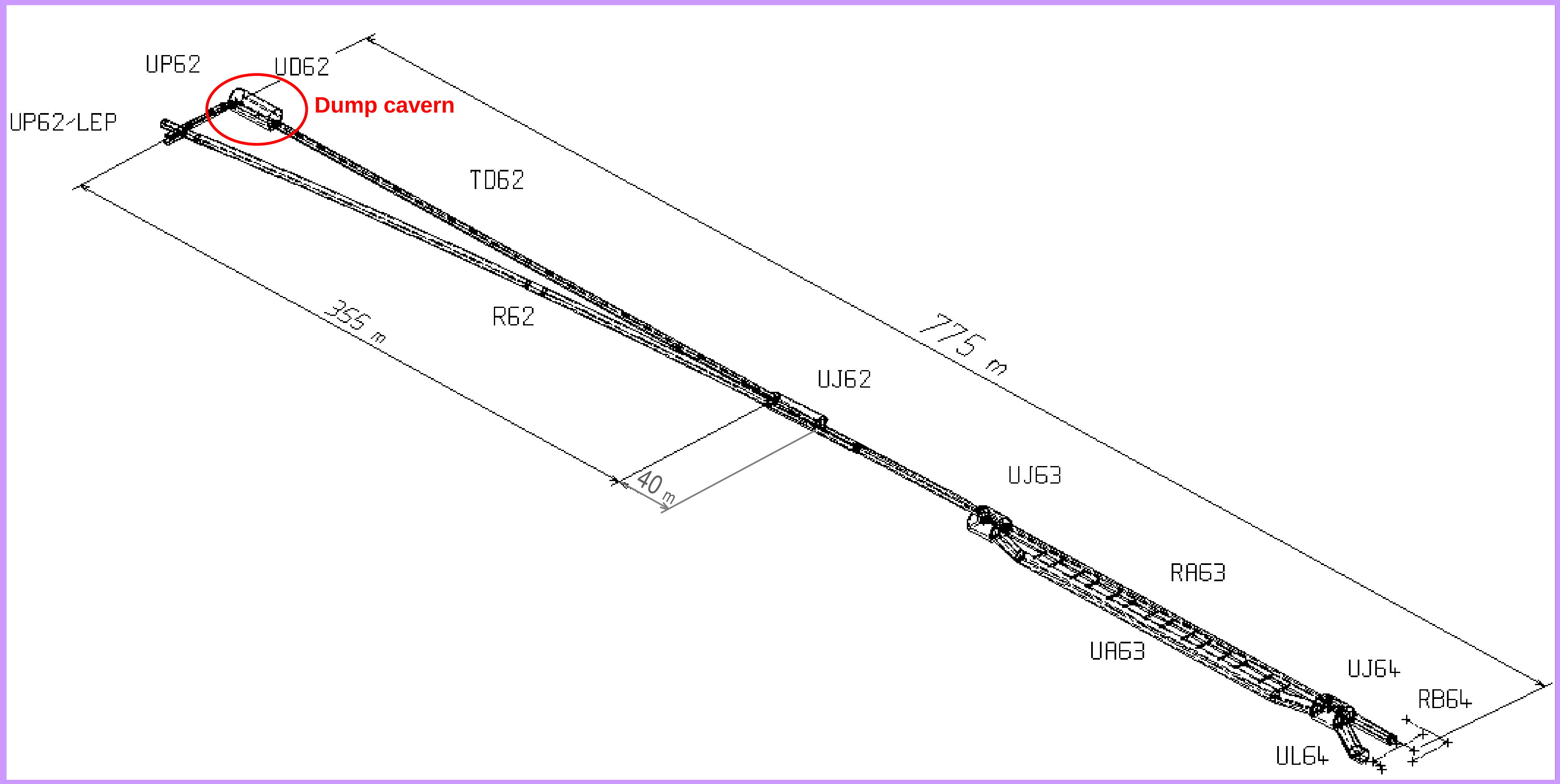


Total 'beamline' length :

975m from kicker MKD to dump TDE

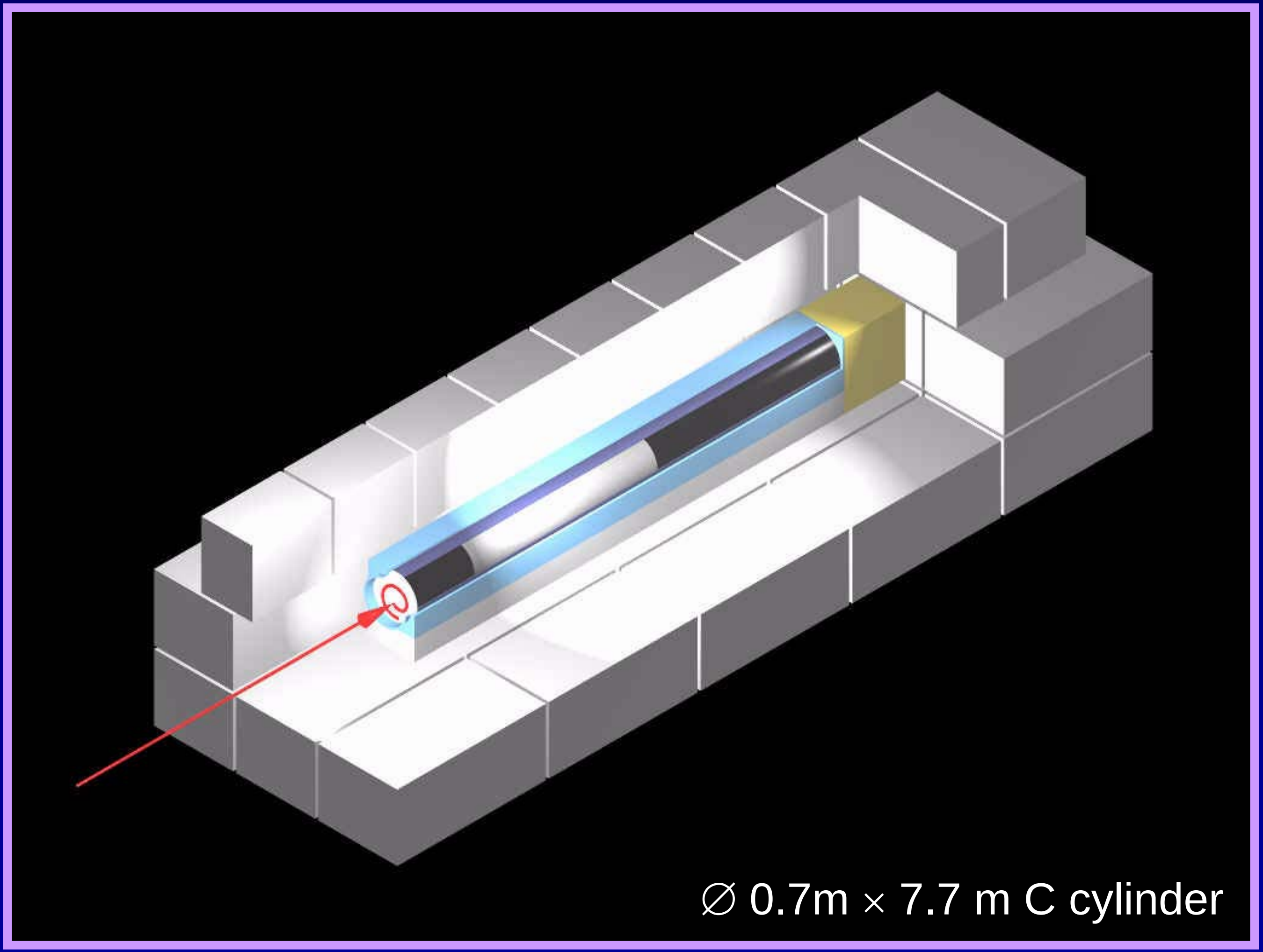
B. Goddard

dump system - tunnel layout



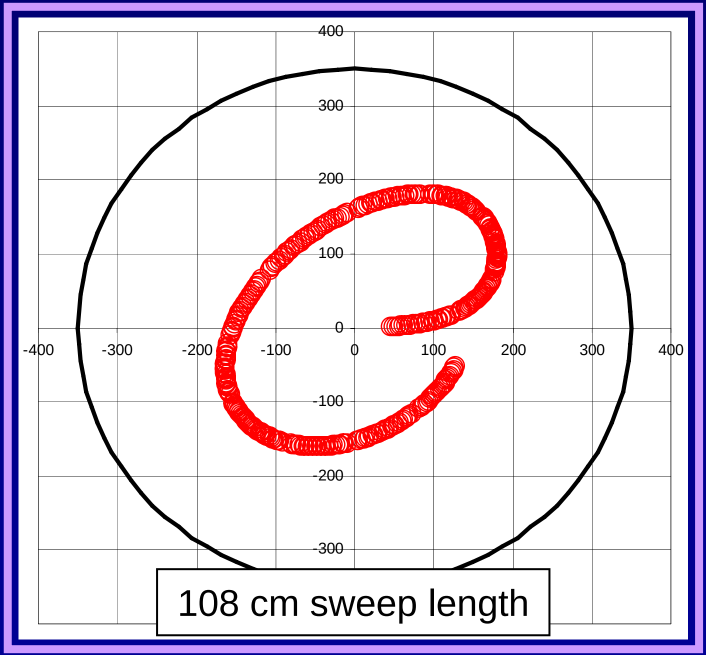
B. Goddard

beam-dump absorber

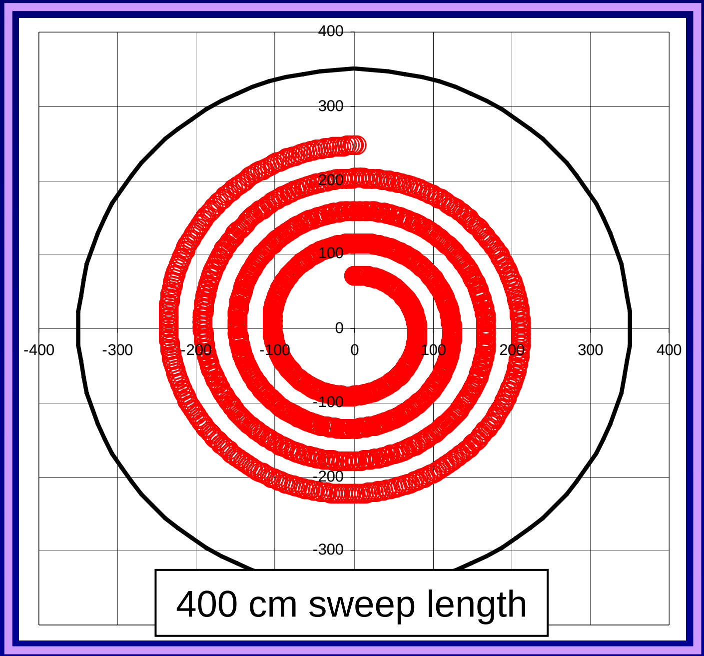


B. Goddard

dilution of dumped beam with spiral sweep on absorber



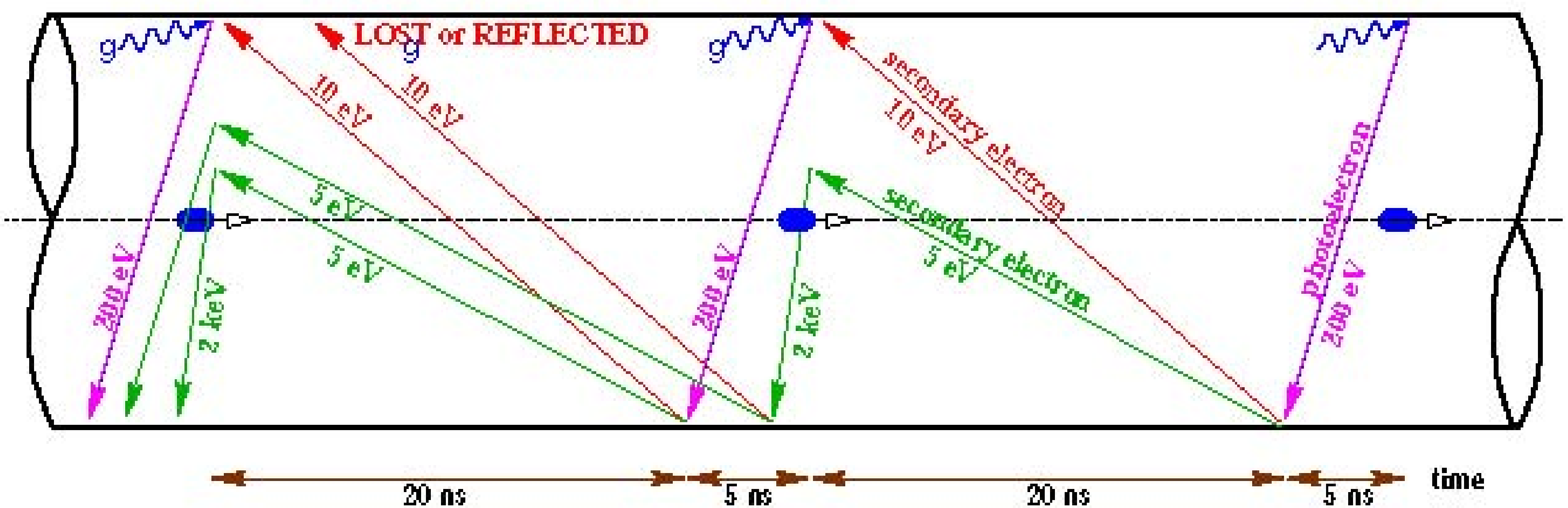
nominal system



future upgrade?

B. Goddard

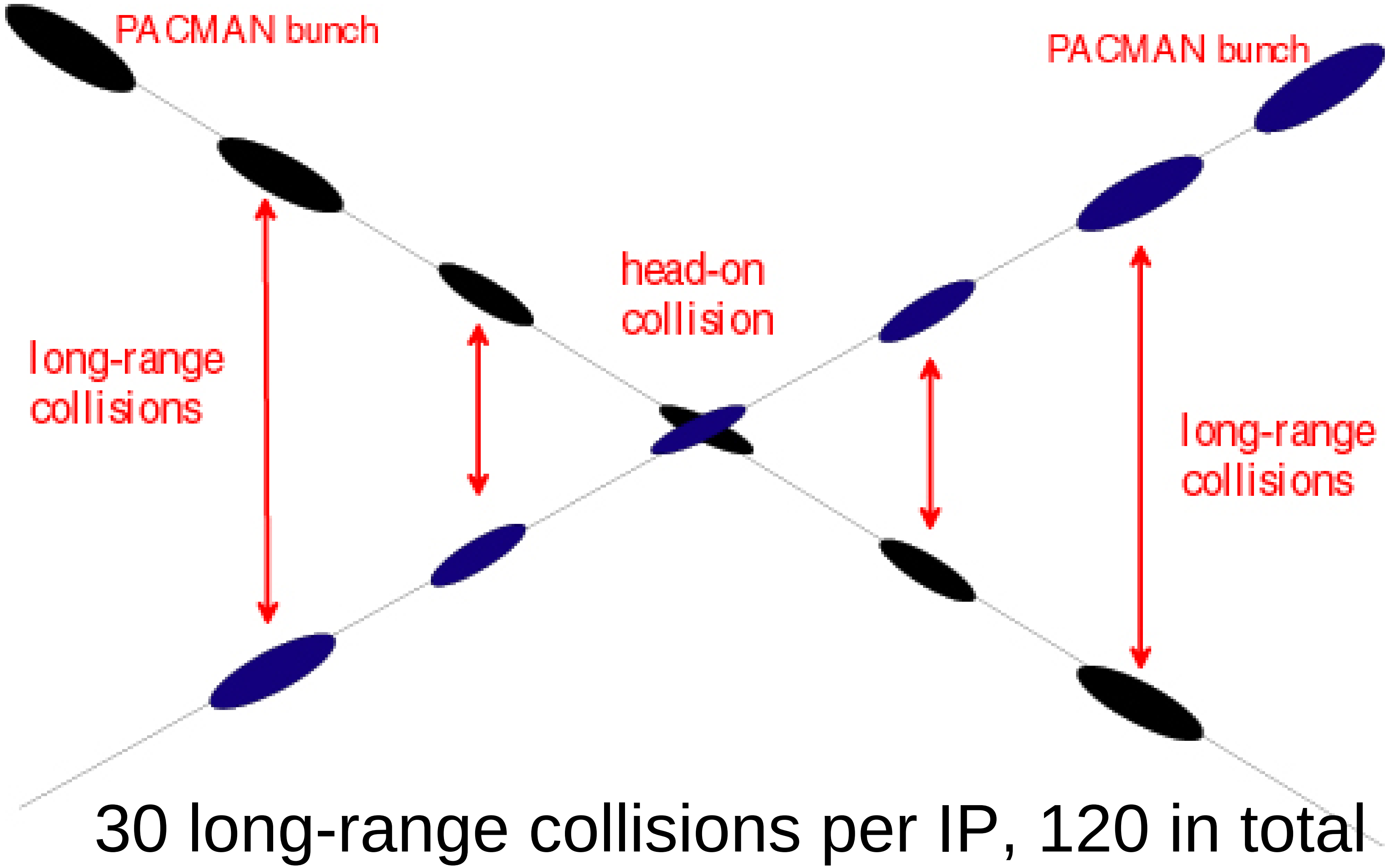
electron cloud in the LHC



schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

[F. Ruggiero]

beam-beam effects at LHC



30 long-range collisions per IP, 120 in total

ion beams in LHC

- **LHC can operate as heavy-ion collider,**
  in particular for ALICE experiment
- **the ion beam is also produced in the injector complex – some additional issues:**
  - e- stripping (wanted and unwanted)
  - e- capture
  - electron cooling
- **ion collimation in LHC still unsolved**
  - ions react differently with primary collimators

Accelerator Options after LHC

- **Hadron colliders:**

Upgrade LHC luminosity $10^{34} \rightarrow 10^{35}$

Upgrade LHC energy 14 → 28 TeV ?

VLHC (40/200 TeV phase I/II)

Not here, CERN participates

- **Lepton colliders:**

ILC (0.5 – 0.8/1.0 TeV)

Consensus: the "next" project

Not here? CERN participates?

CLIC (0.5 – 3 (5?) TeV)

future flagship?

$\mu+\mu-$ collider in TeV class ??

- **Advanced neutrino beams**

Superbeam: ν_μ but not very pure

uses ISR tunnel

Neutrino Factories:

- Based on β decay in ring: ν_e

uses CPS and SPS

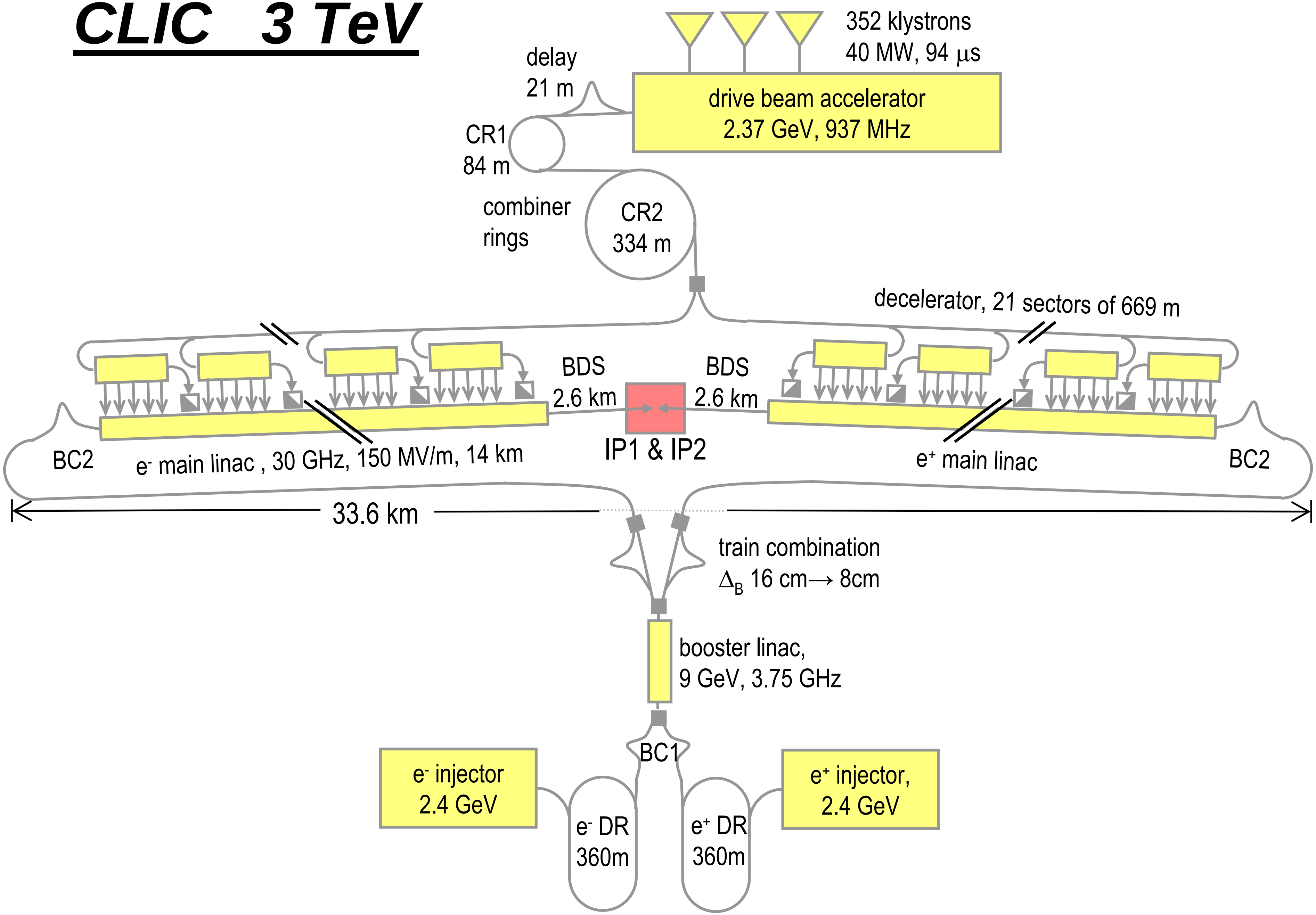
- Based on μ decay in ring: $\nu_e \underline{\nu}_\mu$

Comment: all have synergies with ISOLDE, EURISOL, and neutron-spallation source;

rather decoupled from LHC/ILC results?

K. Hubner

CLIC 3 TeV



352 klystrons
40 MW, 94 μs
delay
21 m
drive beam accelerator
2.37 GeV, 937 MHz
CR1
84 m
combiner
rings
CR2
334 m
decelerator, 21 sectors of 669 m
BDS
2.6 km
BDS
2.6 km
IP1 & IP2
BC2
e- main linac , 30 GHz, 150 MV/m, 14 km
e+ main linac
BC2
33.6 km
train combination
ΔB 16 cm→ 8cm
booster linac,
9 GeV, 3.75 GHz
BC1
e- injector
2.4 GeV
e- DR
360m
e+ DR
360m
e+ injector,
2.4 GeV

topics addressed

- CERN accelerators & beams
- a bit of history
- beam dynamics constraints
- beam parameters
- injection & extraction
- future machines

references

- K. Hubner, “Accelerators at CERN,” CERN Academic Training 13 September 2004
- **M. Benedikt,** “A Walk Through the LHC Injector Chain – Part 1: The PS Complex,” CERN Academic Training Lectures, 2005.
- **P. Collier,** “A Walk Through the LHC Injector Chain – Part 2: The SPS,” CERN Academic Training Lectures, 2005.
- **E. Metral,** Overview of the LHC and its Injector Chain, Seminar at MAX-lab, Lund, Sweden, 27.03.2007
- K.-H. Schindl, “A Walk Through the LHC Injector Chain – Part 3: Ions,” CERN Academic Training Lectures, 2005.
- L. Rossi, The LHC Magnets and Beyond, APS-DBP Newsletter Spring 2007
- R. Assmann, “Phase-2 Collimation Concepts,” LHC-MAC 8 Dec. 2006
- B. Goddard, “Beam Dump,” CARE-HHH-APD workshop HHH-2004, CERN, November 2004
- F. Zimmermann, “Accelerator Physics at the High Energy Frontier,” SLAC Seminar, July 2003.

I will post these talks near the top of my home

http://wwwslap.cern.ch/~frankz

If you have any questions, you can always send me email

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