Injection Painting and Associated HW for 160 MeV PSB H^-

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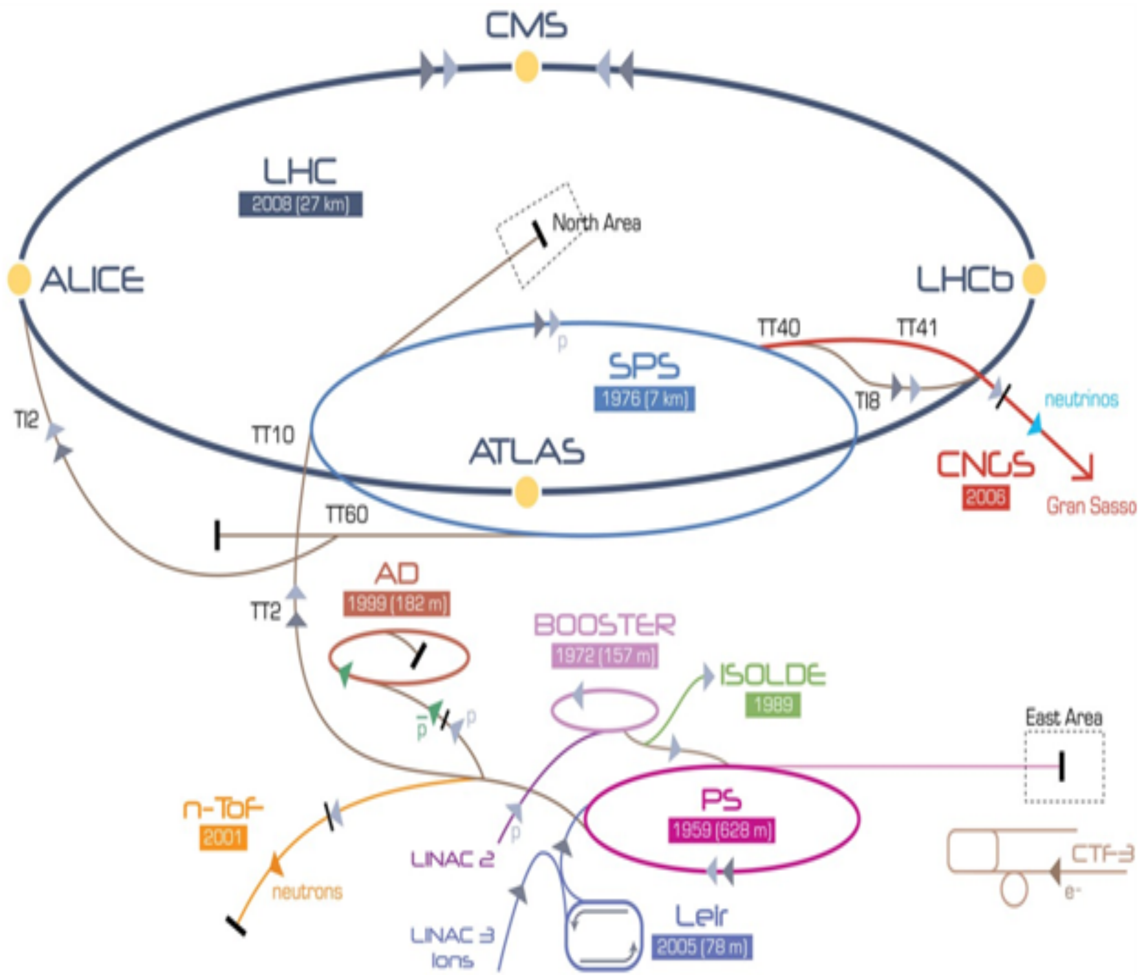
Outlines

- LHC accelerator complex and PS Booster (PSB)
  - Linac4 upgrade (motivation)
  - PSB users and beam requirements
- H^- charge exchange injection: principle and layout
- Injection painting in phase space
  - Longitudinal
  - Transversal (horizontal plane)
- ORBIT tracking simulations of different painting schemes for LHC and CNGS beam
- HW specifications
- Conclusions

The PS Booster in the LHC Complex



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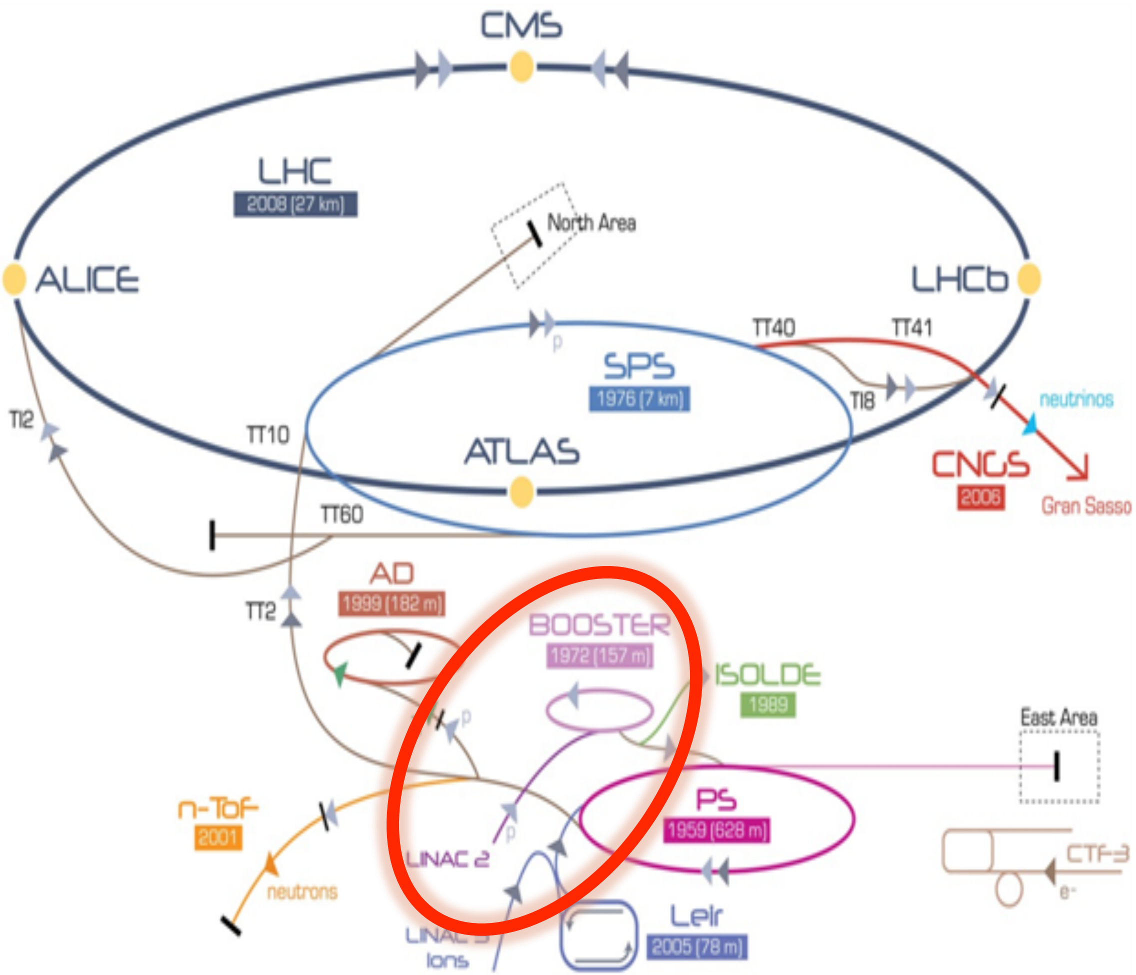
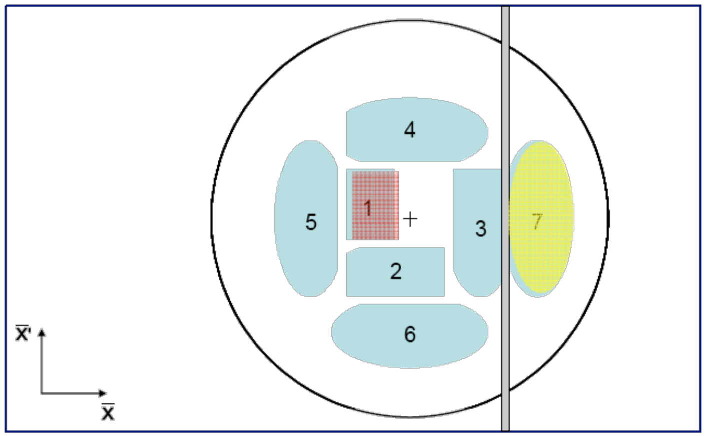


The **PS Booster** (PSB 1972) is the first synchrotron of the LHC proton injection chain.

LINAC 2 injects **50 MeV protons** to the Booster via a conventional **multi-turn** injection with a **septum magnet.**

Turn 7



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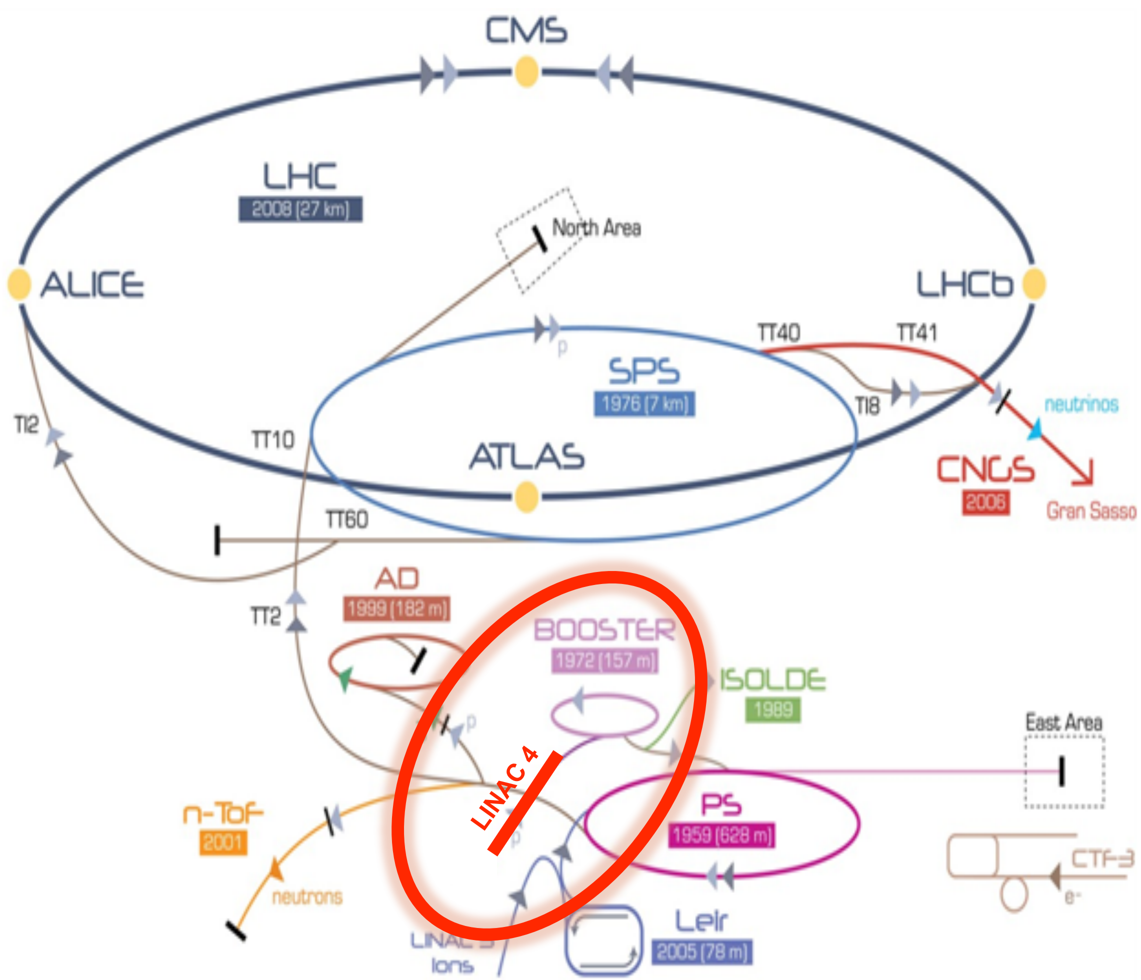

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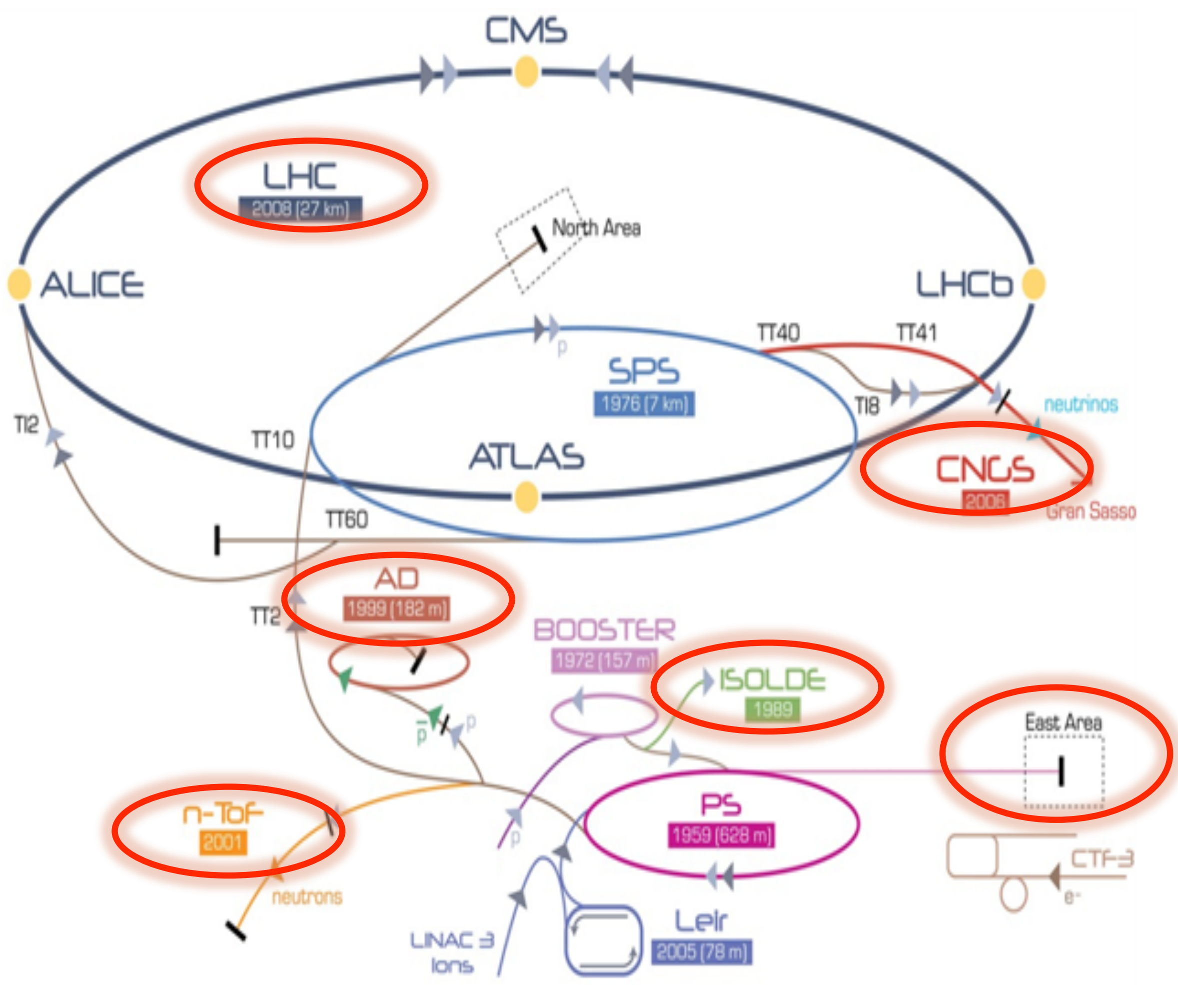
LINAC 4 will replace LINAC 2. It will accelerate **H^- ions** up to **160 MeV** using **charge exchange injection**.

The PS Booster in the LHC Complex



Protons, after being accelerated up to **1.4 GeV** can be directed to the next synchrotron of the acceleration chain (**PS**) or directly to the experiment **ISOLDE** .

The PSB is used to produce different beams (intensity, emittance) for several users:

- LHC
- CNGS
- SPS (fixed target)
- AD target
- TOF
- EAST area

Different Beams Required by Users

User	Description	Intensity per ring [p+]	Emittance H	Emittance V	Injection turns
LHC25	25ns LHC beam	3.25×10^{12}	2.5	2.5	20
LHC50	50ns LHC beam	2.43×10^{12}	2.5	2.5	15
LHC75	75ns LHC beam	$< 2.43\times10^{12}$	2.5	2.5	< 15
LHCPILOT	Early LHC pilot	5.00×10^{9}	2.5	2.5	1
LHCPROBE	Early LHC probe	5.00×10^{9} 2.30×10^{10}	2.5	2.5	1 1
LHCINDIV	Individual bunch LHC physics beam	2.30×10^{10} 1.35×10^{11}	2.5	2.5	1 1
CNGS	CNGS target	6.00×10^{11} 8.00×10^{12}	10	8	4 49
SFTPRO	SPS fixed target	6.00×10^{12}	8	6	37
AD	AD target	4.00×10^{12}	8	6	25
TOF	nTOF beam	9.00×10^{12}	10	10	55
EASTA/B/C	East area targets	1.00×10^{11} 4.50×10^{11}	3	1	1 3
NORMGPS NORMHRS	ISOLDE GPS/HRS target beams	1.00×10^{13}	15	9	62
STAGISO	ISOLDE special targets	3.50×10^{12}	8	4	22

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Motivation For Linac 4

- The Booster main intensity limitation: Direct space charge detuning.

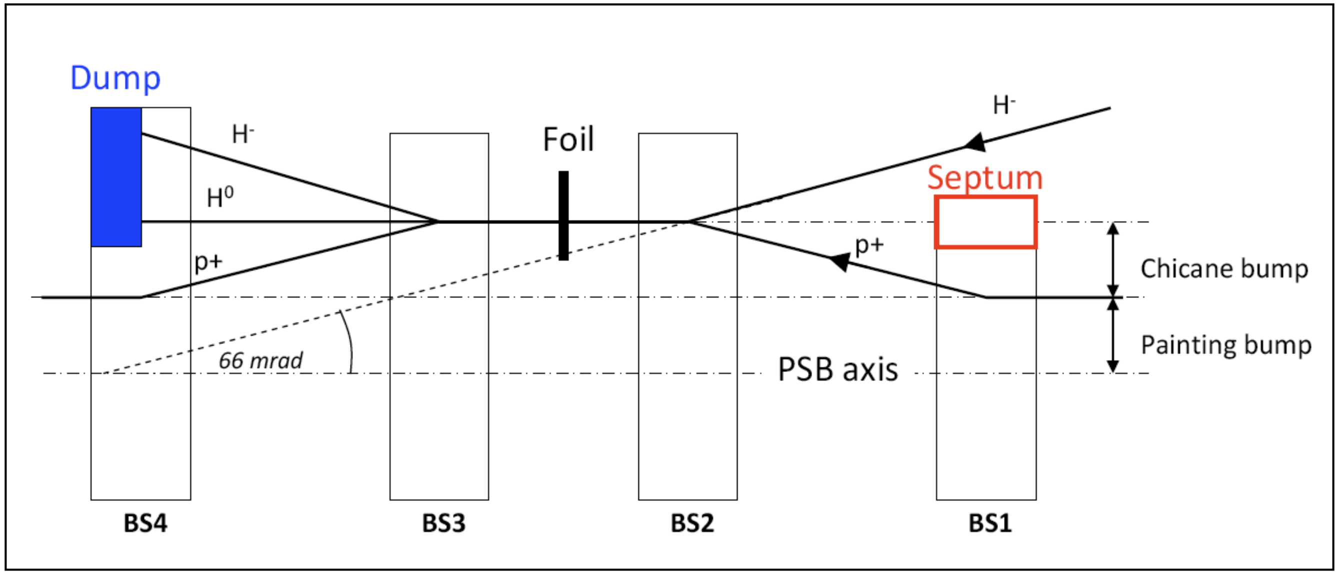
- The effect of the space charge is a tune shift:

$$\Delta Q \propto \frac{N_{particles}}{\varepsilon^{norm} \beta_{rel} \gamma^2}$$

- Mitigation of direct space charge effects improve PSB performance: the injection energy will be increased from 50 MeV to 160 MeV with Linac4 ➔ smaller ΔQ

$$\frac{(\beta_{rel}\gamma^2)_{160\,MeV\,\mathrm{Protons}}}{(\beta_{rel}\gamma^2)_{50\,MeV\,\mathrm{Protons}}} = 2$$

H^- Injection



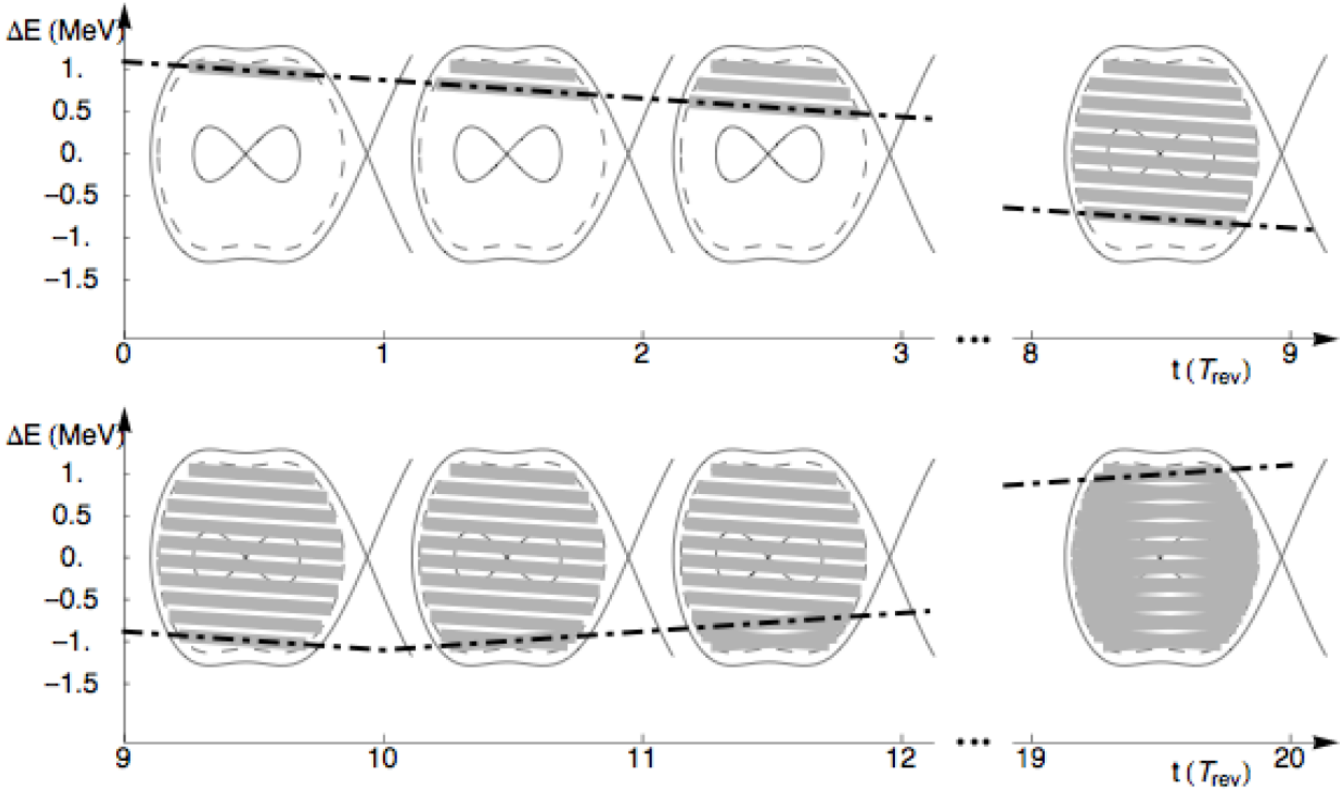
- Horizontal closed orbit bump (chicane)
- Thin carbon stripping foil which convert H^- in p^+ by removing electrons
- p^+ deflected towards PSB axis, H^- and H^0 dumped
- Horizontal painting bump made with 4 KSW magnets (outside injection region)

Chicane Decay Instabilities

- Beam injected in with 66mrad angle wrt PSB axis
- Strength of BS chicane magnets maximum during injection ➔ 45.9 mm orbit bump
- Chicane decays linearly after injection
- RBEND magnets: edge focusing effects at pole faces ➔ perturbation of vertical betatron oscillations
- Solutions:
  - Active compensation: additional trim quadrupoles
  - Passive compensation: pole face rotation
- Passive compensation with 66 mrad pole face rotation (i.e. SBEND magnets) used for the studies presented in the following

Longitudinal painting

- Further attenuation of space charge effects can be obtained by controlling the distribution, in phase space of injected particles
- Energy of the injected beam will be varied to fill the bucket with an equal density distribution.

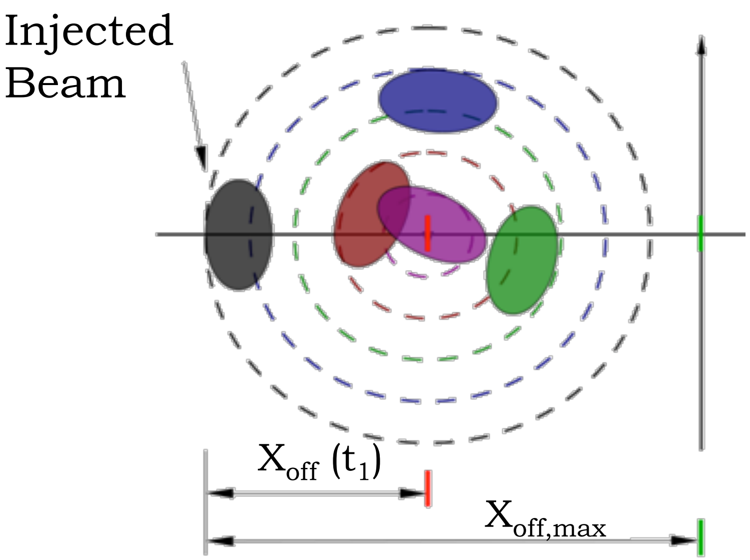


±1.1 MeV energy distribution over a period of 20 turns

Important for beam delivery ($D_x/D_y \neq 0$) and matching!

Transverse Painting Scheme

- Horizontal painting bump implemented
- Fill first the centre and then the outer area of the ellipse in the transverse phase space
- Decay time modulation of four kicker magnets (KSW), installed in the PSB lattice, allow to accomplish transverse phase space painting to required emittance.
- Maximum height of the bump, at injection, depends on the beam and injection parameters

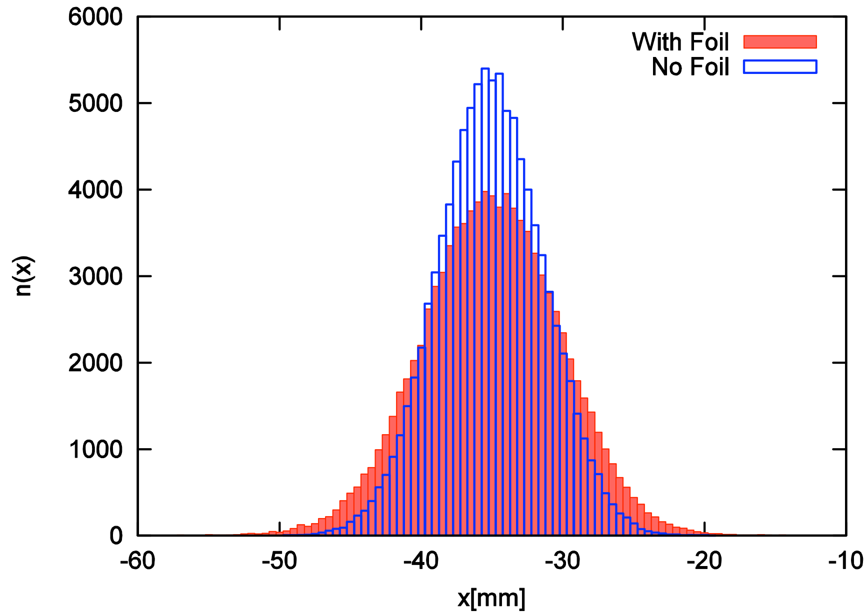


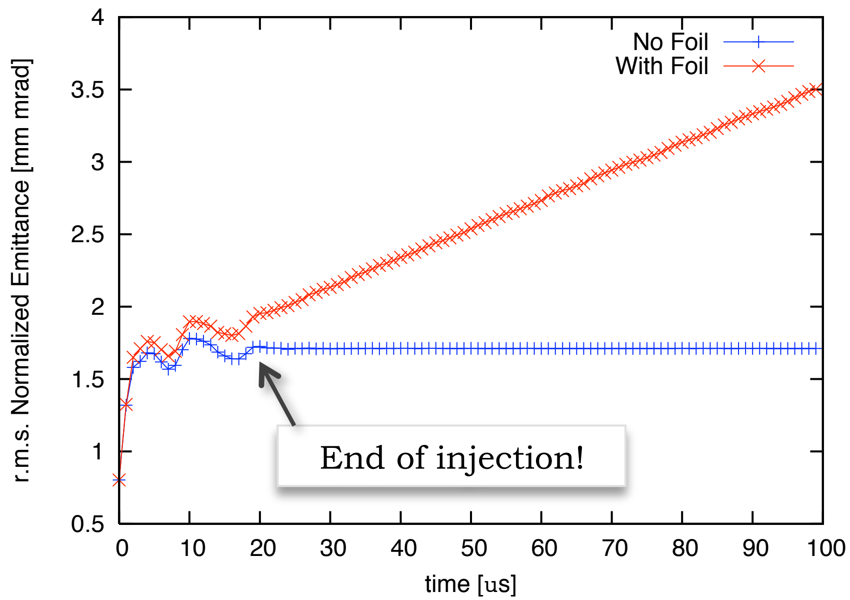
- Vertical beam ellipse areas are partially filled without painting
- Space charge forces reshuffle the particle distribution on successive turns

ORBIT Simulations

- Simulations were performed with the prticle tracking code ORBIT
- H- charge exchange, space charge effects, apertures and acceleration are included
- A routine, implemented in ORBIT, allows to simulate the painting bump (KSW thin lens approximation)
- Initial 6D distribution generated with a “Mathematica” notebook – longitudinal painting is included (500 000 macroparticles)
- Initial lattice generated with MAD8
  - Lattice stays unchanged during injection
  - After injection, lattice has to be reloaded at each turn to simulate chicane fall
- These studies were dedicated to injection painting ➔ particles tracked over 100 turns with fixed lattice

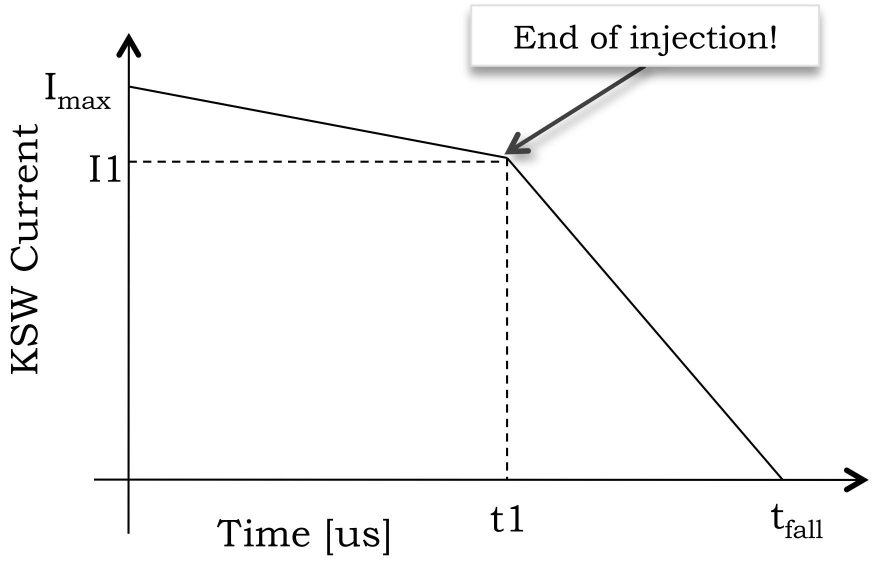
Effect of Stripping Foil on Emittance

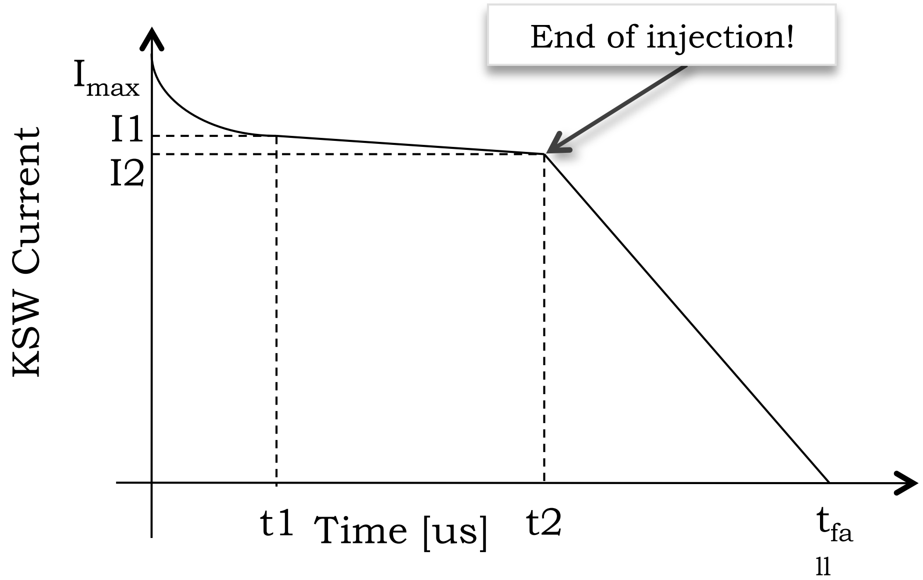




- Beam injected over 20 turns (LHC beam). Emittance preservation important!
- Particle distribution generated for a horizontal position of -35mm (0 offset applied), matched in dispersion (Dx = -1.4 m)
- KSW (painting) bump height is kept fixed at -35mm over 100 turns
- Circulating beam passes through the stripping foil (300ug/cm^2 C) at each turn
- Horizontal emittance increases linearly after injection ➔ ×2 increase in 100 turns
- Circulating beam must be moved away from foil as soon as possible – presently chicane fall time is slow (~5ms), so rely on fast fall of painting bump to do this

KSW Decay – possible waveforms





Linear KSW Decay:

✓ Slow linear KSW decay until end of injection.

✓ Fast decay to 0 in order to move the beam away from the stripping foil (15 us)

Exponential-Linear KSW Decay:

✓ Fast exponential decay over first few turns

✓ Slow linear KSW decay until end of injection.

✓ Fast decay to 0 in order to move the beam away from the stripping foil (15 us)

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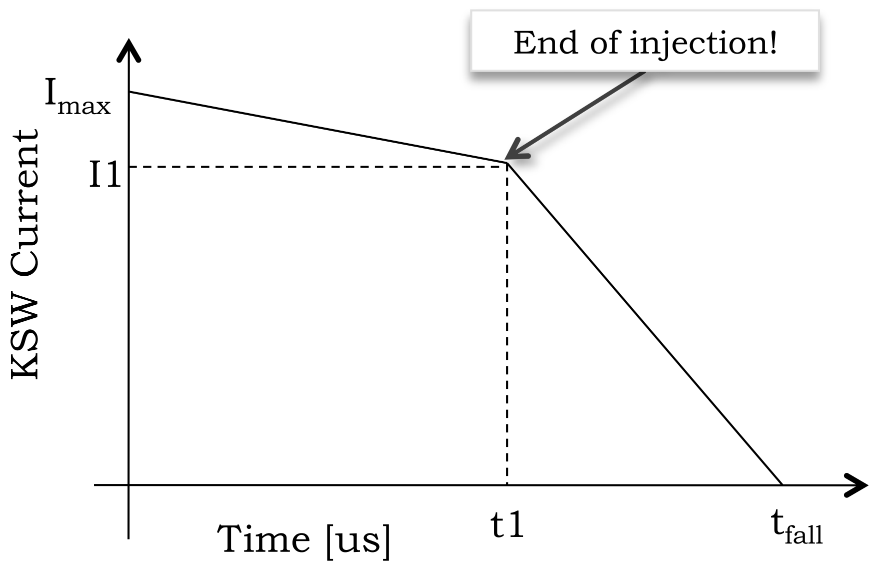
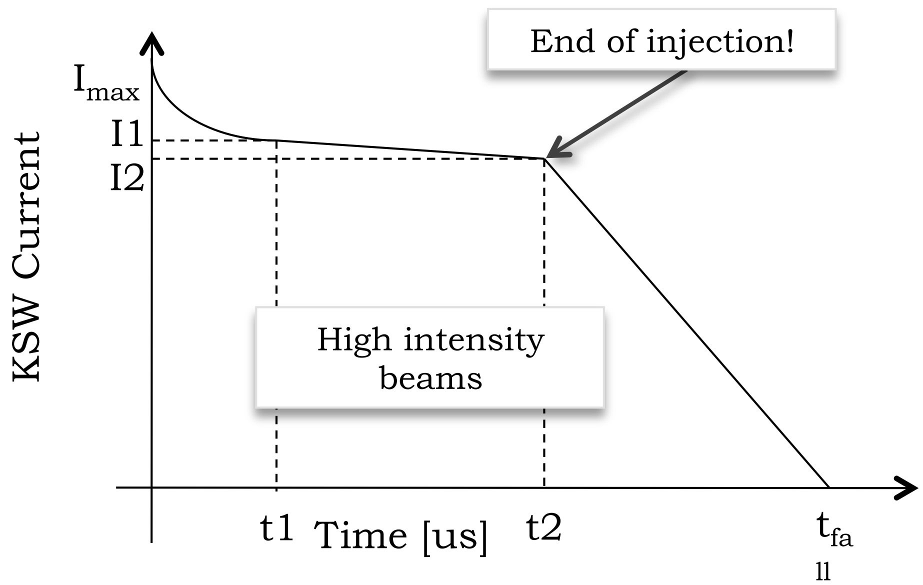




Linear KSW Decay:

✓ Slow linear KSW decay until end of injection.

✓ Fast decay to 0 in order to move the beam away from the stripping foil (15 us)

Exponential-Linear KSW Decay:

✓ Fast exponential decay over first few turns

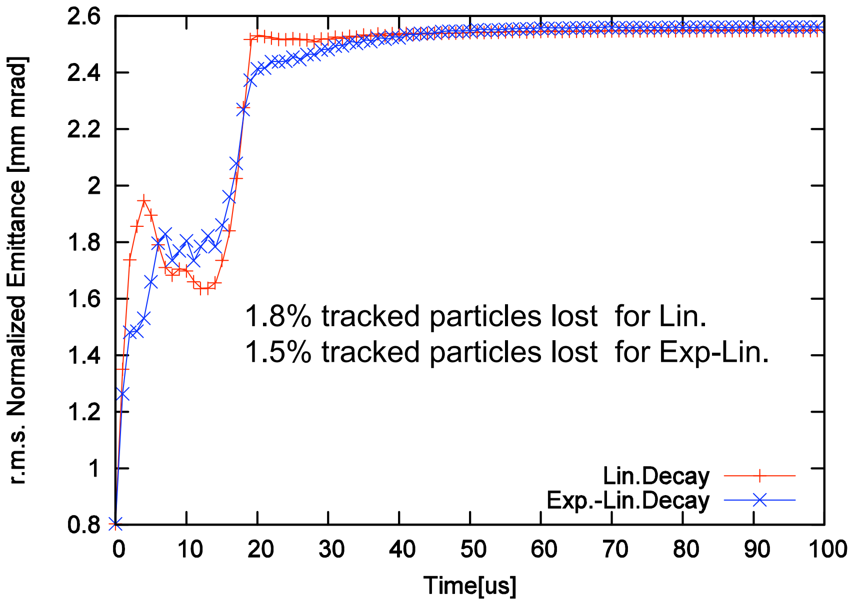
✓ Slow linear KSW decay until end of

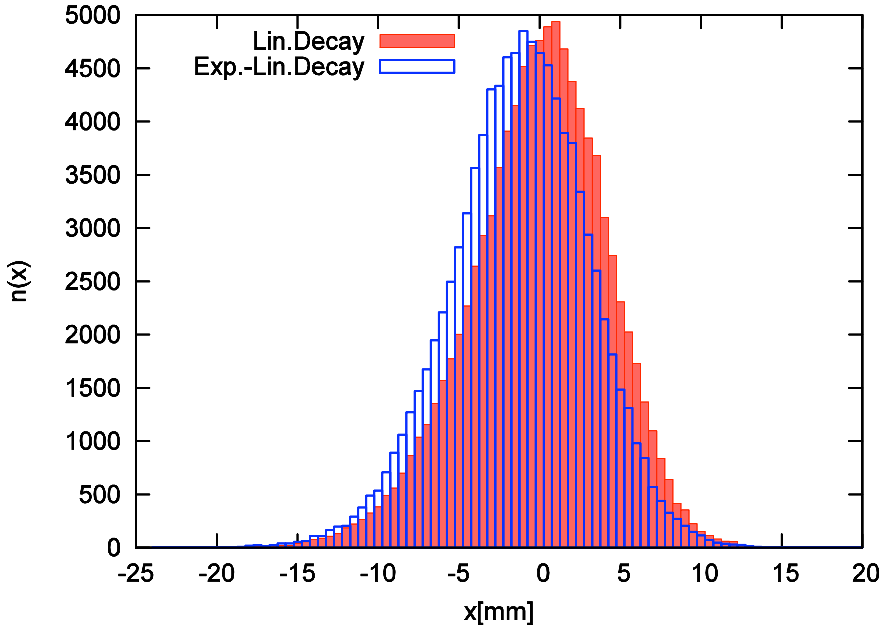
beam

away from the stripping foil (15 us)

Uniform particle distribution ➔ lower charge density ➔ smaller space charge effects

LHC Beam – comparison of KSW decays





Injection over 20 turns, 2.5 mm mrad target emittance for both KSW waveforms

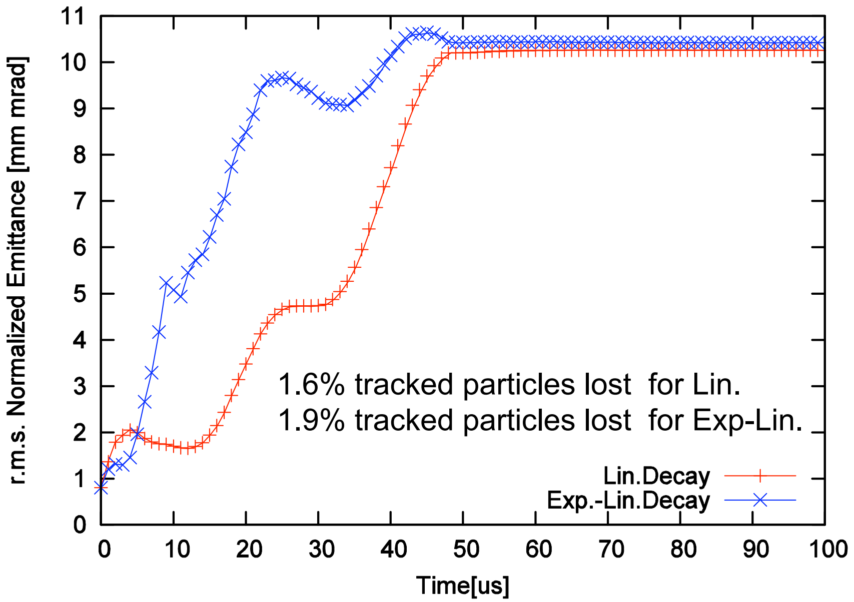
✓No big differences between the two variants

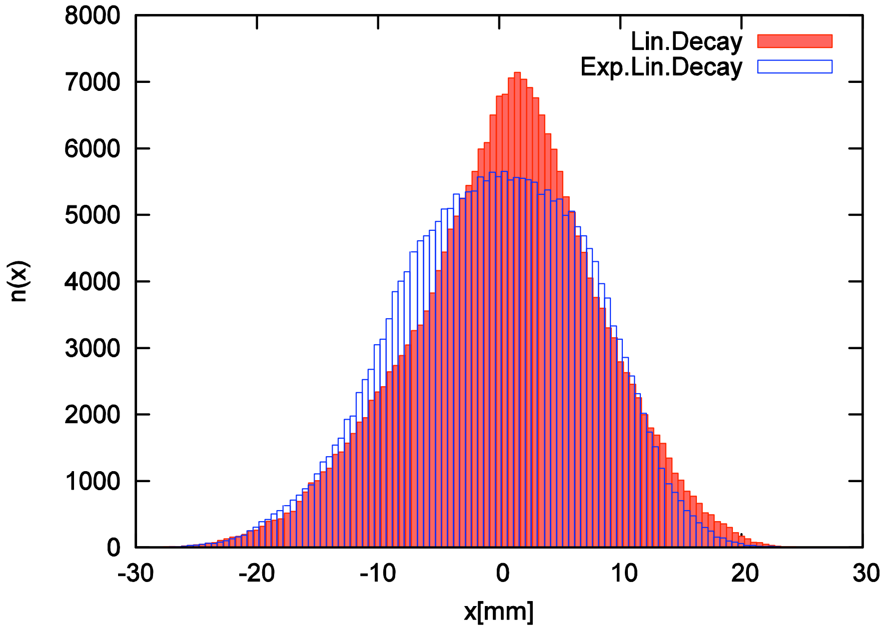
- Peaked particle distribution but low intensity

✓ Initial exponential decay of KSW maybe slightly better:

- Reduces effect of emittance increase due to stripping foil over first turns
- More symmetric distribution around closed orbit after 100 turns

CNGS Beam - comparison of KSW decays





Injection Over 49 turns, 10 mm mrad target emittance

For high intensity beam (injection over a big number of turns) an initial exponential decay of KSW gives a significant improvement of the beam distribution ➔ more uniform distribution for the target emittance, reduced density in core.

Higher number of lost particles (especially over the first turns) ➔ room for improvement

KSW Parameters

	LHC Beam	CNGS Beam
I1	94% I_{max}	71% I_{max}
I2	92% I_{max}	70% I_{max}
t1	7 us	10 us
t2	20 us	49 us
t_{fall}	35 us	64 us

I_{max}: current corresponding to a bump height at the foil of -35 mm

Kicks for a 55 mm bump at the foil:
KSWP16L1: 8.74 mrad ➔ 0.045 T
KSWP1L4: 2.55 mrad ➔ 0.013 T
KSWP2L1: 2.55 mrad ➔ 0.013 T
KSWP16L4: 8.74 mrad ➔ 0.045 T

Functions have to be defined for varying the dI/dt of the KSW during injection.
Different functions for different users ➔ high flexibility is required

KSW Hardware implications

- Require waveform with:
  - Initial exponential fall (1 – 20 us long, ΔI 0-50% I_{max});
  - Then ~constant slope fall (5 – 100 us, ΔI 2-100% I_{max})
  - Final fast slope fall (5-15 us, ΔI 0-70% I_{max})
- Max dI/dt is 15% of I_{max} per us
  - Use this for final fall (move beam off foil)
  - Determines limit of exponential fall time constant
  - Not easy to modify this time constant in the generator – will investigate whether it can be kept constant for all the beam types
- New power supply design anyway needed
  - Two switches for changes of slope needed
- Still investigating whether to power magnets in series, or in parallel, or independently

Conclusions

- H- injection into PSB at 160 GeV assumes painting in H plane
- Orbit simulations to investigate optimum painting forms for KSW HW specification
  - Simulations working for LHC and CNGS beams
  - Importance of fast move of beam off foil – using painting bump
  - Preliminary results prefer Exp-Lin painting, for CNGS
  - To extend to all other beam types
  - Need to compare matched/mismatched dispersion from TL
- Still need to see in detail how required vertical emittances can be obtained
  - Offset of injected beam plus betatron mismatch – to optimize for each beam type