LEIR Commissioning and Performance

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on behalf of the I-LHC and LEIR teams

Acknowledgements:

LEIR is the result of the work of many people from several departments at CERN and outside CERN,

Special thanks to M.Chanel for help and advice

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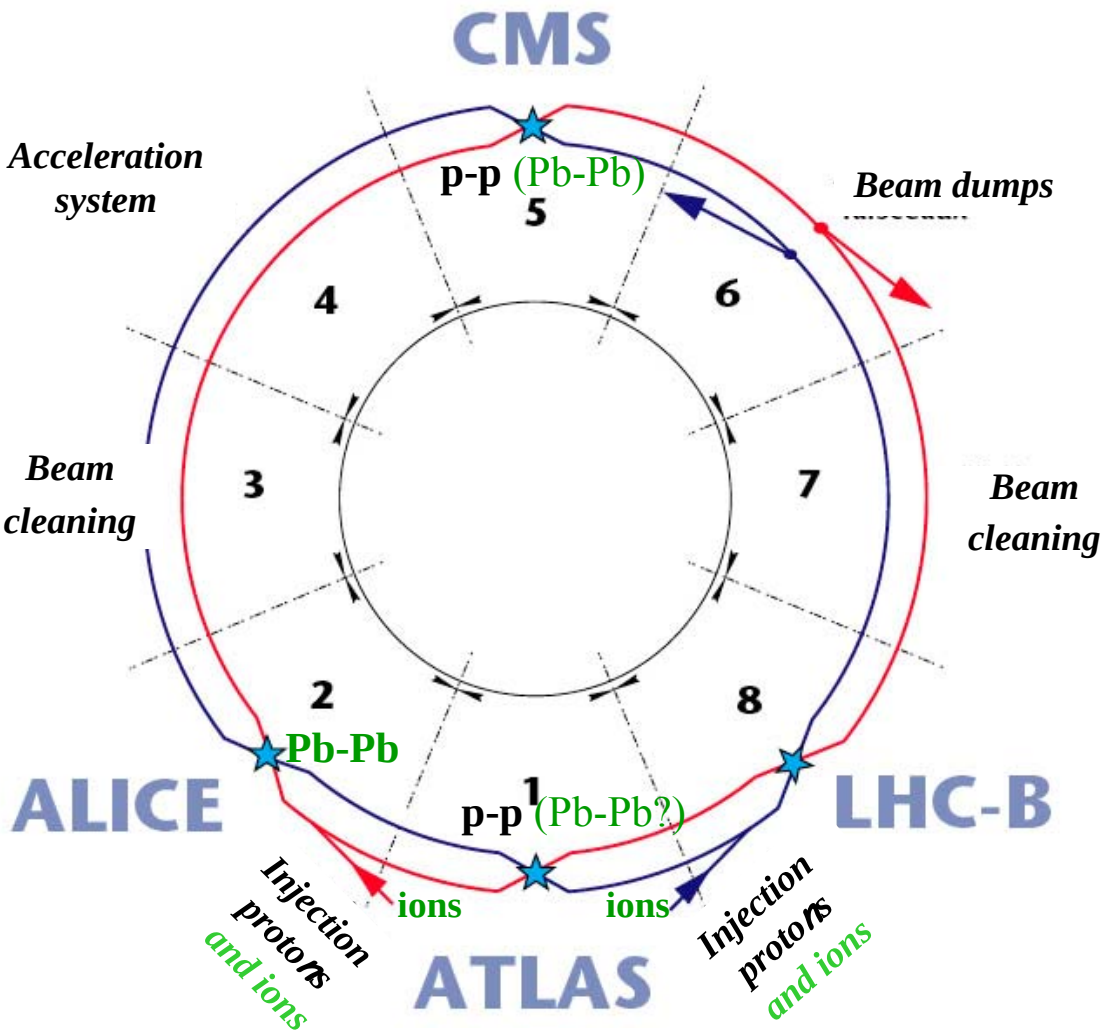
Introduction

- LHC (Large Hadron Collider) main diet : protons.
- In addition, ion operation during several weeks per year :
  - ALICE experiment optimized to observe ion collisions
  - CMS and ALTLAS intend to take data with ions as well
  - Initially Pb ↔ Pb operation
  - Later (likely, but not in baseline) :
    - p ↔ Pb
    - Lighter ions (e.g. In, Kr, Ar, O).



Introduction

- No way to satisfy LHC needs with the pre-LHC-era ion chain.
- Accumulation with electron cooling in LEIR to produce the bright beams needed (chosen amongst several proposals after tests in the 90ies).

- Nominal Lumi achievable in LHC ? (LHC limitations: collimation, bound free pair production), demanding for whole chain!
- Early LHC Ion Operation Scheme :
  - Lower Luminosity 5×10^{25} $cm^{-2}s^{-1}$ (instead of 10^{27} $cm^{-2}s^{-1}$) useful for first physics
  - Nominal bunch population (instrumentation),
  - Simplified injector chain and faster LHC filling,
  - Gain experience on LHC ion operation without danger to damage the machine.

Overview of the ion chain for LHC

Protons

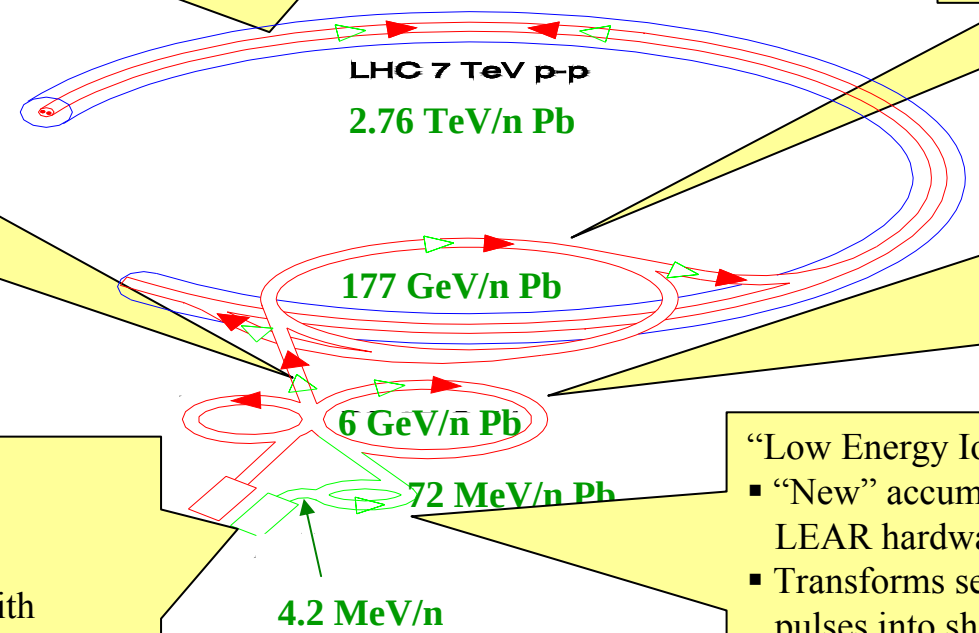
Pb Ions

LHC (two ring collider):
- Filling with 12 SPS batches and 592 bunches during ~10min/ring
- Limitations: Collimation, Ions capturing the electron from an electron positron pair

SPS:
- Accumulation of up to 13 PS/LEIR cycles
- Limited by space charge tune shift, IBS ?

Transfer PS to SPS:
Stripping Pb^{54+} to Pb^{82+} in low ß insertion

PS:
- Provides bunch structure (spacing) for nominal beam
- Complicated RF gymnastics (with new low level RF) for nominal beam)



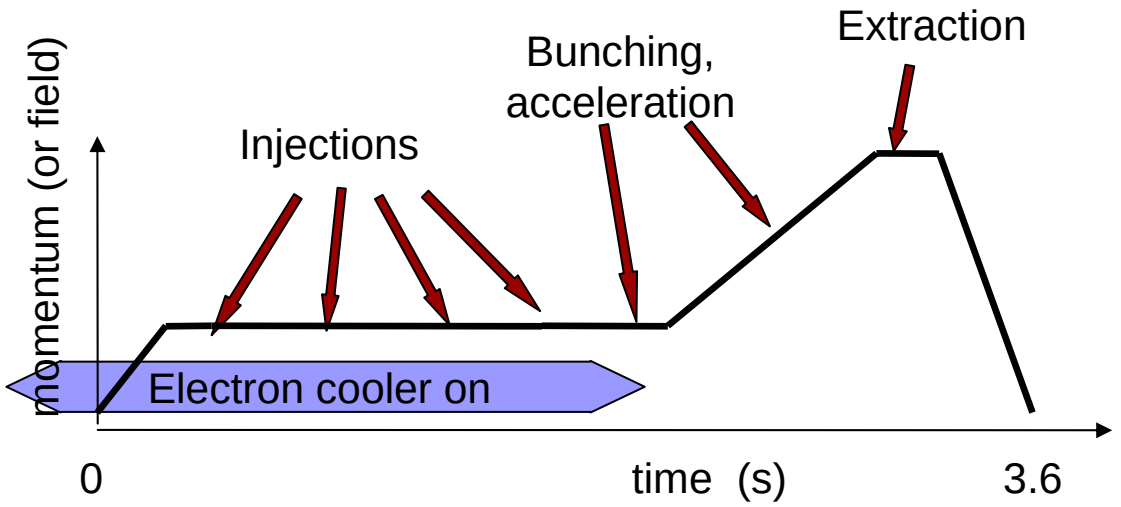
Ion Linac 3 :
- New ECR source (200µA of Pb^{27+}) in collaboration with CEA Grenoble)
- 5 Hz repetition rate
- Stripping Pb^{27+} to Pb^{54+}
- Energy ramping for LEIR injection

"Low Energy Ion Ring" LEIR:
- "New" accumulator (using existing LEAR hardware) added to ion chain
- Transforms several long Linac3 pulses into short dense bunches
- Multiturn injection with stacking in momentum and both transverse phase spaces
- New state-of the-art electron cooler constructed by a BINP team

Overview of the ion chain for LHC

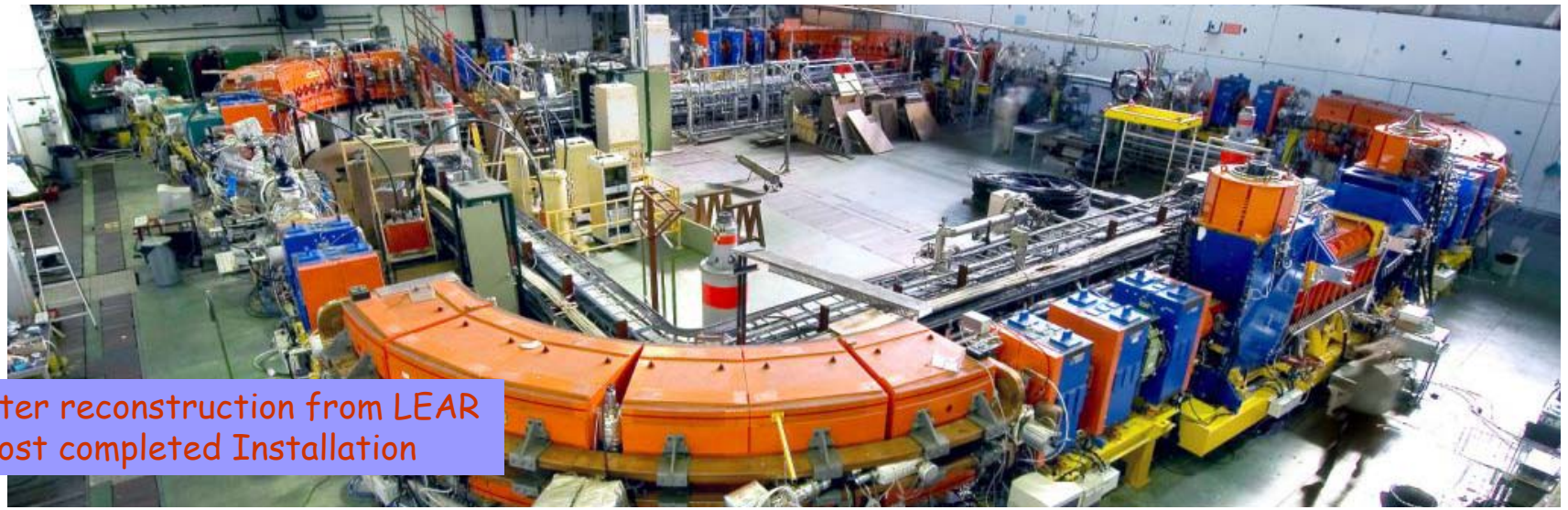
	Linac 3	LEIR3		PS		SPS		LHC	
Parameter		nominal	early	nominal	early	nominal	early	nominal	early
energy per nucleon	4.2 MeV	4.2 MeV		5.9 GeV		72 MeV		2.76 TeV	
Charge state	27→54	27 → 54		54 → 82		82		82	
Shots accumulated		~5-7	1	1	1	8,12,13	4	12	16
LHC bunches/shot (filling)	≤ 1	4	1	4	1	≤ 52	4	592	62
Ions/LHC bunch		$2.25\ 10^8$		$1.2\ 10^8$		$0.9\ 10^8$		$0.7\ 10^8$	
Ions/shot (filling)	$11.5\ 10^8$	$9\ 10^8$	$2.25\ 10^8$	$4.8\ 10^8$	$1.2\ 10^8$	$\leq 47\ 10^8$	$3.6\ 10^8$	$415\ 10^8$	$43\ 10^8$
Bunch spacing		350 ns		99.8 ns	1350ns	99.8 ns	1350ns	99.8 ns	1350 ns
Norm. rms emittance	0.25 μm	0.7 μm		1.0 μm		1.2 μm		1.5 μm	
Long. emitt./LHC bunch ($4\ \pi\ \sigma_E\ \sigma_\tau$)		0.025 eVs/n		0.05 eVs/n		0.24 eVs/n		1 eVs/n	
rms bunch length		50 ns		1 ns		0.41 ns		0.25 ns	
Cycle/Filling time	>200ms	3.6s	2.4s	3.6s	2.4s	~50 s	~15 s	~10 min	~4 min
β*								0.5 m	1.0 m
Initial luminosity (10^{27} $cm^{-2}s^{-1}$)								1	0.05
Initial lumi. decay time (2 experiments)								~5.5 hrs	~ 10 hrs

LEIR Overview



Accumulation alternates :

- Elaborate multiturn injection :
  - Stacking in three phase planes,
  - Needs momentum ramping and dispersion at injection,
  - 70 turns (200 μs) with >50% efficiency every 200 to 400 ms.
- Fast electron cooling :
  - New cooler constructed (BINP)

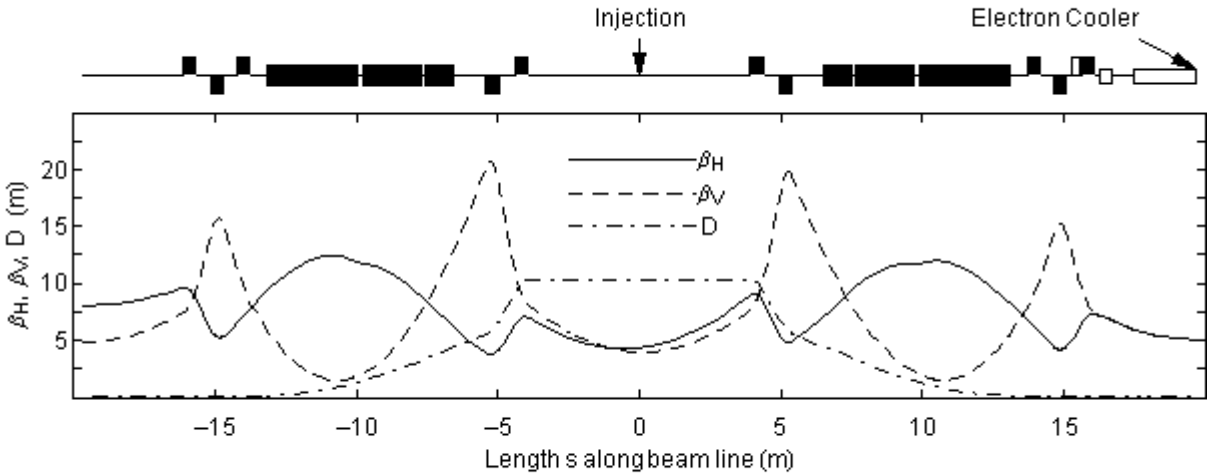


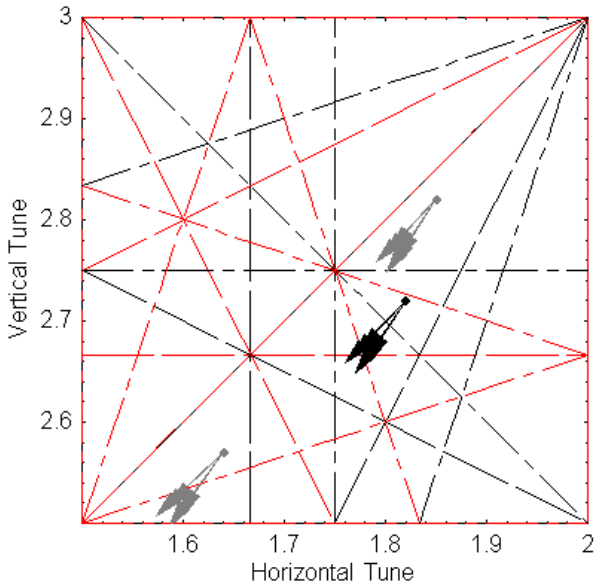
LEIR after reconstruction from LEAR
Almost completed Installation

LEIR Overview

- Basic shape: square
  - with long bending section in corners
  - four long straights
- Requirements (rather different for injection and cooling):
  - Injection and cooling in adjacent straights
    - Injection: large (normalized) dispersion,
    - Cooler: small dispersion (large momentum spread injcted) and ß ~ 5 m
  - Neglecting cooler periodicity two and symmetry
  - Sufficient acceptances and suitable working point
  - Cooler introduces coupling:
    - Compensated with short solenoids (plus skew quads)
    - Additional focusing compensated globally (readjustment of all quad families and trim power converter close to cooler)
    - No periodicity any more, but still one symmetry plane.

LEIR Overview

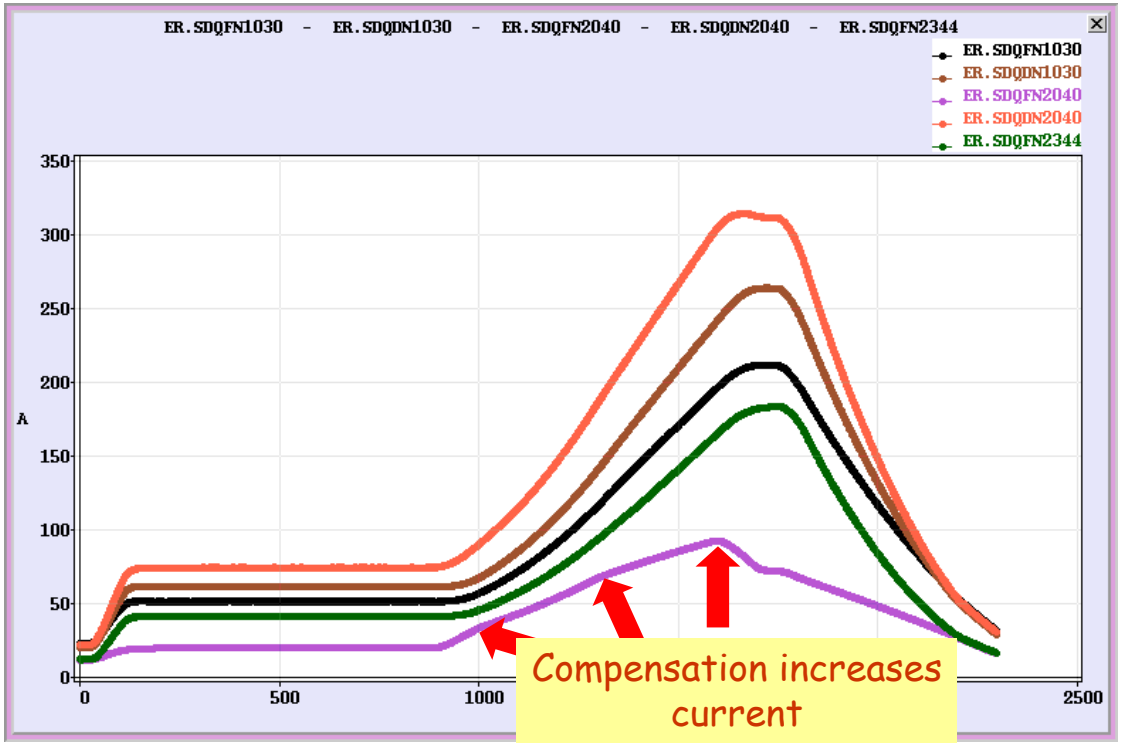




- Lattice functions for one half of LEIR and working point (black: nominal working point, grey: alternative working points)

LEIR – Acceleration and Eddy Currents

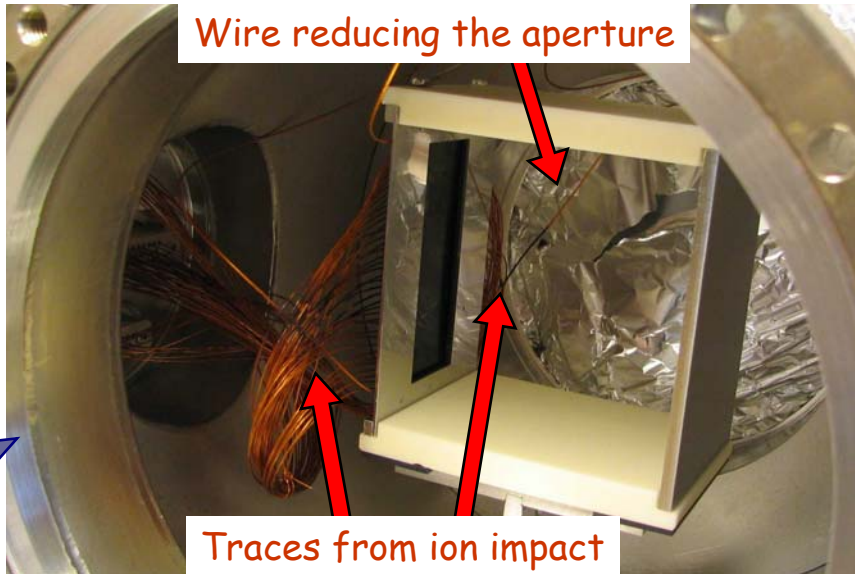
- Acceleration (transverse optics perturbations):
  - C-shaped magnet & vacuum chamber not isolated w.r.t. ground,
  - Net current along the chamber,
  - Gradient "seen" by beam,
- Correction needed:
  - Readjustment of quad currents (5 families),

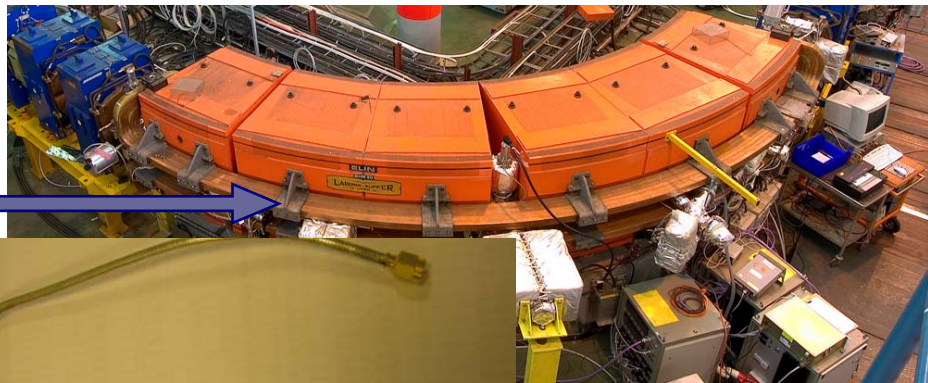


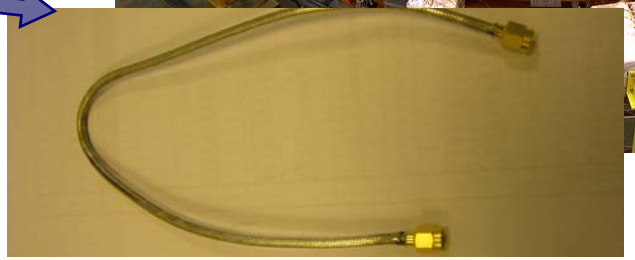
Measured Quadrupole currents along the machine cycle with compensation of gradients in bends during ramp

LEIR Commissioning and first runs (brief Summary)

- Injection Line in Spring 2005
  - In parallel to Ring Installation
  - Some difficulties with Matching and Controls
- Ring commissioning start in autumn
  - Start with O^{4+} (expected longer life-time ??)
  - Controls (new developments for LHC applied/tested with LEIR)
  - Circulating beam and good injections efficiency rather quickly
  - Progress slowed down due to short life-time: Ions hit a Beam Ionisation Profile Monitor
  - Weak signs of cooling only
  - Pick-up Cable problem:
    - Ramp induced currents damage pick-up cables
      - Ramp temporarily reduced



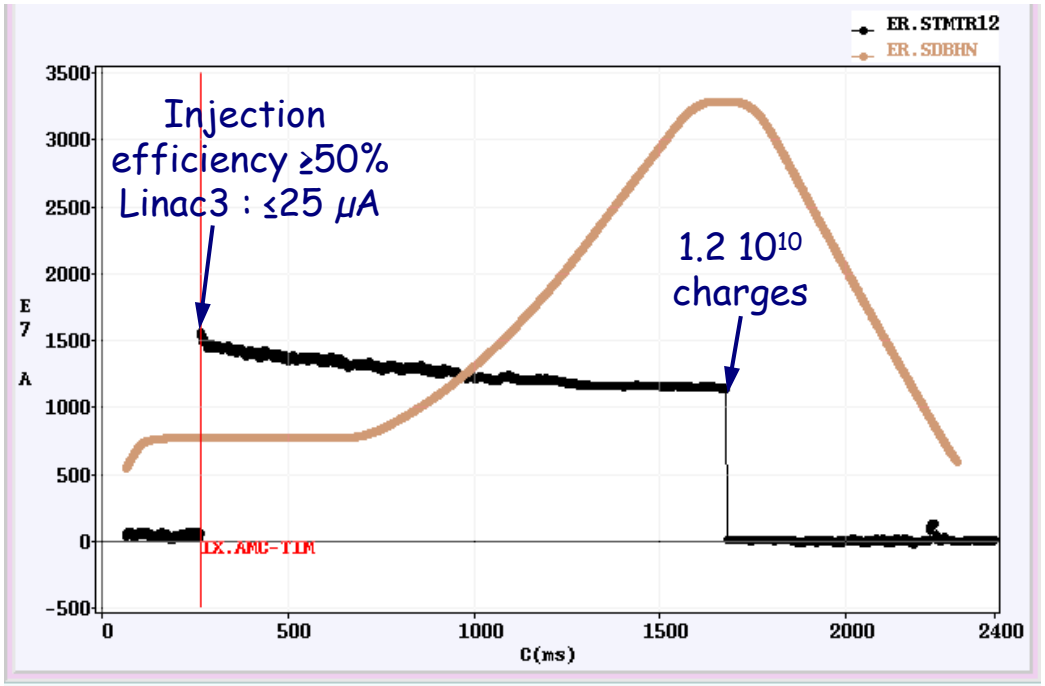


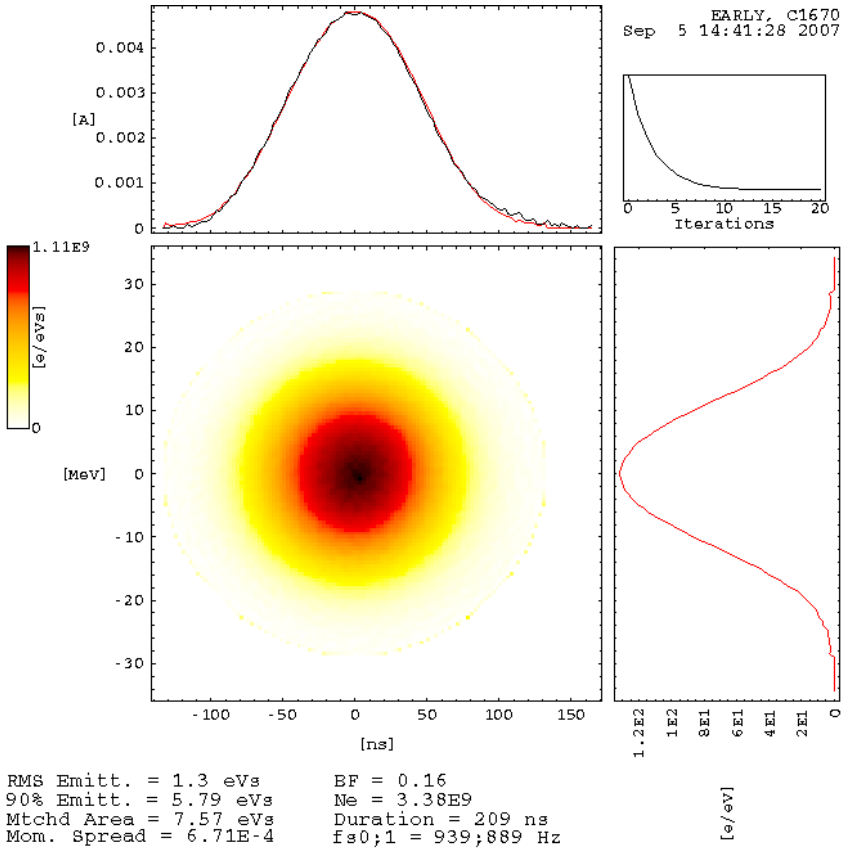


LEIR Commissioning and first runs (brief Summary)

- Shutdown in January & February 2006:
  - Replacement/improvement of Ionisation Profile Monitor (absorbers)
  - Definite fix of Pick-up cable problem
- Completion of LEIR commissioning with Pb^{54+}
  - Some work on injection matching needed again
  - Hardware fixes during "shutdown" very beneficial
  - Cooling and accumulation observed quickly (better life-time)
  - Acceleration and ejection and transfer to the PS injection
- LEIR commissioning completed on 12th May 2006
  (early beam demonstrated – two injections and faster acceleration)
- First LEIR run in autumn 2006 to provide "early" to the PS
  - Fast start with beam (after delay due to cooler collector vacuum leak)
  - Fluctuations of injection line and efficiency due to PS stray field
- Second LEIR run started in August 2007 (provide beam to the SPS)
  - Again smooth start-up and operation

LEIR Performance – "early" beam

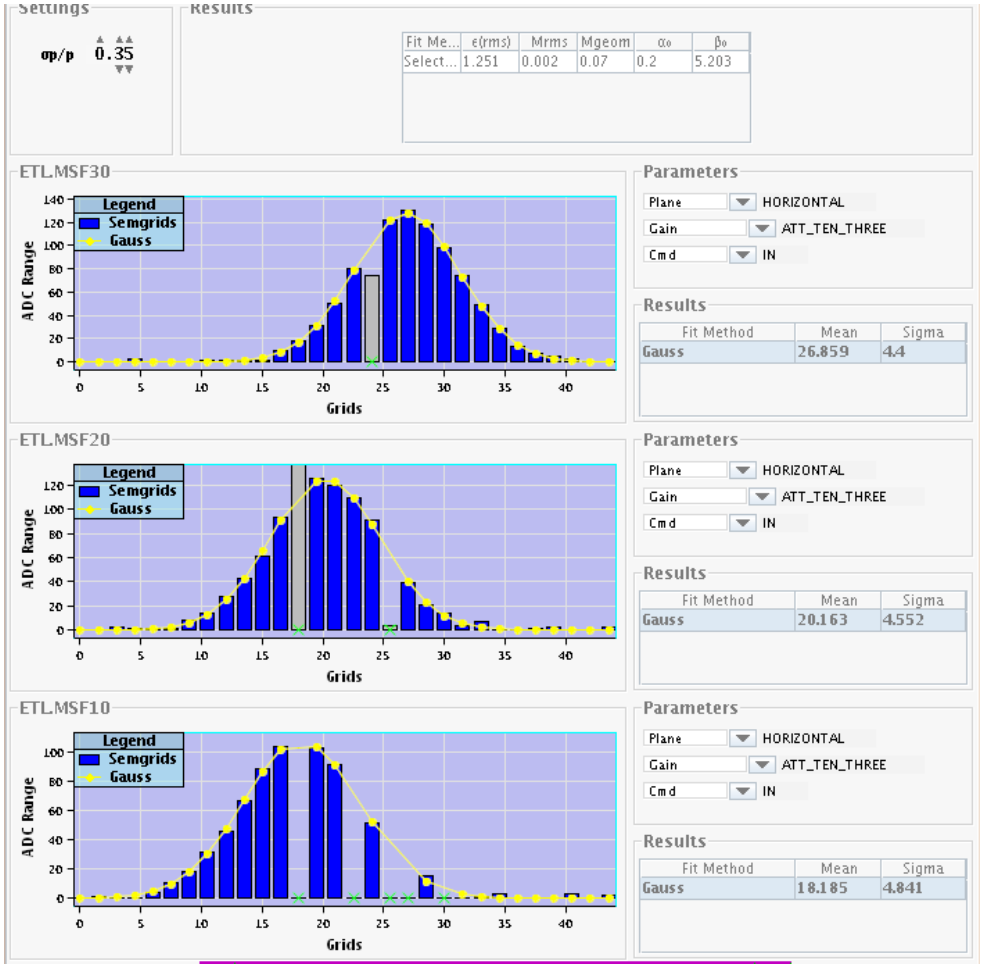




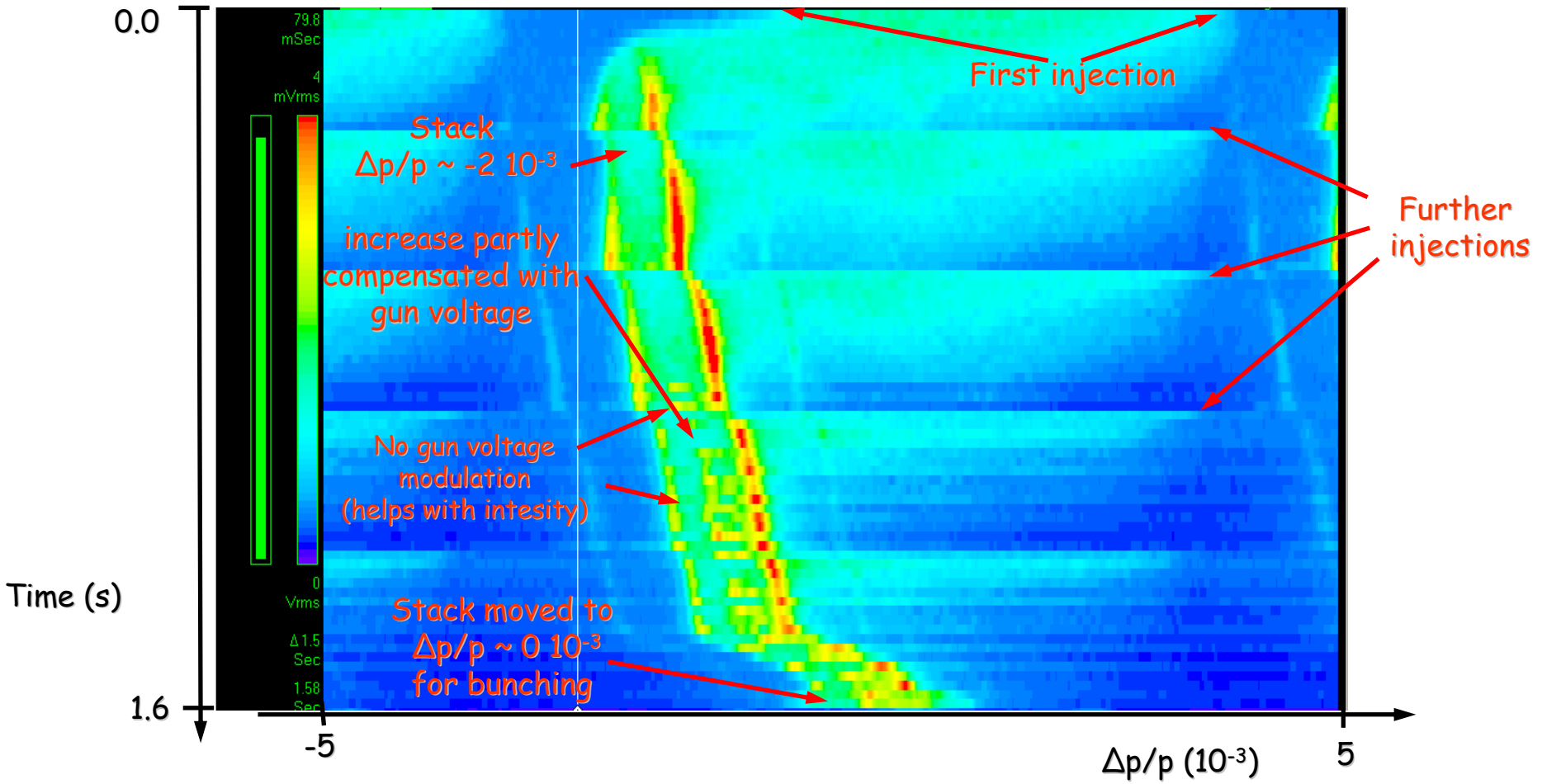
- Properties of the "Early beam" in LEIR measured this year:
  - One Linac3 shot just sufficient: 2.25^8 10 Pb^{54+} ($1.2\ 10^{10}$ charges) required
  - Longitudinal emittance: measurements gives rms emittance for entire nucleus
    - (4/208n)*1.3 eVs = 0.025 eV/n (as specified)

LEIR Performance – "early" beam

- Transverse emittances:
  - application gives one rms physical emittances
  - Horizontal: $\varepsilon^*_{rms} = 0.5\ \mu m$ (larger than in 2006, but o.k.)
  - Vertical: $\varepsilon^*_{rms} = 0.2\ \mu m$

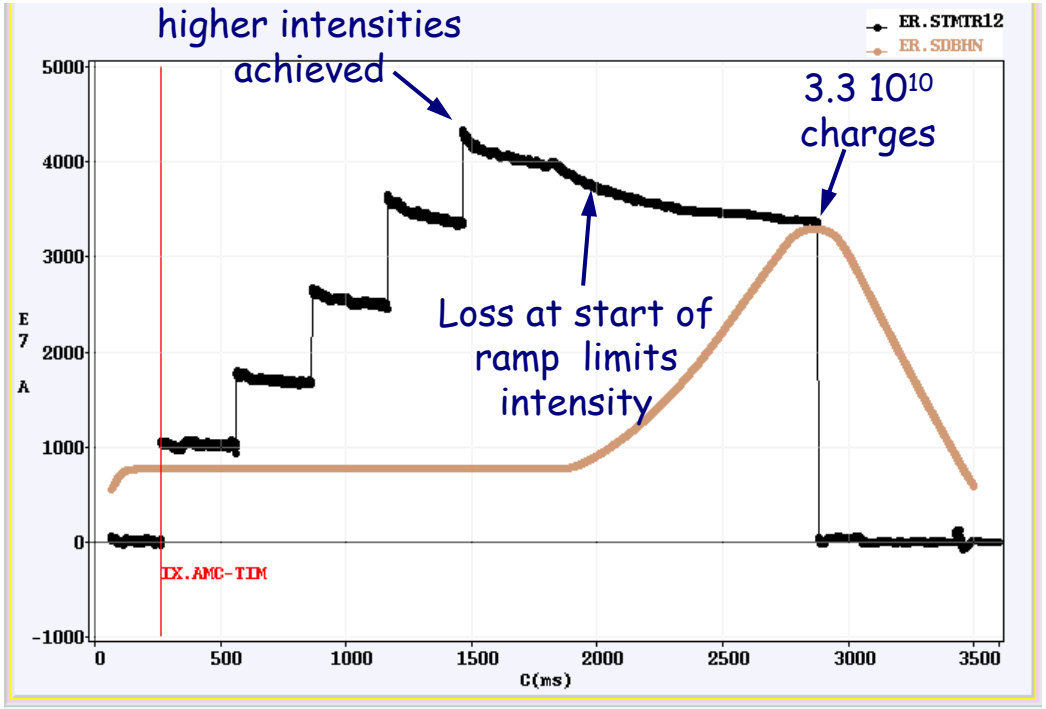


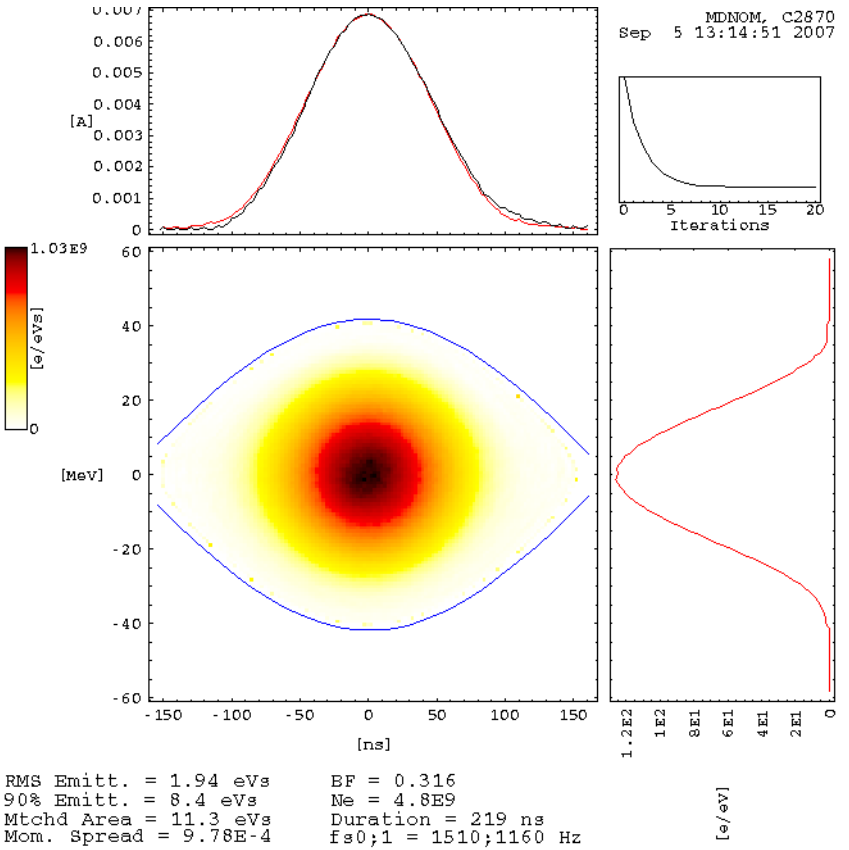
LEIR Performance – nominal beam



- Evolution of longitudinal Schottky spectra during accumulation (measured with a commercial FFT spectrum analyser)

LEIR Performance – nominal beam





- Properties of the "nominal beam" in LEIR measured this year:
  - Accumulation of up to 5 shots => intensity needed after accumulation
  - Loss at beginning of ramp (more pronounced for higher intensities) => only ~2/3 of design intensity at ejection
  - Emittances well within specifications

LEIR Performance – Comparison with Design

	Nominal		"early"	
Parameter	design	obtained	design	obtained
Linac3 current (μA)	50	25	50	25
Cycle time (s)	3.6	3.6	2.4	2.4
Inj. efficiency (%)	50	50	50	50
Accumulated. Int. (10^8 Pb^{54+})		~10		~2.5
Int. for PS (10^8 Pb^{54+})	9	~7	2.25	2.25
Hor. norm. rms emitt. (μm)	0.7	0.5	0.7	0.52
Vert. norm. rms emit. (μm)	0.7	0.2	0.7	0.24
Long. emitt. $4\pi\ \sigma_E\sigma_\tau$ per bunch (eVs/n)	0.05	0.04	0.025	0.025

- Early beam: design performance achieved (smaller emittances)
- Nominal beam: design intensity at ejection not (yet) obtained (small emittances)

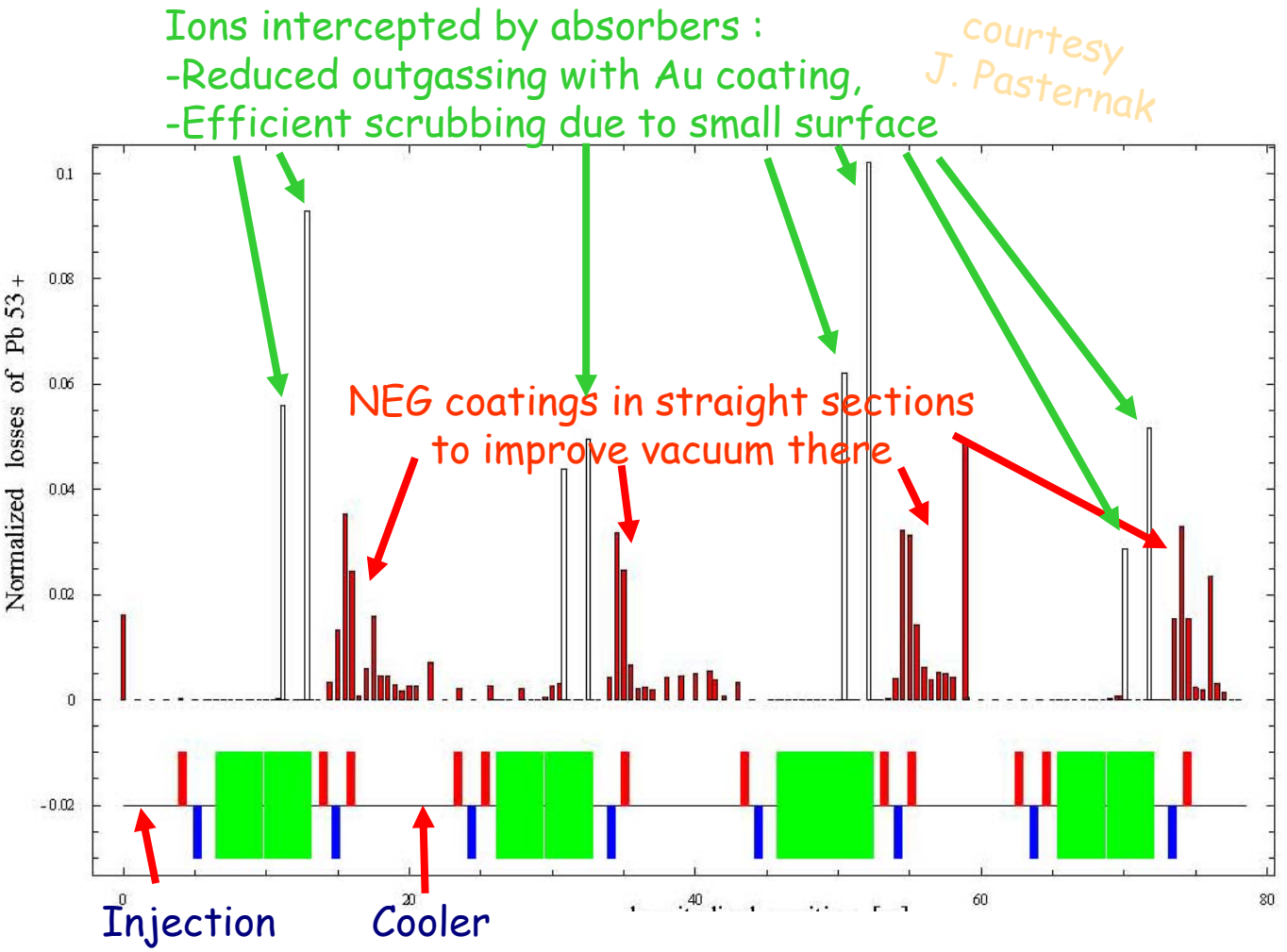
LEIR Performance – Dynamic Vacuum and Beam Life-Time

Avalanche-like pressure rise :

- ions lost due to rest gas electron capture (or loss) (Pb^{54+}-> Pb^{53+}),
- every lost ion desorbs many rest gas molecules.

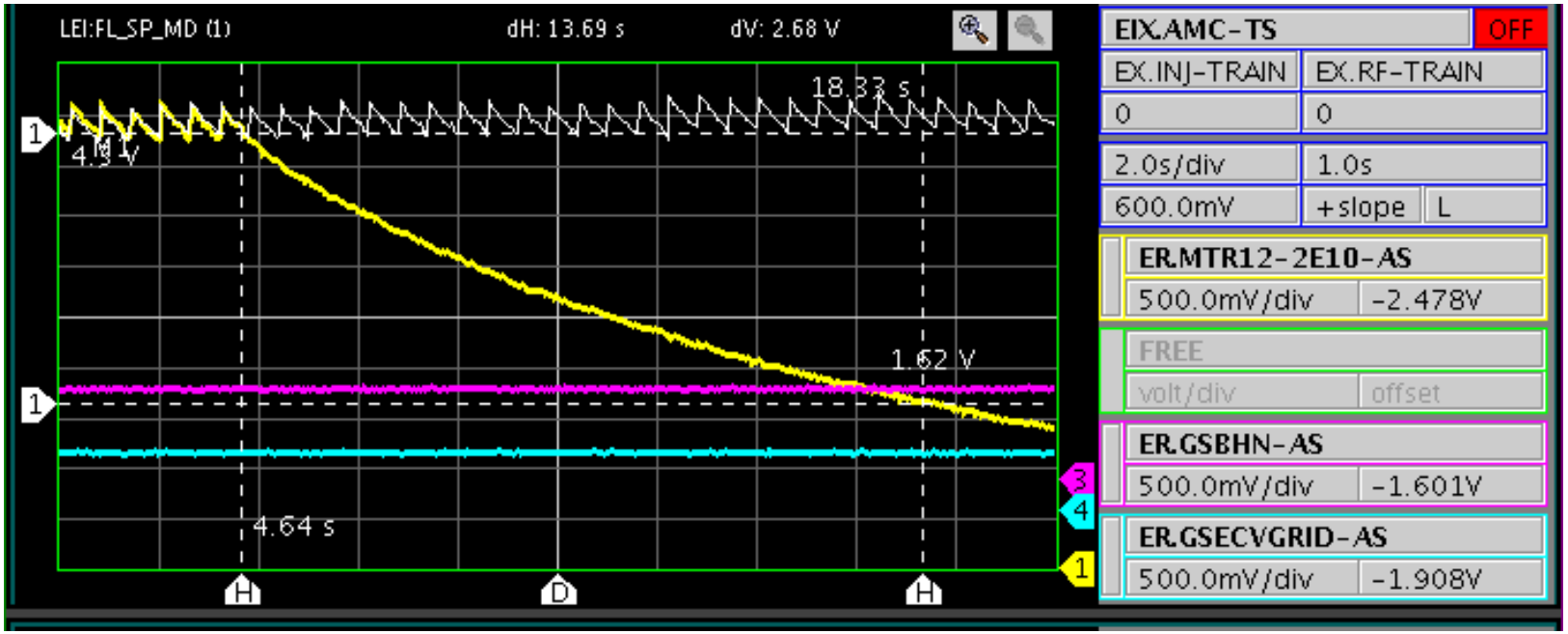
LEIR upgrades based on measurements at Linac 3 (AT/VAC & Linac 3 team)

Limitation of tests in '97 successfully cured !



Loss pattern of Pb^{53+} ions around the LEIR ring with collimators and homogeneous gas density

LEIR Performance – Dynamic Vacuum and Beam Life-Time

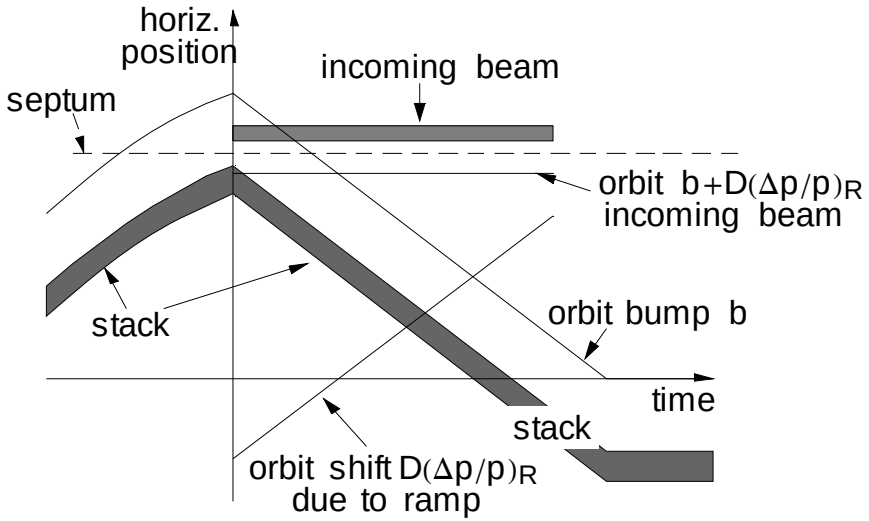


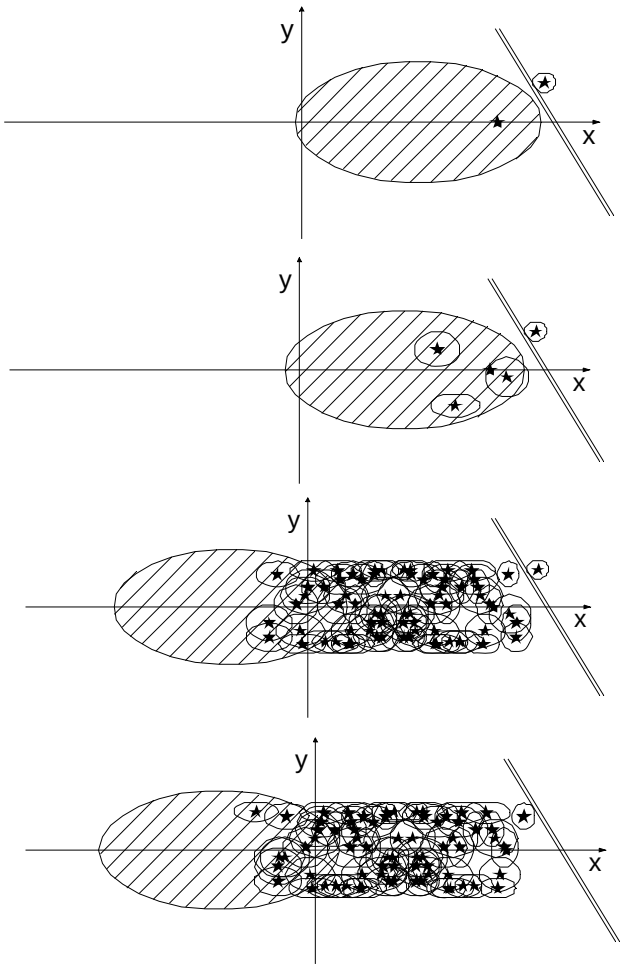
- Beam intensity (yellow trace) versus time after long accumulation
- About 16 10^8 Pb^{54+} ions accumulated (saturation) – not the record
- Beam life-time ~14 s (with cooling !!)
- ➢ Dynamic beam life-time not a limitation at present (for "normal" cycles)
- Small influence of position of movable collimators

Summary and Outlook

- LEIR successfully installed and commissioned:
  - Commissioning completed in May 2006 with the demonstration of the "early" LHC ion beam
- LEIR becoming an operational machine:
  - "Early" beam delivered in routine operation for PS and SPS
  - Transfer of LEIR operation to the new Common Control Center
  - Work in parallel on nominal beam (not considered a priority), to sort out technical problems and, to better understand the machine
- Outlook:
  - First LHC Pb ion run probably in 2009 ?
  - Studies on SPS ion fixed target experiments with lighter ions just started
  - LEIR run next year ? (may be with lighter ions in view of SPS fixed target)

LEIR Injection





1st turn of incoming beam

After 3 turns

End of injection (70 turns)

After collapse of the bump

Principle :

- bumper moves orbit inwards,
- energy ramping moves orbit outwards,
- constant betatron amplitude for incoming beam.

Result :

- long pulses pulses and good efficiency,
- Large momentum spread, relatively small emittances,
- Good for fast accumulation with electron cooling.