LEIR Operations for the LHC and Future Plans

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with help from
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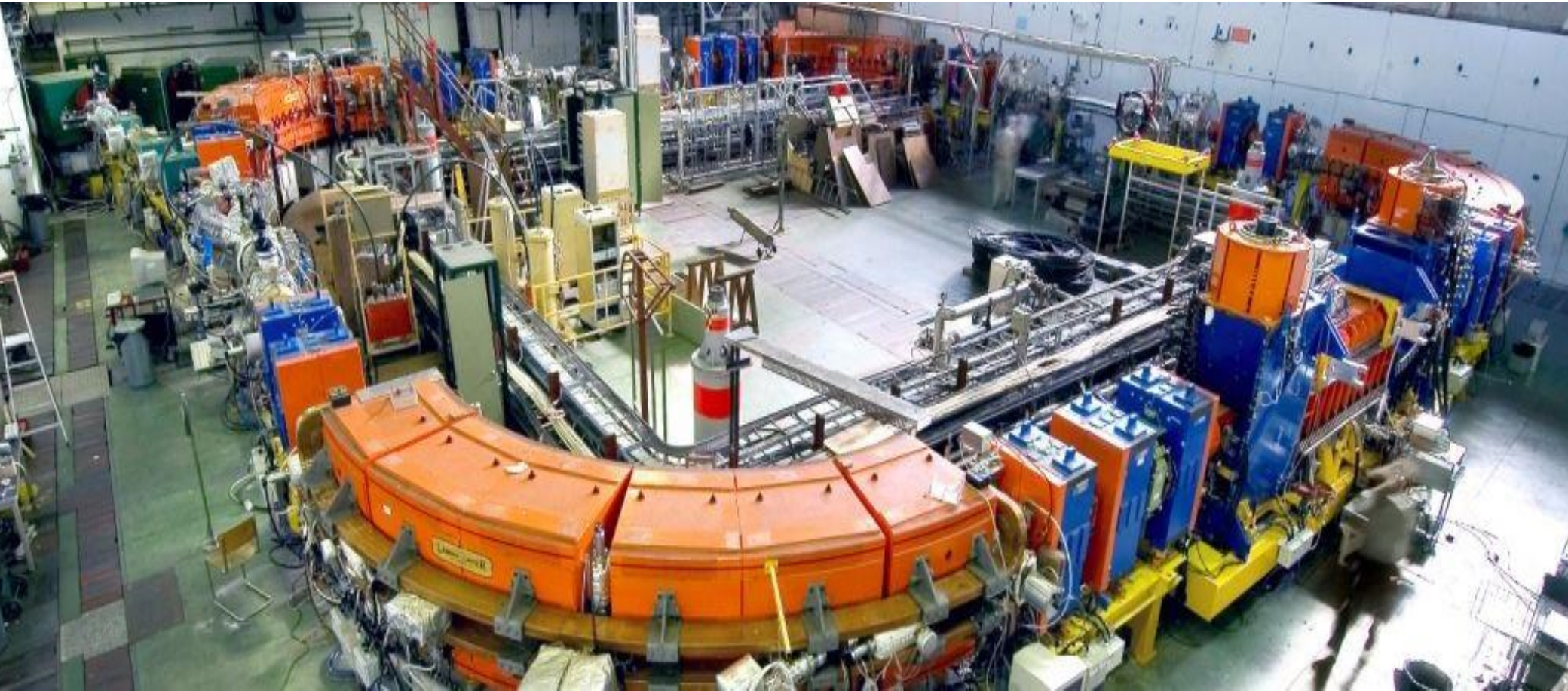
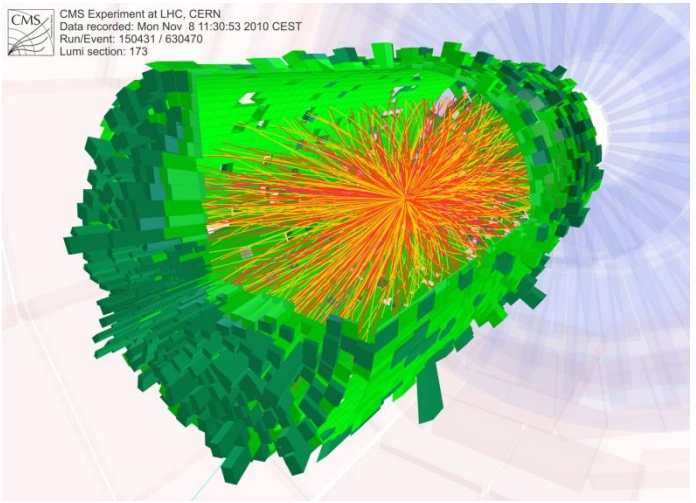
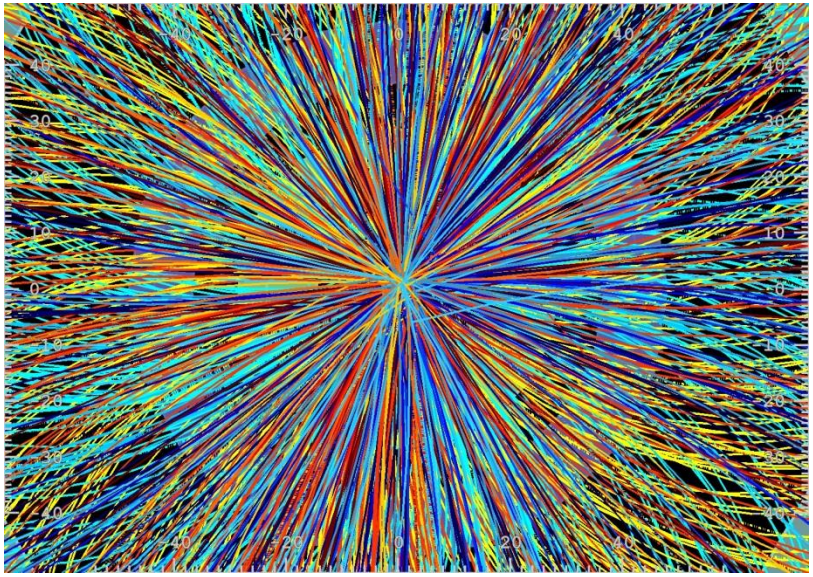
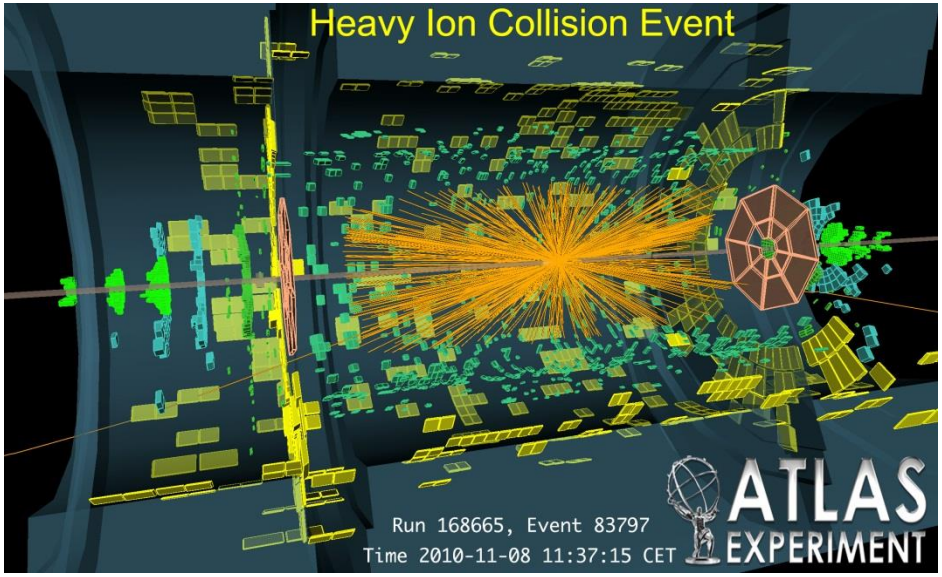


I-LHC: the LHC as an Ion Collider

- First Pb-Pb (2010-2011)
- then p-Pb (2013)
- then other ion species (not yet approved)
- At 7ZTev, Pb-Pb nominal $\mathcal{L} = 10^{27}$ cm^{-2}s^{-1}

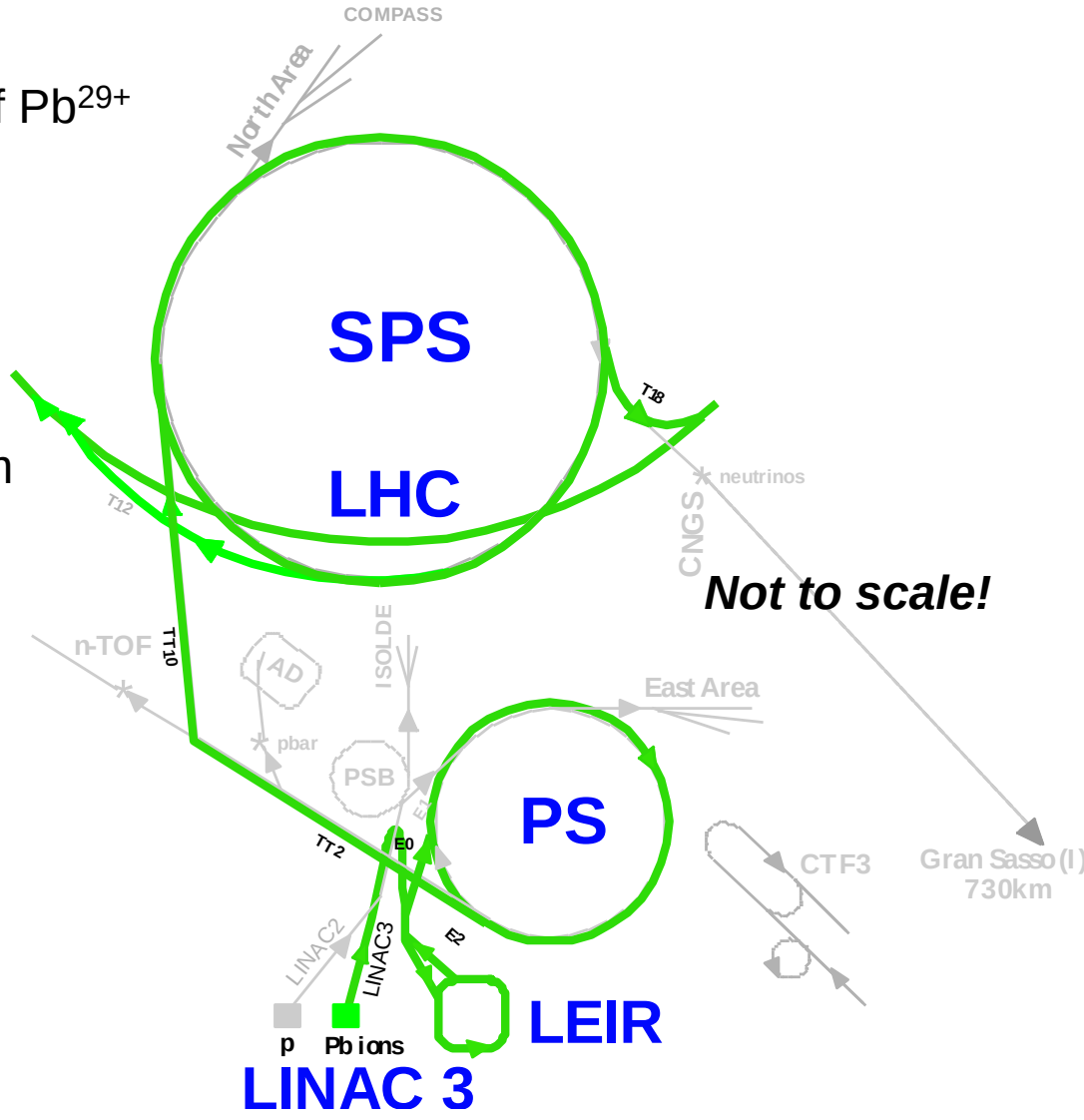






The Ion Injection Chain

- ECR ion source
  - Provides highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Accelerates Pb^{29+} to 4.2 MeV/u
  - Strips to Pb^{54+}
- Low Energy Ion Ring
  - Accumulates and cools Linac 3 beam
  - Prepares bunch structure for PS
  - Accelerates to 72 MeV/u
- Proton Synchrotron
  - Defines LHC bunch structure
  - Accelerates to 5.9 GeV/u
  - Strips to Pb^{82+}
- Super Proton Synchrotron
  - Defines filling scheme
  - Accelerates to 177GeV/u



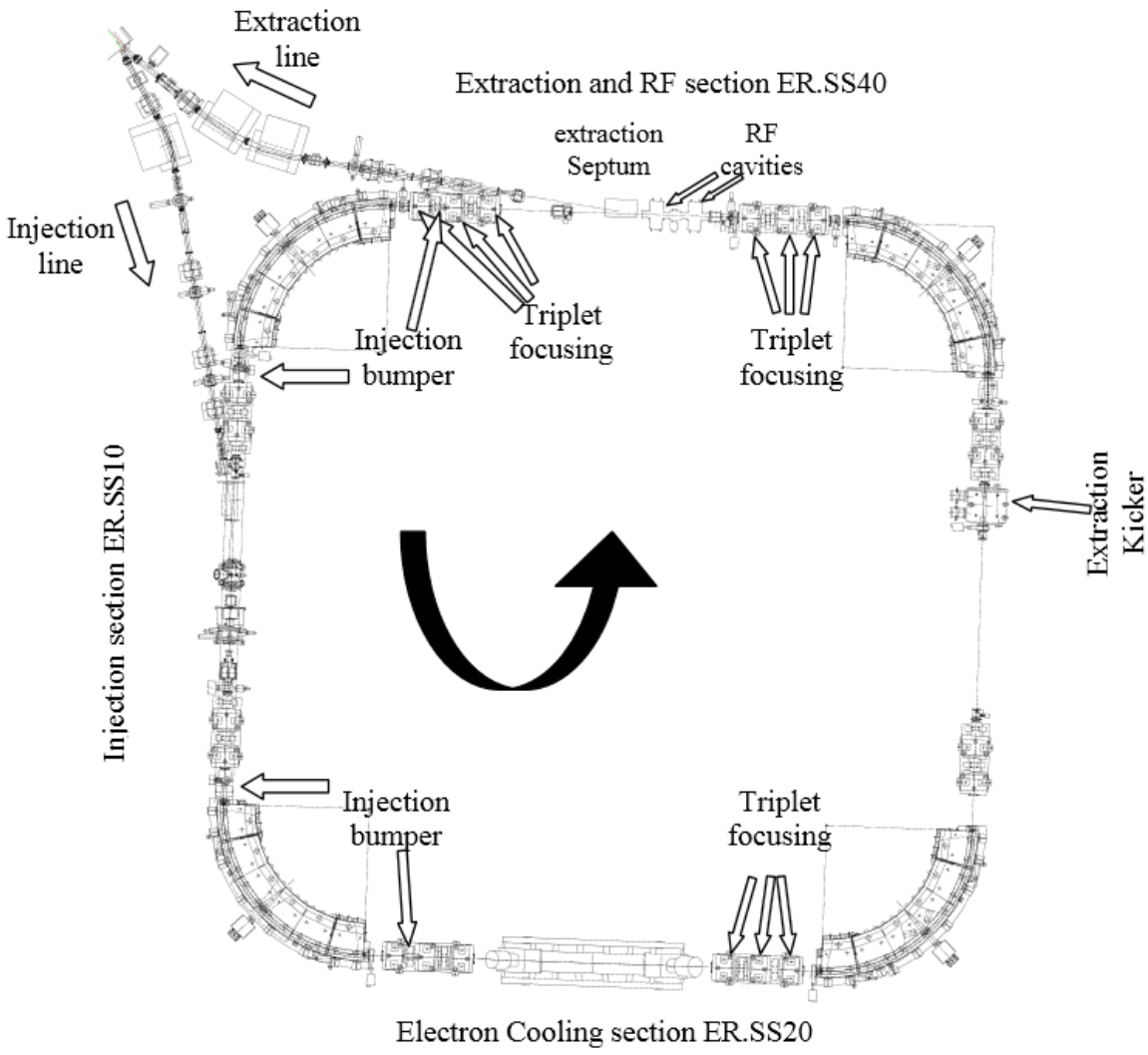
The Low Energy Ion Ring

- Accumulates ions for LHC bunches
- Keeps their H, V and // emittances small
- Brings Linac3 ion beam to PS injection energy range

▶ 3 plane stacking
▶ Cooling
▶ Acceleration

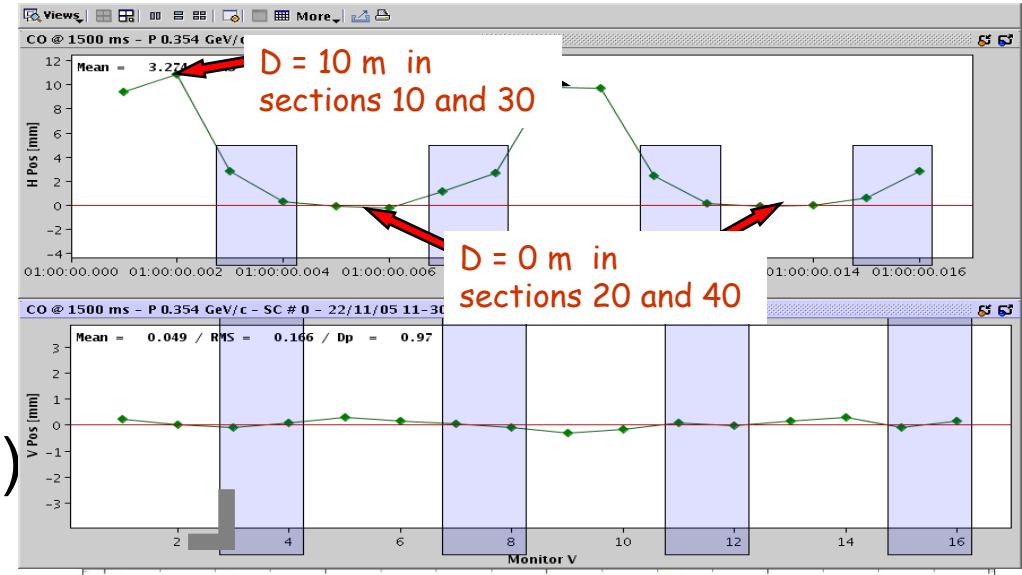
LEIR layout

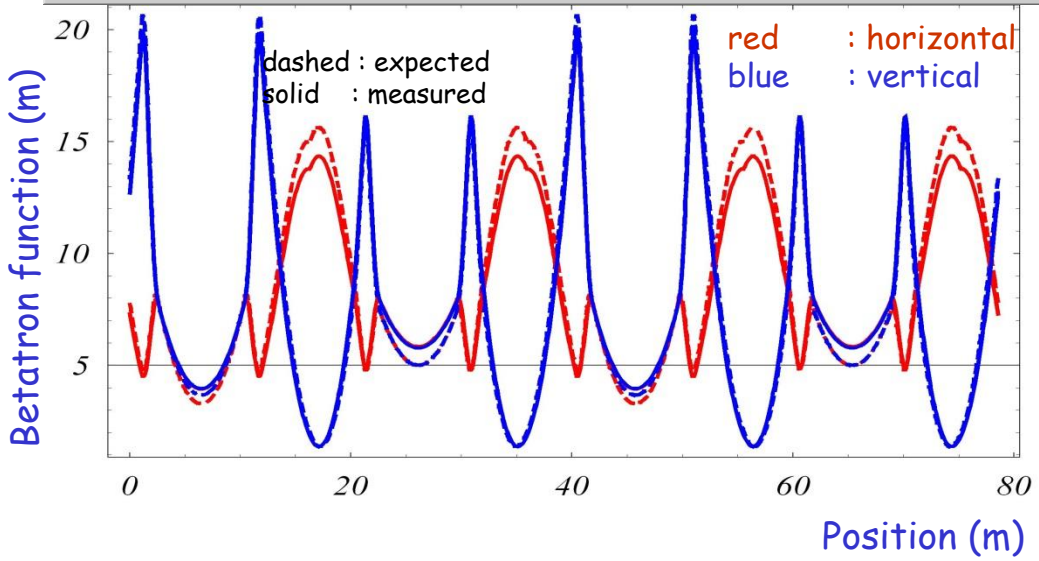
- Circumference 78.54 m
  - From old LEAR
- Doublets in odd straight sections
  - Injection
  - Ejection kickers
- Triplets in even straight sections
  - Electron cooler
  - RF
  - Ejection septum
- Common in/e-jection line
  - Pulsed between values at each cycle



A few parameters

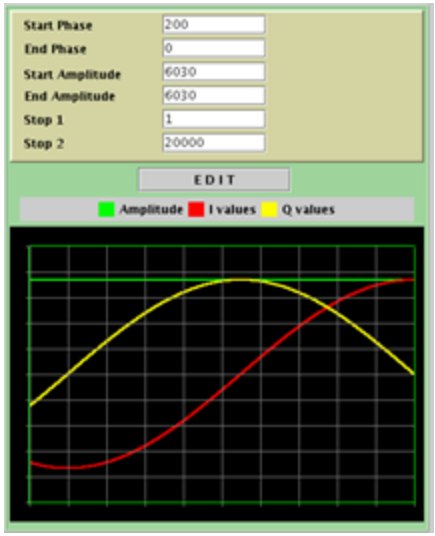
- Energy = 4.2 – 72 MeV/u
- Bρ = 1.12 – 4.8 Tm
- f_{REV} = 0.361 – 1.423 MHz
- (Q_H, Q_V) = (1.82, 2.72)
- Operated below transition ($\gamma_t \approx 2.87$)
- D=0 at cooler, ejection & RF
- D=10m at injection 10 m
- $\beta_{H,V}$ = 5m in cooler
- $\beta_{H,V}$ = 4m at injection
- Acceptances H/V 60/40 μm
- Momentum acceptance ± 4×10^{-3}

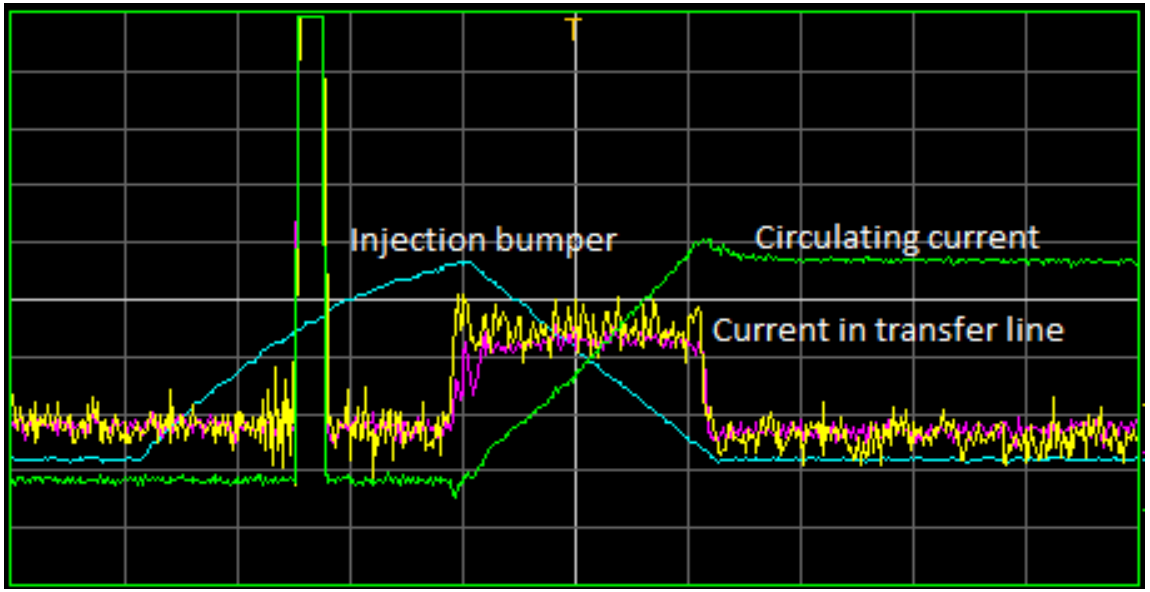


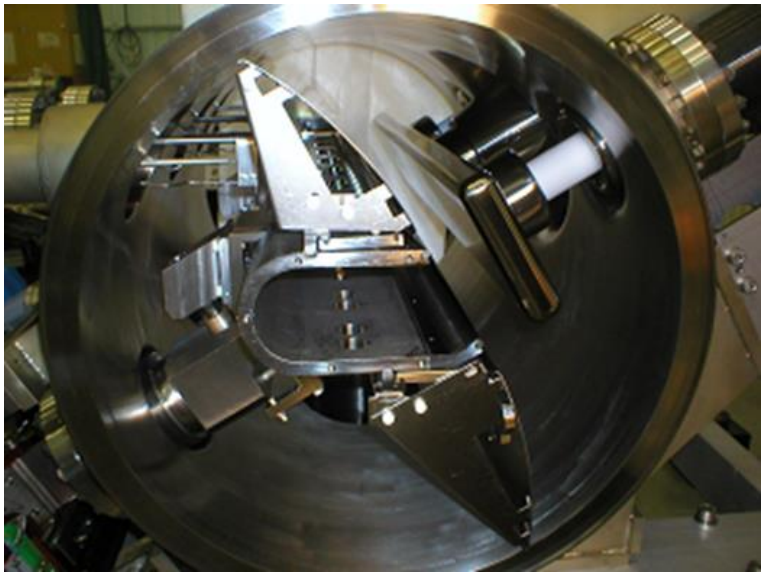


3-plane stacking injection scheme

Multiturn injection of the 200μs linac pulse,
with additional stacking in the vertical phase space:
- inclined electrostatic injection septum
- horizontal orbit bump
- momentum ramping cavity in injection line
- constraints on working point (0.1 from coupling diagonal)
- up to 200ms repetition rate



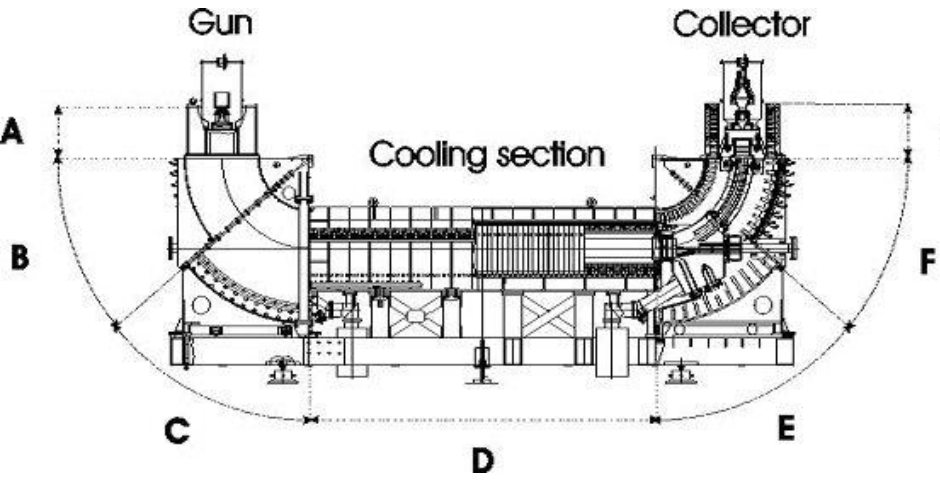


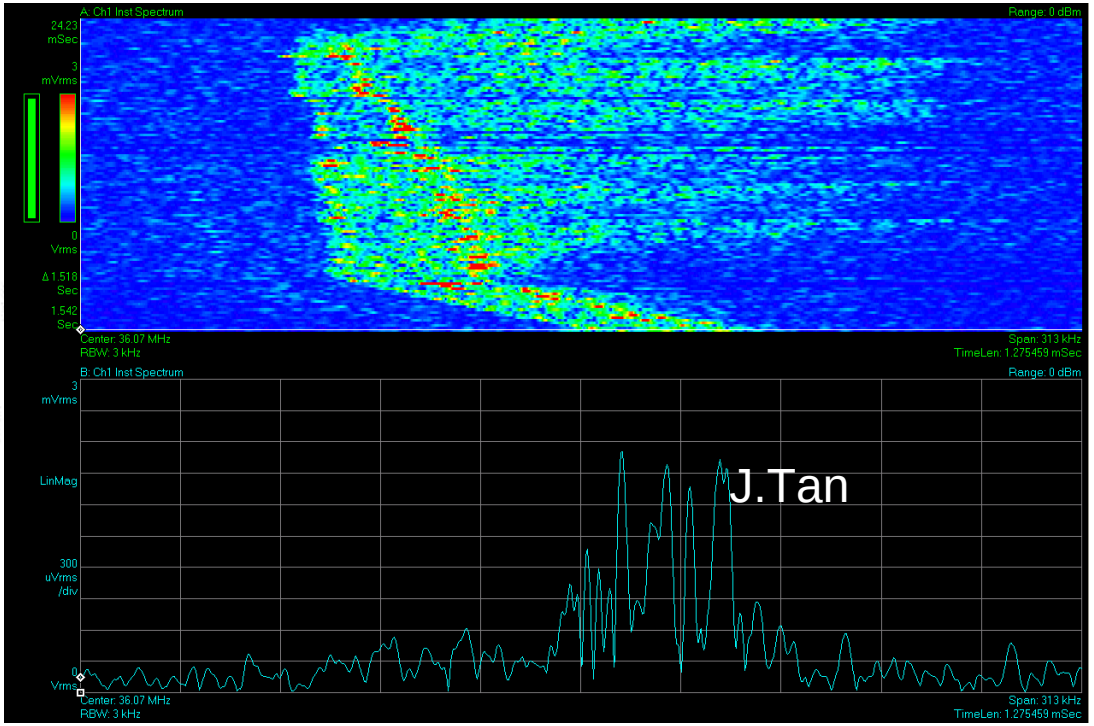


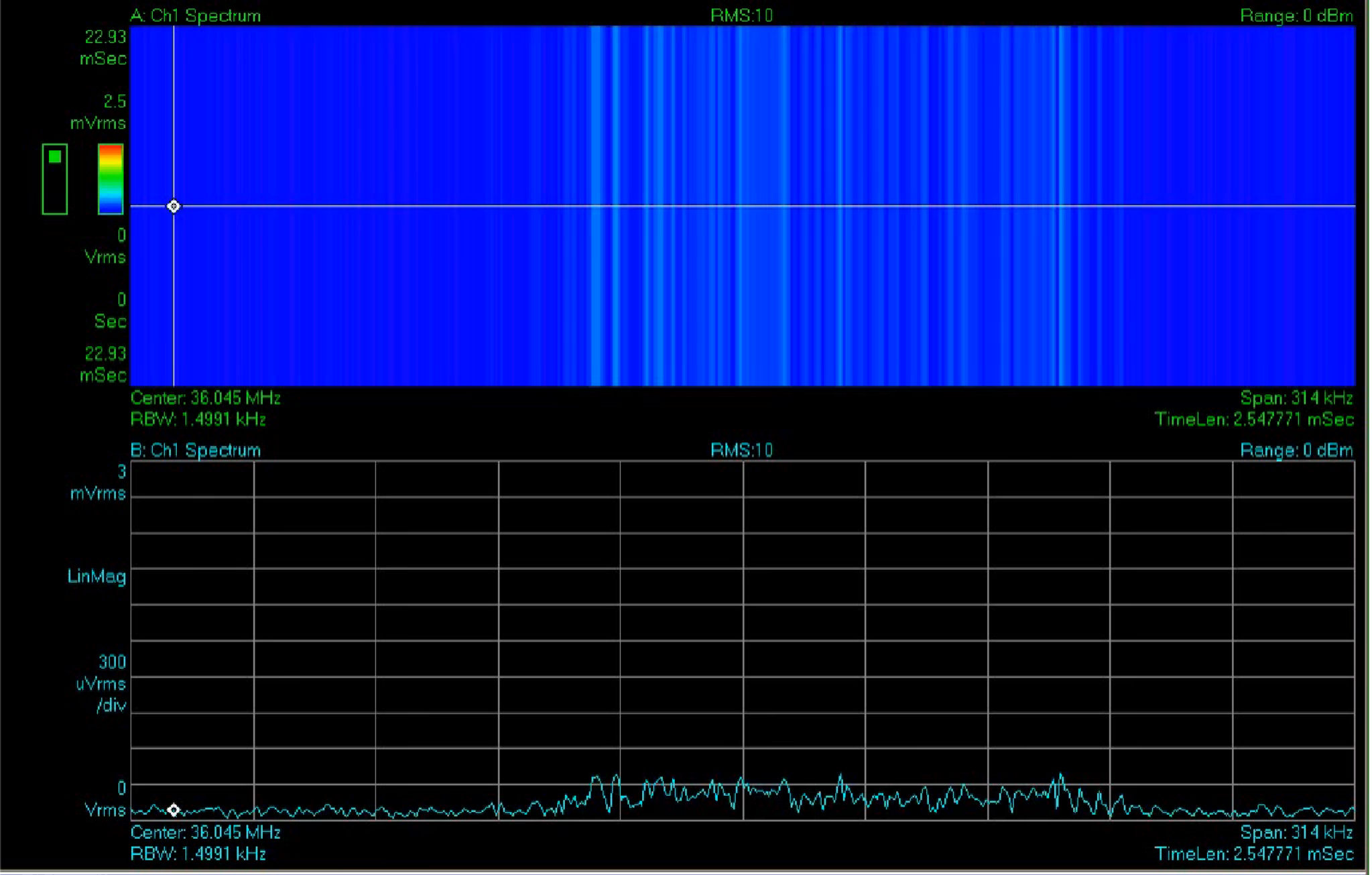
Efficiency on paper ≈70% for ≈70 turns injected
(over 50% achieved)

LEIR's Electron Cooler

- Cools down the newly injected beam, then drags it to the stack
- High perveance
- 300 mA operating electron current (up to 600mA)
- See G.Tranquille's poster WEPPO15 "Performance Update of the LEIR Electron Cooler"







Trace A Marker: 22.9296 mSec 35 898 990.0 Hz 84.1152 uVrms

Trace B Marker: 35 898 990.0 Hz 84.1152 uVrms

Single sweep - paused - recording <Temporary File>

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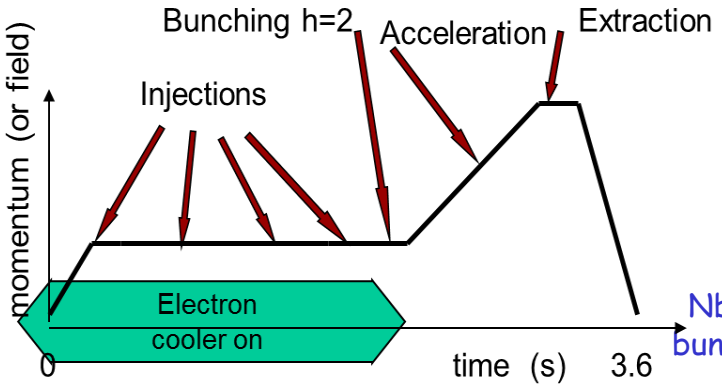
The LHC Ion Injector chain: the (initial) Nominal Scheme



	Nb of bunches	Pb ions / (future) LHC bunch	Harmonic number / Frequency
LEIR (9 10^8 Pb ions / 3.6 s)	2		2
PS after 1st splitting	4	2.25 10^8	16-14-12-24
PS after 2nd splitting		1.2 10^8	
TT2 after stripper	4 pairs		24-21 -169-423
SPS at injection (43.2 s flat-bot), after 13 (12, 8) transfers from PS	52 (32, 8) pairs	Bunch splitting & ε_l Blow-up → ΔQ_{SPS} = 0.05	200 MHz
SPS at extraction, after 13 (12, 8) transfers from PS	52 (32, 8)	9 10^7	100 MHz + 200 MHz
LHC at injection, after 12 transfers from SPS	592	7 10^7	400 MHz

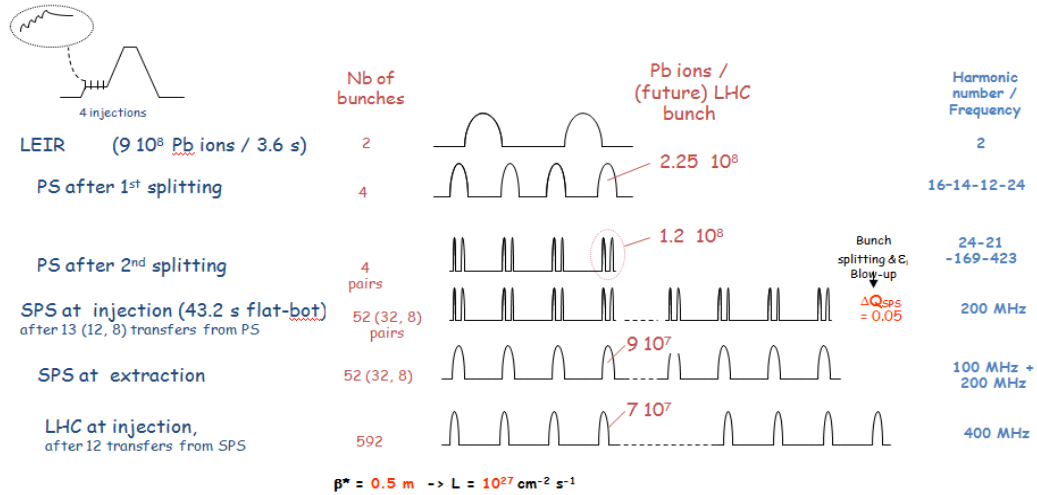
β^* = 0.5 m -> L = 10^{27} cm^{-2} s^{-1}

I-LHC Parameters for Nominal Luminosity

	ECR Source	Linac 3	LEIR	PS	SPS	LHC
Output energy	2.5 KeV/u	4.2 MeV/u	72.2 MeV/u	5.9 GeV/u	177 GeV/u	2.76 TeV/u
^{208}Pb charge state	29+	29+ ➔54+	54+	54+ ➔82+	82+	82+
Output Bρ [Tm]		2.12 ➔1.14	4.80	86.7 ➔57.3	1500	23350
bunches/ring			2 (1/8 of PS)	4	52	592
ions/pulse	$9\ 10^9$	$1.15\ 10^9$	$9\ 10^8$	$4.8\ 10^8$	$4.7\ 10^9$	$4.1\ 10^{10}$
ions/LHC bunch	**$1.1\ 10^{10}$.**	**$1.45\ 10^9$**	**$2.25\ 10^8$**	**$1.2\ 10^8$**	**$9\ 10^7$**	**$7\ 10^7$**
bunch spacing [ns]				100	100	100
ε*(norm. rms) [μm]	0.07	0.25	0.7	1.0	1.2	1.5
ε (phys., rms) [μm]	30	2.6	1.75	0.14	0.0063	0.0005
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	~10'fill/ring

Initial plan for Nominal luminosity

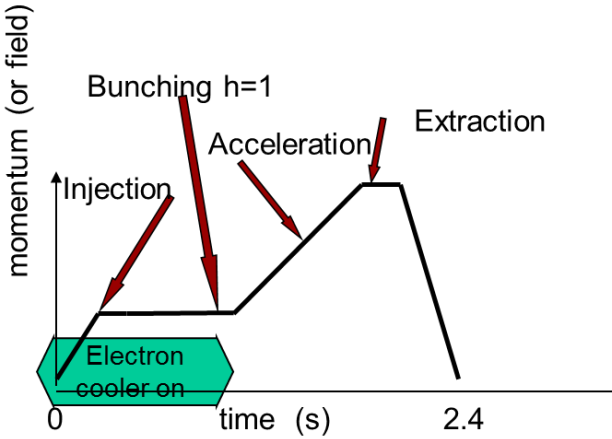
- "Nominal beam" in Design Report
  - $\mathcal{L} = 10^{27}cm^{-2}s^{-1}$ at 7 ZTeV
  - ~600 bunches of $7x10^7$ Pb^{82+} ions
  - $\varepsilon_{H,V} = 1.2\mu m$
  - $\beta^* = 0.5m$
  - To combat IBS and space charge on SPS flat bottom, Complicated gymnastics in PS & SPS (splitting in bunchlets in PS, recombining in SPS using 100MHz system).
    - Scheme questioned in Chamonix XII (2003)
    - Decision to start with "EARLY" scheme, single bunch from LEIR > PS > SPS
      10 times less bunches in the LHC, and twice β^* yielding 20 times smaller $\mathcal{L}$



Until 2012 the LHC was limited to 3.5 ZTeV

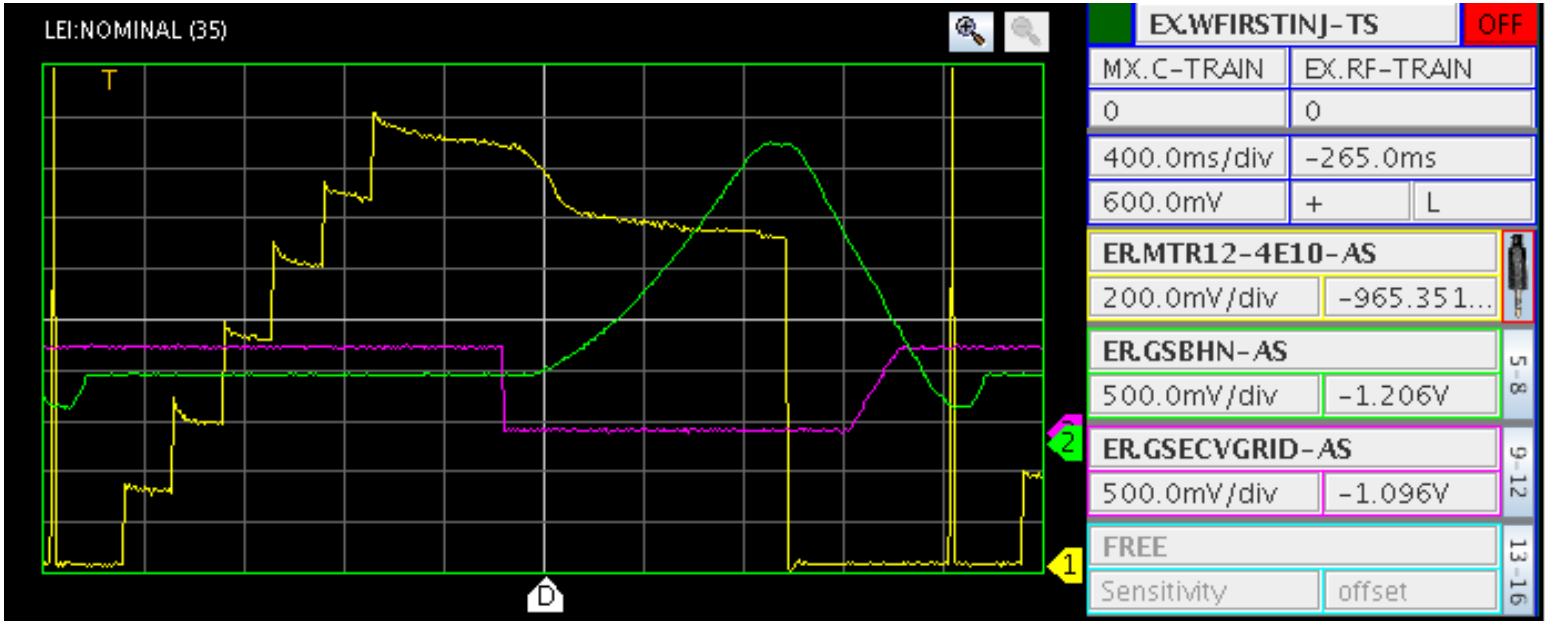
- At half energy, $\mathcal{L}$ divided by 4 (scales with E^2)
  - Twice emittances expected in each plane
  - Twice β^* in each plane (as the beam is larger up/downstream IP)
  - 4x beam section $\sigma_x \cdot \sigma_z$

- First run in 2010 with single bunch "Early beam" demonstrated that bunchlets are unnecessary, and raised the bar high for 2011 run:
  - 137 bunches of 10^8 Pb^{82+} ions
  - $\varepsilon_H = 0.6\mu m$
  - $\varepsilon_V = 1.0\mu m$
  - $\beta^* = 3.5$ m
  - $L = 3.10^{25}$ $cm^{-2}s^{-1}$ at 3.5 ZTeV to be compared to $\mathcal{L} = 5.10^{25}$ $cm^{-2}s^{-1}$ at 7 ZTeV



- Modified "Nominal beam" in 2011 by suppressing the splitting in the PS, and shortening the batch spacing to 200ns in the SPS:
  - 358 bunches of 1.4 10^8 Pb^{82+} ions
  - $\varepsilon_{H,V} = 0.9\mu m$
  - $\beta^* = 1$ m
  - $\mathcal{L} = 5.10^{26}$ $cm^{-2}s^{-1}$ at 3.5 ZTeV to be compared to $\mathcal{L} = 10^{27}$ $cm^{-2}s^{-1}$ at 7 ZTeV
- Similar LEIR and PS beam for p-Pb in 2013

Scheme in 2011 and 2013



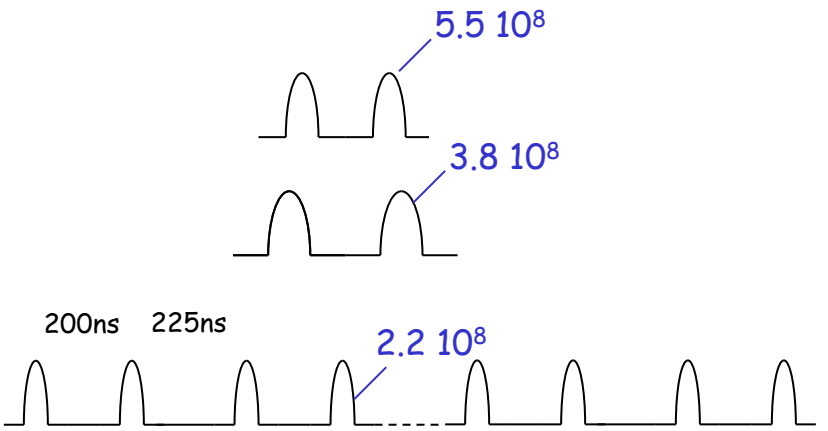
7, 5, **6** injections

At 5Hz rep. rate

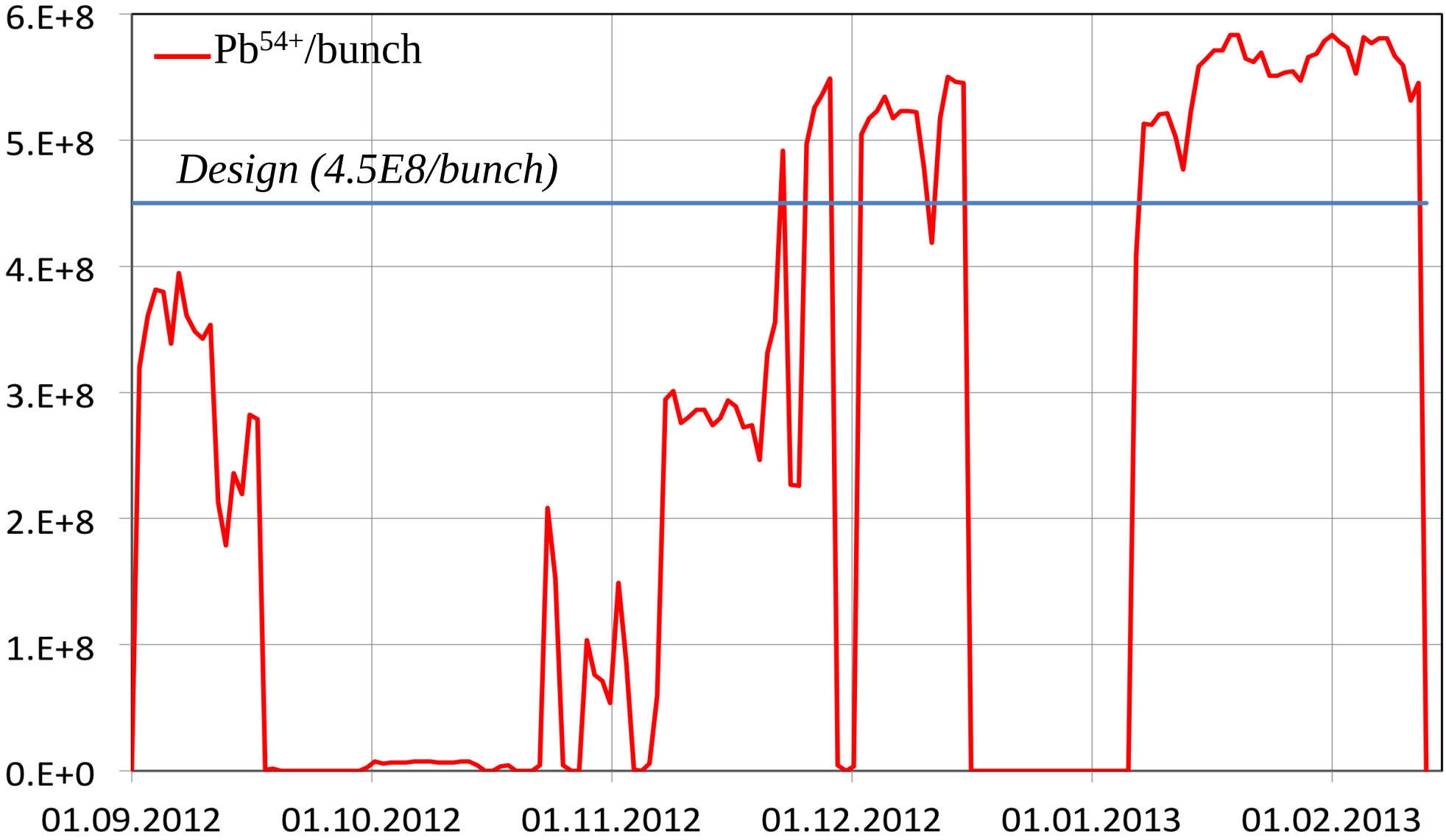
LEIR (1.1×10^9 Pb ions / 3.6 s)

PS batch ***expansion***
bunch spacing = 200 ns

SPS at extraction,
after 12 transfers from PS,
Batch spacing = 225 ns for p-Pb
(200 for Pb-Pb)

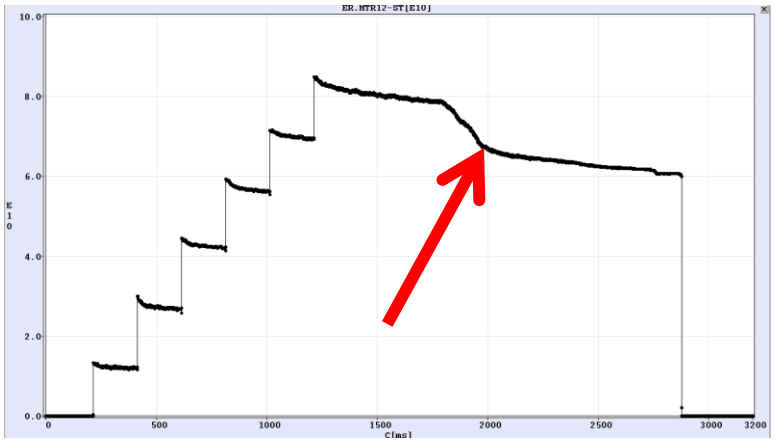


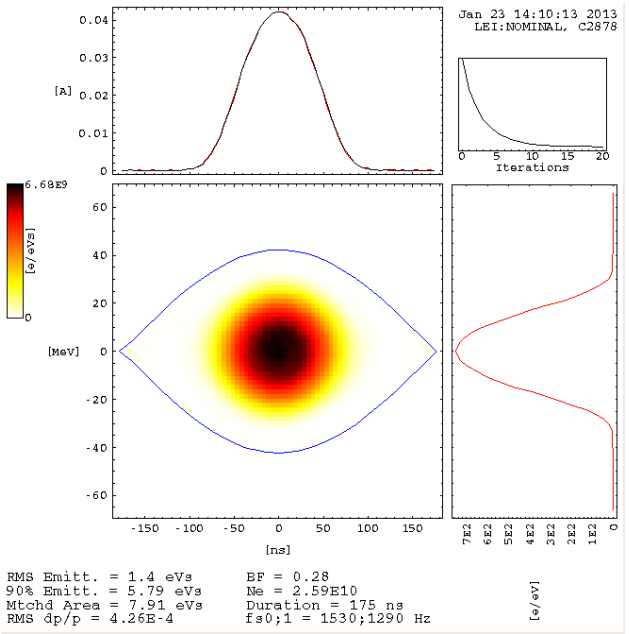
Intensity evolution in 2012-13

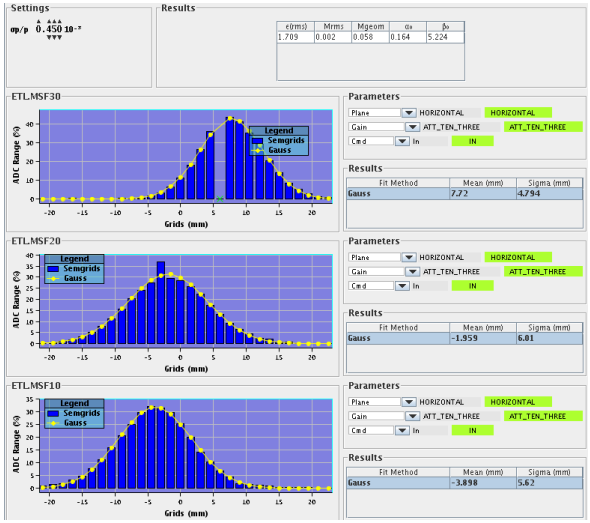


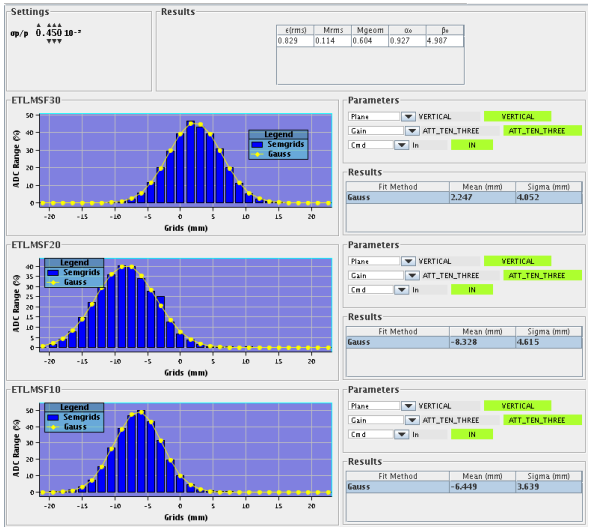
LEIR Performance in 2013

	design	P-Pb run 2013
n_b [Ions/bunch]	2.25E8	2.75E8
ε^*_{HV} (1σ) [μm]	0.7	< 0.7
$\varepsilon_{//}$ (2σ) [eV.s/u/bunch]	0.025	0.03



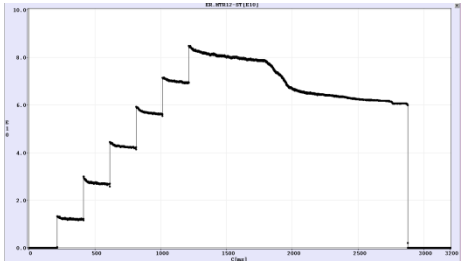


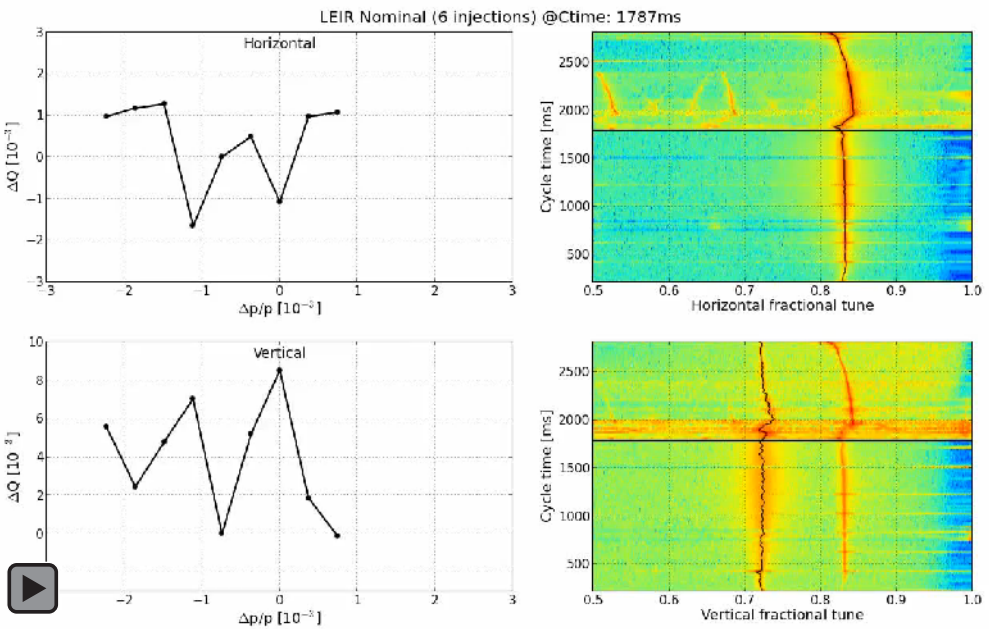


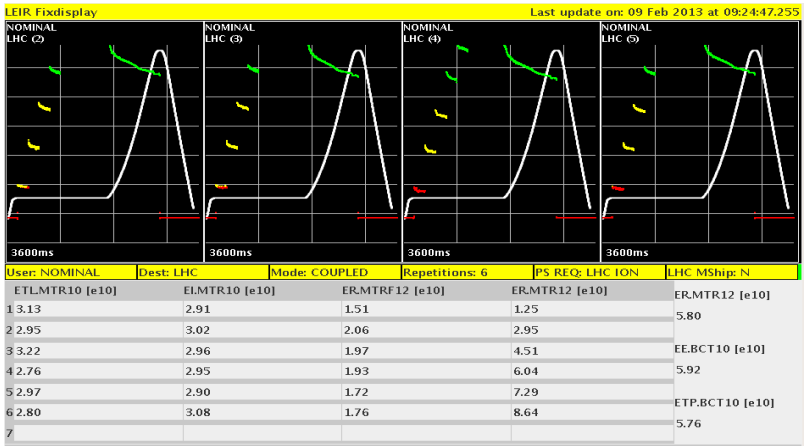


Remaining Issues

- Fluctuations of Linac3 current
  - modifies electron energy in cooler
  - in turn modifying energy of ion beam before RF capture
  - Manual adjustment of capture frequency
- Deviations from model (positive Q'_V)
- Loss at beginning of ramp
  - Will need more studies with beam
- Consolidation of diagnostics



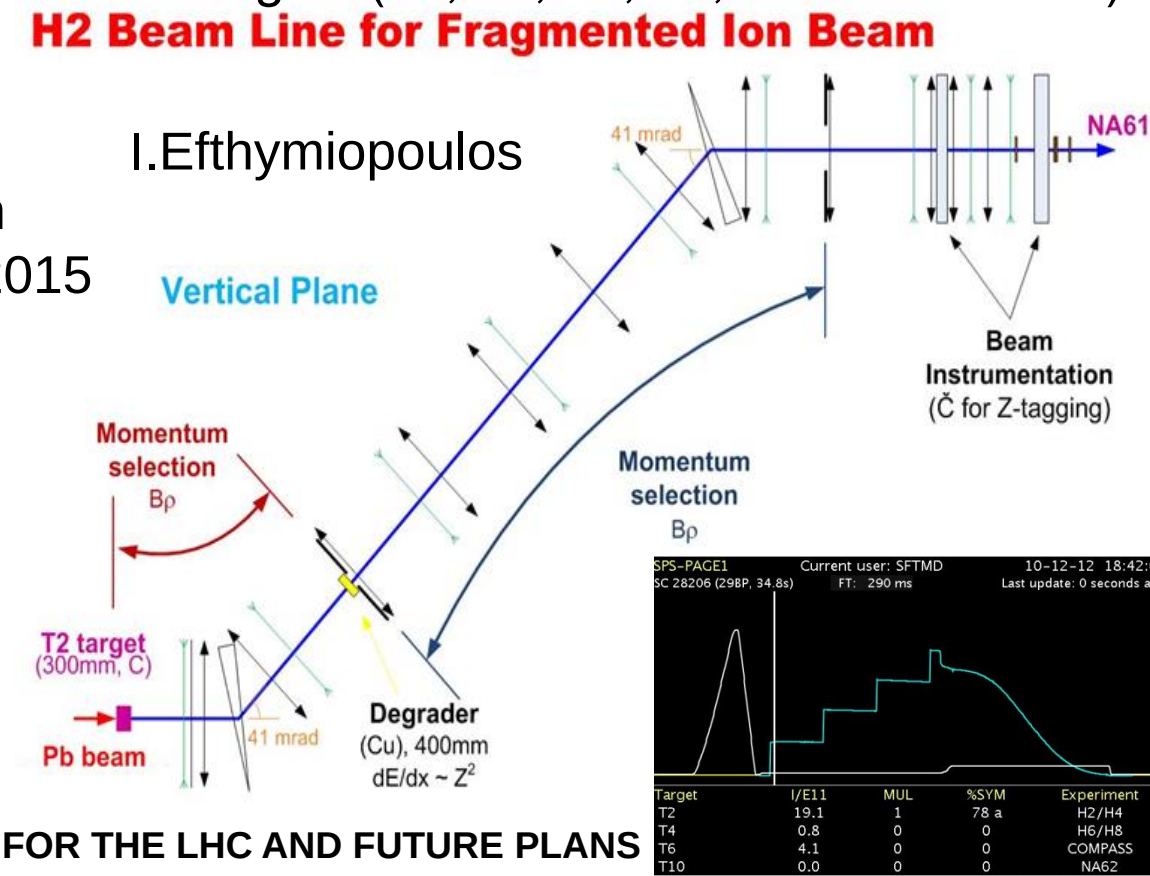




M.Bodendorfer

SPS Fixed Target Programme

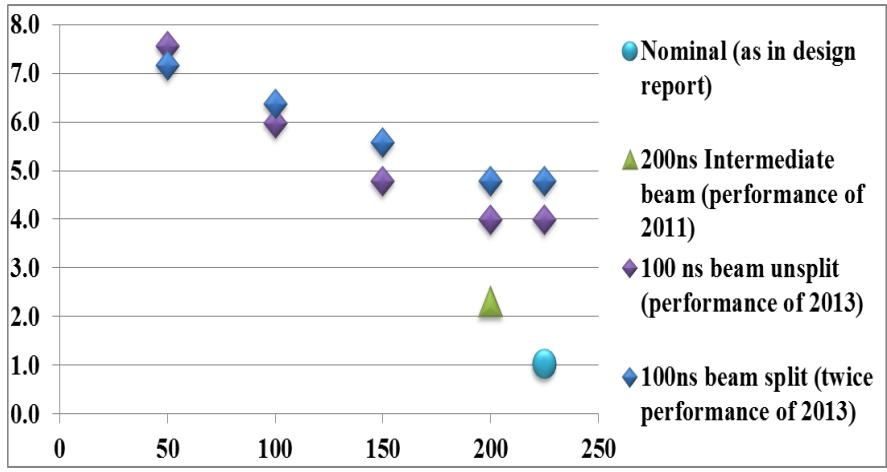
- NA61/SHINE requested Be, incompatible with LHC Pb programme
- Fragmented Pb beam delivered, using same beam definition as LHC
  - Allowed to prepare Nominal beam in parallel in 2011 (free MD time)
  - SHINE's Be programme completed: 6 energies (13, 20, 30, 40, 80 & 160GeV/u)
- New requests for Ar & Xe
  - Ar in Linac in 2013, rest of chain in 2014, 6 week physics run in 2015
  - Xe in Linac & chain in 2016, planned physics run in 2017
  - Schedule in competition with Pb for LHC and studies on Pb



Future LHC beams

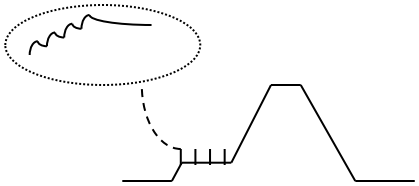
- After LS1: $\mathcal{L} = 4.10^{27}$ cm^{-2}s^{-1} at 7 ZTeV possible by replacing batch expansion by compression in the PS, and increasing number of injections in SPS
- After LS2:request to increase peak luminosity beyond $\mathcal{L} = 6.10^{27}$ cm^{-2}s^{-1} at 7 ZTeV (missing factor ~3 compared to 2011)
- Increase the number of bunches in the collider
  - Keep number of ions/bunch in LEIR
  - batch compression to 50ns in the PS
  - decrease batch spacing in the SPS

  Or:
  - Double number of ions/bunch in LEIR and reinstate splitting to 100 ns in the PS (but factor 20% still missing)
    - need to address the loss at acceleration, if possible at all
    - Increase injection rep rate to 10Hz



- … provided LHC can digest and keep the beam quality during its long injection plateau, cf talk TUPM1HA02 by M.Schaumann's:
  "Why does the LHC need a Stochastic Cooling System?"

100/50 ns scheme after LS2



6 injections

	Nb of bunches	Pb ions/bunch	Harmonic number
LEIR (10^9 Pb ions / 3.6 s)	2	5 10^8	2
PS batch compression + rebucketing Bunch spacing = 100ns	2	100ns, 3.8 10^8	16–18-21-169
SPS at extraction, after 24 transfers from PS, Batch spacing = 50 ns	48	100ns 50ns, 2.2 10^8	4653…4620
LHC at injection, after 19 transfers from SPS	~912	1.7 10^8	35640

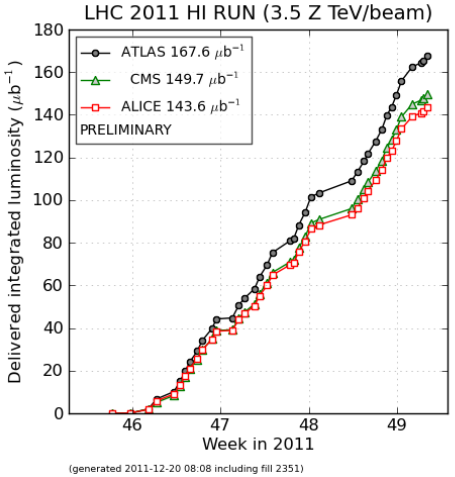
β* = 0.4 m -> L = 7x10^{27} cm^{-2} s^{-1}

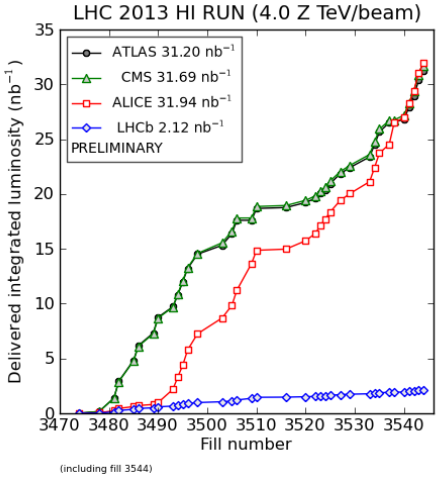
For completeness: Bio-medical experiments

- Request for lighter ions (C, He, …p)
- Will need
  - to redesign a slow extraction
  - install an extraction line
  - a second ion source
- No schedule for the moment

Conclusion

- LEIR's contribution to the success of the LHC HI programme has been essential
- The machine will be more and more in demand over the coming years:
  - for the LHC
  - for the SPS fixed target programme,
  - possibly for bio-medical experiments.
- Some issues still need to be addressed, which will necessitate studies with beam.





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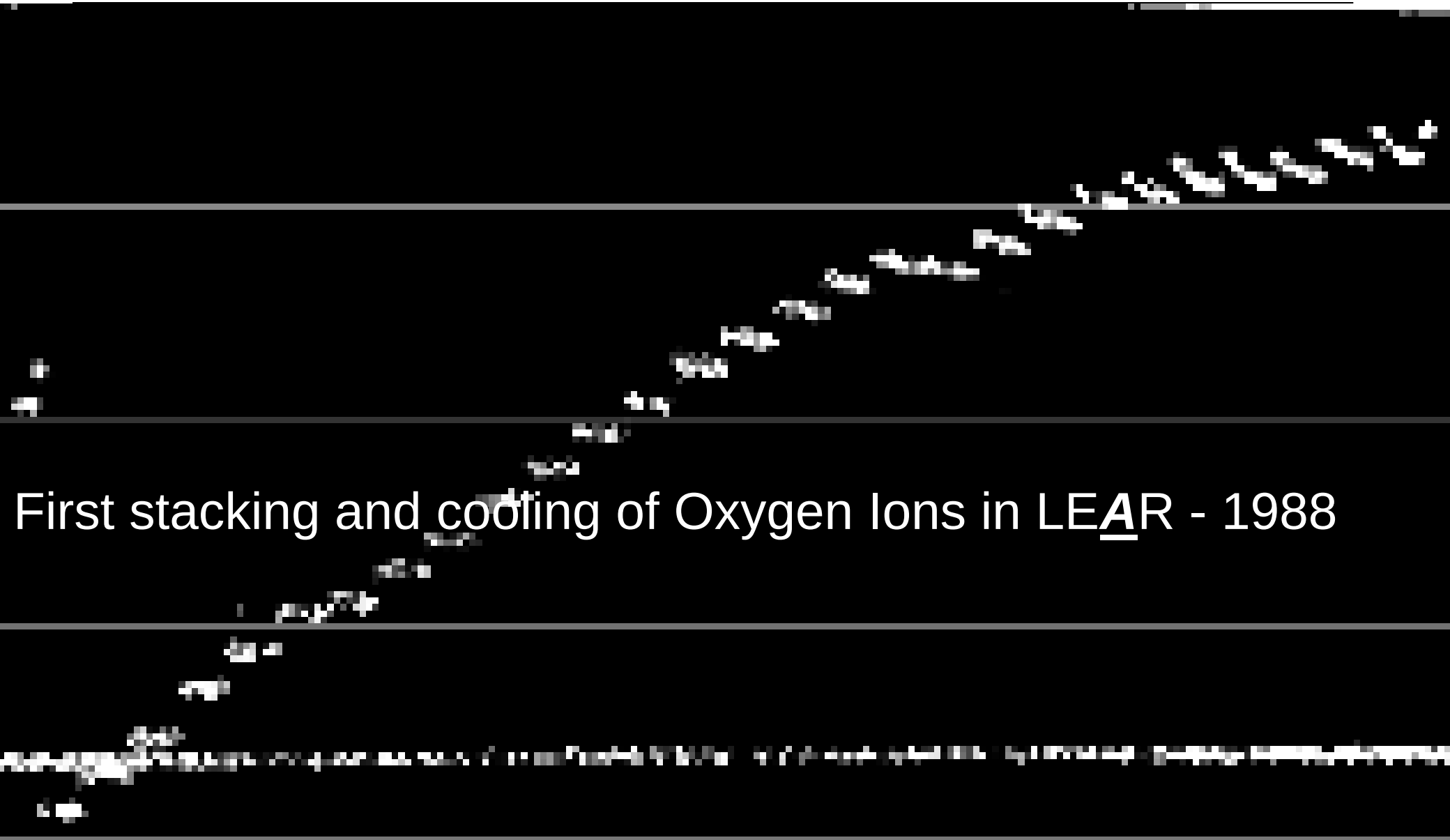

First stacking and cooling of Oxygen Ions in LE***A***R - 1988