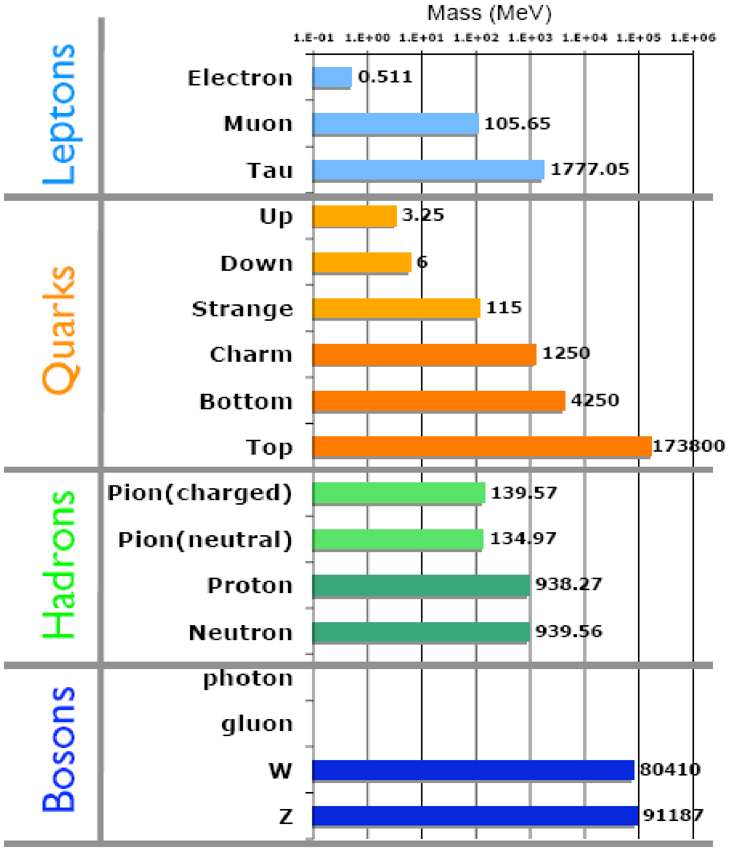
The Large Hadron Collider

Lyn Evans

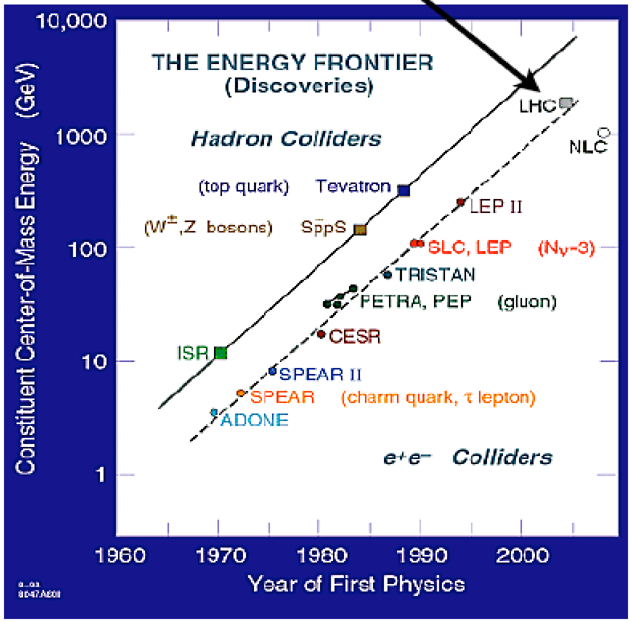
Kruger 2010 Workshop

Kruger Gate 5th December 2010

History/Energy Line vs Discovery



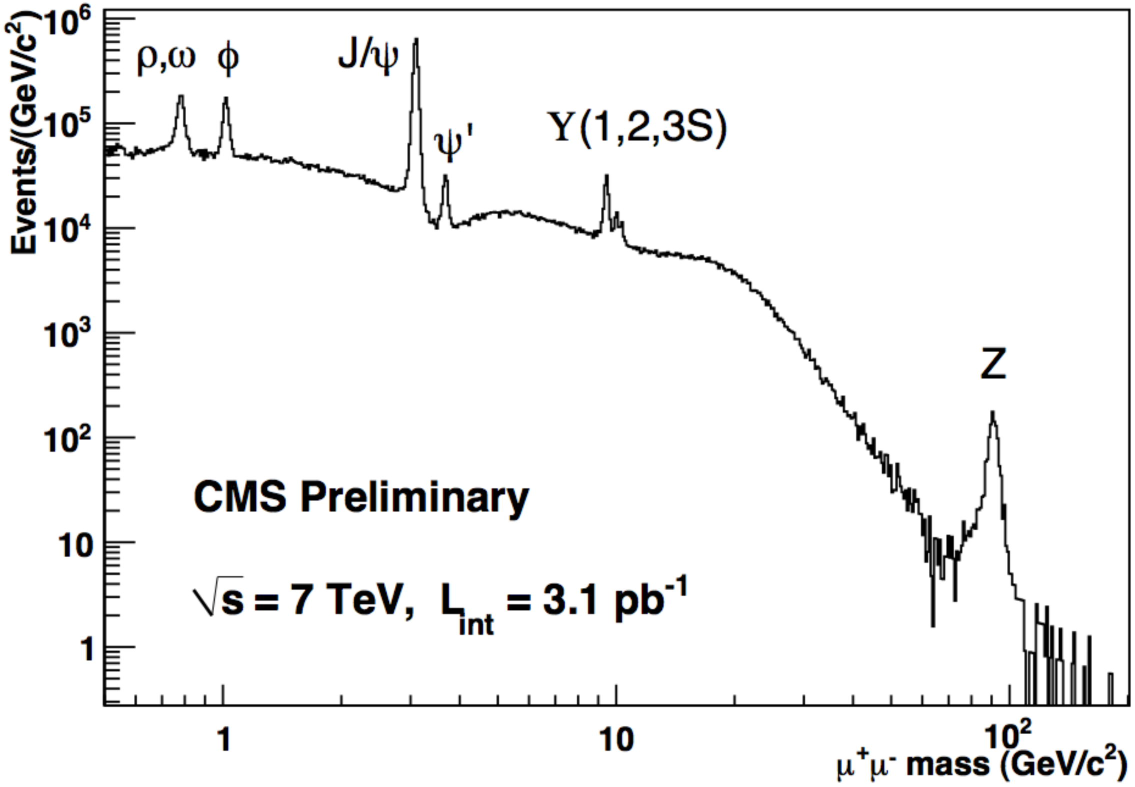
Higgs and super-symmetry ?
Or something else maybe



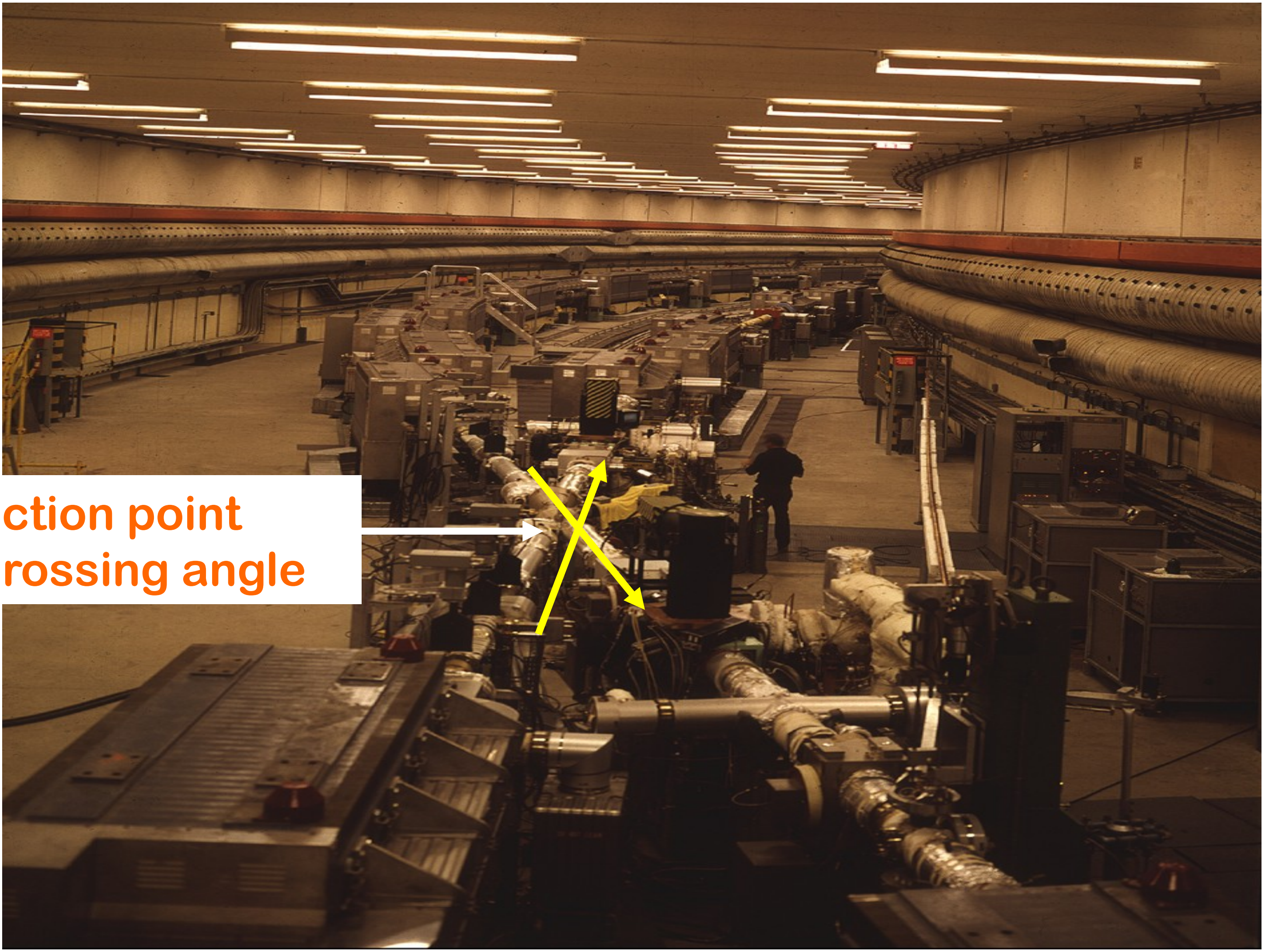
Behind the history plot is hidden the technological development required for each step

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either $\bar{p}$-p as Tevratron, p-p as LHC)

CMS Muon Pairs Mass



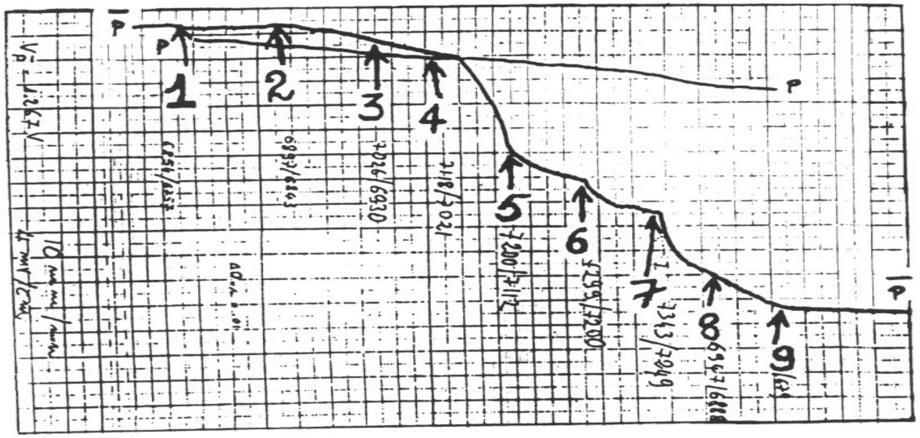
ISR



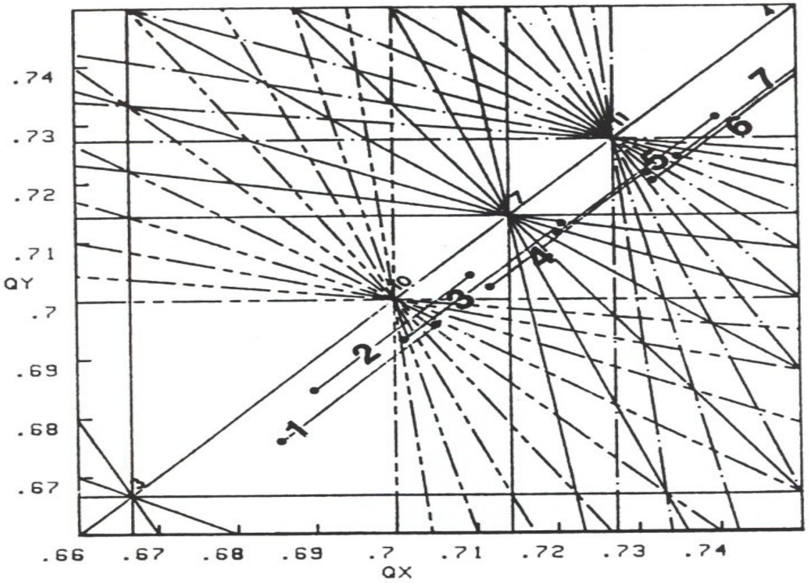
Interaction point with crossing angle

Antimatter

A Beam-Beam Resonance Scan at the SPS Collider

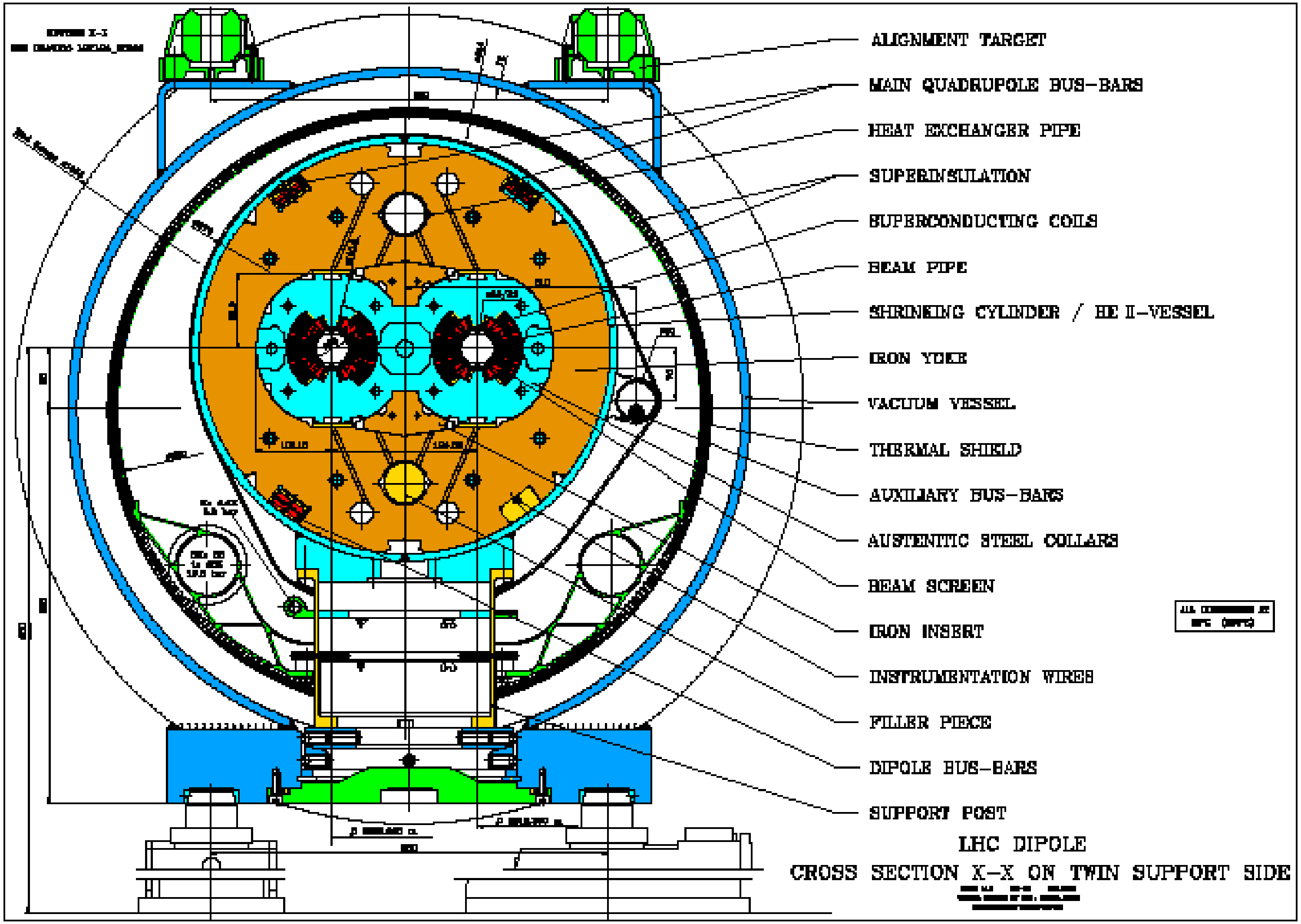


a)

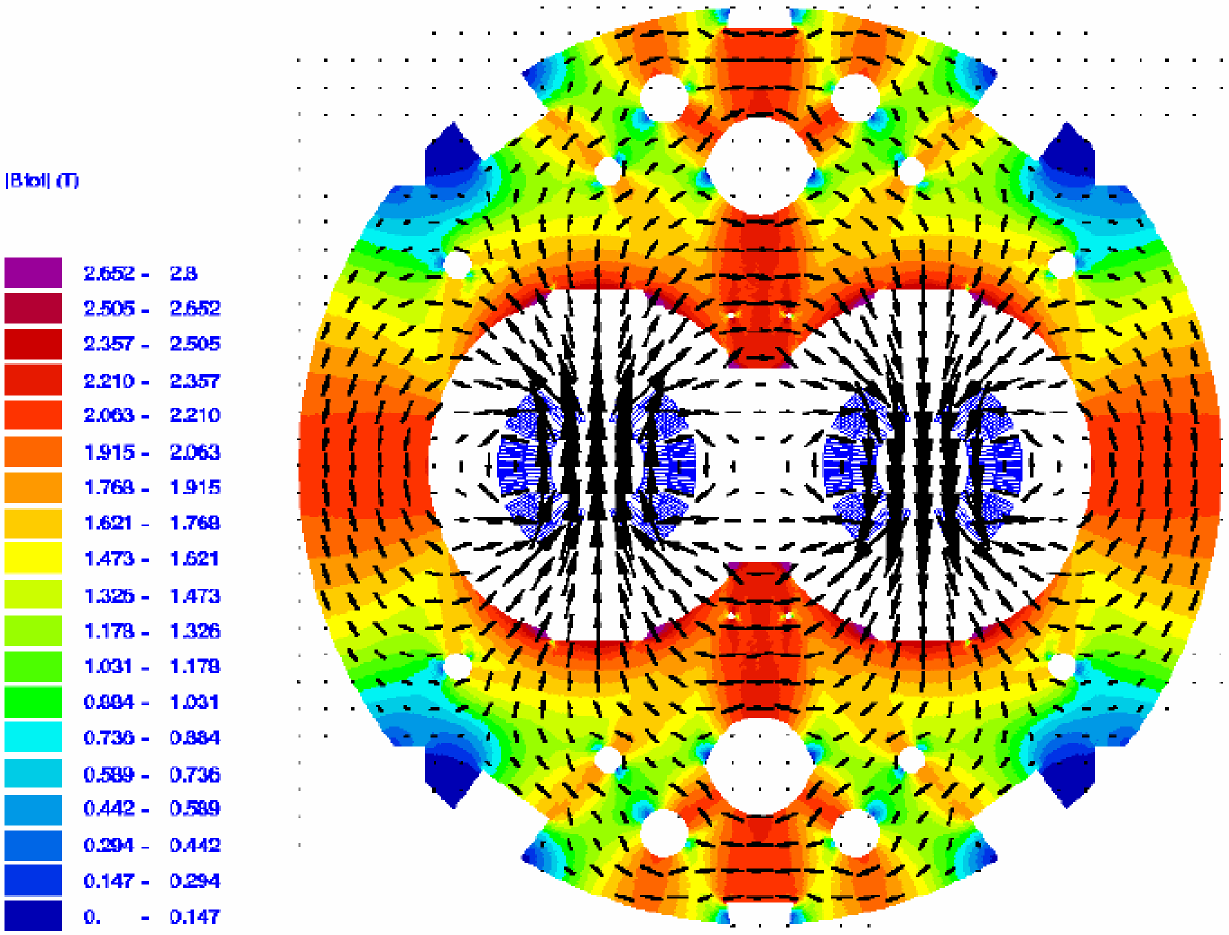


23 Kms of superconducting Magnets

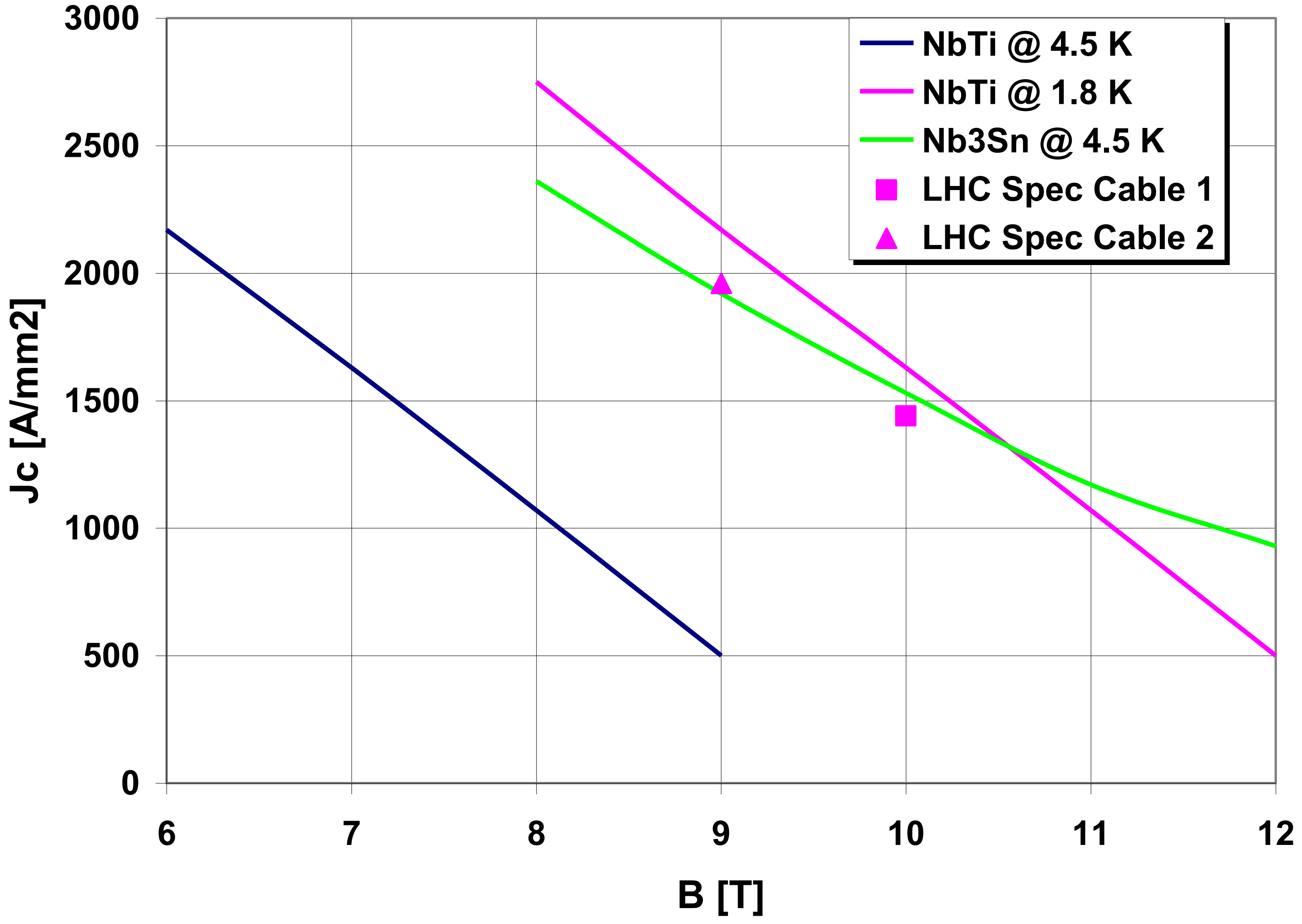
Cryodipole Cross-Section



Dipole magnetic flux plot

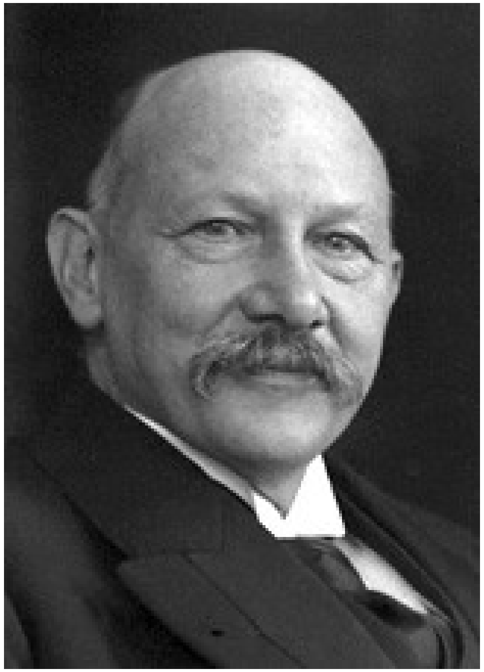


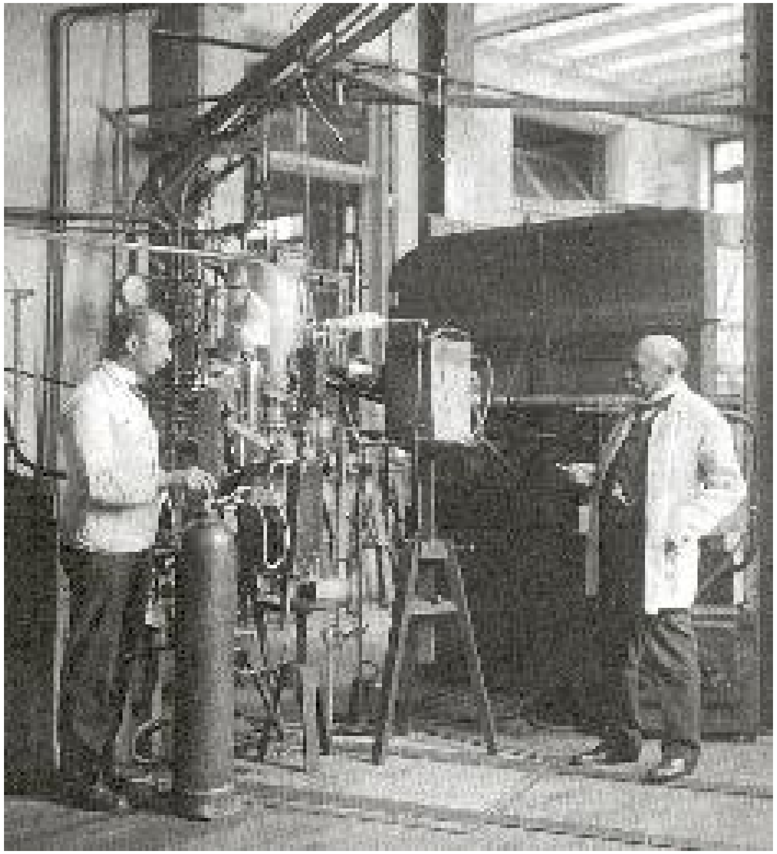
Critical current Density of technical Superconductors



...at the Physics Laboratory of Leyden, Helium was first liquified

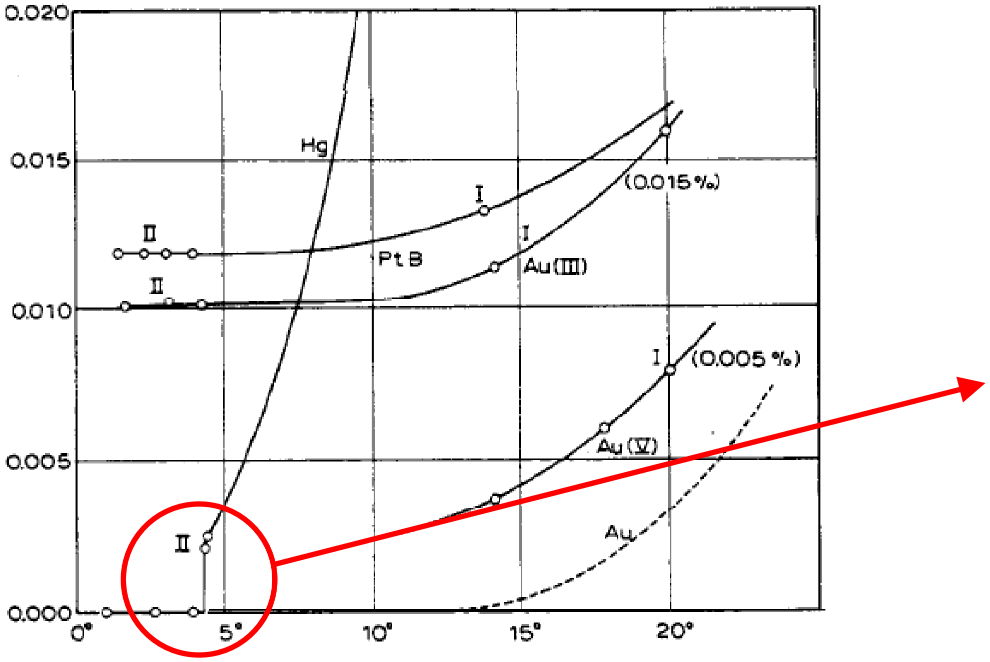
Heike Kamerlingh Onnes





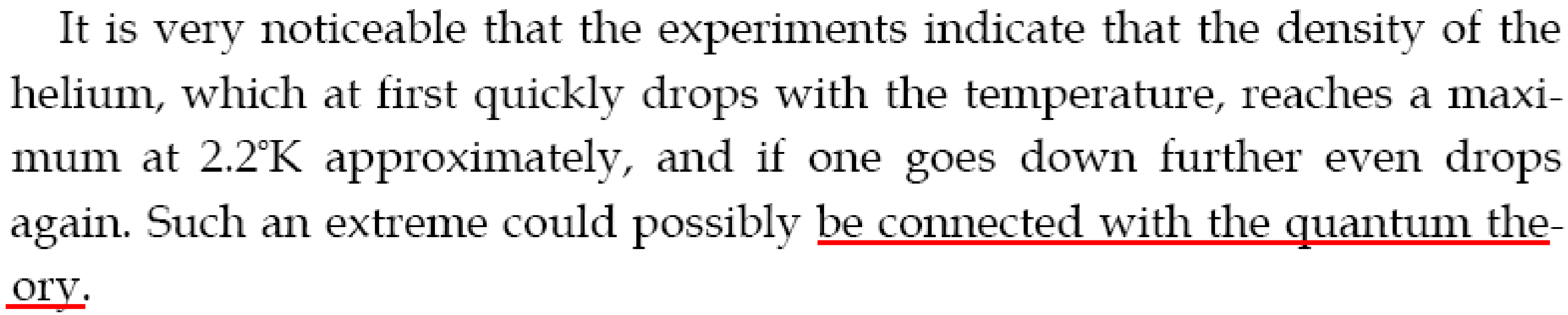
"Door meten tot weten"
To knowledge through measurement

Discovery of Superconductivity (1911)



Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.

Hint of a quantum Effect…?

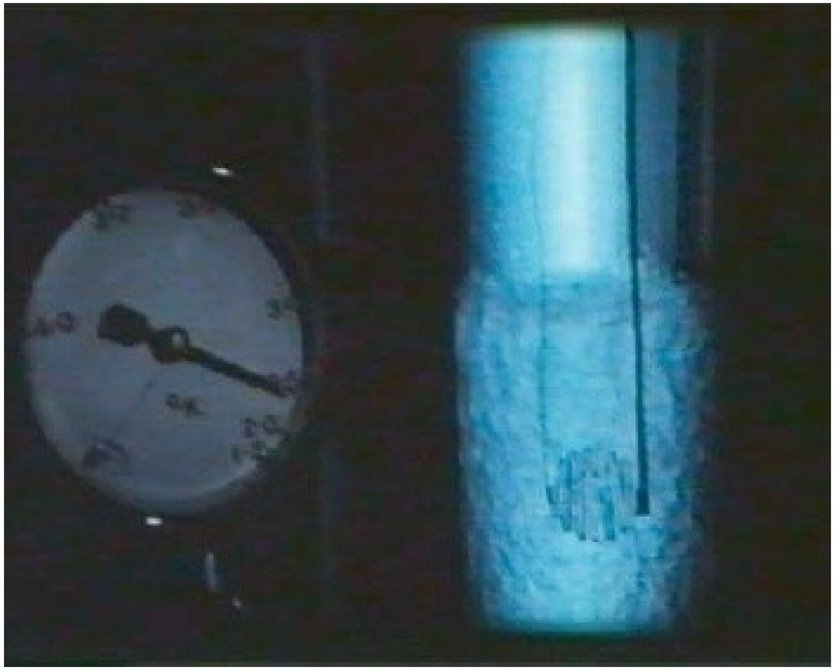


It is very noticeable that the experiments indicate that the density of the helium, which at first quickly drops with the temperature, reaches a maximum at 2.2°K approximately, and if one goes down further even drops again. Such an extreme could possibly be connected with the quantum theory.

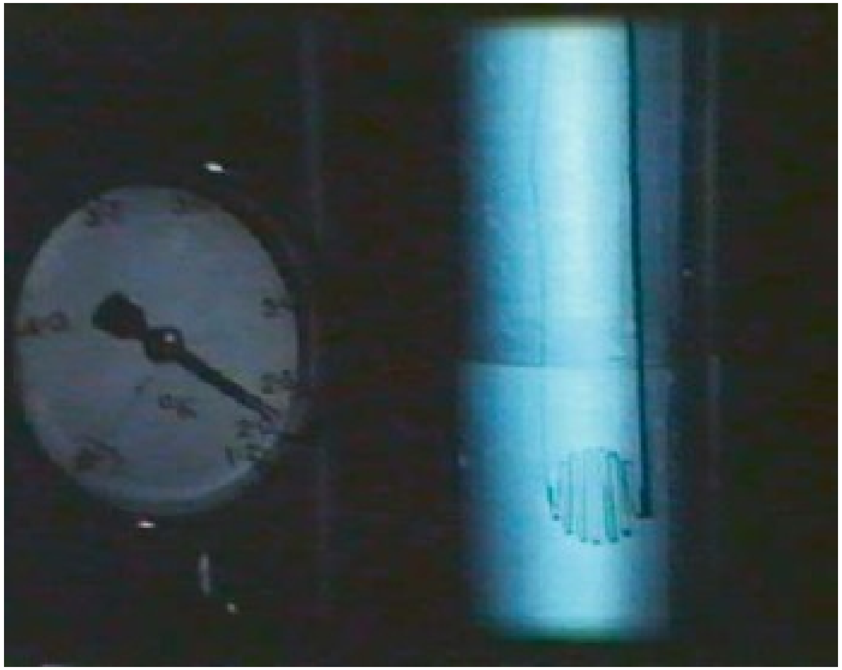
Discovery of superfluidity in He II (1938)

J.F. Allen & A.D. Misener (Cambridge)
P.L. Kapitsa (Moscow)

Vaporization of liquid helium



He I (T=2.4 K)



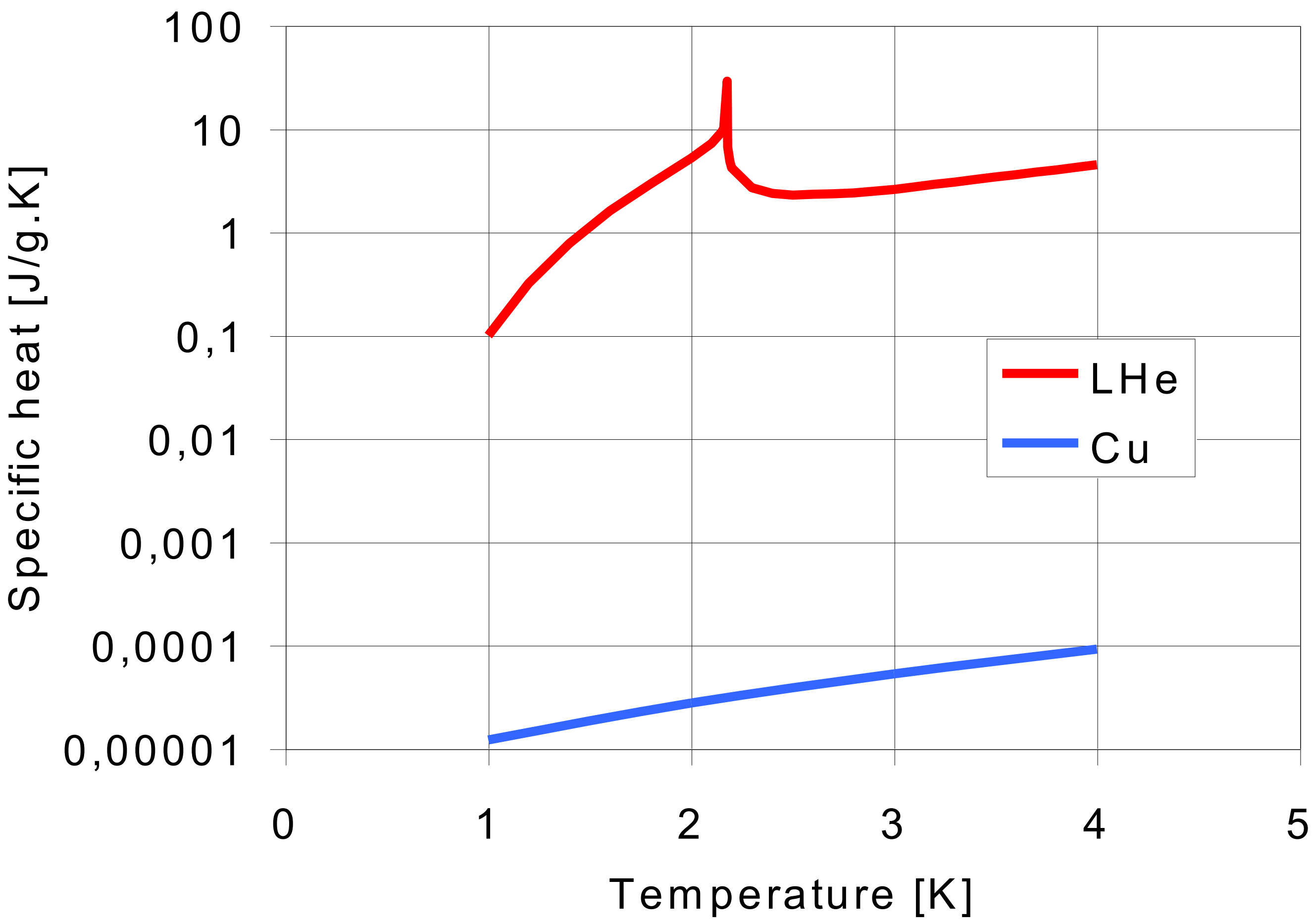
He II (T=2.1 K)

J. F. Allen

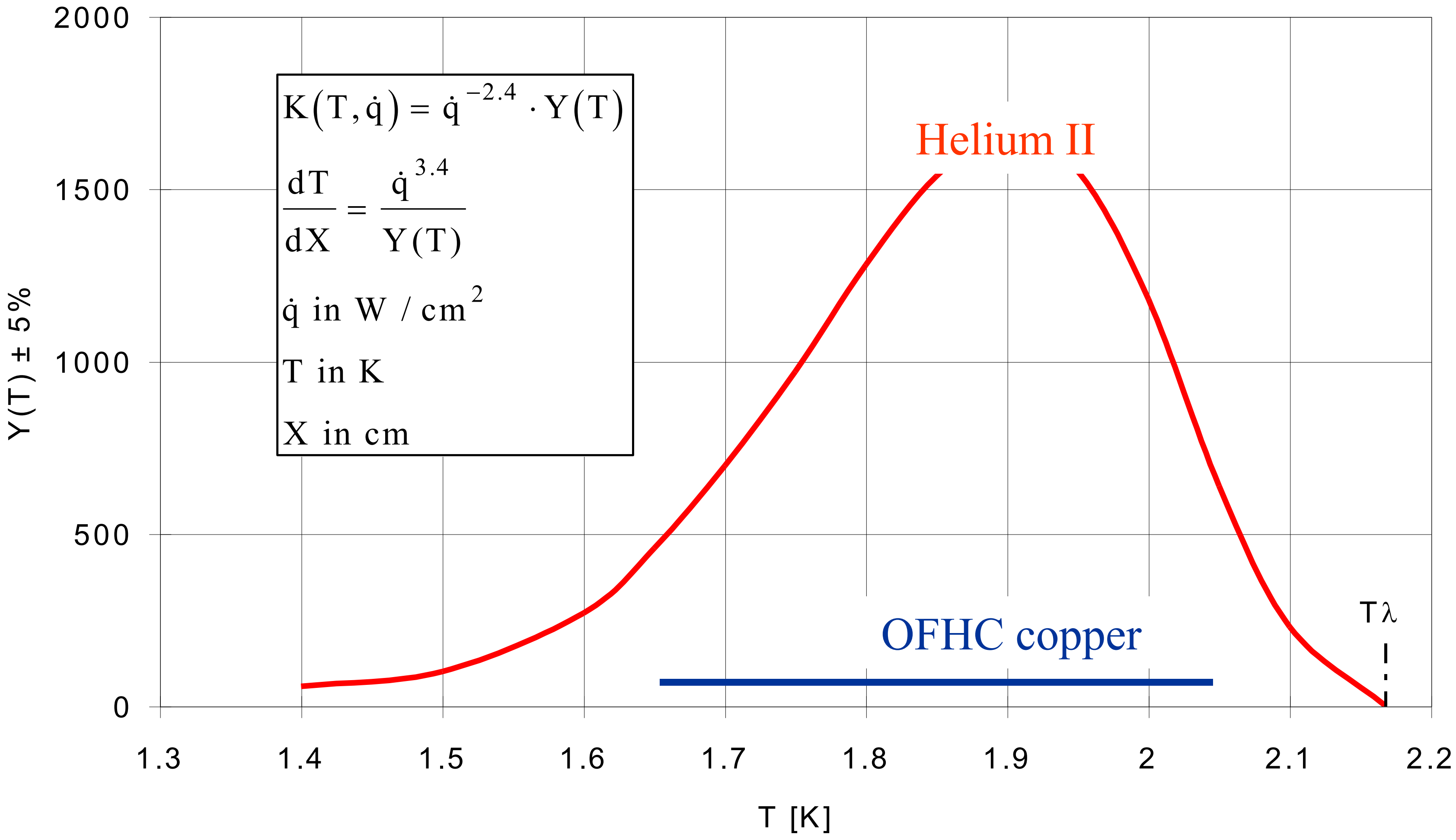
« In my PhD work in Toronto on superconductivity, I had often seen the sudden cessation of boiling at the lambda temperature T_λ but had paid it no particular attention. It never occured to me that it was of fundamental significance. »

J. Allen, Physics World, November 1988, p 29.

Specific heat of LHe and Cu



Equivalent thermal conductivity of He II



$$K(T,\dot{q}) = \dot{q}^{-2.4} \cdot Y(T)$$

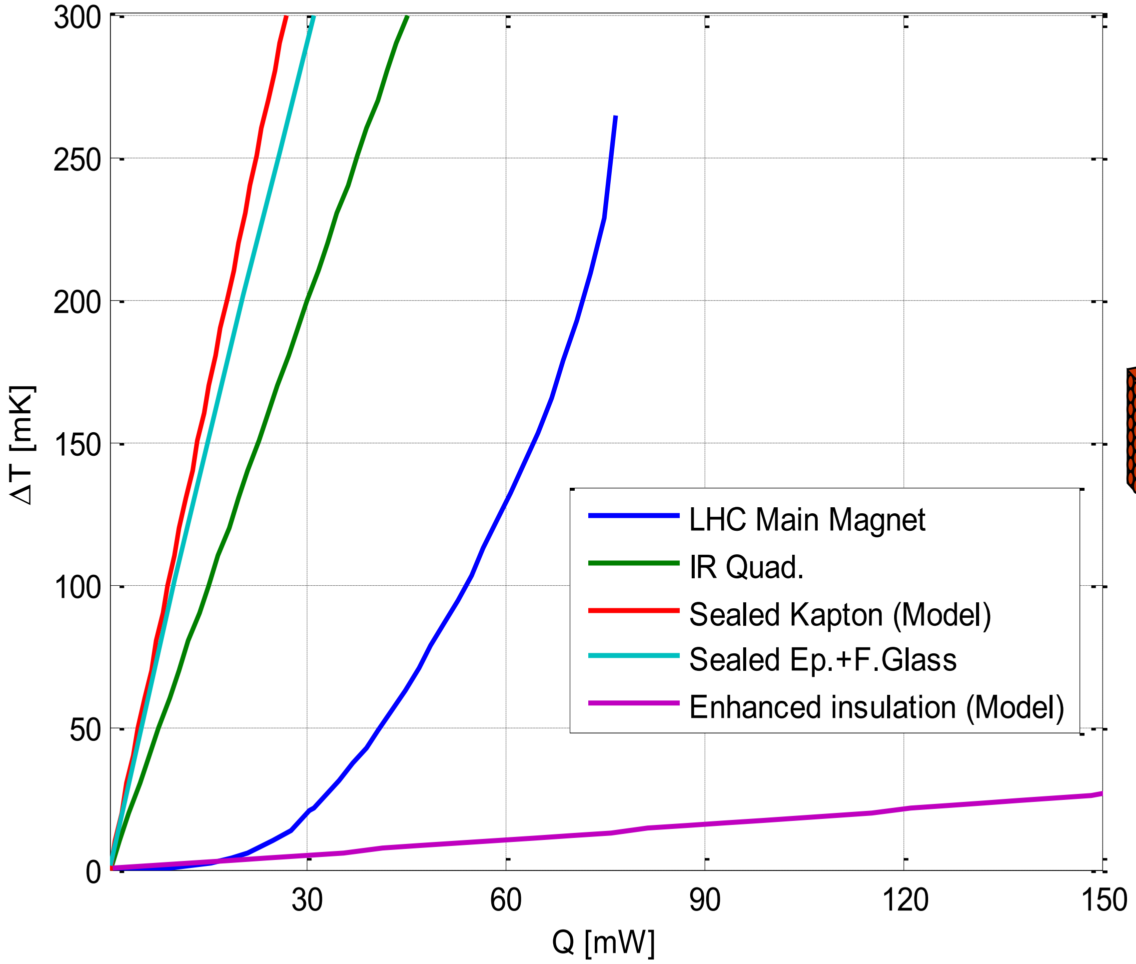
$$\frac{dT}{dX} = \frac{\dot{q}^{3.4}}{Y(T)}$$

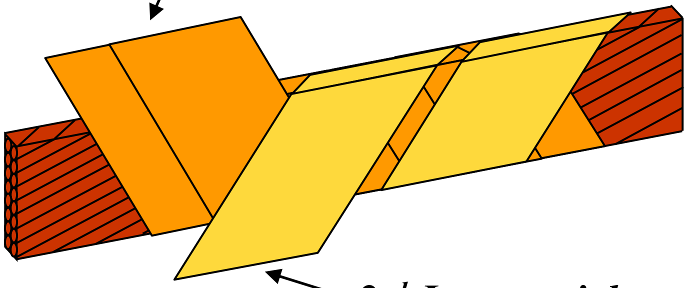
$\dot{q}$ in W / cm^2

T in K

X in cm

Insulation and heat removal





1^{st} Layer with overlap
(*to provide enough*
surface current path:
200V/cm ***&***
*to avoid punch through****)***

2^{nd} Layer with or
w/out spacing
and glue on 1 or 2
sides

This translate in about 10 W/m of heat tr. from coil to the bath

150ns bunch train performance, 22/09 to 29/10

Energy	TeV	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
Bunch intensity	1.E+10	10.0	10.0	10.5	10.3	10.0	10.6	11.5	12.2
Bunches per beam		24	56	104	152	204	248	312	368
Colliding in 1 5 8		16	47	93	140	186	233	295	348
Emittance	µm	3.30	2.20	2.80	2.90	2.60	2.40	2.60	2.40
β*	m	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
Luminosity 1 & 5	$cm^{-2} s^{-1}$	4.6E+30	2.0E+31	3.5E+31	4.8E+31	6.8E+31	1.0E+32	1.4E+32	2.1E+32
Event rate / Xing	Hz	1.5	2.3	2.0	1.8	2.0	2.4	2.6	3.2
BBTS / Xing		0.0037	0.0055	0.0046	0.0043	0.0047	0.0054	0.0054	0.0062
BBTS for 3 Xing		0.0111	0.0166	0.0137	0.0130	0.0141	0.0161	0.0162	0.0187
Protons		2.4E+12	5.6E+12	1.1E+13	1.6E+13	2.0E+13	2.6E+13	3.6E+13	4.5E+13
% nominal		0.7	1.7	3.4	4.8	6.2	8.1	11.1	13.9
Current	mA	4.3	10.1	19.6	28.1	36.0	47.1	64.8	81.0
Stored energy	MJ	1.3	3.1	6.1	8.7	11.2	14.7	20.2	25.2
			1366						

Touschek Scattering

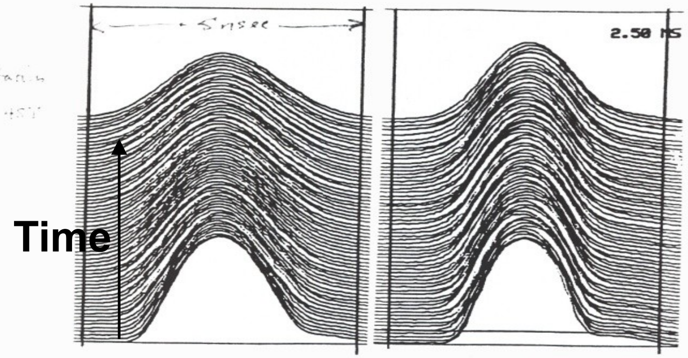
As particles perform their betatron and synchrotron oscillations, they exchange energy due to multiple Coulomb scattering. The correct frame of reference to understand the phenomenon is the rest frame of the beam. The transverse rms momenta $\sigma'x,y$ are unchanged by this transformation whereas the longitudinal momentum σp is transformed into $\sigma p/g$. In a highly relativistic beam like the LHC, the longitudinal plane is therefore very “cold” compared with the transverse planes and one would expect a damping of the transverse dimensions and an increase in the energy spread, which would be good for luminosity preservation. This indeed does occur in the vertical plane although the damping time is very long. Unfortunately, in the regions where the dispersion is not zero (most of the machine), a particle changes its energy by Coulomb scattering but does not change its position and therefore finds itself on the wrong orbit for its momentum. It can only make a betatron oscillation around its new equilibrium orbit, adding a heating term that completely swamps the slow damping in the radial plane.

Intrabeam Scattering in the SPS. Top Bunch Lengthening with Time for a strong Proton Bunch (left) and a weak Antiproton Bunch (right) Bottom. IBS Growth Rate compared with Theory.

INTRABEAM SCATTERING.

longitudinal and transverse emittance growth

Limitation

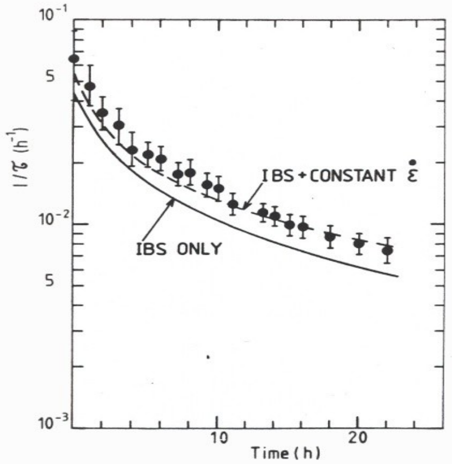


p bunch 1.6×10^{11}

$\bar{p}$ bunch 2×10^{10}

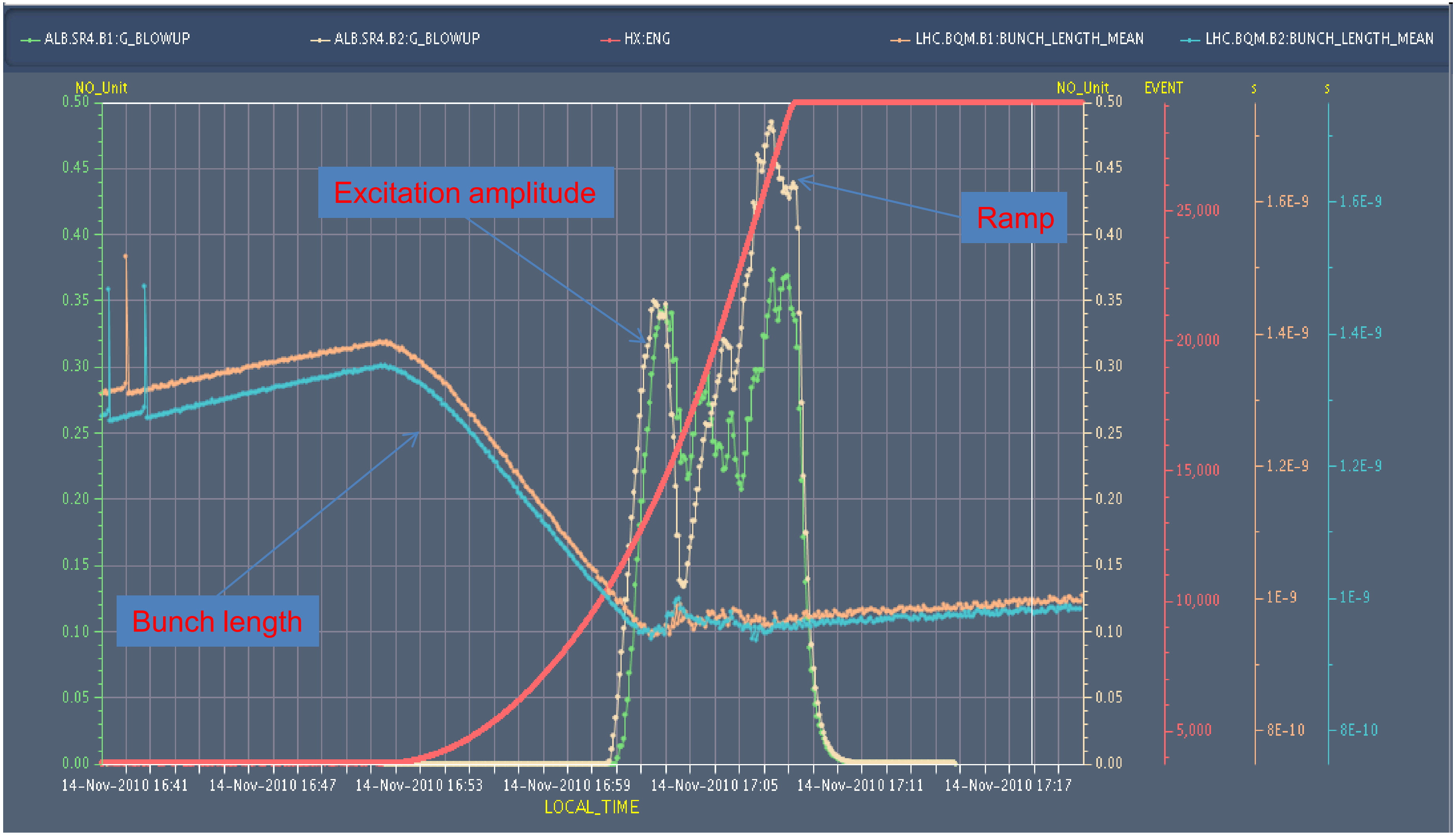
longitudinal blowup.

limitation



Transverse blowup.

Emittance Blow Up during Ramp – 3



Excitation amplitude

Ramp

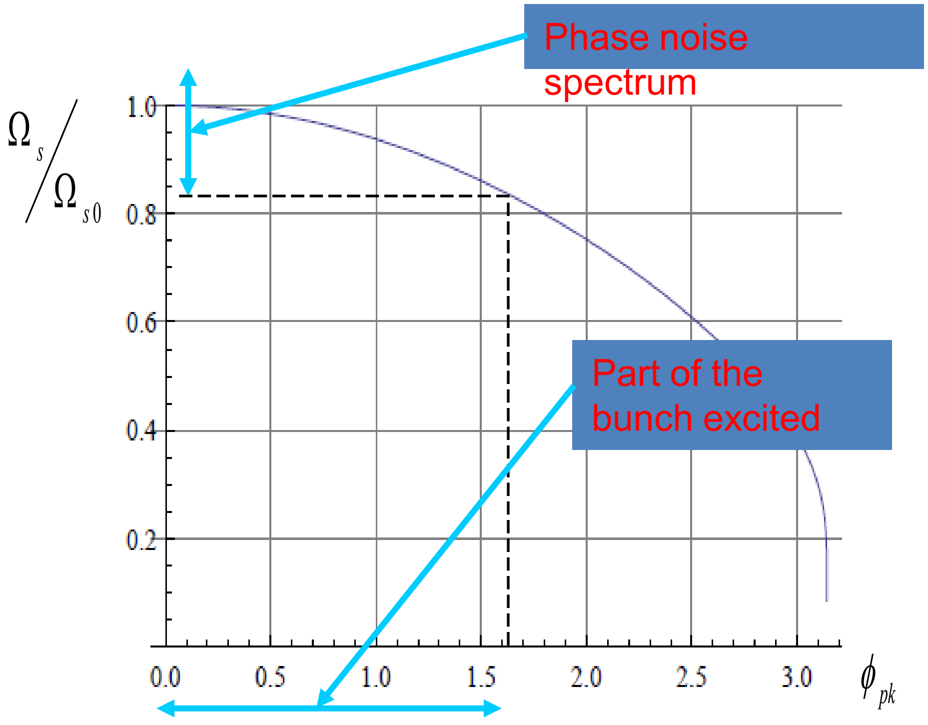
Bunch length

Emittance Blow Up during Ramp – 1

- Rectangular Phase Noise Power Spectral density that excites only the core
  - avoid tails and losses
  - hit: 6/7 $f_s < f < 1.1\ f_s$
    - corresponds to a 1.2 ns window in the core
  - and follow f_s along the ramp
    - from 57 Hz to 28 Hz

Method developed by Joachim for the SPS

- Algorithm to adjust the amplitude of the excitation x_n from a measurement of the instantaneous bunch length (mean) L_n and comparison to target L_0
- target bunch length L_0 1 ns for ions
  - was 1.2 ns for protons

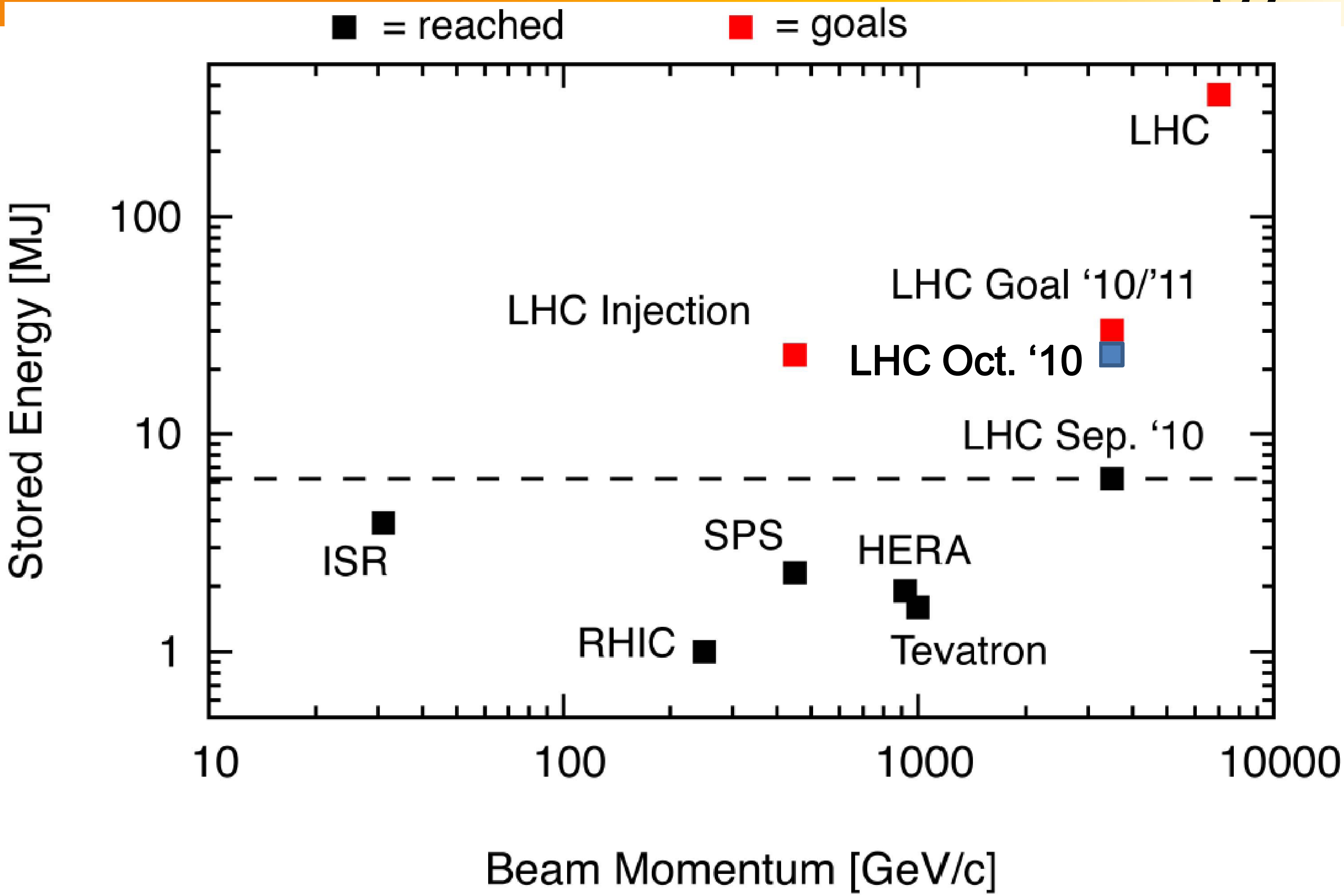


Phase noise spectrum

Part of the bunch excited

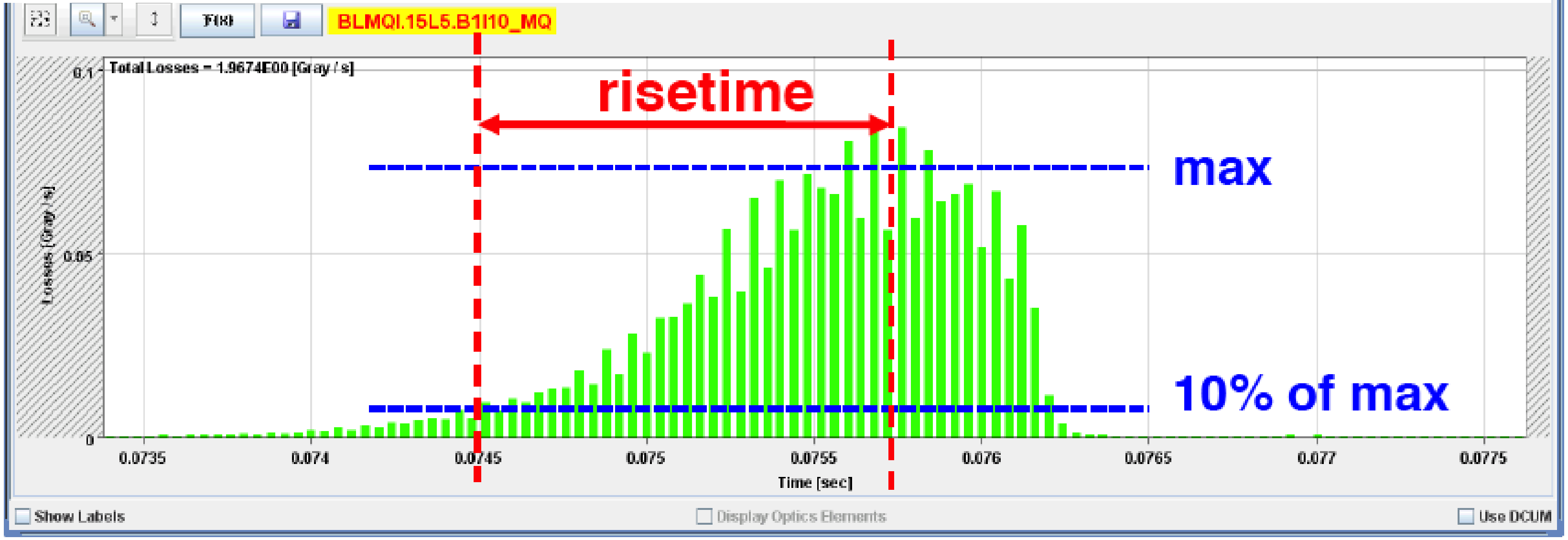
$$x_{n+1} = a.x_n + g.(L_0 - L_n)$$
$$\text{if} \quad x_{n+1} \leq 0 \quad \text{then} \quad 0 \rightarrow x_{n+1}$$
$$\text{if} \quad x_{n+1} \geq 1 \quad \text{then} \quad 1 \rightarrow x_{n+1}$$

LHC now on its own in terms of stored energy



UFO - Unidentified Falling Object (fast local loss)

- Sudden local losses
- No quench, but preventive beam dump
- Rise time on the ms scale
- Working explanation: dust particles falling into beam creating scatter losses and showers propagating downstream



Mitigated by change of BLM threshold

- UFO dump rate has gone down significantly since we increased the thresholds at SC elements (except triplets) by a factor 3.
  - *12 UFOs before change of threshold.*
  - *But there are still coming at a steady rate (see E. Nebot del Busto).*
  - *No quench with UFOs.*

- 2 UFOs since threshold change:
  - *UFO near LHCb leading to dump by LHCb – not the LHC BLMs.*
  - *Ultra-fast and somehow non-standard UFO at BSRT.*

- Even though the UFO rate seems to be under control now, UFOs will become a problem if we ever increase the energy since the quench and BLM thresholds will come down again (factor 2-3 !).

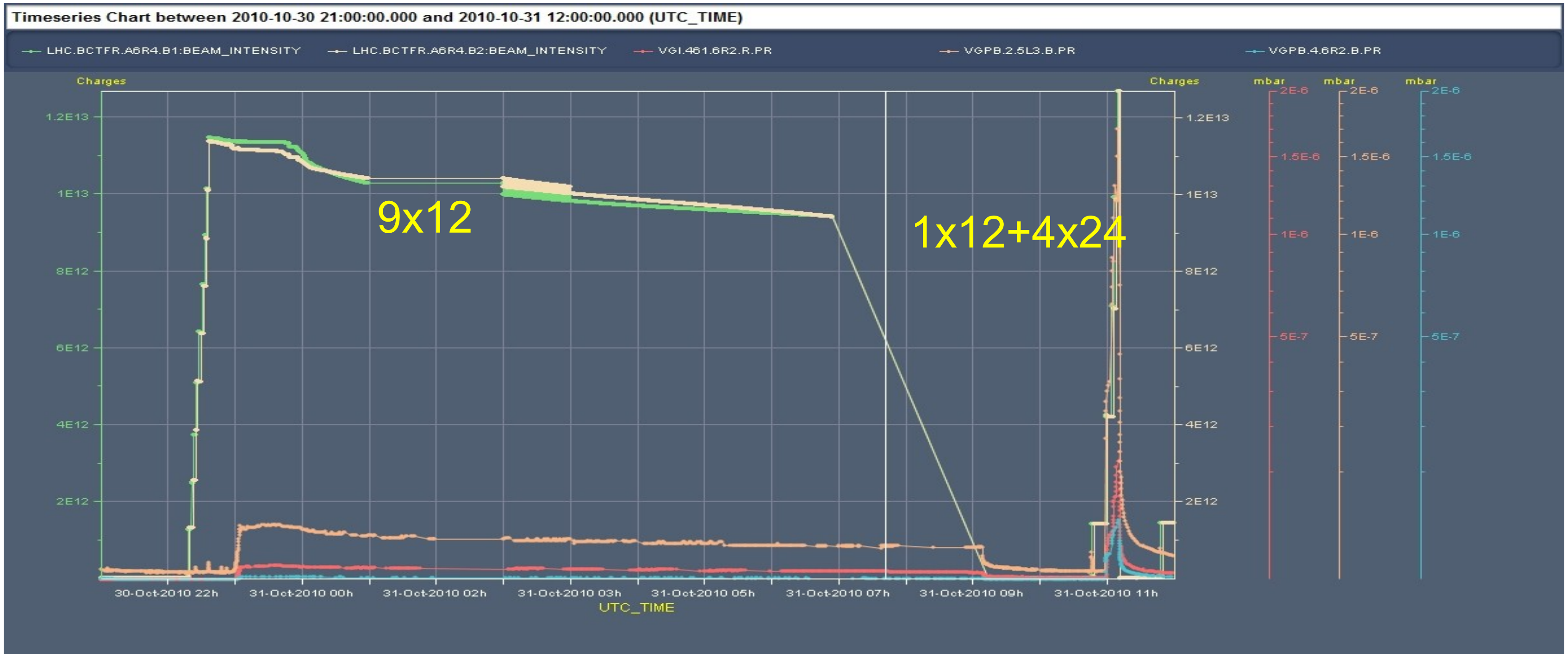
- To be looked at/understood
  - UFO mechanism
  - Possible cleaning by beam
  - Actions for 2012 stop

50ns run (29/10 to 04/11)

- Motivation (in view of effects seen during 150ns operation)
  - Exploration of physics conditions with 50ns spacing
  - Injection and capture efficiency
  - Behaviour of Beam Instrumentation and RF and damper systems
  - Behaviour of vacuum system

- Planning adapted as observations were made
  - Injection and capture of trains of 12
  - Physics fill with 9x12 bunches + end of fill beam-beam studies
  - Large increase in vacuum pressure when injecting trains of 24 bunches
  - Beam stability at injection
  - Systematic measurements of pressure rise in the straight sections and heat load in the arcs for different filling patterns to provide input for simulations and guide predictions:
    - Dependence on bunch intensity
    - Dependence on bunch train length
    - Dependence on bunch train spacing
  - Measurements for the characterization of the scrubbing

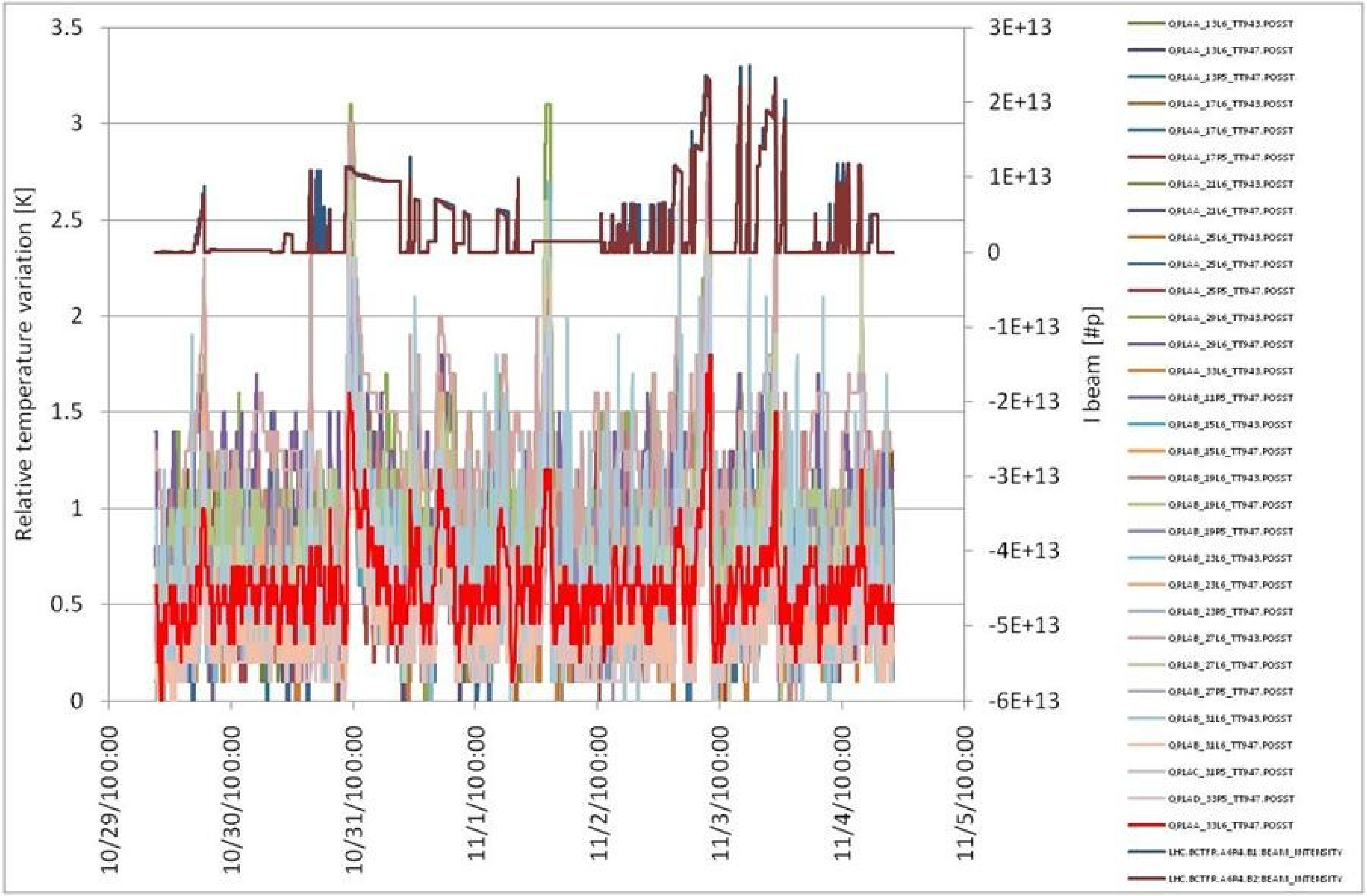
Pressure rises with trains of 24



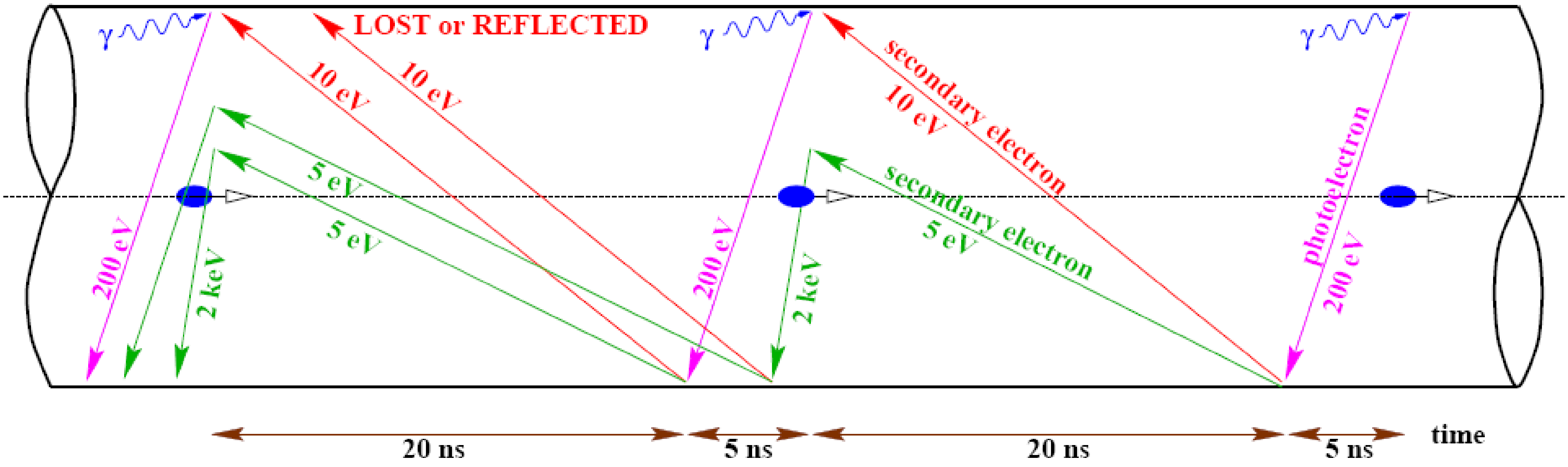
- Vacuum Interlock due to pressure increase on the penning gauges VGPB.773.6L7.R on the cold-warm transition of the Q6L7.R. Beams circulating in different vacuum chambers
- Unexpected for this number of bunches

Heat load on beam screens

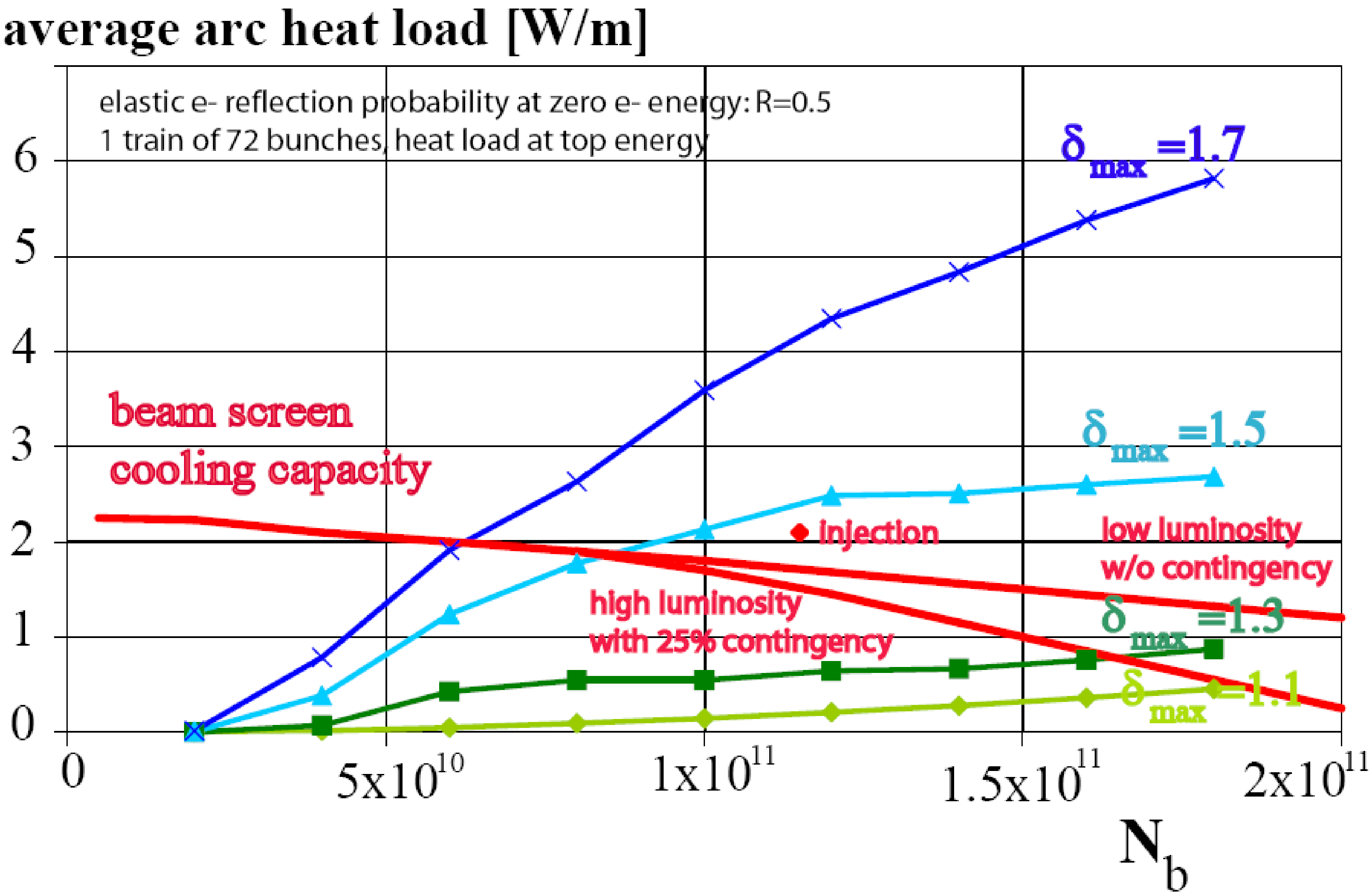
- Observed temperature increases on the beam screens in all the arcs in correspondence with 50 ns beam injection



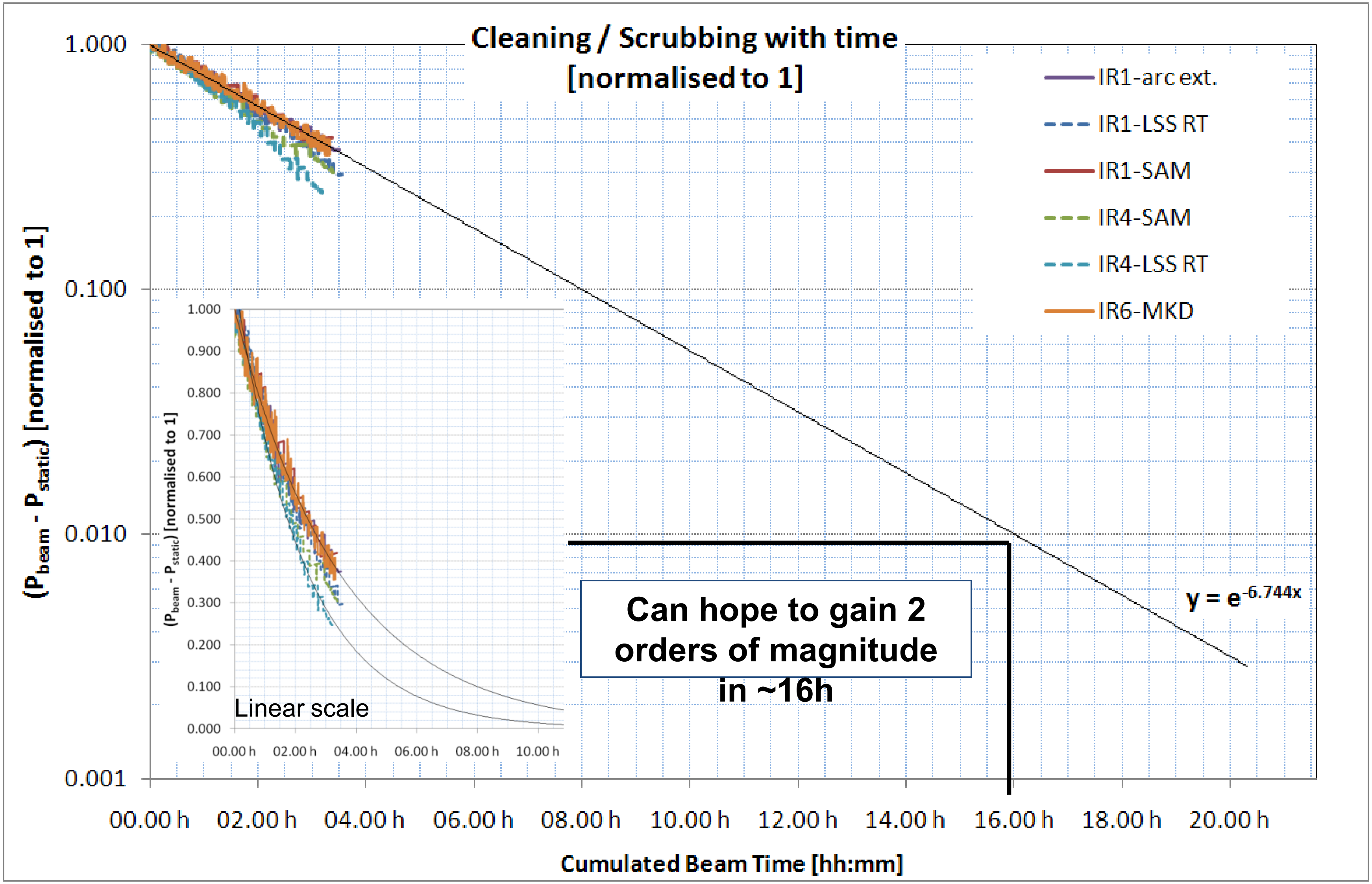
The Electron Cloud Effect



Simulated Heat Load as a Function of SEY



Scrubbing in the LSS

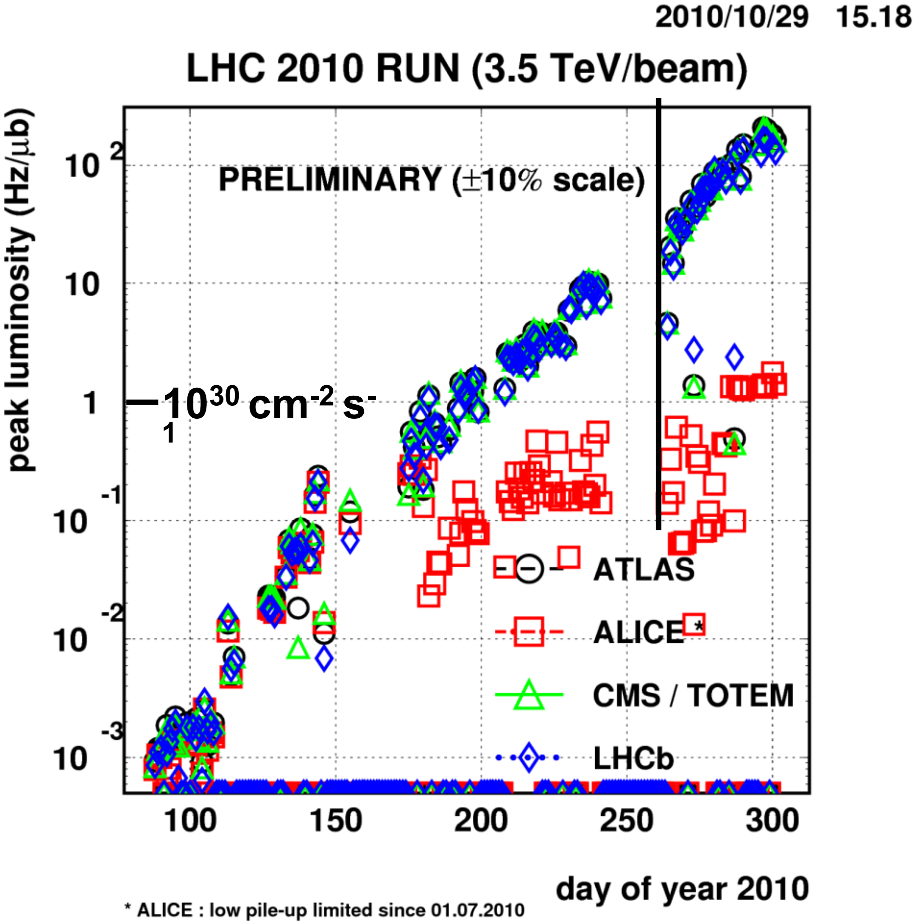


Can hope to gain 2 orders of magnitude in ~16h

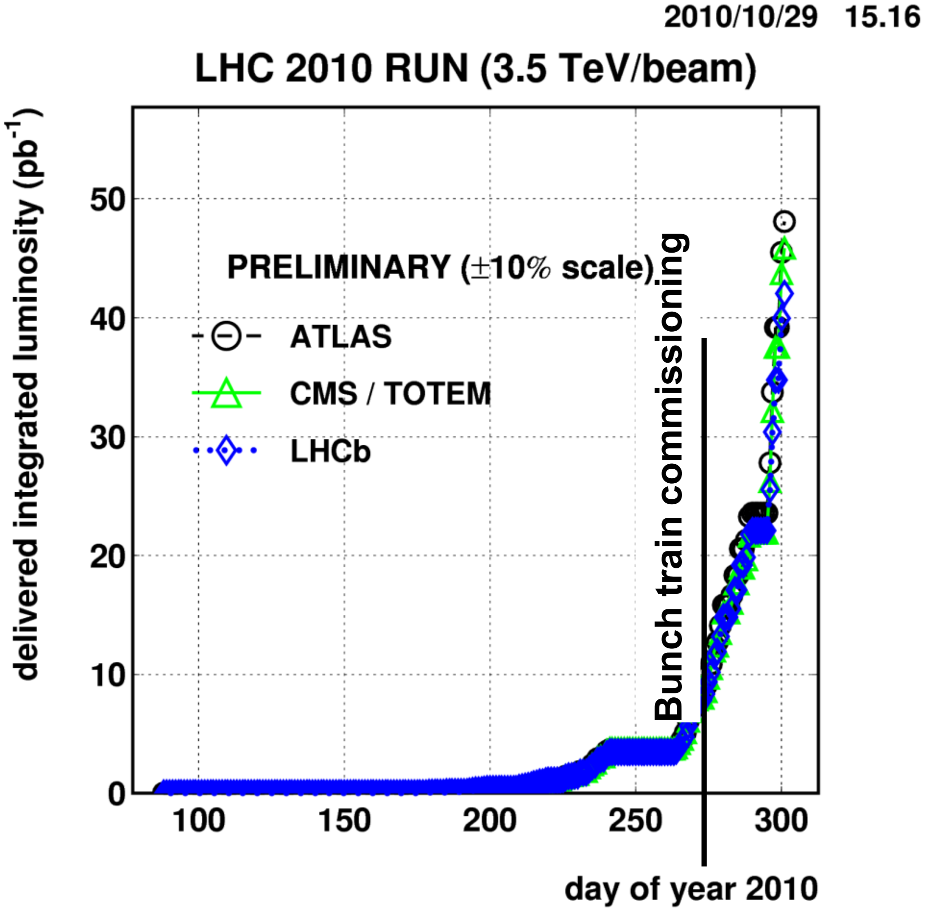
Luminosity Evolution 2010

5 orders of magnitude in ~200 days

~50 pb^{-1} delivered, half of it in the last week !



* ALICE : low pile-up limited since 01.07.2010



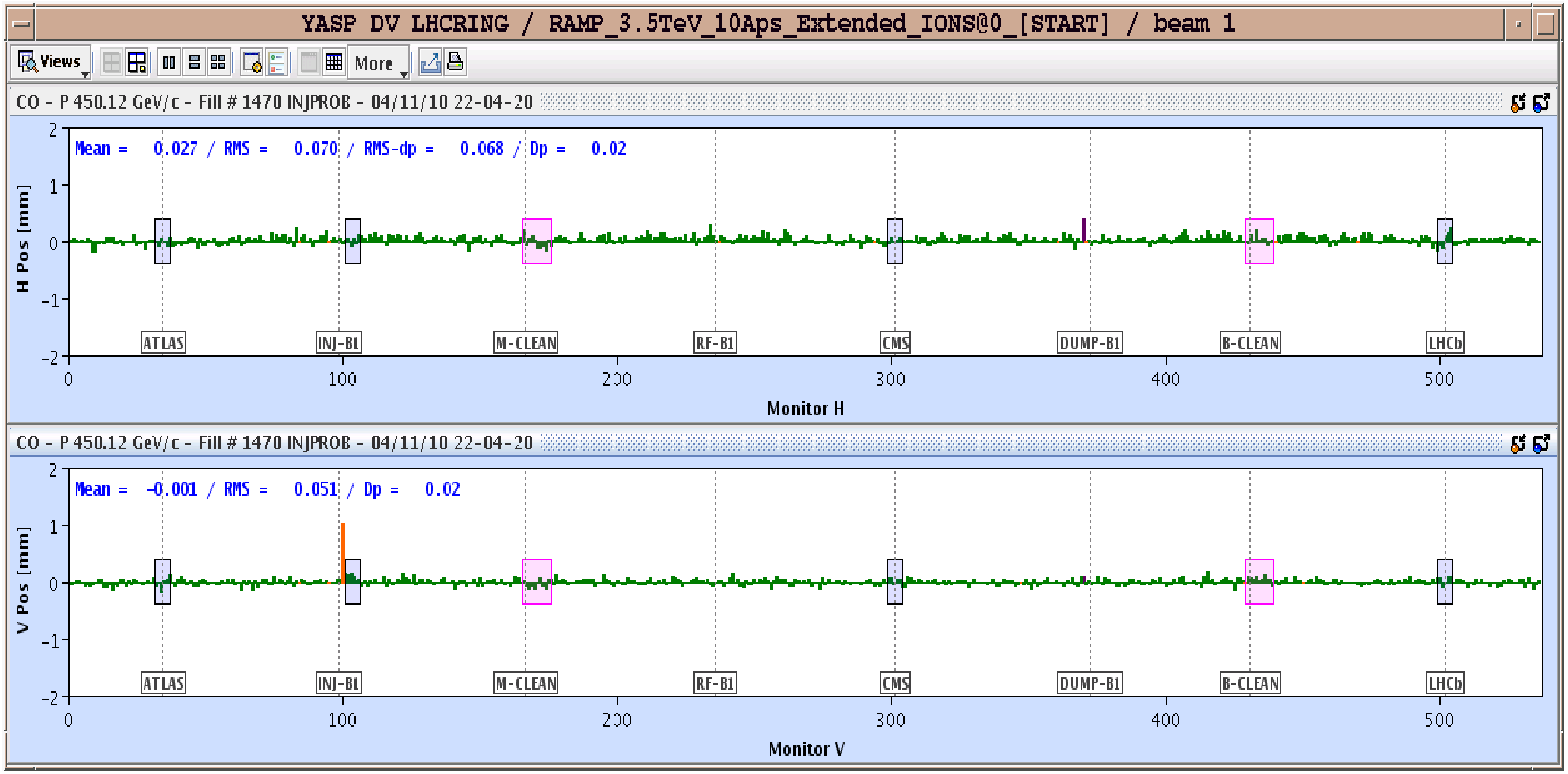
75 nsec operation

Due to the asymmetry of the detector, LHC-b is displaced by 3 RF half wavelengths (11.25m) with respect to the symmetry point.
The only two “magic” bunch spacings where all four IP’s are illuminated naturally are 25 nsec and 75 nsec. For all other separations special bunches have to be put in for LHC-b that do not collide elsewhere.

Tests with 75 nsec have shown no electron cloud effect except in the common vacuum chamber. This can easily be controlled.

75 nsec operation is an attractive option for 2011 whilst “scrubbing” is taking place.

Pb Orbit compared to p Orbit – No Steering !



YASP DV LHCRING / RAMP_3.5TeV_10Aps_Extended_IONS@0_[START] / beam 1

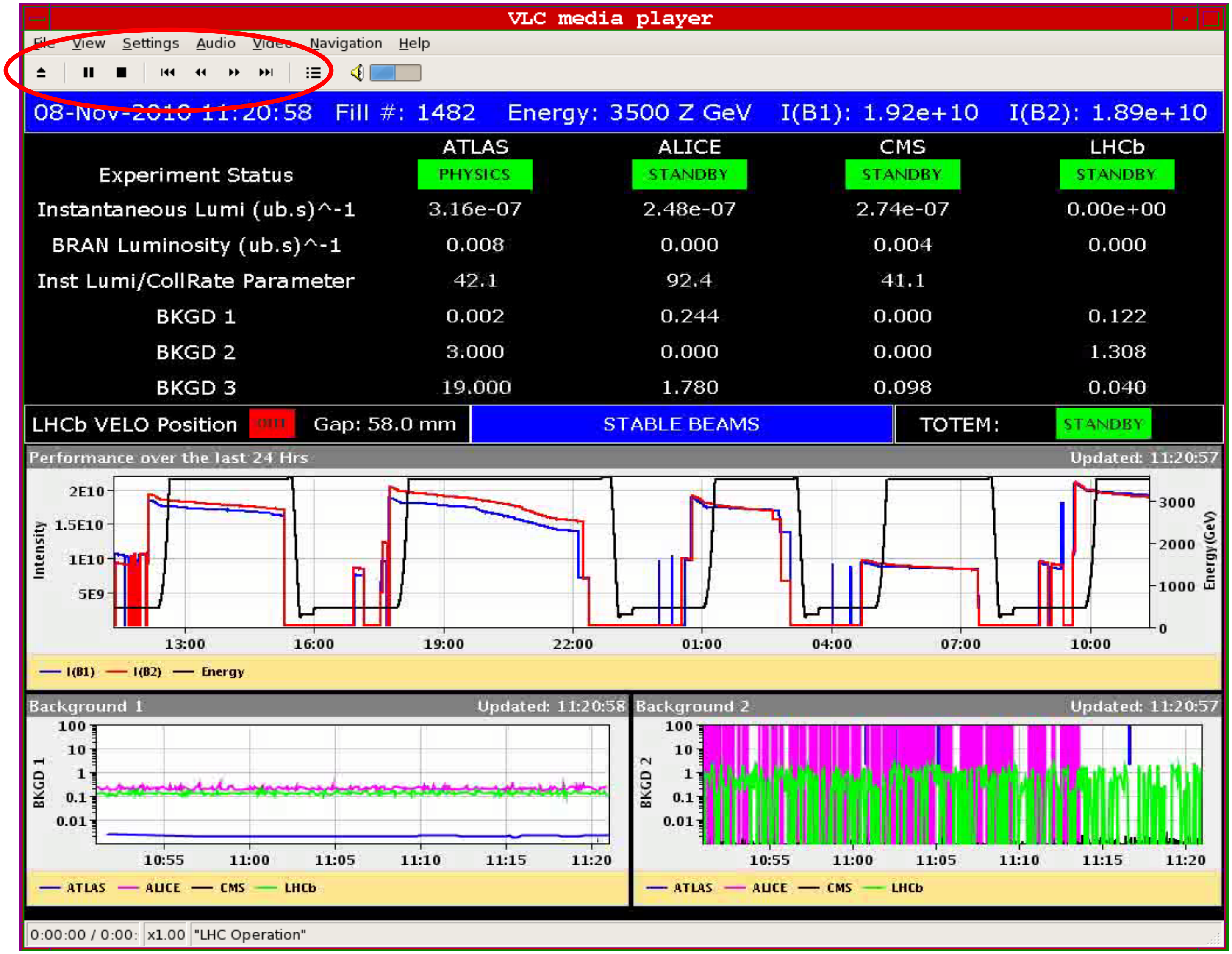
CO - P 450.12 GeV/c - Fill # 1470 INJPROB - 04/11/10 22-04-20

Mean = 0.027 / RMS = 0.070 / RMS-dp = 0.068 / Dp = 0.02

CO - P 450.12 GeV/c - Fill # 1470 INJPROB - 04/11/10 22-04-20

Mean = -0.001 / RMS = 0.051 / Dp = 0.02

First stable Beams (2 bunches per beam)



08-Nov-2010 11:20:58 Fill #: 1482 Energy: 3500 Z GeV I(B1): 1.92e+10 I(B2): 1.89e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	3.16e-07	2.48e-07	2.74e-07	0.00e+00
BRAN Luminosity (ub.s)^-1	0.008	0.000	0.004	0.000
Inst Lumi/CollRate Parameter	42.1	92.4	41.1	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	3.000	0.000	0.000	1.308
BKGD 3	19.000	1.780	0.098	0.040

LHCb VELO Position OUT Gap: 58.0 mm STABLE BEAMS TOTEM: STANDBY

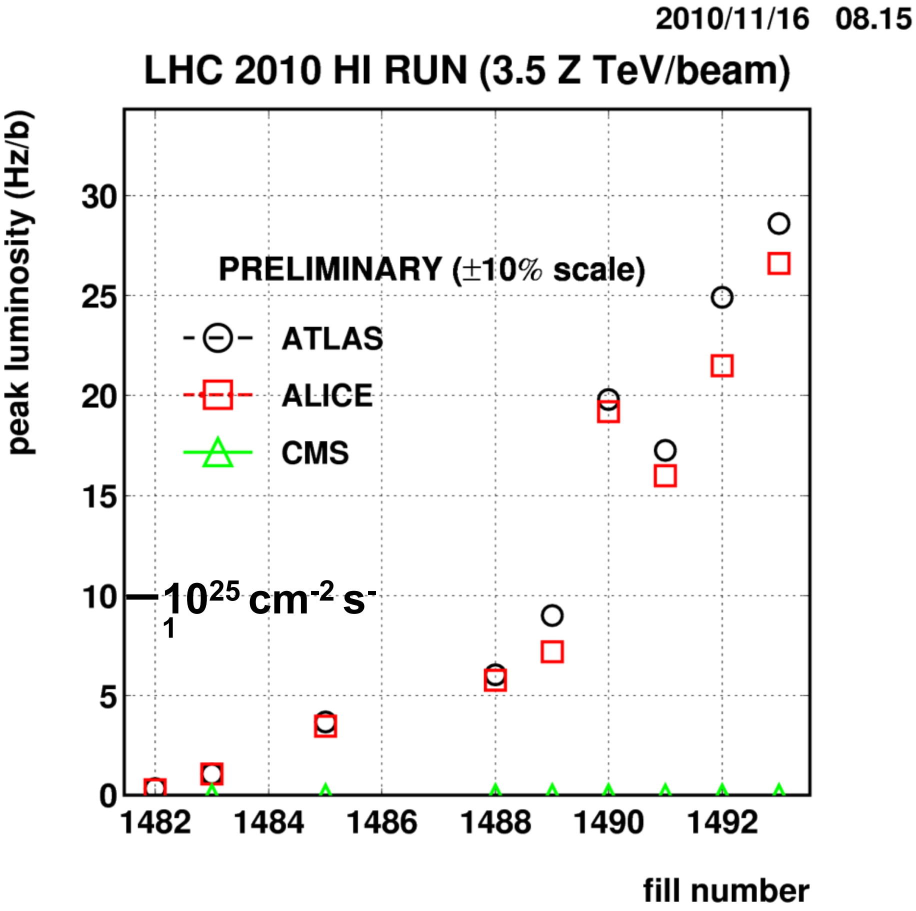
Performance over the last 24 Hrs Updated: 11:20:57

Background 1 Updated: 11:20:58

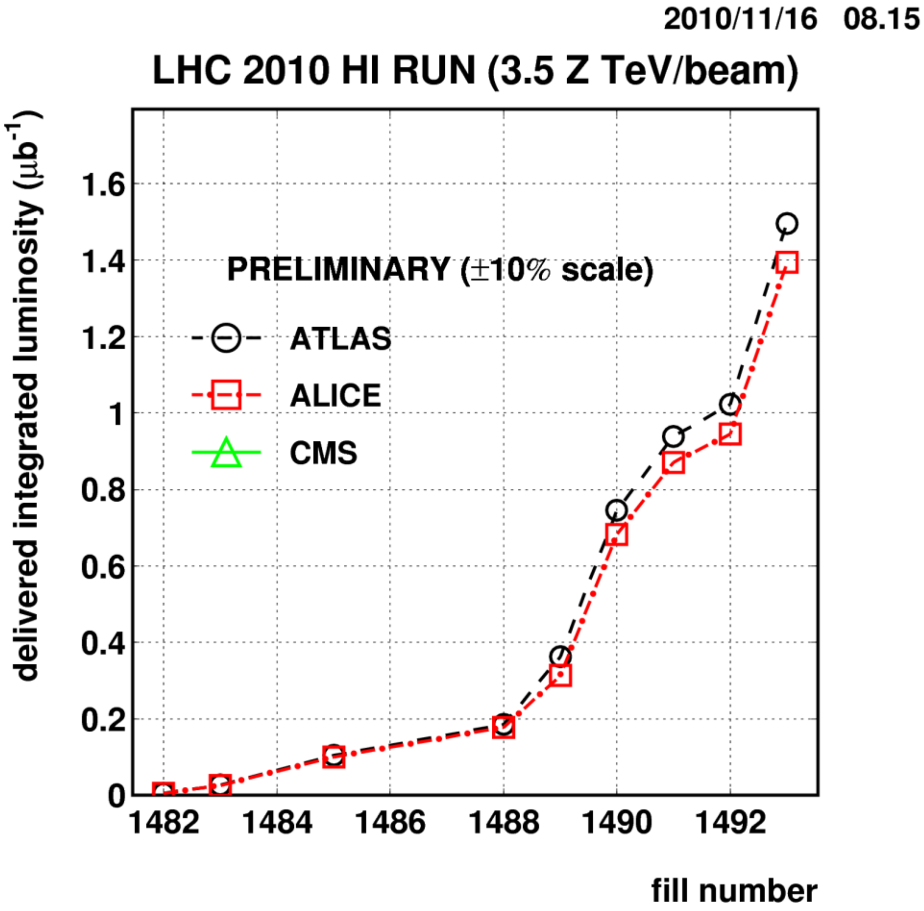
Background 2 Updated: 11:20:57

0:00:00 / 0:00: x1.00 "LHC Operation"

Luminosity Evolution (not quite up-to-date)



10^{25} cm^{-2} s^{-1}



2011: “Reasonable” Numbers

- 4 TeV
- 936 bunches (75 ns)
- 3 micron emittance
- 1.2 x 10^{11} protons/bunch
- beta* = 2.5 m, nominal crossing angle

Peak luminosity	6.4 x 10^{32}
Integrated per day	11 pb^{-1}
200 days	2.2 fb^{-1}
Stored energy	72 MJ

Usual warnings apply – see problems, problems above

Ultimate Reach

- 4 TeV
- 1400 bunches (50 ns)
- 2.5 micron emittance
- 1.5 x 10^{11} protons/bunch
- beta* = 2.0 m, nominal crossing angle

Peak luminosity	2.2 x 10^{33}
Integrated per day	38 pb^{-1}
200 days	7.6 fb^{-1}
Stored energy	134 MJ

Usual warnings particularly apply – see problems, problems above

Summary

- Bunch train operation with 150ns was a big success
  - Bunch intensity ~ nominal
  - Normalised emittance ε_n in collision ~ 2.5 µm
  - Maximum bunches/colliding 1 & 5 368/348
  - Peak luminosity ~ 2 10^{32} cm^{-2} s^{-1}
  - Delivered luminosity ~ 50 pb^{-1}
  - Plenty of interesting data
  - A few interesting (intensity-related) effects
- 50ns run
  - Very useful few days
  - Should allow definition of strategy for 2011 (together with ongoing studies)
- Ion run
  - Very fast switch from p to Pb
  - Quickly up to nominal performance for 2010
- 75 nsec run
  - No e-cloud
  - Interesting mode of operation in 2011