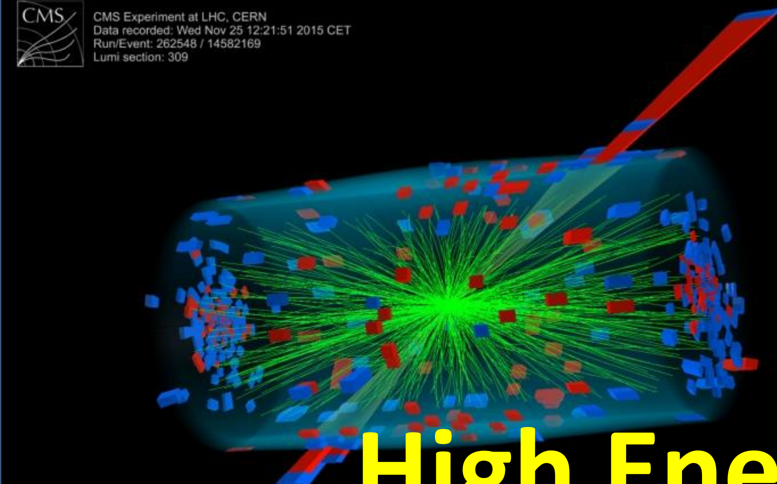
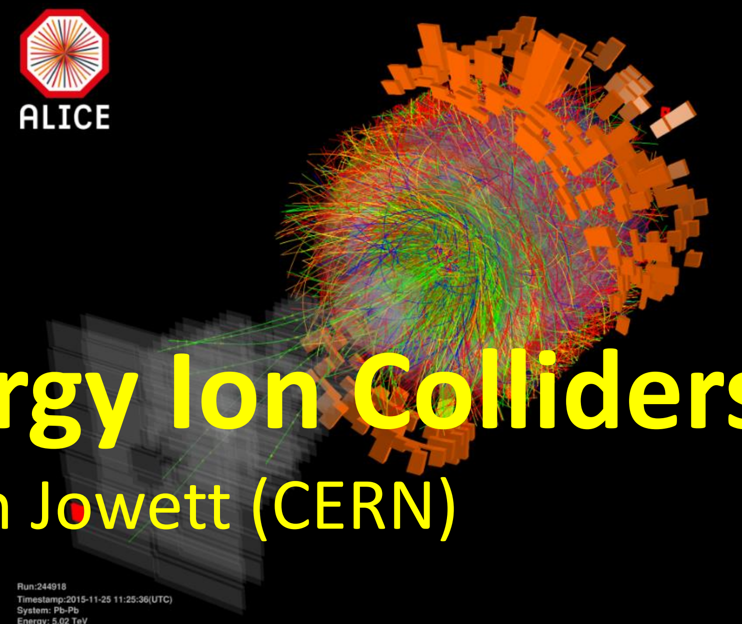
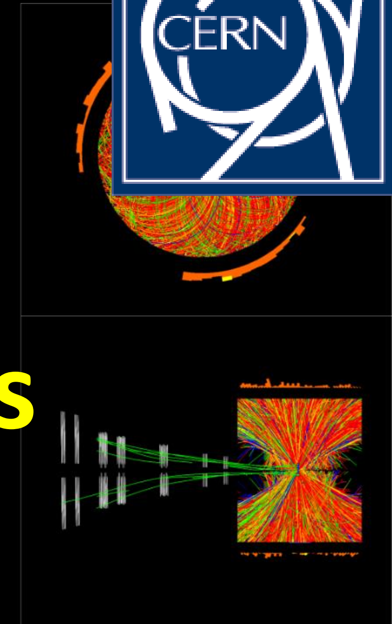
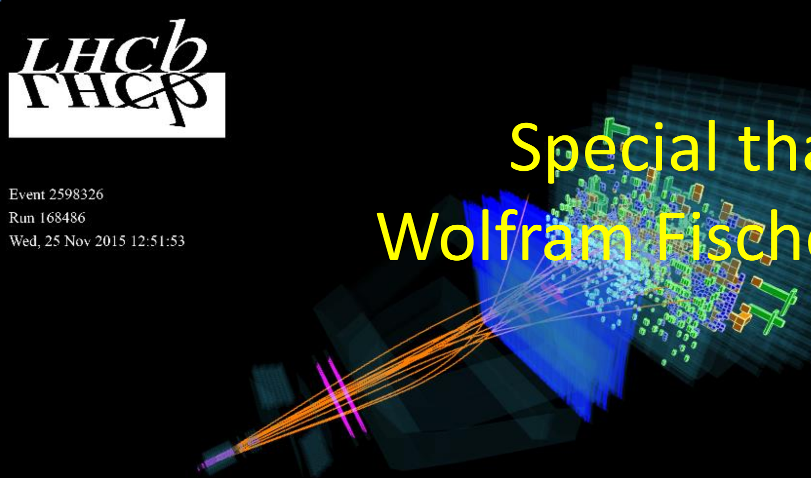






High Energy Ion Colliders

John Jowett (CERN)



Special thanks for material to:
Wolfram Fischer, Michaela Schaumann

Outline

- Some history of hadron colliders
- Basic physics and conventions for ion beams
- Physics of extremely high-energy nuclear collisions
- RHIC
- LHC Pb-Pb collisions
- LHC p-Pb collisions
- Ultimate modes of hadron collider operation
- Brief mention of Electron-Ion Collider

History of hadron colliders in the 20th century

- 1970s:
  - First hadron collider, the ISR at CERN operated
    - Mainly p-p collisions, but also first ppbar, d and α (just a few days)
  - Construction of larger pp collider ISABELLE started
  - But growing conviction that linear e+e- colliders were the future …
- 1980s:
  - Two ppbar colliders, SppS and Tevatron, major discoveries
  - ISABELLE abandoned
  - LHC pp collider feasibility study (1983-4) for late 1990s …
  - UNK pp collider construction (21 km tunnel completed)
  - SSC pp collider, 80 km tunnel construction started
- 1990s:
  - UNK abandoned
  - first ep collider HERA operated
  - SSC abandoned
  - RHIC construction in ISABELLE tunnel
  - LHC pp collider approved, including mention of Pb+Pb for ALICE, CMS experiments

History of hadron colliders in the 21st century

- 2000:
  - RHIC collider at Brookhaven, in ISABELLE tunnel, collides first heavy ions Au+Au, then polarized p+p, many other species, outpouring of discoveries in heavy-ion physics
- 2009-10:
  - LHC first p+p and Pb+Pb collisions … Higgs discovery in 2012
- Now:
  - All (both) hadron colliders in the world have substantial heavy-ion programmes
  - All hadron collider experiments in the world study heavy-ion collisions, transition to precision physics
- Future:
  - Electron-ion collider in USA (the next collider?)
  - Heavy-ion (and p+p) collisions at HE-LHC, SppC and FCC ?

Recall: Luminosity of a hadron collider

$$L = \frac{N^2 k_c f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_c f_0 \gamma}{4\pi\,\varepsilon_n \beta^*} F(\theta_c)$$

Hour glass factor: $F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$

- Parameters in luminosity
  - No. of particles per bunch N
  - No. of bunches per beam k_b
  - No. of bunches collliding at IP k_c
    - ($k_c < k_b$)
  - Relativistic factor γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

Equal amplitude functions:

$\beta_x^* = \beta_y^* = \beta^*$,

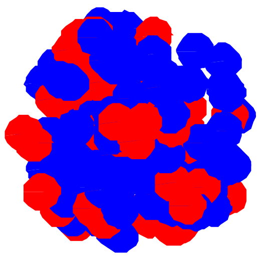
Geometric and normalised emittance:

$$\varepsilon_x^* = \varepsilon_y^* = \varepsilon^* = \frac{\varepsilon_n}{\sqrt{\gamma^2 - 1}}$$

$\Rightarrow$ Round beams at IP:

$$\sigma_x^* = \sigma_y^* = \sigma^* \;;\; \sqrt{\frac{\beta^* \varepsilon_n}{\gamma}}$$

(N.B. LHC uses RMS emittances.)



Mass of ions/nuclei

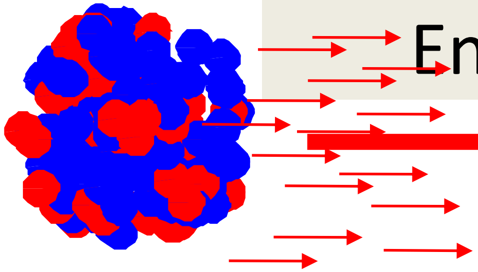
General ion of charge Qe and mass m and nucleon number ("mass number") A.

Mainly collide fully-stripped ions, bare nuclei, where $Q = Z$,
e.g., in LHC we use $^{208}\text{Pb}^{82+}$ with $Z = 82, A = 208$,

$$\begin{aligned} m &= 207.976652071\,\text{u} - 82 m_e \\ &= (193.729 - 82 \times 0.000511)\,\text{GeV} / c^2 \\ &= 193.687 \text{ GeV} / c^2 \end{aligned}$$

N.B. $208 m_p = 195.161 \text{ GeV} / c^2$ is a poor approximation!
For this species the binding energy of the 82 electrons < 1 MeV.

Energy of ions/nuclei and nucleons



Nucleus of charge Ze and mass m and nucleon number ("mass number") A.

Energy and momentum related as square of 4-momentum vector, $P = (E/c, \mathbf{p})$

mass is basic Lorentz-invariant

$$\mathrm{P}^2 = E^2/c^2 - p^2 = m^2c^2$$

Traditionally, in low-energy ion accelerators, the kinetic energy per nucleon is quoted in parameter lists:

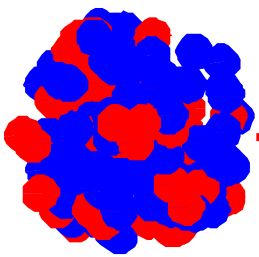
$$E_{Kn} = \frac{\sqrt{\mathrm{p}^2c^2 + m^2c^4} - mc^2}{A} \approx \frac{E}{A} \text{ at high energy,}$$

but this quantity does not appear in any equation of motion!

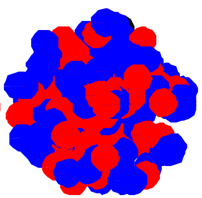
Avoid confusion by never using any kind of "energy per nucleon" in calculations, just quote it at the end. At LHC, we use the conventional, more precise, notations:

$$E \approx pc = \underbrace{7.02\,Z\ \text{TeV}}_{\substack{\text{Energy per charge,}\\ \text{relation to proton energy}}} = \underbrace{2.76\,A\ \text{TeV}}_{\text{Energy per nucleon}} = \underbrace{574\ \text{TeV}}_{\substack{\text{Simply the energy}\\ \text{of the particle,}\\ \text{for all calculations}}}$$

- Luminosities quoted for lead nuclei may seem low compared to pp or e^+e^-
- But comparisons are more meaningful on the basis of nucleon pair luminosities



$$L = 5.0 \times 10^{27} \text{ (Pb)(Pb) cm}^{-2}\text{s}^{-1}$$
$$= 2.2 \times 10^{32} \text{ (nucleon)(nucleon) cm}^{-2}\text{s}^{-1}$$



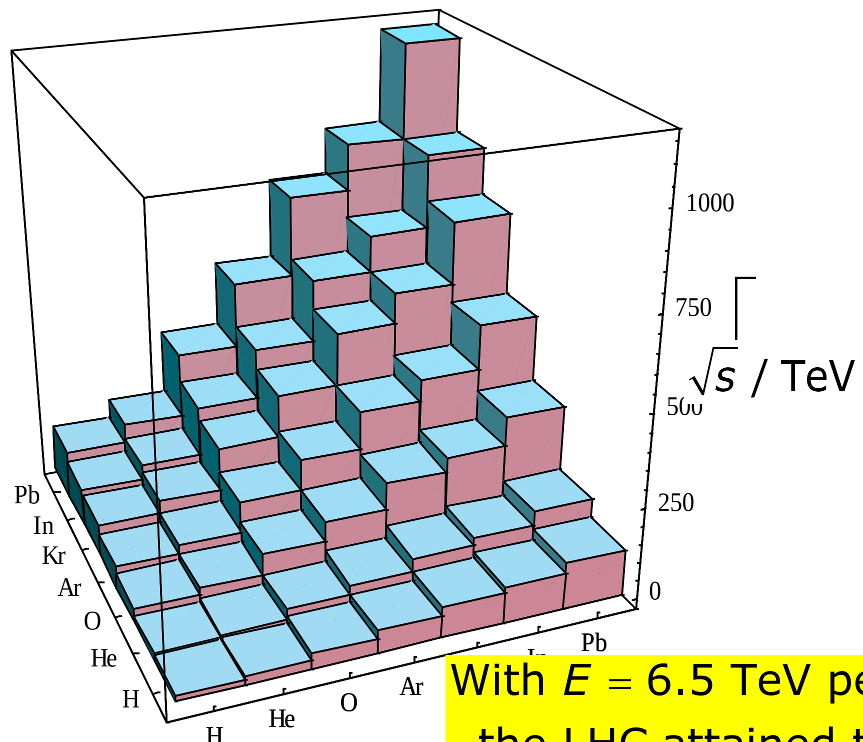
In general case of two different colliding species, the nucleon-nucleon luminosity is defined as

$$L_{NN} = A_1 A_2 L$$

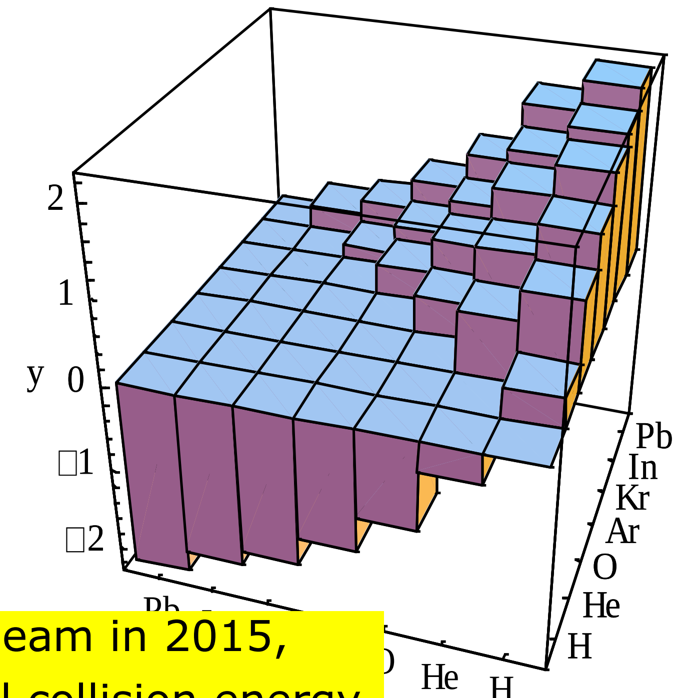
Kinematics of nuclear collisions

Centre-of-mass energy and velocity/rapidity in collisions of nuclei of charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

$$\sqrt{s} = (P_1 + P_2)^2 \approx 2c\, p_p \sqrt{Z_1 Z_2}, \qquad \frac{\mathbf{v}_{\mathrm{CM}}}{c} = \frac{(\mathbf{p}_1 + \mathbf{p}_2)}{c(E_1 + E_2)} \approx \frac{Z_1 - Z_2}{Z_1 + Z_2}, \quad y = \frac{1}{2}\log\frac{Z_1}{Z_2}$$



$p_p = 7\ \mathrm{TeV}/c$

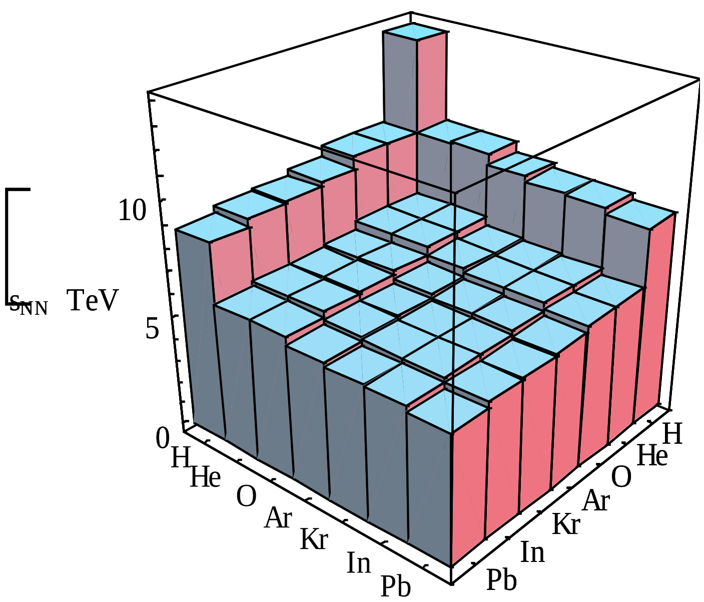


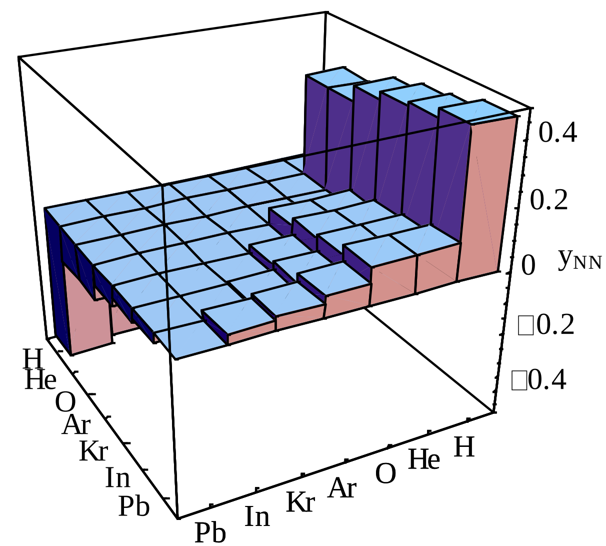
With $E = 6.5$ TeV per beam in 2015, the LHC attained total collision energy $\sqrt{s} > 1000$ TeV $= 1$ PeV in fm^3 volumes.

Kinematics of colliding nucleon pairs

Centre-of-mass energy and velocity/rapidity for nucleon pairs in collisions of ions of charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

$$\sqrt{s_{NN}} \approx 2c\,p_p\sqrt{\frac{Z_1 Z_2}{A_1 A_2}}, \qquad \frac{v_{\mathrm{CMNN}}}{c} \approx \frac{Z_1/A_1 - Z_2/A_2}{Z_1/A_1 + Z_2/A_2}, \qquad y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2}$$





$p_p = 7\,\mathrm{TeV}/c$

Exercise: derive all formulas on this and previous slide.

Sign change w.r.t. CM of whole system.

Ion Collider history to 2014

Table 1. Ion combinations in long and short notation*, and center-of-mass energy ranges per nucleon pair $\sqrt{s_{NN}}$ for ISR [1–3], RHIC [5], and LHC [6]. The symbol ↑ in the short notation indicates spin-polarized beams. Planned extensions are given in square brackets.

Species combination		Nucleon pair center-of-mass energy $\sqrt{s_{NN}}$ (GeV)		
		ISR	RHIC	LHC
$^{1}H^{1+} + ^{1}H^{1+}$				
$^{1}H^{1+} + ^{1}H^{1+}$				
$^{1}H^{1+} + ^{1}\bar{H}^{1+}$				
$^{1}H^{1+} + ^{2}H^{1+}$				
$^{1}H^{1+} + ^{3}He^{2+}$				
$^{1}H^{1+} + ^{4}He^{2+}$				
$^{1}H^{1+} + ^{27}Al^{13+}$				
$^{1}H^{1+} + ^{197}Au^{79+}$				
$^{1}H^{1+} + ^{208}Pb^{82+}$				
$^{2}H^{1+} + ^{2}H^{1+}$				
$^{2}H^{1+} + ^{197}Au^{79+}$				
$^{3}He^{2+} + ^{197}Au^{79+}$				
$^{4}He^{2+} + ^{4}He^{2+}$				
$^{40}Ar^{18+} + ^{40}Ar^{18+}$				
$^{63}Cu^{29+} + ^{63}Cu^{29+}$				
$^{63}Cu^{29+} + ^{197}Au^{79+}$				
$^{197}Au^{79+} + ^{197}Au^{79+}$	Au + Au	—	[5.0] 7.7–200	—
$^{208}Pb^{82+} + ^{208}Pb^{82+}$	Pb + Pb	—	—	2760–3153 [5518]
$^{235}U^{92+} + ^{235}U^{92+}$	U + U	—	192.8	—

*p or $^{1}H^{1+}$ (proton) is the nucleus of the ^{1}H atom (hydrogen); p̄ (p-bar or antiproton) is the antiparticle to p (proton); d or $^{2}H^{1+}$ (deuteron) is the nucleus of the ^{2}H atom (deuterium); h or $^{3}He^{2+}$ (helion) is the nucleus of the ^{3}He atom (helium-3); α or $^{4}He^{2+}$ (alpha) is the nucleus of the ^{4}He atom (helium-4).

Since 2014, LHC has also collided

Pb+Pb at 5.02 (very briefly at 5.13) TeV
p+Pb, Pb+p at 8.16 TeV
Xe+Xe at 5.44 TeV

RHIC has also collided
p+Au, p+Al, …
and is about to collide
Zr, Ru, more Au

From W. Fischer, J.M. Jowett, "Ion Colliders"

Reviews of Accelerator Science and Technology
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Hot and dense matter in Pb-Pb collisions at LHC

Exercise: check all these numbers

Quark Gluon Plasma (QGP) created in Pb-Pb collisions.

Nuclear fusion temperature at core of sun $T_{\text{sun}} = 1.6 \times 10^7$ K

Temperature of QGP (thermal photon spectrum measured by ALICE, the highest temperature ever measured in a lab):

$T_{\text{ALICE}} = 304$ MeV / $k_B = 3.5 \times 10^{12}$ K=200,000 T_{sun}

Energy density in QGP: $u_{\text{QGP}} \approx 15$ GeV/fm^3

Total electrical energy generated in Europe in a year: $U_{\text{Ey}} = 3.6 \times 10^{12}$ kWh

Imagine pumping all that energy into as sphere of radius r and calculate the value of r needed to achieve the same energy density

$$\frac{U_{\text{Ey}}}{(4/3)\pi r^3} = u_{\text{QGP}} \Rightarrow r = 1.1\ \mu\text{m}$$, a speck of very fine dust, mass 140 kg

Density = $10^{15} \times$ (density of metallic Pb)

World annual electrical energy production ~ 1 mole of LHC Pb-Pb collisions

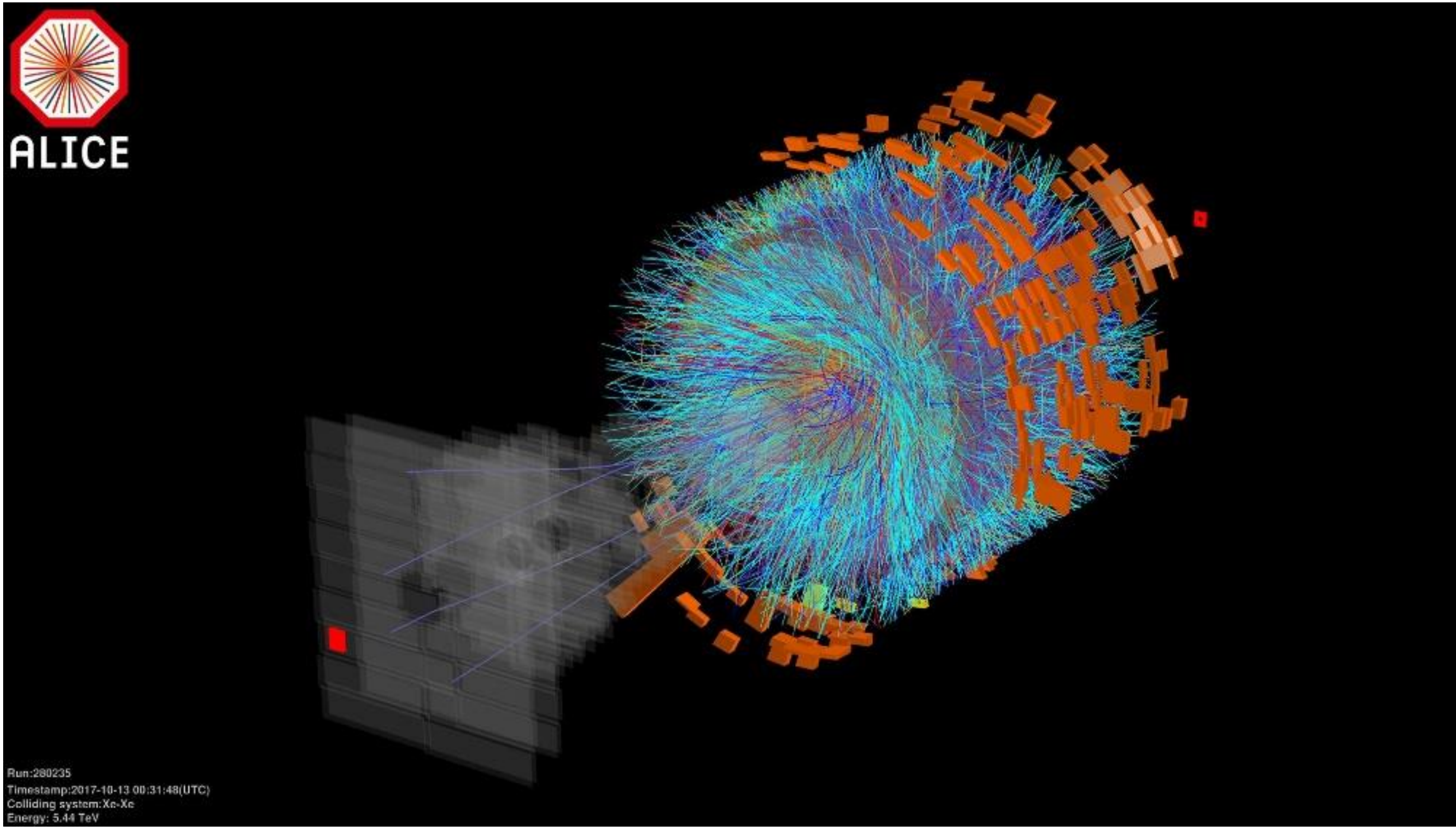
LHC is an extraordinary concentrator of energy.

“Heavy-ion” physics – what is it about?

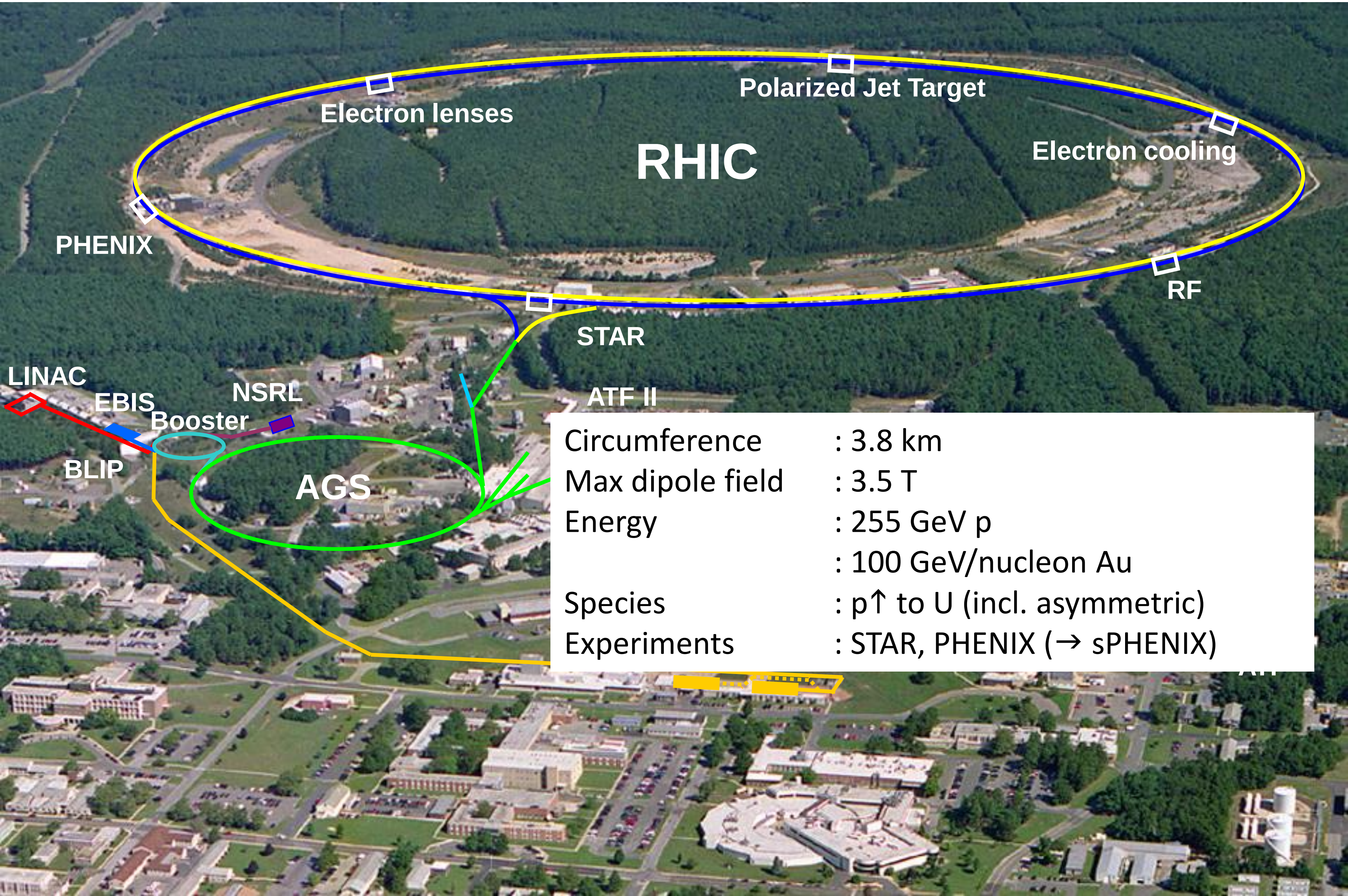
- Unimaginably extreme conditions, similar to those that prevailed in the first microseconds of cosmic history, nuclear matter as we know it does not exist.
- Above a temperature of T_c=160/k_B MeV, quarks and gluons inside the nucleons (i.e., protons or neutrons) are deconfined, forming the Quark-Gluon Plasma (QGP).
- This occupies a volume that is nevertheless large enough to be considered thermalised bulk matter with meaningful thermodynamic and hydrodynamic properties such as temperature, flow and viscosity.
- Indeed, Quantum Chromodynamics (QCD) is the only sector of the Standard Model of particle physics whose thermodynamical behaviour can be directly studied in the laboratory.
- Many-body properties of a non-Abelian quantum field theory.
- The LHC experiments have confirmed the discovery at RHIC that this new state of matter is the most nearly perfect liquid, with the lowest viscosity, found in Nature.
- As it expands and cools, it condenses back into a hadron gas.
  - From the distributions of hadrons emerging from this ``freeze-out'' stage, the experiments can infer many of the the properties of the QGP.
  - Further information is carried by muons and photons.
  - ``Soft'' physics of particles produced with low transverse momenta Is well-modelled by relativistic viscous hydrodynamics.
- Proton-nucleus and (rare) proton-proton collisions have been found to exhbit apparent collective effects despite small system size – current hot topic.

- Nuclear collisions *also* allow experimentation with extreme electromagnetic fields (later).

Xe-Xe collision in LHC, 13 October 2017

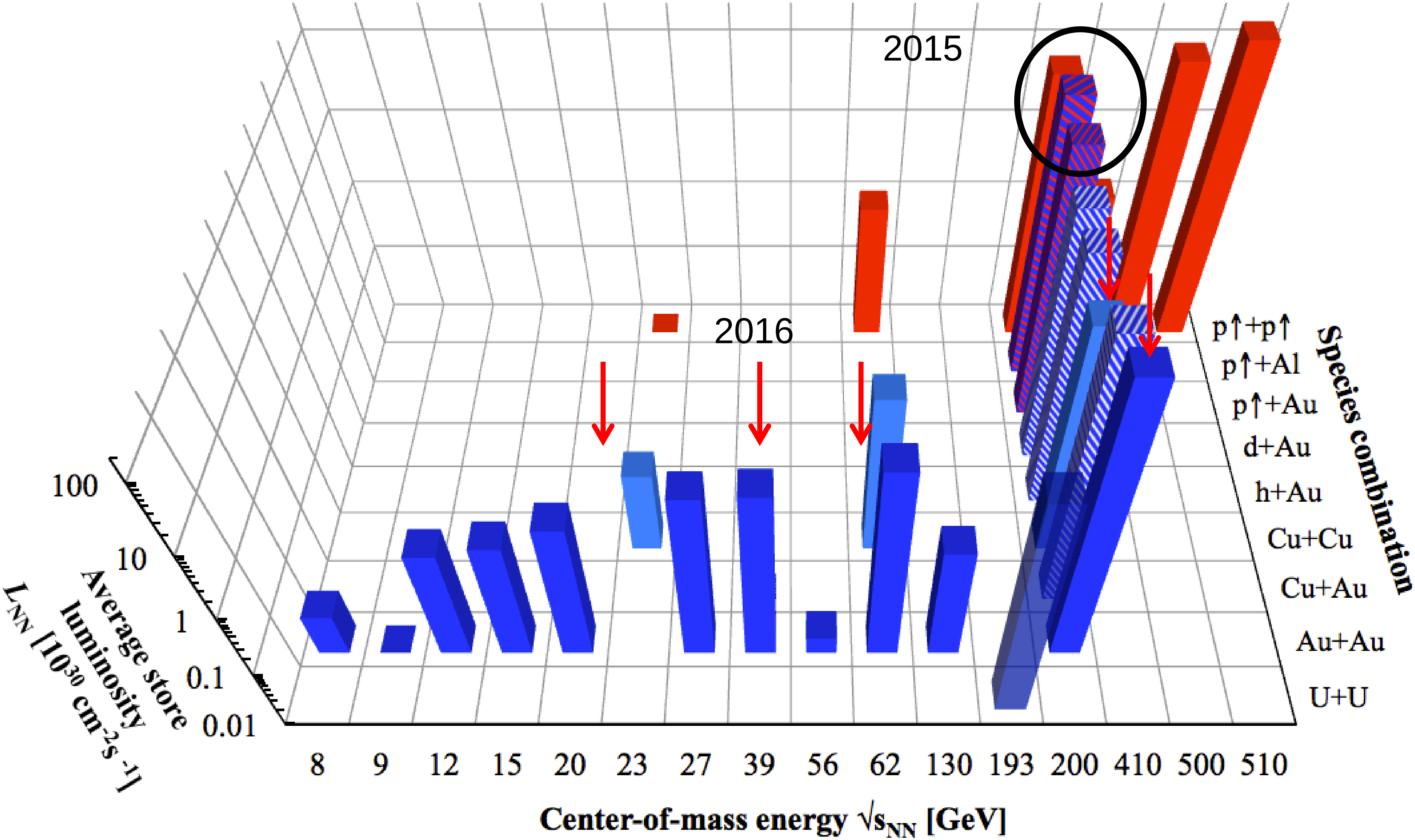


Relativistic Heavy Ion Collider – main parameters



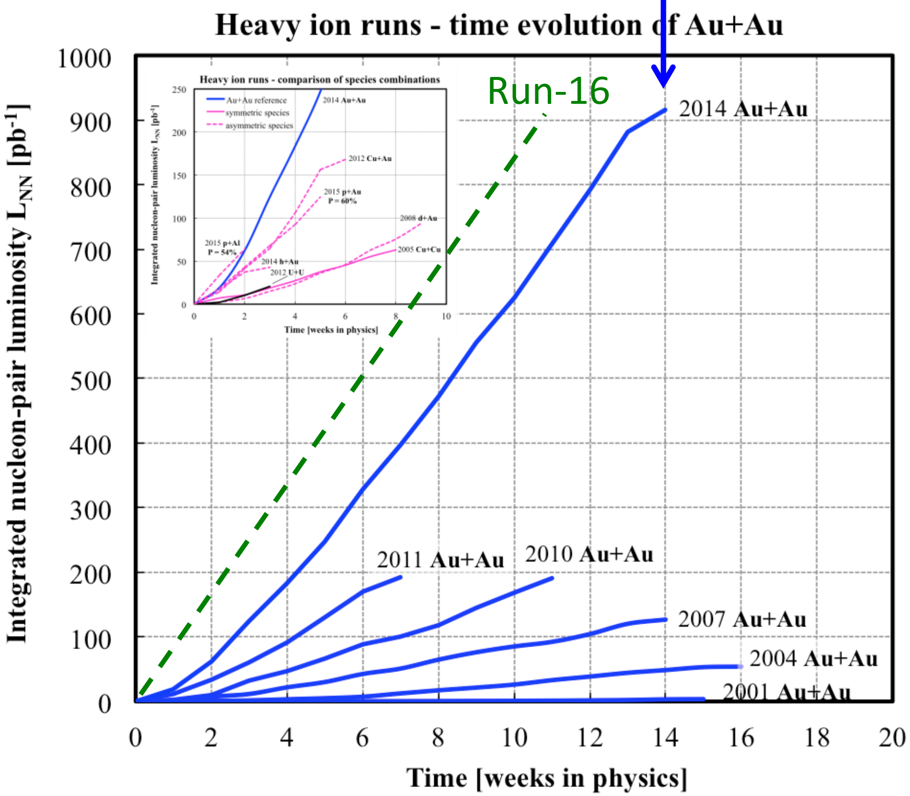
Circumference	: 3.8 km
Max dipole field	: 3.5 T
Energy	: 255 GeV p
	: 100 GeV/nucleon Au
Species	: p↑ to U (incl. asymmetric)
Experiments	: STAR, PHENIX (→ sPHENIX)

RHIC – all running modes 2001 to 2015

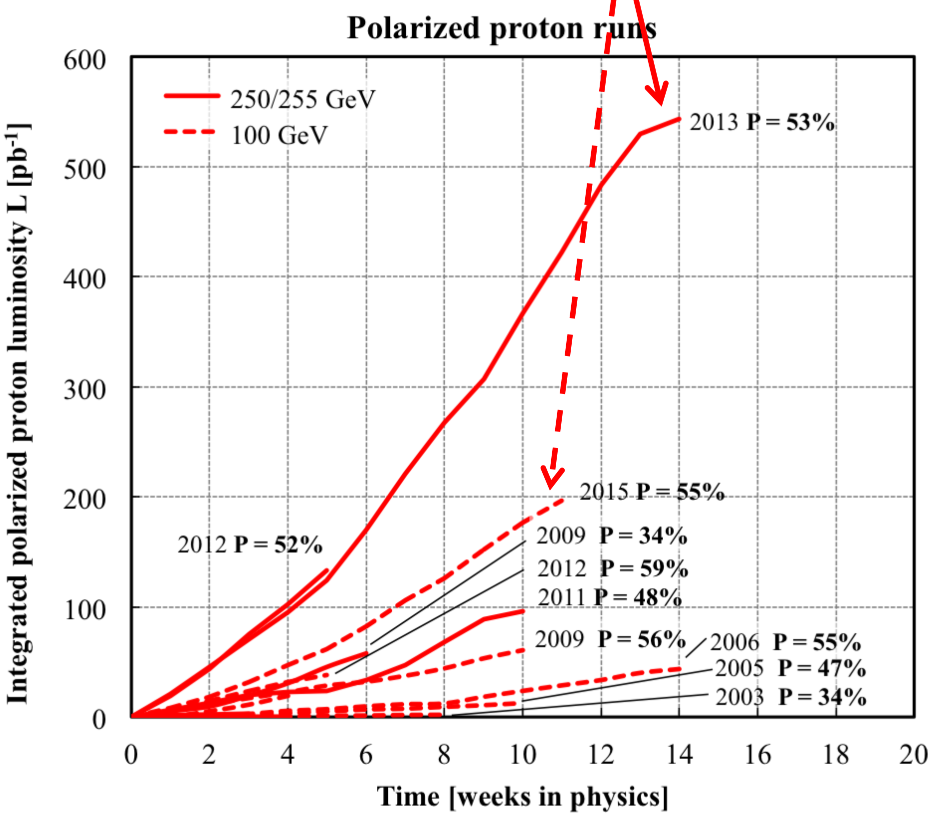


Delivered Integrated Luminosity and Polarization

Run-14 Au+Au luminosity exceeds all previous Au+Au runs combined

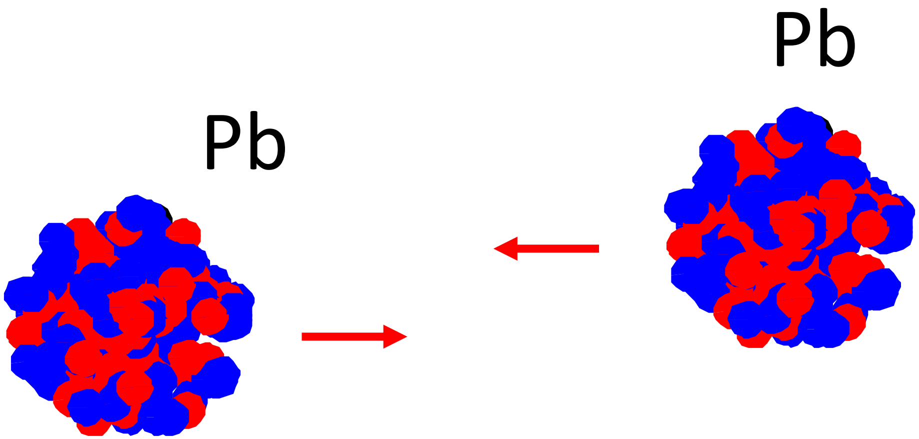


Run-13 p+p luminosity exceeds all previous p+p runs combined,
Run-15 all previous 100 GeV runs



<u>Nucleon-pair luminosity</u>: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

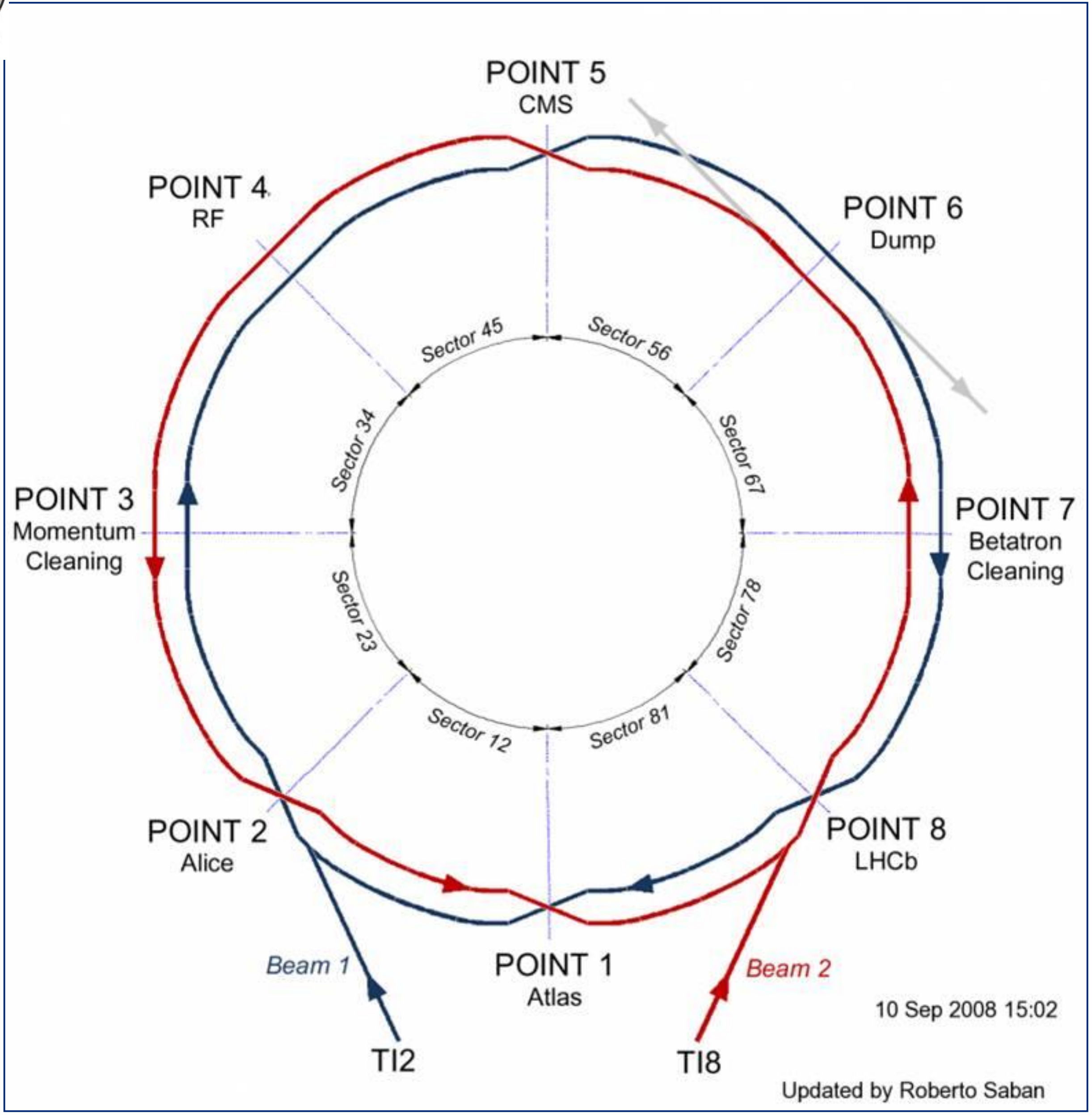
Dramatic increase in performance as a result of R&D, capital projects, Accelerator Improvement Projects, and replacement of obsolete technology



LEAD-LEAD COLLISIONS AT LHC

"Future collider" for many years still

LHC orientation

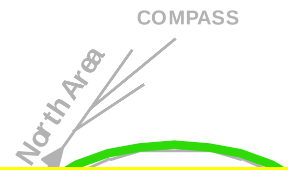


Four large and highly capable heavy-ion physics experiments:
ALICE, CMS
Then ATLAS
LHCb since 2012

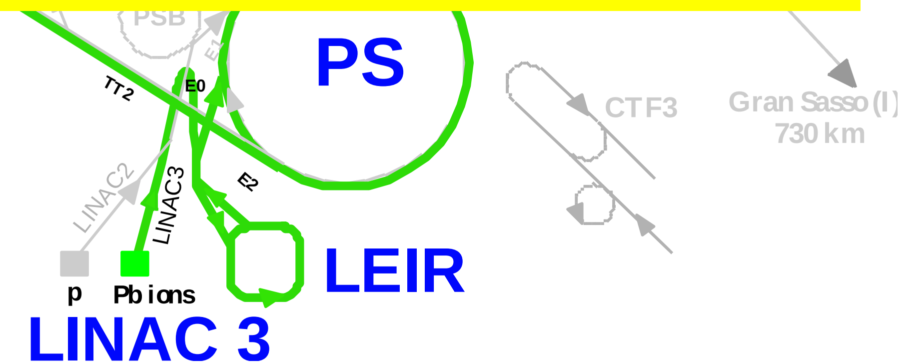
Also LHCf (cosmic ray physics).

LHC Ion Injector Chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR inject
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and coo
  - Prepare bunch struc
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

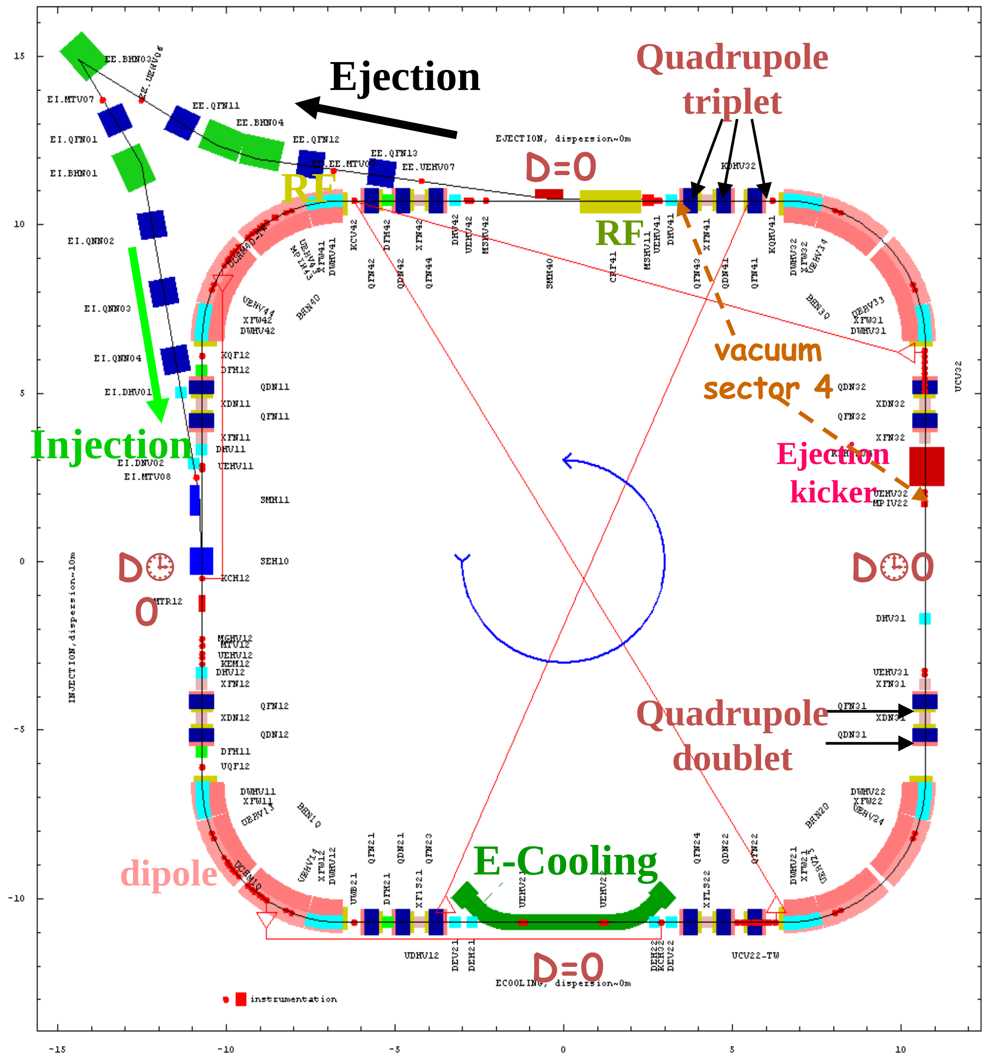


I-LHC construction and commissioning project (2003-2010) successfully concluded.
Vital role in creating the high brightness nuclear beams needed by LHC (vs. fixed target).
Already delivered “Early” beam with parameters significantly beyond design in 2010.
Mostly commissioned for more complex “Nominal” beam.



LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25p m (1/8 PS)
- Multiturn injection into horizontal+vertical+longitudinal phase planes
- Fast Electron Cooling : Electron current from 0.5 to 0.6 A with variable density
- Dynamic vacuum (NEG, Au-coated collimators, scrubbing)



LHC Pb Injector Chain:
Design Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	Linac 3 →(4)	LEIR →	PS →(13,12,8)	SPS →(12)	LHC
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^9$	$1.15\ 10^9$ [1])	$9\ 10^8$	$4.8\ 10^8$	$\le 4.7\ 10^9$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^9$**	**$1.15\ 10^9$**	**$2.25\ 10^8$**	**$1.2\ 10^8$**	**$9\ 10^7$**	**$7\ 10^7$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

Stripping foil

[1] 50 eμA$_e$ x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons,

$$\varepsilon^* \equiv \varepsilon_n = \sqrt{\gamma^2 - 1}\,\varepsilon_{x,y} \text{ is : invariant in ramp.}$$

Design intensity now exceeded by factor 3 !!

LHC Design Parameters for Pb-Pb (~2001)

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$cm^{-2} s^{-1}$	$\sim 5 \times 10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		$\mathbf{7 \times 10^7}$	$\mathbf{7 \times 10^7}$
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

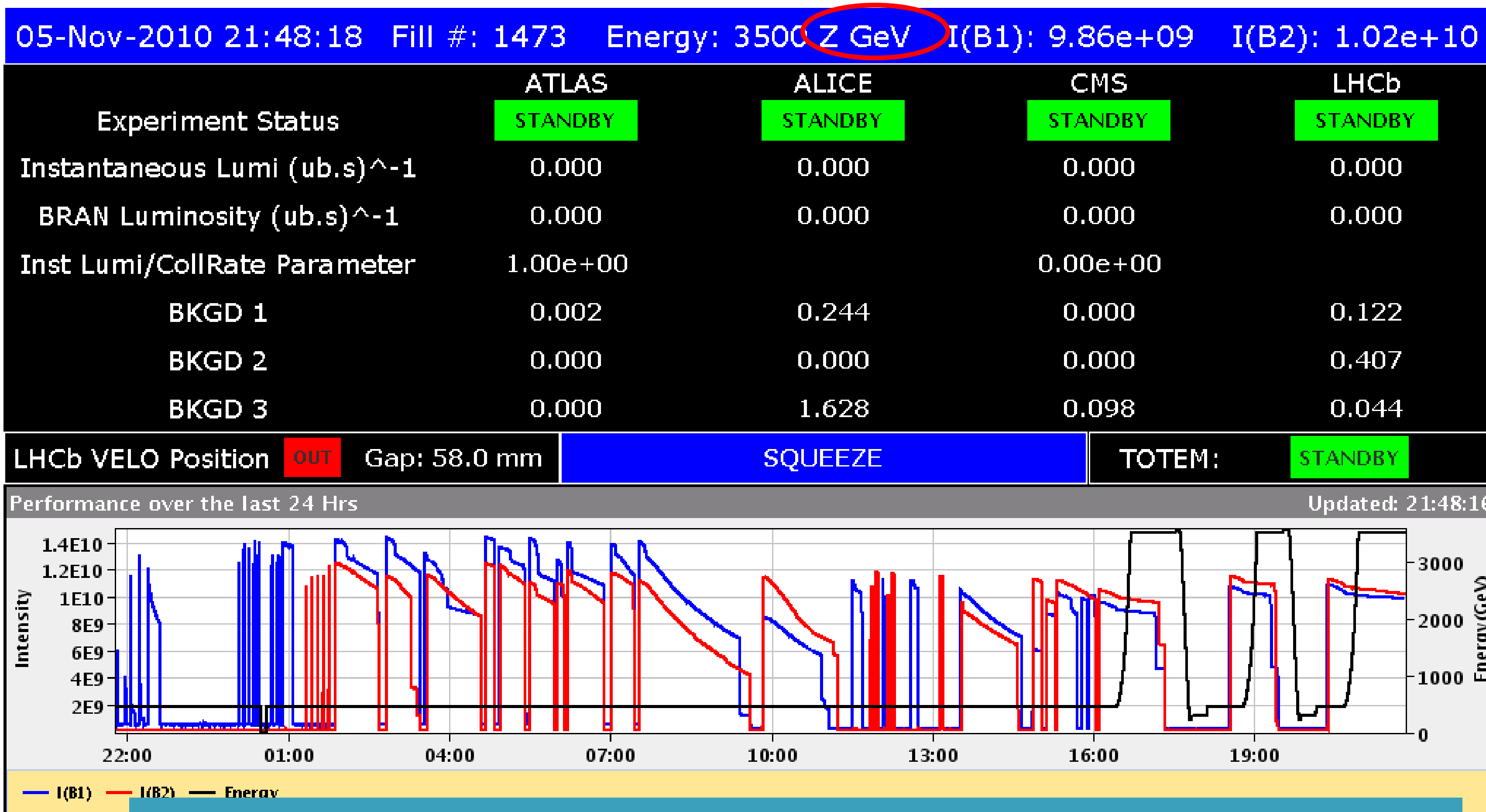
At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

Design performance now far exceeded.

Single-particle dynamics, beam optics

- Exercise: starting from the Lorentz force equation and introducing suitable rescalings of the time variable, demonstrate the equal rigidity principle, that particles of different electric charge Z, but equal *p/Z* can circulate on the same orbits in a static magnetic field depending only on position.
- In practice, this tells us that, if we have commissioned the closed orbit and optics of a collider ring for one (non-radiating) species, it should work for another species of the same rigidity *except for any electric or time-varying magnetic fields. Typically an adjustment of the RF frequency and injection timing is sufficient for the latter.*

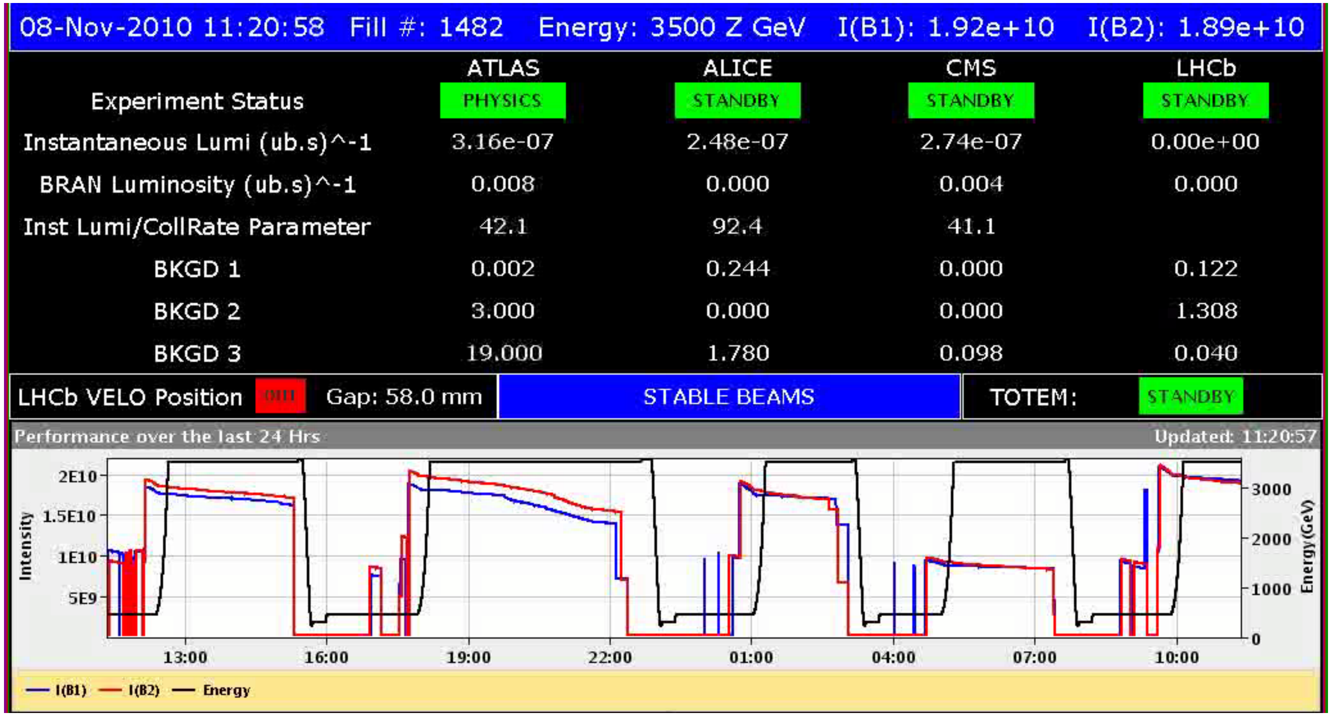
Heavy Ion Run: first 24 h, Thu-Fri 4-5 Nov 2010



Beam 1
Circ.
& Captu

Rapid commissioning plan exploited established proton cycle to speed through initial phase of magnetic setup (injection, ramp, squeeze) . Collision crossing angles and collimation conditions different.

Monday morning: First Stable Beams for Pb-Pb



First stable beam with 2 bunches/beam (1 colliding)

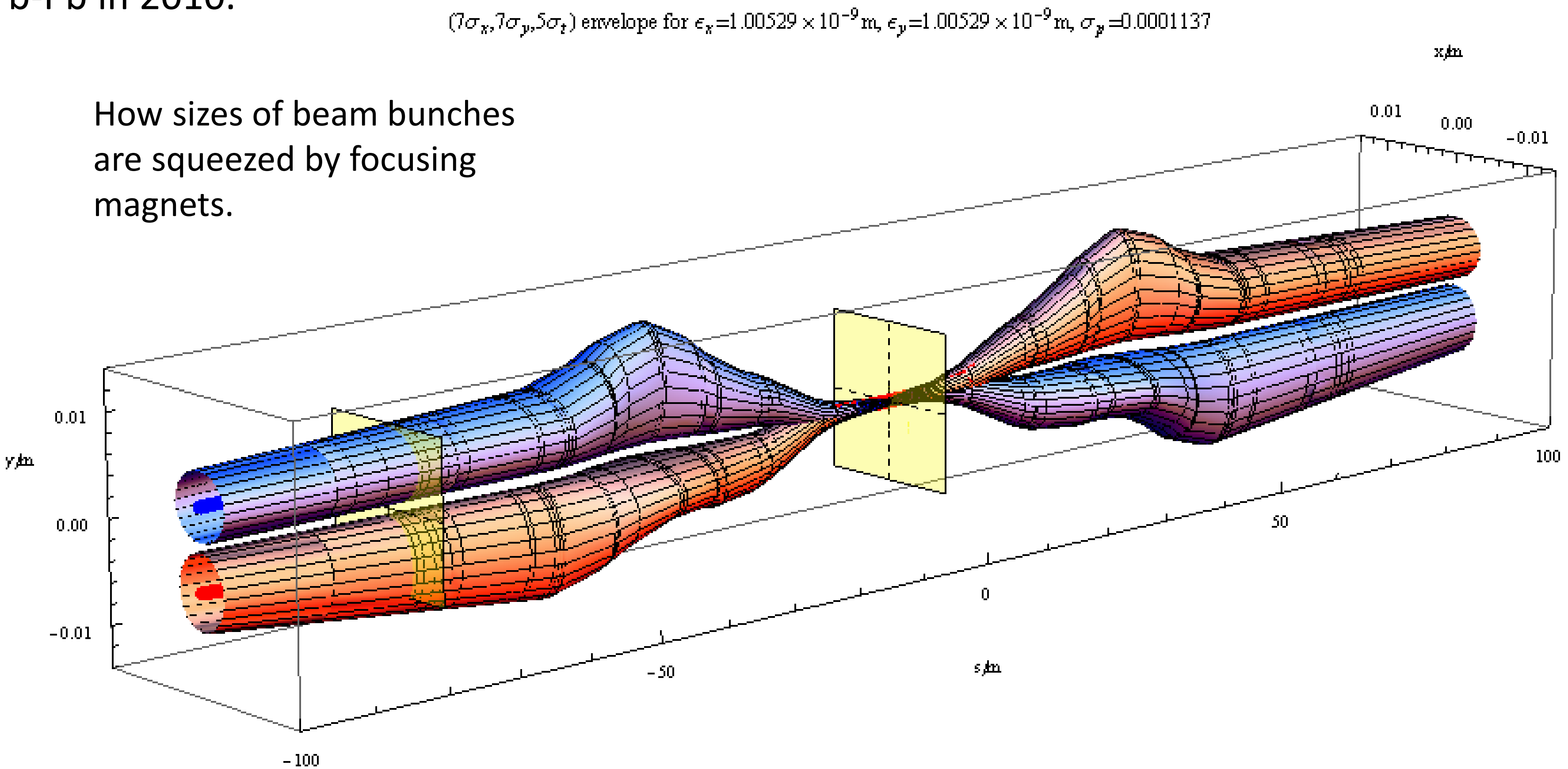
Later same day, 5 bunches/beam, then increased on each fill: 17, 69, 121
Factor 100 in peak luminosity within 6 days.
Many interesting new RF manipulations in LHC in first 2 weeks.
Ion injectors exceeded design intensity/bunch by 70%.

In later Pb-Pb runs, LHC optics commissioning became so efficient that we diverged more and more from the p-p optics.
In 2018, we are preparing a completely new variant of the optics.

Beam envelopes around ALICE experiment

Collision conditions for Pb-Pb in 2010.

How sizes of beam bunches are squeezed by focusing magnets.



Zero crossing angle at IP (external crossing angle compensates ALICE spectrometer magnet bump). Beam pipe is about twice transverse size of box.

Where is the new beam physics?

- Optics etc, mostly similar to other beams
- Charge per bunch is usually ~10% of proton bunches
  - Impedance driven collective effects, generally not a problem
  - Traditional beam-beam effects from collective fields also weak.
  - Space charge in lower energy machines is an exception
- However charge per particle is up to two orders of magnitude higher than protons and most of the interesting beam physics of nuclear beams is due to this:
  - IBS
  - New beam-beam effects from ultra-peripheral nuclear collisions – see later

Intra-beam scattering (IBS)

- Detailed theory covered elsewhere in CAS

Intrabeam scattering. The emittance growth rates due to intrabeam scattering can be written as [37]

$$\frac{d}{dt}\begin{pmatrix}\epsilon_x\\ \epsilon_y\\ \epsilon_s\end{pmatrix} = \frac{N_b c}{\gamma \epsilon_x \epsilon_y \epsilon_s}\,\frac{r_0^2 Z^4}{A^2}\begin{pmatrix}F_x\\ F_y\\ F_s\end{pmatrix}, \qquad (7)$$

where the functions $F_{x,y,s}$ are functions of the lattice parameters and beam sizes averaged over the machine circumference ($F_{x,y,s}$ also have some γ dependence) [37]. Intrabeam scattering is particularly strong for ions with high charge states Z. For heavy ions at the end of the RHIC accelerator chain, the factor $N_b Z^4/A^2$ is typically an order of magnitude larger than that for protons. As with space charge, a low charge state Z is preferred at low energies to minimize intrabeam scattering effects.

Always an important source of emittance growth times ~ few hours in heavy-ion colliders, particularly at injection.

Effect can be modelled with non-linear differential equations (various approaches to calculating the *F* functions) or various types of multi-particle simulation.

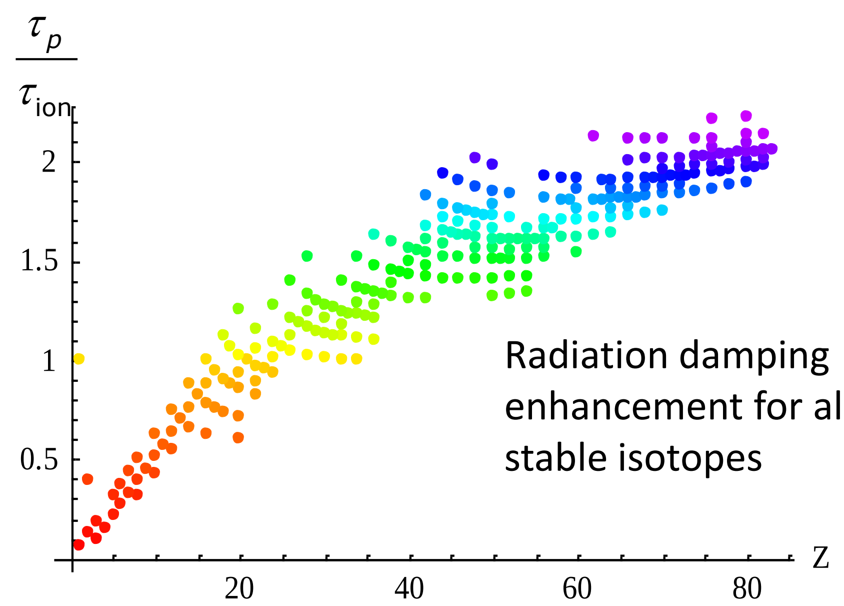
In either approach, equations are coupled to evolution of intensity (luminosity burn-off, see later, other losses), radiation damping, etc.

Synchrotron Radiation from Pb nuclei

- Nuclear charge radiates *coherently* at relevant wavelengths (~ nm)
- Scaling with respect to protons *in same ring, same magnetic field*
  - Radiation damping for Pb is *twice as fast as for protons*
    - Many very soft photons
    - Critical energy in visible spectrum
- In LHC at 7 Z TeV, transverse emittance damping time of 12.6 h can be fast enough to overcome IBS at full energy and intensity

$$\frac{U_{\rm ion}}{U_{\rm p}} \simeq \frac{Z^6}{A^4} \simeq 162, \qquad \frac{u^c_{\rm ion}}{u^c_{\rm p}} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

$$\frac{N_{\rm ion}}{N_{\rm p}} \simeq \frac{Z^3}{A} \simeq 2651, \qquad \frac{\tau_{\rm ion}}{\tau_{\rm p}} \simeq \frac{A^4}{Z^5} \simeq 0.5$$



Lead is (almost) best, deuteron is worst.

Beam instrumentation

- Low charge/bunch aas a major concern for LHC
  - BPMs intensity threshold – no problem in the end
  - Emittance: harder than protons
    - WS: Wire scanner at low energy and intensity – best absolute calibration
    - BSRT: synchrotron light from nuclei appeared in first ramp (world first!), only bunch-by-bunch – typical large spread in emittance set in at injection
    - Beam-gas ionisation (BGI) monitor should provide continuous measurement of average emittance, being resolved

Meet the real Dr Strangelove

Had Edward Teller, the father of the H-bomb, trusted the Russians the cold war might have ended sooner, writes Peter Goodchild

Peter Goodchild
Thu 1 Apr 2004 02.35 BST

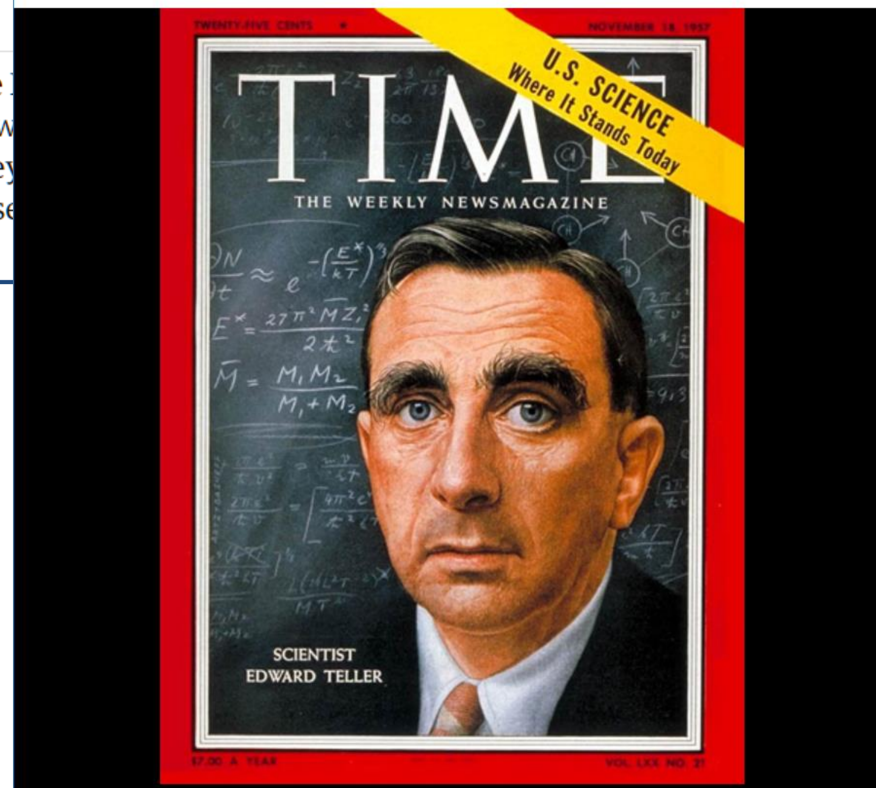
https://www.theguardian.com/science/2004/apr/01/science.research1

I first met Edward Teller, the Hungarian-born physicist and father of the I while researching a television series about Robert Oppenheimer. Teller w as the embodiment of Dr Strangelove, the eponymous scientist in Stanley Kubrick's classic black comedy, and though he hated the association, it se appropriate enough.

TIME

Edward Teller | Nov. 18, 1957

PREVIOUS WEEK'S COVER | FOLLOWING WEEK'S COVER



Cover Credit: BORIS ARTZYBASHEFF

But still giving talks 30 years later …

Nuclear Instruments and Methods in Physics Research B24/25 (1987) 1–2 1
North-Holland, Amsterdam

Keynote address

REMARKS ABOUT FIELDS OF HIGH INTENSITY

Edward TELLER

Lawrence Livermore National Caboratory, P.O. Box 808, L-O, Livermore, CA 94550, USA

At high field strength any known material will break down by the production of electrons and massive production of pairs will occur. This phenomenon is discussed when heavy ions of $\gamma \approx 100$ c approach to within one nuclear radius, pair production involving electrons and mesons must be between the nuclei might be coupled to pairs of magnetic monopoles.

(SSC), protons of $\gamma = 20000$ meet. In the Relativistic Heavy Ion Collider (RHIC), two uranium nuclei with $\gamma = 100$ may interact. Much higher frequencies and energies are reached in the SSC. The maximum field strength is also somewhat higher in the SSC. But in the SSC the duration of the encounter τ is so short that the dependence of the factor $(\tau\omega_m)^2$ limits the number of pairs that one can expect.

The case of overlapping fields for uranium nuclei has been discussed by Gould [1] and Weiss [2] when two nuclei moving with $\gamma = 100$ in opposite directions collide. They have shown that there is ample production of electron–positron pairs, production of μ-mesons and even some production of τ-mesons. This is due to the fact that the electric fields add while the magnetic fields subtract so that for a short period the invariant $\mathscr{E}^2 - \mathscr{H}^2$ becomes very large.

One should also notice that pair production will also occur when two uranium nuclei miss each other so that the nearest approach of the two surfaces is of the order of 10^{-12} cm. Then between the two nuclei the electric fields will subtract and the magnetic fields will add. $\mathscr{E}^2 - \mathscr{H}^2$ will become equally large (in absolute values). If τ is not much more than $\hbar/mc^2$ pair production can occur. The approximate upper limit of the rest energy is

$$mc^2 = \frac{\hbar c \gamma}{r_N},$$

where r_N is the radius of the colliding nuclei.

: 100 GeV at LHC →

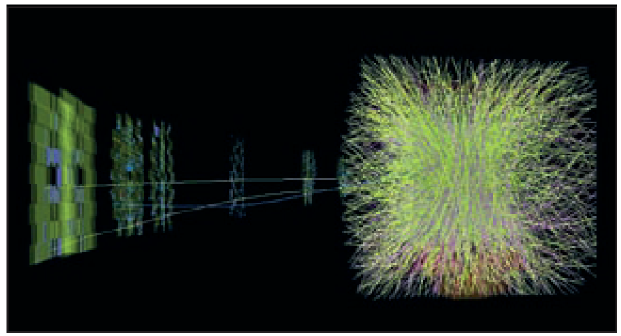
Pb-Pb collisions produce both the messiest (high-multiplicity) and the cleanest events at the LHC.

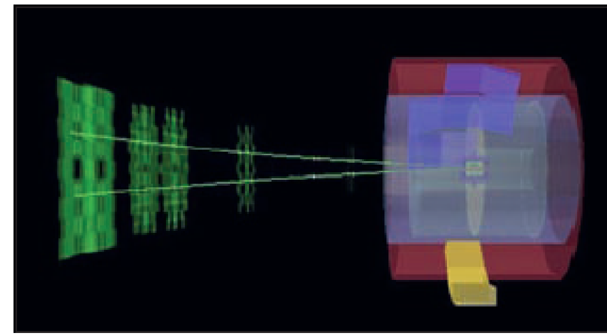
Using the LHC as a photon collider

ALICE

The protons and nuclei accelerated by the LHC are surrounded by strong electric and magnetic fields. These fields can be treated as an equivalent flux of photons, making the LHC the world's most powerful collider not only for protons and lead ions but also for photon–photon and photon–hadron collisions (*CERN Courier* October 2007). This is particularly so for beams of multiply charged heavy-ions, where the number of photons is enhanced by almost four orders of magnitude compared with the singly charged protons (the photon flux is proportional to the square of the ion charge).

The ALICE collaboration has recently taken advantage of this effect in a study of coherent photoproduction of J/ψ mesons in lead–lead (PbPb) collisions. The J/ψ is detected through its dimuon decay in the muon arm of the ALICE detector, which also provides the trigger for these events. The relevant collisions typically occur at impact





J/ψ candidates in a central PbPb collision (left) and in an ultra-peripheral collision (right).

events (see figure) stands in sharp contrast to central heavy-ion collisions, where thousands of particles are produced.

These interactions carry an interesting message about the partonic substructure of heavy nuclei. Exclusive photoproduction of heavy vector mesons is believed to be a good probe of the nuclear gluon distribution. The cross-section measured in a heavy-ion collision Pb+Pb → Pb+Pb+J/ψ is a convolution of the equivalent photon spectrum with the photonuclear cross-section for γ+Pb → J/ψ+Pb. The latter exchange of two gluons.

At the rapidities (y around 3) studied in ALICE, J/ψ photoproduction is sensitive mainly to the gluon distribution at values of Bjorken-x of about 10^{-2}. Although the experimental error is rather large, the conclusion from ALICE is that the data favour models that include strong modifications to the nuclear gluon distribution, known as nuclear shadowing.

● Further reading

B Abelev *et al.* (ALICE collaboration) 2012

Photon-photon processes at the collision point

$$\text{BFPP:}\quad {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$
$$\sigma = 281\ \text{b},\quad \delta = 0.01235$$

$$\text{EMD1:}\quad {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + \text{n},$$
$$\sigma = 96\ \text{b},\quad \delta = -0.00485$$

$$\text{EMD2:}\quad {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{206}\text{Pb}^{82+} + 2\text{n},$$
$$\sigma = 29\ \text{b},\quad \delta = -0.00970$$

Strong luminosity burn-off of beam intensity.

Each of these makes a secondary beam emerging from the IP with rigidity change that may quench bending magnets.

$$\delta = \frac{1 + \Delta m / m_{\text{Pb}}}{1 + \Delta Q / Q} - 1$$

Discussed for LHC since Chamonix 2003 … see several references.

Hadronic cross section is 8 b (so luminosity debris contains much less power).

Cross-section for BFPP

Involved topic, numerous references …

Extrapolation from SPS measurements at lower energy in Grafström et al, PAC99

Our main reference:

Meier et al, Phys. Rev. A, **63**, 032713 (2001), calculation for Pb-Pb at LHC energy

JMJ @ Chamonix 2003

TABLE I. Cross section for the bound-free pair production of *one* ion *only* for different bound states are given for RHIC and LHC conditions for different ion-ion collisions. Also given are the parameters A and B to be used in Eq. (28) for the dependence on the Lorentz factor γ_c.

Bound state	σ(RHIC) (b)	σ(LHC) (b)	A (b)	B (b)
^{1}H-^{1}H	$\gamma_c=250$	$\gamma_c=7500$		
$1s$	2.62×10^{-11}	4.25×10^{-11}	5.36×10^{-12}	-3.40×10^{-12}
$2s$	3.28×10^{-12}	5.31×10^{-12}	6.70×10^{-13}	-4.23×10^{-13}
$2p(1/2)$	3.75×10^{-17}	6.10×10^{-17}	7.73×10^{-18}	-5.20×10^{-18}
$2p(3/2)$	1.47×10^{-17}	2.41×10^{-17}	3.10×10^{-18}	-2.42×10^{-18}
$3s$	9.70×10^{-13}	1.57×10^{-12}	1.98×10^{-13}	-1.26×10^{-13}
^{20}Ca-^{20}Ca	$\gamma_c=125$	$\gamma_c=3750$		
$1s$	1.61×10^{-2}	2.92×10^{-2}	3.84×10^{-3}	-2.48×10^{-3}
$2s$	2.00×10^{-3}	3.62×10^{-3}	4.78×10^{-4}	-3.07×10^{-4}
$2p(1/2)$	1.39×10^{-5}	2.52×1[illegible]	[illegible]	[illegible]
$2p(3/2)$	3.63×10^{-6}	6.70×1[illegible]	[illegible]	[illegible]
$3s$	5.90×10^{-4}	1.07×1[illegible]	[illegible]	[illegible]
^{47}Ag-^{47}Ag	$\gamma_c=109$	γ_c=32[illegible]		
$1s$	3.51	6.46[illegible]	[illegible]	[illegible]
$2s$	4.33×10^{-1}	7.98×1[illegible]	[illegible]	[illegible]
$2p(1/2)$	2.81×10^{-2}	5.21×1[illegible]	[illegible]	[illegible]
$2p(3/2)$	3.80×10^{-3}	7.16×1[illegible]	[illegible]	[illegible]
$3s$	1.26×10^{-1}	2.34×1[illegible]	[illegible]	[illegible]
^{79}Au-^{79}Au	$\gamma_c=100$	γ_c=30[illegible]		
$1s$	94.9	176	23.8	−14.7
$2s$	12.1	22.4	3.04	−1.87
$2p(1/2)$	3.62	6.77	9.27×10^{-1}	-6.56×10^{-1}
$2p(3/2)$	2.10×10^{-1}	4.01×10^{-1}	5.62×10^{-2}	-4.93×10^{-2}
$3s$	3.46	6.40	8.67×10^{-1}	-5.34×10^{-1}
^{82}Pb-^{82}Pb	$\gamma_c=99$	$\gamma_c=2957$		
$1s$	121	225	30.4	−18.7
$2s$	15.5	28.8	3.91	−2.39
$2p(1/2)$	5.21	9.76	1.34	-9.46×10^{-1}
$2p(3/2)$	2.78×10^{-1}	5.33×10^{-1}	7.50×10^{-2}	-6.61×10^{-2}
$3s$	4.42	8.20	1.11	-6.79×10^{-1}
^{92}U-^{92}U	$\gamma_c=97$	$\gamma_c=2900$		
$1s$	263	488	66.0	−39.0
$2s$	34.4	63.7	8.63	−5.10
$2p(1/2)$	16.7	31.3	4.30	−3.00
$2p(3/2)$	6.77×10^{-1}	1.30	1.83×10^{-1}	-1.63×10^{-1}
$3s$	9.67	17.9	2.43	−1.44

Electron can be captured to a number of bound states, not only 1s.

Concern about Pb-Pb at LHC

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 459 (2001) 51–57

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

Localized beampipe heating due to e^- capture and nuclear

Lawrence Ber

Received 1

Abstract

At heavy ion colliders, two
one of the nuclei, and photon
mass ratio by well-defined an
their energy in a localized reg
collider optics. For medium
more than an order of mag
inadequate. The altered-rigid
and used for fixed target exp

PACS: 29.20.-c; 07.89. + b; 25.20

Keywords: Ion colliders; Beam l

At RHIC, the local heating due to altered-rigidity beams is within the available cooling capacity. At the LHC, these altered rigidity beams have higher powers, up to 36 W. At the same time, the target regions are shorter than at RHIC, and the cooling capacities are somewhat lower, because the LHC uses supercooled magnets. With niobium beams, the expected heating is 3.2 W/m, 16 times the expected beam heat load of 0.2 W/m. For lead, the 'standard' ion choice, the heating is 2.6 W/m, 13 times the expected load.

These loads are close to the expected quench limit of 8 W/m. When the detailed distribution of energy deposition is considered, electron capture from either lead or niobium beams might deposit enough energy to cause a magnet quench. With GDR, the heat loads are lower, but may be problematic for niobium and calcium beams.

These estimates are based on back-of-the-envelope calculations; the uncertainties are correspond-

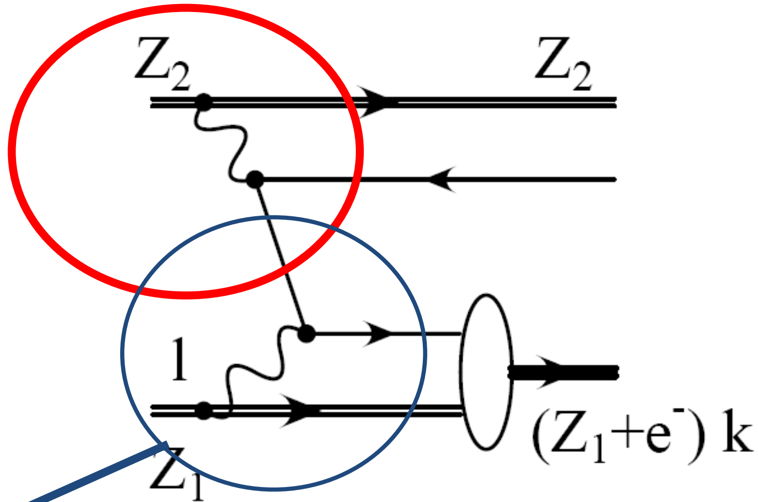
Pointed out that UPC processes not only affected beam lifetime (as was already known) but created losses from collisions that could potentially quench superconducting magnets.

Used available estimates of LHC dipole magnet quench limits (via B. Jeanneret) that indicated the heating of the magnet coil would exceed available cooling.

No proper model of beam optics (just a uniform field), angles of incidence, shower calculations, etc.

Pb-Pb BFPP cross-section (heuristic)

Pair production $\propto Z_1^{\,2} Z_2^{\,2}$



G. Baur et al, Phys. Rept. 364 (2002) 359

Radial wave function of $1s_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right)$$

$$\Rightarrow \quad \Psi(0) : Z_1^{\,3/2} \quad \Rightarrow \quad |\Psi(0)|^2 : Z_1^{\,3}$$

Cross section for Bound-Free Pair Production (BFPP) (various authors)

$$Z_1 + Z_2 \to \left(Z_1 + e^-\right)_{1s_{1/2},K} + e^+ + Z_2$$

has very strong dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2} \left[A \log \gamma_{CM} + B\right]$$

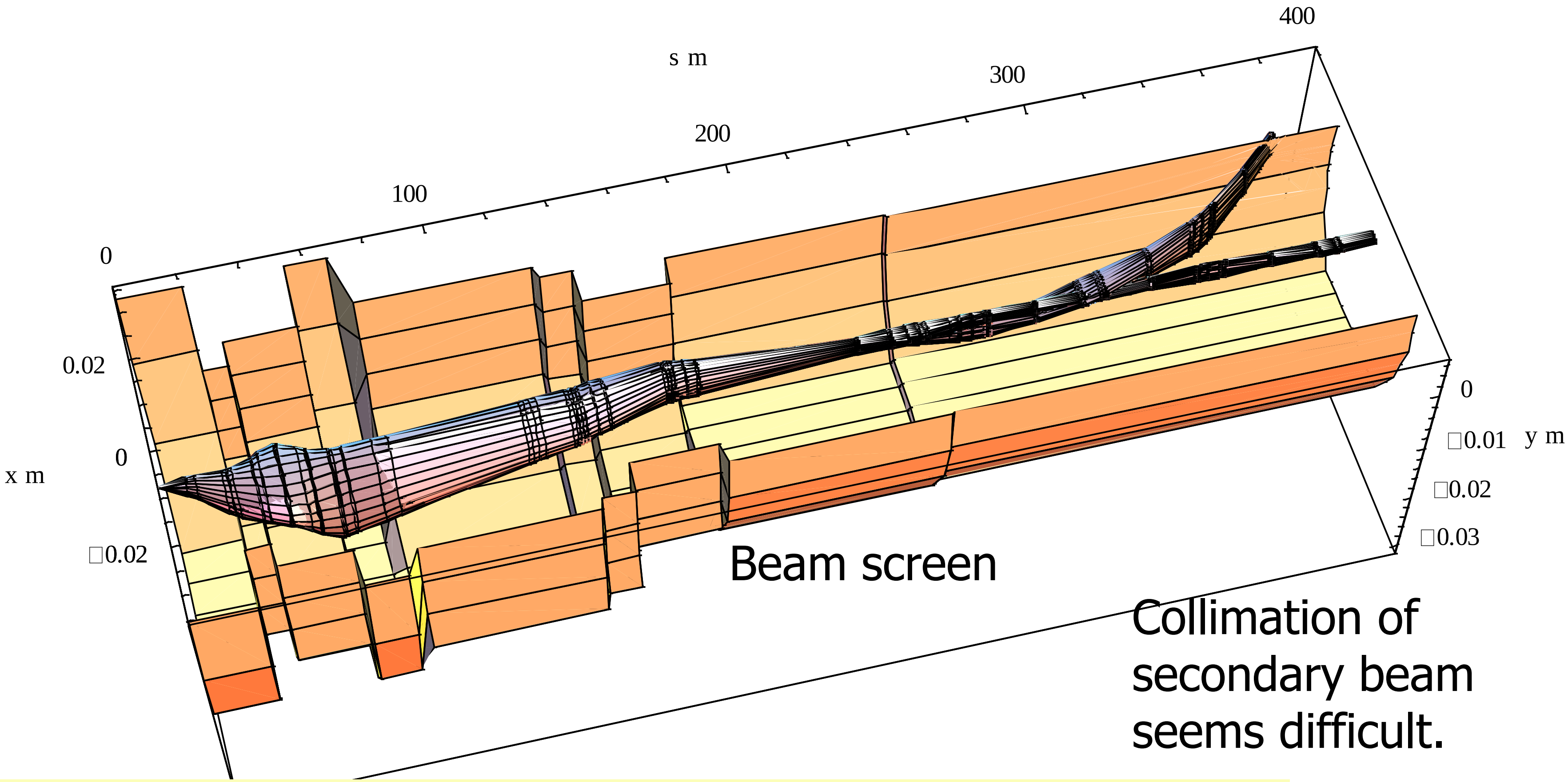
$$\propto Z^7 \left[A \log \gamma_{CM} + B\right] \quad \text{for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

Total cross-section : $Z_2^{\,2} Z_1^{\,5}$

Main and BFPP secondary beams

5σ beam envelopes, emerging to right of IP2



Collimation of secondary beam seems difficult.

Uncorrected strong chromatic effects of low-b insertion
⇒ cannot use linear beam sizes for Pb^{71+} beam

First detection of BFPP secondary beam at RHIC

Went to RHIC during Cu-Cu run in 2005, realising that BFPP would hit beam pipe (unlike Au-Au). Power in BFPP beam at limits of measurement.

PRL **99,** 144801 (2007) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2007

Observations of Beam Losses Due to Bound-Free Pair Production in a Heavy-Ion Collider

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LBNL, Berkeley, California, USA
(Received 13 June 2007; published 3 October 2007)

We report the first observations of beam losses due to bound-free pair production at the interaction point of a heavy-ion collider. This process is expected to be a major luminosity limit for the CERN Large Hadron Collider when it operates with $^{208}Pb^{82+}$ ions because the localized energy deposition by the lost ions may quench superconducting magnet coils. Measurements were performed at the BNL Relativistic Heavy Ion Collider (RHIC) during operation with 100 GeV/nucleon $^{63}Cu^{29+}$ ions. At RHIC, the rate, energy and magnetic field are low enough so that magnet quenching is not an issue. The hadronic showers produced when the single-electron ions struck the RHIC beam pipe were observed using an array of photodiodes. The measurement confirms the order of magnitude of the theoretical cross section previously calculated by others.

DOI: 10.1103/PhysRevLett.99.144801 PACS numbers: 29.20.Dh, 25.75.−q

PRL **99,** 144801 (2007) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2007

TABLE I. BFPP cross sections, typical peak luminosity, BFPP rates and relative changes in magnetic rigidity at RHIC and LHC. Values are taken directly where possible, or estimated by fitting sums of contributions of the form (2), to the information in Ref. [12]. $\delta = 1/(Z-1)$ is the fractional deviation of the magnetic rigidity.

	σ_{BFPP} (barn)	$L/10^{27}$ (cm^{-2} s^{-1})	BFPP rate (kHz)	δ (%)
LHC Pb-Pb 2759 GeV/nucleon	281	1	281	1.2
RHIC Au-Au 100 GeV/nucleon	114	3	342	1.3
RHIC Cu-Cu 100 GeV/nucleon	0.2	20	4	3.6
RHIC Cu-Cu 31 GeV/nucleon	0.08	1	0.08	3.6

PRL **99,** 144801 (2007) PHYSICAL RE

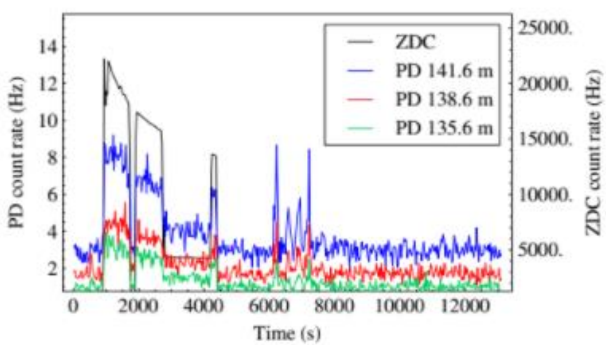
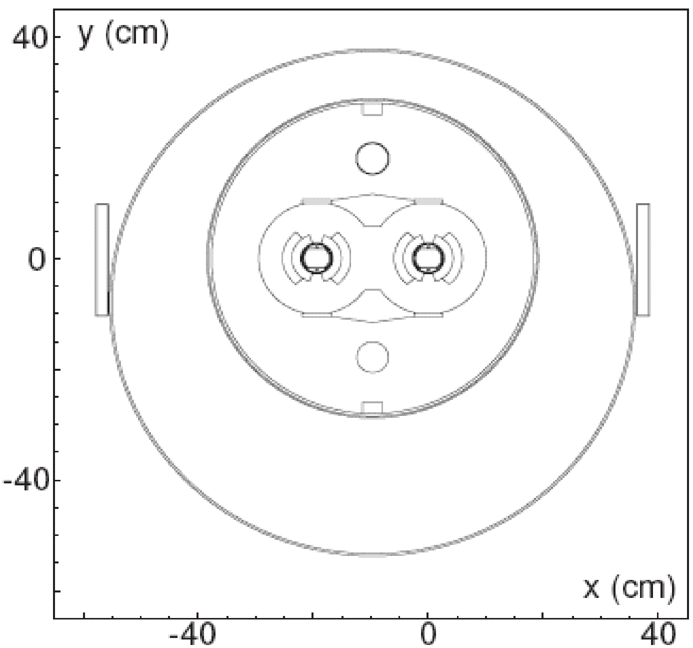


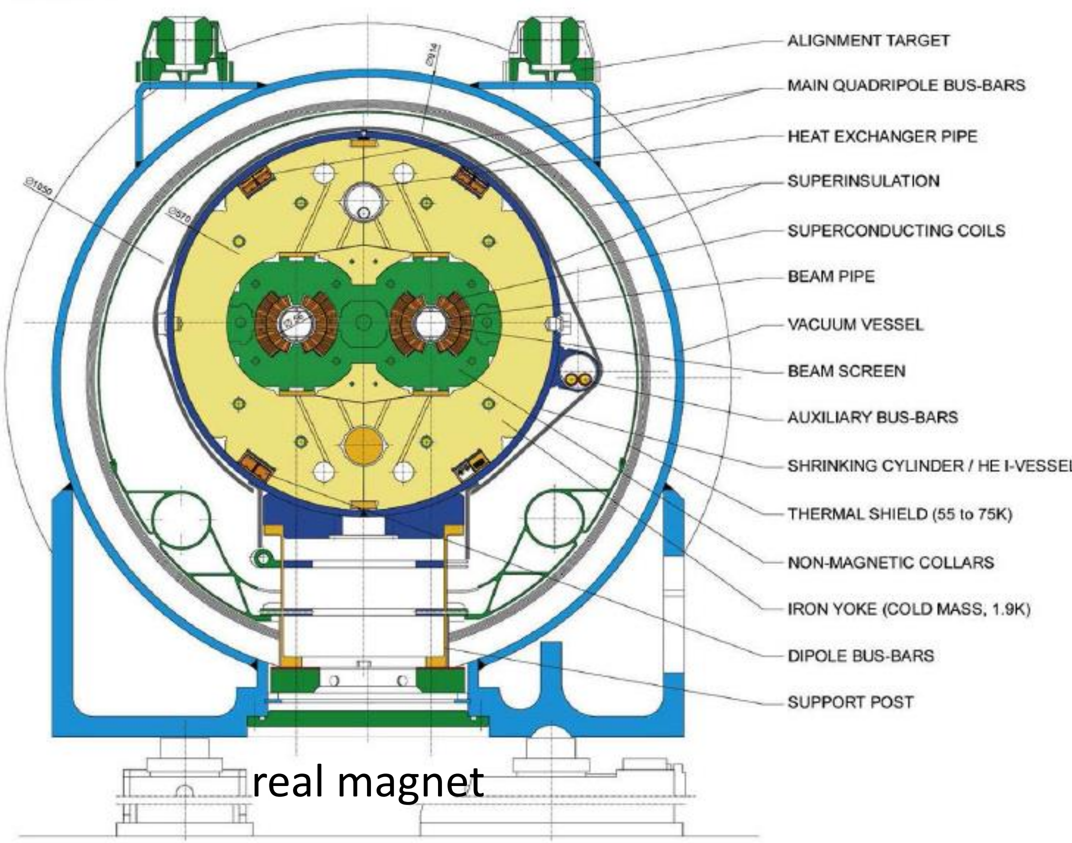
FIG. 4 (color online). Count rates measured on the ZDC luminosity monitors (black, right scale) and the three PDs with the highest signal [shades of gray, left scale (colors online)] during a store with the WPD. The data was binned in 30 sec intervals. A clear correlation between the luminosity and the PD count rates can be seen.

FLUKA shower simulation for LHC

- FLUKA simulation to estimate the heat load in the dispersion suppressor dipole at IP2
- impact coordinates of lost BFPP particles from tracking fed as starting conditions to FLUKA
- 3D model of LHC main dipole



FLUKA model



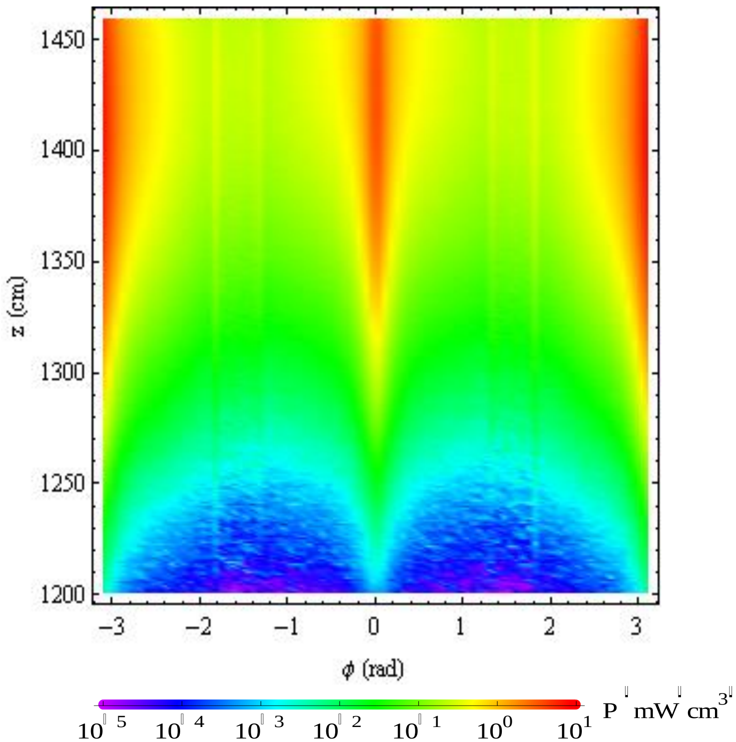
real magnet

Simulated power deposition in LHC dipole

Power deposition from FLUKA in the inner coil layer, averaged over width of coil,

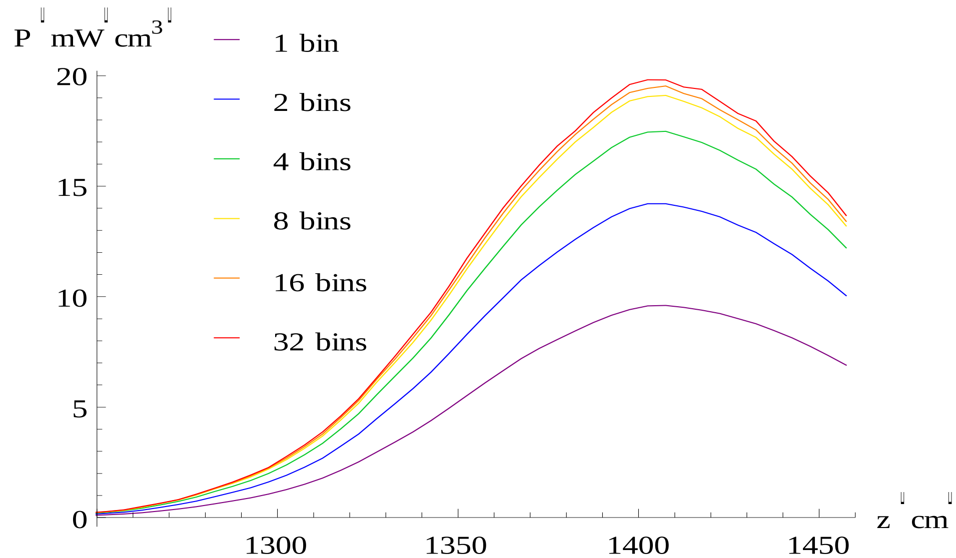
normalized with BFPP cross section and luminosity:

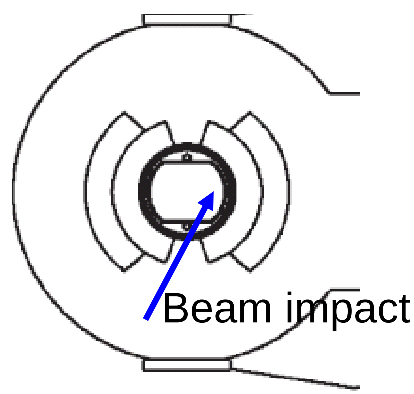
$$P_{tot} = \sigma_{BFPP} \mathcal{L} E_{particle}$$



Energy deposition longitudinally in hottest bin, different radial binnings.

88 bins in φ (cable), 5 cm longitudinal cell size





in LHC design report:

Quench limit= 4.5 mW/cm^3

R. Bruce, D. Bocian

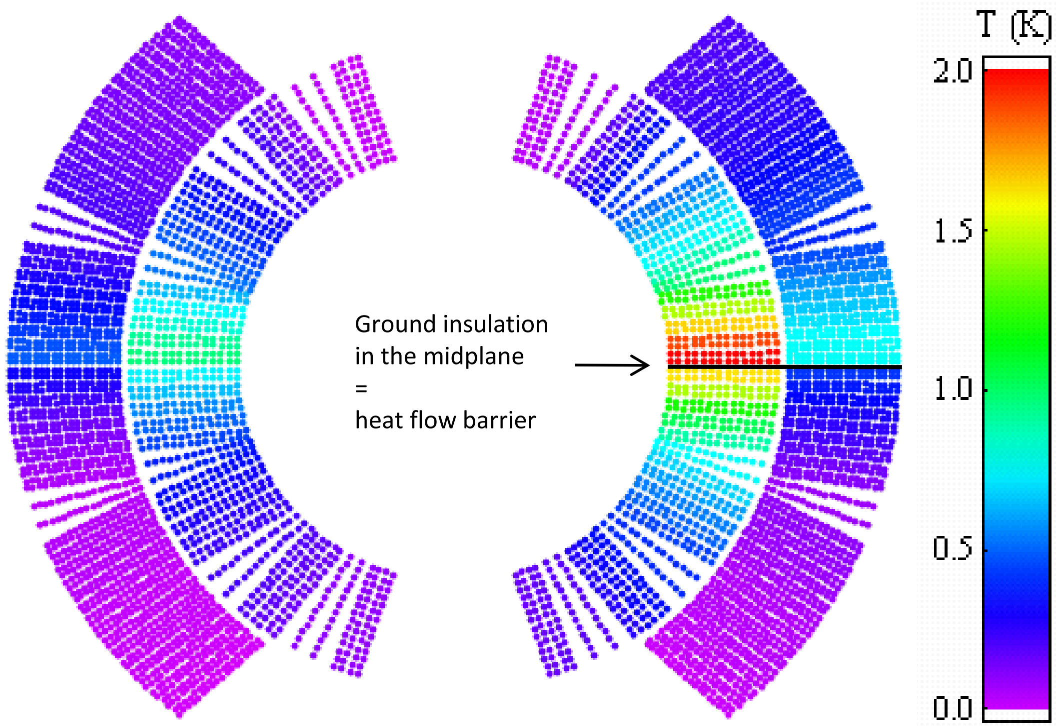
Quench limit simulations

➢ **temperature distribution for nominal LHC ion beam conditions, corresponding to 95% of loss energy peak in the coil (23.1 mW/m) and 95% loss energy peak in the coldbore (76.3 mW/m)**

➢ **quenching cable is located at the coil mid-plane**

➢ **this temperature map corresponds to nominal magnet current (11850 A)**

Temperature map in the MB dipole magnet coil after heat load



Peak temperature rise in the coil ΔT= 2.0 K
Peak temperature rise in the cold bore ΔT=1.4K

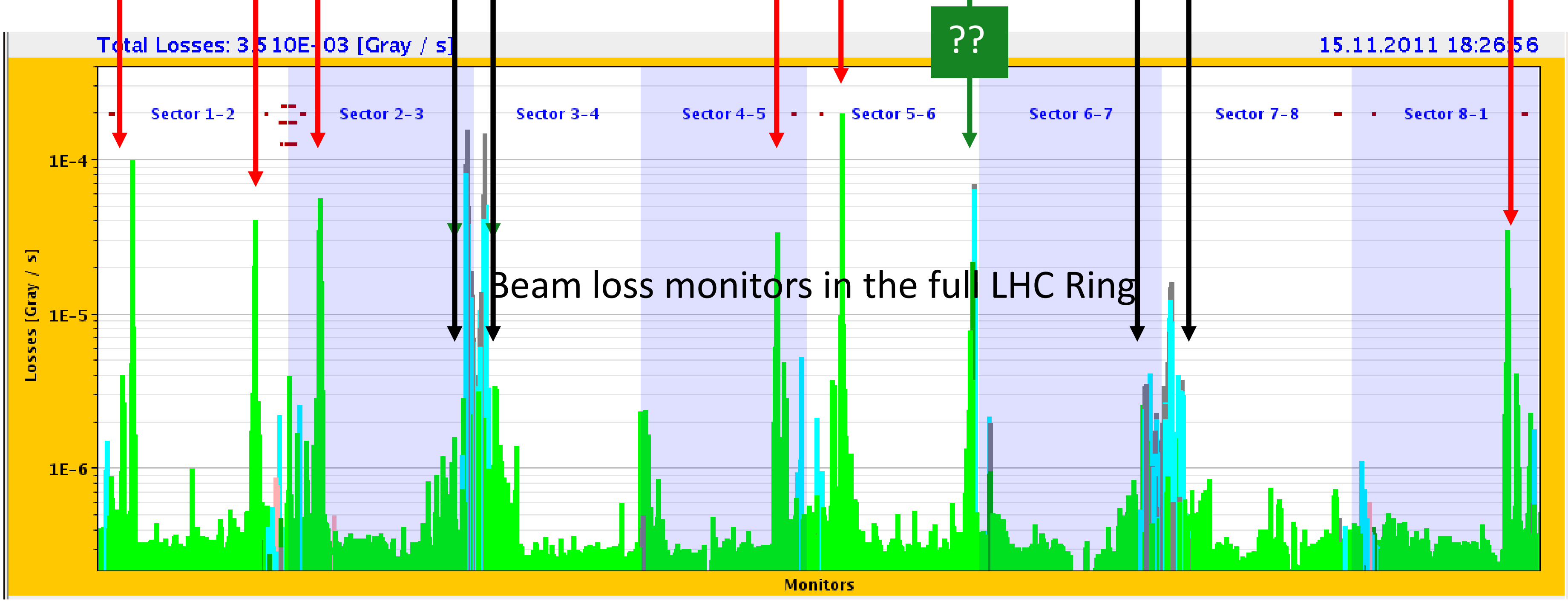
For nominal LHC ion beam conditions (beam optics ver. 6.500)

Steady-state losses during Pb-Pb Collisions in 2011

Bound-free pair production secondary beams from IPs

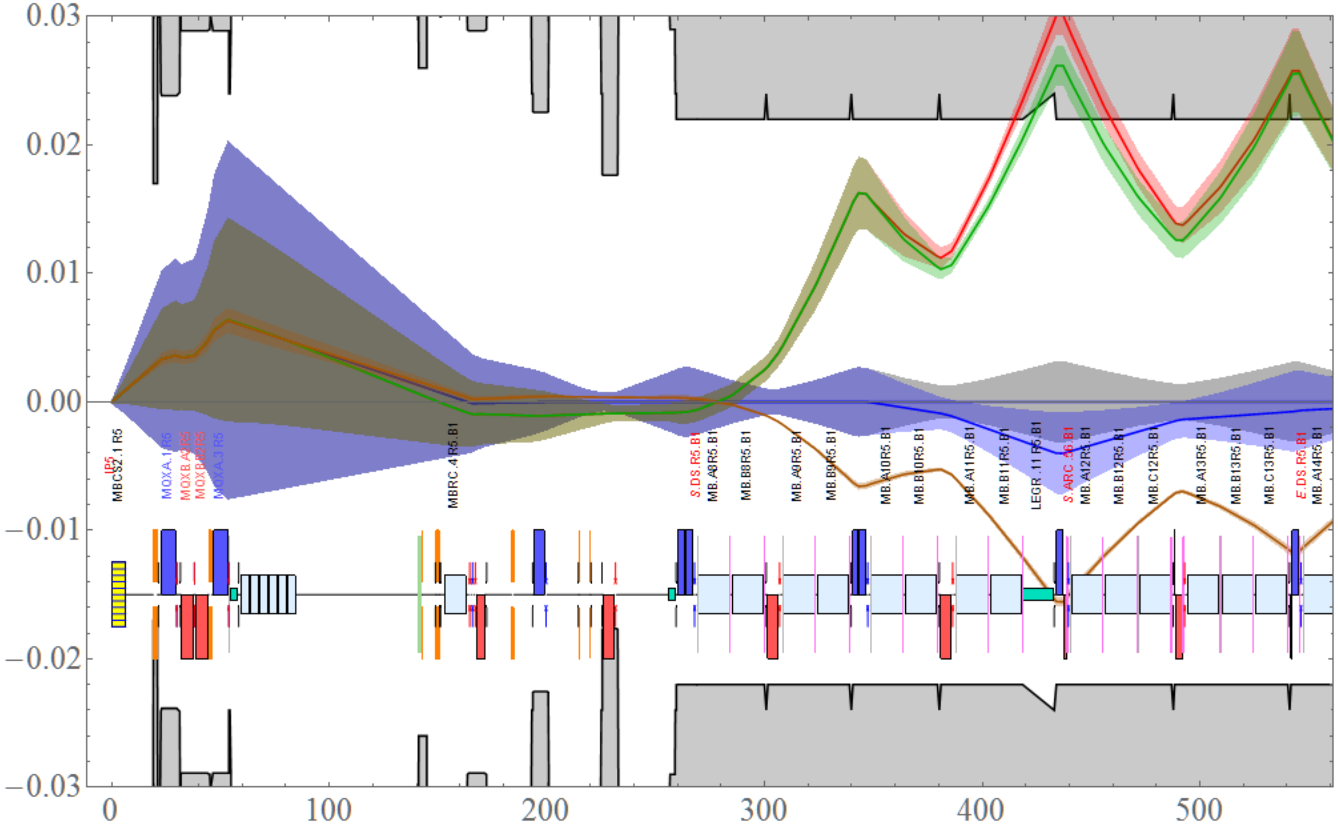
IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators

Losses from collimation inefficiency, nuclear processes in primary collimators



No time to discuss major topic of heavy-ion collimation in this talk.

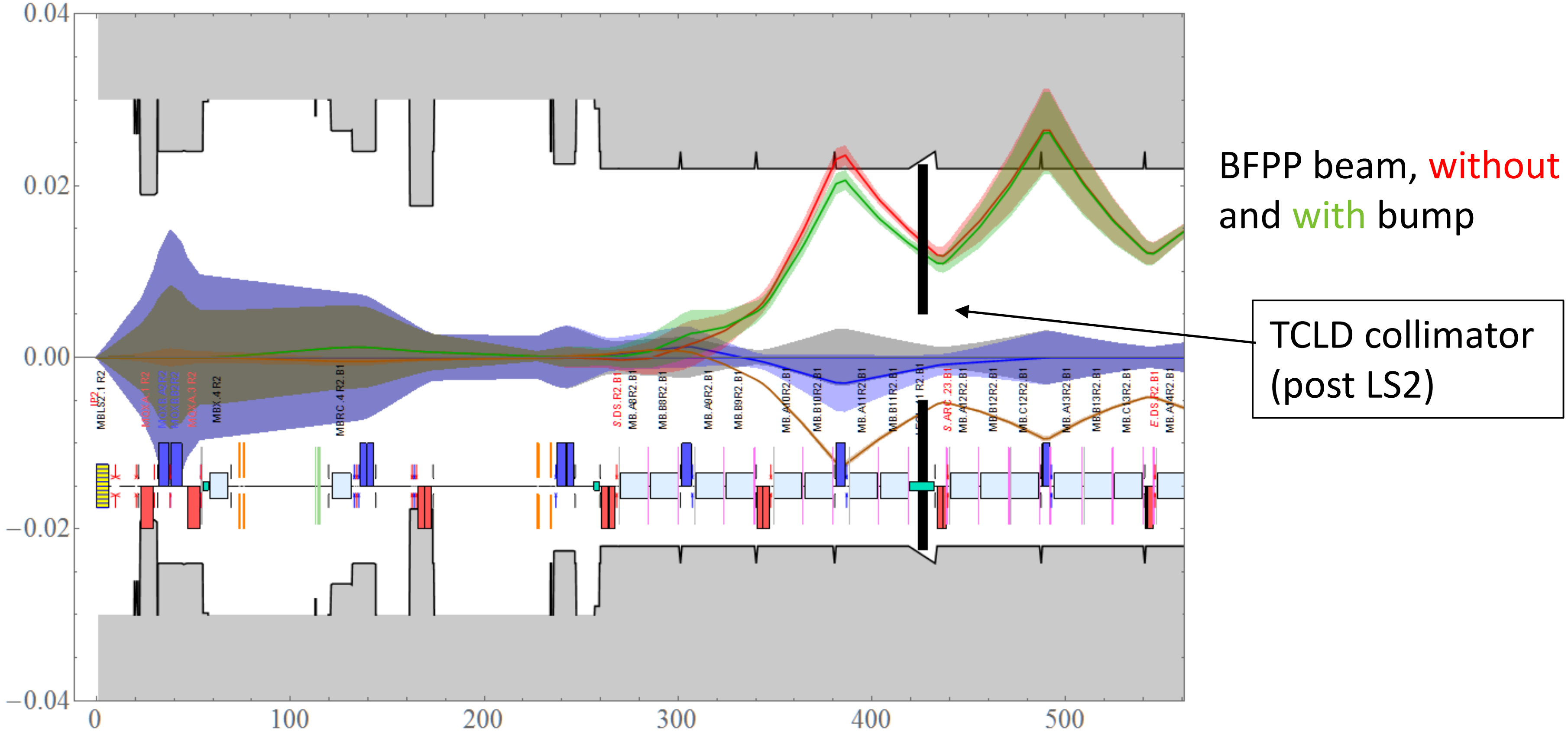
Orbit bumps are effective mitigation for CMS (or ATLAS)



BFPP beam, without and with bump

- Primary loss location close to the connection cryostat - details slightly optics-dependent (If necessary, bumps should avoid quenches at the start of physics
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available corrector strengths
- We applied bumps like these with ~ 3 mm amplitude around CMS and ATLAS from the beginning of the run

Orbit bumps alone are not effective for ALICE



- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam
- With levelled luminosity in ALICE, quenches are not expected in Run 2

Tests of strategy during 2015 Pb-Pb run

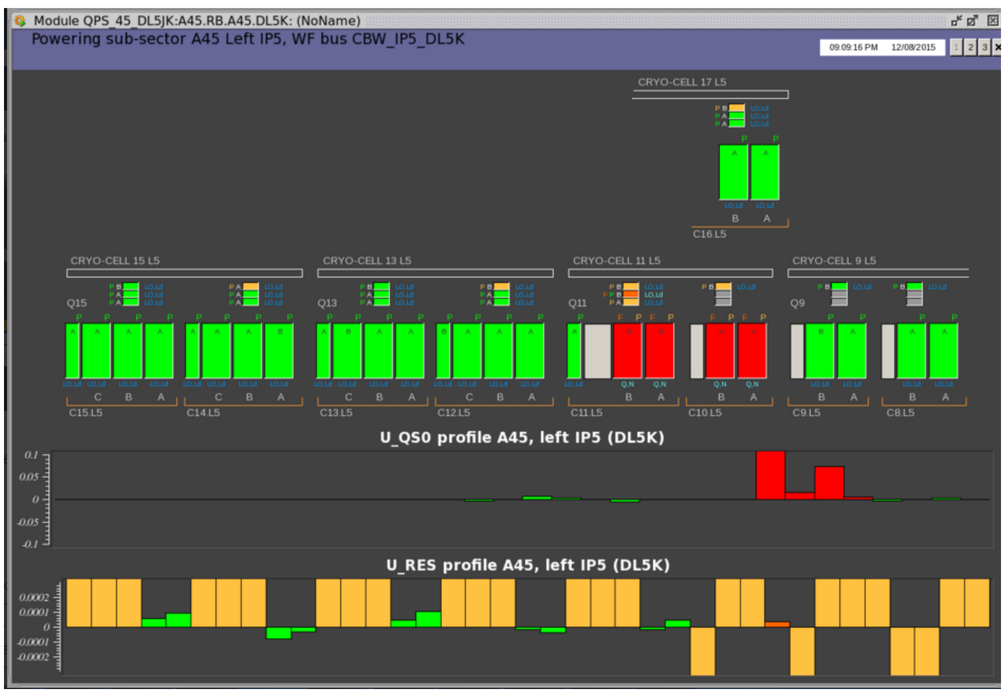
- For safety, mitigation bumps were implemented at 3 mm amplitude in validated physics setup
  - Expected to move losses around ATLAS/CMS into connection cryostat
    - Not quite true on left of IP5 – luminosity losses at start of later fills came close to (raised) BLM dump thresholds
  - Moved losses beyond connection cryostat in IR2
    - Levelled luminosity not expected to be a concern
- MD study around IP5 would attempt to quench by manipulating bump to move losses back into connection cryostat in controlled way
  - Based on latest estimates of steady state quench level, we did not expect a quench … but we tried anyway.
  - But potentially an extremely clean measurement.

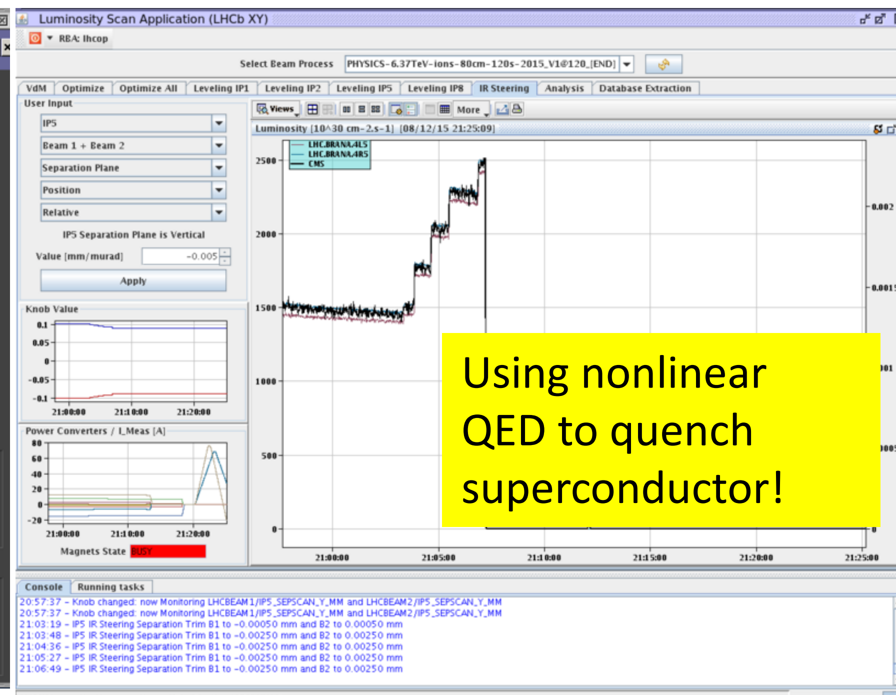
BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for one fill 8/12/2015 evening.
- Prepared as for physics fill, separated beams to achieve moderate luminosity in IP5 only.
- Changed amplitude of BFPP mitigation bump from -3 mm to +0.5 mm to bring loss point well within body of dipole magnet (it started just outside).
- Put IP5 back into collision in 5 μm steps.
- Unexpectedly quenched at luminosity value (CMS):

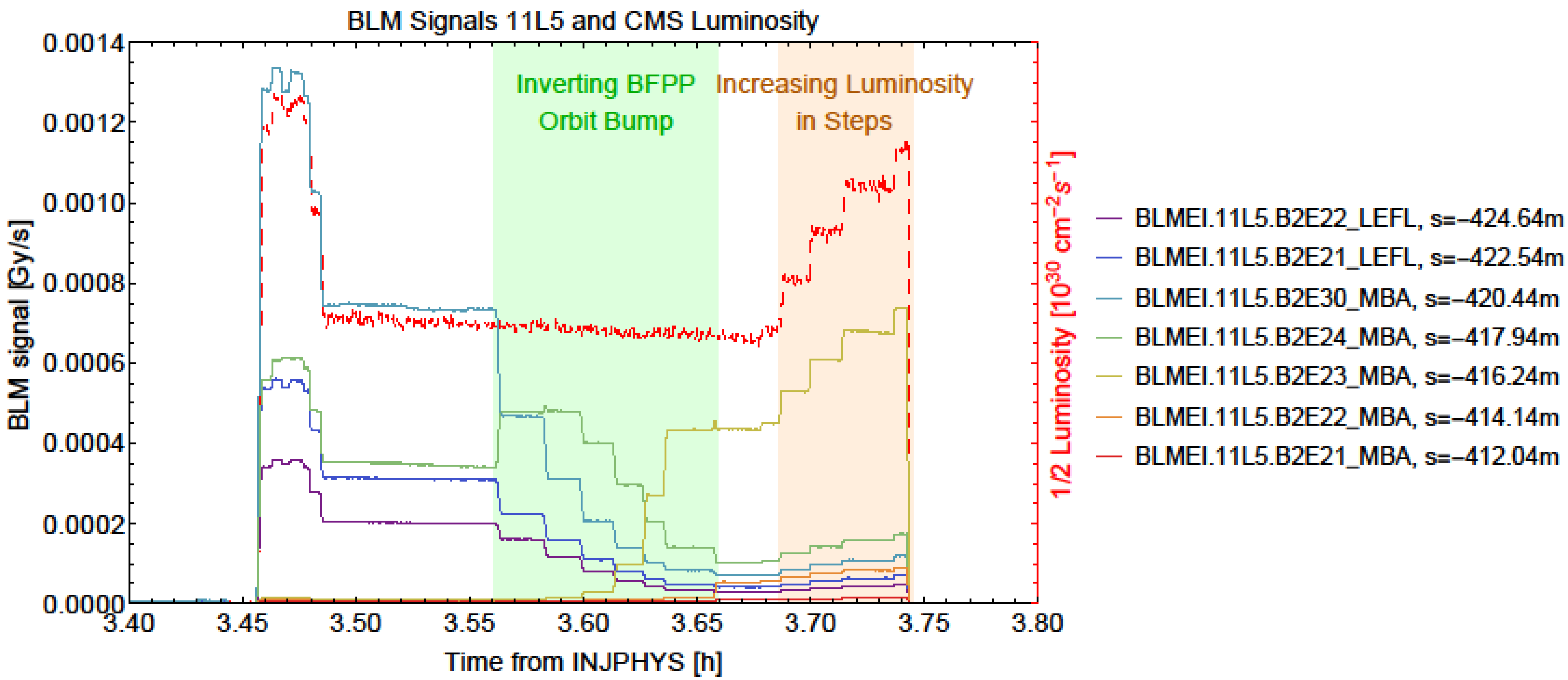
$$L \approx 2.3 \times 10^{27}\ \mathrm{cm^{-2}s^{-1}}$$

$$\Rightarrow \quad 0.64\ \text{MHz event rate, about 45 W of power in } Pb^{81+} \text{ beam into magnet}$$

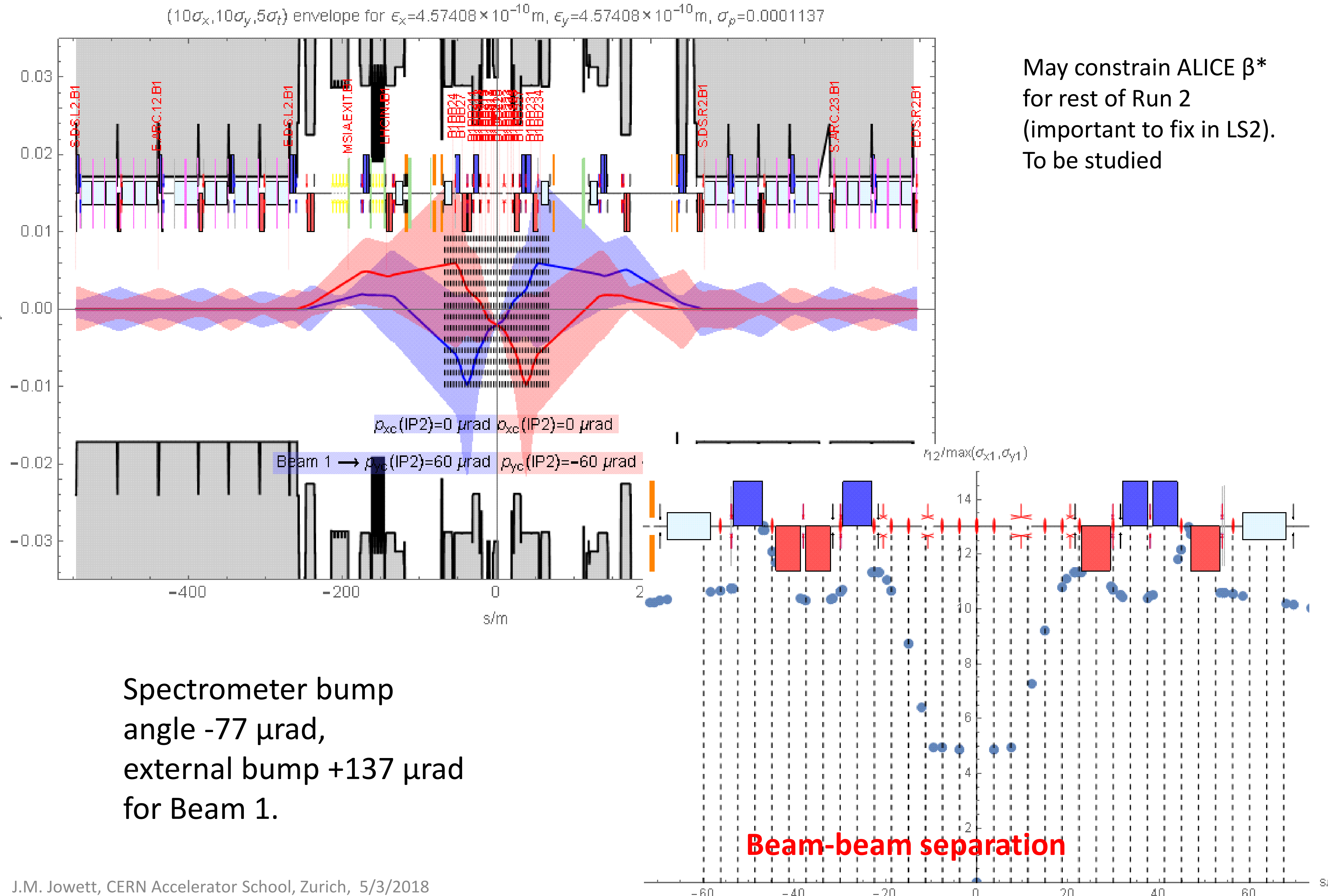




Luminosity and BLM signals during measurement



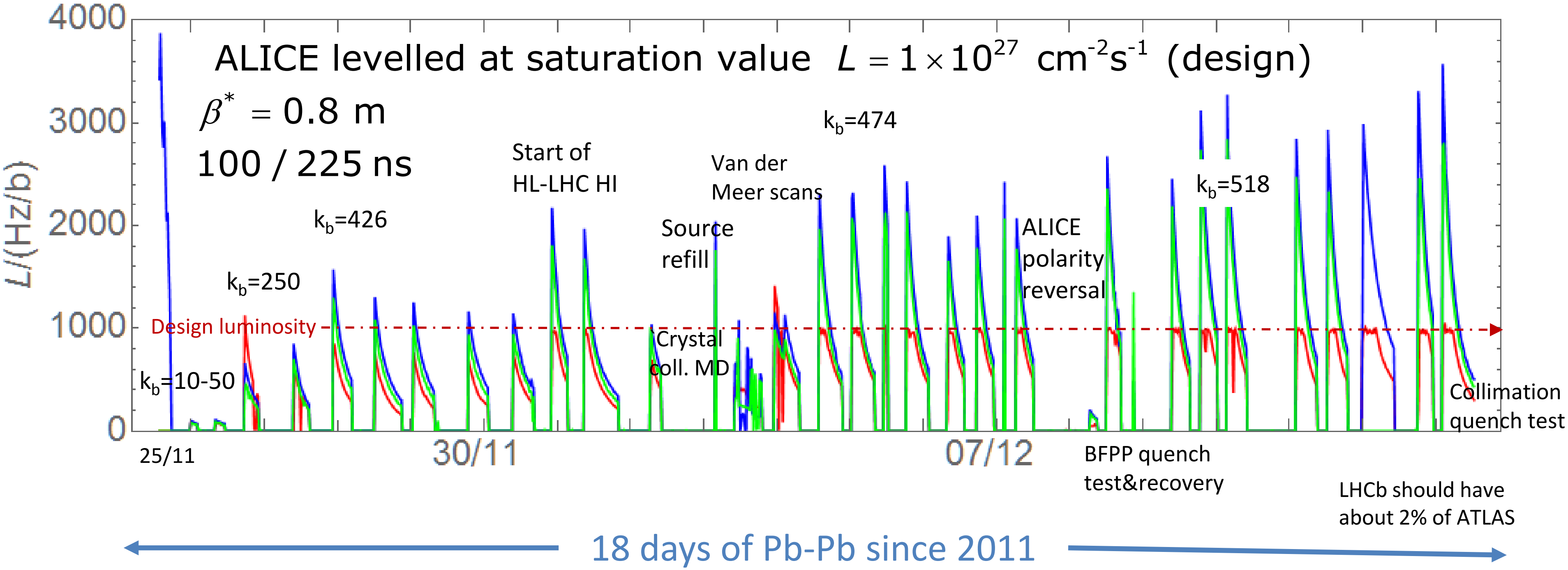
Spectrometer ON_ALICE=-7/6.37 (start of Pb-Pb run)



May constrain ALICE β* for rest of Run 2 (important to fix in LS2). To be studied

Spectrometer bump angle -77 μrad, external bump +137 μrad for Beam 1.

Pb-Pb peak luminosity at 3×design in 2015



Heavy-ion runs of LHC are very short but very complex.
Experiments have many requests for changes of conditions.

This run was preceded by a week of equivalent energy p-p collisions to provide reference data.

Completely different from classical operation of Tevatron or LHC p-p.

25/11

Integrated nucleon-nucleon luminosity in Run 1 + 2015

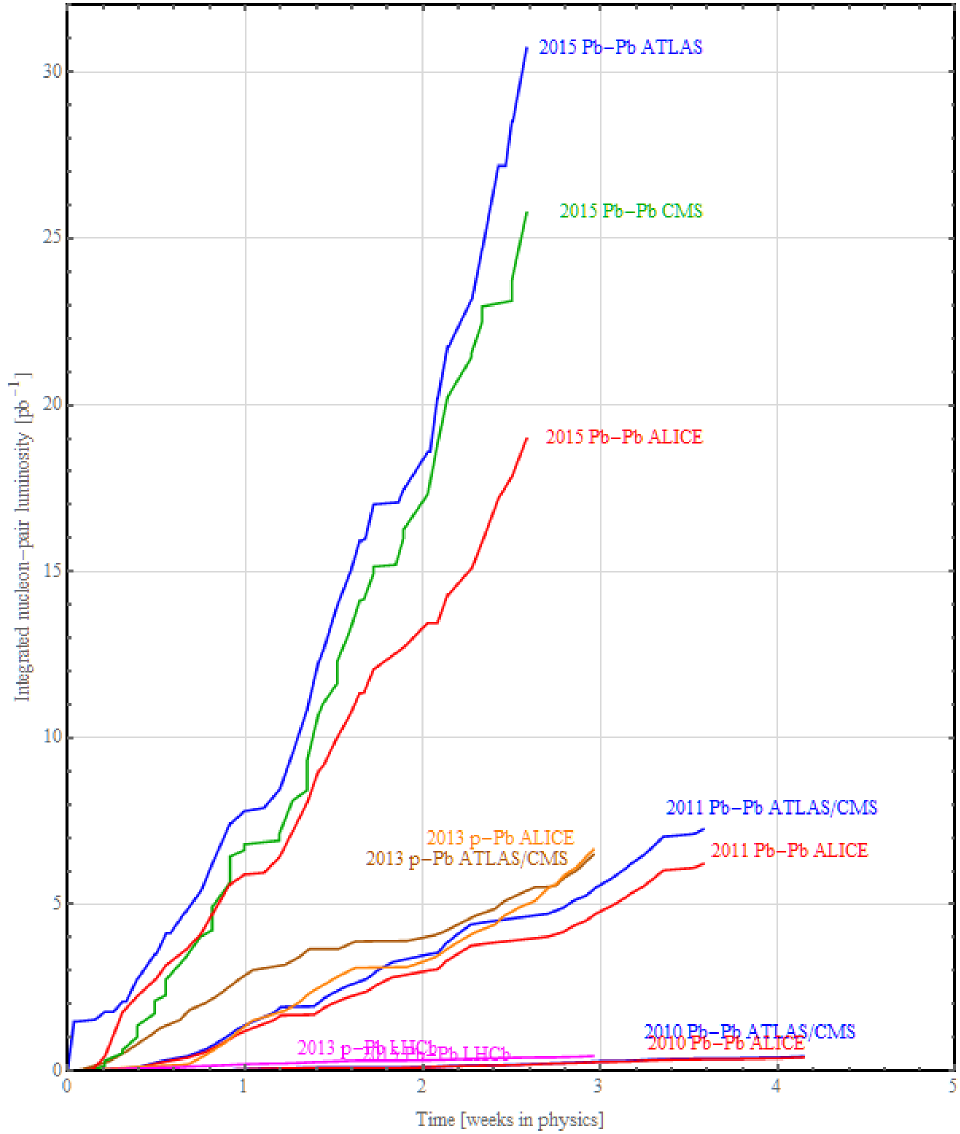
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of
1 AA nb^{-1} = 43 NN pb^{-1}
in Run 2 (=2015+2018)

Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

$$\sqrt{s_{NN}} = 5.02\ \text{TeV}$$

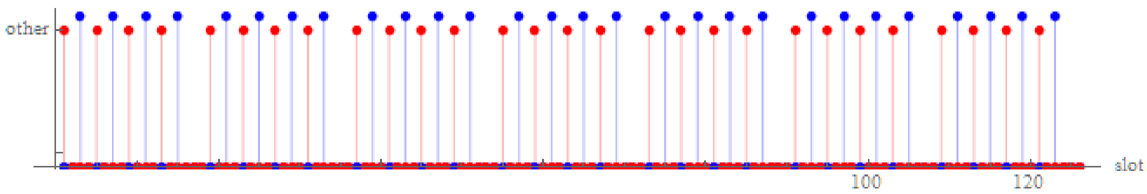
$$\Rightarrow E_b = \begin{cases} 6.37Z\ \text{TeV} & \text{in Pb-Pb} \\ 4\ Z\ \text{TeV} & \text{in p-Pb} \end{cases}$$

But annual 1-month runs are getting shorter and more complicated … 2015 included p-p reference data and included LHCb.

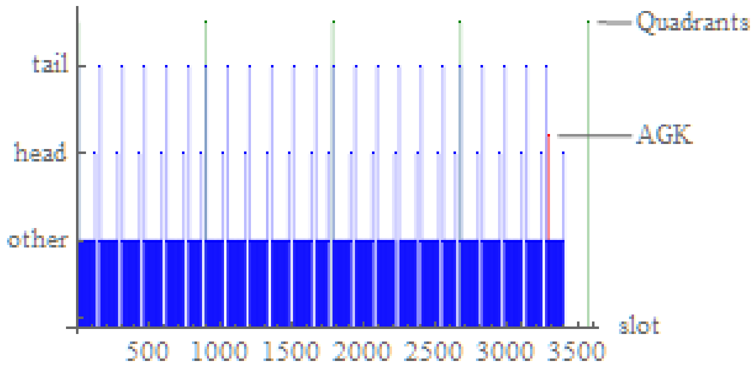


2012 pilot p-Pb run not shown (1 fill but major physics output)

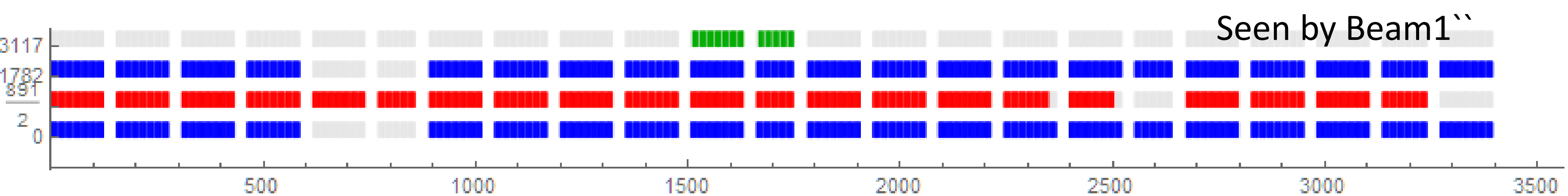
Bunch filling scheme example (future)

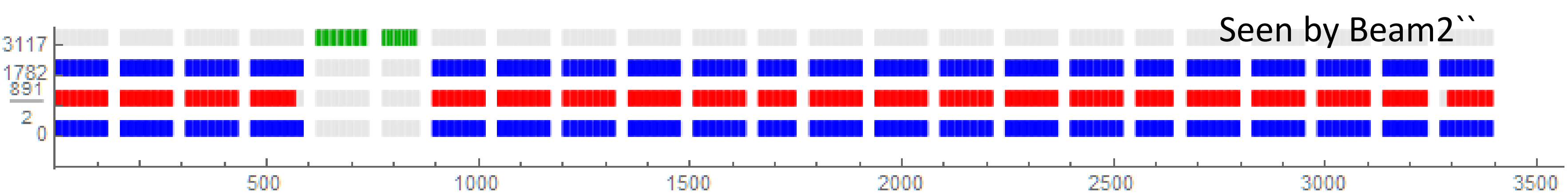


56 bunch SPS train after slip-stacking



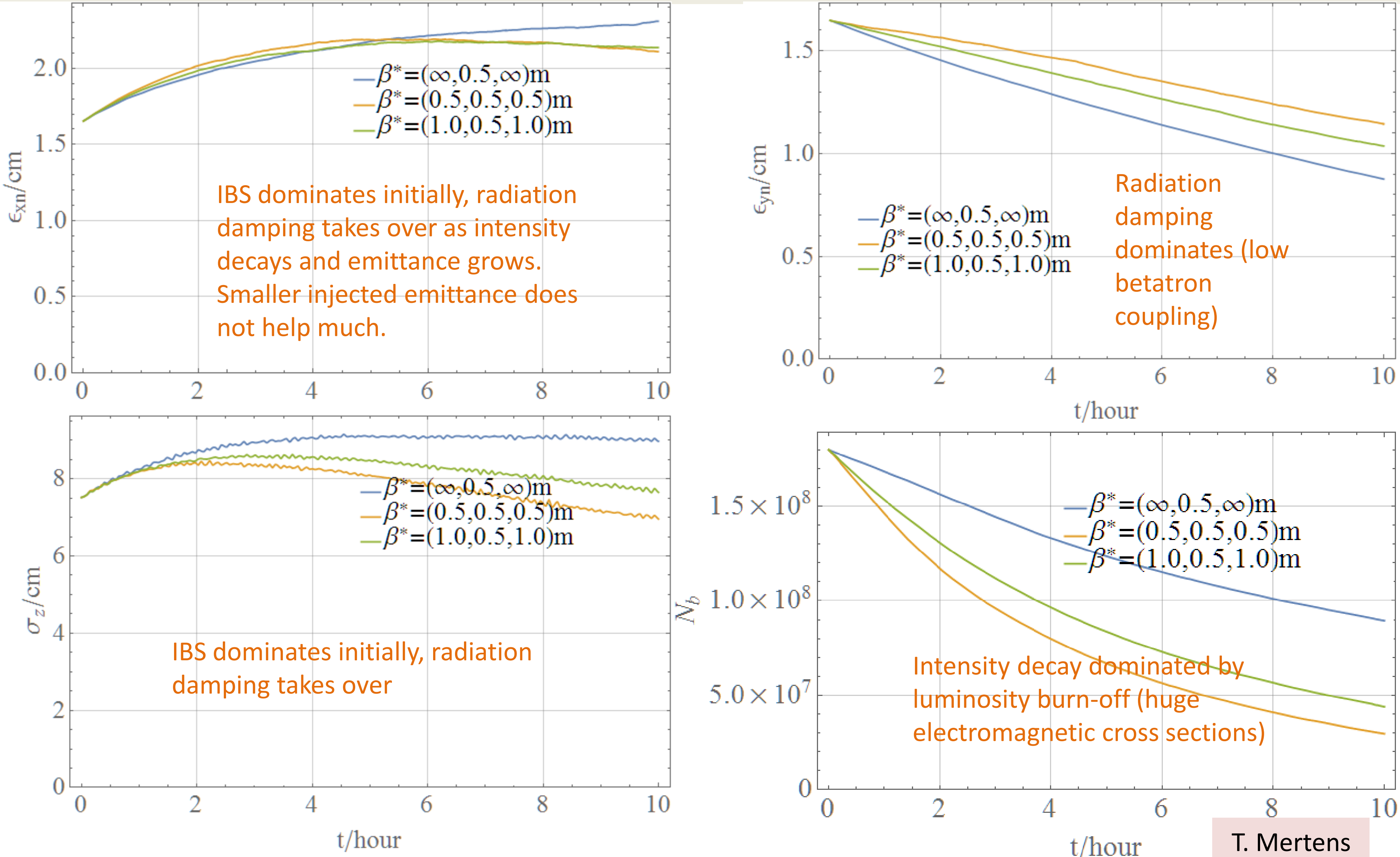
Displace two trains in Beam 2 to make collisions in LHCb





23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).

CTE Simulation of (typical) colliding bunch pair future Pb-Pb

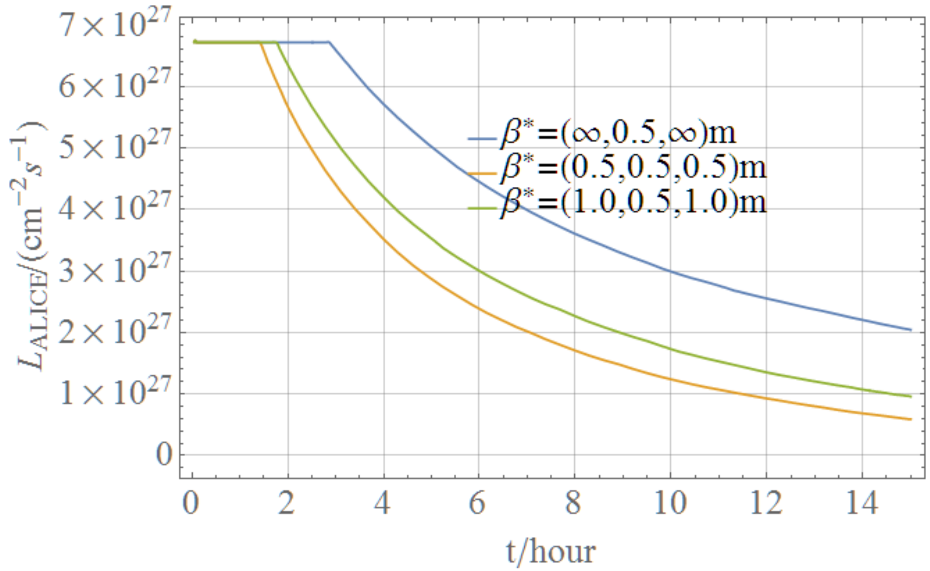


Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities.

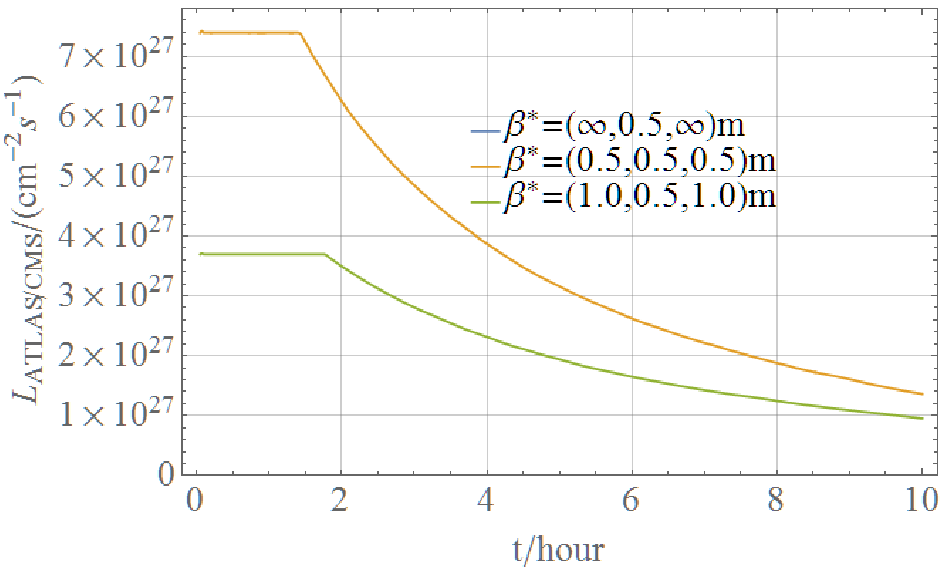
Different evolution according to luminosity-sharing scenario.

(Does not include additional emittance growth usually seen in operation.)

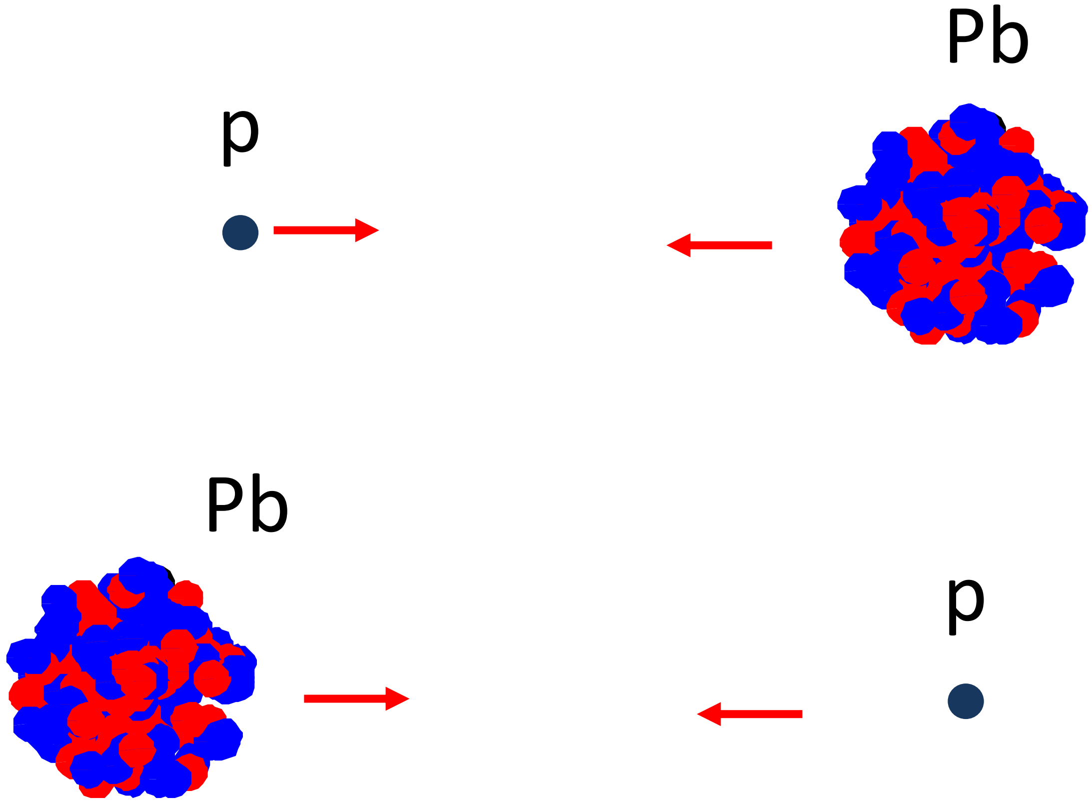
Luminosities in an ideal (prolonged) fill



ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding



ATLAS or CMS



PROTON-LEAD COLLISIONS IN LHC

First asymmetric collisions at LHC

History of proton-nucleus collisions at LHC (1)

- Long considered desirable by experiments but never included in baseline design of LHC
- 2003: RHIC finds a way to collide deuterons and gold nuclei but this way is not open to LHC …
- 2005 CERN workshop on pA in LHC
  - Predicted that p-Pb in LHC could work (despite RHIC …)
  - Physics case written up much later

IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **39** (2012) 015010 (28pp) doi:10.1088/0954-3899/39/1/015010

Proton–nucleus collisions at the LHC: scientific opportunities and requirements

C A Salgado[1], J Alvarez-Muñiz[1], F Arleo[2], N Armesto[1], M Botje[3], M Cacciari[4], J Campbell[5], C Carli[6], B Cole[7], D D'Enterria[8,9], F Gelis[10], V Guzey[11], K Hencken[12,23], P Jacobs[13], J M Jowett[6], S R Klein[13], F Maltoni[14], A Morsch[8], K Piotrzkowski[14], J W Qiu[15], T Satogata[15], F Sikler[16], M Strikman[17], H Takai[15], R Vogt[13,18], J P Wessels[8,19], S N White[15], U A Wiedemann[20], B Wyslouch[21,24] and M Zhalov[22]

Relation between Beam Momenta

- LHC accelerates protons through the momentum range

$$0.45\ \text{TeV (injection from SPS)} \leq p_p \leq 7\ \text{TeV (collision)}$$

  - p_p is measure of magnetic field in main bending magnets
- The two-in-one magnet design of the LHC fixes the relation between momenta of beams in the two rings (equal "*magnetic rigidity*")

$$p_{\text{Pb}} = Z p_{\text{p}}$$

where $Z = 82, A = 208$ for fully stripped Pb in LHC

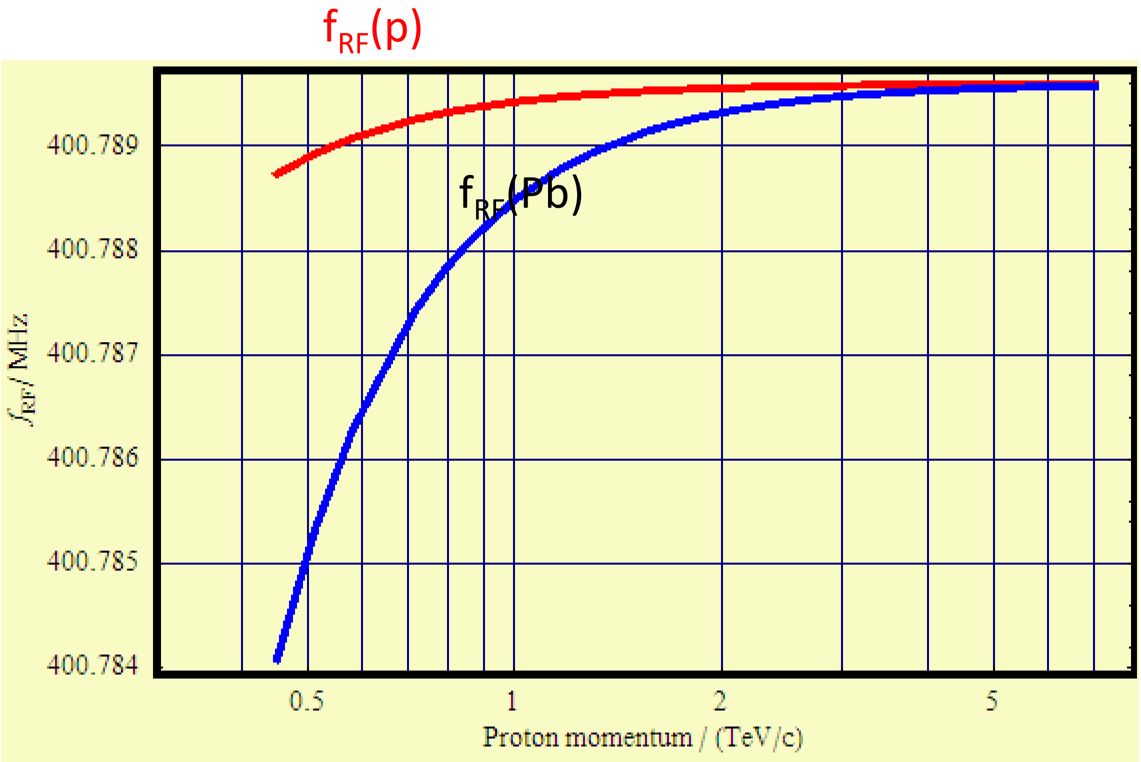
RF Frequency for p and Pb in LHC

Revolution time of a general particle, mass *m*, charge *Q*, is

$$T\left(p_p, m, Q\right) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_p}\right)^2}$$ and RF frequency $$f_{RF} = \frac{h_{RF}}{T\left(p_p, m, Q\right)}$$

where the harmonic number $h_{RF} = 35640$ in LHC

RF frequencies needed to keep p or Pb on stable *central* orbit of constant length *C* are different at low energy.



No problem in terms of hardware as LHC has independent RF systems in each ring.

Distorting the Closed Orbit

- Additional degree of freedom: adjust length of closed orbits to compensate different speeds of species.
  - Done by adjusting RF frequency

$$T\left(p_{\mathrm{p}}, m, Q\right) = \frac{C}{c}\sqrt{1 + \left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2}\,(1 + \eta\delta)$$

where $\delta = \dfrac{(p - Qp_{\mathrm{p}})}{Qp_{\mathrm{p}}}$ is a fractional momentum deviation and

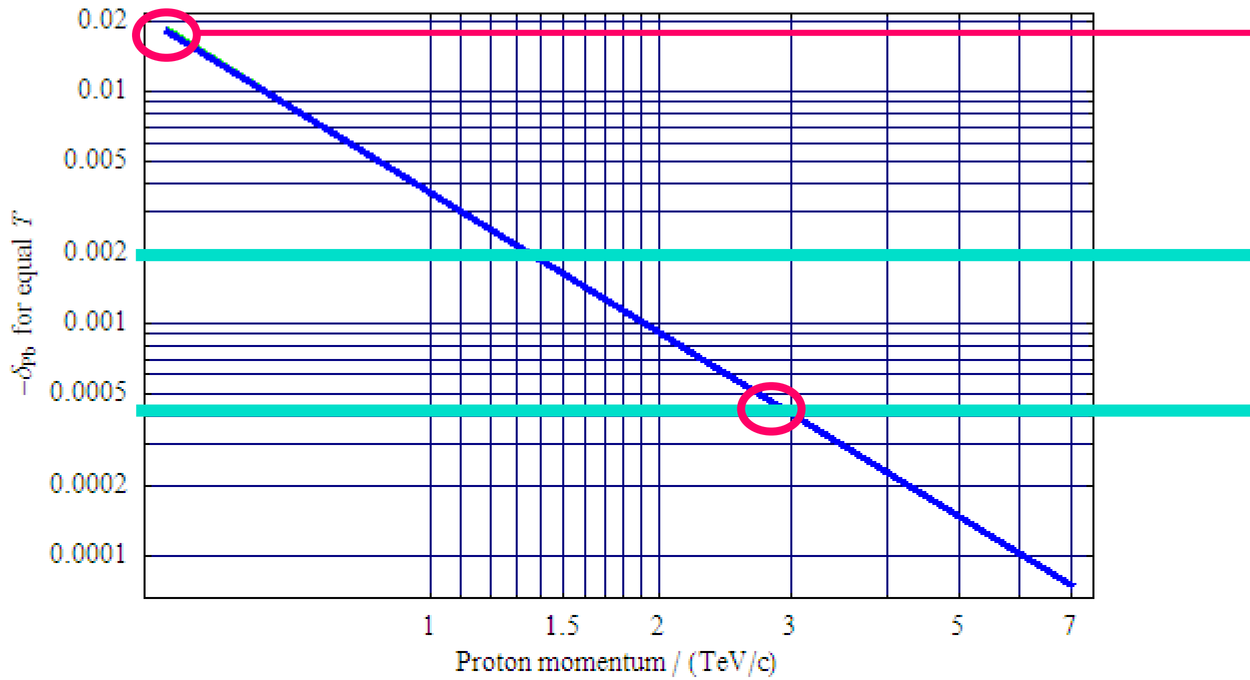
the phase-slip factor $\eta = \dfrac{1}{{\gamma_T}^2} - \dfrac{1}{\gamma^2}$, $\gamma = \sqrt{1 + \left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\gamma_T = 55.8$ for LHC optics.

Moves beam on to off-momentum orbit, longer for $\delta > 0$.

Horizontal offset given by dispersion: $\Delta x = D_x\left(s\right)\delta$.

Momentum offset required through ramp

Minimise aperture needed by $\delta_{\mathrm{p}} = -\delta_{\mathrm{Pb}} = \dfrac{c^2 {\gamma_T}^2}{4 p_{\mathrm{p}}^2} \left(\dfrac{m_{\mathrm{Pb}}^2}{Z^2} - m_{\mathrm{p}}^2 \right).$



2% - would move beam by 35 mm in QF!!

Limit with pilot beams

Limit in normal operation
(1 mm in arc QD)

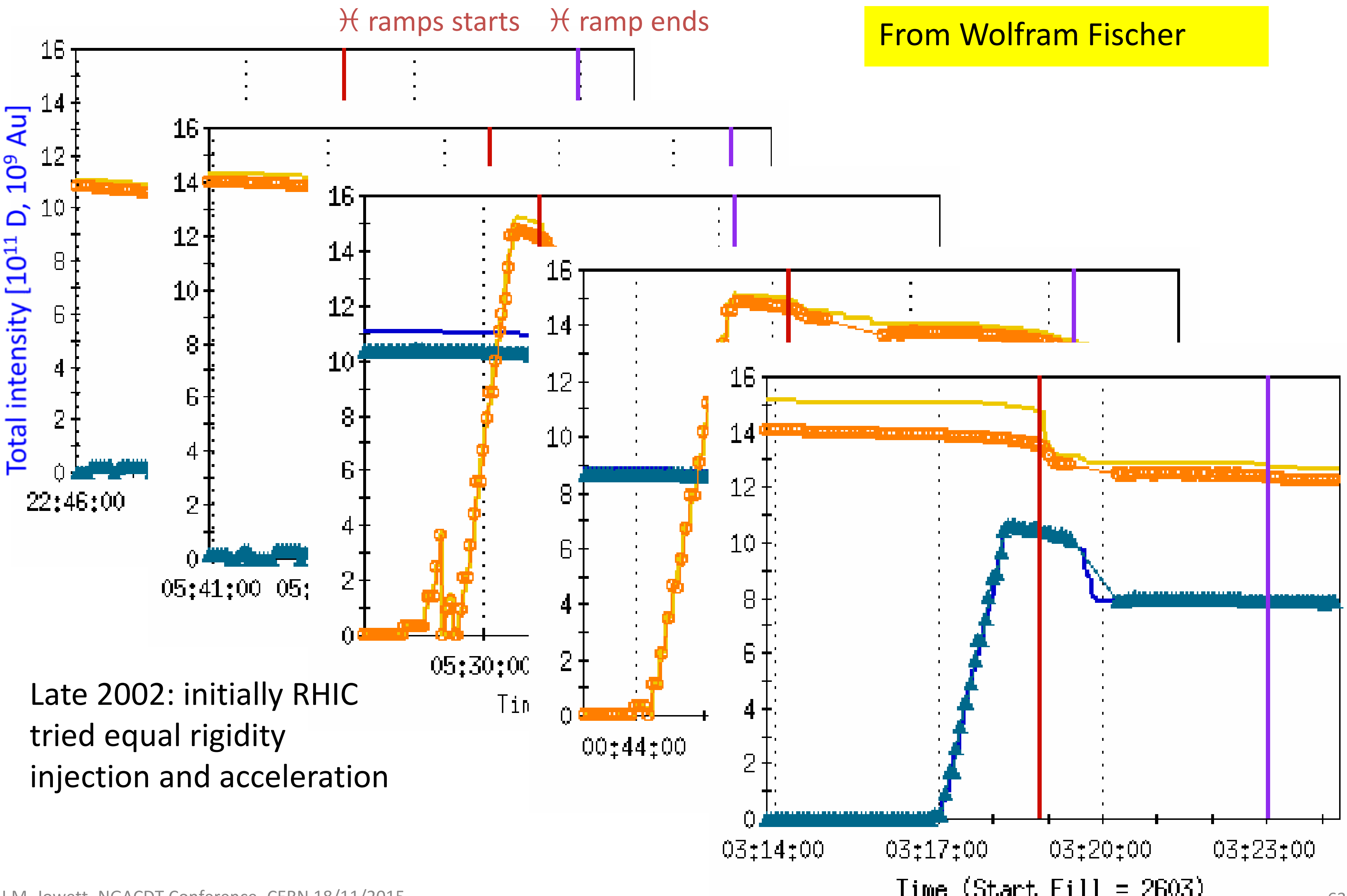
Revolution frequencies must be equal for collisions at top energy.

Lower limit on beam energy for p-Pb collisions, *E*=2.7 Z TeV.

RF frequencies must be unequal for injection, ramp!

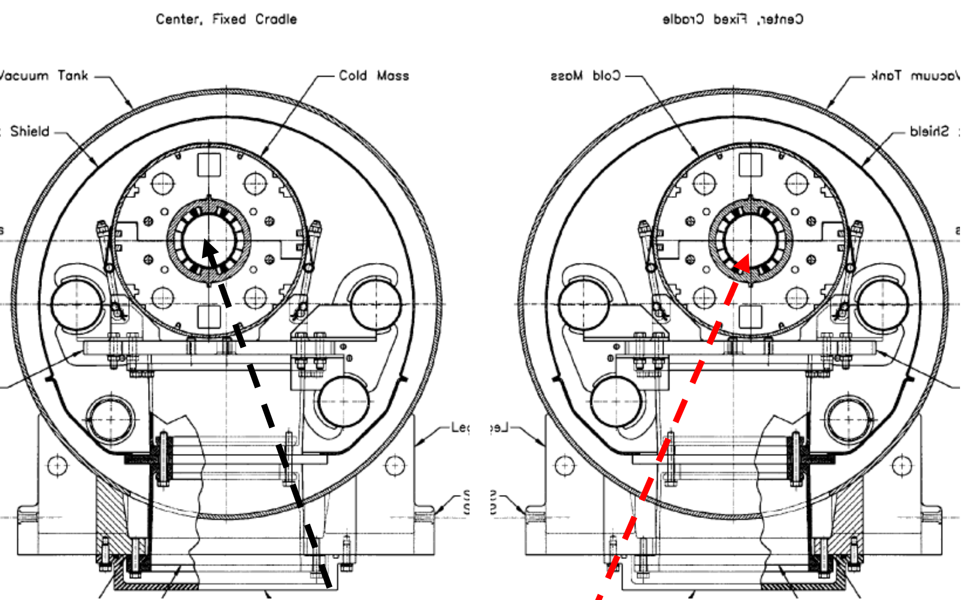
RHIC d-Au injection and ramp $(B\rho)_d = (B\rho)_{Au}$

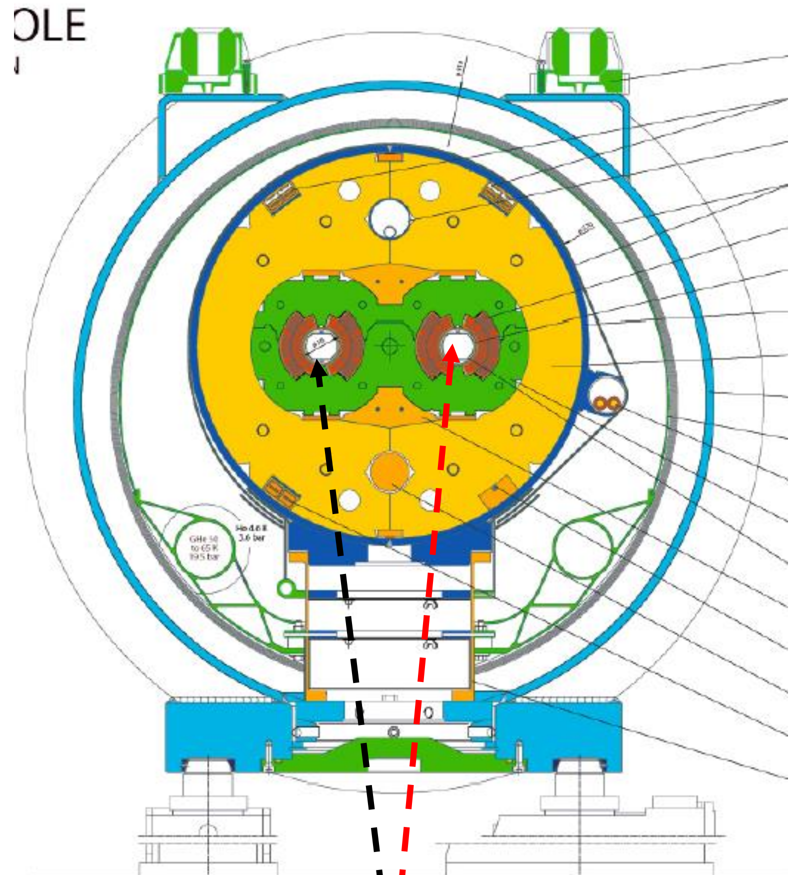
From Wolfram Fischer



Late 2002: initially RHIC tried equal rigidity injection and acceleration

Critical difference between RHIC and LHC





RHIC: Independent bending field for the two beams – they abandoned equal-rigidity and switched to equal-frequency d-Au.

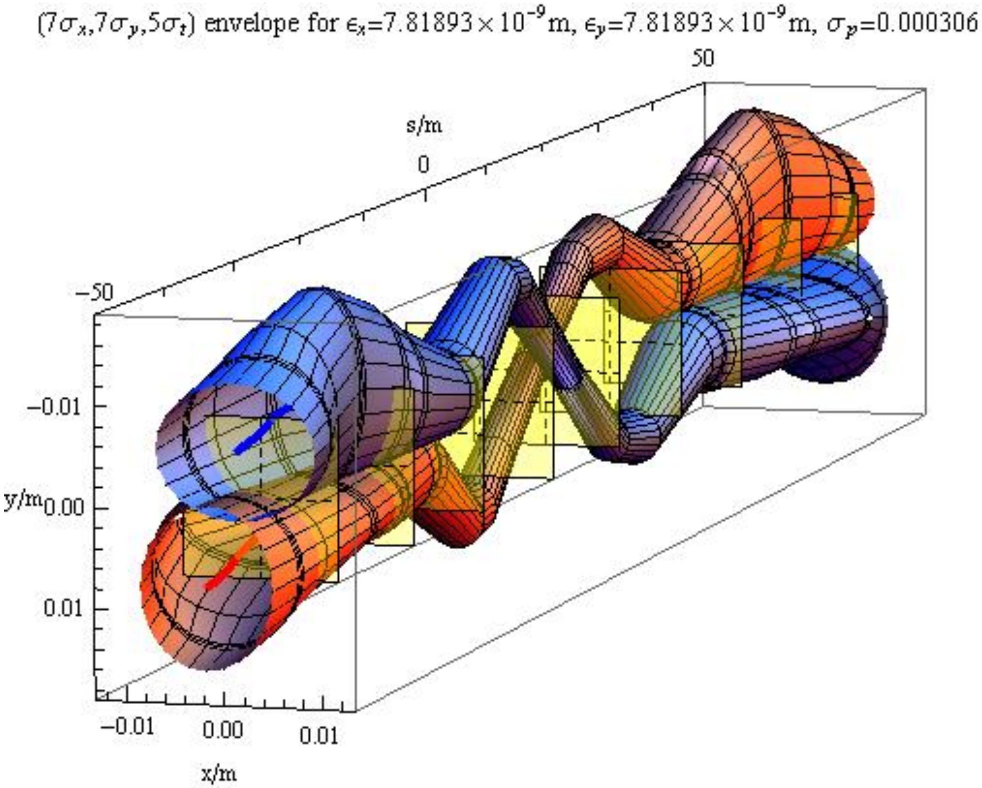
LHC: Identical bending field in both apertures of
two-in-one dipole – no choice

Outline of p-Pb physics cycle (Pb-p similar)

- Inject p beam in Ring 1, f_{RF1} for p
- Inject Pb beam in Ring 2, f_{RF2} for Pb
- Ramp both beams on central orbits
  - Orbit feedback decouples RF frequencies
- Bring f_{RF} together to lock, beams are slightly off central orbits
- RF re-phasing to position collision point
- Squeeze
- Change ALICE crossing angle to collision configuration
- Collide

At injection the proton beam makes 8 more revolutions per minute than the Pb beam

Beam envelopes around ALICE at injection

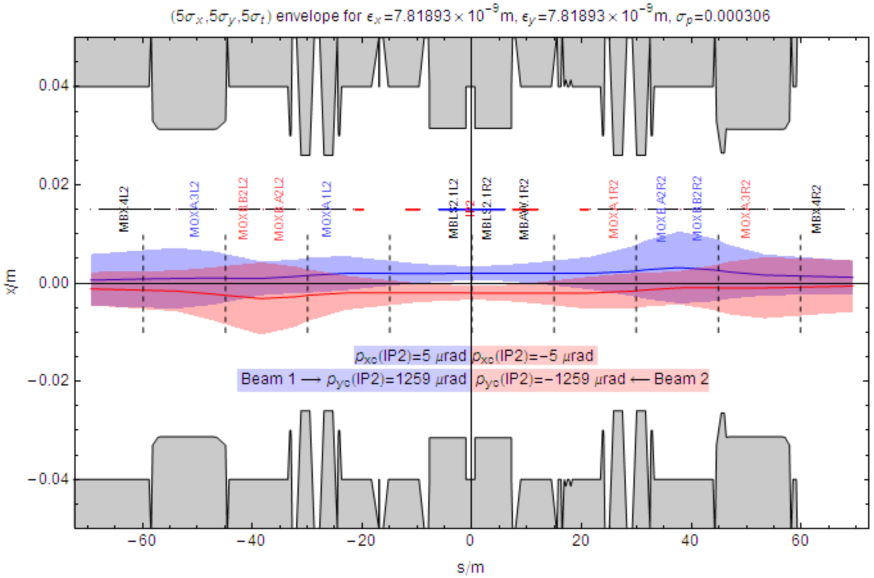


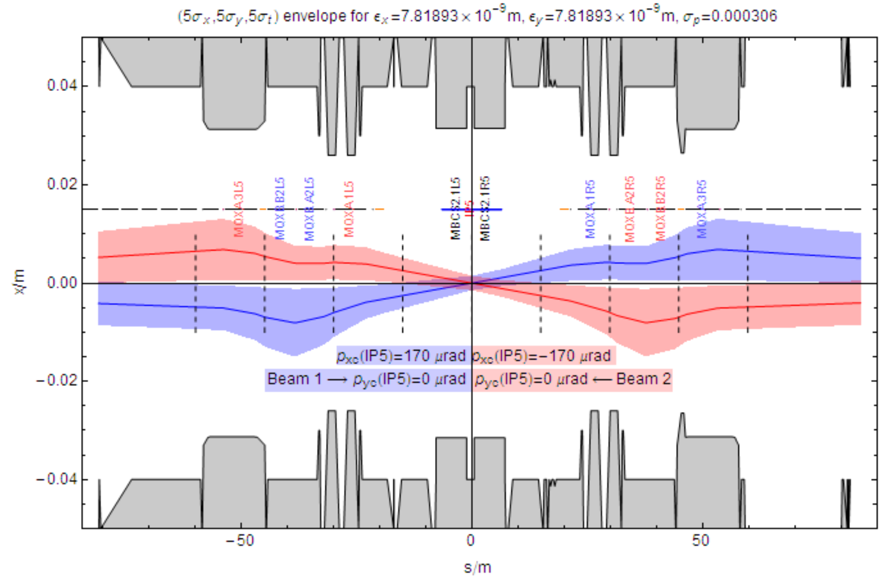
Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (also in physics).

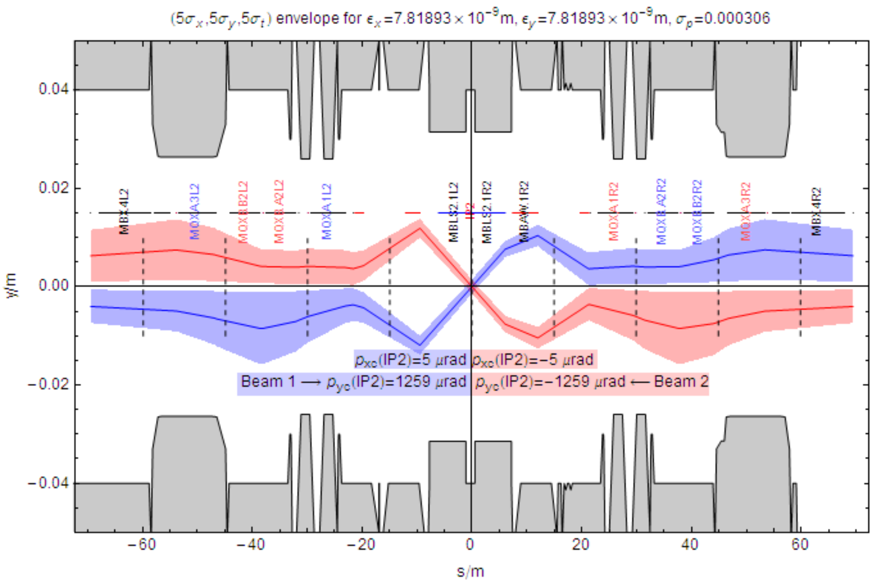
Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.

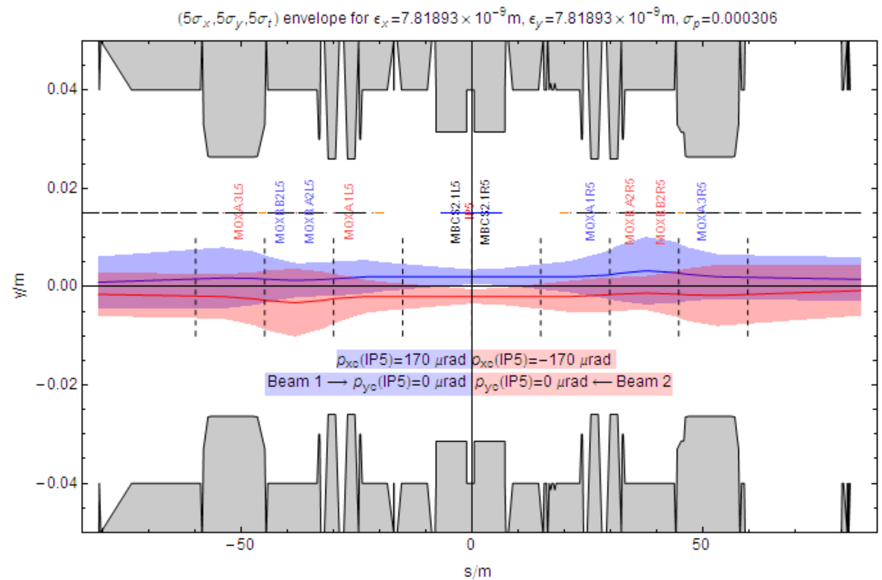
Other experiments have different separation schemes …

ALICE – Separation at injection - CMS

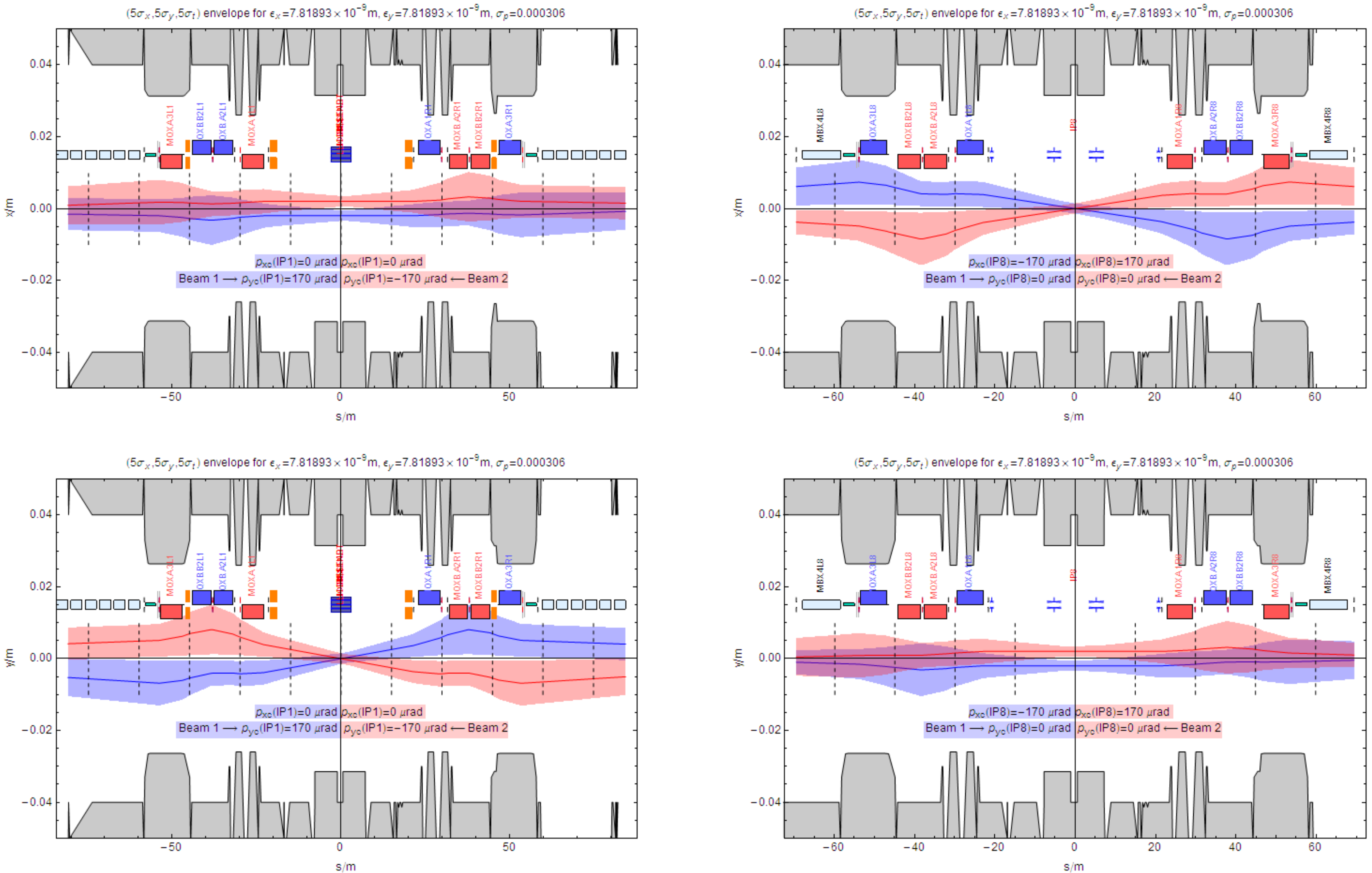








ATLAS - Separation at injection - LHCb



Long-range beam-beam effects

For separations x, y ? $\sigma_{x,y}$, the (angular) beam-beam kick on a particle of charge Ze, due to an opposing beam of total charge Ne is

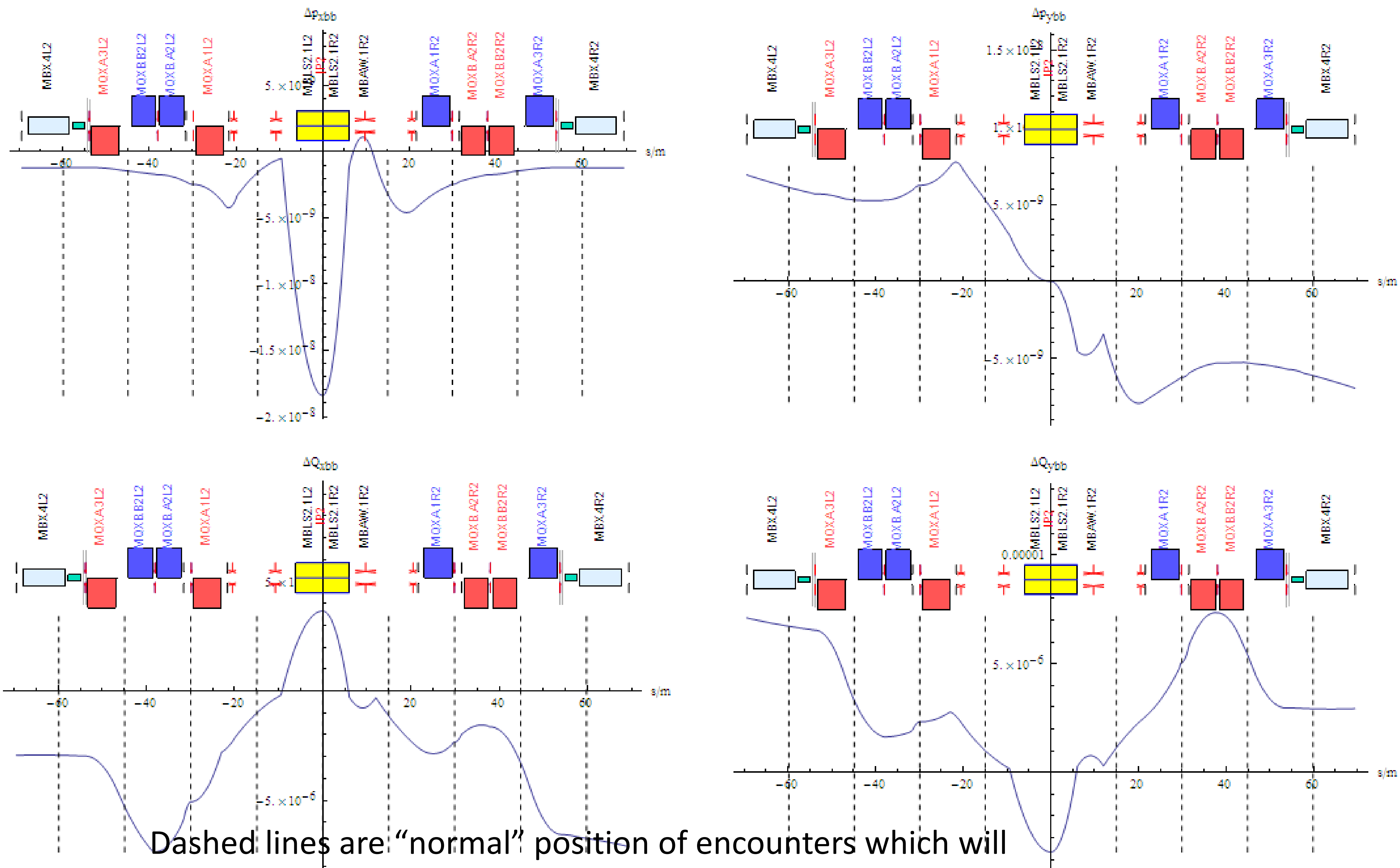
$$(\Delta p_x, \Delta p_y) = \frac{2ZNr_0}{\gamma} \frac{(x, y)}{x^2 + y^2}, \qquad \text{where} \quad r_0 = e^2 / (4\pi ò_0 mc^2)$$

and gives rise to perturbative betatron tune-shifts

$$\Delta Q_{x,y} = -\frac{\beta_{x,y}}{4\pi} \partial_{x,y} \Delta p_{x,y} = \frac{ZNr_0}{2\pi\gamma} \frac{(\beta_x, -\beta_y)(x^2 - y^2)}{(x^2 + y^2)^2}$$

LHC separation configurations were chosen to minimise the tune effects in physics ("footprint").

Example: beam-beam for Pb around ALICE



Dashed lines are "normal" position of encounters which will move 15 cm along IR on next turn …

Encounter points move at speed $V = \dfrac{v_{\mathrm{p}} - v_{\mathrm{Pb}}}{2} = 1734\ \mathrm{m/s} = 0.15\ \mathrm{m/turn}$

Hamiltonian is no longer periodic in s.

Excites modulational resonances

$$\underbrace{m_x Q_x + m_y Q_y}_{\substack{m_{x,y}=1,2,\ldots \\ \text{transverse modes}}} = p + \underbrace{k}_{\substack{\text{Bunch harmonic,} \\ 891 \\ \text{or at most } 3564}} \underbrace{\left(\frac{v_{\mathrm{p}} - v_{\mathrm{Pb}}}{2c}\right)}_{\substack{3.\times 10^{-6} \text{ at injection,} \\ \text{decreases in ramp}}} \; ; \quad m_x, m_y, p, k \in \mathbb{Z}$$

Known as "overlap knock-out resonances" at the ISR.

However with LHC tunes, $Q_x \approx 64.3, Q_x \approx 59.3$, only extremely high-order resonance conditions can be satisfied.

Very unlikely to be a problem (similar in RHIC, W. Fischer).

Diffusion models

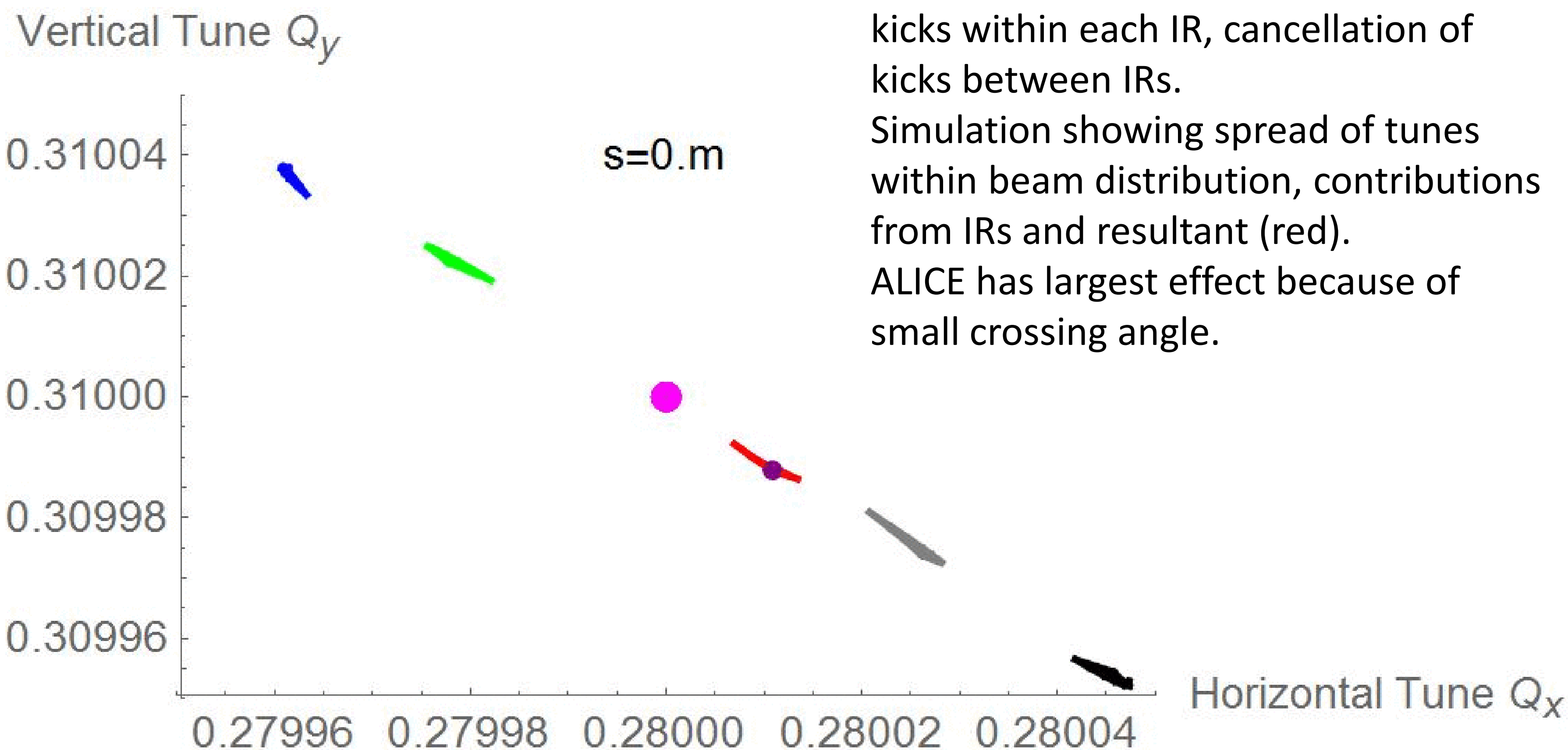
- Naively regarding the kicks as purely random
  - Works fairly well for RHIC data (W. Fischer)

$$\frac{d\varepsilon_{x,yn}}{dt} = \frac{1}{2} f_0 \sqrt{\gamma^2 - 1} \left[\beta_{x,y}(s) \left(\Delta p_{x,y}(s) \right)^2 \right]$$

where [..] denotes mean-square deviation
gives an emittance doubling time around 40 min

- Better calculate combination of beam-beam kicks on a particle on a given turn as the encounters move
  - Add them up with proper betatron phases
    - Partial compensations
  - Take out static component (closed-orbit) from long-term averaging and look at fluctuations around it
  - RMS fluctuation gives emittance growth rate
- More elaborate simulation models (Marc Jebramcik) now providing further understanding of differences in beam dynamics between RHIC and LHC

One way to see why p-Pb injection works in LHC



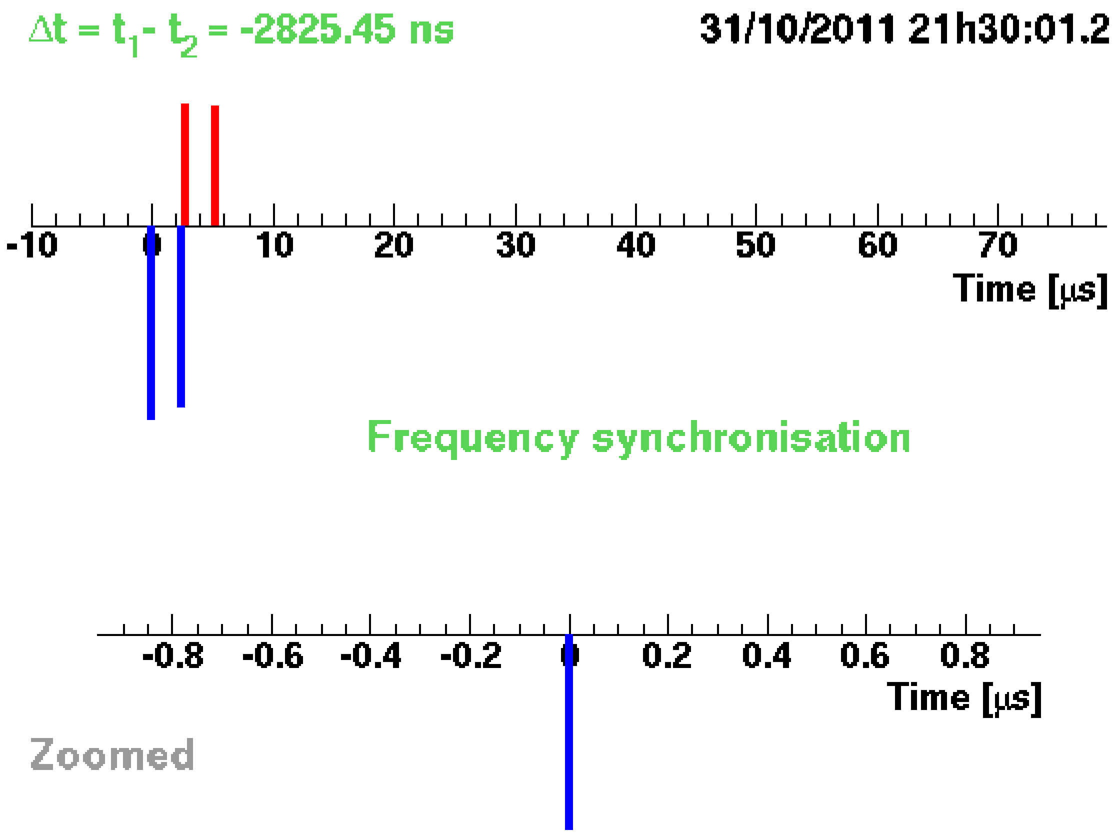
Modulation of beam-beam kicks as encounters slide along IRs due to unequal revolution frequencies.
At LHC, unlike RHIC, effects are less (higher energy, some compensation of kicks within each IR, cancellation of kicks between IRs.
Simulation showing spread of tunes within beam distribution, contributions from IRs and resultant (red).
ALICE has largest effect because of small crossing angle.

M.A. Jebramcik

History of proton-nucleus collisions at LHC (2)

- 2006 First paper at European Particle Accelerator Conference, in Edinburgh
- Early 2011, LHC Chamonix workshop – go-ahead given for feasibility tests on LHC
- Preparation of LHC systems during 2011
- 31/10/2011 successful feasibility test
- Early 2012, after high Pb-Pb luminosity in Nov 2011, experiments *really* want p-Pb comparison data
- 13/9/2012 Successful pilot collision run (one night) yields new physics - the largest jump in collision energy, factor 25 (of given collision type), in history of particle accelerators
- Jan-Feb 2013 first full physics run
- Nov 2016 second run, multiple collision conditions including higher energy, almost 9 times “design” luminosity

Ramping, then moving the collision point by 9 km



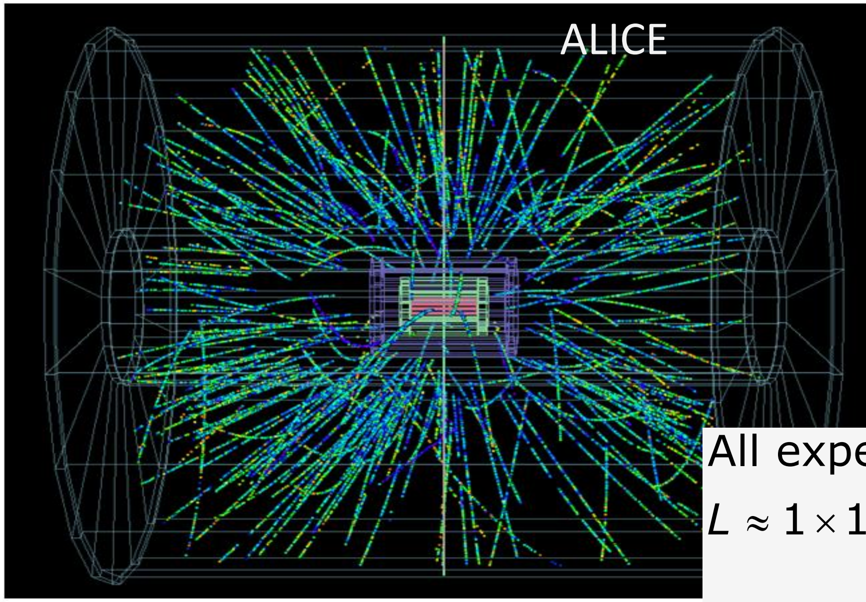
Real-time clock

RF cogging by Philippe Baudrenghien

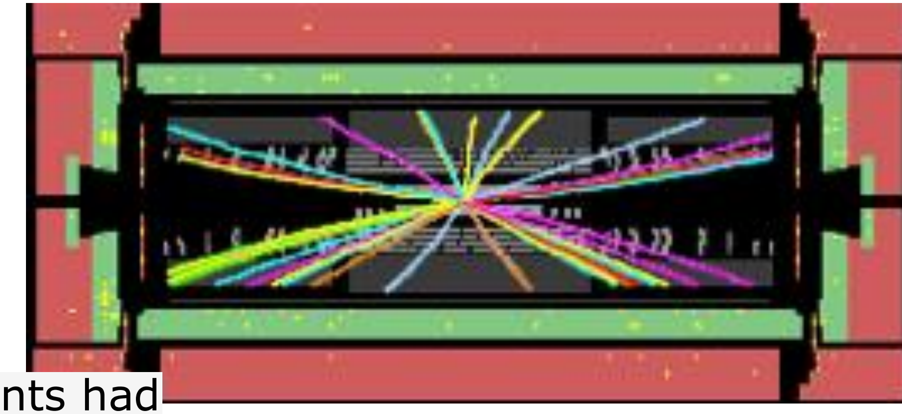
Video from BPTX beam position monitor timing data by Thilo Pauly (ATLAS)

This was the first time, later this was done much more quickly.

Collisions in all experiments

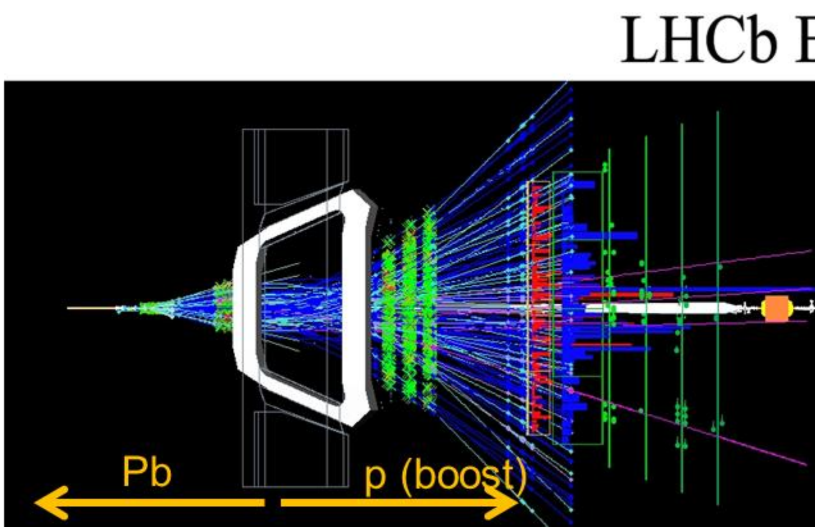


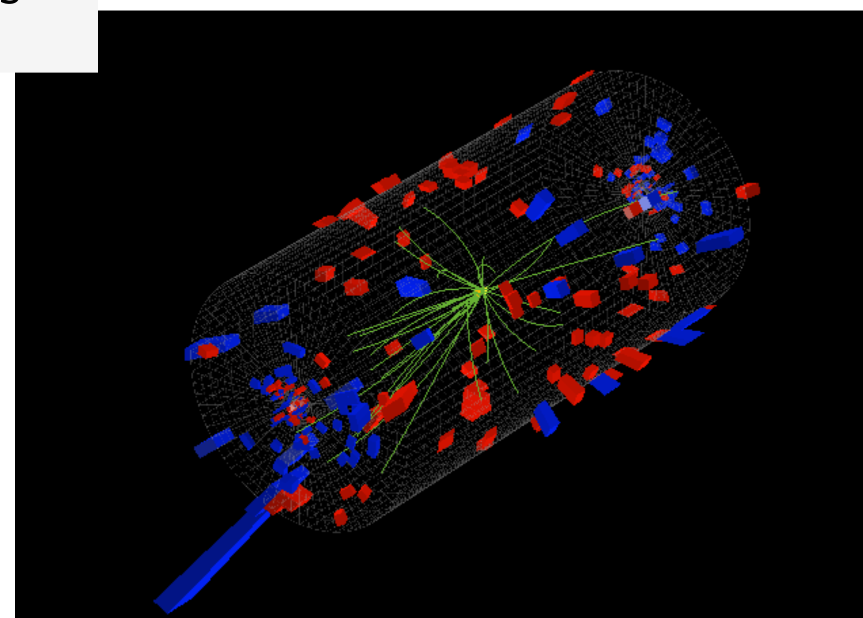
ATLAS



All experiments had

$L \approx 1 \times 10^{26}\ \text{cm}^{-2}\text{s}^{-1}$





CMS

Some of the members of the ion team celebrate proton–ion collisions in the CERN control centre, but the road to success is not always easy.

Reine Versteegen

Michaela Schaumann

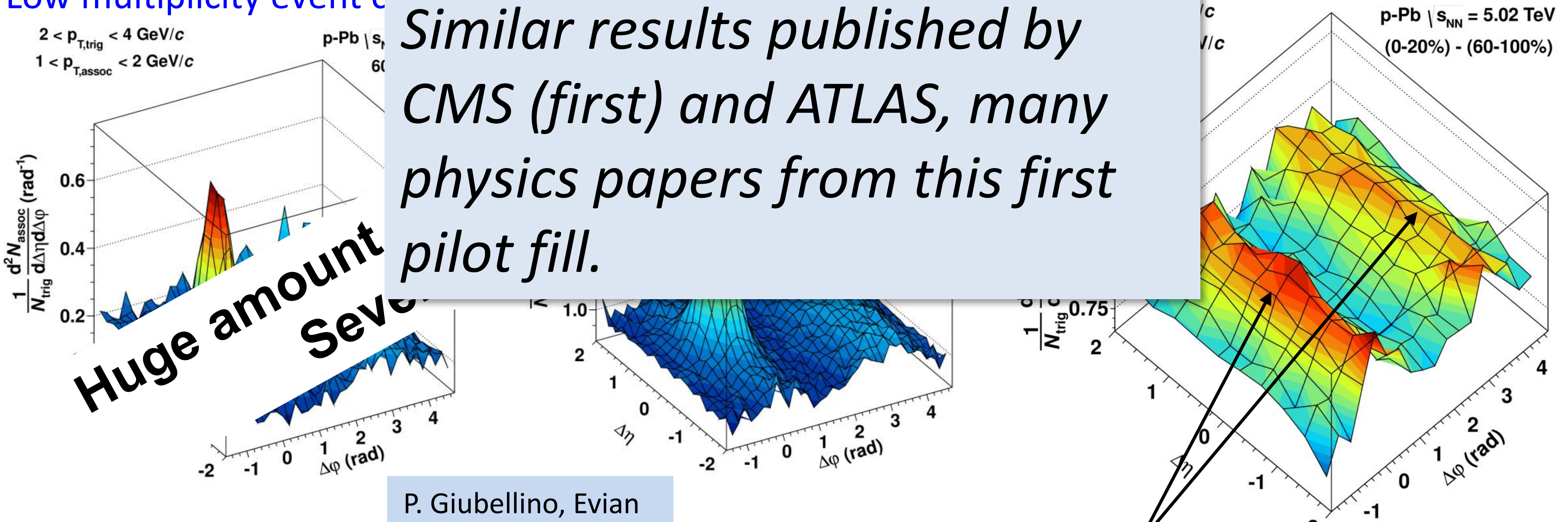
Reyes Alemany-Fernandez

Carlos Salgado (guest theorist)

- A double-ridge structure appears, with remarkable properties:
  - Can be expressed in terms of $v_{2,3}$, Fourier coefficients of single particle distribution, with $V_{2,3}$ increasing with p_T and v_2 also with multiplicity
  - **Same yield near and away side for all classes of p_T and multiplicity: common underlying process**
  - Width independent of yield
  - No suppression of away side observed (its observation a… …t RHIC is considered a sign of saturation effects)
  - In agreement with viscous hydro calculations ?'…

…ing a new window in the field
…4 h of collisions

Low multiplicity event c…



Huge amount …
Seve…

Similar results published by CMS (first) and ATLAS, many physics papers from this first pilot fill.

P. Giubellino, Evian Dec 2012

Double-ridge structure

Proton-nucleus programme status

Feasibility and first run at 4 Z TeV in 2012/13.

Complex 2016 run plan determined after Chamonix 2016:

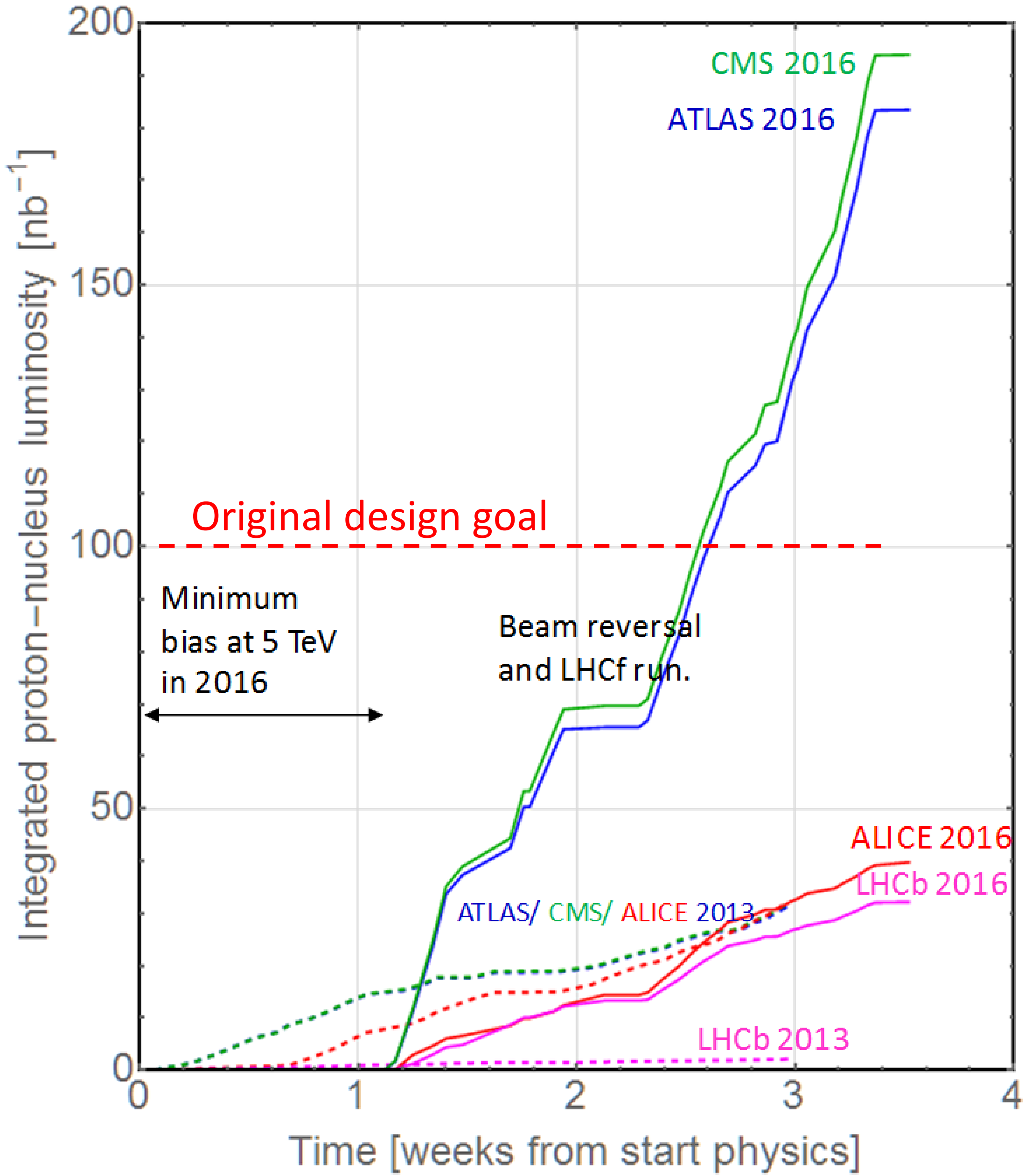
Minimum bias run at 4 Z TeV mainly for ALICE

High luminosity run for all experiments (+LHCf) at 6.5 Z TeV, with beam reversal p-Pb and Pb-p.

Ie, 2 new optics and 3 setups with full qualifications in 1 month.

Asymmetric beams, unequal frequency ramp, cogging for collisions off-momentum, etc.

Many filling schemes used for luminosity sharing.



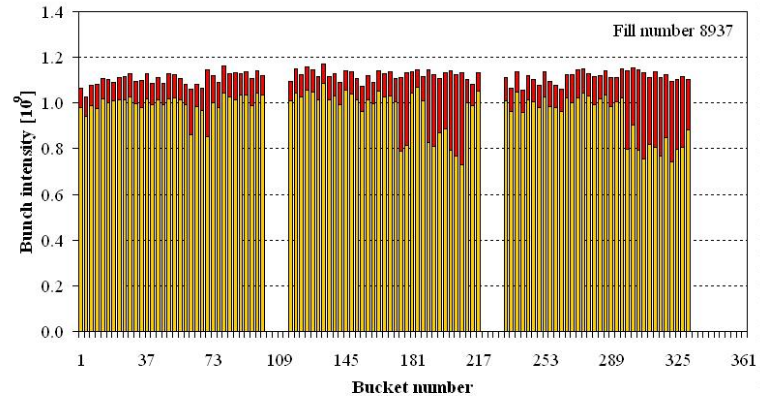
ULTIMATE MODES OF HADRON COLLIDER OPERATION

Cooling beams to collide (nearly) all the particles

Performance limits – RHIC ions, high energy

- Bunch intensity N_b, limited by
  injectors => EBIS, bunch merges in
  Booster and AGS
  transition instability
  aim for 2x10^9 in store ultimately

$$L(t) = \frac{1}{4\pi} f_0 N \frac{N_b^2(t)}{\varepsilon(t)\beta^*(t)} h(\beta^*, \sigma_s, \theta)$$



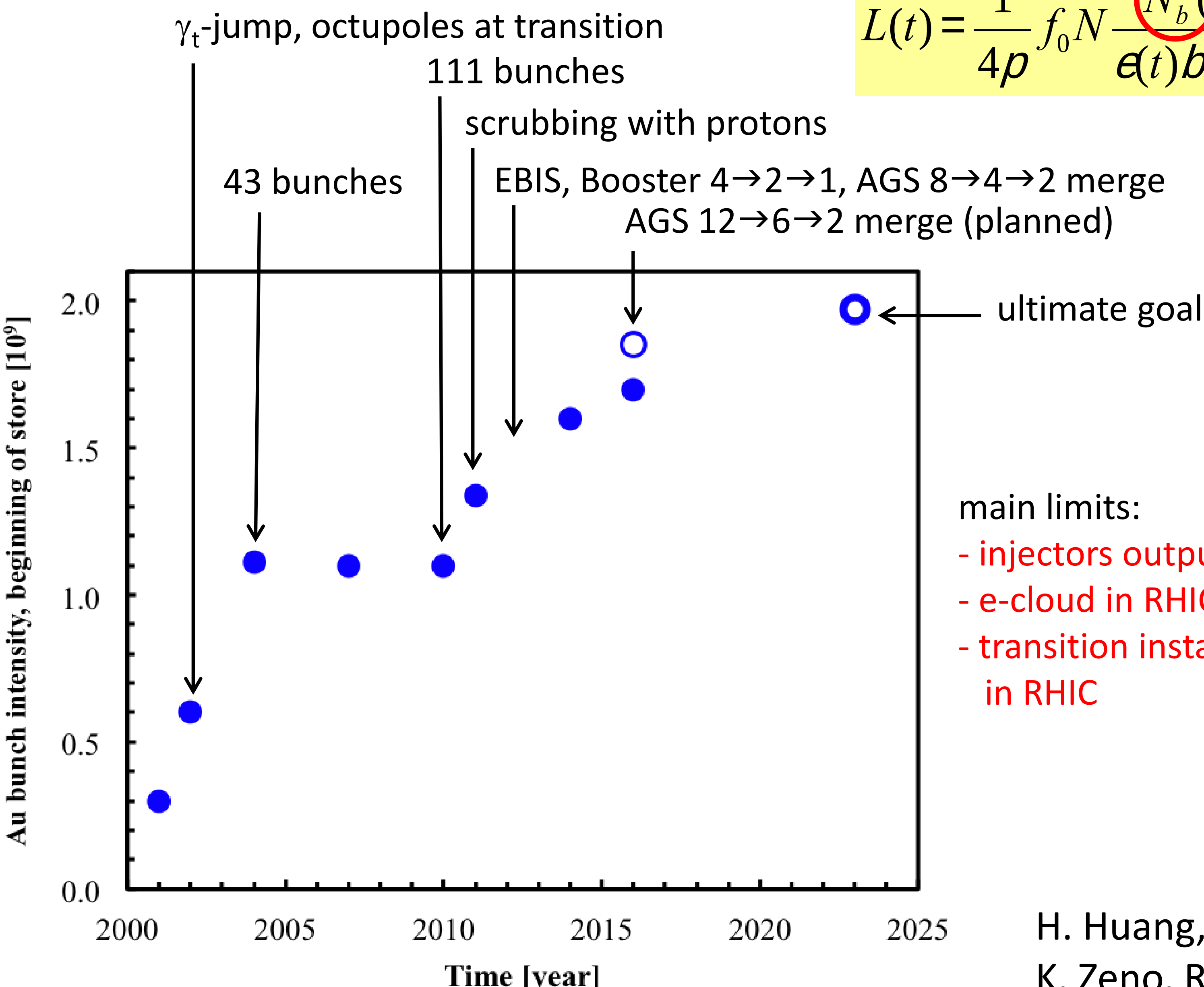
- Intrabeam scattering
  => stochastic cooling
  => 56 MHz SRF (stronger longitudinal focusing)

- Lattice with small β* and large off-momentum dynamic aperture
  with hourglass factor ≈0.5 at end of store, need large β* reduction
  any lattice change must not result in additional beam losses
  (momentum spread with 56 MHz SRF will be increased)
  dynamic β* reduction after emittance decreased by cooling

•Goal is to have burn-off as the dominant beam loss mechanism.

Au bunch intensity evolution

$$L(t) = \frac{1}{4\pi} f_0 N \frac{N_b^2(t)}{\varepsilon(t)\beta^*(t)} h(\beta^*, \sigma_s, \theta)$$

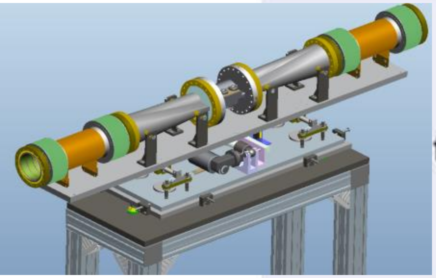


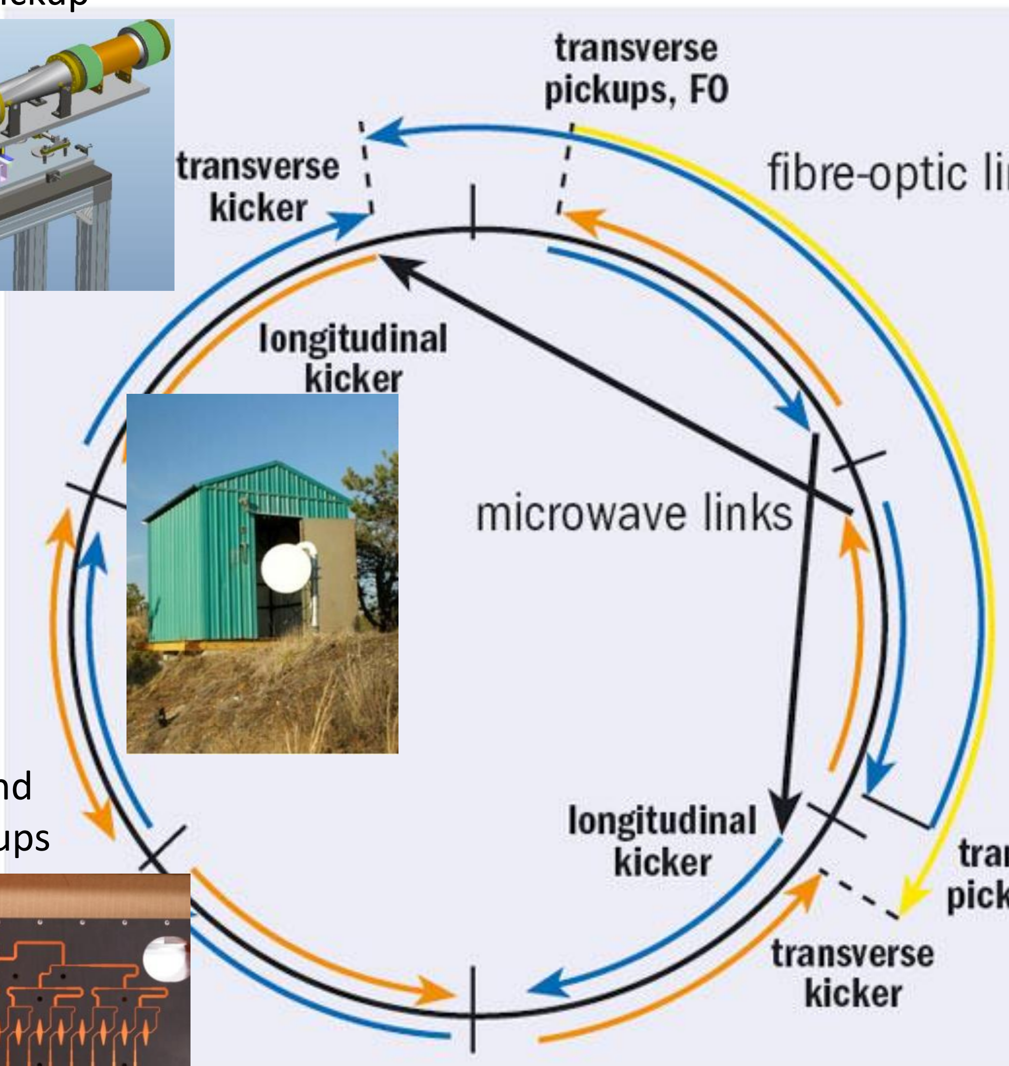
main limits:
- injectors output
- e-cloud in RHIC
- transition instability
  in RHIC

H. Huang, K. Gardner,
K. Zeno, RF, et al.

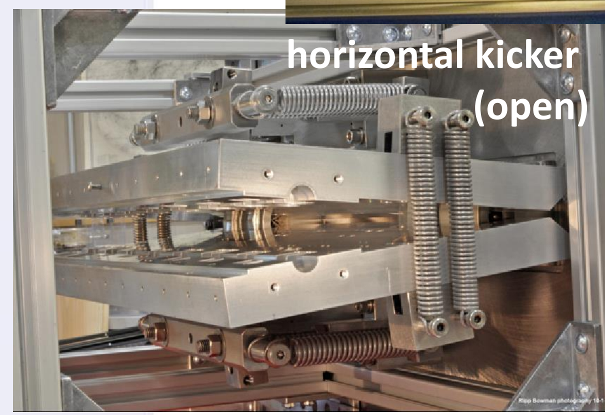
3D stochastic cooling for heavy ions

longitudinal pickup

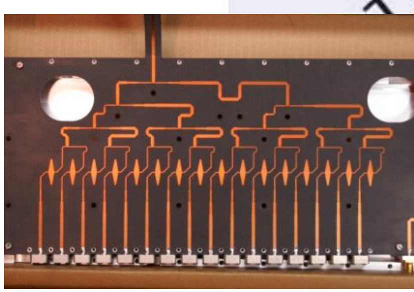




longitudinal kicker cavity (half side with waveguides)



horizontal and vertical pickups

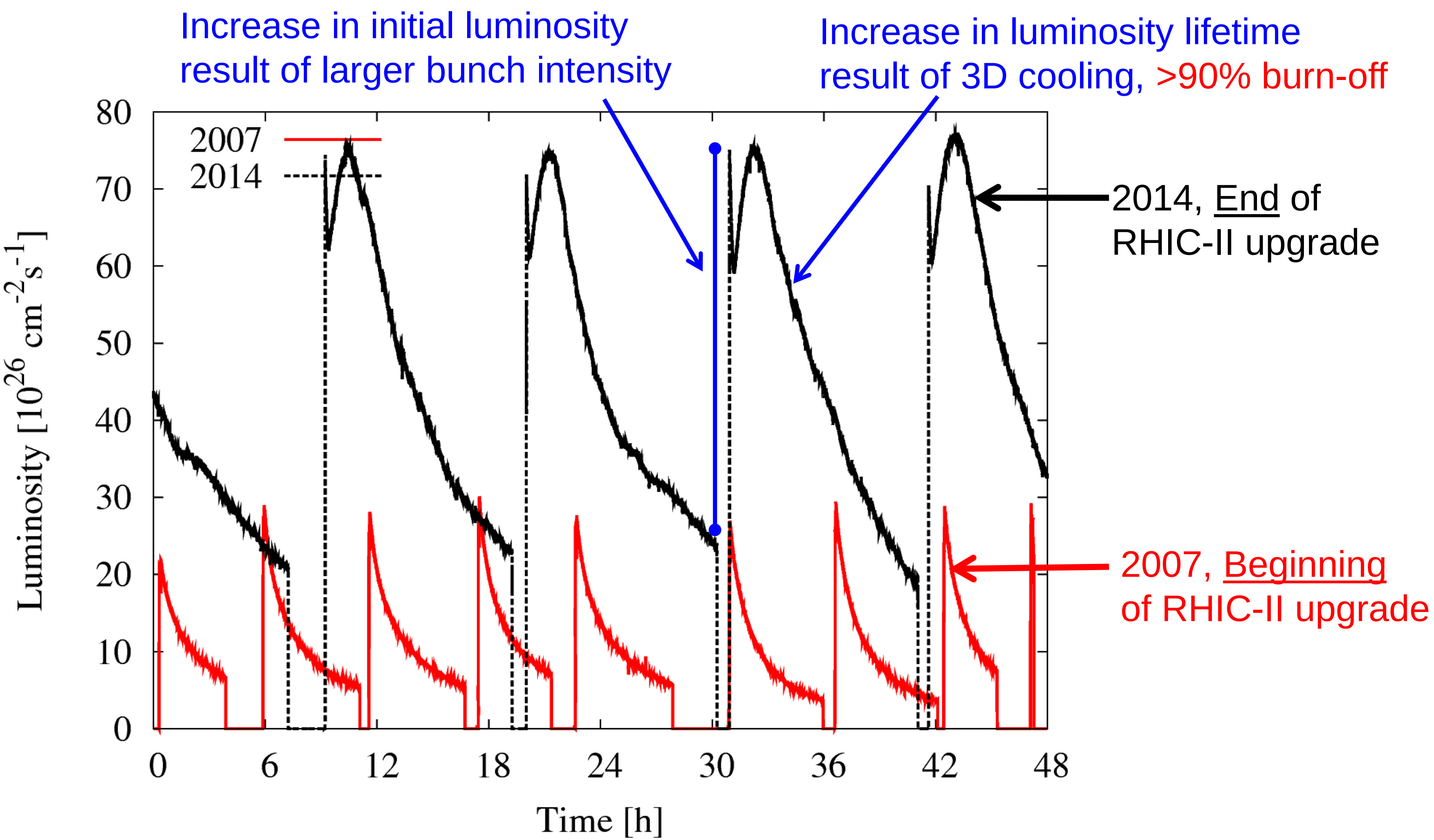


vertical kicker (closed)

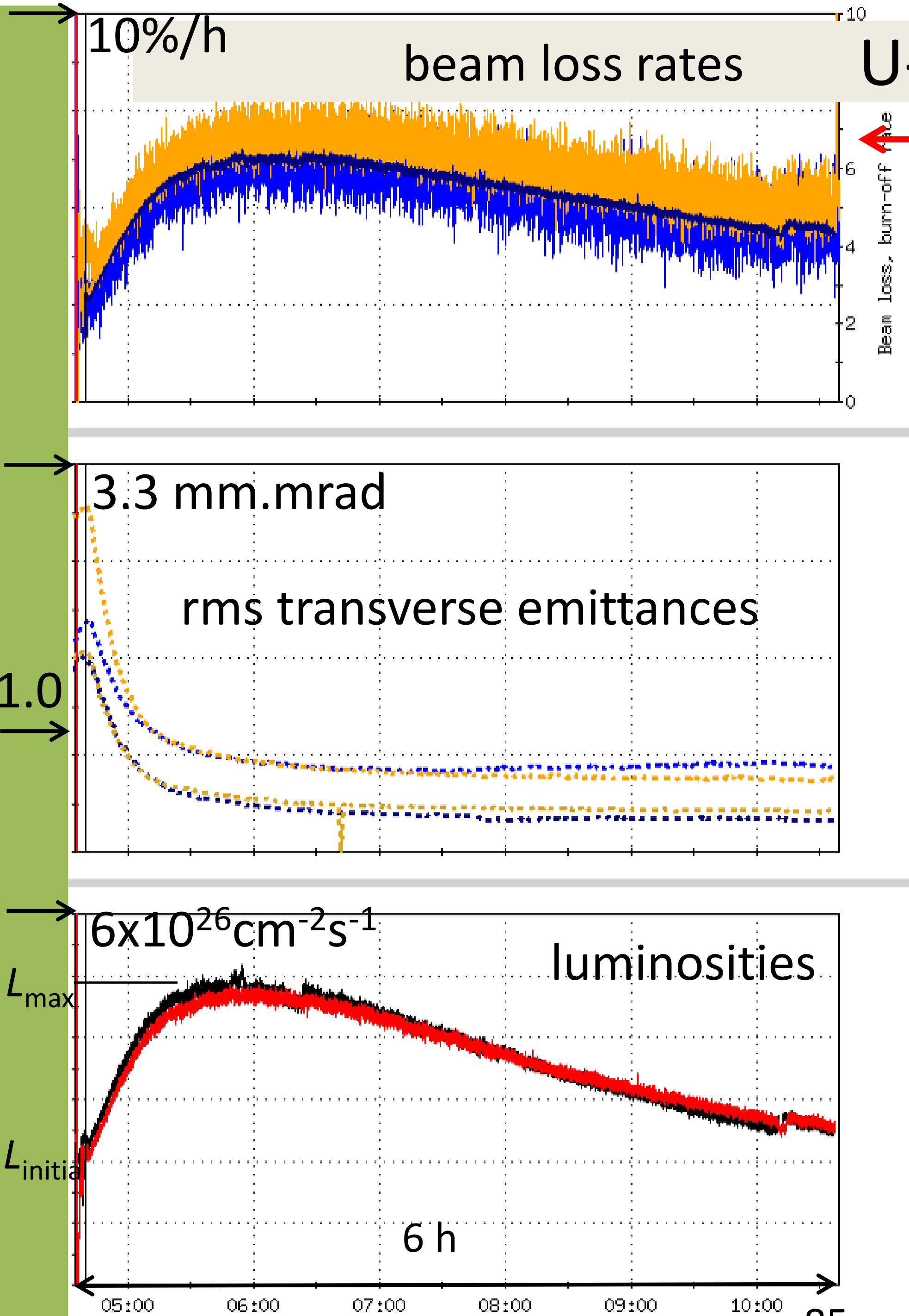
5-9 GHz, cooling times ~1 h

M. Brennan, M. Blaskiewicz, F. Severino, PRL **100** 174803 (2008); K. Mernick PRSTAB, PAC, EPAC

Delivering RHIC-II luminosity



U-U store – new mode in 2012



(1) Lattice optimized for large off-momentum dynamic aperture, not for smallest β* (Y. Luo)

$$L \propto \frac{N_b^2}{\beta^*} H\left(\frac{\beta^*}{\sigma_s}\right)$$

(2) Minimum loss rates given by total U-U cross sections, 2 largest contributions from BFPP and EMD:

	Au-Au	U-U
BFPP	117 b	329 b
EMD	99 b	160 b

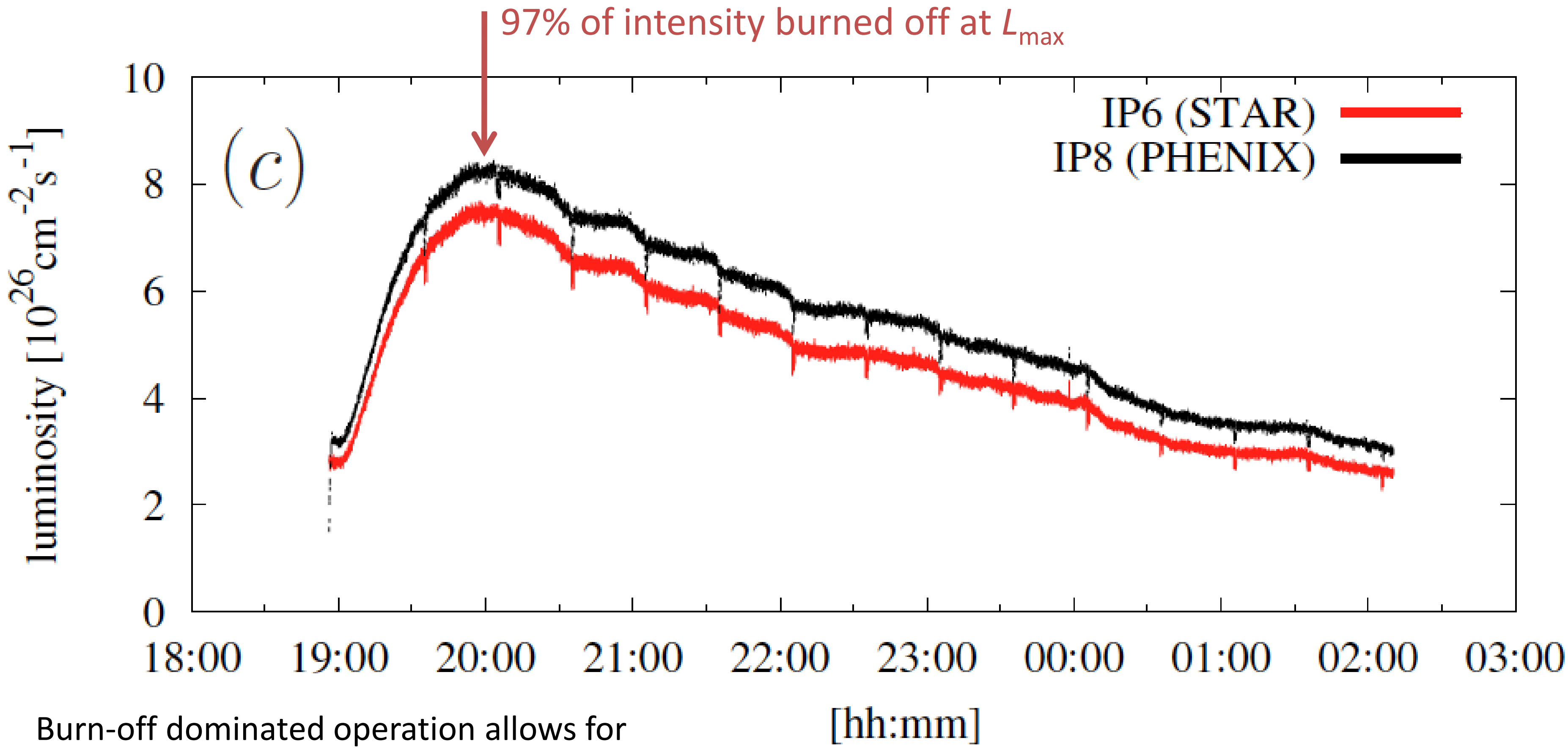
$\sigma_{BFPP} \propto Z^7$

Nearly all beam loss though luminosity (burn-off)!

3D stochastic cooling leads to new feature in hadron collider:

$L_{max} > L_{initial}$

Operation at burn-off limit in U+U



Burn-off dominated operation allows for determination of total U+U cross section – and comparison with calculation (mostly QED) (published in Phys. Rev. C) =>

$$\frac{dN_B(t)}{dt} = \frac{dN_Y(t)}{dt} = -\left[\mathcal{L}_6(t) + \mathcal{L}_8(t)\right]\sigma_{tot}$$

Measurement of the total cross section of uranium-uranium collisions at $\sqrt{s_{NN}} = 192.8$ GeV

tz, M. Blaskiewicz, D. Gassner, K.A. Drees, Y. Luo, M. Minty, P. Thieberger, and M. Wilinski
Brookhaven National Laboratory, Upton, NY 11973, USA

I.A. Pshenichnov
Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

Heavy ion cross sections totaling several hundred barns have been calculated previously for the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). These total cross

FCC Pb-Pb General Parameters

	LHC achieved	HL-LHC baseline	FCC-hh baseline	FCC-hh ultimate
Circumference	26.66 km		**97.75 km**	
Beam Energy [Z TeV]	6.5	7	**50**	
β-function at the IP [m]	0.6	0.5	**1.1**	**0.3**
No. Ions per bunch [1e8]	2.2	1.8	**2.0**	
Transv. normalised emittance [μm.rad]	~1.5	1.65	**1.5**	
Bunch spacing [ns]	100	50	**100**	**50**
Number of bunches	518	1256	**2760**	**5400**
Stored energy/beam [MJ]	10	21	**362**	**709**
Stored energy/beam at Injection [MJ]	0.7	1.5	**24**	**47**

new layout

LHC experience

30% larger beam size as protons

more than 10x smaller as for protons

Beam Evolution Studies

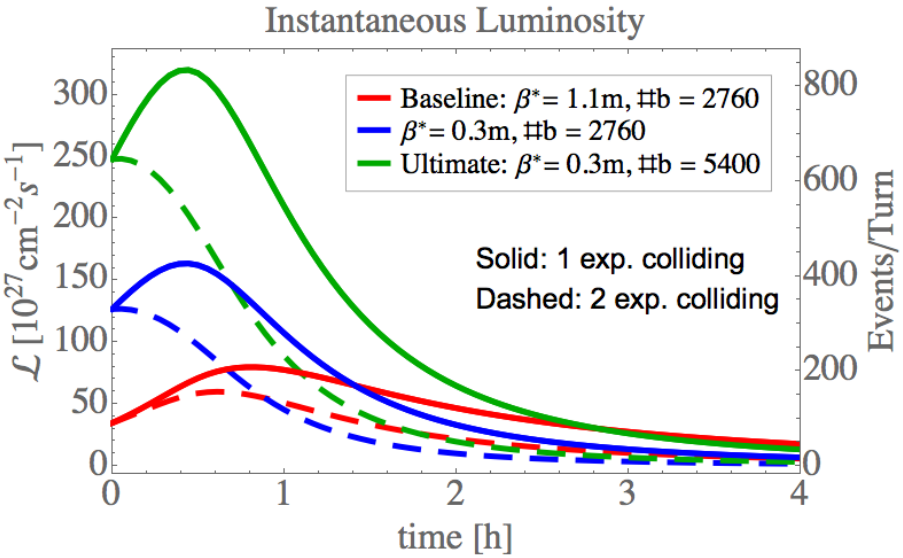
- Time evolution of beam parameters obtained from numerical solution of a **system of four coupled differential equations**
  - dN/dt, $d\varepsilon_{xy}/dt$, $d\sigma_s/dt$.
  - Includes luminosity burn-off, intra-beam scattering (IBS) and synchrotron radiation damping

- Pb damps ~2x faster than protons.
  - radiation damping times for Pb ~0.5h

- Initial IBS is weak, but damping is very fast.
  → Fast emittance decrease at the beginning of the fill until IBS starts to counteract the damping.

Plots of beam evolution can be found in the Extra Slides.

Pb-Pb Luminosity Evolution



Scenarios:

- Baseline and Ultimate
- 1 (solid) and 2 (dashed) experiments in collisions in **main IPs**

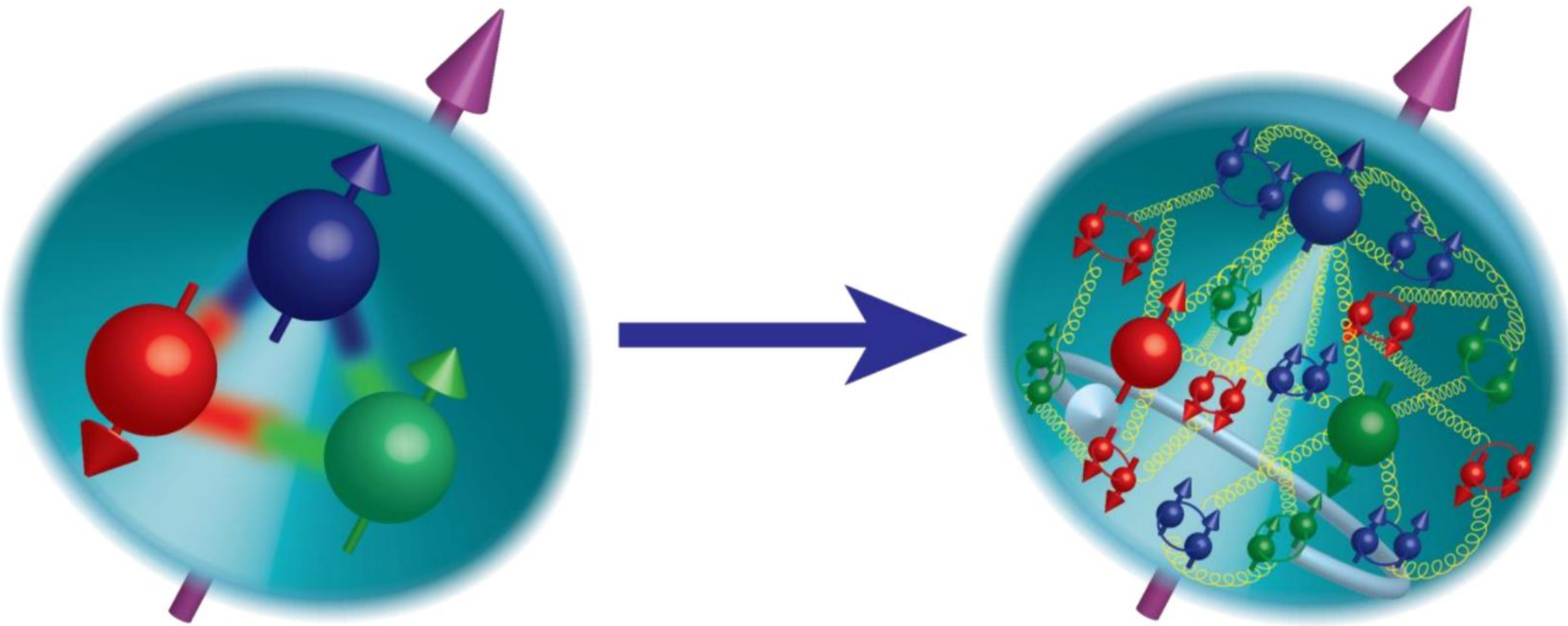
The available total integrated luminosity is shared.

Case of a special heavy-ion experiment installed in secondary IP:
→ *larger β*, less colliding bunches*
→ Luminosity would be reduced
→ We do NOT consider this scenario at present.

Electron-Ion Collider

- Proposed for construction in USA
  - Potentially the first “Future Collider” to be built in the world
- Two candidate designs:
  - eRHIC at Brookhaven National Lab
    - Uses existing RHIC ring and adds electron ring
  - JLEIC at Jefferson Lab
    - Uses existing CEBAF electron accelerator, adds hadron and electron rings
- Both designs aim to collide e- and eA with eN luminosity comparable to LHC and both beams polarized.
  - ~1000 times ep luminosity of HERA
  - Huge range of new accelerator concepts and technology to be deployed.

One Electron-Ion Collider physics topic: structure of proton



1970s picture: proton was composed of three valence quarks, with spins neatly adding up to observed total spin 1⁄2.

21st century: quarks, sea quark-antiquark pairs and gluons;
total spin is composed of that of the elementary spins (colored arrows) and orbital motion (light blue arrow).

Courtesy: Zein-Eddine Meziani

Take-home messages

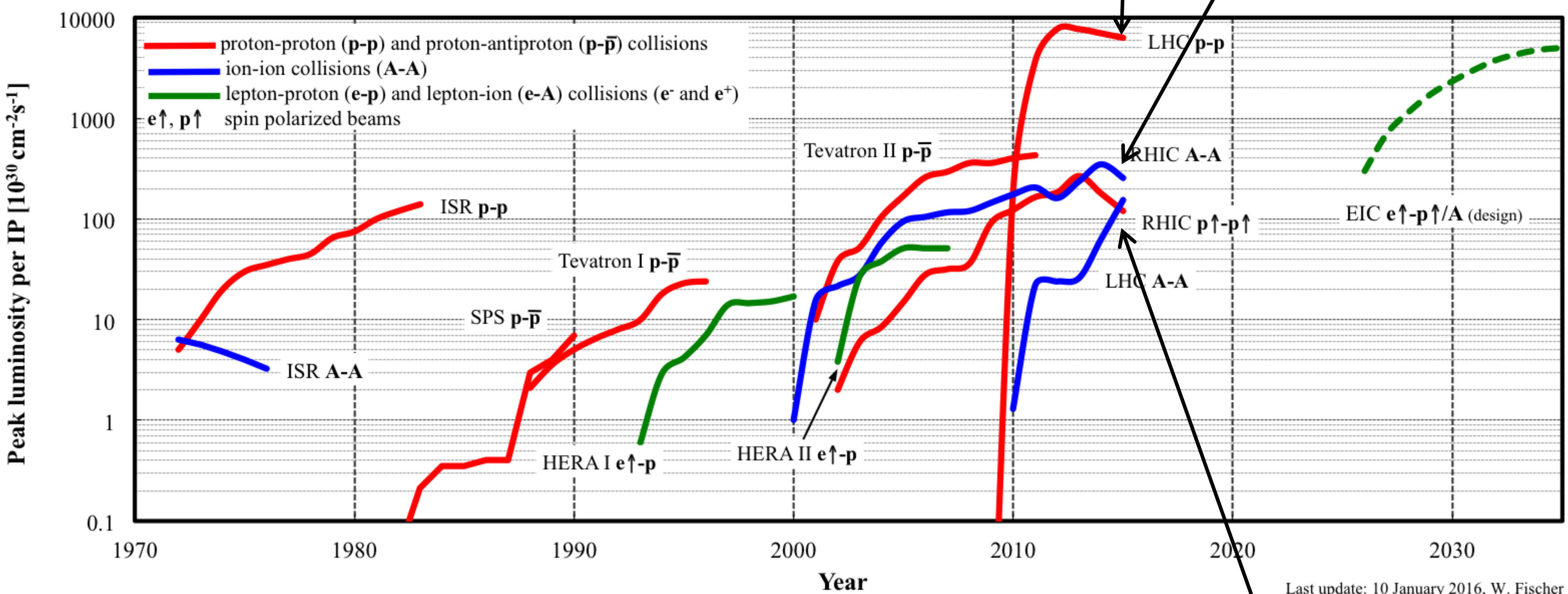
- Large colliders are most often built to find or measure the properties of elementary particles
  - Always the focus of project management …
- But they can do more … sometimes at low cost.
- Nuclear collisions at RHIC and LHC have greatly extended a whole new field of physics
  - (following previous fixed target)
- There are other examples which may also have important physics cases:
  - Polarized beams, e+e-, ep, eA, pp, pd, ^{3}He, …
  - Monochromatized (e+e-) beams, …
- Diversity pays off, not only in collider physicists, but in the colliders themselves.
- Talk to, and understand, your physics community!

BACKUP SLIDES

Hadron collider luminosities

LHC 25 ns bunch spacing at 6.5 TeV
(previously 50 ns at 4 TeV, e-cloud)

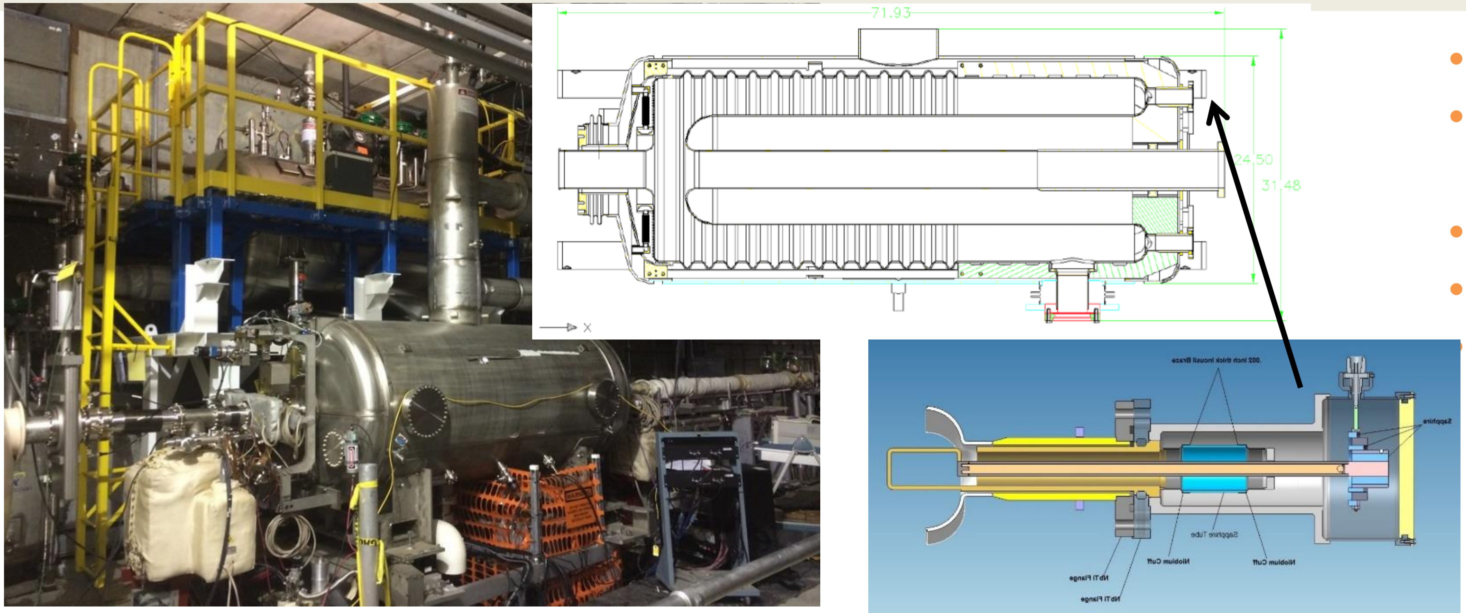
RHIC 100 GeV p↑+p↑
(previously 255 GeV)



average or leveled luminosity L_{avg} now more important than peak luminosity L_{peak} (burn-off in RHIC, pile-up limit in LHC)

RHIC p↑+A
(previously A+A,
cool only 1 beam)

RHIC 56 MHz SRF



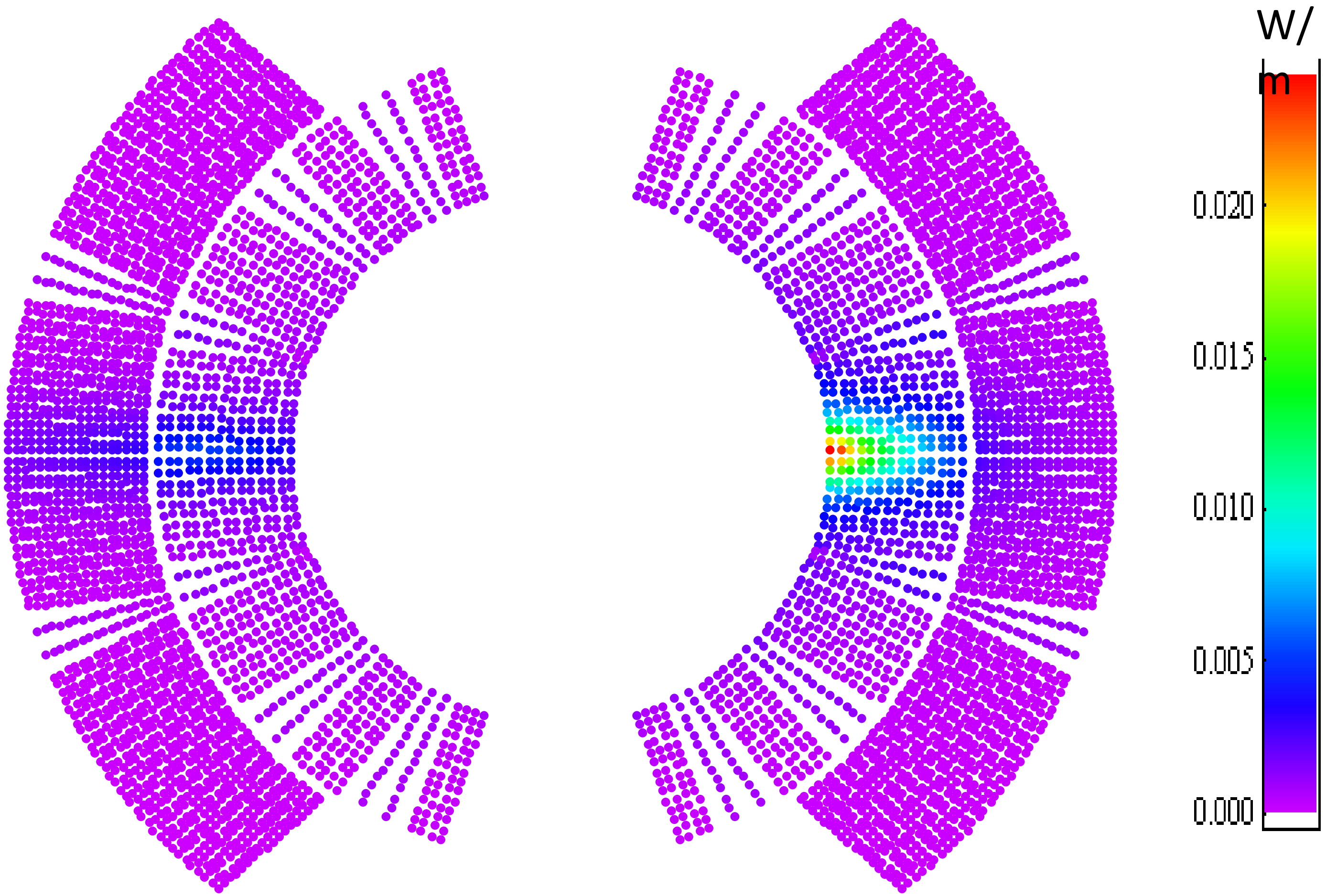
- λ/4 Nb resonator
- common to both beams
- beam driven
- 56 MHz, 2 MV
- L +30−50%

- quenches in re-designed HOM damper (installed for beam stability) limit voltage to ~420 kV (reached design without HOM damper)
- Removed HOM damper for Run-16 again

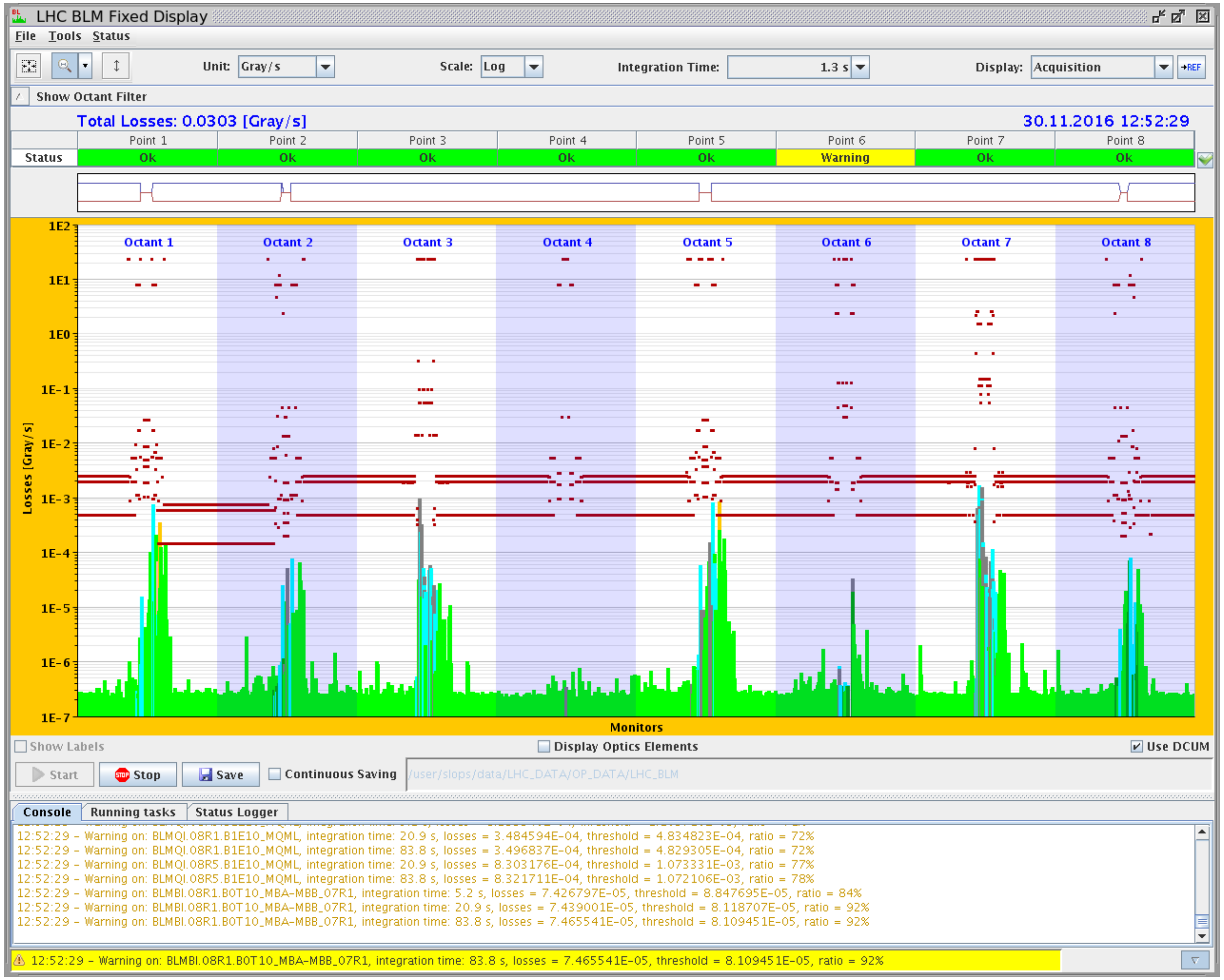
- Plan for Run-16:
  - Use Fundamental Mode Damper (FMD) at partially retraction position
  - 500 kW power extracted at 2 MV, need to limit power to 10 kW
  - If successful (voltage turn-on without beam instability), expect up to 1 MV

Input to network simulation

- Combining detailed simulated energy deposition from "real beam loss" with thermal network model of magnet
- input to network model:

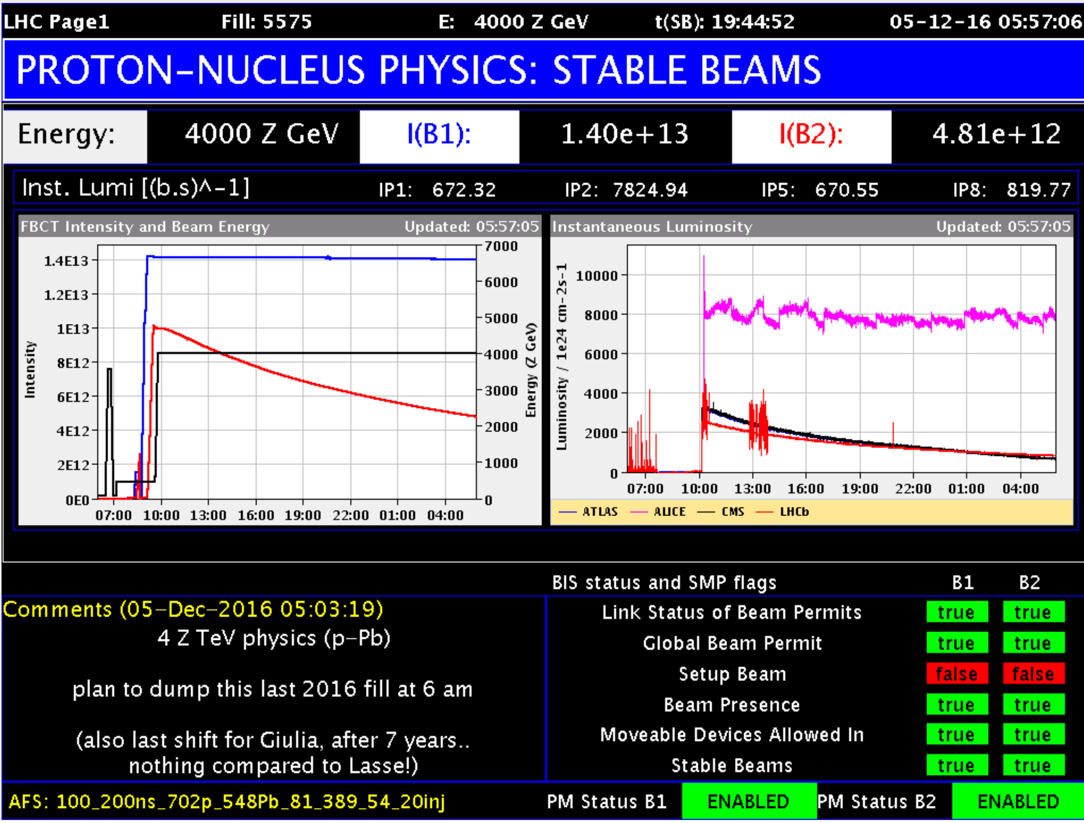


Peak luminosity limited by Pb luminosity debris



- BLMs over 92% of threshold in Sector 12, Pb beam luminosity debris, right of IP1
- Similar losses right of IP5
- Discussion with Machine Protection, decided not to change thresholds at this stage, limit p intensity, manually limit luminosity at start of fill for last few days.

Last LHC fill of 2016 - back to p-Pb at 5 TeV

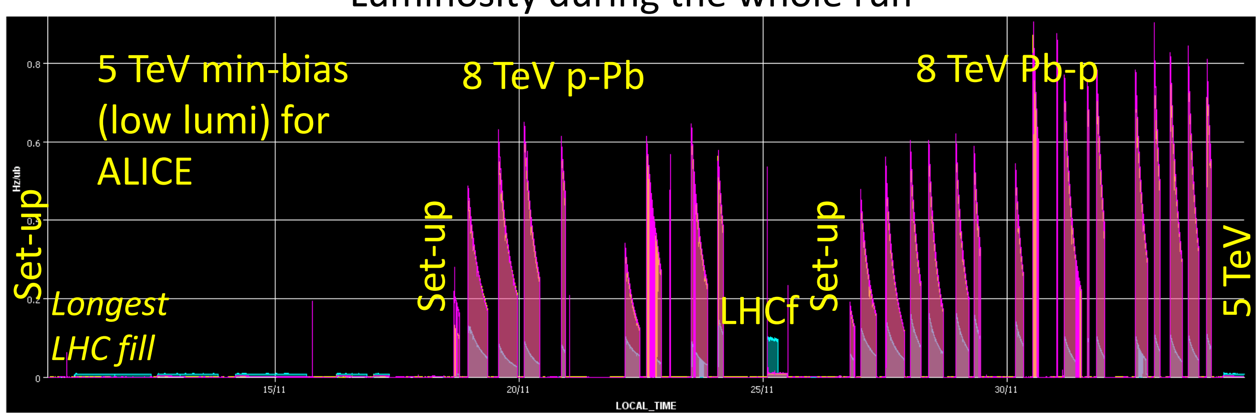


Fast switch back to original conditions to top-off ALICE minimum-bias data-taking.

Levelled 19h50 in Stable Beams, dumped at 06:02 Monday 5 Dec.

Complex run made possible by extraordinary quality of LHC construction and operation, excellent performance of ALL the injectors together.

Luminosity during the whole run



Outline plan

- Physics motivation
  - Quark-gluon plasma and early universe ,
  - single particle dynamics vs collective phenomena
  - perfect liquid, collectivity on smallest scales
  - Event images - high multiplicities
  - Statistical phenomena,
  - Much of the surprising physics discovered at LHC and RHIC
- Basics of ion beams
  - Just a charged particle with a mass!!
  - Relations of charge, mass/A, energy /Z /A, gamma,
  - Energy per nucleon never relevant in accelerator physics
  - Equivalent proton energy
  - Pp and e+e- colliders- problems come from high charge per bunch, HI colliders problems come from high charge/particle
  - Low energy ion accelerators, kinetic energy
- Collisions of heavy nuclei
  - CM energy for equal B rings (not RHIC), CM rapidity exercise
  - LHC > 1 PeV but sNN
  - LHC runs different species at same sNN
  - Energy density and temperature in collisions
    - European energy production in speck of dust exercise
  - Luminosity, AA or NN
  - Nuclear collisions
    - Accelerator physics and nuclear physics become closely intertwined
  - Ultraperipheral collisions
    - Weizsacker Williams and virtual quanta
    - Some key processes
      - Photonuclear EMD
      - Pair production copious
        - » BFPP
    - HI collisions also make the simplest events, show ALICE example Jpsi

Outline

- ISR, RHIC, LHC
- All hadron colliders are now HI colliders, all experiments, fraction of papers

- Injectors
  - LHC and RHIC examples
  - Luminosity depends on
- Optics, collisions schemes
  - Special requirements for ZDCs, forward neutrons
- Beam kinetics
  - Nuclei radiate coherently for synchrotron radiation
  - Radiation damping twice that of p
  - IBS
  - Luminosity burn off
  - Minimum bias p-Pb in LHC 2016
- Beam losses
  - BFPP luminosity limit
  - Quench test using nonlinear QED
  - Collimation of nuclear beams
- Asymmetric collisions
  - ISR
  - RHIC
  - LHC
- Future after LHC
  - FCC (or maybe HE-LHC)
- Near future
  - EIC likely the world's next collider but in USA
    - Perhaps you will go and work on it?
    - Strucure of the nucleon, gluons, spin puzzle
    - Challenges of luminosity, polarization, species, cooling