THE LHC AS A PROTON-NUCLEUS COLLIDER

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Abstract: Following its initial operation as a proton-proton (p-p) and heavy-ion ($^{208}Pb^{82+}$-$^{208}Pb^{82+}$) collider, the LHC is expected to operate as a p-Pb collider. Later it may collide protons with other lighter nuclei such as $^{40}Ar^{18+}$ or $^{16}O^{8+}$. We show how the existing proton and lead-ion injector chains may be efficiently operated in tandem to provide these hybrid collisions. The two-in-one magnet design of the LHC main rings imposes different revolution frequencies for the two beams in part of the magnetic cycle. We discuss and evaluate the consequences for beam dynamics and estimate the potential performance of the LHC as a proton-nucleus collider.

LHC has independent injector chains up to PS machine for ions (Linac, LEIR) and protons (Linac 2, Booster); p-p and Pb-Pb collisions normally done with different bunch train structures in LHC.

For p-Pb collisions, create proton bunch train to match that of Pb ions.

Two possible schemes discussed in paper:

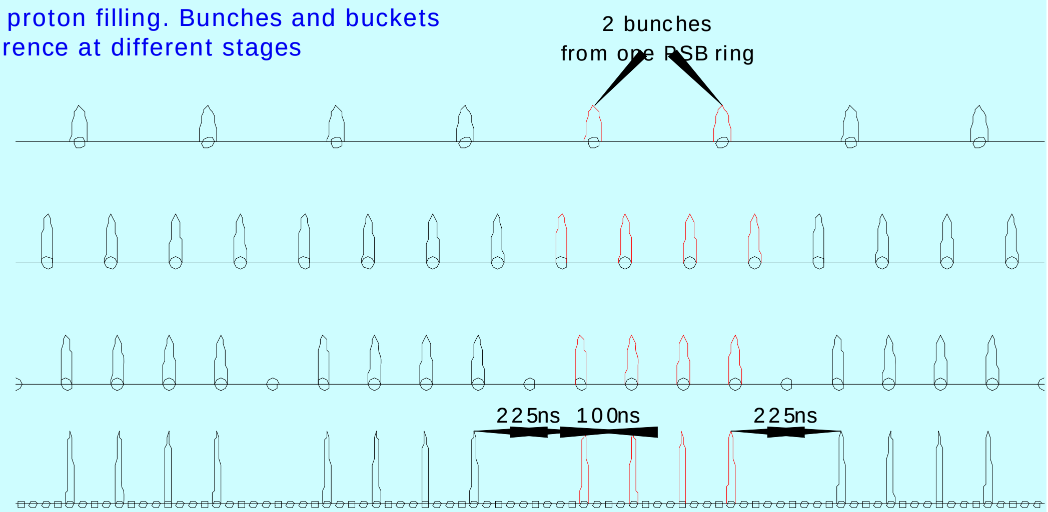
- Simple
- More efficient elaborate scheme.

RF gymnastics in the PS for fast proton filling. Bunches and buckets (circles) around the PS circumference at different stages

Injection:
- four (or one) PSB rings $h_{PSB}=2$
- into $h_{PS}=8$ buckets

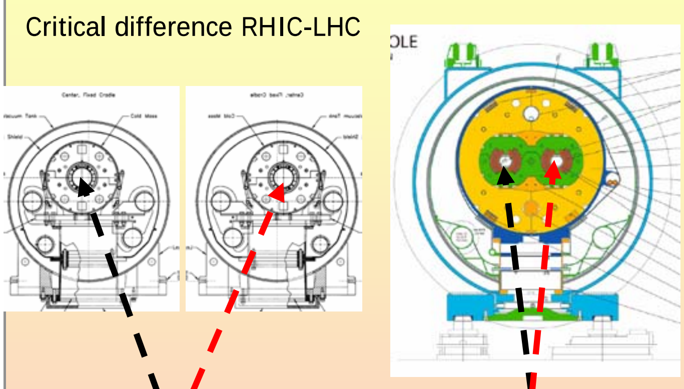
At intermediate energy:
- Bunch splitting and $h_{PS}=16$
- Transfer to $h_{PS}=20$ insert empty buckets

At top energy:
- transfer to h=84 (40 MHz) for correct bunch spacing
- 80 MHz RF to shorten bunches



Two-in-one magnet design determines parameters of hybrid collisions

Critical difference RHIC-LHC



RHIC: Independent bending field for the two beams

LHC: Identical bending field in both apertures of two-in-one dipole

RHIC: equal rigidity (unequal revolution period) gave emittance blow-ups, intensity limit from moving beam-beam encounters in ramp.

LHC accelerates protons through momentum range

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

Two-in-one magnet design fixes the lead ion momentum

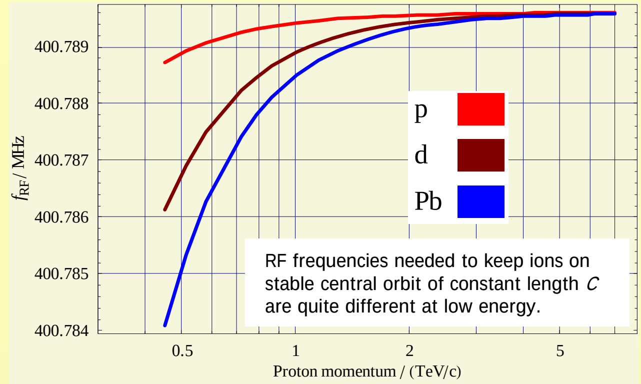
$$\frac{p_{Pb}}{Q} = p_p$$

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

	p-p	Pb-Pb	p-Pb	d-Pb
E/TeV	7	574	(7,574)	(7,574)
E_N/TeV	7	2.76	(7,2.76)	(3.5,2.76)
$\sqrt{s}/\mathrm{TeV}$	14	1148	126.8	126.8
$\sqrt{s_{NN}}/\mathrm{TeV}$	14	5.52	8.79	6.22
y_{CM}	0	0	2.20	2.20
y_{NN}	0	0	-0.46	-0.12

You can download a preprint of the paper or this poster at
http://cern.ch/jowett/epac2006/

Revolution frequency problem



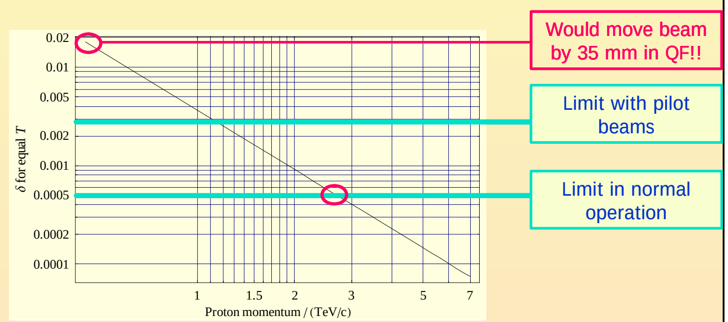
Compensate different speeds by adjusting closed orbit length.

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

where $\delta = \frac{(p - Q p_p)}{Q p_p}$ and $\eta = \frac{1}{\gamma_T^{\,2}} - \frac{1}{\gamma^2}$, $\gamma = \sqrt{1+\left(\frac{Q p_p}{mc}\right)^2}$, $\gamma_T = 55.8$ for LHC.

Moves beam on to off-momentum orbit, longer for $\delta > 0$, $\Delta x = D_x(s)\,\delta$.

Minimise aperture needed by $\delta_p = -\delta_{Pb} = \frac{c^2\gamma_T^{\,2}}{4p_p^2}\left(\frac{m_{Pb}^2}{Z_{Pb}^2} - m_p^2\right)$.



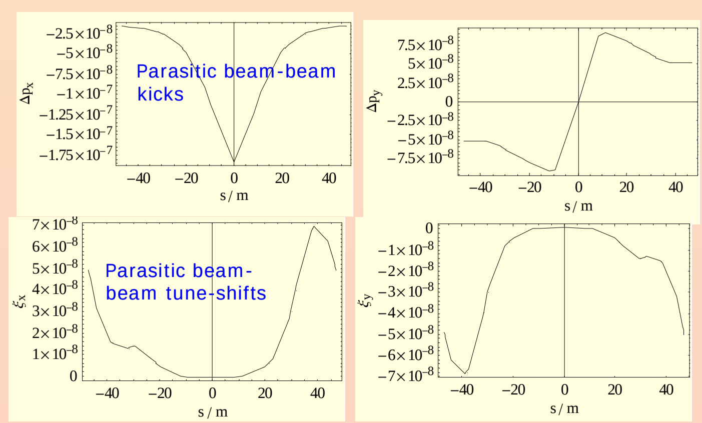
Revolution frequencies must be equal for collisions.
Hard lower limit on energy of p-Pb collisions, Ep=2.7 TeV
Energy where RF frequencies can become equal in ramp.

Beam-beam encounters move at

$$V = \frac{v_p - v_{Pb}}{2} = 1734 \text{ m/s} = 0.15 \text{ m/turn}$$

Excites modulational resonances (c.f. "overlap knock-out" at ISR):

$$m_x\nu_x + m_y\nu_y = p + k\underbrace{\frac{c\left(T_{Pb} - T_p\right)}{S_b}}_{0.01};\quad m_x, m_y, p, k \in \mathbb{Z}$$



Assumes Pb ion bunch with nominal intensity $N_b = 7\times10^7$,
proton bunch with 10% nominal intensity $N_b = 1.15\times10^{10}$,
nominal emittances (equal geometric beam sizes).

With Pb ion bunch structure in both beams, gives luminosity
$L = 1.5\times10^{29}$ cm^{-2}s^{-1}, in p+Pb collisions at the LHC.

Also independent transverse feedback, etc.
Conclusion: Proton-nucleus collisions appear feasible at LHC.