Optimization of Peak & Integrated Luminosity

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Peak luminosity: *Two independent LHC beams…*

Bunch intensities — **Number of bunches** — **Beam-beam offsets** (horizontal & vertical)

$$\mathcal{L} = \frac{N_{b1}\, N_{b2}\, f_{rev}\, k_b}{2\pi\sqrt{(\sigma_{x_1}^2 + \sigma_{x_2}^2)(\sigma_{y_1}^2 + \sigma_{y_2}^2)}} \cdot \exp\left\{ -\frac{(\overline{x}_1 - \overline{x}_2)^2}{2(\sigma_{x_1}^2 + \sigma_{x_2}^2)} - \frac{(\overline{y}_1 - \overline{y}_2)^2}{2(\sigma_{y_1}^2 + \sigma_{y_2}^2)} \right\}$$

Beam sizes at the IP (horizontal & vertical)

Optimize peak luminosity:

Increase	bunch intensities number of bunches
Decrease	beam-beam offsets beam sizes at IP’s

Optimization of peak luminosity:

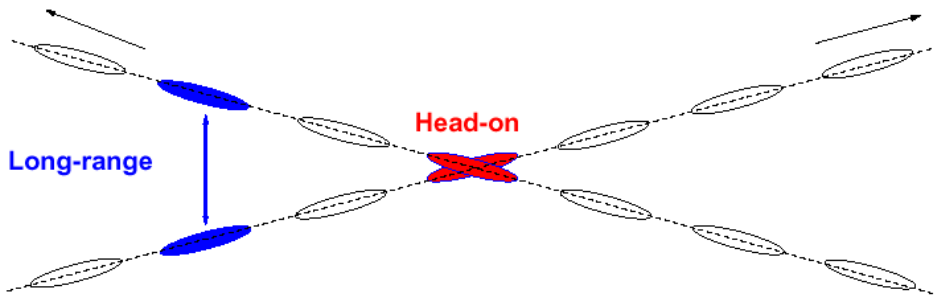
		Nominal	Constraints
Increase	bunch intensities	1.05e11	Beam-beam
	number of bunches	2808	Tertiary beam halo
			Electron cloud instability
			Cryogenic heat load
			Background, # events/cross
Decrease	beam-beam offsets		
	beam sizes at the IP:		
	- emittance	3.75 μm	Instabilities, scattering
	- IP beta functions	0.5/0.5 m	Beam-beam
			Dynamical aperture
			Physical aperture
			Background

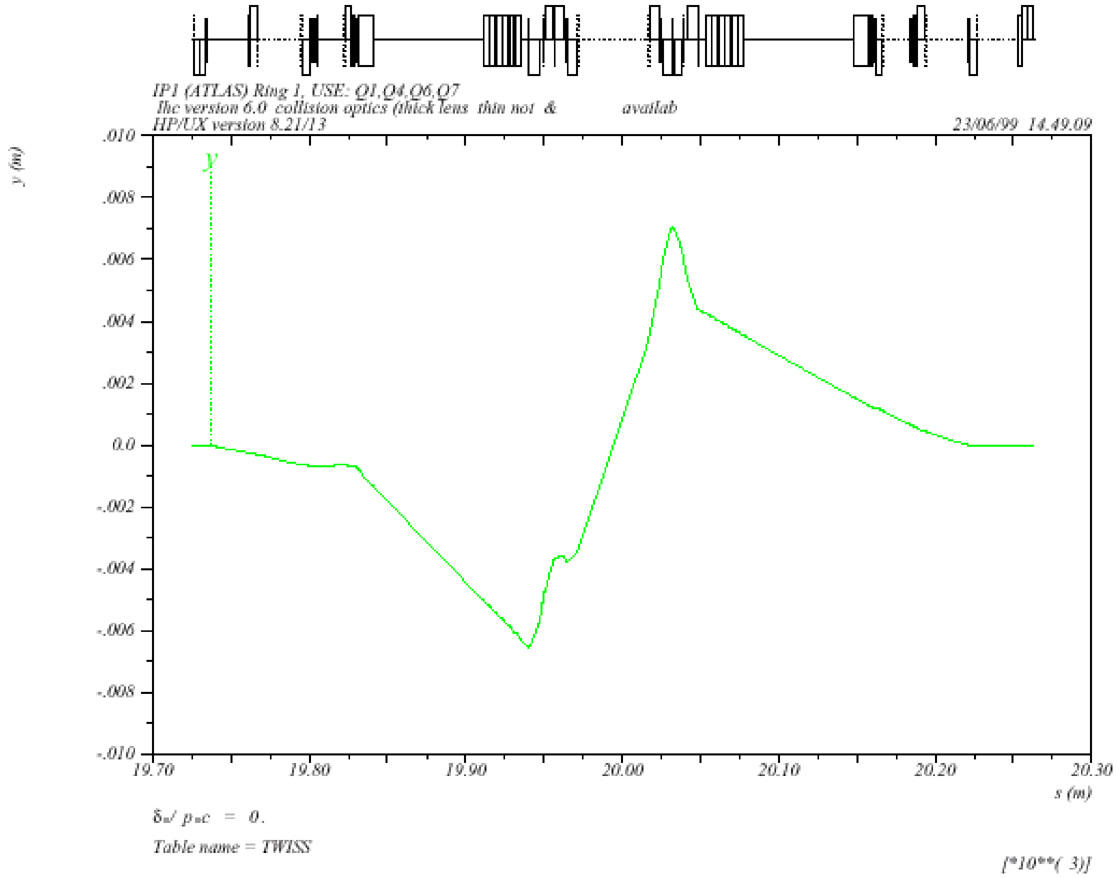
Optimize crossing angles for beam separation at parasitic crossings.
physical aperture (orbit), dynamical aperture (multipole correction).

Emittance: Orbits, dispersion, beta beating, tunes, … Equalize emittance for beam-beam

20% in the SPS, particles in non-linear regime

Beam-beam crossing: *W. Herr et al*





Adjust beam-beam crossing to nominal!

Ideally:

All bunches should see equal beam-beam effects, small enough to not limit luminosity.

Challenge of high beam power:

Machine	E_b	N_p	N_b	Energy/bunch	Energy/beam
SSC	20000 GeV	0.8e10	17424	25.7 kJ	446.7 MJ
LHC-p	7000 GeV	10.5e10	2808	116.7 kJ	331.0 MJ
LHC-p	450 GeV	10.5e10	2808	7.5 kJ	21.3 MJ
ISR	31 GeV	7.9e14			3.9 MJ
SPS	450 GeV	11.0e10	4×72	7.9 kJ	2.3 MJ
HERA-p	920 GeV	7.0e10	180	10.6 kJ	1.9 MJ
Tevatron	1000 GeV	27.0e10	36	43.3 kJ	1.6 MJ
SppS	450 GeV	15.0e10	6	10.8 kJ	64.9 kJ
SNS	1 GeV	2.1e14			33.6 kJ
LHC-Pb	2760 GeV	0.0094e10	608	8.6 kJ	5.2 MJ
RHIC	100 GeV	0.1e10	55	3.2 kJ	173.6 kJ
TESLA	250 GeV	2.0e10	2820	0.8 kJ	2.3 MJ
CLIC	1500 GeV	0.4e10	154	1.0 kJ	148.0 kJ
KEKB	8 GeV	1.3e10	5120	16.7 J	85.3 kJ
PEP-II	9 GeV	2.1e10	1658	30.3 J	50.2 kJ
LEP2	104 GeV	45.0e10	4	7.5 kJ	30.0 kJ
SLAC (E158)	45 GeV	6.5e11			4.7 kJ
SLC	50 GeV	4.0e10	2	0.3 kJ	0.6 kJ

100 times higher than previously achieved!

SC environment imposes strict quench limits:

10^{-9} of beam power can quench a magnet.

Regular particle losses:

due to particle diffusion, scattering, beam-beam…
(beam lifetimes of 10-40 h)

Loose about 10^9 particles per turn

↓

Primary collimators scatter protons at > 6 σ

↓

Secondary collimators capture protons at > 7 σ but produce tertiary halo

↓

Tertiary halo is lost in **triplets around IP's** (10 σ at nominal physics)

↓

Quench if locally more than 10^5 protons/s/m

Beam losses in the IP regions will likely limit the beam intensity allowed into the machine and/or the IP betas.

Lower intensity:

Less bunches or less **bunch intensity** (trade-off beam-beam to electron cloud?).

Expect **many, many different bunch intensities** and **bunch patterns**.

LHC schedule:

(L. Evans DG/DI/LE/jf/2001-37)

1.4. – 30.9.2004	Sector test.	
31.12.2005	Ring closed.	
1.2.2006	First beam.	3 month commissioning
1.4.2006	First collisions.	
1.5. – 31.7.2006	Shutdown	
1.8.2006 – 28.2.2006	Physics run	
	Accumulate 10 fb^{-1} in 7 months	
1.3. – 12.4.2007	Lead ion run.	

Running schemes: *(F. Ruggiero, LCC 2001)*

Initial running:	Bunch intensity:	**0.275e11**
	Number of bunches:	**2520**
	Emittance:	**1.0 μm**
	Beta function:	**1.0/1.0 m**
	Luminosity:	**1.1 10^{33} cm^{-2} s^{-1}**
Intermediate running:	Bunch intensity:	0.55e11
	Number of bunches:	2808
	Emittance:	1.875 μm
	Beta function:	0.75/0.75 m
	Luminosity:	3.4 10^{33} cm^{-2} s^{-1}
Nominal running:	Bunch intensity:	**1.1e11**
	Number of bunches:	**2808**
	Emittance:	**3.75 μm**
	Beta function:	**0.5/0.5 m**
	Luminosity:	**10 10^{33} cm^{-2} s^{-1}**

Important variables for optimization of peak luminosity (IP):

- Transverse position of IP
- Transverse beam-beam separation
- Longitudinal beam-beam overlap
- Emittances of both beams, bunch to bunch (10-20%)
- Beta functions at IP
- Crossing angle
- Separation orbit
- Rates of particle loss due to beam-beam (luminosity)
- Rates of particle loss due to tertiary halo
- Bunch intensity
- Bunch pattern (number of bunches, spacing, gaps)
- Background
- Instantaneous luminosity

Information on some of those variables will go in both directions…

Optimize integrated luminosity:

Minimize repair and set-up time

- Restrict operation to **“safe” intensity**
- Increase **reliability** during shutdown
- Extensive cabling, alignment, magnet **checks during shutdown**
- **Limited** number of optics (β^*) or other major **changes**

Minimize length of turn-around (physics to physics)

- **Shorter filling** times (inject faster or less intensity)
- **Faster ramp** (can limit intensity)
- **Slower ramp**, if beam aborts during ramp

Maximize length of physics fills and luminosity lifetime

- **Avoid beam aborts**
- Restrict tuning to **safe parameter** range
- Allow for **safety margin** in equipment

Estimate of integrated luminosity I:

O. Bruning 2001

Assume:

Intra-beam scattering	Beam blow-up with τ = 100 h (nom)
Beam-restgas scattering	Intensity decay with τ = 85 h (nom)
Beam-beam interaction	Intensity decay with τ = 16 h (nom) (1/2 value, 2 high luminosity IP's)

Neglect: Radiation damping, ripple blowup, dynamical β^* squeeze
Losses due to non-linearities, collective instabilities

Exponential beam lifetime: τ_{lumi} **= 14.8 h** (approximation)

Turn-around time T_{turn}
Lumi lifetime τ_{lumi}

Optimal length of physics run T_{run}

T_{turn} / τ_{lumi}	1	6	10	20	[hours]
6.5	3	6	9.5	11.5	T_{run}
10	4	9	11.5	15	
15	5	12	15	20	
19	5.5	13	16.5	22	

O. Bruning

Estimate of integrated luminosity II:

Assume 200 days of running.

HERA after 11 years

T_{turn} / τ_{lumi}	1	6	10	20	[hours]
15	122	78	65	47	L_{tot}
20	127	86	72	54	[fbarn^{-1}]

O. Bruning

A good turn-around time is crucial for achieving high integrated luminosity.

Expect about **10 hours** turn-around…

Integrated luminosity with nominal parameters: **~ 70 fbarn^{-1}**

Lead-ion run:

Lead-ion collider			
Energy per charge a	E/Q	[TeV/charge]	*7*
Energy per nucleon b	E/A	[TeV/u]	2.76
Centre-of-mass total	E_{CM}	[TeV]	*1148*
Dipole field	B_{MAX}	[T]	8.386
Transverse normalized emittance	ϵ^*	[μ m]	1.5
β at IP. *(coll.)*	β^*	[m]	0.5
r.m.s beam radius at IP.	σ^*	[μ m]	15
Crossing angle (per beam)		[μ rad]	$\leq$100
Longitudinal emittance *(inj.)*	ϵ_l	[eV.s/charge]	1
Longitudinal emittance *(coll.)*	ϵ_l	[eV.s/charge]	2.5
r.m.s bunch length *(coll.)*	σ	[cm]	7.5
r.m.s energy spread *(coll.)*	σ E/E	10^{-3}	0.114
Bunch spacing	t_b	[ns]	124.75
Bunch harmonic number	h_b	Not integer	(712.8)
Number of bunches per ring	n_b		608

Filling time per LHC ring		[min]	9.8	
Number of ions per bunch	N_b	10^7	6.3	9.4
Number of ions per beam	N	10^{10}	3.5	5.2
Ion intensity per beam		[mA]	5.2	7.8
Initial luminosity per bunch	$\mathcal{L}_0^b$	[10^{24} cm^{-2} s^{-1}]	1.4	3.2
Initial total luminosity	$\mathcal{L}_0$	[10^{27} cm^{-2} s^{-1}]	0.85	1.95
IBS emittance growth *(inj.)*		[h]	7.6	5.1
IBS emittance growth *(coll.)*		[h]	14.6	9.8
Luminosity lifetime		[h]	10	6.7

Table: The LHC parameters: Lead-ion collider (125 ns bunch spacing at SPS injection, one low- β experiment).

Heavy ions:

$\tau_L = \tau_L / N_{IP}$

$L \sim L / N_{IP}$

Intensity limited due to SPS space charge.

Light Ions:

(Ca)

Limit due to IBS

No constraint on #IP's

Beam-beam:

No issue for ion running

Smaller crossing angle allows more aperture in the triplet.

Conclusion:

Some preliminary estimates to give us an idea…

Details will all depend on the build quality of the LHC and eventual unforeseen problems (as they almost always appear).

Make sure machine and experiments work well together to collect as much luminosity as possible:

E.g.: Reasonably flexible but sufficiently strict interlock and veto system.
Use to the full extent information from the experiments for the machine and vice versa (what can be measured with what accuracy in what time?).