Maps for Electron Cloud in LHC

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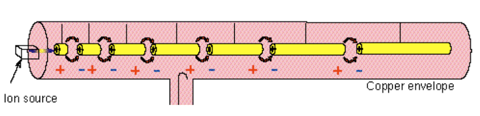
Digression on accelerators

Particle accelerators increase the energy of bunches of elementary particles (electrons, protons, anti-protons, positrons, ions) for a variety of purposes. **High energy physics research**: Accelerated particles are smashed together or against a fixed target to study the products of the interaction and have a closer look into the basic elements of matter. **Nuclear physics research**: Interactions of fully stripped ions with targets to investigate the structure, interactions, and properties of the nuclei. **Production of synchrotron light** (extremely bright and coherent beams of high energy photons - ultraviolet and X ray) used in the study of atomic structure, chemistry, condensed matter physics, biology, and technology. **Medical applications** (e.g. cancer treatment with hadron bombarding). **T**he performance of accelerators is generally related to the number of particles, packed in a little space, that they can accelerate and the energy that they can reach. **High density and high energy beams are desirable!** **F**rom the equation of the Lorentz force, it is clear that particles can only be accelerated with electric fields, whereas magnetic fields can only be used for guiding the particles along the desired paths/orbits. **Motion of particles is relativistic**, i.e. as their velocity tends to become close to the speed of light, a large increase in energy will correspond to little increase in speed.

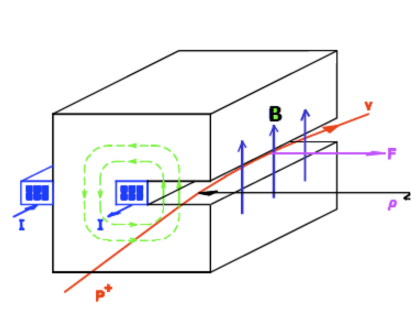
$$\nabla\cdot\vec{E}=\frac{\rho}{\epsilon_0}\qquad \nabla\cdot\vec{B}=0\qquad \vec{F}=e\left(\vec{E}+\vec{v}\times\vec{B}\right)=\frac{d\vec{p}}{dt}$$

$$\nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}\qquad \nabla\times\vec{B}=\mu_0\vec{J}+\mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t}$$

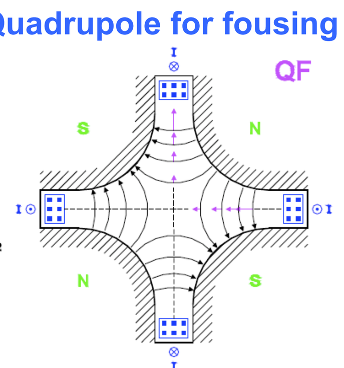
Linear accelerator, mainly electric fields



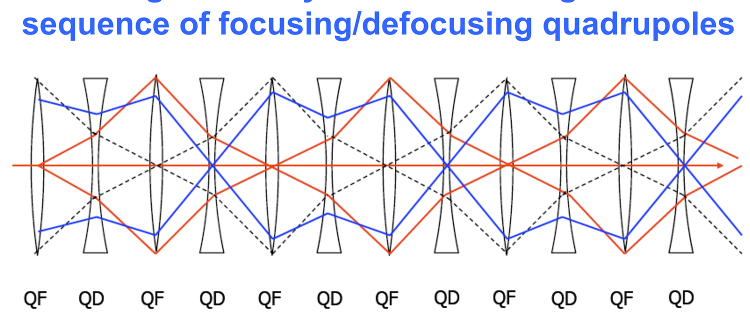
Dipole for bending



Quadrupole for fousing



Focusing is usually achieved through a sequence of focusing/defocusing quadrupoles



Use of the electric field

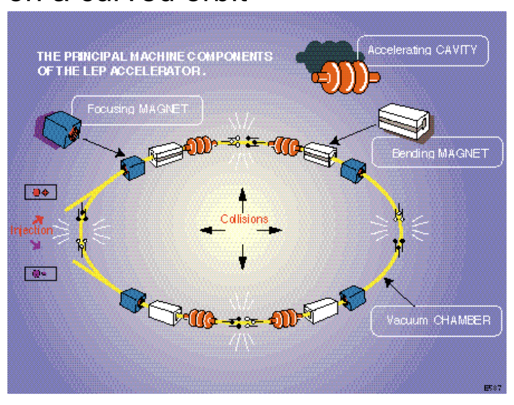
$$E = -\nabla\phi - \partial A/\partial t$$

Acceleration by DC voltages:
- Cockcroft & Walton rectifier generator
- Van de Graaff electrostatic generator
- Tandem electrostatic accelerator

Acceleration by time-varying fields:

$$\nabla\times E = -\partial B/\partial t$$

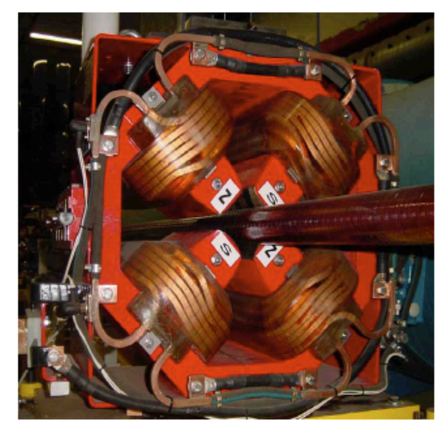
Circular accelerator, e.g. a synchrotron collider, it needs dipolar magnetic fields for bending particles on a curved orbit



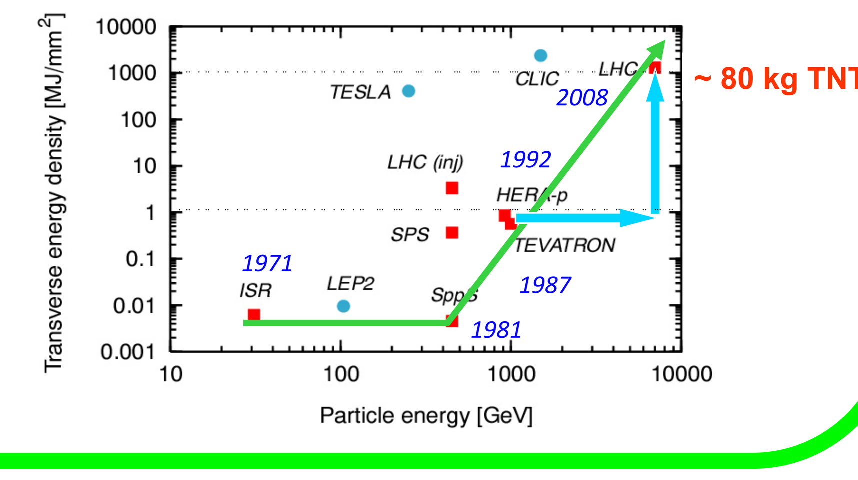
In the ideal world all the particles would have the same momentum and would circulate forever on the nominal orbit of a perfect accelerator, **but** … The elements are not perfectly aligned. The electromagnetic fields can never perfectly match the desired ones (Fringe fields and non-linearities). Particles in a bunch have different momenta. Accelerated particles emit synchrotron radiation and lose energy. Particles undergo collisions with the molecules of the rest gas. Particles interact with each other within the bunch through the electromagnetic field of the particle distribution through two-particle encounters (short or long range). Particles interact electromagnetically with the surrounding environment. They lose energy. Bunches can become unstable.

Dipole for bending

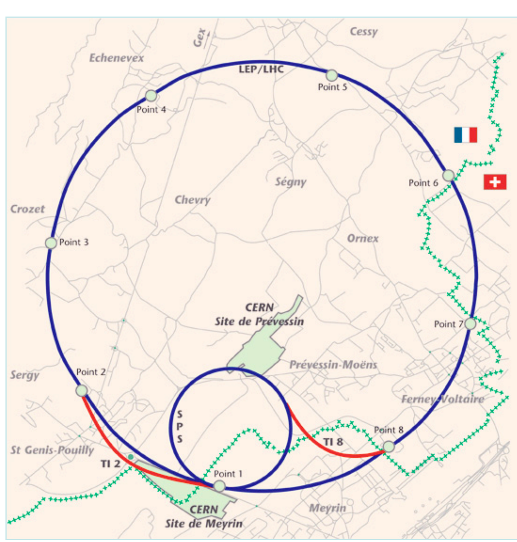
Quadrupole for fousing

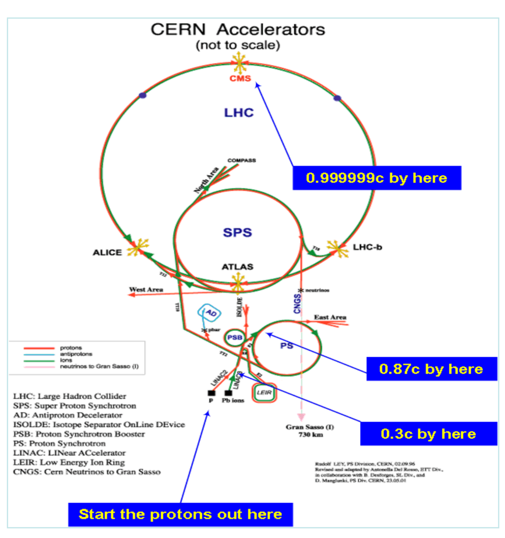


pp, ep, and ppbar collider history



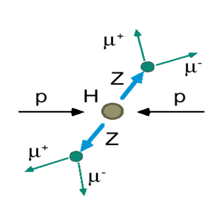
A brief summary about LHC (Large Hadron Collider)

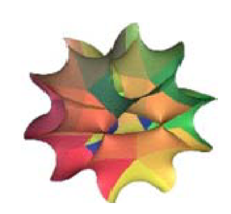




LHC luminosity

We want to deliver high luminosity at the maximum beam energy for maximum physics reach

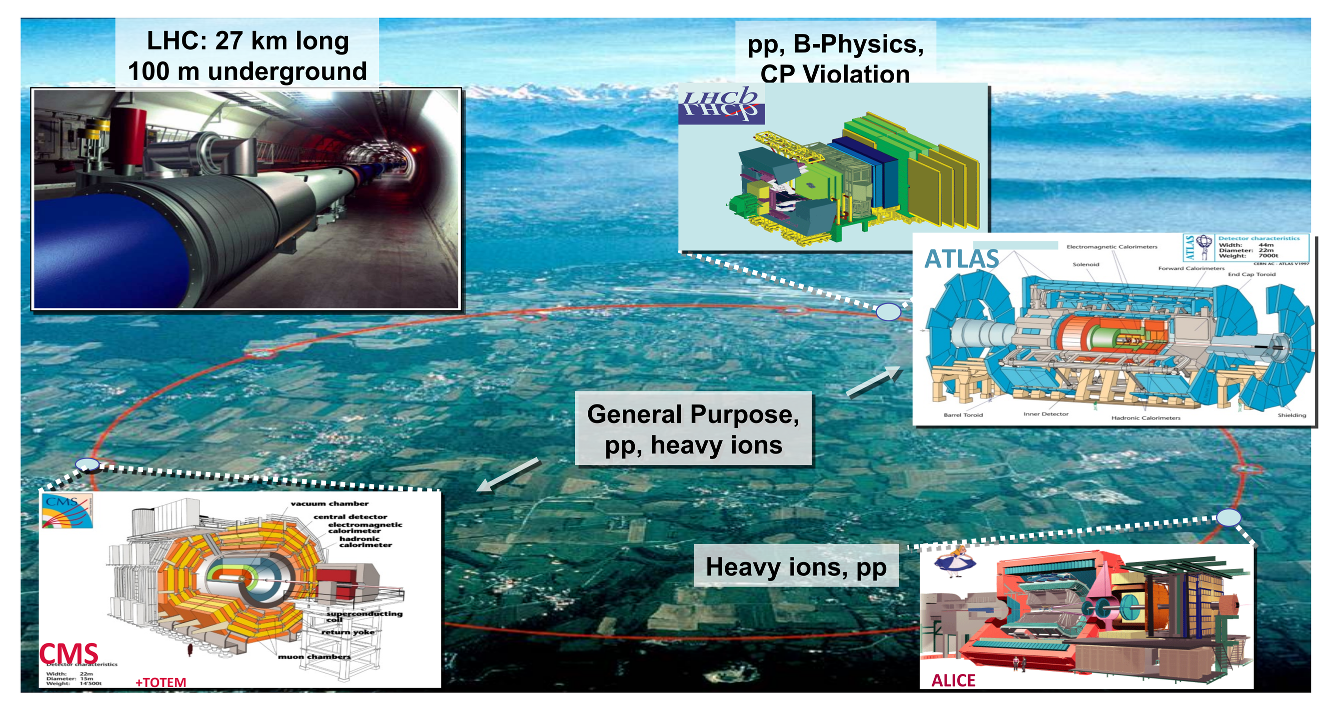




Maximize LHC luminosity

$$L = F\,\frac{N_{b1}N_{b2}f_{rev}k_b}{2\pi\sqrt{\left(\sigma_{x1}^2+\sigma_{x2}^2\right)\left(\sigma_{y1}^2+\sigma_{y2}^2\right)}}.\exp\left\{-\frac{\left(\bar{x}_1-\bar{x}_2\right)^2}{2\left(\sigma_{x1}^2+\sigma_{x2}^2\right)}-\frac{\left(\bar{y}_1-\bar{y}_2\right)^2}{2\left(\sigma_{y1}^2+\sigma_{y2}^2\right)}\right\}$$

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



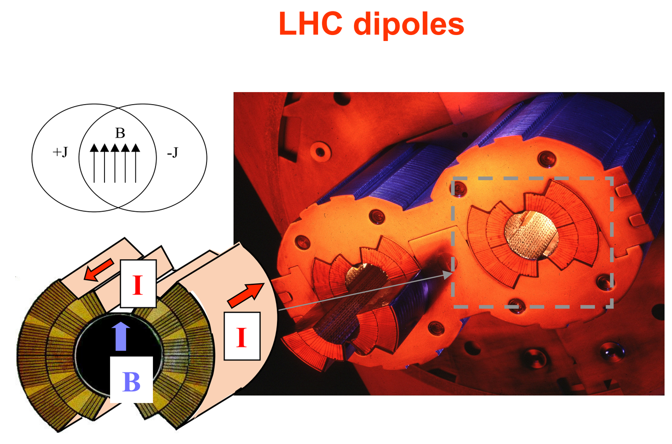
To produce the high magnetic fields we need very high currents.
Very high thermal conductivity (3000 time high grade copper)
Very low coefficient of viscosity … can penetrate tiny cracks, deep inside the magnet coils to absorb any generated heat.
Very high heat capacity … stabilizes small transient temperature fluctuations.

Some LHC key parameters (at 7 TeV)

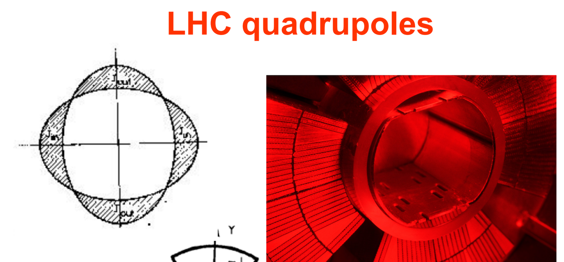
Machine circumference: 26.658883 Km; Bending radius: 2.80395 Km; Number of dipoles: 1232; Main dipole length: 14.3 m; Momentum at injection: 450 GeV/c; Momentum at collision: 7 TeV/c; Dipole field (at 450 GeV): 0.535 T; Dipole field: 8.33 T; Revolution frequency: 11.245 kHz; Bunch length: 1.06 ns (7.5 cm); Bunch Intensity: 1.15 x 1011; Number of bunches: 2808; Beam size: 16 μm; Total beam energy: 362 MJ per beam.

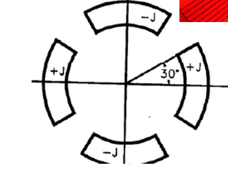
High bunch intensity: Beam-beam, collective effects
Many bunches: total beam power, crossing angle, long range beam-beam, beam diffusion
Small beam size: triplet aperture, triplet field errors

LHC dipoles



LHC quadrupoles





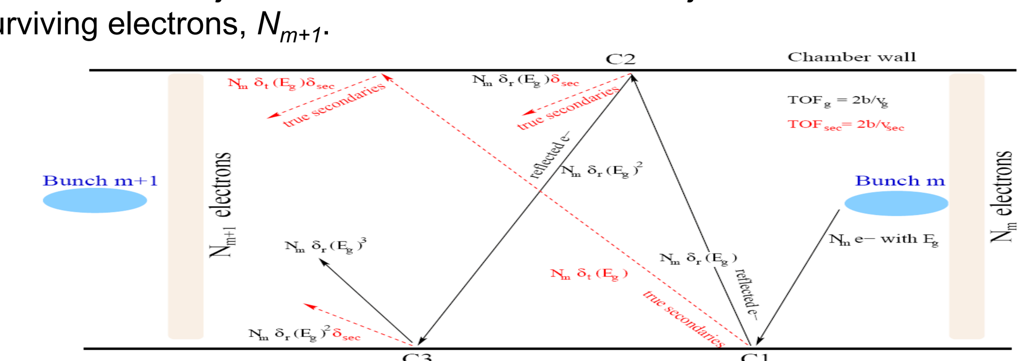
Two intersecting ellipses, rotated by 90°, generate a perfect quadrupole fields.

*LHC was inaugurated on 10.09.2008. A low intensity "probe" bunch (2 x 10^9 p) was injected into LHC, circulated and was stored for 20 minutes within the first 2 days. **An incident occurred on the 19.09.2008, while ramping up one of the magnets in sector 45 (without beam). The damage to the magnets and the He leak following the incident have caused 1 year long repair works.***

Electron cloud in LHC

Schematic analysis of the evolution of electron cloud

- The bunch m arrives at the location where the N_m electrons are uniformly distributed and initially at rest.
- After the bunch passage, electrons are accelerated towards the chamber wall with energy E_g and have their first wall collision, C_1, when two new jets are created.
- The first jet, with energy E_g and $N_m\delta_r$ electrons, corresponds to backscattered electrons (black line) and the second jet, with low energy and $N_m\delta_t$ electrons, to the the scondaries (red dotted line).
- Before bunch $m+1$ arrives, these two jets perform several wall collisions, which in turn create more jets. The contribution of all these jets becomes the number of surviving electrons, N_{m+1}.



Electron cloud effects

1. The electron cloud develops quickly as photons striking the vacuum chamberwall knock out electrons that are then accelerated by the beam, gain energy, and strike the chamber again, producing more electrons.
2. The peak secondary electron yield (**SEY**) of typical vacuum chamber materials is >1 even after surface treatment, leading to amplification of the cascade.
3. The interaction between the electron cloud and a beam leads to the electron cloud effects such as single- and multi-bunch instability, tune shift, increase of pressure and so on.
4. The build-up of a quasi-stationary electron cloud through beam can be accurately modeled using sophisticated computer simulation codes like ECLOUD, PEI, POSINST.

Electron cloud map:linear coefficient

$$\rho_{m+1}=a\rho_m$$

$$a=\frac{N_{m+1}}{N_m}=\delta_r\left(E_g\right)^n+\delta_t\left(E_g\right)\delta_s\left(E_s\right)^{\xi}\frac{\delta_s\left(E_s\right)^{n\xi}-\delta_r\left(E_g\right)^n}{\delta_s\left(E_s\right)^{\xi}-\delta_r\left(E_g\right)}$$

$E_s \cong 5$ eV

E_g: gain energy $(?\ \ E_s)$

$\delta_t(E)$: function of secondary electrons

$\delta_r(E)$: function of reflected electrons

$\delta_s(E)=\delta_t(E)+\delta_r(E)$

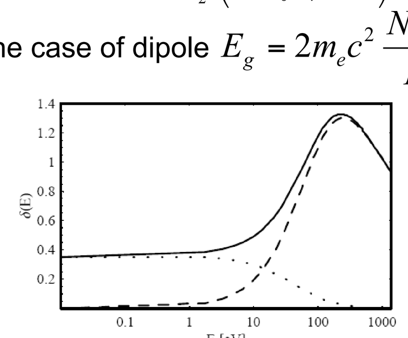
$\xi=\sqrt{E_s/E_g}$

n: number of collisions for the monoenergetic jet with energy E_g

The average energy gain of a uniformly distribueted cloud of N electron in a cylindrical beam pipe is

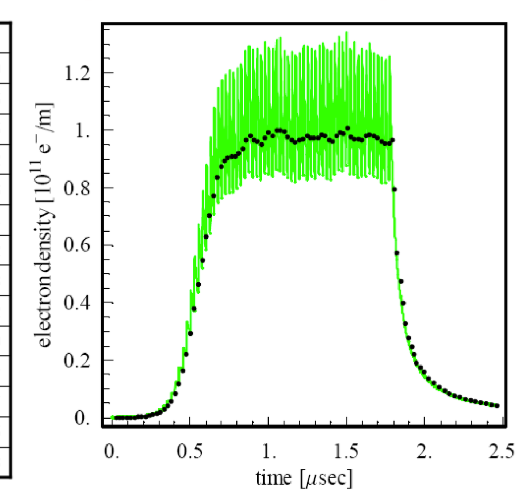
$$E_g=m_ec^2\frac{ZN_br_e}{\sqrt{2\pi}\sigma_z}\left(\ln\frac{R_p}{c_0\sigma_r}-\frac{1}{2}\right)$$

and in the case of dipole $E_g=2m_ec^2\frac{N_b^2r_e^2}{R_p^2}\ln\frac{R_p}{\sigma_r}$



Electron cloud build up in a LHC dipole

Parameter	Unit	Value
Beam particle Energy	GeV	7000
Bunch spacing	ns	25
Bunch length	m	0.075
Number of bunches N_b	-	72
Number of particles per bunch N	10^{11}	0.8 to 1.6
Bending field B	T	8.4
Length of bending magnet	m	14.2
Vacuum screen half height	m	0.018
Vacuum screen half width	m	0.022
Circumference	m	27000
Primary photo-emission yield	-	7.98 10^{-4}
Maximum SEY δ_{max}	-	1.3 to 1.7
Energy for max SEY E_{max}	eV	237.125
Energy width for secondary e^-	eV	1.8



Map for electron cloud

For a given beam pipe characteristics (SEY, Chamber dimensions, etc.) the evolution of the electron density is only driven by the bunch passing by, and the existing electron density before the bunch passed by

$$\rho_{m+1}=F\left(\rho_m\right)$$

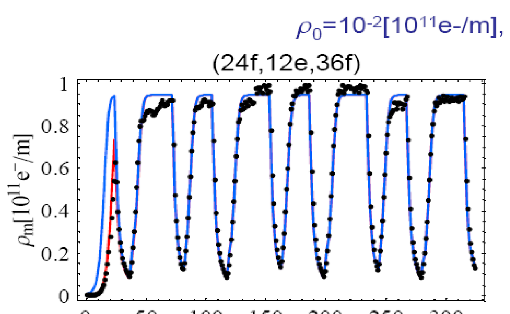
Simplify the Electron Cloud problem into a small number of mathematical parameters. For typical RHIC parameters the bunch-to-bunch evolution of the electron density can be represented by a cubic map**:**

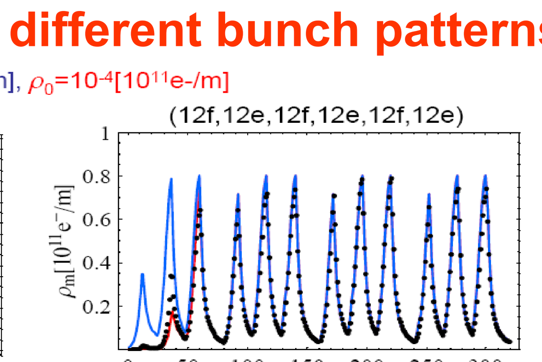
$$\rho_{m+1}=a\rho_m+b\rho_m^{\ 2}+c\rho_m^{\ 3}$$

where ρ_m is the bunch-to-bunch average of the electron linear density.

E-cloud evolution for different bunch patterns

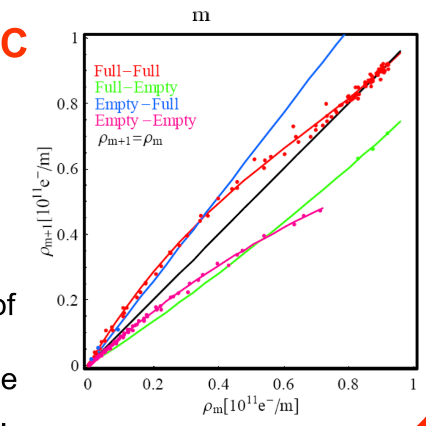
$\rho_0=10^{-2}[10^{11}e\text{-}/m]$, $\rho_0=10^{-4}[10^{11}e\text{-}/m]$





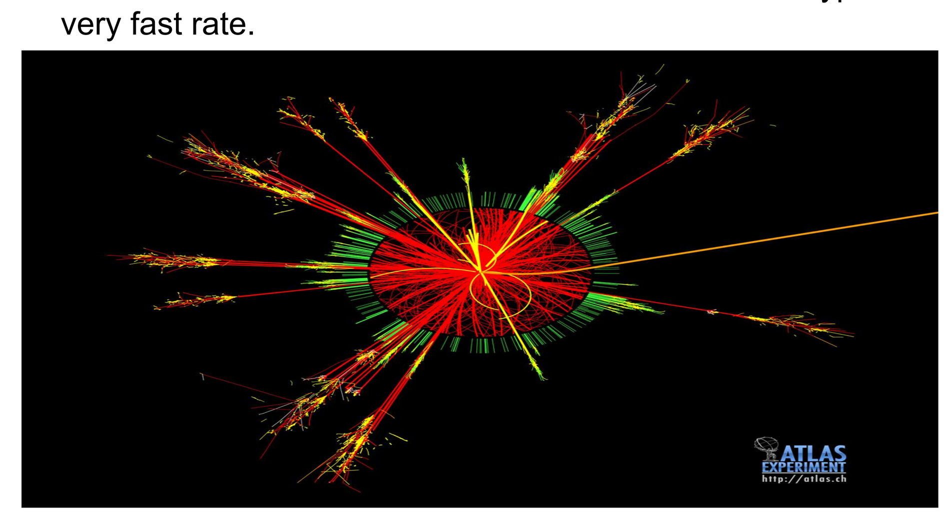
Building the cubic map for LHC

δ_{max} = 1.7; N = 1.2 1011; 4 trains of 72 bunches; Bunch pattern: 24f 12e 36f; 8 Bunches gap; Four different sets of map coefficients are needed to describe the electron density evolution. Map results do not depend on the initial electron density; Relative error under 20%; For a given set of the physical parameters (Bunch Intensity, SEY, etc.), differenet Bunch Patterns can be described using the same Map coefficients.



When the LHC will restart working ...

The detectors will record from beam collision events of type at a very fast rate.



The Standard Model of particles, SU(5) Theory, will be experimentally tested.

… and

To operate LHC, as well as to use and improve ist performances will be a huge challenge for Experimental physicists
- Machine physicists and operators;
- Software engineers (data handling and controls);
- Hardware specialists (RF, magnets, power supplies, instrumentation, cryogenics, etc.).

Conclusions and Outlook

1. The electron cloud build-up in an LHC can be described using a cubic map;
2. The coefficients of this map are functions of the pipe and beam parameters. This dependence can be extrapolated from simulation codes;
3. The map coefficients are independent of the fill pattern,and they can be used to simulate the bunch to bunch evolution of electron cloud for different bunch filling patterns, obtaining a reduction by orders of magnitude in the simulation time;
4. An approximate formula has been derived for the linear coefficient in the map that can be used to estimate the safe regions in the machine parameter space;
5. Work is in order to calculate the higher order terms in the map.