The CERN Accelerator School holds courses in all of the member states of CERN

Superconductivity for Accelerators

The CERN Accelerator School

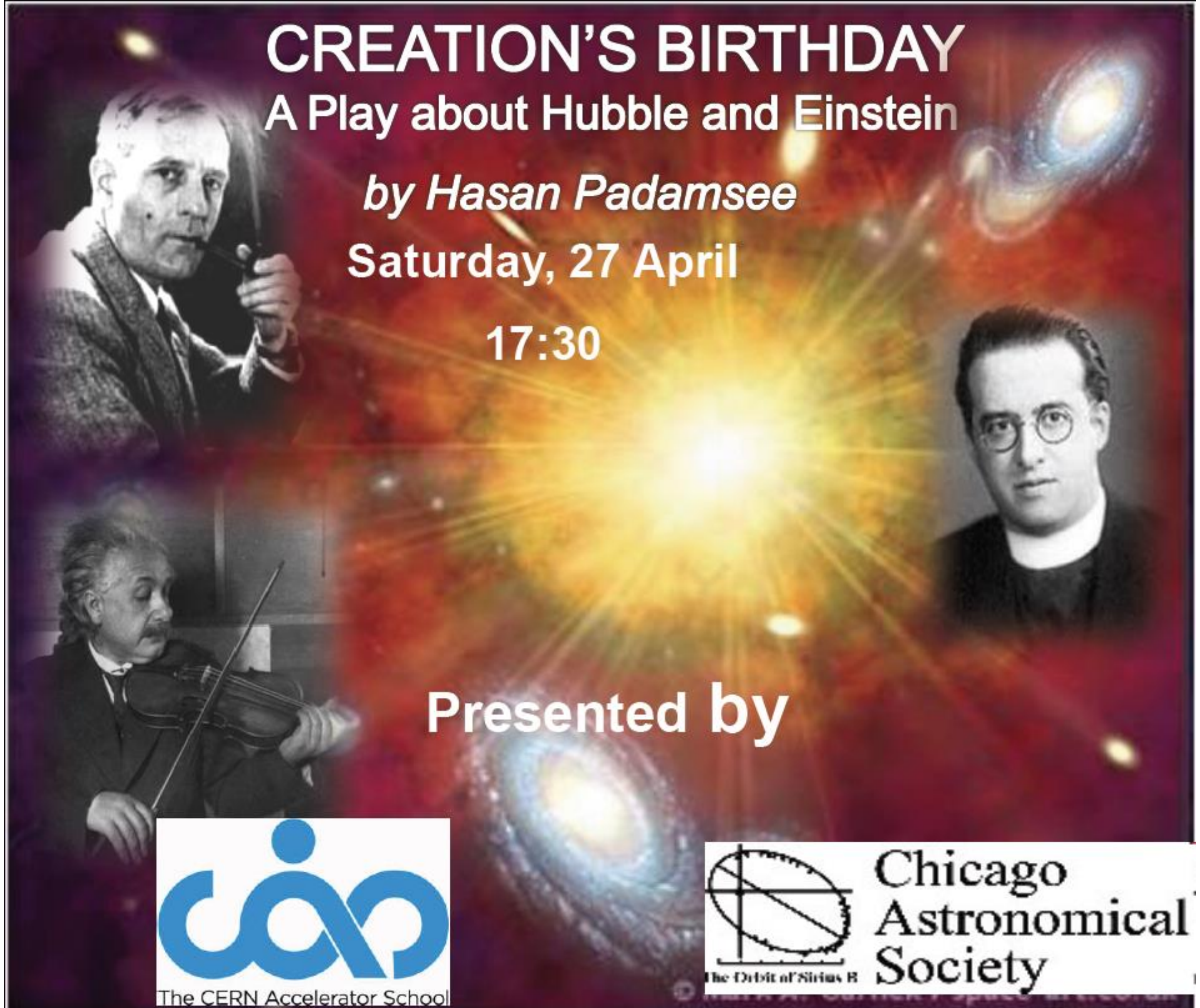
- Numerous changes in last weeks

- Background
- RF
- Magnets
- Technology
- Case studies
- Seminars
- Event

PROGRAMME FOR SUPERCONDUCTIVITY FOR ACCELERATORS
24 April – 4 May 2013, Erice, Italy

Time	Wednesday 24 April	Thursday 25 April	Friday 26 April	Saturday 27 April	Sunday 28 April	Monday 29 April	Tuesday 30 April	Wednesday 1 May	Thursday 2 May	Friday 3 May	Saturday 4 May
09:00 10:00	ARRIVAL DAY	Introduction R. Bailey	AC/RF Superconductivity G. Ciovati	Cavity Design & Ancillaries II H. Padamsee	EXCURSION	Superconductors for Magnets I R. Flukiger	Mechanical Design of SC Magnets I F. Toral	Cryostat Design I V. Parma	Stability of SC Cables L. Bottura	Superconductor Dynamics F. Gomory	DEPARTURE DAY
10:00 11:00		Basic Thermodynamics for SC P. Duthil	Material Properties at LT P. Duthil	Fabrication & Materials W. Singer		Principles of SC Magnet Design H. Ten Kate	Heat Transfer & Cooling Techniques I B. Baudouy	Heat Transfer & Cooling Techniques II B. Baudouy	Protection of SC Magnets H. Ten Kate	Vacuum Techniques for SC Devices P. Chiggiato	
		COFFEE	COFFEE	COFFEE		COFFEE	COFFEE	COFFEE	COFFEE	COFFEE	
11:30 12:30		Superconductivity I D. Larbalestier	HOMS and Heating B. Holzer	Limitations & Possible Solutions C. Antoine		Superconductors for Magnets II R. Flukiger	Mechanical Design of SC Magnets II F. Toral	Cryostat Design II V. Parma	Superfluid He Technology/ Applications P. Lebrun	Manufacturing and Testing L. Rossi	
		LUNCH	LUNCH	LUNCH		LUNCH	LUNCH	LUNCH	LUNCH	LUNCH	
15:00 16:00		Transverse Beam Dynamics B. Holzer	Refrigeration I A. Alekseev	Measurement Techniques I D. Reschke		Superconducting Cables P. Bruzzone	FREE AFTERNOON	Case Study Work	Case Study Presentations	Current Leads, Links and Buses A. Ballarino	
16:00 17:00		Superconductivity II D. Larbalestier	Refrigeration II A. Alekseev	Measurement Techniques II D. Reschke		Magnetic Design of SC Magnets E. Todesco		Case Study Work	Case Study Presentations	Large SC Magnet Systems P. Vedrine	
		TEA	TEA	TEA		TEA		TEA	TEA	TEA	
17:30 18:30		Longitudinal Beam Dynamics B. Holzer	Cavity Design & Ancillaries I H. Padamsee	Event Creation's Birthday H. Padamsee		Seminar NMR/MRI T. Havens		Seminar HTS Power Applications M. Noe	Case Study Presentations	Case Study Summary P. Ferracin	
18:30		Case Study Introduction L. Bottura	Seminar ITER N. Mitchell							Closing Talk	
20:00	Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	Banquet	Dinner	

The CERN Accelerator School



Originally Shown at Fermilab

How did boxing champ, war-hero, and prodigy astronomer - Edwin Hubble - gang up with a moon-shine peddling janitor and a Jesuit priest to defeat the champion of science, Albert Einstein, expand our Universe, and figure out Creation's Birthday?

Case Studies

- Coordinator
  - Paulo Ferracin
    - with Ezio Todesco, Luca Bottura, Claire Antoine
- 6 topics
- 18 Groups of 5 or 6
- Presentations on Thursday May 2
  - 18 in 3 hours!
- Introduction to this at 18.30 (Luca Bottura)

Practical information

- Handouts
- Web sites
  - https://cas.web.cern.ch/cas/Erice-2013/Erice-after.htm
  - https://indico.cern.ch/conferenceDisplay.py?confId=194284
  - https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=194284

- Lunch and dinner
  - List of restaurants where you just have to sign
  - Drinks you have to pay for
- Banquet
  - Where and when
- Excursion
  - What and departure details
- Photo
  - When

Superconductivity for Accelerators

- There are some 30 000 accelerators around the world
- Nearly all are for industrial or clinical use
  - Scientific research community (~few 100)
  - Synchrotron light sources
  - Ion beam analysis
  - Photon or electron therapy
  - Hadron therapy
  - Radioisotope production
  - Ion implantation
  - Neutrons for industry or security
  - Radiation processing
  - Electron cutting and welding
  - Non-destructive testing

Linacs
Cyclotrons
FFAGs
Synchrotrons
Colliders

e-, e+
p, pbar, ions
μ-, μ+, ν

Sources

A look at particle accelerators

- What is an accelerator ?
- What science do we need ?
- The High Energy Frontier
- Other frontiers

With thanks or apologies to all from whom I have stolen slides or ideas used at CAS

- Chris Prior
- Werner Herr
- Bernhard Holzer
- Maurizio Vretenar
- Mike Siedel
- Shinji Machida
- Oliver Bohne Frankenheim
- Andy Wolski

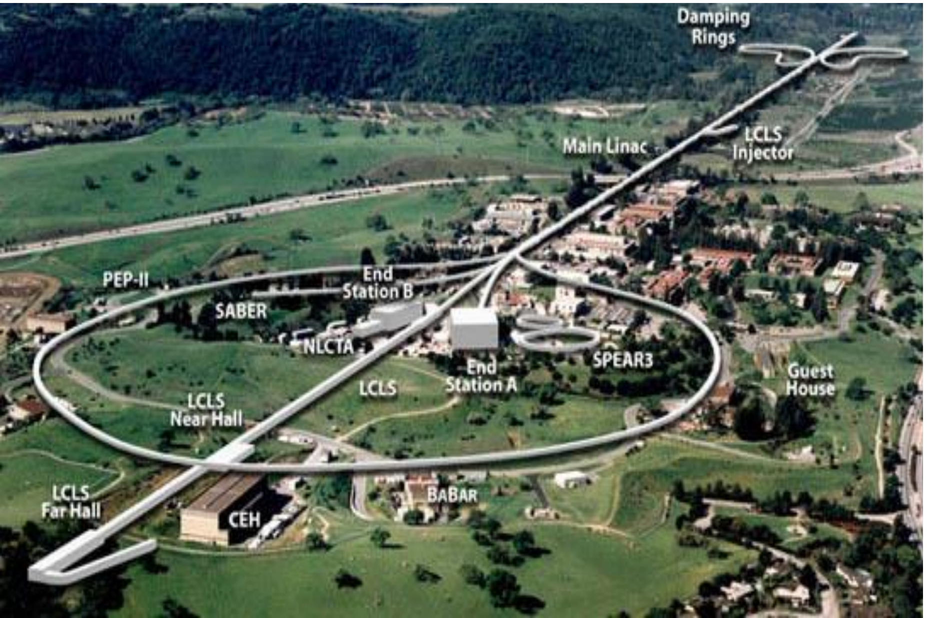
A definition of an Accelerator

The CERN Accelerator School

- A particle accelerator is a device that
  - Provides a beam of energetic particles
  - Employs a vacuum chamber in which the particles travel
  - Employs electric fields to impart energy to the particles
  - Employs magnetic fields to steer and focus the beam
  - For research applications, often provides collisions
    - Either against a fixed target, or between two beams of particles

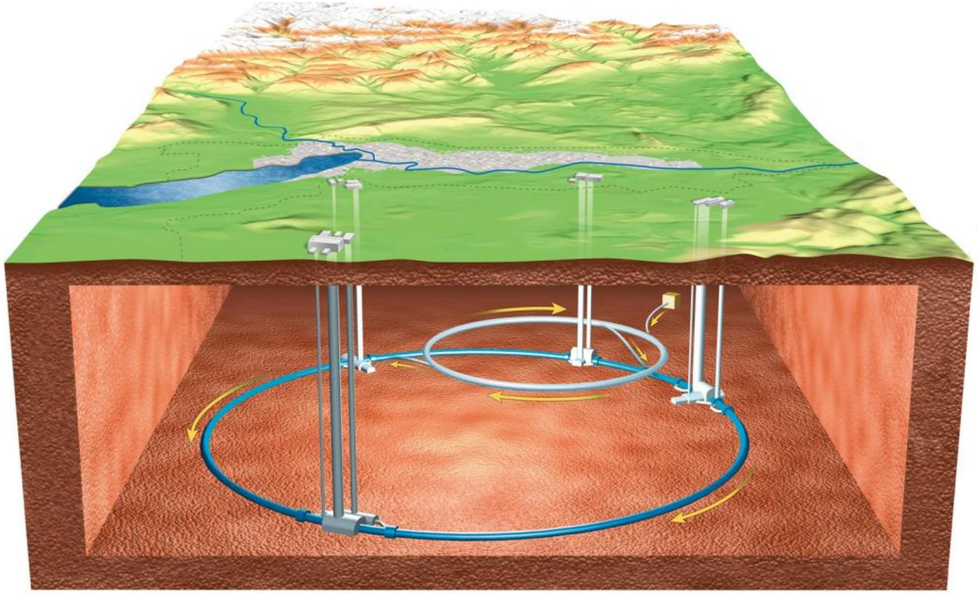
Linear accelerator
Beam travels from one end to the other

SLAC Accelerator Complex, 1990s



Circular accelerator
Beam repeatedly circulates around ring

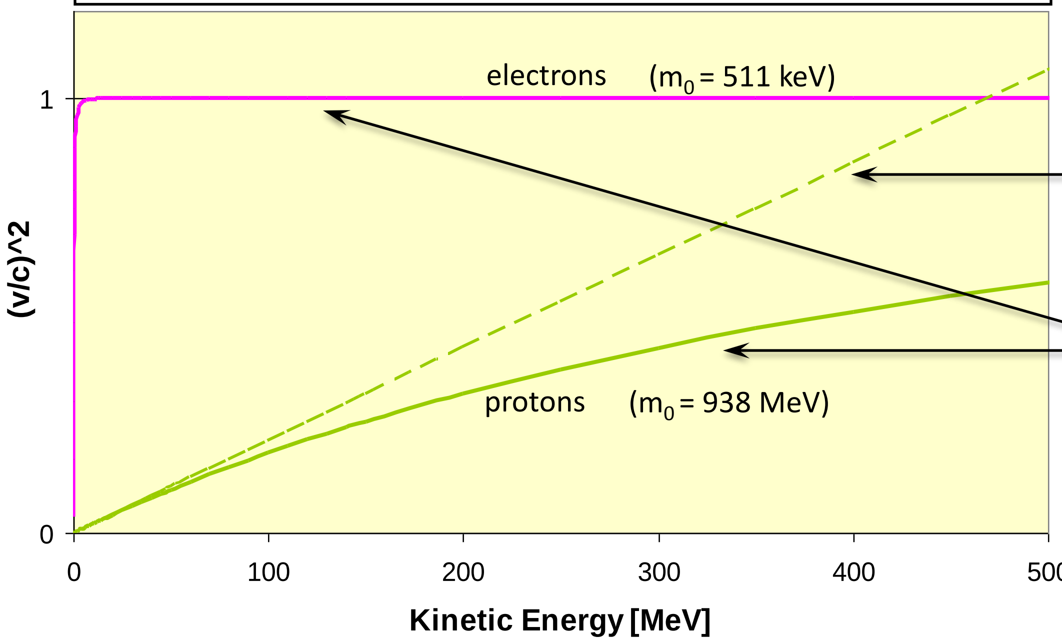
CERN Accelerator Complex, 1990s



Linear and circular accelerators

- In linear accelerators, the beam crosses the accelerating structures only once
- In circular accelerators, the beam repeatedly crosses the same accelerating structure
- Linear accelerators are the only ones that can be used in the domain where the particle velocity is increasing
- Things are very different for electrons and protons

$\beta^2=(v/c)^2$ vs kinetic energy T



Classic (Newton) relation:

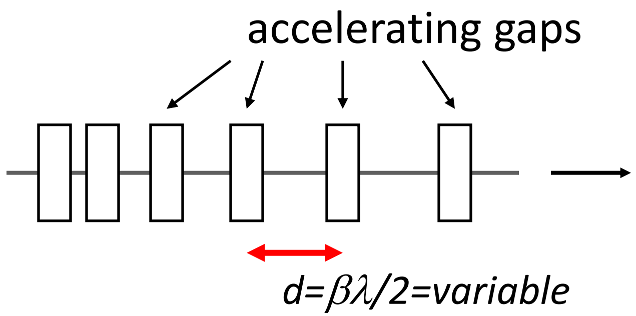
$$T = m_0 \frac{v^2}{2}, \quad \frac{v^2}{c^2} = \frac{2T}{m_0 c^2}$$

Relativistic (Einstein) relation:

$$\frac{v^2}{c^2} = 1 - \frac{1}{\sqrt{1+T/m_0 c^2}}$$

Linear Accelerators

The CERN Accelerator School



$$d = \frac{\beta c}{2f} = \frac{\beta\lambda}{2}, \quad \beta c = 2d\,f$$

Linear Accelerators are used for:

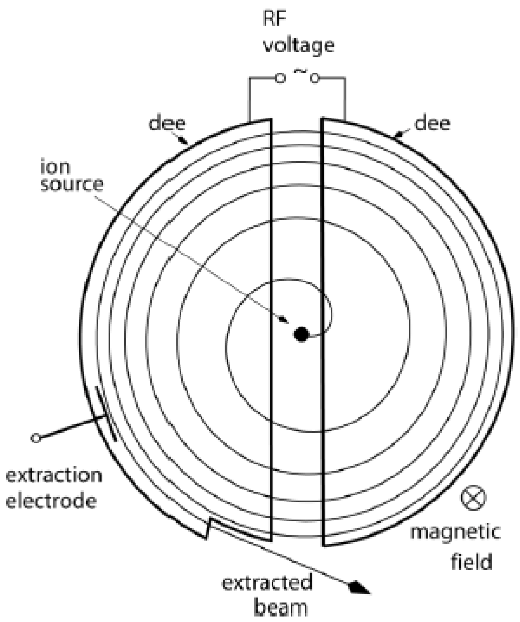
1. Low-Energy acceleration (injectors to synchrotrons or stand-alone): for protons and ions, linacs can be synchronous with the RF fields in the range where velocity increases with energy. When velocity is ~constant, synchrotrons are more efficient (multiple crossings instead of single crossing). Protons : $\beta = v/c = 0.51$ at 150 MeV, 0.95 at 2 GeV.

2. High-Energy acceleration in the case of:

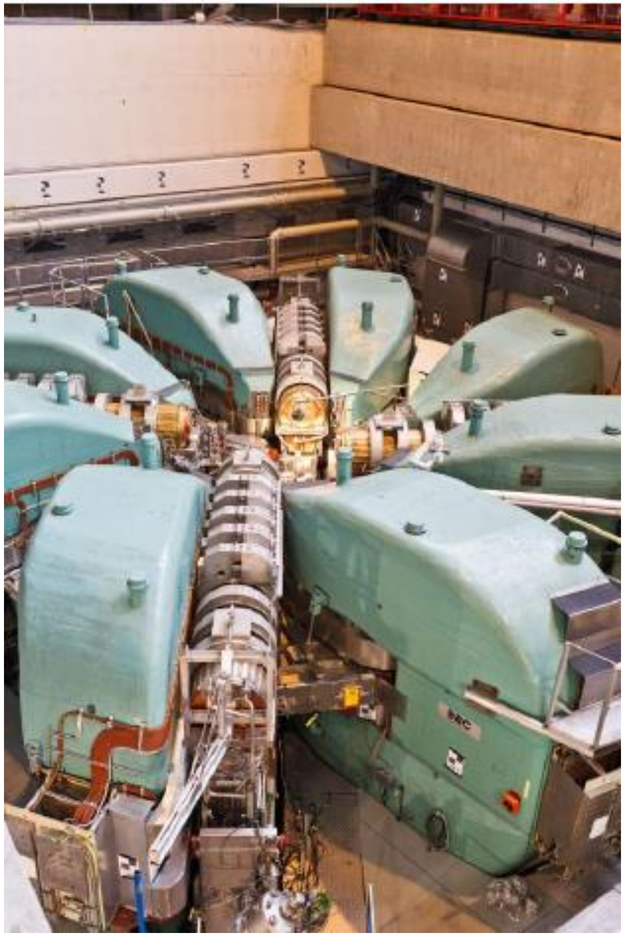
   - Production of high-intensity proton beams in comparison with synchrotrons, linacs can go to higher repetition rate, are less affected by resonances and have more distributed beam losses. Higher injection energy from linacs to synchrotrons leads to lower space charge effects in the synchrotron and allows increasing the beam intensity.

   - High energy linear colliders for leptons, where the main advantage is the absence of synchrotron radiation.

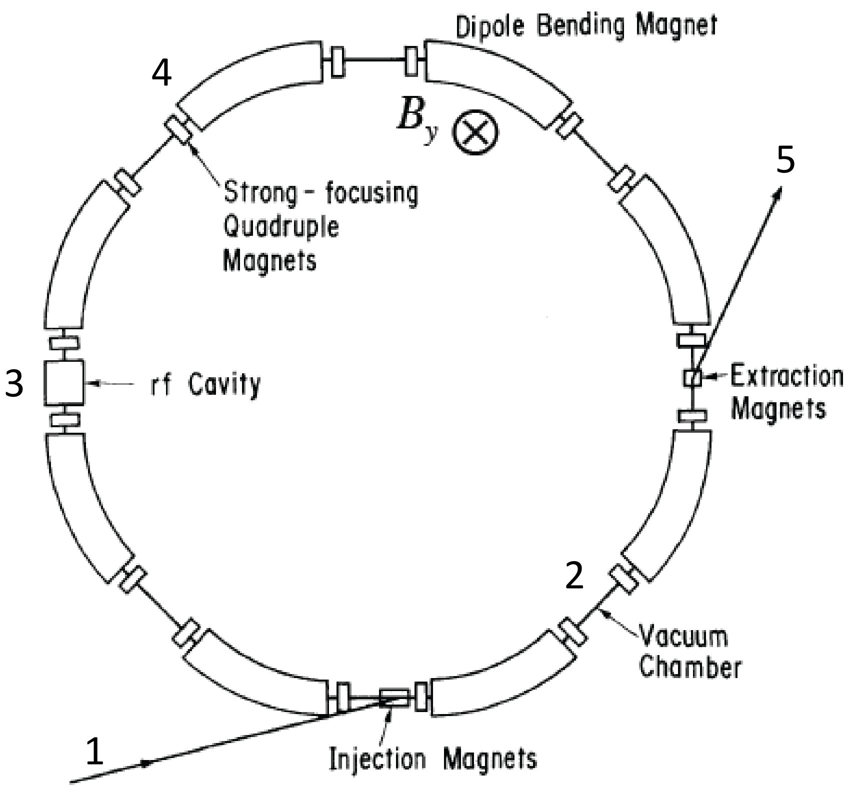
Cyclotrons



- Compact and simple
- Efficient
- Energy limited to ~ 1 GeV
- Injection / extraction critical



Synchrotrons



- Separated function
- Flexibility
- Scalability

1. Provides a beam of energetic particles
2. Employs a vacuum chamber in which the particles travel
3. Employs electric fields to impart energy to the particles
4. Employs magnetic fields to steer and focus the beam
5. For research applications, often provides collisions

Beam

The CERN Accelerator School

- The name given to a stream of energetic particles moving at speeds up to the speed of light. Indeed the choice of name is by analogy to a beam of light.

- Not always continuous – bunches

- In High Energy Physics
  - Typical bunch length a few cm, spacing a few m
  - Typical transverse size measured in µm
  - Typical bunch intensities several 10^{10} particles
  - Typical velocities are ultra relativistic, or $\beta \cong 1$

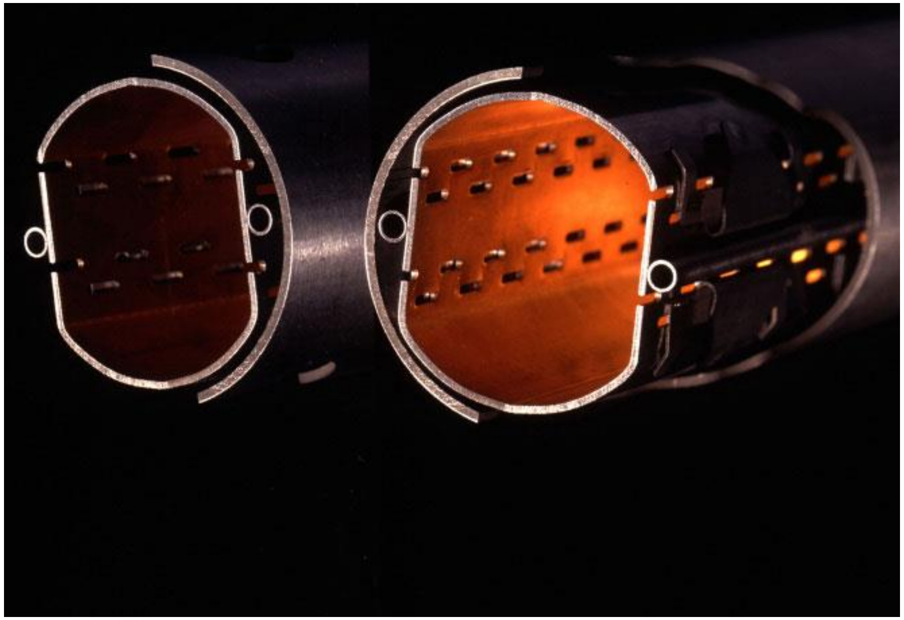
Vacuum chamber

- This is a metal pipe (also known as the beam pipe) inside which the beam of particles travels. It is kept at ultrahigh vacuum to minimise the amount of gas present to avoid collisions between gas molecules and particles in the beam.

Ultrahigh vacuum 10^{-10} Torr

1 atm = 760 mm Hg = 760 torr
1 atm ~ 1 bar = 100 000 Pa
1 pascal (Pa) = force of 1 Newton per m^2

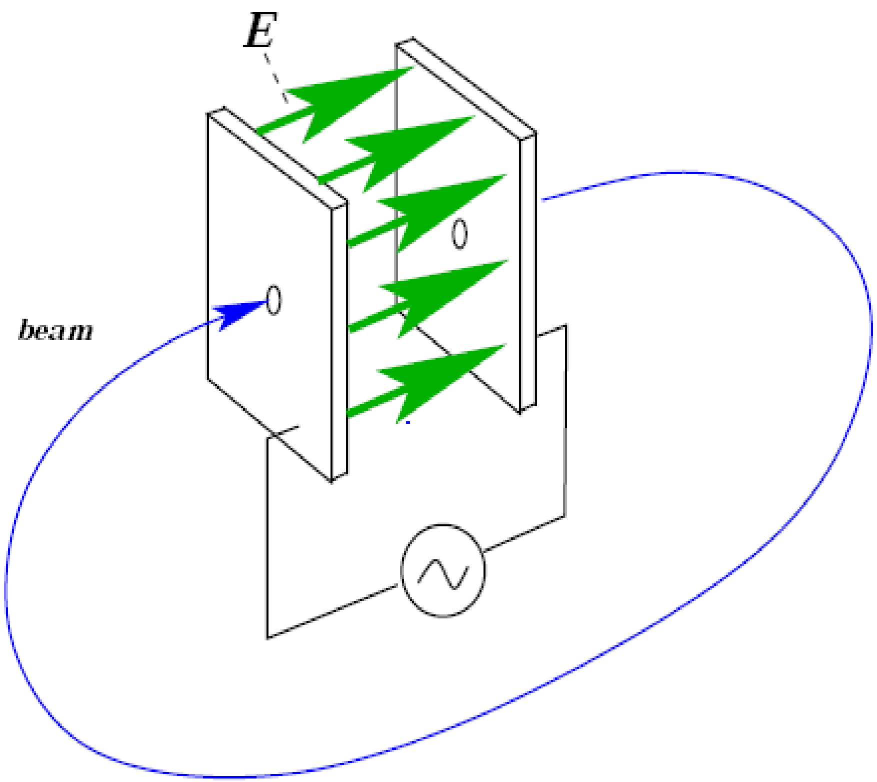
So 10^{-10} Torr ~ 10^{-10} mbar ~ 10^{-8} Pascal

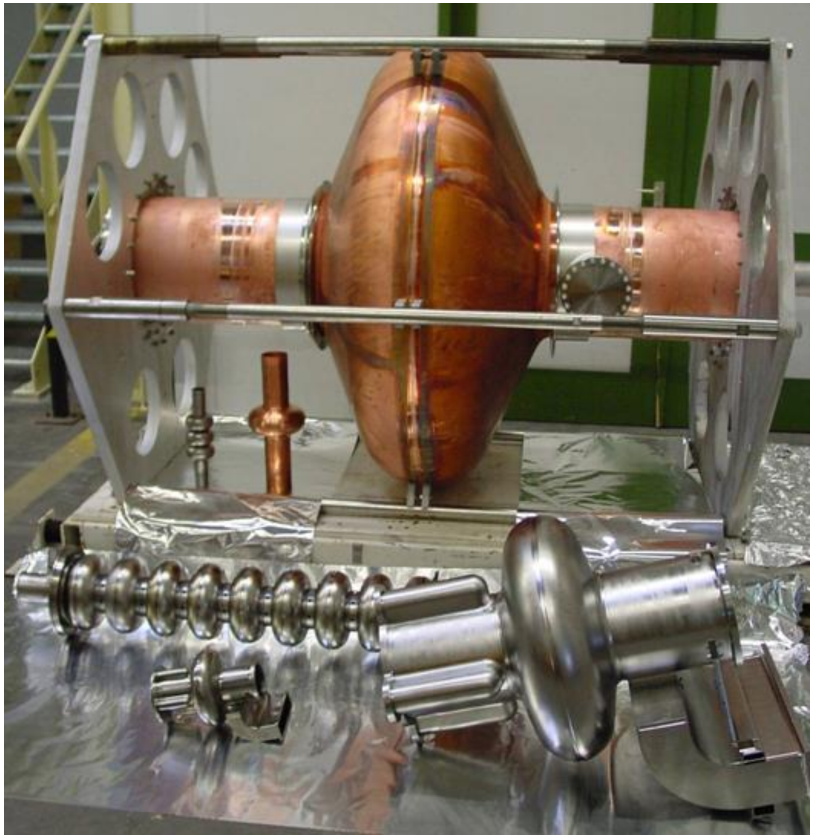


The pressure in the beam-pipes of the LHC is about ten times lower than on the moon

RF electric fields

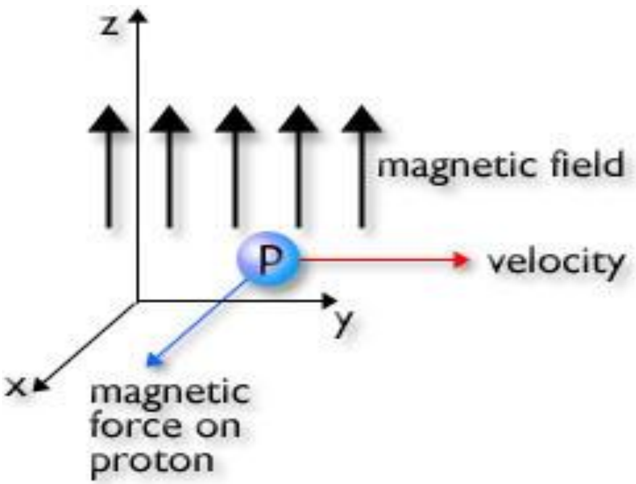
- These give energy to a beam of particles. RF cavities are located intermittently along the beam pipe. Each time a beam passes the electric field, some of the energy is transferred to the particles.

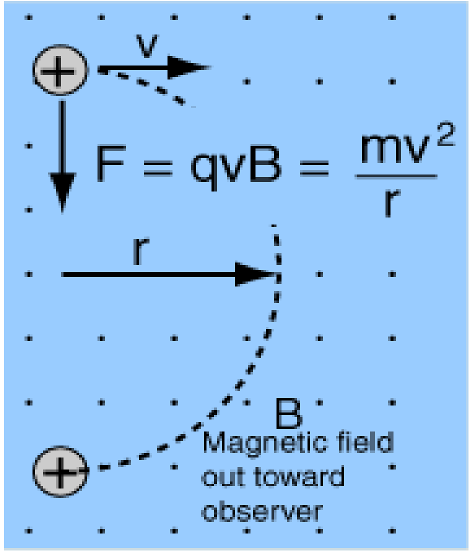




Magnetic fields

- Dipole magnets are used to bend the path of a beam of particles. The more energy a particle has, the greater the magnetic field needed to bend its path.



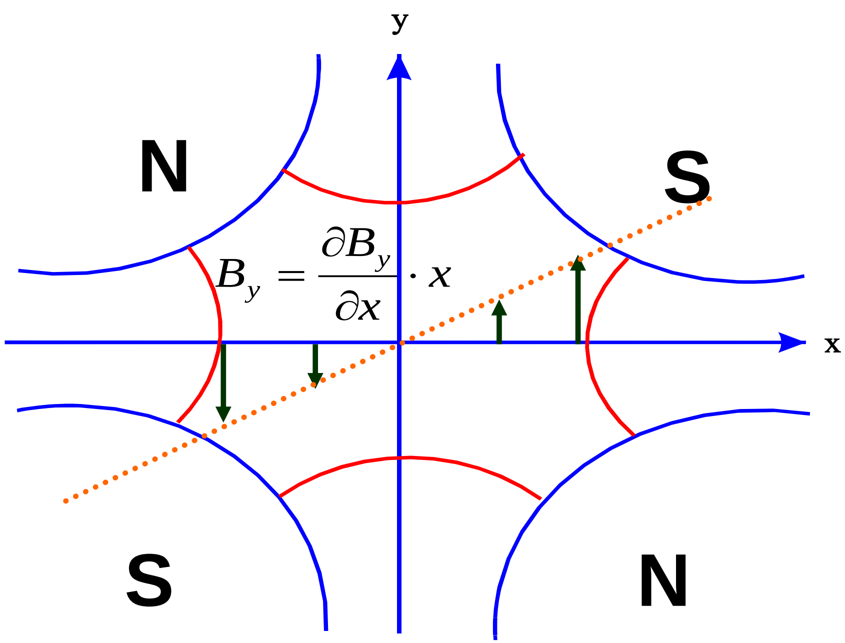


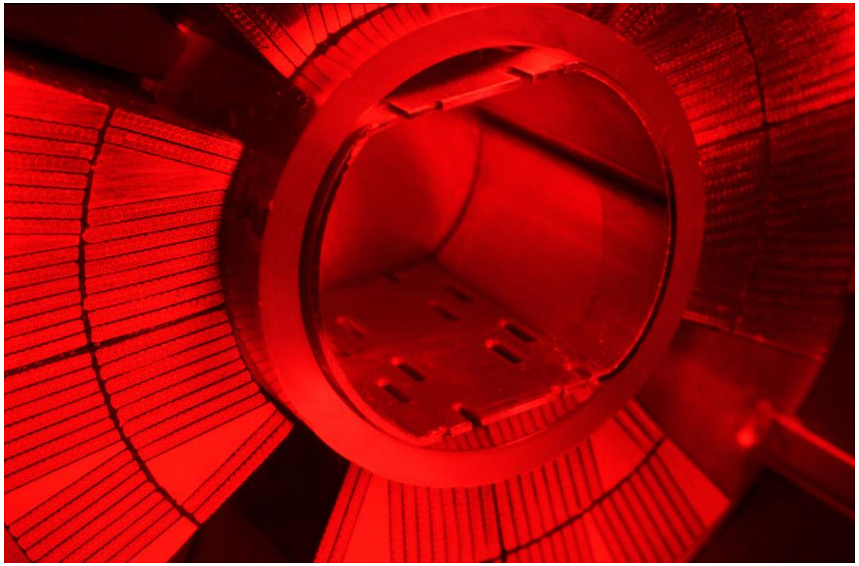
$$B\rho = p/e = m_0 v\gamma/e$$

$$B\rho\,[Tm] = 3.335641\; E\,[GeV] \qquad (10^9/c)$$

Magnetic fields

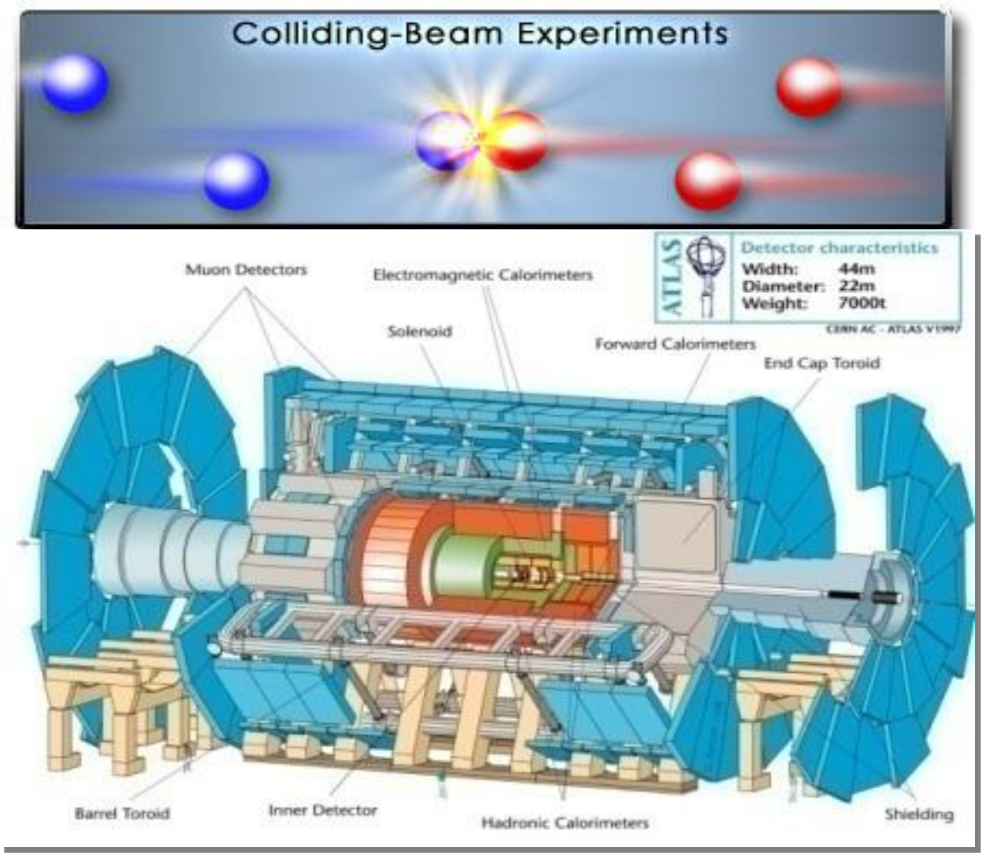
- Quadrupole magnets are used to focus the beam, gathering all the particles closer together (similar to the way lenses are used to focus a beam of light).
- Sextupoles similarly correct chromatic effects.
- Octupoles, decapoles and higher order also employed.

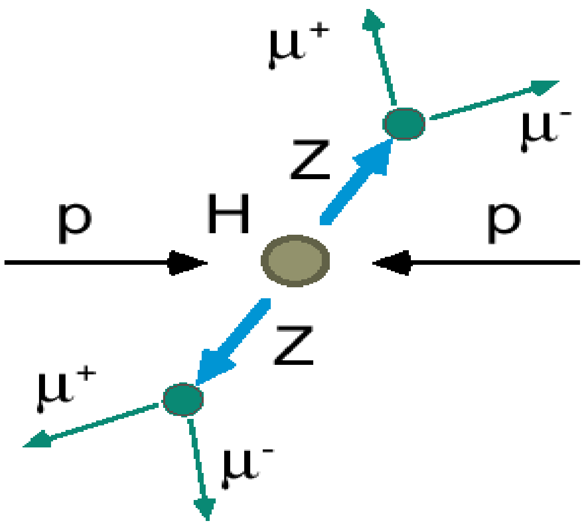




Collisions

- Counter-rotating beams are magnetically steered so that they collide. Detectors are built around the collision point





Collider

- Why do we collide beams in an accelerator?

- Consider two beams, same particle mass m
  - Beam 1 energy and momentum E_1 p_1
  - Beam 2 energy and momentum E_2 p_2
  - What counts is the energy in centre of mass E_{CM}

- In general, available energy is $E_{CM} = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2}$

- With an accelerator reach of 7 TeV (LHC)

  - Fixed target case, $p_2 = 0$ $$E_{CM} = \sqrt{2E_1 m + 2m^2} \approx 115 GeV$$

  - Collider case, $p_1 = -p_2$ $$E_{CM} = E_1 + E_2 = 14 TeV$$

What science do we need ?

- Relativity
- Electromagnetic theory
- Transverse beam dynamics
- Longitudinal beam dynamics
- Linear Imperfections and Resonances
- Synchrotron Radiation
- Electron Beam Dynamics
- Space Charge Effects
- Multi-Particle Effects
- Non-Linear Dynamics
- Landau Damping
- Colliding Beam Physics
- …

Relativity and Electromagnetic Theory

The CERN Accelerator School

Lorentz Transformations and 4-Vectors

$$t' = \gamma\left(t - \frac{vx}{c^2}\right)$$
$$x' = \gamma(x - vt)$$
$$y' = y \quad \text{where } \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$
$$z' = z$$

$$\Longrightarrow \begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & -\frac{\gamma v}{c} & 0 & 0 \\ -\frac{\gamma v}{c} & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix}$$

Maxwell's equations (1863)

$$\nabla \cdot \vec{D} = \rho$$ Gauss' Electrical Flux Theorem

$$\nabla \cdot \vec{B} = 0$$ Gauss' Law for Magnetism

$$\nabla \wedge \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$ Faraday's Law

$$\nabla \wedge \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$$ Ampere's Law

In vacuum

$$\vec{D} = \epsilon_0 \vec{E}, \quad \vec{B} = \mu_0 \vec{H}, \quad \epsilon_0 \mu_0 c^2 = 1$$

Lorentz force

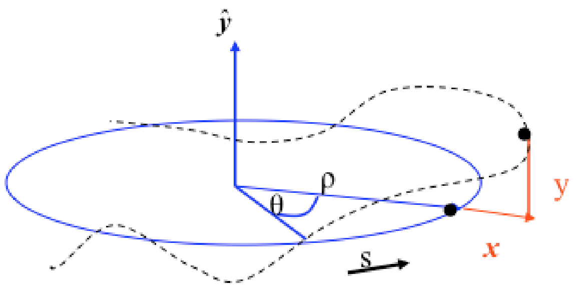
- Implicit in relativistic formulation of Maxwell's equations
- Describes the force on a charged particle moving in an em field

$$\vec{f} = q(\vec{E} + \vec{v} \wedge \vec{B})$$

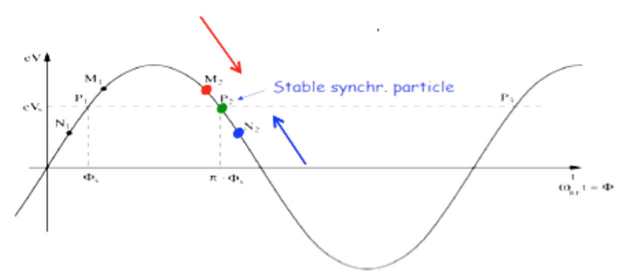
$\vec{E} = 0$ $\qquad$ $\vec{B} = 0$

$$\vec{f} = q\,\vec{v} \wedge \vec{B} \qquad\qquad \vec{f} = q\,\vec{E}$$

Transverse Beam Dynamics



Longitudinal Beam Dynamics



Perfect world and otherwise

- In the perfect (transverse) world

$$M_{foc} = \begin{pmatrix} \cos(\sqrt{|K|}s) & \frac{1}{\sqrt{|K|}}\sin(\sqrt{|K|}s) \\ -\sqrt{|K|}\sin(\sqrt{|K|}s) & \cos(\sqrt{|K|}s) \end{pmatrix}_0$$

$$M_{defoc} = \begin{pmatrix} \cosh\sqrt{|K|}l & \frac{1}{\sqrt{|K|}}\sinh\sqrt{|K|}l \\ \sqrt{|K|}\sinh\sqrt{|K|}l & \cosh\sqrt{|K|}l \end{pmatrix}$$

$$M_{drift} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$

$$M_{total} = M_{QF} * M_D * M_{QD} * M_{Bend} * M_{D*.....}$$

  - Beta function, Emittance, Orbit, Tune

- Field Imperfections
  - Linear (field errors, alignment errors)
  - Non-linear
  - Driven oscillations
  - Resonances
  - Instabilities

Collective effects

- Not only single particle effects
- Recall that a beam is often a train of bunches

- This leads to Collective effects
  - Between charged particles in the same bunch
    - Space charge
  - Between the bunch and the environment
    - Impedance and wake fields
  - Between bunches via this impedance
    - Coupled bunch effects
  - Between bunches in colliding beams
    - Beam beam effects

And quite a bit more !

The CERN Accelerator School

- **CAS Level 1 Introduction to Accelerator Physics**
  - Opening
  - Introduction to Accelerators I, II
  - Relativity
  - E.M. Theory
  - Transverse Dynamics I, II, III, IV
  - Longitudinal Beam Dynamics I, II, III
  - Linear Imperfections & Resonances I, II
  - Synchrotron Radiation
  - Electron Beam Dynamics I, II
  - Multi-Particle Effects I, II
  - Colliding Beam Physics
  - RF Systems I, II
  - Beam Instrumentation I, II
  - Injection & Extraction
  - Transfer Lines
  - Linear Accelerators I, II
  - Power Converters
  - Synchrotron Light Machines
  - FFAGs
  - Warm Magnets
  - SC Magnets
  - Radiation and Radio-Protection
  - Particle Sources
  - FELs
  - Vacuum Systems
  - Cyclotrons
  - Putting It All Together
  - Closing
- **CAS Level 2 Advanced Accelerator Physics**
  - Opening
  - Recap. Transverse Dynamics I, II
  - Recap. Longitudinal Dynamics I, II
  - Introduction to Beam Instrumentation
  - Introduction to Beam Diagnostics
  - RF Basic Concepts
  - Lattice Cells
  - Insertions
  - New Tools for Non-Linear Dynamics I, II
  - Non-Linear Dynamics I, II
  - Sources of Emittance Growth (Hadrons)
  - Space Charge
  - Landau Damping I, II
  - Beam Instabilities I, II
  - Instabilities in Linacs
  - Beam-Beam Effects
  - RF Cavity Design
  - Linear Accelerators
  - RFQ
  - Linear Colliders
  - Low Emittance Machines I, II, III
  - Feedback Systems I, II
  - Insertion Devices
  - FELS
  - Beam Cooling
  - High Brilliance Beam Diagnostics
  - High Field Magnets
  - Timing and Synchronisation
  - Controls
  - Machine Protection & Collimation
  - Overview of Future Accelerators

Basic questions in accelerator design

The CERN Accelerator School

- What is the machine for?

- What energy do we need?
- What intensity do we need?
- What beam size do we need?

High Energy

High Power

High Brightness

- What availability do we need?

- What particles should we use?
- What type of accelerator is best suited?
- What technology should we use?

Proton versus Electron

Main differences		
	Proton	Electron
Structure	uud + gluons	point-like
Rest mass	938 MeV	511 keV (= m_p/1836)
Consequences (of the mass difference)		
$Br = p / e = m_0 v g / e$	Much more magnetic rigidity for protons	
$eU_0 = Ag^4 / r$	Much much stronger synchrotron radiation for electrons	
$\frac{v^2}{c^2} = 1 - \frac{1}{\sqrt{1 + T / m_0 c^2}}$	Electrons relativistic at much lower energies	
Consequences (of the structure)		
Use protons for energy reach, leptons for precision measurements		

Magnetic rigidity

The CERN Accelerator School

$$B r = p / e = m_0 v g / e$$

$$B r \left[Tm \right] = 3.335641 \; E \left[GeV \right]$$

Known	Reason	Example	Free to choose
B	Normal conducting magnets	SPS	E, ρ
E	Want to run on the Z^0 mass	LEP	B, ρ
ρ	Tunnel already there	LHC	E, B

LEP

The CERN Accelerator School

Known	Reason	Example	Free to choose
B	Normal conducting magnets	SPS	E, ρ
E	Want to run on the Z^0 mass	LEP	B, ρ
ρ	Tunnel already there	LHC	E, B

$$Br\,[Tm] = 3.335641\; E\,[GeV] \qquad eU_0 = Ag^4 / r$$

- We need to use e^+ and e^- (for precision measurements)
  - Synchrotron radiation will be an issue
    - Build a big tunnel
    - Use cheap conventional magnets
      - Bending radius in the dipoles 3096 m
      - Bending field needed for 45GeV 0.048 T
  - LEP2 went up to 100 GeV
      - U_0 3 GeV
    - Big expensive SCRF system

LHC

Known	Reason	Example	Free to choose
B	Normal conducting magnets	SPS	E, ρ
E	Want to run on the Z^0 mass	LEP	B, ρ
ρ	Tunnel already there	LHC	E, B

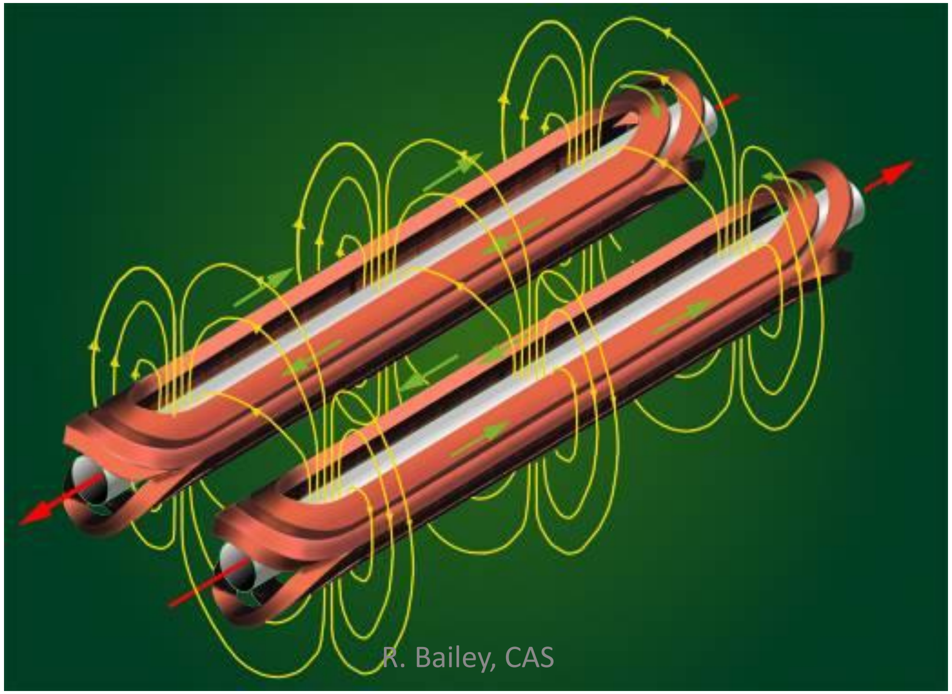
$$Br\,[Tm] = 3.335641\ E\,[GeV] \qquad eU_0 = Ag^4 / r$$

- We want to take protons to highest possible energy
  - Getting the magnetic field is the issue
    - Need superconducting magnets
      - Bending radius in the dipoles 2803 m
      - Bending field needed for 7 TeV 8.33 T
  - Synchrotron radiation not (much of) an issue
      - U_0 0.00001 GeV
    - Small RF system

Principal LHC design parameters

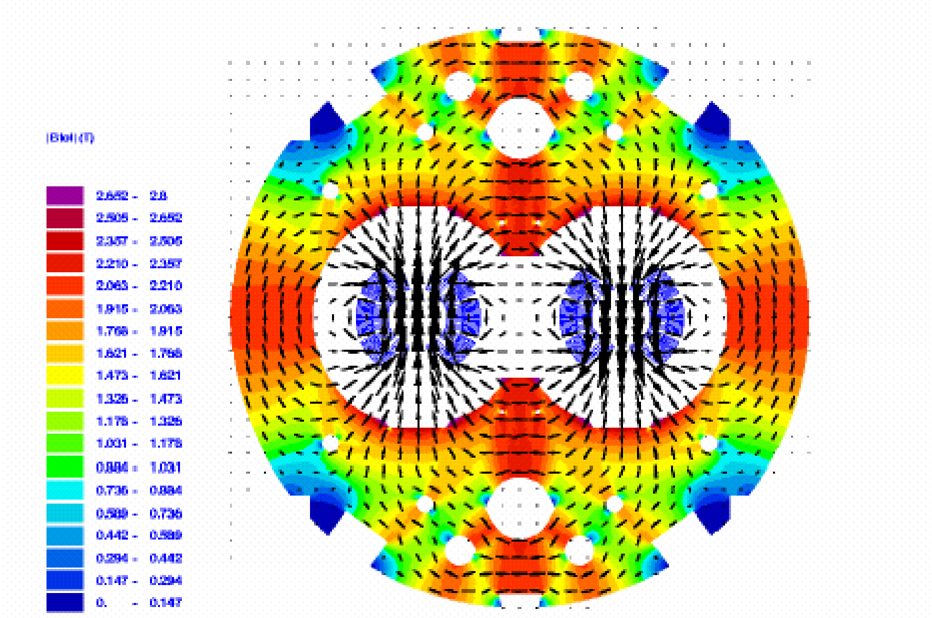
The CERN Accelerator School

- Luminosity (defines rate of doing physics) 10^{34} cm^{-2} s^{-1}
  - Need lots of particles to achieve this rate
  - Hence proton – proton machine (unlike Tevatron or SppbarS)
  - Separate bending fields and vacuum chambers in the arcs

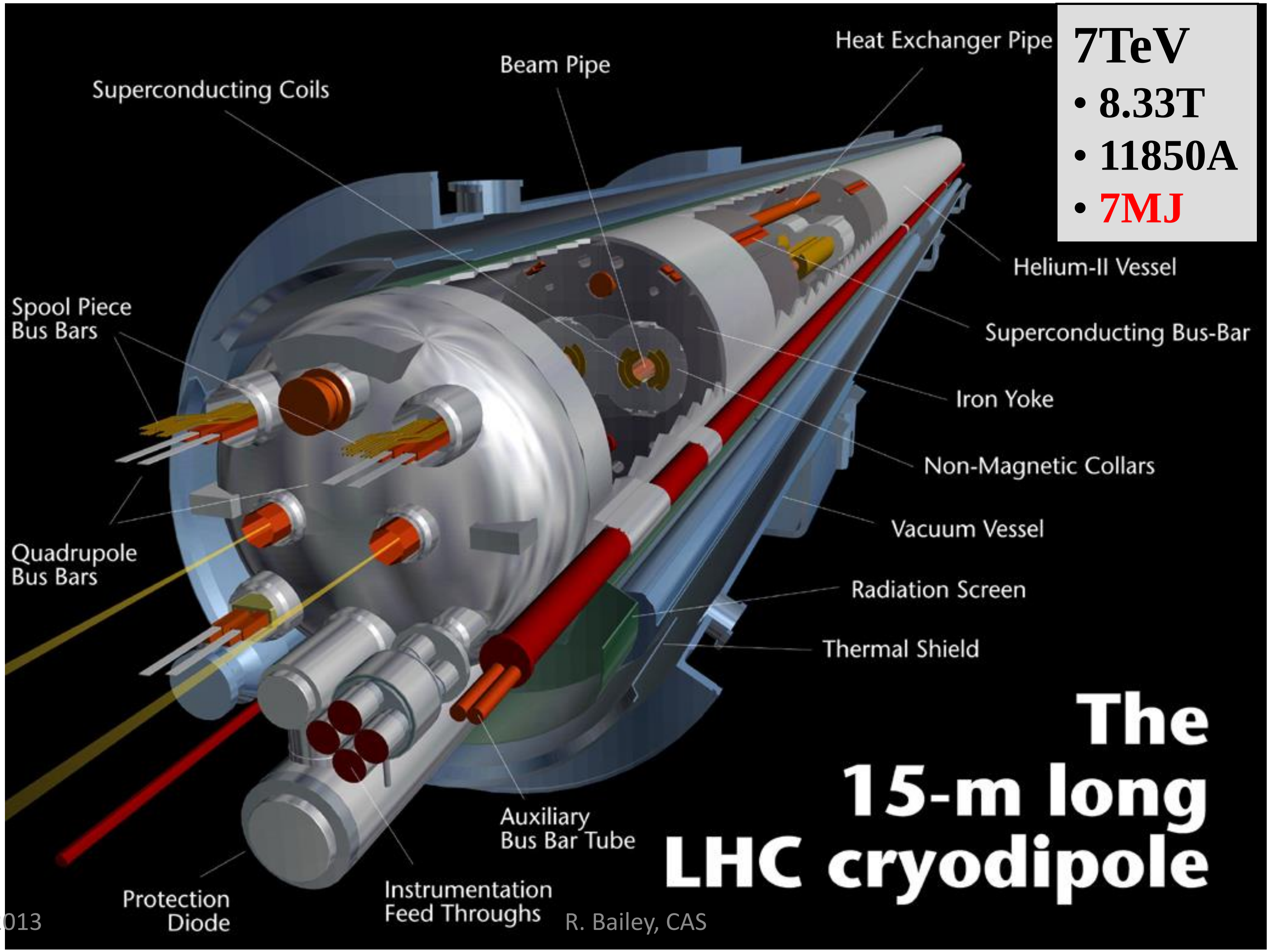


Principal LHC design parameters

- Energy 7TeV per beam ⇔ Dipole field 8.33Tesla
  - Superconducting technology needed to get such high fields
  - Tunnel cross section (4m) excludes 2 separate rings (unlike RHIC)
  - Hence twin aperture magnets in the arcs

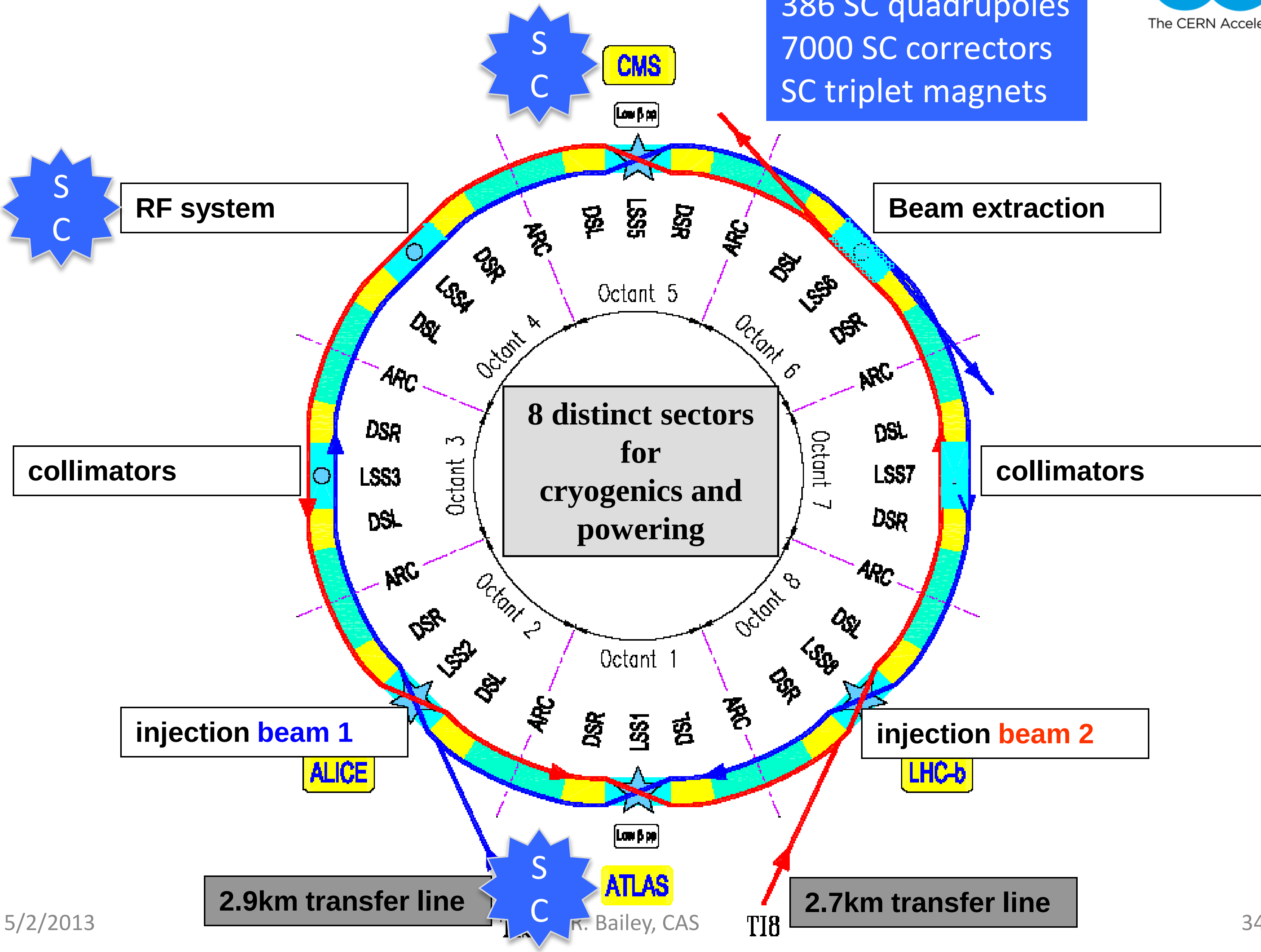


1232 LHC dipoles operating at 1.9K



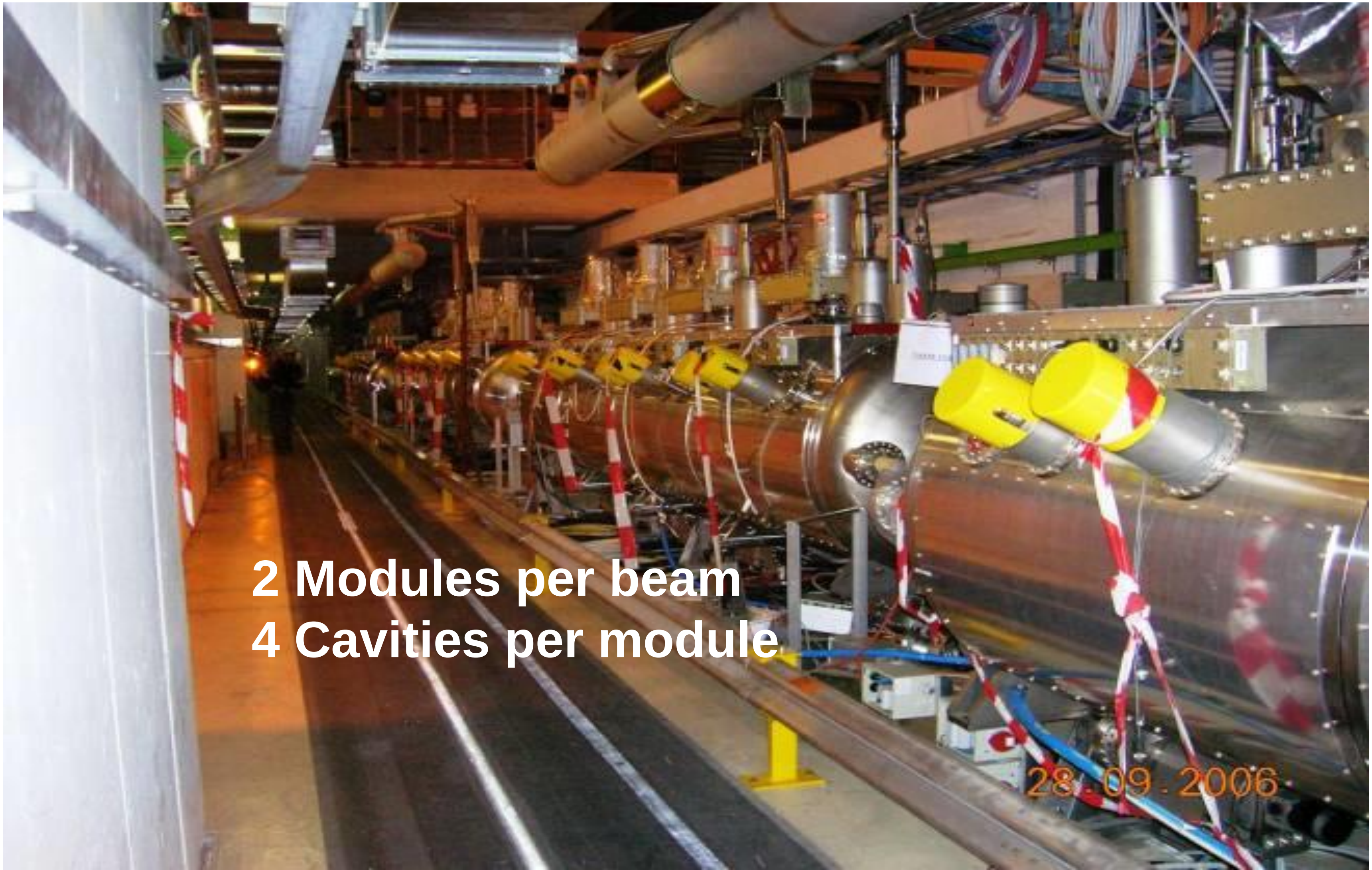
Schematic of the LHC

- 1232 SC Dipoles
- 386 SC quadrupoles
- 7000 SC correctors
- SC triplet magnets



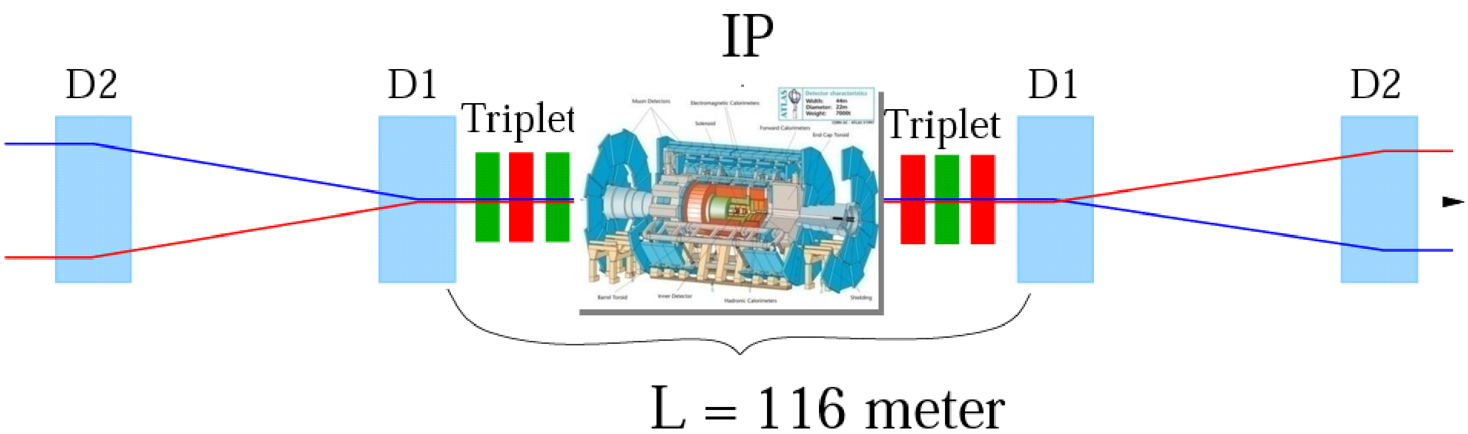
Superconducting RF systems (point 4)

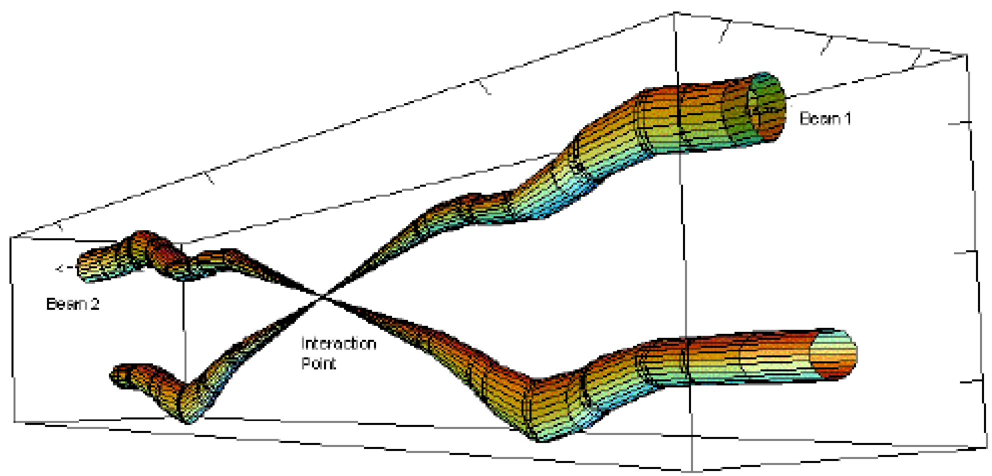
Give energy to the particles as they pass through



Insertion regions (points 1, 2, 5, 8)

Bring beams on axis and focus them at the interaction point



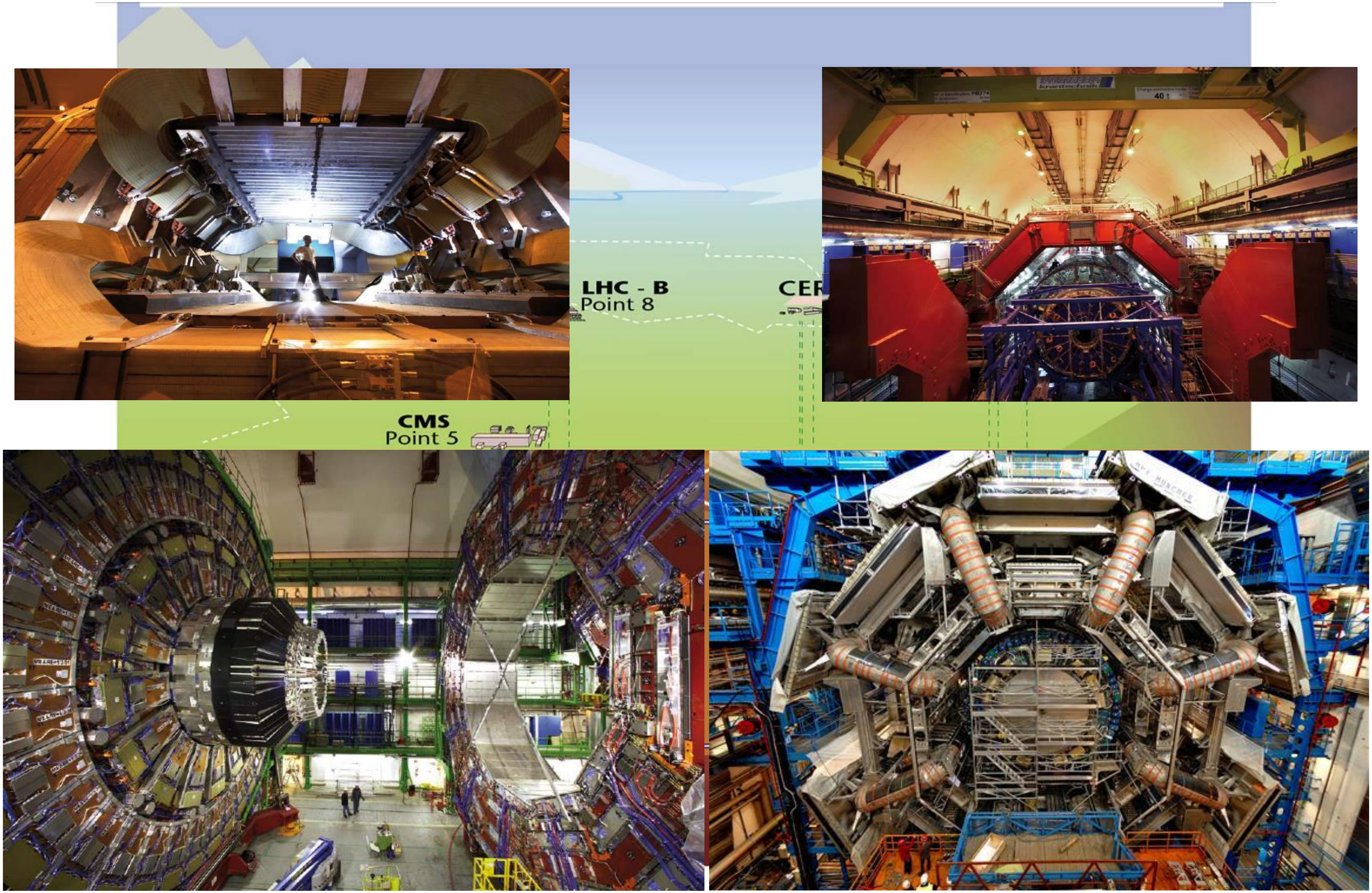


Relative beam sizes around IP1 (Atlas) in collision

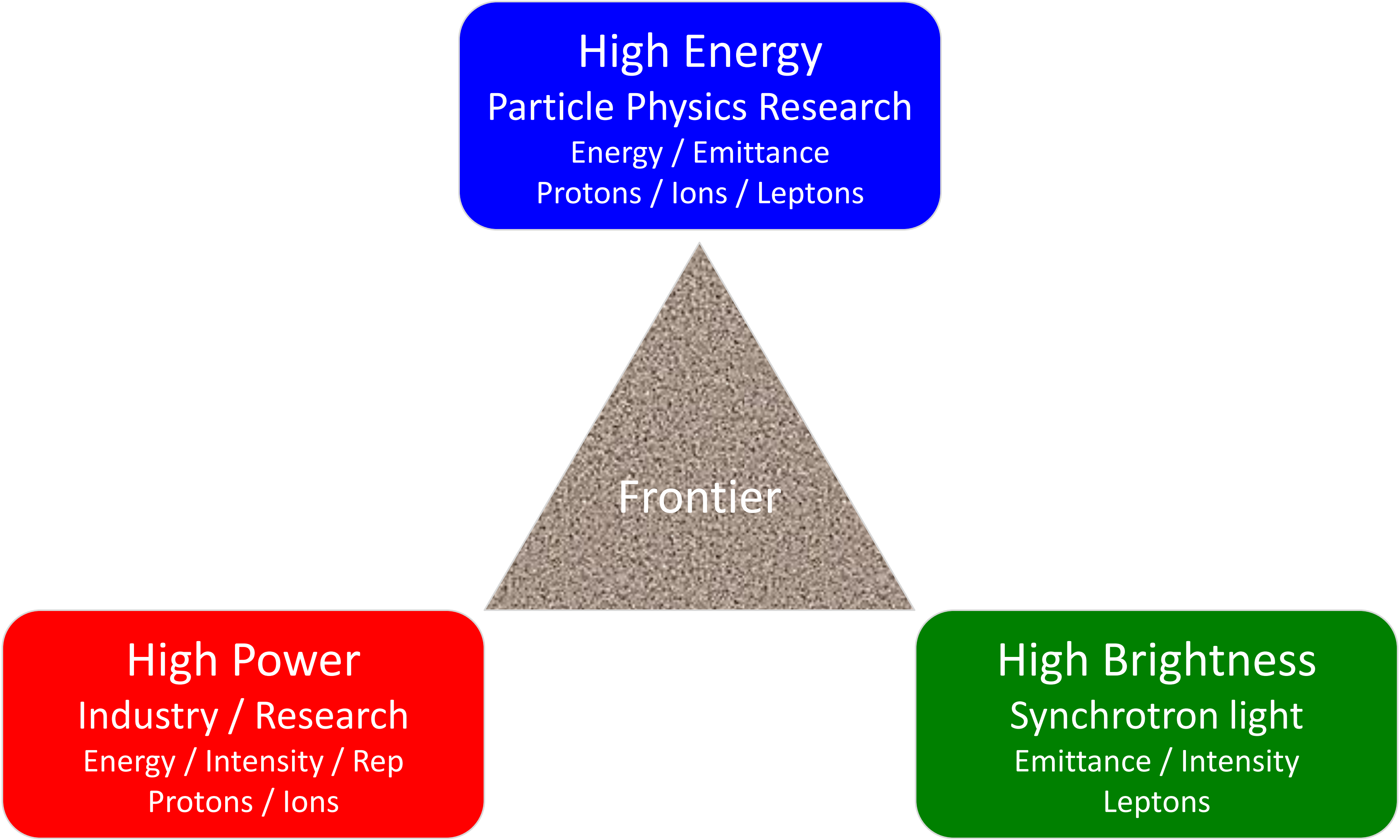
SC Triplets (points 1, 2, 5, 8)

Experiments (points 1, 2, 5, 8)

The CERN Accelerator School



Frontiers of Particle Accelerators



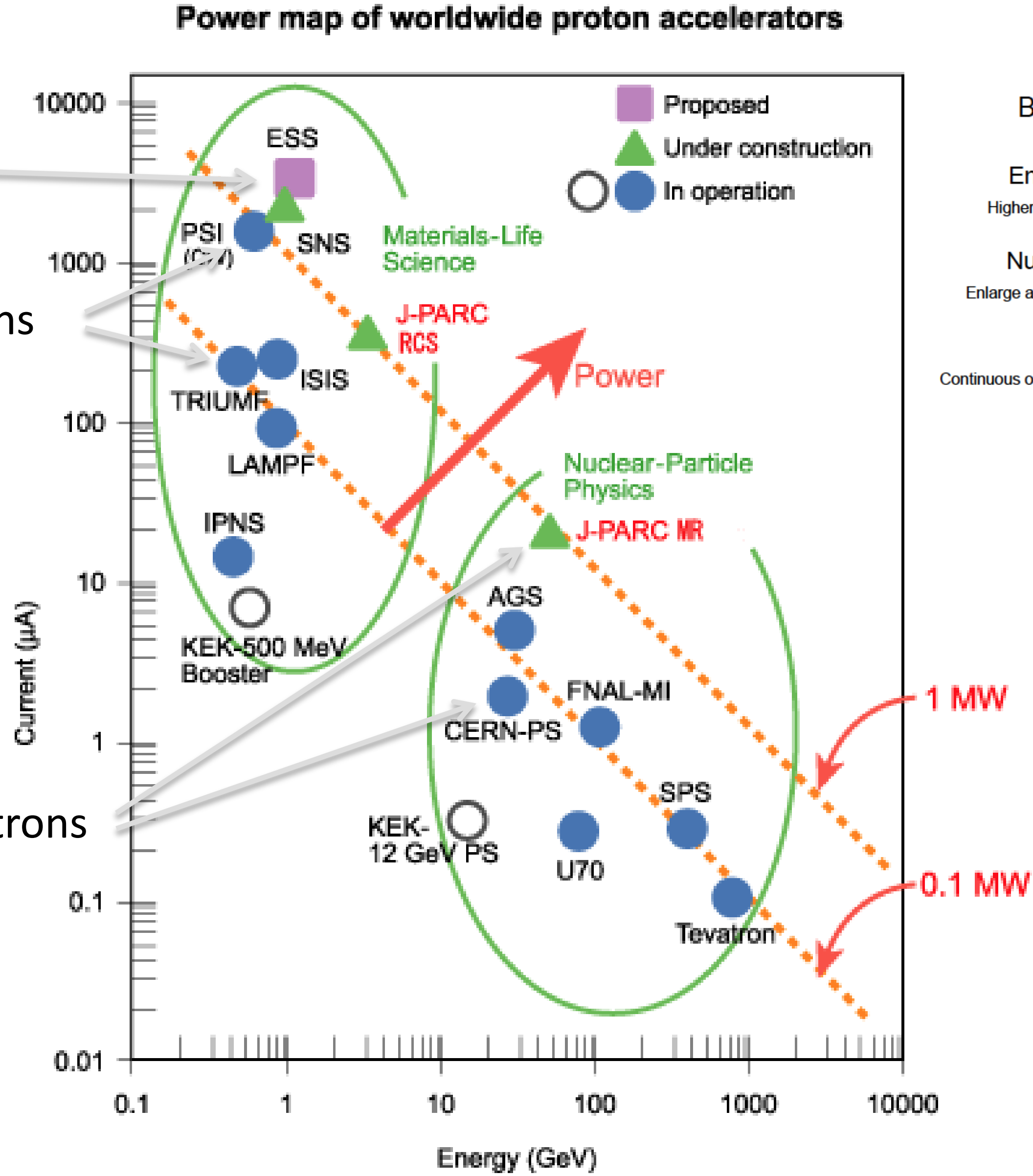
High Power Machines

The CERN Accelerator School

Some are linacs

Some are cyclotrons

Some are synchrotrons



Beam power of accelerator

Energy of individual particle [GeV]

Higher energy is preferable, but size should be moderate

x

Number of particle per beam [ppp]

Enlarge aperture as much as possible to mitigate space charge

x

Repetition rate [Hz]

Continuous operation is the best, but very high repetition is acceptable

Comparison of cyclotrons

	TRIUMF	RIKEN SRC (supercond.)	PSI Ring	PSI medical (supercond.)
particles	H- $\rightarrow$ p	ions	p	p
K [MeV]	520	2600	592	250
magnets (poles)	(6)	6	8	(4)
peak field strength [T]	0.6	3.8	2.1	3.8
R_{inj}/R_{extr} [m]	0.25/3.8...7.9	3.6/5.4	2.4/4.5	-/0.8
P_{max} [kW]	110	1 (86Kr)	1300	0.25
extraction efficiency (tot. transmission)	0.9995 (0.70)	(0.63)	0.9998	0.80
extraction method	stripping foil	electrostatic deflector	electrostatic deflector	electrostatic deflector
comment	variable energy	ions, flexible	high intensity	compact

Comparison of High Power Synchrotrons

	Energy	Radius	Rep. rate	Power	Particles /cycle	Application	Remarks
ISIS, UK	0.8 GeV	168 m	**50 Hz**	0.16 MW	3×10^{13}	Neutrons, muons	RCS
J-PARC RCS, Japan	3 GeV	348 m	25 Hz	**1 MW** (design)	4×10^{13} (design)	Injector for MR, Neutrons,...	RCS, **0.3 MW**
J-PARC MR, Japan	50 GeV	1567 m	0.3 Hz	0.75 MW (design)	**4×10^{14}** (design)	Neutrinos, ...	
CERN PSB	1.4 GeV	157 m	1 Hz	1.5 kW	(4x) 2×10^{12}	LHC injector chain	**4 rings**
CERN PS	26 GeV	630 m	0.3 Hz	25 kW	2×10^{13}	LHC injector chain	
AGS Booster	1.5 GeV	202 m	7.5 Hz	45 kW	2.5×10^{13}	RHIC injector chain	p-Au
AGS	24 GeV	807 m	0.5 Hz	130 kW	**7×10^{13}**	RHIC injector chain	p-Au
SIS-18, GSI	1 GeV/u	216 m	3 Hz	4 kW	**10^{10} Uranium**	Injector for SIS-100, RIBs	p-U
SIS-100, GSI	2.7 GeV/u	1080 m	1 Hz	50 kW	5×10^{11} Uranium	RIBs, pbars	p-U, sc magnets

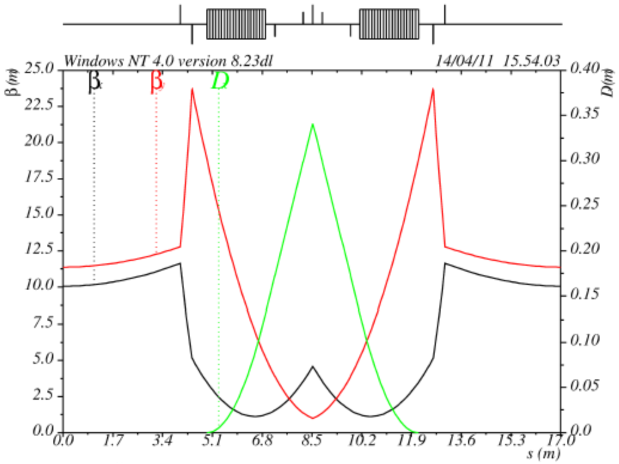
High brightness machines - synchrotrons

The CERN Accelerator School



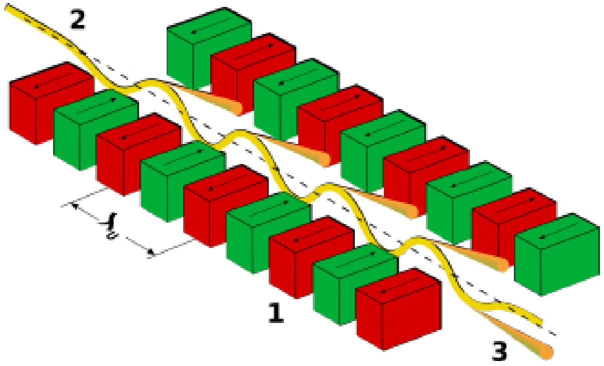



	Elettra	ALBA	DLS	ESRF	APS	SPring-8
Energy	2 GeV	3 GeV	3 GeV	6 GeV	7 GeV	8 GeV
Circumference	259 m	269 m	562 m	845 m	1104 m	1436 m
Lattice type	DBA	DBA	DBA	DBA	DBA	DBA
Current	300 mA	400 mA	300 mA	200 mA	100 mA	100 mA
Hor. emittance	7.4 nm	4.4 nm	2.7 nm	4 nm	3.1 nm	3.4 nm



In a Double Bend Achromat (DBA) lattice, the minimum emittance is given by:

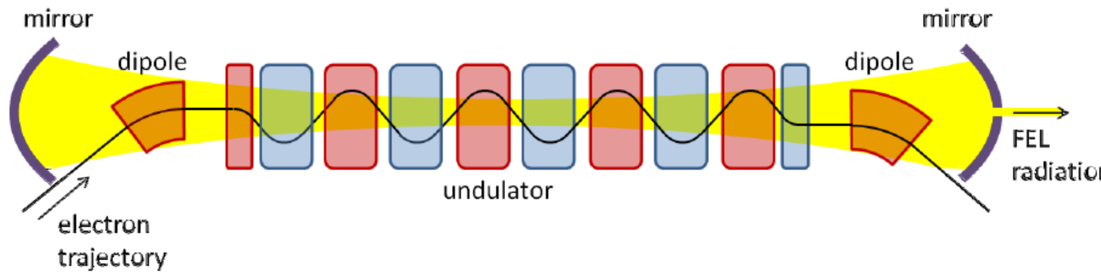
$$\varepsilon_0 \approx \frac{1}{4\sqrt{15}} C_q \gamma^2 \theta^3. \quad (4)$$



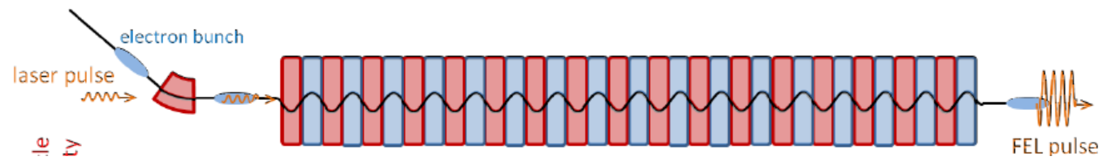
High brightness machines - FELs

Microbunching enhancement leads to exponential increase in the radiation intensity with increasing distance along undulator. Different techniques to get microbunching.

Resonator FEL



Seeded amplifier FEL



Self Amplified Spontaneous Emission or SASE FEL

Total length	3.4 km
Electron beam energy	17.5 GeV
Radiation wavelength	0.05 - 6 nm
X-ray pulse length	$<$100 fs
Peak brilliance	5×10^{33} γ/s/mm^2/mrad^2/0.1% bw