Experimental methods in particle physics

Pásztor Gabriella

Contact: Department of Atomic Physics, room 3.85
E-mail: gabriella.pasztor@ttk.elte.hu

Webpage of lecture:
http://atomfizika.elte.hu/rfkm/rfkm2019.html

Detailed pedagogical introduction to accelerator physics:
http://cdsweb.cern.ch/record/1017689/files/ab-note-2007-014.pdf

Reminder: Accelerators so far

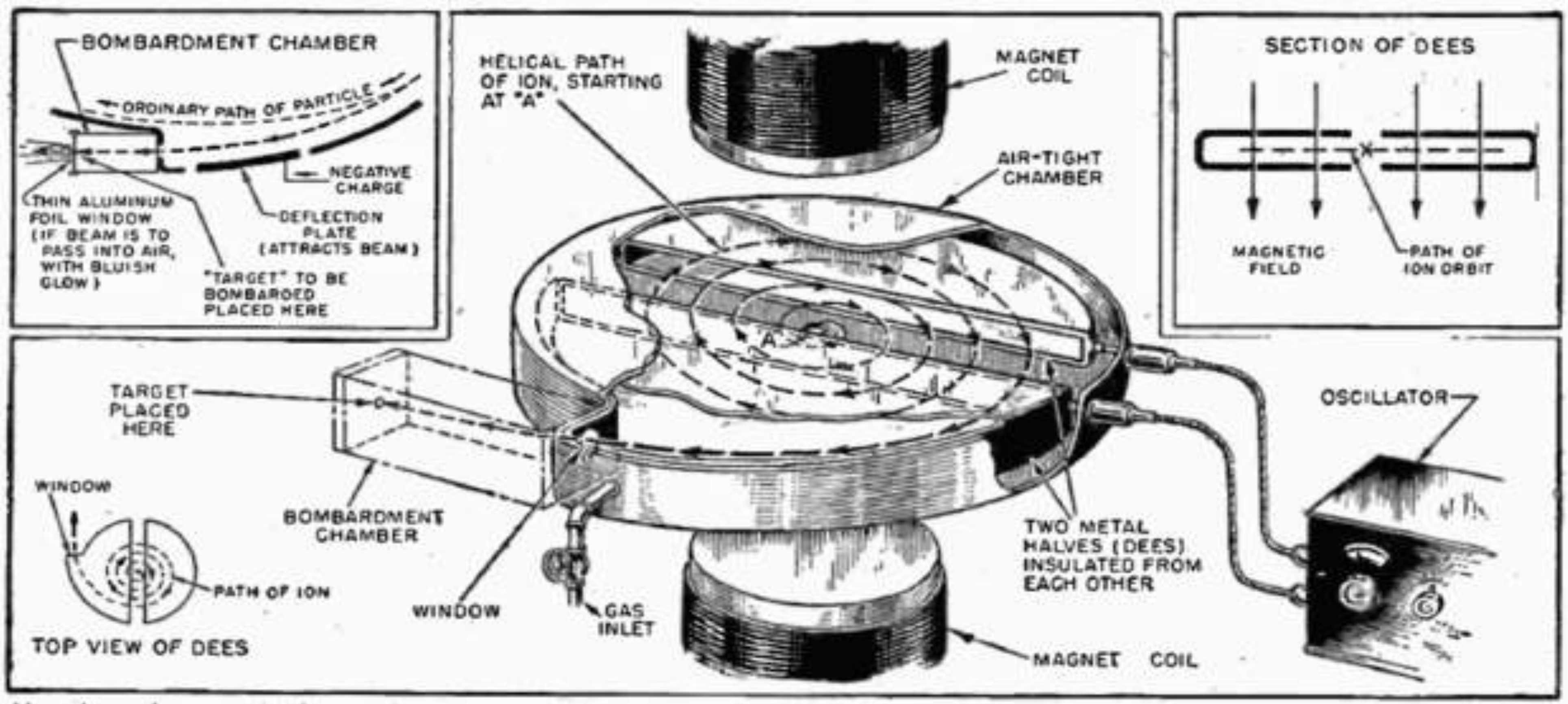
- Van de Graaf generator as accelerator
  - Tandem Van de Graaf starting from negative ions to “double” accelerating power
- Cockcroft-Walton accelerator
  - High direct-current voltage from alternating current voltage using a voltage amplification cascade with diodes acting as switches
- Radio frequency acceleration
  - Bunches (packets) of charged particles travel in RF electromagnetic field in sync with its phases
  - Linac Drift Tube by Wilderoe (also basis of cyclotrons): change potential on tubes (adjacent tubes in opposite phases), tubes also acts as a Faraday cage
  - Alvarez Drift Tube: close RF field into a box, all tubes in same phase
    - LC circuit analogy
  - Modern RF cavities: metallic chambers that contain an oscillating electromagnetic field, cavities shaped to have resonant waves (standing wave acceleration)
    - Early particles decelerated, late ones accelerated keeping the bunch together

Cyclotron

Ernest Lawrence in 1932 at the University of California, Berkeley (Nobel prize in 1939)

Lawrence built several cyclotrons: 69 cm (27 in) 4.8 MeV machine (1932), 94 cm (37 in) 8 MeV machine (1937), 152 cm (60 in) 16 MeV machine (1939)

Energy limit (15 MeV for protons, ~0.1c) due to relativistic effects: particles effectively become more massive, so that their cyclotron frequency drops out of synch with the accelerating RF



The magnet's pole pieces shown smaller than in reality; they are as wide as the dees to create a uniform field!

Synchrocyclotron

- Accelerates the particles in bunches
- Constant magnetic field
- Accelerating fields frequency changes to match the particles mass-dependent cyclotron frequency
- Disadvantages: low beam intensity due to bunching;
  huge magnet of large radius with constant field (demanded by the larger orbit of high energy particles

Isochronous cyclotron

- To accommodate relativistic effects, the magnetic field is increased to higher radii (accelerating frequency kept constant)
- Example: PSI Ring cyclotron in Switzerland (590 MeV, ~0.8c): very high maximum achievable extracted proton current (2.2 mA) → 1.3 MW beam power

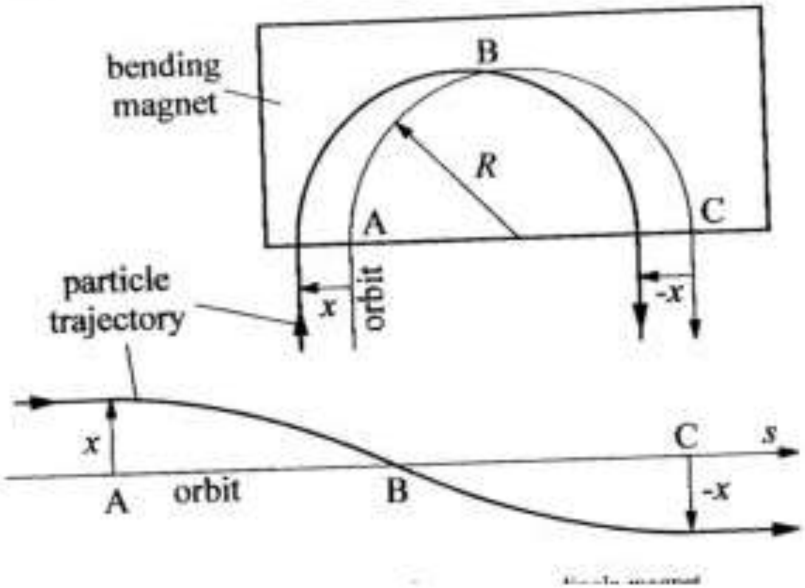
Synchrotrons (discussed already)

Weak focusing at early accelerators

Used in first proton synchrotron, the 3-GeV Cosmotron in 1952 at Brookhaven

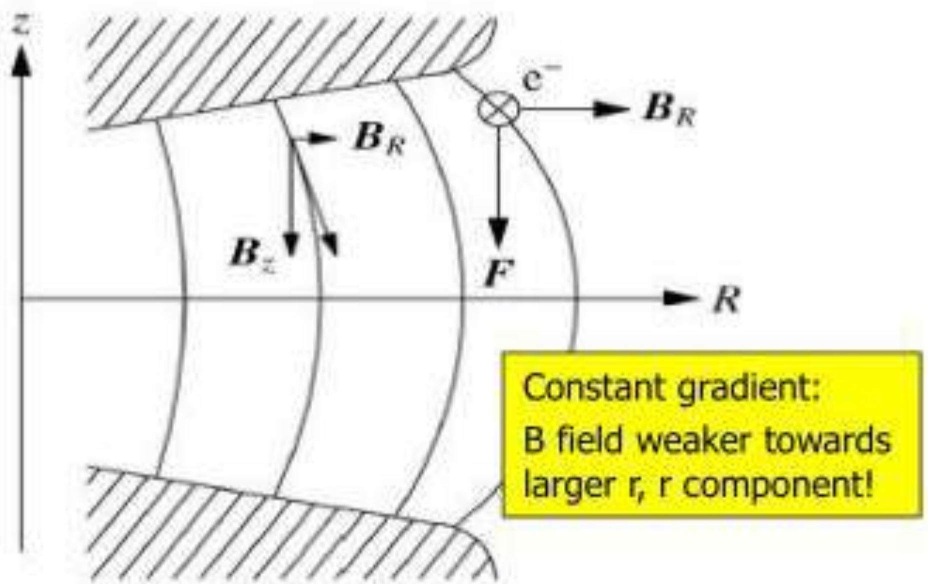
(Weak) transverse focusing:

- Particles tend to leave orbit horizontally and/or vertically (Coulomb repulsion, starting conditions).
- In horizontal plane deflecting dipoles have weak focusing action: Consider particle with distance x to beam:



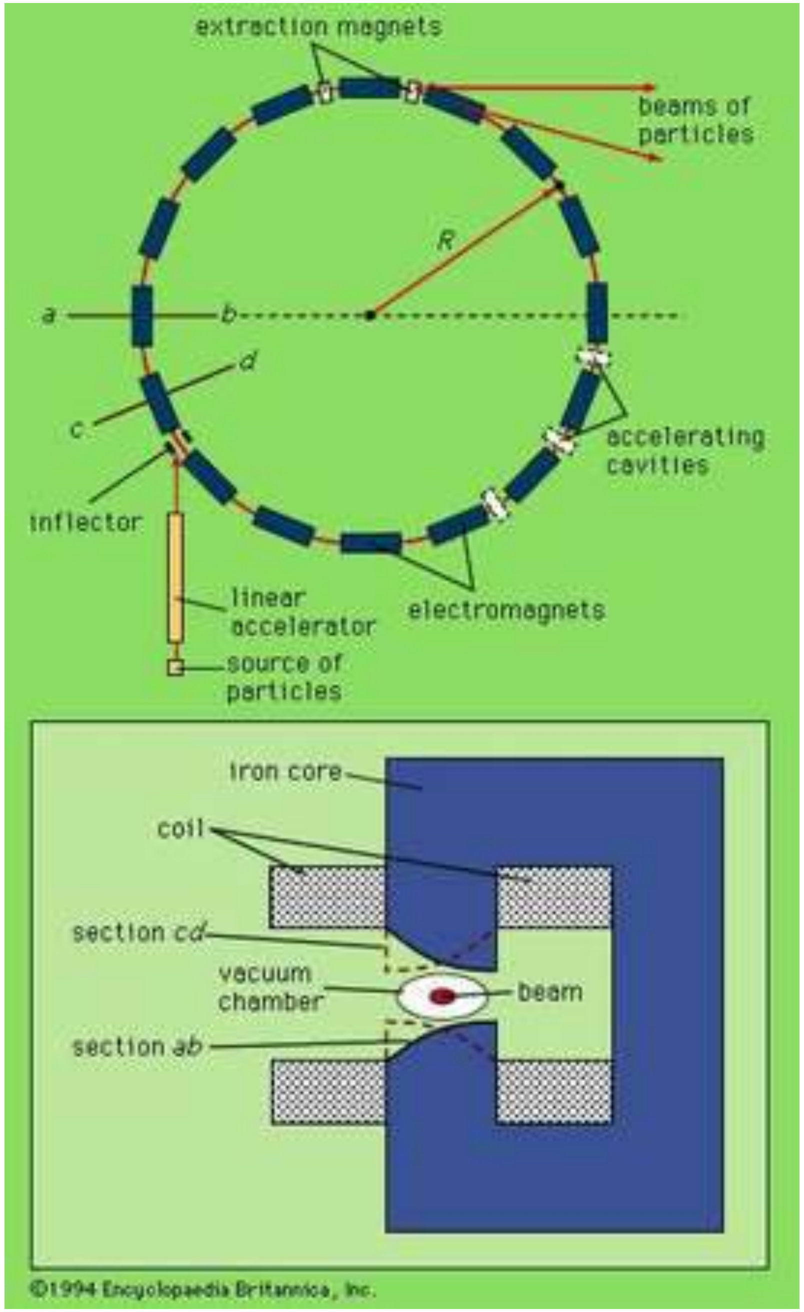
→ Trajectory is bent towards orbit! Focusing! But oscillations!

- Vertically slightly more difficult:
  → constant gradient scheme for magnets with large dipole gaps: Small B_r component.
  → Particles perform oscillations around orbit!



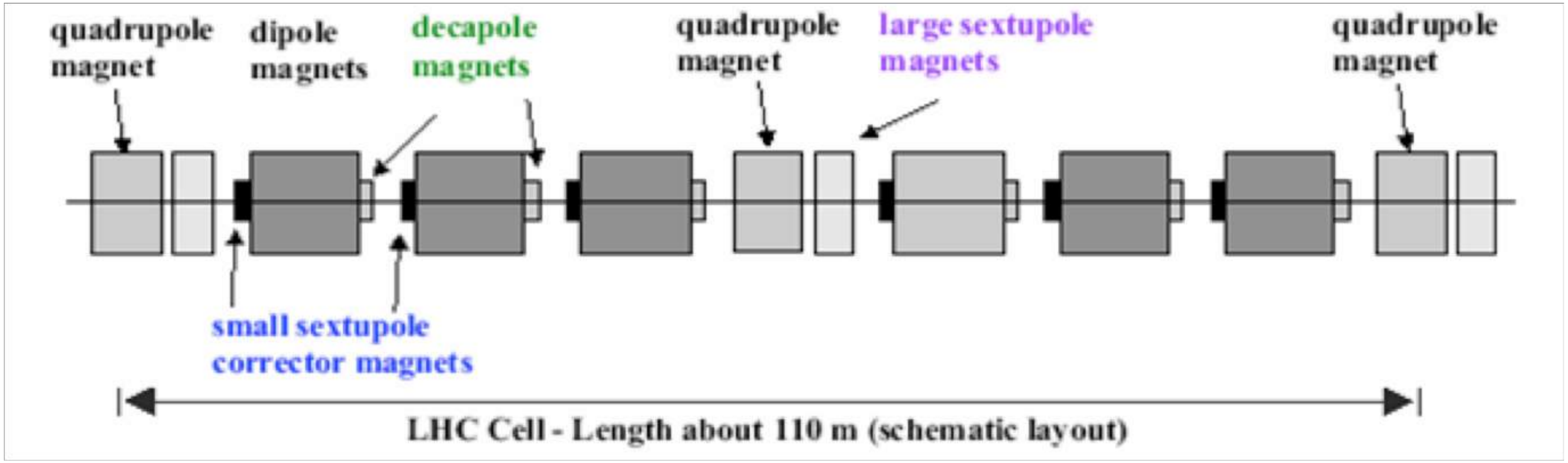
Strong (alternating-gradient) focusing

- First used in a 1.2 GeV electron synchrotron in 1954 at Cornell University
- First proton accelerators with ~30 GeV around 1960
  - Alternating Gradient Synchrotron @BNL
  - Proton Synchrotron @ CERN

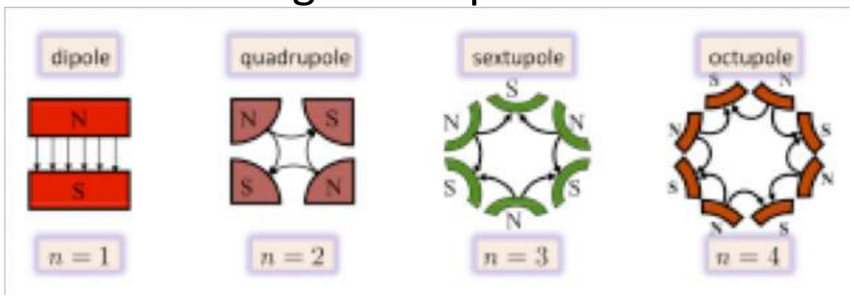


LHC magnet system & strong focusing

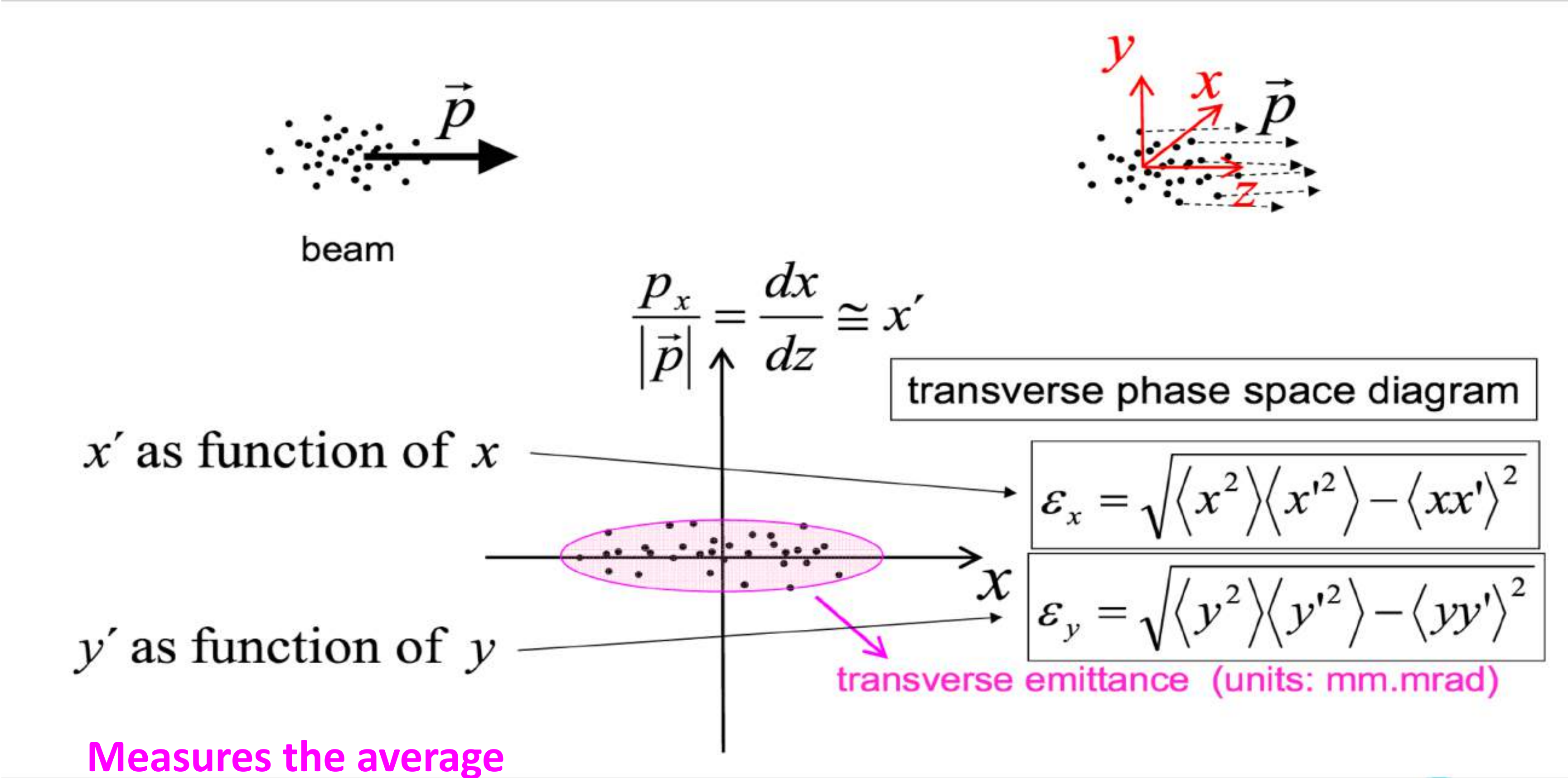
FODO pattern (**F** focuses vertically and defocuses horizontally,
D focuses horizontally and defocuses vertically, **O** is a space or deflection magnet)



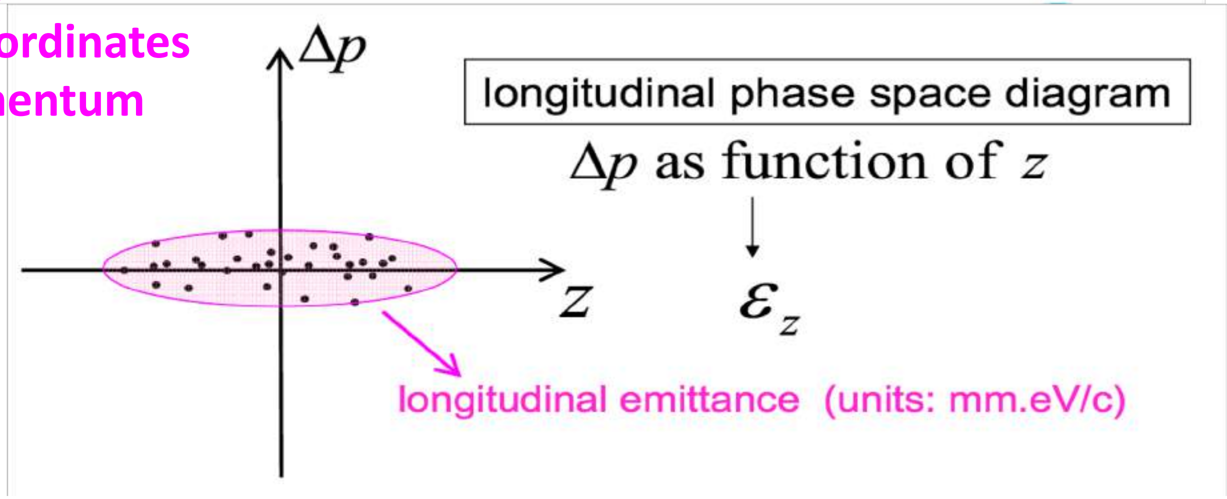
- Dipole magnets: keep the particle beam on a circular path
- Quadrupole magnets: focus the beam
- Sextupole magnets: Correct path of particles with non-nominal momentum (chromatic errors)
- Multipole magnets: Sextupole, octupole és decapole corrector magnets improve the dipole field at the end of the dipoles
  Stabilize the path of particles with large amplitude
  Very important to keep the beam lifetime high



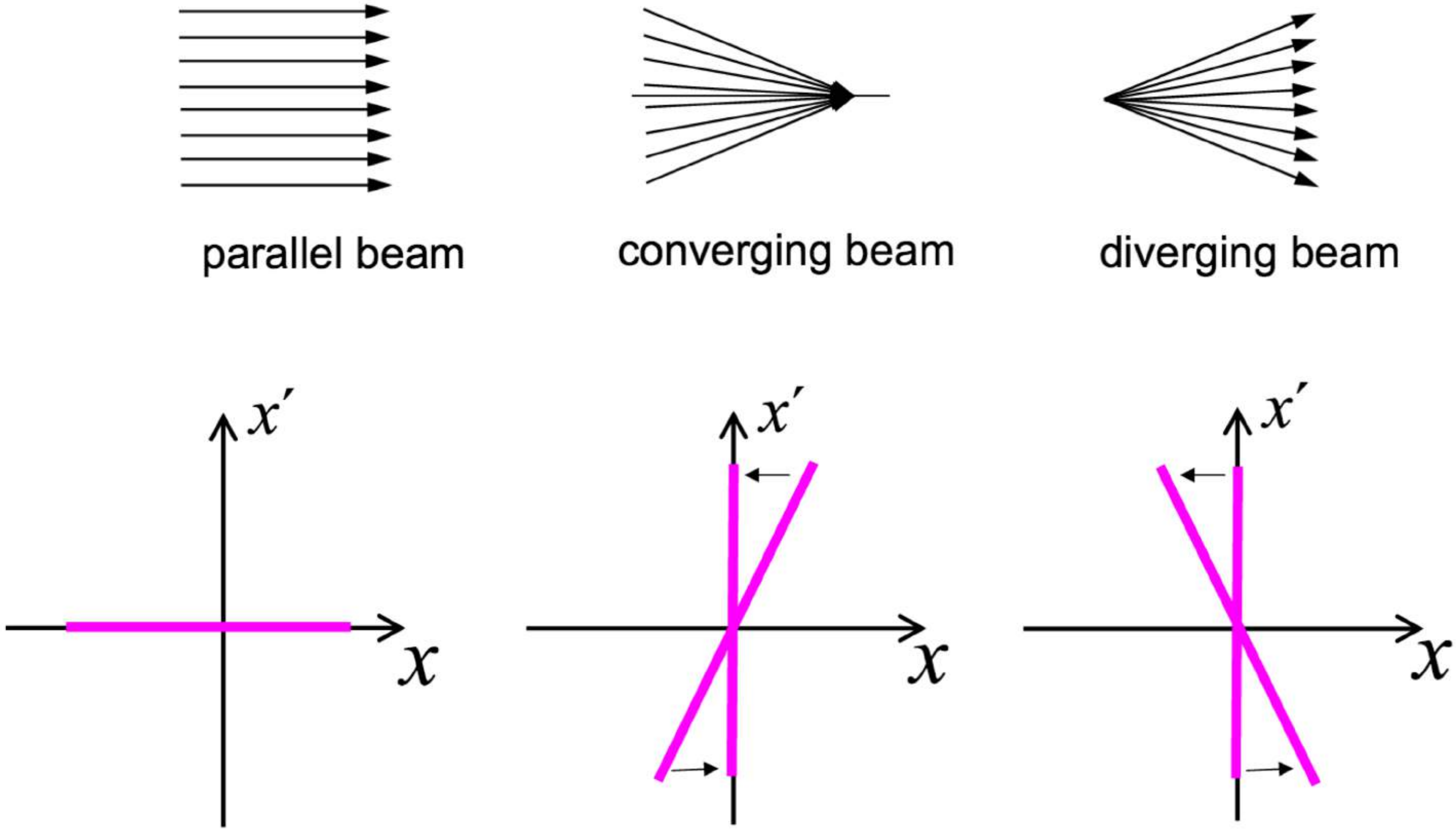
Beam quality: emittance



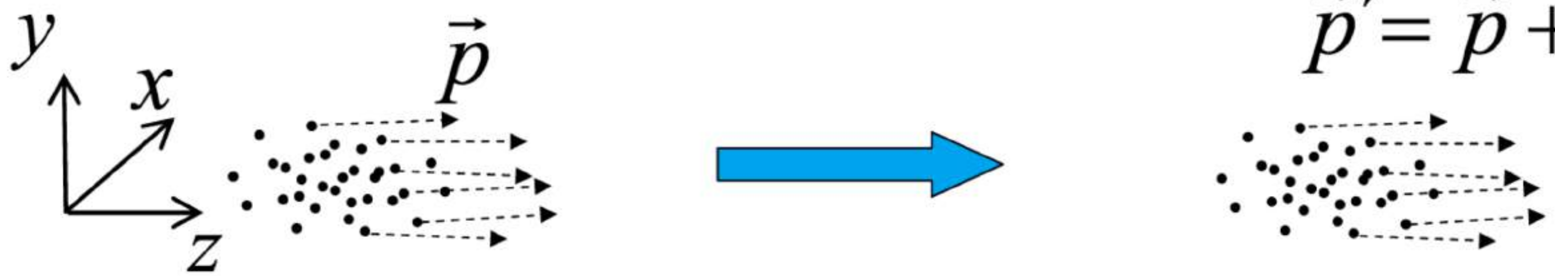
Measures the average spread of particle coordinates in position-and-momentum phase space



Transverse beam emittance



Longitudinal emittance



$\vec{p}$

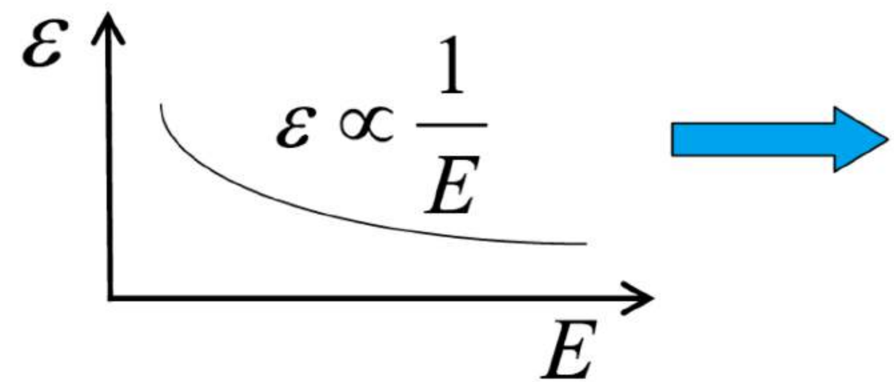
acceleration (only in z direction)

$$\vec{p}\,' = \vec{p} + \Delta\vec{p}_z$$

$\frac{p_x}{|\vec{p}|}$ gets smaller

Normalised emittance

linear accelerators:



$$\varepsilon \propto \frac{1}{E}$$

definition:

normalized emittance:

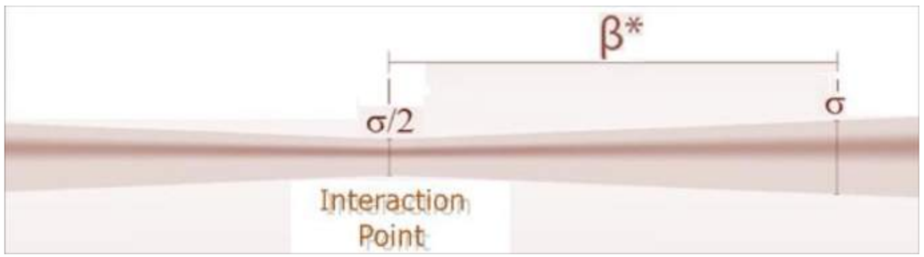
$$\varepsilon_{\mathrm{N}} = \varepsilon \cdot \gamma = \text{constant}$$

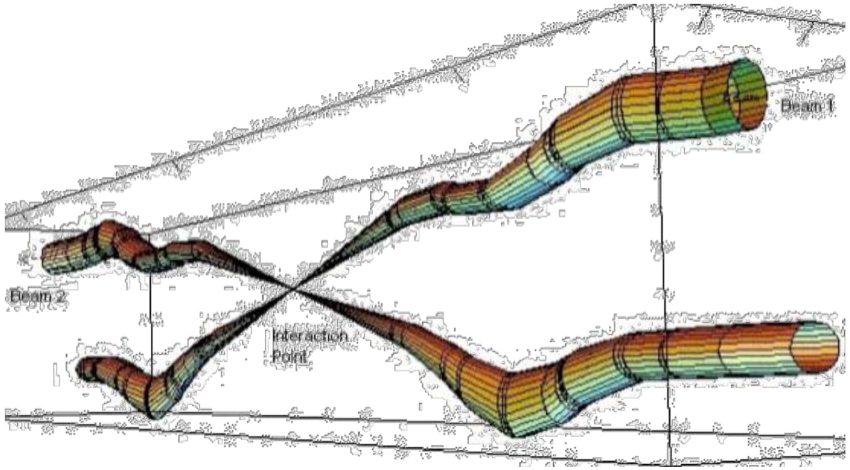
geometrical emittance

LHC design : ε_N = 3.75 μm

Amplitude function at interaction point: β*

- Amplitude function determined by magnet configuration (especially quadrupole arrangement) and powering
- $\beta = \pi \cdot \sigma^2 / \varepsilon$ [unit = length]
  - σ = beam width, ε = transverse emittance
- β low → beam narrower, "squeezed"
- β high → beam is wide, straight
- Sometimes referred as the distance from the focus point to the point where the beam is twice wide





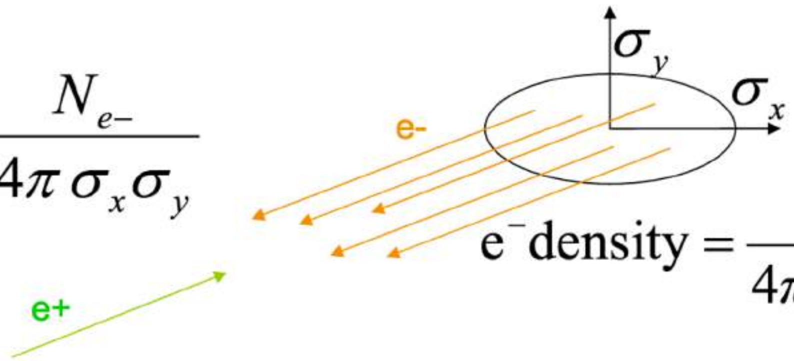
- Nominal β* in LHC: 0.55 m

Luminosity

- Interaction rate: dN/dt = Σ · L
  - Cross-section (Σ): characteristics of the studied process
  - Luminosity (L): characteristics of the accelerator

Note: valid for a single bunch crossing!

$$P_Z(1\,e^+) = \Sigma_z \cdot \frac{N_{e-}}{4\pi\,\sigma_x\sigma_y}$$



$$e^- \text{density} = \frac{N_{e-}}{4\pi \cdot \sigma_x\sigma_y}$$

$$R_Z = \Sigma_z \cdot L = \Sigma_z \cdot \frac{n_b N_{e+} N_{e-}}{4\pi\,\sigma_x\sigma_y}$$

- number of colliding bunches per second (n_b)
- number of positrons per bunch (N_{e+})
- number of electrons per bunch (N_{e-})
- luminosity (L)
- transverse bunch sizes (at the collision point) (σ_x, σ_y)

Single Bunch Instantaneous Luminosity

$$L = f_{orbit}\ N_1\ N_2 \,/\, (4\pi\ \sigma_x\ \sigma_y)$$
$$= f_{orbit}\ N_1\ N_2 \,/\, (4\ \sqrt{(\varepsilon_x\ \beta_x^*)}\ \sqrt{(\varepsilon_y\ \beta_y^*)})$$

f_{orbit} : orbit frequency of accelerator (LHC: 11246 Hz)

Instantaneous luminosity: sum SBIL for all bunch pairs

If bunches are uniform:

$$L = f_{orbit}\ n_{bunch\ pairs}\ N_{particles\ per\ bunch}^{\ 2} \,/\, (4\pi\ \sigma_{beam,x}\ \sigma_{beam,y})$$

For high luminosity:

- High population bunches, high bunch current
- Low emittance, low β*; small bunch size

How to measure luminosity?

- Use detector signal that is linear with luminosity
- Calibrate slope in special running conditions by measuring the accelerator beam parameters

Van der Meer calibration

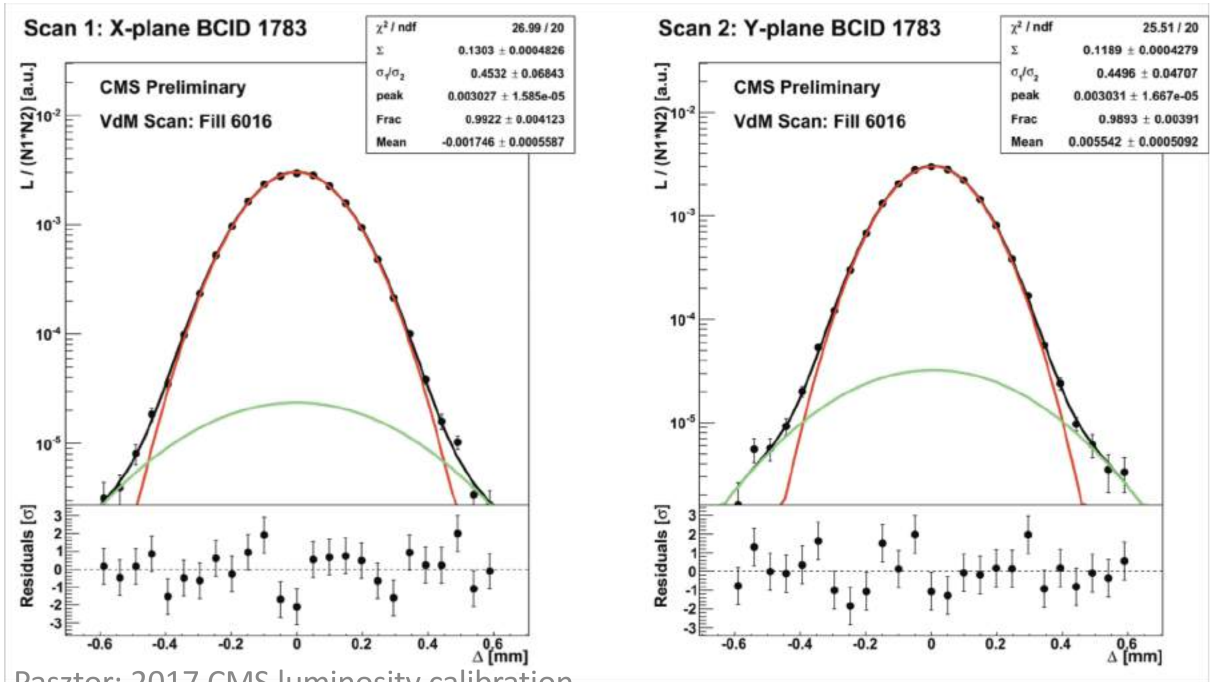
- Luminometers measure rate proportional to luminosity: $\mathcal{L} = R \cdot \sigma_{vis}$
- Absolute calibration (σ_{vis}) from VdM scans
  - The two beams scanned across each other to obtain the overlap shape

$$\mathcal{L}(\Delta x_0, \Delta y_0) = N_1 N_2 f \frac{R(\Delta x_0, \Delta y_0) R(\Delta x_0, \Delta y_0)}{\int_{-\infty}^{+\infty} R(\Delta x_0, \Delta y_0) d(\Delta x) \int_{-\infty}^{+\infty} R(\Delta x_0, \Delta y_0) d(\Delta y)} = \frac{N_1 N_2 f}{2\pi \Sigma_x \Sigma_y}$$

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R_x(\delta) \mathrm{d}\delta}{R_x(0)}$$

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y R(\Delta x_0, \Delta y_0)}{N_1 N_2 f}$$

PLT data after background subtraction

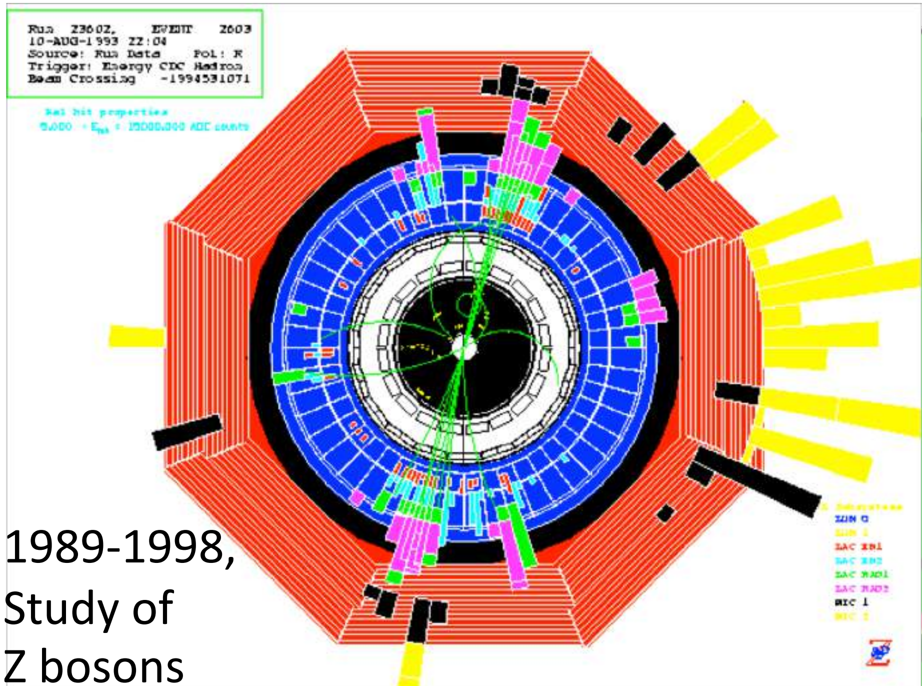


Luminometers in CMS

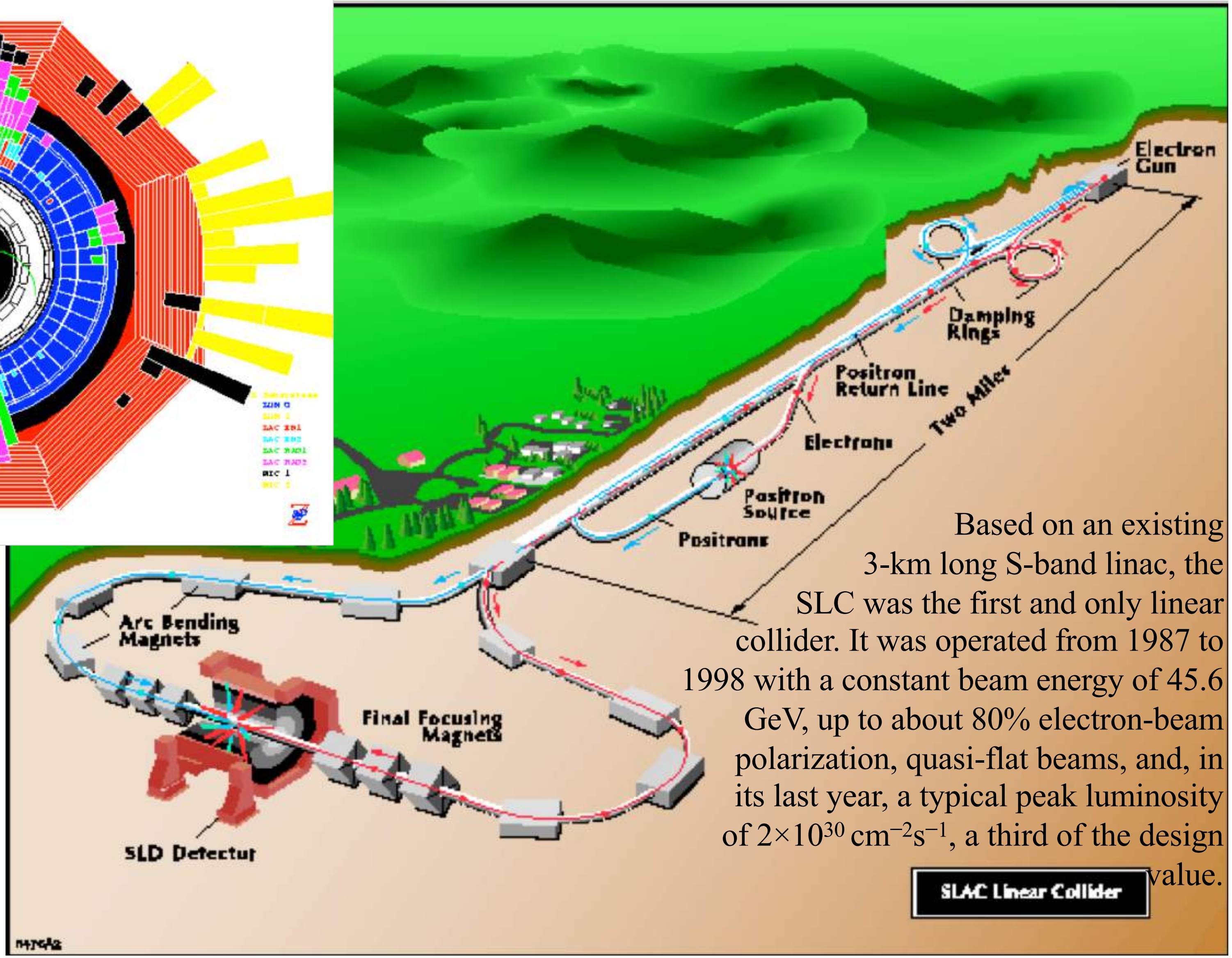
- **BRIL (Beam Radiation, Instrumentation and Luminosity) system**: real-time luminosity and machine induced background measurement independent of main CMS DAQ system
  - Pixel Luminosity Telescope (PLT) with FastOR readout of 2*8*3 phase-0 pixel sensors with 80x52 pixels each: Triple coincidences with zero counting
  - Beam Condition Monitor with Fast 6.25 ns readout (BCM1F), 1.8 m away (collision products and MIB separated in time)
    - 10 silicon sensors
    - 10 split-pad Poly Crystal CVD Diamond sensors
    - 4 split-pad Single Crystal CVD Diamond sensors
  - Hadron Forward Calorimeter (HF) with dedicated readout for luminosity
    - Transverse energy sum (HFET) – primary method in 2017
    - Occupancy (HFOC)
- Offline luminosity measurement
  - Silicon Pixel Detector
    - Pixel Cluster Counting (PCC) – secondary method in 2017
    - Vertex Counting
  - Drift Tubes (DT): Muon Barrel Trigger Primitives
    - Available online to BRIL DAQ but no bunch-by-bunch data

Linear accelerators in particle physics

- Usually in accelerator complexes, first step of acceleration
- SLC (Stanford Linear Collider) @ SLAC electron-positron collider: polarised e^-, E_{beam}= 50 GeV



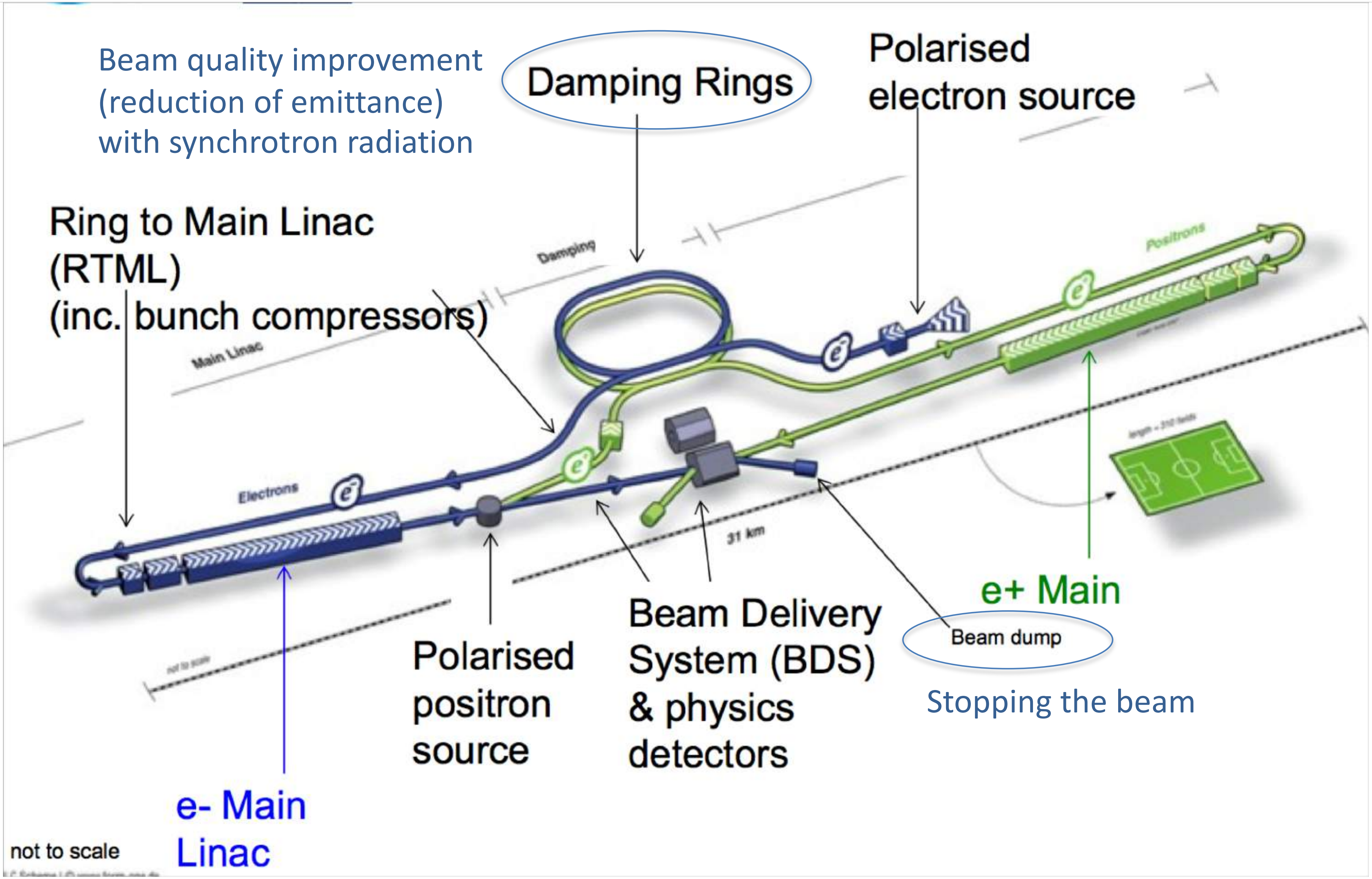
1989-1998,
Study of
Z bosons



Based on an existing 3-km long S-band linac, the SLC was the first and only linear collider. It was operated from 1987 to 1998 with a constant beam energy of 45.6 GeV, up to about 80% electron-beam polarization, quasi-flat beams, and, in its last year, a typical peak luminosity of 2×10^{30} $cm^{-2}s^{-1}$, a third of the design value.

Future accelerators (plans!):

- **ILC**
- **CLIC**


Beam quality improvement
(reduction of emittance)
with synchrotron radiation
Damping Rings
Polarised
electron source
Ring to Main Linac
(RTML)
(inc. bunch compressors)
Damping
Main Linac
Positrons
Electrons
31 km
Polarised
positron
source
Beam Delivery
System (BDS)
& physics
detectors
e+ Main
Beam dump
Stopping the beam
e- Main
Linac
not to scale

international linear collider

ILC: $2 \cdot 10^{10}$ e/bunch * 14 kHz
CLIC: $0.37 \cdot 10^{10}$ e/bunch
LHC: $1.2 \cdot 10^{11}$ p/bunch * 40 MHz

Cavity temperature:
2 K (-271.2 °C or -456 °F)

Detectors:
2, based on complementary technologies

Site:
To be determined in the next phase of the project

ILC Community:
Nearly 300 laboratories and universities around the world are involved in the ILC: more than 700 people are working on the accelerator design, and another 900 people on detector development. The accelerator design work is coordinated by the Global Design Effort, and the physics and detector work by the World Wide Study.

Collisions:
Between electrons and their antiparticles, positrons, in bunches of 5 nanometres (5 billionths of a metre) in height each containing 20 billion particles and colliding 14,000 times per second

Energy:
Up to 500 billion electronvolts (GeV) with an option to upgrade to 1 trillion electronvolts (TeV)

ILC: 0.5 TeV, CLIC: 3 TeV, LHC: 14 TeV

Acceleration Technology:
16,000 superconducting accelerating cavities made of pure niobium

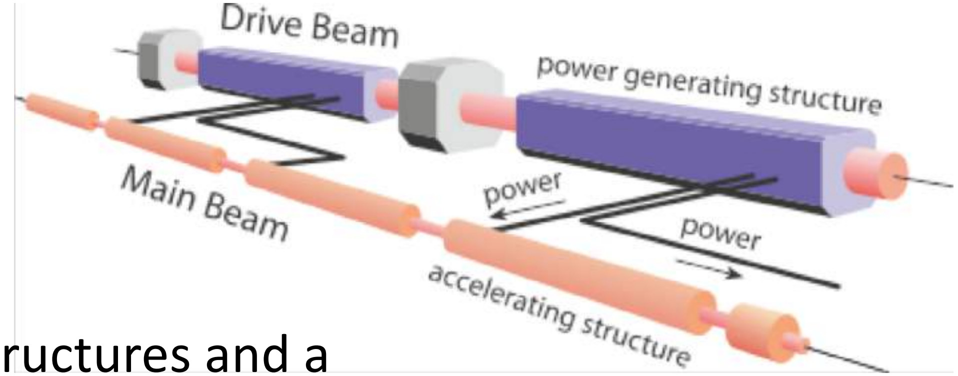
Length:
Approximately 31 kilometres, plus two damping rings each with a circumference of 6.7 kilometres

Accelerating Gradient:
31.5 megavolts per metre

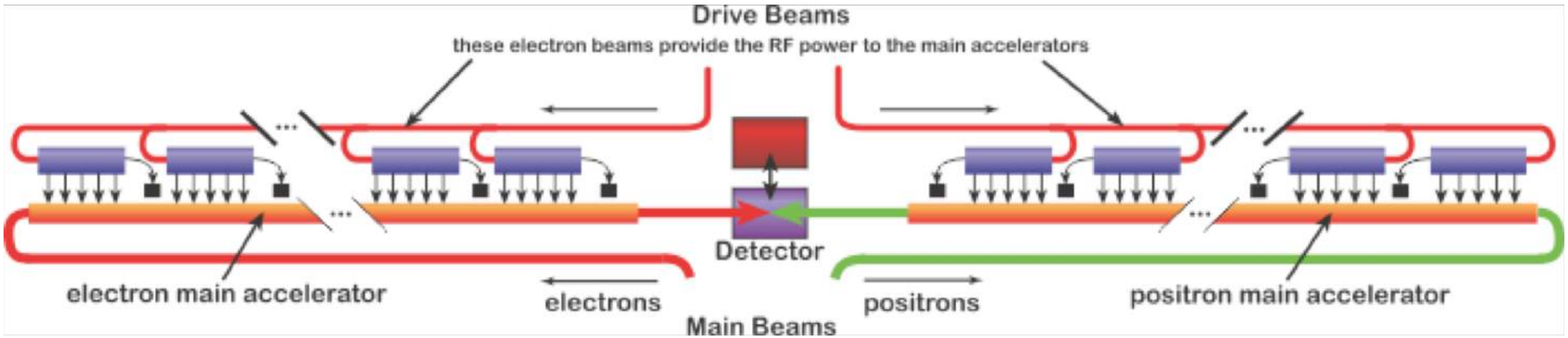
ILC: 31.5 MV/m, CLIC: 100 MV/m, LHC: 5 MV/m

Bunch trains every 200 ms (CLIC: 20 ms)
Bunches every 550 ns (CLIC: 0.5 ns)

CLIC



- The aim is to use radiofrequency (RF) structures and a two-beam concept to produce accelerating fields as high as 100 MV per meter (20 times higher than the LHC) to reach a nominal total energy of 3 TeV, keeping the size and cost of the project within reach
- A drive beam is decelerated in special Power Extraction and Transfer Structures (PETS), and the generated RF power is transferred to the main beam. This leads to a very simple tunnel layout without any active RF components (i.e. klystrons).



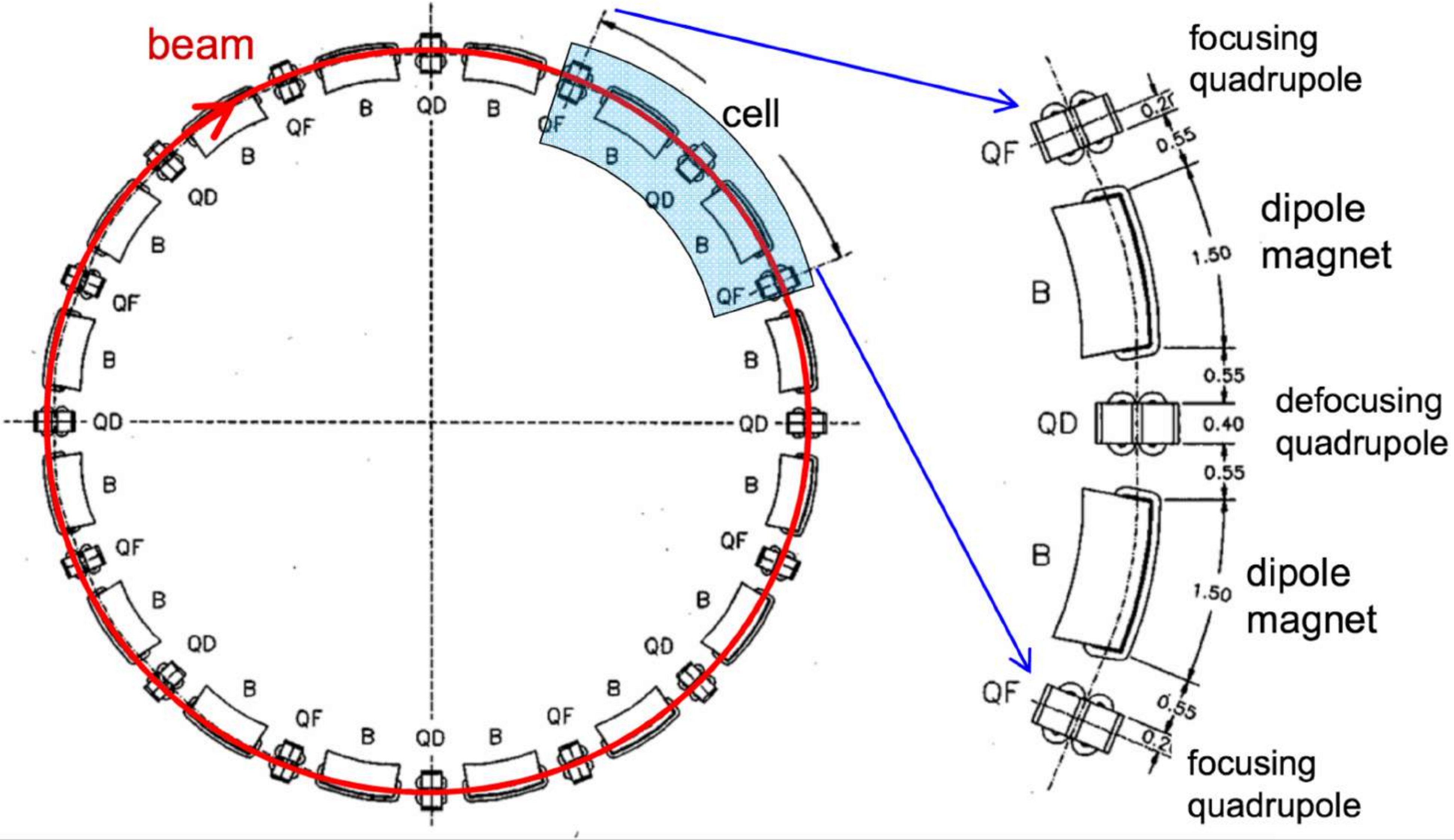
Linear accelerators

	LEP (CERN)	SLC (SLAC)	ILC (TBD)	CLIC (TBD)
Physics start date	1989	1989	TBD	TBD
Physics end date	2000	1998	—	—
Maximum beam energy (GeV)	100 - 104.6	50	250 (upgradeable to 500)	1500 (first phase: 175)
Delivered integrated luminosity per experiment (fb^{-1})	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV	0.022	—	—
Luminosity (10^{30} $cm^{-2}s^{-1}$)	24 at Z peak 100 at > 90 GeV	2.5	1.5×10^4	6×10^4
Time between collisions (μs)	22	8300	$0.55^{\dagger}$	$0.0005^{\ddagger}$
Full crossing angle (μ rad)	0	0	14000	20000
Energy spread (units 10^{-3})	0.7→1.5	1.2	1	3.4
Bunch length (cm)	1.0	0.1	0.03	0.0044
Beam radius (μm)	H: 200 → 300 V: 2.5 → 8	H: 1.5 V: 0.5	H: 0.474 V: 0.0059	H: 0.045 * V: 0.0009
Free space at interaction point (m)	±3.5	±2.8	±3.5	±3.5
Luminosity lifetime (hr)	20 at Z peak 10 at > 90 GeV	—	n/a	n/a
Turn-around time (min)	50	120 Hz (pulsed)	n/a	n/a
Injection energy (GeV)	22	45.64	n/a	n/a
Transverse emittance ($10^{-9}\pi$ rad-m)	H: 20–45 V: 0.25 → 1	H: 0.5 V: 0.05	H: 0.02 V: 7×10^{-5}	H: 2.2×10^{-4} V: 6.8×10^{-6}
β^*, amplitude function at interaction point (m)	H: 1.5 V: 0.05	H: 0.0025 V: 0.0015	H: 0.01 V: 5×10^{-4}	H: 0.0069 V: 6.8×10^{-5}
Beam-beam tune shift per crossing (10^{-4}) or disruption	830	0.75 (H) 2.0 (V)	n/a	7.7
RF frequency (MHz)	352.2	2856	1300	11994
Particles per bunch (units 10^{10})	45 in collision 60 in single beam	4.0	2	0.37

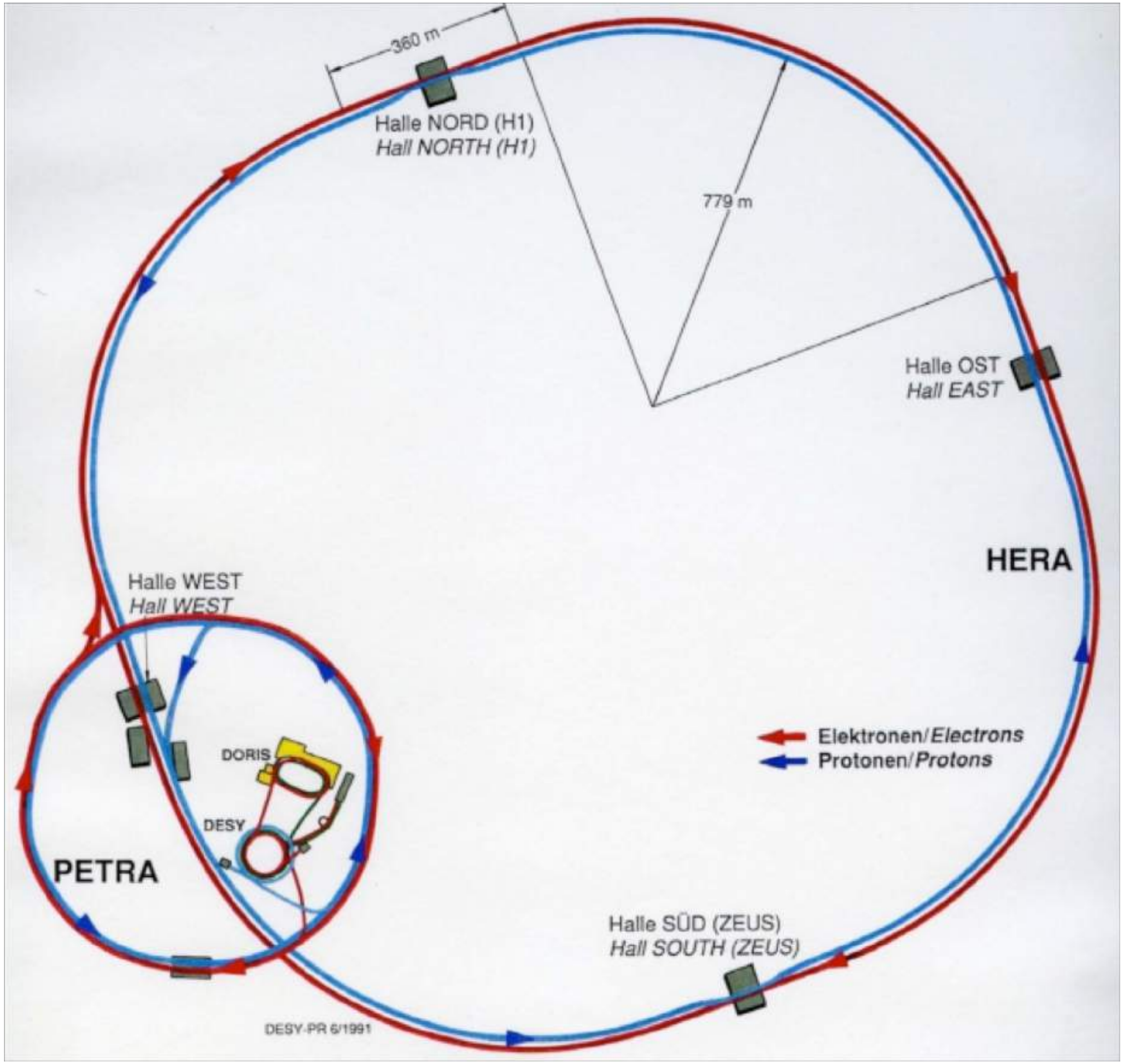
Linear accelerators

	LEP (CERN)	SLC (SLAC)	ILC (TBD)	CLIC (TBD)
Particles per bunch (units 10^{10})	45 in collision 60 in single beam	4.0	2	0.37
Bunches per ring per species	4 trains of 1 or 2	1	1312	312 (in train)
Average beam current per species (mA)	4 at Z peak 4→6 at > 90 GeV	0.0008	6 (in pulse)	1205 (in train)
Beam polarization (%)	55 at 45 GeV 5 at 61 GeV	e^-: 80	e^-: > 80% e^+: > 60%	e^-: 70% at IP
Circumference or length (km)	26.66	1.45 +1.47	31	48
Interaction regions	4	1	1	1
Magnetic length of dipole (m)	11.66/pair	2.5	n/a	n/a
Length of standard cell (m)	79	5.2	n/a	n/a
Phase advance per cell (deg)	102/90	108	n/a	n/a
Dipoles in ring	3280 + 24 inj. + 64 weak	460+440	n/a	n/a
Quadrupoles in ring	520 + 288 + 8 s.c.	—	n/a	n/a
Peak magnetic field (T)	0.135	0.597	n/a	n/a

Circular accelerators



Circular accelerators: HERA



Not precisely circular:
straight sections and arcs

Circular accelerators: LHC

Center of mass energy: 14 TeV

13 TeV @ 2015

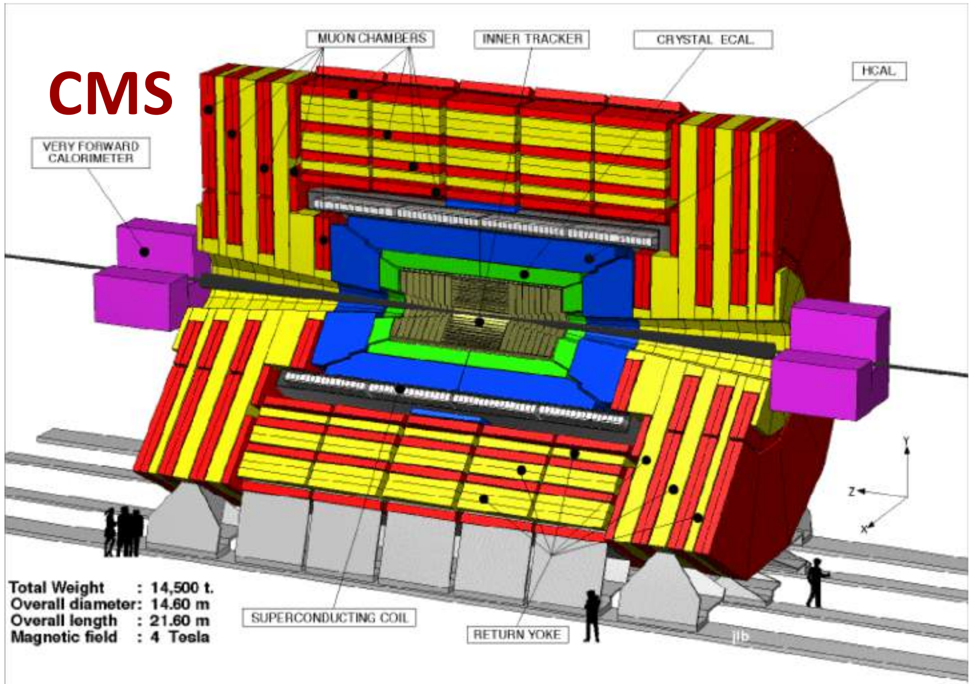
Bunch crossing rate: 40 MHz

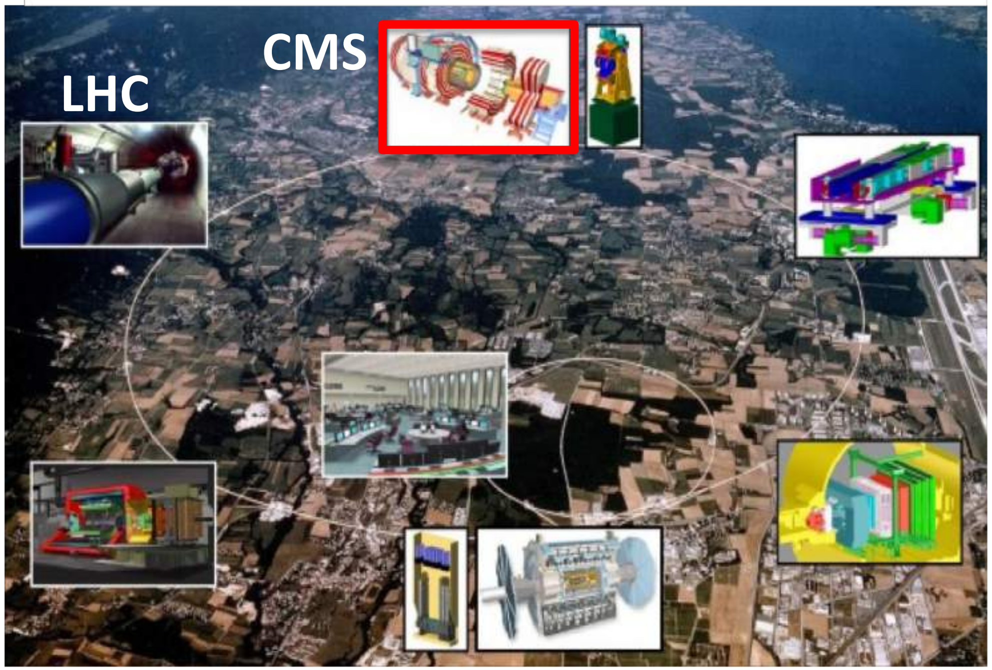
Bunch/beam: 2808

Proton/bunch: $1.15 \cdot 10^{11}$

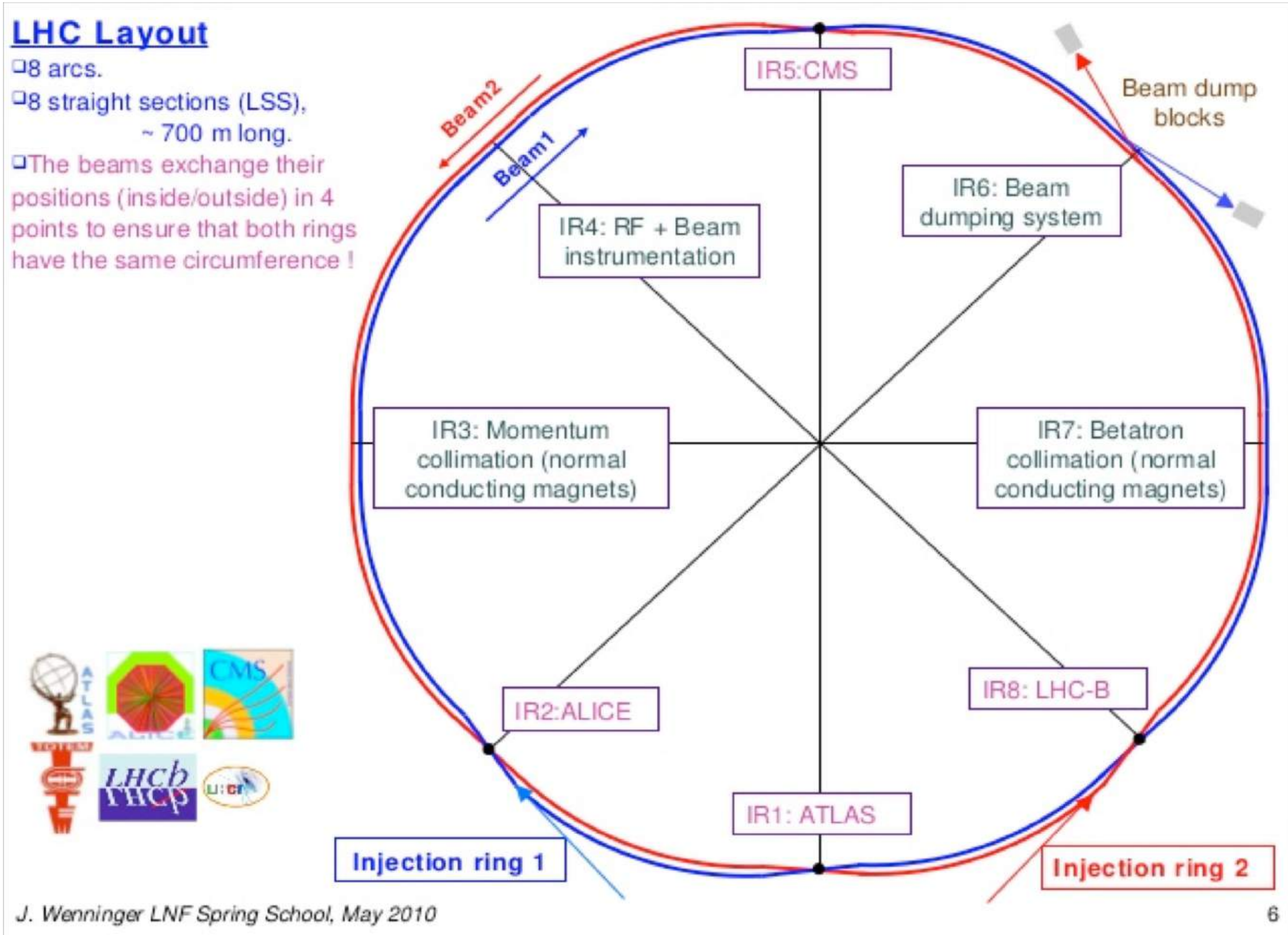
Instantaneous luminosity: 10^{34} $cm^{-2}s^{-1}$

Operated at $1.5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ in 2017 (levelled), expect $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$ in 2018





Circular accelerators: LHC



LHC in numbers

	LHC (CERN)		
Physics start date	2009	2015 (expected)	2023 (HL-LHC)
Physics end date	—		
Particles collided	pp		
Maximum beam energy (TeV)	4.0	6.5	7.0
Maximum delivered integrated luminosity per exp. (fb^{-1})	23.3 at 4.0 TeV 6.1 at 3.5 TeV	40/y to 60/y	250/y
Luminosity (10^{30} $cm^{-2}s^{-1}$)	7.7×10^3	$(1-2) \times 10^4$	5.0×10^4 (leveled)
Time between collisions (ns)	49.90	24.95	24.95
Full crossing angle (μ rad)	290	298	590
Energy spread (units 10^{-3})	0.1445	0.105	0.123
Bunch length (cm)	9.4	9	9
Beam radius (10^{-6} m)	18.8	11.1	7.4
Free space at interaction point (m)	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	≈ 6	≈ 6	≈ 6 (leveled)
Turn-around time (min)	180	240	240
Injection energy (TeV)	0.450	0.450	0.450
Transverse emittance ($10^{-9}\pi$ rad-m)	0.59	0.28	0.36
β^*, ampl. function at interaction point (m)	0.6	0.45	0.15
Beam-beam tune shift per crossing (units 10^{-4})	72	79	110
RF frequency (MHz)	400.8	400.8	400.8
Particles per bunch (units 10^{10})	16	12	22
Bunches per ring per species	1380	2508	2760
Average beam current per species (mA)	400	540	1200

Circumference (km)	26.659
Interaction regions	4 total, 2 high $\mathscr{L}$
Magnetic length of dipole (m)	14.3
Length of standard cell (m)	106.90
Phase advance per cell (deg)	90
Dipoles in ring	1232 main dipoles
Quadrupoles in ring	482 2-in-1 24 1-in-1
Magnet type	s.c. 2 in 1 cold iron
Peak magnetic field (T)	8.3

Nice seminar in 2018 on FCC (organised by Hungarian CMS Group)

- Dániel Barna: Future Circular Collider
  … and the SuShi septum project
  https://indico.cern.ch/event/707573/attachments/1606558/2549335/barna-fcc.pdf

FCC motivation: energy frontier

- A very large circular hadron collider seems to be the only option to reach 100 TeV c.m. collision energy in the coming decades
  - Discovery potential for new particles, far beyond the LHC reach
  - Much higher rates for phenomena in the sub-TeV range → increased precision w.r.t. LHC and possibly ILC

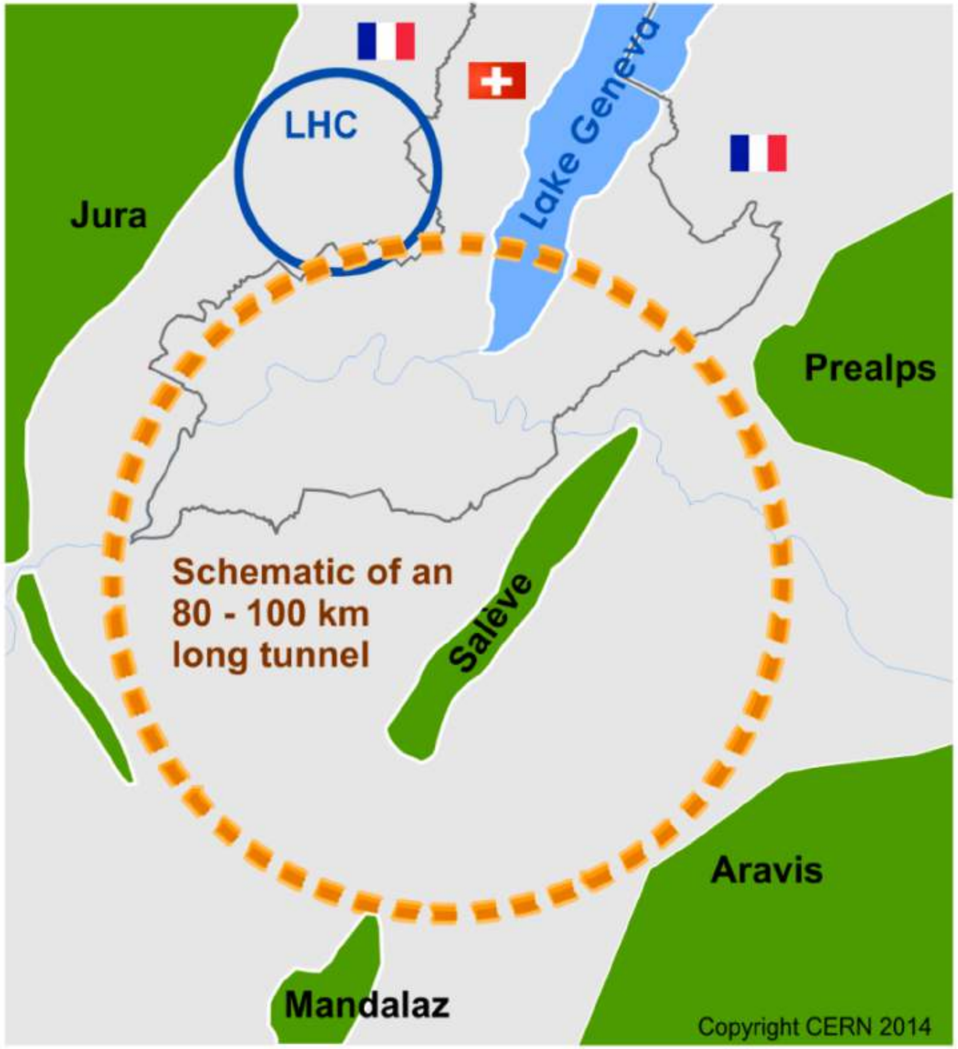
$$p \sim E \sim B_{\mathrm{dipole}} \times R_{\mathrm{bending}} \quad (8\times \text{ increase})$$

$$R_{\mathrm{FCC}} \sim 4 \times R_{\mathrm{LHC}} \quad (\text{circumference: } 27 \text{ km} \rightarrow 100 \text{ km})$$

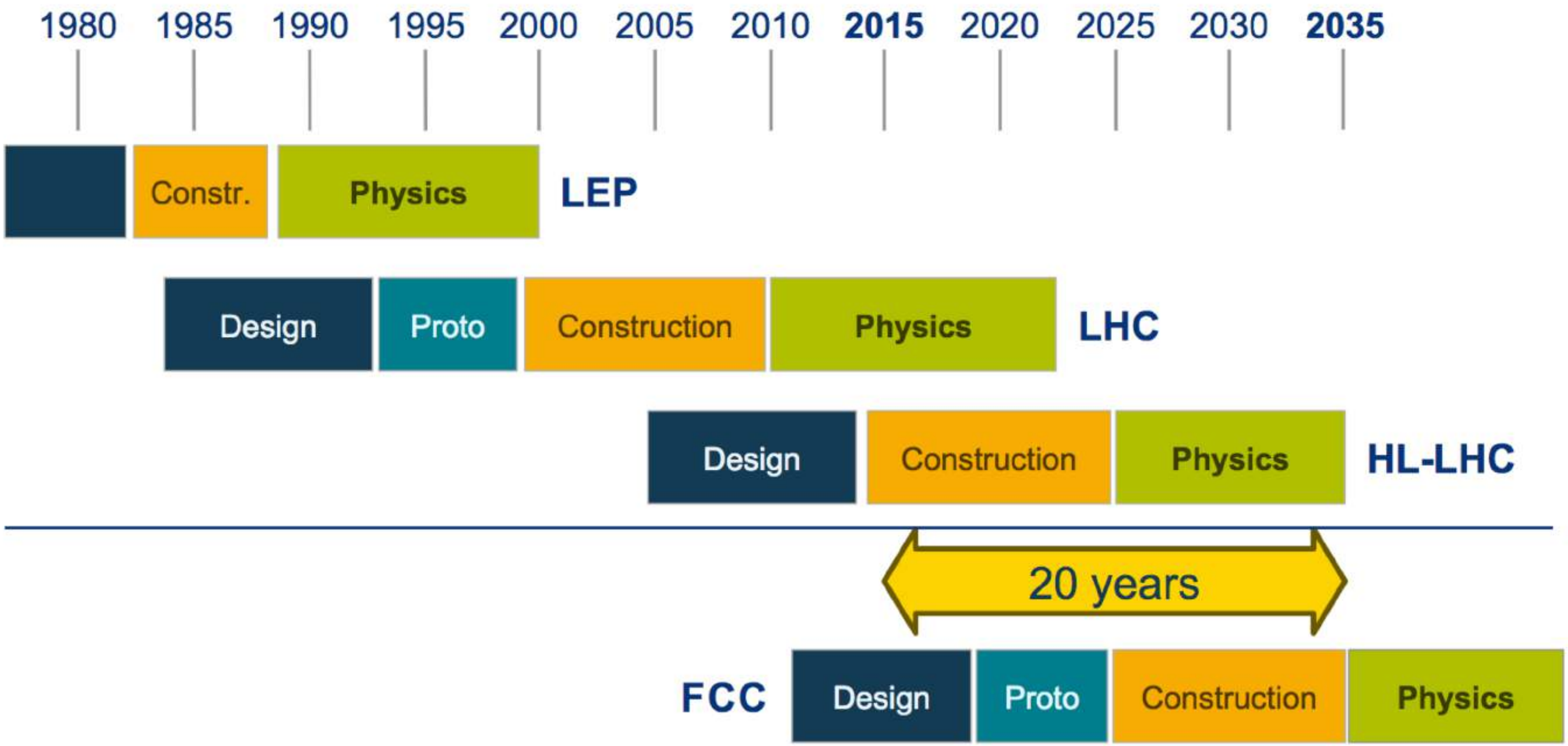
$$B_{\mathrm{FCC}} \sim 2 \times B_{\mathrm{LHC}} \quad (\text{ B: } 8 \text{ Tesla} \rightarrow 16 \text{ Tesla })$$

The FCC ring

- FCC Study launched in 2014 (host: CERN) to study
  - p-p collider with O(100) TeV (FCC-hh)
  - e+e- collider (FCC-ee) as potential intermediate step
  - p-e (FCC-he) as option
  - HE-LHC (LHC with FCC technology)
- Goals:
  - Identify key challenges
  - Propose and **develop** technical solutions
  - Develop conceptual design



Timeline of large-scale colliders



Now is the right time to plan for the period 2035 – 2040
Goal of phase 1: CDR by end 2018 for next update of European Strategy

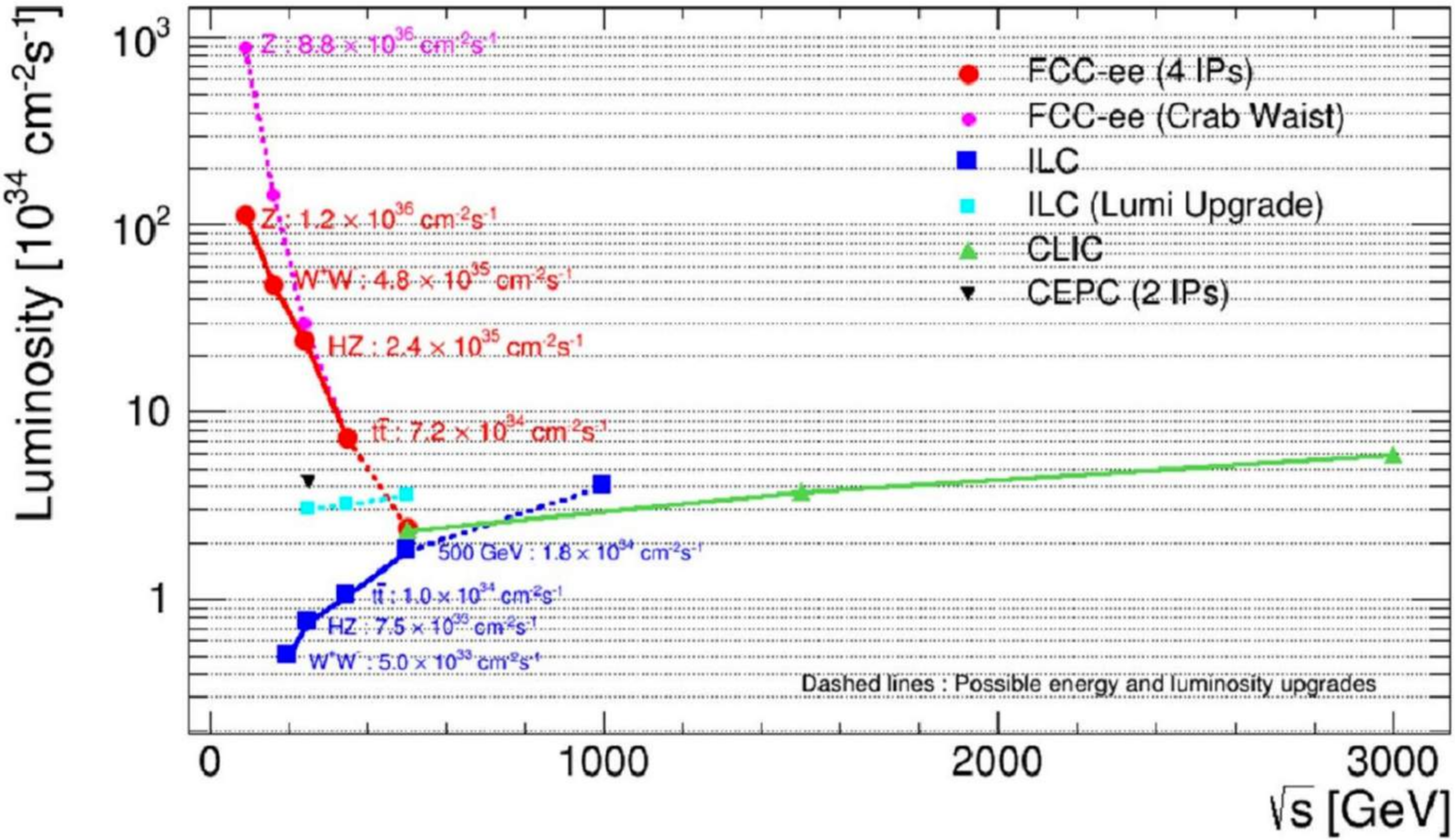
FCC-ee parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	Z		WW	ZH	tt_{bar}	
energy/beam [GeV]	45.6		80	120	175	105
bunches/beam	30180	91500	5260	780	81	4
bunch spacing [ns]	7.5	2.5	50	400	4000	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
beam current [mA]	1450	1450	152	30	6.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	0.0012
energy loss/turn [GeV]	0.03	0.03 (0.06%)	0.33 (0.4%)	1.67 (1.4%)	7.55 (4.3%)	3.34 (3.2%)
synchrotron power [MW] (provided by RF system)	100 (fixed)					22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5

Key challenges:

- Handling of synchrotron radiation
- Powerful and **more efficient** RF systems

Lepton collider luminosities compared

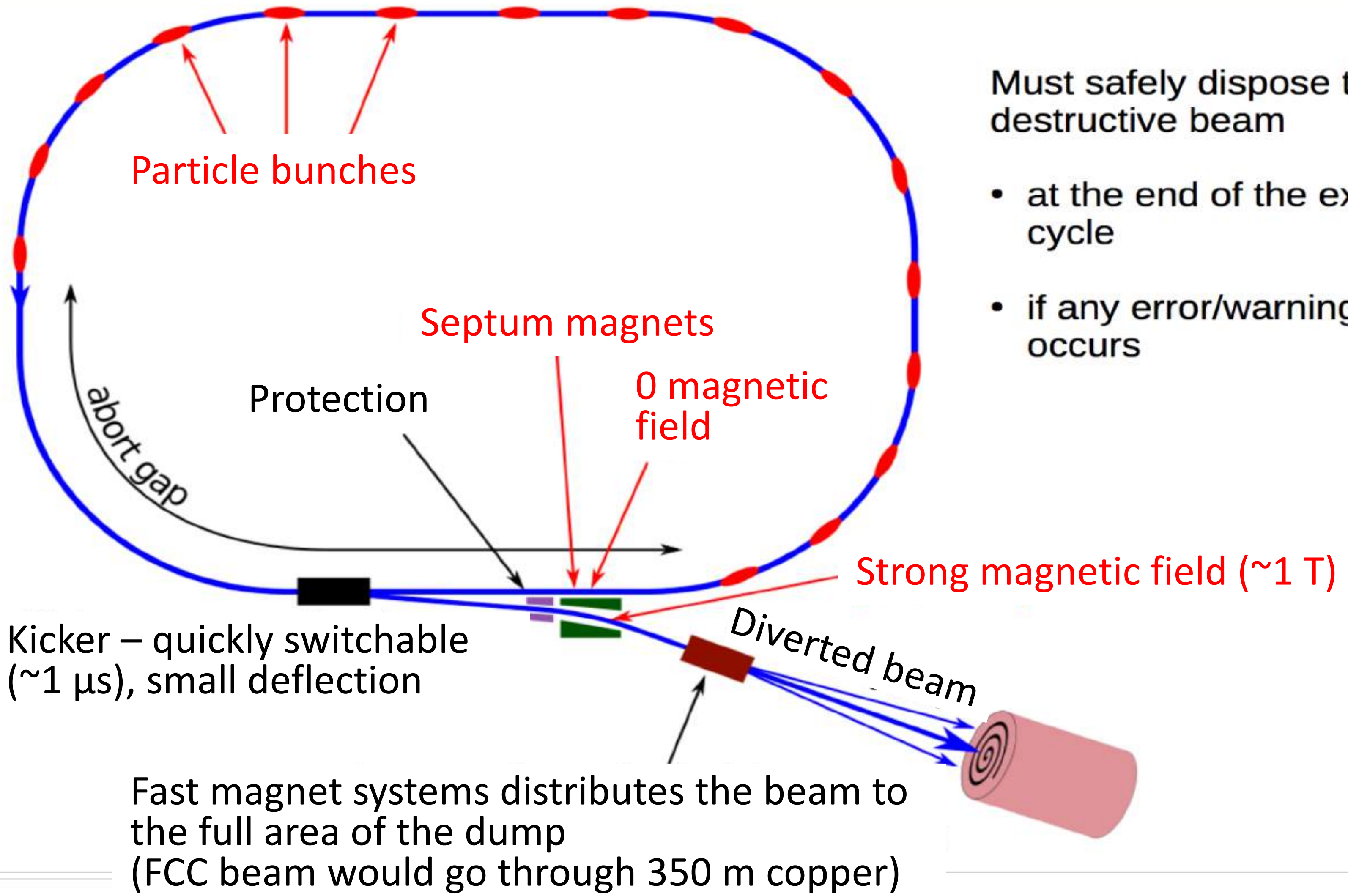


FCC-hh parameters

parameter	FCC-hh		HE-LHC*	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4 (=23 x LHC)		1.2	(0.7) 0.36
synchrotron rad.[W/m/beam]	30		3.6	(0.35) 0.18

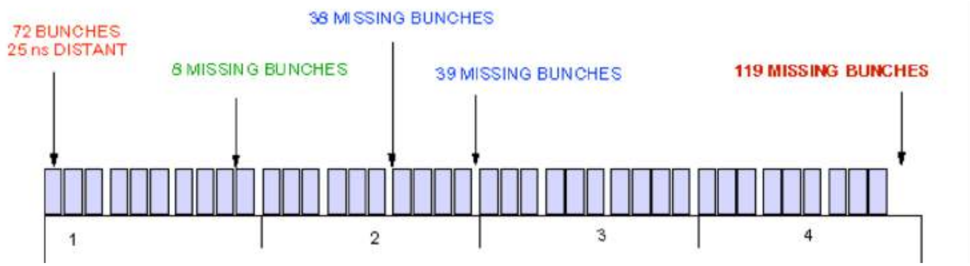
Beam energy can melt 12 tons of copper, or drill a hole of 300 m in copper

Beam dump

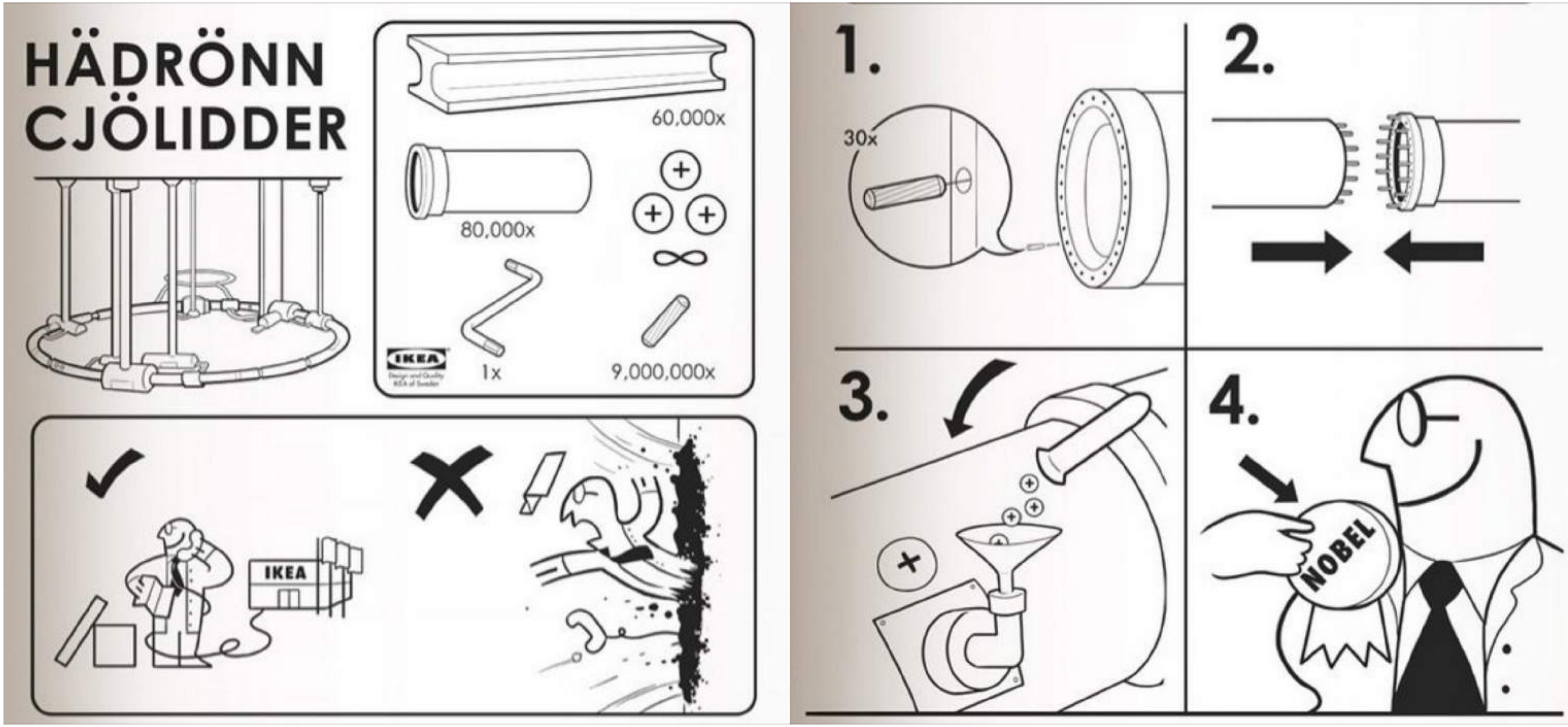


Must safely dispose the extremely destructive beam

- at the end of the experimental cycle
- if any error/warning condition occurs



How can we produce particle beams?

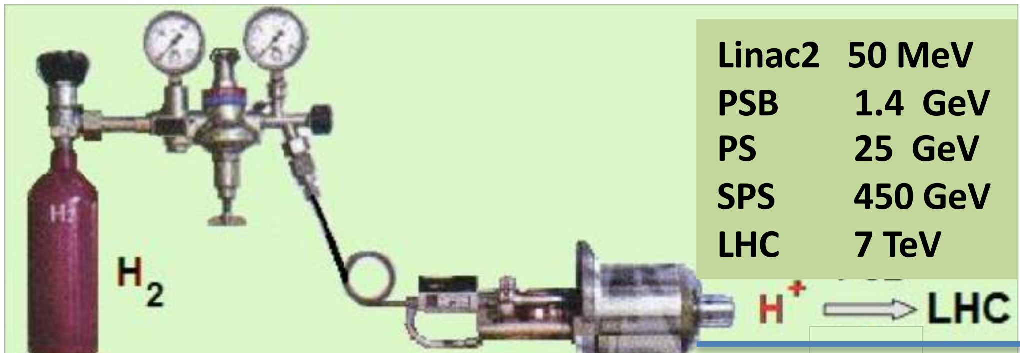


How can we produce particle beams?

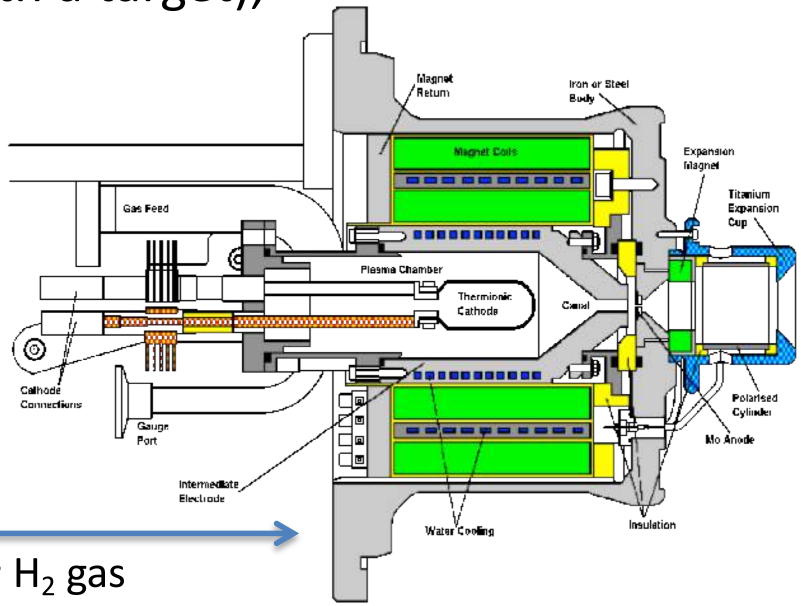
- Electron: thermic cathode, laser-driven semiconductor (GaAs) photocathode (polarised beam!)
- Positron: electromagnetic interaction of a photon or electron with an atomic nucleus, followed by electron-positron pair production (e.g. electron beam fired to material with large atomic number), nuclear β^+ decay
- Proton: break up H_2, then ionize the atoms
- Ion: gas ionisation
- Anti-proton: proton beam fired to a target… select with magnetic field from the wealth of particles produced
- … similarly pion, kaon, muon beams can be produced

LHC proton beam

- Protons of the LHC are produced in Linear accelerator 2 which consists of:
  - an hydrogen gas source,
  - a microwave oven where a hydrogen plasma is made,
  - in the plasma, electrons are no longer tightly bound to protons, thus in the presence of an electric field electrons segregate from protons,
  - the protons enter a Radio Frequency Quadrupole where the beam is both focused into a narrow "strand" and accelerated.
  - The beam is then accelerated to relativistic speeds by an Alvarez linear accelerator.
- The beams are then spliced into packets in the Proton Synchrotron Booster
- The beams then focused, accelerated, tracked and measured while passing through the different accelerators in the chain of CERN accelerators
- Finally the are collided with each other (or with a target), fulfilling their purpose of probing matter at the smallest scales

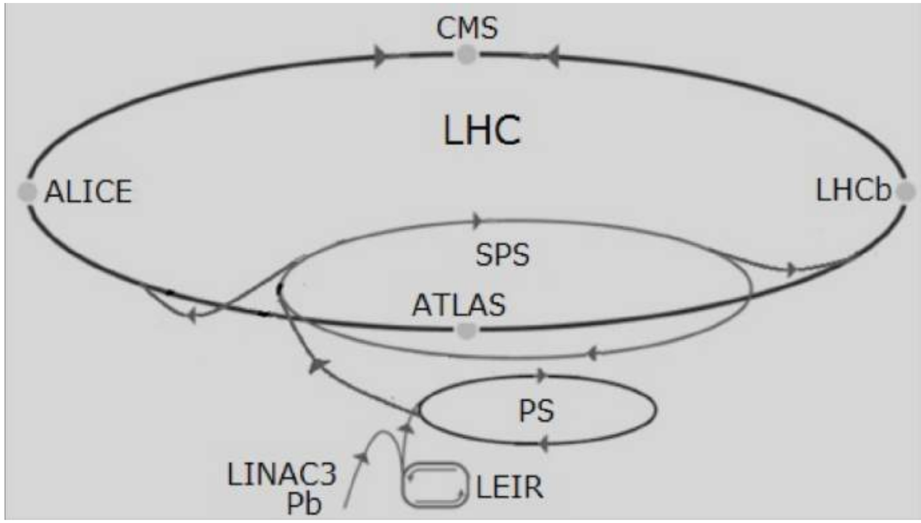


Linac2	50 MeV
PSB	1.4 GeV
PS	25 GeV
SPS	450 GeV
LHC	7 TeV

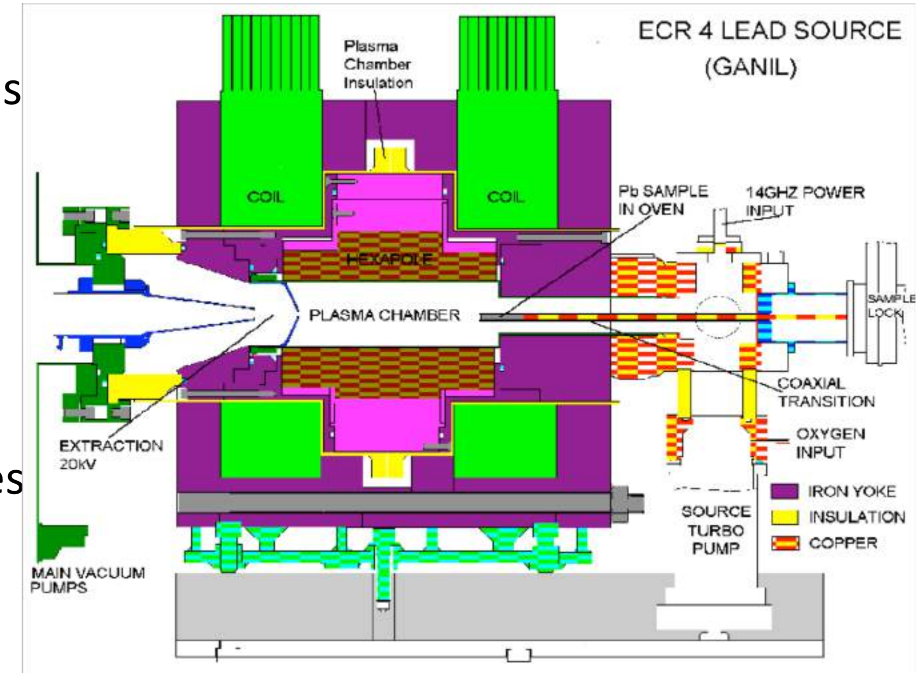


2×2808 (bunch) $\times\ 1.15\cdot10^{11}$ p $= 6\cdot10^{14}$ p / fill ~ 10^{-5} cm^3 H_2 gas

LHC ion beam

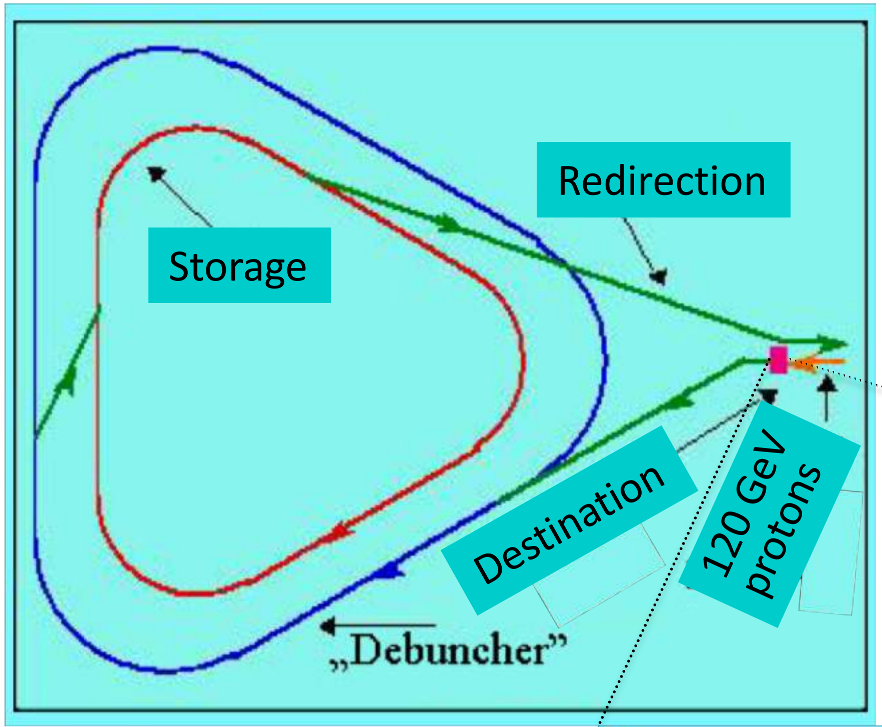


- Pb gas is produced in an oven by slowly heating enriched metallic lead
  - 10 g costs 12000 USD
  - Small amount needed: 500 mg / 2 weeks (= one fill), so price only 2 USD / hour
- In microwave heated plasma oven, the Pb atoms while passing through the plasma loose on average 29 electrons in 30 ms
- As they leave the chamber, the ions are separated and a beam is formed from them in Linac3 (4.5 MeV/nucleon)
- In Low Energy Ion Ring, the beam passes through 300 nm thick foils, that remove further electrons, on average 54 electrons are removed till this step. LEIR cools the beam and and focuses it to have larger intensity, then it accelerates the ion beams (72 MeV/nucleon)
- The PS further accelerates the ions (5.9 GeV / nucleon), and sends them through further foils, producing a Pb^{82+} ion beam
- Via the SPS (177 GeV/nucleon), the beam reaches the LHC

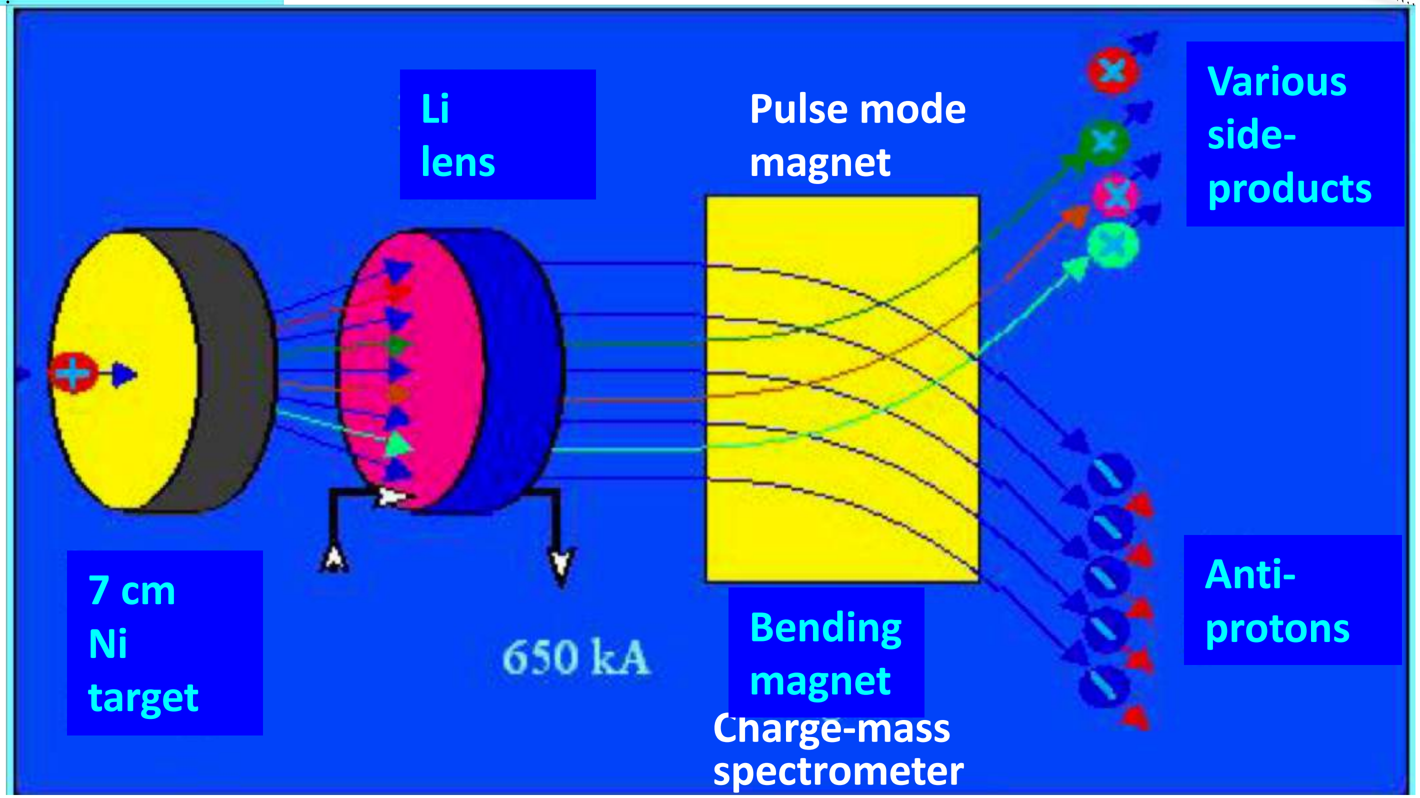


Anti-proton beam

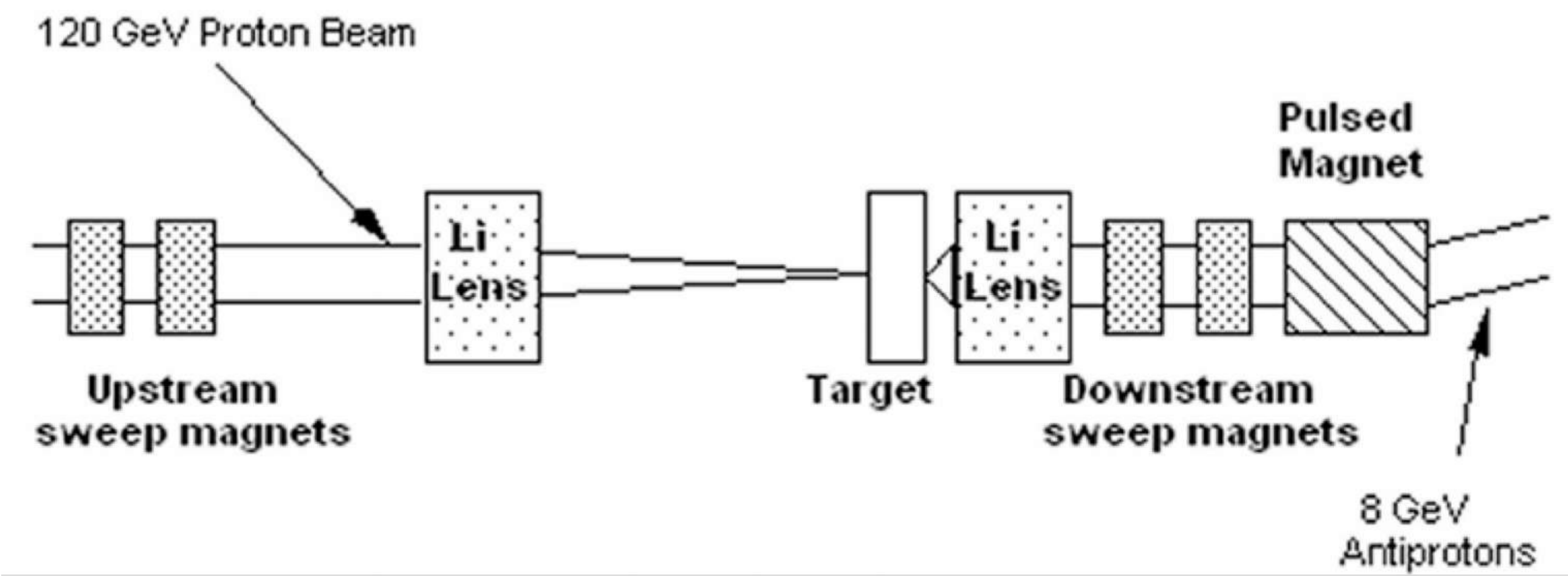
Fermilab anti-proton source



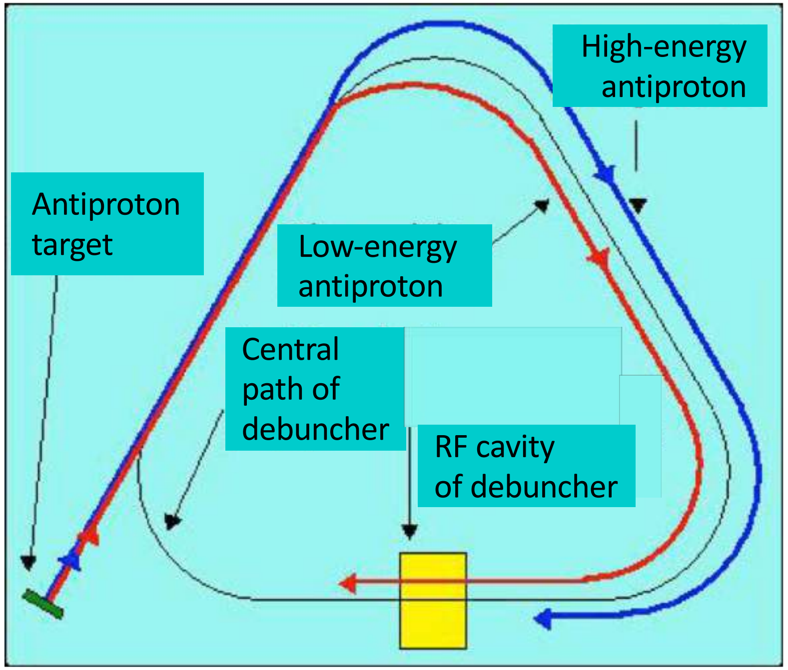
- 120 GeV protons are fired to a Ni target in every 1.5 s
- From 1 M proton, only 20 anti-proton is produced with 8 GeV energy



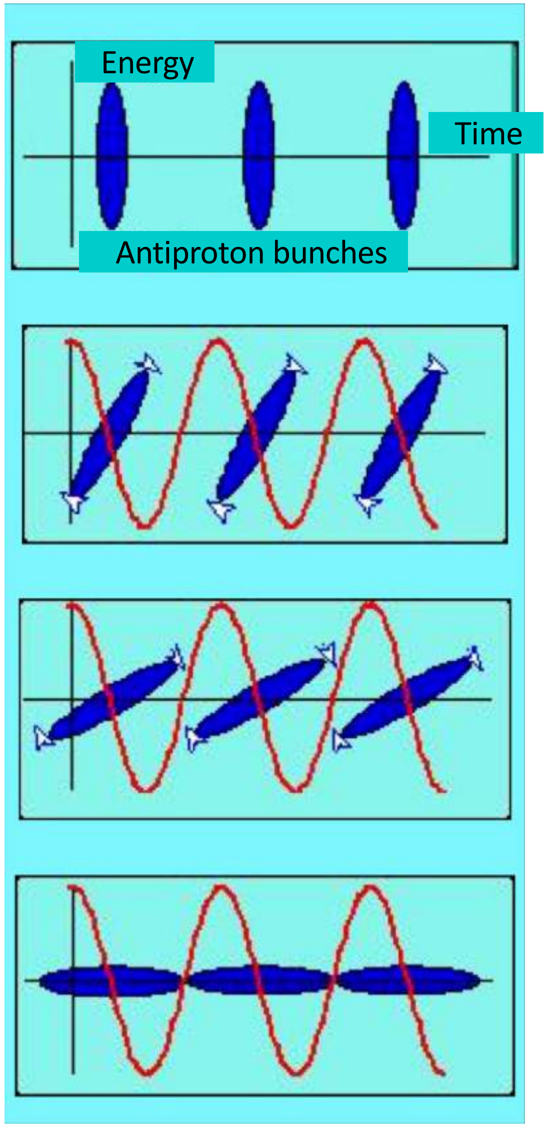
Fermilab anti-proton source



Anti-proton beam



Fermilab anti-proton source



Anti-protons after leaving the target

Anti-protons arriving to the RF cavity
Fast anti-p decelerates, slow anti-p accelerates (they reach the RF at different times)

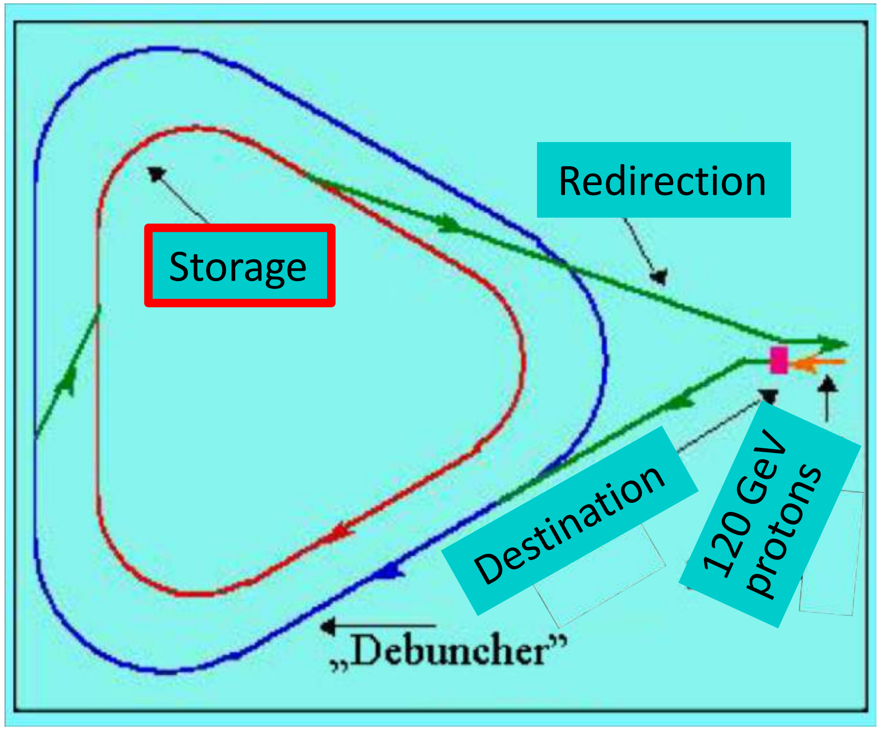
After many cycles

At the end of debunching (100 ms)

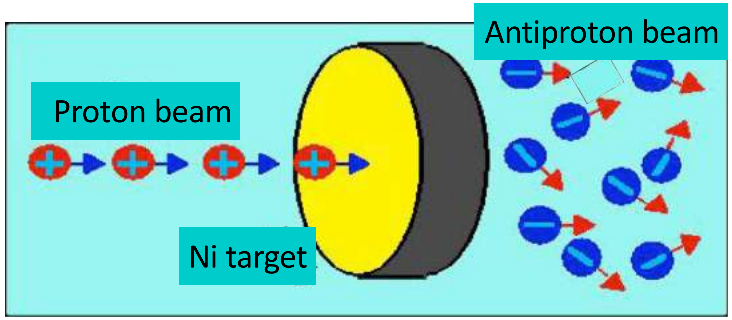
- 120 GeV protons are fired to a Ni target in every 1.5 s
- From 1 M proton, only 20 anti-proton is produced with 8 GeV energy

- **Debuncher**: narrow time distribution (proton RF), wide energy spectrum (anti-p) → narrow energy spectrum, wide packets in time

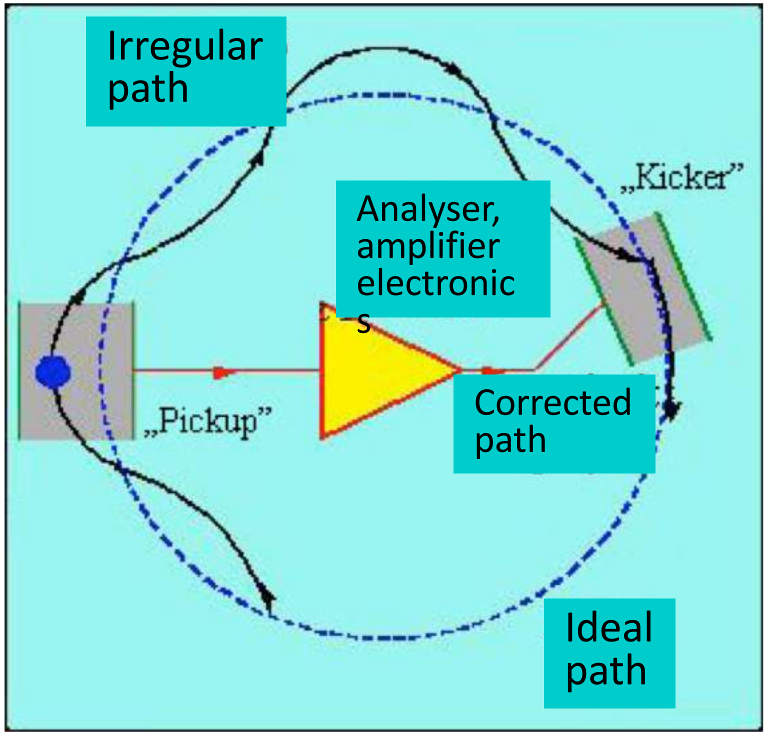
Anti-proton beam



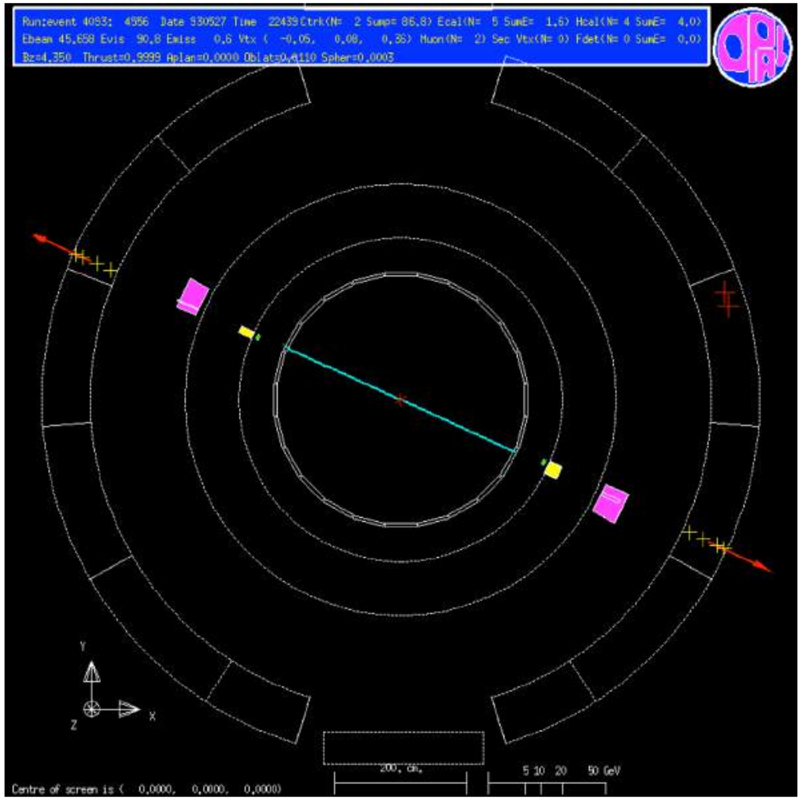
Fermilab anti-proton source

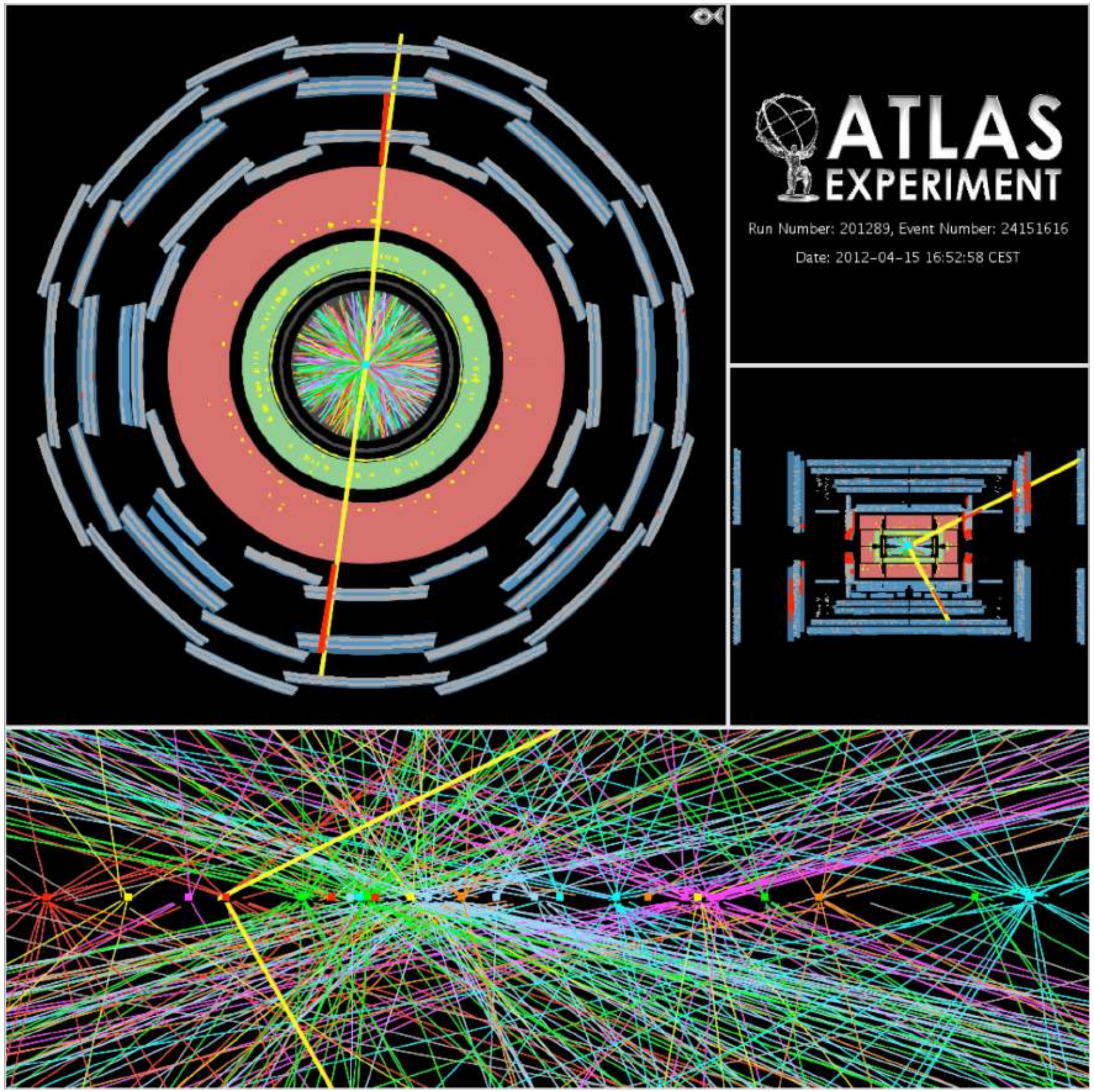


- Anti-protons leaving the target are hot (their energy, position, direction are widely different)
- The hot beam has difficulty to stay in the beam pipe, diffuse, not bright enough
- Stochastic cooling removes randomness (Simon Van der Meer, Nobel prize)
- Used by the debuncher and the accumulator
- Based on feedback
- Electrodes measure the particles "error" signal (position, energy), this signal is sent to the kicker after processing and amplification
- The kicker gives kick to the anti-proton to compensate the measured error



Lepton vs. hadron colliders





- Collision energy
- Known initial state
- Clean events
- ….

Lepton: precision
Hadron: discovery
Complementary machines

Nobel prizes

- Great leaps in accelerator development
  - 1930, <5 inch, 80 keV H^+ ions
  - 2015, 27 km circumference, E_{beam}= 6.5 TeV protons
  - Laboratories around the world: http://www-elsa.physik.uni-bonn.de/accelerator_list.html

- 1939, **Ernest Orlando Lawrence** "for the invention and development of the **cyclotron** and for results obtained with it, especially with regard to artificial radioactive elements"

- 1951: **Sir John Douglas Cockcroft** & **Ernest Thomas Sinton Walton** "for their pioneer work on the transmutation of atomic nuclei by **artificially accelerated atomic particles**"

- 1984, **Carlo Rubbia** & **Simon van der Meer** "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"
  - Van der Meer: **anti-proton cooling** for SPS

- 1988, **Leon M. Lederman**, **Melvin Schwartz** & **Jack Steinberger** "for the **neutrino beam** method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

The next collider?

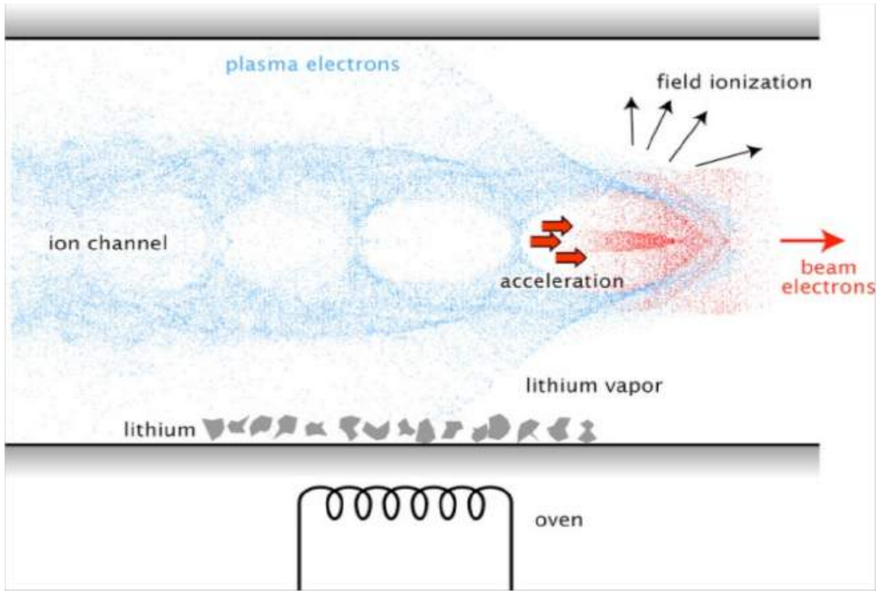
- High Luminosity LHC (HL-LHC)
- International Linear Collider (ILC)?
- Compact Linear Collider (CLIC)?
- Future Circular Collider (FCC, FCC-ee, FCC-ep)?
- Muon collider (R&D: MICE)?

- Plasma accelerator???

Plasma wakefield accelerator

- Cost effective means to accelerate particles on short distances to large energies
  - Already demonstrated 400-500 higher acceleration power than traditional accelerators
- Pairs of electron bunches (each containing 5-6 billion electrons) sent into a laser generated column of plasma inside an oven of hot (e.g. Li) gas
- 1st bunch blasts all the free electrons away -> positively charged (Li) nuclei left behind (blowout regime)
- Blasted electrons fall back behind the 2nd bunch of electrons forming a plasma wake that propels the trailing bunch to higher energies
- Important to have the accelerated electrons with an as small as possible energy spread (one of the main limitations of the method!)
  - Shaping of trailing bunch could help

1) Container filled with (usually superheated) plasma of a very diluted gas (eg. H, Li)
2) Pulsing a laser, create a bunch of ionized electrons that travel through the plasma
3) Pulsing the laser again, produce another bunch, which gathers energy from the wake of the first bunch



Homework 3

1) Deuterons, the nuclei of heavy hydrogen, are accelerated in a cyclotron. Determine the frequency of the voltage source, if the value of magnetic field strength in the cyclotron is 1.5 T. Determine the cyclotron radius for particles, which leave the cyclotron with a kinetic energy of 16 MeV. How many times does the deuteron cross between the “D” electrodes (also called “dees”), if the electrical potential difference between the two dees is 50 kV?
2) In a linear collider the bunches are dumped after each collision, while in LHC bunches circulate and collide many times. The bunch collision rate in a linear collider is therefore relatively low, in order to be able to operate without a too high wall plug power consumption. Assume a linear collider with a bunch collision repetition rate of 50 Hz. Compared to the LHC bunch crossing rate of 40 MHz. The LHC beam size at the interaction point is estimated to be σ_x=σ_y= 17μm (similar transverse dimensions, thus a “round” beam). If we require the same order of magnitude for the luminosity as for the LHC ($10^{34}/cm^2/s$), estimate the corresponding beam size required at the interaction point at a linear collider. Assume here for simplicity that the beam has the same transverse size in both planes (in reality the vertical beam size at the interaction point is much smaller than the horizontal size).
3) The vacuum chamber has a diameter of 40 mm. At s=s_1 there is a focusing quadrupole. The beta function is beta(s_1)=100 m. Find the maximum acceptable value of the emittance. If in z=z_2 there is a defocusing quadrupole and beta=20 m, which is the minimum value of the vacuum pipe diameter?
4) For an electron beam the normalized emittance value is 1 mm-mrad. Being beta=100 m which is the value of the beam size if the energy is 50 MeV? Recalculate the value for 1 GeV
5) During nominal 25 ns operations the LHC circulates 2808 bunches per beam, though the theoretical maximum of bunches is 3564. Why do we have empty bunch positions (even though this choice decreases the instantaneous luminosity of the accelerator?