Accelerators

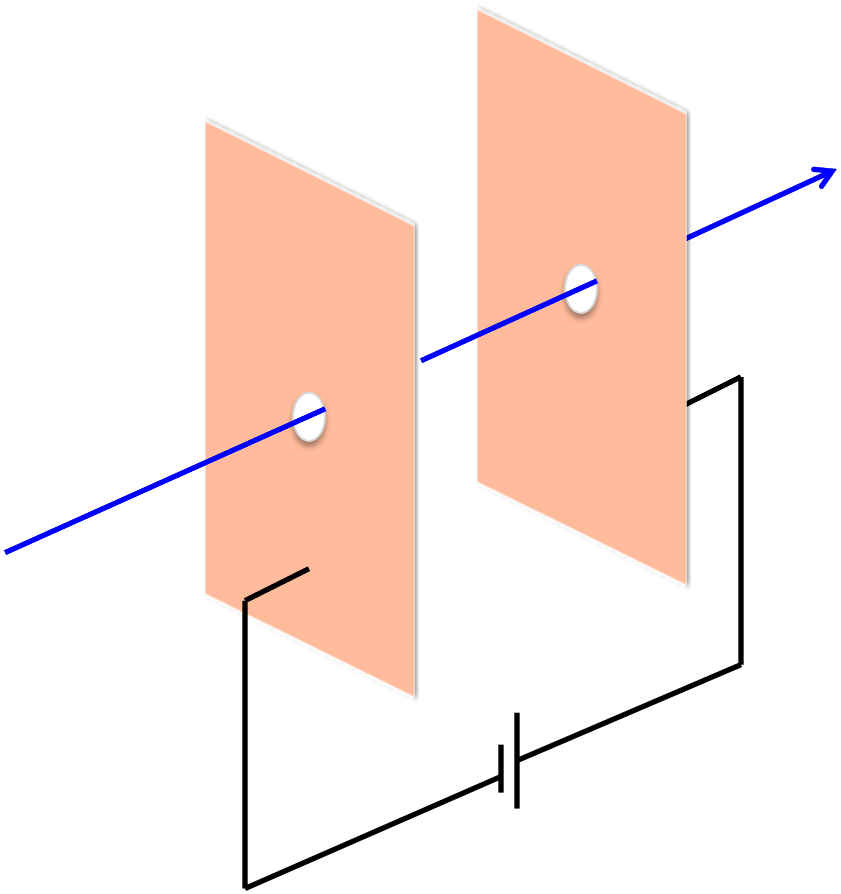
- There are some 30 000 accelerators around the world
- Nearly all are for industrial (20 000) or clinical use (10 000)
  - Scientific research community (~ 100)
  - Synchrotron light sources
  - Ion beam analysis
  - Photon or electron therapy
  - Hadron therapy
  - Radioisotope production
  - Ion implantation
  - 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

Simplest electrostatic accelerator



Energy gain
1 eV is the energy that an elementary charge gains when it is accelerated through a potential difference of 1 Volt 1 eV = 1.6 10^{-19} J
1 keV = 1 000 eV 1 MeV = 1 000 000 eV 1 GeV = 10^9 eV 1 TeV = 10^{12} eV

Energy and wavelength

$$E = \frac{hc}{l}$$

Increasing the energy will decrease the wavelength, allowing to probe deeper into the structure

Visible light

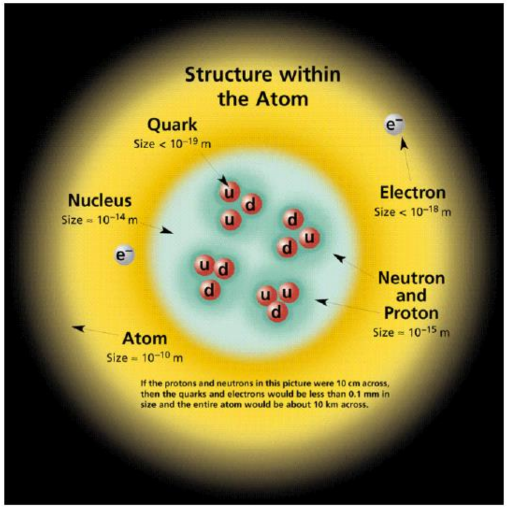
λ = 700 to 400 nm

X rays (100eV to 100keV)

λ = 10 to 0.01 nm

Particle Accelerators

Energy	λ (m)
1 MeV	10^{-12} = 1 pm
1 GeV	10^{-15} = 1 fm
1 TeV	10^{-18} = 1 am



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Energy and mass

Einstein's formula: $E = mc^2$, which for a mass at rest is: $E_0 = m_0 c^2$

The ratio between the total energy and the rest energy $$\gamma = \frac{E}{E_0}$$

The ratio between the velocity and the velocity of light $$\beta = \frac{v}{c}$$

These two relativistic parameters are related

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \sqrt{1-\frac{1}{\gamma^2}}$$

$$\left.\begin{array}{ll} \text{We can write:} & \beta = \dfrac{mvc}{mc^2} \\[2ex] \text{Momentum is:} & p = mv \end{array}\right\} \quad \beta = \frac{pc}{E} \quad or \quad p = \frac{E\beta}{c}$$

Units

$$E = mc^2$$

Through this can express mass in units of eV/c²

$$m(eV/c^2) = m(kg)c^2/1.6.10^{-19}$$

Proton rest mass	1.6726E-27	kg
	938.27	MeV/c²
Electron rest mass	9.1095E-31	kg
	0.511	MeV/c²

$$p = \frac{Eb}{c}$$

Through this can express momentum in units of eV/c

NB In both cases the units are often simply given as eV

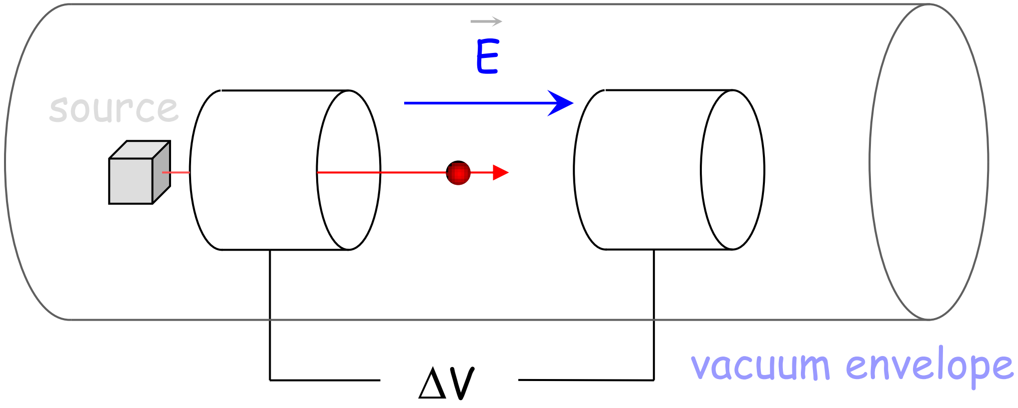
A Practical Example at the CERN PS

- Kinetic energy at injection $E_{kinetic}$ = 1.4 GeV
- Proton rest energy E_0=938.27 MeV/c^2
- The total energy is then: $E = E_{kinetic} + E_0$ = **2.34 GeV**
- We know that $\gamma = \frac{E}{E_0}$, which gives γ = 2.4921
- Using $\beta = \sqrt{1 - \frac{1}{\gamma^2}}$, we get **β = 0.91597**
- Using $p = \frac{E\beta}{c}$ we get p = **2.14 GeV/c**

Energy ≠ Momentum

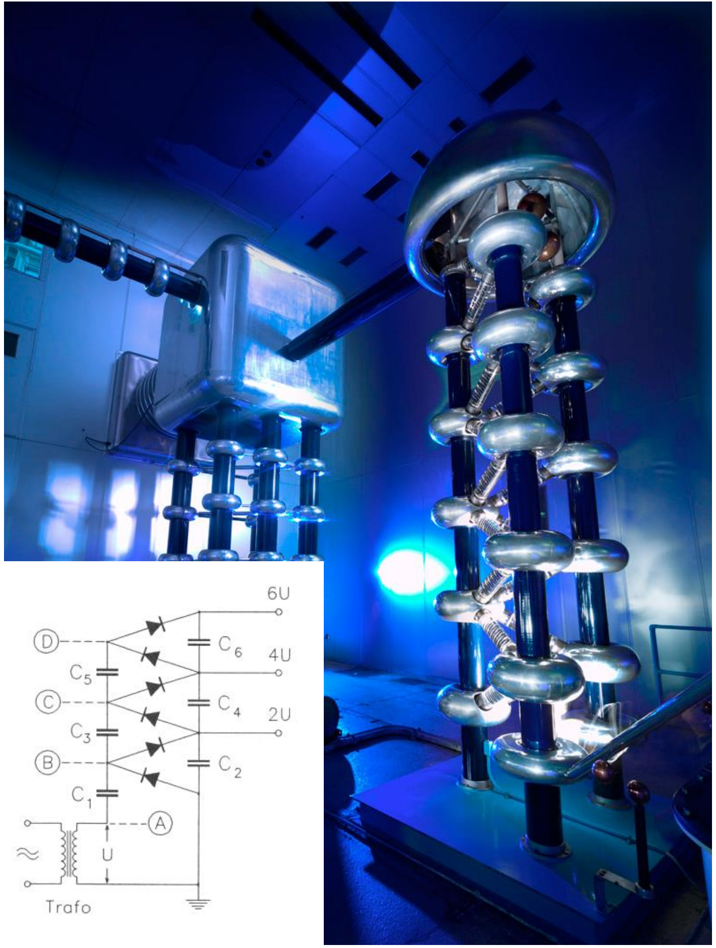
Simplest electrostatic device

Slightly more realistic schematic

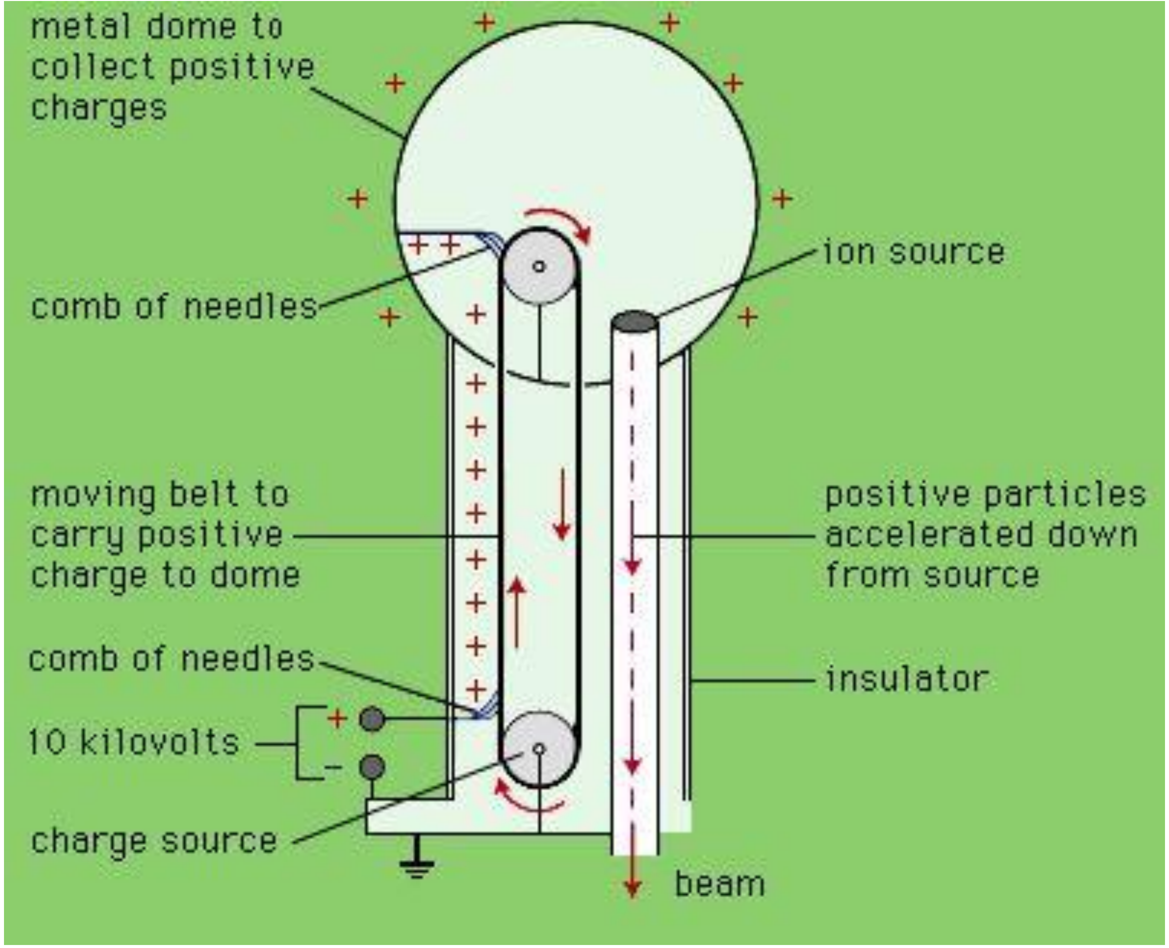


Pushing this simple idea – high voltages

Cockcroft-Walton

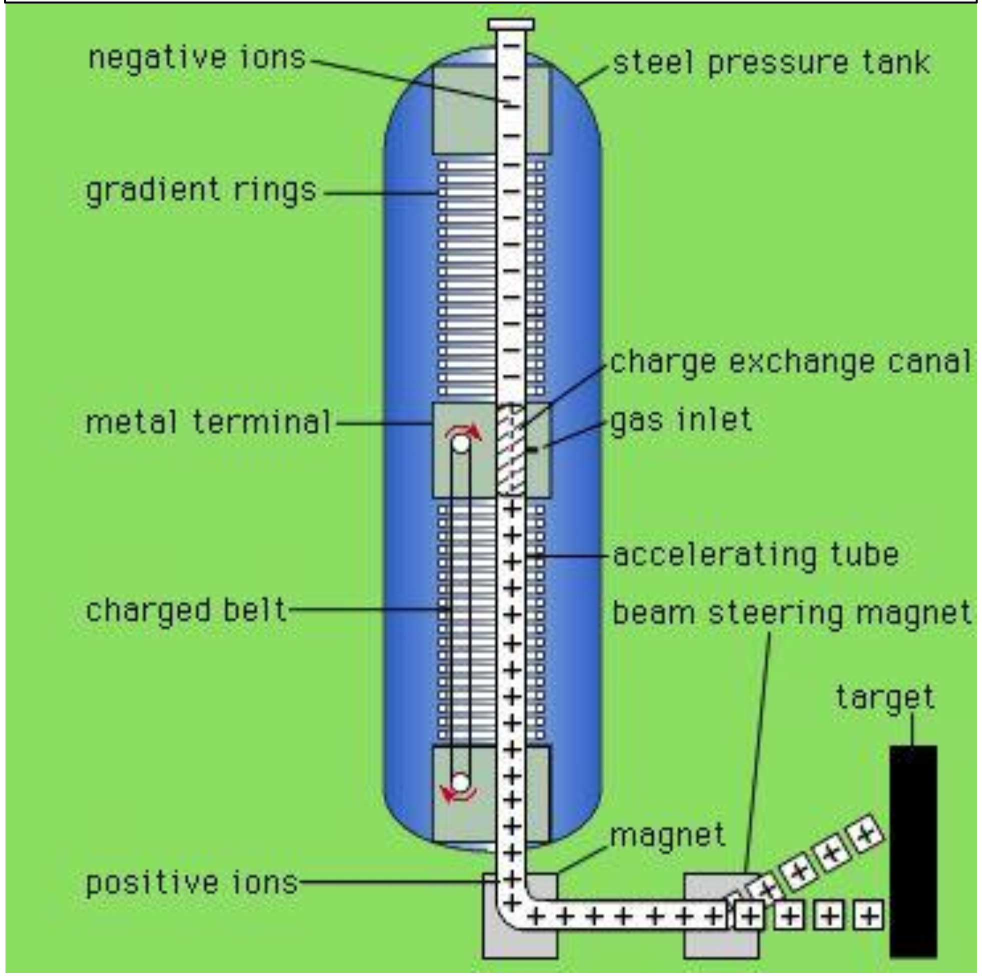


Van der Graaff



Tandem Van de Graaff

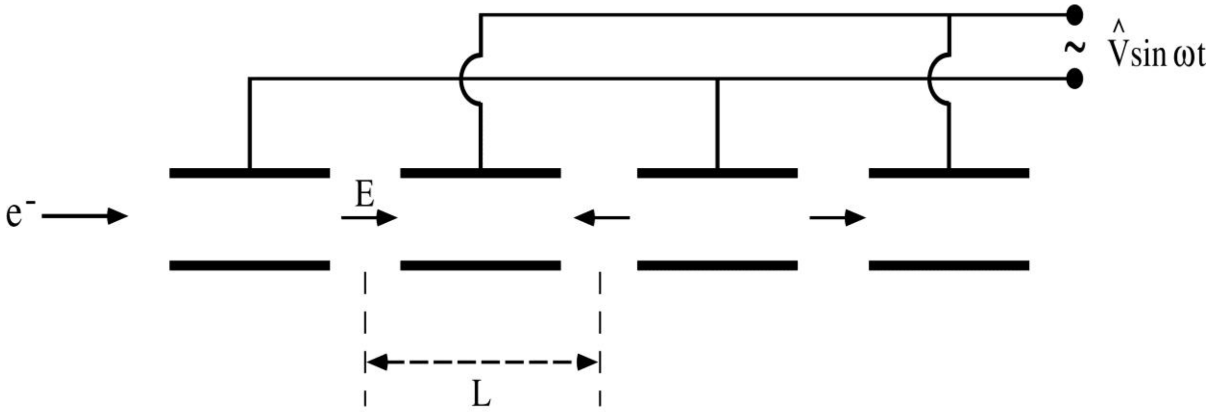
A clever idea to use the voltage twice



These early electrostatic accelerators continue to provide a useful source of low energy particles but ultimately are limited to voltages of around 10 MV by problems of voltage breakdown.

Solution number 1

- Repetitive acceleration in a straight line

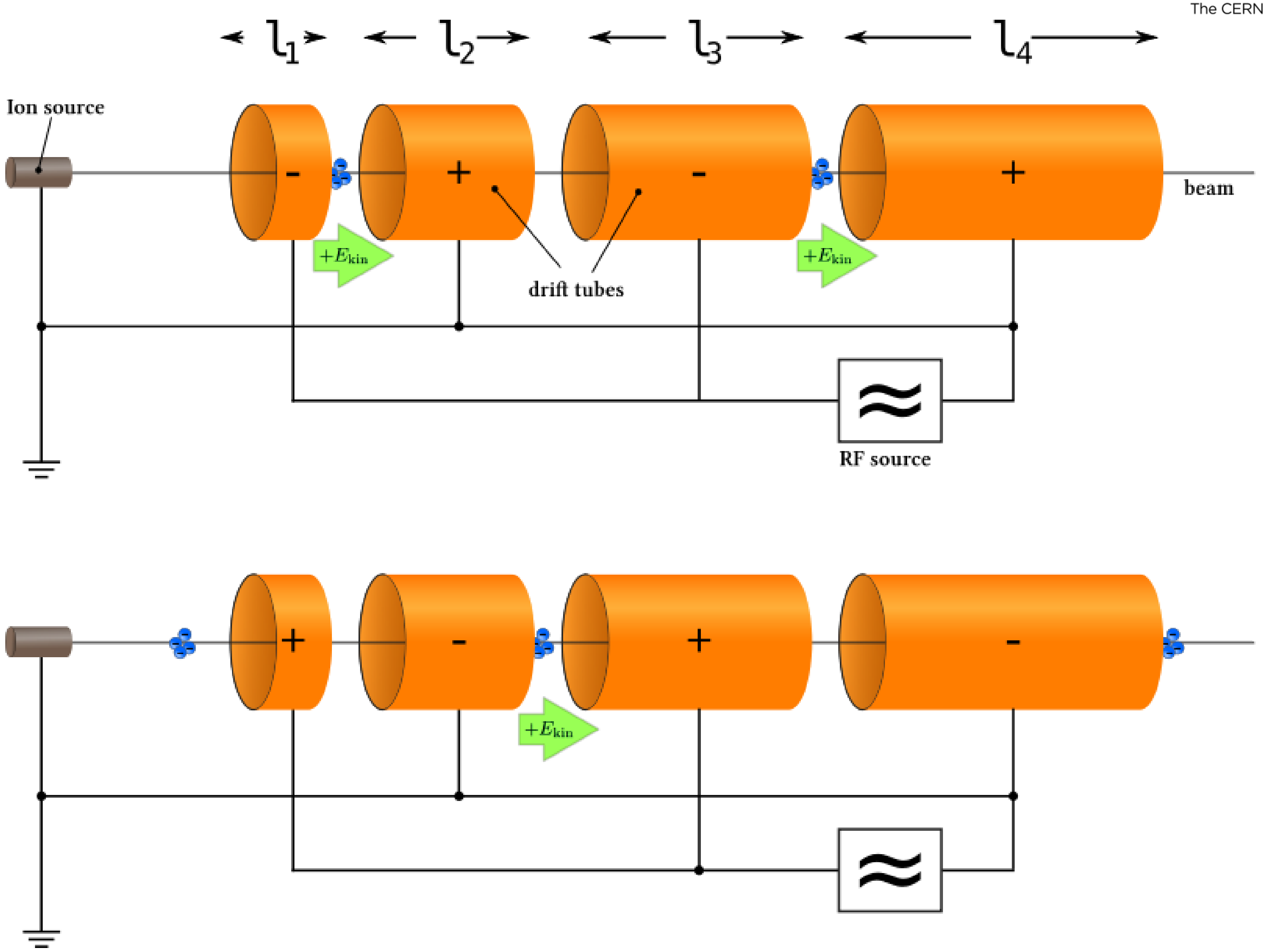


In practice there are cylindrical electrodes (drift tubes) separated by gaps and powered by an oscillator, providing an alternating electric field

Condition for synchronicity; $L \sim \beta\lambda$ where $\beta = v/c$

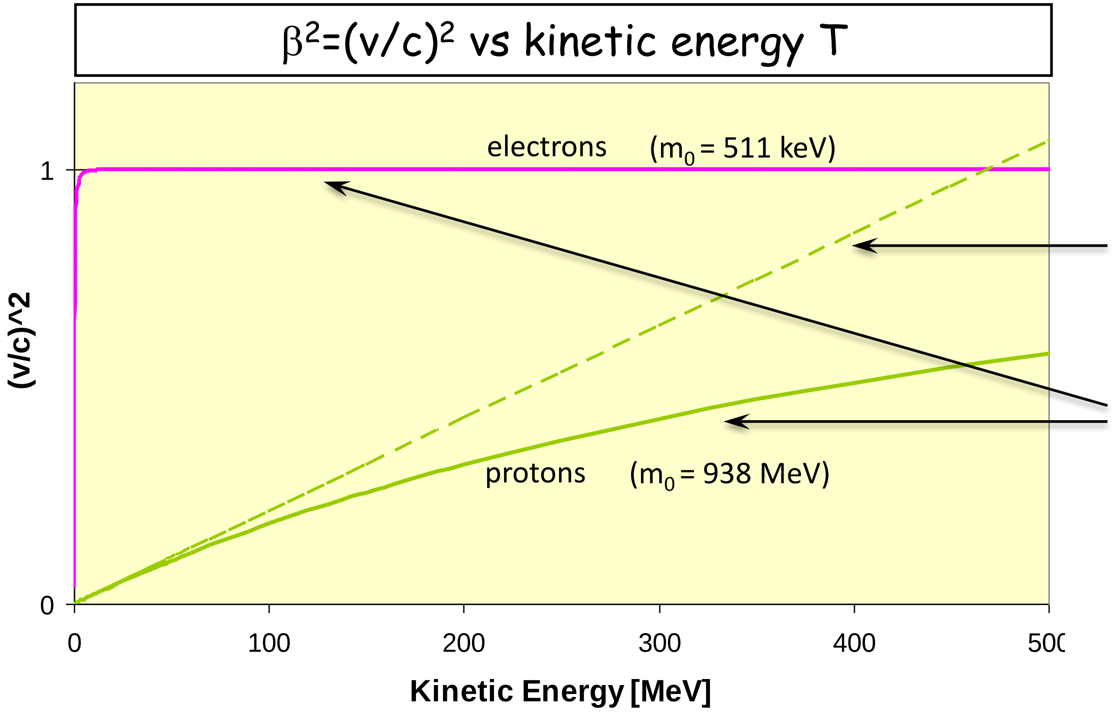
As β increases we need to either increase L or decrease λ (higher frequency)

Alvarez linac (drift tube linac)



Relativistic effects

- The velocity and the energy of the particles are increasing
- Things are very different for electrons and protons
- Once (ultra) relativistic, linacs become much simpler



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:

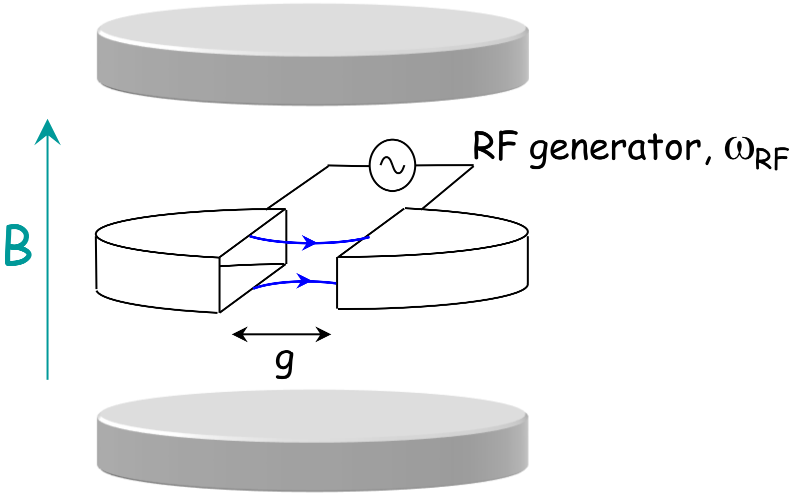
$$\frac{v^2}{c^2} = 1 - \frac{1}{\sqrt{1 + T/m_0 c^2}}$$

Solution number 2

- Repeatedly traverse an accelerating structure
- Implies a circular machine which means a Bending field

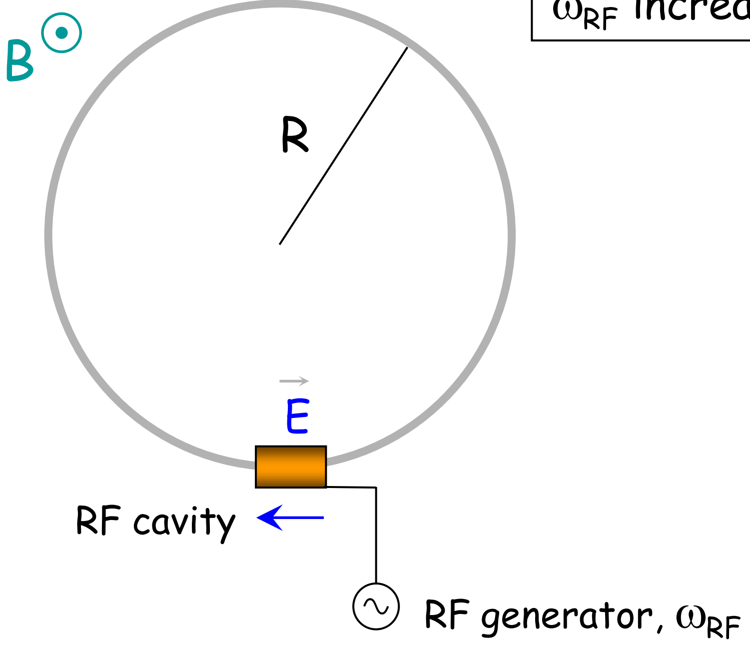
B = constant
ω_{RF} = constant
Spiral orbit

Cyclotron

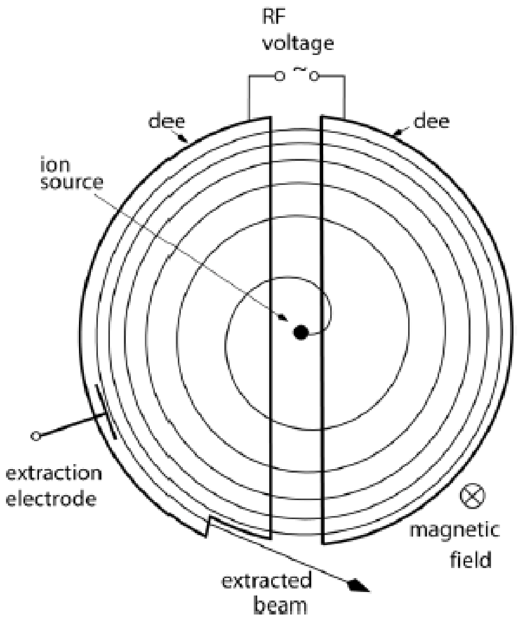


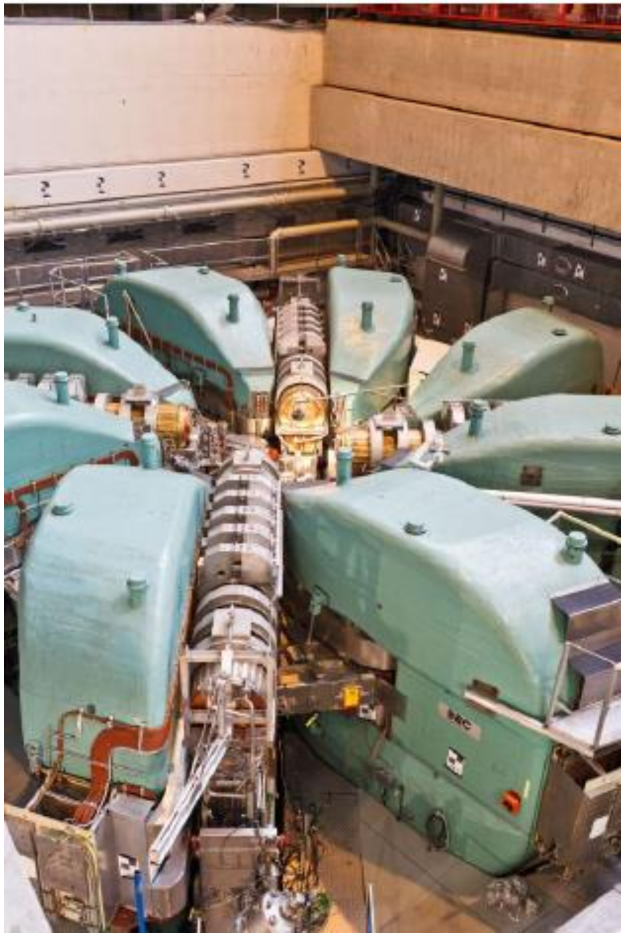
Synchrotron

Constant orbit
B increases
ω_{RF} increases



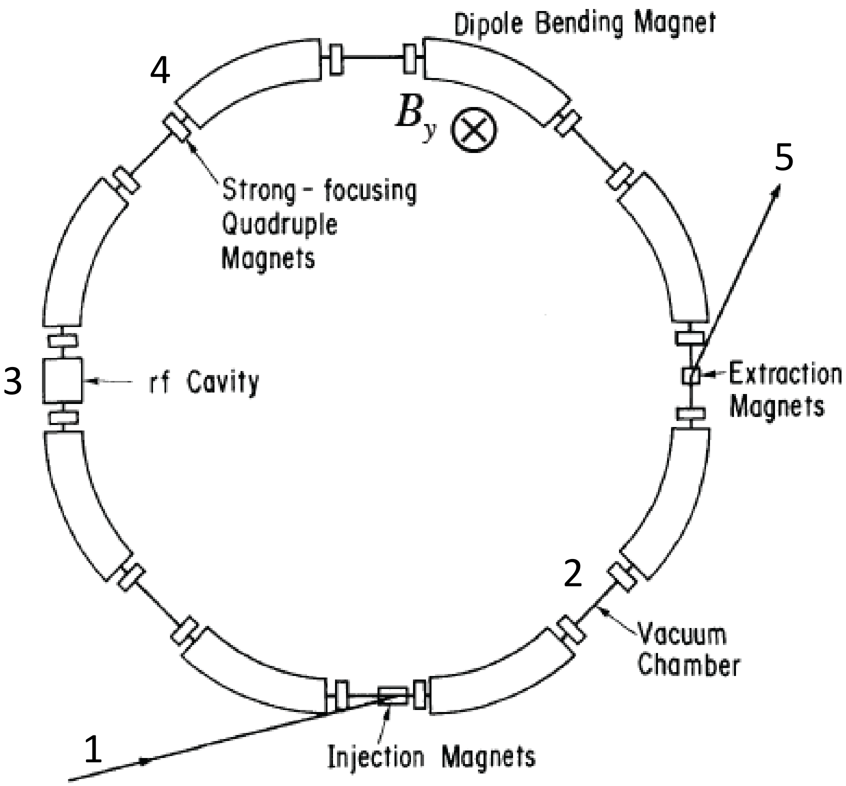
Cyclotrons





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

Synchrotrons

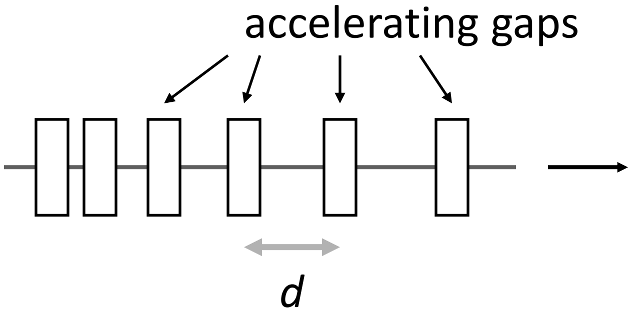


In an ideal world

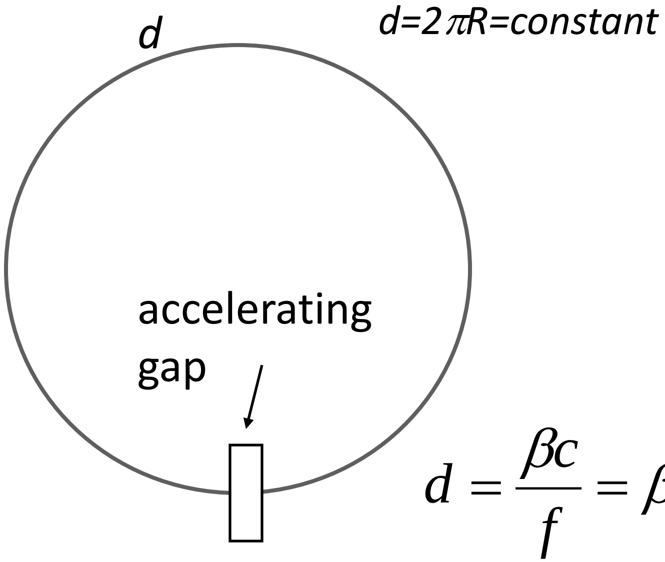
Need an RF oscillator
Need a bending field
Need a vacuum system
Need an injection system
Need an extraction system

- Separated function
- Flexibility
- Scalability

Linear versus circular accelerators (protons)



$$\frac{d}{v} = T \Rightarrow \frac{d}{\beta c} = \frac{1}{f} \Rightarrow d = \frac{\beta c}{f} = \beta\lambda$$



$$d = \frac{\beta c}{f} = \beta\lambda$$

Linear accelerator:

Particles accelerated by a sequence of gaps (all at the same RF phase).

Distance between gaps increases proportionally to the particle velocity, to keep synchronicity.

Used in the range where β increases. “Newton” machine

Circular accelerator:

Particles accelerated by one (or more) gaps at given positions in the ring.

Distance between gaps is fixed. Synchronicity only for β~const, or varying (in a limited range!) the RF frequency.

Used in the range where β is nearly constant. “Einstein” machine

Lorentz force

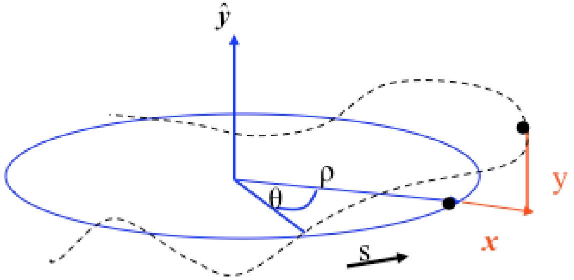
- Implicit in relativistic formulation of Maxwell's equations
- Describes the force on a charged particle moving in an em field

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

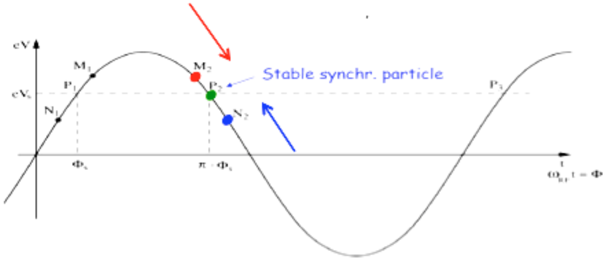
$$\vec{E} = 0 \qquad\qquad \vec{B} = 0$$

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

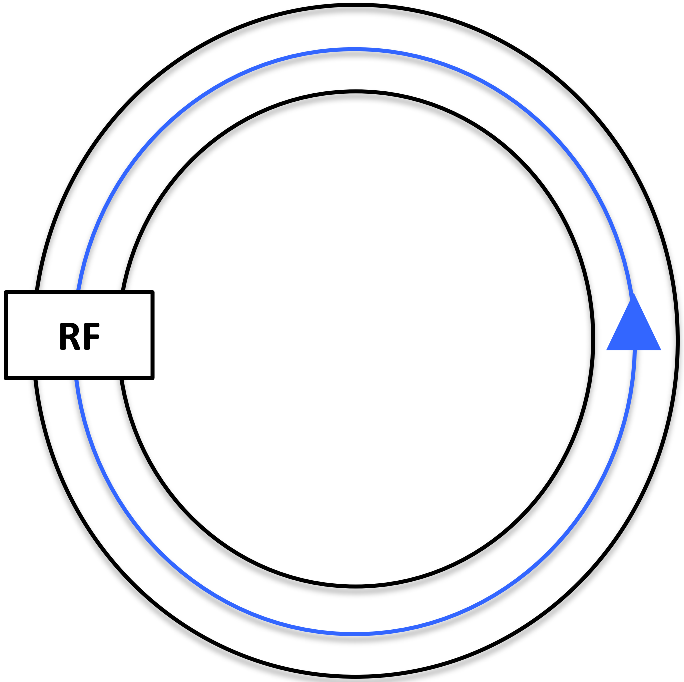
Transverse Beam Dynamics



Longitudinal Beam Dynamics



Synchrotrons



In an ideal machine, an ideal particle would happily circulate on axis for ever

Is this true?

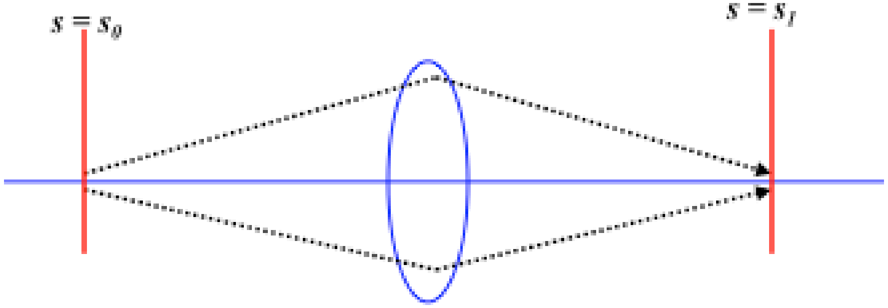
Gravity will cause a vertical displacement of 2cm in 64 ms

In any case, things are never ideal

There are many particles in the machine
They will not all have the same parameters

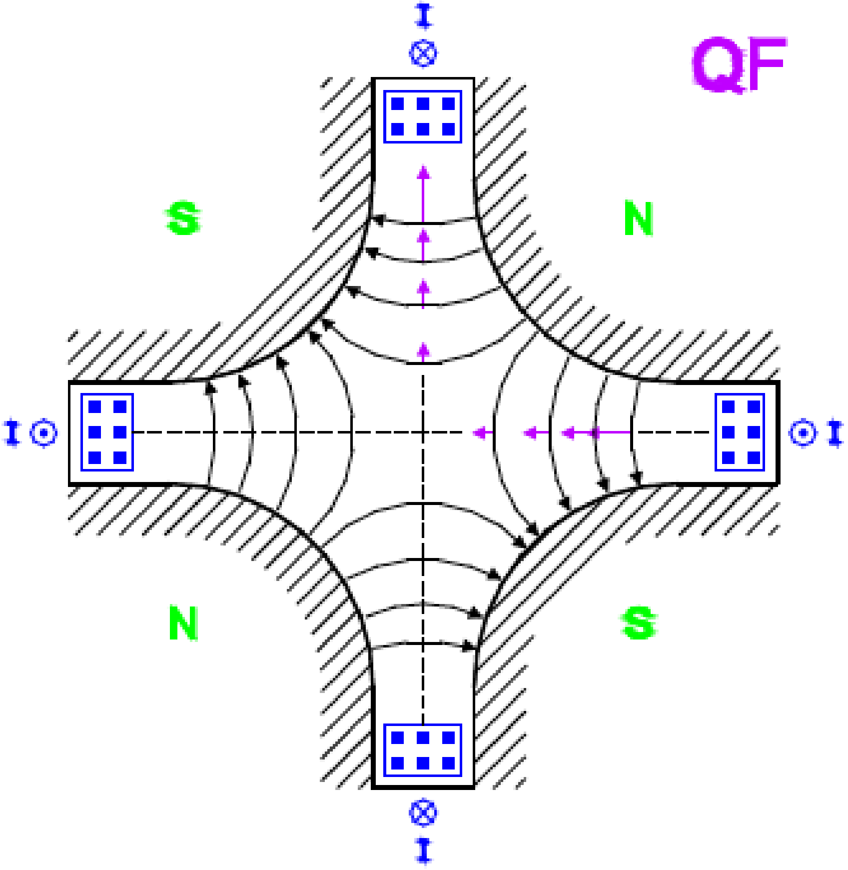
Machine alignment is not perfect
Magnets are not perfect
Power supplies are not perfect
Ground motion

We need to focus the particles



Done with **quadrupole magnets**

Quadrupoles

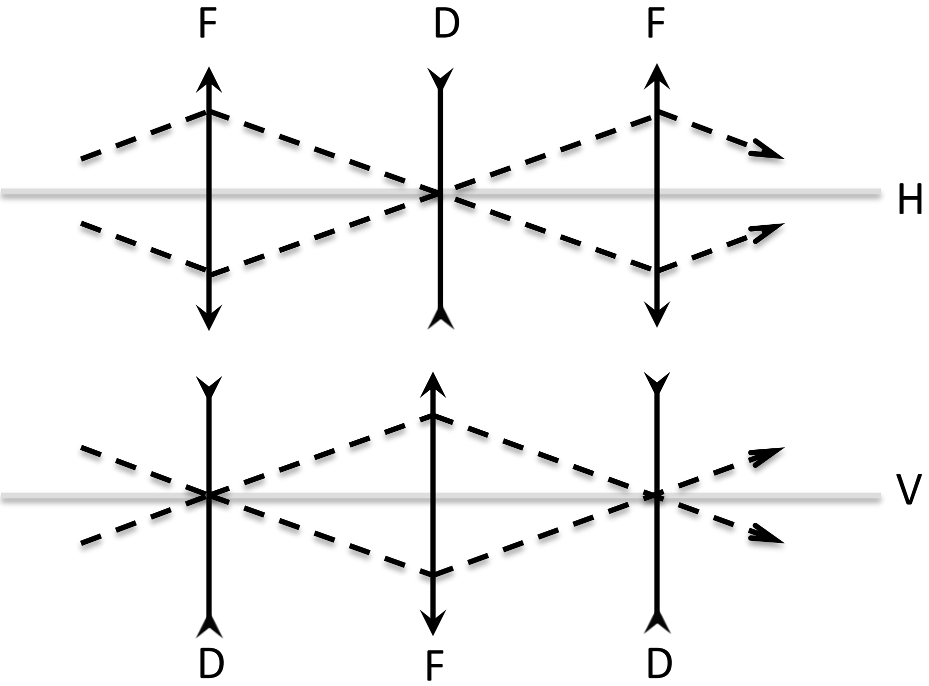


Fortunately, a solution (CLS, 1952)

Concave in one plane is convex in other

Arrange for the beam on axis at D lenses

Known as Alternate Gradient Focusing

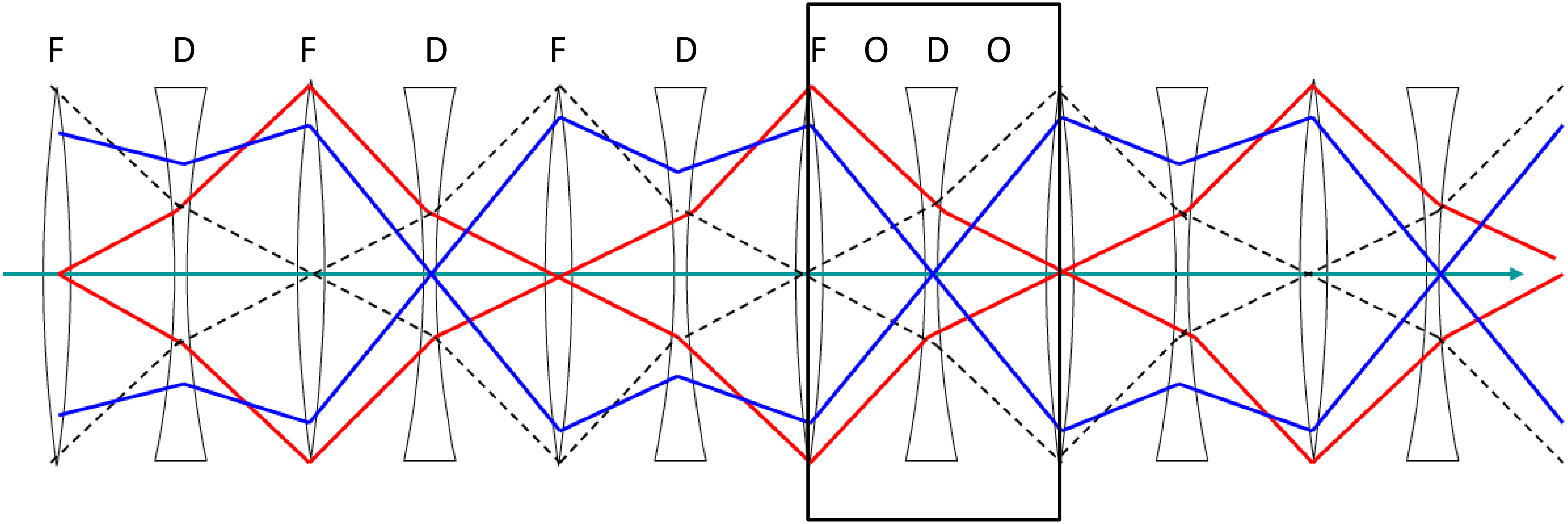


Force increases linearly with displacement

Unfortunately, effect is opposite in H and V

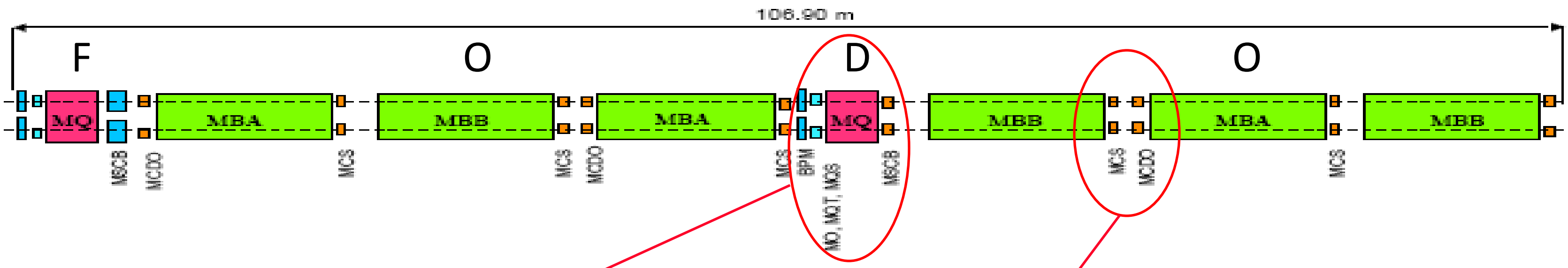
Alternate Gradient Focusing

It turns out that a section composed of alternate focusing and defocusing elements has a net focusing effect, providing that the quadrupoles are correctly spaced.



Horizontally focusing magnets are designated F and defocusing magnets designated D
The drift spaces (or dipoles) in between are designated O
A minimum sequence is therefore known as a FODO cell
One complete oscillation in made in 4 cells (phase advance per cell 90^0)
Number of oscillations made in one full revolution of the machine is the tune, Q

The FODO cell in the LHC



MQT: trim quadrupole

MQS: skew trim quadrupole

MO: lattice octupole

MSCB: sextupole (skew sextupole) + orbit corrector

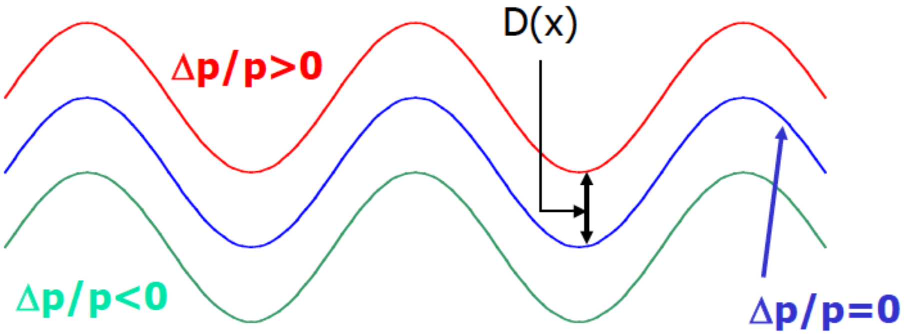
MCS: spool piece sextupole

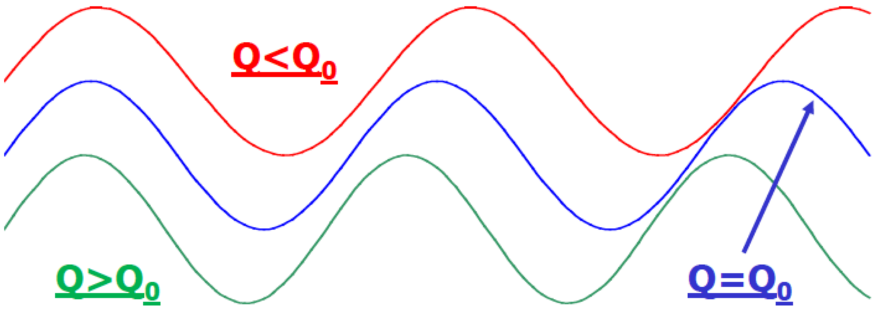
MCDO: spool piece octupole + decapole

- 23 regular FODO cells in each arc
- 106.9m long, made from two 53.45m long half-cells
- Half cell
  - 3 15m cryodipole magnets, each with spool-piece correctors
  - 1 Short Straight Section (~6m long)
    - Quadrupole and lattice corrector magnets

Off-momentum particles ($\Delta p/p \neq 0$)

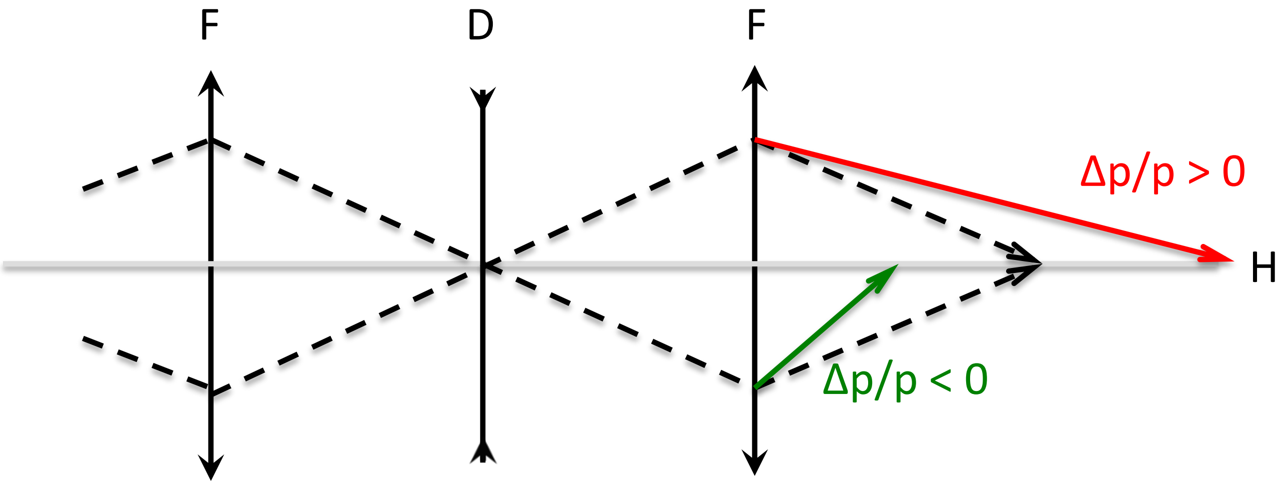
In the dipoles	In the quadrupoles
For $\Delta p/p > 0$ particles are bent less	For $\Delta p/p > 0$ less focusing, lower Q
For $\Delta p/p < 0$ particles are bent more	For $\Delta p/p < 0$, more focusing, higher Q
Equilibrium effect in the quadroles	

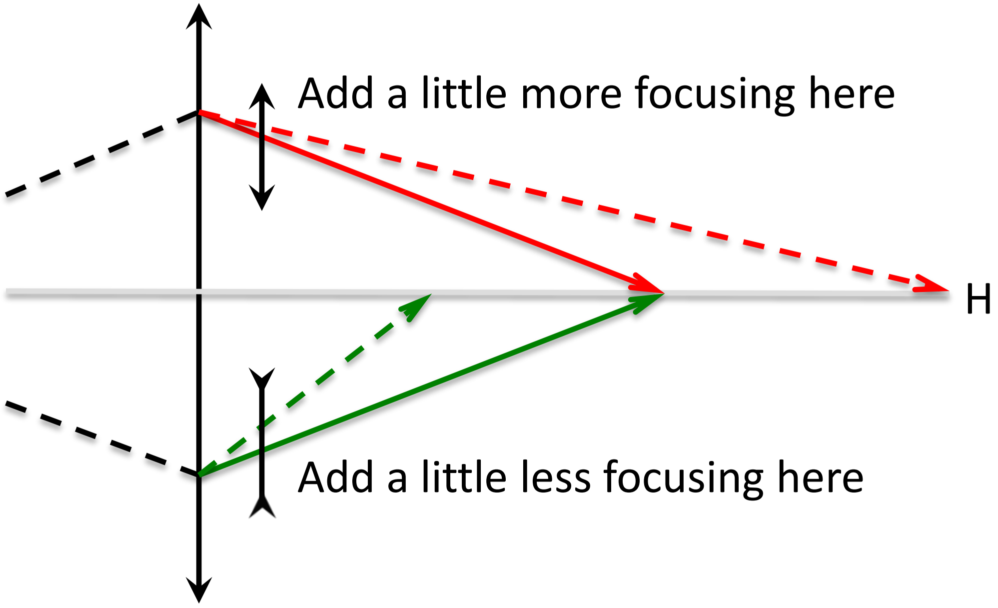




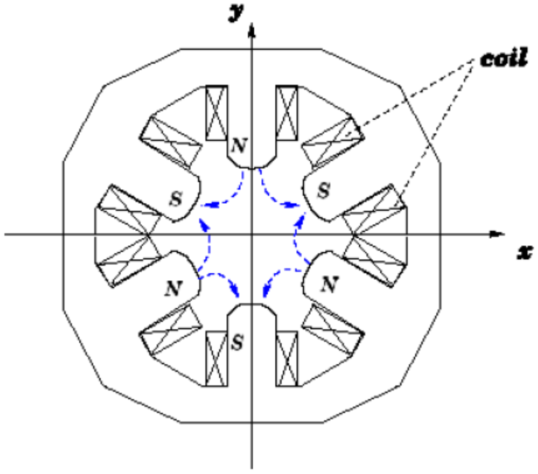
Dispersion D(s)	Chromaticity Q’
$\Delta x = D(s).\ \Delta p/p$	$\Delta Q = Q'.\ \Delta p/p$
Has to fit in the vacuum chamber	Corrected with **sextupole magnets**

Chromaticity correction with sextupoles



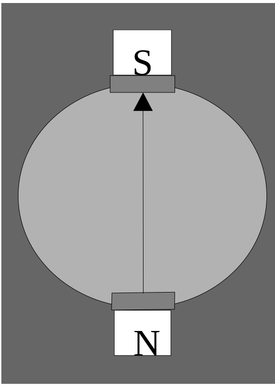

Add a little more focusing here

Add a little less focusing here

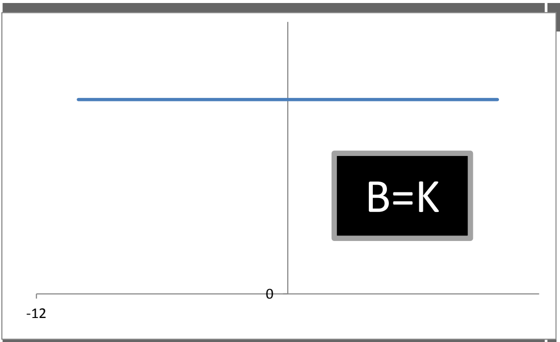


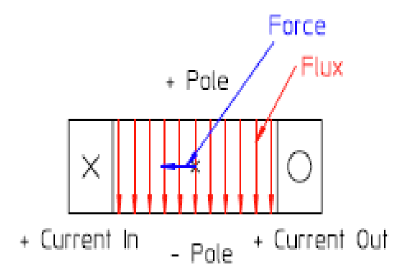
Magnets

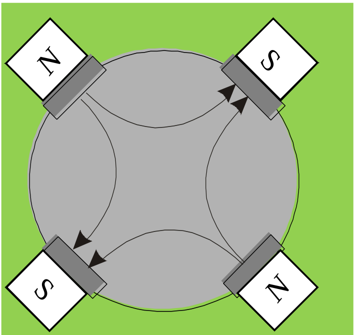
The CERN Accelerator School



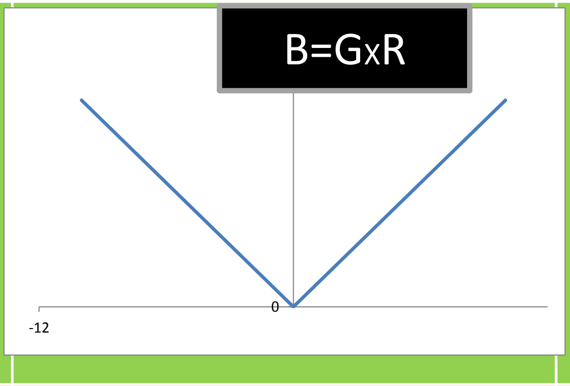
Dipoles=Bending magnets: bend the beam along the set path

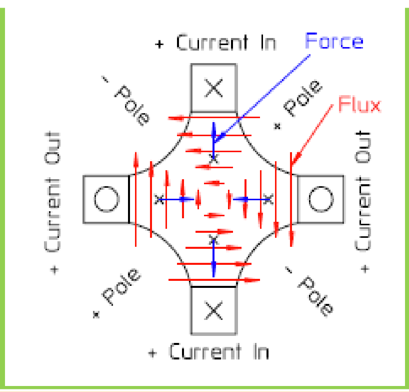


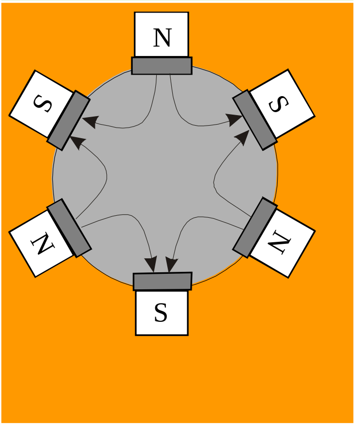




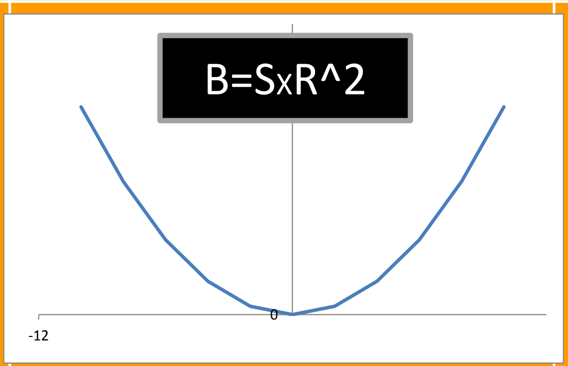
Quadrupoles=Focussing magnets: move the particles back to the centre of the aperture

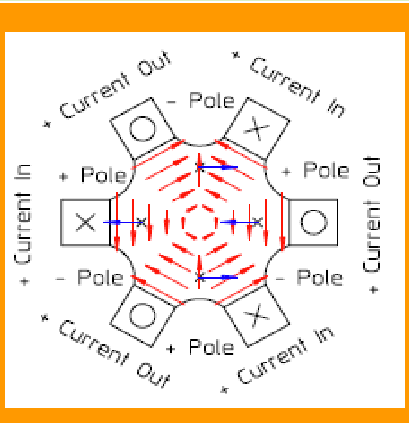






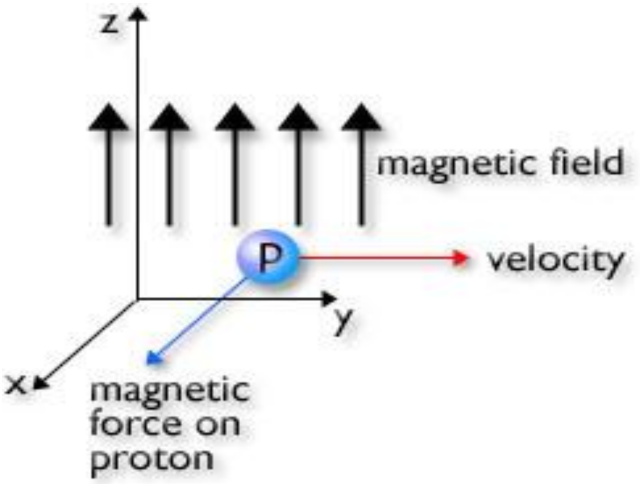
Sextupole=correct for the chromatic aberration caused by the momentum spread in the beam

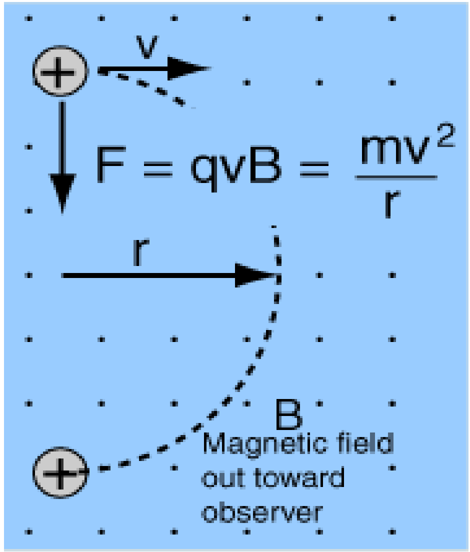




High energy machines

- Synchrotrons are flexible and scalable
- So we use a synchrotron to get to very high energies
- We can learn a lot from just the Bending magnets





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

Magnetic rigidity

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

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

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

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

$$B\rho\,[Tm] = 3.335641\ E\,[GeV] \qquad eU_0 = A\gamma^4 / \rho$$

- 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

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

- 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

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

LHC

The CERN Accelerator School

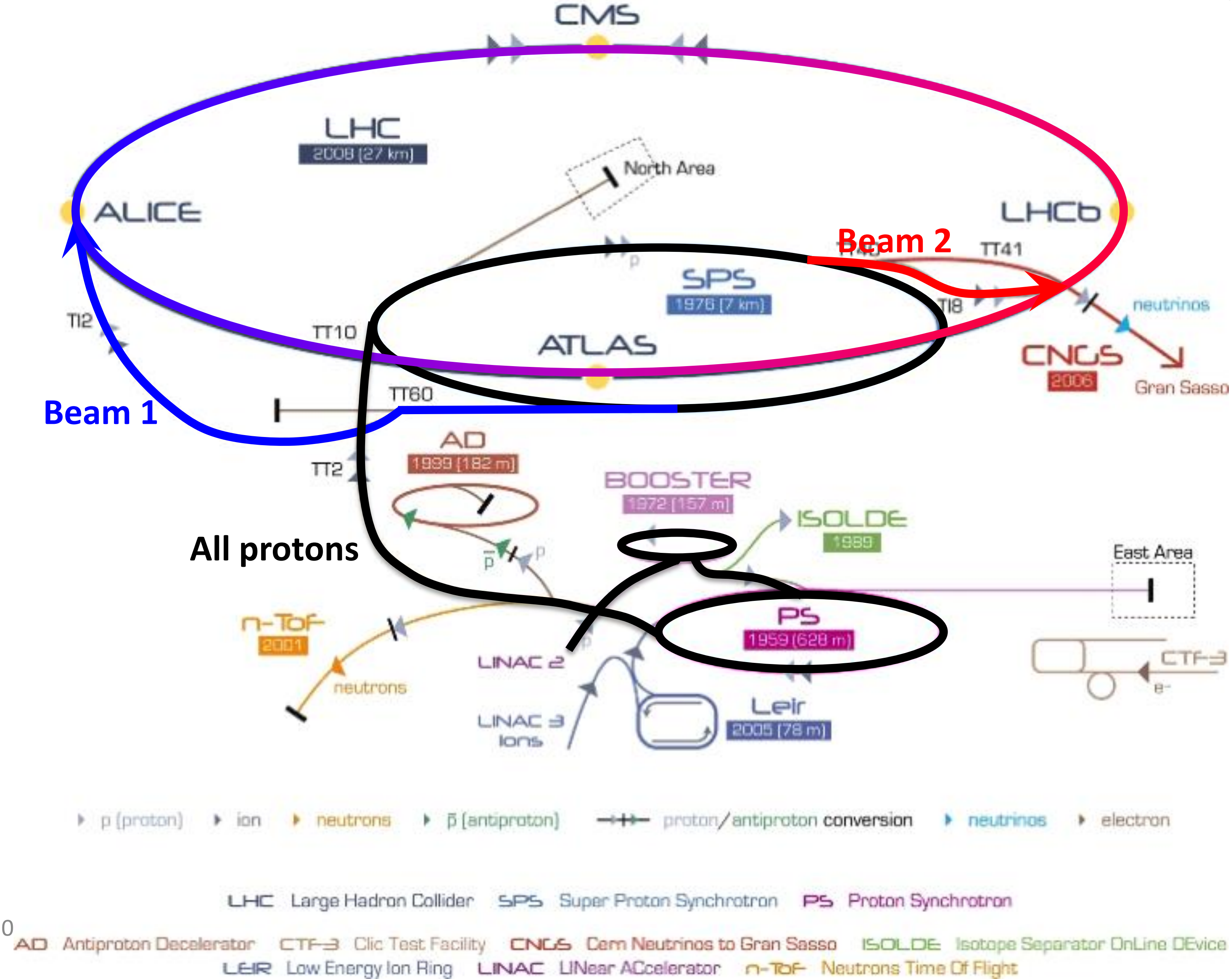
- We started with a 27km tunnel
- We know that we need 8.33T dipole magnets for 7TeV
  - NB for LHC, 2πρ = 17.6km, which is about 66% of 27km

- We know if we collide we make the most of this energy

- What else do we need to know ?
  - Magnets designed for 7TeV do not work at very low field
    - We cannot just build a small linac to provide protons to LHC
    - We need an injection scheme to provide protons > 400 GeV
  - We need high intensities in LHC
    - Injection scheme has to provide this

$$L = \frac{N^2 k_b f}{4ps_x s_y} F = \frac{N^2 k_b f g}{4pe_n b^*} F$$

Accelerators are linked together

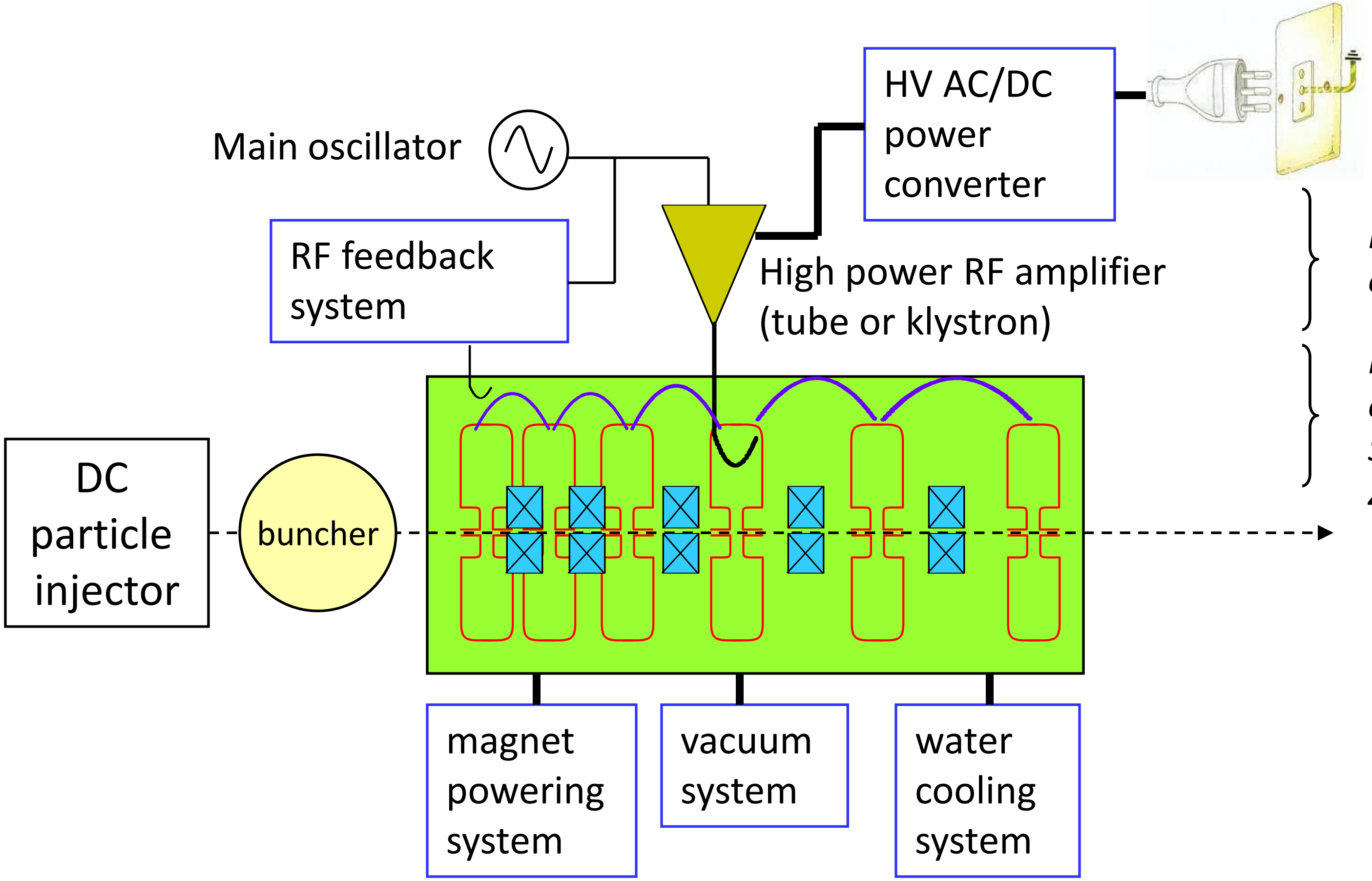


Beam 2

Beam 1

All protons

Linac2 schematic



Main oscillator

RF feedback system

HV AC/DC power converter

High power RF amplifier (tube or klystron)

DC particle injector

buncher

magnet powering system

vacuum system

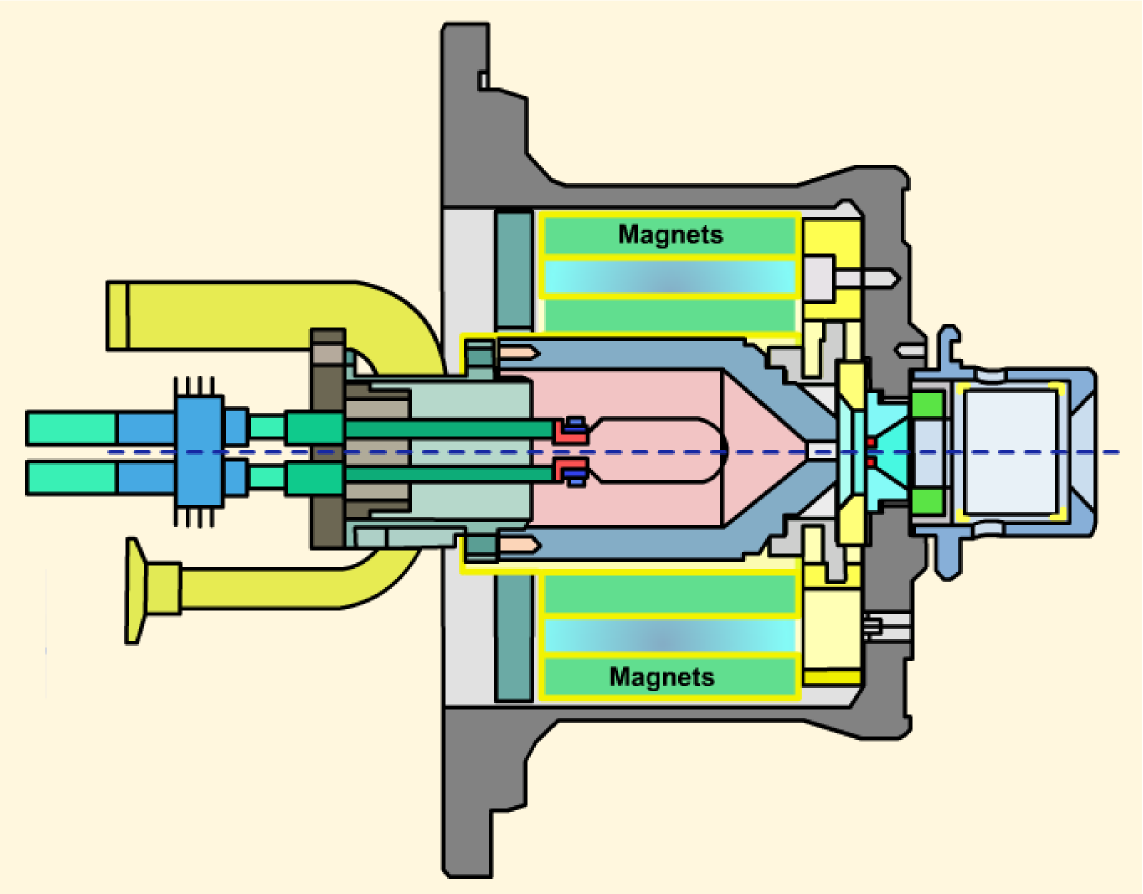
water cooling system

AC to DC conversion efficiency ~90%

DC to RF conversion efficiency ~50%

RF to beam voltage conversion efficiency = SHUNT IMPEDANCE ZT^2 ~ 20 - 60 MΩ/m

Source for linac 2



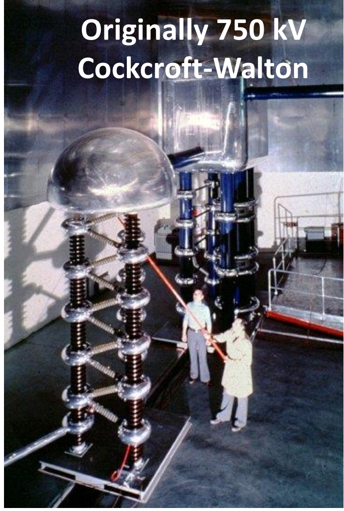
Proton Current	200 mA
Proton Energy	90 keV
Emittance	~0.4 mm.mrad
Pulse for LHC	20us @ 1 Hz
# protons / pulse	2.5×10^{13}
# LHC bunches	~24 *

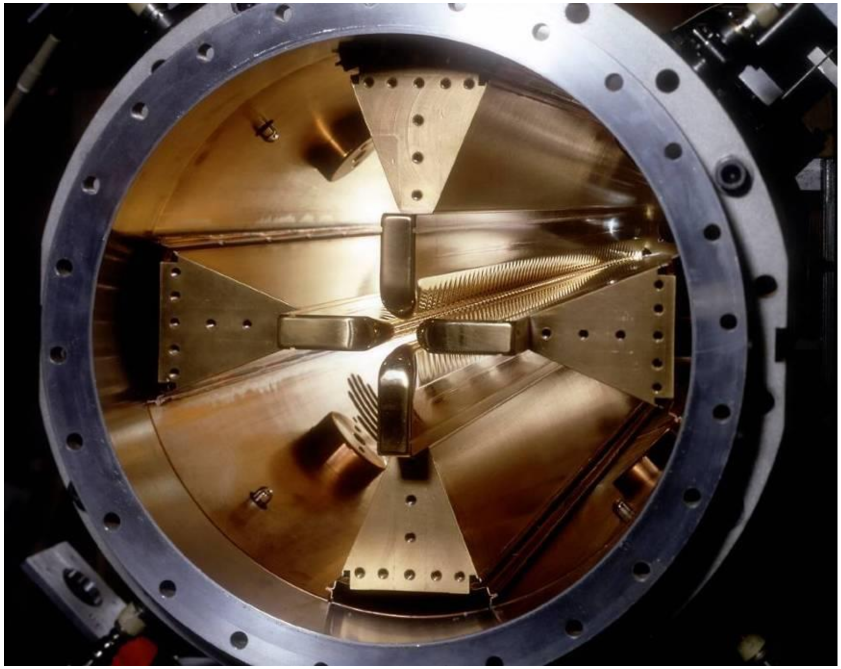
* Creation of LHC bunches is a complicated process, this is an example for 50ns LHC bunches

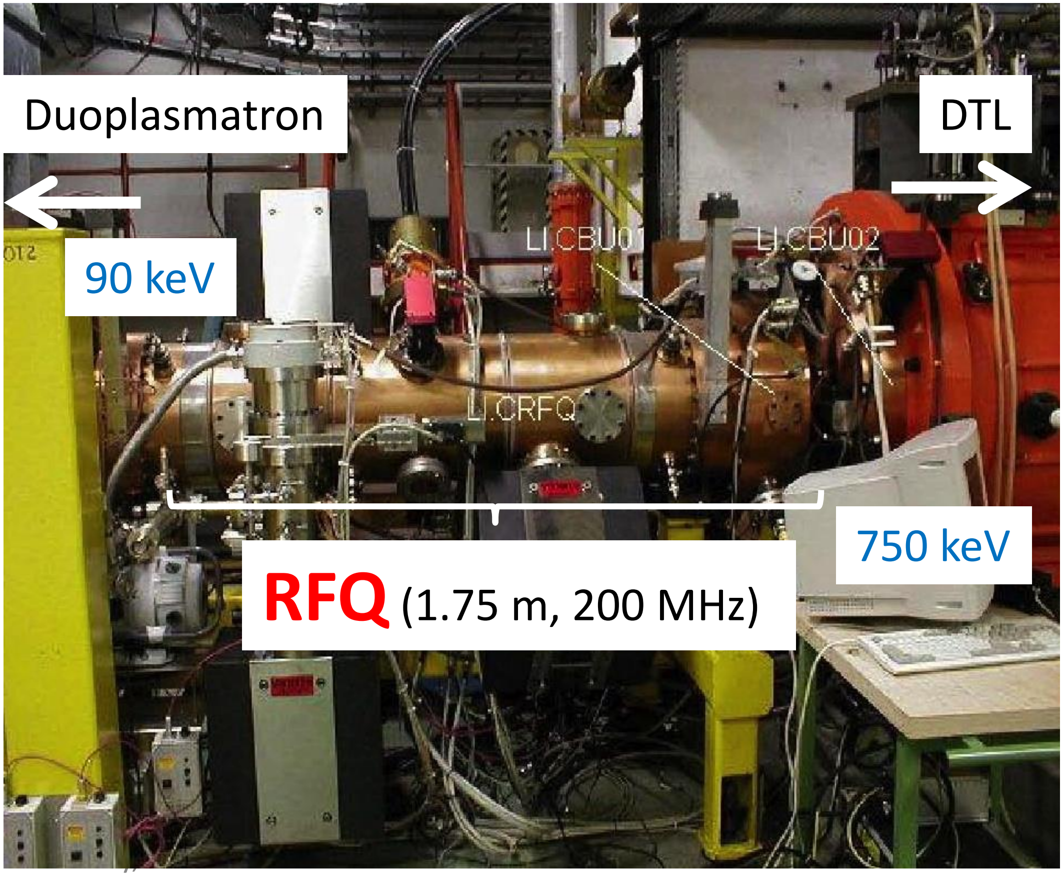
RFQ

The Radio Frequency Quadrupole is a linear accelerator that focuses, bunches and accelerates with high efficiency

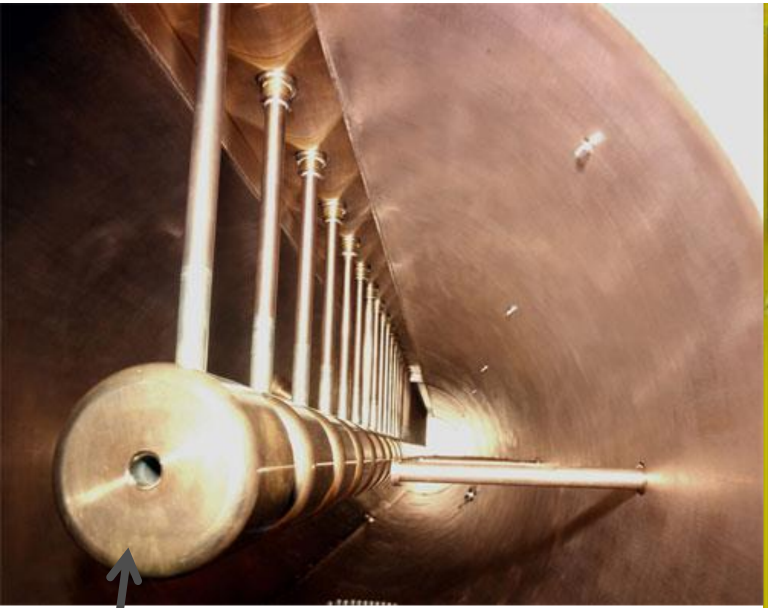
The Linac2 RFQ takes protons from the source at 90 KeV and delivers them bunched to the DTL at 750 keV

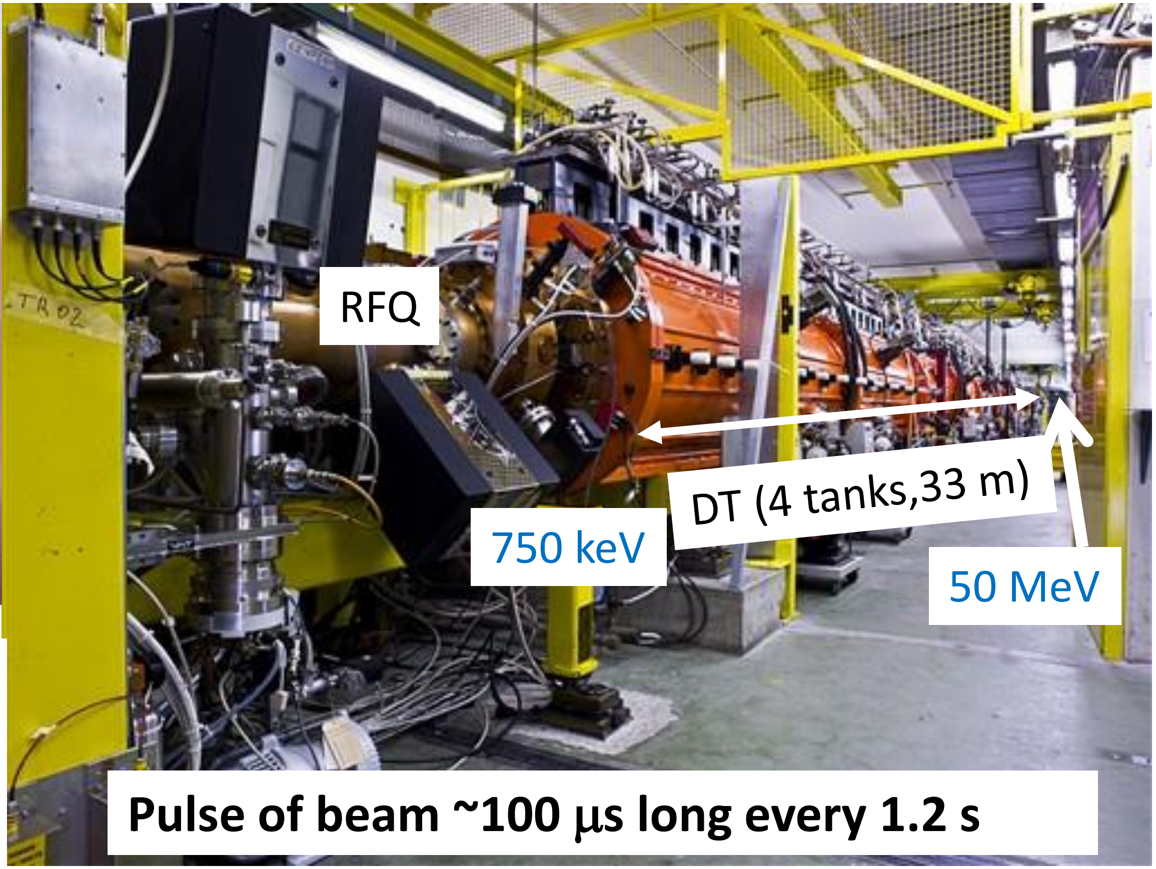






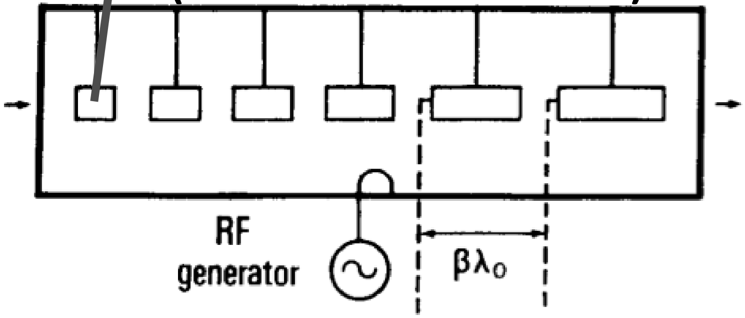
Linac 2 DTL





Pulse of beam ~100 μs long every 1.2 s

DTL (Alvarez structure 1945)



Drift tubes and spacing become larger as the energy increases

Focusing quads inside drift tubes

The Synchrotrons

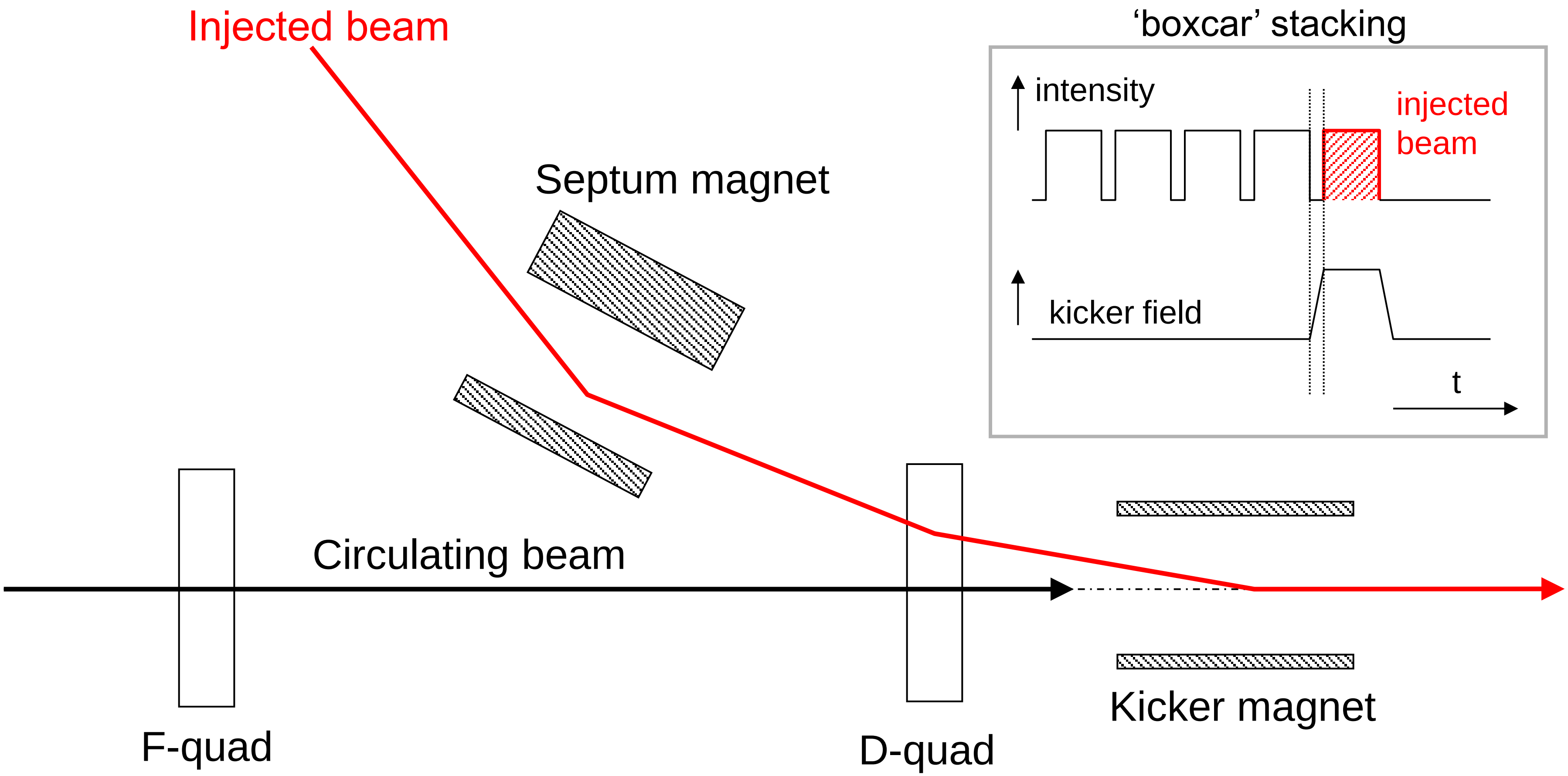
Machine	Injection energy	Extraction energy
Booster	50 MeV	1.6 GeV
PS	1.6 GeV	26 GeV
SPS	26 GeV	450 GeV
LHC	450 GeV	7 TeV

All these machine are conceptually similar (barring a few historical developments)

In practice, LHC is rather different to the others due to

Size (1720 power converters, steady state 63 MW, Peak power 86 MW)
Segmentation of the machine into 8 (Tracking between sectors)
Superconducting (High current Low voltage)
Collider (in a 10h run protons travel 10^{10}km = 72AU ~ diameter of solar system)

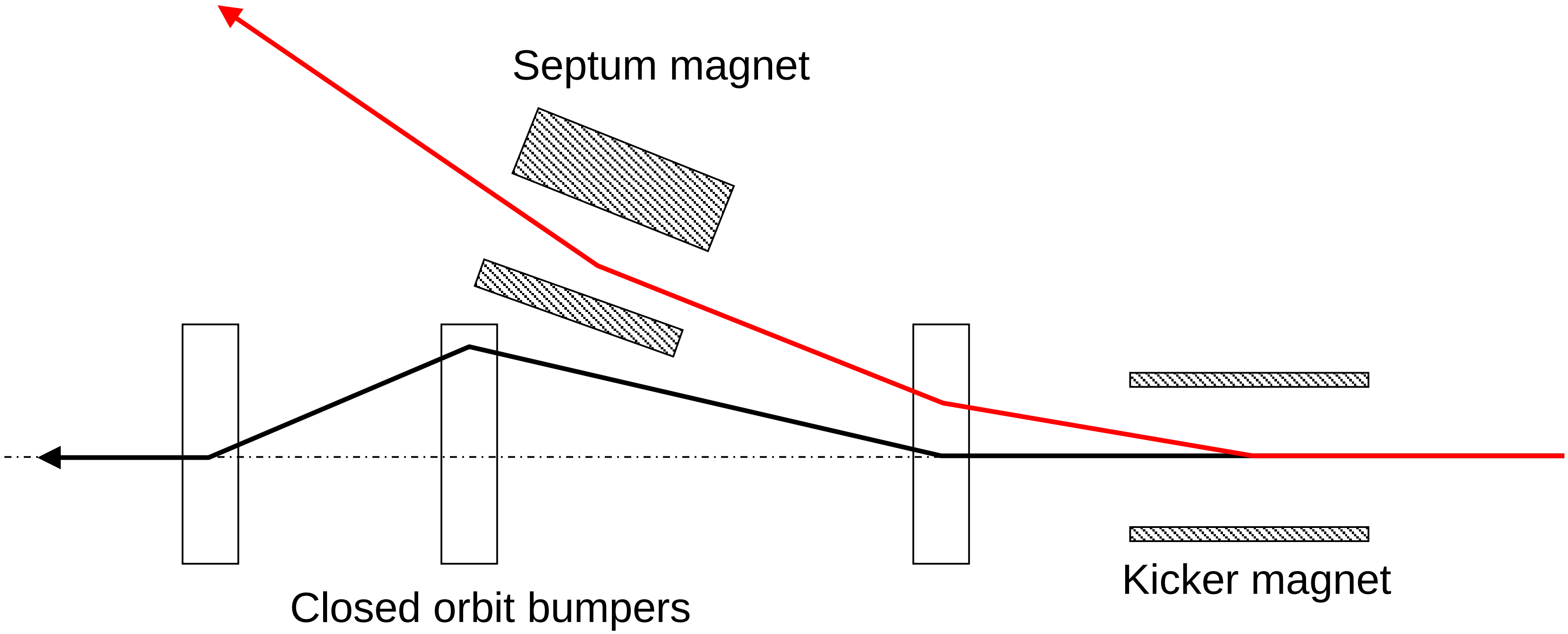
Single-turn injection – same plane



- Septum deflects the beam onto the closed orbit at the centre of the kicker
- Kicker compensates for the remaining angle
- Septum and kicker either side of D quad to minimise kicker strength

Fast single turn extraction

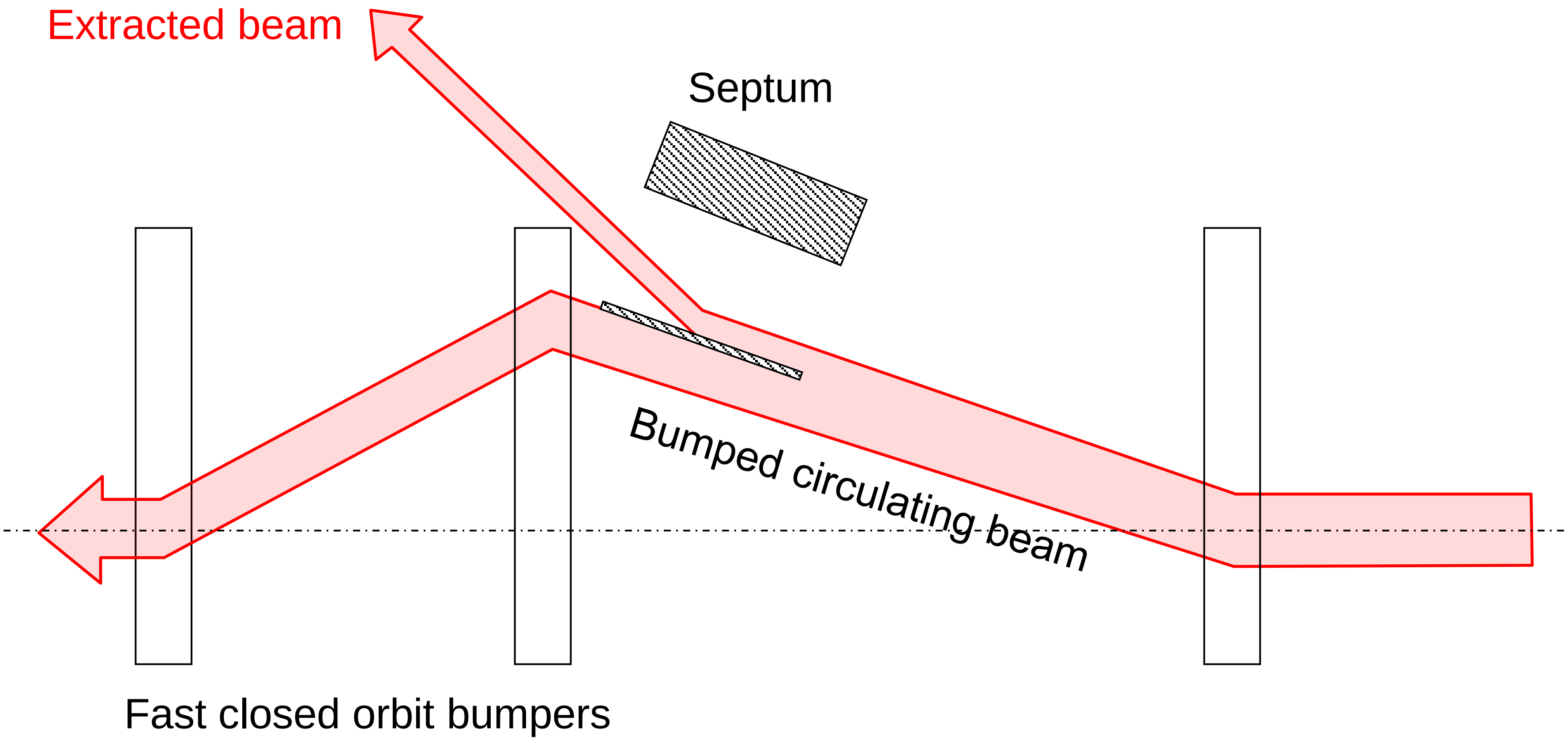
Whole beam kicked into septum gap and extracted.



- Kicker deflects the entire beam into the septum in a single turn
- Septum deflects the beam entire into the transfer line
- Most efficient (lowest deflection angles required) for $\pi/2$ phase advance between kicker and septum

Non-resonant multi-turn extraction

Beam bumped to septum; part of beam ‘shaved’ off each turn.



- Fast bumper deflects the whole beam onto the septum
- Beam extracted in a few turns, with the machine tune rotating the beam
- Intrinsically a high-loss process – thin septum essential

Huge range of parameters just at CERN

Septum Location	Beam momentum (GeV/c)	Gap Height (mm)	Max. Current (kA)	Magnetic Flux Density (T)	Deflection (mrad)
LEIR/AD/CTF (13 systems)	Various	25 to 55	1 DC to 40 pulsed	0.5 to 1.6	up to 130
PS Booster (6 systems)	1.4	25 to 50	28 pulsed	0.1 to 0.6	up to 80
PS complex (8 systems)	26	20 to 40	2.5 DC to 33 pulsed	0.2 to 1.2	up to 55
SPS Ext.	450	20	24	1.5	2.25

Kicker Location	Beam momentum (GeV/c)	# Magnets	Gap Height [V_{ap}] (mm)	Current (kA)	Impedance (Ω)	Rise Time (ns)	Total Deflection (mrad)
CTF3	0.2	4	40	0.056	50	~4	1.2
PS Inj.	2.14	4	53	1.52	26.3	42	4.2
SPS Inj.	13/26	16	54 to 61	1.47/1.96	16.67/12.5	115/200	3.92
SPS Ext. (MKE4)	450	5	32 to 35	2.56	10	1100	0.48
LHC Inj.	450	4	54	5.12	5	900	0.82
LHC Abort	450 to 7000	15	73	1.3 to 18.5	1.5 (not T-line)	2700	0.275

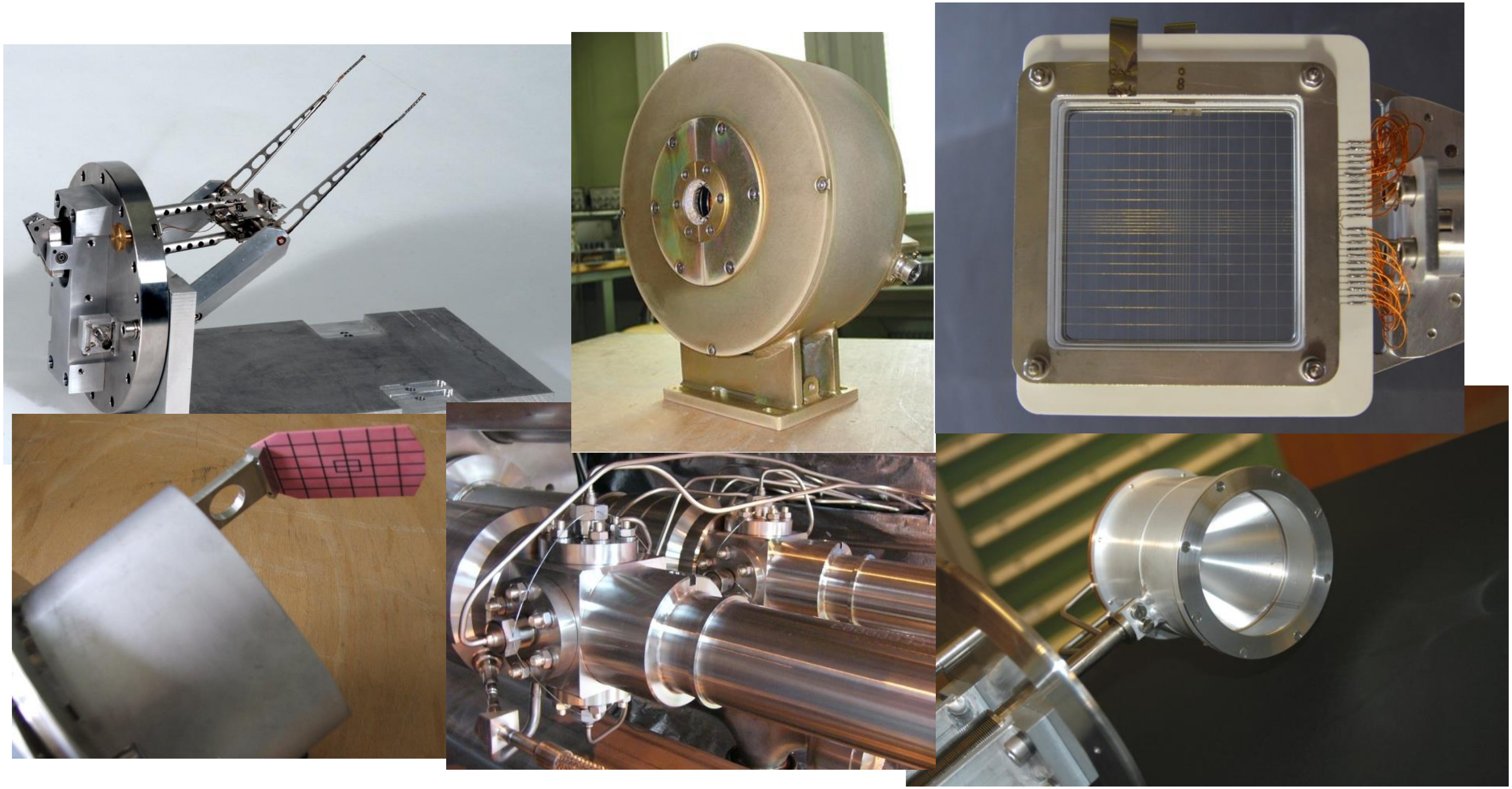
Beam instrumentation

An accelerator can never be better than the instruments measuring its performance

Instrument	**Physical Effect**	**Measured Quantity**	**Effect on beam**
Faraday Cup	Charge collection	Intensity	Destructive
Current Transformer	Magnetic field	Intensity	Non destructive
Wall current monitor	Image Current	Intensity Longitudinal beam shape	Non destructive
Pick-up	Electric/magnetic field	Position, Tune	Non destructive
Secondary emission monitor	Secondary electron emission	Transverse size/shape, emittance	Disturbing, can be destructive at low energies
Wire Scanner	Secondary particle creation	Transverse size/shape	Slightly disturbing
Scintillator screen	Atomic excitation with light emission	Transverse size/shape (position)	Destructive
Residual Gas monitor	Ionization	Transverse size/shape	Non destructive

Beam instrumentation

An accelerator can never be better than the instruments measuring its performance

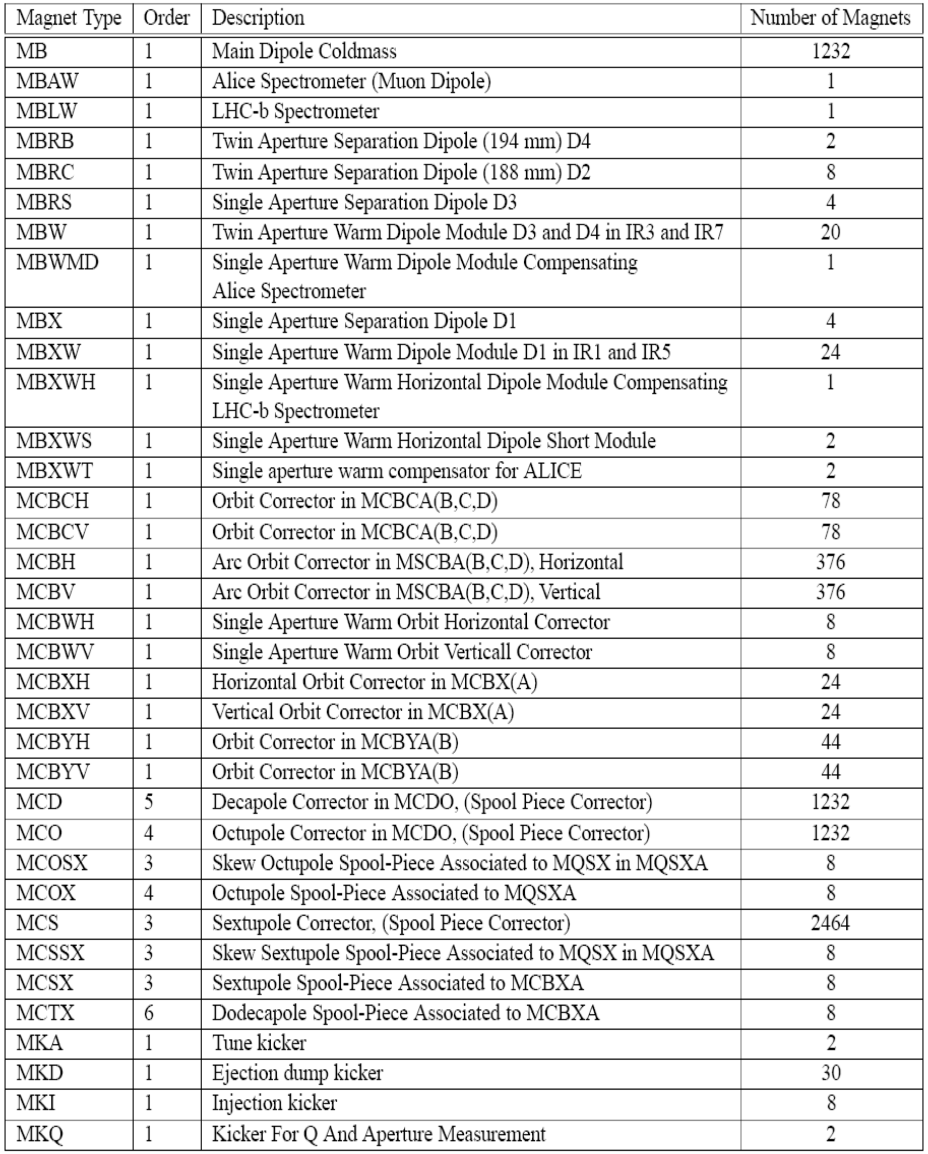


Summary of accelerator systems

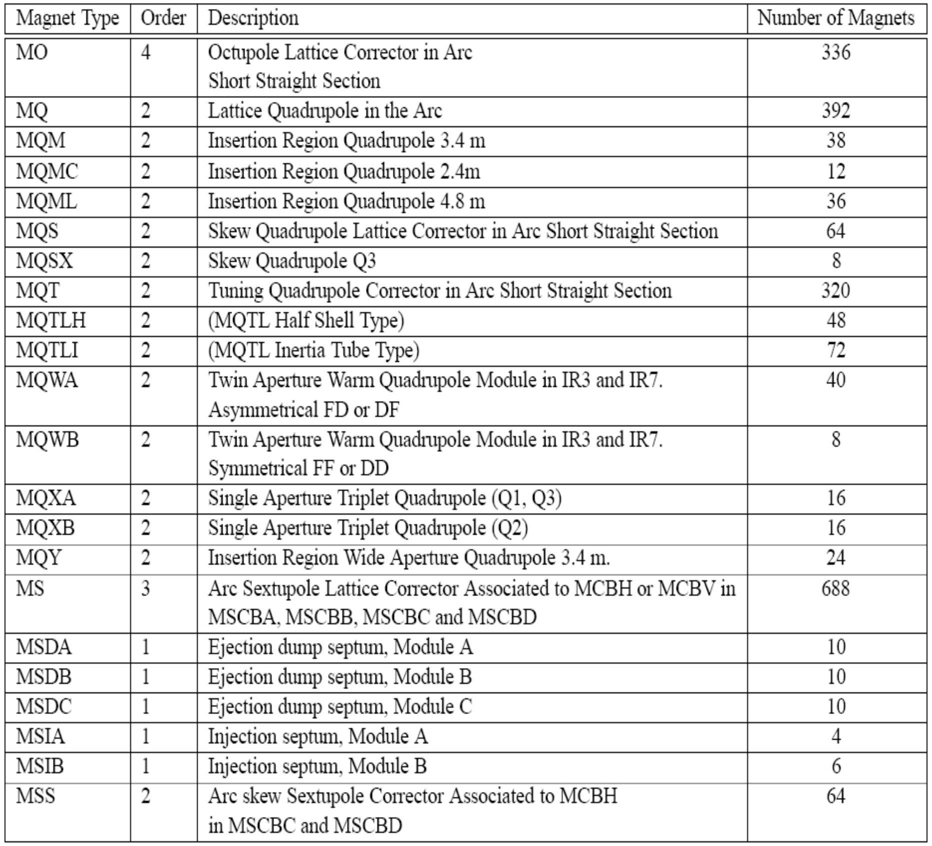
Systems acting on the beam	Auxiliary systems
Magnet systems	Ventilation systems
RF systems	Cooling systems
Sources	Cryogenic systems
Linacs	Vacuum systems
Injection synchrotrons	Access systems
Injection systems	Radiation Protection
Extraction systems	Alignment
Collimation systems	Machine protection systems
Beam Instrumentation	Control systems
Feedback systems	Experiments

All of these need Electrical Distribution Systems and Power Converters

We need a lot of magnets (this is just LHC)



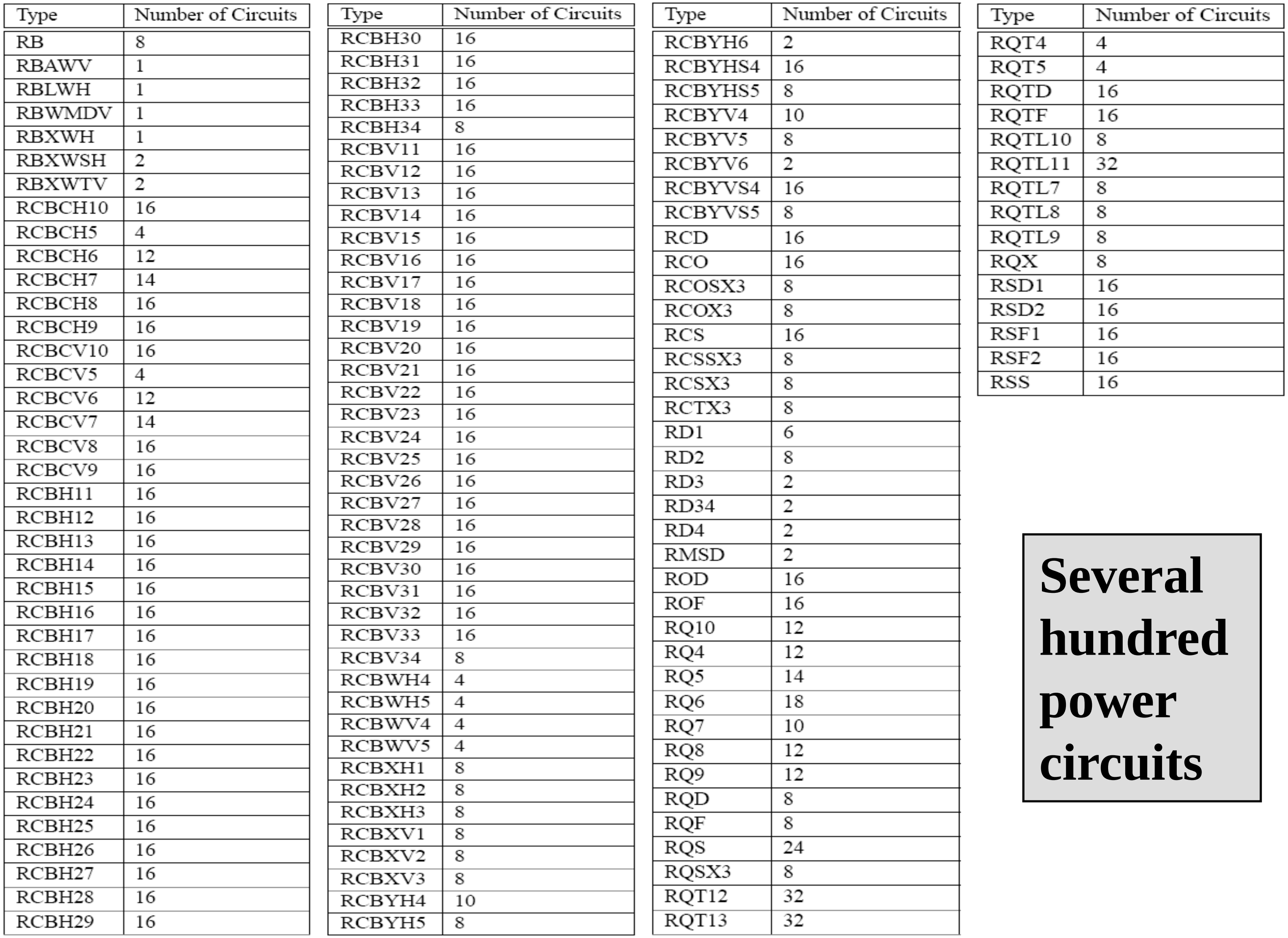
Magnet Type	Order	Description	Number of Magnets
MB	1	Main Dipole Coldmass	1232
MBAW	1	Alice Spectrometer (Muon Dipole)	1
MBLW	1	LHC-b Spectrometer	1
MBRB	1	Twin Aperture Separation Dipole (194 mm) D4	2
MBRC	1	Twin Aperture Separation Dipole (188 mm) D2	8
MBRS	1	Single Aperture Separation Dipole D3	4
MBW	1	Twin Aperture Warm Dipole Module D3 and D4 in IR3 and IR7	20
MBWMD	1	Single Aperture Warm Dipole Module Compensating Alice Spectrometer	1
MBX	1	Single Aperture Separation Dipole D1	4
MBXW	1	Single Aperture Warm Dipole Module D1 in IR1 and IR5	24
MBXWH	1	Single Aperture Warm Horizontal Dipole Module Compensating LHC-b Spectrometer	1
MBXWS	1	Single Aperture Warm Horizontal Dipole Short Module	2
MBXWT	1	Single aperture warm compensator for ALICE	2
MCBCH	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBCV	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBH	1	Arc Orbit Corrector in MSCBA(B,C,D), Horizontal	376
MCBV	1	Arc Orbit Corrector in MSCBA(B,C,D), Vertical	376
MCBWH	1	Single Aperture Warm Orbit Horizontal Corrector	8
MCBWV	1	Single Aperture Warm Orbit Verticall Corrector	8
MCBXH	1	Horizontal Orbit Corrector in MCBX(A)	24
MCBXV	1	Vertical Orbit Corrector in MCBX(A)	24
MCBYH	1	Orbit Corrector in MCBYA(B)	44
MCBYV	1	Orbit Corrector in MCBYA(B)	44
MCD	5	Decapole Corrector in MCDO, (Spool Piece Corrector)	1232
MCO	4	Octupole Corrector in MCDO, (Spool Piece Corrector)	1232
MCOSX	3	Skew Octupole Spool-Piece Associated to MQSX in MQSXA	8
MCOX	4	Octupole Spool-Piece Associated to MQSXA	8
MCS	3	Sextupole Corrector, (Spool Piece Corrector)	2464
MCSSX	3	Skew Sextupole Spool-Piece Associated to MQSX in MQSXA	8
MCSX	3	Sextupole Spool-Piece Associated to MCBXA	8
MCTX	6	Dodecapole Spool-Piece Associated to MCBXA	8
MKA	1	Tune kicker	2
MKD	1	Ejection dump kicker	30
MKI	1	Injection kicker	8
MKQ	1	Kicker For Q And Aperture Measurement	2



Magnet Type	Order	Description	Number of Magnets
MO	4	Octupole Lattice Corrector in Arc Short Straight Section	336
MQ	2	Lattice Quadrupole in the Arc	392
MQM	2	Insertion Region Quadrupole 3.4 m	38
MQMC	2	Insertion Region Quadrupole 2.4m	12
MQML	2	Insertion Region Quadrupole 4.8 m	36
MQS	2	Skew Quadrupole Lattice Corrector in Arc Short Straight Section	64
MQSX	2	Skew Quadrupole Q3	8
MQT	2	Tuning Quadrupole Corrector in Arc Short Straight Section	320
MQTLH	2	(MQTL Half Shell Type)	48
MQTLI	2	(MQTL Inertia Tube Type)	72
MQWA	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Asymmetrical FD or DF	40
MQWB	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Symmetrical FF or DD	8
MQXA	2	Single Aperture Triplet Quadrupole (Q1, Q3)	16
MQXB	2	Single Aperture Triplet Quadrupole (Q2)	16
MQY	2	Insertion Region Wide Aperture Quadrupole 3.4 m.	24
MS	3	Arc Sextupole Lattice Corrector Associated to MCBH or MCBV in MSCBA, MSCBB, MSCBC and MSCBD	688
MSDA	1	Ejection dump septum, Module A	10
MSDB	1	Ejection dump septum, Module B	10
MSDC	1	Ejection dump septum, Module C	10
MSIA	1	Injection septum, Module A	4
MSIB	1	Injection septum, Module B	6
MSS	2	Arc skew Sextupole Corrector Associated to MCBH in MSCBC and MSCBD	64

Several thousand magnets

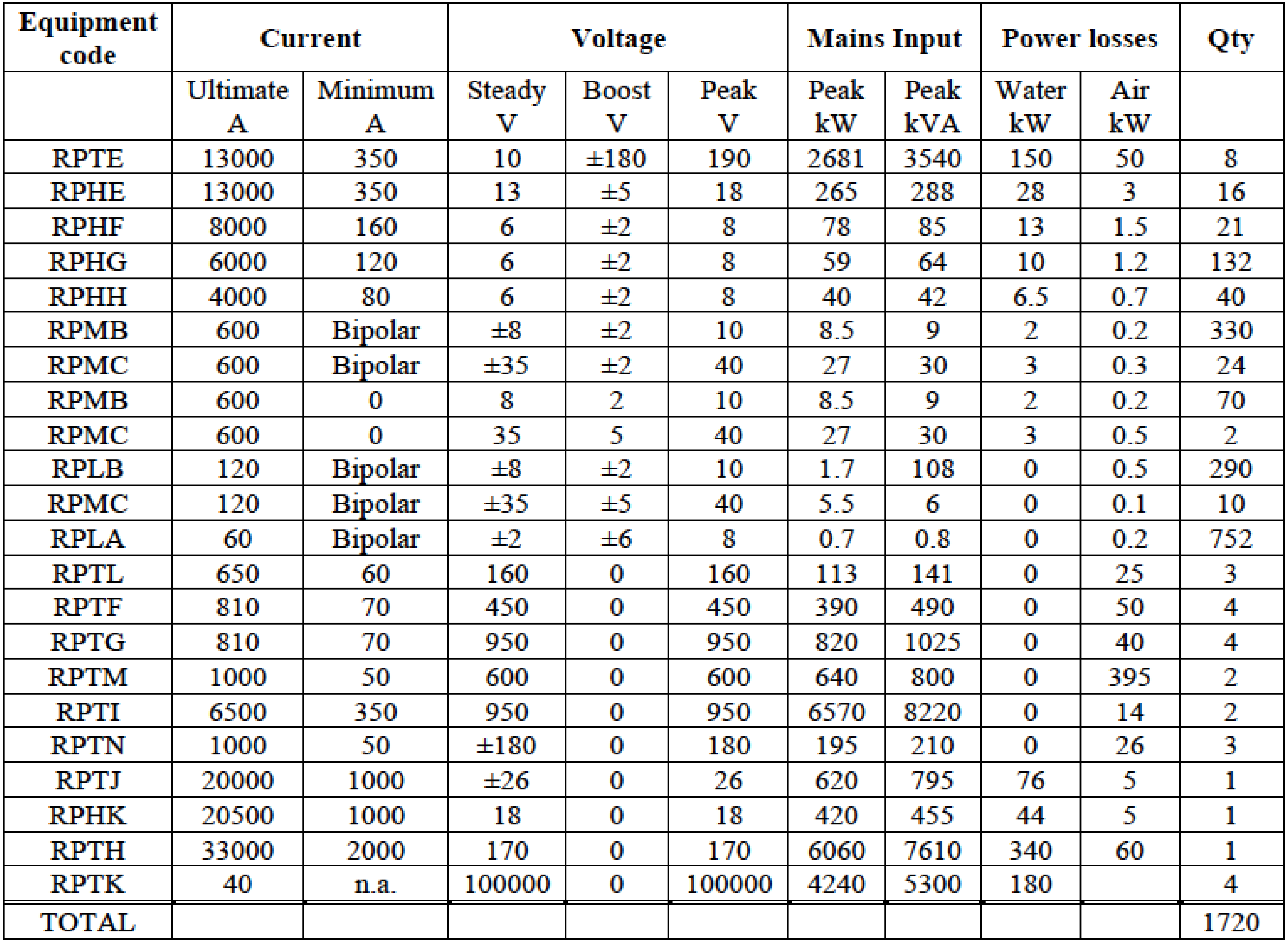
And plenty of power circuits …



Type	Number of Circuits
RB	8
RBAWV	1
RBLWH	1
RBWMDV	1
RBXWH	1
RBXWSH	2
RBXWTV	2
RCBCH10	16
RCBCH5	4
RCBCH6	12
RCBCH7	14
RCBCH8	16
RCBCH9	16
RCBCV10	16
RCBCV5	4
RCBCV6	12
RCBCV7	14
RCBCV8	16
RCBCV9	16
RCBH11	16
RCBH12	16
RCBH13	16
RCBH14	16
RCBH15	16
RCBH16	16
RCBH17	16
RCBH18	16
RCBH19	16
RCBH20	16
RCBH21	16
RCBH22	16
RCBH23	16
RCBH24	16
RCBH25	16
RCBH26	16
RCBH27	16
RCBH28	16
RCBH29	16
RCBH30	16
RCBH31	16
RCBH32	16
RCBH33	16
RCBH34	8
RCBV11	16
RCBV12	16
RCBV13	16
RCBV14	16
RCBV15	16
RCBV16	16
RCBV17	16
RCBV18	16
RCBV19	16
RCBV20	16
RCBV21	16
RCBV22	16
RCBV23	16
RCBV24	16
RCBV25	16
RCBV26	16
RCBV27	16
RCBV28	16
RCBV29	16
RCBV30	16
RCBV31	16
RCBV32	16
RCBV33	16
RCBV34	8
RCBWH4	4
RCBWH5	4
RCBWV4	4
RCBWV5	4
RCBXH1	8
RCBXH2	8
RCBXH3	8
RCBXV1	8
RCBXV2	8
RCBXV3	8
RCBYH4	10
RCBYH5	8
RCBYH6	2
RCBYHS4	16
RCBYHS5	8
RCBYV4	10
RCBYV5	8
RCBYV6	2
RCBYVS4	16
RCBYVS5	8
RCD	16
RCO	16
RCOSX3	8
RCOX3	8
RCS	16
RCSSX3	8
RCSX3	8
RCTX3	8
RD1	6
RD2	8
RD3	2
RD34	2
RD4	2
RMSD	2
ROD	16
ROF	16
RQ10	12
RQ4	12
RQ5	14
RQ6	18
RQ7	10
RQ8	12
RQ9	12
RQD	8
RQF	8
RQS	24
RQSX3	8
RQT12	32
RQT13	32
RQT4	4
RQT5	4
RQTD	16
RQTF	16
RQTL10	8
RQTL11	32
RQTL7	8
RQTL8	8
RQTL9	8
RQX	8
RSD1	16
RSD2	16
RSF1	16
RSF2	16
RSS	16

Several hundred power circuits

Power converters for LHC



Equipment code	Current		Voltage			Mains Input		Power losses		Qty
	Ultimate A	Minimum A	Steady V	Boost V	Peak V	Peak kW	Peak kVA	Water kW	Air kW	
RPTE	13000	350	10	±180	190	2681	3540	150	50	8
RPHE	13000	350	13	±5	18	265	288	28	3	16
RPHF	8000	160	6	±2	8	78	85	13	1.5	21
RPHG	6000	120	6	±2	8	59	64	10	1.2	132
RPHH	4000	80	6	±2	8	40	42	6.5	0.7	40
RPMB	600	Bipolar	±8	±2	10	8.5	9	2	0.2	330
RPMC	600	Bipolar	±35	±2	40	27	30	3	0.3	24
RPMB	600	0	8	2	10	8.5	9	2	0.2	70
RPMC	600	0	35	5	40	27	30	3	0.5	2
RPLB	120	Bipolar	±8	±2	10	1.7	108	0	0.5	290
RPMC	120	Bipolar	±35	±5	40	5.5	6	0	0.1	10
RPLA	60	Bipolar	±2	±6	8	0.7	0.8	0	0.2	752
RPTL	650	60	160	0	160	113	141	0	25	3
RPTF	810	70	450	0	450	390	490	0	50	4
RPTG	810	70	950	0	950	820	1025	0	40	4
RPTM	1000	50	600	0	600	640	800	0	395	2
RPTI	6500	350	950	0	950	6570	8220	0	14	2
RPTN	1000	50	±180	0	180	195	210	0	26	3
RPTJ	20000	1000	±26	0	26	620	795	76	5	1
RPHK	20500	1000	18	0	18	420	455	44	5	1
RPTH	33000	2000	170	0	170	6060	7610	340	60	1
RPTK	40	n.a.	100000	0	100000	4240	5300	180		4
TOTAL										1720

Basic questions in accelerator design

- What is the machine for?

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

High Energy

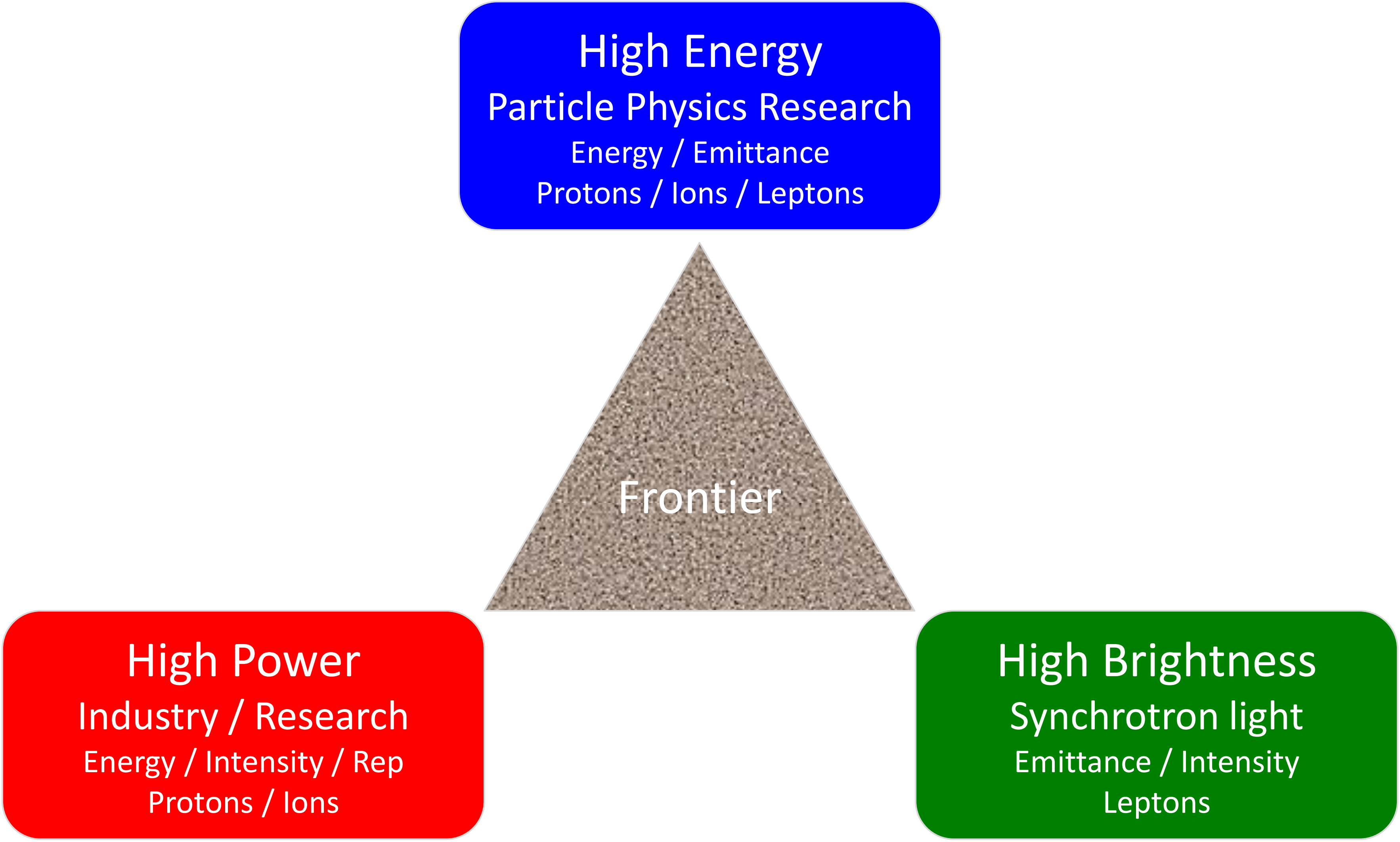
High Power

High Brightness

- What availability do we need?

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

Frontiers of Particle Accelerators



High Energy
Particle Physics Research
Energy / Emittance
Protons / Ions / Leptons

Frontier

High Power
Industry / Research
Energy / Intensity / Rep
Protons / Ions

High Brightness
Synchrotron light
Emittance / Intensity
Leptons