Collider, Accelerator physics

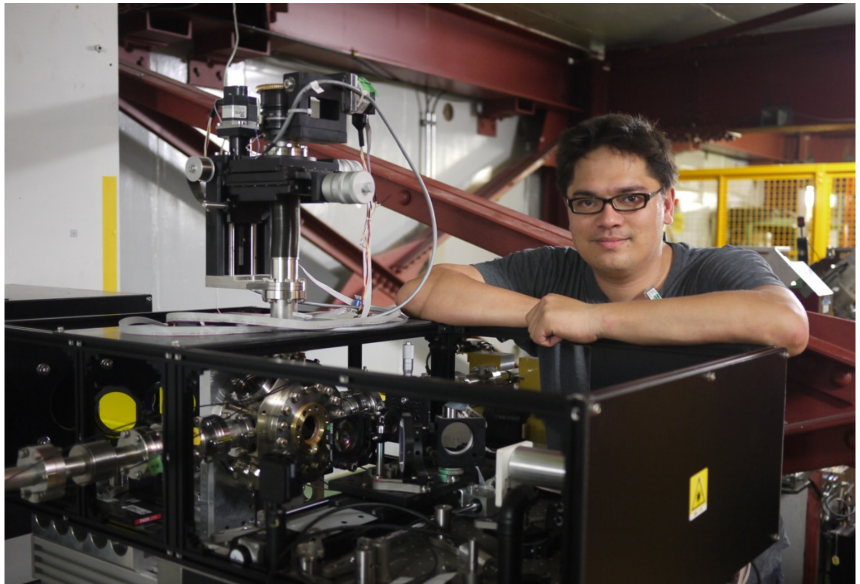
Dr S.T. Boogert
Accelerator physicist at the John Adams Institute at Royal Holloway

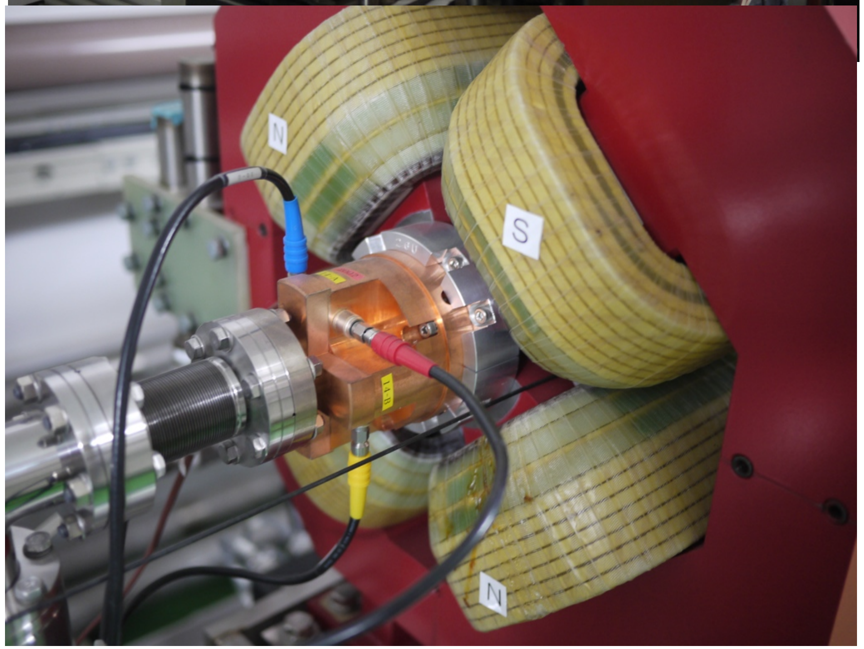
15th November 2012
University of London post-graduate lectures

My research (diagnostics)

- CLIC and ILC
- Mainly diagnostics
  - How to measure electron beams
- Laser wire
  - Collide 1 um high power laser (1 GW) with 1 um electron beam
- Beam position monitors
  - Measure beam position to 10s of nanometers
- EM radiation for charged particles beams

Former life : HERA, QCD, top quark, energy spectrometery





Outline

- Historical overview
- Enough accelerator physics, scaling and UG physics to understand the problems
  - Acceleration
  - Luminosity production
- Machines to address these problems
  - International linear collider/Compact Linear Collider
  - Muon collider
  - Large hadron collider and its upgrade
- Exotic acceleration

Recent history

- Tevatron shut down
- LHC moving into large scale data collection, higher energy and luminosity
- International efforts towards
  - High energy or high luminosity LHC
  - International linear collider, Compact Linear collider, Muon collider
  - Beam and laser drive plasmas
  - Exotics! Dielectric wakefield, meta-materials

Particle physics

- Need events to perform analysis on
  - Stays remarkably constant
- Not the entire picture as we need to think about
  - Beam energy
  - Polarisation
- Composite nature of colliding beams (protons)
  - Of course complications PDFs etc

Number of events

$$N = \sigma L = \sigma \int \mathcal{L}\, dt$$

Cross section Integrated luminosity

$$N = \int \sigma(E_1, E_2, s_1, s_2, \ldots) \cdot \mathcal{L}(E_1, E_2, s_1, s_2, \ldots)\, dt$$

Cross sections

- Probe beam wavelength scales as inverse of energy
- Cross section like inverse of energy squared
- Desire to reach high energies based on
  - High mass states, SUSY
  - Decreasing probe wavelength

Cross-section [m^2] Matter wavelength [m]

$$\sigma = \lambda^2$$

De Broigle wavelength Ultra-relativistic

$$\lambda = \frac{h}{p} \sim \frac{h}{E}$$

Beam energy

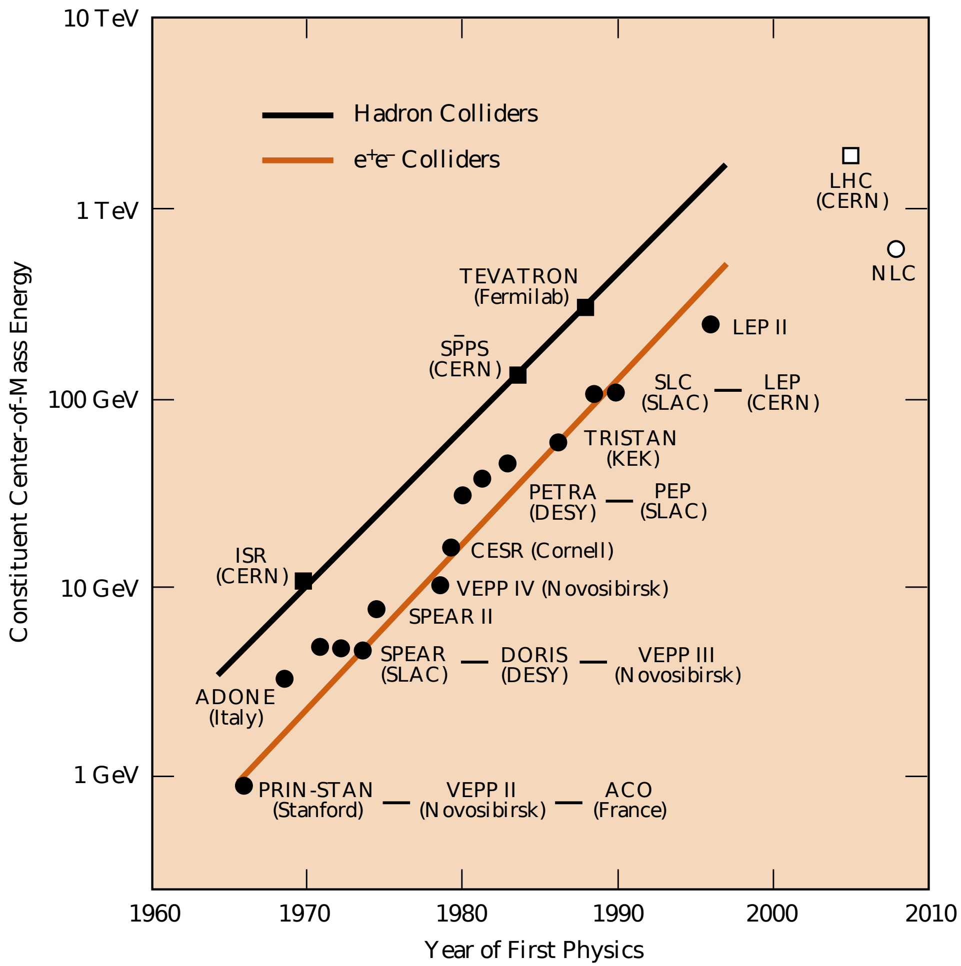
Point-like cross section scales as

$$\sigma \sim \frac{1}{E^2}$$

Energy frontier

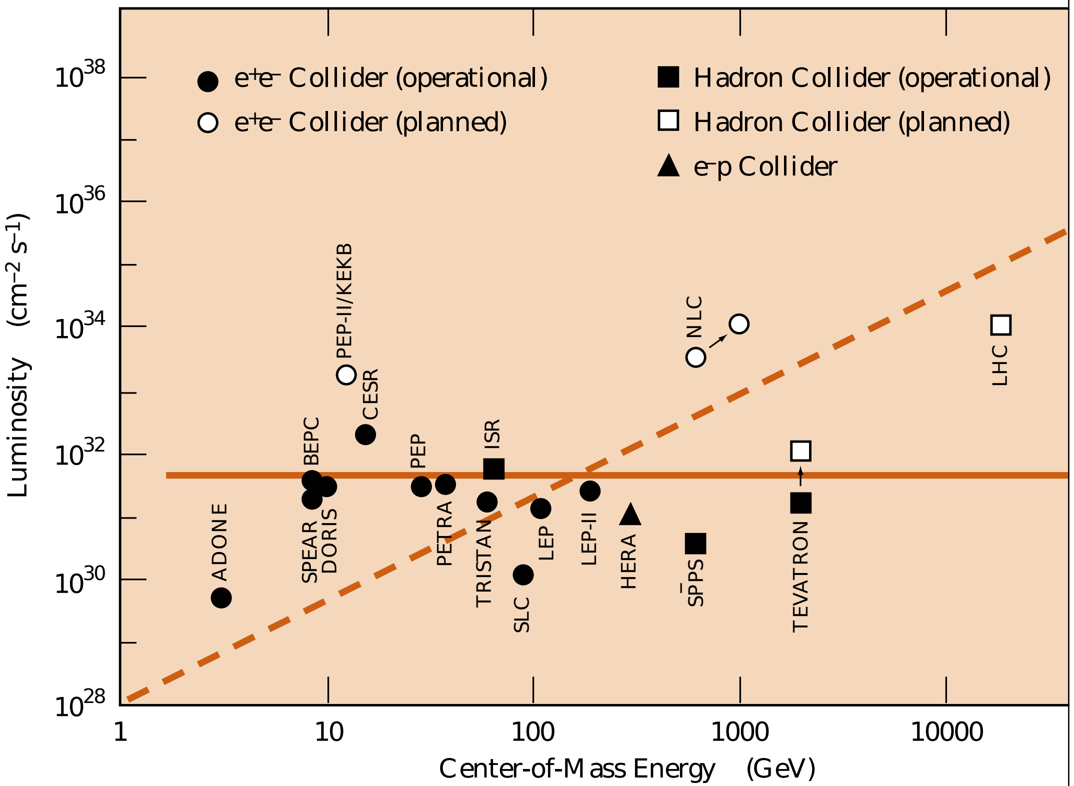
- Historical progress has been power law like for most of the last 70 years
  - Vast majority of recent machines were synchrotrons
  - Notable exceptions
    - SLC
    - NLC/ILC
- Large hadron collider

$$\lambda = \frac{h}{p} \sim \frac{h}{E} \qquad \sqrt{s} > 2M_X$$



Luminosity frontier

- Need corresponding rise in luminosity
  - Higher luminosity brings all the challenges for detectors
    - High event rates
    - Pile up
  - Beam beam interactions
  - Beamstrahlung



Designing a machine

- Particle species
  - Electrons/positrons
  - Protons/anti-protons
  - Muons/anti-muons
- Beam energy
- Spin
- Luminosity

- How do you produce anti-particles?
- Once produced how you does one keep them? (muon collider)
- Once collided what is done with the spent beams?
- Accelerator and detector protection

Accelerator much more than just...

- Particle production
- Damping, cooling or preparation
- Injection and extraction
- Acceleration
- Collimation (betatron, energy etc)
- Diagnostics and controls
- Machine (and detector) protection
- Beam delivery and luminosity production
- Technology spin off
  - Lowe energy machines, medical applications, applied physics, materials, blah, blah

Acceleration

Lorentz force law

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

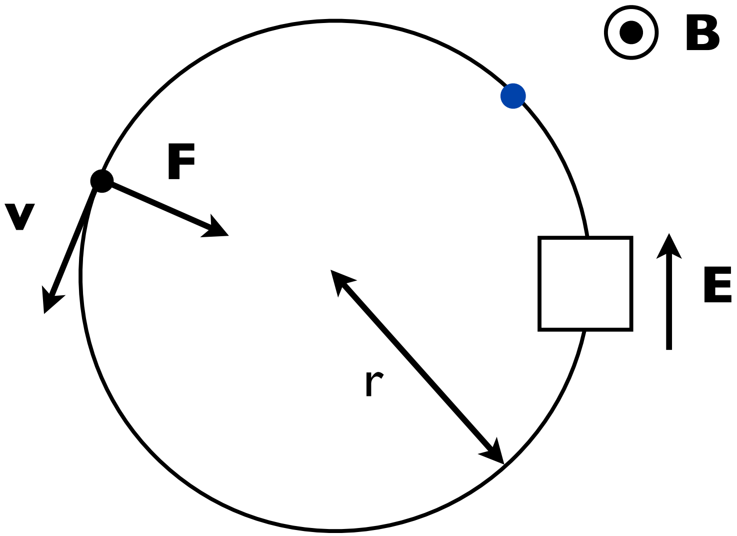
Electric field Velocity Magnetic field

Energy change

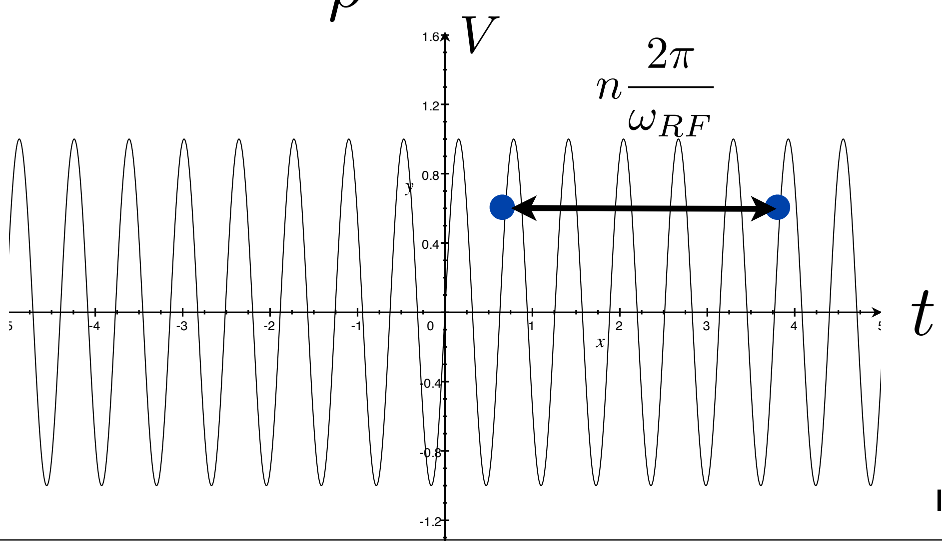
$$\Delta E = \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{F} \cdot d\mathbf{r}$$

- Simple 2nd year electromagnetism
  - Electric field (either static or more commonly time varying) to accelerate, or more appropriately increase energy of beam
  - Magnetic part of Lorentz force used to guide and focus
    - Dipole magnets : to bend
    - Quadrupole : to focus or defocus

Synchrotron



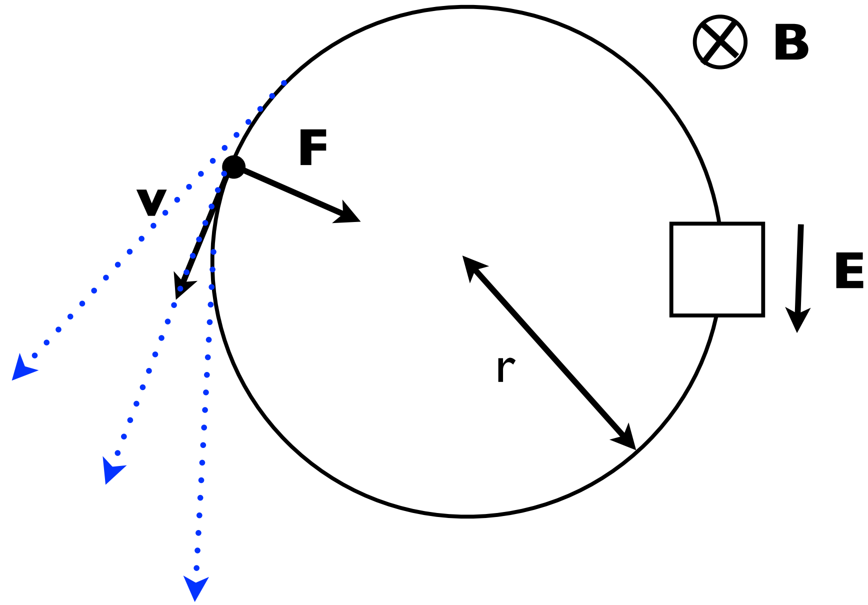
$$qBV = \frac{m_0 V^2}{\rho} \qquad B\rho = p/q$$



- Work horse of modern particle physics
  - Huge legacy of discovery
    - W/Z, Gluon, Higgs, SUSY?
  - Increase energy whilst synchronously increasing bending magnet strength
  - Stable storage of high beam current/power
- Magnetic field proportional to momentum

Synchrotron radiation limits

- Why not just build bigger LEP?
  - Reuse accelerating section every revolution of particle bunch
  - Power loss due to synchrotron radiation
  - LEP2 was practical limit for electron-positron synchrotron



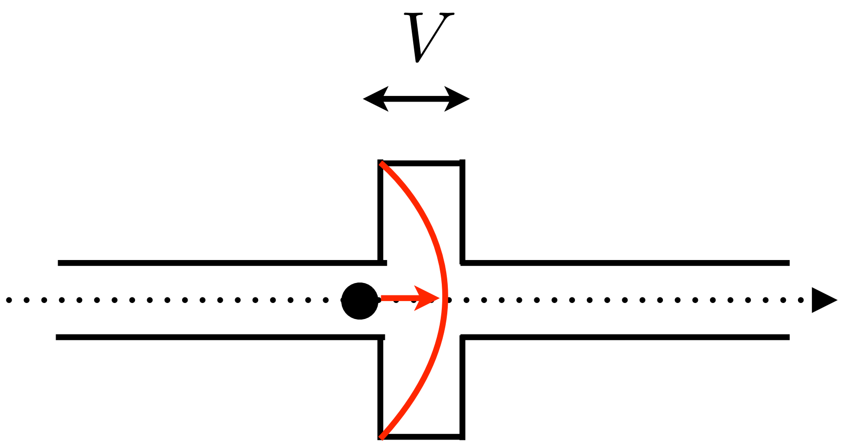
Power
$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3 \rho^2}\gamma^4$$

Energy loss per turn $$W = 8.85 \times 10^{-5} E^4 / \rho$$

Beam energy Magnetic radius

Absolute limits on acceleration

- Need to create large on axis electric fields
  - Accelerating gradient
    - Superconducting
      - ~35 MeV/m
    - Normal conducting
      - ~100 MeV/m
- Much beyond these values there is high voltage breakdown



Machine length [m] Beam energy [MeV]

$$S = \frac{E}{dV/dS}$$

Accelerating gradient [MeV/m]

Luminosity

- What luminosity is required for measurement?
  - Need some knowledge of x-section
- Simple relationship between number of particles, frequency of collision and beam sizes
- Need a montage...!

Luminosity [s^{-1} m^{-2}]

Bunch populations

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

Frequency of collisions [Hz]

Beam RMS sizes [m]

$$\sigma = \sqrt{\epsilon\beta}$$

Emittance [m]

Beta function [m]

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

Emittance

- Emittance is a invariant measure of phase space (spatial) occupied by charged particle beam
  - Product of spatial width and angular width
  - Normalised emittance invariant under forces due to Lorentz forces
  - Can change emittance needed for light source, ILC and CLIC

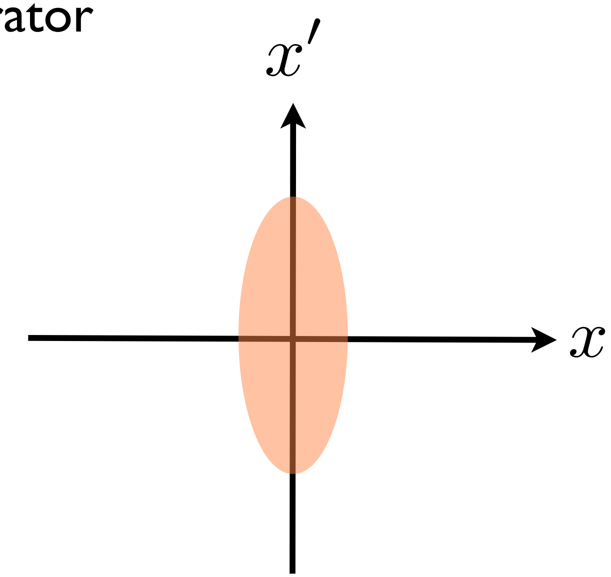
particle position particle angle

$$\epsilon^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2$$

$$x' = \frac{\partial x}{\partial s} = \frac{p_x}{p_s}$$

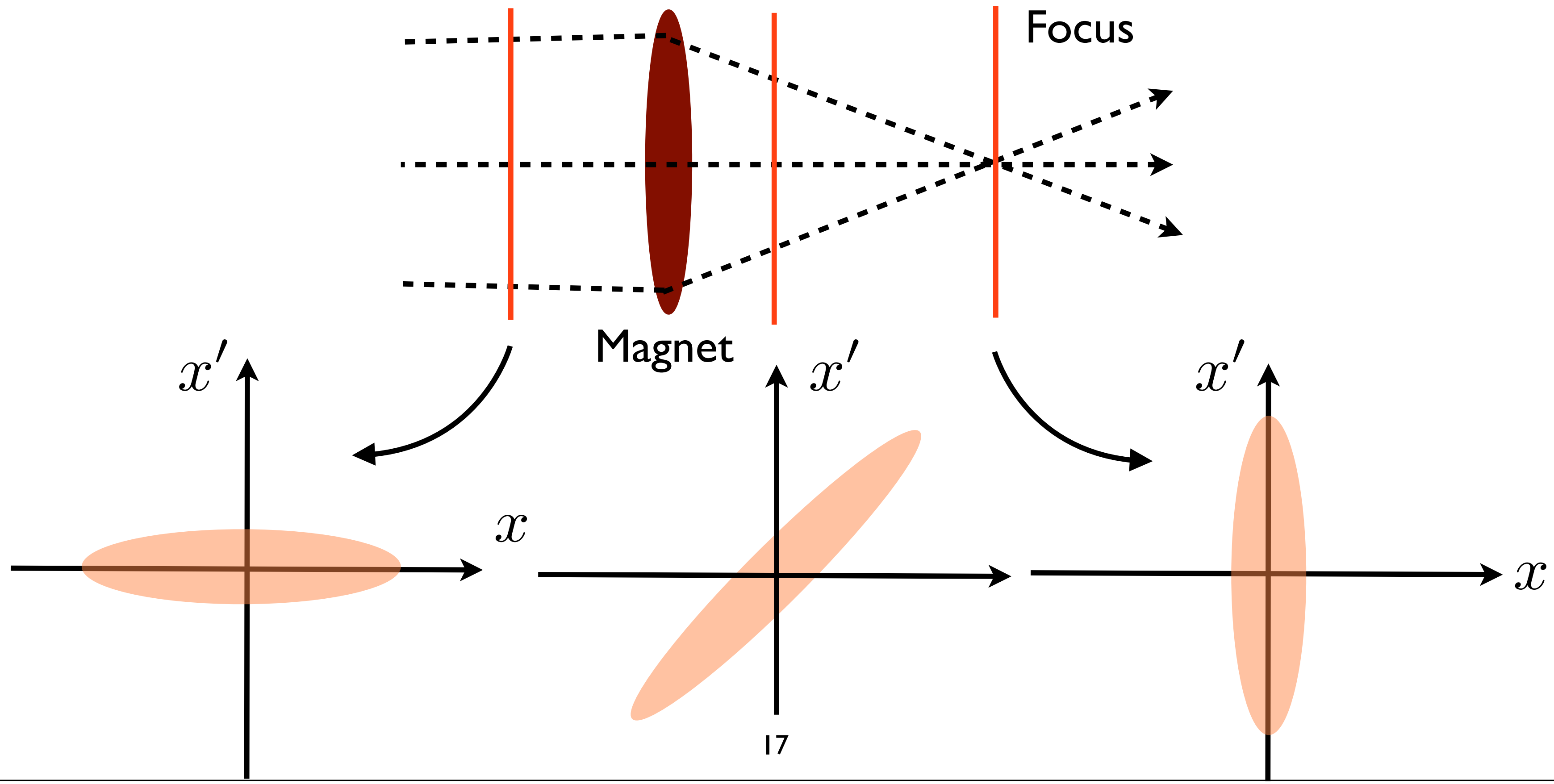
Momentum components

Distance along accelerator



Magnets

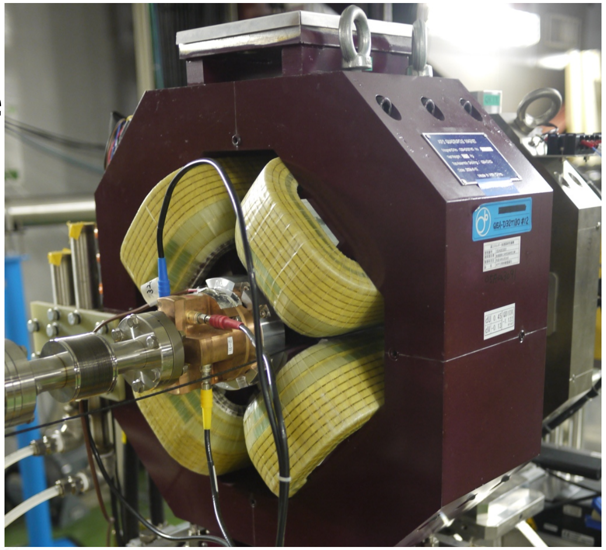
- Quadrupole magnets effectively act as lenses
  - Focusing in one plane and defocusing in the other
  - For example transform

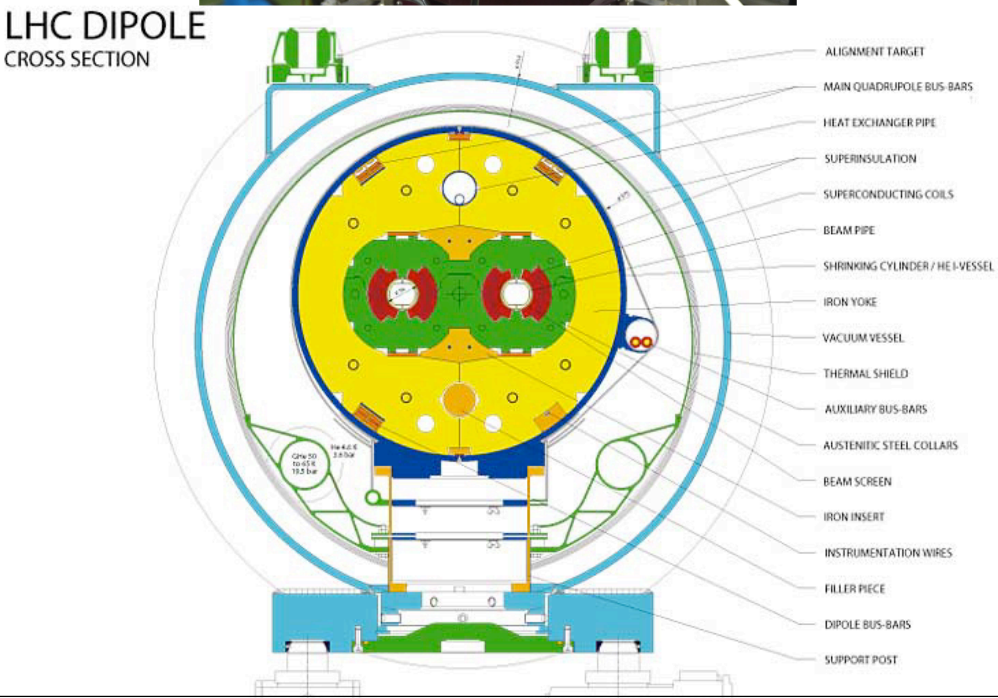


Accelerator magnets

- Normal and super-conducting
  - Dipoles and quads
- Beam losses effect super conductors
  - Quench
- High energy large momentum, so big magnets, high currents large resistive losses

NC quadrupole

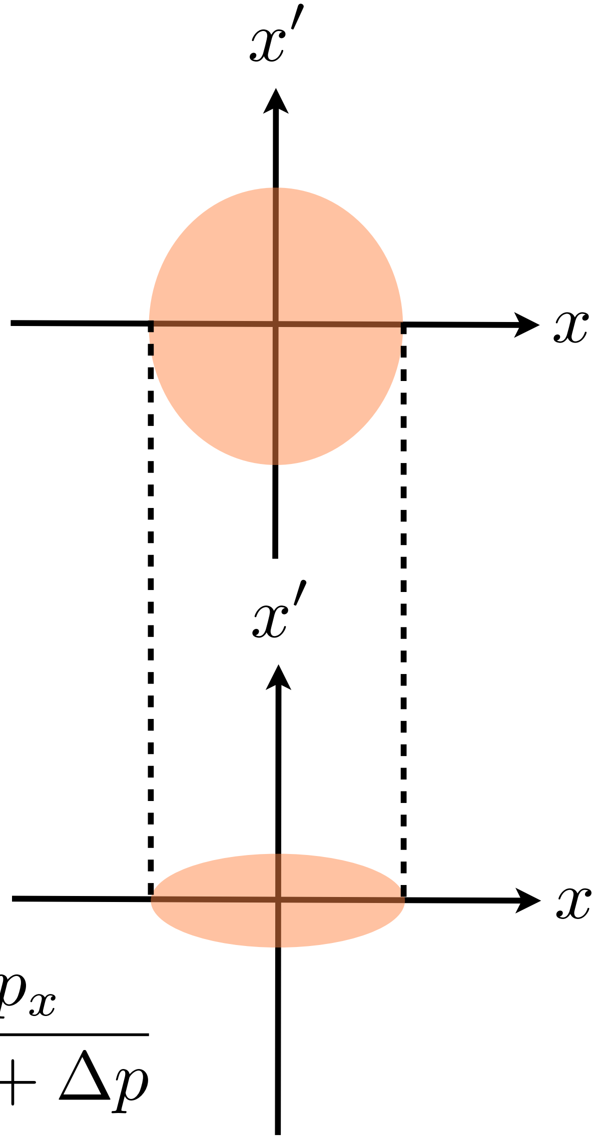




Acceleration

- Acceleration only in direction of motion
  - Increase longitudinal component of momentum
  - Position is untouched
  - Overall the emittance is reduced
- Normalised emittance

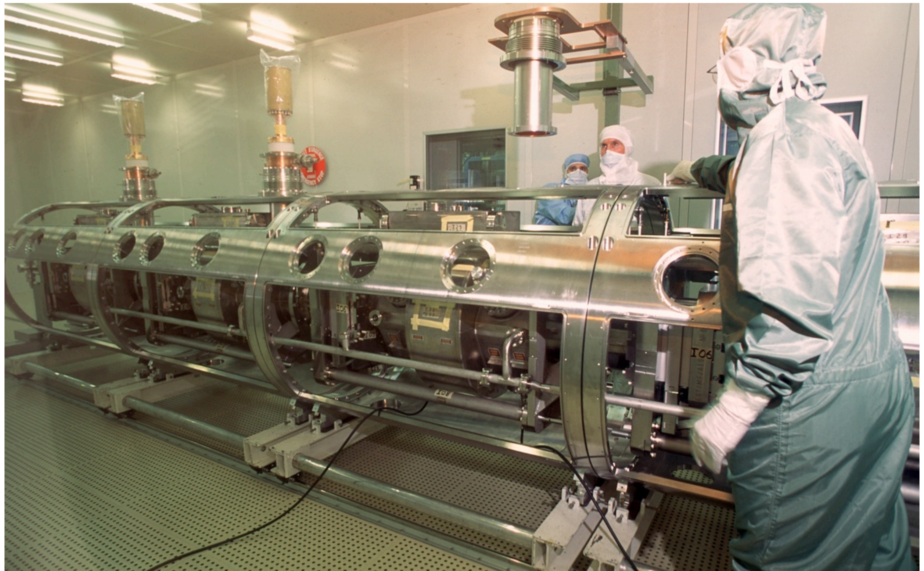
$$\epsilon_n = \beta\gamma\epsilon$$

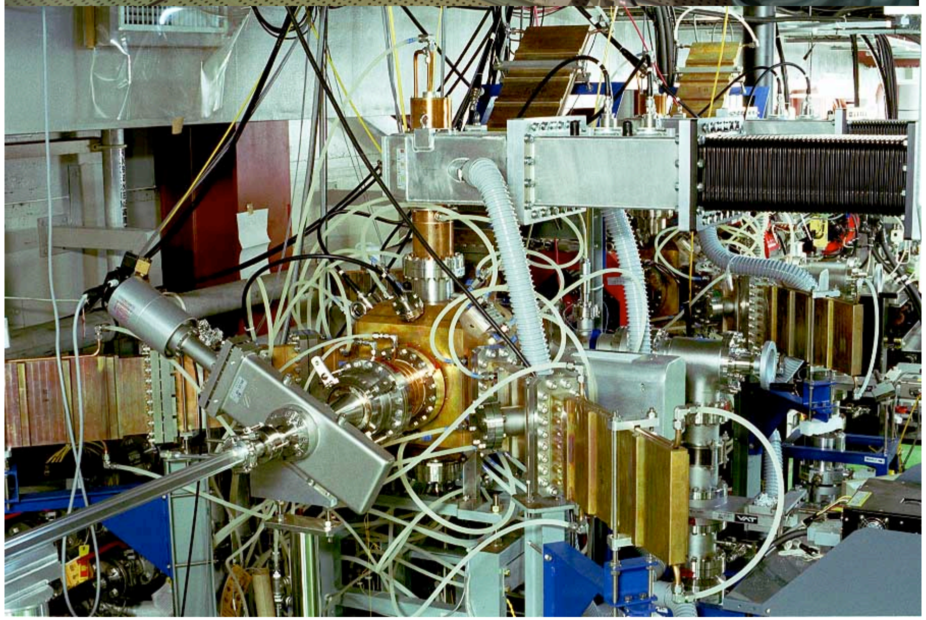


$$x' = \frac{p_x}{p_s + \Delta p}$$

Accelerating cavities

- Need to create high electric fields
  - LHC has 8 cavities per beam
    - 2 MV, so 16 MeV per turn
      - 11245 turns/s
      - 0.18 TeV/s
  - Ramp time?





Optical functions

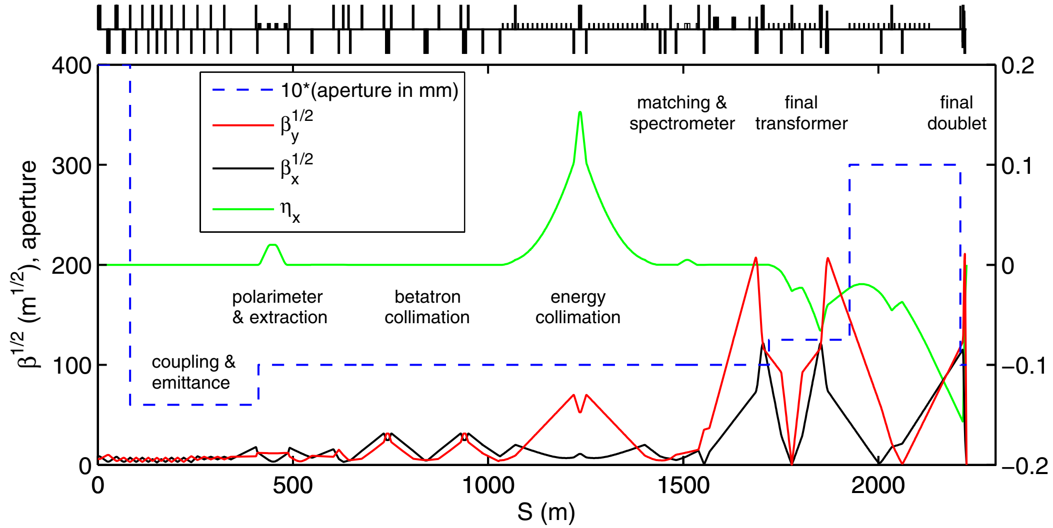
- Beam phase space described in 6 dimensions

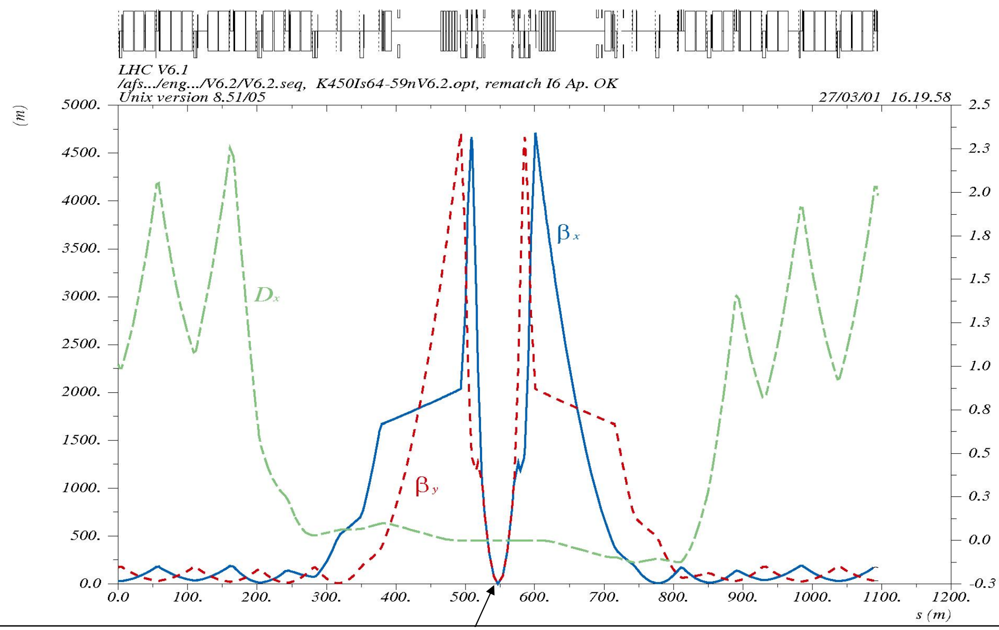
$$\mathbf{v} = (x, x', y, y', E, t)$$

- Transformation of vector through magnetic elements

$$\mathbf{v}' = \mathbf{M}\mathbf{v}$$

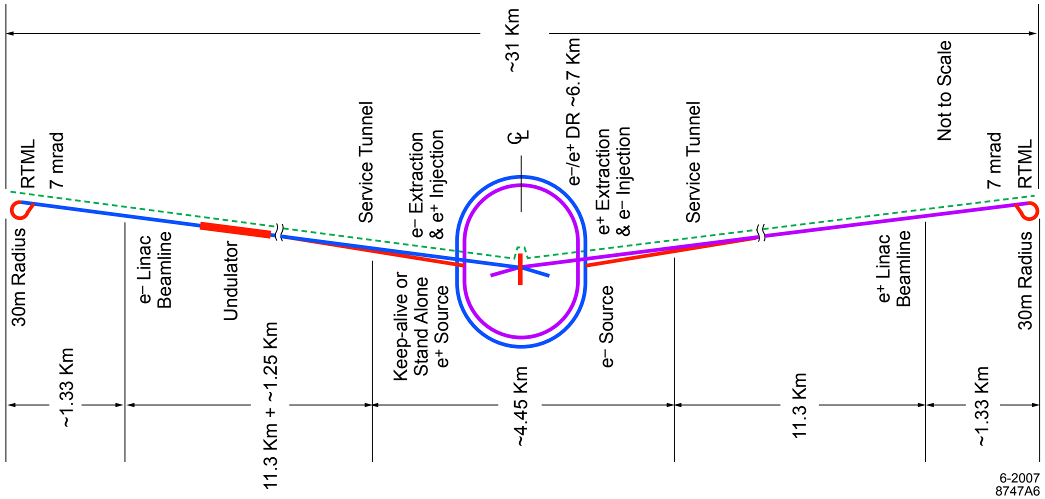
- Beta functions tell us about relationship between position and angle
- Dispersion between energy and time etc etc

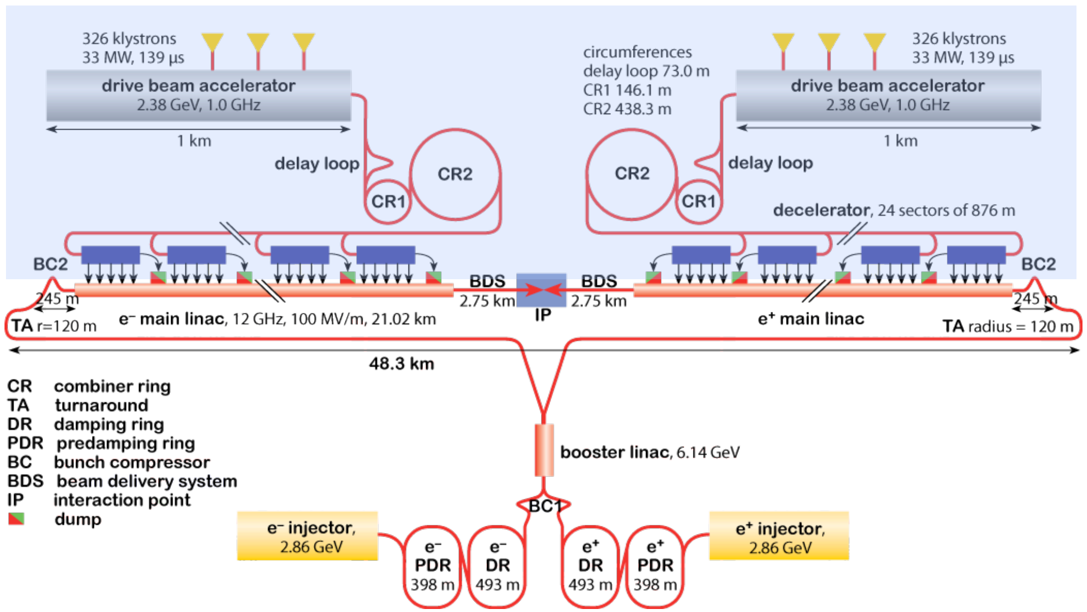




Linear colliders

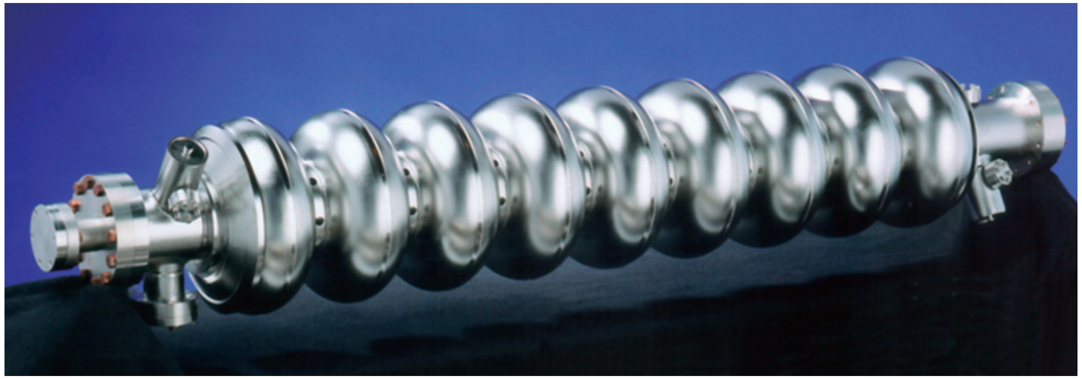
- Two different options available
  - International Linear Collider (ILC)
    - 1 TeV : Super conducting
  - Compact LInear Collider (CLIC)
    - 3 TeV : Normal
- Avoid the problem of SR losses
  - ILC problem : No SUSY < 500 GeV
  - CLIC problem : Boundary of technological limits

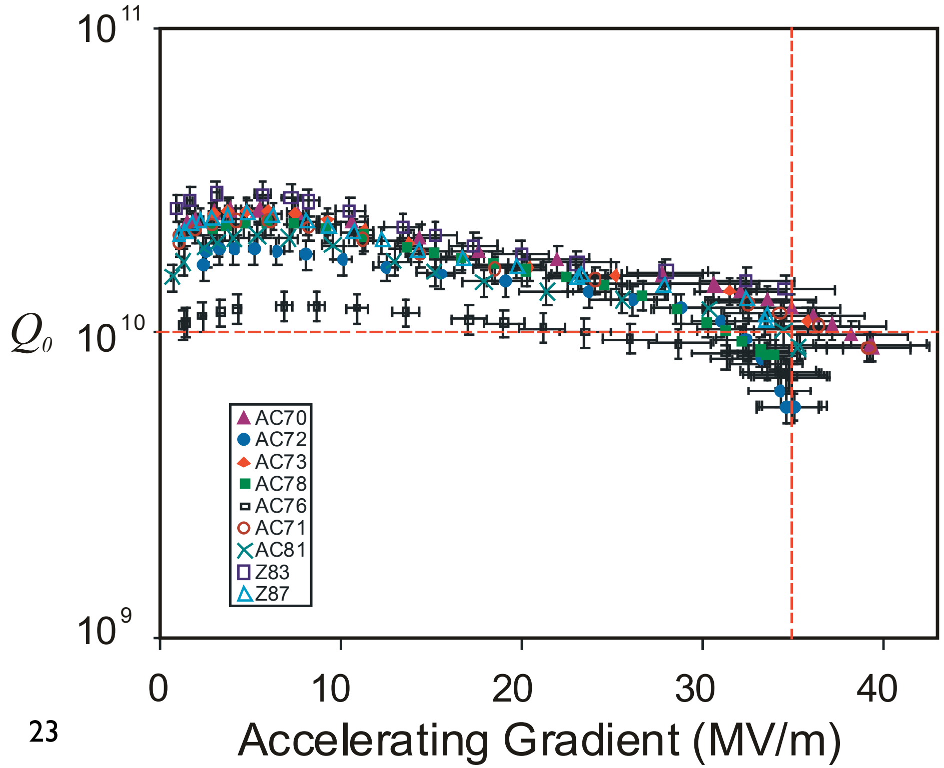




Linear Collider accelerator

- Gradients of 35 MeV/m required
- ILC uses
  - Niobium cavities
  - 1.2 GHz RF
- Above this the super conductor quenches
  - Type II SC, largest magnetic penetration of any element
  - Remember Maxwell's equations



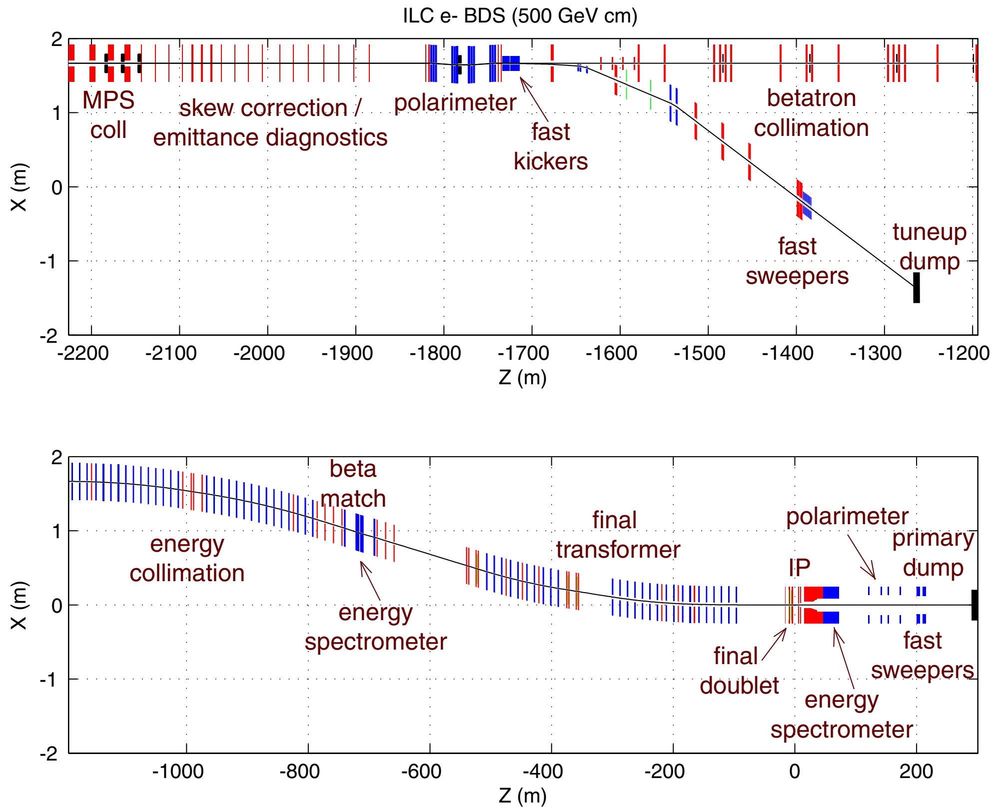


Beam delivery system

- Major challenge for lepton colliders is the luminosity

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

Parameter	Units	Value
Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	639/5.7
Nominal beam divergence at IP, θ^*, x/y	μrad	32/14
Nominal beta-function at IP, β^*, x/y	mm	20/0.4
Nominal bunch length, σ_z	μm	300
Nominal disruption parameters, x/y		0.17/19.4
Nominal bunch population, N		2×10^{10}
Beam power in each beam	MW	10.8
Preferred entrance train to train jitter	σ_y	< 0.5
Preferred entrance bunch to bunch jitter	σ_y	< 0.1
Typical nominal collimation aperture, x/y		8–10/60
Vacuum pressure level, near/far from IP	nTorr	1/50



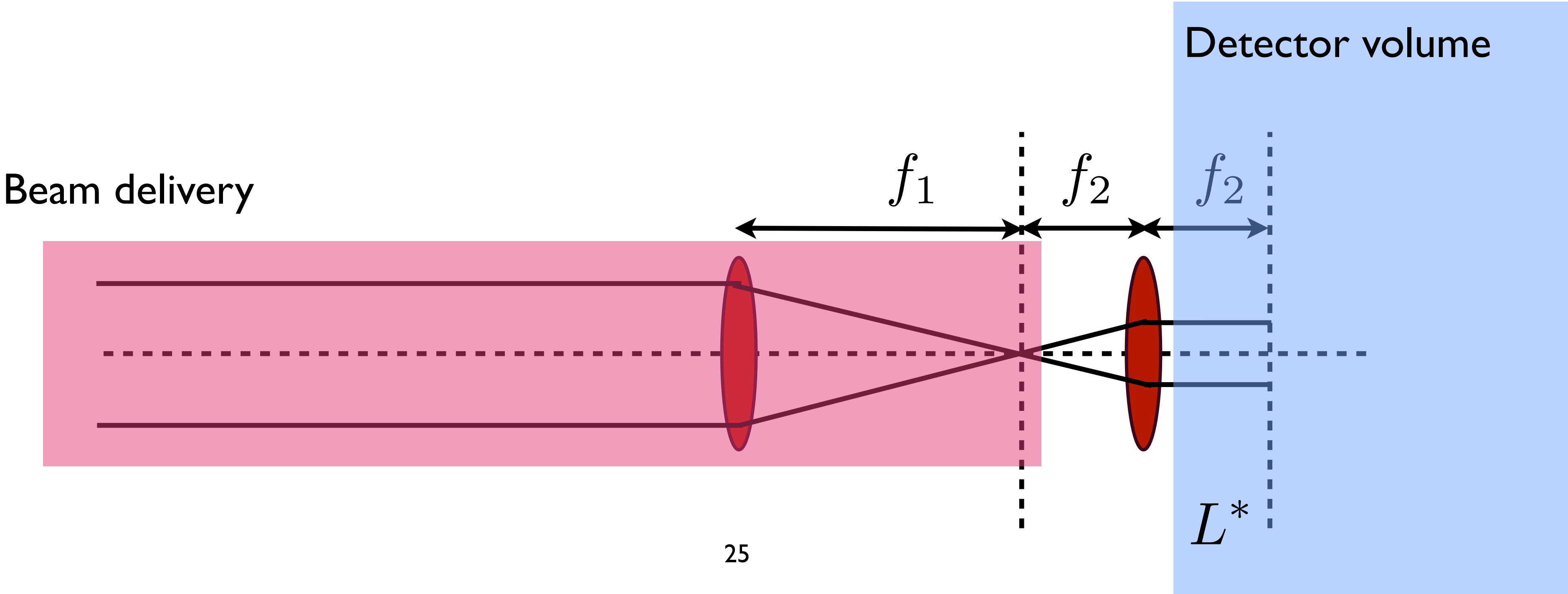
Interaction point focusing

- So we need strong foci
  - Strong magnets (lenses)
  - Short focal length
  - Large beam size on input

Generally need large demagnification 300 ILC $M = \frac{f_1}{f_2}$

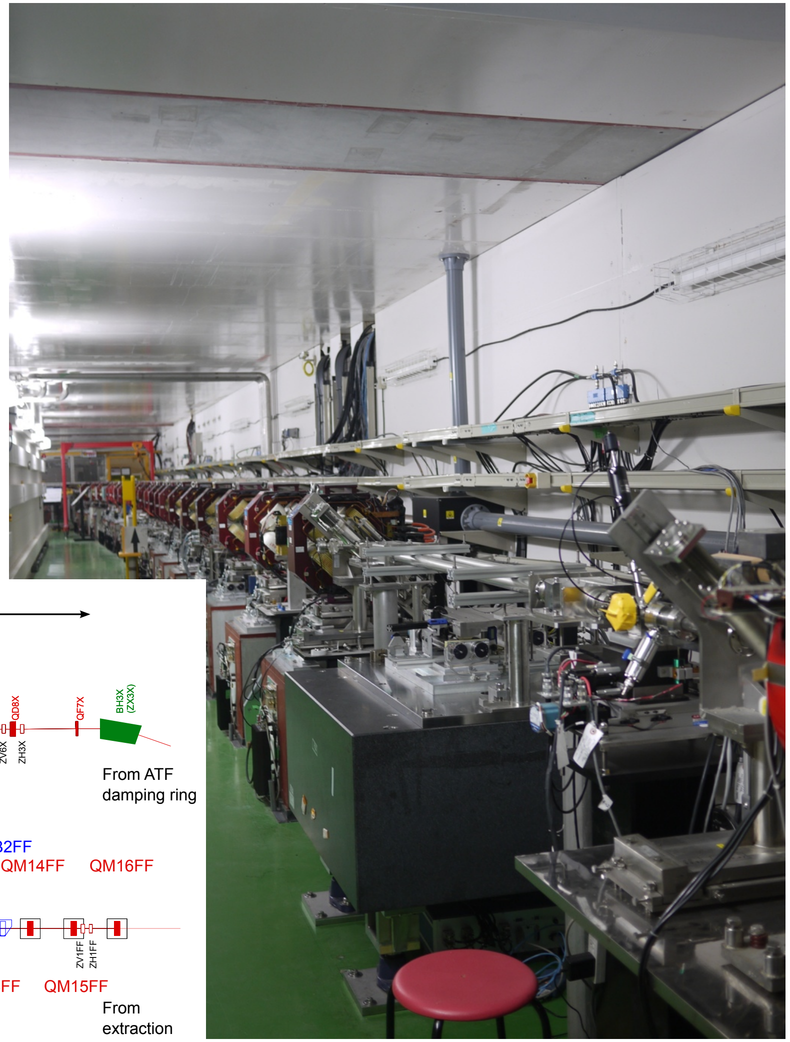
Need small size, set $L^* = 2\ \mathrm{m}$

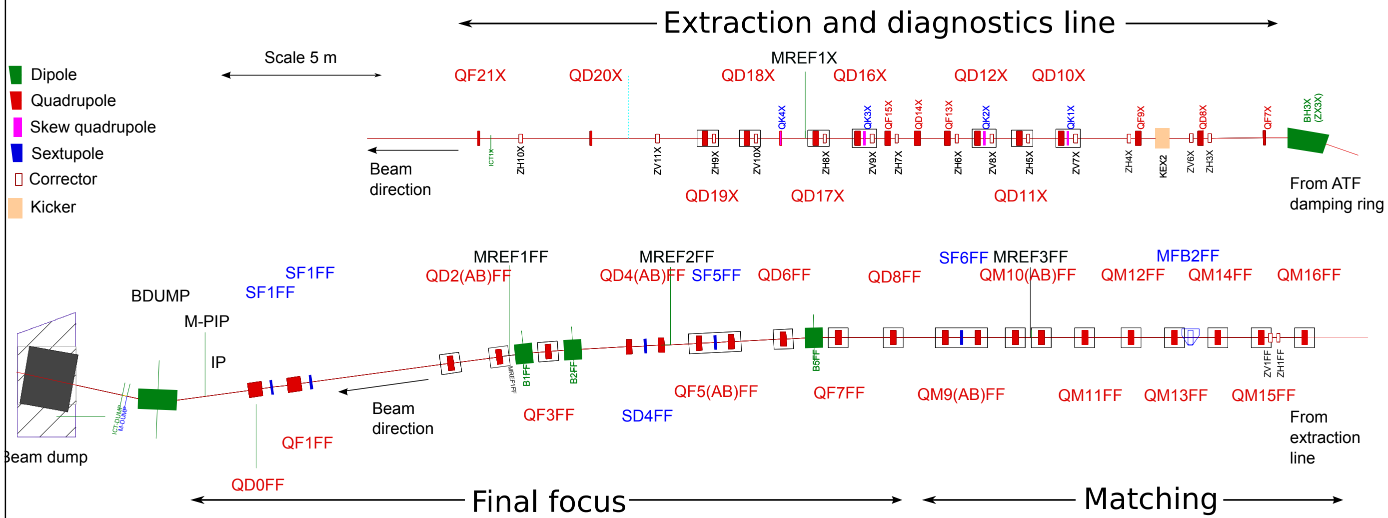
Sets optical system length $f_2 = 600\ \mathrm{m}$



Accelerator test facility 2

- Facility to test ideas of beam focusing
  - Aim to achieve 35 nm vertical beam size
  - Using 1.3 GeV electron beam





Beam power

- Another way to look at luminosity
  - Look at it in terms of beam power and efficiency
  - How do we pay for luminosity
- Luminosity directly proportional to input power and efficiency
  - £££££ or $$$$$ or €€€€€, CHF? JPY?

$$\mathcal{L} = N_b f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} H_D$$

$$P_{beam} = f E N_b N_1 = \underset{\text{Efficiency}}{\eta} \overset{\text{Grid power}}{P_{grid}}$$

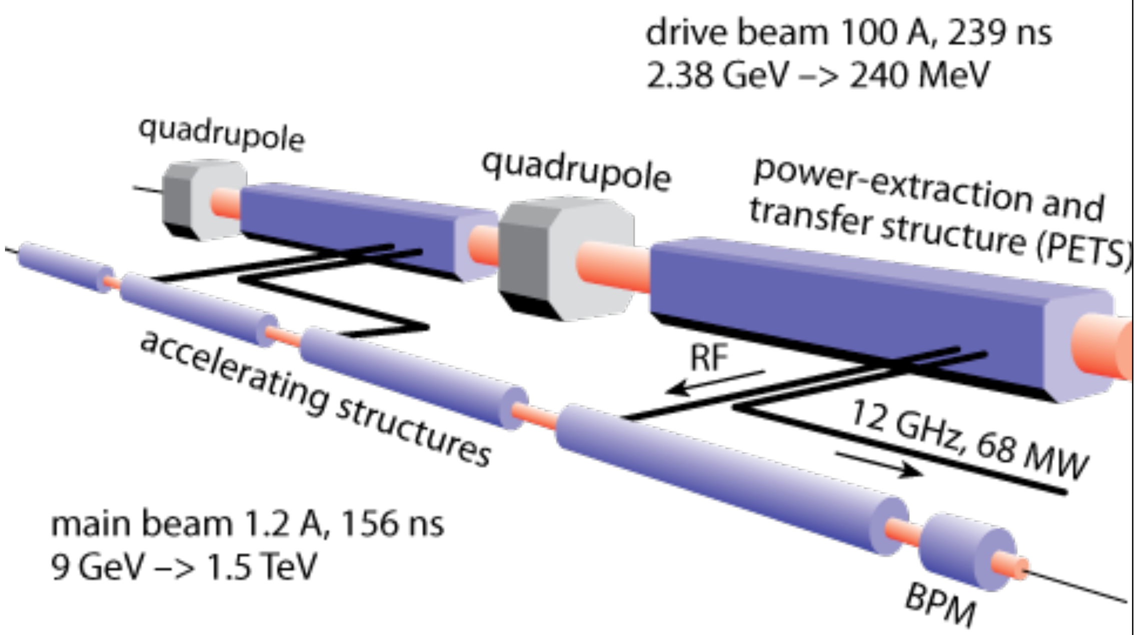
$$\mathcal{L} = \frac{N}{4\pi\sigma_x\sigma_y} H_D \frac{\eta P_{grid}}{E}$$

$$\mathcal{L} \sim \frac{P_{beam}}{E_{CM}} = \frac{\eta P_{grid}}{E_{CM}}$$

Compact linear collider

- Getting to TeV
  - Super conducting acceleration even with 50 MeV/m
    - 60 km in length!
    - Cryogenic power, RF power
  - Need more efficient method of making beam power
- Novel transformer power transformation systems

$$\mathcal{L} \sim \frac{P_{beam}}{E_{CM}} = \frac{\eta P_{grid}}{E_{CM}}$$

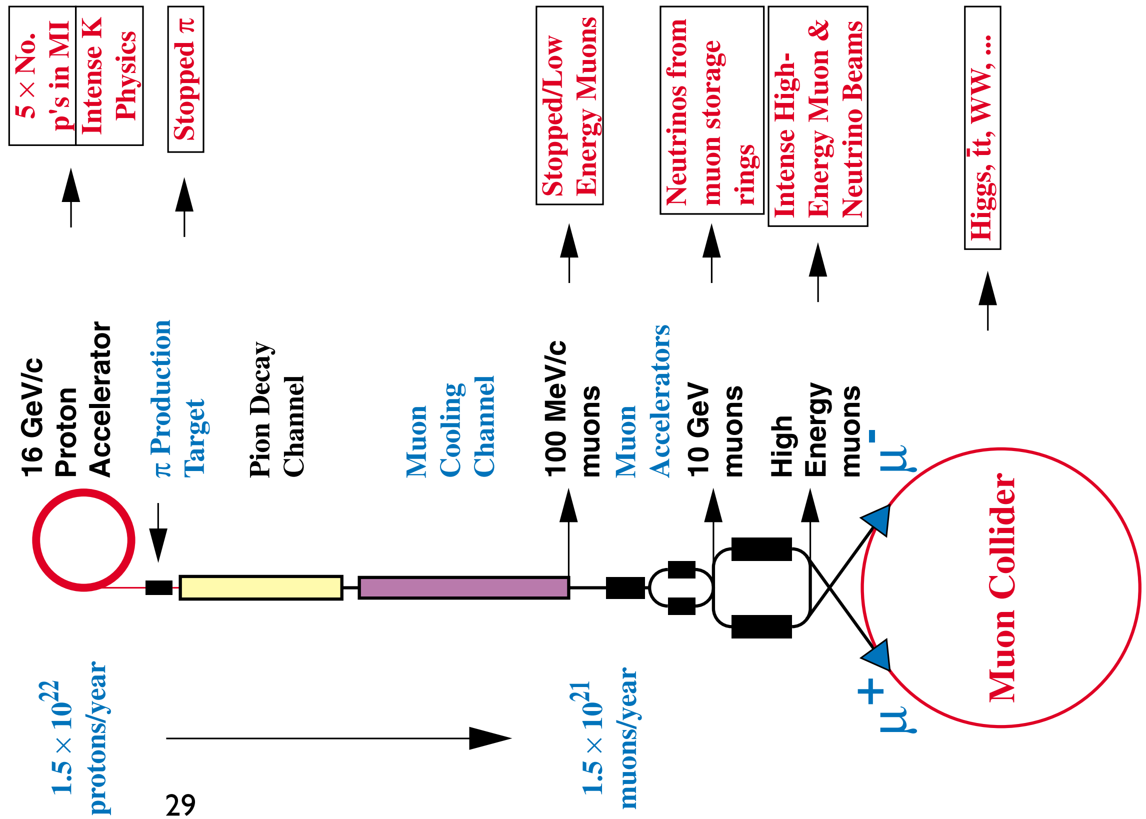


Muon collider

- Muons are difficult.
  - to make enough of them
  - to accelerate quickly
- 200 times less massive than electron
  - No SR losses

$$\mathcal{L} \sim \frac{P_{beam}}{E_{CM}} = \frac{\eta P_{grid}}{E_{CM}}$$

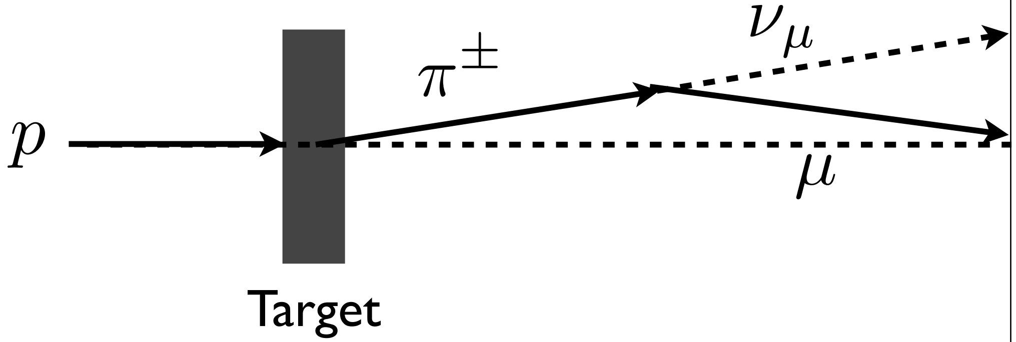
$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3\rho^2}\gamma^4$$

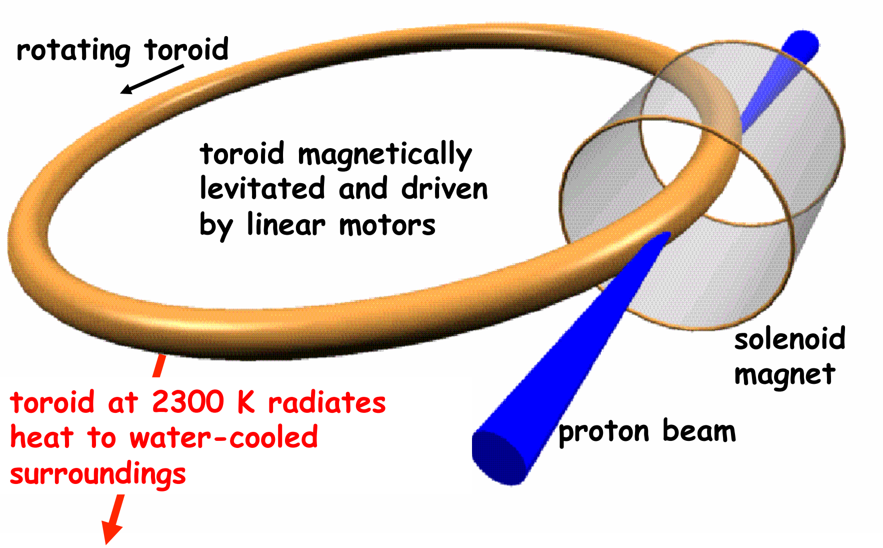


Muon production

- High power/current proton driver
- Target must take ~4 MW of power
  - Mercury jet
  - Solid tungsten
  - Small tungsten spheres, with cooling
  - Powder jet of tungsten??
- Magnetically levitated rotation toroid????
- Transverse momentum of muons?

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$



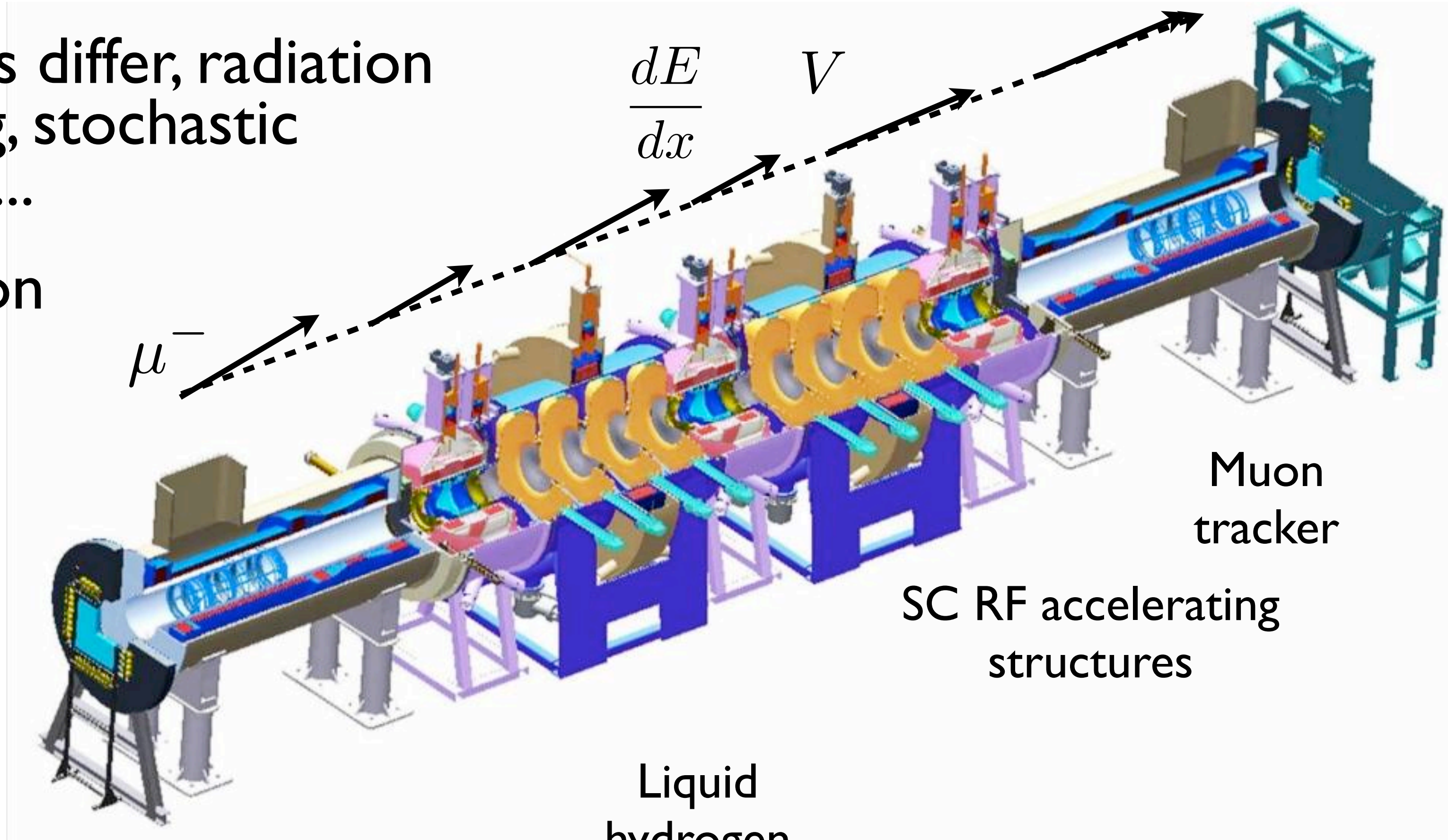


ISIS at RAL

Muon emittance and cooling

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

- Cooling needed for most facilities ILC, CLIC, LHC, Muon
  - Methods differ, radiation damping, stochastic cooling....
  - Ionisation



MICE experiment at RAL

Fast acceleration of muons

$$\mathcal{L} = f\frac{N_1 N_2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

- Synchrotron does not work for Muon acceleration
- Need to accelerate quickly

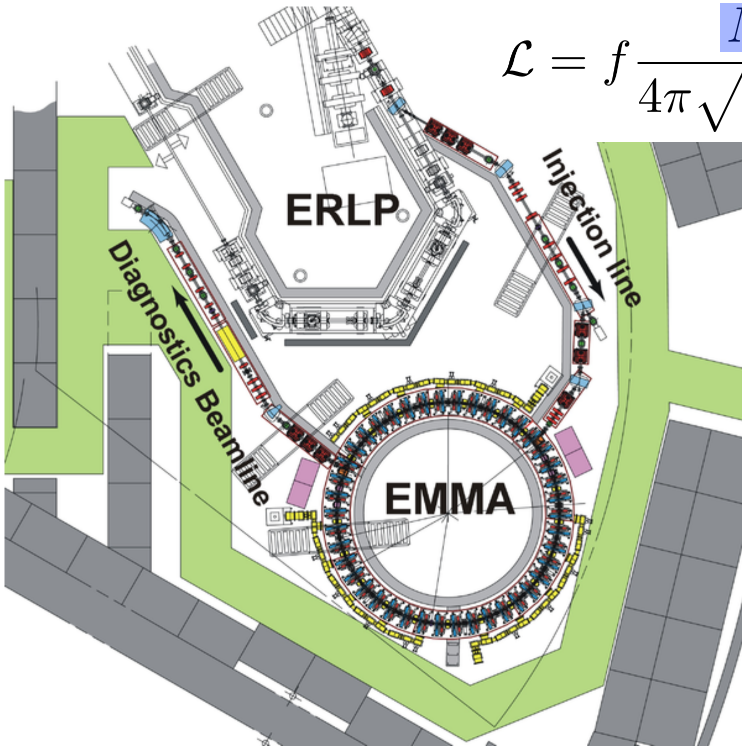
$$\tau = \gamma\tau_0$$

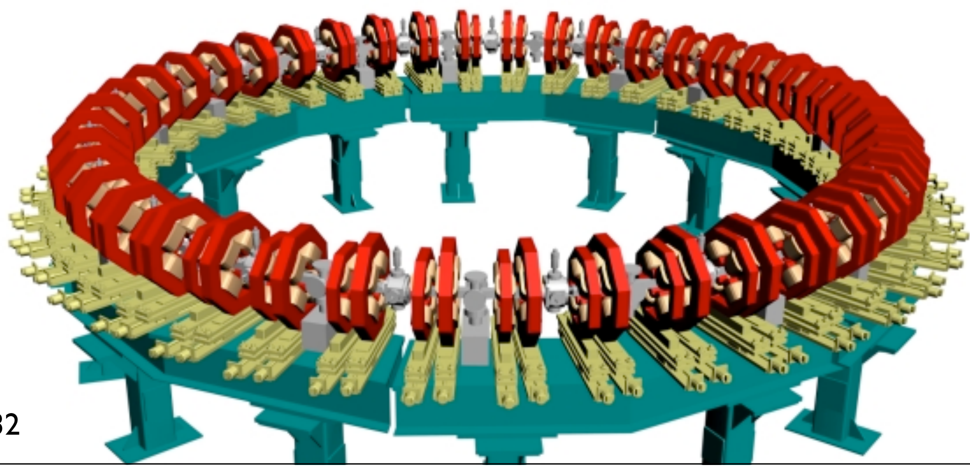
- Can't because

$$B\rho = p/q$$

- Typically

$$B \propto I$$



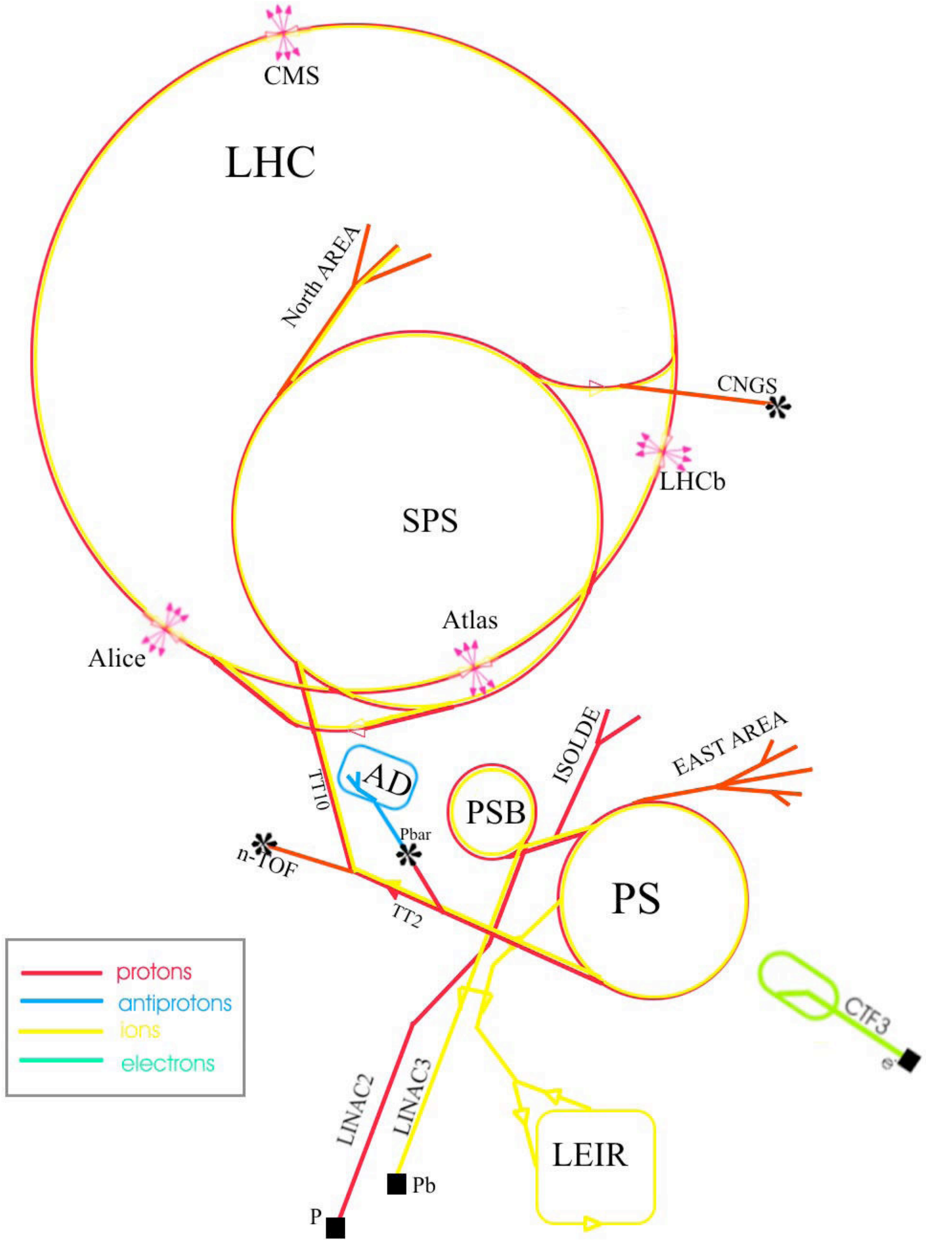


EMMA at Daresbury laboratory

Large hadron collider

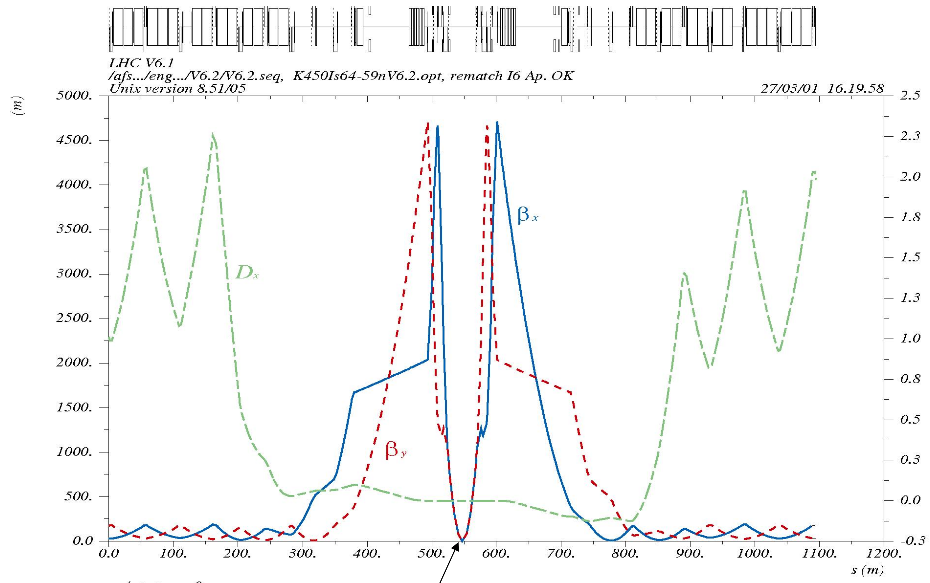
- Options for LHC upgrade
  - High luminosity
  - High energy

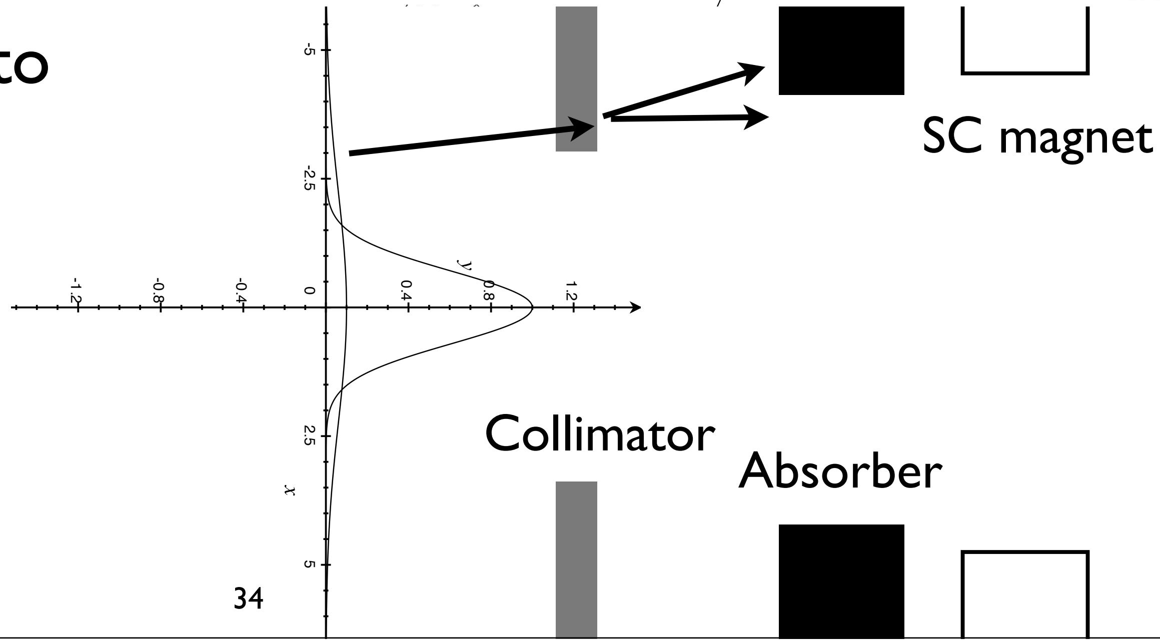
Parameters	'white book'	nominal	ultimate
# bunches	3564	2808	2808
ppb	$0.34\ 10^{11}$	$1.15\ 10^{11}$	$1.7\ 10^{11}$
β^*	1 m	0.55 m	0.5 m
ε / γ	1.07 µm	3.75 µm	3.75µm
full crossing angle	100 µrad	285µrad	315µrad
events / crossing	1 <-> 4	19.2	44.2
L [$cm^{-2}\ sec^{-1}$]	$0.1\ 10^{34}$	$1\ 10^{34}$	$2.4\ 10^{34}$
luminosity lifetime*	56 h	15 h	10 h
stored beam energy	121 MJ	366 MJ	541 MJ



Collimation

- Collimation is to remove unwanted particles
  - Off position-angle
  - Off energy
- Smallest beta functions, beam size at IR regions
  - Loose particles into detector
  - Worse damage accelerator





LHC upgrades

- What would you do with the LHC?
  - Need to start thinking now
  - High energy
    - Access to heavier states
  - Higher luminosity
    - More precise measurements
    - Need more particles, smaller beam size and higher frequency collisions

1) Upgrade pre-accelerators
2) Injection system

5) Change RF and timing systems... experimental triggers?

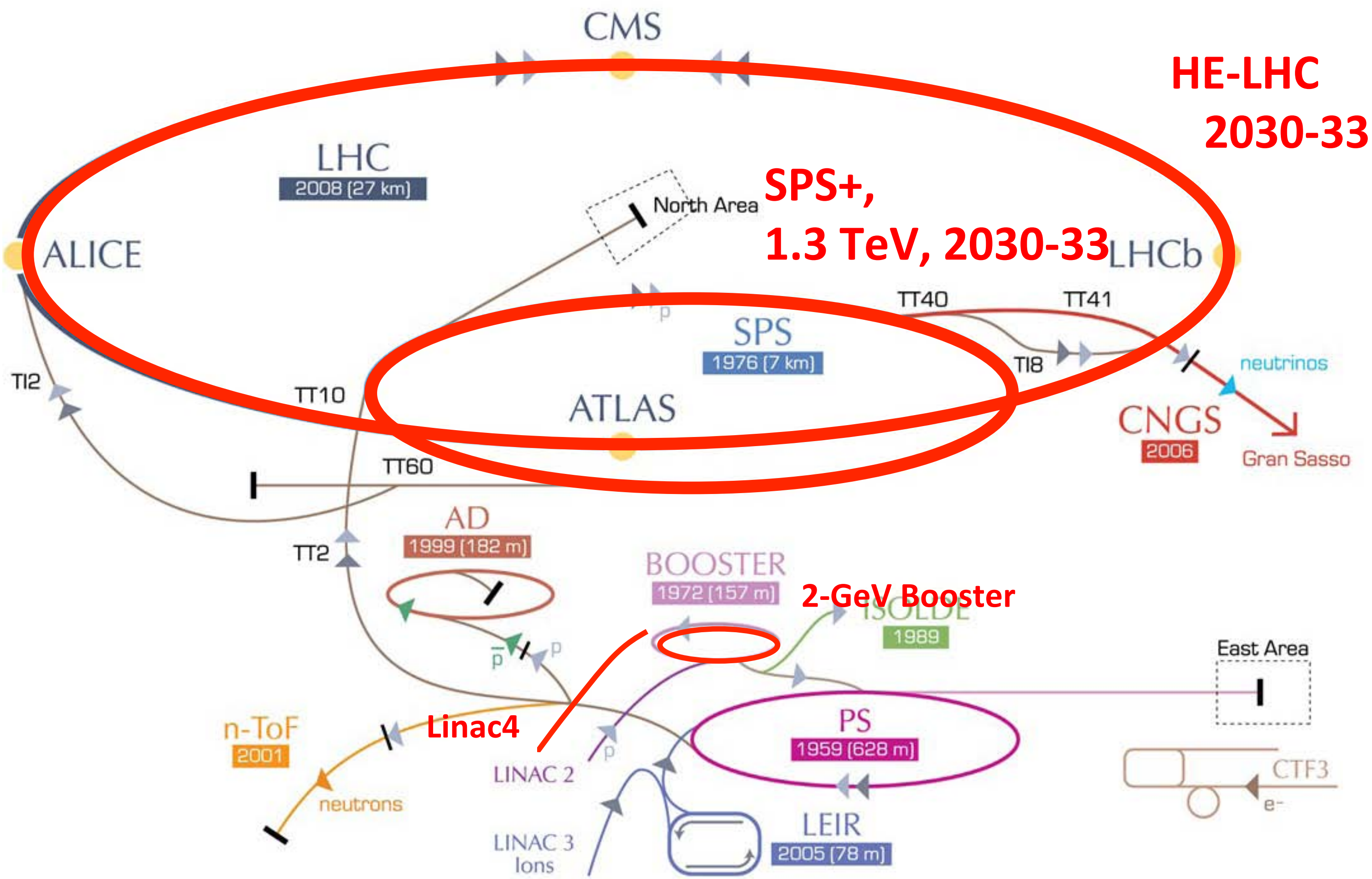
$$\mathcal{L} = f \frac{N_1 N_2}{4\pi \sigma_x \sigma_y}$$

3) Reduce beta functions or emittance
4) Crab crossing system

High energy LHC

$$B\rho = p/q$$

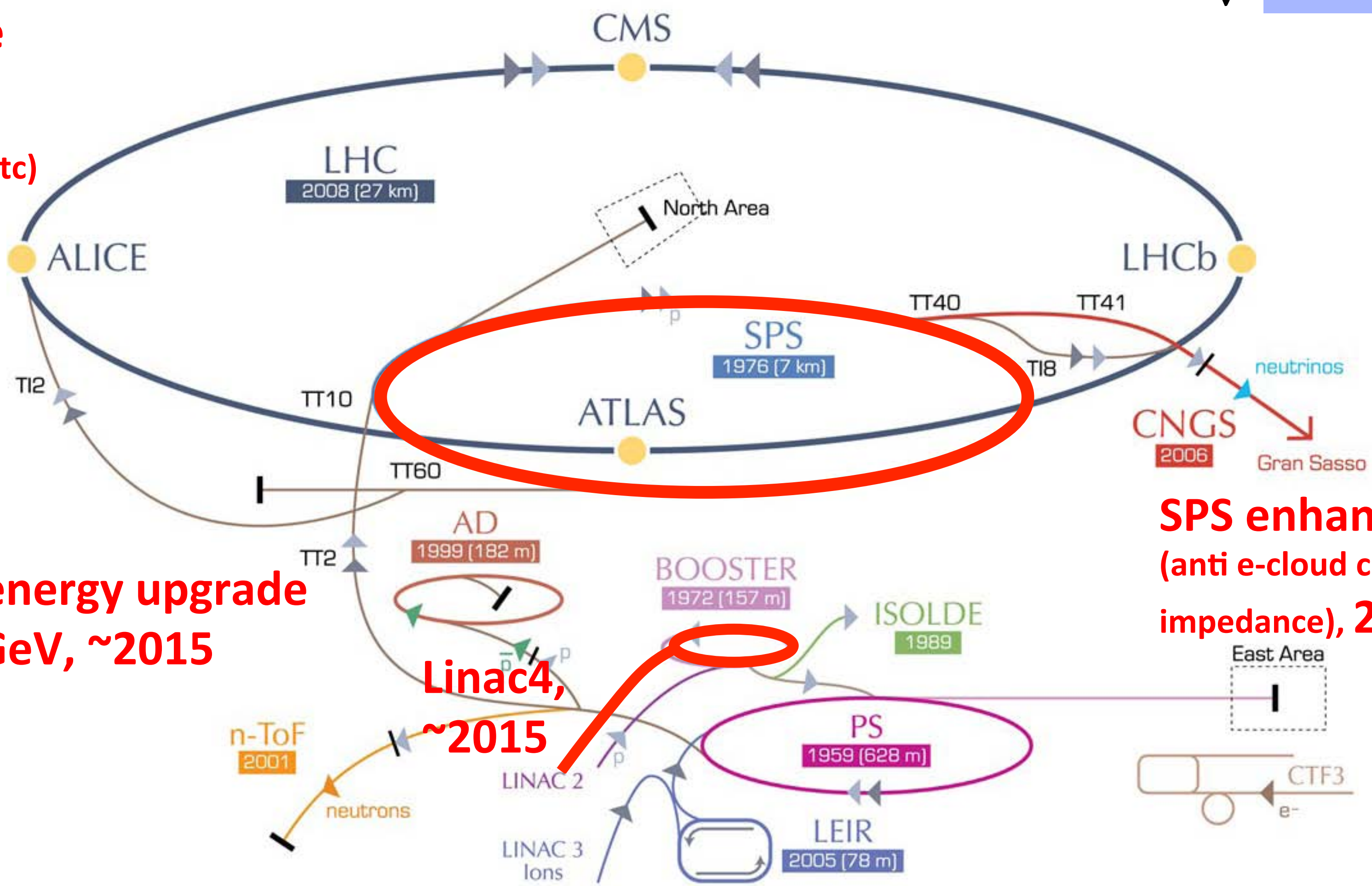
To reach higher energies require stronger magnetic fields
• Research in new SC magnet technology



High luminosity LHC

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

IR upgrade
(detectors,
low-b quad's,
crab cavities, etc)
~2020-21



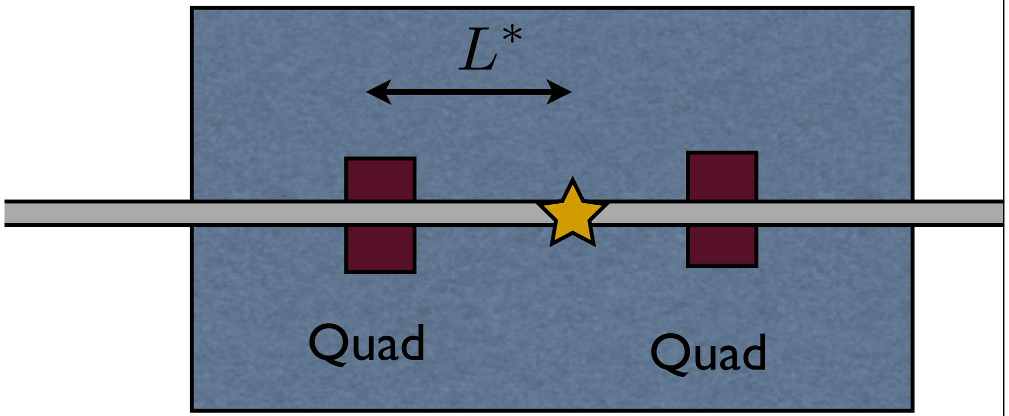
SPS enhancements
(anti e-cloud coating,RF,
impedance), 2012-2021

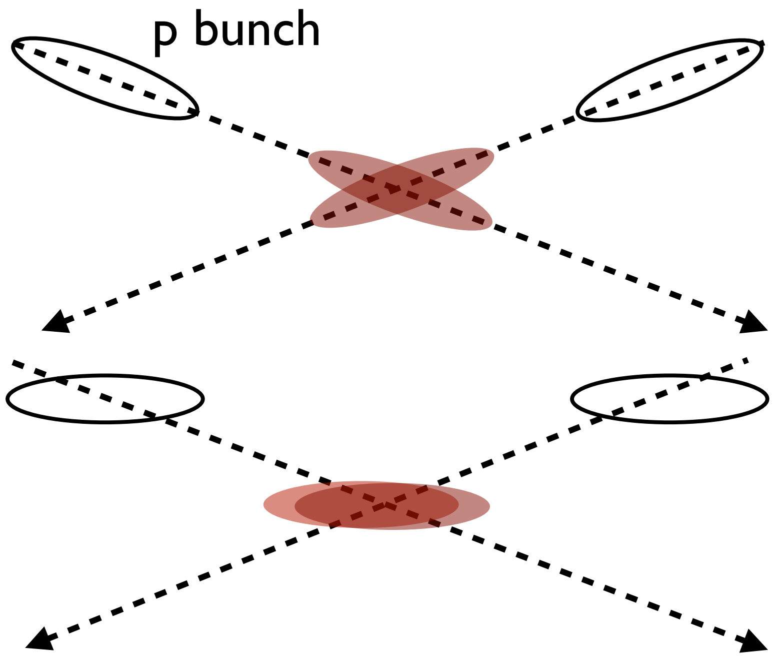
Booster energy upgrade
1.4 → 2 GeV, ~2015

Linac4,
~2015

IR upgrade (L* & crab crossing)

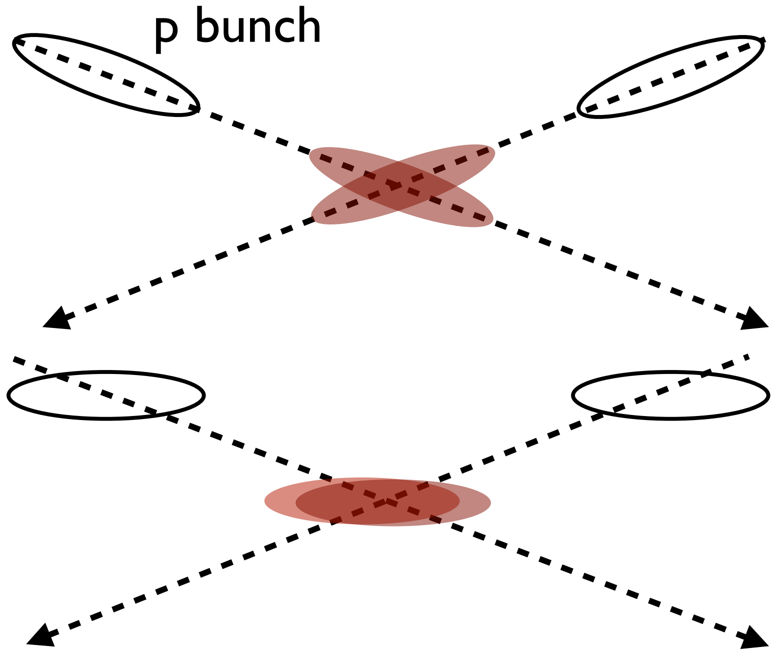
- Squeeze the beta functions at the IR point
  - Smaller beam sizes
  - Collimation will change
  - Larger beam power
  - Detector and machine protection
- Interesting point is crab crossing
  - Extra luminosity





Crab crossing angle

$$\frac{L(\theta_c)}{L_0} \approx \left[1 + \left(\frac{\sigma_z}{\sigma_x^*} \tan(\theta_c / 2) \right)^2 \right]^{1/2}$$



Exotic acceleration

- Compact acceleration
  - Need higher gradients
    - Plasma
    - Dielectric wake-fields
    - Photonic crystals
    - Direct laser
- Principle is still power transformation need better efficiency and less break-down

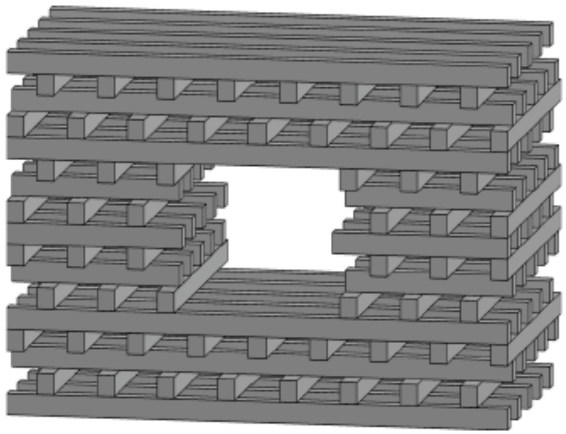
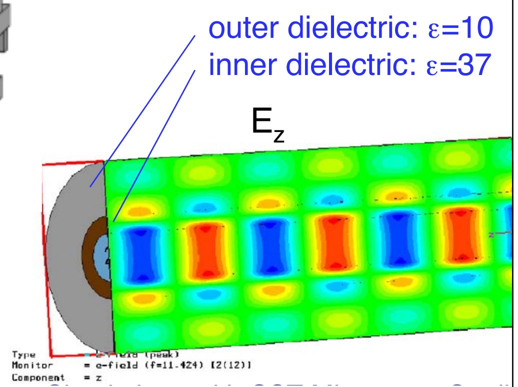
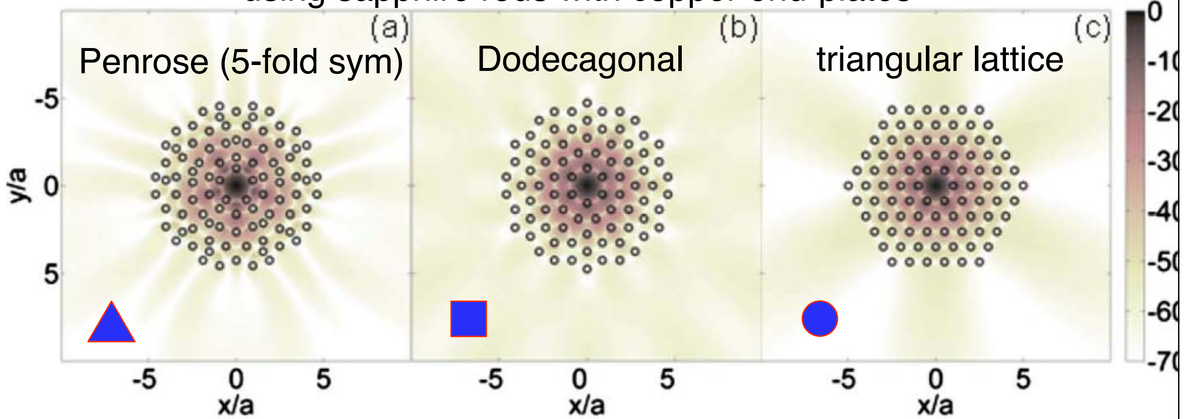


FIG. 3. A symmetric waveguide.

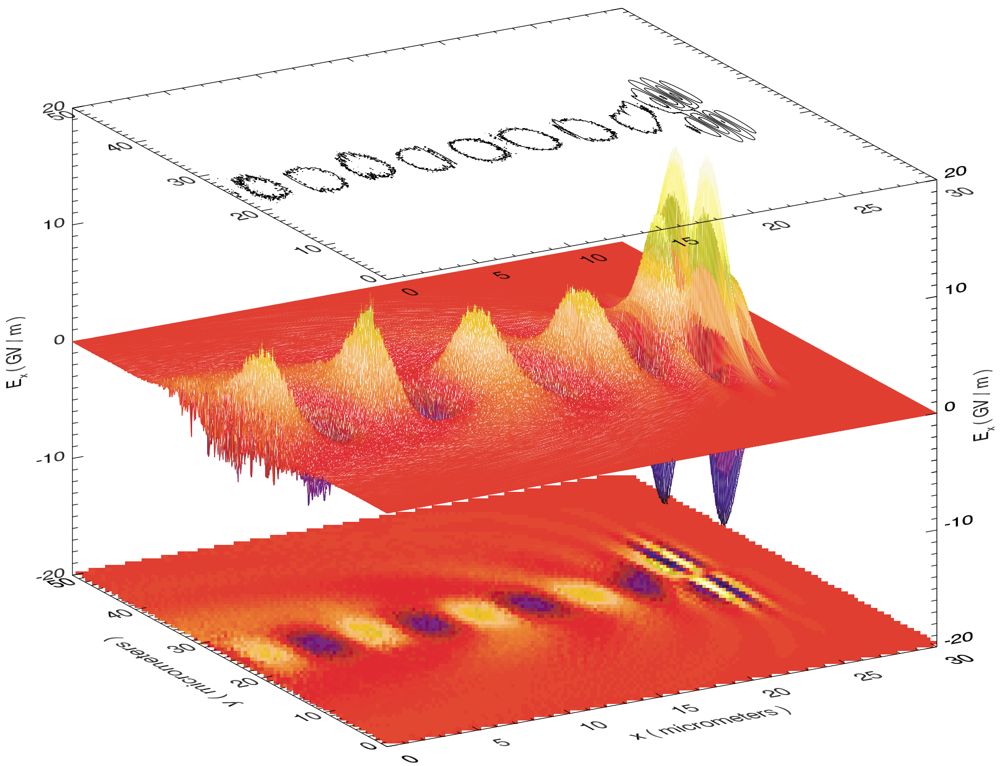


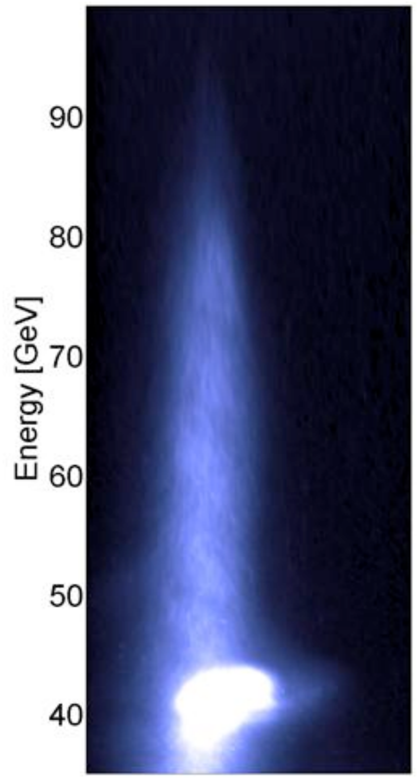
using sapphire rods with copper end-plates



Plasma wakefield acceleration

- Break down limits electron acceleration ~few TeV
  - Higher efficiency





Experiments at the SLAC Final Focus Test Beam (FFTB) Facility demonstrated high-gradient acceleration over meter scale distances.
A single bunch of 42GeV electrons produced by the 3km SLAC linac was used to both drive and sample the wakefield in an 85cm long lithium plasma of density 2.7 x 1017 e-/cm3. Particles in the front of the bunch lost energy driving the wake while particles in the back of the bunch were accelerated to over 85GeV in just 85cm. The accelerated electrons were dispersed in energy by a magnetic field in a region of air. The Cherenkov light emitted by the electrons passing through the air was imaged onto a CCD camera to record the beam spectrum.

Summary

- Many different technologies and ideas
  - Talk focused on lepton colliders
  - What about proton/ion-electron, what about high-L, low-E lepton like B-factories, g-2, etc
- Ability to decode technical issues with future colliders
  - LHC upgrades
  - Future lepton colliders (electron and muon)
- Accelerator physics here applies well
  - Machines which might be built in the next 2 decades..... unclear
  - Laser or beam PWA possible, but technically difficult

Revision ;-)

Parameter	Units	Value
Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	639/5.7
Nominal beam divergence at IP, θ^*, x/y	μrad	32/14
Nominal beta-function at IP, β^*, x/y	mm	20/0.4
Nominal bunch length, σ_z	μm	300
Nominal disruption parameters, x/y		0.17/19.4
Nominal bunch population, N		2×10^{10}
Beam power in each beam	MW	10.8
Preferred entrance train to train jitter	σ_y	< 0.5
Preferred entrance bunch to bunch jitter	σ_y	< 0.1
Typical nominal collimation aperture, x/y		8–10/60
Vacuum pressure level, near/far from IP	nTorr	1/50

Parameters	'white book'	nominal	ultimate
# bunches	3564	2808	2808
ppb	$0.34\ 10^{11}$	$1.15\ 10^{11}$	$1.7\ 10^{11}$
β^*	1 m	0.55 m	0.5 m
ε / γ	1.07 µm	3.75 µm	3.75µm
full crossing angle	100 µrad	285µrad	315µrad
events / crossing	1 <-> 4	19.2	44.2
L [cm^{-2} sec^{-1}]	$0.1\ 10^{34}$	$1\ 10^{34}$	$2.4\ 10^{34}$
luminosity lifetime*	56 h	15 h	10 h
stored beam energy	121 MJ	366 MJ	541 MJ

TABLE XIV. Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 yr = 10^7 s.

CoM energy (TeV)	3	0.4		0.1	
p energy (GeV)	16	16		16	
p's/bunch	2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill	4	4		2	
Repetition rate (Hz)	15	15		15	
p power (MW)	4	4		4	
μ/bunch	2×10^{12}	2×10^{12}		4×10^{12}	
μ power (MW)	28	4		1	
Wall power (MW)	204	120		81	
Collider circumference (m)	6000	1000		350	
Average bending field (T)	5.2	4.7		3	
rms $\Delta p/p\%$	0.16	0.14	0.12	0.01	0.003
6D $\epsilon_{6,N}$ $(\pi m)^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)	785	700	450	450	450
Luminosity $cm^{-2}\,s^{-1}$	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year			1.9×10^3	4×10^3	3.9×10^3

Main-linac parameters		
Centre-of-mass energy	E_{CM}	3 TeV
Linac repetition rate	f_{rep}	100 Hz
RF frequency of linac	$\omega/2\pi$	30 GHz
Acceleration field (loaded)	G_a	150 MV/m
Energy overhead		8%
Active length per linac	L_A	10.74 km
Total two-linac length	L_{tot}	27.5 km
RF power at structure input	P_{st}	229 MW
RF pulse duration	Δt_p	102 ns
Number of drive-beams/linac	N_D	22
Number of structures per linac		21 470
AC-to-RF efficiency	η_{RF}^{AC}	40.3%
RF-to-beam efficiency	η_b^{RF}	24.4%
AC-to-beam efficiency	η_b^{AC}	9.8%
AC power for RF production	P_{AC}	300 MW

Revision II ;-)

TABLE XIV. Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 yr $= 10^7$ s.

CoM energy (TeV)	3	0.4		0.1	
p energy (GeV)	16	16		16	
p's/bunch	2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill	4	4		2	
Repetition rate (Hz)	15	15		15	
p power (MW)	4	4		4	
μ/bunch	2×10^{12}	2×10^{12}		4×10^{12}	
μ power (MW)	28	4		1	
Wall power (MW)	204	120		81	
Collider circumference (m)	6000	1000		350	
Average bending field (T)	5.2	4.7		3	
rms $\Delta p/p\%$	0.16	0.14	0.12	0.01	0.003
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)	785	700	450	450	450
Luminosity cm^{-2} s^{-1}	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year			1.9×10^3	4×10^3	3.9×10^3

References

- ILC
  - http://tesla.desy.de/new_pages/TDR_CD/start.html
  - http://www.linearcollider.org/about/Publications/Reference-Design-Report
- CLIC
  - http://clic-study.web.cern.ch/clic-study/
- Muon collider
  - http://mice.iit.edu/
  - http://www.fnal.gov/pub/muon_collider/resources.html
- LHC
  - Proceedings of LHC-LUMI-05
- Exotic acceleration
  - https://slacportal.slac.stanford.edu/sites/ard_public/facet/Pages/Default.aspx/
  - http://www.ireap.umd.edu/AAC2010/