Special Topic: Overview and Tricks of the Trade

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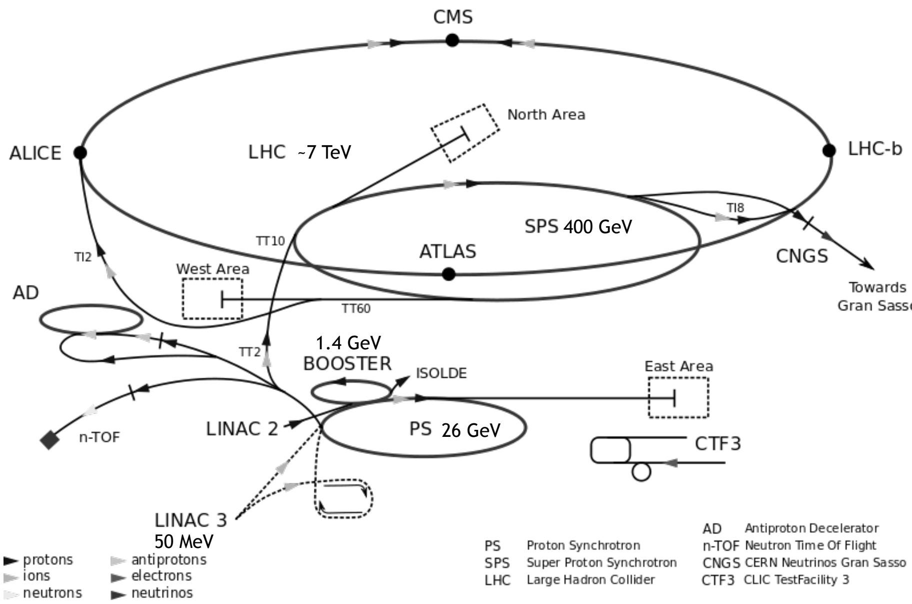
Multi-stage acceleration

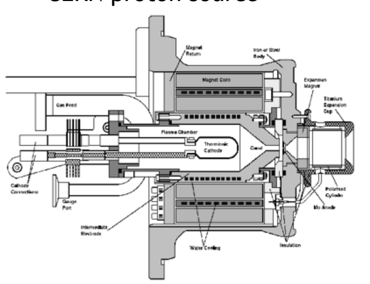
- Early synchrotrons had low energy injection and provided all the acceleration in a single stage.
- The energy range of a single synchrotron is limited by
  - An aperture large enough for the injected beam is unreasonably large at high field.
  - Hysteresis effects result in excessive nonlinear terms at low energy (very important for colliders)
- Typical range 10-20 for colliders, larger for fixed target
  - Fermilab Main Ring: 8-400 GeV (50x)
  - Fermilab Tevatron: 150-980 GeV (6.5x)
  - LHC: 400-7000 GeV (17x)
- The highest energy beams require multiple stages of acceleration, with high reliability at each stage
- How is this done?

Example: CERN Accelerator Complex

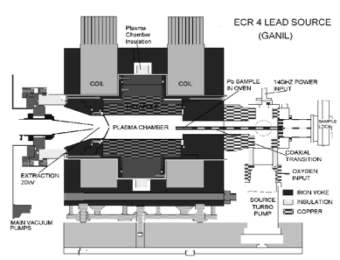


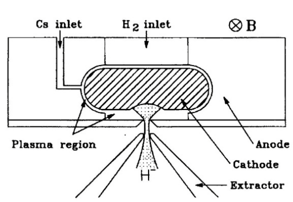
Getting started: Ion sources

CERN proton source



CERN Lead source



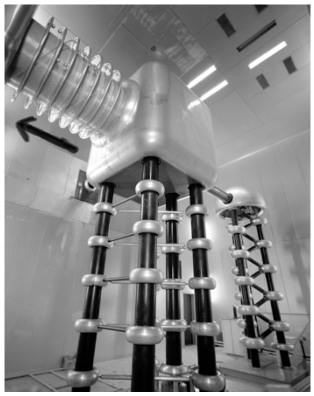


FNAL H- source. Mix Cesium with Hydrogen to add electron. (why? we'll get to that)

Typically 10s of keV and mAs to 10s of mA of current Want to accelerate as fast as possible before space charge blows up the beam!

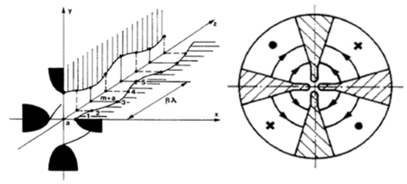
Initial acceleration

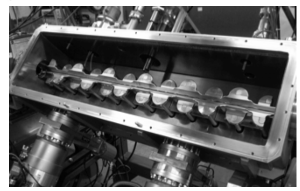
Old: Static



Static acceleration from Cockcroft-Walton.
FNAL = 750 keV
max ~1 MeV

New: RF Quadrupole (RFQ)





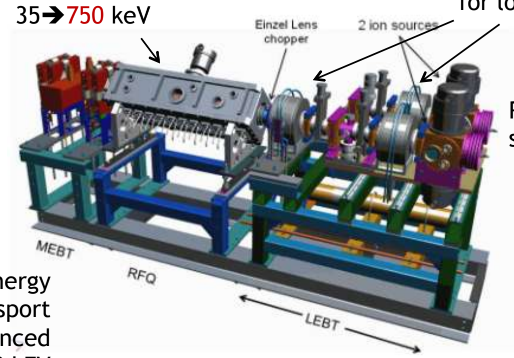
RF structure combines an electric focusing quadrupole with a longitudinal accelerating gradient.

Early stages

- The front end of any modern hadron accelerator looks something like this (Fermilab front end)

200 MHz RFQ: 35➔750 keV

Solenoidal focusing for low energy beam



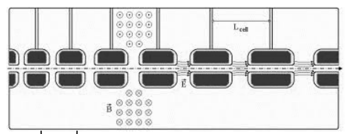
Redundant H^- sources: 0-35 keV

Medium Energy Beam Transport (MEBT, pronounced “mebbit”): 750 kEV

Low Energy Beam Transport (LEBT, pronounced “lebbit”): 35 keV

Drift Tube (Alvarez) Cavity

- Because the velocity is changing quickly, the first linac is generally a Drift Tube Linac (DTL), which can be beta-matched to the accelerating beam.
- Put conducting tubes in a larger pillbox, such that inside the tubes *E=0*



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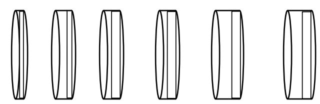
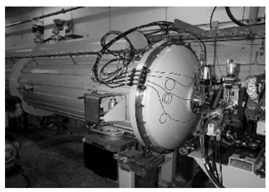
Bunch of pillboxes



$d = \frac{v}{f}$ ← Gap spacing changes as velocity increases

Drift tubes contain quadrupoles to keep beam focused



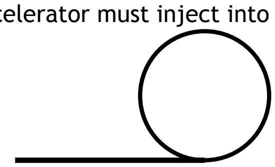
Fermilab low energy linac

Inside

- As energy gets higher, switch to "pi-cavities", which are more efficient

Linac -> synchrotron injection

- Eventually, the linear accelerator must inject into a synchrotron

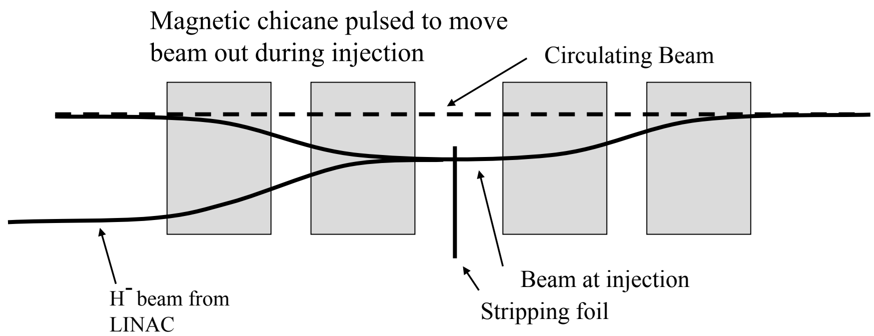


- In order to maximize the intensity in the synchrotron, we can
  - Increase the linac current as high as possible and inject over one revolution
    - There are limits to linac current
  - Inject over multiple (*N*) revolutions of the synchrotron
    - Preferred method
- Unfortunately, Liouville's Theorem says we can't inject one beam on top of another
  - Electrons can be injected off orbit and will "cool" down to the equilibrium orbit via synchrotron radiation.
  - Protons can be injected a small, changing angle to "paint" phase space, resulting in increased emittance

$$\epsilon_S \geq N\epsilon_{LINAC}$$

Synchrotron emittance ↗ ← Linac emittance

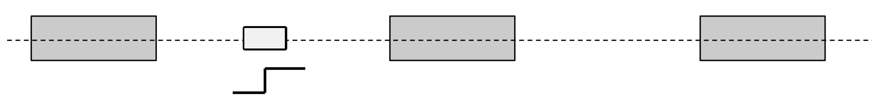
Ion (or charge exchange) injection



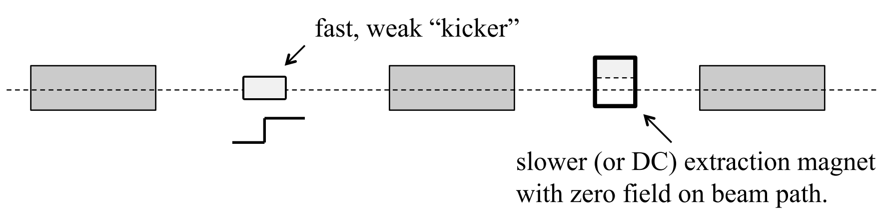
- Instead of ionizing Hydrogen, and electron is added to create H^-, which is accelerated in the linac
- A pulsed chicane moves the circulating beam out during injection
- An injected H^- beam is bent in the opposite direction so it lies on top of the circulating beam
- The combined beam passes through a foil, which strips the two electrons, leaving a single, more intense proton beam.
- Fermilab was converted from proton to H^- during the 70's
- CERN *still* uses proton injection, but is in the process of upgrading (LINAC4 upgrade)

Injection and extraction

- We typically would like to extract (or inject) beam by switching a magnetic field on between two bunches (order ~10-100 ns)

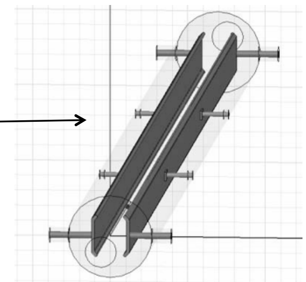


- Unfortunately, getting the required field in such a short time would result in prohibitively high inductive voltages, so we usually do it in two steps:



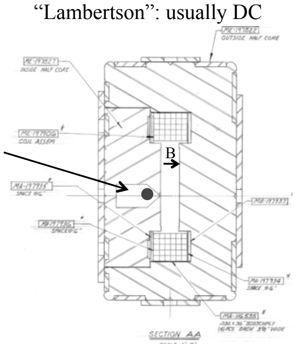
Extraction hardware

"Fast" kicker
- usually an impedance matched strip line, with or without ferrites



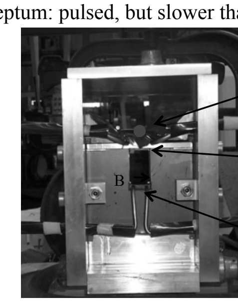
"Slow" extraction elements

"Lambertson": usually DC



circulating beam (B=0)

Septum: pulsed, but slower than the kicker



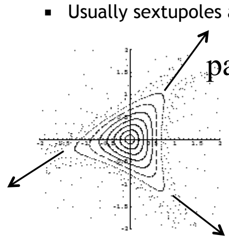
circulating beam (B=0)

current "blade"

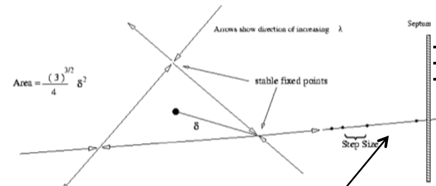
return path

Slow Extraction (not important for colliders)

- Sometimes fixed target experiments want beam delivered *slowly* (difficult)
- To do this, we generate a harmonic resonance
  - Usually sextupoles are used to create a 3rd order resonant instability



particle flow

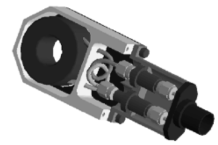


E

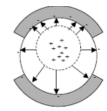
Particles will flow out of the stable region along lines in phase space into an electrostatic extraction field, which will deflect them into an extraction Lambertson

- Tune the instability so the escaping beam exactly fills the extraction gap between interceptions (3 times around for 3rd order)
  - Minimum inefficiency ~(septum thickness)/(gap size)
  - Use electrostatic septum made of a plane of wires. Typical parameters
    - Septum thickness: .1 mm
    - Gap: 10 mm
    - Field: 80 kV

Standard beam instrumentation



- Bunch/beam intensity are measured using inductive toriods



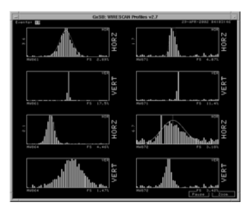
- Beam position is typically measured with beam position monitors (BPM's), which measure the induced signal on a opposing pickups

$$\Delta y \cong C \frac{I_{Top} - I_{Bottom}}{I_{Top} + I_{Bottom}}$$

- Longitudinal profiles can be measured by introducing a resistor to measure the induced image current on the beam pipe -> Resistive Wall Monitor (RWM)

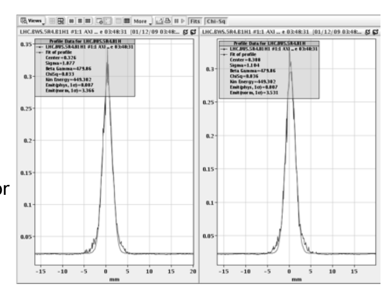
Beam instrumentation (cont'd)

- Beam profiles in beam lines can be measured using secondary emission multiwires (MW's)



Beam profiles in MiniBooNE beam line

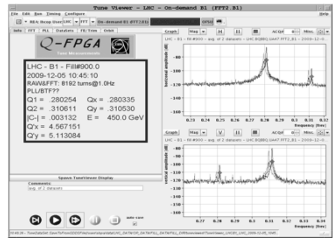
- Can measure beam profiles in a circulating beam with a "flying wire scanner", which quickly passes a wire through and measures signal vs time to get profile



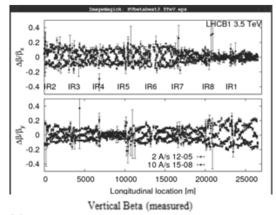
Flying wire signal in LHC

- Non-destructive measurements include
  - Ionization profile monitor (IPM): drift electrons or ions generated by beam passing through residual gas
  - Synchrotron light
    - Standard in electron machines
    - Also works in LHC

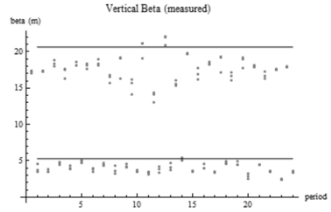
Measuring lattice parameters



- The fractional tune is measured by Fourier Transforming signals from the BPM's
  - Sometimes need to excite beam with a kicker



- Beta functions can be measured by exciting the beam and looking at distortions
  - Can use kicker or resonant ("AC") dipole

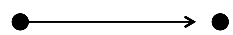


- Can also measure the by functions indirectly by varying a quad and measuring the tune shift

$$\Delta\nu = \frac{1}{4\pi}\frac{\beta}{f}$$

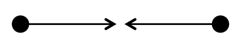
Moving on: The Case for Colliders

- If beam hits a stationary proton, the "center of mass" energy is

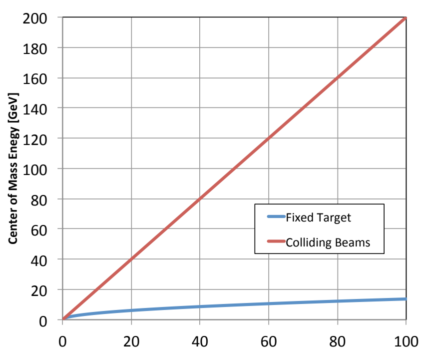


$$E_{\text{CM}} = \sqrt{2E_{\text{beam}}m_{\text{target}}c^2}$$

- On the other hand, for colliding beams (of equal mass and energy) it's



$$E_{\text{CM}} = 2E_{\text{beam}}$$



- To get the 14 TeV CM design energy of the LHC with a single beam on a fixed target would require that beam to have an energy of 100,000 TeV!
  - *Would require a ring 10 times the diameter of the Earth!!*

Getting to the highest energies requires colliding beams

Luminosity of Colliding Beams

- For equally intense Gaussian beams

$$L = f \frac{N_b^{\,2}}{4\pi\sigma^2} R$$

Collision frequency → f; Particles in a bunch → N_b; Transverse size (RMS) → σ; Geometrical factor → R:
- crossing angle
- hourglass effect

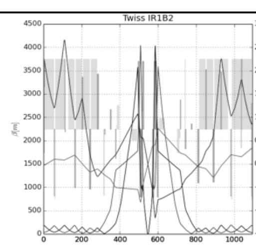
- Using $\sigma^2 = \frac{\beta^* \epsilon_N}{\beta\gamma} \approx \frac{\beta^* \epsilon_N}{\gamma}$ we have

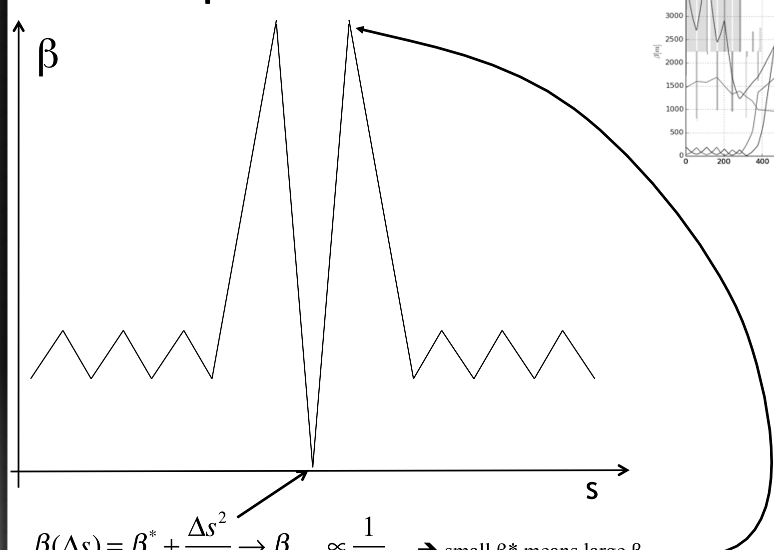
$$L = f_{rev} \frac{1}{4\pi} n_b N_b^2 \frac{\gamma}{\beta^* \epsilon_N} R$$

Revolution frequency → f_{rev}; Number of bunches → n_b; Particles in bunch → N_b; prop. to energy → γ; Normalized emittance → ϵ_N; Betatron function at collision point ➔ want a small β*! → β^*

Record e+e- Luminosity (KEK-B):	2.11×10^{34} cm^{-2}s^{-1}
Record p-pBar Luminosity (Tevatron):	4.06×10^{32} cm^{-2}s^{-1}
Record Hadronic Luminosity (LHC):	7.0×10^{33} cm^{-2}s^{-1}
LHC Design Luminosity:	1.00×10^{34} cm^{-2}s^{-1}

Limits to β*





$$\beta(\Delta s) = \beta^* + \frac{\Delta s^2}{\beta^*} \rightarrow \beta_{max} \propto \frac{1}{\beta^*}$$

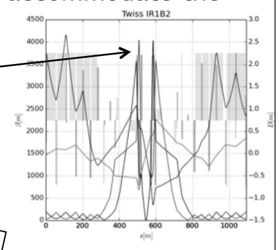
➔ small β* means large β (aperture) at focusing triplet

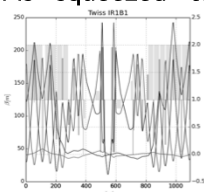
The "squeeze"?

- In general, synchrotrons scale all magnetic fields with the momentum, so the optics remain constant – with one exception.
- Recall that because of adiabatic damping, beam gets smaller as it accelerates.

$$\sigma_x = \sqrt{\frac{\beta_x \epsilon}{\beta\gamma}} \propto \frac{1}{\sqrt{p}}$$ factor of ~4 for LHC

- This means all apertures must be large enough to accommodate the injected beam.
  - This a problem for the large β values in the final focus triplets
- For this reason, injection optics have a larger value of β*, and therefor a smaller value of β in the focusing triplets.
- After acceleration, beam is "squeezed" to a smaller β* for collision





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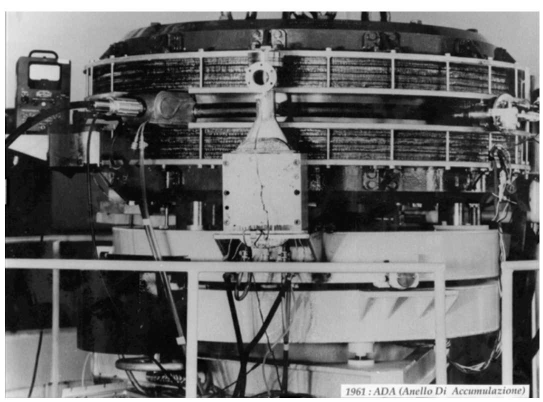
First e^+e^- Collider

- ADA (Anello Di Accumulazione) at INFN, Frascati, Italy (1961)
  - 250 MeV e^+ x 250 MeV e^-
  - L~10^{25} $cm^{-2}s^{-1}$



- It's easier to collide e+e-, because synchrotron radiation naturally "cools" the beam to smaller size.

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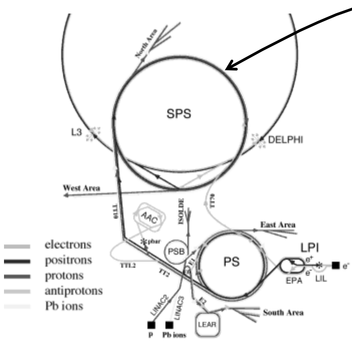
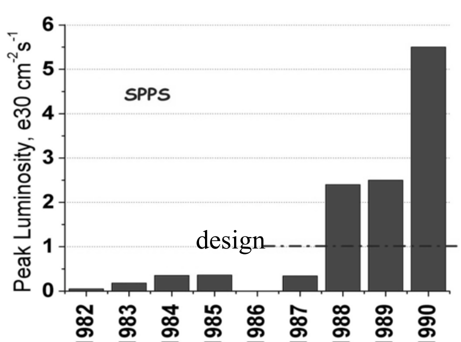
History: CERN Intersecting Storage Rings (ISR)

- First hadron collider (p-p)
- Highest CM Energy for 10 years
  - Until Sp$\bar{p}$S
- Reached it's design luminosity within the first year.
  - Increased it by a factor of 28 over the next 10 years
- Its peak luminosity in 1982 was 140x10^{30} $cm^{-2}s^{-1}$
  - a record that was not broken for 23 years!!

Sp$\bar{p}$S: First proton-antiproton Collider



- Protons from the SPS were used to produce antiprotons, which were collected
- These were injected in the opposite direction and accelerated
- First collisions in 1981
- Discovery of W and Z in 1983
  - Nobel Prize for Rubbia and Van der Meer

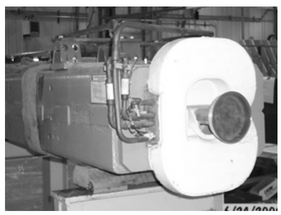


- Energy initially 270+270 GeV
- Raised to 315+315 GeV
  - Limited by power loss in magnets!
- Peak luminosity: 5.5x$10^{30}$$cm^{-2}s^{-1}$
  - ~.2% of current LHC

Superconductivity: Enabling Technology

- The maximum Sp$\bar{p}$S energy was limited by the maximum power loss that the conventional magnets could support in DC operation
  - $P = I^2R$ proportional to B^2
  - Maximum practical DC field in conventional magnets ~1T
  - LHC made out of such magnets would be roughly the size of Rhode Island!
- Highest energy colliders only possible using superconducting magnets
- Must take the bad with the good
  - Conventional magnets are simple and naturally dissipate energy as they operate

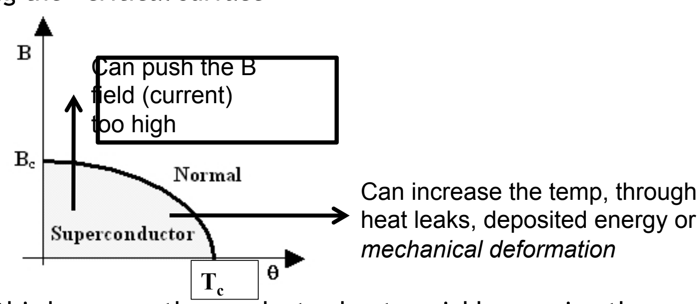
Superconducting magnets are complex and represent a great deal of stored energy which must be handled if something goes wrong



$$E \propto B^2$$

When is a superconductor not a superconductor?

- Superconductor can change phase back to normal conductor by crossing the "critical surface"



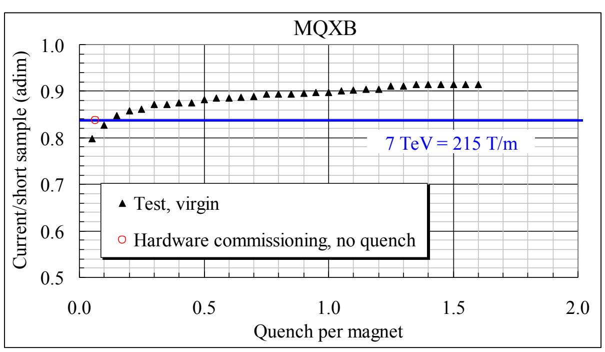
- When this happens, the conductor heats quickly, causing the surrounding conductor to go normal and dumping lots of heat into the liquid Helium➔"quench
  - all of the energy stored in the magnet must be dissipated in some way
- Dealing with quenches is the single biggest issue for any superconducting synchrotron!

Quench Example: MRI Magnet*

*pulled off the web. We recover our Helium.

Magnet "training"

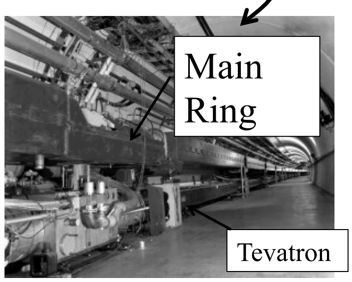
- As new superconducting magnets are ramped, electromechanical forces on the conductors can cause small motions.
- The resulting frictional heating can result in a quench
- Generally, this "seats" the conductor better, and subsequent quenches occur at a higher current.
- This process is knows as "training"



Milestones on the Road to a Superconducting Collider

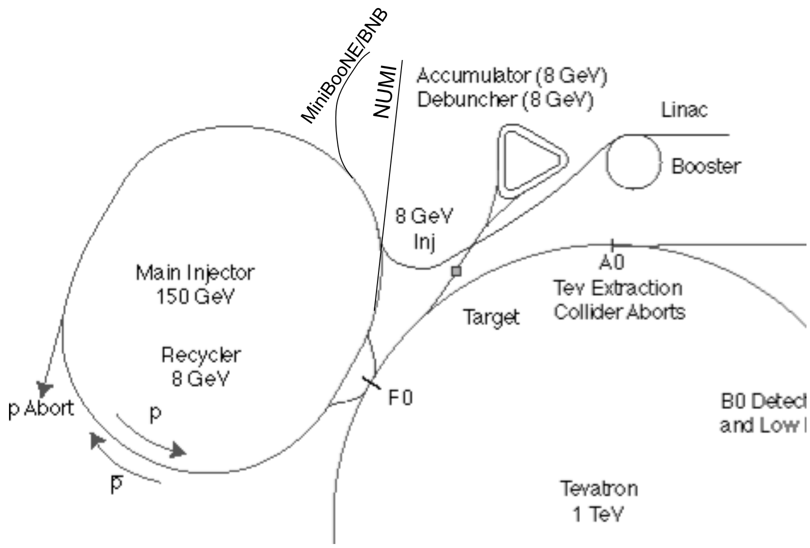
- 1911 – superconductivity discovered by Heike Kamerlingh Onnes
- 1957 – superconductivity explained by Bardeen, Cooper, and Schrieffer
  - 1972 Nobel Prize (the second for Bardeen!)
- 1962 – First commercially available superconducting wire
  - NbTi, the "industry standard" since
- 1978 – Construction began on ISABELLE, first superconducting collider (200 GeV+200 GeV) at Brookhaven.
  - 1983, project cancelled due to design problems, budget overruns, and competition from…

Tevatron: First Superconducting Synchrotron



- 1968 – Fermilab Construction Begins
- 1972 – Beam in Main Ring
  - (normal magnets)
- Plans soon began for a superconducting collider to share the ring.
  - Dubbed "Saver Doubler" (later "Tevatron")
- 1985 – First proton-antiproton collisions in Tevatron
  - Most powerful accelerator in the world *for the next quarter century*
- 1995 – Top quark discovery
- Reached $L=4.06\times10^{32}$ $cm^{-2}s^{-1}$
  - Breaking ISR p-p record
- 2011 – Tevatron shut down after successful LHC startup

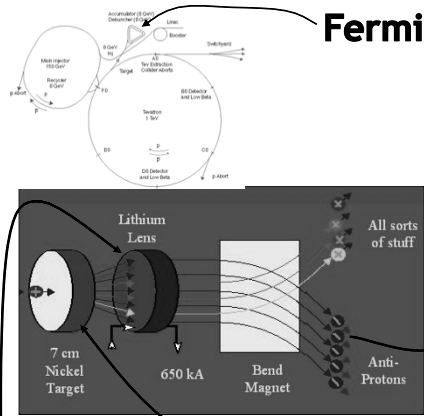
The Fermilab Accelerator Complex



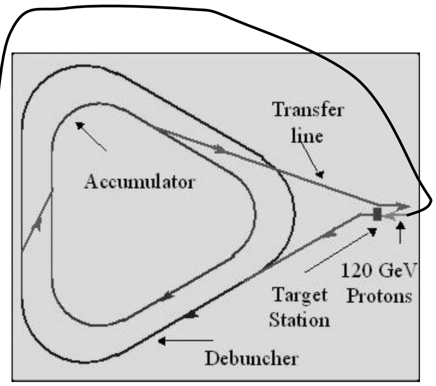
"Stack and Store" cycle

- The Linac accelerated beam to 400 MeV, and injected it into the Booster
- The Booster accelerated beam from 400 MeV to 8 GeV and transferred it to the Main Injector.
- The Main Injector accelerated beam from 8 GeV to 120 GeV, and this beam was used to produce 8 GeV antiprotons.
- Antiprotons were accumulated for roughly 1 day.
- These were then accelerated by the Main Injector to 150 GeV, and injected into the Tevatron.
- The Tevatron accelerated protons and antiprotons to 980 GeV and collided them for ~1 day.

Fermilab Antiproton Source

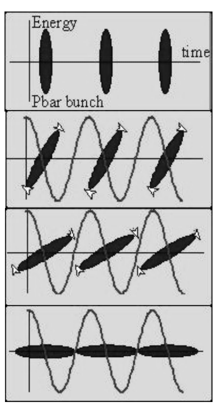


- 120 GeV protons strike a target, producing many things, including antiprotons.
- a Lithium lens focuses these particles (a bit)
- a bend magnet selects the negative particles around 8 GeV. Everything but antiprotons decays away.



- The antiproton ring consists of 2 parts
  - – the Debuncher
  - – the Accumulator.

Antiproton Source - debunching



Particles enter with a *narrow* time spread and *broad* energy spread.

High (low) energy pbars take more (less) to go around…

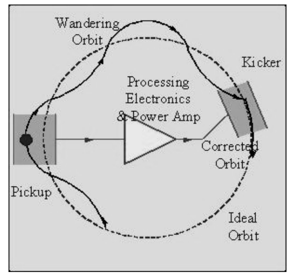
…and the RF is phased so they are decelerated (accelerated),

resulting in a *narrow* energy spread and *broad* time spread.

At this point, the pBars are transferred to the accumulator, where they are “stacked”

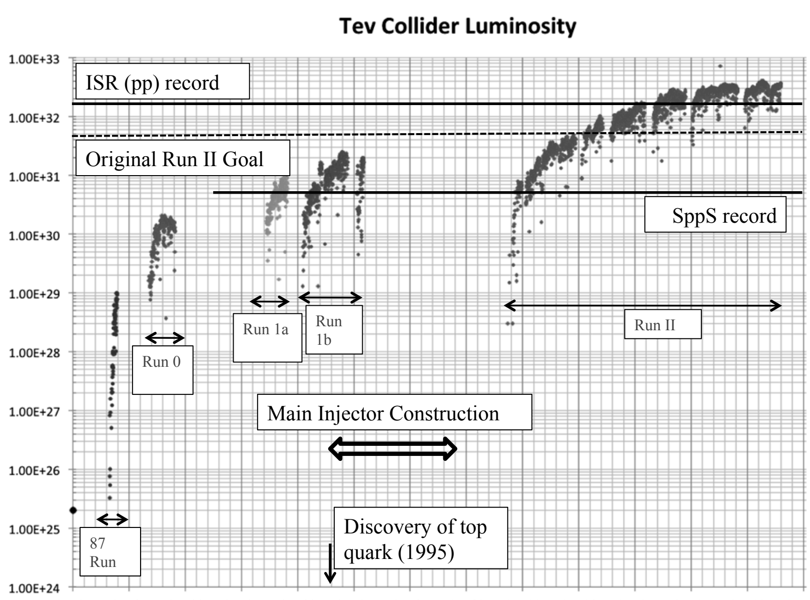
Stochastic cooling of antiprotons

- Positrons will naturally "cool" (approach a small equilibrium emittance) via synchrotron radiation.
- Antiprotons must rely on active cooling to be useful in colliders.
- Principle: consider a single particle which is off orbit. We can detect its deviation at one point, and correct it at another:
- But wait! If we apply this technique to an ensemble of particles, won't it just act on the centroid of the distribution? Yes, but…



- Stochastic cooling relies on "mixing", the fact that particles of different momenta will slip in time and the sampled combinations will change.
- *Statistically*, the mean displacement will be dominated by the high amplitude particles and over time the distribution will cool.

History of Fermilab Luminosity



Proton-Proton vs. Proton-antiproton

- Beyond a few hundred GeV, most interactions take place between gluons and/or virtual "sea" quarks.
  - No real difference between proton-antiproton and proton-proton
- Because of the symmetry properties of the magnetic field, a particle going in one direction will behave exactly the same as an antiparticle going in the other direction
  - Can put protons and antiprotons in the *same* ring
    - This is how the SppS (CERN) and the Tevatron (Fermilab) did it.
- The problem is that antiprotons are hard to make
  - Can get >1 positron for every electron on a production target
  - Can only get about *1 antiproton for every 50,000 protons* on target!
  - It took a day to make enough antiprotons for a "store" in the Fermilab Tevatron
  - Ultimately, the luminosity is limited by the antiproton current.

Antiprotons for LHC?

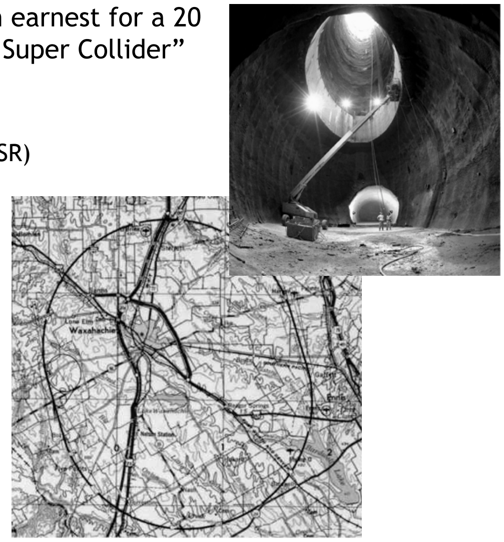
- At the design luminosity of the LHC, the antiproton "burn" rate would be

$$\sigma_{p\bar{p}}\mathcal{L} = (100\ \text{mbarns})(10^{34}) = (.1\times 10^{24})(10^{34}) = 10^{9}\ \frac{\bar{p}}{s}$$

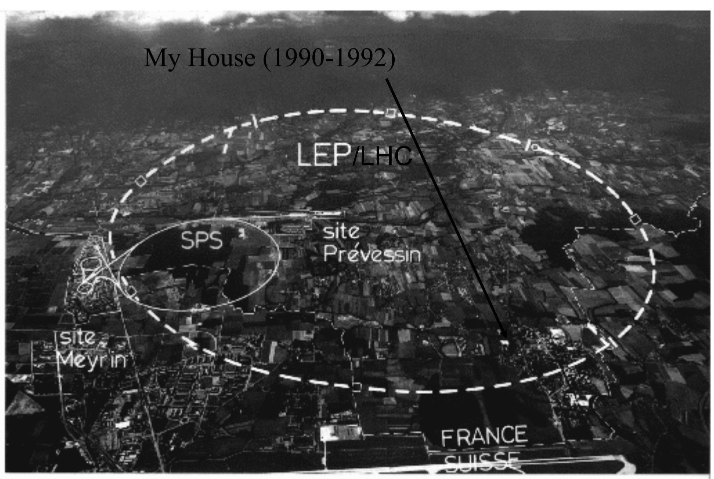
- The is about 15 times the maximum production rate achieved by the Fermilab antiproton source
  - No one has a good idea how to do this
  - The required proton beam would be megawatts (=neutrino beam)
- For this reason, it was long recognized that the next collider would be proton proton.

A Detour on the Road to Higher Energy

- 1980's - US begins planning in earnest for a 20 TeV+20 TeV "Superconducting Super Collider" or (SSC).
  - 87 km in circumference!
  - Two separate beams (like the ISR)
  - Considered superior to the "Large Hadron Collider" (LHC) then being proposed by CERN.
- 1987 – site chosen near Dallas, TX
- 1989 – construction begins
- 1993 – amidst cost overruns and the end of the Cold War, the SSC is cancelled after 17 shafts and 22.5 km of tunnel had been dug.
- 2001 – After the end of the LEP program at CERN, work begins on reusing the 27 km tunnel for the 7 TeV+ 7 TeV LHC

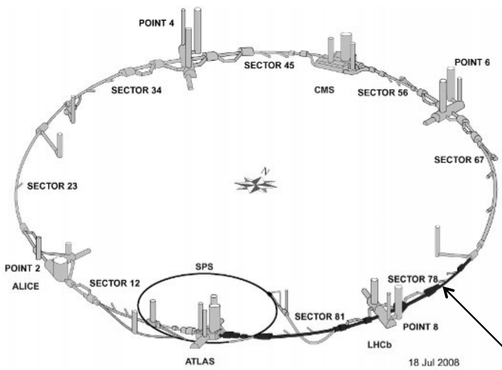


LHC: Location, Location, Location…



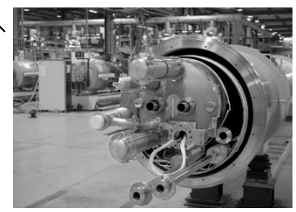
- Tunnel originally dug for LEP
  - Built in 1980's as an electron positron collider
  - Max 100 GeV/beam, but 27 km in circumference!!

LHC Layout and Numbers



Design:

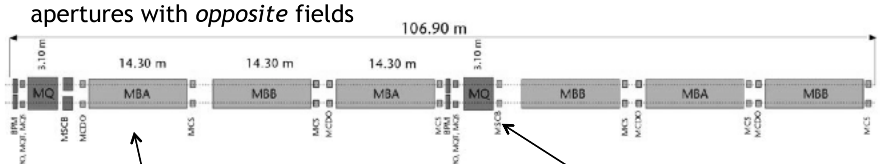
- 7 TeV+7 TeV proton beams
  - Can't make enough antiprotons for the LHC
  - Magnets have two beam pipes, one going in each direction.
- Stored beam energy 150 times more than Tevatron
  - Each beam has only 5×10^{-10} grams of protons, but has the energy of a train going 100 mph!!
- These beams are focused to a size *smaller than a human hair* to collide with each other!



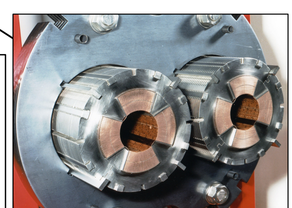
- 27 km in circumference
- 2 major collision regions: CMS and ATLAS
- 2 "smaller" regions: ALICE and LHCb

Standard LHC FODO Cell

- e^+e^- or proton-antiproton (opposite charge) colliders had particles going in *opposite* directions in the *same* beam pipe
- Because the LHC collides protons (same charge), the magnets have two apertures with *opposite* fields



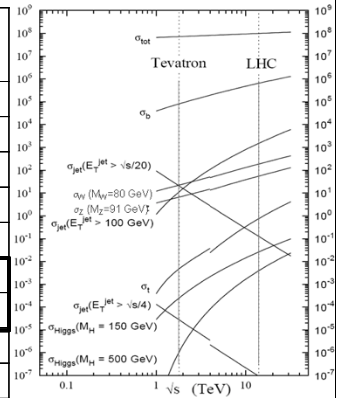
dipoles (B_{max} = 8.3 T)



quadrupoles

Nominal LHC Parameters Compared to Tevatron

Parameter	Tevatron	"nominal" LHC
Circumference	6.28 km (2*PI)	27 km
Beam Energy	980 GeV	7 TeV
Number of bunches	36	2808
Protons/bunch	275×10^9	115×10^9
pBar/bunch	80×10^9	-
Stored beam energy	1.6 + .5 MJ	366+366 MJ*
Magnet stored energy	400 MJ	10 GJ
Peak luminosity	3.3×10^{32} $cm^{-2}s^{-1}$	1.0×10^{34} $cm^{-2}s^{-1}$
Main Dipoles	780	1232
Bend Field	4.2 T	8.3 T
Main Quadrupoles	~200	~600
Operating temperature	4.2 K (liquid He)	1.9K (superfluid He)

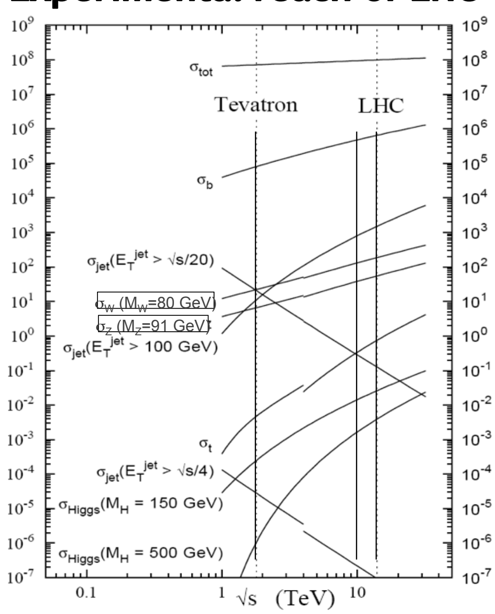


Increase in cross section of up to 5 orders of magnitude for some physics processes

*Each beam = TVG@150 km/hr ➔ very scary numbers

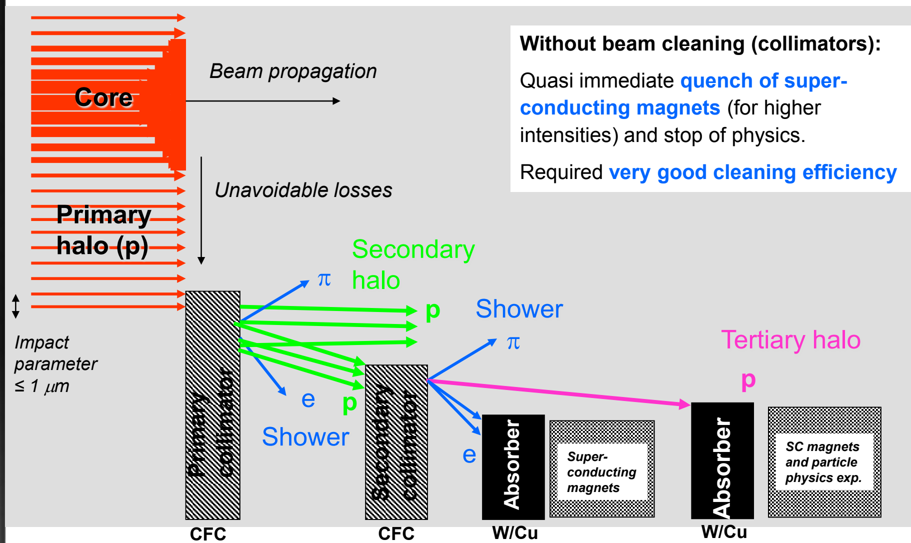
1.0×10^{34} $cm^{-2}s^{-1}$ ~ 50 fb^{-1}/yr= ~5 x total TeV data

Experimental reach of LHC vs. Tevatron



- The rate of physical processes depends strongly on energy
  - For some of the most interesting searches, the rate at the LHC will be 10-100 times the rate at the Tevatron.
- Nevertheless, still need about 30 times the luminosity of the Tevatron to study the most important physics

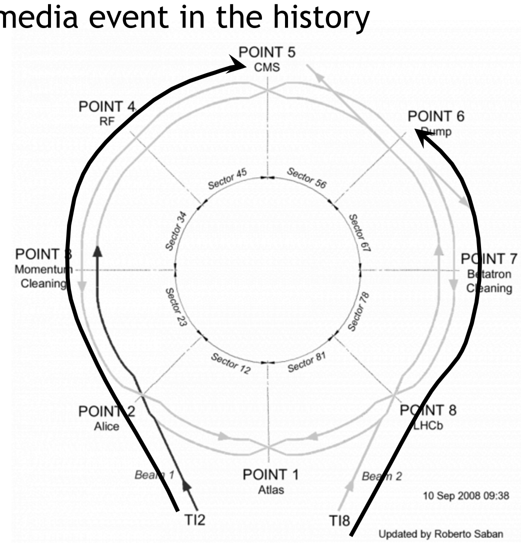
Protecting the Machine: Multi-stage Collimation



R. Assmann

September 10, 2008: The Big Day

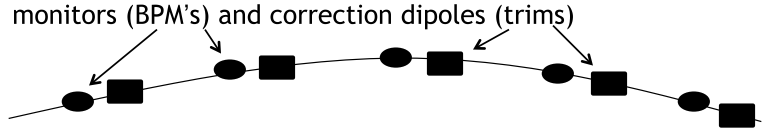
- Plotted the biggest media event in the history of science
- This plot shows how far beam had been prior to Sept. 10.



Progress prior to event

Orbit correction

- Generally, beam lines or synchrotrons will have beam position monitors (BPM's) and correction dipoles (trims)



- We would like to use the trims to cancel out the effect of beamline imperfectins, ie

$$-\Delta x_i = \sum A_{ij}\theta_j$$

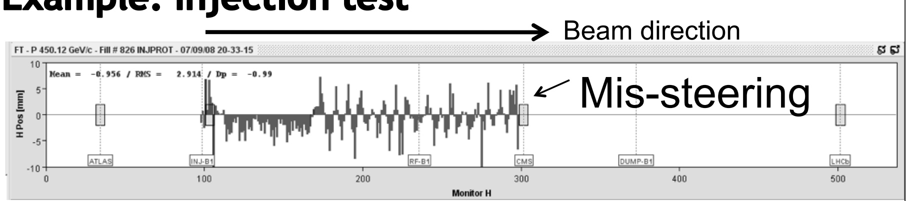
Cancel displacement at BPM *i* due to imperfections

Setting of trim *j*

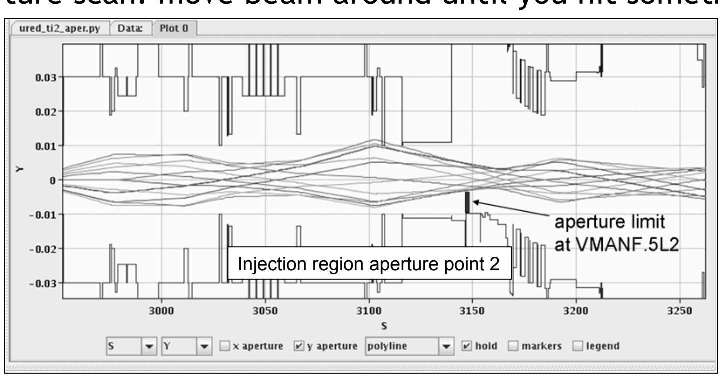
- Can express this as a matrix and invert to solve with standard techniques
  - If n=m, can just invert
  - If n>m, can minimize RMS

$$-\begin{pmatrix}\Delta x_0\\ \Delta x_1\\ \vdots\\ \Delta x_n\end{pmatrix}=\begin{pmatrix}A_{00} & A_{01} & \cdots & A_{0m}\\ A_{10} & A_{11} & \cdots & A_{1m}\\ \vdots & \vdots & \ddots & \\ A_{n0} & A_{n1} & & A_{nm}\end{pmatrix}\begin{pmatrix}\theta_0\\ \theta_1\\ \vdots\\ \theta_m\end{pmatrix}$$

Example: Injection test

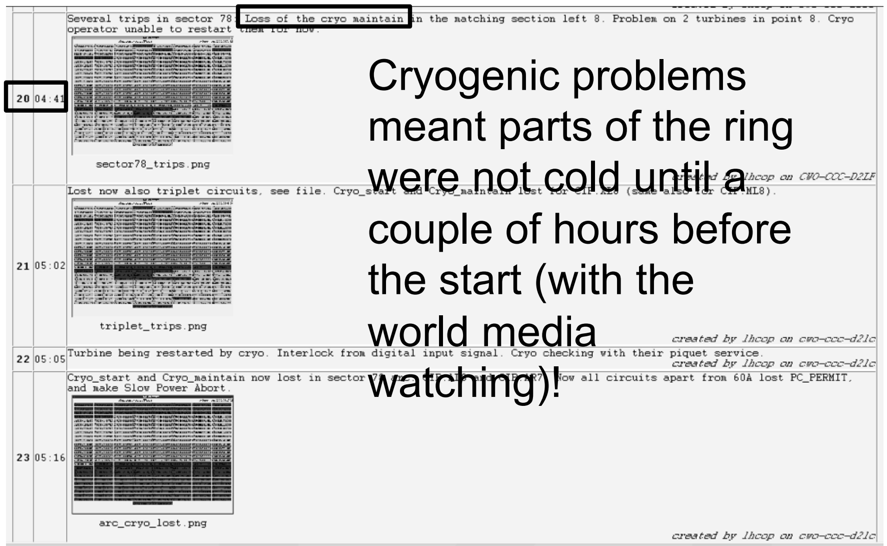


- Aperture scan: move beam around until you hit something



Close call: the event that almost wasn't

- From the LHC eLogBook:



Cryogenic problems meant parts of the ring were not cold until a couple of hours before the start (with the world media watching)!

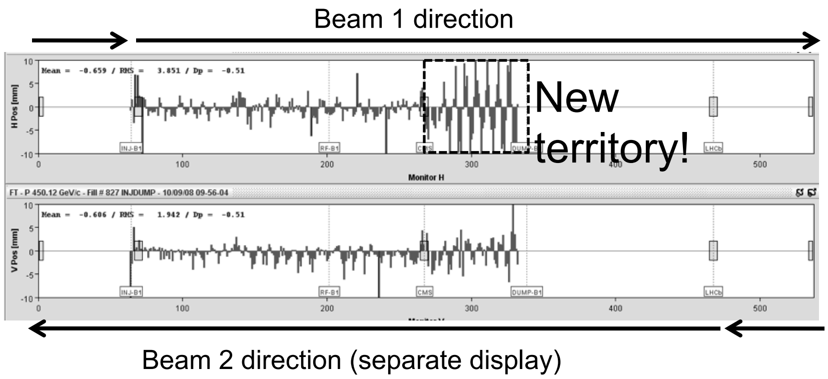
Nevertheless, the party started on schedule

CERN Control Centre (CCC)

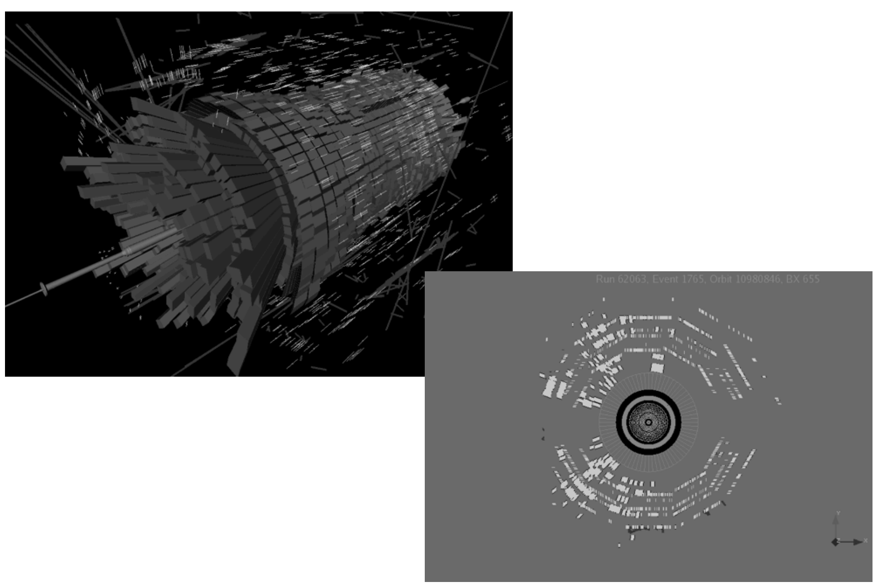
Fermilab "Pajama Party"

Started with beam one (clockwise) at 9:35

- General procedure
  - Proceed one octant at a time, closing collimators at the next point.
  - Take several shots to correct beam deviation



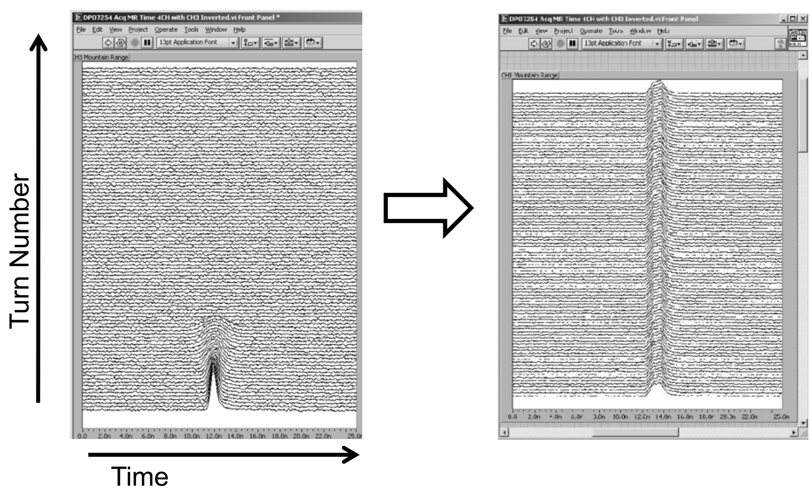
Beam seen in CMS



Timeline (CEDT)

- 9:35 – First beam injected
- 9:58 – beam past CMS to point 6 dump
- 10:15 – beam to point 1 (ATLAS)
- 10:26 – First turn!
- …and there was much rejoicing

After initial circulation: captured beam



- Everything was going great until *something very bad happened* on September 19th
  - Initially, CERN kept a tight lid on news

Nature abhors a (news) vacuum…

- Italian newspapers were very poetic (at least as translated by "Babel Fish"):

  "the black cloud of the bitterness still has not been dissolved on the small forest in which they are dipped the candid buildings of the CERN"

  *"Lyn Evans, head of the plan, support that it was better to wait for before igniting the machine and making the verifications of the parts."**

- Or you could Google "What really happened at CERN":

Strange Incident at CERN
Did the LHC Create a Black Hole?
And if so, Where is it Now? **
by
George Paxinos
in conversation with
"An Iowan Idiot"

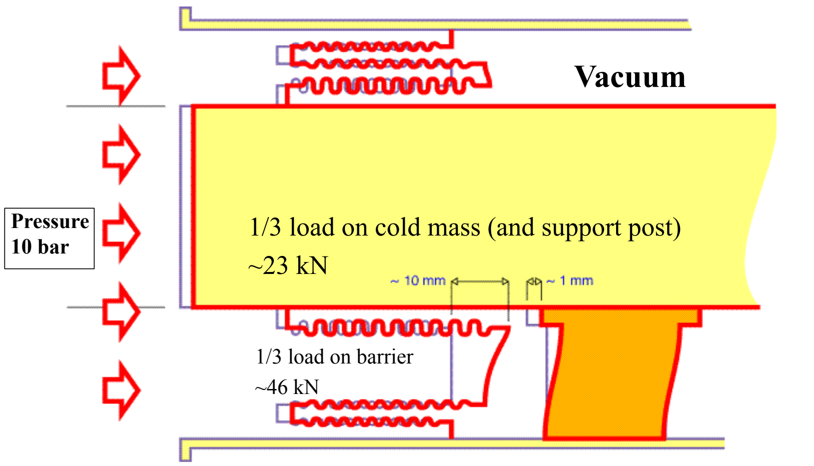
* "Big Bang, il test bloccato fino all primavera 2009", Corriere dela Sera, Sept. 24, 2008
**http://www.rense.com/general83/IncidentatCERN.pdf

What (really) really happened on September 19th*

- Sector 3-4 was being ramped to 9.3 kA, the equivalent of 5.5 TeV
  - All other sectors had already been ramped to this level
  - Sector 3-4 had previously only been ramped to 7 kA (4.1 TeV)
- At 11:18AM, a quench developed in the splice between dipole C24 and quadrupole Q24
  - Not initially detected by quench protection circuit
  - Power supply tripped at .46 sec
  - Discharge switches activated at .86 sec
- Within the first second, an arc formed at the site of the quench
  - The heat of the arc caused Helium to boil.
  - The pressure rose beyond .13 MPa and ruptured into the insulation vacuum.
  - Vacuum also degraded in the beam pipe
- The pressure at the vacuum barrier reached ~10 bar (design value 1.5 bar). The force was transferred to the magnet stands, which broke.

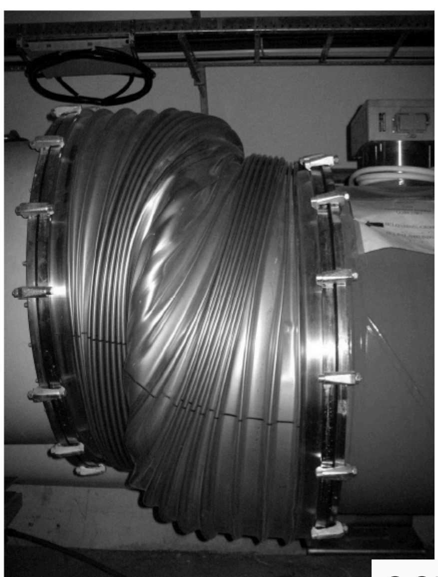
*Official talk by Philippe LeBrun, Chamonix, Jan. 2009

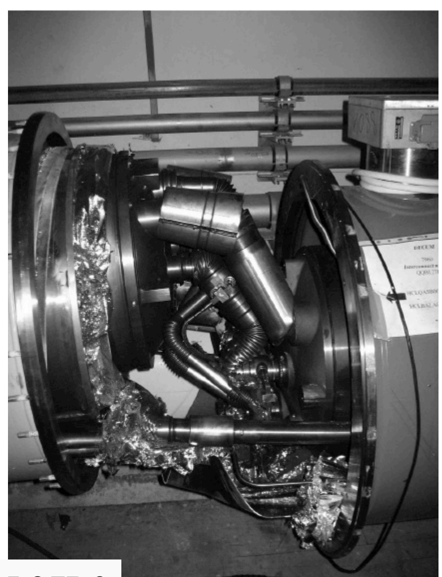
Pressure forces on SSS vacuum barrier



Total load on 1 jack ~70 kN V. Parma

Collateral damage: magnet displacements





QQBI.27R3

Collateral damage: secondary arcs

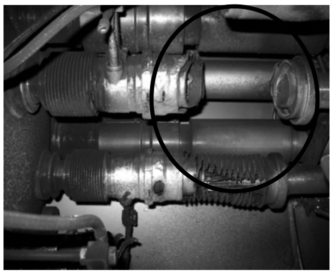
QQBI.27R3 M3 line

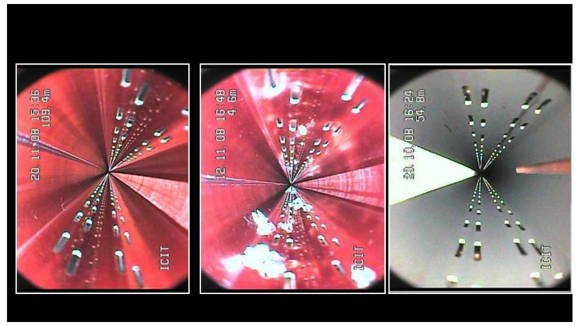
QBBI.B31R3 M3 line

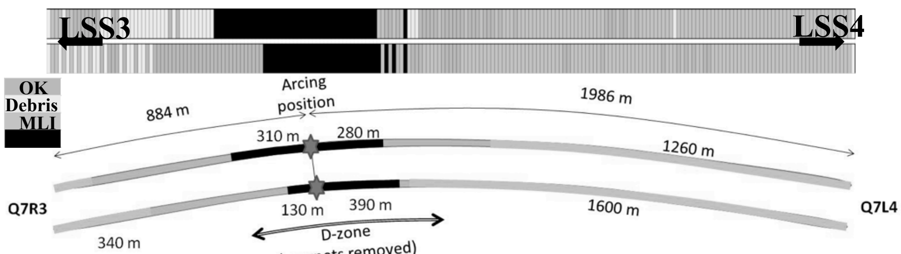
Collateral damage: ground supports

Collateral damage: Beam Vacuum

Arc burned through beam vacuum pipe





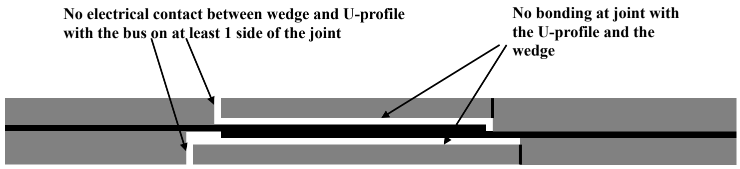


Important questions about Sept. 19

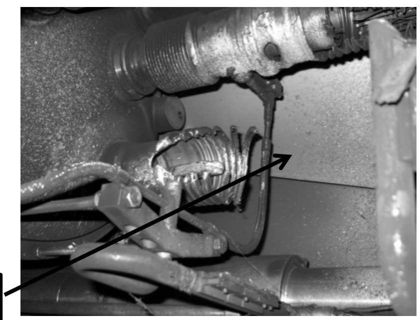
- Why did the joint fail?
  - Inherent problems with joint design
    - No clamps
    - Details of joint design
    - Solder used
  - Quality control problems
- Why wasn't it detected in time?
  - There was indirect (calorimetric) evidence of an ohmic heat loss, but these data were not routinely monitored
  - The bus quench protection circuit had a threshold of 1V, a factor of >1000 too high to detect the quench in time.
- Why did it do so much damage?
  - The pressure relief system was designed around an MCI Helium release of 2 kg/s, a *factor of ten* below what occurred.

What happened?

Working theory: A resistive joint of about 220 nΩ with bad electrical and thermal contacts with the stabilizer



- Loss of clamping pressure on the joint, and between joint and stabilizer
- Degradation of transverse contact between superconducting cable and stabilizer
- Interruption of longitudinal electrical continuity in stabilizer



Problem: this is where the evidence used to be

A. Verweij

Interim Improvements (2008-2009)

- Bad joints
  - Test for high resistance and look for signatures of heat loss in joints
  - Warm up to repair any with signs of problems (additional three sectors)
- Quench protection
  - Old system sensitive to 1V
  - New system sensitive to .3 mV
- Pressure relief
  - Warm sectors (4 out of 8)
    - Install 200mm relief flanges
    - Enough capacity to handle even the maximum credible incident (MCI)
  - Cold sectors
    - Reconfigure service flanges as relief flanges
    - Reinforce floor mounts
    - Enough capacity to handle the incident that occurred, but not quite the MCI

After the first shutdown

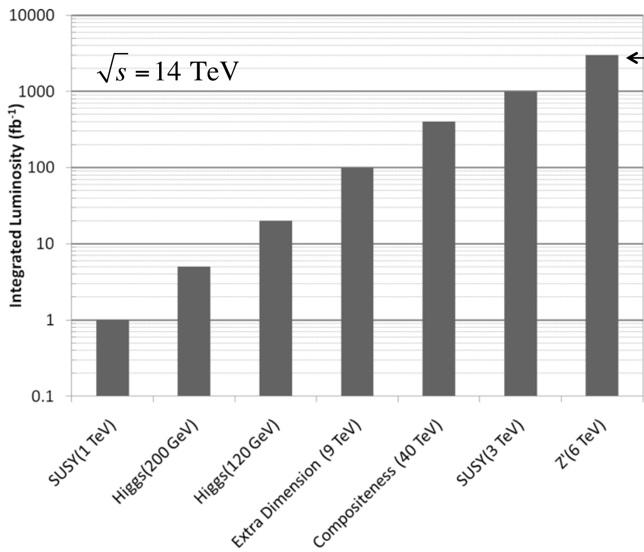
- 2009
  - November 20th: Particles circulate again
  - Based on a detailed thermal model of the joints and failure scenarios, it's decided to limit energy to 3.5 TeV
- 2010
  - March 30th: 3.5 + 3.5 TeV collisions
    - Energy limited by flaw which caused accident
- 2012
  - January (Chamonix meeting): based on observed performance and revised modeling, it's decided to increase energy to 4 TeV.
  - April 5th: Energy increased to 4 + 4 TeV
  - July 4th: Announced the discovery of the Higgs

- 2013
  - Feb. 14th: Start 2 year shutdown to address design flaw and allow full energy operation
  - ALL (~10000) joints resoldered, clamped and radiographed.
  - Remaining sectors outfitted with improved pressure relief.

After the shutdown

- After repairs are completed, accelerator will come back up in 2015 at something close to the design energy
  - At least 6.5 TeV/beam
- The LHC will be the centerpiece of the world's energy frontier physics program for at least the next 15-20 years.

Longer Term: The Big Picture



$3000\ \mathrm{fb}^{-1}$
~ 50 years at nominal LHC luminosity!

The future begins now

How can we increase the luminosity??

Limits to LHC Luminosity*

Total beam current, limited by machine protection(!), e-cloud and other instabilities

Brightness, limited by
- PSB injection energy
- PS
- Max tune-shift

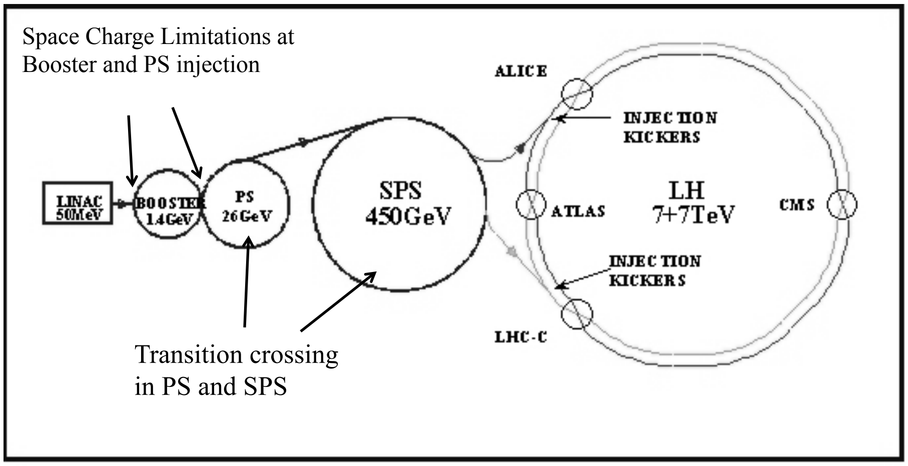
$$L = \left(\frac{\gamma f_{rev}}{4\pi}\right)\frac{n_b N_b}{\beta^*}\left[\left(\frac{N_b}{\varepsilon_N}\right)R_\phi\right]$$

β*, limited by
- magnet technology
- chromatic effects

Geometric factor, related to crossing angle…

*see, eg, F. Zimmermann, "CERN Upgrade Plans", EPS-HEP 09, Krakow, for a thorough discussion of luminosity factors.

Current LHC Acceleration Sequence and Brightness Issues

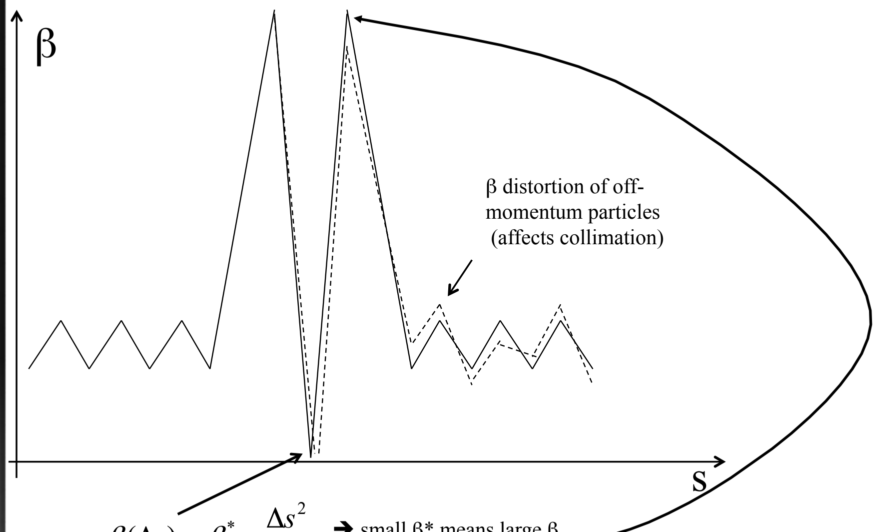


Schematic ONLY. Scale and orientation not correct

Addressing brightness issues

- There are plans to address two of the major sources of emittance blowup in the injector chain
  - Injection from the LINAC into the PS Booster
    - The current linac uses proton painting at 50 MeV
    - New LINAC4 will use ion injection at 160 MeV
  - Space charge at injection into PS
    - Extraction energy of the PS Booster will be increased from 1.4 to 2.0 GeV
- These upgrades are scheduled to take place during Long Shutdown 2

Limits to β*



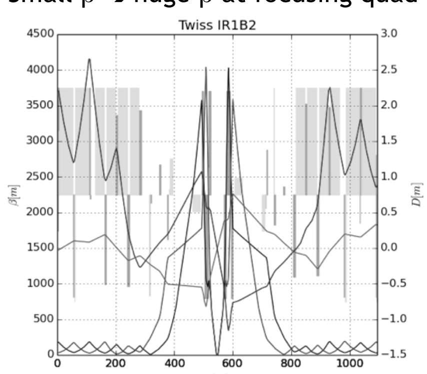
$$\beta(\Delta s) = \beta^* + \frac{\Delta s^2}{\beta^*}$$

➔ small β* means large β (aperture) at focusing triplet

Overview and Tricks of the Trade USPAS, Hampton, VA, Jan. 26-30, 2015 69

The Case for New Quadupoles

- HL-LHC Proposal: β*=55 cm ➔ β*=10 cm
- Just like classical optics
  - Small, intense focus ➔big, powerful lens
  - Small β*➔huge β at focusing quad



Existing quads
- 70 mm aperture
- 200 T/m gradient

Proposed for upgrade
- 140 mm aperture
- 200 T/m gradient
- Field 70% higher at pole face

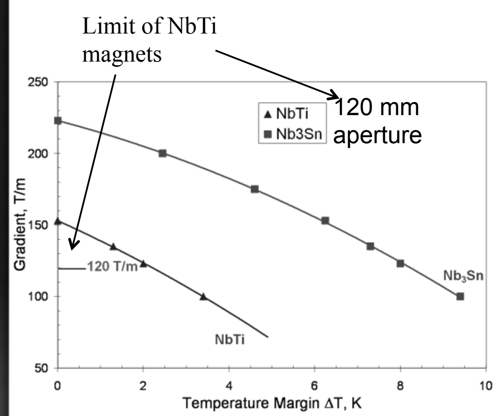
➔ Beyond the limit of NbTi

- Need bigger quads to go to smaller β*

Overview and Tricks of the Trade USPAS, Hampton, VA, Jan. 26-30, 2015 70

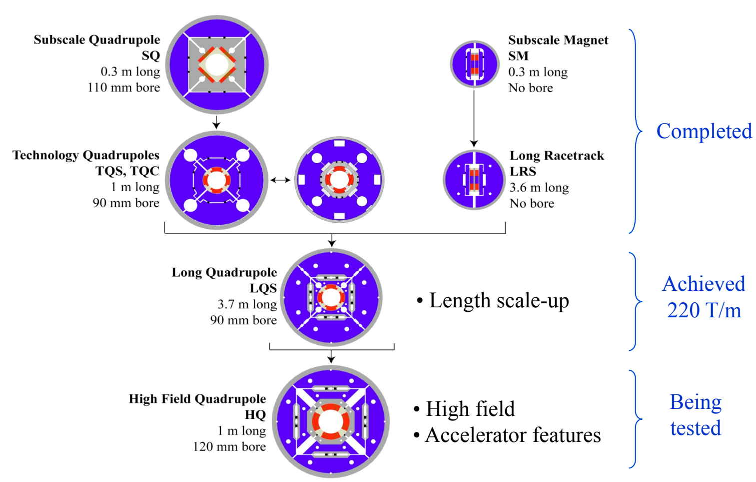
Motivation for Nb_3Sn

- Nb_3Sn can be used to increase aperture/gradient and/or increase heat load margin, relative to NbTi

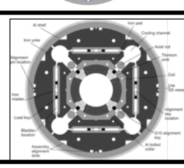


- Very attractive, but no one has ever built accelerator quality magnets out of Nb_3Sn
- Whereas NbTi remains pliable in its superconducting state, Nb3Sn must be reacted at high temperature, causing it to become brittle
  - Must wind coil on a mandril
  - React
  - Carefully transfer to yolk

US-LARP Magnet Development Tree

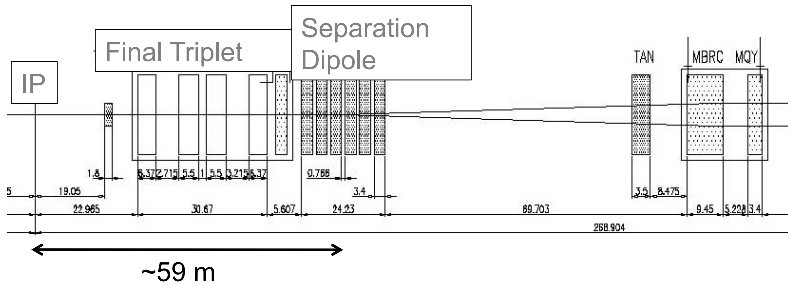


LHC Prototype
4 m long
150 mm bore



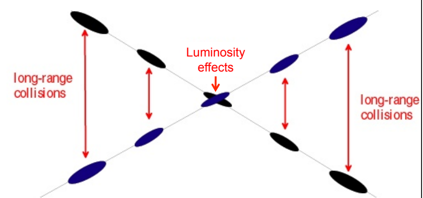
Being designed jointly with CERN

IR Layout: the need for a crossing angle



- Nominal Bunch spacing: 7.5 m
- Collision spacing: 3.75 m
- ~2x15 parasitic collisions per IR
  - Remember: ALL of these would cause equal tune shifts

⟹ Need Crossing Angle



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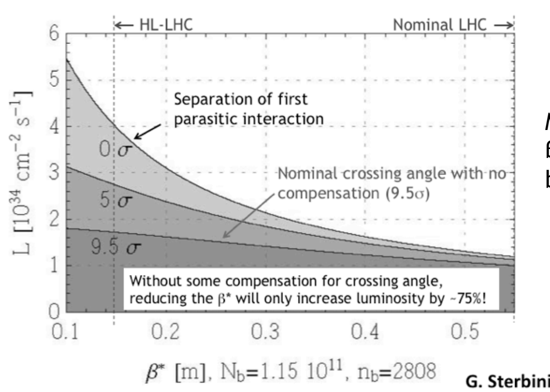
Crossing Angle Considerations

- Crossing angle reduces luminosity

"Piwinski Angle"

$$L = \left(\frac{\gamma f_{rev}}{4\pi}\right)\frac{n_b N_b}{\beta^*}\left[\left(\frac{N_b}{\varepsilon_N}\right) R_\phi\right] \Rightarrow R_\phi = \frac{1}{\sqrt{1+\phi_{piw}^2}};\quad \phi_{piw} \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$



G. Sterbini

Minor effect at current β*, but largely cancels benefit of lowering β*

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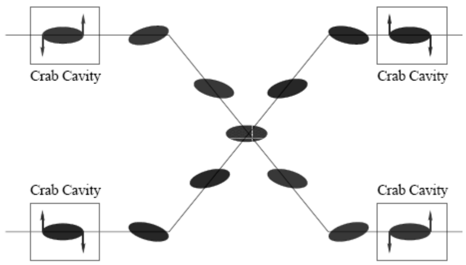
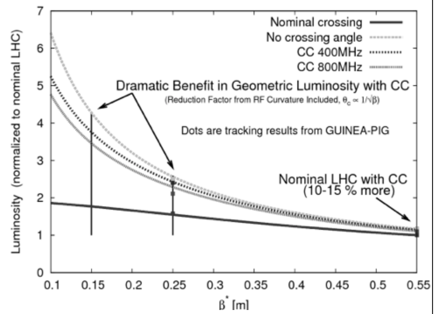
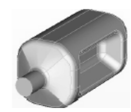
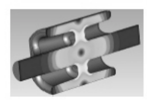
Baseline Approach: Crab Cavities

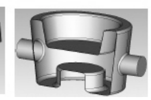




- Technical Challenges
  - Crab cavities have only *barely* been shown to work.
    - Never in hadron machines
  - LHC bunch length ➔ low frequency (400 MHz)
  - 19.2 cm beam separation ➔ "compact" (exotic) design



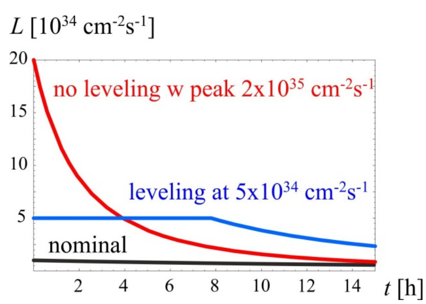


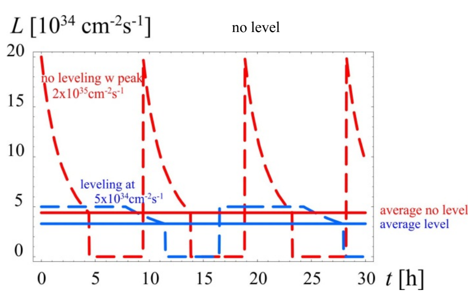


- Additional benefit
  - Crab cavities may help level luminosity!

Luminosity Leveling

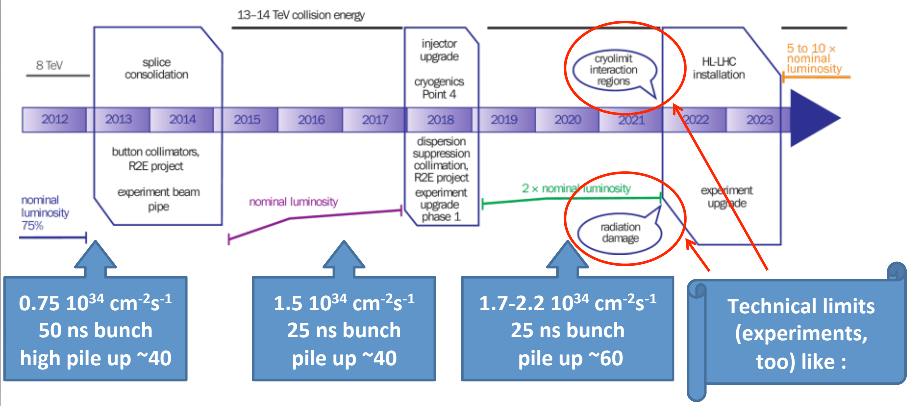
- Original goal of luminosity upgrade: >10^{35} $cm^{-2}s^{-1}$
  - Leads to unacceptable pileup in detectors
- New goal: 5×10^{34} *leveled* luminosity





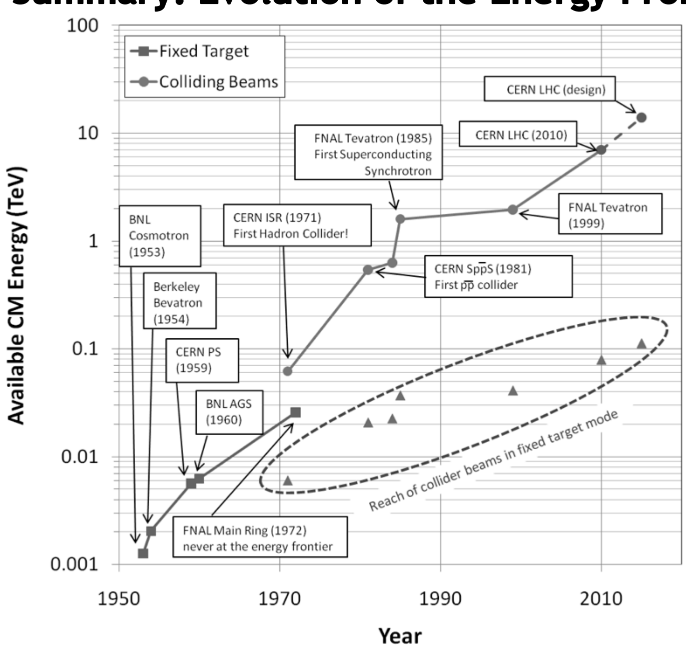
- Options
  - Crab cavities ← "Crab kissing" – sort of complicated
  - β* modifications
  - Lateral separation

Long Term Plan*



*L. Rossi, LARP/HL-LHC Meeting, Nov. 2013

Summary: Evolution of the Energy Frontier

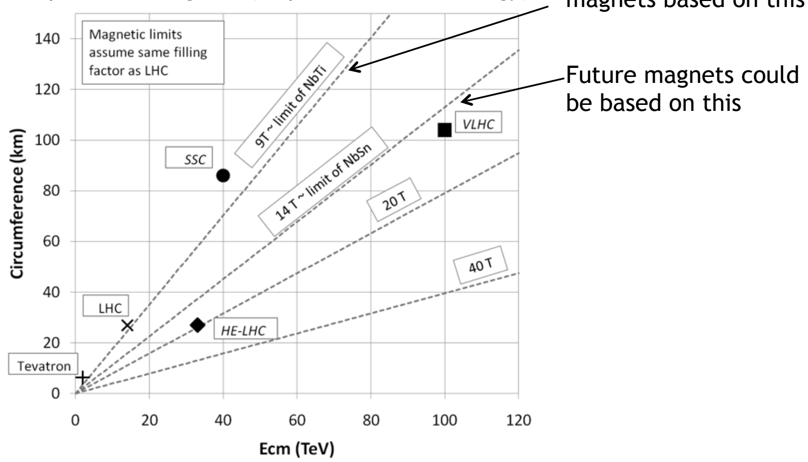


~a factor of 10 every 15 years

This will not continue

What next?

- The energy of Hadron colliders is limited by feasible size and magnet technology. Options:
  - Get very large (~100 km circumference)
  - More powerful magnets (requires new technology)



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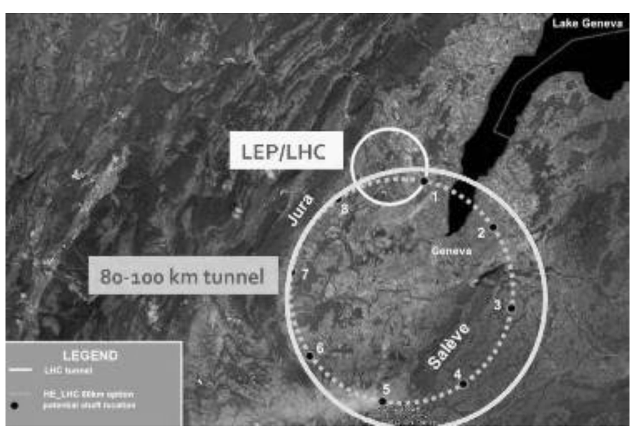
Future Circular Collider (FCC)

- Currently being discussed for ~2030s
- 80-100 km in circumference
- Niobium-3-Tin (Nb_3Sn) magnets.
- ~100 TeV center of mass energy



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Some things to think about for FCC

- Recall that luminosity is given by

$$L = f_{rev} \frac{1}{4\pi} n_b N_b^2 \frac{\gamma}{\beta^* \epsilon_N} R$$

- If we wanted to keep just 10^{34} luminosity (probably not enough), the γ factor would let us back down on N_b a bit, but to keep the crossing rate the number of bunches would increase with the circumference so stored energy would be

$$U_{VLHC} \approx U_{LHC} \frac{E_{VLHC}}{E_{LHC}} \sqrt{\frac{E_{LHC}}{E_{VLHC}}} \frac{C_{VLHC}}{C_{LHC}} = U_{LHC} \sqrt{\frac{50}{7}} \frac{100}{27}$$

$$= 10 \times U_{LHC}$$

$$= 3.6 \text{ GJ}$$

← ~1 ton on TNT = Scary!

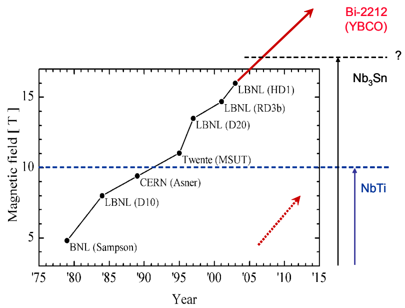
- What are the options to make it more compact, and or go to even higher energies?

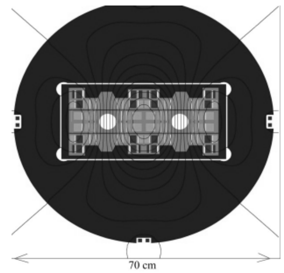
Superconductor Options

- Traditional
  - NbTi
    - Basis of ALL superconducting accelerator magnets to date
    - Largest practical field ~8T
  - Nb_3Sn
    - Advanced R&D
    - Being developed for large aperture/high gradient quadrupoles
    - Larges practical field ~14T
- High Temperature
  - Industry is interested in operating HTS at moderate fields at LN_2 temperatures. We're interested in operating them at high fields at LHe temperatures.
    - MnB_2
      - promising for power transmission
      - can't support magnetic field.
    - YBCO
      - very high field at LHe
      - no cable (only tape)
    - BSCCO (2212)
      - strands demonstrated
      - unmeasureably high field at LHe

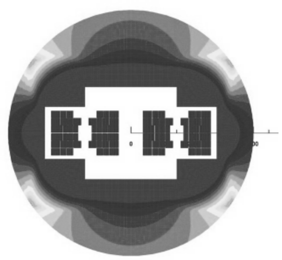
Focusing on this, but very expensive
➔ pursue hybrid design

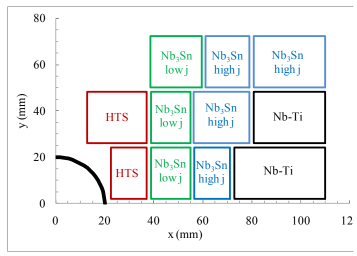
Potential Designs





P. McIntyre 2005 – 24T ss Tripler, a lot of Bi-2212 , Je = 800 A/mm2





E. Todesco 2010
20 T, 80% ss
30% NbTi
55 %NbSn
15 %HTS
All Je < 400 A/mm2

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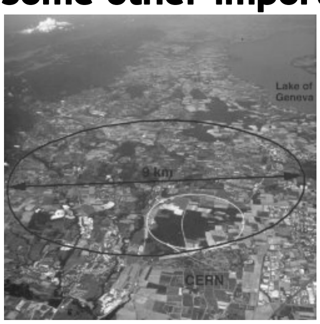
Some other important accelerators (past):

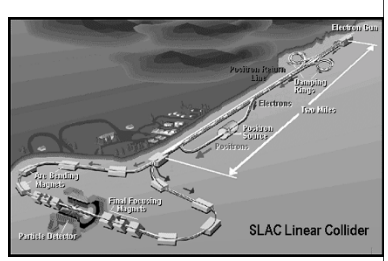


LEP (at CERN):

- 27 km in circumference
- e+e-
- Primarily at $2E=M_Z$ (90 GeV)
- Pushed to E_{CM}=200GeV
- L = 2E31
- **Highest energy *circular* e+e- collider that will ever be built.**
- **Tunnel now houses LHC**

SLC (at SLAC):

- 2 km long LINAC accelerated electrons AND positrons on opposite phases.
- $2E=M_Z$ (90 GeV)
- polarized
- L = 3E30
- **Proof of principle for linear collider**



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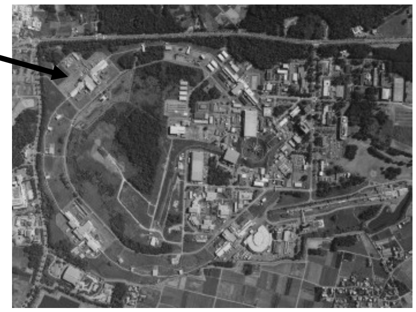
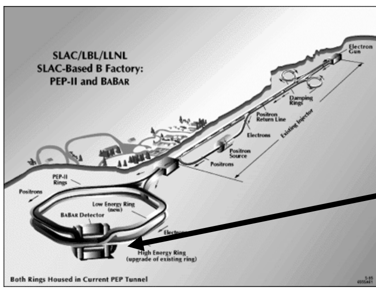
B-Factories

- B-Factories collide e+e- at E_{CM} = M(ϒ(4S)).
-Asymmetric beam energy (moving center of mass) allows for time-dependent measurement of B-decays to study CP violation.



KEKB (Belle Experiment):

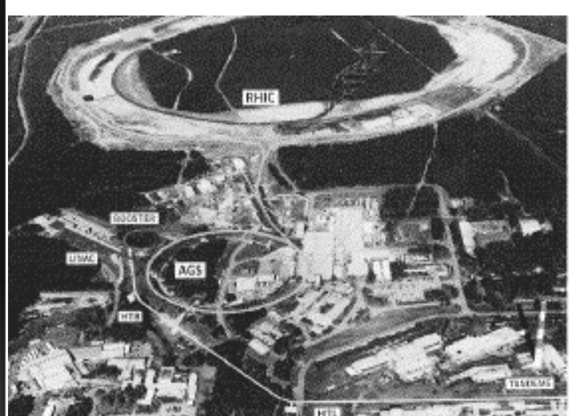
- Located at KEK (Japan)
- 8GeV e- x 3.5 GeV e+
- Peak luminosity 1E34



PEP-II (BaBar Experiment)

- Located at SLAC (USA)
- 9GeV e- x 3.1 GeV e+
- Peak luminosity 0.6E34

Relativistic Heavy Ion Collider (RHIC)



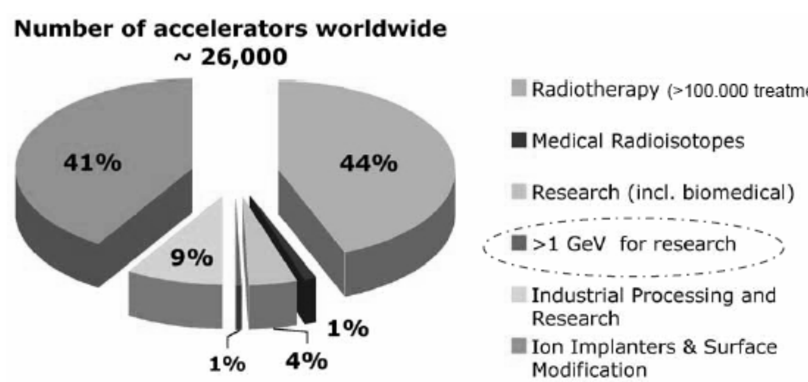
- Located at Brookhaven:
- Can collide protons (at 28.1 GeV) and many types of ions up to Gold (at 11 GeV/amu).
- Luminosity: 2E26 for Gold
- **Goal: heavy ion physics, quark-gluon plasma, ??**

Continuous Electron Beam Accelerator Facility (CEBAF)

Jlab, the aerial view

- Locate at Jefferson Laboratory, Newport News, VA
- 6GeV e- at 200 uA continuous current
- Nuclear physics, precision spectroscopy, etc

Research machines: just the tip of the iceberg



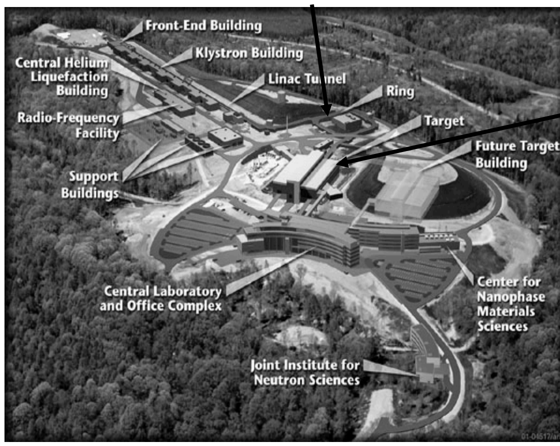
Annual growth is several percent

Sales >3.5 B$/yr

Value of treated good > 50 B$/yr **

Example: Spallation Neutron Source (Oak Ridge, TN)

A 1 GeV Linac will load 1.5E14 protons into a non-accelerating synchrotron ring.

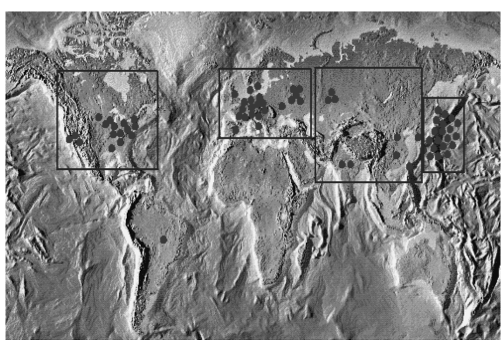


These are fast extracted onto a Mercury target

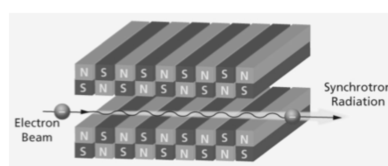
This happens at 60 Hz -> 1.4 MW

Neutrons are used for biophysics, materials science, industry, etc…

Light sources: too many to count



- Put circulating electron beam through an "undulator" to create synchrotron radiation (typically X-ray)
- Many applications in biophysics, materials science, industry.
- New proposed machines will use very short bunches to create coherent light.



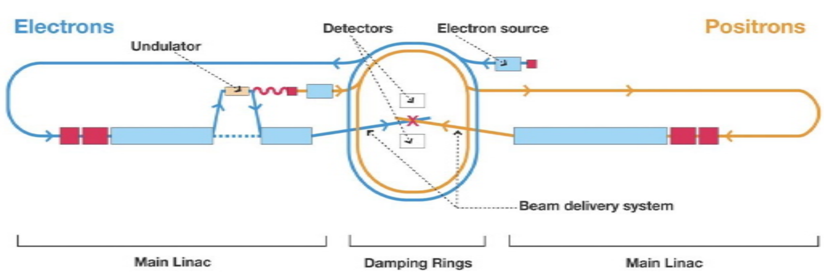
Other uses of accelerators

- Radioisotope production
- Medical treatment
- Electron welding
- Food sterilization
- Catalyzed polymerization
- Even art…

In a "Lichtenberg figure", a low energy electron linac is used to implant a layer of charge in a sheet of lucite. This charge can remain for weeks until it is discharged by a mechanical disruption.

The future: International Linear Collider (ILC)?

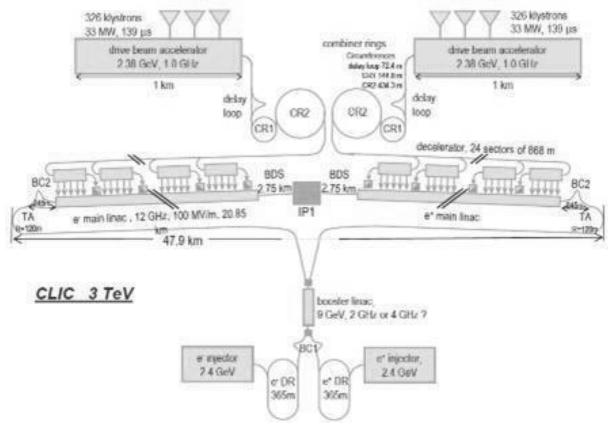
- LEP was the limit of circular e^+e^- colliders
  - Next step must be linear collider
  - Proposed ILC 30 km long, 250 x 250 GeV e^+e^-



- BUT, we don't yet know whether that's high enough energy to be interesting
  - Need to wait for LHC results
  - What if we need more?

"Compact" (ha ha) Linear Collider (CLIC)?

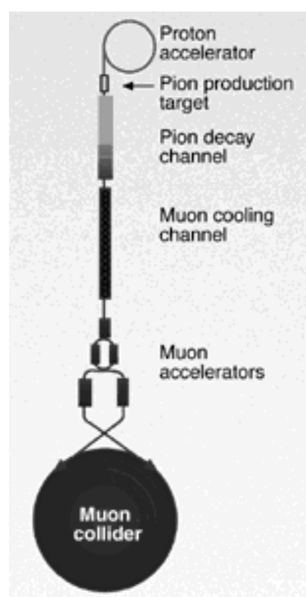
- Use low energy, high current electron beams to drive high energy accelerating structures



- Up to 1.5 x 1.5 TeV, but VERY, VERY hard

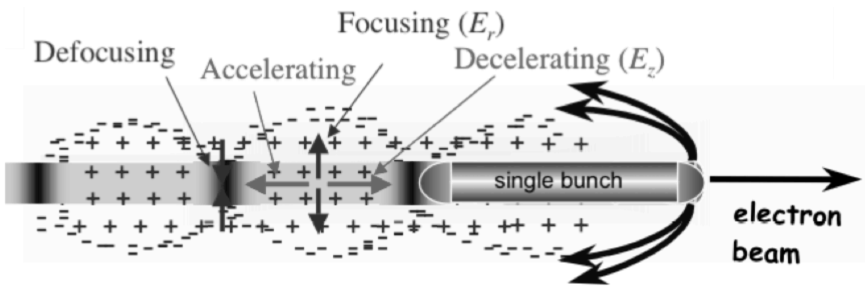
Muon colliders?

- Muons are pointlike, like electrons, but because they're heavier, synchrotron radiation is much less of a problem.
- Unfortunately, muons are unstable, so you have to produce them, cool them, and collide them, before they decay.



Wakefield accelerators?

- Many advances have been made in exploiting the huge fields that are produced in plasma oscillations.



- Potential for accelerating gradients many orders of magnitude beyond RF cavities.
- Still a long way to go for a practical accelerator.