Particle Accelerators Part 2

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8/18/10

Today’s outline

- Some “tricks of the trade”
  - Ion injection
  - Beam injection/extraction/transfer
  - Instrumentation
- Special topic
  - pBars
- Case Study: LHC
  - Design Choices
  - Superconductivity
  - Specifications
  - “The Incident”
  - Current status
  - Future upgrades
- Overview of other accelerators
  - Past
  - Present
  - Future

Linac -> synchrotron injection

- Most accelerators start with a linear accelerator, which injects into a synchrotron

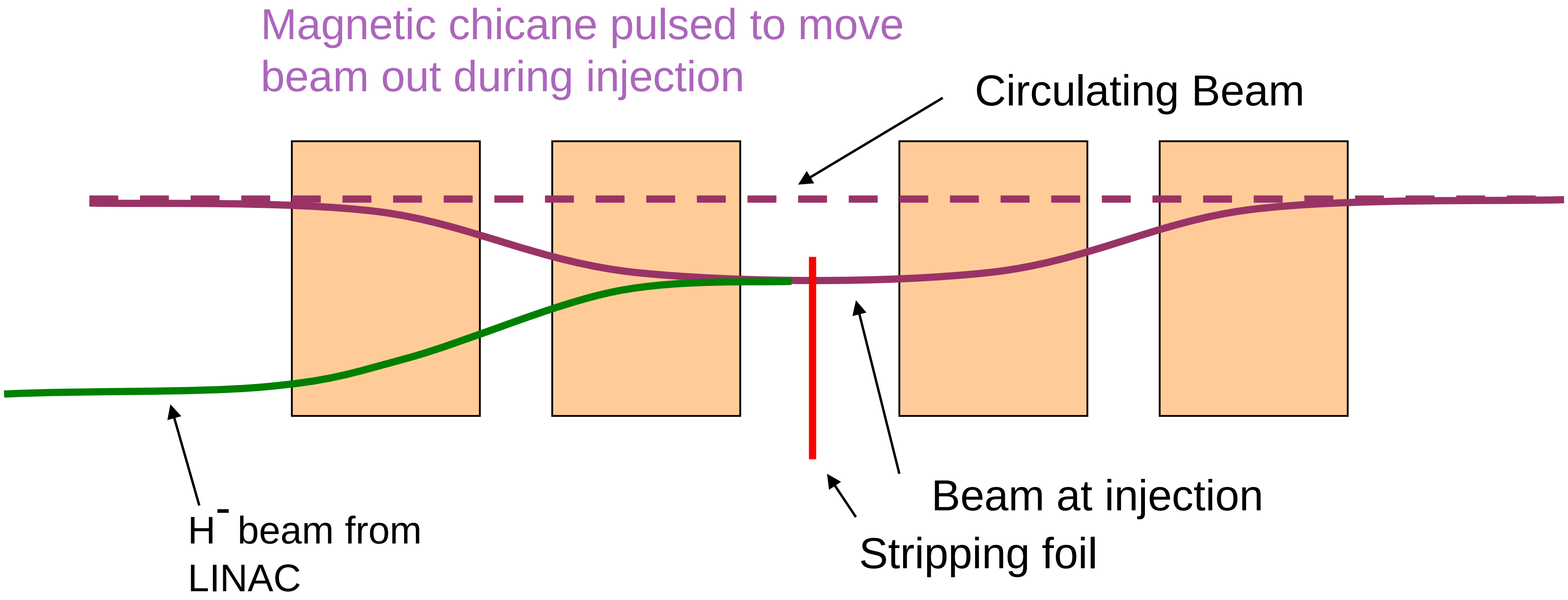
- In order to maximize the intensity in the synchrotron, we can
  - Increase the linac current as high as possible and inject over one revolution
    - There are limits to linac current
  - Inject over multiple (*N*) revolutions of the synchrotron
    - Preferred method
- Unfortunately, Liouville’s Theorem 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

$$\varepsilon_S \geq N\varepsilon_{LINAC}$$

Synchrotron emittance

Linac emittance

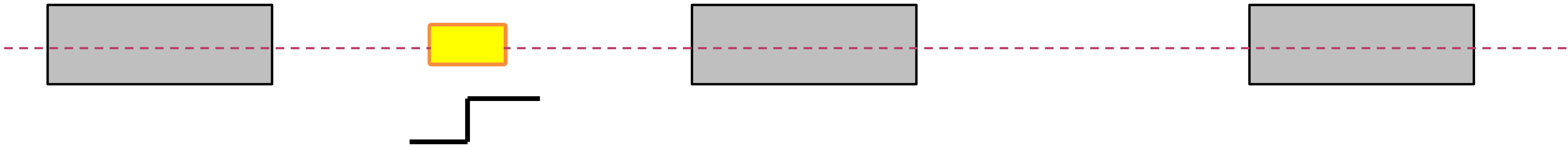
Ion (or charge exchange) injection



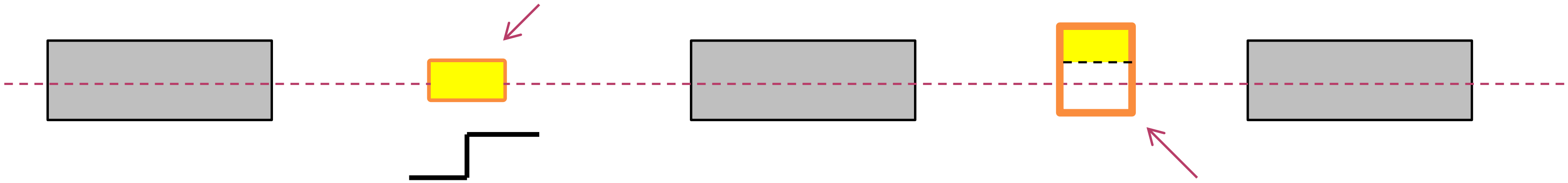
- Instead of ionizing Hydrogen, and electron is added to create H^-, which is accelerated in the linac
- A pulsed chicane moves the circulating beam out during injection
- An injected H^- beam is bent in the opposite direction so it lies on top of the circulating beam
- The combined beam passes through 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.

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:



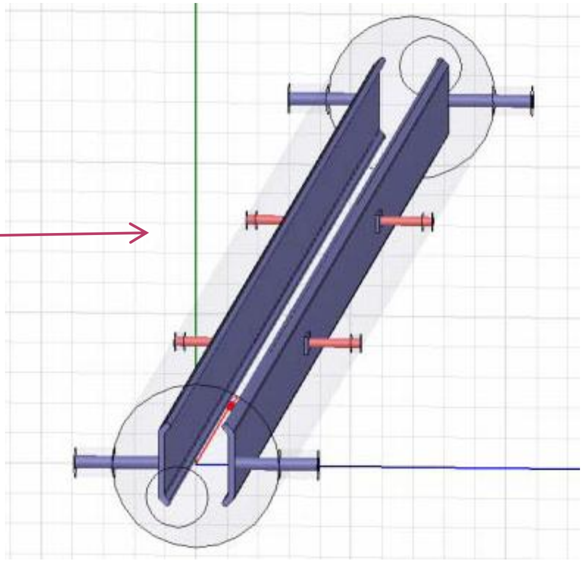
fast, weak “kicker”

slower (or DC) extraction magnet with zero field on beam path.

Extraction hardware

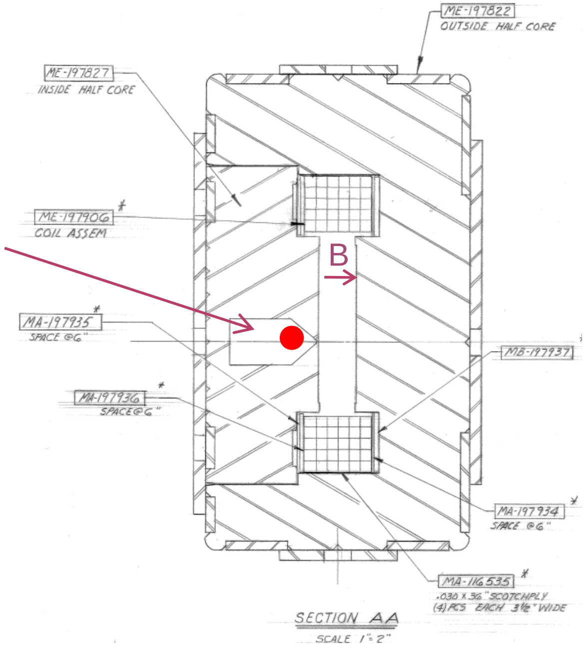
“Fast” kicker

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



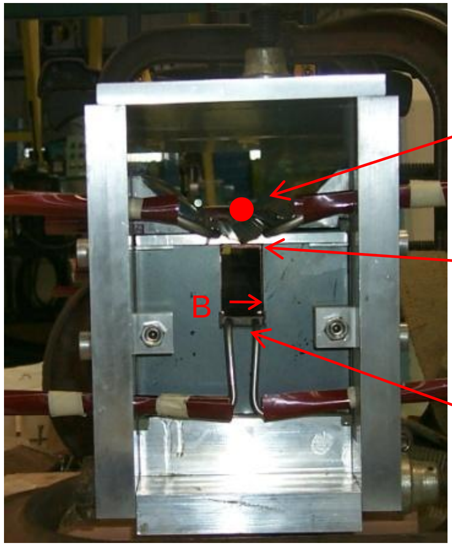
“Slow” extraction elements

“Lambertson”: usually DC



circulating beam (B=0)

Septum: pulsed, but slower than the kicker



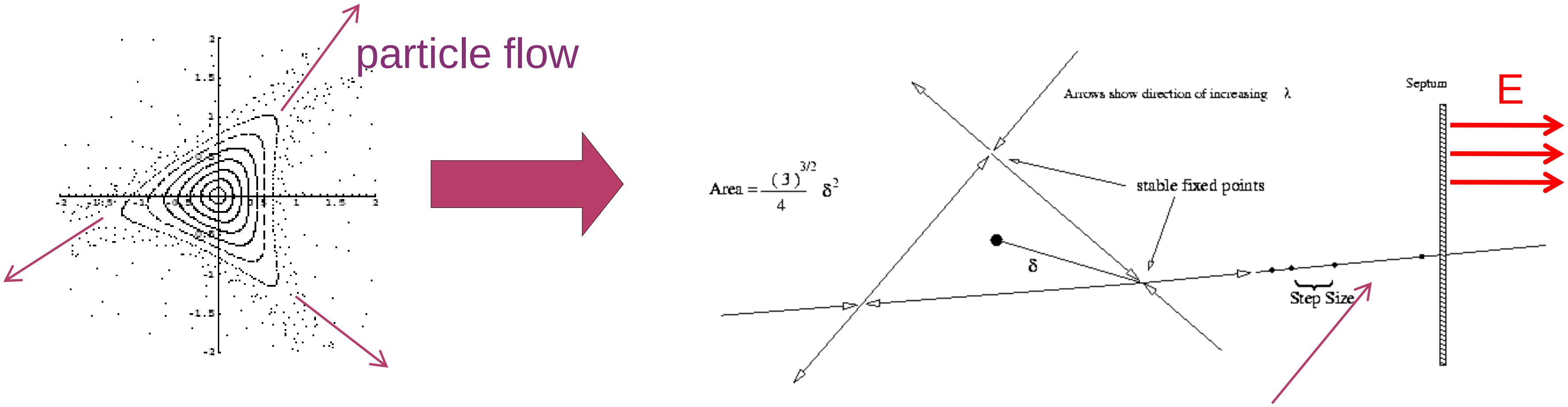
circulating beam (B=0)

current “blade”

return path

Slow Extraction

- A harmonic resonance is generated
  - Usually sextupoles are used to create a 3rd order resonant instability

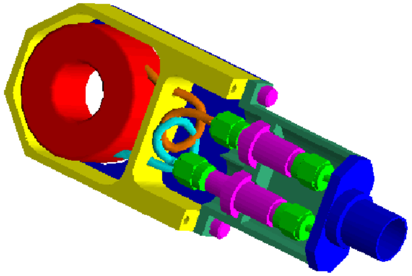


Particles will flow out of the stable region along lines in phase space into an electrostatic extraction field, which will deflect them into an extraction Lambertson

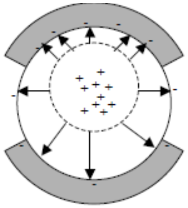
- Tune the instability so the escaping beam exactly fills the extraction gap between interceptions (3 times around for 3rd order)
  - Minimum inefficiency ~(septum thickness)/(gap size)
  - Use electrostatic septum made of a plane of wires. Typical parameters
    - Septum thickness: .1 mm
    - Gap: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

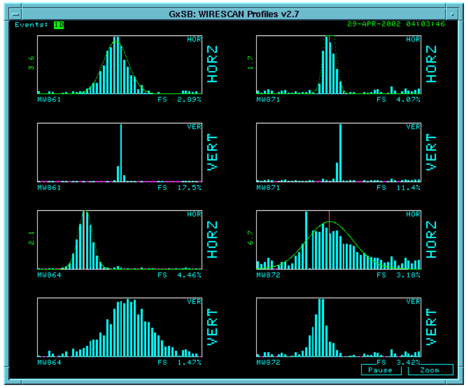


$$\Delta y \cong C \frac{I_{Top} - I_{Bottom}}{I_{Top} + I_{Bottom}}$$

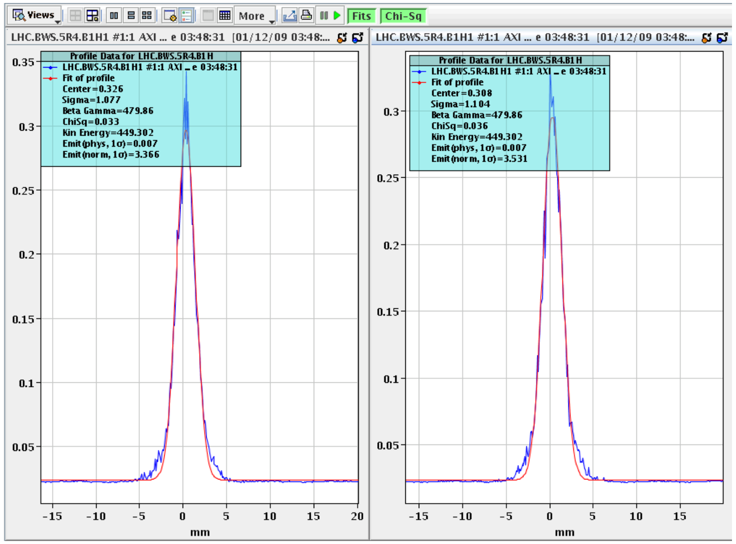
- Longitudinal profiles can be measured by introducing a resistor to measure the induced image current on the beam pipe -> Resistive Wall Monitor (RWM)

Beam instrumentation (cont'd)

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



Beam profiles in MiniBooNE beam line



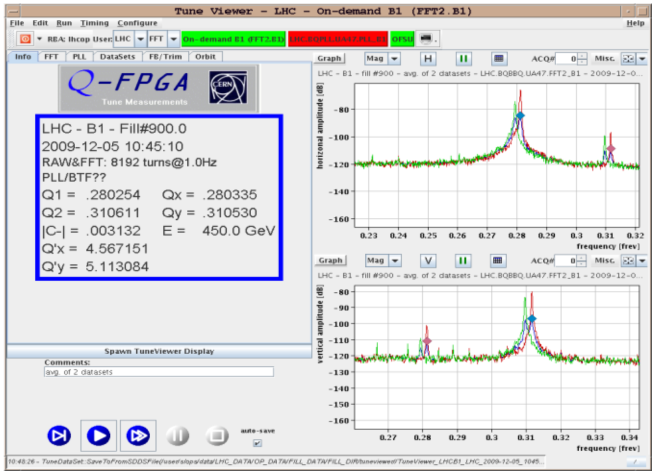
Profile Data for LHC.BWS.5R4.B1H
LHC.BWS.5R4.B1H1 #1:1 AXI _ e 03:48:31
Fit of profile
Center=0.326
Sigma=1.077
Beta Gamma=479.86
ChiSq=0.033
Kin Energy=449.302
Emit(phys, 1σ)=0.007
Emit(norm, 1σ)=3.366

Profile Data for LHC.BWS.5R4.B1H
LHC.BWS.5R4.B1H1 #1:1 AXI _ e 03:48:31
Fit of profile
Center=0.308
Sigma=1.104
Beta Gamma=479.86
ChiSq=0.036
Kin Energy=449.302
Emit(phys, 1σ)=0.007
Emit(norm, 1σ)=3.531

Flying wire signal in LHC

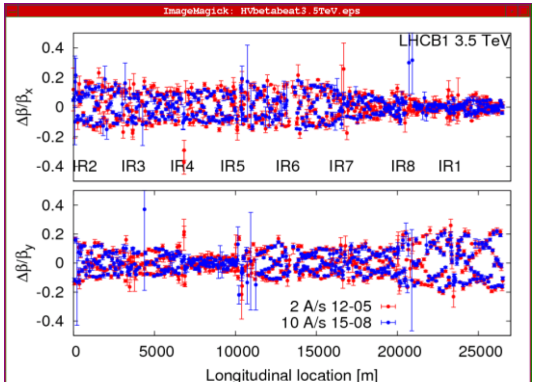
Measuring lattice parameters

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



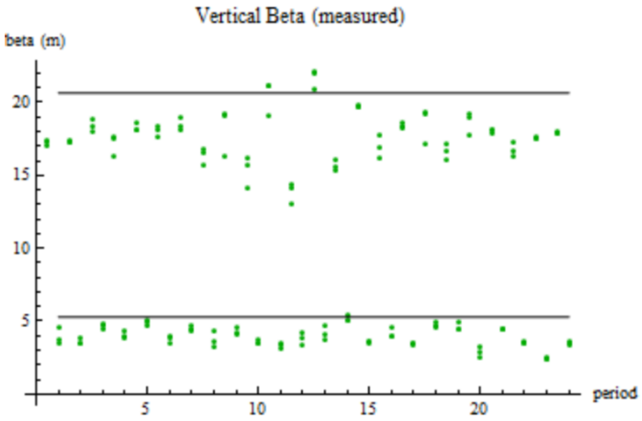
LHC - B1 - Fill#900.0
2009-12-05 10:45:10
RAW&FFT: 8192 turns@1.0Hz
PLL/BTF??
Q1 = .280254 Qx = .280335
Q2 = .310611 Qy = .310530
|C-| = .003132 E = 450.0 GeV
Q'x = 4.567151
Q'y = 5.113084

- 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

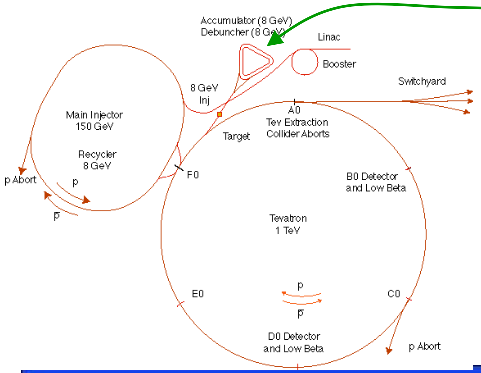
$$\Delta\nu = \frac{1}{4\pi}\frac{\beta}{f}$$

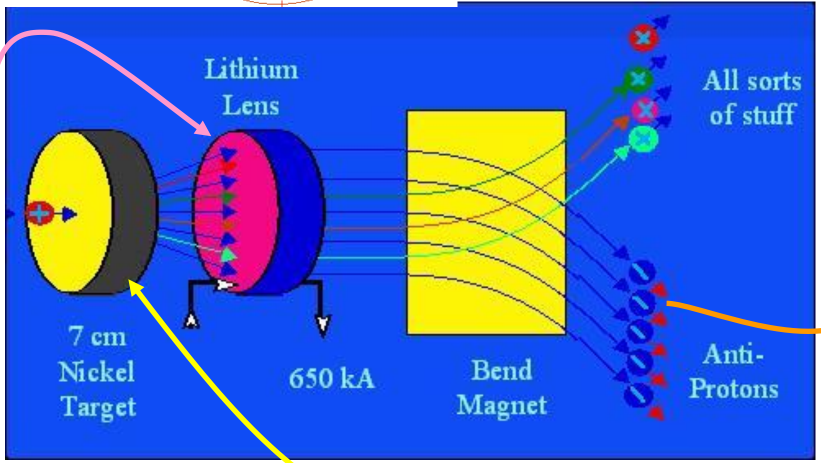


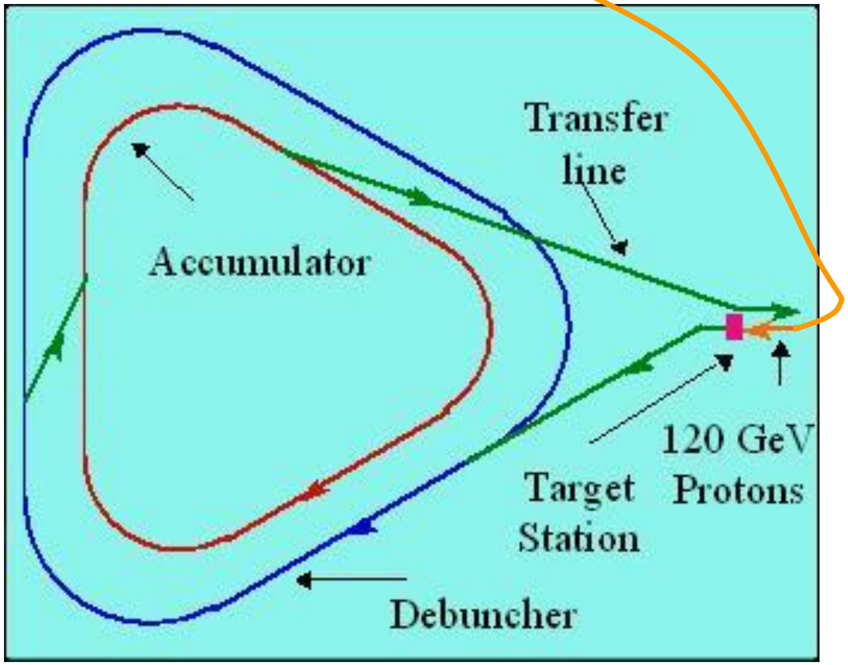
A case study: the LHC

- How were the choices made?
  - Colliding beams vs. fixed target ✓ **Done**
  - Protons vs. electrons ✓ **Done**
  - Proton-proton vs. proton anti-proton
  - Superconducting magnets
  - Energy and Luminosity

Special Topic: Fermilab Antiproton Source



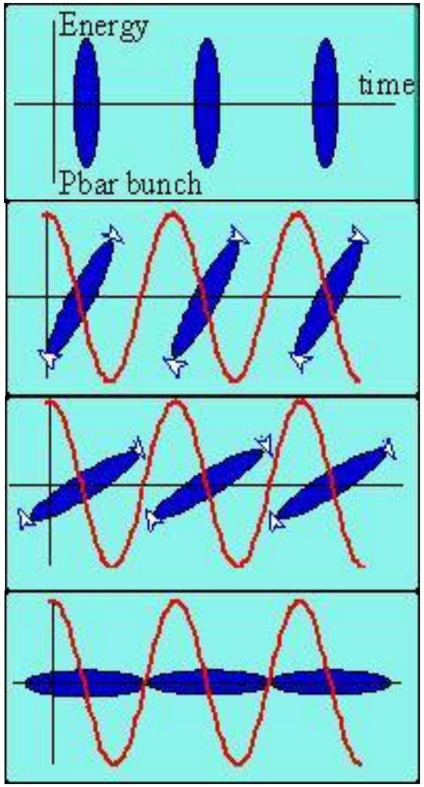




- 120 GeV protons strike a target, producing many things, including antiprotons.
- a Lithium lens focuses these particles (a bit)
- a bend magnet selects the negative particles around 8 GeV. Everything but antiprotons decays away.

- 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…

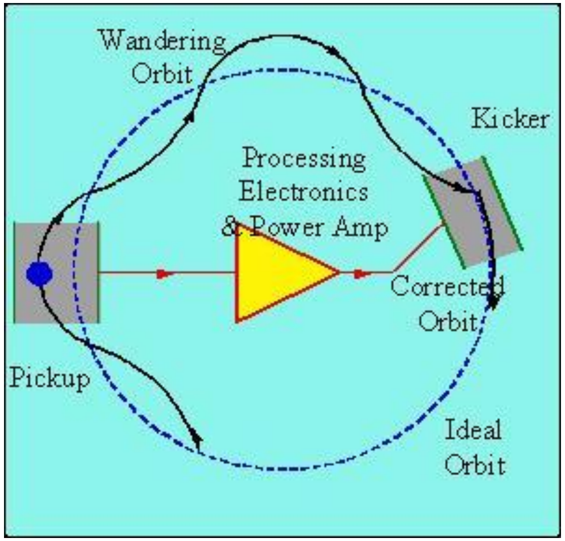
…and the RF is phased so they are decelerated (accelerated),

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.

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) have done 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!
  - Takes a day to make enough antiprotons for a "store" in the Fermilab Tevatron
  - Ultimately, the luminosity is limited by the antiproton current.
- Thus, the LHC was designed as a proton-proton collider.

Superconducting magnets

- For a proton accelerator, we want the most powerful magnets we can get
- Conventional electromagnets are limited by the resistivity of the conductor (usually copper)

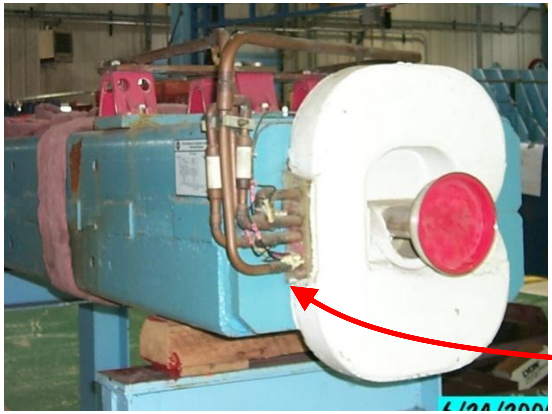
Power lost

$$P = I^2 R \propto B^2$$

Square of the field

- The field of high duty factor conventional magnets is limited to about 1 Tesla
  - An LHC made out of such magnets would be 40 miles in diameter – approximately the size of Rhode Island.
- The highest energy accelerators are only possible because of superconducting magnet technology.

Issues with superconducting magnets

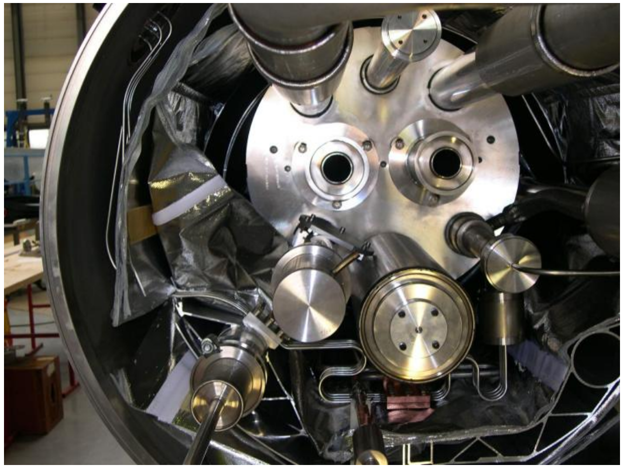


- Conventional magnets operate at room temperature. The cooling required to dissipate heat is usually provided by fairly simple low conductivity water (LCW) heat exchange systems.

- Superconducting magnets must be immersed in liquid (or superfluid) He, which requires complex infrastructure and cryostats
- Any magnet represents stored energy

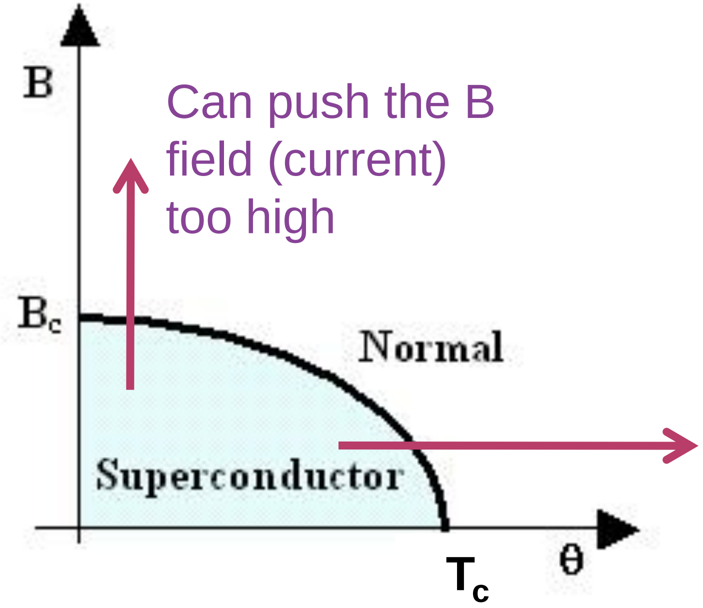
$$E = \frac{1}{2}LI^2 = \frac{1}{2\mu}\int B^2 dV$$

  - In a conventional magnet, this is dissipated during operation.
  - In a superconducting magnet, you have to worry about where it goes, *particularly when something goes wrong*.



When is a superconductor not a superconductor?

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



Can push the B field (current) too high

Can increase the temp, through heat leaks, deposited energy or *mechanical deformation*

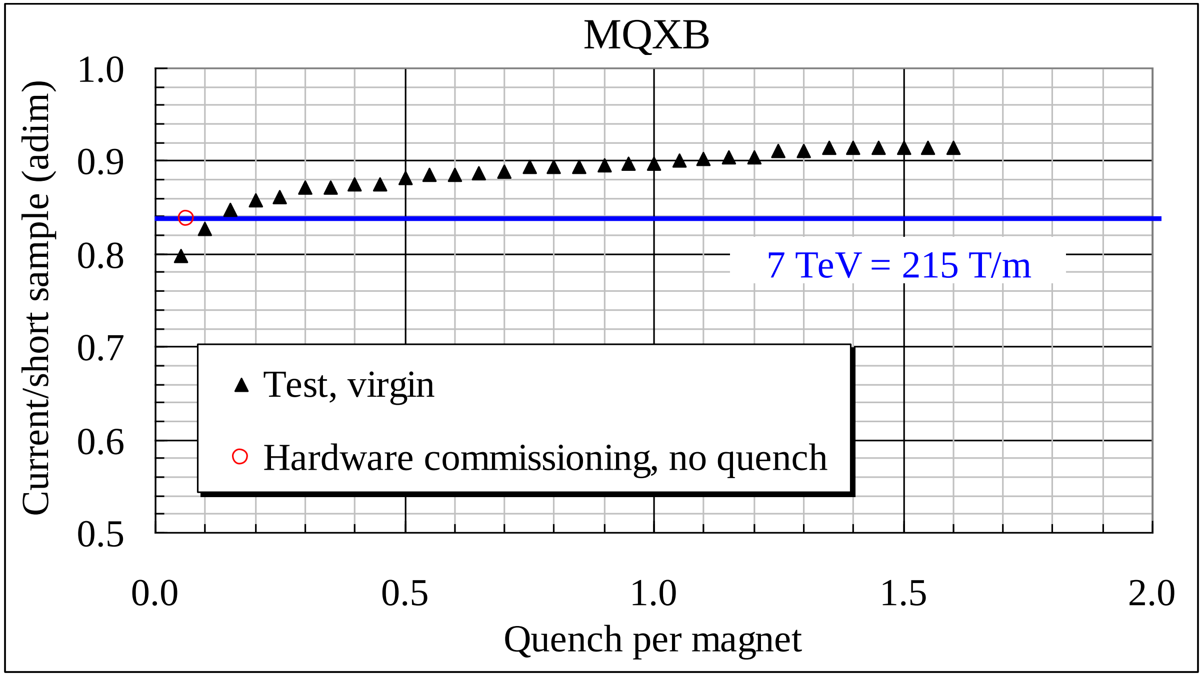
- When this happens, the conductor heats quickly, causing the surrounding conductor to go normal and dumping lots of heat into the liquid Helium
- This is known as a "quench".

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"

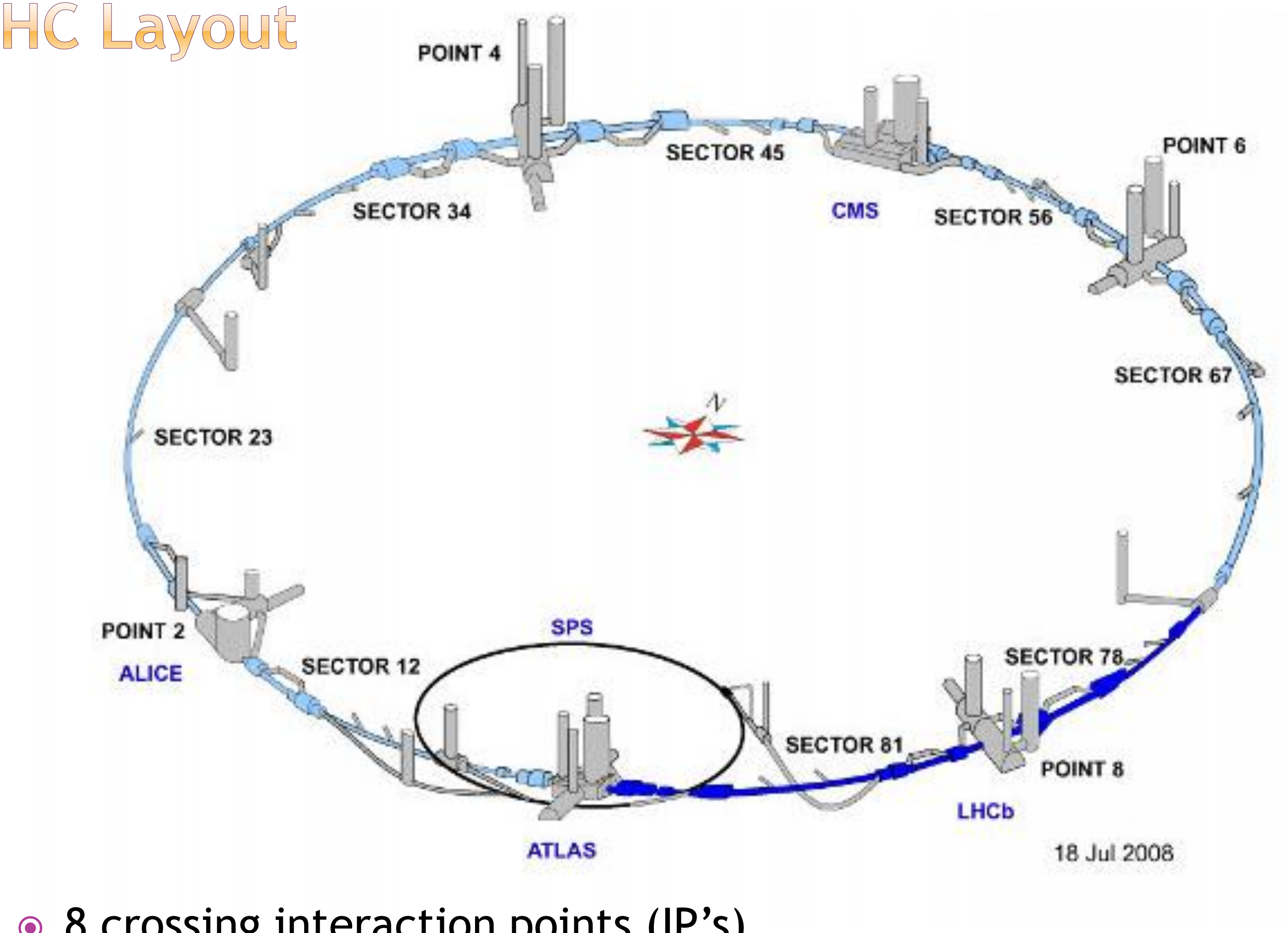


Nominal LHC parameters compared to Tevatron

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	$275\text{x}10^9$	$115\text{x}10^9$
pBar/bunch	$80\text{x}10^9$	-
Stored beam energy	1.6 + .5 MJ	366+366 MJ*
Initial luminosity	$3.3\text{x}10^{32}$ ($\text{cm}^{-2}\text{s}^{-1}$)	$1.0\text{x}10^{34}$($\text{cm}^{-2}\text{s}^{-1}$)
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)

*2 MJ ~ “stick of dynamite” -> Very scary

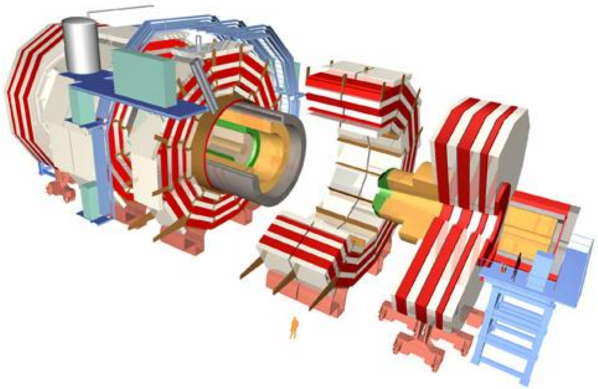
LHC Layout



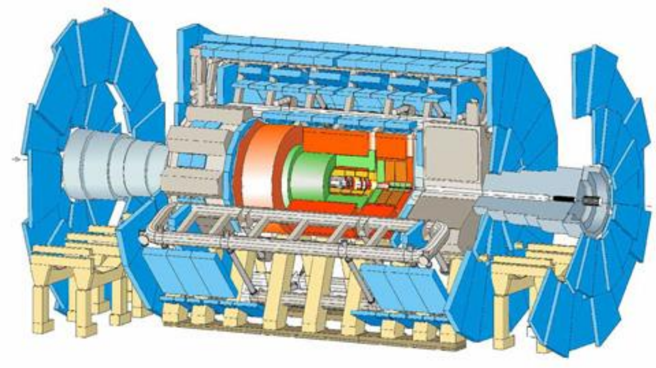
- 8 crossing interaction points (IP's)
- Accelerator sectors labeled by which points they go between
  - ie, sector 3-4 goes from point 3 to point 4

CERN experiments

- Damn big, general purpose experiments:

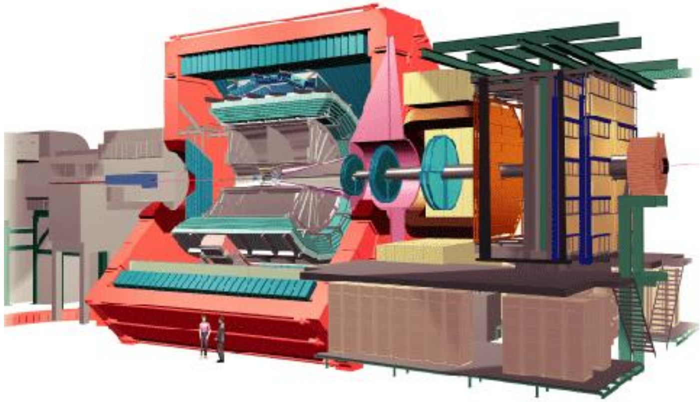


Compact Muon Solenoid (CMS)

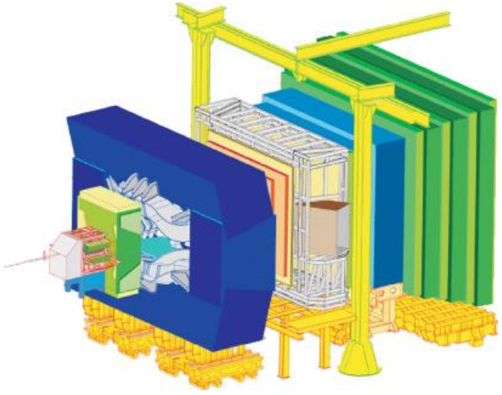


A Toroidal LHC ApparatuS (ATLAS)

- "Medium" special purpose experiments:

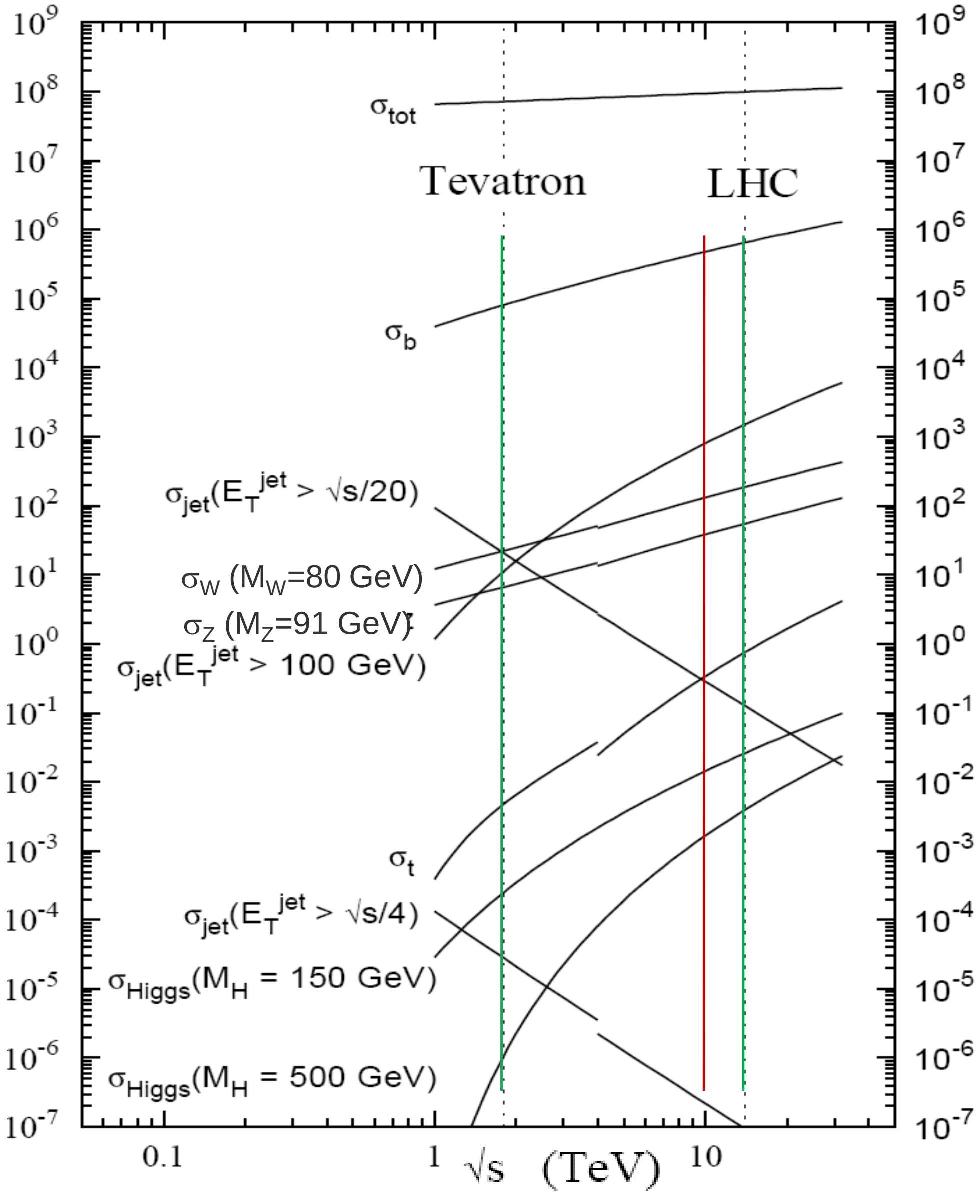


A Large Ion Collider Experiment (ALICE)



B physics at the LHC (LHCb)

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

Sept 10, 2008: The (first) big day

- 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

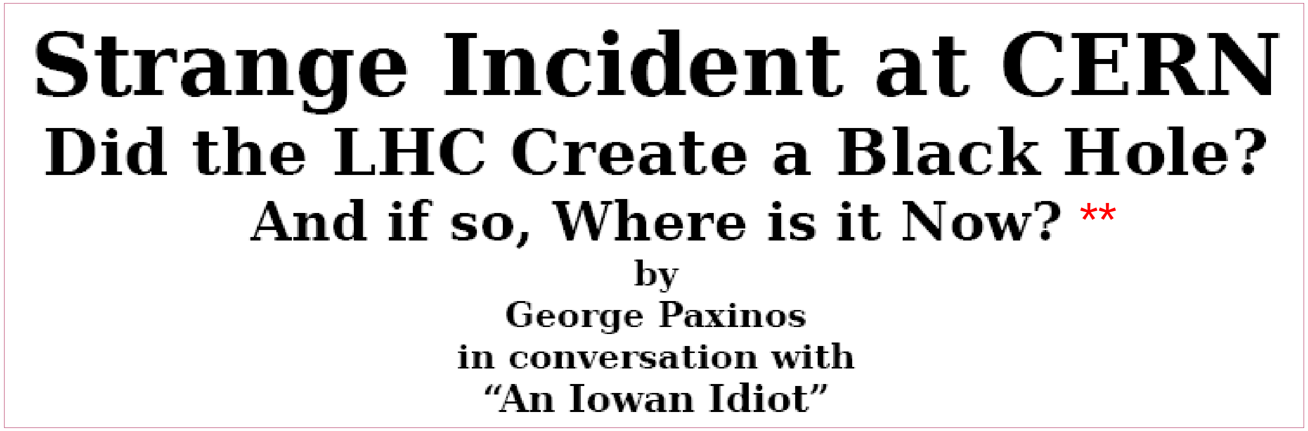
Commissioning proceeded smoothly and rapidly until September 19th, when *something* very bad happened

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

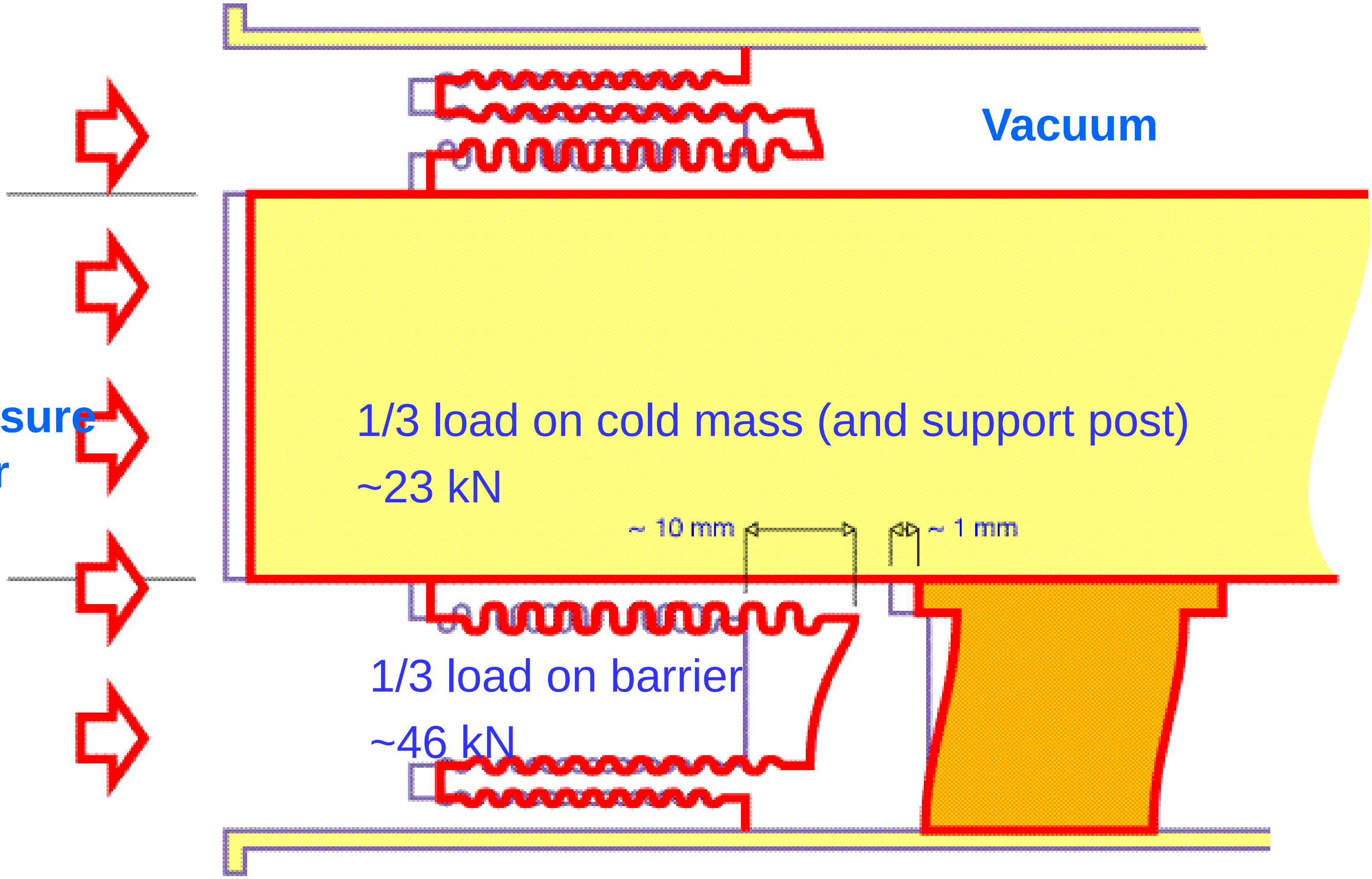
**http://www.rense.com/general83/IncidentatCERN.pdf

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



Vacuum

Pressure
1 bar

1/3 load on cold mass (and support post)

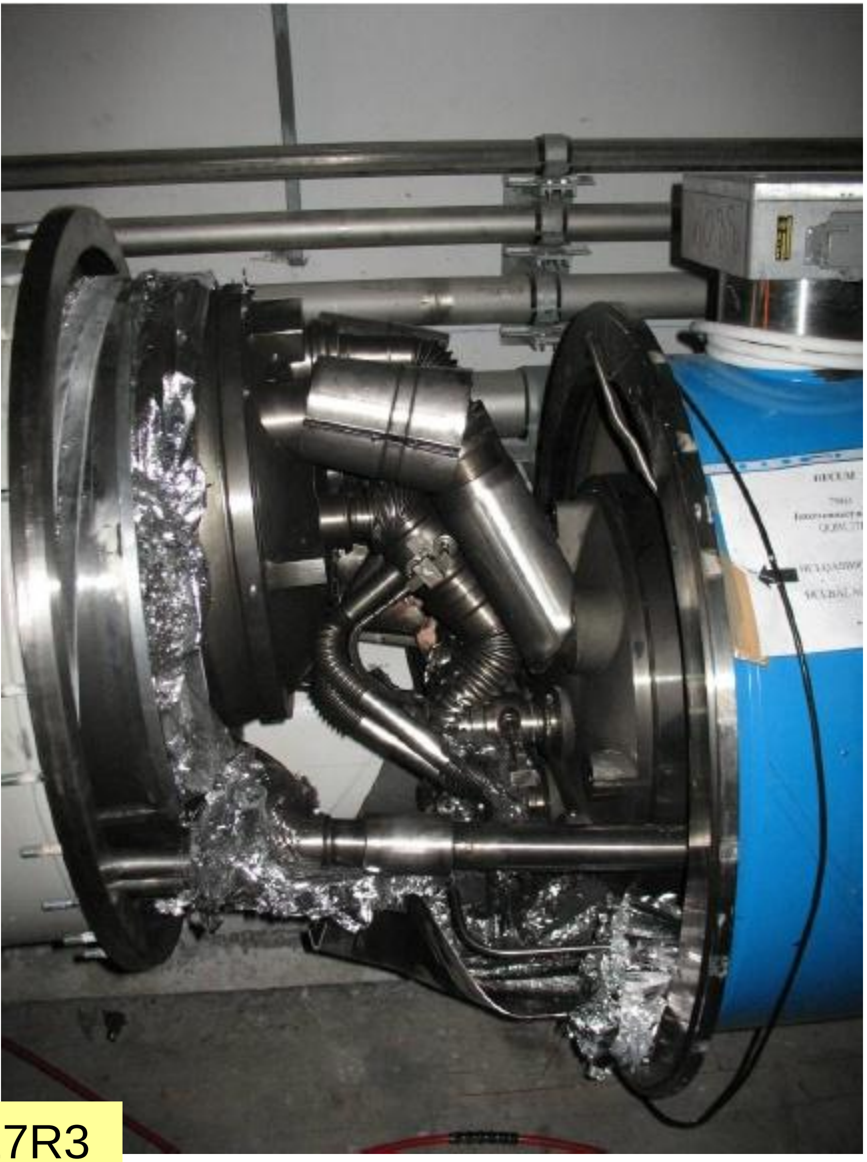
~23 kN

1/3 load on barrier

~46 kN

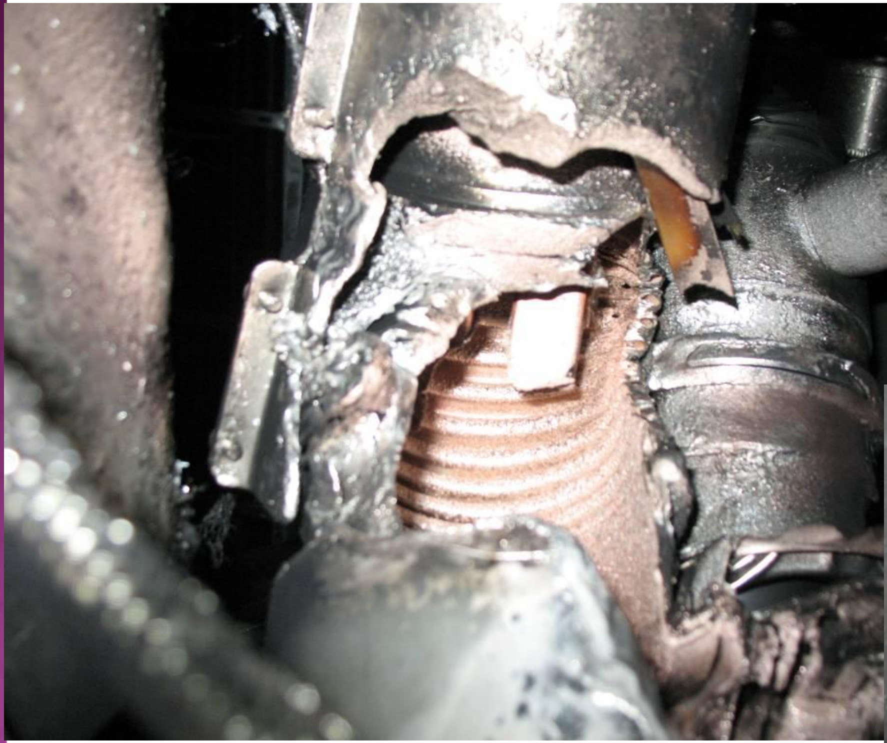
Total load on 1 jack ~70 kN V. Parma

Collateral damage: magnet displacements



QQBI.27R3

Collateral damage: secondary arcs



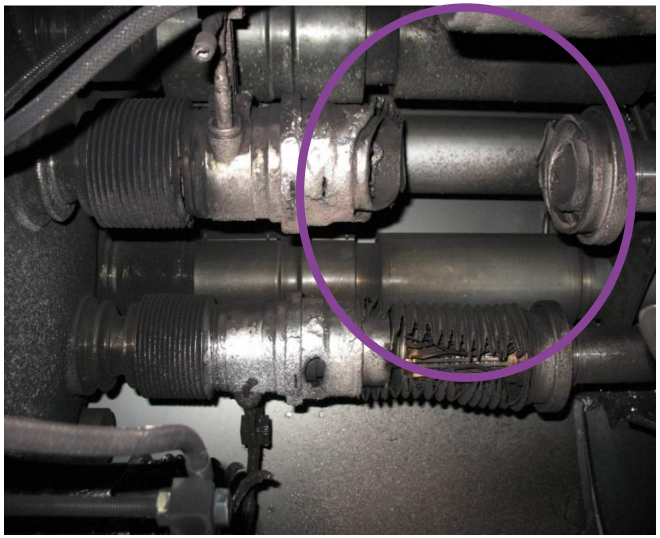
QQBI.27R3 M3 line

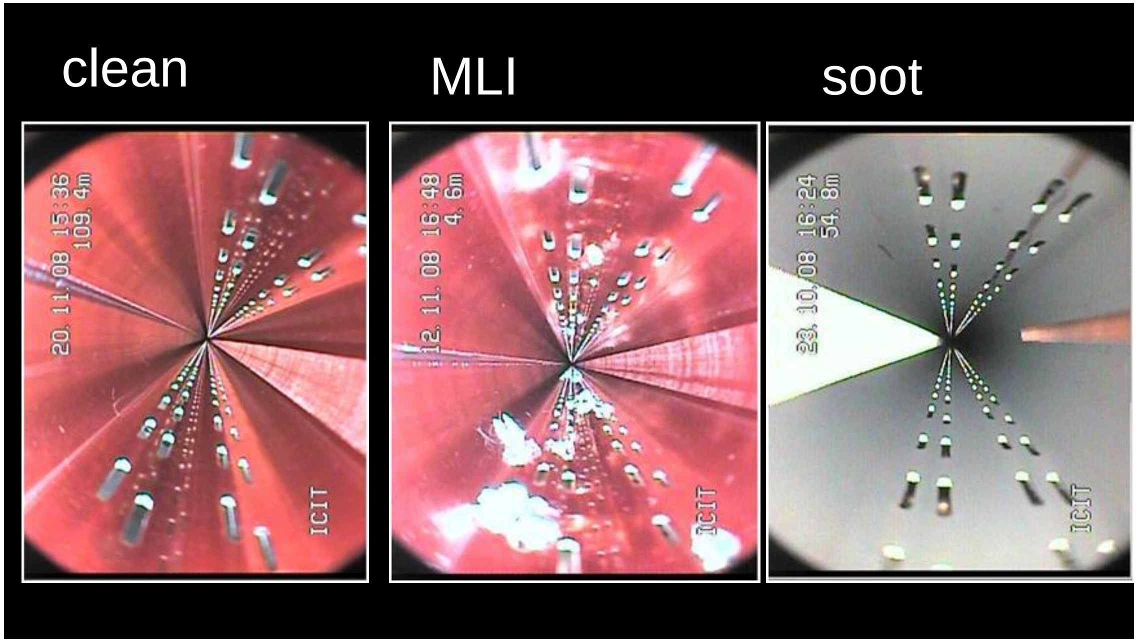
QBBI.B31R3 M3 line

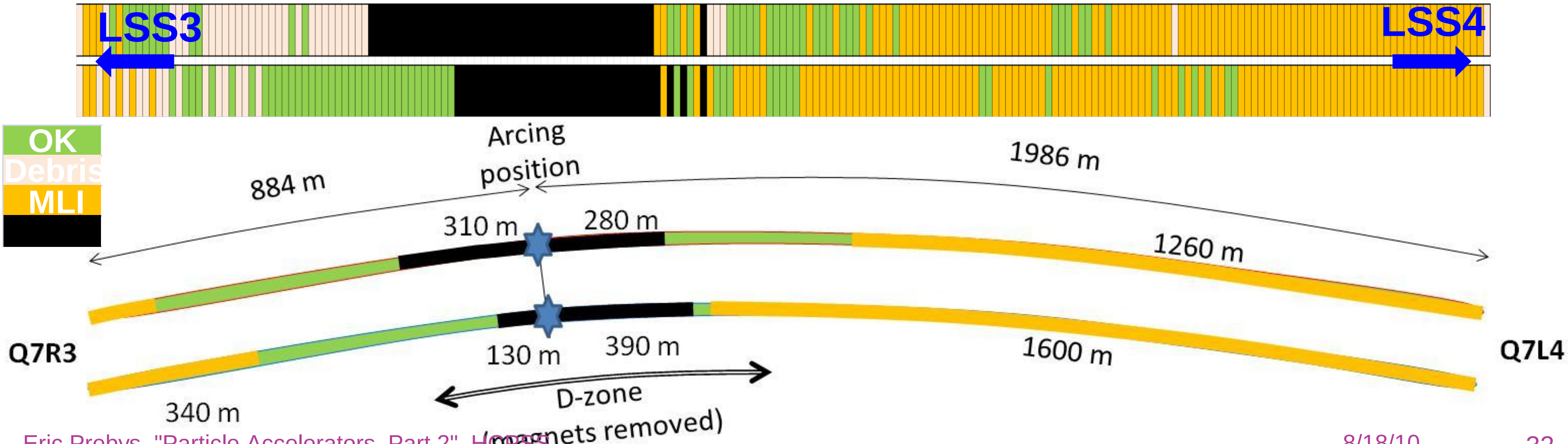
Collateral damage: ground supports

Collateral damage: Beam Vacuum

Arc burned through beam vacuum pipe





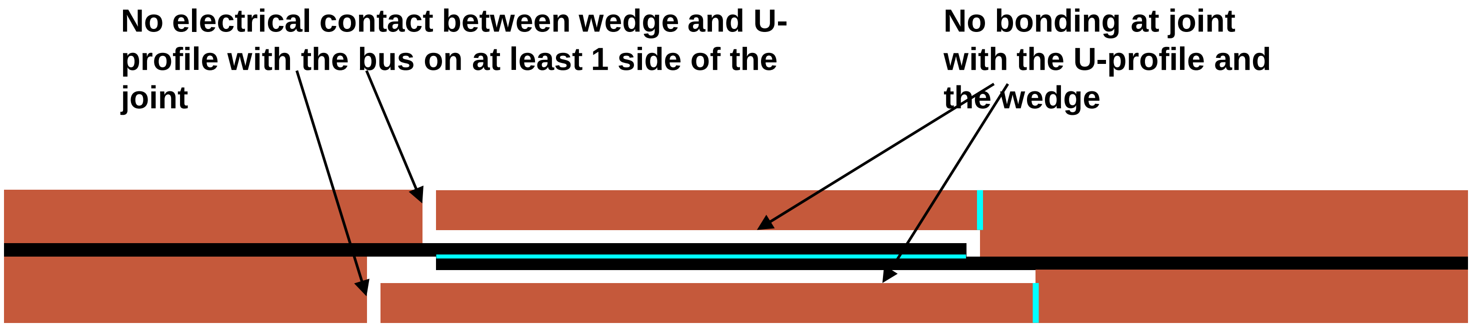


Important questions about Sept. 19

- 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?

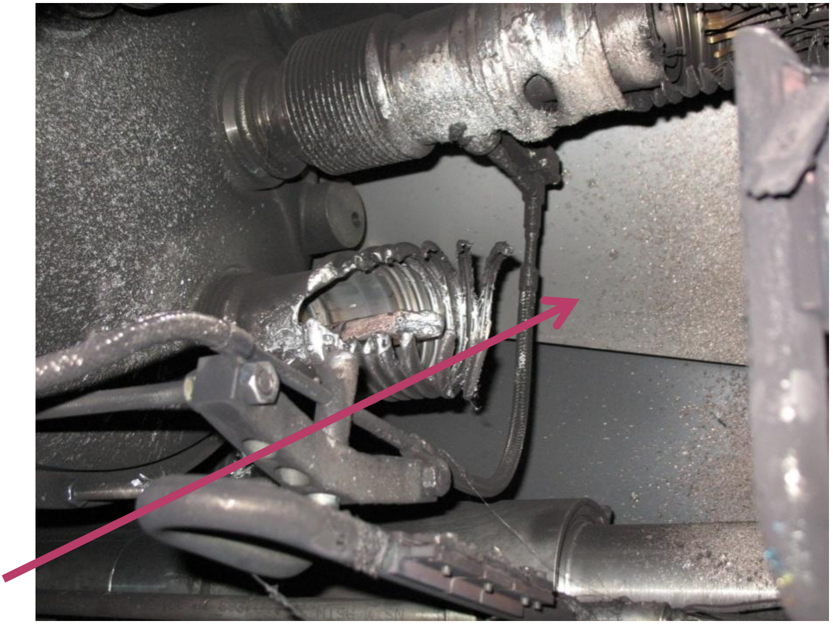
Working theory: A resistive joint of about 220 nΩ with bad electrical and thermal contacts with the stabilizer



No electrical contact between wedge and U-profile with the bus on at least 1 side of the joint

No bonding at joint with the U-profile and the wedge

- 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

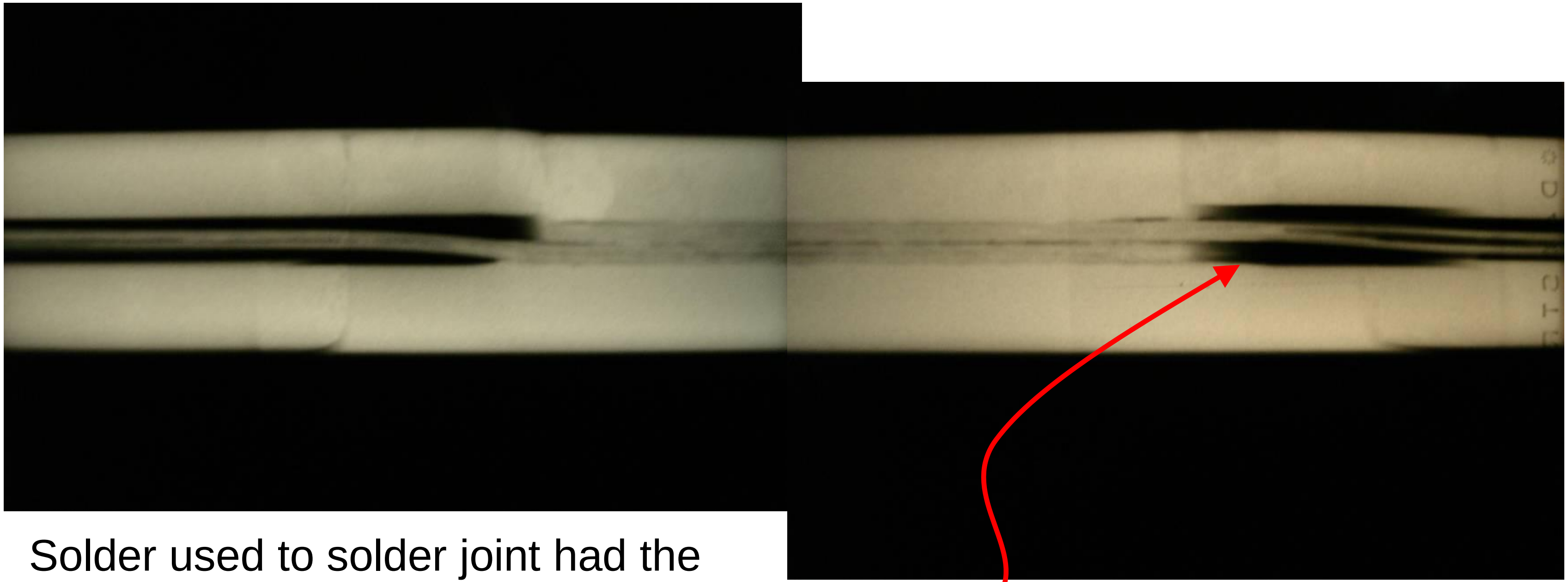
A. Verweij

Improvements

- 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

Bad surprise

- With new quench protection, it was determined that joints would only fail if they had bad thermal *and* bad electrical contact, and how likely is that?
  - Very, unfortunately ⇒ *must* verify copper joint



Solder used to solder joint had the same melting temperature as solder used to pot cable in stablizer

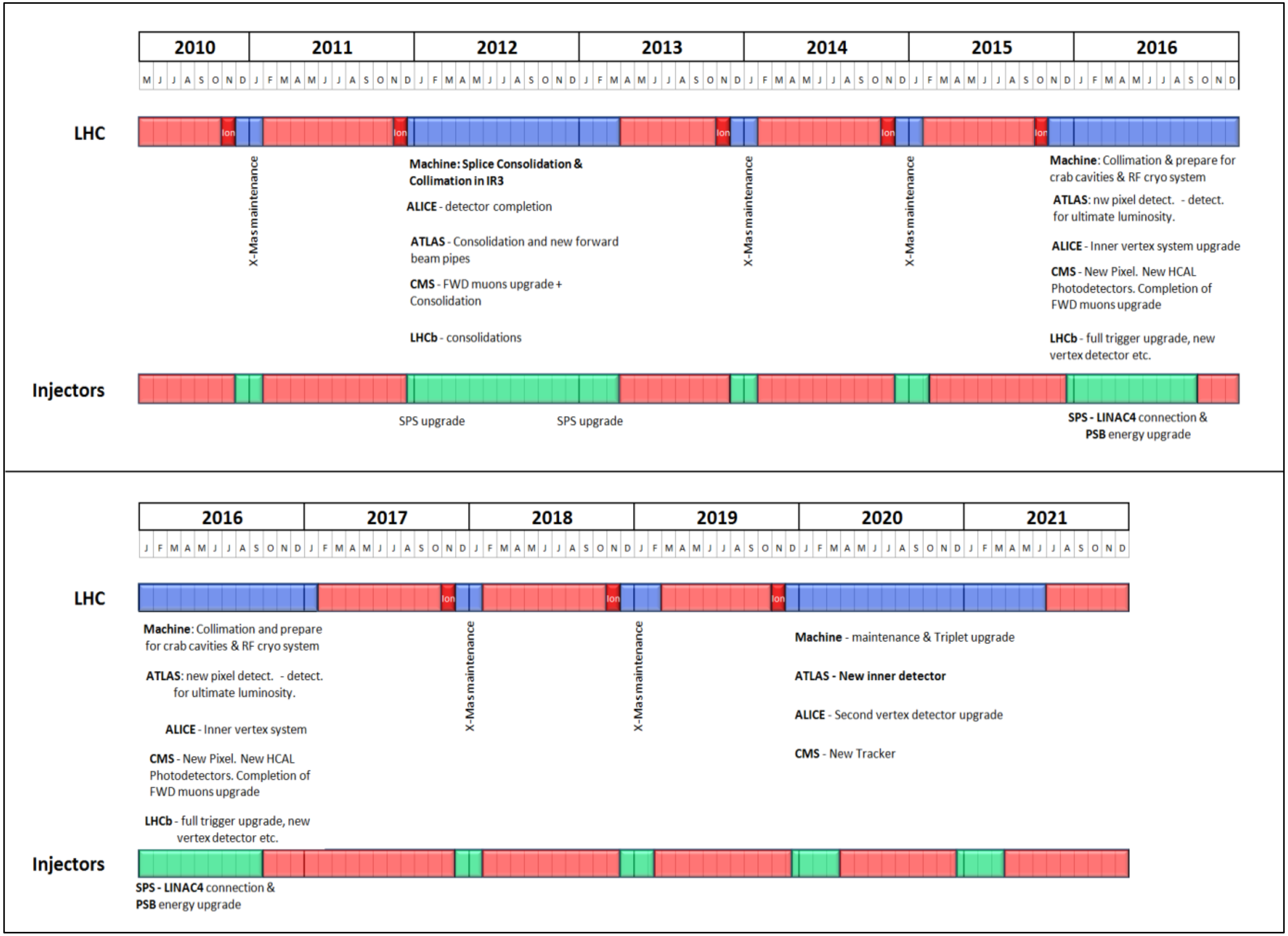
⇒Solder wicked away from cable

- Have to warm up to at least 80K to measure Copper integrity.

Impact of joint problem

- Tests at 80K identified an additional bad joint
  - One additional sector was warmed up
  - New release flanges were NOT installed
- Based on thermal modeling of the joints, it was determined that they might NOT be reliable even at 5 TeV
  - 3.5 TeV considered the maximum safe operating energy for now

Tentative LHC Plan



Machine: Splice Consolidation & Collimation in IR3

ALICE - detector completion

ATLAS - Consolidation and new forward beam pipes

CMS - FWD muons upgrade + Consolidation

LHCb - consolidations

Machine: Collimation & prepare for crab cavities & RF cryo system

ATLAS: nw pixel detect. - detect. for ultimate luminosity.

ALICE - Inner vertex system upgrade

CMS - New Pixel. New HCAL Photodetectors. Completion of FWD muons upgrade

LHCb - full trigger upgrade, new vertex detector etc.

SPS upgrade

SPS upgrade

SPS - LINAC4 connection &
PSB energy upgrade

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Machine - maintenance & Triplet upgrade

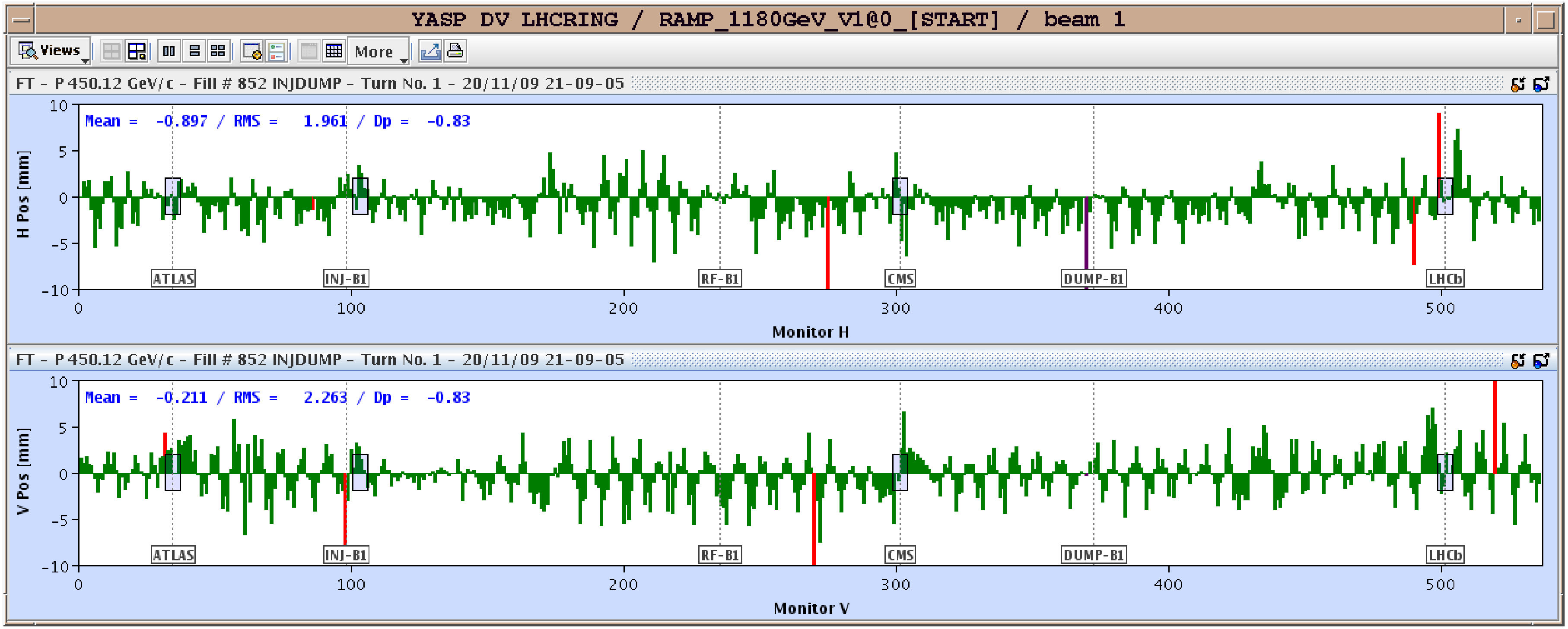
ATLAS - New inner detector

ALICE - Second vertex detector upgrade

CMS - New Tracker

SPS - LINAC4 connection &
PSB energy upgrade

November 20, 2009: Going around…again



YASP DV LHCRING / RAMP_1180GeV_V1@0_[START] / beam 1

FT - P 450.12 GeV/c - Fill # 852 INJDUMP - Turn No. 1 - 20/11/09 21-09-05

Mean = -0.897 / RMS = 1.961 / Dp = -0.83

FT - P 450.12 GeV/c - Fill # 852 INJDUMP - Turn No. 1 - 20/11/09 21-09-05

Mean = -0.211 / RMS = 2.263 / Dp = -0.83

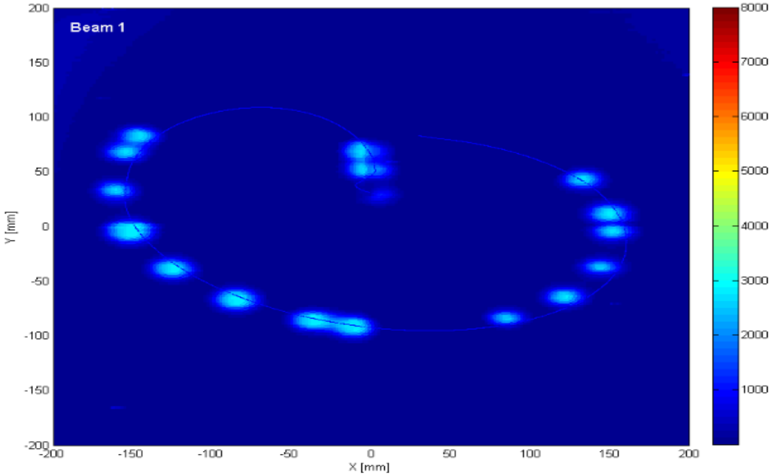
- Total time: 1:43
- Then things began to move with dizzying speed…

Progress since start up

- Sunday, November 29th, 2009:
  - Both beams accelerated to 1.18 TeV simultaneously
  - LHC Highest Energy Accelerator
- Monday, December 14th
  - Stable 2x2 at 1.18 TeV
  - Collisions in all four experiments
  - LHC Highest Energy Collider
- Tuesday, March 30th, 2010
  - Collisions at 3.5+3.5 TeV
  - LHC Reaches target energy for 2010/2011

General plan

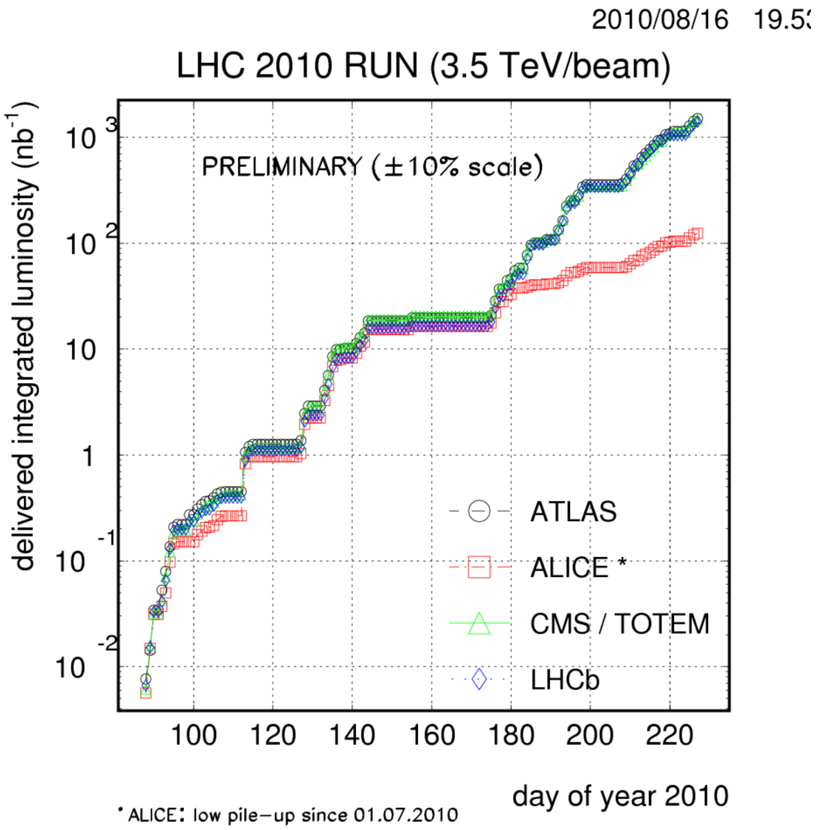
- Push bunch intensity
  - Already reached nominal bunch intensity of 1.1×10^{11}
- Increase number of bunches
  - Up to 156, use symmetrically spaced bunches, then must introduce crossing angle
  - Beyond 156, go to 144 bunch trains with 50 ns bunch spacing
- At all points, must carefully verify
  - Beam collimation
  - Beam protection
  - Beam abort

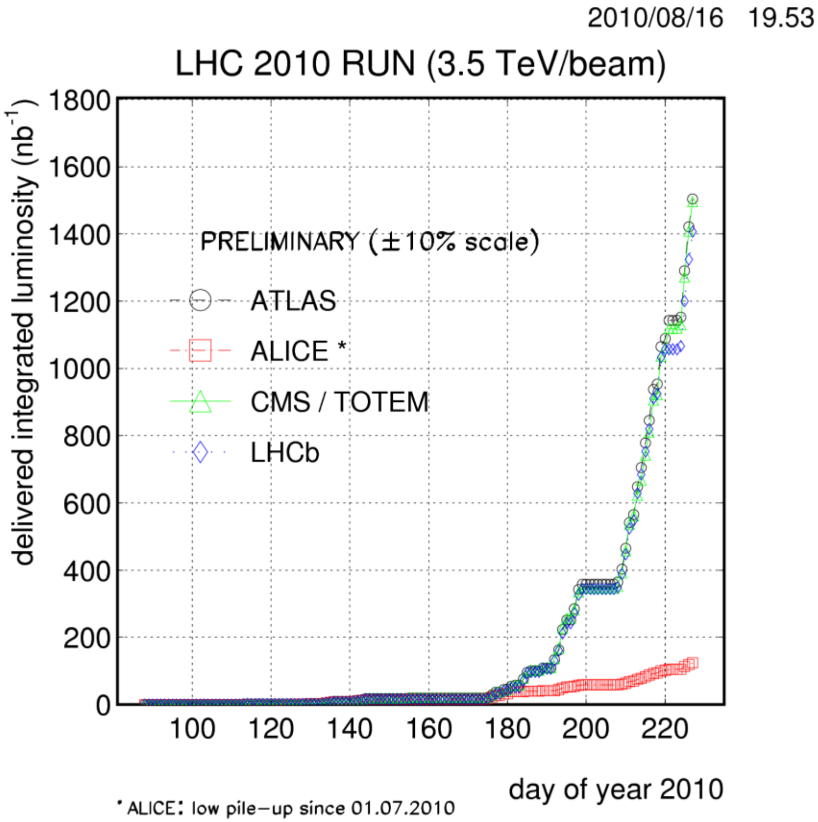


Example: beam sweeping over abort

Current Status

- Reached 25x25 bunches
  - Peak luminosity ~4-5x10^{30} cm^{-2}s^{-1}

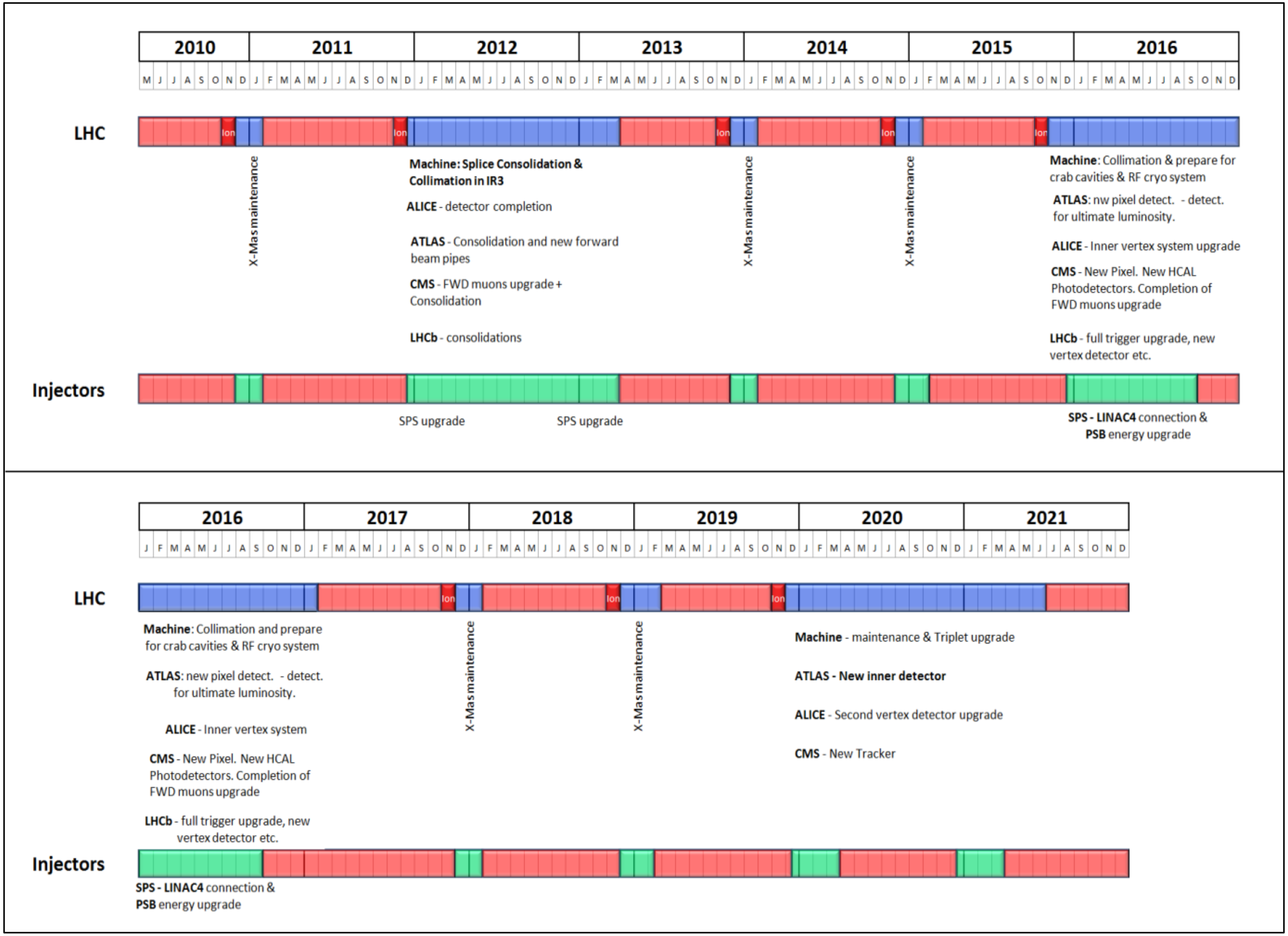




Future plans for LHC (as of Chamonix 2010)

- Run until end of 2011, or until 1 fb^{-1} of integrated luminosity
  - About .1% of the way there, so far
- Shut down for ~15 month to fully repair all ~10000 joints
  - Resolder
  - Install clamps
  - Install pressure relief on all cryostats
- Shut down in 2016
  - Tie in LINAC4
  - Increase Booster energy 1.4->2.0 GeV
  - Finalize collimation system
- Shut down in 2020
  - Full luminosity: 5×10^{34} leveled
  - New inner triplets based on Nb_3Sn
  - Crab cavities

Tentative LHC Plan



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LHCb - full trigger upgrade, new vertex detector etc.

Machine - maintenance & Triplet upgrade

ATLAS - New inner detector

ALICE - Second vertex detector upgrade

CMS - New Tracker

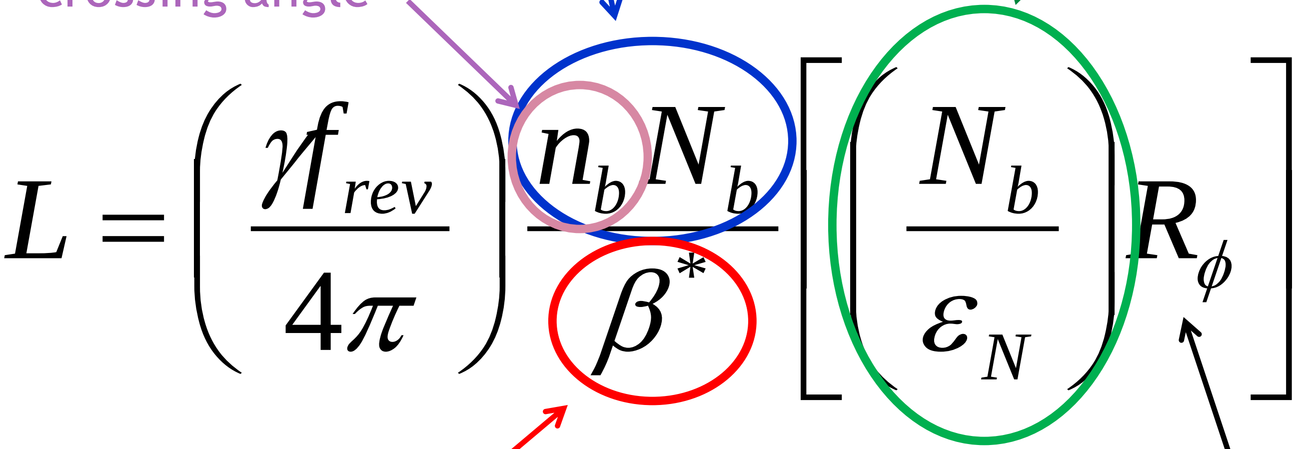
SPS - LINAC4 connection & **PSB** energy upgrade

Understanding LHC Luminosity

Total beam current. Limited by:
- Uncontrolled beam loss!!
- E-cloud and other instabilities

Brightness, limited by
- Injector chain
- Max tune-shift

If n_b>156, must turn on crossing angle



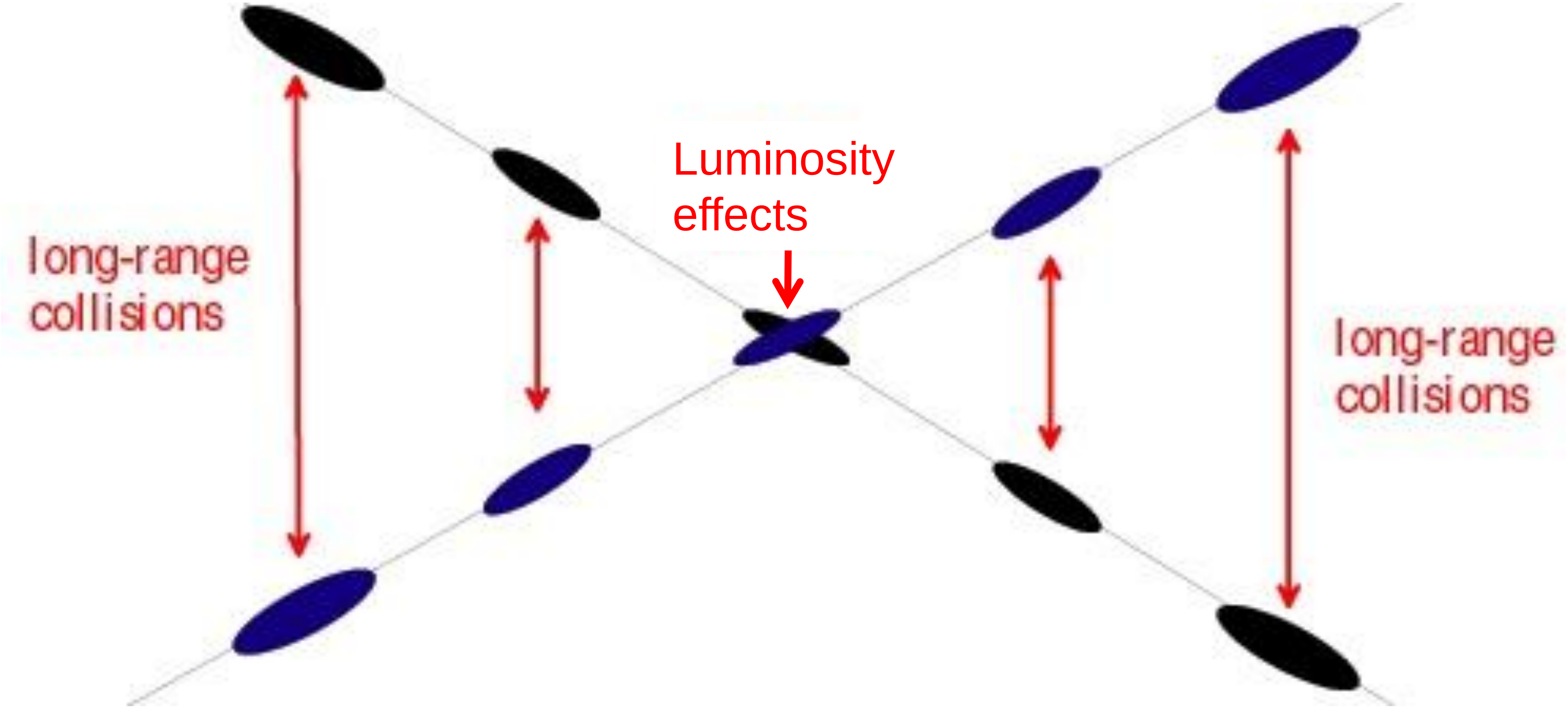
$$L = \left(\frac{\gamma f_{rev}}{4\pi}\right)\frac{n_b N_b}{\beta^*}\left[\left(\frac{N_b}{\varepsilon_N}\right)R_\phi\right]$$

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.

Crossing Angles



Crossing Angle Considerations

- Crossing angle reduces luminosity

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

“Piwinski Angle”

$$R_\phi = \frac{1}{\sqrt{1+\phi_{piw}^{\;2}}}\;;\quad \phi_{piw} \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

- However, crossing angle also reduces tune-shift

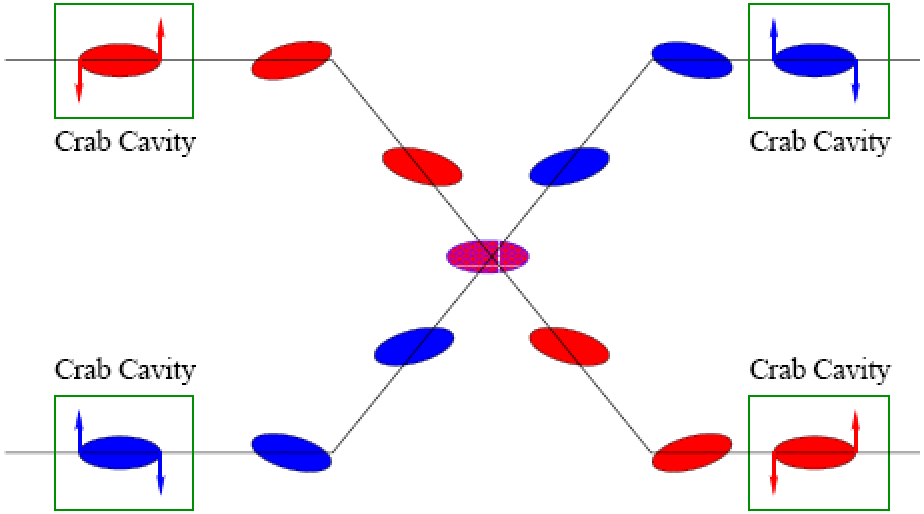
$$\Delta Q_{bb} = \frac{N_b}{\gamma\varepsilon}\frac{r_p}{2\pi}R_\phi\frac{1}{F_{profile}}$$

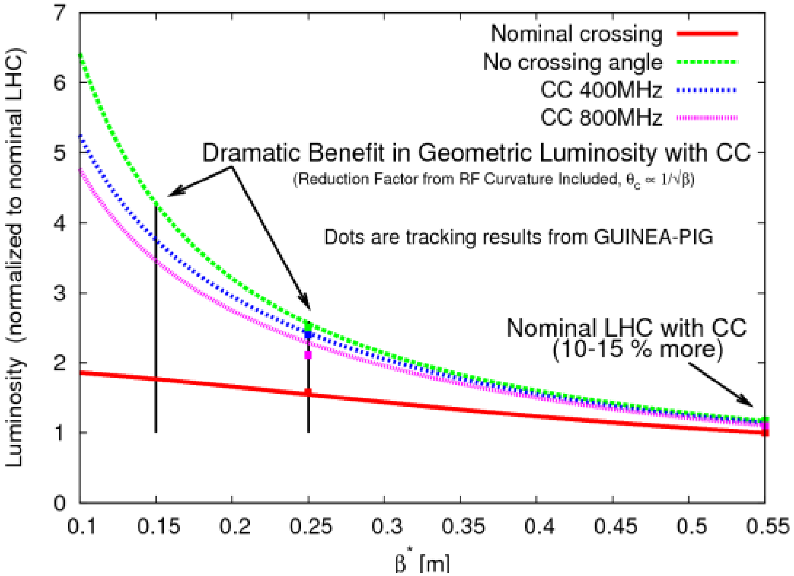
$$\boxed{\begin{aligned} F_{profile} &= 1 \text{ for Guassian beams} \\ &= \sqrt{2} \text{ for flat beams} \end{aligned}}$$

- In principle, the two effects should cancel

$\Longrightarrow$ “Large Piwinksi Angle” (LPA) Solution

Other Option: Crab Cavities





- Possibilities
  - 2 or 4 cavities in “global” scheme
    - Implications for apertures/collimation
  - 8 for full “local”
- Main Technical question
  - Space constraints -> 800 MHz elliptical (simple) versus 400 MHz “exotic”.
- Currently part of the base line proposal

LHC Upgrade Parameters and Options (not quite up to date)

Requires
magnets close
to detectors

Requires
PS2

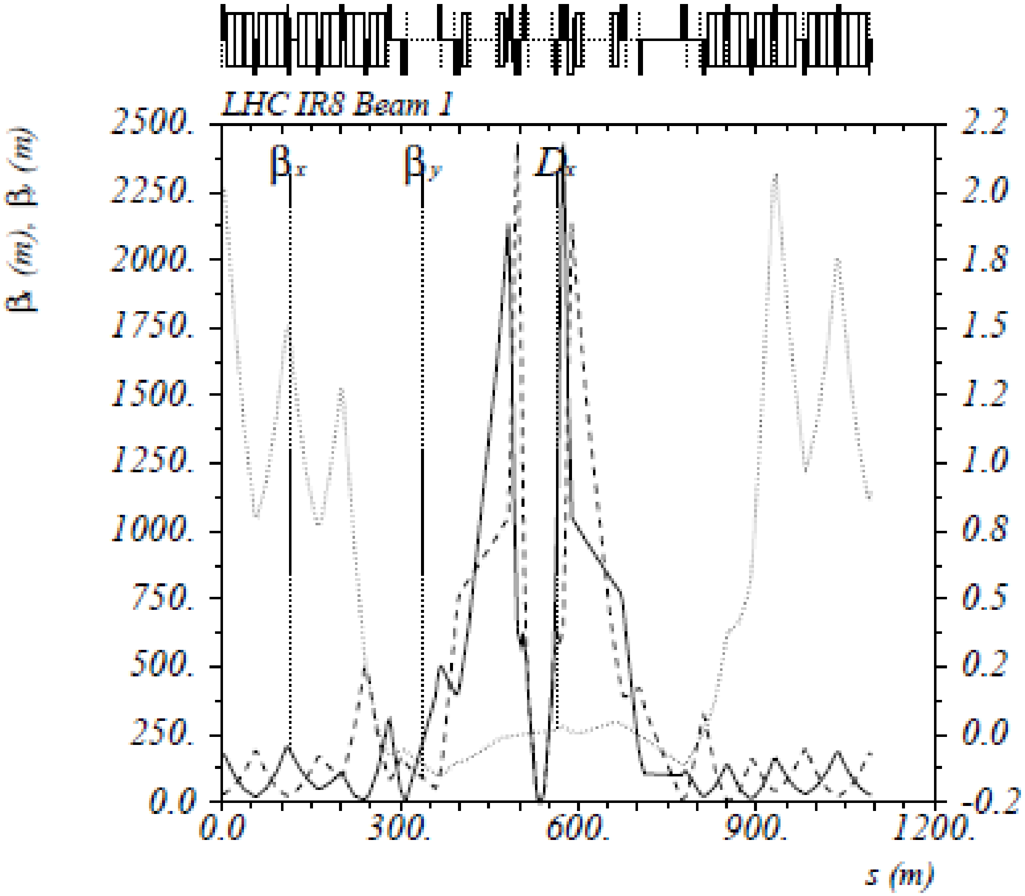
Big pile-up

Parameter	**Symbol**	**Initial**	**Full Luminosity Upgrade**			
			Early Sep.	**Full Crab**	**Low Emit.**	**Large Piw. Ang.**
transverse emittance	ε [μm]	3.75	**3.75**	**3.75**	**1.0**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	**1.7**	**1.7**	**1.7**	**4.9**
bunch spacing	Δt [ns]	25	**25**	**25**	**25**	**50**
beam current	I [A]	0.58	**0.86**	**0.86**	**0.86**	**1.22**
longitudinal profile		**Gauss**	**Gauss**	**Gauss**	**Gauss**	**Flat**
rms bunch length	σ_z [cm]	7.55	**7.55**	**7.55**	**7.55**	**11.8**
beta* at IP1&5	$\beta*$ [m]	0.55	**0.08**	**0.08**	**0.1**	**0.25**
full crossing angle	θ_c [μrad]	285	**0**	**0**	**311**	**381**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.64	**0**	**0**	**3.2**	**2.0**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	**14.0**	**14.0**	**16.3**	**11.9**
peak events/crossing		19	**266**	**266**	**310**	**452**
initial lumi lifetime	τ_L [h]	22	**2.2**	**2.2**	**2.0**	**4.0**
Luminous region	σ_l [cm]	4.5	**5.3**	**5.3**	**1.6**	**4.2**

excerpted from F. Zimmermann, “LHC Upgrades”, EPS-HEP 09, Krakow, July 2009

The need for new quadupoles

- Recall from yesterday
  - Small $\beta^* \Rightarrow$ huge β at focusing quad



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

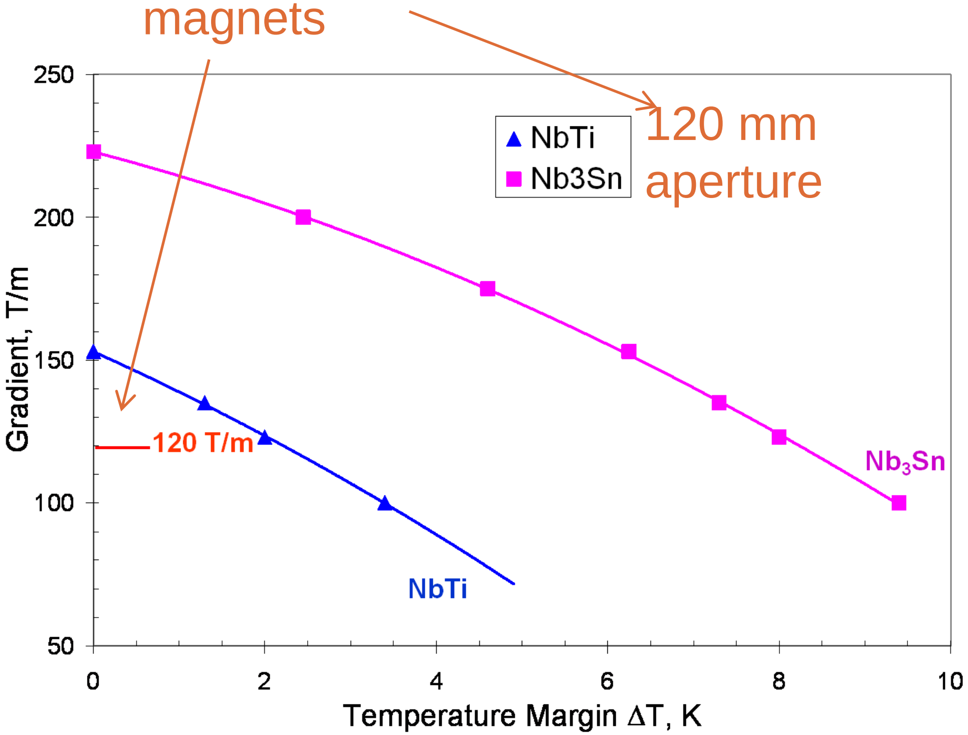
Proposed for upgrade
- At least 120 mm aperture
- 200 T/m gradient
- Field 70% higher at pole face

$\Rightarrow$ Beyond the limit of NbTi

- Need bigger quads to go to smaller β^*

Motivation for Nb_3Sn

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



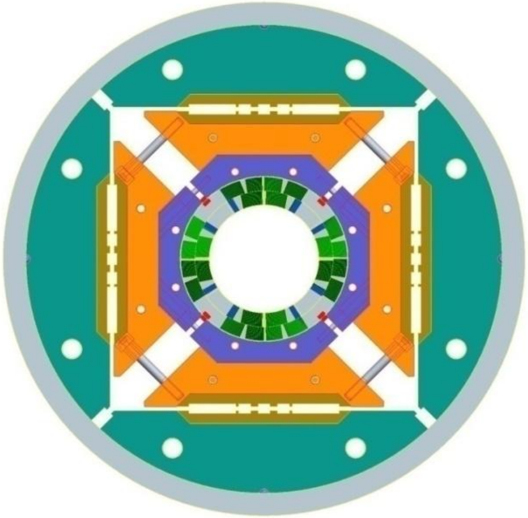
Limit of NbTi magnets

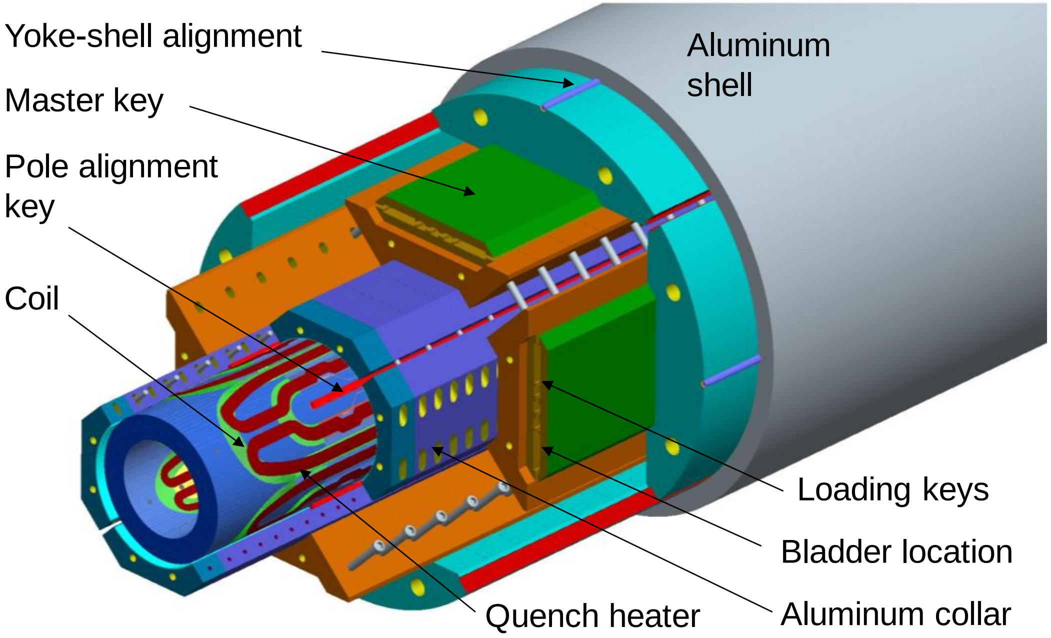
120 mm aperture

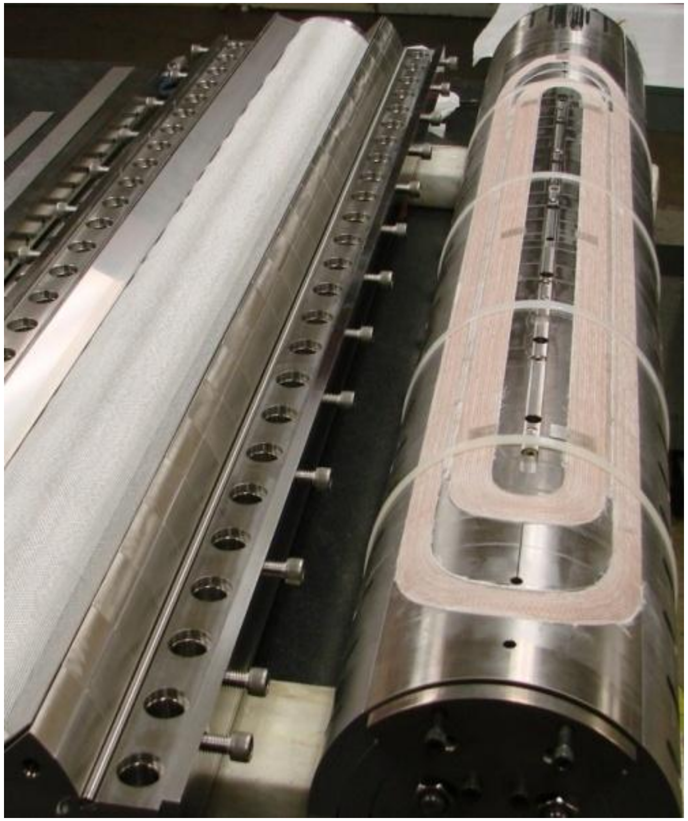
- Very attractive, but no one has ever built accelerator quality magnets out of Nb_3Sn
- Whereas NbTi remains pliable in its superconducting state, Nb3Sn must be reacted at high temperature, causing it to become brittle
  - Must wind coil on a mandril
  - React
  - Carefully transfer to yolk

LARP Design

- 120 mm aperture
- 200 T/m gradient
- Unique “shell” preloading structure
- Testing first 1m long prototype

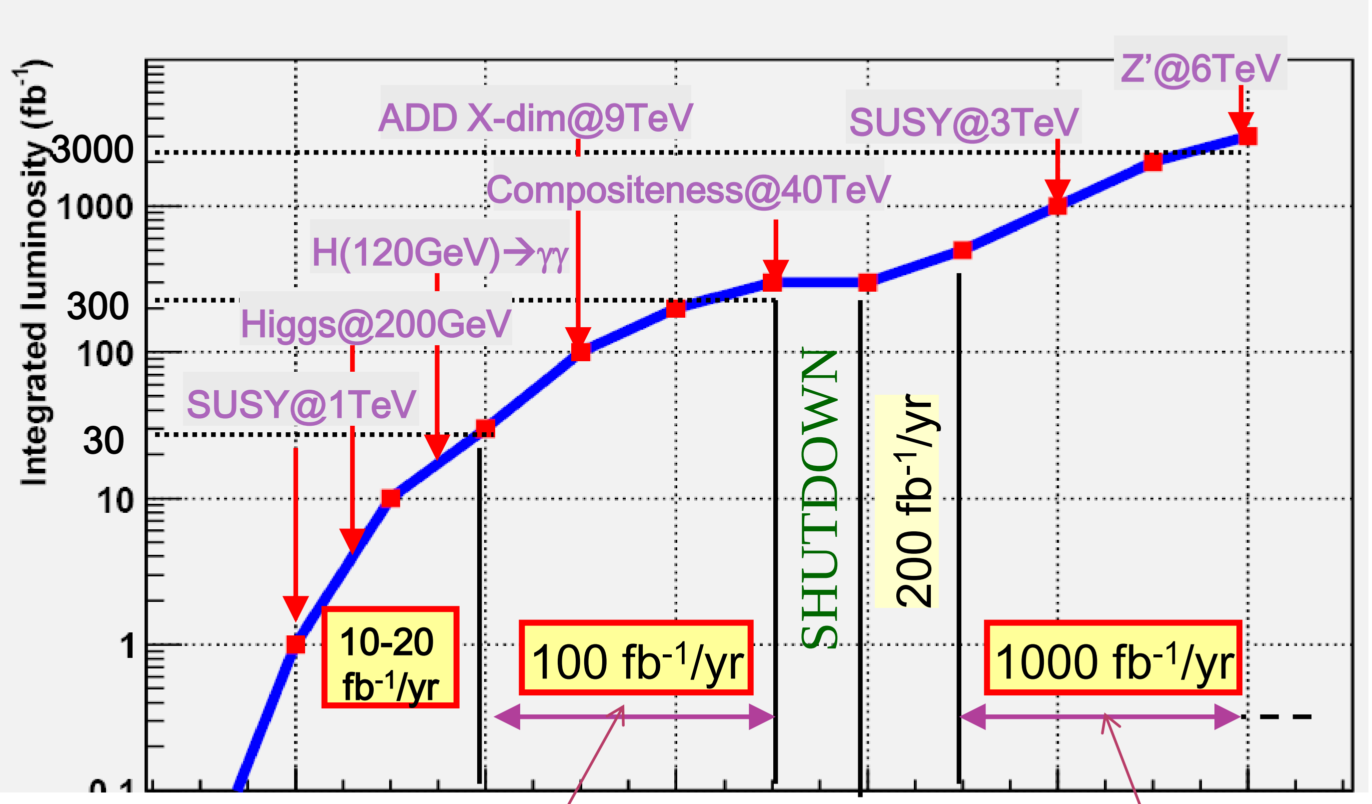






The long road to discovery

- Even with the higher rates, still need a lot of interactions to reach the discovery potential of the LHC



Note: VERY outdated plot. Ignore horizontal scale.

Would probably take until ~2030 to get 3000 fb^{-1}

50 x Tevatron luminosity

500 x Tevatron luminosity (will probably never happen)

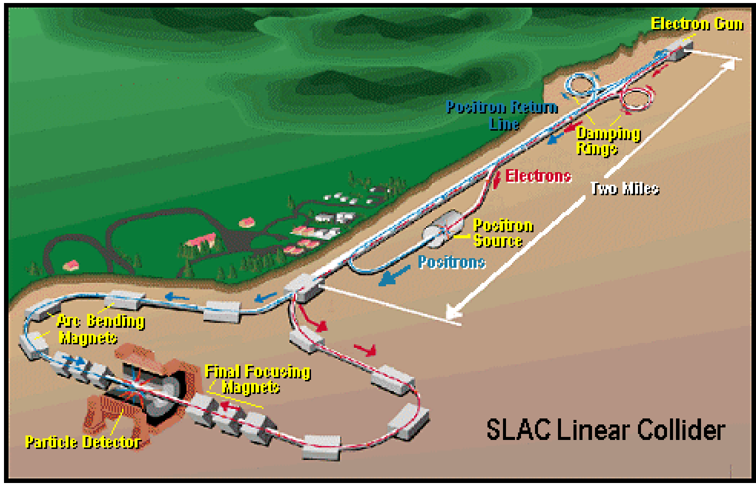
Some other important accelerators (past):

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**



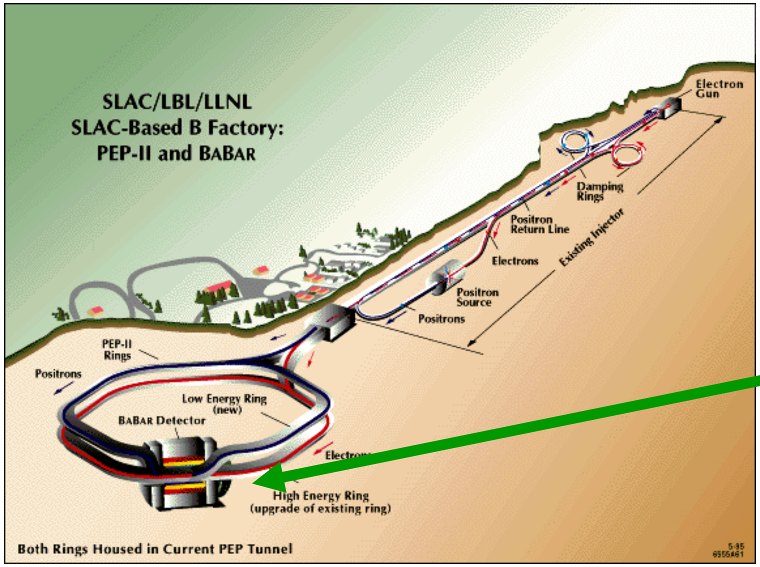
B-Factories

- B-Factories collide e+e- at $E_{CM} = M(\Upsilon(4S))$.

-Asymmetric beam energy (moving center of mass) allows for time-dependent measurement of B-decays to study CP violation.

KEKB (Belle Experiment):

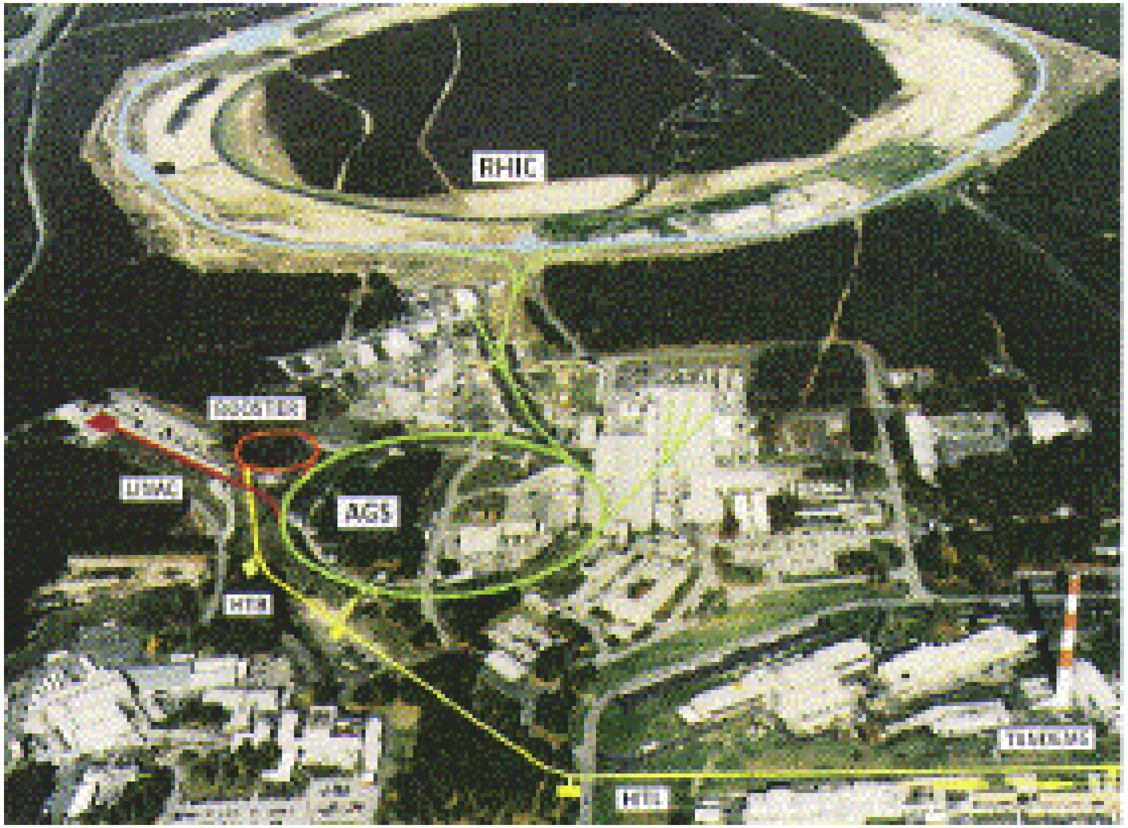
- Located at KEK (Japan)
- 8GeV e- x 3.5 GeV e+
- Peak luminosity >1e34



PEP-II (BaBar Experiment)

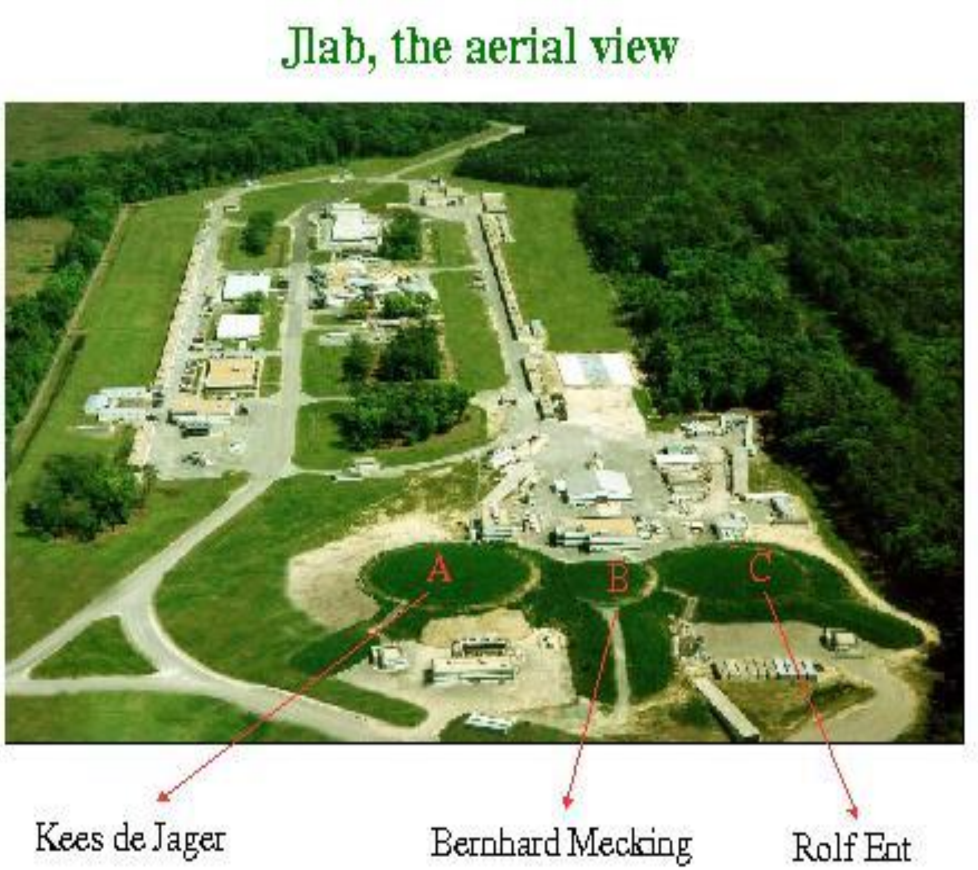
- Located at SLAC (USA)
- 9GeV e- x 3.1 GeV e+
- Peak luminosity >1e34

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, ??**

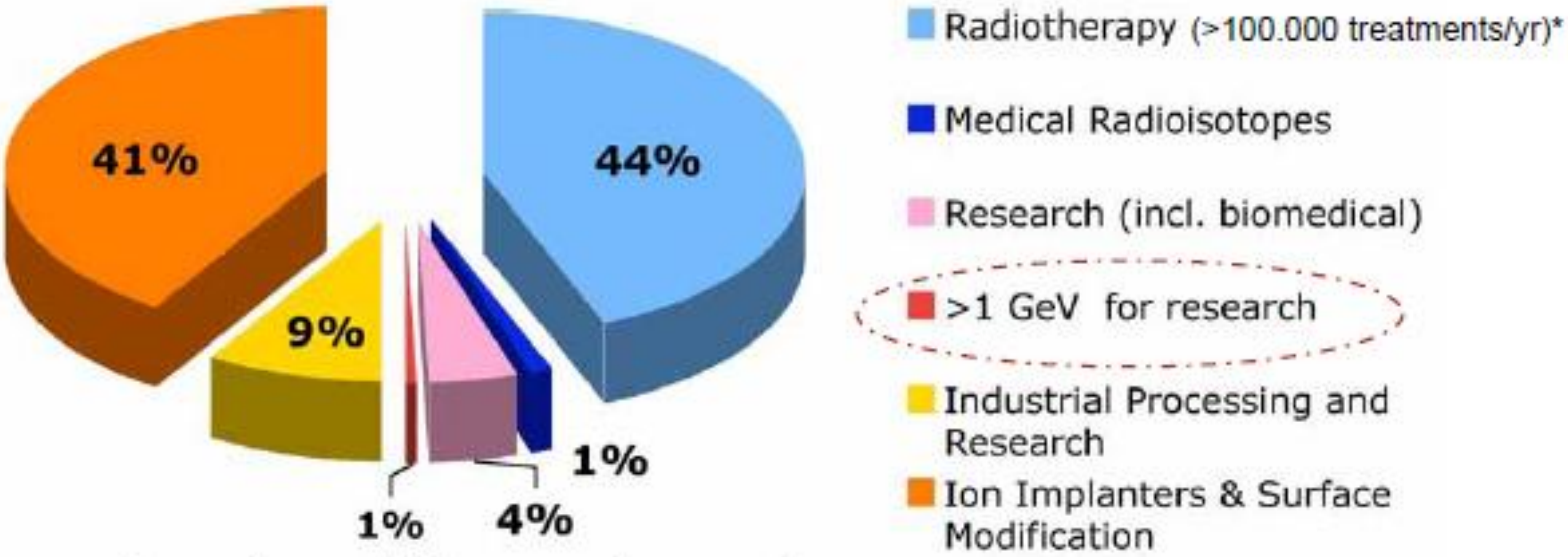
Continuous Electron Beam Accelerator Facility (CEBAF)



- 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

Number of accelerators worldwide
~ 26,000



Annual growth is several percent

Sales >3.5 B$/yr

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

Example: Spallation Neutron Source (Oak Ridge, TN)

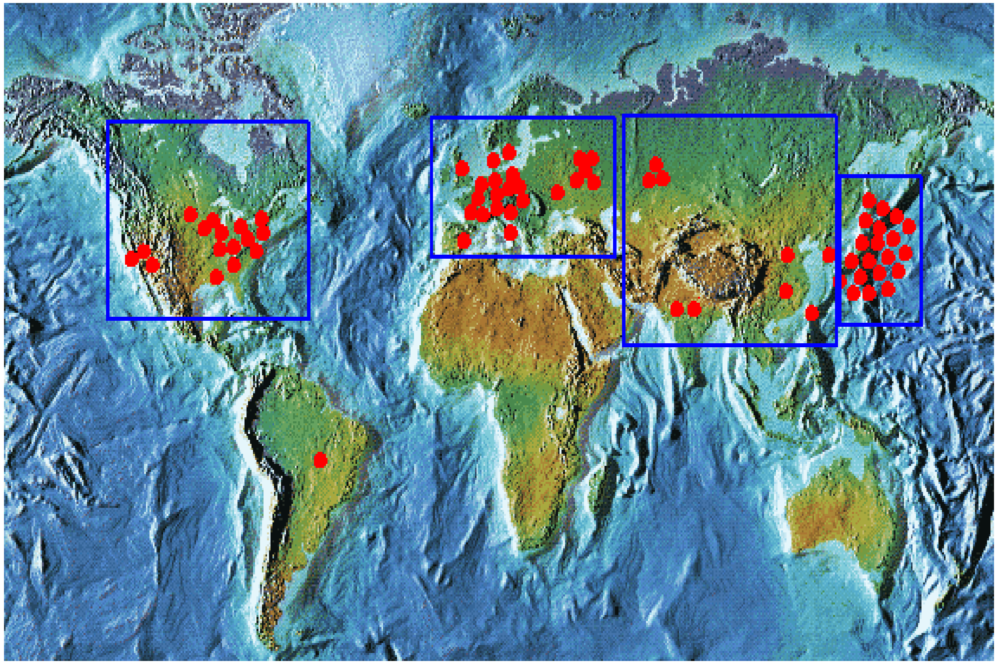
A 1 GeV Linac will load 1.5E14 protons into a non-accelerating synchrotron ring.

These are fast extracted onto a Mercury target

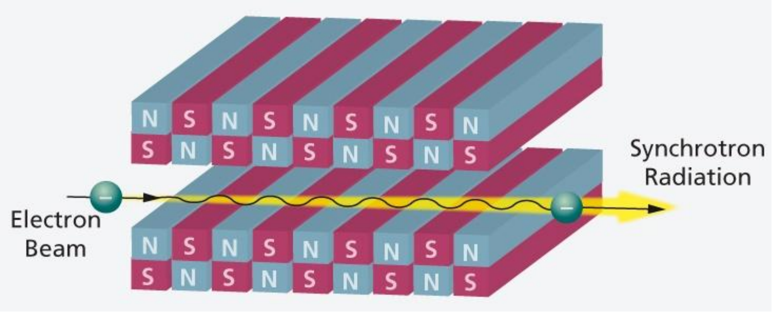
This happens at 60 Hz -> 1.4 MW

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

Light sources: too many to count

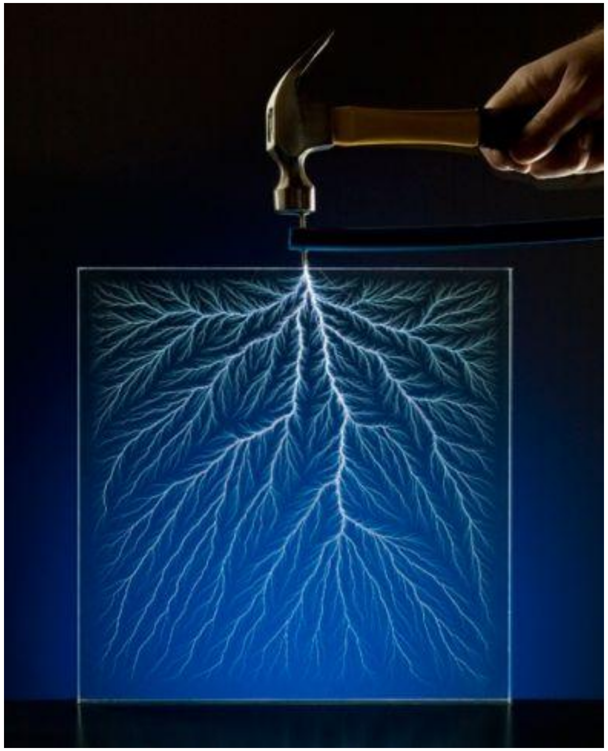


- Put circulating electron beam through an "undulator" to create synchrotron radiation (typically X-ray)
- Many applications in biophysics, materials science, industry.
- New proposed machines will use very short bunches to create coherent light.



Other uses of accelerators

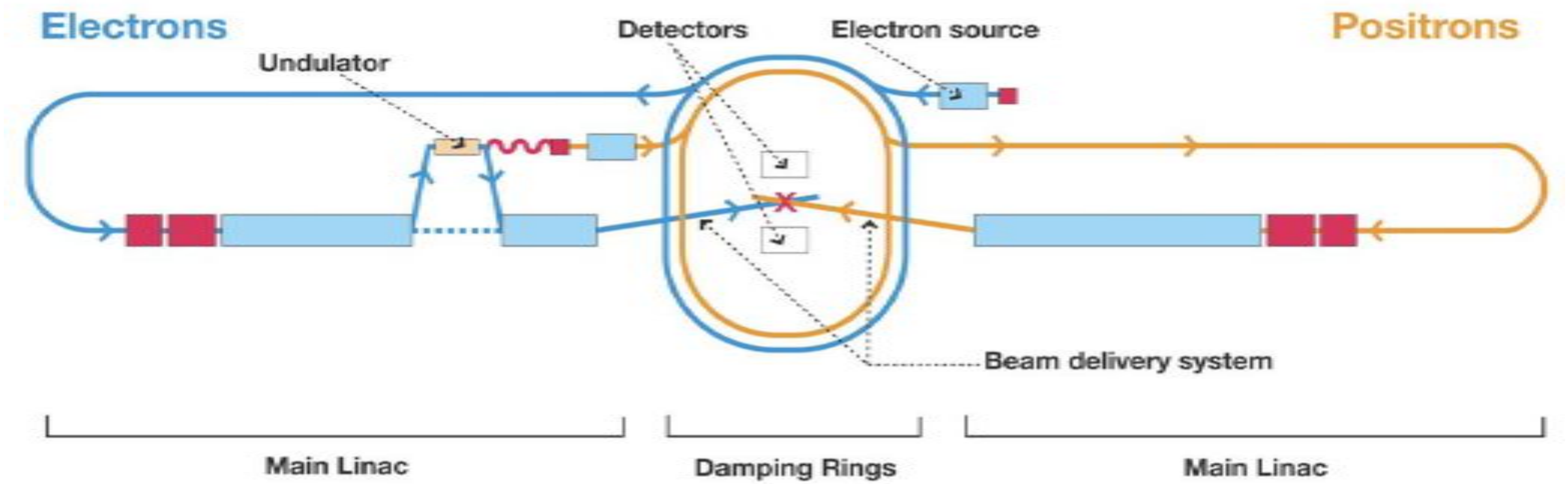
- Radioisotope production
- Medical treatment
- Electron welding
- Food sterilization
- Catalyzed polymerization
- Even art…



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)?

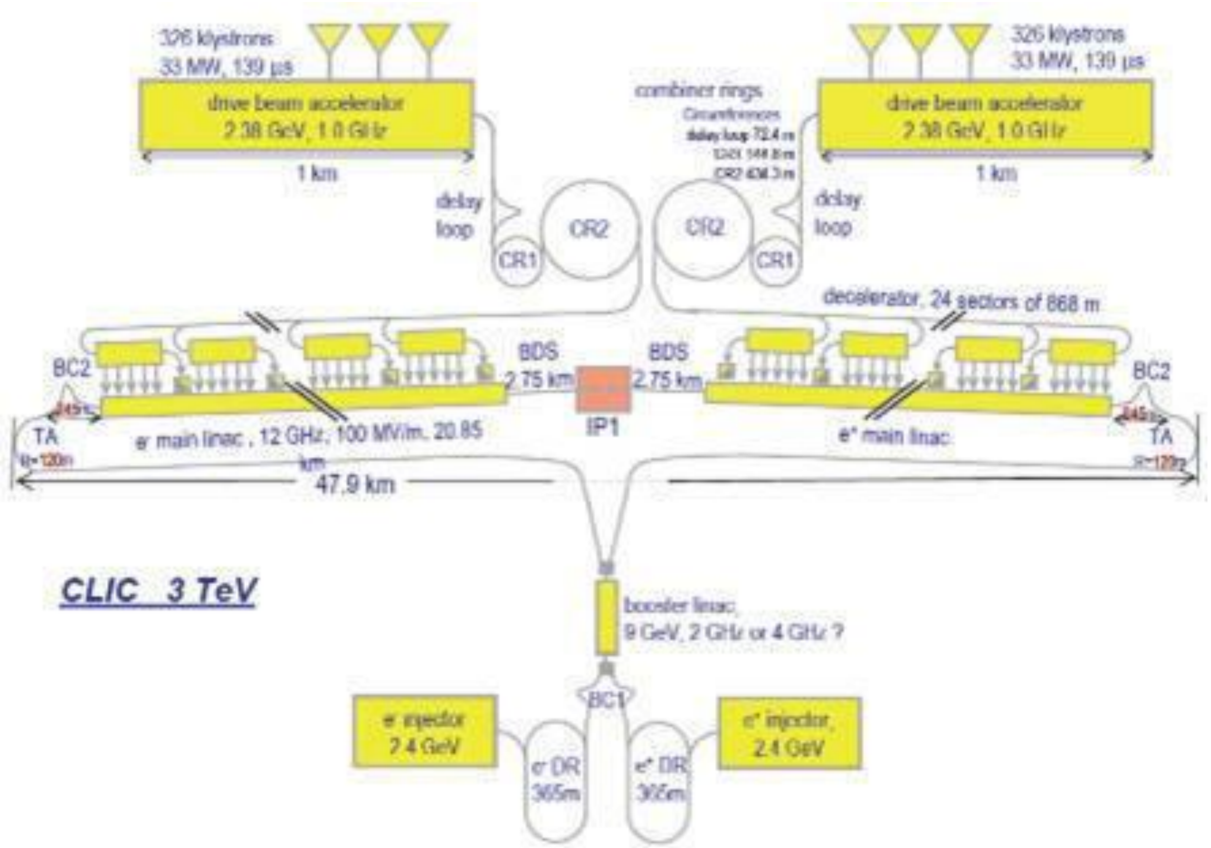
- LEP was the limit of circular e^+e^- colliders
  - Next step must be linear collider
  - Proposed ILC 30 km long, 250 x 250 GeV e^+e^-



- 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)?

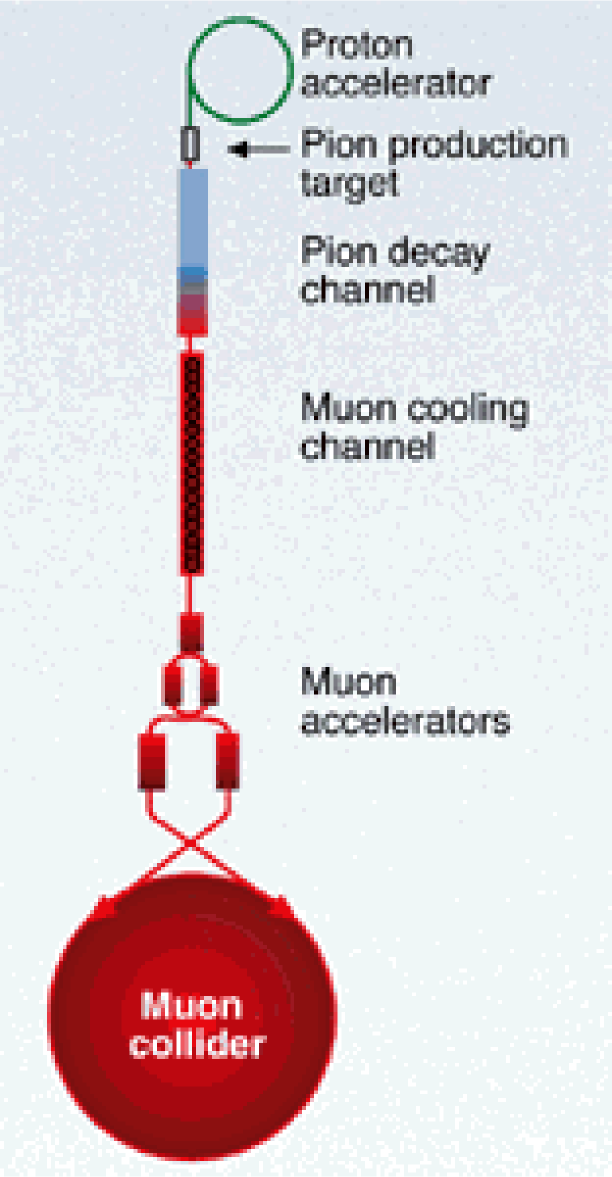
- Use low energy, high current electron beams to drive high energy accelerating structures



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

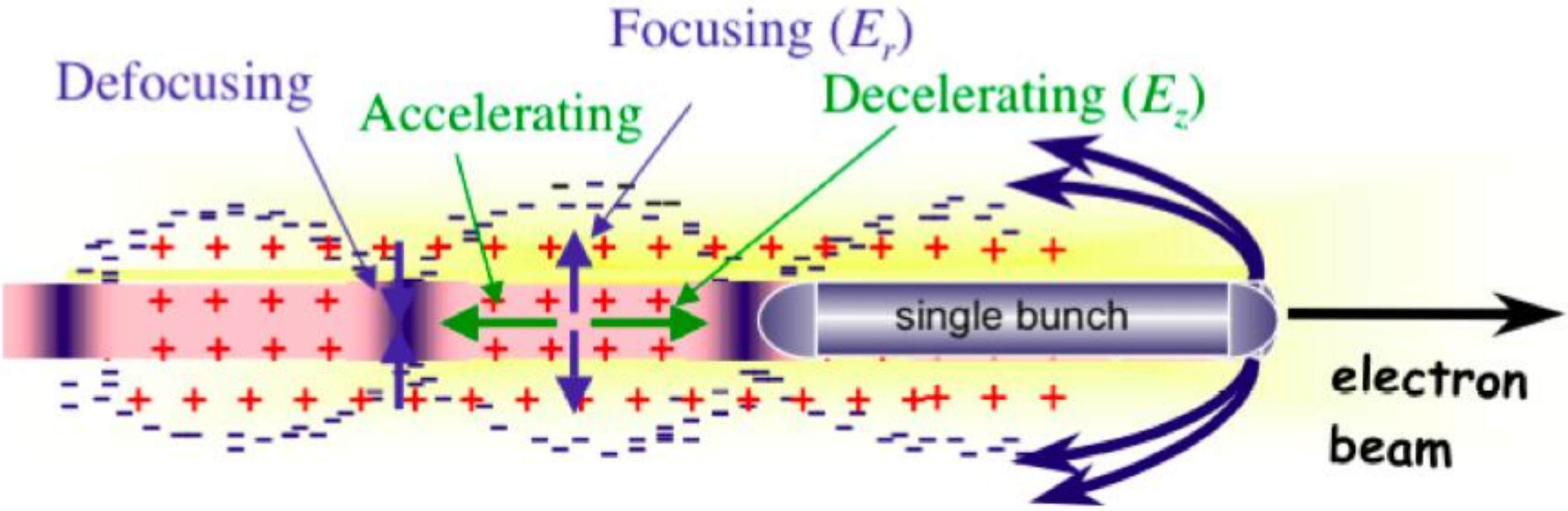
Muon colliders?

- 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.

Summary and Conclusion

- Still lots of fun ahead.