HCPSS 2014

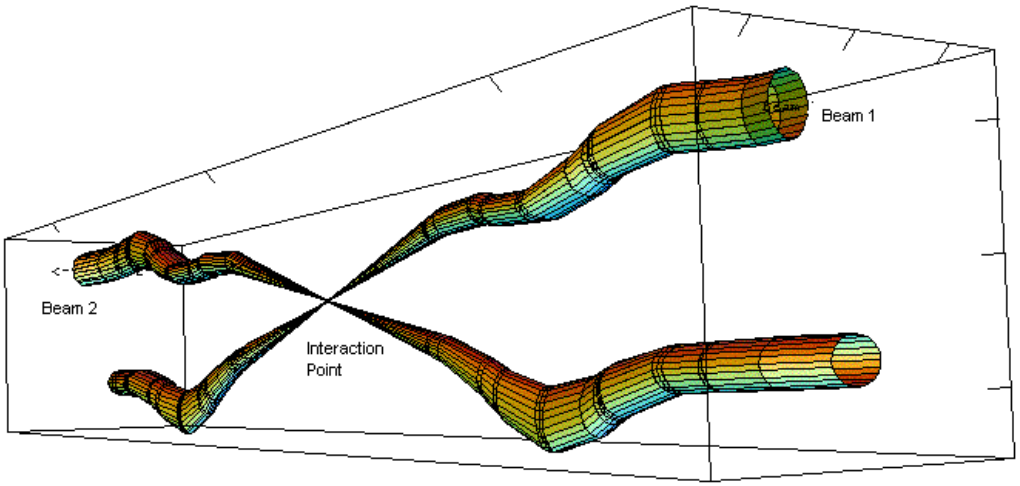
Hadron Collider Physics Summer School

August 11 - 22, 2014 Fermi National Accelerator Laboratory

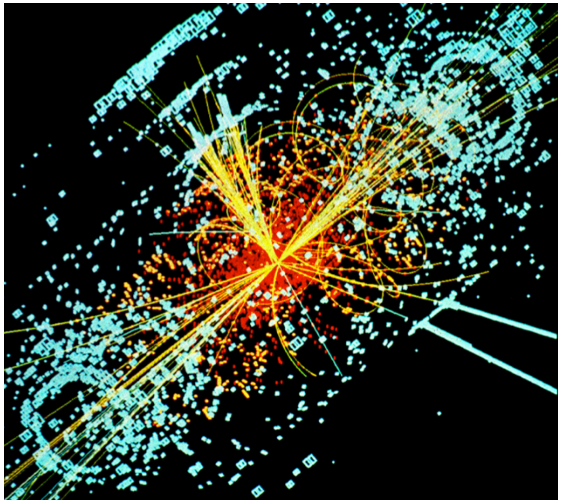
FERMILAB-CERN HADRON COLLIDER PHYSICS Summer School 2014

Hadron Colliders

Eric Prebys, FNAL



Relative beam sizes around IP1 (Atlas) in collision



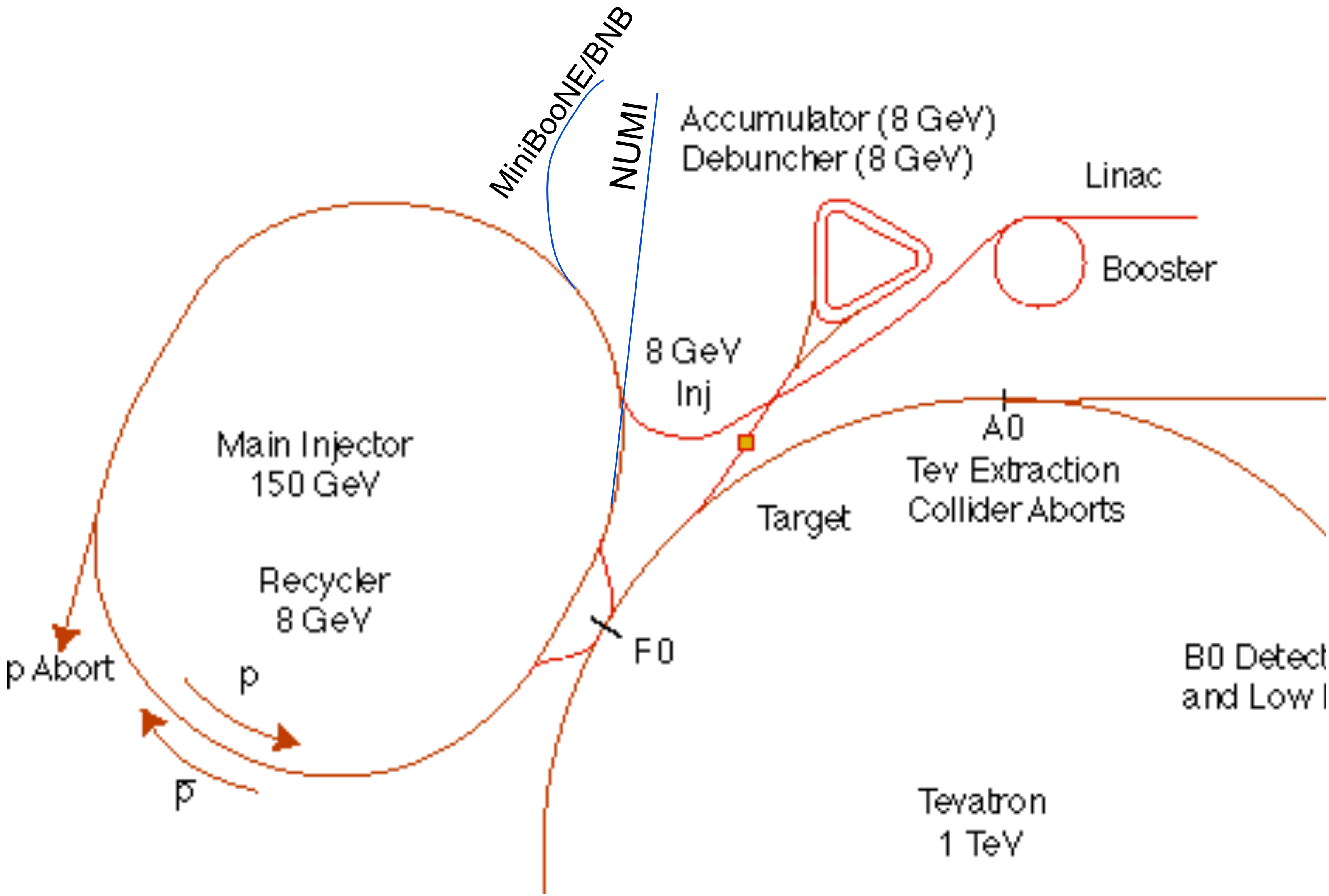
LHC Interaction Region

Lecture 3

Outline

- Tevatron
  - pBar cooling
  - luminosity
- LHC
  - parameters
  - "The Incident"
  - Maximizing luminosity (HL-LHC)
- What's next?

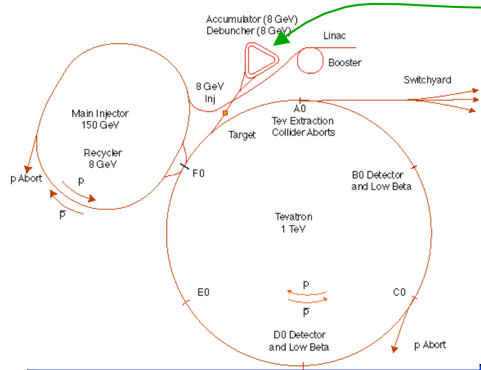
The Fermilab Accelerator Complex

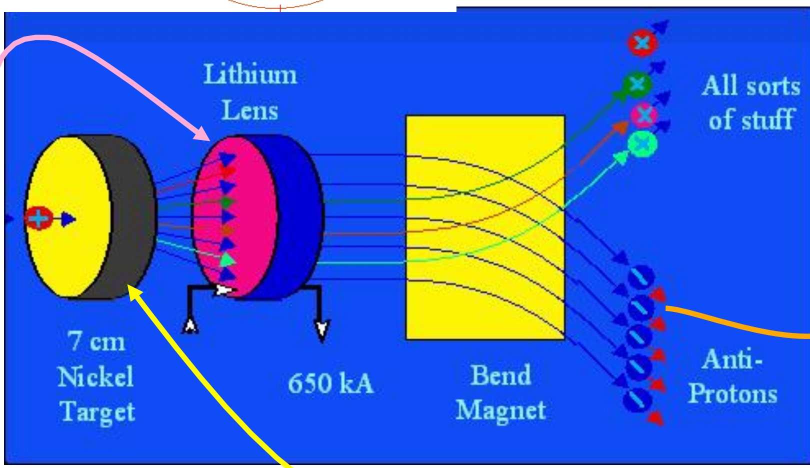


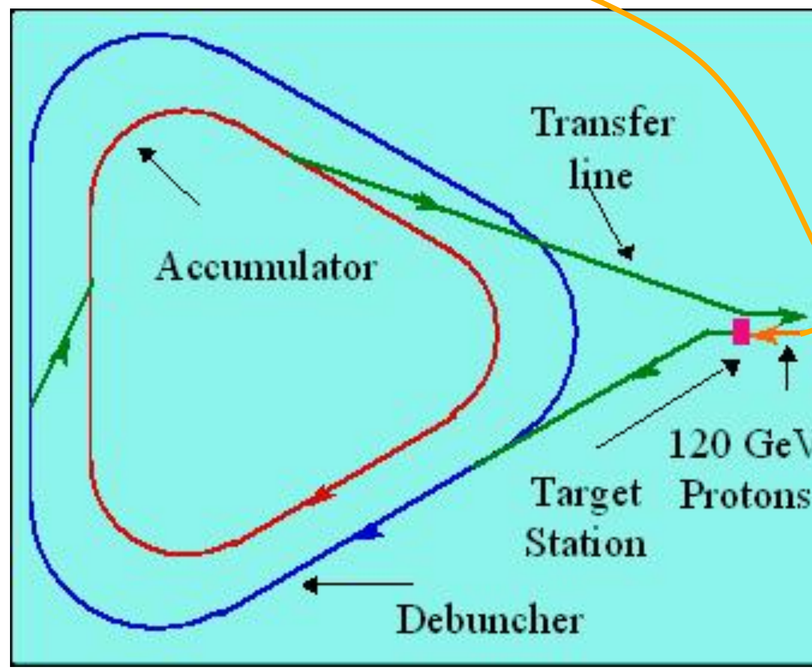
"Stack and Store" cycle

- 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



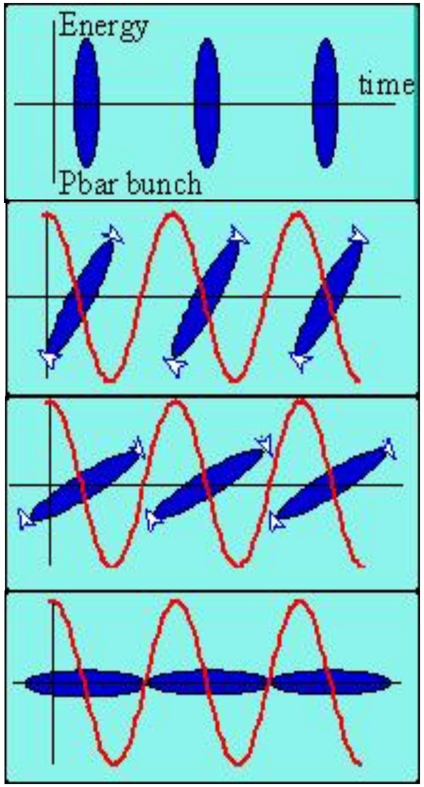




- 120 GeV protons strike a target, producing many things, including antiprotons.
- a Lithium lens focuses these particles (a bit)
- a bend magnet selects the negative particles around 8 GeV. Everything but antiprotons decays away.

- 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…

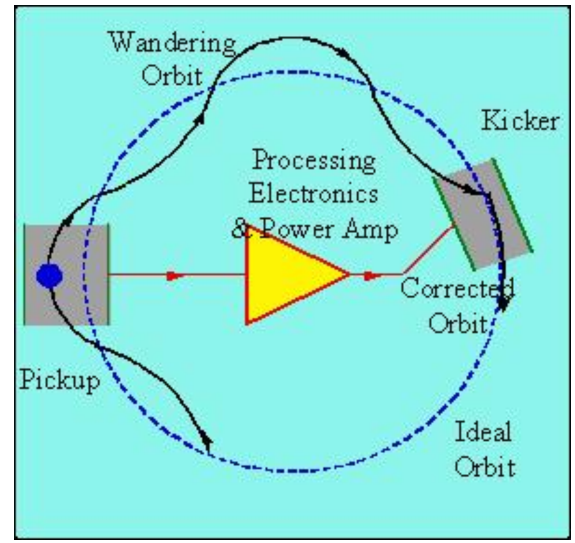
…and the RF is phased so they are decelerated (accelerated),

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

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

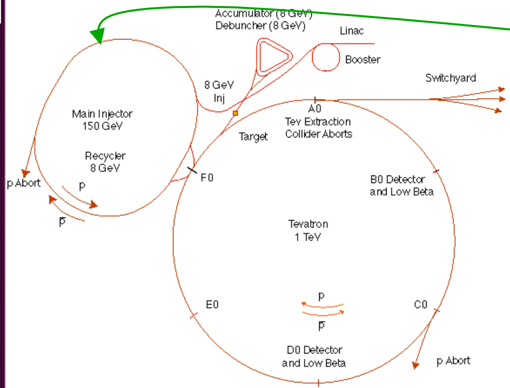
Stochastic cooling of antiprotons

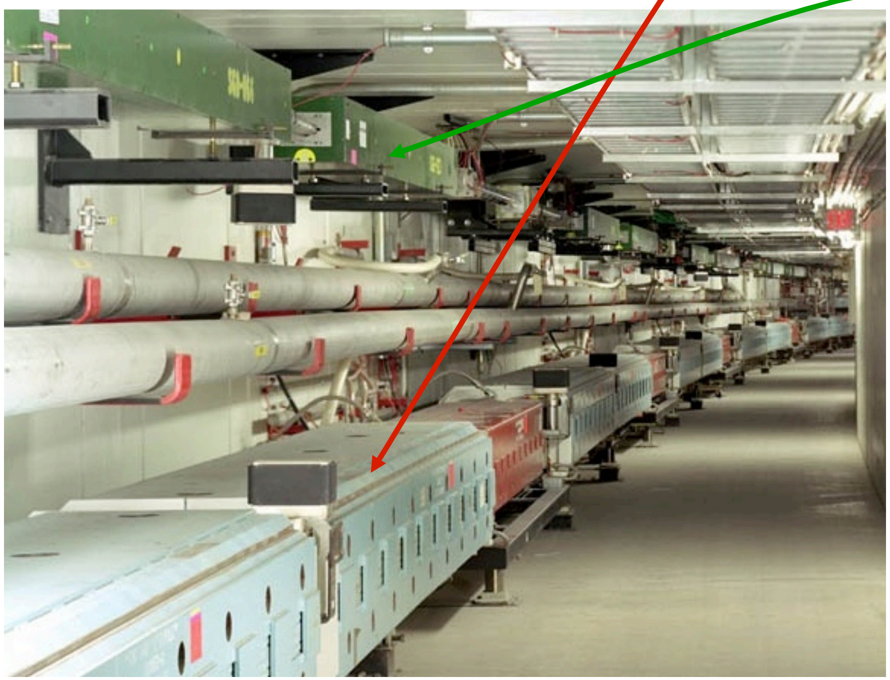
- Positrons will naturally "cool" (approach a small equilibrium emittance) via synchrotron radiation.
- Antiprotons must rely on active cooling to be useful in colliders.
- Principle: consider a single particle which is off orbit. We can detect its deviation at one point, and correct it at another:



- 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.

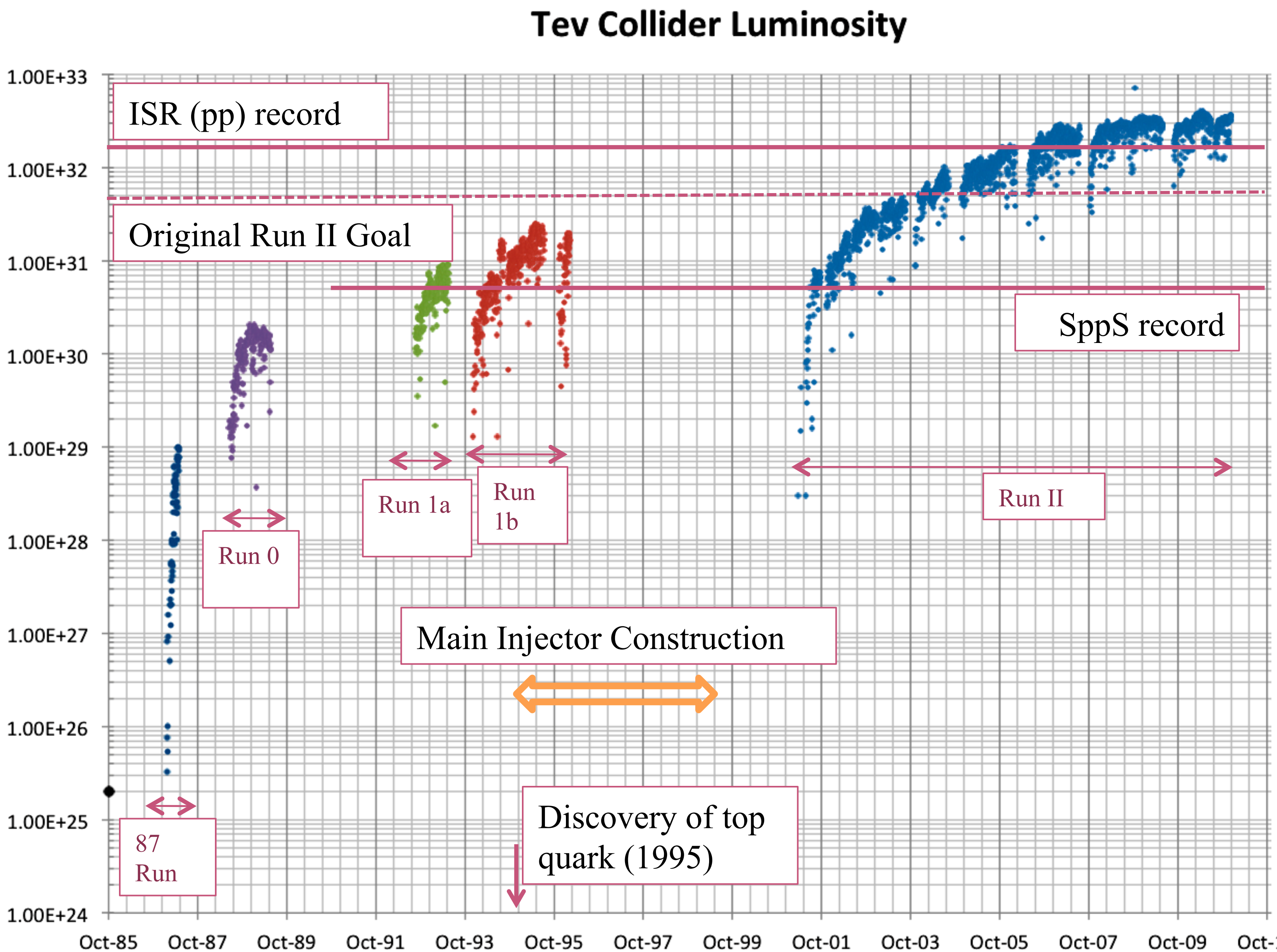
Main Injector/Recycler





- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The 8 GeV Recycler (which shares the same tunnel and stores antiprotons)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.
  - The fixed target area.
  - The NUMI beamline.
- It can accelerate protons OR antiprotons to 150 GeV and inject them into the Tevatron.

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?

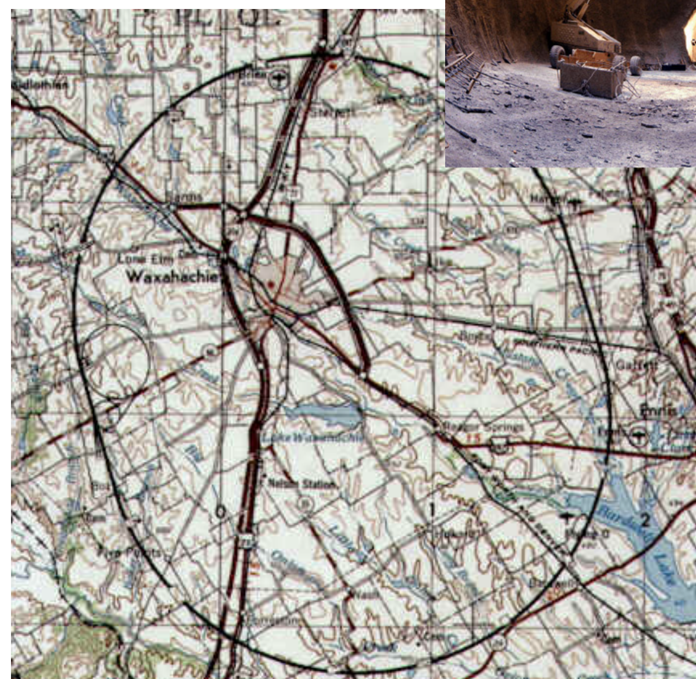
- At the design luminosity of the LHC, the antiproton "burn" rate would be

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

- 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.

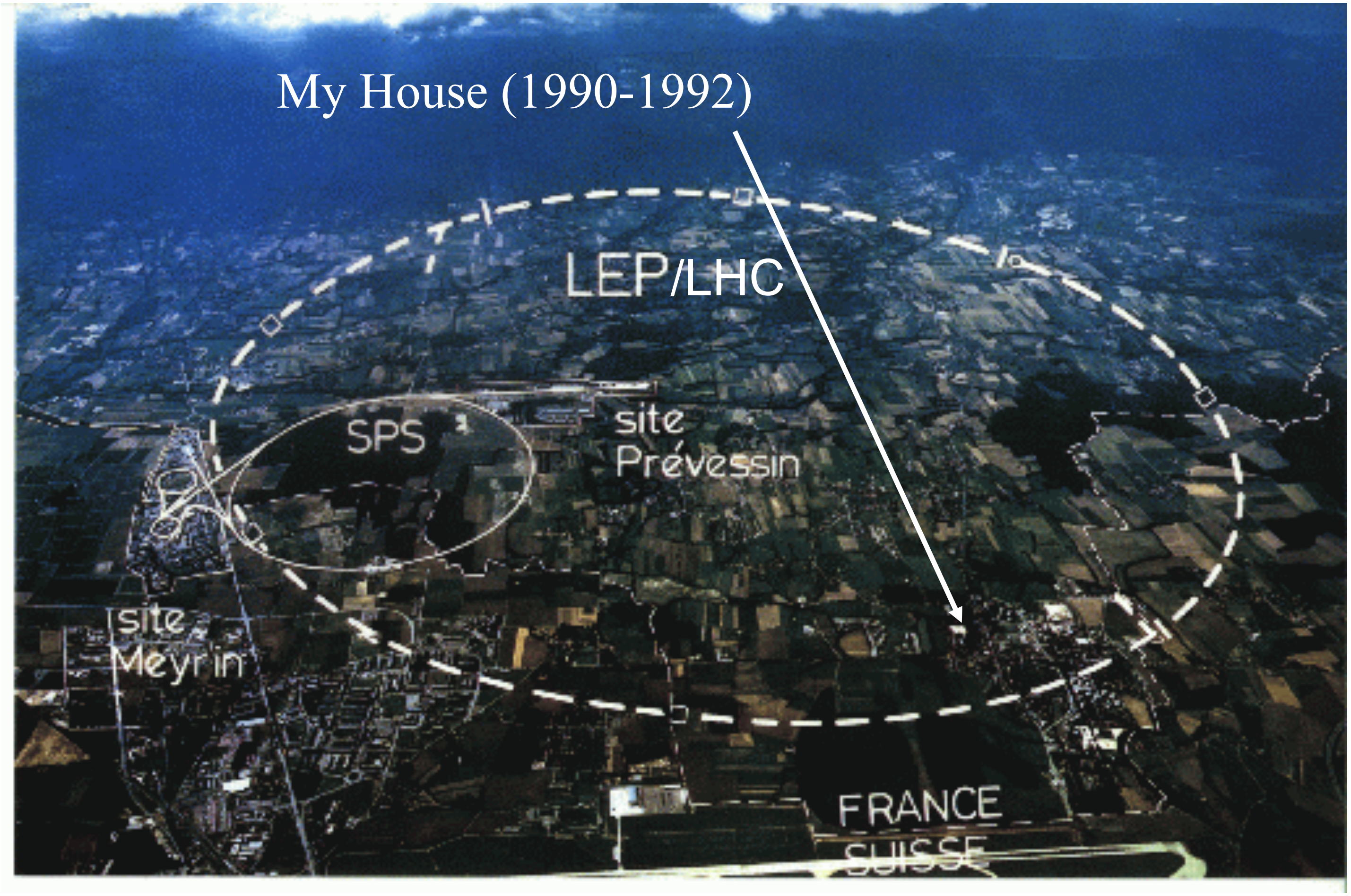
A Detour on the Road to Higher Energy

- 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.



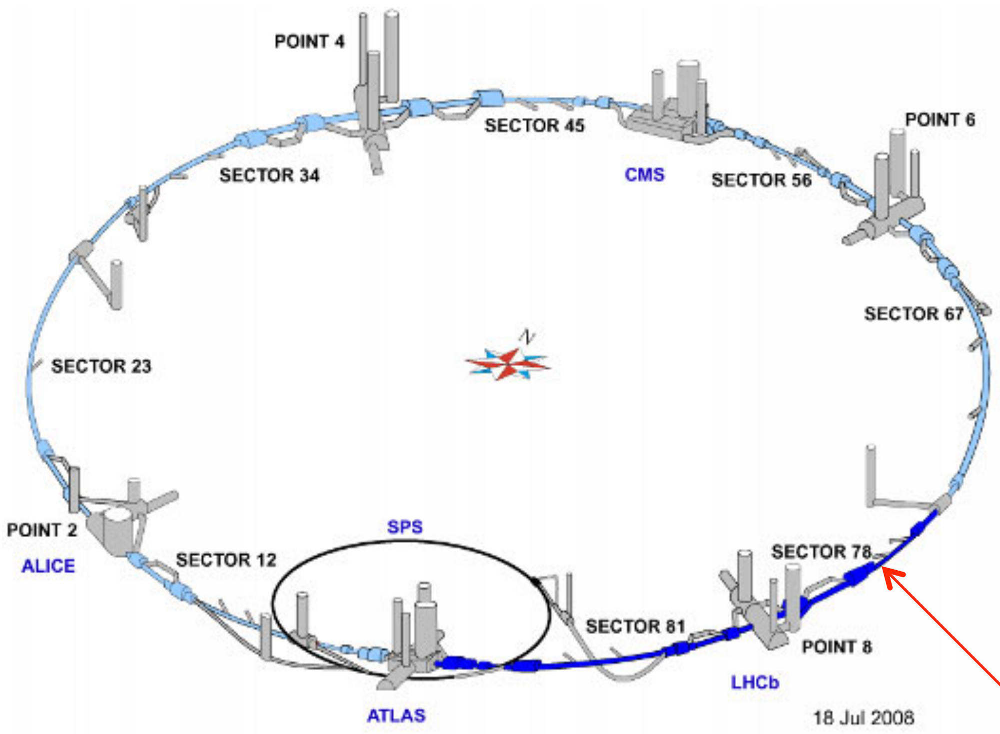
- 1987 – site chosen near Dallas, TX
- 1989 – construction begins
- 1993 – amidst cost overruns and the end of the Cold War, the SSC is cancelled after 17 shafts and 22.5 km of tunnel had been dug.
- 2001 – After the end of the LEP program at CERN, work begins on reusing the 27 km tunnel for the 7 TeV+ 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



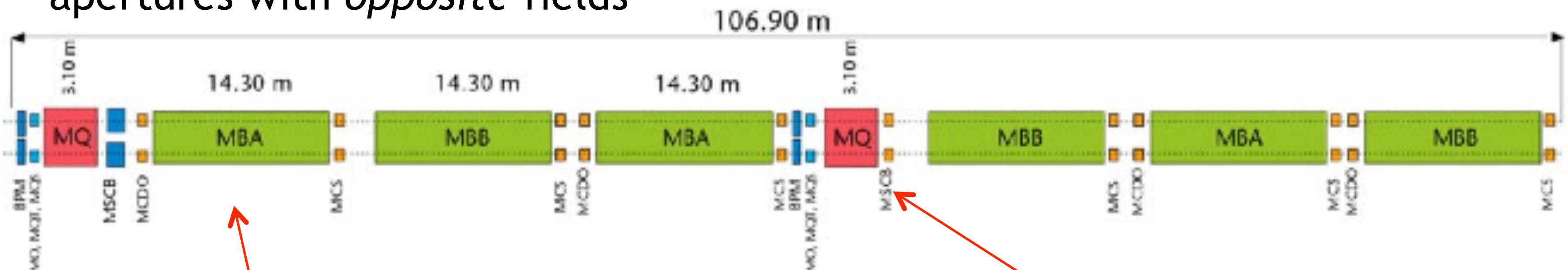
Design:

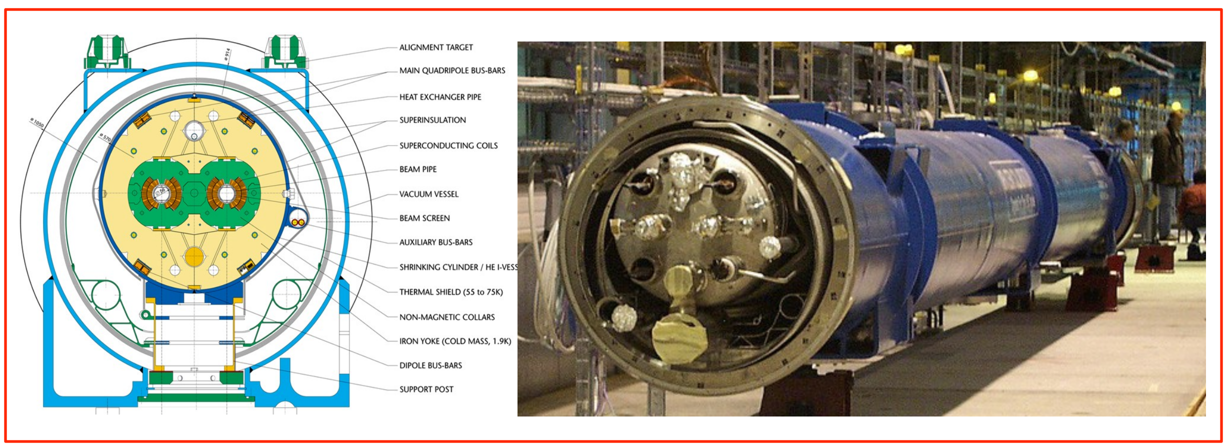
- 7 TeV+7 TeV proton beams
  - Can't make enough antiprotons for the LHC
  - Magnets have two beam pipes, one going in each direction.
- Stored beam energy 150 times more than Tevatron
  - Each beam has only 5×10^{-10} grams of protons, but has the energy of a train going 100 mph!!
- These beams are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

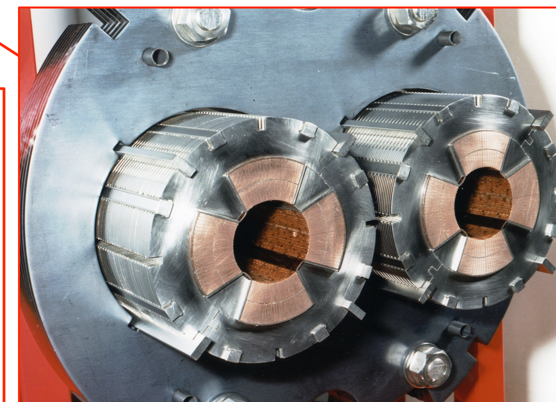
- 27 km in circumference
- 2 major collision regions: CMS and ATLAS
- 2 "smaller" regions: ALICE and LHCb

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





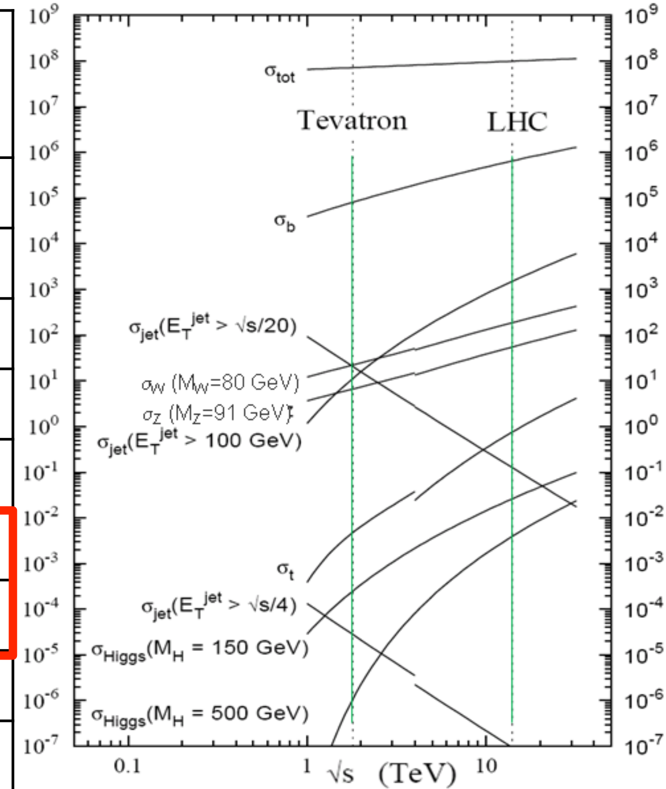


quadrupoles

dipoles (B_{max} = 8.3 T)

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)

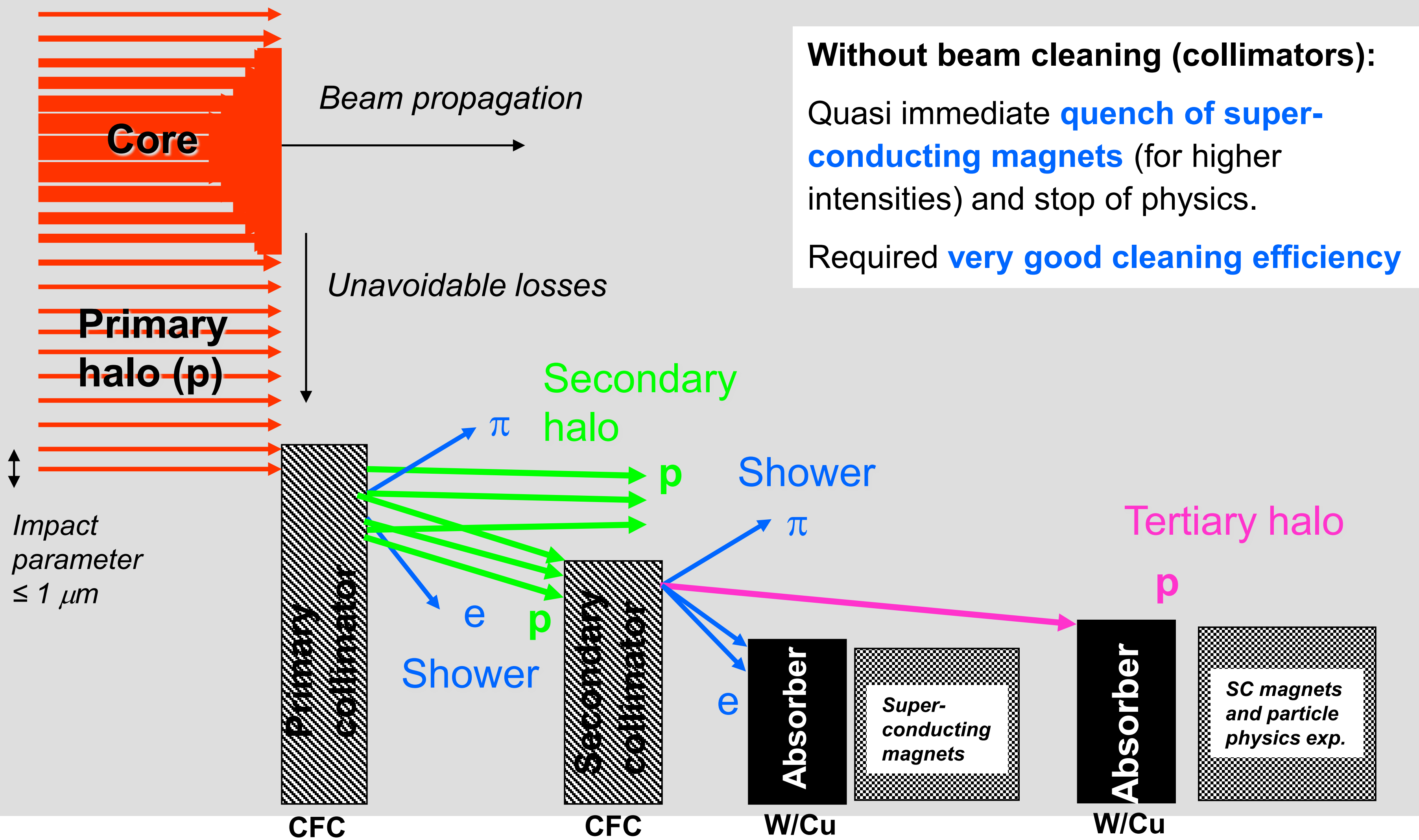


Increase in cross section of up to 5 orders of magnitude for some physics processes

*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

Protecting the Machine: Multi-stage Collimation



Without beam cleaning (collimators):

Quasi immediate **quench of super-conducting magnets** (for higher intensities) and stop of physics.

Required **very good cleaning efficiency**

R. Assmann

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

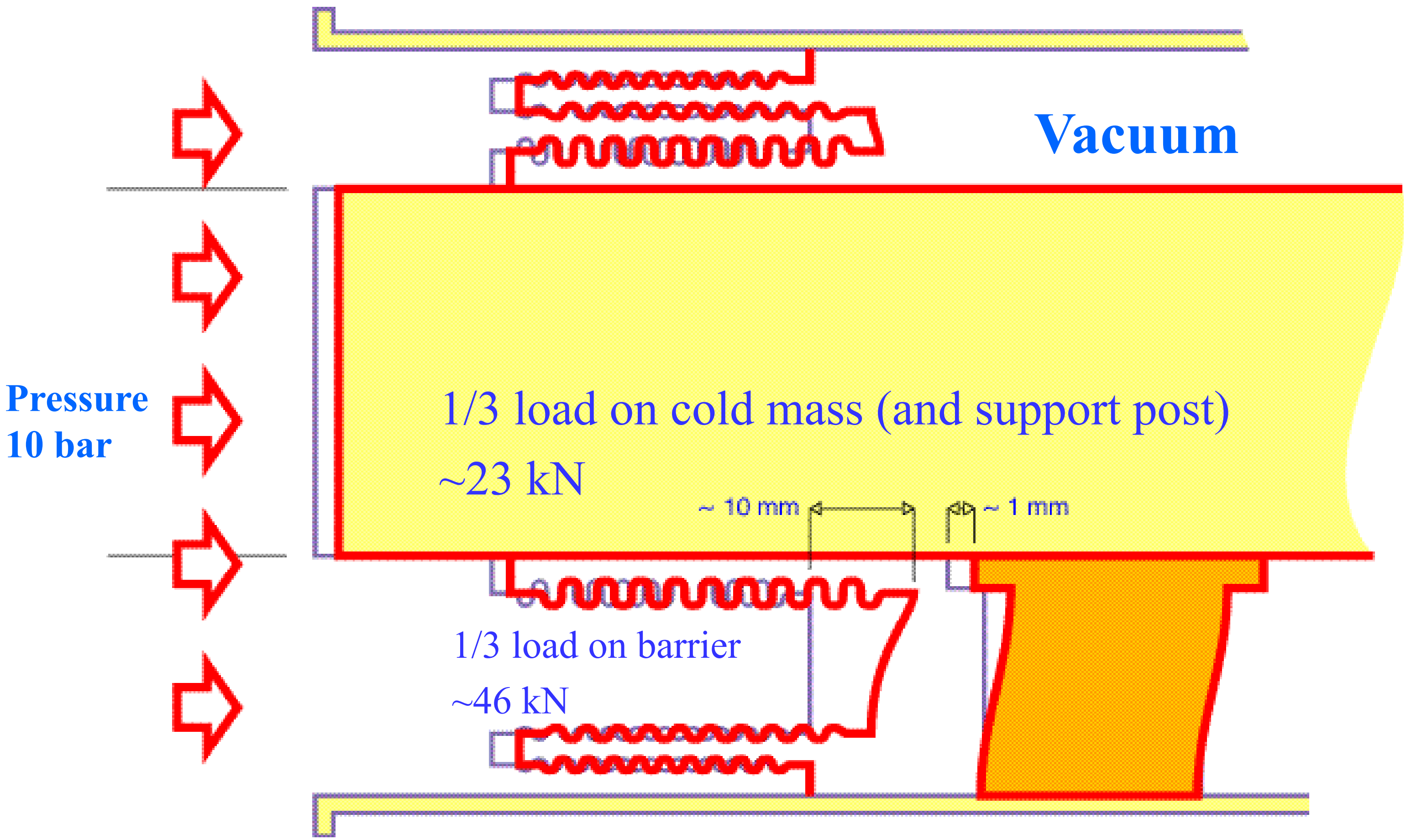
**http://www.rense.com/general83/IncidentatCERN.pdf

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



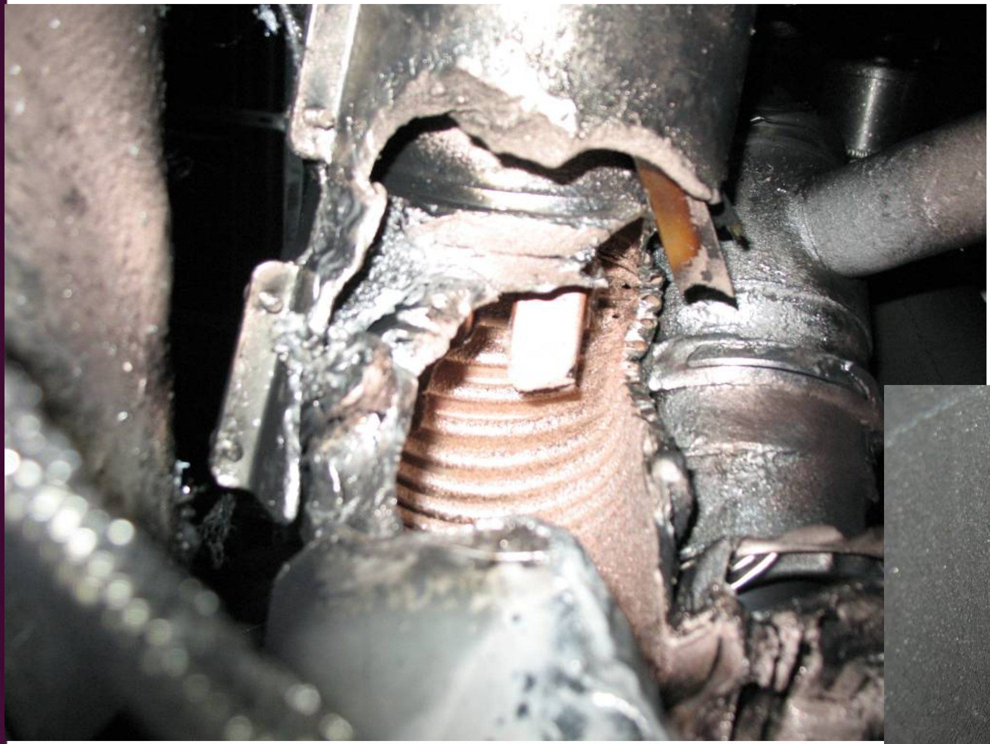
Total load on 1 jack ~70 kN

V. Parma

Collateral damage: magnet displacements

QQBI.27R3

Collateral damage: secondary arcs



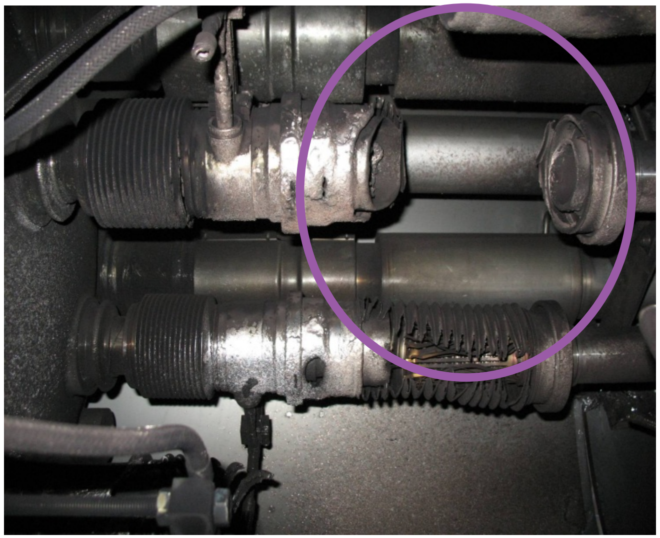
QQBI.27R3 M3 line

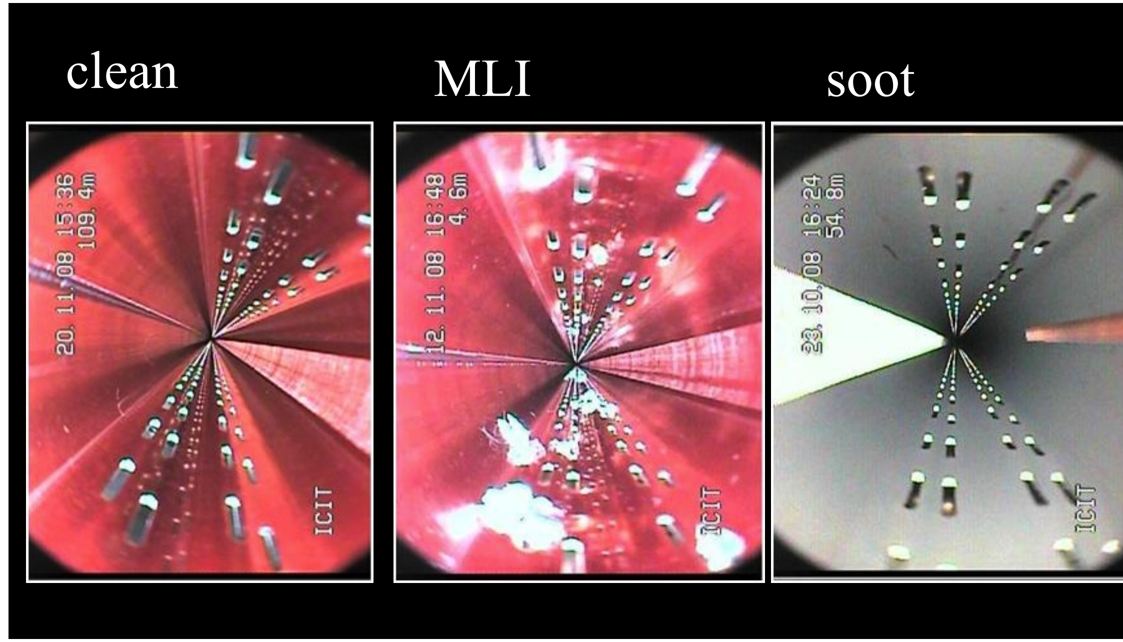
QBBI.B31R3 M3 line

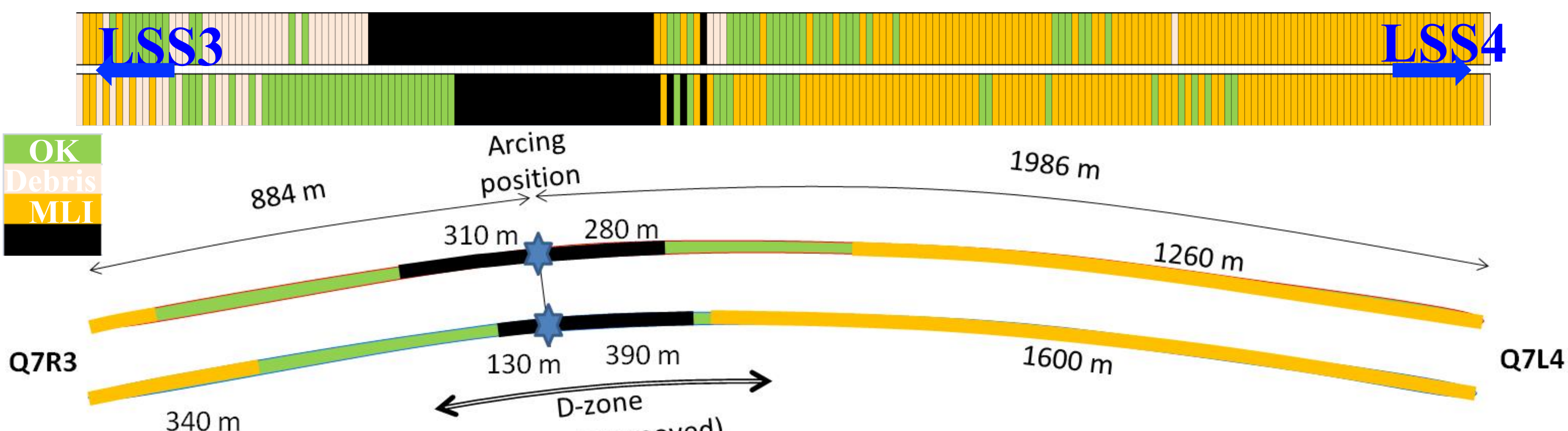
Collateral damage: ground supports

Collateral damage: Beam Vacuum

Arc burned through beam vacuum pipe





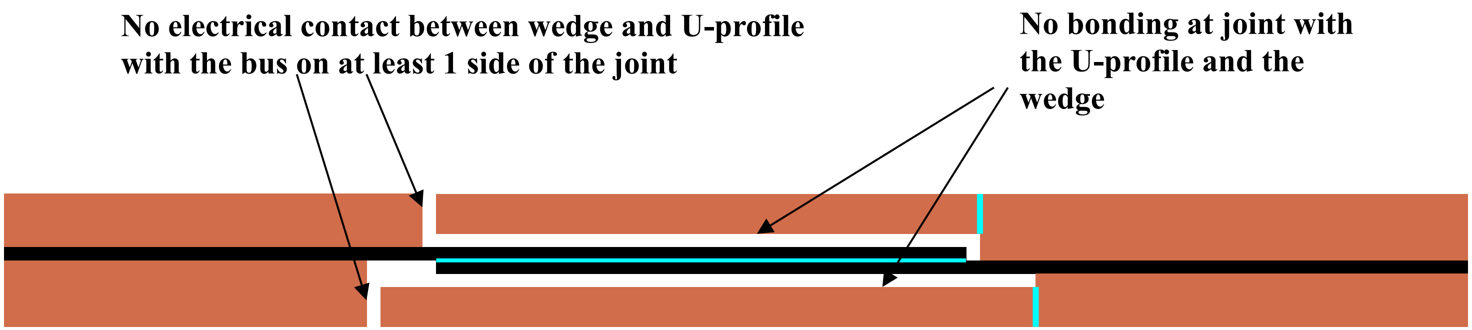


Important questions about Sept. 19

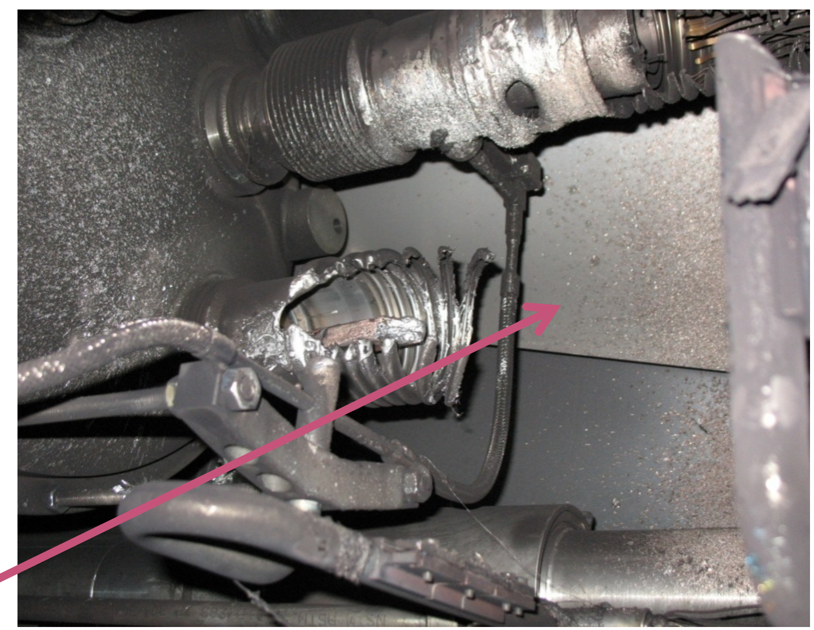
- Why did the joint fail?
  - Inherent problems with joint design
    - No clamps
    - Details of joint design
    - Solder used
  - Quality control problems
- Why wasn't it detected in time?
  - There was indirect (calorimetric) evidence of an ohmic heat loss, but these data were not routinely monitored
  - 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

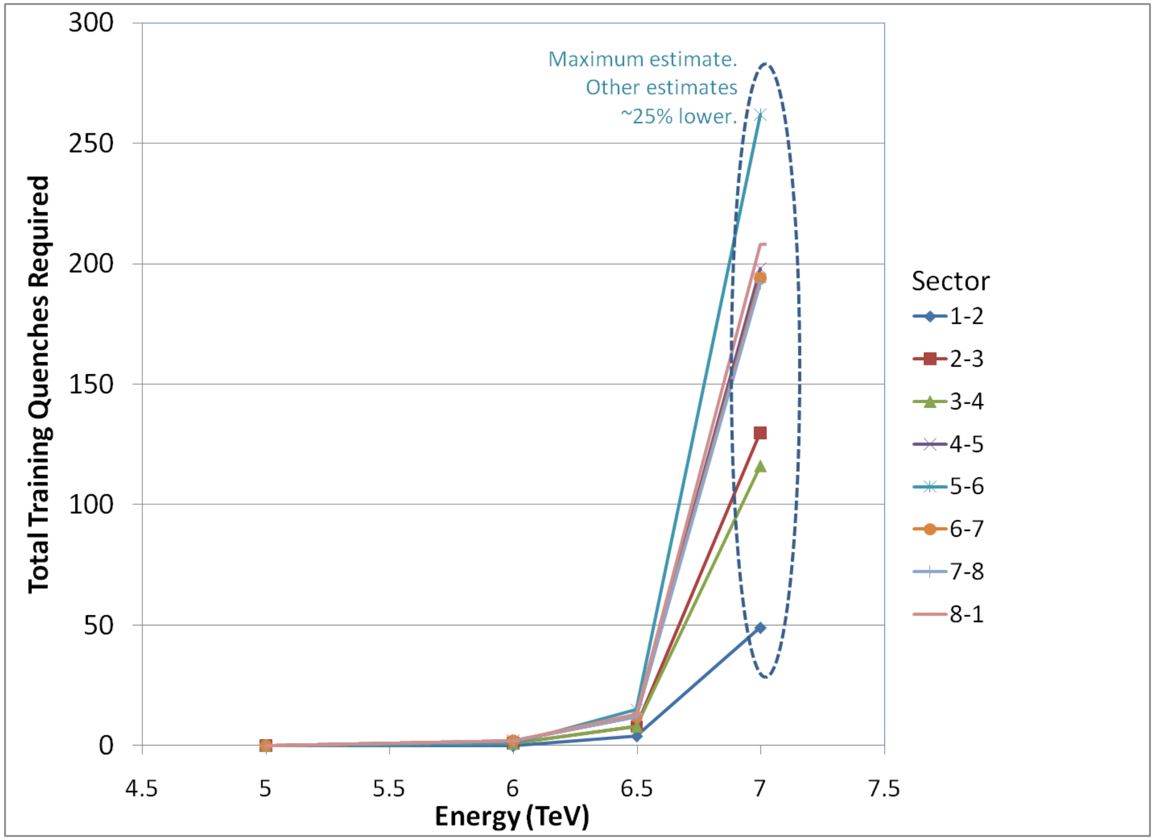
After the first shutdown

- 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.

Energy after LS1?*

- Recall: “lost training” problem before “incident”



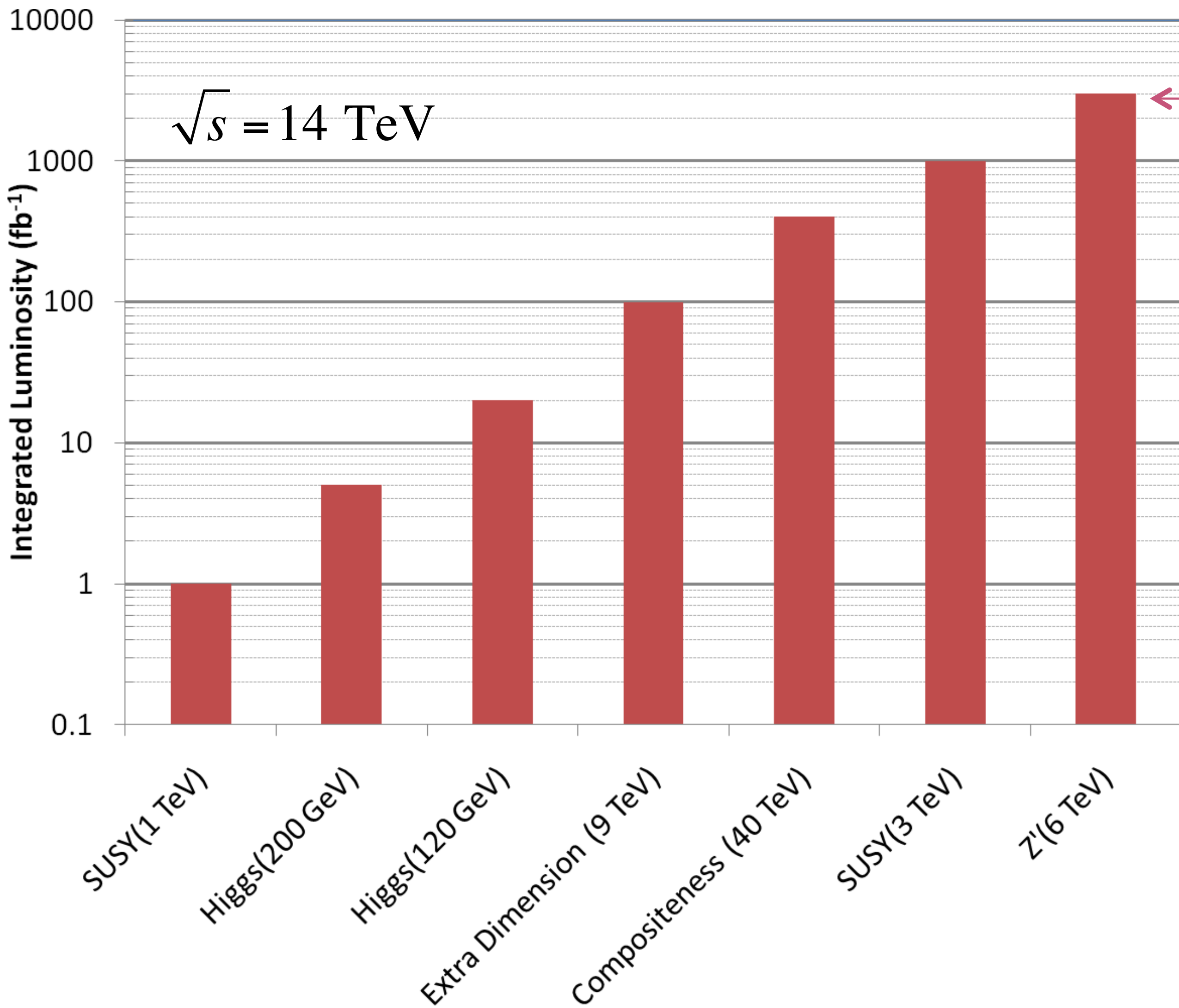
- Note, at high field, max 2-3 quenches/day/sector
  - Sectors can be done in parallel/day/sector (can be done in parallel)
- Ultimate energy somewhere between 6.5 and 7 TeV/beam

*my summary of data from A. Verveij, talk at Chamonix, Jan. 2009

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 fb^{-1}
~ 50 years at nominal LHC luminosity!

The future begins now

How can we increase the luminosity??

Limits to LHC Luminosity*

Brightness, limited by

- PSB injection energy
- PS
- Max tune-shift

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

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

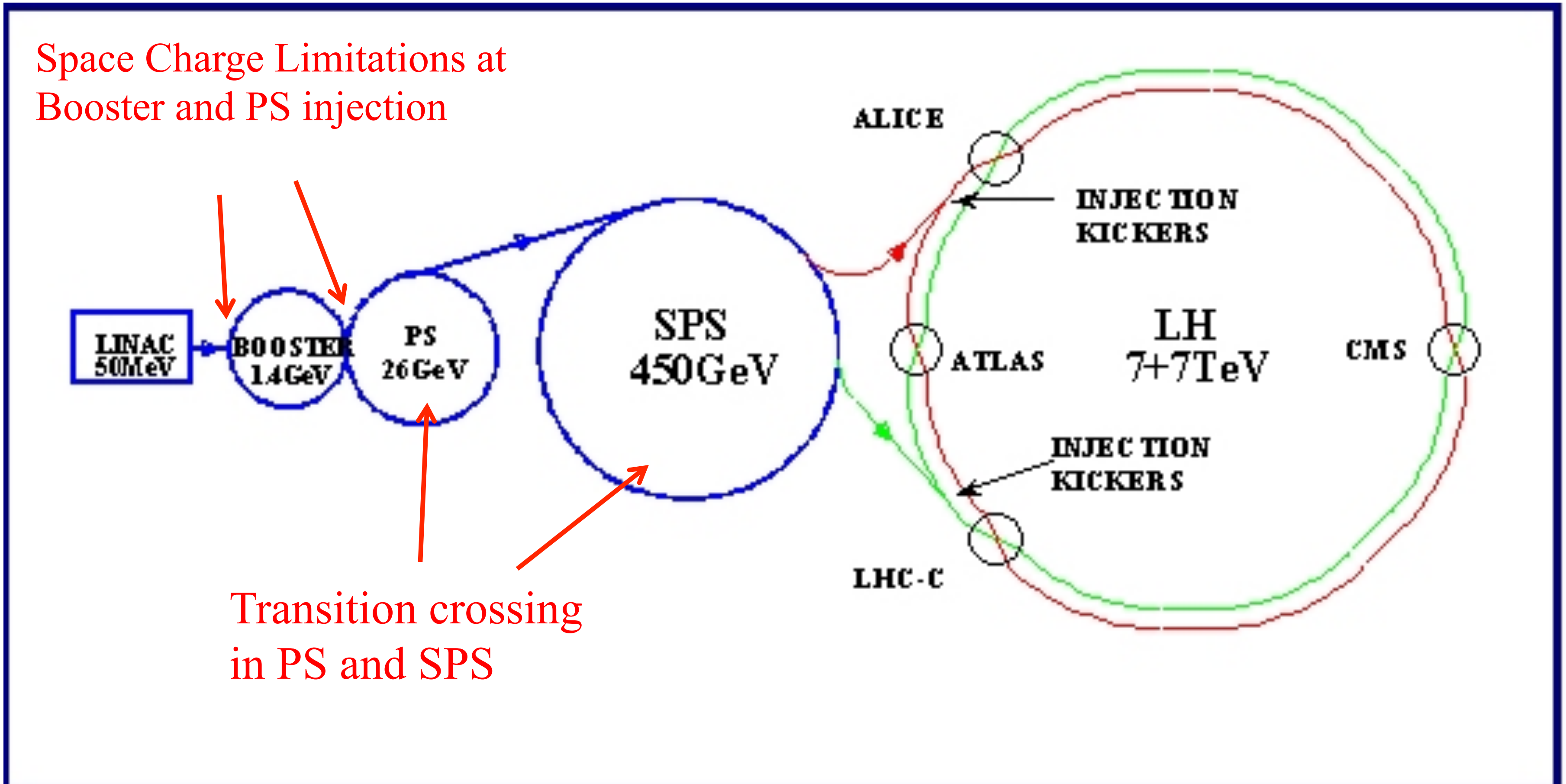
β*, limited by

- 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

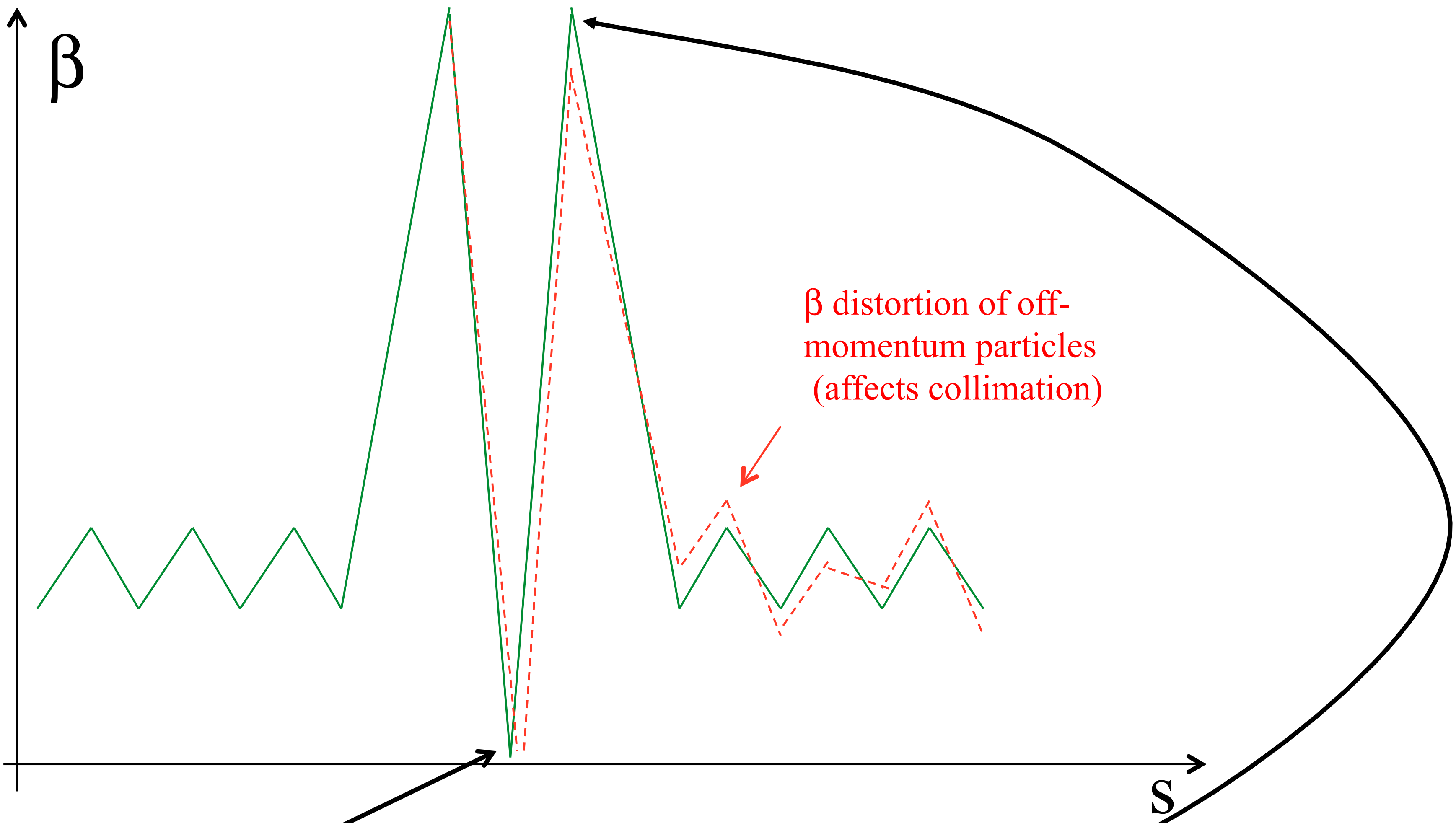


Schematic ONLY. Scale and orientation not correct

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*

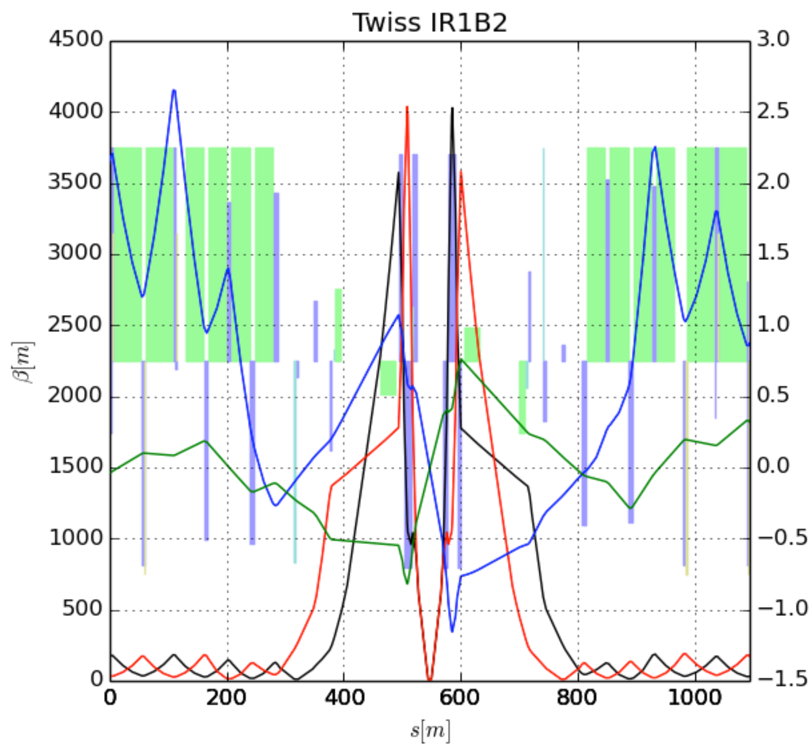


$$\beta(\Delta s) = \beta^* + \frac{\Delta s^2}{\beta^*}$$

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

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

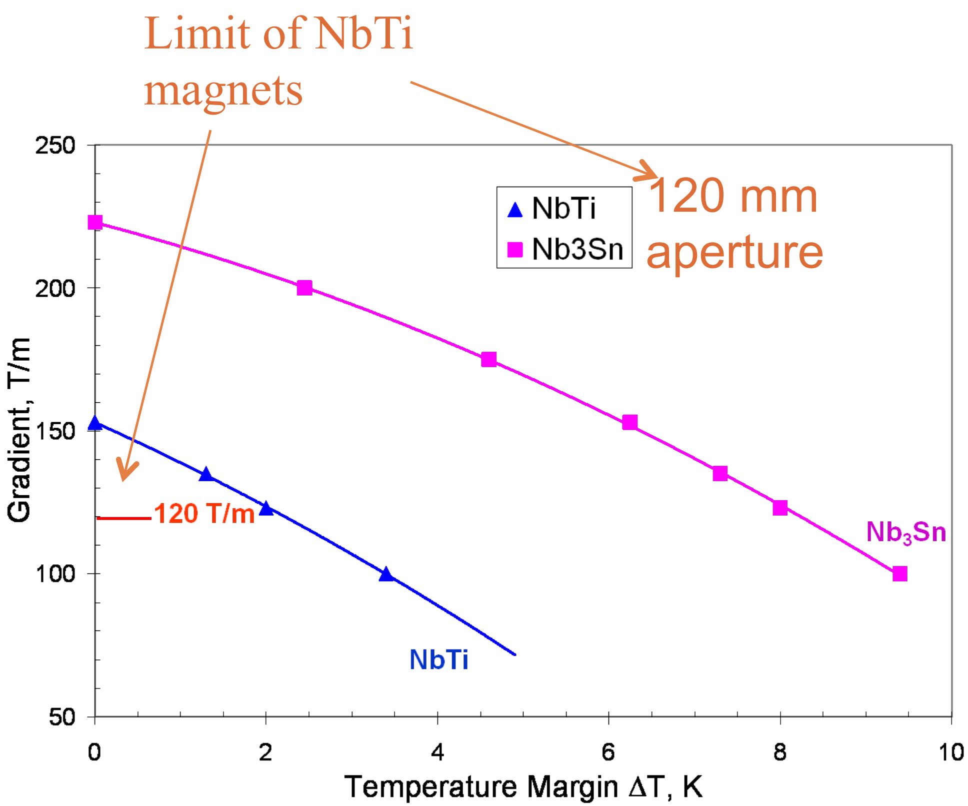
Proposed for upgrade
- 140 mm aperture
- 200 T/m gradient
- Field 70% higher at pole face

➔ Beyond the limit of NbTi

- Need bigger quads to go to smaller β*

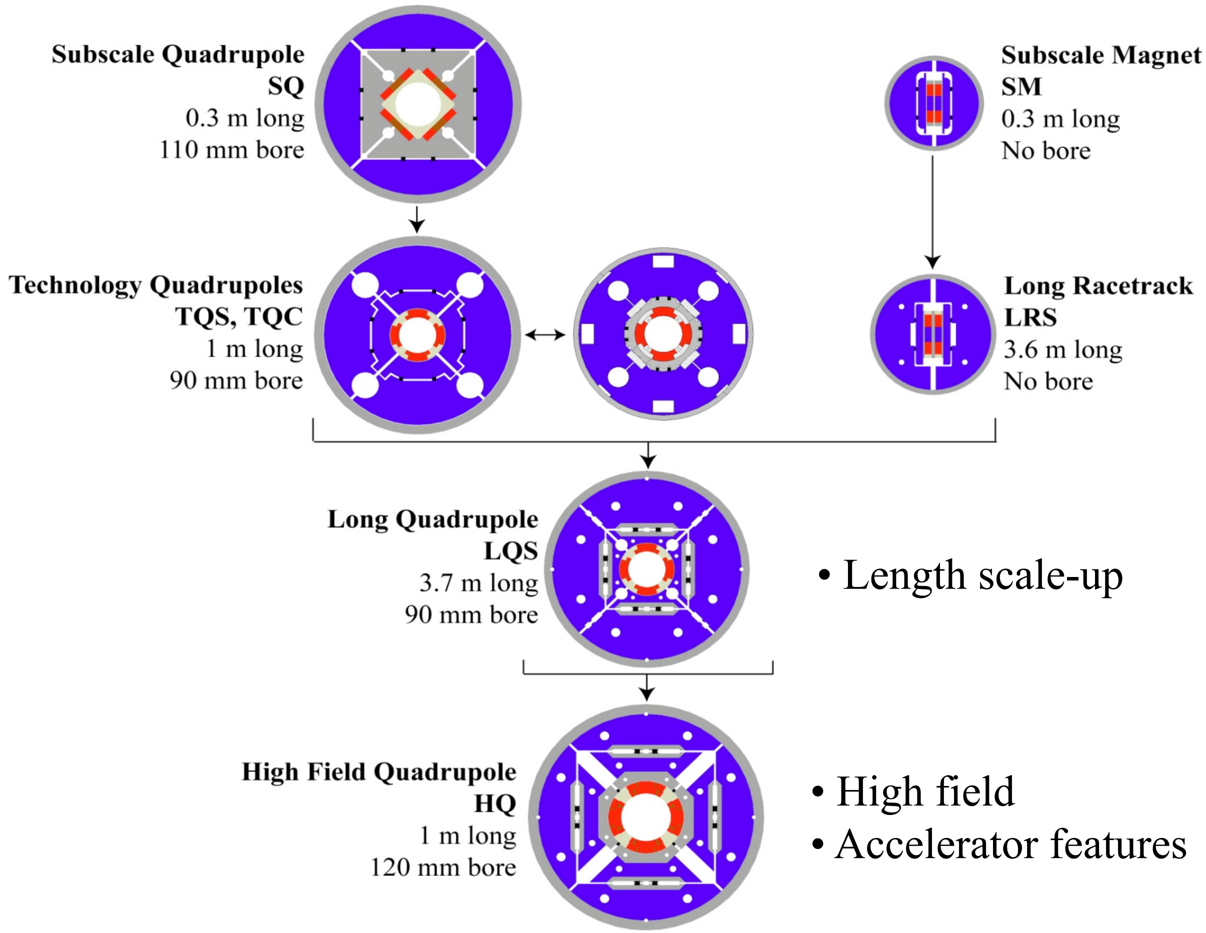
Motivation for Nb_3Sn

- 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



- Length scale-up

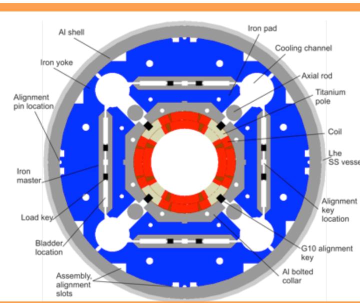
Achieved 220 T/m

- High field
- Accelerator features

Being tested

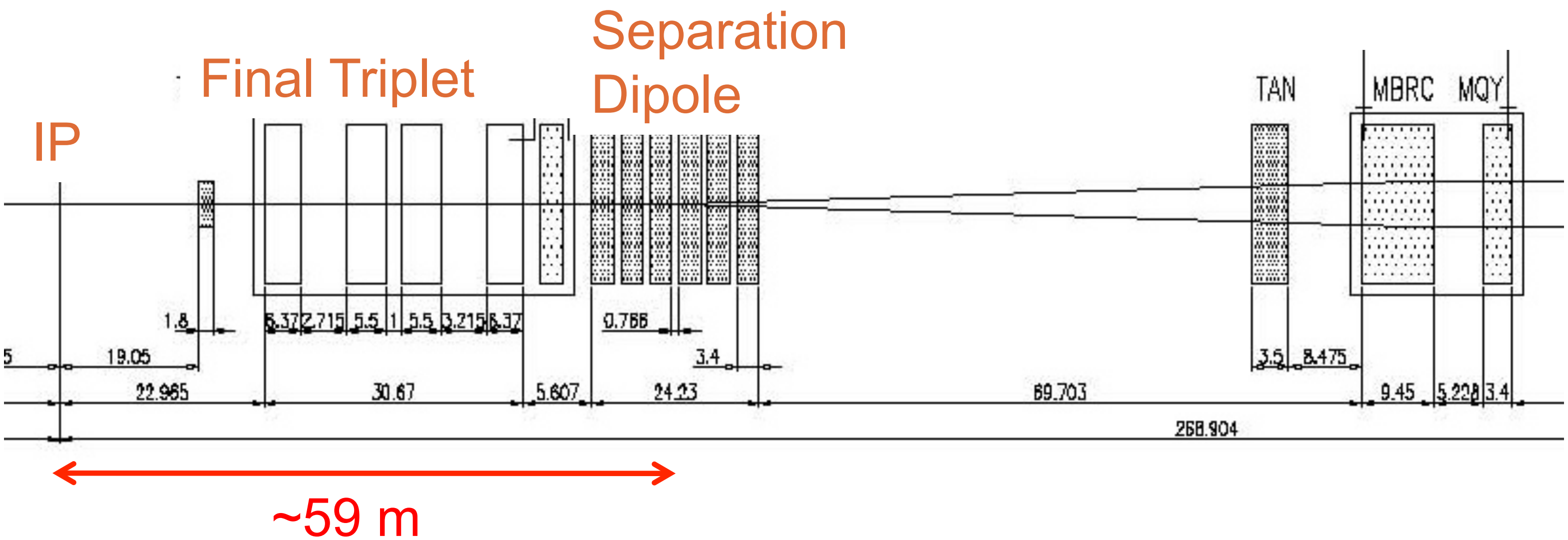
Completed

LHC Prototype
4 m long
150 mm bore

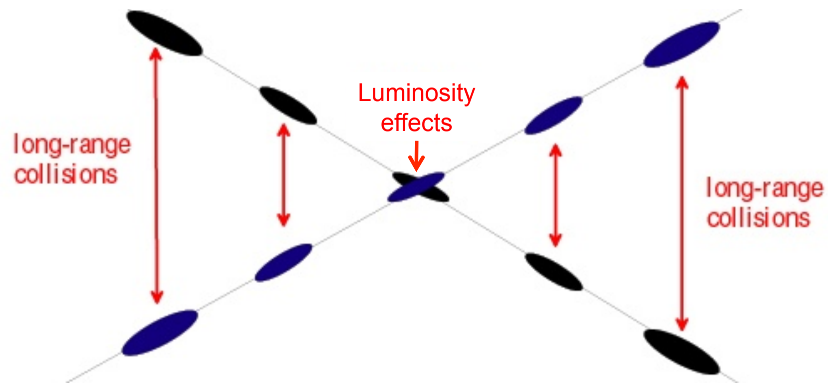


Being designed jointly with CERN

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



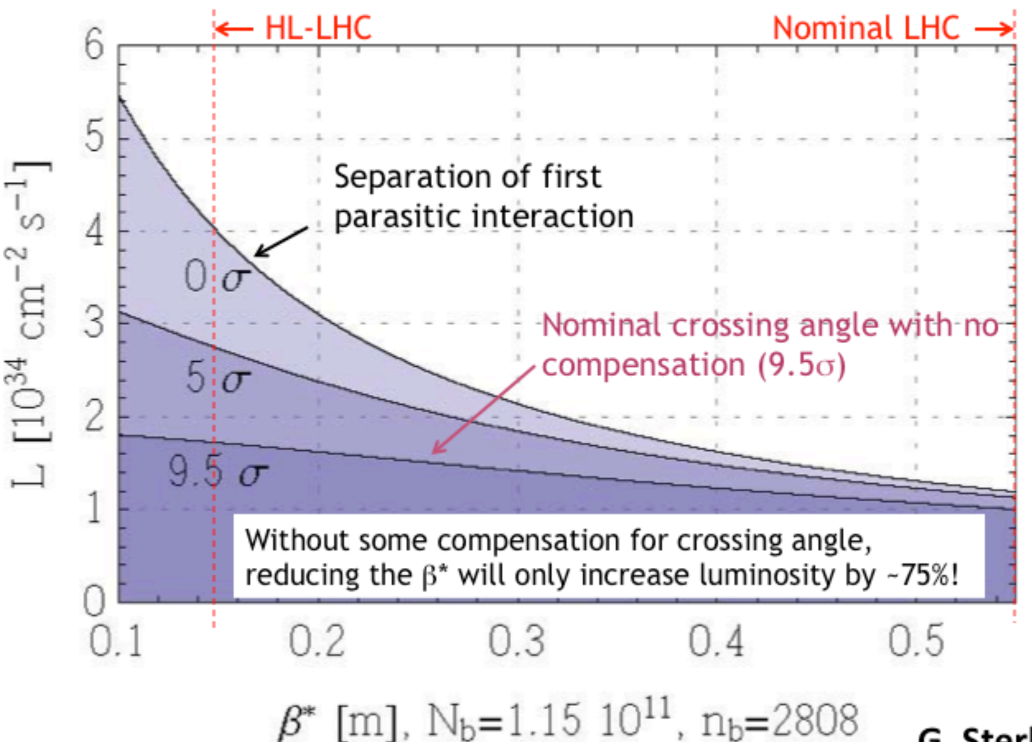
⟹ Need Crossing Angle

Crossing Angle Considerations

- Crossing angle reduces luminosity

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

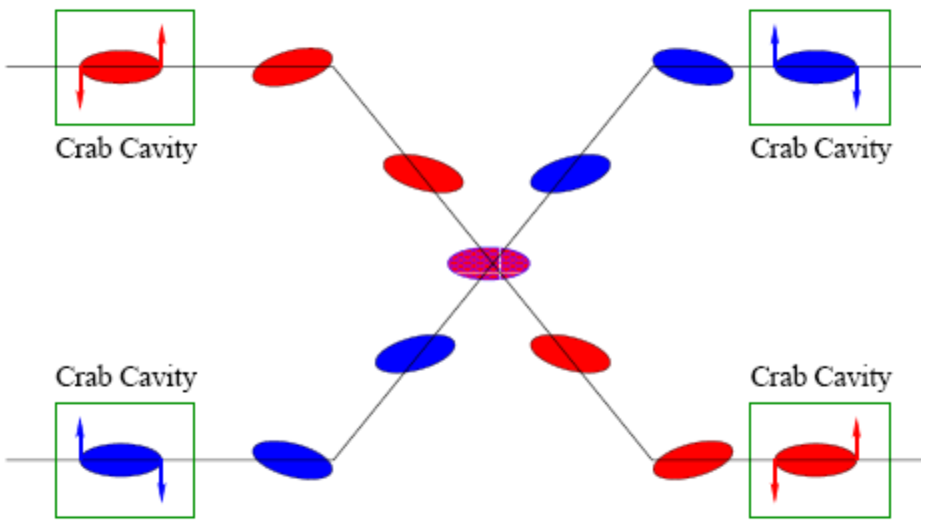
"Piwinski Angle"

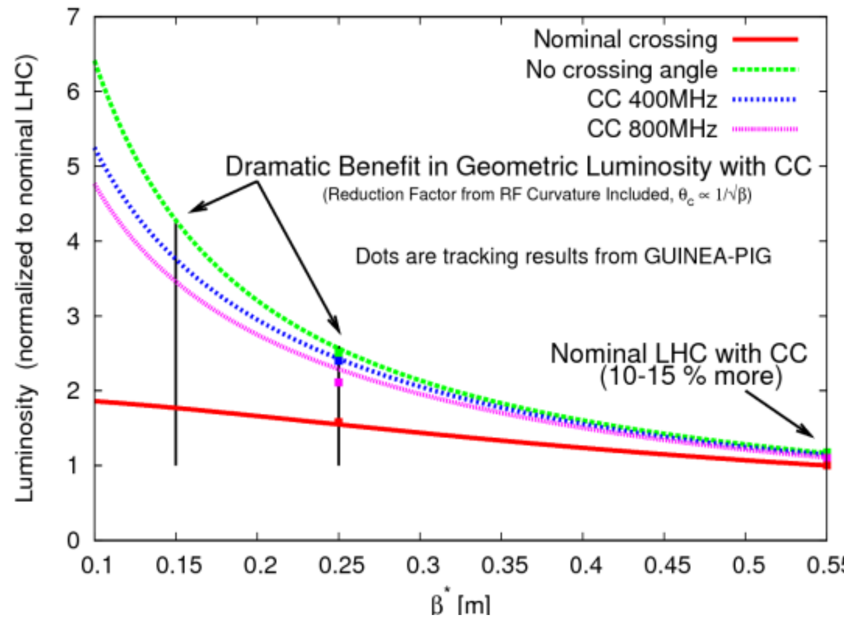


G. Sterbini

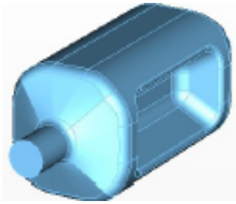
Minor effect at current β*, but largely cancels benefit of lowering β*

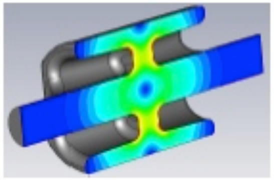
Baseline Approach: Crab Cavities





- 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

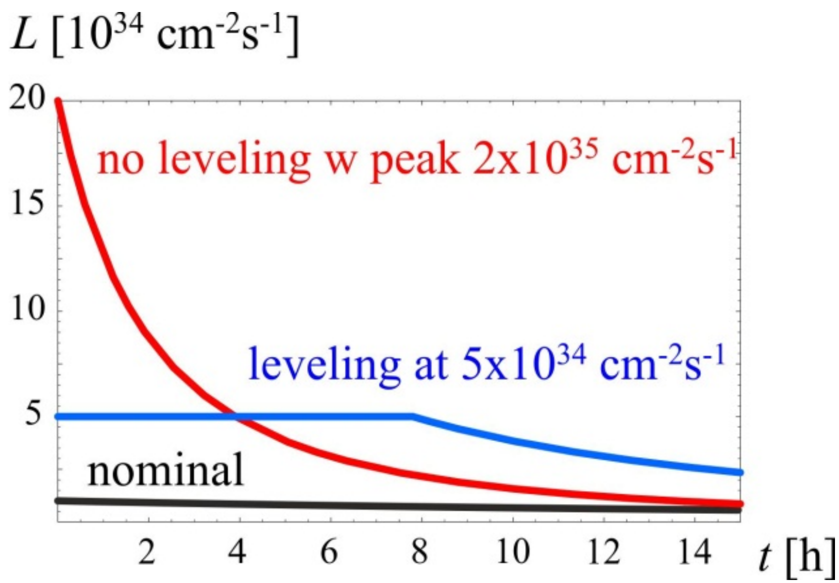


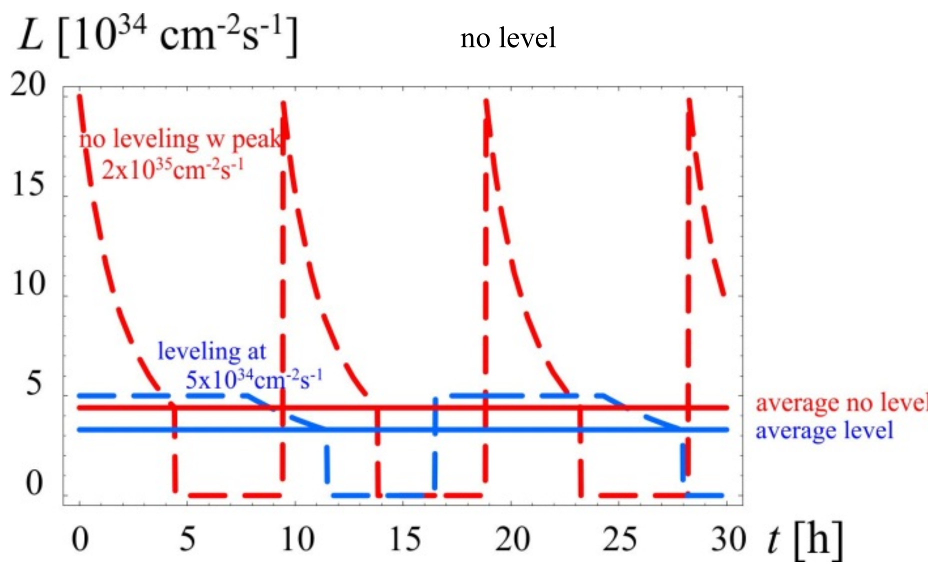


- Additional benefit
  - Crab cavities may help level luminosity!

Luminosity Leveling

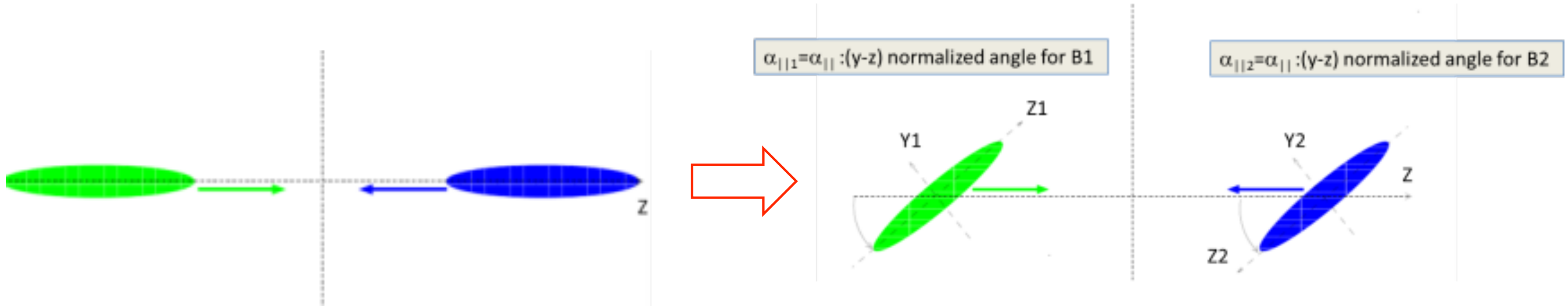
- Original goal of luminosity upgrade: >10^{35} cm^{-2}s^{-1}
  - Leads to unacceptable pileup in detectors
- New goal: 5×10^{34} *leveled* luminosity

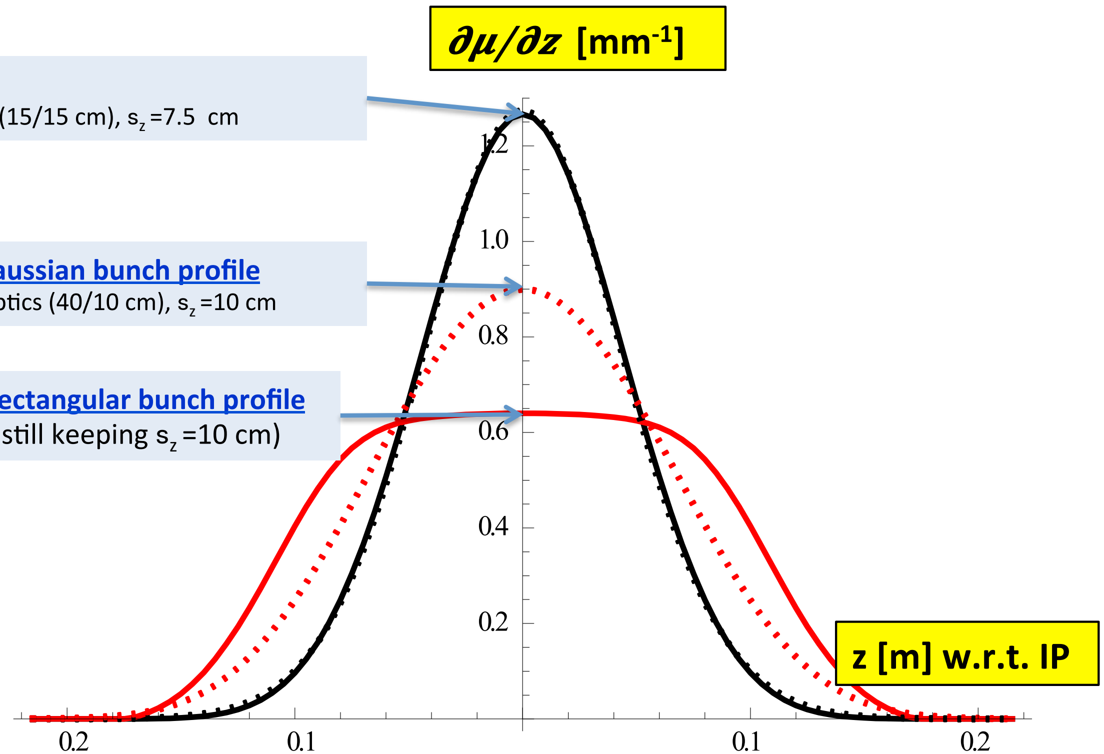




- Options
  - Crab cavities ← "Crab kissing" – sort of complicated
  - β* modifications
  - Lateral separation

Crab Kissing*





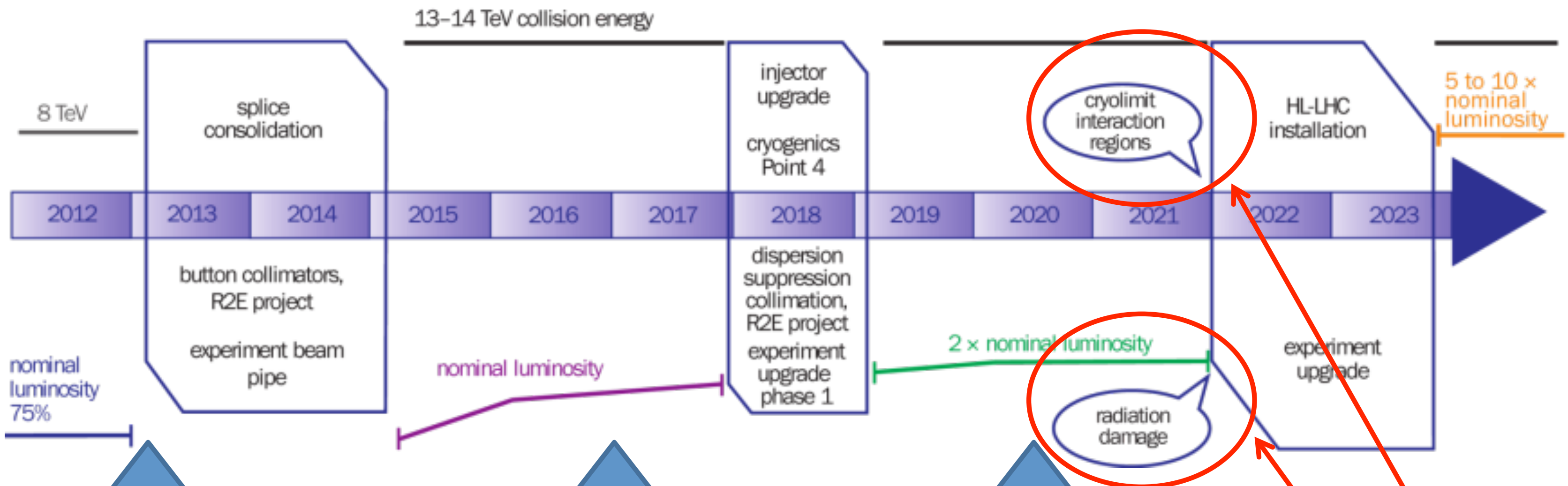
HL-LHC w/o CK scheme
- **12.5 MV crabs in X-plane**, round optics (15/15 cm), s_z =7.5 cm

"HL-LHC+" with CK scheme and **Gaussian bunch profile**
- **7+7 MV crabs in X and || -plane**, flat optics (40/10 cm), s_z =10 cm

"HL-LHC++" with CK scheme and **rectangular bunch profile**
... with 400+800 MHz or 200+400 (still keeping s_z =10 cm)

*S. Fartoukh

Long Term Plan*



$0.75\ 10^{34}\ cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

$1.5\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

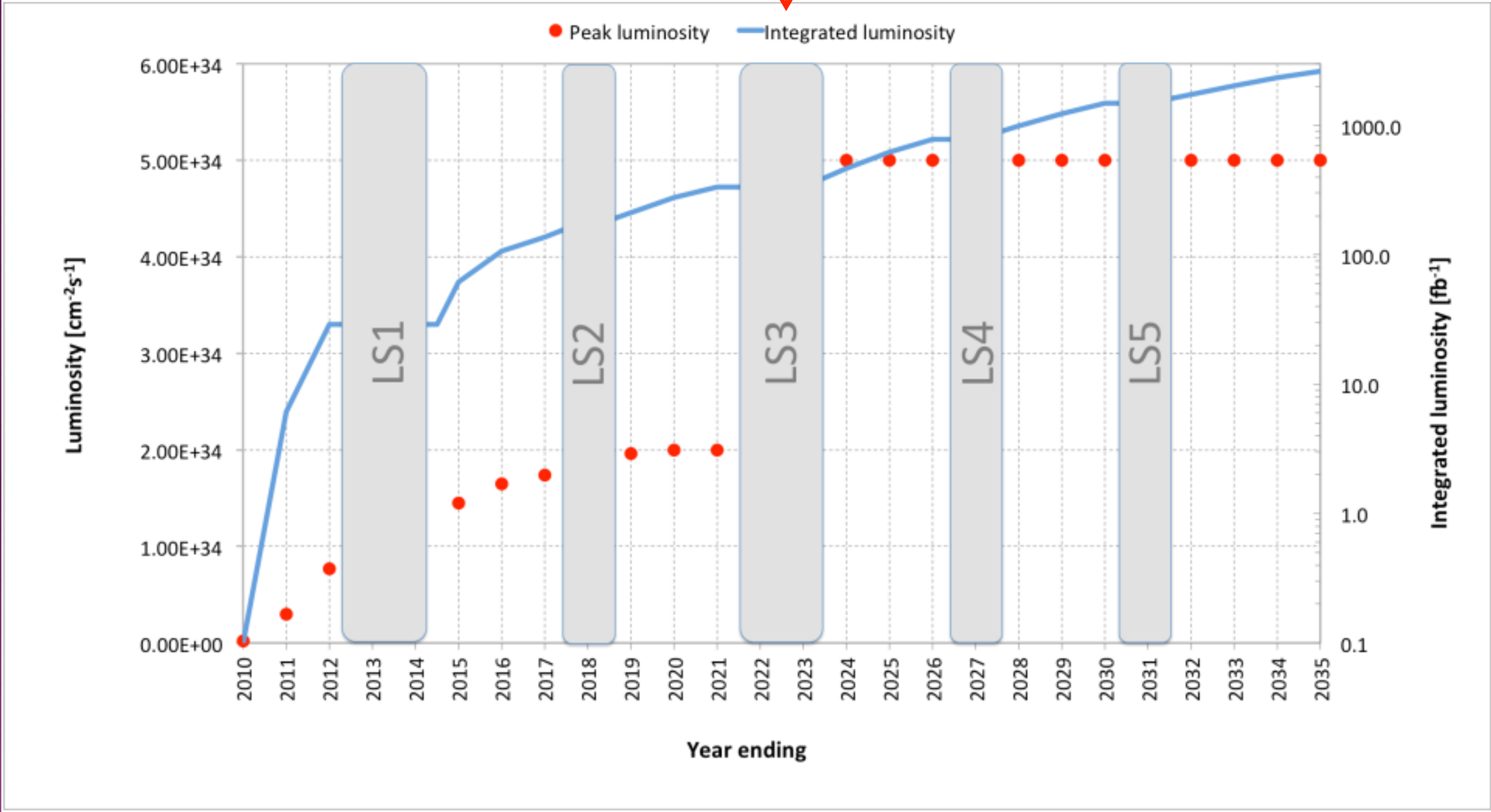
$1.7\text{-}2.2\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

Technical limits (experiments, too) like :

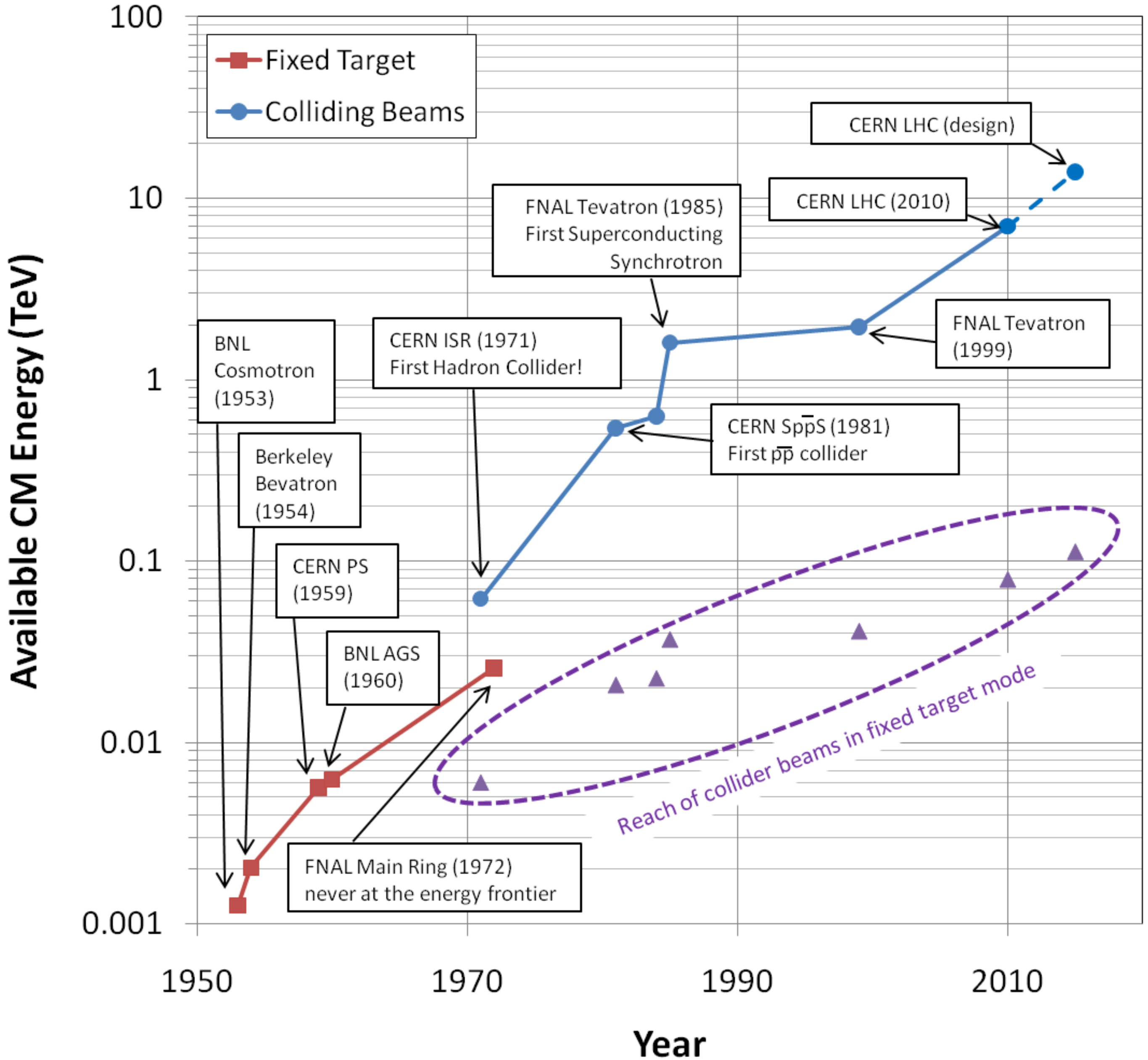
*L. Rossi, LARP/HL-LHC Meeting, Nov. 2013

The Long Game

HL-LHC Upgrades



Summary: Evolution of the Energy Frontier

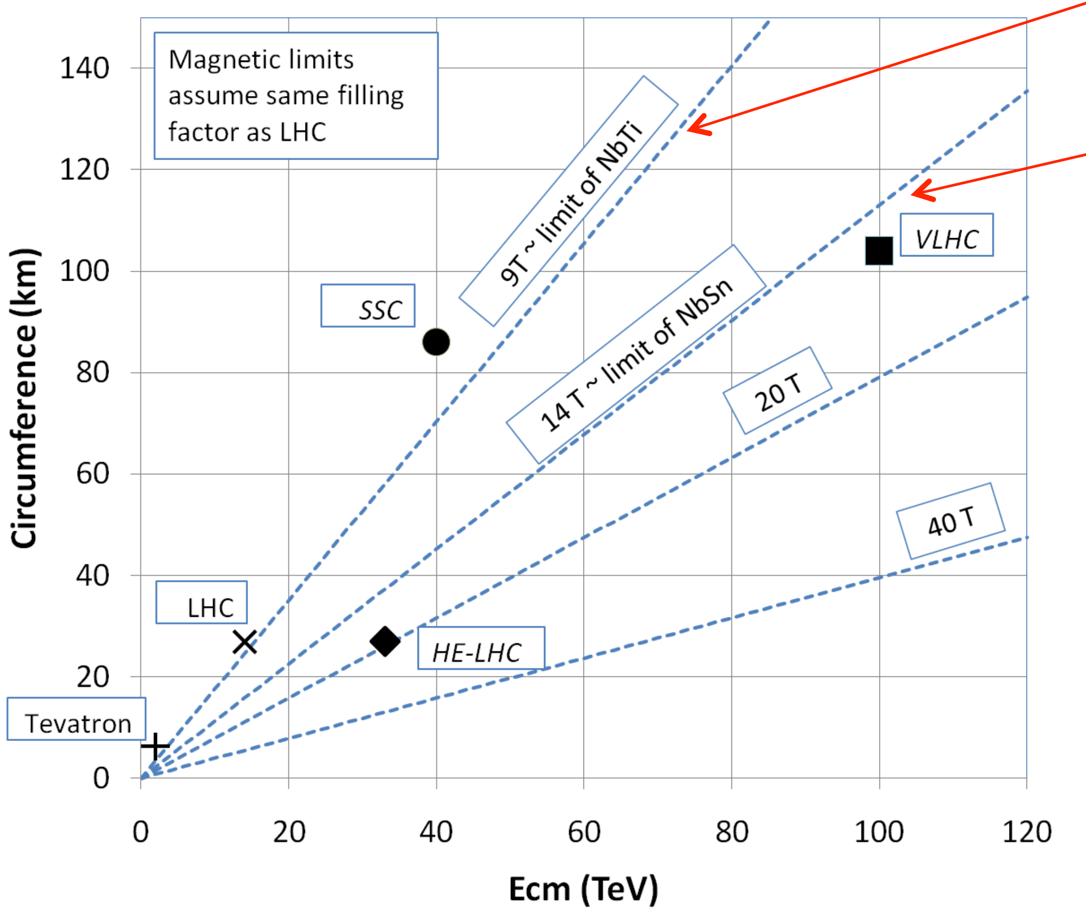


~a factor of 10 every 15 years

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)



All accelerator magnets based on this

Future magnets could be based on this

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

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!

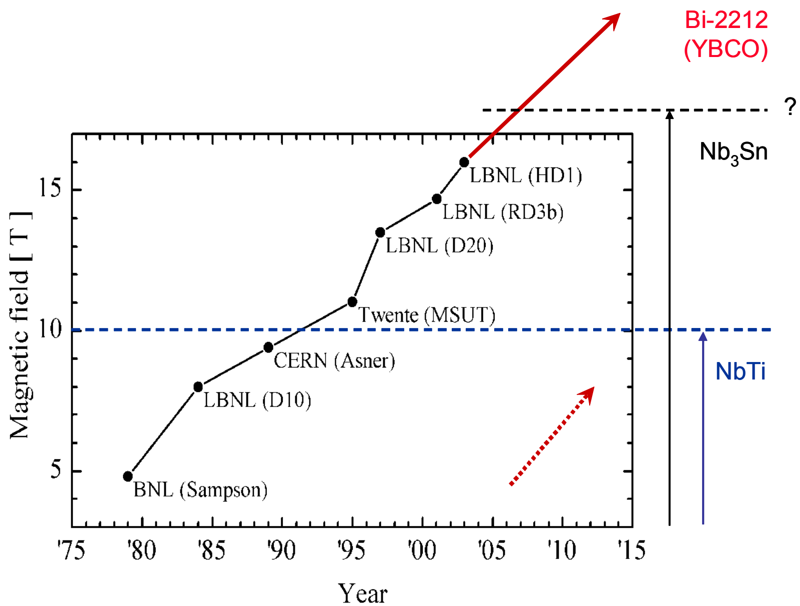
- What are the options to make it more compact, and or go to even higher energies?

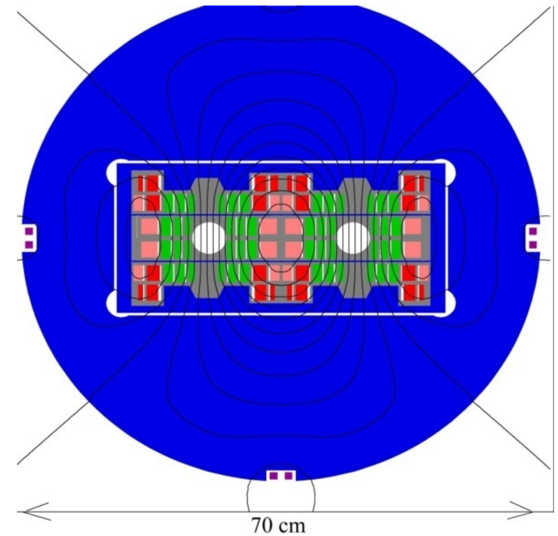
Superconductor Options

- 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

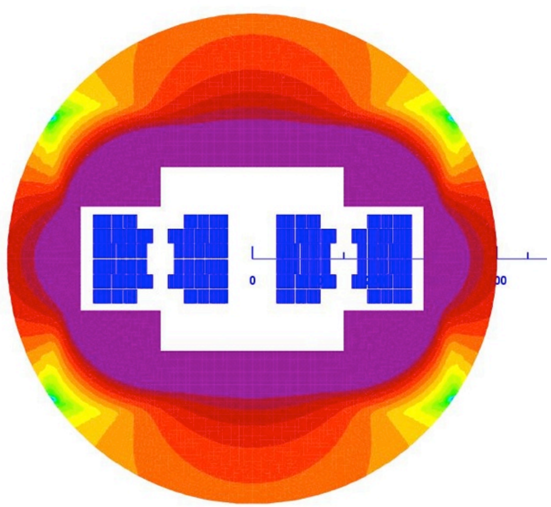
Focusing on this, but very expensive
➔ pursue hybrid design

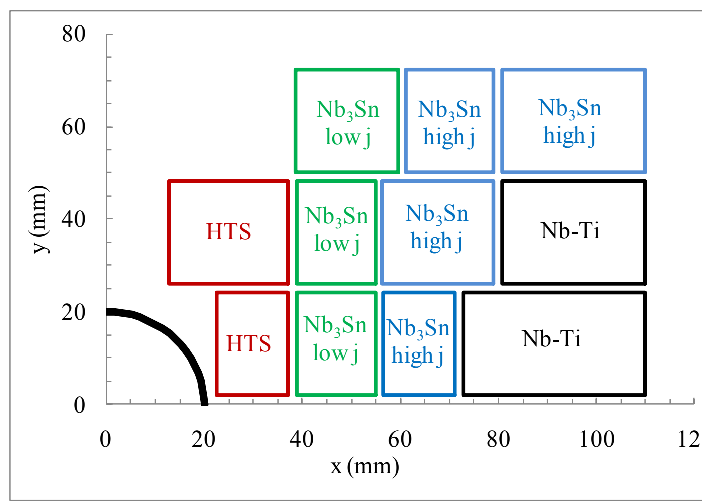
Potential Designs





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

Things I didn't talk about

- Ion colliders
  - Challenges: accelerating different species of ions.
  - Pb-p challenge: RF sets period, but slightly different momentum = slightly different orbit.
- e-p colliders
  - Challenges:
    - efficient high intensity electron beams
    - interaction regions

Opportunity: LARP Toohig Fellowship

- Named for Tim Toohig, one of the founders of Fermilab
- Open to recent PhD’s in accelerator science or HEP.
- Successful candidates divide their time between CERN and one of the four host labs.
- Past
  - Helene Felice, LBNL, now staff
  - Rama Calaga, BNL, now CERN staff
  - Ricdardo de Maria, BNL, now CERN Fellow
  - Themis Mastoridis, SLAC, now CERN Fellow
  - Ryoichi Miyamoto, BNL, now ESS Staff
  - Dariusz Bocian, FNAL, now Ass. Prof. at The Henryk Niewodniczański Institute of Nuclear Physics
  - Valentina Previtali, FNAL, now teaching in Switzerland
- Present
  - Simon White, BNL
  - John Cesaratto, SLAC
  - Ian Pong, LBNL
  - Silvia Verdu Andres, BNL

Further Reading

- Edwards and Syphers "An Introduction to the Physics of High Energy Accelerators"
  - My personal favorite
  - Concise. Scope and level just right to get a solid grasp of the topic
  - Crazy expensive, for some reason.
- Helmut Wiedemann, "Particle Accelerator Physics"
  - Probably the most complete and thorough book around (originally two volumes)
  - Well written
  - Scope and mathematical level very high
- Edmund Wilson, "Particle Accelerators"
  - Concise reference on a number of major topics
  - Available in paperback (important if you are paying)
  - A bit light
- Klaus Wille "The Physics of Particle Accelerators"
  - Same comments
- Fermilab "Accelerator Concepts" ("Rookie Book")
  - http://www-bdnew.fnal.gov/operations/rookie_books/Concepts_v3.6.pdf
  - Particularly chapters II-IV
- USPAS course: http://uspas.fnal.gov/