A pp and an e+e- Collider in a 100 km ring at Fermilab
VLHC/VLEP

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DPF 2013, UC Santa Cruz
August 13-17, 2013

Outline

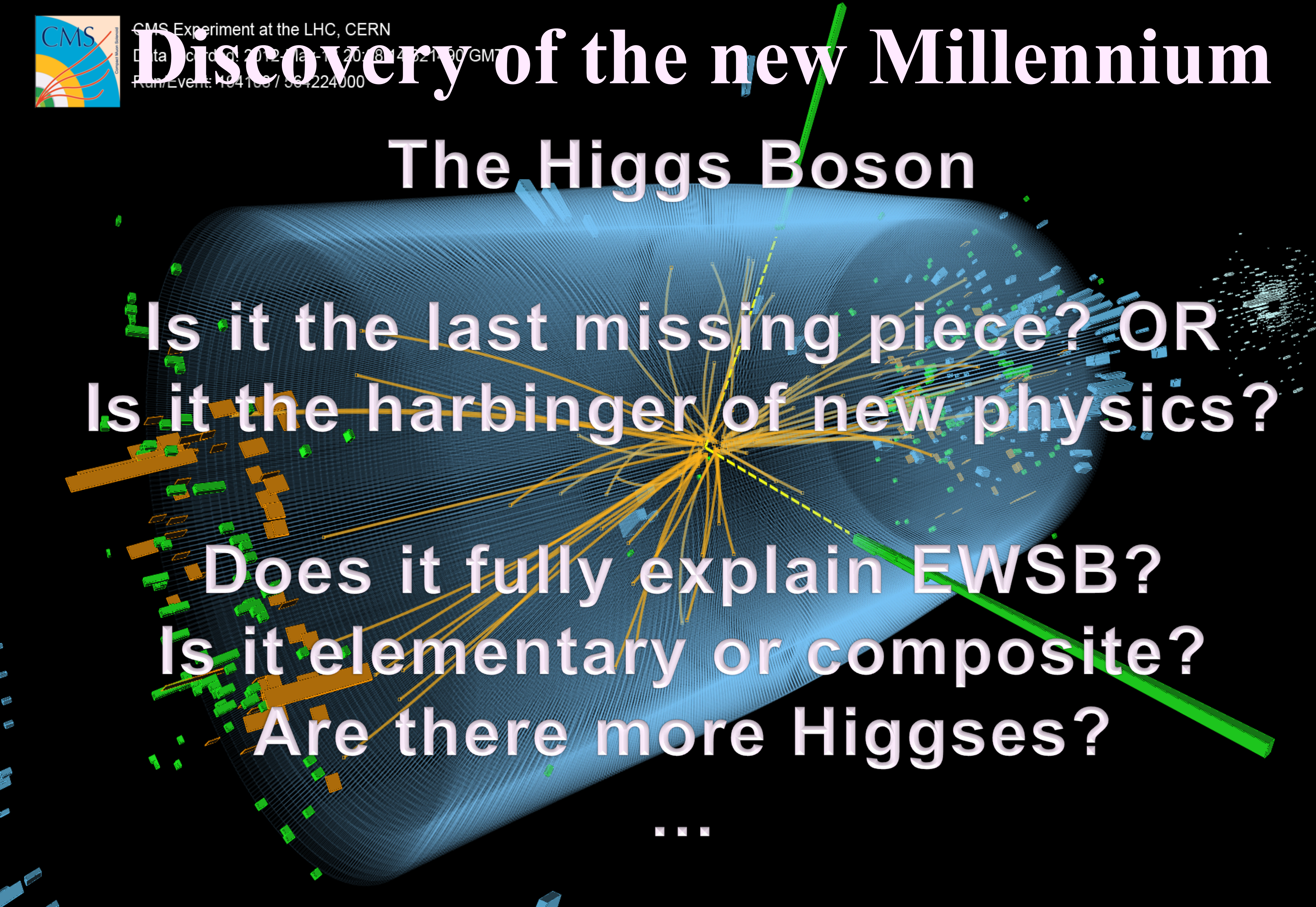
- The Backdrop
  - Higgs Discovery
  - Snowmass 2013
  - VLHC: Some History
- The 2013 Study
  - Snowmass summary
  - 100 TeV pp collider (VLHC) in a 100 km ring
  - 240-350 GeV e+e- Higgs Factory (VLEP)
- Summary

A year ago on July 4th


The Economist
JULY 7TH–13TH 2012
Economist.com
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
A giant leap for science
Finding the Higgs boson


Science
21 December 2012 | $10
BREAKTHROUGH of the YEAR
The HIGGS BOSON
AAAS

Discovery of the new Millennium



The Higgs Boson

Is it the last missing piece? OR
Is it the harbinger of new physics?

Does it fully explain EWSB?
Is it elementary or composite?
Are there more Higgses?

…

So far so good.. hoping for better!

- Thanks to the discovery, the world HEP community is excited, interest in future energy frontier colliders has been reignited, and some old shelved ideas are finding new life.
- The LHC data, so far, indicate that the new particle has properties consistent with a SM Higgs boson. But its measured mass is tantalizingly consistent also with an SM-Higgs-like boson from new physics beyond the SM.
- We are where we had suspected to find ourselves – a low mass SM-like Higgs found, and nothing else! So far. But, that could change!

Physics at the Terascale

- To fully elucidate EWSB and understand the Terascale landscape
  - Study the Higgs boson that has been found (Mass, width, spin-parity, couplings)
  - Search for other physical states at higher mass scales
    - Evidence for SUSY, extra dimensions, heavier gauge bosons W', Z', heavier fermions, ..
  - Measure vector boson scattering and couplings
    - Longitudinal vector boson scattering and VBF production
- An e+e- collider would be a nice complement to the LHC. A hadron collider at ~100 TeV would be a lot more useful!

The Case for a VLHC

- Hadron colliders with their broad-band parton collision energies are Discovery Machine, and can make precision measurements!
- Historically, each time collision energy of hadrons went up significantly, we have discovered new particles.
- Top quark discovered at the Tevatron, after searches at SLC and LEP! And, Higgs discovery came at the LHC.
- However, since we have not found any new physics at $\sqrt{s} = 8$ TeV, if we do find new physics at 13-14 TeV it is likely to be at the limit of LHC reach. (Low hanging fruits?)
- "Regardless of what we will find at the LHC we will eventually want to have a hadron collider operating in the 100 TeV range." - U. Baur, HEPAP subpanel, June 2001

The Case for a VLHC

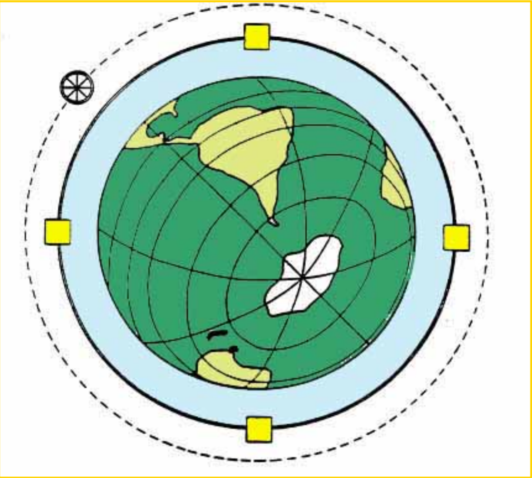
- If some new physics is found at the LHC at 13-14 TeV, then it makes a lot more sense to take a big jump in energy (~an order of magnitude) rather than a small one (~x2)
  - If some heavy "partner" particles are found, VLHC can find the full suite of partners (SUSY)
  - If exotic resonances are found, VLHC can fill out the "tower" of resonances, confirming extra dimensions
  - Complete measurements of vector boson scattering, explore fully the mechanism of EWSB, and SUSY breaking if SUSY is found
- Higgs Boson:
  - VLHC would enable precision measurements of the Higgs including Higgs self-coupling, and rare decays of the Higgs!
- VLHC has direct discovery potential in 10's of TeV range

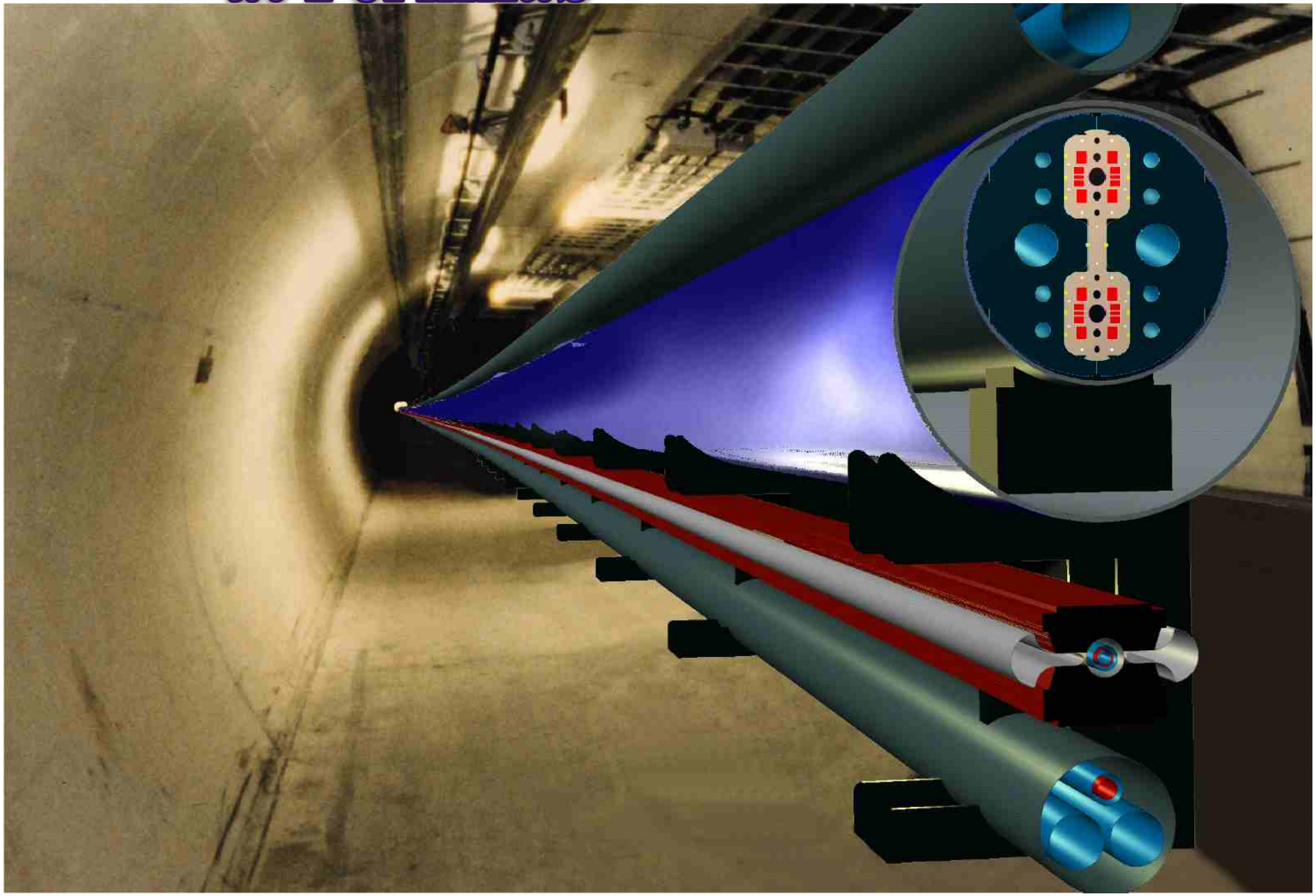
Some History

- US HEP/AP Community has been through some phases of "design" and "construction" for 80 – 500 km machines, in the past three decades.
  - SSC was going to be 87.1 km in circumference, and $\sqrt{s} = 40$ TeV. 23 km tunnel bored and 17 shafts in Texas. $2B spent!
    - Conception: Snowmass 1983, Design: 1988-90; Construction initiated: 1988, Halted: 1993.
  - "VLHC"(1995 -2005) in various incarnations – Primarily 233 km; E_{CM} from 40 TeV (Stage 1) – 200 TeV (Stage 2) . http://vlhc.org/
  - Also considered VLLC (Very Large Lepton Collider) in VLHC tunnel
  - Pipetron: Low Cost Approach to a VLHC, To achieve > 100 TeV E_{CM} collider at the lowest possible $/TeV
- Many workshops, machine/physics/detector studies, HEPAP, VLHC steering committee, etc., R&D for magnets and many other aspects.

Very Large Hadron Collider
at Fermilab

vlhc.org





FNAL-TM-2149
(2001)

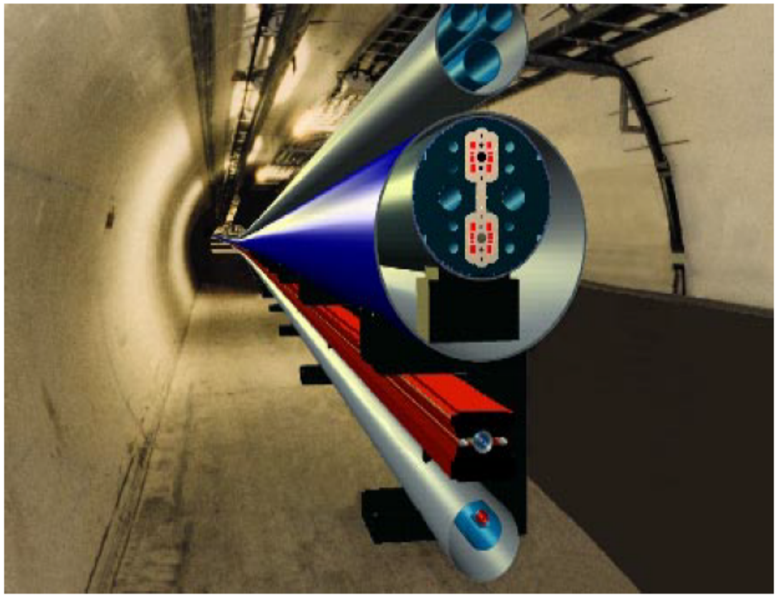
- Design Study for a two-stage Very Large Hadron Collider

VLHC in 2001

- Take advantage of the space and excellent geology near Fermilab.
  - **Build a BIG tunnel.**
  - **Fill it with a "cheap" 40 TeV collider.**
  - **Later, upgrade to a 200 TeV collider in the same tunnel.**

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	200
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Dipole field at collision energy (T)	2	11.2
Average arc bend radius (km)	35.0	35.0
Initial Number of Protons per Bunch	2.6×10^{10}	5.4×10^{9}
Bunch Spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.5
Free space in the interaction region (m)	± 20	± 30
Interactions per bunch crossing at L_{peak}	21	55
Debris power per IR (kW)	6	94
Synchrotron radiation power (W/m/beam)	0.03	5.7
Average power use (MW) for collider ring	25	100

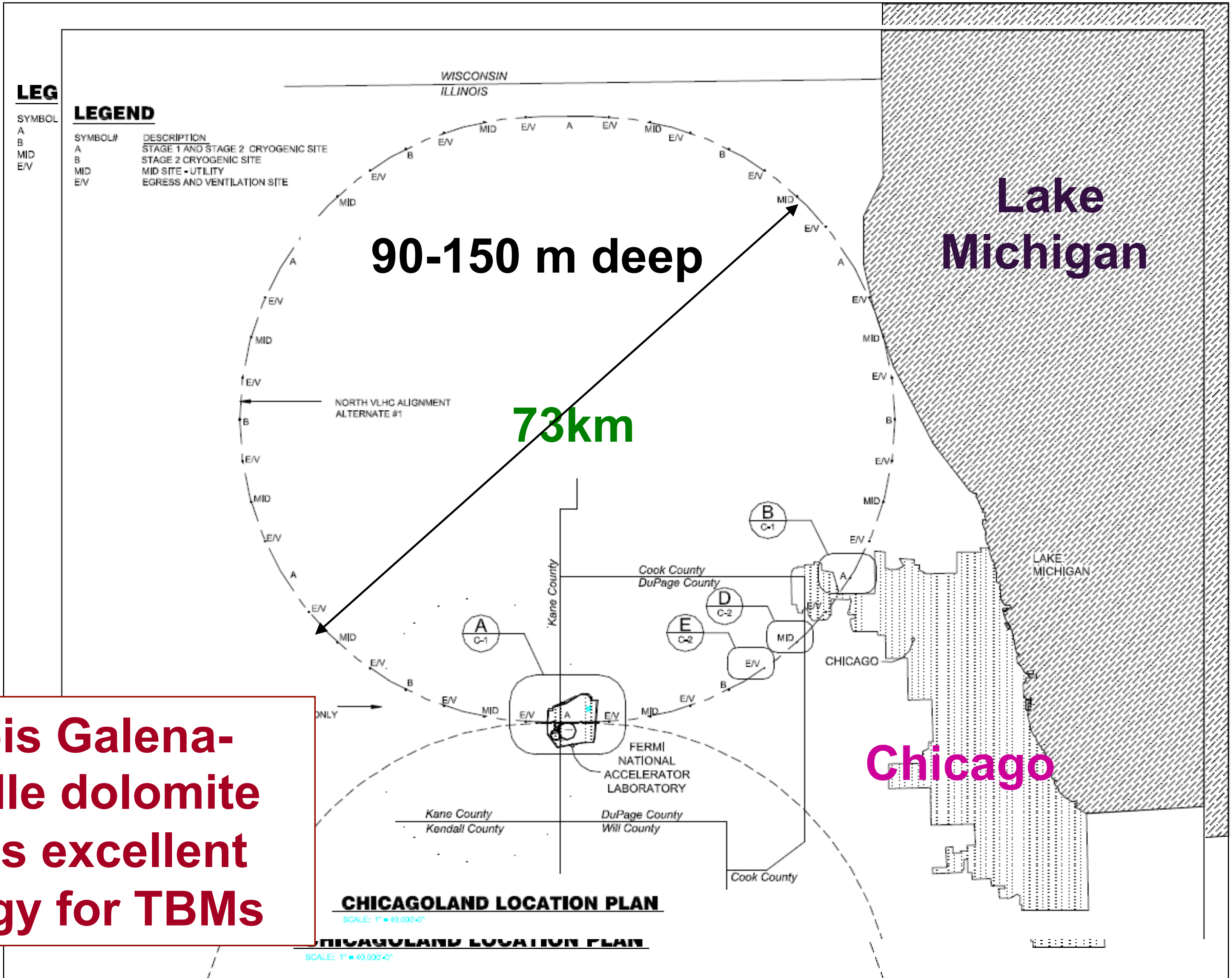
VLHC designs (2001)



- Circumference = 233km
- Stage 1 ring: (1 to 20) TeV/beam
- Stage 2 ring : (20 to 87.5) TeV/beam
- Super-ferric magnets for the 2 T low field, stage 1, Injection from Tevatron
- Nb_3Sn magnets for 10-12 T high field, stage 2. Injection from Stage 1
- Modular design: IRs, utilities, dispersion suppressors etc had lengths in integer units of a half cell.
- Very high beam stored beam energy (~ GJ) in both cases
- Fermilab-TM-2149, Fermilab-TM-2158

A VLLC in the VLHC tunnel was also considered
T. Sen, J. Norem
http://prst-ab.aps.org/pdf/PRSTAB/v5/i3/e031001

233 km VLHC

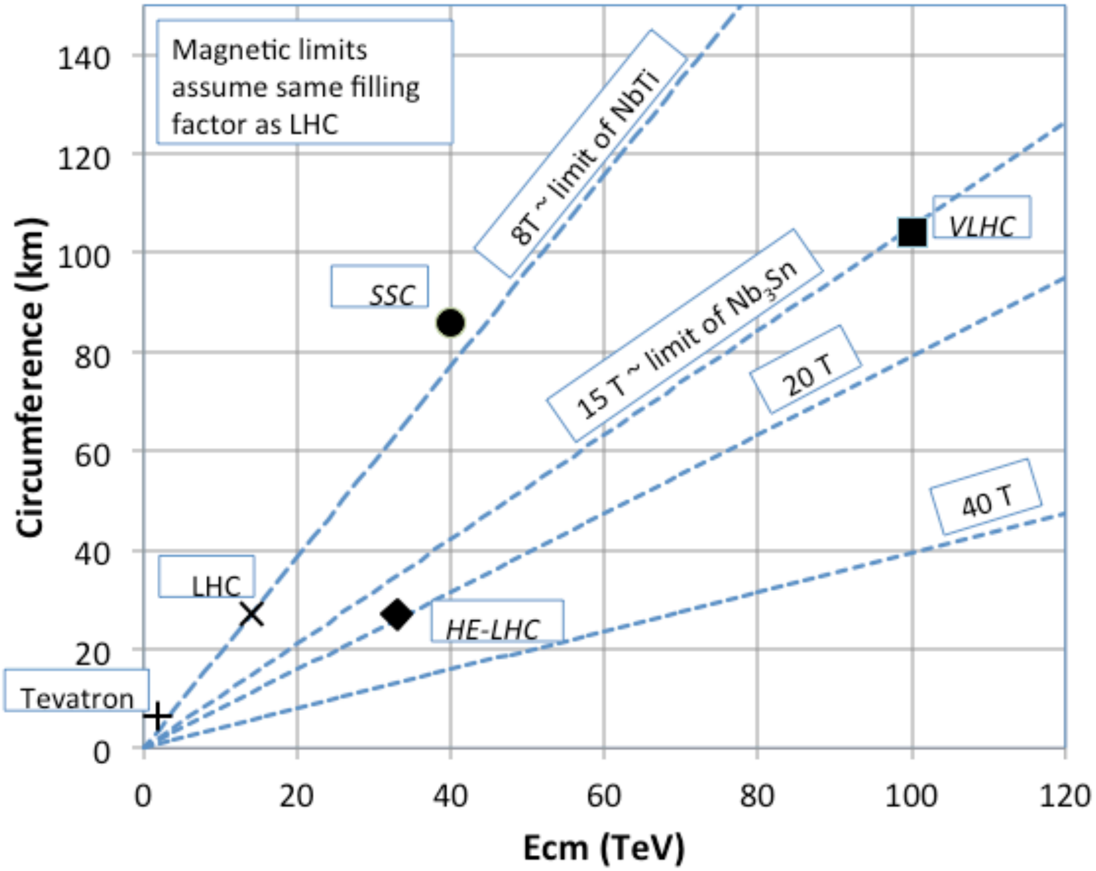


Illinois Galena-Plattville dolomite layer is excellent geology for TBMs

Site studies in Illinois

- We know a lot about the geology and tunneling in Illinois.
  - Thick, homogeneous dolomite at a depth of 300 – 500 ft
  - The Chicago TARP (Tunnel and Reservoir plan): 176 km of tunnel (9 - 33 ft in dia, up to 350 ft underground) completed
  - Studied for SSC, VLHC, ILC,..
- Many siting options for large rings have been studied.

VLHC (2013)



Snowmass Whitepaper

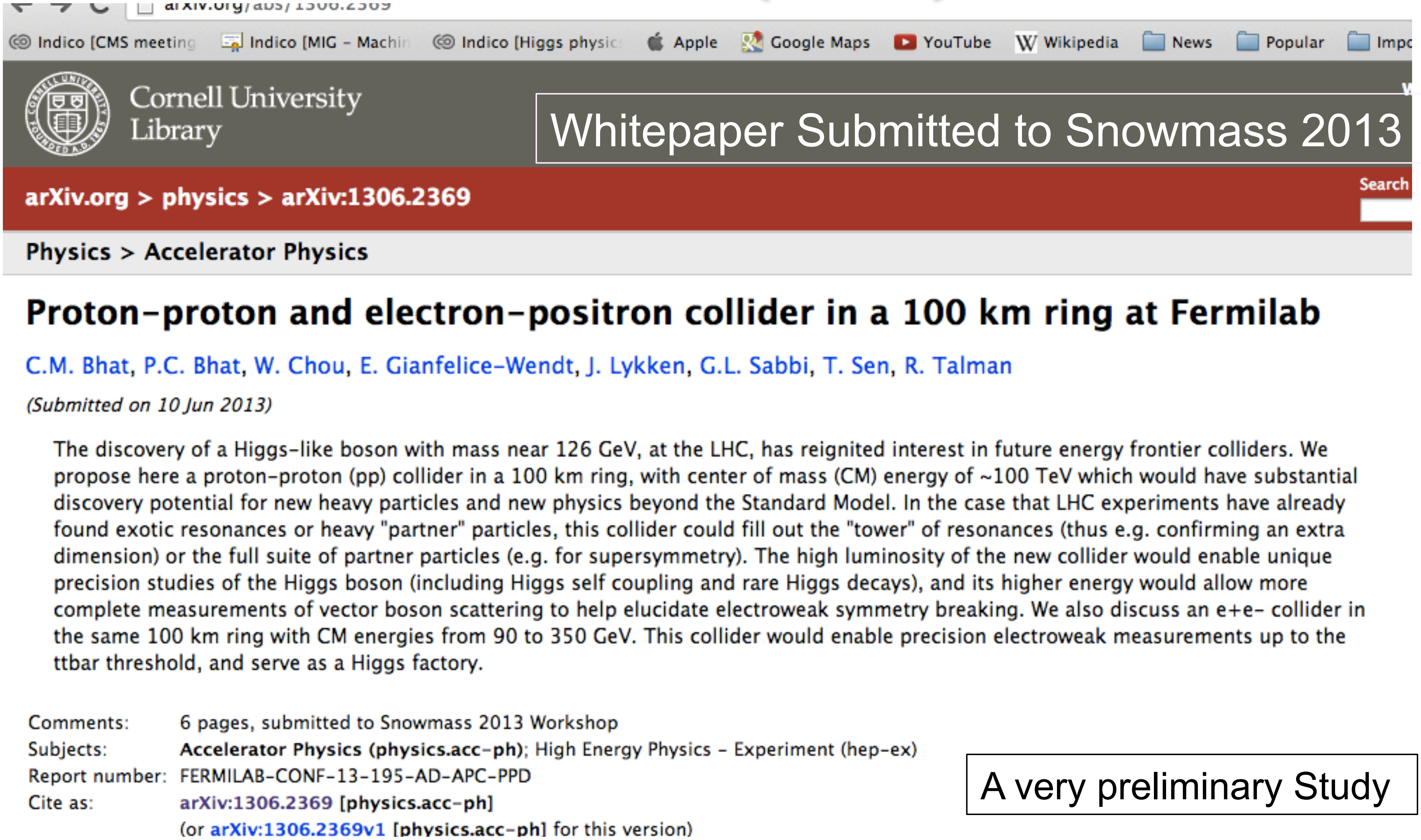
http://arxiv.org/pdf/1306.2369v1.pdf

Use high field (~15 T) Superconducting magnets in a 100 km ring for a 100 TeV pp collider

And/OR host a 240-350 GeV VLEP in 100 km tunnel

We proposed to combine the efforts: TLEP/VHE-LHC/VLHC/VLEP

VLHC (2013)



Whitepaper Submitted to Snowmass 2013

arXiv.org > physics > arXiv:1306.2369

Physics > Accelerator Physics

Proton-proton and electron-positron collider in a 100 km ring at Fermilab

C.M. Bhat, P.C. Bhat, W. Chou, E. Gianfelice-Wendt, J. Lykken, G.L. Sabbi, T. Sen, R. Talman

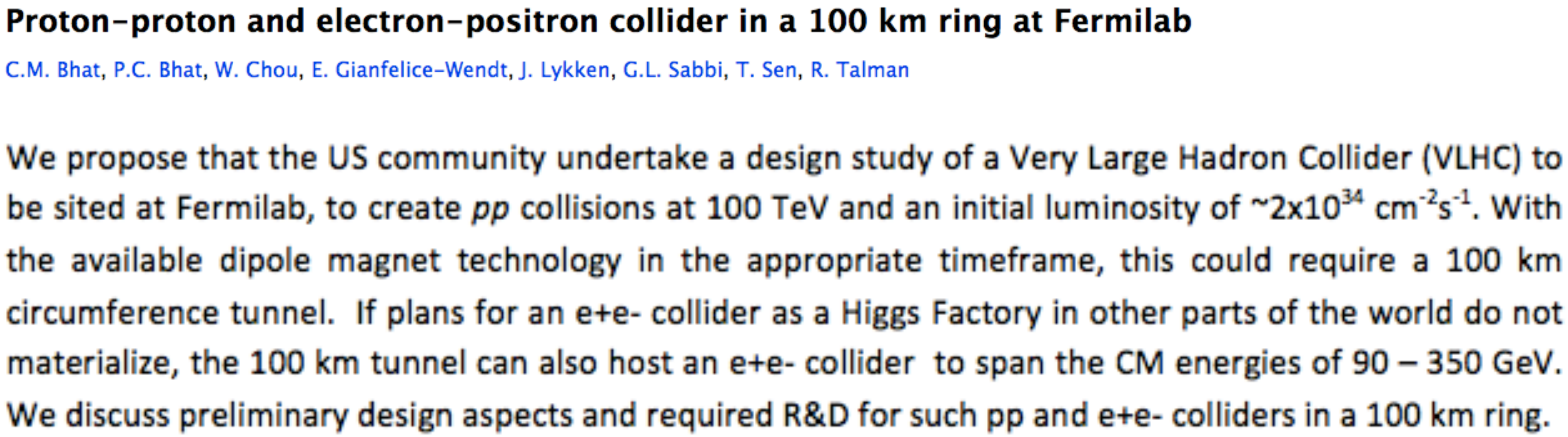
(Submitted on 10 Jun 2013)

The discovery of a Higgs-like boson with mass near 126 GeV, at the LHC, has reignited interest in future energy frontier colliders. We propose here a proton-proton (pp) collider in a 100 km ring, with center of mass (CM) energy of ~100 TeV which would have substantial discovery potential for new heavy particles and new physics beyond the Standard Model. In the case that LHC experiments have already found exotic resonances or heavy "partner" particles, this collider could fill out the "tower" of resonances (thus e.g. confirming an extra dimension) or the full suite of partner particles (e.g. for supersymmetry). The high luminosity of the new collider would enable unique precision studies of the Higgs boson (including Higgs self coupling and rare Higgs decays), and its higher energy would allow more complete measurements of vector boson scattering to help elucidate electroweak symmetry breaking. We also discuss an e+e- collider in the same 100 km ring with CM energies from 90 to 350 GeV. This collider would enable precision electroweak measurements up to the ttbar threshold, and serve as a Higgs factory.

Comments:	6 pages, submitted to Snowmass 2013 Workshop
Subjects:	**Accelerator Physics (physics.acc-ph)**; High Energy Physics - Experiment (hep-ex)
Report number:	FERMILAB-CONF-13-195-AD-APC-PPD
Cite as:	**arXiv:1306.2369 [physics.acc-ph]**
	(or arXiv:1306.2369v1 [physics.acc-ph] for this version)

A very preliminary Study

arXiv:1306.2369



Proton–proton and electron–positron collider in a 100 km ring at Fermilab

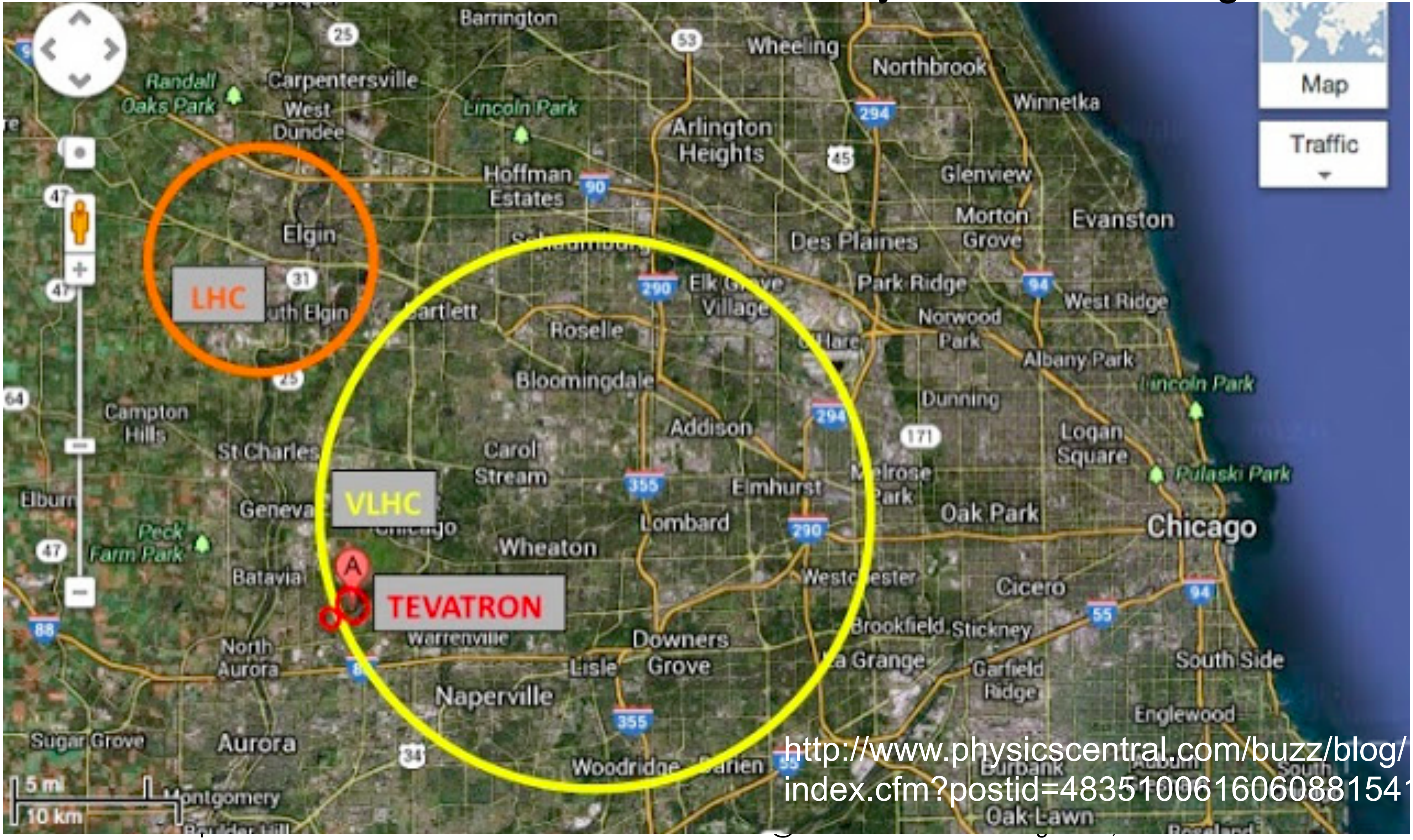
C.M. Bhat, P.C. Bhat, W. Chou, E. Gianfelice-Wendt, J. Lykken, G.L. Sabbi, T. Sen, R. Talman

We propose that the US community undertake a design study of a Very Large Hadron Collider (VLHC) to be sited at Fermilab, to create *pp* collisions at 100 TeV and an initial luminosity of ~2×10^{34} $cm^{-2}s^{-1}$. With the available dipole magnet technology in the appropriate timeframe, this could require a 100 km circumference tunnel. If plans for an e+e- collider as a Higgs Factory in other parts of the world do not materialize, the 100 km tunnel can also host an e+e- collider to span the CM energies of 90 – 350 GeV. We discuss preliminary design aspects and required R&D for such pp and e+e- colliders in a 100 km ring.

We also presented the work at the TLEP workshop at Fermilab July 25 -26, 2013 (days before Snowmass)
PB & T. Sen

100 km ring for VLHC/VLEP

http://arxiv.org/pdf/1306.2369v1.pdf PhysicsCentral Blog



http://www.physicscentral.com/buzz/blog/index.cfm?postid=48351006160608815

What are long term "big questions"

regarding accelerator-based HEP capabilities

Snowmass CSS2013 Summary on Frontier Capabilities

- *How would one build a 100 TeV scale hadron collider?*
- *How would one build a lepton collider at >1 TeV?*
- *How would one generate 10 MW of proton beam power?*
- *Can multi-MW targets survive? If so, for how long?*
- *Can plasma-based accelerators achieve energies & luminosities relevant to HEP?*
- *Can accelerators be made 10x cheaper per GeV? Per MW?*

These are issues for the long term future

Proton colliders beyond LHC

Snowmass CSS2013 Summary on Frontier Capabilities

- US multi-lab study of VLHC is still valid (circa 2001);
  - Snowmass has stimulated renewed interest/effort in US
    - 2013 Snowmass white paper
- We recommend participating in international study for colliders in a large tunnel (CERN-led) ???
- Study will inform directions for expanded U.S. technology reach & guide long term roadmap
  - Beam dynamics, magnets, vacuum systems, machine protection, …

Extensive interest expressed in this possibility

Hadron Colliders (Past and Present)

	ISR	SPS	Tevatron	RHIC (pp)	LHC (2012)
Circumference [km]	0.94	6.9	6.3	3.8	26.7
Energy [GeV]	31	315	980	255	4000
Number of bunches	dc	6	36	107	1380
Bunch spacing [ns]	-	1150	396	108	50
Bunch intensity [$\times 10^{11}$]	-	2.75	(3.1/1)	2.0	1.7
Particles/beam [$\times 10^{14}$]	9.8	7.8/4.2	112/36	143	3089
Trans. rms Emitt [μm]		1.5/0.15	(3/1.5)	3.3	2.5
Beam-beam tune shift	0.0035x8	0.005x3	0.013x2	0.007x2	0.01x2
Luminosity [$\times 10^{32}$ cm^{-2}s^{-1}]	1.3	0.06	4.0	2.3	77
# of events/crossing			12		37
Stored beam energy [MJ]	0.005	0.04	1.75/0.57	0.57	140

VLHC 2013: The Challenges

- The main technological challenge –
  - Superconducting high field magnets 15 -20 T (Nb_3Sn ?)
- Design Challenges:
  - IR optics, Collimation system, ..
- Operational Challenges
  - Machine protection to cope with many GJs of beam energy
    - Would require novel techniques in collimation
  - Protecting SC magnets from high doses of synchrotron radiation
    - R&D in Photon stops, vaccum chamber design
  - Beam dynamics: Electron Cloud mitigation, Beam-beam
    - Experience from Tevatron, LHC
  - Beam monitoring/diagnostics
- Of course –
  - The BIG tunnel, COST, Logistics

Design Parameters

	VLHC (2013)	LHC (design)
Circumference [km]	100	26.7
Top Energy [TeV]	50	7
Peak Luminosity [$\times10^{34}$ cm^{-2} s^{-1}]	4.6	1
Bunch Intensity [$\times10^{11}$]	0.15	1.15
Number of Bunches	17255	2808
β^*_x/β^*_y (m)	0.5 / 0.05	0.55 / 0.55
Norm. rms. ($\varepsilon_x,\varepsilon_y$) [μm]	1.5 , 1.5 (initial)	3.75 , 3.75
Beam size at IP (x,y) [μm]	(3.8, 1.2)	16.7, 16.7
Bunch length, rms (cm)	2.7	7.5
Crossing angle [μrad]	90	255
Beam Current (A)	0.12	0.58
Beam lifetime from pp [h]	11.3	18.4
Stored energy (MJ)	2073	362
# of interactions/crossing	132	19 (37 in 2012)

→ x2 for HL-LHC

pp design Parameters - 2

Synchrotron Radiation

	VLHC (2013)	LHC (design)
Energy loss per turn [keV]	4424	6.7
Power loss /m in main bends [W/m]	7.9	0.21
Synchrotron radiation power/ring [kW]	549	3.6
Critical photon energy [eV]	4074	44.1
Longitudinal emittance damping time [h]	0.55	13
Transverse emittance damping time [h]	1.1	26

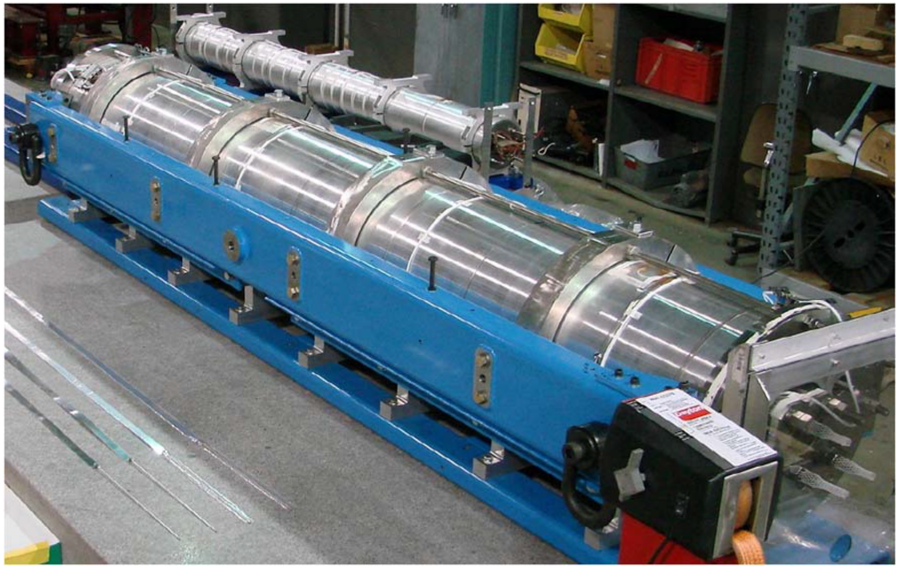
	VLHC (2013)	LHC (design)
Rms beam size in arc [mm]	0.07	0.3
Rms energy spread [x10^{-4}]	0.37	1.1
Longitudinal emittance growth time [h]	149	61
Transverse emittance growth time [h]	198	80

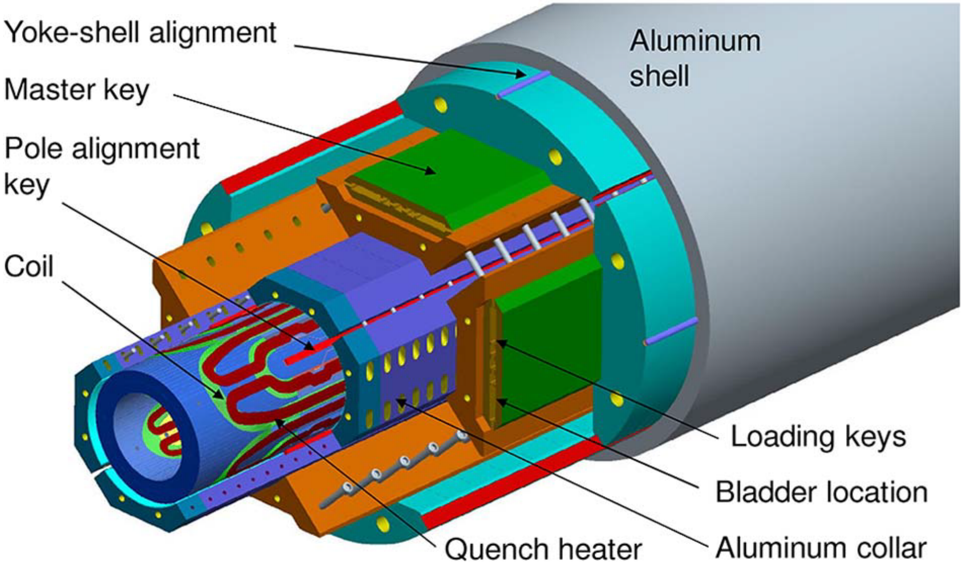
Luminosity limits

Constant: $\xi = 0.012/\text{IP}$, $\beta_y^* = 0.05$ m

	LHC Value	Assumed Value	Beam current[A}	Luminosity [x 10^{34} $cm^{-2}s^{-1}$]
Stored beam energy	362 MJ	5 GJ	0.59	15
Radiation power density in dipoles	0.21 W/m	10 W/m	0.16	8.1
Interactions/crossing	20	150	-	5.2
IR debris power	1 kW	50 kW	-	4.1

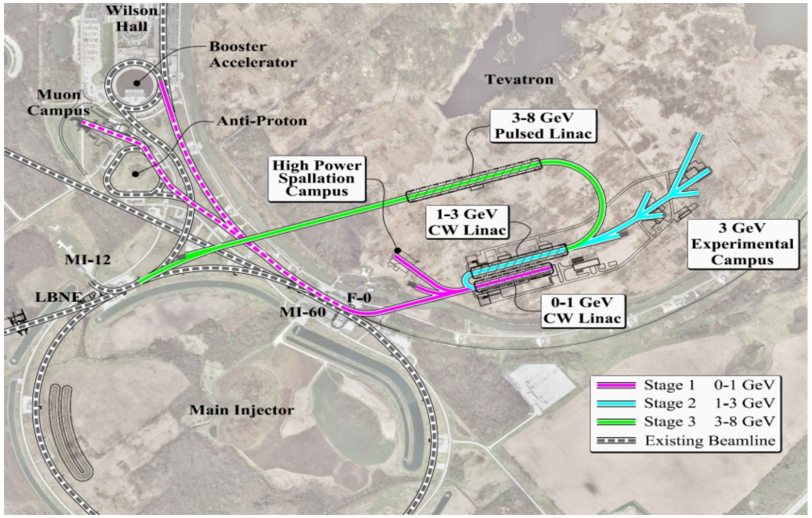
LARP Magnet Development

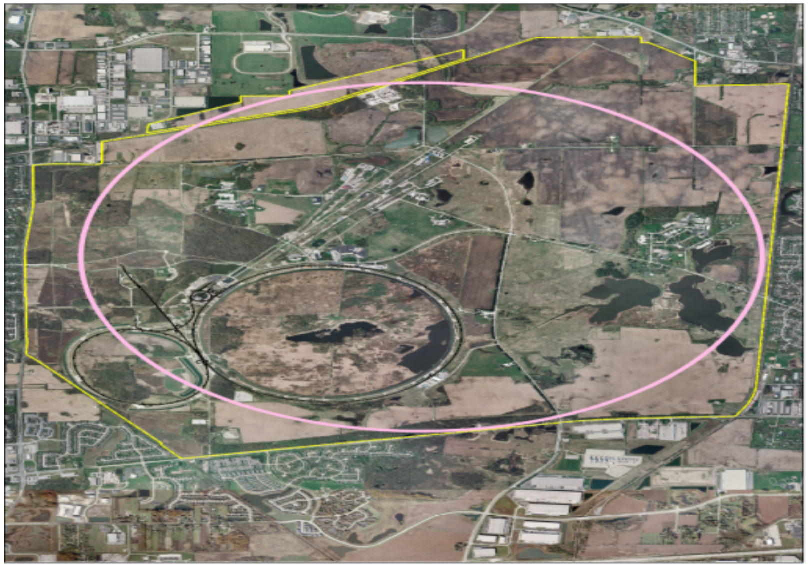




- Building IR magnets using Nb_3Sn coil for HL-LHC
- Dipoles with 16T fields have been built (LBNL, FNAL, BNL – US LARP)
- Large aperture (120 mm) quads with 12T pole tip fields achieved in July 2013.
- R&D continuing on hybrid NbTi, Nb_3Sn and HTS cable to achieve 20 T in dipoles.

Injectors for the collider





- Project X high intensity low emittance 8 GeV beam
- Main injector to deliver 150 GeV beam
- New injector to accelerate from 150 to ~ 3 TeV

  - Reuse Tevatron tunnel with 16 T magnets

  - Build a site filler tunnel (~ 16 km) with lower field magnets

e^+e^- Collider (VLEP)

VLEP Design Issues

- RF Power!
  - Assume rf power available to be 100 MW
  - R&D needed to improve efficiency of wall plug power to beam power conversion
- Field quality in low field dipole magnets
  - Dipole magnets in the arcs: 0.001 – 0.05 T
- Vacuum system
  - to cope with high radiation load and photons in MeV range
- Top-up injection
- Beam dynamics

Design parameters

Parameter	Units	Value
Circumference	km	100
Energy	GeV	120
Luminosity	10^{34} cm^{-2} s^{-1}	1.8
(βx^*, βy^*)	cm	20, 0.2
Particles/bunch	10^{11}	7.9
Number of bunches		34
Emittance (εx, εy)	nm	(16, 0.08)
Beam-beam tune shifts		0.095, 0.135
Bremsstrahlung lifetime	min	101

Rf parameters

Parameter	Units	Value
Energy lost/turn	GeV	1.5
Rf voltage	GV	3.9
Rf acceptance		0.03
Synchrotron radiation power/beam	MW	19.5
Rf power per beam	MW	50

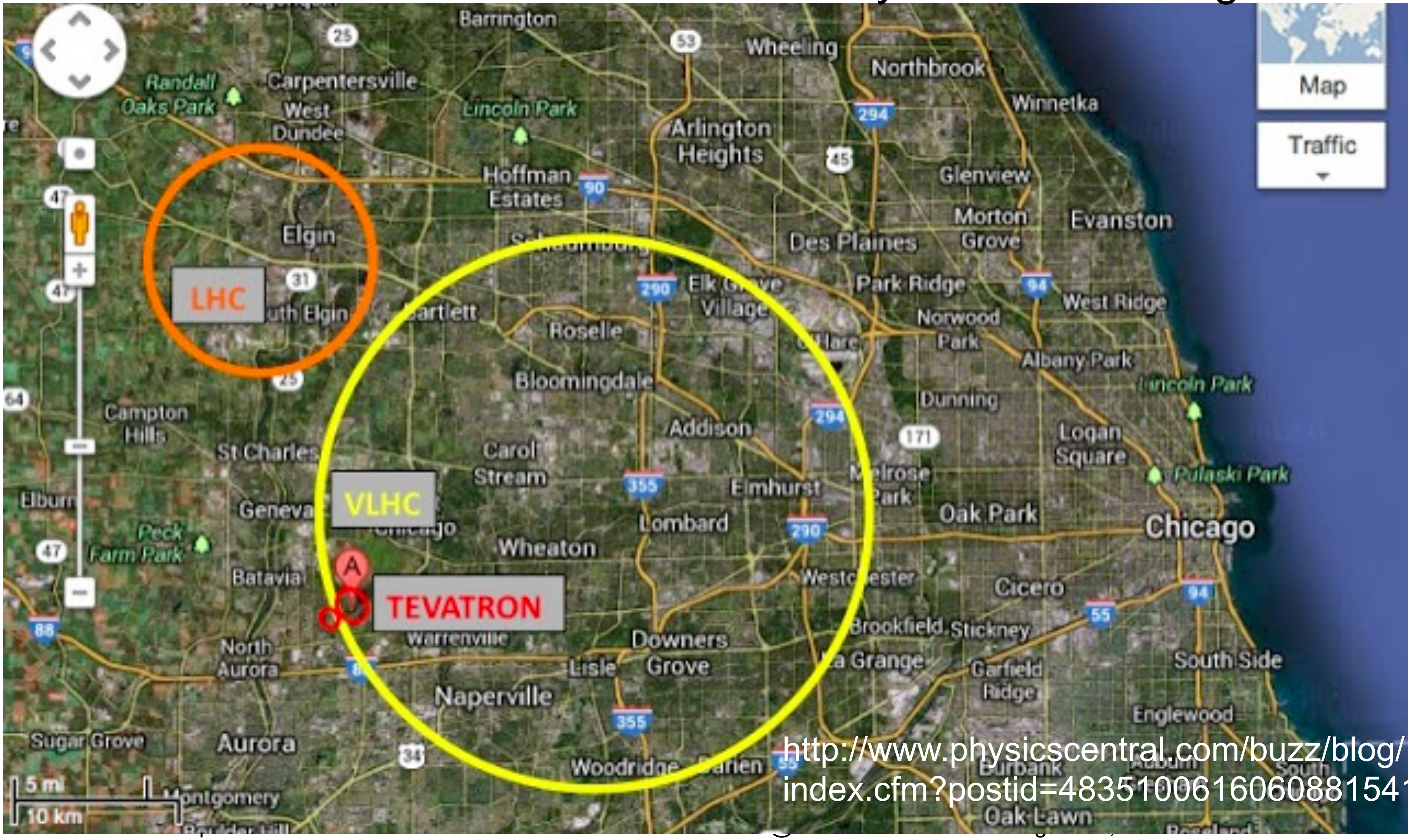
Injectors: top-up injector in the same tunnel, 12 -120 GeV;
Current Fermilab complex for up to 12 GeV

Summary

- To fully elucidate EWSB and to explore the Terascale physics, a 100 TeV pp collider would be the machine to build!
- An e+e- Higgs factory would be complementary to Hadron Collider studies of the Higgs boson.
- In the context of Snowmass community study, we have explored some design parameters of a VLHC (pp) and VLEP (e+e-) colliders in a 100 km ring.
- We propose a US-led multi-lab design study, and R&D for these colliders that could be sited at Fermilab.
- In the meantime, let us keep up with Accelerator R&D, and hope for some breakthroughs!

100 km ring for VLHC/VLEP

http://arxiv.org/pdf/1306.2369v1.pdf PhysicsCentral Blog



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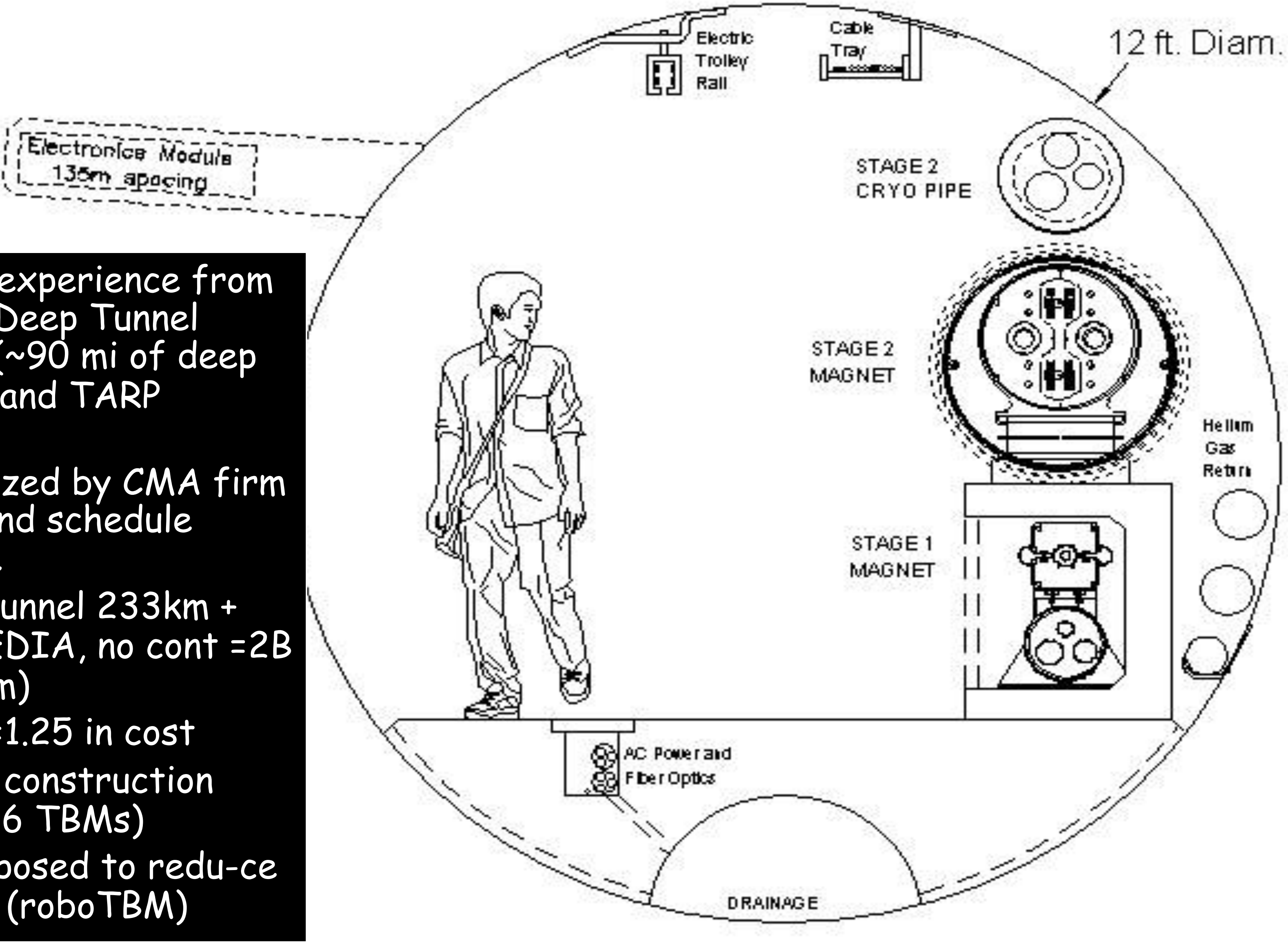
Back-up

VLHC

VLHC (2001) Tunnel Cross Section



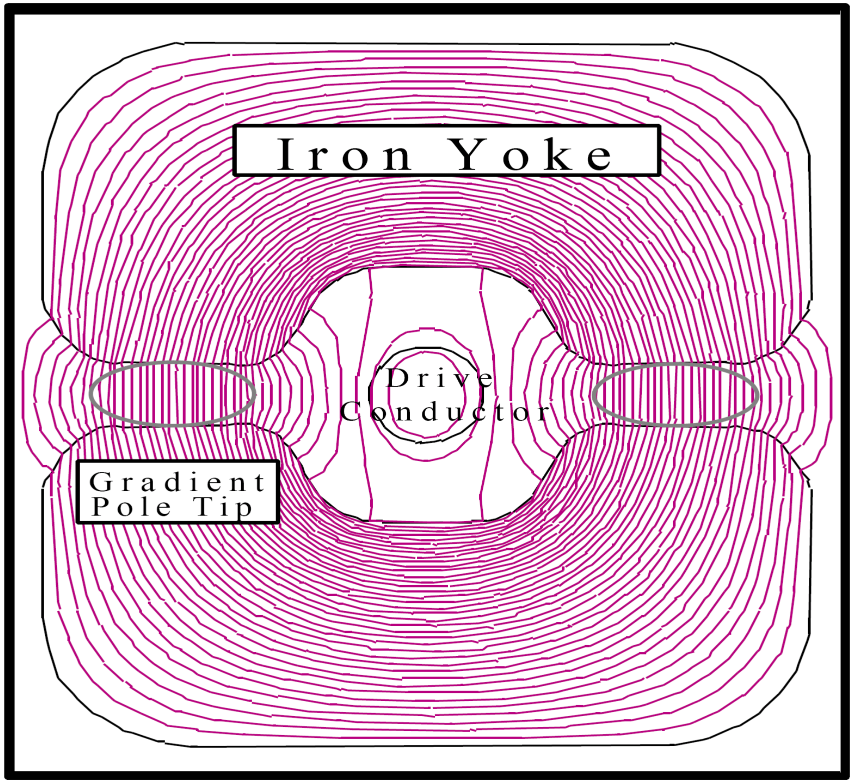
- A lot of experience from Chicago Deep Tunnel project (~90 mi of deep tunnels) and TARP project
- Summarized by CMA firm in cost and schedule estimate
- 12’ dia tunnel 233km + shafts+EDIA, no cont =2B $ (9k$/m)
- 16’/12’=1.25 in cost
- ~60 wks construction (4m/hr 16 TBMs)
- R&D proposed to redu-ce the cost (roboTBM)

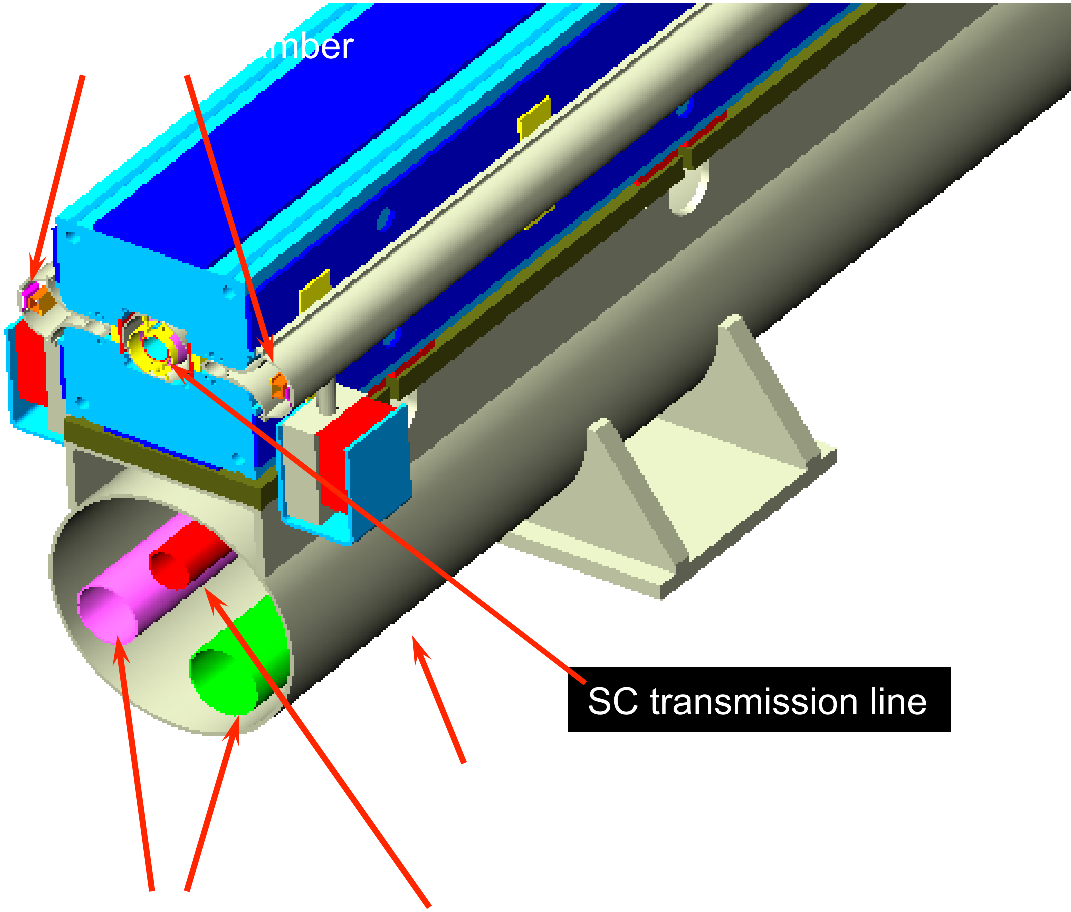
What's done by 2005

- Tunnel cost and schedule exercise by CMA firm
- Transmission line design
- 100kA power supply and HTS leads built, QPS
- 104kA transmission line test in MP6
- Superferric magnets designed & optimized
- 14 m of SF magnets built and tested
- Good accelerator quality B-field measured at inj energy up to 1.96T
- Collider Phase I designed (ZDR)
- Many AP issues addressed (e.g.instabilities)
- Thorough bottoms-up cost estimate

Shiltsev
2007

Transmission Line Magnet

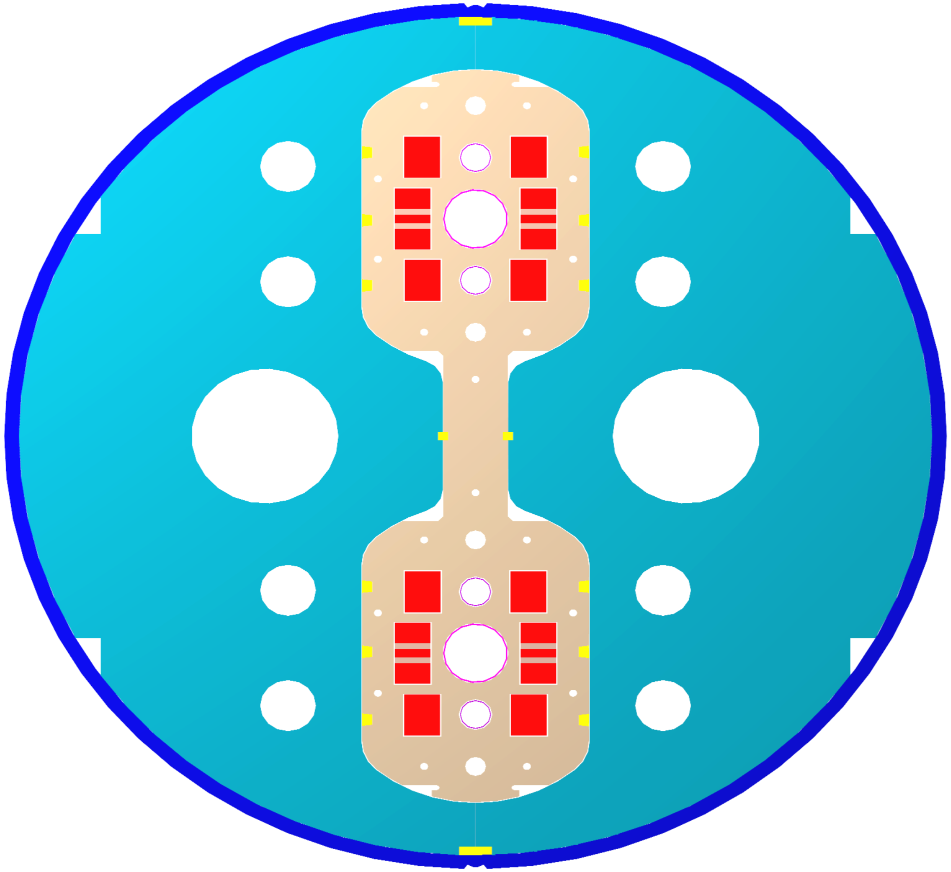


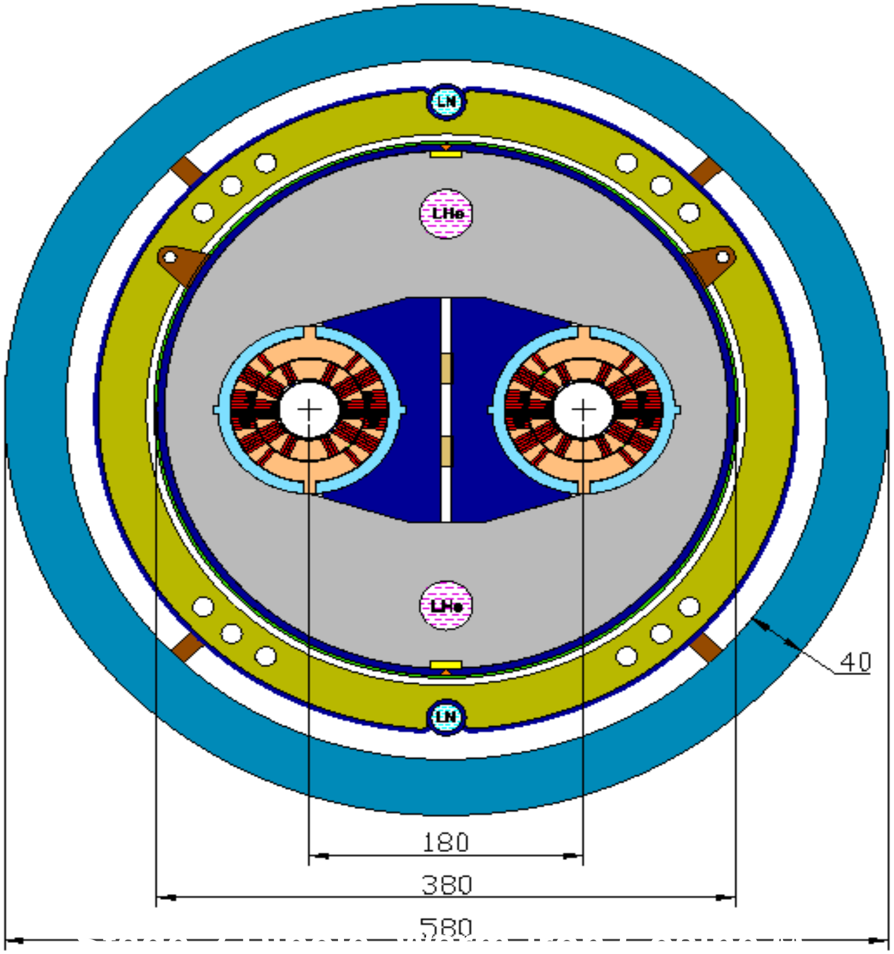


- warm iron and vacuum system
- superferric: 2T bend field
- 100kA Transmission Line
- alternating gradient (no quads)
- 65m Length

Stage-2: 10T+ Magnets

- There are several magnet options for Stage 2. Presently Nb_3Sn is the most promising superconducting material, e.g. LHC IR Upgrade magnets are being developed by US LARP

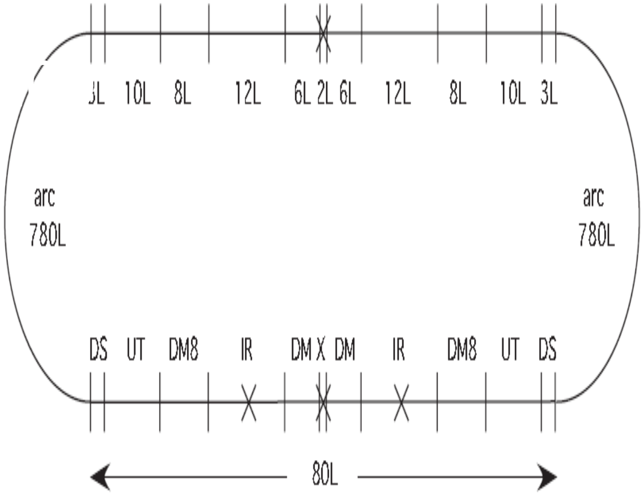


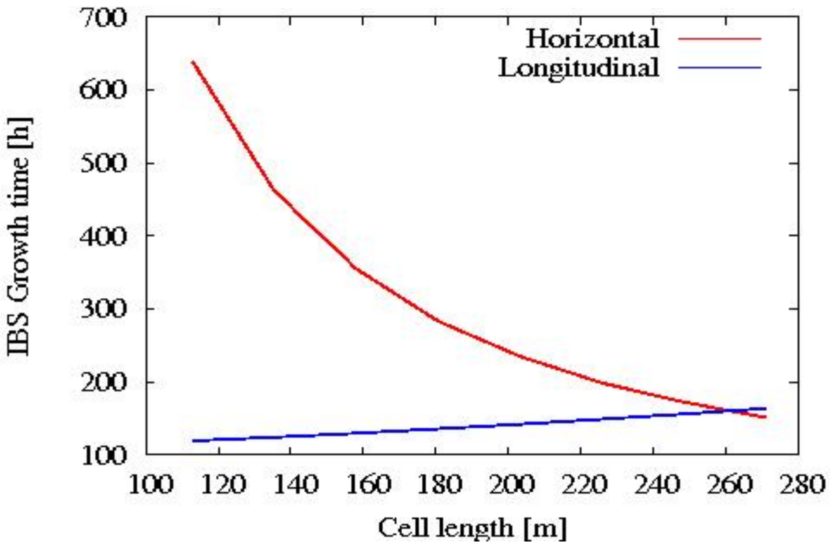


Design parameters

- Use similar principles as VLHC design in 2001
- Rf frequency: integer mulitple of 53 MHz rf in the Main Injector and Tevatron (easier transfers)
- Low bunch intensity for small emittance
  - Upgrades to injectors can provide higher bunch intensities

Principles of Design (2013)





- 50 TeV in a 100 km ring with 16T dipoles.
- Synchrotron radiation dominated hadron collider. Damping time ~ 1 hr; integrated luminosity is nearly independent of the initial emittance
- All modules in units of half cell length
- Cell length = integer multiple of bunch spacing. Ensures bunches collide in all detectors.
- Bunch spacing = integer multiple of Tevatron 53 Mhz bucket length.
- Cell length affects chromaticity, equilibrium emittance, IBS growth times, sensitivity to field errors,…

Luminosity

- Luminosity

$$L(t) = \frac{\gamma}{2\, e\, r_p} \left[\frac{\sqrt{\kappa}}{(1+\sqrt{\kappa})}\right] * \frac{\xi_x(t)}{\beta_y{}^*} * I_b\,(\mathrm{t}) * \mathrm{F}(\sigma_z, \sigma_T, \varphi_C(\mathrm{t}))$$

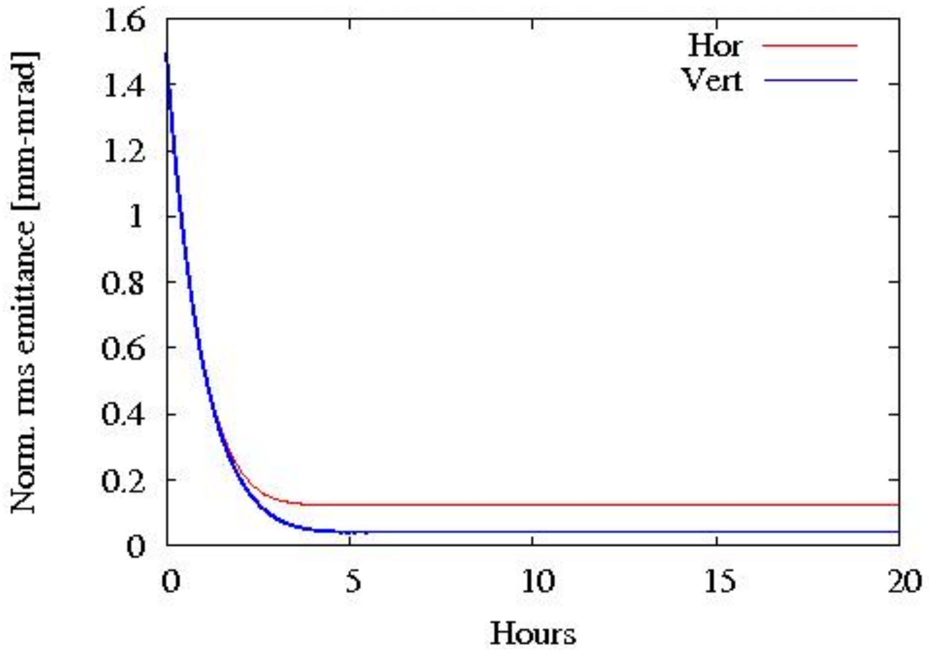
$$\kappa \equiv \beta_y{}^* / \beta_x{}^*$$

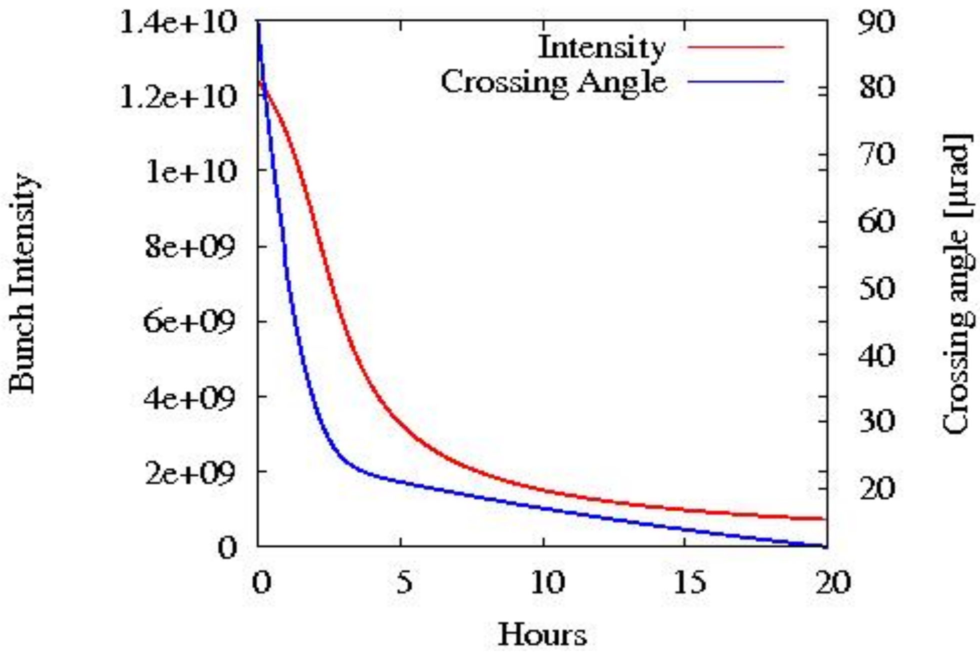
Optimize

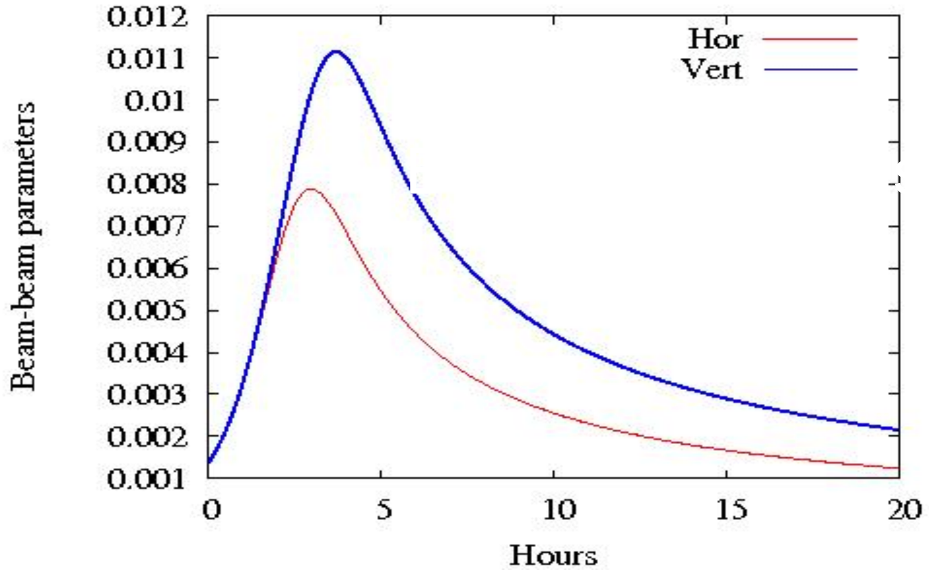
- β^* and aspect ratio κ
- Beam-beam parameter ξ
- Beam and bunch current : e-cloud, TMCI at injection, ..
- Bunch length σ_z
- Crossing angle ϕ_c

Time Evolution

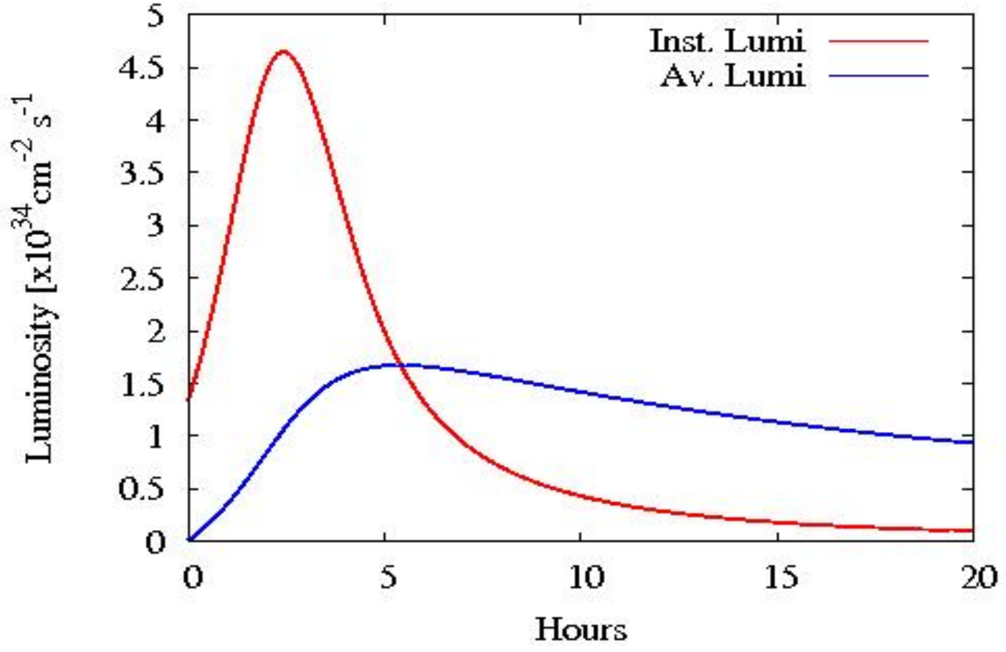
- The model includes radiation damping and intra-beam scattering.
- Longitudinal emittance is kept constant by noise injection

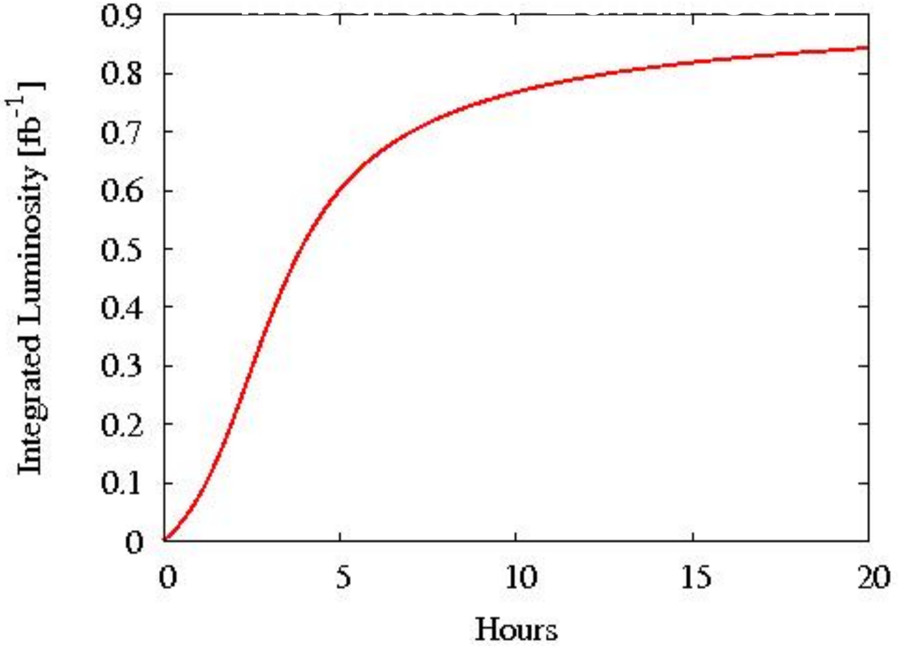






Time evolution - 2





Flat beams

Pros

- β_x* increases by ~ 1/(2 κ_ε) for the same luminosity
- Early separation with a dipole; fewer long-range interactions.
- β_x^{max}, β_y^{max} smaller; centroid of a doublet is closer to the IP
- Lower linear and nonlinear chromaticity with a doublet
- Smaller luminosity loss with horizontal crossing;

  σ_x* (flat) > σ_x* (round)

Cons

- β_y* decreases by ~2 for same luminosity
- Design of the first 2-in1 quad is challenging, beam separation is small; affects field quality
- Neutral particles from IP are directed to center of 1st quad; ~1/3rd of IP debris power.

  - place absorber between dipole and 1st quad

  - design two half quads (under study at LHC)

R&D in Accelerator Physics

IR Optics

- Implement a local chromaticity correction scheme for low β_y*.
- Increase the crossing angle ("Large Piwinski angle" regime) while keeping beam-beam tune shift constant and allow lower β_y^*. Respect beam current and chromaticity limits.
- Explore possibility of placing 1st dipole inside detector from the outset.

Beam Dynamics

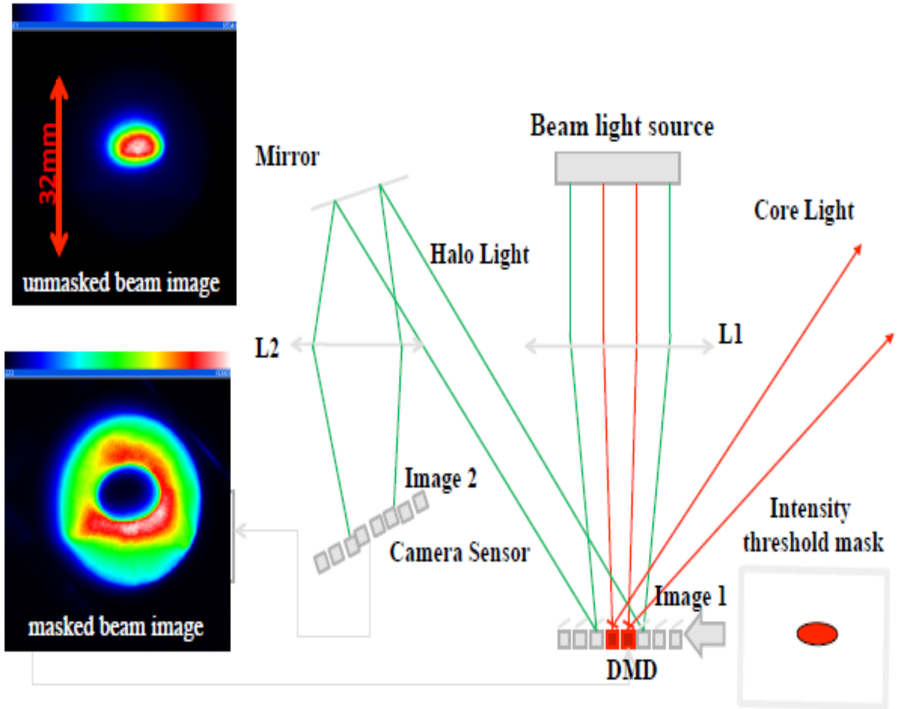
- ☐ Resonance free optics – relax field quality and allow smaller aperture, improve operational stability
- ☐ Crab cavity design and operation .
- ☐ Electron cloud mitigation

R&D in beam diagnostics

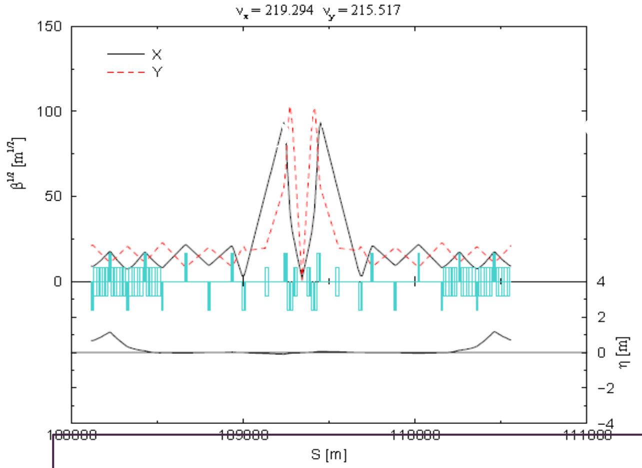
- Beam loss monitor - Require high reliability and large dynamic range. In LHC, particle loss > 2 x 10^{-6} will quench a magnet.

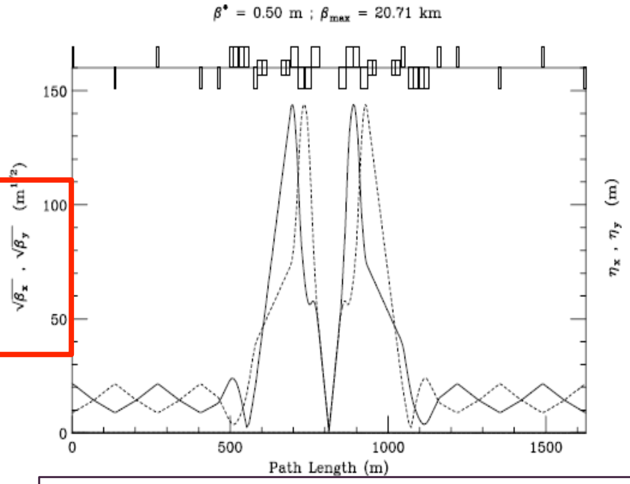
- Beam size and position monitors using Optical Diffraction Radiation, and other non-invasive techniques

- Beam halo monitors with high dynamic range. One example



IR concepts





Doublet Optics for flat beams

- Symmetric optics about the IP. First quad in doublet on both sides has to be vertically focusing
- In a pp collider, this requires 2 apertures for the 2 beams
- Dipole before the doublet to separate the beams into the apertures
- Tight control on vertical dispersion and coupling to maintain $\kappa_\varepsilon = \varepsilon_y/\varepsilon_x < 1$. Done routinely in e+e- colliders.

e+e-

Beam Current and Luminosity (e+e-)

- Power limited regime. Synchrotron radiation power from both beams limited to 100 MW. Beam current is determined by

$$I = \left(\frac{2C_\gamma E^4}{e\rho}\right)^{-1} P_T, \qquad \mathscr{L} \propto \frac{I^2}{M_B}$$

- Minimum number of bunches compatible with single bunch intensity limits
- Luminosity in terms of beam-beam parameter, beta function and power

$$\mathscr{L}\gamma^3 = \frac{3}{16\pi r_e^2(m_e c^2)}\rho\left[\frac{\xi_y P_T}{\beta_y^*} H(\beta_y^*, \sigma_z)\right]$$

Comments on the VLEP design

- Rf acceptance set to 3% for mitigating beamstrahlung. If this is enough (requires detailed study), then a full energy injector may not be required.
- Rf voltage of 3.9 GV is comparable (~10%) to that in LEP2
- There can be two detectors to double the # of Higgs events if IR chromaticity can be well compensated
- Synchrotron radiation power load (0.9 kW/m) and high critical energy (314 keV) imply that vacuum system R&D may be needed but these could be comparable to light sources.
- Energy could be extended up to 175 GeV/beam at the same rf power, with lower luminosity.

Injection Scenarios

Scenario 1:
400 MeV linac,
Accumulator ring,
Booster, Main
Injector

Scenario 3:
1 GeV linac,
Accumulator ring,
Superconducting
Fast Ramping
Synchrotron

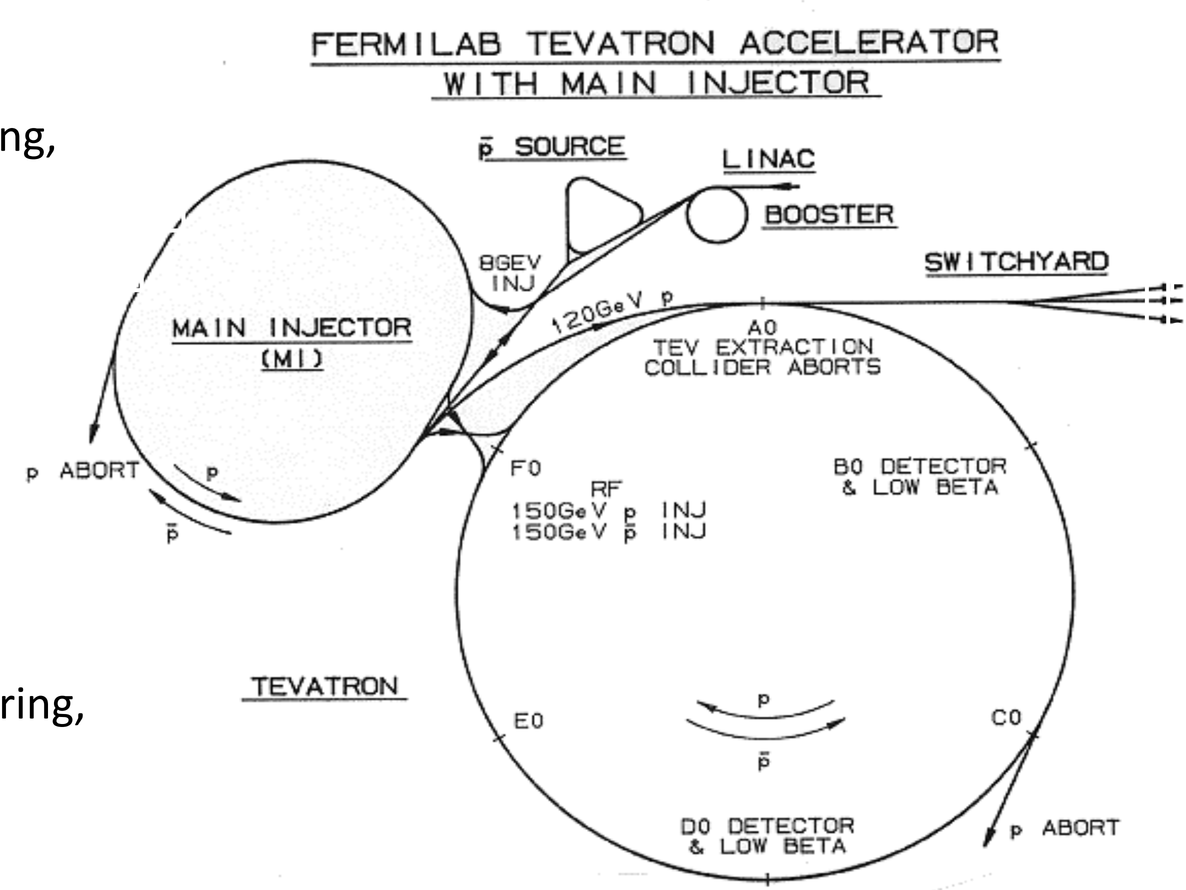


Figure 1-2. Schematic View of the Main Injector Connections to the Booster, Antiproton Source, Tevatron and Switchyard.

Scenario 2:
3 GeV linac,
Accumulator ring,
Main Injector

Scenario 4:
Recirculating linac, e
+ damping ring

e+e- parameters - 2

	Units	Value
Dipole field	T	0.03
Cell length	m	143.6
Dipole fill factor		0.76
Bend angle per cell	mrad	10.6
γ_t		148
Beam current	mA	12.9
Rf frequency	MHz	650
Over voltage parameter		2.6
Longitudinal damping time	turns	79
Critical energy	keV	314
rms energy spread		9.3×10^{-4}
Synchrotron tune		0.223
rms bunch length	mm	3.2

TLEP Parameters

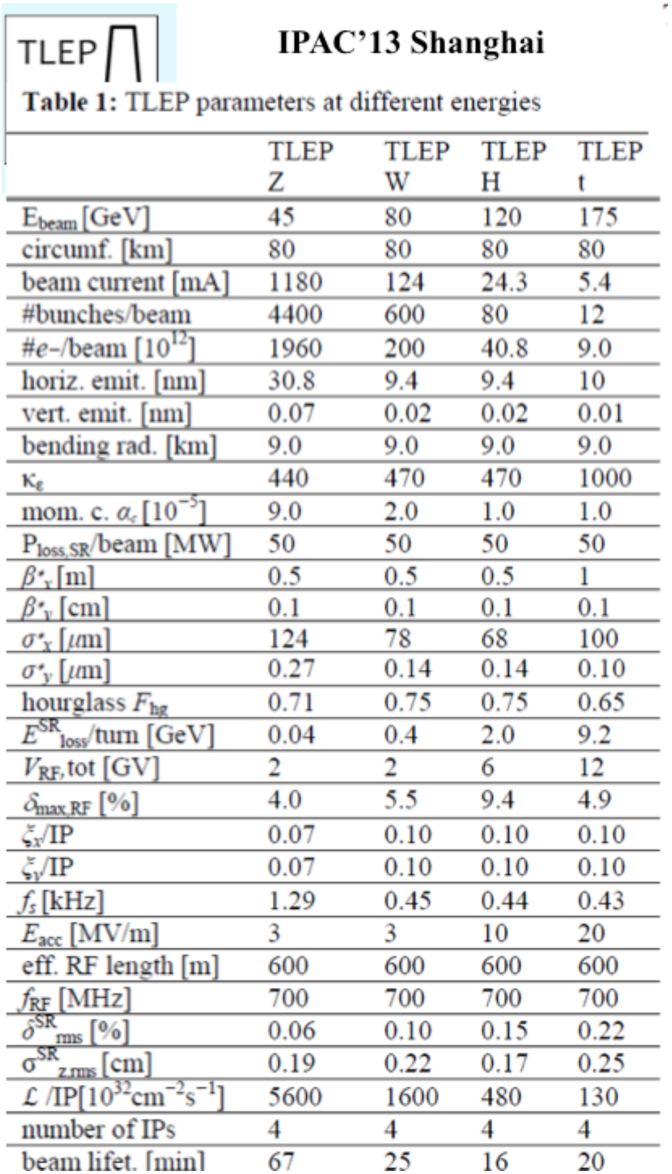


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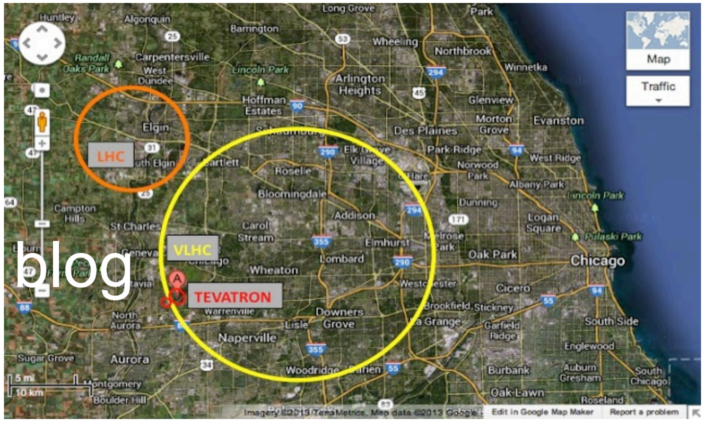
Table 1: TLEP parameters at different energies

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	45	80	120	175
circumf. [km]	80	80	80	80
beam current [mA]	1180	124	24.3	5.4
#bunches/beam	4400	600	80	12
#e−/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
$V_{RF,}$tot [GV]	2	2	6	12
$\delta_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$/IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	67	25	16	20

Design Concepts: Summary



VLHC: 100 TeV pp collider

- Explored parameters for Integrated luminosity ~ 1 fb^{-1} / store
- IR debris power and pile-up impose the strongest restrictions to higher luminosity
- R&D on integrable nonlinear optics, beam-beam compensation, novel diagnostics, radiation damage, new tunneling techniques, … to reduce cost.
- Machine protection will be critical

120-120 GeV e+e- collider

- Explored parameters for ~45000 Higgs events/year/detector
- βy^* (& luminosity) limited by IR chromaticity.
- R&D on beamstrahlung, IR chromaticity compensation, synchrotron radiation management, …
- RF requirements similar to LEP2