A pp and e+e- collider in a 100km ring at Fermilab

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Outline

Motivation

- Snowmass study
- TLEP design study in a 80 km ring
- Past studies of VLHC and VLLC in a 233 km ring in 2001

- Now a “more modest” ring of circumference = 100 km
- Design of a pp collider with 100 TeV CM energy
- Design of an e+e- collider with 240-350 GeV CM energy
- No discussion of
  - Cost
  - Politics of acquiring 100 km of real estate

Hadron Colliders - Wikipedia

Hadron colliders	
Intersecting Storage Rings	CERN, 1971–1984
Super Proton Synchrotron	CERN, 1981–1984
ISABELLE	BNL, cancelled in 1983
Tevatron	Fermilab, 1987–2011
Relativistic Heavy Ion Collider	BNL, 2000–present
Superconducting Super Collider	Cancelled in 1993
Large Hadron Collider	CERN, 2009–present
High Luminosity Large Hadron Collider	Proposed, CERN, 2020–
Very Large Hadron Collider	Theoretical

Hadron Colliders

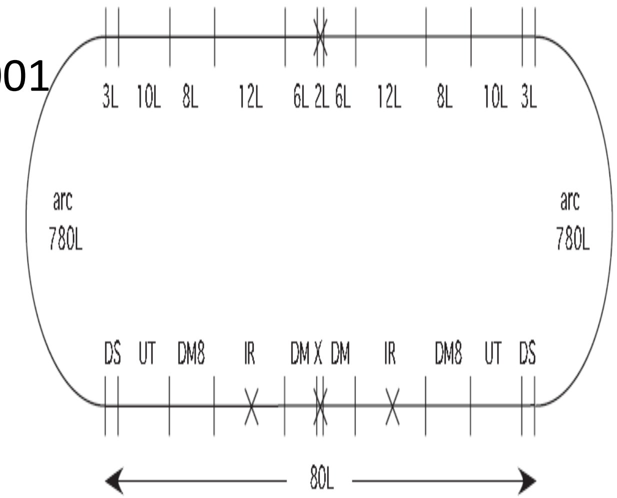
	ISR	SPS	Tevatron	RHIC (pp)	LHC (2012)
Circumference [km]	0.94	6.9	6.3	3.8	26.7
Energy [GeV]	31	315	980	255	4000
Number of bunches	dc	6	36	107	1380
Bunch spacing [ns]	-	1150	396	108	50
Bunch intensity [$x10^{11}$]	-	2.75	(3.1/1)	2.0	1.7
Particles/beam [$x\ 10^{14}$]	9.8	7.8/4.2	112/36	143	3089
Trans. 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 [$x10^{32}\ cm^{-2}s^{-1}$]	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 designs (2001)

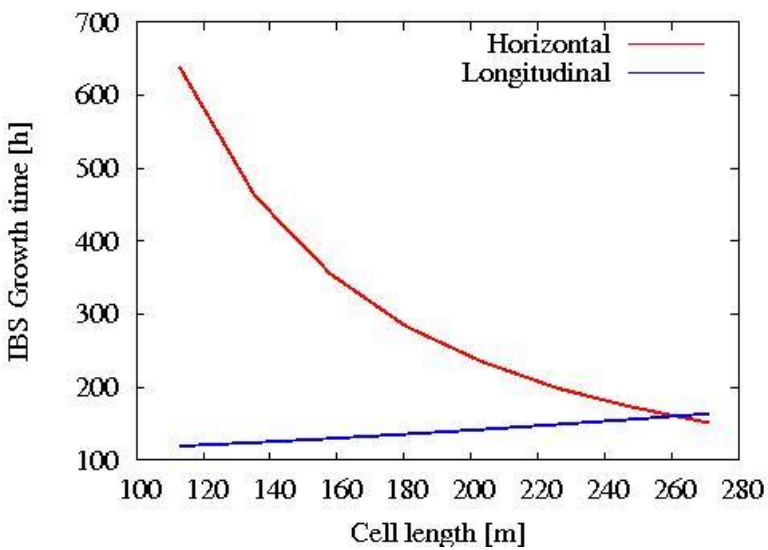
- Circumference = 233km
- Stage 1 ring: (1 to 20) TeV
- Stage 2 ring : (20 to 87.5) TeV
- Super-ferric magnets for the 2 T low field, stage 1, Injection from Tevatron
- Nb_3Sn magnets for 10T high field, stage 2. Injection from Stage 1
- Modular design: IRs, utilities, dispersion suppressors etc had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

Principles of Design (2013)

VLHC 2001



Intrabeam scattering



- 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,…

Design parameters

	VLHC (2013)	LHC (design)
Circumference [km]	100	26.7
Top Energy [TeV]	50	7
Peak Luminosity [$x10^{34}$ cm^{-2} s^{-1}]	4.6	1
Bunch Intensity [$x10^{11}$]	0.12	1.15
β^*_x/β^*_y (m)	0.5 / 0.05	0.55 / 0.55
Norm. rms. (ε_x,ε_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)	2095	362
# of interactions/crossing	132	19 (37 in 2012)

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

Intra-beam scattering

	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

Path to higher luminosity

Luminosity expression

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

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

The crossing angle can be made dynamical for "luminosity leveling"

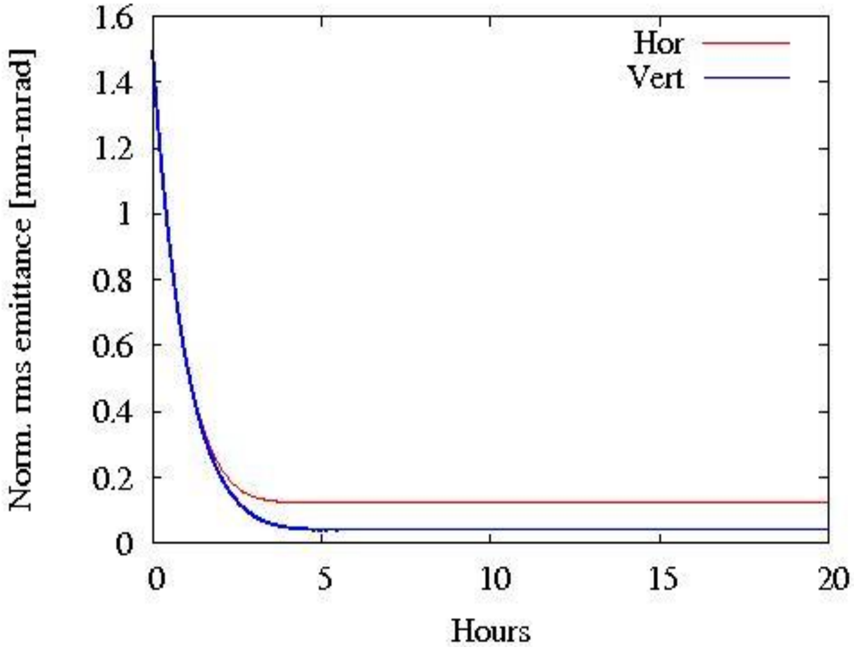
Optimize

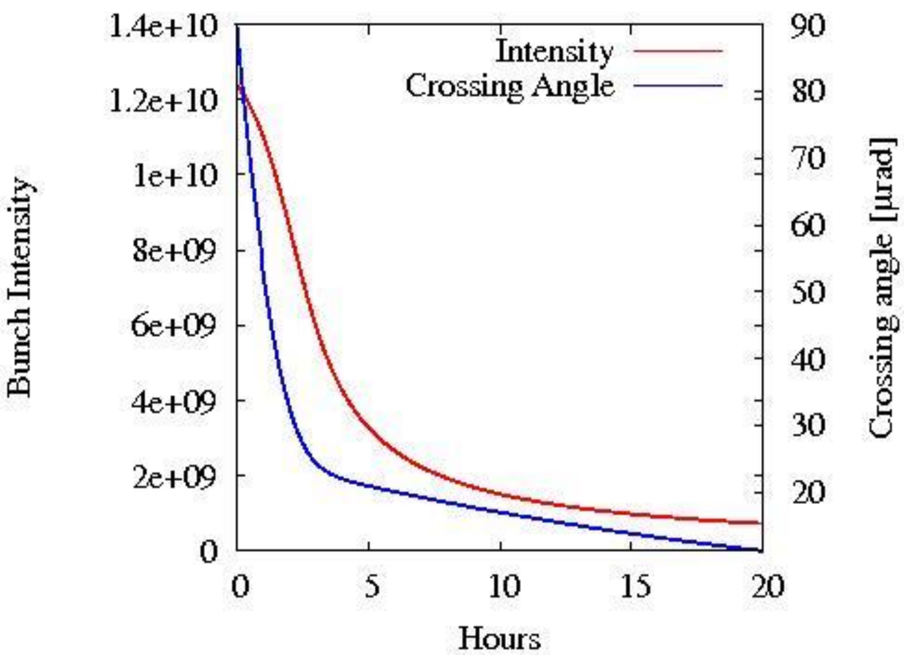
- β^* and aspect ratio κ
- Beam-beam parameter ξ
- Beam and bunch current : e cloud, TMCI at injection, other instabilities
- Bunch length σ_z
- Crossing angle ϕ_C

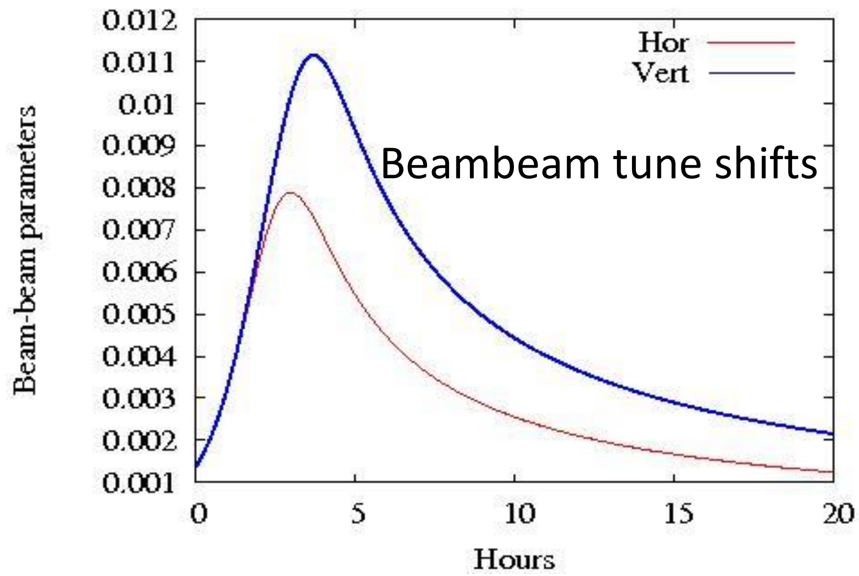
Time Evolution

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

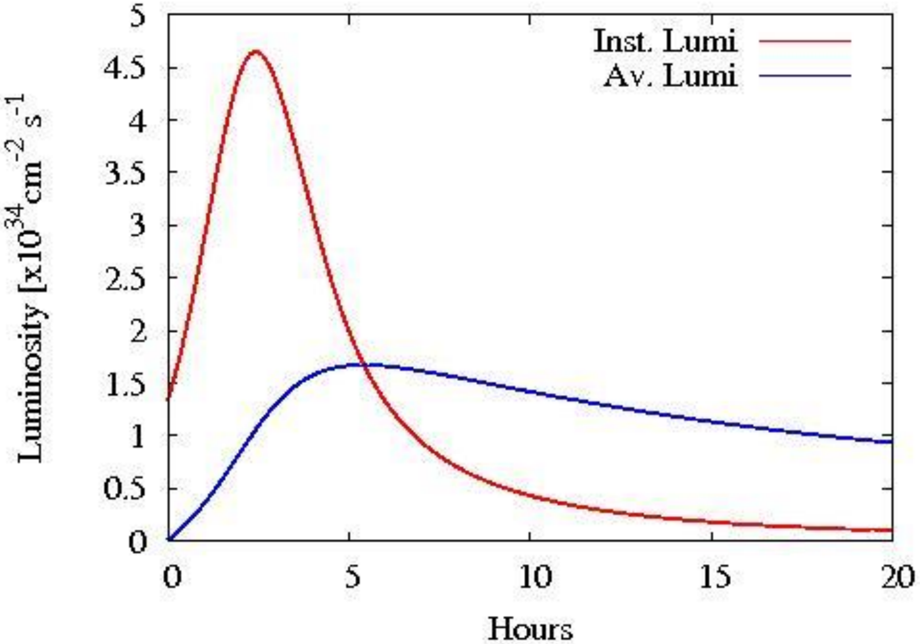
Transverse emittances



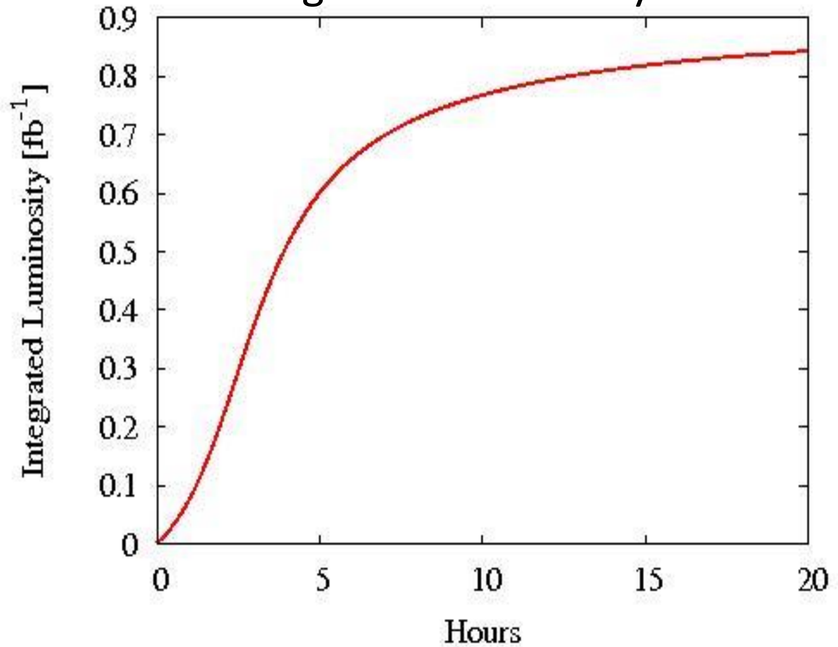




Time evolution - 2

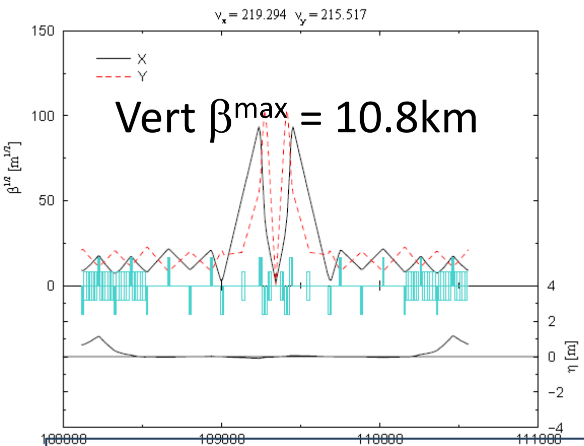


Integrated Luminosity



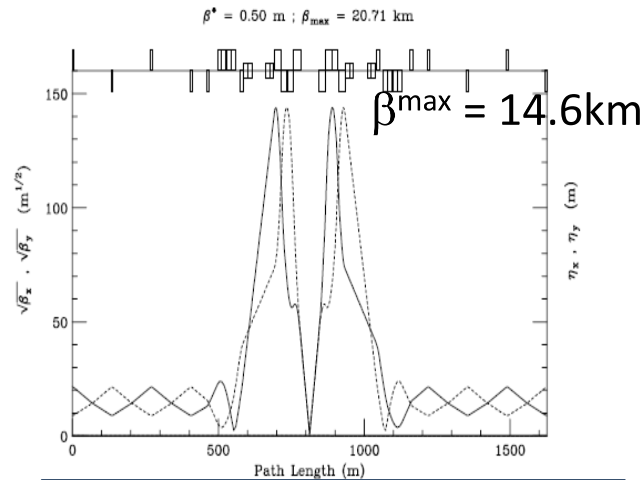
Peak Luminosity = 4.6 x 10^{34} cm^{-2} s^{-1}
Optimal store time ~ 6 hours
Integrated luminosity over a 10 hr store ~ 0.8 fb^{-1}

IR concepts



Doublet Optics, flat beams

VLHC 2001 Designs



Triplet Optics, round beams

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.

Flat beams

Pros

- β_x* increases by ~ $1/(2\ \kappa_\varepsilon)$ 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)

Limits on β*

- Crossing angle φ_c limit

Beam separation in the IR

n_{sep}~ (10-12) (units of beam size)

To prevent luminosity loss

$\rightarrow (\varphi_c \sigma_z/(2\sigma_T) \leq 1 \rightarrow$

$$\beta^* \geq (5-6)\,\sigma_z$$

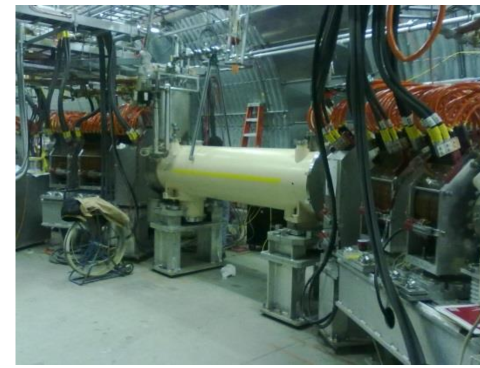
A crab cavity to restore luminosity removes this limit

- Hourglass limit $\beta^* \geq \sigma_z$
- IR Chromaticity $\propto \hat{\beta}/f \sim 1/\beta^*$
- Aperture of final focus quadrupoles

Beam-beam limits

Head-on : ξ achieved :
0.013 (Tevatron), ~ 0.01 (LHC)
Damping may allow even higher tune shifts

Electron lens in RHIC



Long-range interactions
- Compensation with current carrying wire demonstrated at RHIC
- Space reserved in the LHC

Luminosity limits

Constant: ξ = 0.012/IP, β_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

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

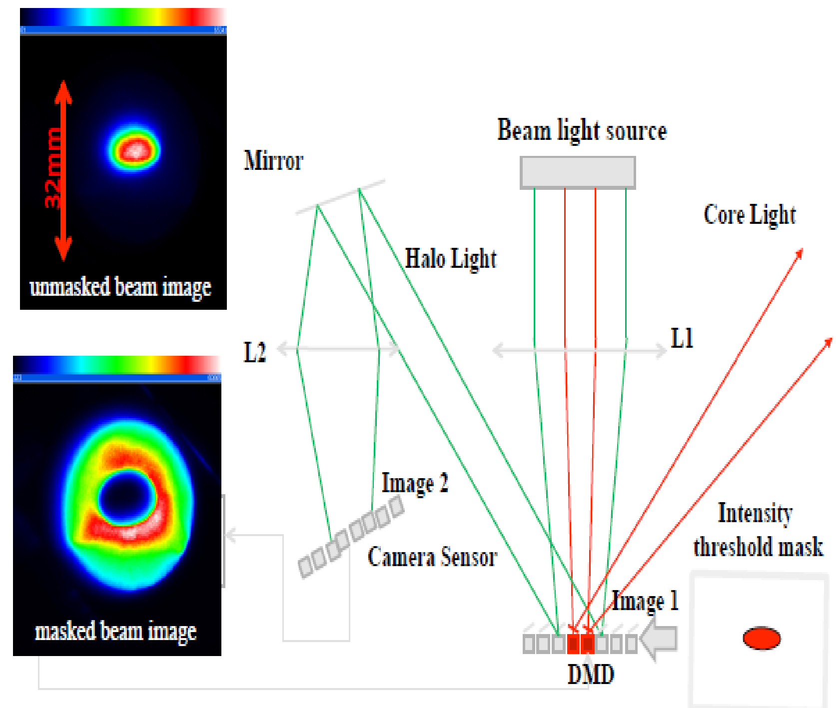
- ❑ Resonance free optics – relax field quality and allow smaller aperture, improve operational stability
- ❑ Crab cavity design and operation .
- ❑ Electron cloud mitigation

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

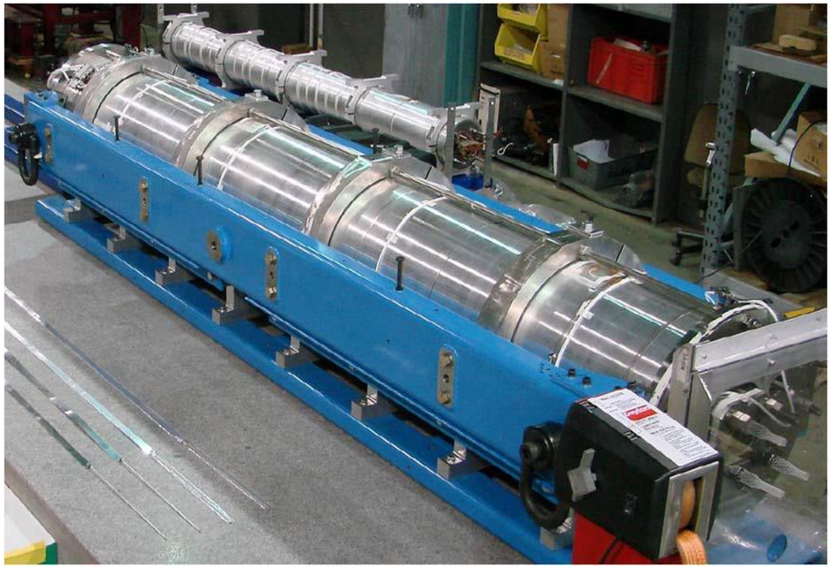


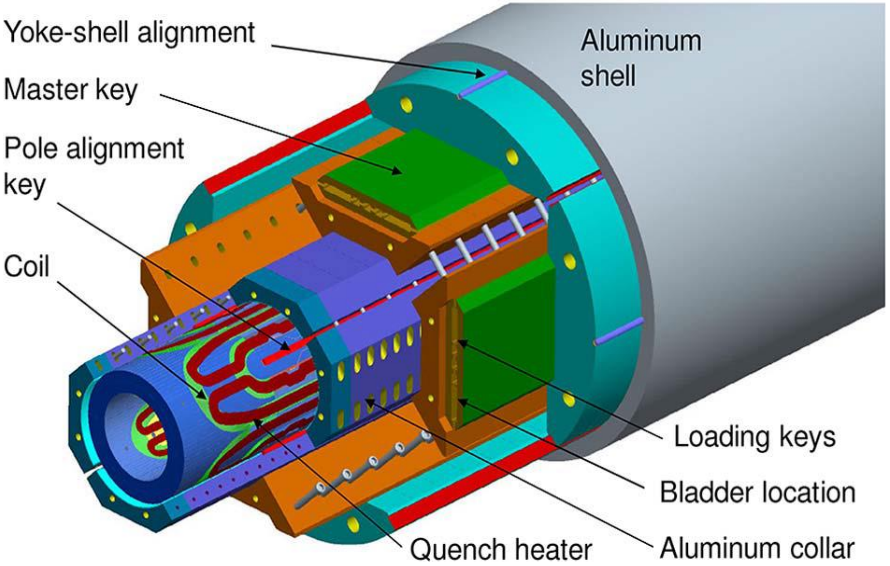
Dynamic range > 10^5

R. Fiorito et al, Phys. Rev ST-AB July 2012

LARP Magnet Development

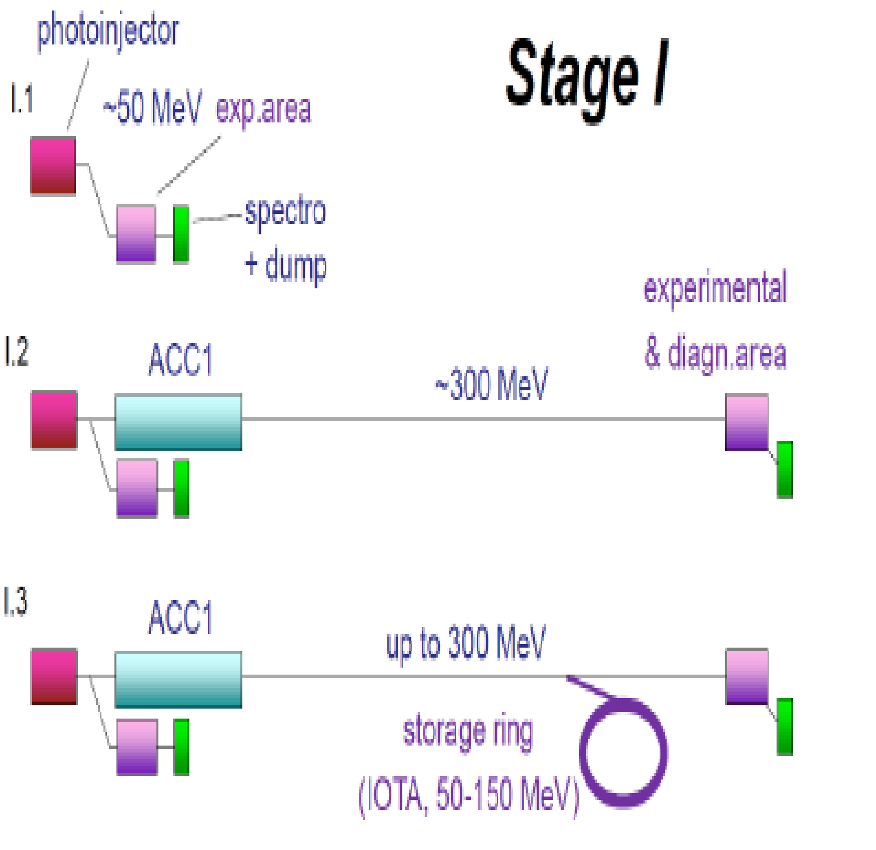
G.L. Sabbi





- Building IR magnets using Nb_3Sn coil for HL-LHC
- Dipoles with 16T fields have been built
- 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.

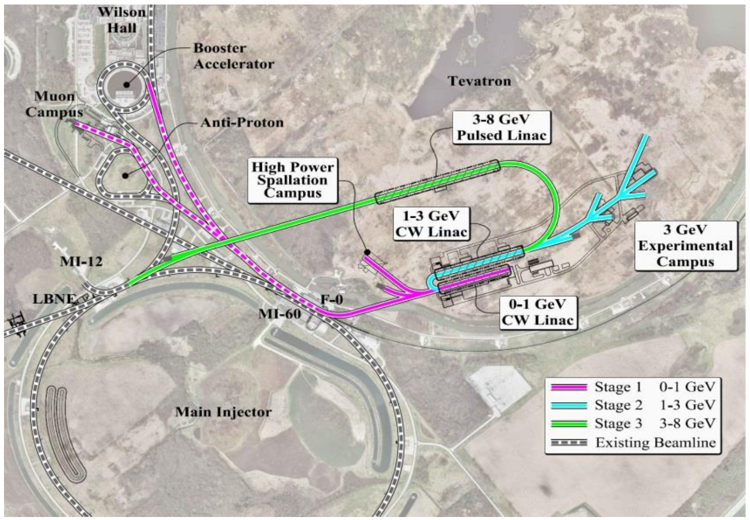
R&D Facilities

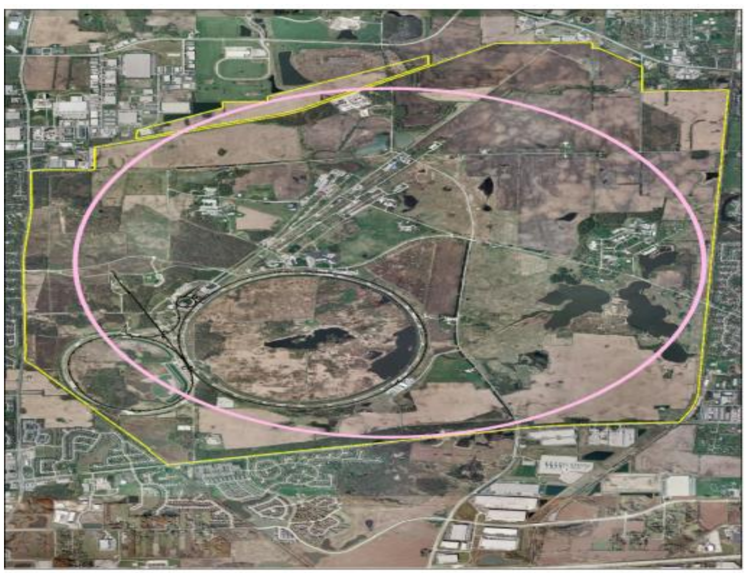


ASTA Layout – Stage I

- ASTA
  - IOTA ring for integrable optics & larger tune spreads
  - IOTA ring for optical stochastic cooling & reducing halo
  - Space charge compensation with elens
  - Radiation damage of materials
- Project X for development of beam halo monitor, high intensity proton beam

Injectors for the collider





- Project X for 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 in a 100 km ring

Beam Current and Luminosity

- 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

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

Design parameters

Beam parameters at top energy

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

Comments on the 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 RD 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 2:
3 GeV linac,
Accumulator ring,
Main Injector

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

Scenario 4:
Recirculating linac,
e+ damping ring

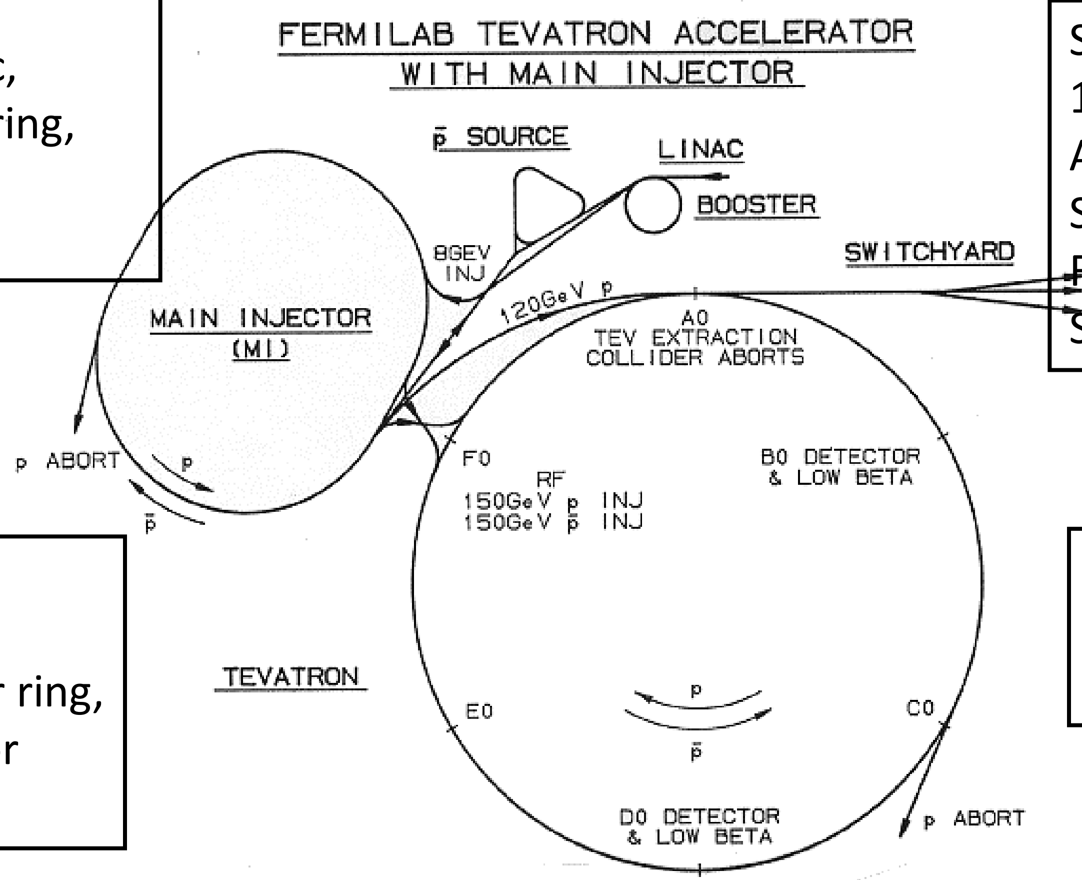
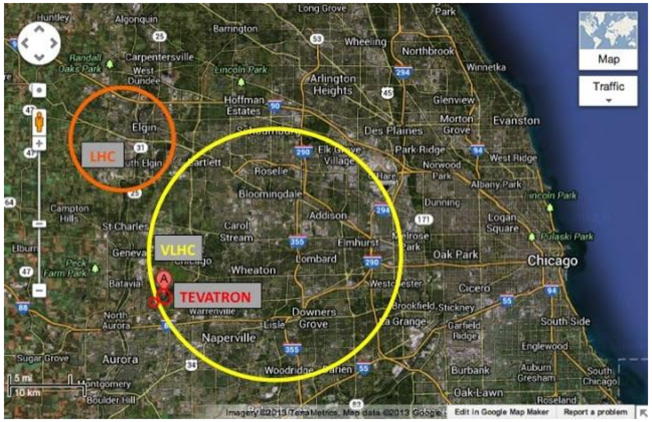


Figure 1-2. Schematic View of the Main Injector Connections to the Booster, Antiproton Source, Tevatron and Switchyard.

Summary

Physics central blog



50-50 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
- β_y^* (& luminosity) limited by IR chromaticity.
- R&D on beamstrahlung, IR chromaticity compensation, synchrotron radiation management, …
- RF requirements similar to LEP2

Additional slides

pp design Parameters - 3

Lattice

	VLHC (2013)	LHC (design)
Cell Length [m]	225.8	106.9
Main bend field [T]	15.1	8.3
Phase advance /cell [deg]	90	90
$(\beta^{max}, \beta^{min})$ in arc [m]	(385, 66)	180, 30
(D_x^{max}, D_x^{min}) in arc [m]	(2.5, 1.2)	2.0, 0.95
γ_t	95.5	55.7

Rf system

	VLHC (2013)	LHC (design)
Revolution frequency [kHz]	2.96	11.25
Harmonic number	215214	35640
Rf voltage	80	16
Synchrotron frequency [Hz]	7.25	21.4
Bucket area [eV-sec]	20.8	8.0
Bucket half height /rms energy spread	5.3	3.3

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

Beam Dynamics in the e+-e- collider

- Local chromaticity correction needs to be designed
- Dynamic Aperture over a wide momentum range
- Bunch intensity limitations

  - TMCI: High frequency Rf cavities may pose a limit.

  - Synchrotron radiation from quads increases with beam size, which increase with intensity due to beam-beam
- Beam-beam limitations, dynamic beta, beam backgrounds, flip-flop, coherent effects,
- Synchro-betatron resonances with large Qs
- Synchrotron radiation from quadrupoles in the IR, backgrounds