High Field VLHC

G. Dugan, LNS, Cornell University

General Features of the VLHC

High field parameters

Lattice features

Partition function manipulation

Interaction region

Injector Options

Magnets

Vacuum

Cryogenics

Summary

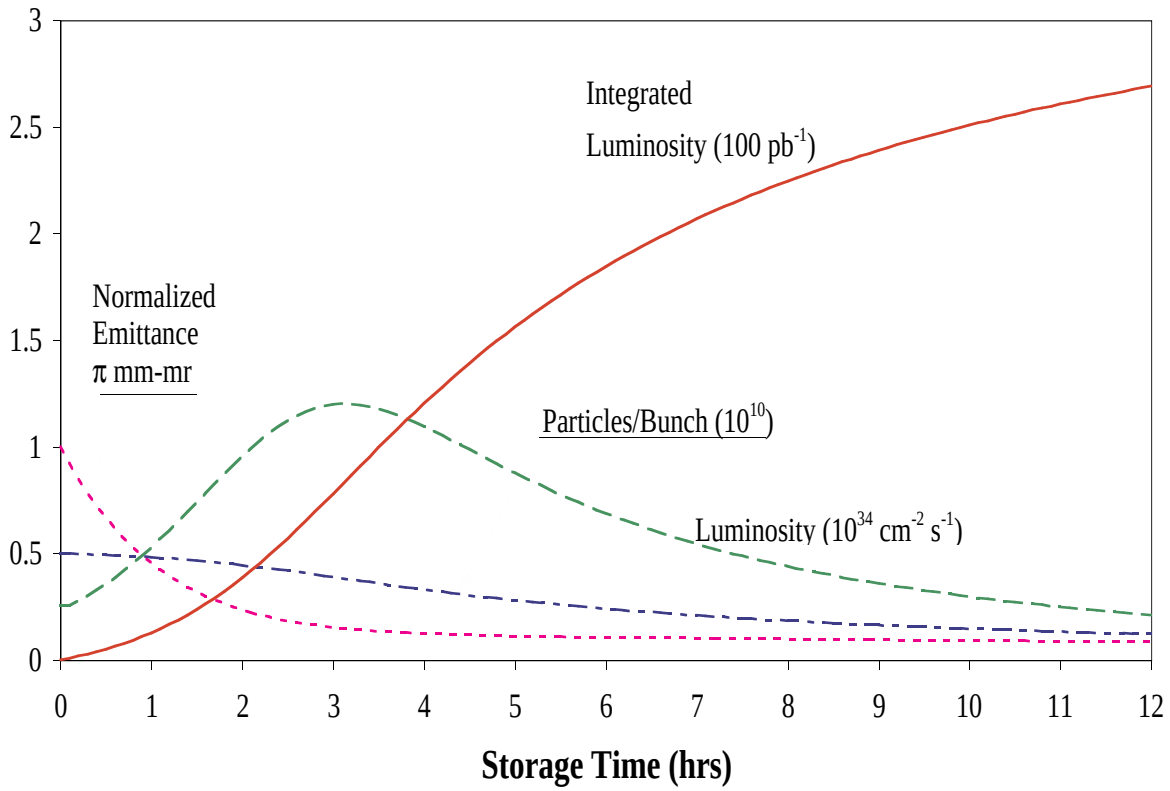
General Features of a third-generation (E_{CM} = 100 TeV) hadron collider

1. **Physics at the energy frontier:** ***a discovery machine***
2. Luminosity > 10^{34} cm^{-2} sec^{-1}
3. Uses superconducting magnet technology
4. Requires a conservative design approach which insures reliability at the design goals
5. Must be as cost-effective as possible
6. Will be an internationally-supported effort

Snowmass '96 machine parameters

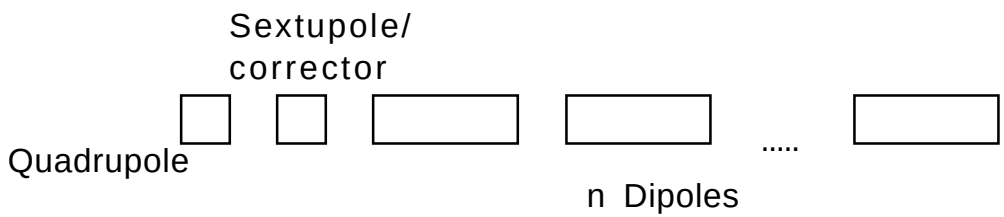
Parameter	**High field-new technology**	**High field-known technology**	**Units**
CM Energy	100	100	TeV
Dipole field	12.6	9.5	T
Circumference	104	138	km
Synchrotron radiation damping time (horizontal amplitude)	2.6	4.6	hr
Synchrotron radiation damping time (energy)	1.3	2.3	hr
Initial/peak luminosity	.35/1.2	.35/1.0	10^{34} $cm^{-2}sec^{-1}$
β^*	20	20	cm
Bunch spacing	16.7	16.7	nsec
Beam stored energy	.89	1.18	GJ
Synchrotron radiation power/ring	189	143	kW
Revolution frequency	2.89	2.18	kHz
Synchrotron frequency	8.9	5.8	Hz
Energy loss/turn	3678	2778	keV
Total current	.05	.05	Amp
$<\beta>$	255	255	m
Tune	65	86	
Half cell length (assumed 90^ocells)	200	200	m
Beam pipe radius	1.65	1.65	cm
Beam pipe	Cold, Cu	Cold, Cu	

Beam parameters vs. storage time



Arc lattice features

Cell parameters:
Phase advance: 90º
Separated function



The cell length/aperture tradeoff:

Cell length L, **good field radius** r_{GF},

$$L \propto \frac{\gamma_I}{\varepsilon_n} r_{GF}^2, \quad r_{GF} \propto d_c^2$$

Can we build a <u>combined function</u> high-field machine in which we retain transverse radiation damping?

Schemes for damping control in a VLHC:

- Duomagnetic lattice
- Robinson wigglers

Radiation damping rates

$$\alpha_0 = \frac{P_\gamma}{2E}$$ P_γ =radiation power E =beam energy

x-damping rate: $\alpha_x = J_x \alpha_0$

E-damping rate: $\alpha_E = J_E \alpha_0$

y-damping rate: $\alpha_y = J_y \alpha_0$

The Robinson theorem relates the partition numbers:

$$J_x + J_y + J_E = 4$$

Partition numbers and radiation integrals

N =number of cells; L=half-cell length
ρ=bend radius; D=dispersion;

$$J_y = 1$$

$$J_x = 1 - \frac{I_4}{I_2}$$

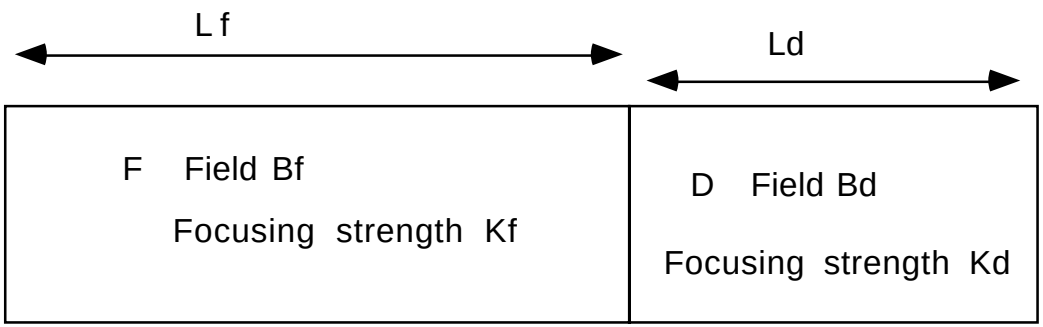
$$J_E = 2 + \frac{I_4}{I_2}$$

$$I_2 = \oint \frac{ds}{\rho^2} = \frac{2NL}{\rho^2} \qquad K = \frac{1}{B\rho}\frac{dB}{dx}$$

$$I_4 = \oint \frac{ds}{\rho^3} D\left(1 + 2K\rho^2\right)$$

$$\approx \frac{2NL}{\rho} K\left[\langle D\rangle_{Focus} - \langle D\rangle_{Defocus}\right]$$

Duomagnetic combined function FD lattice



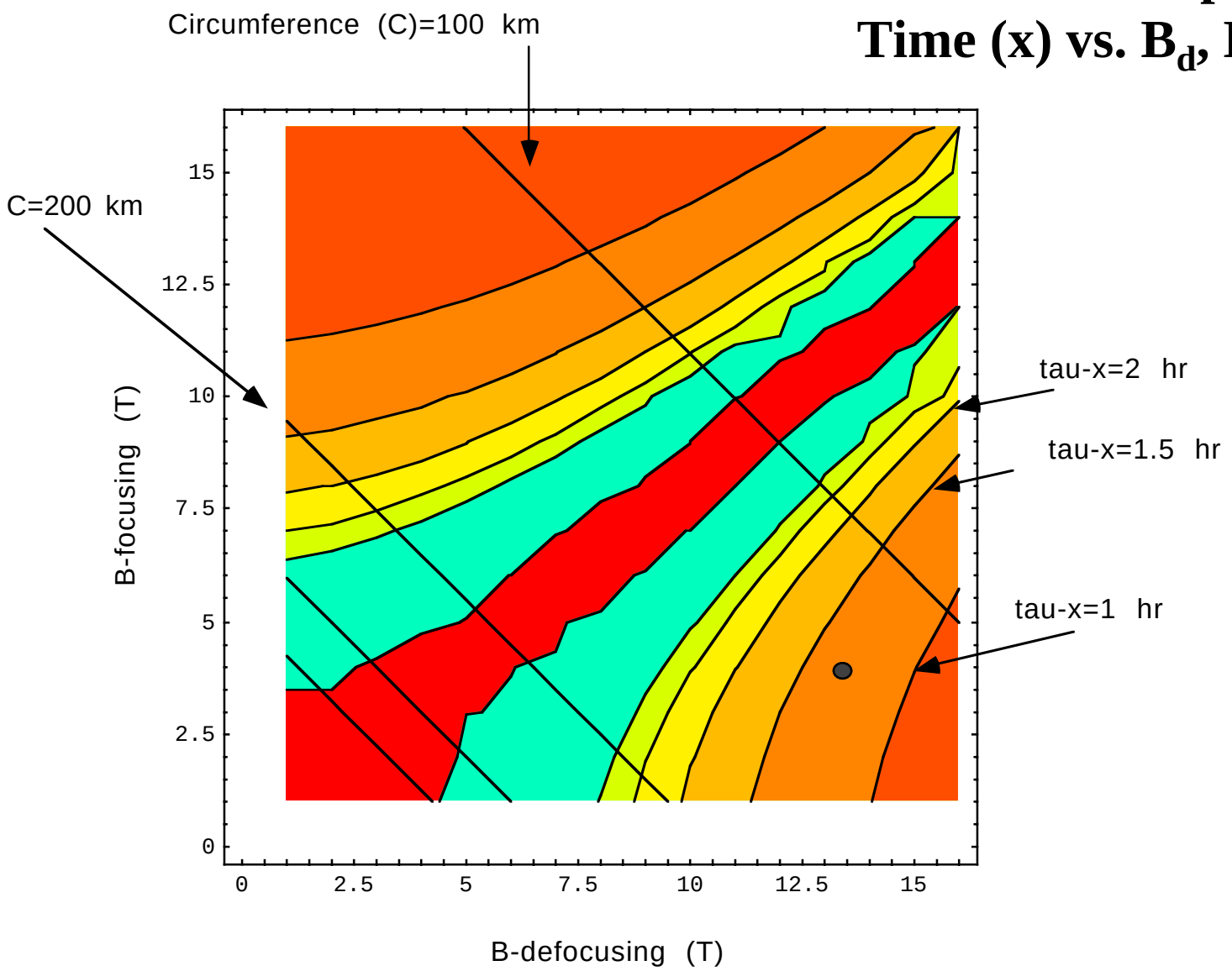
Radiation integral $$I_4 = 2N\left(\frac{L_f K_f \langle D\rangle_f}{\rho_f} + \frac{L_d K_d \langle D\rangle_d}{\rho_d}\right)$$

To get $I_4 \le 0$, we need $B_d > B_f$.. Consider two cases:

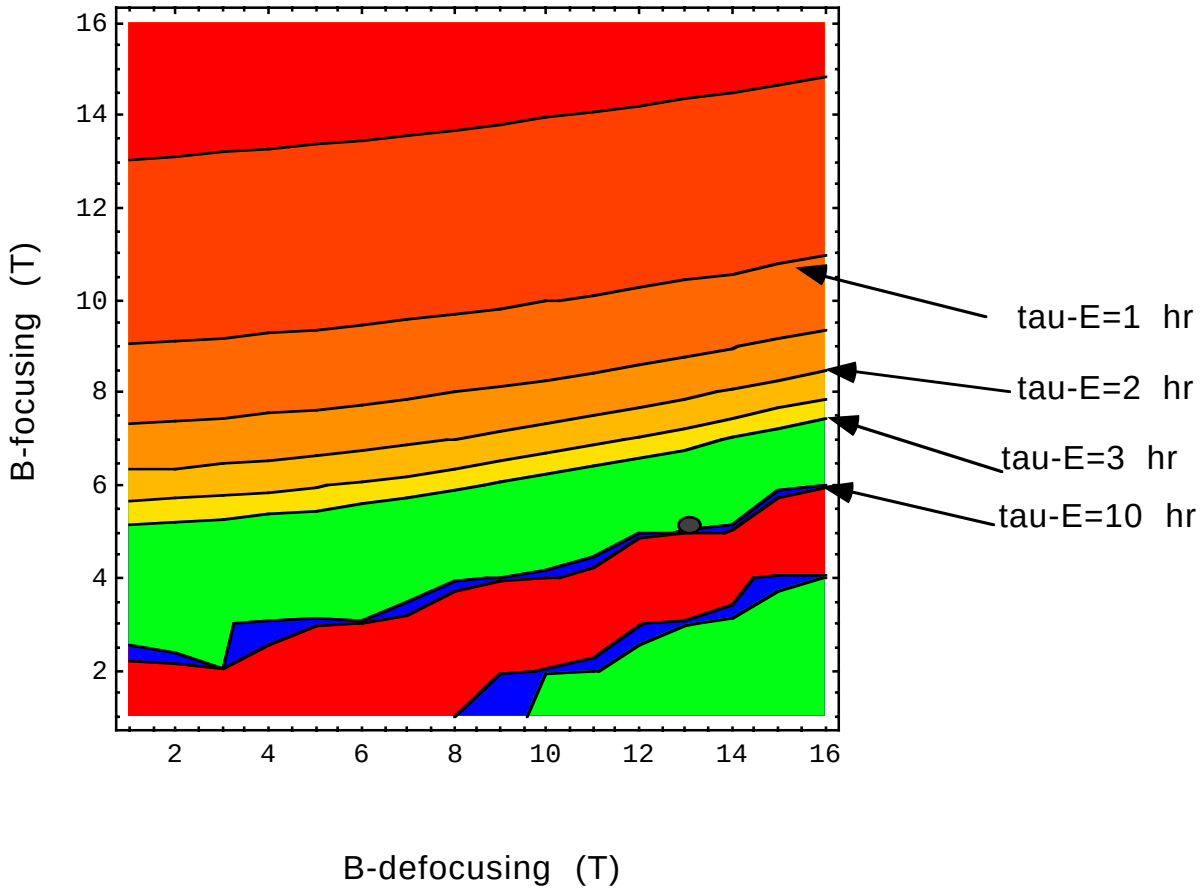
(a). $L_f = L_d,\ \ K_f = -K_d$

(b). $K_f \rho_f = -K_d \rho_d \Rightarrow \ \dfrac{1}{B_f}\dfrac{dB_f}{dx} = -\dfrac{1}{B_d}\dfrac{dB_d}{dx}$

Radiation damping Time (x) vs. B_d, B_f



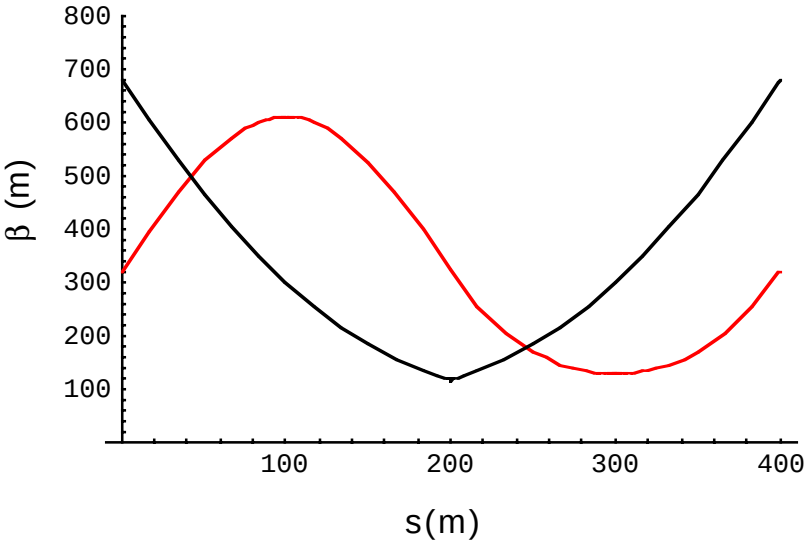
Radiation damping Time (E) vs. B_d, B_f



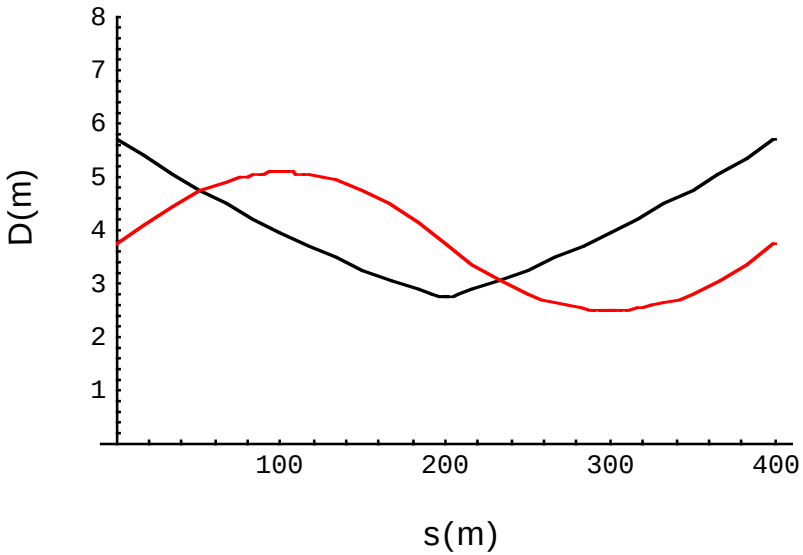
Design example and comparison with separated function

	Combined Function	Separated Function	Units
Defocusing Field	13.125	8.75	T
Focusing Field	4.375	8.75	T
Field Gradient	10.2	140	T/m
Phase/cell	90	90	degrees
Cell length	400	400	m
Number of cells	300	300	
Circumference	140	140	km
Tune	74	74	
x-damping time	1.4	5.1	hr
E-damping time	47.6	2.5	hr
Rms normalized emittance	37	150	nm
Rms del-e/e	23	3.9	ppm
Energy loss/turn	3.18	2.54	MeV
Momentum Compaction	1.50E-04	1.82E-04	

Lattice function comparison
Red-combined function Black-separated function



Beta function



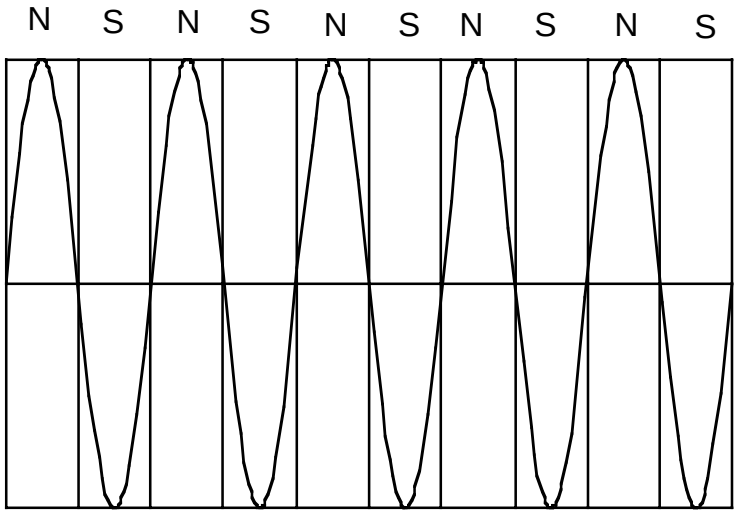
Dispersion function

Robinson Wigglers

Wiggler field B_w, length L_w

Wiggler field gradient $\frac{dB_w}{dx}$

Dispersion in wiggler D_w



$$I_4 = I_{4,ring} + \frac{L_w}{\rho_w^2}\frac{D_w}{B_w}\frac{dB_w}{dx}$$

Design example parameters:

B_w=10 T ;D_w=5 m; $\frac{dB_w}{dx}$ =100 T/m;

Period=10 m; Wiggle amplitude=25 μm

Design example results, Robinson Wigglers

Parameter	High Field Separ. Func.		High Field Comb. Func.		Low field Comb.func.		Unit
Energy	50.0		50.0		50.0		TeV
Dipole Field	12.5		12.5		2.0		TeV
Current	0.04		0.04		0.1		A
SR power	145.0		145.0		52.4		kW
Damping time-x	2.4	0.8	-2.4	2.6	-114.0	3.8	hr
Damping time-E	1.2	20.0	0.6	1.1	28.5	-4.4	hr
rms normalized emittance	128.0	44.0		138.0		0.1	nm
rms relative energy spreac	4.7	19.5	3.3	4.6	1.3		ppm
Wiggler length		5.0		5.0		11.6	km
Wiggler power		2.8		2.8		16.1	kW

Interaction Region: FLAT BEAMS

(Peggs, Harrison, Pilat, Syphers)

If the vertical dispersion and the linear coupling are well-controlled in the arcs, the vertical emittance will damp to a value much smaller than the horizontal emittance, resulting in *flat beams* as in an electron storage ring.

Implications:

- **The final focus optics can be a doublet, rather than a triplet**
- **The peak beta function is typically x10 smaller, for the same β*, than with round beam triplet optics=> field quality demands in the final focus quads are relaxed**
- **Long-range tune shifts (mostly vertical) occuring before the beams separate tend to be smaller**

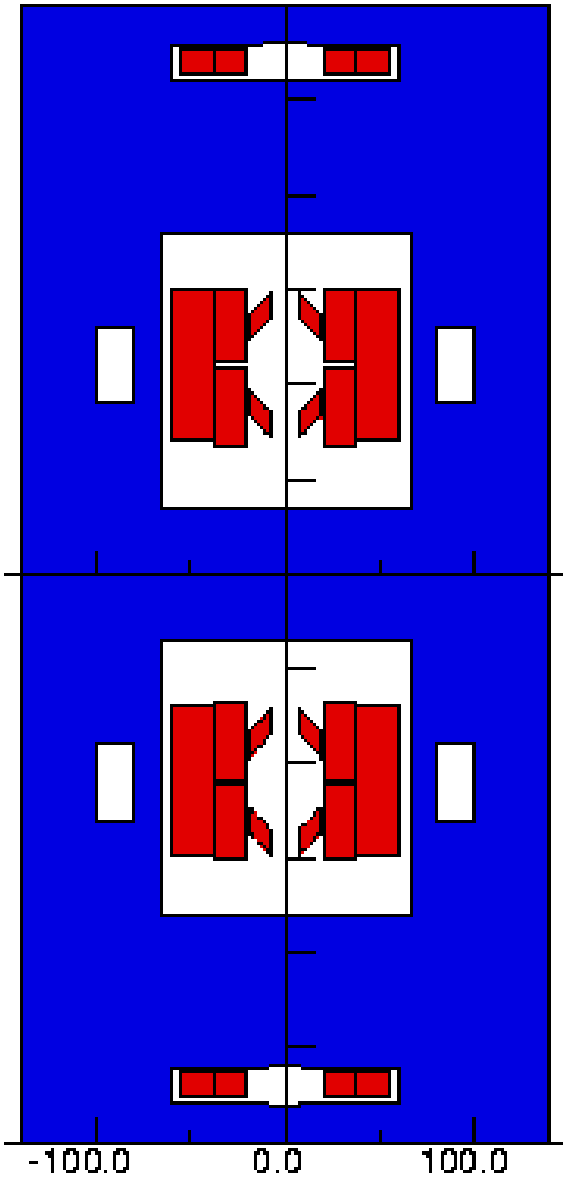
Injector Options

- Injector in same tunnel as high-field collider, with common magnet
- High-field collider with low-field full energy injector

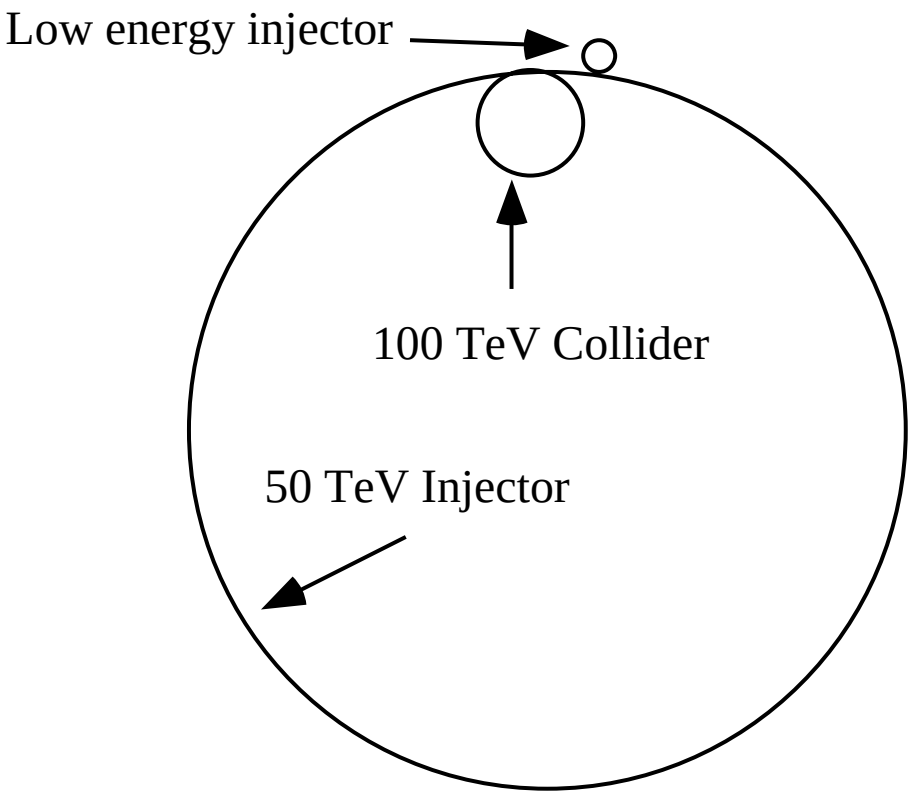
Injector in same tunnel as high-field collider, with common magnet

Common-coil magnet with dual low field, high field apertures

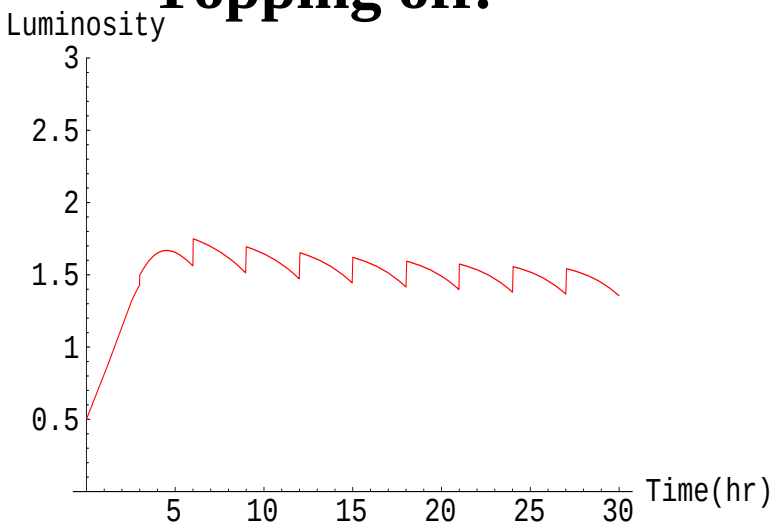
R. Gupta



Low field injector
High field collider



Topping off:



Magnets: Conductor Options

- Nb_3Sn

- VLHC spec: $J_c > 2000 A/mm^2$ at 12 T, 4° K; <20 μm filaments
- Strain-sensitive, wind and react technology required; small filament diameters difficult to achieve

- HTS

- Very high critical field (>30 T); useful from 4°-30° K; strain-intolerant (like A-15 compounds); moderate to high J_c
- Most likely candidates:BSCCO-2212,-2223; YBCO-123

High Field Magnet Programs

- Fermilab: focus is on an 11 T magnet: 50 mm Nb_3Sn cos-theta dipole
- LBL: Nb_3Sn common-coil block magnet
  - short (1 m) prototype tested at 6 T
  - Ultimate goal: 14 T, highly modular design;
- BNL: Common-coil block magnet; hybrid with NbTi background coils, modular Nb_3Sn or HTS inserts
- TAMU: Nb_3Sn segmented block coil, using stress management techniques; 16 T

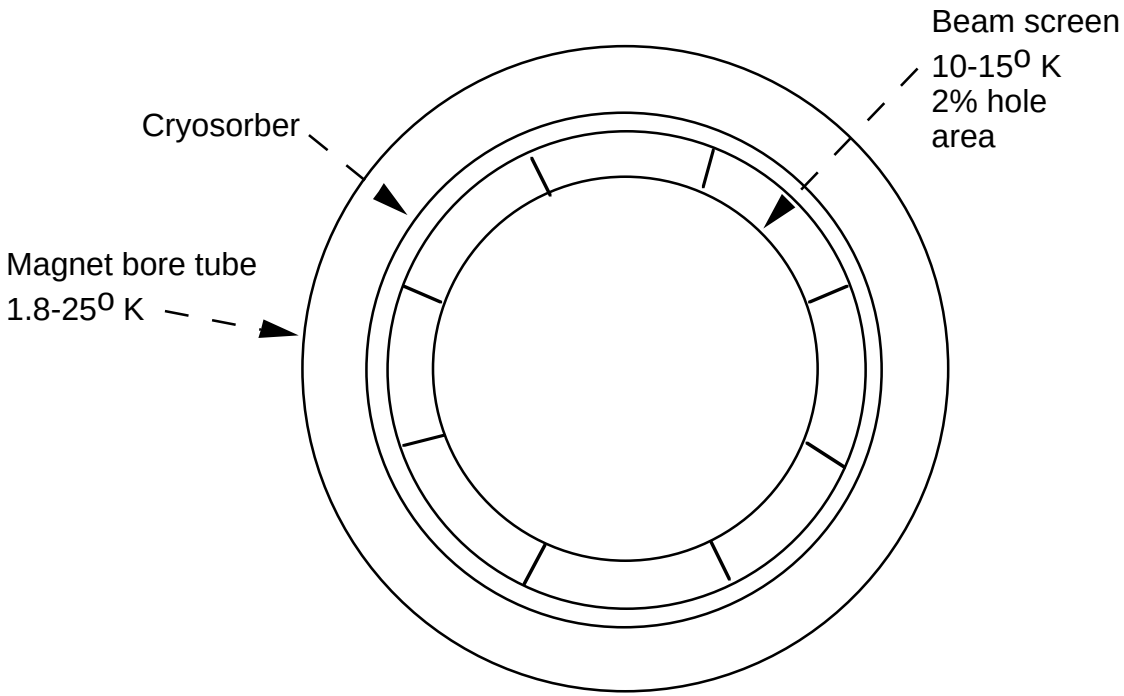
Vacuum

(W. Turner, Snowmass)

Synchrotron radiation power: 190 kW; beam lifetime (τ_{pp} = 32 hrs)

Ringwide average vacuum requirement
for **τ_{gas}~5τ_{pp}: 1.8 nTorr RTE CO**

Needs a liner with distributed cryosorber at 10-15° K to intercept synchrotron radiation and pump photodesorbed gases



Design simplifies if magnets use HTS at ~10-15°K

liner can be integrated to magnet bore tube

Magnets above~15° K: H_2 is no longer cryosorbed, liner must be cooled separately from the magnet

Cryogenics

- Large synchrotron radiation load, intercepted with the beam screen, implies large cryogenic system
- High temperature magnet operation would simplify the system

From Snowmass '96 (MacAshan, Mazur)
Comparison of Cryogenic Systems for Different VLHC Magnets

Collider Magnet Operating Temp.	Ring Size	№ of Stat. (inc. 1 IR)	Heat Load					Ideal Pwr	Wall-Plug Power
K	km		1.8 K	4.5 K	20 K	50 K	Leads	MW	MW
NbTi, 1.8	138	20	115	413	0	1644	920	45	180
Nb3Sn, 4.5	104	18	0	66	420	1080	940	18	72
HTS, 25	104	18	0	15	590	1080	940	14	54

Summary-high field VLHC

<u>Major challenges</u>

- Taking full advantage of radiation damping to simplify accelerator design and reduce cost
- Developing an economical high field magnet
- Handling the synchrotron radiation power and associated vacuum issues