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Beam Effects in the VLHC

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Introduction: VLHC Parameters Classification

VLHC is a virtual machine yet, parameters are floating with different degree of freedom. All parameters can be divided in four groups:

Fixed parameters:

Beam Energy	50 TeV
Luminosity	10^{34} s^{-1} cm^{-2}

Approximately fixed parameters:

Parameter	Low field	High field	Comments
Magnet field	2.0 T	10-14 T	Technology
Aperture(gap)	16-18-20mm	30-45mm	Beam pipe, cost,technology
Bunch spacing	18.9 ns	18.9 ns	MI RF 53 MHz
RF frequency	477MHz	477MHz	9x53MHz (7-25)x53
Bunch length, rms	5-10 cm	5-10 cm	
Beta @ IP	15-50 cm	15-50 cm	IP design
Transverse Emittance	1-3	1-3	Pi mm mrad rms, SR, IBS, cool

“Free” parameters (substantial freedom):

Lattice
- instabilities need lower <beta>
- cost saving arguments
- aperture+other constraints

Longitudinal emittance
- 0.2-5 eV*sec do not affect luminosity while can help to damp some instabilities
- coalescing (?)

Acceleration time
- duty factor, RF power

Other parameters can be derived:

zeroth-order parameter list

Parameter	Units	Low Field	High field
Energy	E, TeV	50	50
Peak Luminosity	L, 10**34	1	1
Inj.energy	E inj, TeV	3	3
B-field	B, T	2.04	11.6
Circumference	C, km	520	95
Rev. frequency	F_0, Hz	577	3156
Bunch spacing	l_{bb} , ns	18.9	18.9
No. of bunches	B	92000	16800
P/bunch	N_p, 10**10	1.5	1.5
Total protons	10**15	2.76	0.5
Stored energy	GJ	22	4
Tune	ν	270.765	37.385
Slip factor	η	1.4 10**-5	7.2 10**-4
# FODO half cells		2100	350
Half-cell length	Lcell, m	246	260

Phase/cell	μ	90	60
Beta max/min/avg	β, m	840/144/492	900/300/600
Max dispersion	D_x, m	2	23
Pipe _ size	a, mm	9	16.5
Transv. emitt	$\varepsilon_{T,}$ π mmmrad, rms	2.5	2.5
Long. Emitt (inj)	ε_L, eV*sec	0.3 (0.2)	(0.3) 0.2
Beam current	I_B, ,mA	127	127
Bunch current	I_b, μA	1.4	7.6
SR loss/turn	E_{SR}, MeV	0.6	3.4
Damping time,long	τ_L,hrs	40.4	1.3
RF frequency	f_{RF}, MHz	477	477
Harmonic number	h_{RF}, 10**5	8.28	1.5
RF Voltage (inj)	U_{RF}, MV	4 (200)	7 (40)
Acceleration time	T_{acc} , min	13.6	12.4
Bucket area (inj)	A_L ,eV*sec	9 (16)	4 (2.2)
Synchr. tune (inj)	ν_s ,10*-3	.38 (10)	1 (14)
Synchr. freq (inj)	f_s,Hz	0.22 (5.8)	5.6 (44)
Bunch length (inj)	σ_s cm, rms	4.1 (2.6)	5.6(5.2)
Dp/p, rms (inj)	10**-4	0.14 (2.4)	0.08 (0.68)

Emittance growth issues:

a) <u>Inevitable transverse emittance growth</u>

Multiple Coulomb scattering in residual gas

*10% increase over 10000 hrs @ 10**-9 Torr*

Quantum fluctuations of synchrotron radiation

10% increase over 15 min (High Field)
or 5000 hrs (Low Field option)

b) transverse emittance growth due to external noises

takes place if uncorrected over *decoherence* time of about 1/x=1000 turns in the VLHC

Requirement of less then 10% emittance growth over characteristic time interval t_L :

Process	Low-Field	High-Field
Inelastic beam-gas	6 mos	6 mos
Transverse IBS	6 mos	2 days
L "burn-out"	300 hrs	54 hrs
Tr. SR damp-time	81 hrs	2.6 hrs
Store	10 hrs	20 hrs
t_L	10 hrs	2.6 hrs

External noise tolerances*:

	Low-Field	High-Field
Quads vibration,rms	1.2 A	3 A
dB/B, rms (integral _ cell)	2.3e-10	.7e-10
betatron frequency	80-160 Hz	0.6-1.2 kHz

* assumptions: separated functions FODO lattice, 2Quads+2Dipoles/cell

Summary of external noise effects:

high-frequency ground vibrations are studied experimentally, we aware of the problem, and straightforward and easy to implement cure exists – feedback system to damp coherent betatron oscillations

experimental R&D request: to develop experimental technique and to measure magnetic field fluctuations in the VLHC dipole prototypes (reference magnets) with high accuracy of about 10 microGauss in frequency band of 50-1500 Hz.

experimentally measured RF noises will not cause significant growth of longitudinal emittance

Collective Effects

- **Coherent synchrotron tune shift @ 50TeV**
- **Longitudinal microwave instability @ 50 TeV**
- **Transverse mode coupling instability @ 3 TeV**
- **Resistive wall multi-bunch instability @ 3 TeV**
- **Effects are more severe in the low-field VLHC**

Coherent synchrotron tune shift @ 50TeV

The coherent synchrotron tune shift is driven by inductive longitudinal broad band impedance. To preserve Landau damping, the synchrotron tune shift must remain smaller than the synchrotron tune spread. It leads to upper limit for the impedance:

$$\mathrm{Im}(Z/n)_{eff} < (6/\pi^3)\,(h_{RF}{}^3\, U_{RF}/I_{bunch})\,(\sigma_s/R)^5$$

	Low Field	High Field
Estimate on Im(Z/n)	0.1 Ohm	0.03 Ohm
Threshold CSTSI	0.2 Ohm*	0.4 Ohm

* increased longitudinal emittance upto 1 eV*sec; 0.01 Ohm @ 0.3 eV*sec

The instability is rather weak and can be eliminated by a) increasing bunch length, b) reducing slope of RF wave with a second RF system at a higher frequency, c) low-power longitudinal feedback for first modes (e.g, quadrupole; dipole to be damped by mandatory phase locked loop).

Longitudinal microwave instability @ 50TeV

Also known as "turbulent bunch lengthening", the instability leads to a blow-up of the longitudinal emittance above certain threshold (instead of just a distortion of the potential well). The instability is caused by coupling of the beam to the very high frequency part of the impedance, and does not lead to the beam loss. Threshold is given by:

$$|Z/n|_{eff} < (1/\mathrm{sqrt}(2\pi))\ (h_{RF}\ U_{RF}\ /I_{bunch})\ (\sigma_s/R)\hat{}3$$

	Low Field	High Field
Estimate on |Z/n|	0.2 Ohm	0.05 Ohm
Threshold LMWI	0.7 Ohm*	0.9 Ohm

* increased longitudinal emittance upto 1 eV*sec; 0.12 Ohm @ 0.3 eV*sec

Increasing the bunch length would lead to acceptable safety factor.

Transverse mode coupling instability @ 3TeV

Also known as "strong head-tail" (contrary to "weak head-tail" due to chromaticity). Both coherent bunch motion and head-tail motion are driven by transverse wide-band impedance and become unstable above certain threshold, with characteristic growth time of a fraction of synchrotron period (see cartoon and figure). The TMCI due to mostly RW impedance has threshold of:

$$N_{p,thr} < 1.4e10 * (E_p/3TeV) * (\nu_s/0.01) * (a/9mm)^3 * (550km/C) * (400m/\langle\beta\rangle) * \sqrt{\sigma_s/10cm}$$

	Low Field	High Field
Protons/bunch, Np/10^10	1.5	1.5
TMCI Threshold	1.7	28.*

* for HF, most of the impedance comes not from RW (bellows, BPMs, etc.)

The TMCI has been observed in many electron machines (PETRA, PEP, VEPP-4, LEP), but not in proton rings.

Opportunities to increase the TMCI threshold:

	potential gain
thin Cu, Ag coating	1.3
asymmetric beam pipe	1.5…3
RF quadrupole	2…4
"Head-tail" feedback	2…5

R&D opportunities:

- Beam studies at the Tevatron/? (tuneshift vs intensity)
- Study TMCI in the Tevatron with an "electron lens" – tunable Z_T (I_e, $B_{solenoid}$)
- RF quadrupole experiment @ VEPP-4

Transverse coupled-bunch instability @ 3TeV

Total beam current effect driven by low-frequency transverse impedance due to resistive walls. Instability increment in number of turns is given by:

$$\tau_{RW} f_0 = (\sqrt{2}\pi)(E_p / e\, I_B\, Z_0) * (a^3 / \langle\beta\rangle) * (\Delta\nu \sigma_{Al} / cR^3)^{1/2}$$

	Low Field	High Field
Beam current, mA	127	127
RW increment, turns	0.4	180

These increments can be handled by feedback systems. Even in low-field option the instability can be *easily* damped by a multi-stage feedback (see cartoon). The technique is not speculative and should not be controversial (a similar system has been used to damp RW instability in the Main Ring).

Electron cloud instability @ 50TeV

This instability arises due to a combination of photoemission and secondary emission from the vacuum chamber wall, by which, for each passing bunch train, an electron cloud builds up in the beam pipe. Interaction with this electron cloud can amplify small perturbation in the orbit of the individual bunches, which results in a multi-bunch instability. The instability growth times can be estimated as:

$$\tau_{ion}=(4\pi\gamma_p\nu_\beta)/(N_B\, r_p c\, W_1(l_{bb}))$$

	Low Field	High Field
Rise time due to e-cloud	3-4 s	0.5 s *

* based on F.Zimmermann, CERN-LHC-95 (1997).

Feedback systems at the VLHC

- FB to damp resistive wall coupled bunch and injection errors: high gain
  narrow band 100 kHz
- Wide-band FB to damp the rest of bunch to bunch modes: one turn delay
  26 MHz band (2/bunch spacing)
- Head –tail (TMCI) feedback: small gain
  mode 0: band 26 MHz
  mode 1: carrier frequency 3 GHz
  band 26 MHz
- FB to suppress emittance growth
- Longitudinal feedbacks

Beam-beam effects

- Head-on tune shift x=0.0008-0.008
- Long-range tune shifts (IR design)
- Crossing angle @ IP (L, SBRs), alternative crossing angles at 2 IRs
- Flat beams: **"… allow larger b*, lower max betas, easier beam separation, reduced LR tune shifts."**

  S.Peggs, et.al, PAC'99
- "round beams", e.g. "Mobius accelerator"

$b_x = b_y$ $e_x = e_y$ $n_x = n_y$