Summary of the Working Group II "RF, Instabilities and Feedback Systems". VLHC Accelerator Technology Workshop, TJNAF, Feb. 8-11, 1999.

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I. SCOPE

There were 14 participants in the "RF, Instabilities and Feedback" Working Group sessions: W.Barry and G.Lambertson (LBL), P.Limon, J.Maclachlan, E.Malamud, J.Marriner, V.Shiltsev, and M.Syphers (FNAL), D.Sutter (DoE), L.Teng (ANL), J.Delayen, L.Doolittle, V.Lebedev, C.Reece (TJNAF). A total of 9 talks were presented:

T1	W.Barry	Multibunch feedback systems at the ALS
T2	L.Doolittle	On RF choice for the VLHC
T3	J.Maclachlan	Is electron cooling relevant to VLHC?
T4	E.Malamud	Discussion of bunch spacing at the VLHC
T5	J.Marriner	On transverse multibunch instability and FB
T6	J.Marriner	On choice of the RF parameters
T7	V.Shiltsev	General parameter list of the VLHC
T8	V.Shiltsev	On TMCI at the VLHC
T9	V.Shiltsev	External noise issues at the VLHC

Below, we will make references according to the talk number (see left column). Some of these talks and this summary are available electronically at **http://www.vlhc.org/AT_proc.html**. In addition to numerous discussions during and after the talks, we arranged some 2 hours for individual "home-work" (Tue., Feb.9) and devoted about 2 hours to discuss the draft of this summary (Wed., Feb.10).

Besides "Scope", this summary consists of three sections:
II. VLHC parameters, RF parameters, Specification of Requirements
III.Instabilities, Emittance Growth and Cures (Feedback)
IV. R&D opportunities.

II. VLHC PARAMETERS, RF PARAMETERS, AND SPECIFICATION OF REQUIREMENTS

It was realized [T7] that the parameters for the not-yet-designed VLHC are floating. The degree of freedom varies significantly, so all parameters were divided into 4 groups depending on their possible range of variation:

Fixed parameters	**not too much freedom**
Approximately fixed parameters	**variation within factor of 3**
Free parameters	**variation larger than factor of 3**
Derived parameters	**calculated from other parameters**

A. Fixed parameters

Those are **beam energy** $E_b = 50$ TeV and the collider **luminosity** $L = 10^{34}\, s^{-1} cm^{-2}$ - they are fixed *a priori* by physics considerations.

B. Approximately fixed parameters

The **dipole magnetic field** $B \approx 2$T in the case of low-field (LF) option of the VLHC, and $B = 10 - 14$T for high-field (HF) option of the VLHC are approximately fixed. Freedom in the dipole field is limited by the choice of magnet technology. Closely related to B, and also technology dependent, is the **beam pipe aperture**. It varies very little for LF - around $a = 9$mm (half gap) and varies somewhat more for HF - $a = 10...20$mm (radius). In the case of HF, the beam aperture is reduced from the physical coil aperture by necessity of a synchrotron radiation beam screen. The choice of a significantly affects the magnet cost.

Another approximately fixed parameter is **bunch spacing**. The first order assumption is $l_{bb} = 18.9$ns which is the period of 53 MHz RF system of the Fermilab Main Injector (thought to be the injector to the 3 TeV VLHC Booster). It was shown [T4] that larger l_{bb} would increase the number of inelastic interactions/crossing $n_{int} \approx t_{bb}[ns]$ and would give a larger head-on beam-beam tune shift parameter $\xi \approx 0.003/\sqrt{t_{bb}/25ns}$. Both are undesirable, but the total beam power decreases ($P_{stored} \propto 1/\sqrt{t_{bb}}$). LHC has $t_{bb} \approx 25$ns. Present day detector triggering technology appears to disfavor the bunch spacing of 10ns or less.

Another detector-related requirement is to keep the number of interactions per unit length low (i.e. less than 0.2-0.3 int/mm would allow vertex recognition). This leads to the desire to a have longer luminous region, and therefore, **bunch length**. The latter could be as long as $\sigma_s = 5...10$cm rms. Correspondingly, one has to consider the **beta-function at IP** as an approximately fixed parameter, too. These considerations limit the minimum value of β^* to about 10-15 cm while the maximum value of about 50 cm is determined by the need of high luminosity. The issue should be considered further at the VLHC Accelerator Physics workshop and by lattice designers.

Transverse beam emittance at injection is thought to be somewhat fixed by the injector chain but depending on the bunch population it may vary within the range $\varepsilon_n = 1...3$ mm·mrad (normalized, in FNAL units 6-18 π). The emittance evolution at the experiment energy depends on choice of B, e.g., the HF option is less dependent on the injection emittance because of synchrotron radiation damping. Nevertheless, the emittance and beam size should provide enough freedom for the beam orbit inside the aperture limit at the injection. One possible way to reduce the emittance at injection is to implement "electron cooling" into one of the injector chain accelerators. An appropriate set-up would be about 20 times (in terms of "electron current $\times$ electron beam length) the electron cooler currently under development at FNAL [T3]. Cooling at the top energy of 50 TeV can be realistically considered as beneficial for the LF option only. It would require an expensive 25 GeV high-current electron ring and extremely tight tolerances on the e-beam quality and alignment with respect to proton beams.

RF frequency f_{RF} also is "an approximately free parameter". First of all, the frequency should be a multiple of the FNAL MI frequency of 53 MHz - that would make synchronization and injection easier. The list of possible frequencies with comments on available experience on superconducting RF at different accelerator labs is given below [T2]:

Harmonic	f_{RF}, MHz	bucket(cm)	f_{RF}, MHz	existing lab
1	53.105	188		
2	106.210	94		
3	159.315	63		
4	212.420	47		
5	265.525	38		
6	318.630	31		
7	371.735	27	352	CERN
8	424.840	24		
9	477.945	21	500	DESY
10	531.050	19	508	KEK
11	584.155	17		
12	637.260	15.7		
13	690.365	14.5	700	APT
14	743.470	13.4		
15	796.575	12.5		
16	849.680	11.8		
17	902.785	11.0		
18	955.890	10.5		
19	1008.995	9.9		
20	1062.100	9.4		
21	1115.205	9.0		
22	1168.310	8.6		
23	1221.415	8.2		
24	1274.520	7.8		
25	1327.625	7.5	1300	HEPL, TESLA
			1497	CEBAF, Saclay
			2997	Darmstadt

Relative merits of superconducting RF cavities vs copper ones are:

Superconducting:	Copper:
Shorter Beamline space	Lower capital cost
Lower impedance R/Q	No cryogenic infrastructure required
(most probably) Lower operating cost	More predictable reliability

SC RF greatly reduces the cost of additional *unloaded* RF voltage (RF gear capital cost, electrical operating cost). In low beam current cases, or cancelling beam phase cases, this can be used for accelerating voltage. In a high current synchrotron, this can be used for longitudinal focusing. There are many choices of control the RF system, e.g. a) vector control; b) magnitude/phase control; c) analog control; d) digital control. Historical problems have been traced to Higher Order Modes. They are difficult to deal with, since the environment only turns on with beam. Copper cavities have better intrinsic damping. With SC RF cavities, the problems are usually with the couplers. Specifying needs at main and HOM frequencies is key to starting a design.

A general conclusion was that SC RF system is somewhat more favorable at superconducting accelerator, although there is no serious problem in using normal-conducting RF.

A crude first parameter list for the VLHC RF is given below [T2]:

f_{RF}	MHz	478	1274
Operating temperature T	K	4.2	2.0
E_{acc}	MV/m	6	12
Shunt R/Q	Ohm/m	1000	1000
Coupler		coax	waveguide
cells/cavity		4	7
Volts/cavity	MV	7.5	9.9
Beam current I_B	mA	127	127
$\cos(\theta)$		0.5	0.5
V.I	kW	480	630
Length of bucket	cm	21	7.8
Voltage Cost	$ /V	.06	.015
200 MV for LF injection			
number of cavities		27	20
40 MV for HF			
number of cavities		5	4

We choose a total voltage of 200 MV for the low-field case and 40MV for the high-field case so that each case has the same acceleration time of about 15 min from 3 to 50 TeV.

C. Free parameters

These are thought to be the **acceleration time** T_{acc}, longitudinal emittance ε_L and the lattice. It was concluded that for practical simulations we can take $T_{acc} \approx 15$ min, if the time is much longer one loses the machine duty factor, while if it is much shorter then more RF is needed, more magnet voltage is needed, and it is more difficult to cool the AC losses in the magnets. Naturally, more detailed studies should be done using luminosity evolution models for both LF and HF options. Longitudinal emittance in the range of $0.2...3\,eV \cdot sec$ rms does not affect the luminosity and the other parameters too much, while larger emittances can even help to damp instabilities. As for the lattice, it is relevant that numerous transverse instabilities have longer risetime in a lattice with smaller average beta-function $< \beta >$. On the other hand, choice of the lattice must be done taking into account many other physical considerations as well cost saving arguments.

Finally, Table 1 presents the VLHC 0^{th} order parameter list that was used for further analysis of instabilities in the VLHC [T2,T4,T6,T7].

TABLE I. Zeroth order VLHC parameter list

Parameter	units	Low-field	High-field
Proton Energy,	E_p, TeV	50	50
Luminosity,	L, $s^{-1}cm^{-2}$	10^{34}	10^{34}
Injection Energy,	E_{inj}, TeV	3	3
Dipole field ,	B, T	2.0	11.6
Circumference,	C, km	520	95
Rev. frequency,	f_0, Hz	577	3156
Bunch spacing,	l_{bb}, ns	18.9	18.9
No. bunches,	N_b	92000	16800
Bunch intensity,	N_p	$1.5 \cdot 10^{10}$	$1.5 \cdot 10^{10}$
Total protons,	N_{tot}	$2.76 \cdot 10^{15}$	$0.5 \cdot 10^{15}$
Tune,	ν,	270.765	37.385
Slip factor,	η	$1.4 \cdot 10^{-5}$	$7.2 \cdot 10^{-4}$
No. half cells,		2100	350
1/2-cell length,	L_{cell}, m	246	260
Phase/cell,	μ, deg	90	60
β-max/min/avg,	β, m	840/144/492	900/300/600
Max dispersion,	D_x, m	2	23
Pipe 1/2 size,	a, mm	9	16.5
RMS emittance,	$\varepsilon_n,\ 10^{-6}\, m$	1.0	2.5
Longitudinal emittance (rms),	ε_L, eV·sec	0.3	0.3
Mean beam current,	I_B, mA	127	127
SR loss/turn,	E_{SR}, MeV	0.6	3.4
Longitudinal damping time,	τ_l, hrs	40.4	1.3
RF frequency,	f_{RF}, MHz	477	477
RF harmonics,	$h_{RF} = f_{RF}/f_0$	$8.28 \cdot 10^5$	$1.5 \cdot 10^5$
RF voltage (inj),	U_{RF}, MV	4(200)	7(40)
Acceleration time,	T_{acc}, min	13	13
RF bucket area (inj),	A, eV·sec	9(16)	4(2.2)
Synchr. tune (inj),	ν_s	0.00038(0.01)	0.001 (0.014)
RMS bunch length (inj),	σ_s, cm	4.1(2.6)	5.6(7.2)
RMS mom.spread (inj),	$\Delta P/P$, 10^{-5}	1.4 (25)	0.9 (9.1)
Interaction focus	β^*, cm	50	50
Interactions/crossing (max)	n_{int}	25.8	31
Vertices/mm	$n_{int}/\sqrt{\sqrt{2}\pi}\sigma_s$	0.3	0.26

III. INSTABILITIES, EMITTANCE GROWTH AND CURES (FEEDBACK)

A. Instabilities

There are several instabilities which may take place in the VLHC. Some of them are rather "weak" in the sense that they do not lead to beam loss (e.g., coherent synchrotron tune shift, longitudinal microwave instability) or have slow growth rates (instability due to photoelectrons). Others are "strong" - like TMCI or the resistive wall coupled-bunch instability. All the effects are more severe in the low-field option of the VLHC. Nevertheless, we have found that **none of the instabilities can be considered as a "show-stopper" for either low-field or high-field VLHC. Even at the current status of accelerator physics and tecnology there appear to be enough tools to damp/eliminate all of the instabilities.**

a. Coherent synchrotron tune shift at 50 TeV. 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 an upper limit for the impedance:

$$Im(Z/n)_{eff} \leq \frac{6}{\pi^3} \frac{h_{RF}^3 U_{RF}}{I_{bunch}} \left(\frac{\sigma_s}{R}\right)^5. \quad (1)$$

Comparison of the impedance estimates and threshold numbers is given below:

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

An increased longitudinal emittance up to 1 eV·sec is used in these estimates, while the threshold would be as low as 0.01 Ohm for $\varepsilon_l = 0.3$ eV·sec, i.e. 10 times less than the machine impedance in the LF.

The instability is rather weak and can be eliminated by any of the following: a) increasing the bunch length, b) reducing the slope of the RF wave with a second RF system at a higher frequency, c) low-power longitudinal feedback for first modes (e.g., quadrupole, sextupole, etc; dipole mode will be damped anyway by a mandatory phase locked loop). Such an instability was observed at the SPS [1].

b. Longitudinal microwave instability at 50TeV Also known as "turbulent bunch lengthening", the instability leads to a blow-up of the longitudinal emittance above certain threshold (instead of just distortion of the RF 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 beam loss (see again Ref. [1] for observations in the ISR). The threshold is given by:

$$|Z/n|_{eff} \leq \frac{1}{\sqrt{2\pi}} \frac{h_{RF} U_{RF}}{I_{bunch}} \left(\frac{\sigma_s}{R}\right)^3. \quad (2)$$

Comparison of the impedance estimates and threshold numbers is given below:

	Low Field	High Field
Estimated Im(Z/n)	0.2 Ohm	0.05 Ohm
Threshold TMWI	0.7 Ohm	0.9 Ohm

Again, an increased longitudinal emittance upto 1 eV·sec is used in the estimates. The threshold would be about 0.12 Ohm for $\varepsilon_l = 0.3$ eV·sec, i.e. two times less than the machine impedance in the LF. Therefore, increasing the bunch length would lead to an acceptable safety factor.

c. Transverse mode coupling instability at 3 TeV. Also known as "strong head-tail" (in contrast to "weak head-tail" which is due to chromaticity). Frequencies of coherent bunch motion (mode 0) and head-tail motion (mode 1) are shifted by transverse wide-band impedance toward each other. Above a threshold the frequencies become equal and instability occurs with characteristic growth time of a fraction of synchrotron period.

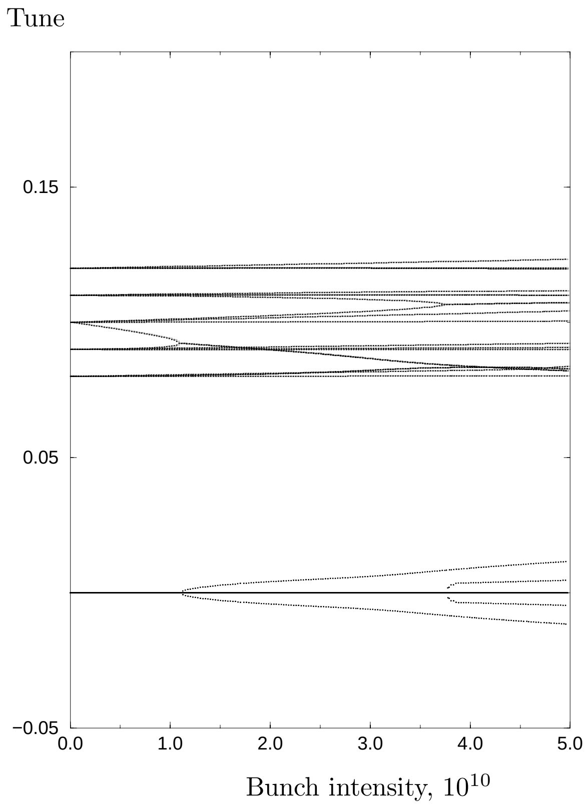

FIG. 1. Eigentunes (vertical axis) versus number of protons per bunch (horizontal axis). The fractional part of the betatron tune is 0.1; upper lines are real part, and lower ones are imaginary part of eigentunes.

Fig.(1) from [2] demonstrates coupling of 0 and -1 azimuthal modes due to resistive wall impedance (simulations).($<\beta>=600$m, $\nu_s = 0.01$, $\sigma_s = 0.1$m, $E = 3$TeV, $C = 550$km; fractional part of the betatron tune $\nu_\beta = 0.1$.)

The TMCI in the LF VLHC is mostly due to RW impedance (>90% contribution) and has a threshold of [2],[T8]:

$$N_p \approx 1.8 \cdot 10^{10} \times$$

$$\times \sqrt{\frac{\sigma_s}{.1\mathtt{m}}} \cdot \frac{E}{3\mathtt{TeV}} \cdot \frac{\nu_s}{0.01} \cdot (\frac{a}{0.9\mathtt{cm}})^3 \cdot \frac{550\mathtt{km}}{C} \cdot \frac{320\mathtt{m}}{<\beta>}, \tag{3}$$

Comparison of the 0th order design number of protons per bunch and the TMCI threshold is given below:

	Low Field	High Field
Protons/bunch, $N_p/10^{10}$	1.5	1.5
TMCI Threshold, $N_p/10^{10}$	1.7	28.

Note, that for HF, most of the impedance (about 90%) does come from bellows, BPMs, RF, kickers, etc., and RW contribution is about 10% only. One can see that the safety factor $S = N_{thr}/N_p \propto 1/\sqrt{L}$ is about 1 in the LF VLHC, i.e., not large enough.

This instability was observed at many electron storage rings (PETRA, PEP, VEPP-4, LEP) which usually tend to increase the synchrotron tune ν_s in order to increase the TMCI threshold. To date there is no solid evidence of the "strong-head tail" instability in proton machines [4]. For example, the Tevatron resistive wall broadband impedance contributes about 0.8 MΩ/m to the transverse impedance. A detailed estimate of the impedance made by K.Y.Ng [6] gives a *total* transverse impedance about 3-4 times larger. There is some experimental evidence of the longitudinal broadband impedance as large as $(Z/n)^{TeV} \sim 10\Omega$ [7]. From that, one can estimate the transverse broadband impedance as $Z_\perp = 2R(Z/n)/a^2 = 10\,M\Omega$/m. For the given spread of the impedance of (3-10) MΩ/m we get the threshold bunch populations of $N_{th}^{TeV} = (12 - 3.7) \cdot 10^{11}$. Since maximum number of protons per bunch in the Tevatron to date has not exceeded $3.3 \cdot 10^{11}$, the Tevatron intensity is below the threshold.

However, it is expected the proton TMCI will be important at injection into the SPS, when it works with LHC parameters and in the VLHC.

d. Ways to increase the TMCI threshold. There are "trivial" ideas of increasing the TMCI threshold by decreasing C, or increasing aperture a, injection energy E_{inj} or bunch length σ_s. Unfortunately, most of these parameters are fixed or approximately fixed (see discussion in Section II above). A smaller beta function $< \beta >$ and larger synchrotron tune can help, too - see Eq.3 - but may cause a significant cost increase (more quadrupoles, more powerful RF system).

Less obvious and more interesting approaches are listed below:

method	potential threshold increase
coalescing at 50 TeV	2...9
thin Cu, Ag coating	$\simeq 1.3$
asymmetric beam pipe	1.5...3
RF quadrupole	2...4
AC chromaticity	$\simeq 10$
Feedback system	2...5...(more?)

Let us consider these techniques:

- Instead of injection into every 9th RF bucket (if $f_{RF} = 477MHz = 9 \cdot f_{MIRF}$), one can fill more buckets and thus, reduce the single bunch intensity (up to) 9 times. Of course, after acceleration to the top energy of 50 TeV one needs to coalesce every 9 bunches into one in order to get the design luminosity. To be effective, the coalescing process must not cause a significant increase in transverse emittance (while the longitudinal emittance requirement is not strong - see discussion in Section II). The technique is routinely used in the Tevatron collider injector chain.

- The use of thin coating of conducting material with conductivity better than Al alloy can help as $N_{thr} \propto \sqrt{conductivity}$. For example, 10 μm layer of copper or silver (2-3 times corresponding skin-depth at bunch frequencies of about 3 GHz) will give a 30-40% threshold increase.

- Recently, it was demonstrated in Ref. [11], that the absence of axial symmetry of the beam pipe leads to the appearance of an additional wake-force component which is proportional to the coordinate of the trailing particle in the bunch (while in axisymmetric structures, the force has a component which is proportional to the leading particle coordinate only). As a result, betatron oscillation frequencies of the head and tail of the bunch become unequal, and such a detuning leads to an increase of the TMCI threshold. Results of computer simulations [T8] have shown that, for example, in a flat beam chamber geometry with half-gap a, one can expect threshold increase of the order of 3-3.5 with respect to a round beam pipe with radius a (that factor consists of factor of 2 in geometrical wake reduction and about 1.5-1.75 of improvement due to detuning wake effect). However, it may be that the transverse coupled-bunch instability would require a round vacuum chamber, i.e., in contradiction with the TMCI consideration. Further studies and numerical simulations of the detuning wakes in elliptic chambers are under way.

- One more opportunity to counteract effectively the TMCI was considered recently in Ref. [10]. Introduction of a correlated tune spread from head to tail of the bunch using RF quadrupoles has shown significant increase of the threshold if the spread is several times the synchrotron tune ν_s. The idea is similar to the BNS-damping in linear electron-positron colliders which was experimentally proven as an effective way to counteract beam break-up in SLAC Linear Collider. Figure 2 below shows an increase of the TMCI threshold in the LF VLHC driven by resistive wall wake with a head-tail tune spread generated by an RF quadrupole [T8]:

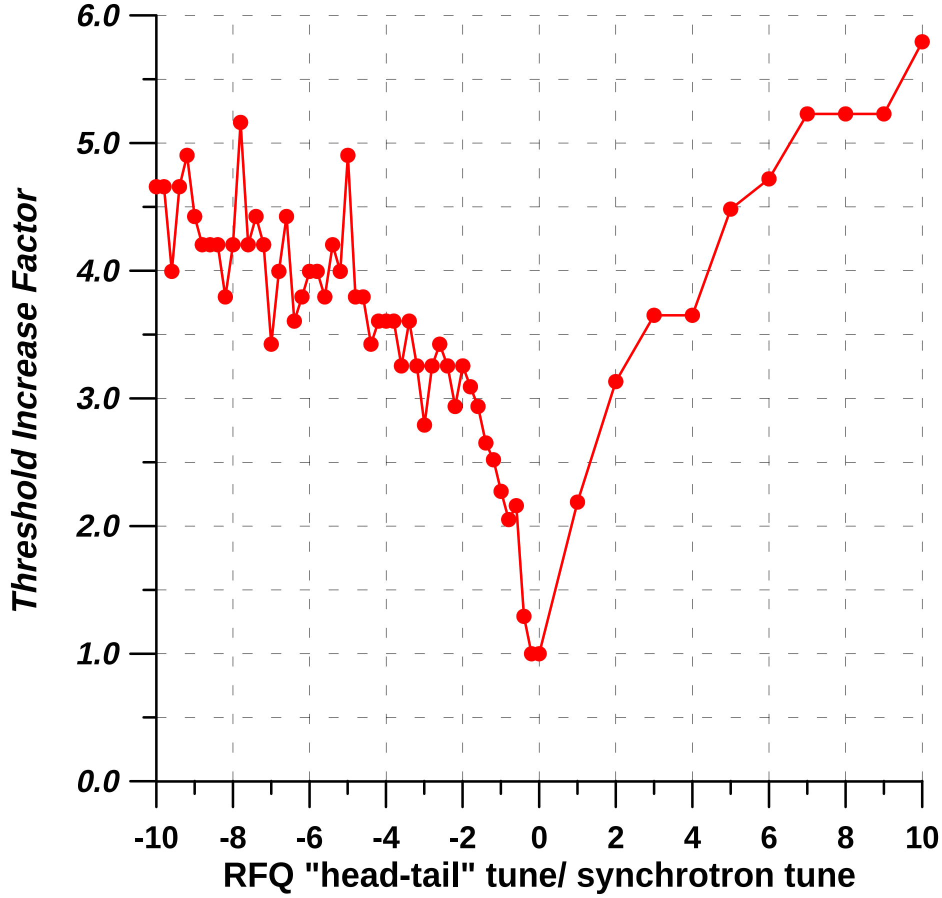

FIG. 2. The TMCI threshold vs RF quadrupole tune spread parameter $\Delta\nu_{RFQ}(1 \cdot \sigma_s)/\nu_s)$.

The RF quadrupole for the VLHC seems to be a rather feasible technique as it requires only 20 m of superconducting RF cavities (or about 50 m of copper cavities) with a quadrupole mode excited. A major concern of the technique is that beam footprint due to RFQ induced incoherent tune spread can be too large to tolerate.

- a similar effect can be obtained by increasing lattice chromaticity ξ. It was suggested in [12] to have time-variable chromaticity $\xi = (\Delta nu/\nu)/(\Delta p/p)$ in the ring:

$$\xi(s) = \xi_0 + \xi_1 * sin(\omega_s s/c). \tag{4}$$

It is demonstrated that the AC scheme not only provides damping of the weak head-tail instability but also increases the TMCI threshold due to Landau damping and rotation of the head-tail phase. Possible TMCI threshold increase is given by

$$N_{thr}/N_{thr}(\xi_1 = 0) \simeq 1 + 0.6 \cdot \xi_1 \nu (\delta p/p)/\nu_s. \tag{5}$$

E.g., for parameters of the LF VLHC with $\xi_1 = 2$ (i.e., AC chromaticity about twice the natural one) we get the threshold increase at injection of about 9. As with the RF quadrupole, foreseeable limitation would be reduction of dynamic aperture due to resonances. There is the possibility to reduce resonance excitation with very fast chromaticity modulation when different parts of the ring have different but constant in time $\xi(s)$ [13].

- There were several attempts in the past to increase the TMCI threshold with use of a feedback system. A resistive feedback doubles the threshold in PEP (see [8] and references therein) and in VEPP-4M storage rings [9]. Relevant VLHC parameters (bunch length, synchrotron tune) are close to the VEPP-4M parameters. So, it can be assumed, that conventional feedback has to help at VLHC, as it does at the VEPP-4M collider.

  Special kind of the "head-tail" feedback to damp the TMCI was considered recently [5],[T8]. Essentially, it is based on high-frequency pick-up(s) and kicker(s) which allow to distinguish "head-tail" motion (azimuthal modes) of portions of 10 cm long bunches (rms). After amplification, one turn delay and 90^o betatron phase adjustment, the signal goes into the kicker, that results in the mode "-1" suppression. The tune shift of mode "0" is suppressed by conventional resistive/reactive feedback system, and as the result, the mode coupling takes place at larger N_{thr}. Though preliminary results are very promising [T8], the method needs more analytical and numerical studies.

  Generally speaking, the threshold increase factors for the different methods listed above can not be multiplied, e.g., RF quadrupole can not provide too much TMCI damping in addition to the AC chromaticity scheme if the latter is implemented and generates the maximum allowable tune spread. Nevertheless, a combination of two or three appropriate methods can give safety factors in LF VLHC of the order of $S \simeq 6-20$ (note, that $L \propto S^2$).

e. Coupled-bunch instability at 3TeV This effect is proportional to the total beam current and is driven by the low-frequency transverse impedance due to finite conductivity of the beam pipe walls. Instability growth time can be expressed in number of turns:

$$N^{RW} \equiv \tau_{RW} \cdot f_0 = \frac{\sqrt{2\pi}(E_p/e)a^3}{I_B Z_0 < \beta >}\sqrt{\frac{\Delta\nu\sigma_{Al}}{cR^3}}. \quad (6)$$

Rough estimates of N^{RW} at the injection energy of 3TeV are given below:

	Low Field	High Field
Mean beam current, I_B, mA	127	127
RW coupled-bunch increment N^{RW}, turns	0.4	180

At first glance, these numbers look somewhat scary especially in the LF option. Nevertheless, taking into account that 0.4 turns is equal to approximately 200 km of the ring circumference, we concluded that such increments can be (easily) damped with use of distributed feedback systems as proposed in [T5]. A general view of the system is presented in Fig.3. The system is based on the installation of several, e.g., 10, separate feedback systems around the ring. Each of the feedback systems provide strong damping of low-frequency coupled-bunch modes (bandwidth of 100-200 kHz) by transmitting a pick-up signal to the kicker via coaxial cable. Naturally, the signal propagates slower than protons in the ring and, therefore, the kick is applied to succeeding bunches. For example, using foam cable with $\beta \simeq 0.8$ to transmit signal over 500 m (that corresponds to 90^o phase advance between pickup and kicker), the system will introduce a delay of about $(1-\beta)\cdot 500 = 100$m. The latter is much less than the lowest mode wavelength of about $\Delta\nu \cdot C \simeq 200$ km, thus, the relevant phase shift is very small $\phi = 100m/200km = 5\cdot 10^{-4}$rad and will not affect the feedback operation. Of course, it will not be true for higher order coupled-bunch modes with frequencies $f_n = |\nu - n| f_0$ above 200-300kHz, and one have to take care of these modes with use of additional standard one-turn-delay feedback system with lower gain (the instability growth time $N^{RW} \propto \sqrt{f_n}$), like one which successfully works at the ALS [T1].

There is also a possibility to increase N^{RW} by changing the LF VLHC parameters: for example, if one reduces β^* from 50 cm to 10 cm (5 times), average beta-function from $< \beta >= 400$m to 200 m (2 times), then the instability growth time can be increased 10 times to $N^{RW} = 4$ turns. Correspondingly, the instability can be damped with a smaller total number of the feedback sub-systems.

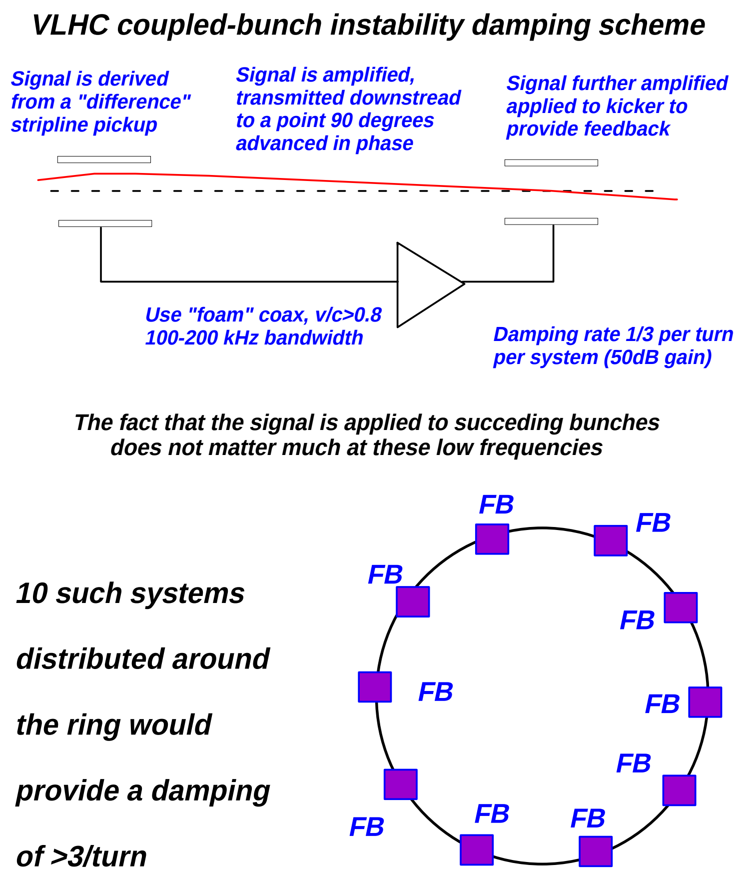

FIG. 3. System to damp resistive walls coupled-bunch instability.

B. Emittance growth

Turn-to-turn dipole magnetic field fluctuations and vibration of quadrupole magnets are of concern, because they can excite coherent beam motion. If the motion is not corrected over *decoherence time* of about $1/\xi_{beam-beam} \approx 1000$ turns, than the coherent motion will be transfered into transverse emittance increase and can cause substantial emittance growth over the characteristic beam life-time (at top energy, of course). One can see from the table, that the characteristic time interval τ_L is about 10 hours in LF and 2.6 hours in HF VLHC:

Process	Low Field	High Field
Inelastic beam-gas growth time	6 months	6 months
Transverse IBS growth time	6 months	2 days
Luminosity "burn-out" time	300 hrs	54 hrs
Transverse SR damping time	81 hrs	2.6 hrs
Store duration	10 hrs	20 hrs
Characteristic time τ_L	10 hrs	2.6 hrs

If one requires that the transverse emittance growth is less than 10% over the time τ_L then one get following tolerances on δX and $(\delta B/B)$ *at betatron frequency* f_β:

	Low Field	High Field
Betatron frequency, $f_\beta = f_0 \Delta\nu$, Hz	80-160	0.6-1.2 kHz
Quadrupole vibration, rms δX, μm	$1.2 \cdot 10^{-4}$	$3 \cdot 10^{-4}$
Field fluctuations, $(\delta B/B)$, rms	$2.3 \cdot 10^{-10}$	$0.7 \cdot 10^{-10}$

These estimates have been made assuming simple separated function FODO lattices, while a lattice with combined function magnets (as planned for LF) can ease the tolerances up to factor of 3 (details can be found in [14]).

Extensive experimental studies of high-frequency vibrations have been performed at the Fermilab site and in several deep tunnels in the Illinois dolomite [15]. From these data, one can conclude that the measured vibrations in deep tunnels are smaller than the tolerances for both LF and HF options, while cultural noise level in the Tevatron tunnel is several times above the VLHC tolerances. The cure exists: one has to damp excitation of the coherent beam oscillations with use of a feedback system faster than the decoherence time (see references in [14]). The low frequency, coupled bunch mode damper system discussed in Section III would provide adequate damping. Figure 4 demonstrates **computer simulated** emittance growth in the LF VLHC due to **measured** Tevatron quadrupole vibrations and the suppression with a feedback system [15].

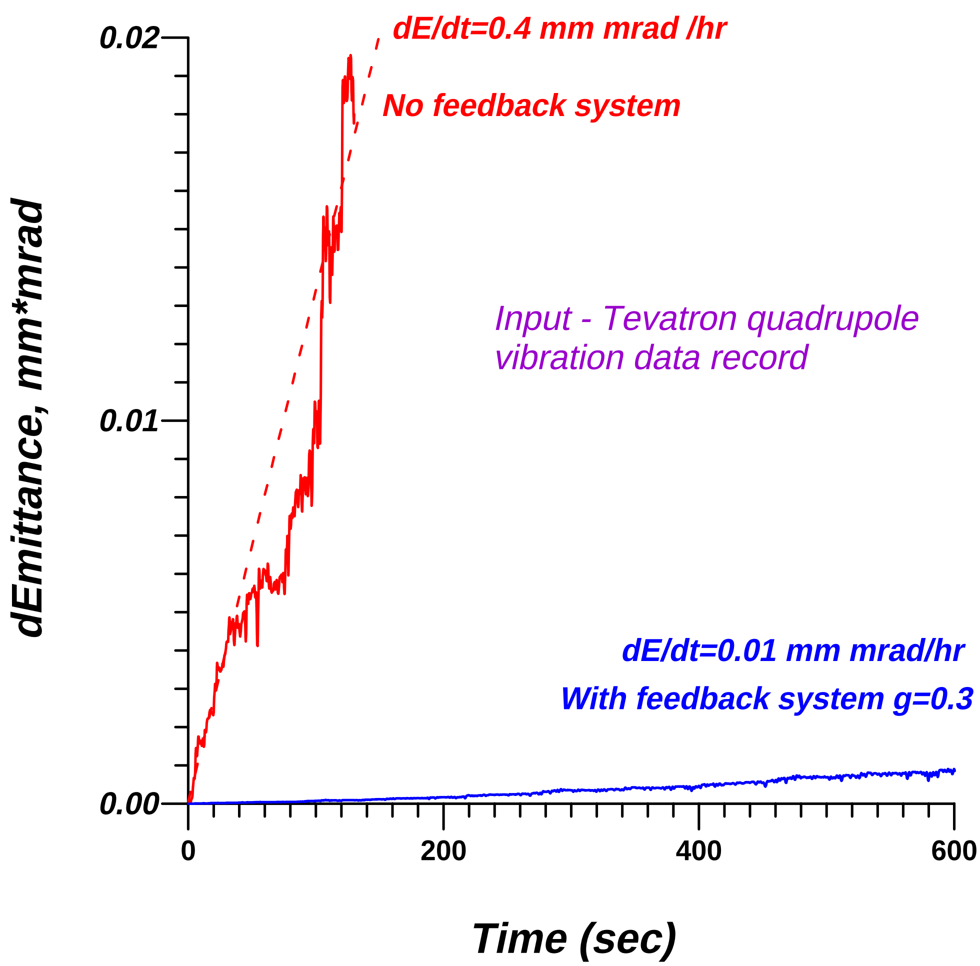

FIG. 4. Transverse normilized emittance growth in the VLHC (simulation) without and with a feedback system. Measured Tevatron quadrupole vibration record is taken as input for the simulation.

Currently, most of the concern comes from the lack of experimental data on magnetic field fluctuations in dipole magnets. The problem is that the ability of the feedback system to reduce the emittance growth rate is limited and in the case of very strong external noises, the machine still may suffer from too fast emittance growth.

C. Feedback systems

A list of FB systems which may be necessary to implement in the VLHC is presented below:

	System	Comments
System 1	FB to damp resistive wall coupled bunch and injection errors	high gain narrow band 100-200 kHz
System 2	Damping of high frequency bunch-to-bunch modes	one turn delay 26 MHz bandwidth (MI RF/2)
System 3	TMCI feedback 3a) to damp mode 0 3b) to damp mode 1	small gain 26 MHz bandwidth 3GHz carrier frequency 26 MHz band
System 4	FB to suppress emittance growth	moderate gain 5kHz bandwidth (26MHz?)
System 5	Longitudinal feedback	

Note, that the same hardware can be used for System 1 and System 4.

IV. R&D OPPORTUNITIES

There are several R&D opportunities discussed at the Workshop:

1. TMCI studies:

   - The question why the TMCI has not been observed at the proton machines should be studied in detail. In particular, we propose a measurement of the tune shift vs bunch intensity at the Tevatron. Existing data on the weak head-tail instability (due to chromaticity) at the Tevatron can be analyzed in order to get an estimate of the transverse impedance of the ring.
   - The TMCI can be intentionally excited by controlled increase of the Tevatron impedance due to an electron beam (an R&D project on beam-beam compensation at the Tevatron is under way, the beam of electrons will be used to improve antiproton dynamics [16]). Wake fields due to the electron beam can cause the instability if the solenoid magnetic field is less than some threshold value (of the order of 17 kG) [17].
   - Detuning wake studies can include a) simulation of the detuning wakes in realistic geometry with available codes, like TBCI, ABCI; b) on-bench measurements of the detuning wakes excitation by loops(?) at high frequencies in beam-pipe samples; c) detuning wake measurements with use of short intense electron beams (from a photoinjector) traveling in an asymmetric environment (e.g. in between two parallel ceramic plates).
   - The RF quadrupole can be designed, fabricated and tested at an existing electron machine. A good candidate is VEPP-4 (Novosibirsk) where the TMCI limits single bunch intensity, and bunch length and synchrotron frequency are comparable with the VLHC design parameters.
   - Evaluation of different kinds of feedback systems for the TMCI suppression can be done with numerical codes [18], and a prototype feedback system could be built and tested.

2. Coupled-bunch instabilities suppression: the effectiveness of multistage feedback system with small delay (to damp the resistive wall coupled-bunch instability) has to be studied numerically. Experimental studies could concentrate on gain limitations in these systems.

3. External noise studies:

   - While ground vibrations have been thoroughly studies experimentally, there is an urgent need to obtain data on the magnetic field fluctuations. An experimental technique to measure field fluctuations at frequencies from 50 Hz to 1500 Hz with accuracy of about $(\delta B/B) \simeq 10^{-10}$ has to be developed. Noise spectra can be measured in the VLHC prototype magnets, although similar data from reference magnets (e.g. HERA, RHIC, etc.) are of interest, too.
   - The longitudinal emittance evolution model needs data on the RF phase and amplitude jitter. RF noise spectra have been measured and are available [T2]. Some work is necessary to evaluate the longitudinal emittance growth due to these noises.

4. The topics of certain interest for the VLHC RF system are

   - higher order modes (HOMs) in cavities and damping of these modes;
   - power couplers for powers approaching MW.

   Major accelerator labs have already put much effort and funds into these issues, so, a proposal of a separate R&D program does not seem to be appropriate [T2]. At the same time there is need for more detailed analysis of the HOMs effects in the VLHC and specification of HOMs requirements.

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[1] L.Evans, AIP Conf. Proc. 127 (1985).
[2] V.Danilov, V.Shiltsev, Preprint FNAL TM-2042 (1998).
[3] J.Rogers, in *Proceedings of the DPF/DPB Summer Study on New Directions for High Energy Physics* (Snowmass, CO, 1996), unpublished (see "pink book" on VLHC).
[4] S.Peggs, Part. Accel., **50**, 19 (1995).
[5] V.V.Danilov, J.Marriner, V.Shiltsev, simulations of the feedback to damp TMCI presented at the VLHC Workshops (1999).
[6] K.Y.Ng, *Report to the Fermilab Technical Advisory Committee Second Meeting* (unpublished, July 1995).
[7] G.Jackson, private communication (1998).
[8] S.Mayers, in *Proceedings of the 1987 IEEE PAC, Washington, DC* (IEEE, New-York, 1987), p.503.
[9] M.M.Karliner, *et al.*, in *Proceedings of the Fifth European Particle Accelerator Conference, Barcelona, 1996* (Institute of Physics Publishing, Bristol, Philadelphia, 1996).
[10] V.V.Danilov,*Phys. Rev. ST - Accel. Beams,* **1**, 041301 (1998);
Preprint FNAL TM-2033 (1997).
[11] A.Burov, V.Danilov, *Phys. Rev. Letters, vol. 82* (1999), 2286;
FNAL-TM-2050 (1998).
[12] W.H.Cheng, A.M.Sessler, J.S.Wurtele, *Proc. 1997 PAC, Vancouver* (1997), 1614;
Phys. Rev. E, **56**, No.4 (1997), 4695.
[13] V.Shiltsev, A.Burov, private communication.
[14] V.Shiltsev, FNAL-TM-1987 (1996).
[15] B.Baklakov,*et. al, Phys. Rev. ST - Accel. Beams,* **1**, 031001 (1998).
[16] V.Shiltsev, V.Danilov, D.Finley, A.Sery FERMILAB-Pub-98/260 (1998).
[17] A.Burov, V.Danilov, and V.Shiltsev, *Phys. Rev. E*, **59, n.3** (1999); FNAL-Pub-98/195 (1998).
[18] there are different codes written by V.Danilov (multi-mode analysis), V.Shiltsev (macroparticle tracking) and G.Sabbi (TRISIM - beamlets dynamics code).