BEAM INSTABILITIES IN VERY LARGE HADRON COLLIDER

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Abstract

The Very Large Hadron Collider (VLHC) is a superconducting proton-proton collider with approximately 100 TeV cm and approximately $10^{34}\,s^{-1}cm^{-2}$ luminosity [1]. Currently, beam dynamics in this future accelerator is the subject of intensive studies within the framework of the US-wide VLHC R&D program. This presentation summarizes recent developments in the field. Besides general discussion on relevant VLHC parameters, we consider various beam instabilities and ways to avoid them. Finally, we outline possibilities for theoretical and experimental R&D.

1 COLLIDER PARAMETERS

At the energies contemplated, protons and anti-protons behave almost undistinguishably and the VLHC is foreseen as a pp collider. The 150 GeV rapid cycling Fermilab Main Injector produces a beam with the required quality to feed the 3 TeV VLHC Booster accelerator, followed by 50+50 TeV VLHC. The 3 TeV Booster has to be capable of cycling rapidity to fill the VLHC in a reasonable time. The parameters for the machine are not yet all fixed. The amount of freedom varies a lot from parameter to parameter. For example, the beam energy $E_b = 50$ TeV and the collider luminosity $L = 10^{34}\,s^{-1}cm^{-2}$ are fixed *a priori* by physics considerations [2]. The dipole magnetic field $B \approx 2$ T in the case of the low-field (LF) option, and $B = 10-14$ T for the high-field (HF) option 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 the necessity of a synchrotron radiation beam screen. The choice of a significantly affects the magnet cost.

Another approximately fixed parameter is the bunch spacing. The first order assumption is $l_{bb} = 18.9$ ns which is the period of the 53 MHz RF system of the Fermilab Main Injector. Larger l_{bb} would increase the number of inelastic interactions/crossing $n_{int} \propto t_{bb}$ and would give a larger head-on beam-beam tune shift parameter $\xi \propto \sqrt{t_{bb}}$. 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 bunch spacing of 10 ns 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. One has aslo to consider the beta-function at the interaction point as an approximately fixed parameter. These considerations limit the minimum value of β^* to about 15 cm while the maximum value of about 50 cm is determined by the need for high luminosity.

Table 1: 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, $N_p/10^{10}$	0.82	1.5
Total protons, $N_{tot}/10^{15}$	1.5	0.5
Tune, ν,	533.765	37.385
Slip factor, $\eta/10^{-5}$	0.4	72
No. half cells,	4200	350
1/2-cell length, L_{cell}, m	122	260
Phase/cell, μ, deg	90	60
Average beta, $<\beta>$, m	246	600
Max dispersion, D_x, m	0.5	23
Pipe 1/2 size, a, mm	9	16.5
RMS emittance, $\varepsilon_n,\ 10^{-6}\,m$	1.0	2.5
Long. emitt.(rms), ε_L, eV·sec	2	0.3
Mean beam current, I_B, mA	69	127
SR loss/turn, E_{SR}, MeV	0.6	3.4
Long. damping time, τ_l, hrs	40.4	1.3
RF frequency, f_{RF}, MHz	477	477
RF harmonic number, h_{RF}	8.28·10^5	1.5·10^5
RF voltage (inj), U_{RF}, MV	4(200)	7(40)
Acceleration time, T_{acc}, min	13	13
Bucket area (inj), A, eV·sec	18(31)	4(2.2)
Synchr. tune (inj), $\nu_s/10^{-3}$	0.2(5)	1 (14)
Bunch length (inj), σ_s, cm	7.6(5.5)	5.6(7.2)
Mom.spread (inj), $(\frac{\delta P}{P})/10^{-5}$	3.5 (100)	0.9 (9.1)
IP focus, β^*, cm	15	50
Head-on b.b. tune shift, ξ	0.001	0.0007
Int./crossing (max) n_{int}	24.7	31
Vertices/mm, $n_{int}/\sqrt{\sqrt{2}\pi\sigma_s}$	0.16	0.26

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 collider energy depends on the choice of B, e.g., the HF option is less dependent on the injection emittance because of synchrotron radiation damping.

RF frequency f_{RF} also is "an approximately free parameter". To make synchronization and injection easier, the frequency should be a multiple of the FNAL Main Injector RF frequency of 53 MHz. Multi MV 477 MHz (=9×53 MHz) superconducting RF is considered for the VLHC [3].

Longitudinal emittance ε_L and the lattice are thought to be free parameters. 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 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. On the other hand, choice of the lattice must be done taking into account many other physical considerations as well as cost saving arguments. Table 1 presents the VLHC 0^{th} order parameter list that is used for further analysis of instabilities.

2 BEAM 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 the low-field or high-field VLHC. Even at the current status of accelerator physics and technology there appear to be enough tools to damp/eliminate all of the instabilities.**

Transverse mode coupling instability at 3 TeV. This is 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 the 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 a synchrotron period.

TMCI in the LF VLHC is mostly due to RW impedance (>90% contribution) and has a threshold of [5]:

$$N_{thr} \approx 1.24 \cdot 10^{10} \times$$

$$\times \sqrt{\frac{\sigma_s}{.1\mathtt{m}}} \cdot \frac{E}{3\mathtt{TeV}} \cdot \frac{\nu_s}{0.005} \cdot \left(\frac{a}{0.9\mathtt{cm}}\right)^3 \cdot \frac{520\mathtt{km}}{C} \cdot \frac{250\mathtt{m}}{<\beta>}. \quad (1)$$

Fig.1 demonstrates coupling of 0 and -1 azimuthal modes due to resistive wall wake $W_1(s) = -2C/\pi a^3 \cdot \sqrt{c/\sigma s}$ in the low-field VLHC. Five azimuthal modes and four radial modes are taking into account. The presented multimode analysis (see details in [5]). shows that above $N_p = 1.8 \cdot 10^{10}$ a positive imaginary part of the eigenfrequency appears (see lines marked by), that corresponds to unstable motion. Paramters of simulations are $<\beta>= 320$m, $\nu_s = 0.01$, $\sigma_s = 0.1$m, $E = 3$TeV, $C = 550$km, and round Al vacuum pipe with radius $a = 9$ mm is considered.

Comparison of the number of protons per bunch from Table 1 and the TMCI threshold is given below:

	Low Field	High Field
Protons/bunch, $N_p/10^{10}$	0.82	1.5
TMCI Threshold, $N_{thr}/10^{10}$	1.1	28.

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

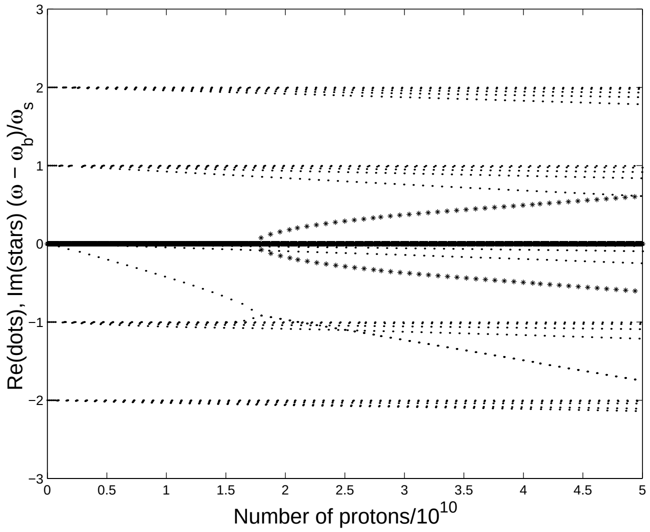

Figure 1: Beam eigenfrequencies vs. number of protons per bunch. Dots are for real part of frequency, stars are for imaginary part.

This instability was observed at many electron storage rings (PETRA, PEP, VEPP-4, LEP) which usually 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. For example, there is a large spread of the Tevatron transverse broadband impedance estimates $Z_\perp = (3-10)$ MΩ/m (the resistive wall contributes about 0.8 MΩ/m) [5]. That yields threshold bunch populations of $N_{th}^{TeV} = (12 - 3.7) \cdot 10^{11}$. Since the 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. It is expected the proton TMCI will be important at injection into the SPS, when it works with LHC parameters [6] and in the VLHC.

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. A smaller beta function $<\beta>$ and larger synchrotron tune can help, see Eq.1, but may cause a significant cost increase (more quadrupoles, more powerful RF system). Less obvious and more interesting approaches are:

method	threshold increase
coalescing at 50 TeV	2-9
thin Cu, Ag coating	$\simeq 1.3$
asymmetric beam pipe	1.5-3
RF quadrupole	4
AC chromaticity	$\simeq$10
Feedback system	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 above). The technique is routinely used in the Tevatron collider injector chain.

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

Recently, it was demonstrated in Ref.[9], 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. For example, in a flat beam chamber geometry with half-gap a, one can expect a threshold increase of the order of 3-3.5 with respect to a round beam pipe with radius a (that factor consists of a factor of 2 in geometrical wake reduction and about 1.5-1.75 of improvement due to the detuning wake effect). However, it may be that the transverse coupled-bunch instability would require a round vacuum chamber, i.e., in contradiction to the TMCI consideration. Further studies and numerical simulations of the detuning wakes in elliptic chambers are under way.

One more opportunity to counteract effectively TMCI was considered recently in Ref.[10]. Introduction of a correlated tune spread from the head to the tail of the bunch using RF quadrupoles has shown a significant increase of the threshold if the spread is several times the synchrotron tune ν_s. The idea is similar to BNS-damping in linear electron-positron colliders which was experimentally proven as an effective way to counteract beam break-up in the 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. 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 is that the beam footprint due to RFQ induced incoherent tune spread can be too large to tolerate.

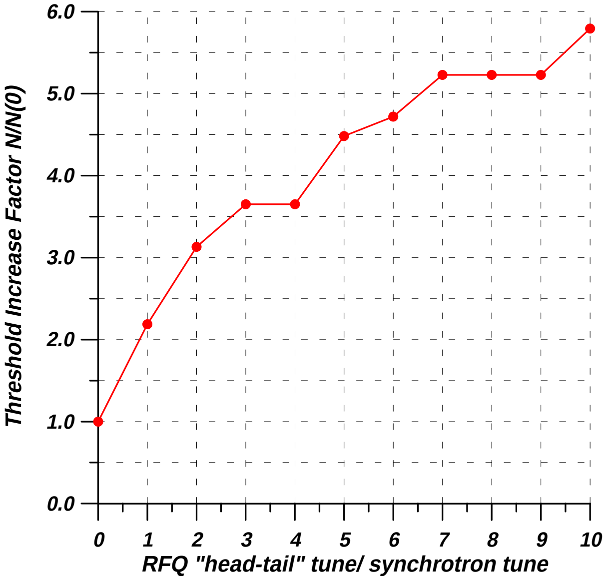

Figure 2: The TMCI threshold vs RF quadrupole tune spread parameter $\left(\frac{\Delta\nu_{RFQ}(1\cdot\sigma_s)}{\nu_s}\right)$.

A similar effect can be obtained by increasing lattice chromaticity ξ. It was suggested in [11] to have a time-variable chromaticity $\xi = (\Delta\nu/\nu)/(\Delta p/p)$ in the ring:

$$\xi(s) = \xi_0 + \xi_1 * sin(\omega_s s/c). \qquad (2)$$

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

$$N_{thr}/N_{thr}(\xi_1 = 0) \simeq 1 + 0.6 \cdot \xi_1 \nu(\delta p/p)/\nu_s. \qquad (3)$$

E.g., for parameters of the LF VLHC with $\xi_1 = 2$ (i.e., AC chromaticity about twice the natural one) we get a threshold increase at injection of about 9. As with the RF quadrupole, a 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 $\xi(s)$.

The TMCI threshold can be increased with use of a feedback system. Resistive feedback doubles the threshold in PEP (see [7] and references therein) and in the VEPP-4M storage rings [8]. 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.

A special kind of the “head-tail” feedback can further increase the TMCI threshold. Essentially, it is based on high-frequency pick-up(s) and kicker(s) which distinguishing “head-tail” motion (azimuthal modes) or 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 mode “-1” suppression. The tune shift of mode “0” is suppressed by a conventional resistive/reactive feedback system, and as a result, the mode coupling takes place at larger N_{thr}. Though preliminary results are very promising (4-10 times threshold increase), 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 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 $S \simeq 6-20$ (which corresponds to a luminosity enhancement of S^2).

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

$$N^{RW} \equiv \tau_{RW}\cdot f_0 = \frac{\sqrt{2\pi}(E_p/e)a^3}{I_B Z_0 < \beta >}\sqrt{\frac{\Delta\nu\sigma_{Al}}{cR^3}}. \tag{4}$$

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

	Low Field	High Field
Mean beam current, I_B, mA	69	127
Risetime N^{RW}, turns	1.5	180

At first glance, these numbers look somewhat scary especially in the LF option. Nevertheless, taking into account that one turn is equal to approximately 500 km of the ring circumference, we conclud that such increments can be (easily) damped with use of distributed feedback systems. 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 the signal over 500 m (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 200-300 kHz, and one has to take care of these modes with the use of an additional standard one-turn-delay feedback system with lower gain (the instability growth time $N^{RW} \propto \sqrt{f_n}$).

Electron cloud instability at 50TeV 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 transverse multi-bunch instability. The instability growth time can be estimated as [14]:

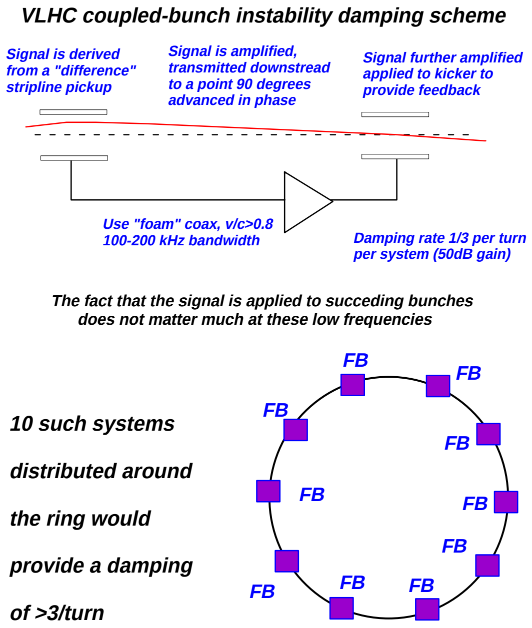

Figure 3: Principle of the VLHC resistive wall coupled bunch instability damper.

$$\tau \approx \frac{4\pi\gamma\nu}{N_p r_p c W_1(l_{bb})}, \tag{5}$$

where $W_1(l_{bb})$ is the transverse wake due to electrons. Only a few neighboring bunches can interact via the cloud. Eq.(5) gives $\tau \approx 10-15$ s for LF and about 0.5 s (1600 turns) for HF. In HF the instability is stronger than the resistive wall instability at 50 TeV and has to be damped by a bunch-by-bunch feedback system.

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. This leads to an upper limit for the impedance:

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

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 the 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 [4]. 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	0.4 Ohm	0.4 Ohm

The VLHC intensity is below threshold in both cases. Note that the longitudinal emittance $\varepsilon_l = 2$ eV·s for the LF case [1] and $\varepsilon_l = 0.3$ eV·s for the HF case.

Longitudinal microwave instability at 50 TeV Also known as "turbulent bunch lengthening", the instability leads to a blow-up of the longitudinal emittance above a 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 Ref. [4] for observations in the ISR). The threshold is given by:

$$|Z/n|_{eff} \leq \frac{1}{\sqrt{2\pi}} \frac{h_{RF} U_{RF}}{I_{bunch}} \left(\frac{\sigma_s}{R}\right)^3. \qquad (7)$$

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

	Low Field	High Field
Estimated $\|Z/n\|$	0.2 Ohm	0.05 Ohm
Threshold TMWI	1.4 Ohm	0.9 Ohm

Again, the longitudinal emittance of 2 eV·sec in the LF case leads to an acceptable safety factor. The threshold would be about 0.2 Ohm in LF for $\varepsilon_l = 0.5$ eV·sec, i.e. close to the machine impedance.

Feedback systems There are several feedback systems to be implement in the VLHC:

- transverse narrow band system (100-200 kHz) to damp resistive wall coupled bunch modes, injection errors, and the emittance growth;
- transverse one turn delay 26 MHz bandwidth feedback system for damping high frequency bunch-to-bunch modes and mode 0 of single bunch motion;
- transverse very wide band (3GHz) feedback is needed to damp the first head-tail mode of the single bunch motion;
- longitudinal feedback.

3 R&D OPPORTUNITIES

The question why TMCI has not been observed at 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.

TMCI can be intentionally excited by a controlled increase of the Tevatron impedance due to "an electron lens" being constructed for beam-beam compensation in the Tevatron [12]. 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) [13].

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 wake excitation at high frequencies in beam pipes; 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).

An RF quadrupole can be designed, fabricated and tested at an existing electron machine. A good candidate is VEPP-4M (Novosibirsk, Russia) where 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 TMCI suppression can be done with numerical codes, and a prototype feedback system could be built and tested.

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. Another subject of studies can be the detuning wake effect on the coupled bunch instability in the VLHC.

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[1] the Main Injector can provide beams with smaller longitudinal emittance, e.g., $\varepsilon_l = 0.5$ eV·s, that would lead to the threshold as low as 0.01 Ohm that is 10 times less than the machine impedance in the LF.