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Collective Effects and Impedances in the RLHC(s)[*]

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ABSTRACT

We estimate coupling impedances and collective instability thresholds for the high- and low-field options for the 50 TeV on 50 TeV Really Large Hadron Colliders discussed at the 1996 Snowmass workshop. Because of the large circumference of these machines, transverse instabilities tend to be dominant. The challenges for the high-field machine are similar in kind and magnitude to those faced by the LHC, and are expected to be solved at the LHC. The low-field machine faces new challenges. Because of its warm, small radius aluminum beampipe and large circumference, there is a large broadband resistive wall impedance which must be controlled to avoid the transverse mode coupling instability. A new set of low-field RLHC parameters was produced by the RLHC working group to avoid this instability. Both the high- and low-field machines require transverse feedback to stabilize the beam against a multibunch resistive wall instability. The resistive wall risetime is less than one turn for the low-field machine, which will require a feedback system based on yet-to-be-developed technology.

I. INTRODUCTION

An impedance working group [1,2] within the Really Large Hadron Collider subgroup examined collective stability issues for both the high- and low-field options for the RLHC. Our intention was to estimate the impedance of these machines, to identify the dominant instabilities, and to calculate the thresholds for these instabilities. In making these estimates, we found that the original parameters for the low-field option would not provide stability against transverse mode-coupling, which prompted a change of parameters for this machine [3]. We also examined the scaling of stability thresholds vs. half-cell length, to understand whether the reductions in cost achieved by maximizing the half-cell length in the high-field machine had negative consequences for stability.

The machine parameters relevant to collective stability are listed below. These values are taken or derived from the "Snowmass parameter set" refined at the workshop and listed in the RLHC Working Group Summary [4]. Only the 50 TeV beam energy machines are considered. The high field machine considered is the version based on 9.5 T dipole magnets. Instability thresholds discussed here apply to beams at injection energy, where the thresholds are lowest. During the Snowmass workshop the injection energy of the machines under discussion was raised from 1 TeV to 3 TeV, which is favorable for collective stability.

Table I: RLHC partial parameter list.

Parameter	Units	LHC	High field	Low field
Beam energy	TeV	7	50	50
Injection energy	TeV	0.45	3	3
R (radius)	m	4255	21960	102800
L (half-cell length)	m	50	200	300
$<\beta>$	m	71	255	382
slip factor	10^{-6}	224	134	13.8
RF frequency	MHz	400	360	360
V'_{RF}	MV/m	67.1	755	755
V_{RF}	MV	8	100	100
Q_s (injection)		0.0048	0.0109	0.0075
σ_s (injection)	cm	12.9	2.86	4.29
h_{RF} (harmonic num)		35640	165132	775440
I_{beam}	A	0.6	0.05	0.09
N_{bunches}		3565	27522	129240
I_{bunch}	μA	168	1.8	0.70

II. IMPEDANCE MODEL

A. High-field option

The vacuum chamber of the high-field RLHC was assumed to be similar to that of the LHC, for which good impedance estimates are available. Because of the synchrotron radiation heat load, a cooled perforated beampipe liner is needed. The broadband impedance from the sliding joints, beam monitors, liner slots, and surface resistance were simply scaled by the number of vacuum chamber components from the LHC values, assuming that the number of components per half-cell is the same.

B. Low-field option

1. Vacuum chamber

The vacuum chamber of the low-field RLHC is forseen to be a room temperature aluminum extrusion with a pumping antechamber, very similar in cross section to

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chambers in electron storage rings. The extrusion is of high strength, high resistivity alloy with a 1 mm inner layer of high purity aluminum to minimize the surface resistance [5]. The beampipe is to assembled by welding and would be rigidly clamped at short intervals to prevent it from squirming during a mild bake, so that no (or very few) sliding joints are required. Only the ends of the pumping slots contribute to the impedance, so if these slots are nearly continuous, their impedance is negligible. The resistivities of the high-purity and high-resistivity alloy layers are 2.7×10^{-8} and 5.7×10^{-8} Ω m [6], respectively. The planned half-aperture of the beampipe was increased to 9 mm to reduce the broadband resistive wall impedance.

The low-field RLHC impedance was estimated by direct calculation of the resistive-wall impedance (as described in the next section) and by scaling the LHC beam monitor impedance with the number of half-cells in the machine. The longitudinal and transverse impedance estimates for the RLHCs are tabulated in Tables II and III.

Table II: RLHC longitudinal impedance model (*Z/n*).

Element	Units	LHC	High field	Low field
Sliding joints	Ω	0.081	0.020	
Beam monitors	Ω	0.040	0.010	0.007
Pumping slots	Ω	0.016	0.004	
Total *Z/n*	Ω	0.137	0.034	0.007

Table III: RLHC transverse impedance model.

Element	Units	LHC	High field	Low field
Sliding joints	MΩ/m	2.06	2.66	
Beam monitors	MΩ/m	3.03	3.90	12.2
Pumping slots	MΩ/m	0.55	0.71	
Resistive wall	MΩ/m	0.058	0.075	132
Total *Z*	MΩ/m	5.70	7.35	144

2. Resistive wall impedance

Calculation of the transverse impedance at the lowest betatron frequencies is complicated by the fact that the skin depth at those frequencies ($\omega_\beta \approx 4.5\times10^4$ s^{-1}) exceeds the chamber thickness. For $\omega_\beta << 4.5\times10^4$ s^{-1}, the transverse impedance is actually determined by the iron pole face, and the reactive part becomes capacitive rather than inductive.

The transverse broadband impedance in the low-field machine is, surprisingly, dominated by the resistive wall impedance $Z_\mathrm{T}^\mathrm{RW}(\omega)$, even though it peaks at zero frequency, and falls as $\omega^{-1/2}$. An estimate of the effective broadband impedance is obtained by evaluating $Z_\mathrm{T}^\mathrm{RW}(\omega)$ at $\omega = 1/\sigma_t$ [7]. A better estimate is made by integrating $Z_\mathrm{T}^\mathrm{RW}(\omega)$ over the beam spectrum. One then finds that

$$\begin{aligned}\mathrm{Im}\left(Z_\mathrm{T}^\mathrm{RW}\right)_{eff} &= \frac{\Gamma(1/4)}{\sqrt{\pi}}\,\mathrm{Im}\left[Z_\mathrm{T}^\mathrm{RW}\left(\omega = 1/\sigma_t\right)\right] \\ &= 2.05\,\mathrm{Im}\left[Z_\mathrm{T}^\mathrm{RW}\left(\omega = 1/\sigma_t\right)\right]\end{aligned} \tag{1}$$

This integration is insensitive to the fact the the skin depth is larger that the chamber thickness at the lowest betatron frequencies, because the chief contribution to the integral comes from frequencies where the skin depth is much less than the thickness of the high-purity aluminum layer.

III. MULTIBUNCH INSTABILITIES

A. Resitive wall instability

The most severe multibunch instability for the RLHCs will be the transverse resistive wall instability. This is a consequence of the very long, small-radius chambers common to both machines. For the high-field machine, the transverse resistive-wall risetime (in turns) is greater than that of the LHC, and is long enough to control comfortably with active feedback. In the case of the low-field machine, the high resistivity of the room temperature chamber produces a very fast risetime which must be controlled by a feedback system that is beyond the present state-of-the-art. Table IV shows the resistive wall growth rates taken from the RLHC Working Group Summary [4].

Table IV: Resistive wall risetimes.

Units	LHC	High field	Low field
turns	295	310	0.36

IV. SINGLE BUNCH INSTABILITIES

A. Coherent synchrotron tune shift

We identified the loss of Landau damping from a coherent tune shift, the longitudinal microwave instability, and the transverse mode coupling instability as the most serious instability mechanisms in the RLHCs.

The synchrotron tune shift must remain smaller than the synchrotron tune spread to preserve longitudinal Landau damping. This requirement leads to the inequality:

$$\mathrm{Im}\left(\frac{Z_\mathrm{L}}{n}\right)_{eff} \le \frac{6}{\pi^3}\frac{h_\mathrm{RF}^3 V_\mathrm{RF}}{I_b}\left(\frac{\sigma_s}{R}\right)^5 \tag{2}$$

B. Longitudinal microwave instability

The condition for stability against the longitudinal microwave instability is given by:

$$\left|\left(\frac{Z_\mathrm{L}}{n}\right)_{eff}\right| \le \frac{12}{\pi^3}\frac{h_\mathrm{RF} V_\mathrm{RF}}{I_b}\left(\frac{\sigma_s}{R}\right)^3 \tag{3}$$

The longitudinal single-bunch instability thresholds for the RLHCs, in terms of the effective longitudinal impedance

Z/n, are shown in Table V. These thresholds are comfortably larger than the estimated impedances in Table II.

Table V: RLHC longitudinal instability thresholds.

Effect	Units	LHC	High field	Low field
Coherent longitudinal tune shift	Ω	1.61	0.181	0.163
Longitudinal microwave instability	Ω	4.52	7.84	3.12

C. Transverse mode-coupling instability

The transverse mode-coupling instability (TMCI) is due to the shift of the $m = 0$ (rigid-bunch) head-tail mode frequency toward the $m = -1$ head-tail frequency by the broadband transverse impedance. The condition for stability is:

$$\mathrm{Im}\left(Z_T\right)_{eff} \le \frac{8Q_s\sigma_s}{\langle\beta\rangle I_b R}\frac{E}{e} \tag{4}$$

The transverse single-bunch instability thresholds, in terms of the effective transverse impedance, are shown in Table VI.

Table VI: RLHC transverse instability thresholds.

Effect	Units	LHC	High field	Low field
Transverse mode-coupling instability	MΩ/m	12.2	742	281

The TMCI threshold for the low-field RLHC is a factor of two larger than the estimated transverse impedance (dominated by the resistive wall impedance) in Table III. E. Malamud points out that by raising the RF voltage and frequency, by further increasing the beampipe aperture, or by reducing the charge per bunch at injection and coalescing bunches part way up the ramp, one may gain more margin for luminosity upgrades [8]. Several attempts have been made to use active electronics to damp or avoid TMCI in electron storage rings. A resistive feedback was used in VEPP-4M to double the instability threshold [9]. A reactive feedback was used at LEP to increase the threshold by 5% [10]. Resistive feedback is believed not to work at LEP because of the impedance between the pickups and kickers. The same difficulty is present (and much worse) for the larger-circumference RLHCs, so passive methods of increasing the TMCI threshold may be the only practical ones.

V. SCALING WITH HALF-CELL LENGTH

Many of the transverse and longitudinal parameters of a hadron storage ring are set by the choice of half-cell length. The cost depends on the half-cell length as well. S. Peggs notes that the choice of half-cell length made for previously planned hadron machines may be too conservative.

We investigated the dependence of instability thresholds on half-cell length. The energy, dipole magnet field, and transverse and longitudinal emittances were accepted as fixed inputs. The additional assumption was made that the contributions to the transverse beam size from the transverse emittance and the energy spread are equal, which appears to be a reasonable from the point of view of minimizing the machine aperture [11]. We find the following scalings for machine parameters:

$$\langle\beta_x\rangle \propto L, \quad Q_s \propto L^{-1}, \quad \sigma_s \propto L^{3/2}\,; \tag{4}$$

for loss of Landau damping through coherent synchrotron tune shift:

$$\left[\mathrm{Im}\left(\frac{Z_\mathrm{L}}{n}\right)_{eff}\right]_{thresh} \propto h_\mathrm{RF}^2 L^{7/2} \qquad (h_\mathrm{RF}\text{ fixed}), \tag{5.1}$$

$$\left[\mathrm{Im}\left(\frac{Z_\mathrm{L}}{n}\right)_{eff}\right]_{thresh} \propto V_\mathrm{RF}^{-2} L^{-9/2} \qquad (V_\mathrm{RF}\text{ fixed}); \tag{5.2}$$

for the longitudinal microwave instability:

$$\left|\left(\frac{Z_L}{n}\right)_{eff}\right|_{thresh} \propto L^{1/2}\,; \tag{6}$$

and for the transverse mode coupling instability:

$$\left[\mathrm{Im}\left(Z_T\right)_{eff}\right]_{thresh} \propto L^{-1/2}. \tag{7}$$

There is no severe collective instability penalty to be paid for a longer half-cell length. In the case of the coherent synchrotron tune shift (Equations 5.1 and 5.2) it is necessary to decrease the RF voltage (and increase its frequency) to maintain the same instability threshold.

VI. CONCLUSIONS

Because of the large circumferences of the RLHCs, transverse instabilities tend to dominate. The most important multibunch effect is the transverse resistive wall instability, and the dominant single bunch effect is the transverse mode coupling instability driven by the broadband resistive wall impedance. The high-field option is very much like the LHC in impedance and instability thresholds, and so collective instability issues for that machine have, in principle, already been solved. The low-field option has a large transverse resistive wall impedance due to its small radius warm beampipe and its large circumference, but with the increased beampipe radius and higher injection energy in the new parameter set this machine is stable against TMCI. The resistive wall risetime for the low-field machine is less than one turn, so a feedback or feedforward system capable of extremely fast damping would need to be developed for this machine.

The effect of the half-cell length on collective stability was found to be modest.

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