International Task Force Joint Meeting: Discussion on TMCI and impedance matters

M. Migliorati

on behalf of the TMCI sub-group of the SuperKEKB International Task Force

TMCI sub-group core members

- Contact person: Mauro Migliorati (SAPIENZA - Università di Roma)

- Sub-contact person: Takuya Ishibashi (KEK, vacuum system incl. collimator)

- Kazuhito Ohmi (KEK, beam dynamics)
- Demin Zhou (KEK, beam dynamics)
- Shinji Terui (KEK, vacuum system incl. collimator)

A first meeting has been held on 27/8/2021 with the following presentations:

- Introduction of TMCI members, collimators, tune shift and instability measurements - Speaker: Takuya ISHIBASHI (KEK ACCL)
- Impedance and wakefield model - Speaker: Demin ZHOU (KEK ACCL)
- TMCI and localized impedance - Speaker: Kazuhito OHMI (KEK ACCL)

TMCI sub-group people

Mailing list of the group to share and discuss topics about TMCI:
skb-itf-tmci@ml.post.kek.jp

To join the TMCI sub-group, send an email to takuya.ishibashi@kek.jp.

Members of the mailing list (27/8/2021)

Kazuro Furukawa (KEK)
Makoto Tobiyama (KEK)
Mauro Migliorati (University of Rome/INFN)
Mika Maszawa (KEK)
Rogelio Tomas (CERN)
Tadashi Koseki (KEK)
Takuya Ishibashi (KEK)
Tor Raubenheimer (SLAC/Stanford University)
Yusuke Suetsugu (KEK)

Emanuela Carideo (CERN PhD)
Nicolas Mounet (CERN)
Demin Zhou (KEK)
Kazuhito Ohmi (KEK)
Mikhail Zobov (INFN – LNF)
Shinji Terui (KEK)
Hiroyuki Nakayama (KEK)
Frank Zimmerman (CERN)
Yoshihiro Funakoshi (KEK)
Katsunobu Oide (KEK)

Goals of the TMCI sub-group

- Understand the observed transverse blow-up under different machine conditions
- Build a machine impedance model able to reproduce the instability
- Find some solutions to mitigate the instability

There could be three main activities:
1) Machine studies
2) Impedance model and simulations
3) Theoretical activity

For each of these activities we need to identify a person in charge and manpower.
Of course interactions with the other subgroups are fundamental.
Some people are and can be involved in the other subgroups.

TMCI: theory

- The **Vlasov** equation describes the collective behaviour of a multiparticle system under the influence of electromagnetic forces.

A. Chao

$$\frac{\partial\psi}{\partial s} + y'\frac{\partial\psi}{\partial y} + p_y'\frac{\partial\psi}{\partial p_y} + z'\frac{\partial\psi}{\partial z} + \delta'\frac{\partial\psi}{\partial\delta} = 0$$

$$\psi(y, p_y, z, \delta; s)$$

The steps to study the Vlasov equation in case of instability are generally the following:

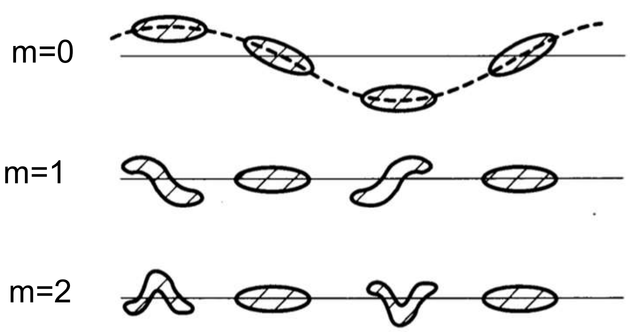
1) Use a perturbation method: $\psi = \psi_0 + \Delta\psi$
2) Introduce the transverse force induced by the wakefields
3) Expand the perturbation as sum of coherent modes of oscillations

TMCI: theory

The characteristics of the transverse coherent modes are the following:

- the bunch is supposed to have only a dipole moment in the transverse plane
- This dipole moment is not constant longitudinally. Depending on the longitudinal mode number m, its longitudinal structure may be simple or complicated

From A. Chao book



- The modes are called transverse modes, but the transverse structure is a pure dipole and the main task is to find their longitudinal structure
- the Vlasov equation needs to take into account both the transverse and the longitudinal phase spaces. Fortunately, however, the transverse structure of the beam is simple

TMCI: theory

4. There are several methods to solve the Vlasov equation.
5. In general an infinite set of linear equations is obtained. The eigenvalues represent the coherent frequencies and the eigenvectors the corresponding modes.
6. The eigenvalue system is of the kind

$$(\Omega - \omega_\beta - m\omega_s)\alpha_{mk} = \sum_{m'=-\infty}^{\infty} \sum_{k'=0}^{\infty} M_{kk'}^{mm'} \alpha_{m'k'}$$

The matrix elements depend also on chromaticity. When this is zero, the only instability for low intensity beams is due to high Q resonators. If the chromaticity is different from zero, single azimuthal modes can be unstable (differently from the longitudinal case). This instability is called head-tail instability. This is not an intensity threshold mechanism and can occur even at low intensity.

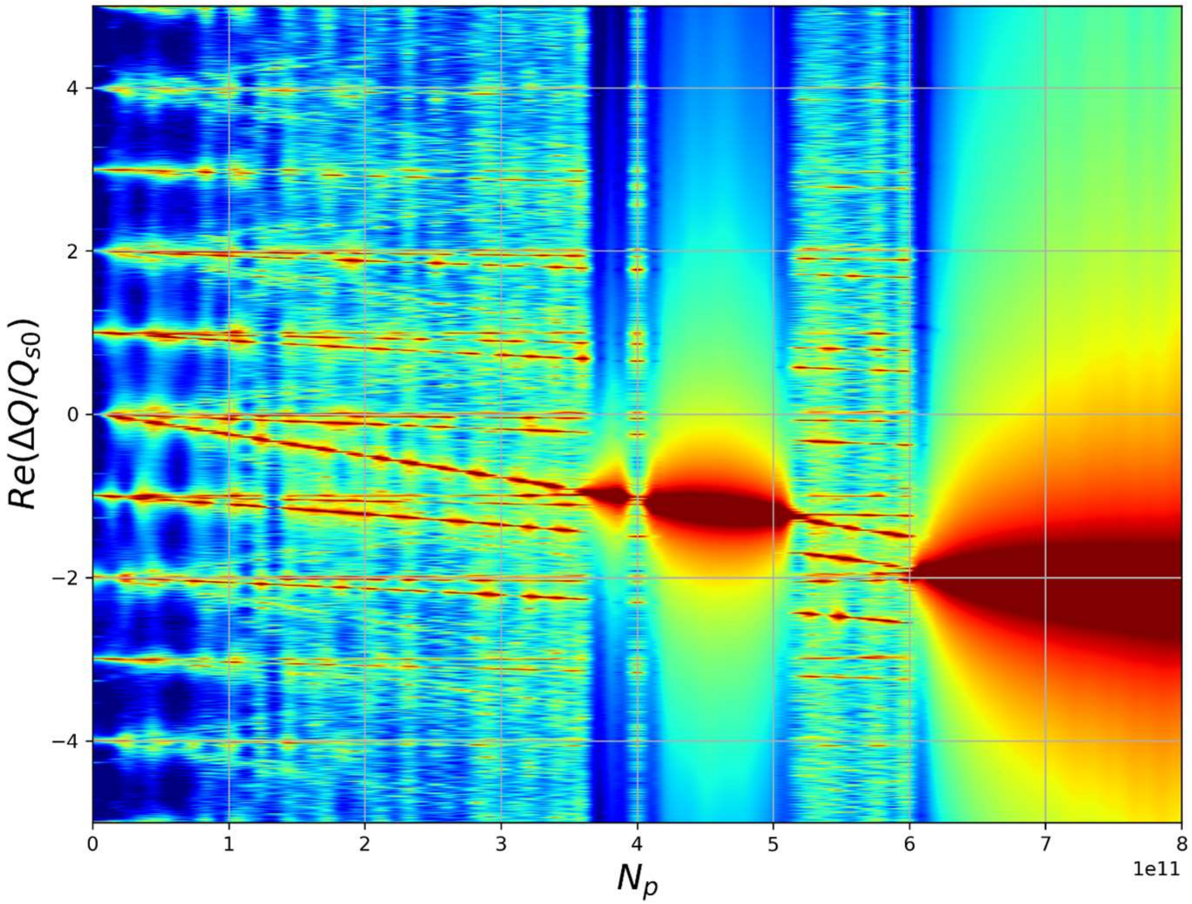
TMCI: example at high intensity

- At high intensity we need to solve the eigenvalue system and coupling between different azimuthal modes can occur

Frequencies of some coherent oscillation modes obtained with PyHEADTAIL tracking code by performing the FFT of

$$\frac{1}{N}\sum x_i z_i^n$$

over all the macroparticles

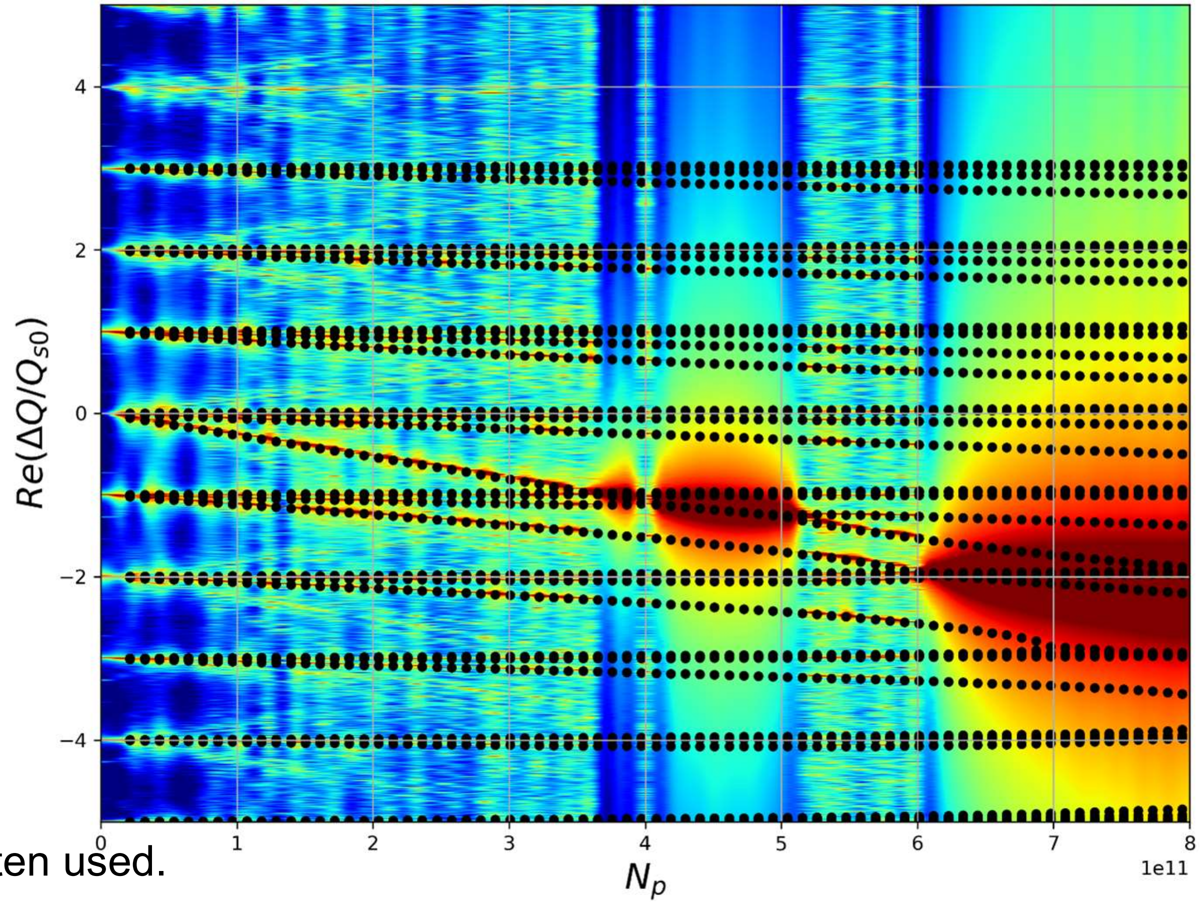


TMCI: example at high intensity

- At high intensity we need to solve the eigenvalue system and coupling between different azimuthal modes can occur

Black points: E. Métral, GALACTIC Vlasov solver

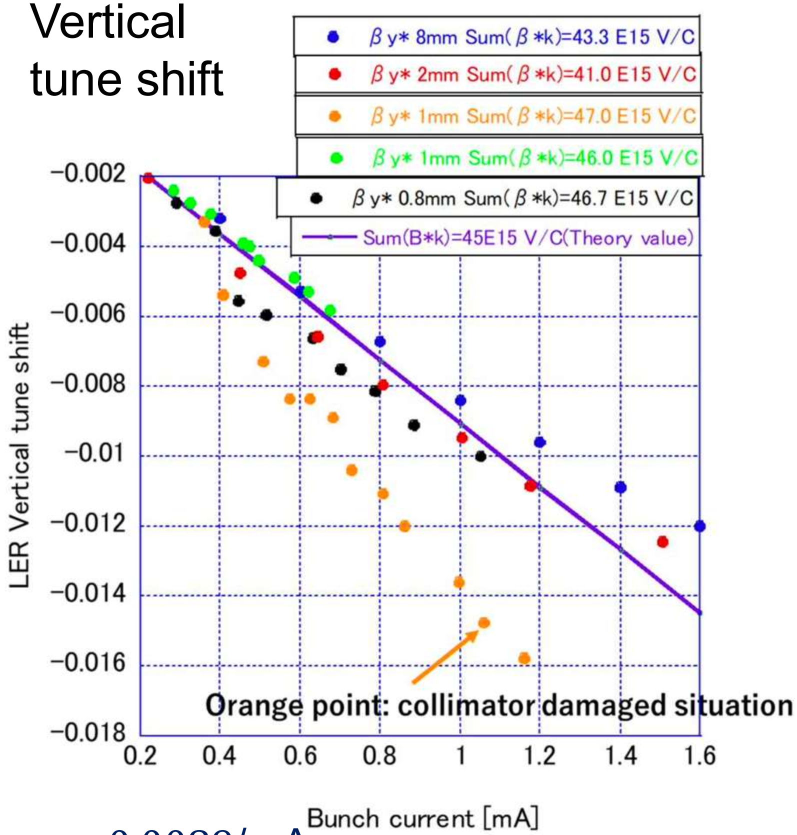
NB: in the past MOSES code from Y. H. Chin and, more recently, the NHT from A. Burov and DELPHI from N. Mounet are often used.



Observations and some results of the studies related to TMCI

S. Terui: Particle Accelerator Society Japan

Vertical tune shift



slope ~ 0.0089/mA

Instability threshold

With a slope of 0.0089/mA, a tune shift of the order of half the synchrotron tune ($0.022/2 = 0.011$) is reached with a current of about 1.24 mA.

From direct observations, the beam size blow-up is in the order of ~0.9 mA (depending on the betatron tune, chromaticity, …)

The tune shift value gives a larger threshold than blow-up observations. The instability doesn't seem to be due to a coupling of modes 0 and -1.

Observations and some results of the studies related to TMCI

Possible explanations on discrepancy:

- Localized impedance
- Missing impedance sources
- Effect of longitudinal impedance which modifies synchrotron tune (potential well distortion and/or microwave)
- Other effects (extension of TMCI, as: detuning impedance, nonlinear chromaticity, synchro-betatron resonances and x-y coupling, space charge, …)
- A combination of the above effects?

Observations and some results of the studies related to TMCI

The beam dynamics is quite complicated. Chromaticity (and tune) dependence (from S. Terui):

- When the vertical tune is 0.56, the current threshold (determined by a beam size blow-up) does not change with chromaticity
- When the vertical tune is > 0.6, the current threshold increases with chromaticity (1.4 → 4.4). But injection efficiency is sometimes reduced
- When the vertical tune is 0.59, the current threshold increases (0.9 → 1.0 mA) with chromaticity (1.4 → 4.4) and bunch by bunch feedback gain is +12 dB. But background noise in Belle2 increases
- When the vertical tune is 0.59, the current threshold increases(0.9 → 1.12 mA) when the vertical chromaticity is negative (-0.4) and bunch by bunch feedback gain is +12 dB

Some results on collective effects and tune shift

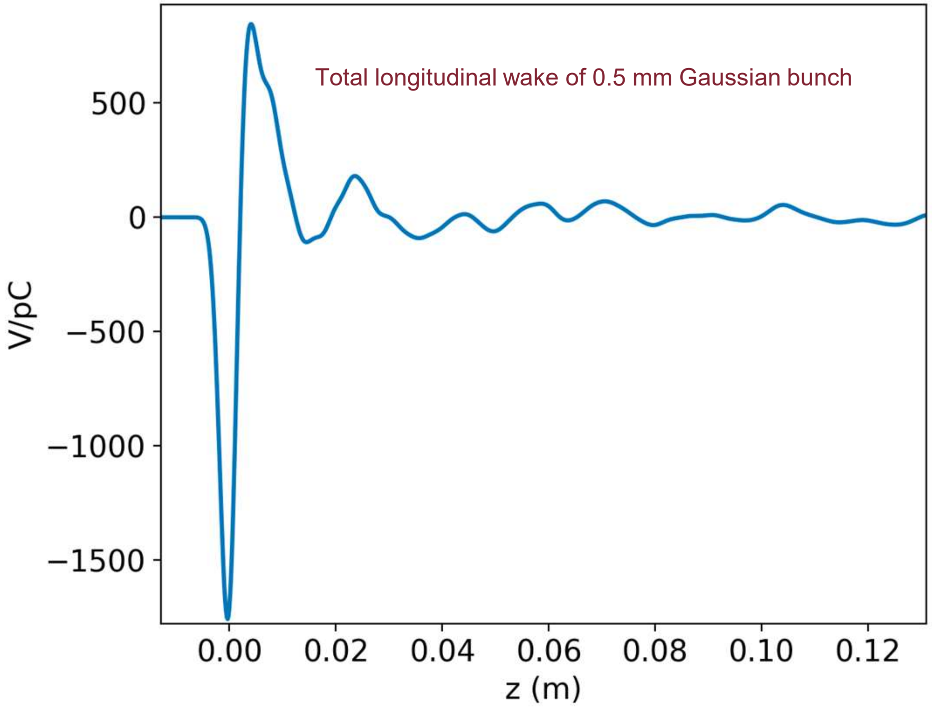
The work on impedance model for KEKB and SuperKEKB was done by D. Zhou together with colleagues of hardware and collimation groups.

The longitudinal impedance budget was constructed with design configurations.

D. Zhou et al., Impedance calculation and simulation of microwave instability for the main rings of SuperKEKB, in Proceedings of IPAC'14, Dresden, Germany

Table 1: Impedance budget for the SuperKEKB main rings. Summarised are the contributions to the loss factor $k_{||}$ [V/pC], the fitted resistance R [Ω] and inductance L [nH] for each type of components. The resistances and inductances are calculated at the nominal bunch lengths of σ_z=5 and 4.9 mm for LER and HER, respectively.

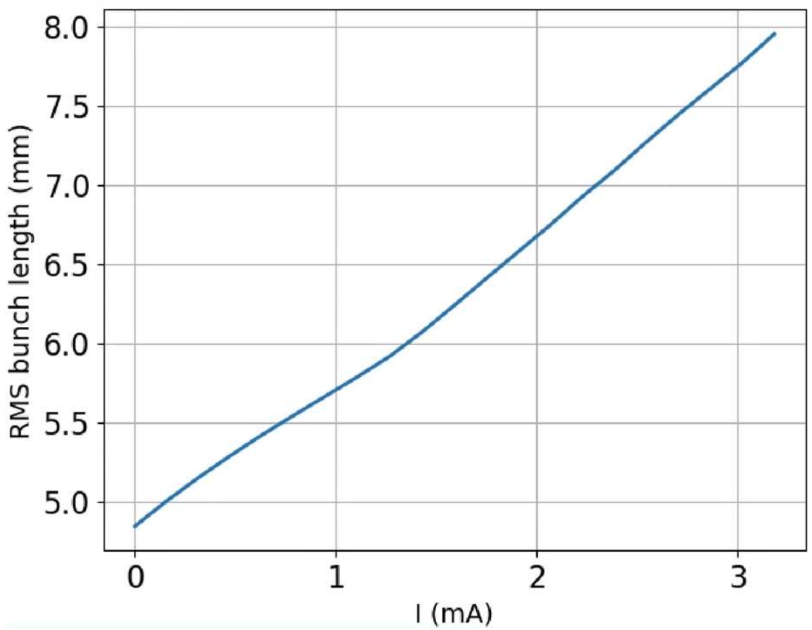
Component	LER			HER		
	$k_{\|\|}$	R	L	$k_{\|\|}$	R	L
ARES cavity	8.9	524	-	3.3	190	-
SC cavity	-	-	-	7.8	454	-
Collimator	1.1	62.4	13.0	5.3	309	10.8
Res. wall	3.9	231	5.7	5.9	340	8.2
Bellows	2.7	159	5.1	4.6	265	16.0
Flange	0.2	13.7	4.1	0.6	34.1	19.3
Pump. port	0.0	0.0	0.0	0.6	34.1	6.6
SR mask	0.0	0.0	0.0	0.4	21.4	0.7
IR duct	0.0	2.2	0.5	0.0	2.2	0.5
BPM	0.1	8.2	0.6	0.0	0.0	0.0
FB kicker	0.4	26.3	0.0	0.5	26.2	0.0
FB BPM	0.0	1.1	0.0	0.0	1.1	0.0
Long. kicker	1.8	105	1.2	-	-	-
Groove pipe	0.1	3.8	0.5	-	-	-
Electrode	0.0	0.7	5.7	-	-	-
Total	19.2	1137	36.4	29.0	1677	62.1

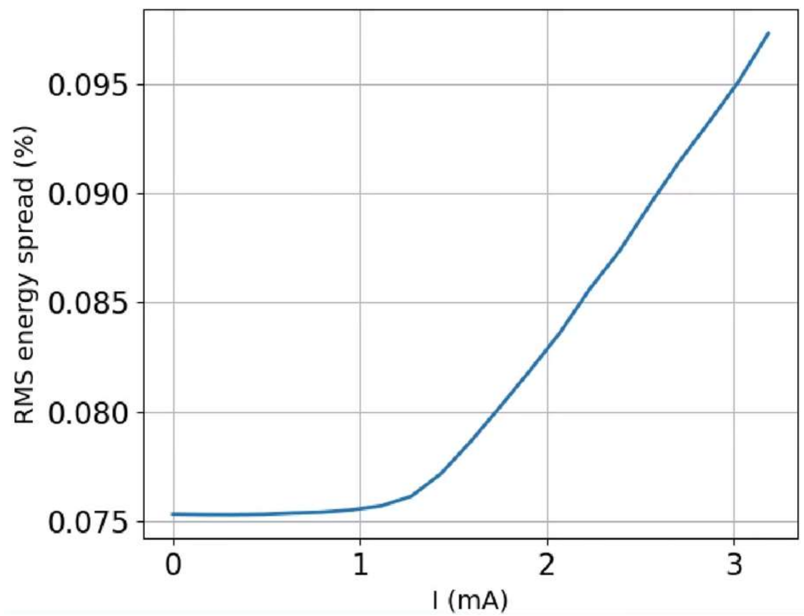


Some results on collective effects and tune shift

With PyHEADTAIL we started some simulations of collective effects by using the machine impedance model for both the longitudinal and transverse cases.

The longitudinal case was simulated to check if the code was in agreement with studies performed by D. Zhou. Some differences in the microwave threshold are due to the way of treating the CSR.



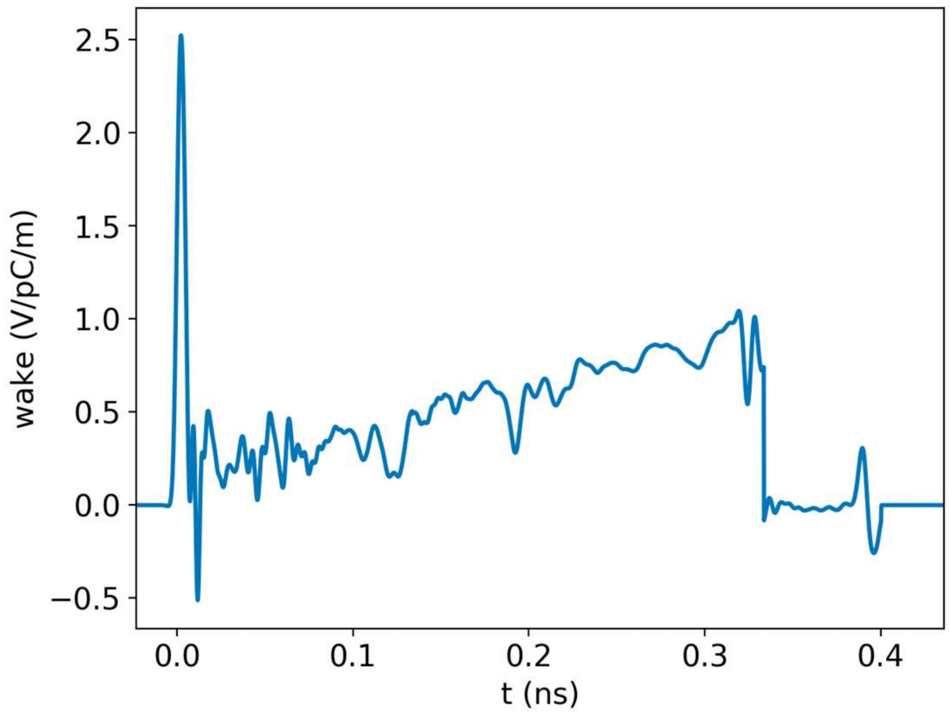


Some results on collective effects and tune shift

Transverse case: wakefield model (D. Zhou)

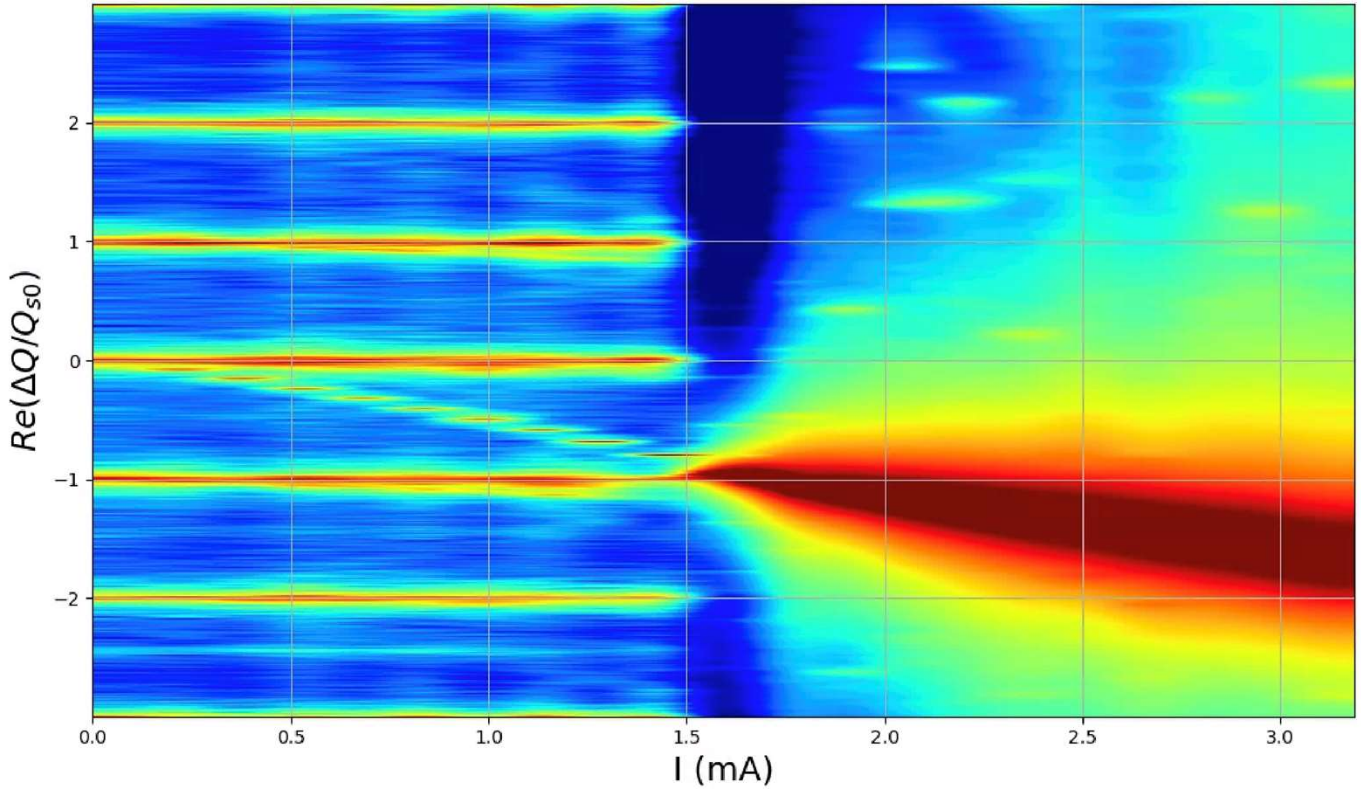
Short-bunch (0.5mm) wakefield of all components in 2016 (Phase-1 of SuperKEKB commissioning).
Some limitations:
This is simply a sum of all wakes together.
No weighting over beta functions was done.
The model is old and can be far from the current machine condition. The main difference is from collimators, which are believed to be the main sources of the TMCI threshold.
In this model the dipolar and quadrupolar wakes were not separated.

The new impedance model is under development.



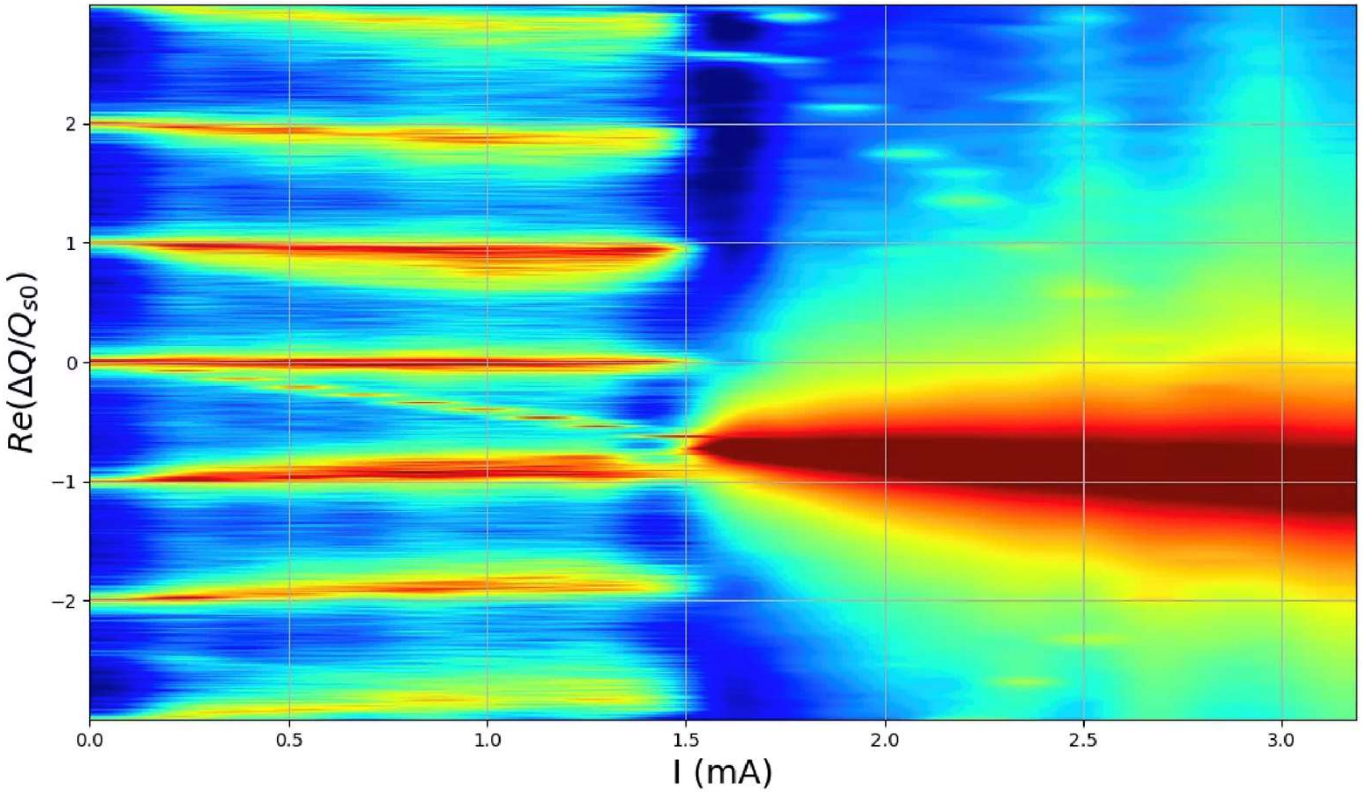
Some results on collective effects and tune shift

By multiplying by 16 the transverse wakefield, tune shift and TMCI threshold obtained by PyHEADTAIL are the following ($\nu_y = 0.59322$)



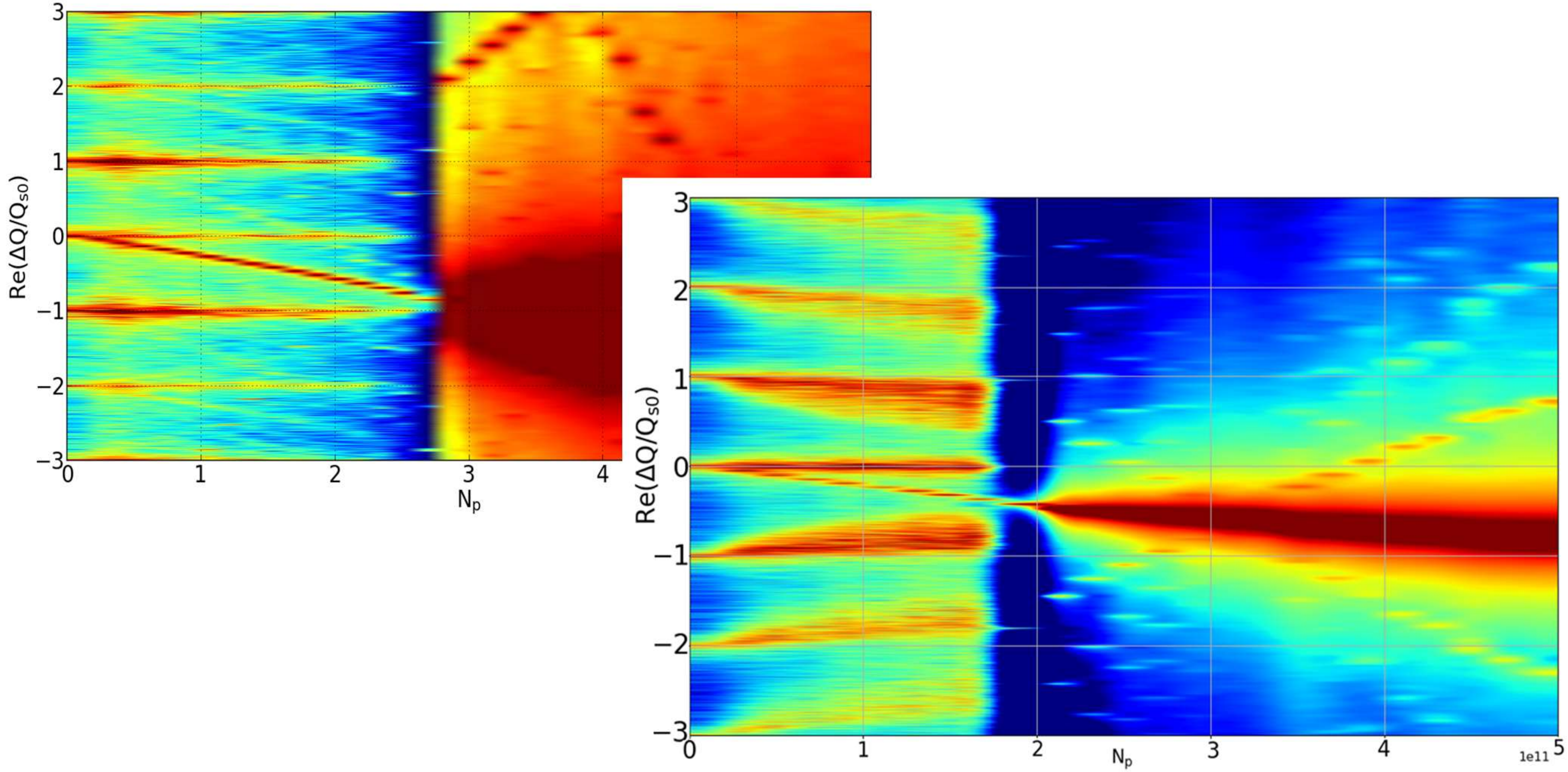
Some results on collective effects and tune shift

Effect of longitudinal wake on transverse one ($\nu_y = 0.59322$)



Some results on collective effects and tune shift

Effect of longitudinal wake on transverse one: case of FCC-ee



Some results on collective effects and tune shift

Question of localized impedance

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-LEP-TH/84-21

TRANSVERSE MODE COUPLING INSTABILITY DUE TO LOCALIZED STRUCTURES

F. Ruggiero

Geneva, November 1984

ABSTRACT

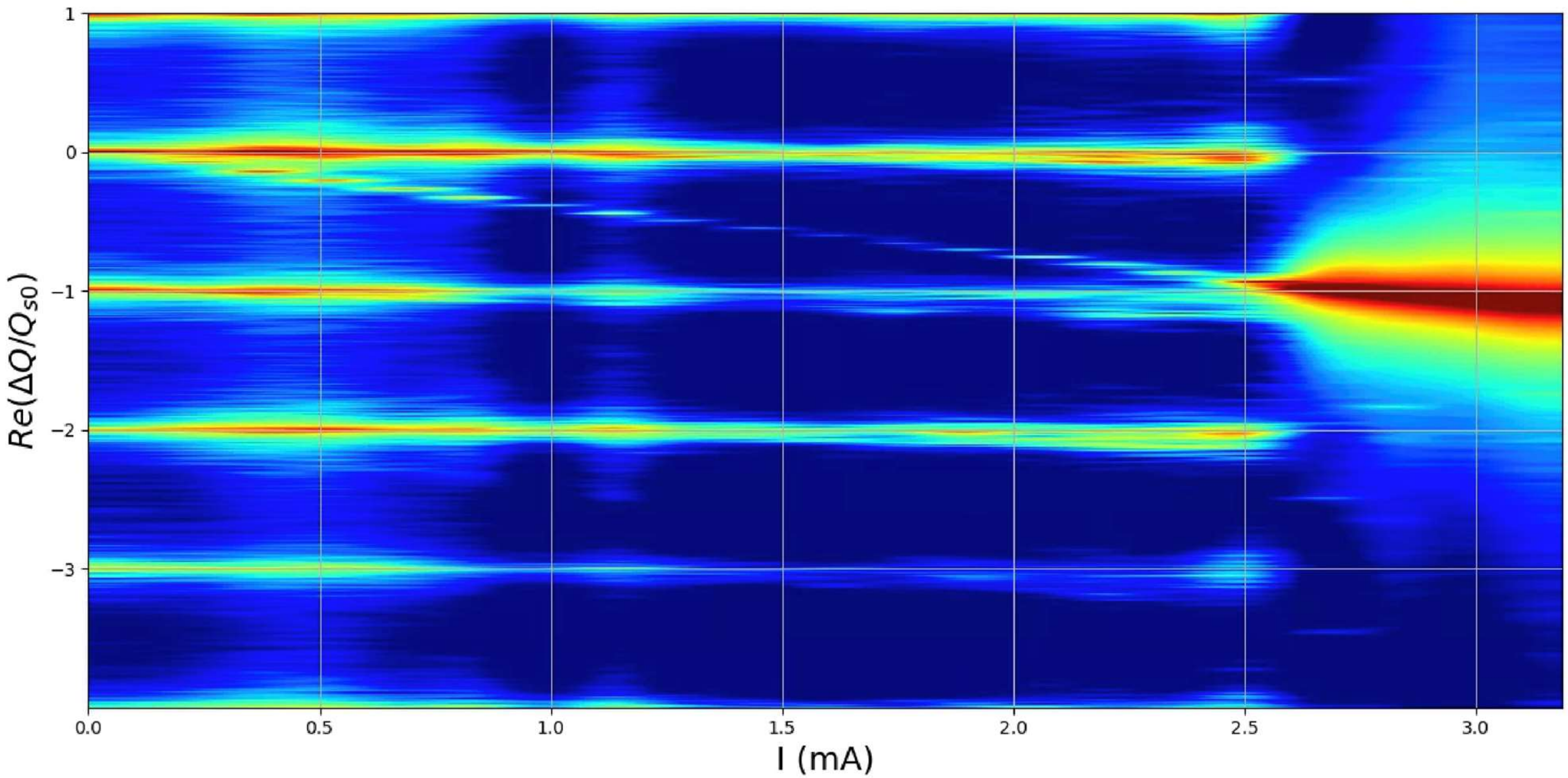
A relativistic charged particle passing through localized structures of a storage ring, like RF-cavities, induces electromagnetic wakefields which react on the following particles. If the beam current is increased beyond a threshold value, this phenomenon leads to a fast single bunch instability generally described in terms of transverse mode coupling.

Starting from the Vlasov equation for a simplified model of electron-positron machine, we show the existence of instability stop-bands at currents below threshold, which are due to the coupling between high order and low order dipole modes. Since the global effect of wakefields is represented by a transverse kick localized at a single point of the machine, the stop-band pattern repeats periodically every half-integer in the betatron tune ν_z. Denoting the synchrotron tune by ν_s and for ν_z in the range [0, 1/2], the bunch may become unstable at very low currents when ν_z approaches the resonant values $\nu_z = n\,\nu_s$ or $\nu_z = 1/2 - n\,\nu_s$.

Some results on collective effects and tune shift

Effect of localized impedance. Same wake and input but

$$\nu_y = 0.5 - \nu_s = 0.47788$$



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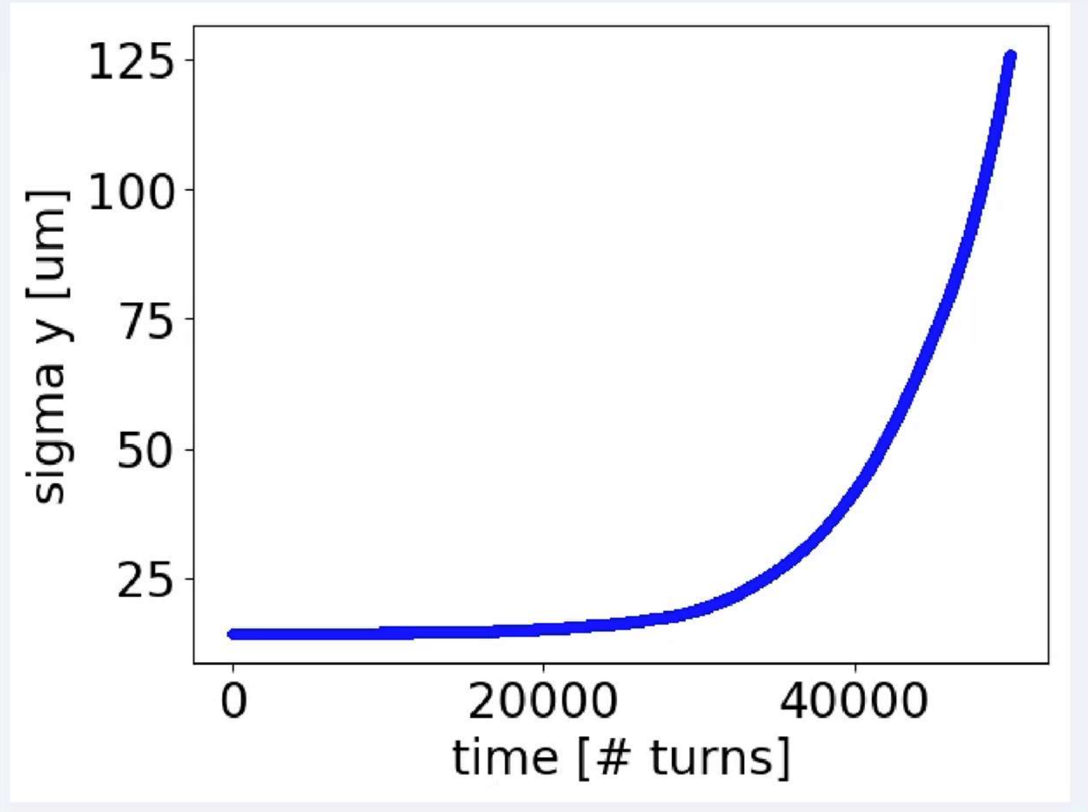

I =0.8 mA

TMCI in other machines

EPAC 98

EXPERIMENTAL AND THEORETICAL STUDIES OF TRANSVERSE SINGLE BUNCH INSTABILITIES AT THE ESRF

J. Jacob, P Kernel, R Nagaoka, J.-L. Revol, A Ropert, ESRF, Grenoble, France
G Besnier, University of Rennes, France

2.1 Zero vertical chromaticity

At zero chromaticity, according to theory, we could observe the coupling of mode 0 and -1 (Fig. 1).

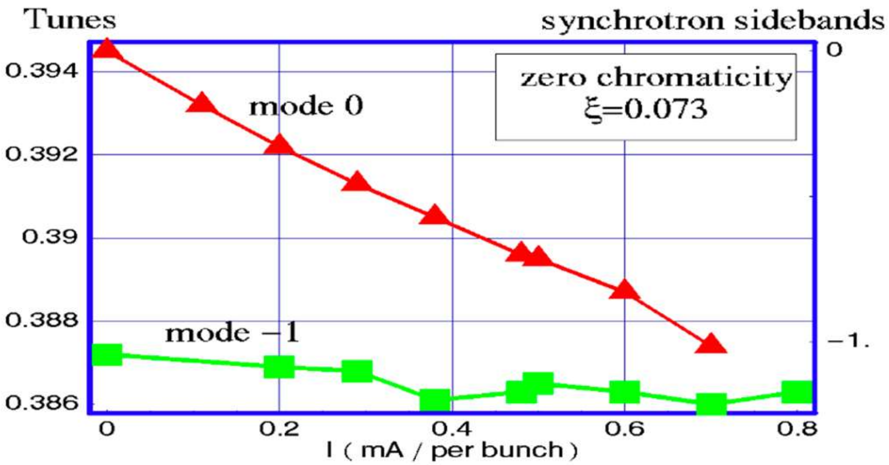

Figure 1: Observation of mode coupling

2.3 High vertical chromaticity

At high ξ, the strong detuning of the main peak of the tune spectrum covers a large number of synchrotron satellites with no sign of mode coupling (Fig. 3). At a

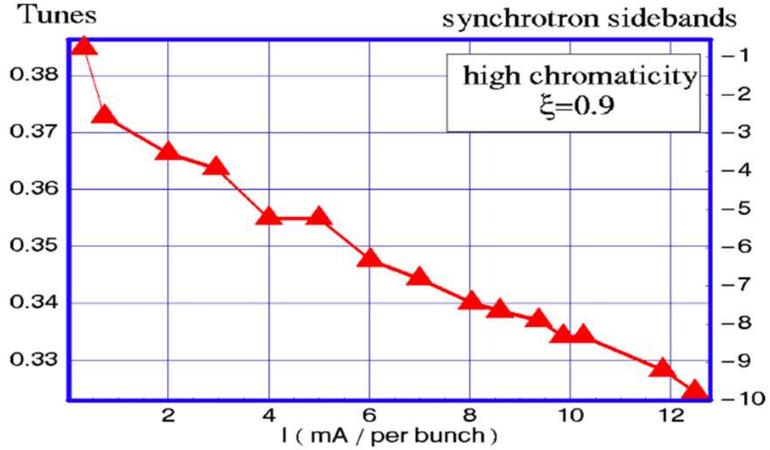

Figure 3: High chromaticity regime

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2.4 Intensity threshold

The simulation predicts a strong dependency of the instability threshold on a chromaticity larger than 0.5 which was checked for different bunch lengths (Fig. 4). At very high value, the maximum current is limited by the saturation of the injection possibly induced by the reduction of the transverse acceptance. The current instability threshold is determined by the blow-up of the vertical transverse profile and the spontaneous signal on the tune monitor.

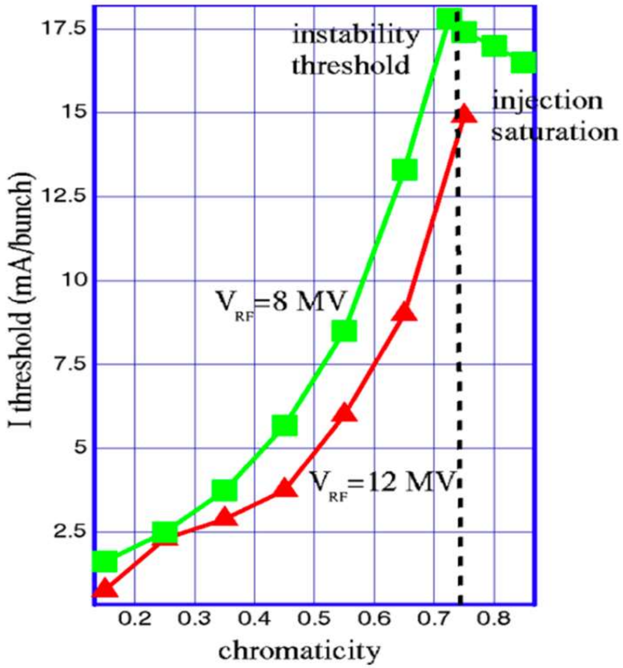


Figure 4: Intensity threshold

TMCI in other machines

TUPP020 Proceedings of EPAC08, Genoa, Italy

ANALYSIS OF COLLECTIVE EFFECTS AT THE DIAMOND STORAGE RING

[1,2]R. Bartolini, [1]C. Christou, [1]R.T. Fielder, [1]M. Jensen, [1]A. Morgan, [1]S. Pande, [1]G. Rehm and [1]C. Thomas,
[1]Diamond Light Source Ltd, Oxfordshire, UK and [2]John Adams Institute, University of Oxford, UK

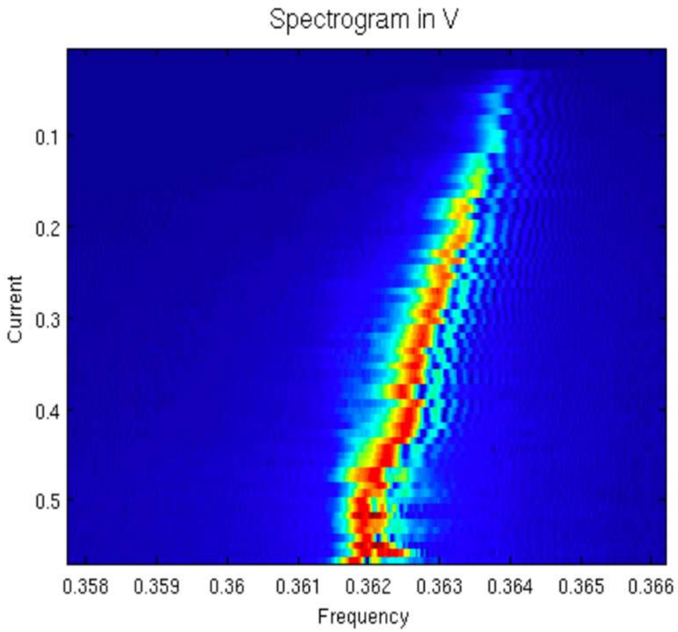


Figure 2: Vertical tuneshift with current and TMCI detected in the vertical plane.

Increasing the chromaticity to $(\xi_x, \xi_x) = (2, 2)$ stabilises the TMCI and it was possible to inject current in the single bunch beyond the TMCI threshold. Nevertheless at positive chromaticity the classical head-tail modes become unstable and the injected current is still limited. The tuneshift with current is negligible in the horizontal plane and 1.3 kHz/mA in the vertical plane. Several head-tail modes are excited as the current increases as reported in Fig. 4. Injection is finally saturated at 3.3 mA when the head tail mode –3 becomes strongly excited.

TMCI in other machines

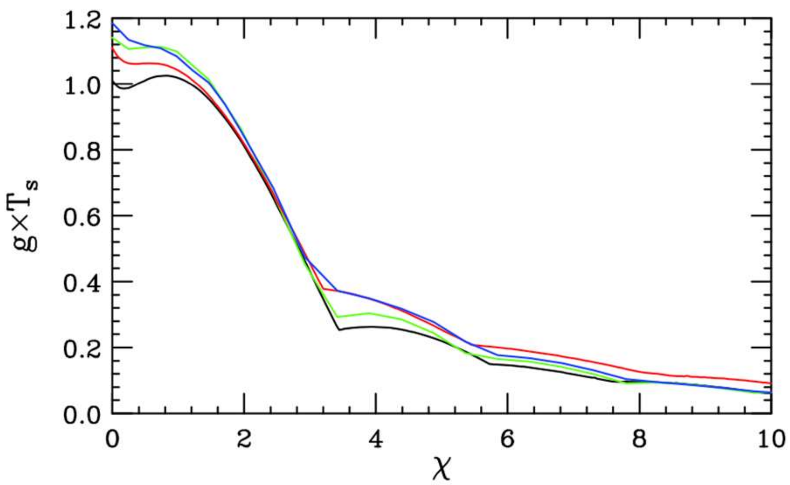
The new synchrotrons can be limited by TMCI due to their small vacuum chamber size.

This is mainly for the regimes with small number of bunches and high intensity. In the multi-bunch regimes, generally, this is not a problem (low charge).

In most cases the chromaticity helps to increase the TMCI threshold but ...

Y. H. Chin, A. W. Chao, M. M. Blaskiewicz, Y. Shobuda, Phys Rev AB 20, 071003 (2017)

TMCI has been observed in rings (both electron and proton rings) only with relatively short bunches. In a short bunch, it needs a significantly larger chromaticity to produce a large χ (say, more than several). Figure 23 shows that the growth factor changes a little when χ stays within a few. It implies that the TMCI threshold can be hardly improved by increasing the chromaticity if it is within a reasonably attainable value (namely, $\chi \leq$ a few). That may explain why the chromaticity has not been an effective tool to mitigate TMCI in many machines.



TMCI in other machines

ISBN 978-3-95450-180-9 Proceedings of NAPAC2016, Chicago, IL, USA WEA3CO04

IMPEDANCE CHARACTERIZATION AND COLLECTIVE EFFECTS IN THE MAX IV 3 GeV RING*

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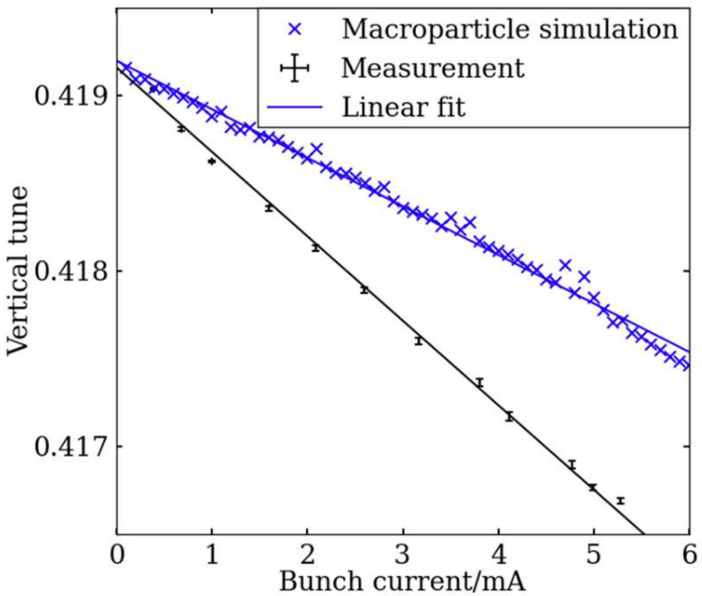
G. Skripka, Å. Andersson, P. F. Tavares,
MAX IV Laboratory, Lund University, SE-221 00 Lund, Sweden



impedance model calculated using GdfidL. The tune shift obtained experimentally, $-0.481 \pm 0.002\ \mathrm{A}^{-1}$, is a factor of 1.8 larger than the one obtained in tracking, a similar level of discrepancy as in the longitudinal plane, see previous section. Furthermore, the macroparticle tracking predicts a transverse mode-coupling instability (TMCI) at a single bunch current of 5.5 mA, about where the total tune shift reaches one synchrotron tune. No signs of TMCI (beam loss, hard limit on accumulated current) were seen in experiment despite the impedance being larger than predicted.

Actions and Countermeasures

- Develop an impedance model able to reproduce the observations
- Machine studies: betatron tune scan, chromaticity, etc.
- Increase/change of synchrotron frequency (for both TMCI and localized impedance)
- Decrease the beta function at the collimators' position, …
- Nonlinear tapering of collimators (see, e. g. https://accelconf.web.cern.ch/p07/PAPERS/WEOAC04.PDF). Some issues could remain, in particular due to the reliability of accuracy of electromagnetic codes with very small gaps

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Thank you for your attention