

Session 4: Instability Theory and Modeling

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ICFA Mini-workshop on Impedances and Beam Instabilities in Particle
Accelerators

- Transverse Mode Coupling (TMCI):
 - Analytical Solutions and Theory
 - Models of TMCI with SC and impedances
 - impact of different longitudinal distribution functions
 - influence of chromaticity on TMCI
 - Simulations
 - Should use exact analytic models for benchmarking
- Micro-bunching instability in LINACs
- Circulant matrix formalism $\longleftrightarrow$ 2-particle model
- Electron cloud and beam-ion instabilities

Simulations and checking

- For estimates that are sufficiently realistic to design an accelerator it appears that simulations are necessary.
- How do you know your code is right?
- For SC with linear RF and a parabolic line density we have Neuffer's exact longitudinal solutions [5].
- For boxcar bunches in linear RF with SC we have Sacherer's exact transverse solutions [6].
- For hollow bunches in a square well we have numerically exact transverse solutions with SC and wake potentials that are sums of (complex) exponentials. [7,8]
- A new basis expansion technique generalizing [6] appears to give *convergent solutions with wakefields* [9]

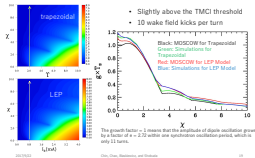
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- analytic models proposed which should be reproduced by any simulation as benchmark

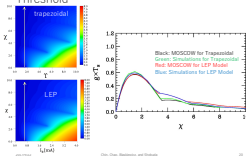
Yong Ho Chin: Chromaticity Effect on Head-tail Instabil.

Simulations with TRANFT Code



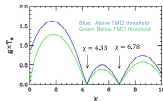
- finite chromaticity does not improve TMCI threshold for reasonably low chromaticities
- 2-particle model can reproduce critical chromaticity behaviour
- trapezoidal model for Vlasov analysis and macro-particle simulations can well replace realistic wake models (e.g. LEP)

Simulations Slightly Below TMCI Threshold



Growth Factor in the Two Particle Model

- Similar behaviors but not quite in accord quantitatively.



Timofey Zolkin: TMCI at Strong Space Charge

2.1 Spectra for const-wake (ABS)

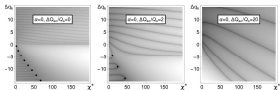


Figure: Spectra for the ABS model and const-wake ($\Delta Q_{sc}/Q_s = 0, 2, 20$).

- monotonic increase of threshold for mode 0 and -1 coupling instability with space charge is true e.g. for negative constant wakes

- oscillating wakes (e.g. sin and cos) can lead to very different, not necessarily monotonically increasing behaviour

- universal plots apply to different longitudinal distribution functions

2.2 TMCI threshold as a function of SC (ABS)

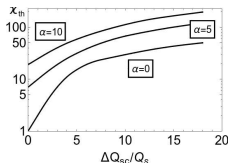
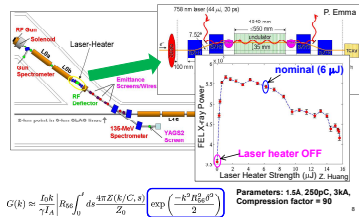


Figure: TMCI threshold as a function of space charge for the ABS model with the constant and exponential wakes (after M. Blaskiewicz).

Daniel Ratner: Microbunching Instabil. and Laser Heating

Suppression of MBI

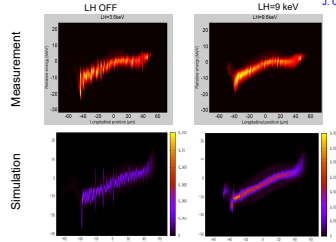


- increase of momentum spread by laser heating in dispersive region mitigates microbunching instability

Benchmarking for LCLS II: Simulations vs. Measurements

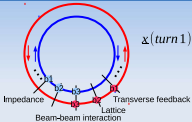
June 18 500 A data, with XTCAV

Images courtesy
J. Qiang



Xavier Buffat: Circulant Matrix Formalism

Coherent one turn matrix

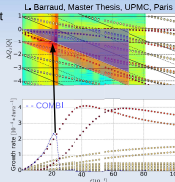

$$\begin{aligned}\mathbf{x}(\text{turn } 1) &= M_{\text{step } 2N} \cdots M_{\text{step } 2} M_{\text{step } 1} \mathbf{x}(0) \\ &= M_{\text{One turn}} \mathbf{x}(0)\end{aligned}$$

- In a general way, the model can be understood as the development and normal mode analysis of the one turn matrix for all bunches of the two beams
 - Need to derive the linearised coherent forces in a given basis
 - The circulant matrix model basis

Stability mechanisms

Landau damping

- In configurations with strong synchrotron coupling (e.g. HL-LHC), the instability occurs at any beam-beam tune shift
- Landau damping from the beam-beam induced tune spread is usually effective if the coherent modes frequency is within the incoherent tune spread and its side bands [Y. Alexahin, W. Herr]



L. Barraud, Master Thesis, UPMC, Paris

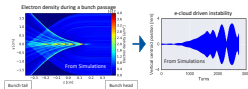
- circulant matrix formalism equivalent to Vlasov solving via eigenmodes
- conceptually an extension of 2-particle model
- benchmarked with many other codes
- predictions vs. measurements at LHC

Annalisa Romano: Electron Cloud Instabilities

Electron cloud induced instability

The *distortion of the cloud* induced by the bunch passing through (pinch effect) can give rise to coherent instabilities and emittance growth

- if e.g. the head of the bunch is slightly displaced, an asymmetric pinch will take place which will kick the following bunch particles toward the higher density region
- After several turns, the motion of the head is transferred to the tail
- After a sufficient number of turns, the unstable coherent motion has propagated to the whole bunch

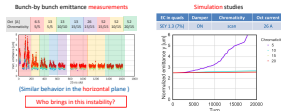


- electron cloud (EC) instabilities simulated with strong-strong macro-particle model
- EC in dipole magnets at high bunch intensities non-detrimental
- EC in dipole magnets at low bunch intensities at flat-top energy $\Rightarrow$ vertical instability
- EC in quadrupolar magnets at injection plateau $\Rightarrow$ horizontal and vertical instability

EC observations vs simulations : LHC quadrupoles

The LHC operation with 25 beams can be very challenging $\rightarrow$ strong EC regime

- Strong *instability development*, leading to an emittance blow-up observed both in the *horizontal and vertical* plane at injection energy
- Large chromaticity values, relatively high octupoles current and a fully functional feedback system were needed to reach a satisfactory emittance preservation.



Lotta Methner: Fast Beam-ion Instabilities

Fast beam-ion instability

Two-stream instability like electron cloud $\rightarrow$ similarities and differences:

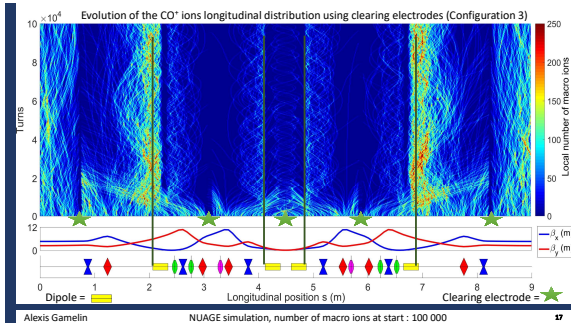
- Ion density increases with every bunch – effect stronger at tail of trains



- Ions hardly move during a bunch passage $\rightarrow$ different dynamics
 - “Build-up” depends on ion trapping around beam
 - Ions transfer information on bunch centroid position to the trailing bunch(es)
 $\rightarrow$ coupled bunch instability

- electron beams can suffer from fast instabilities with ions
 - simulations with PyECLOUD-PyHEADTAIL
 - gas leak in LHC (16L2) causes serious problems for LHC operation, suggested mechanisms:
 - 1 proton beam – ion instability possible but extremely high gas density needed
 - 2 EC from gas ionisation requires very high electron densities ($\rightarrow$ strong ion space charge)
 - 3 possibly three-beam instability mechanism needed
- $\Rightarrow$ on-going efforts

Alexis Gamelin: 3D Ion Cloud Dynamics



- weak-strong model for electron beam (weak) – ion (strong) motion
- investigate mitigation of beam – ion instabilities by clearing electrodes
- longitudinal motion of ions important for mitigation scenarios

Thank you for your attention!