SPS Transverse Mode Coupling Instability with Space Charge

Adrian Oeftiger

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Motivation for Simulations

Transverse Mode Coupling Instability:

- found in SPS for Q26 optics, measured
  - ⟶ intensity limit
  - ⟶ mechanism and mitigation method using lower $Q_{x,y}$ (i.e. lower Q_s) developed over several theses
  - ⟶ Q20 optics threshold much higher than Q26, measured!
  - ⟹ even for higher brightness, TMCI exists and is a hard intensity limit!
- theory and simulation work by A. Burov, T. Zolkin and M. Blasciewicz predicted **vanishing TMCI limit** for strong space charge ("rigid slice model"), while D. Quatraro and G. Rumolo's simulations reported an only slightly **shifted TMCI limit**
  - ⚠ seeming contradiction between experiment and some simulations
  - ⟶ dependency on wake type found (Burov, Zolkin and Blasciewicz)
- recent theory work by Y. Alexahin includes incoherent tune spread ("soft slice model"), does not exhibit vanishing TMCI

⟹ self-consistent space charge simulations with PyHEADTAIL using Gaussian beams

SPS Parameters

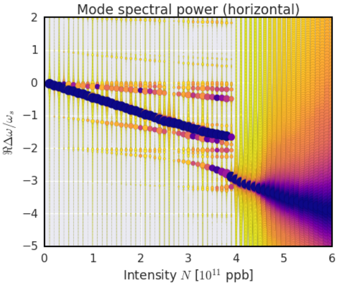
parameter	value
intensity	$0 < N < 6 \times 10^{11}$
transverse tunes	$Q_{x,y} = (20.13, 20.18)$
synchrotron tune	$Q_s \approx 0.017$
chromaticity	$Q'_{x,y} = 0$
RF voltage	$V_{RF} = 5.75\,\mathrm{MV}$
injection energy	$26\,\mathrm{GeV}$

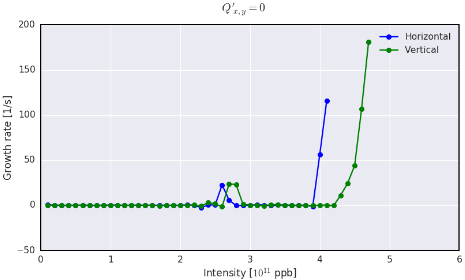
⟶ single bunch, linear synchrotron motion

⟶ no damper, no octupole currents

⟶ idealised broad-band resonator models (starting from circular axi-symmetric model)

Transverse Mode Coupling Instability





Without space charge, horizontal plane:

⟶ modes 0 and -1 couple around $N = 2.6 \times 10^{11}$ ppb

⟶ modes -2 and -3 couple around $N = 4 \times 10^{11}$ ppb

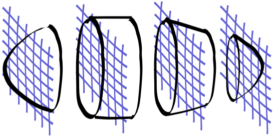
SPS TMCI at injection for Q20: Convergence scan in macro-particles (2.5D PIC space charge with adaptive grid)

Set-up

Set-up:

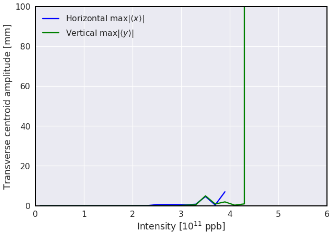
- smooth approximation, 200 space charge kicks along ring
- 1 impedance kick per turn with 500 slices

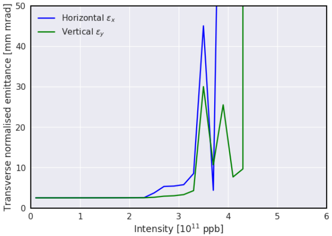
  ⟶ circular axi-symmetric broad-band (BB) resonator
- compare between low and high resolution
  - 32 vs. 500 (i.e. same like impedance) longitudinal number of transverse grids to solve free-space Poisson equation
  - correspondingly 1×10^6 vs. 15×10^6 $\text{macro}-\text{particles}$
- simulate for 20 000 turns



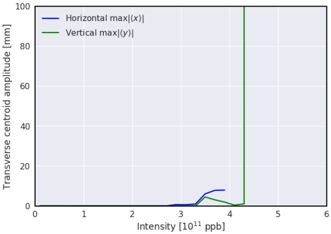
Convergence Scan

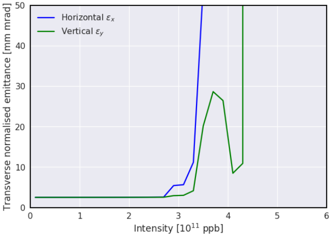
Low Resolution





High Resolution





Conclusion from Convergence Scan

Comparing low with high resolution:

- qualitative behaviour of macroscopic emittance and centroids look approximately the same (besides weird dips in low resolution)
- emittance growth and centroid impact take off from initial $\epsilon_{x,y} = 2.5\,\mathrm{mm\,mrad}$ at different intensities!

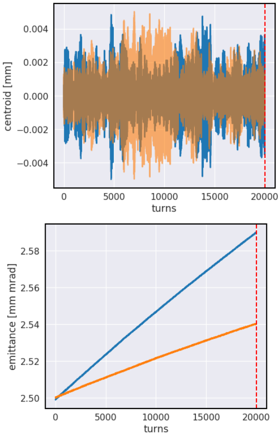
$\longrightarrow$ low resolution more unstable

- significant horizontal centroid amplitude growth rates (including emittance growth!) start at
  - low resolution: $N_{th} = 2.5\,\mathrm{ppb}$
  - high resolution: $N_{th} = 2.9\,\mathrm{ppb}$
- irregular centroid motion starts at
  - low resolution: $N_{th} = 2.1\,\mathrm{ppb}$
  - high resolution: $N_{th} = 2.9\,\mathrm{ppb}$ (same as above!)

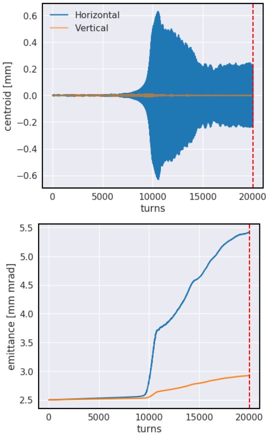
show only high resolution on next slides...

Impact Horizontal on Vertical

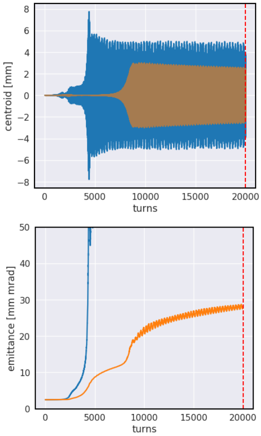
$N = 2.7 \times 10^{11}$ ppb



$N = 2.9 \times 10^{11}$ ppb

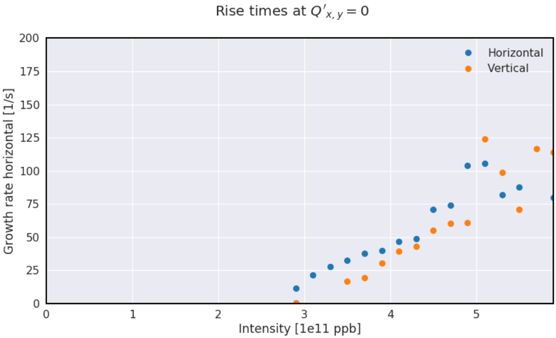


$N = 3.7 \times 10^{11}$ ppb



⟶ horizontal growth impacts vertical plane first before vertical TMCI

⚠ different initial space charge condition for vertical instability!



- extract growth rate from first growth (before $\Delta\epsilon_{x,y} > 5\%$)

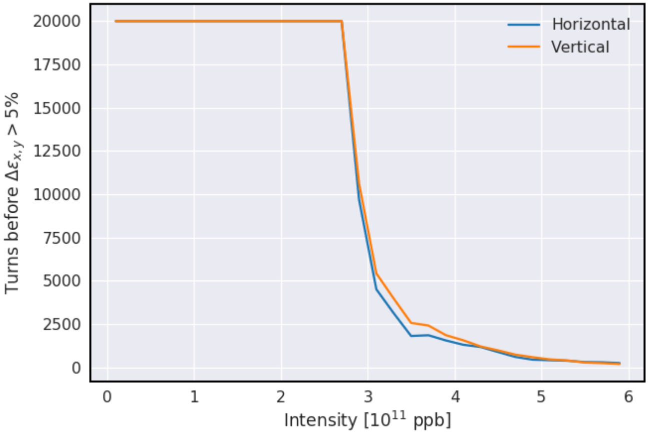
$\Longrightarrow$ horizontal figures oppose "suppression of TMCI due to SC" hypothesis

- vertical growth rates are imprint of horizontal TMCI
- difficult to disentangle planes: don't trust vertical growth rates!
- growth rates don't show clear structure of final $\epsilon_{x,y}$ (3 slides ago)

$\Longrightarrow$ mode 0&-1 coupling seems to be gone :-) ($N < 2.9$ ppb stable!)

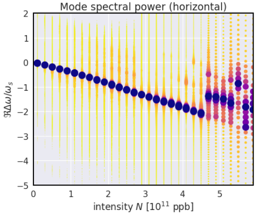
Constant Emittance Windows

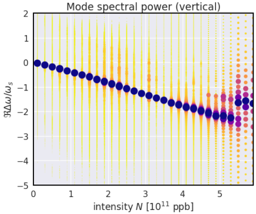
Turns of simulation during which emittance growth remains below 5%:



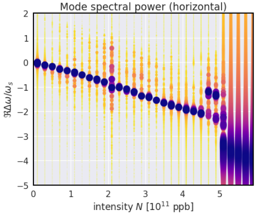
Spectra (and Impact of Window)

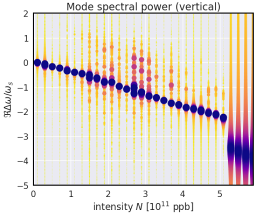
spectrum while $\Delta\epsilon_{x,y} < 5\%$





spectrum until turn 1024

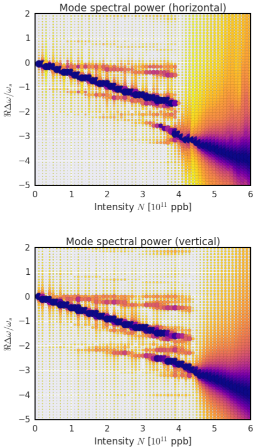




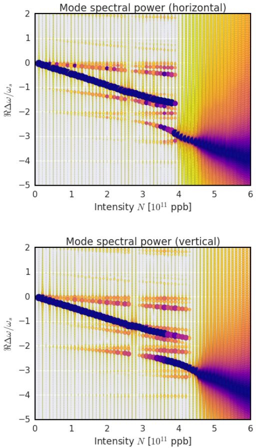
$\Longrightarrow$ before modes -2&-3 couple, dominant modes seem to be 1 and 2!

Spectra (and Impact of Window): no SC

spectrum until turn 512



spectrum until turn 2048



$\Longrightarrow$ without space charge, modes -2&-3 couple directly!

SPS TMCI at injection for Q20: Comparison of broad-band resonator models (no space charge!)

Context

Context of study:

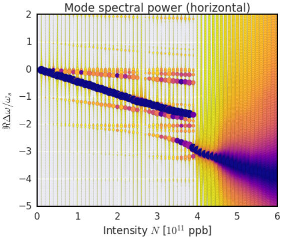
- for a circular axi-symmetric broad-band (BB) resonator impedance model, the TMCI seem to hit earlier in the horizontal plane
  - $Q_x = 20.13 < 20.18 = Q_y$ for Q20 optics is the only asymmetry between transverse planes

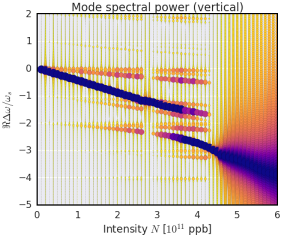
  $\longrightarrow$ due to vertical TMCI observed in SPS experiments, we are interested in the vertical TMCI threshold from simulations

  $\longrightarrow$ without space charge there is no coupling

  $\Longrightarrow$ in this case we can use full circular BB model and simply ignore the horizontal plane
- space charge couples the two transverse planes!

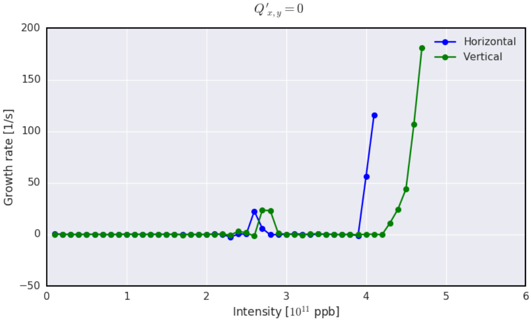
  $\longrightarrow$ need to remove horizontal TMCI in model to cleanly investigate the vertical plane – options:
  1. artificially remove horizontal impedance from circular axi-symmetric case by setting horizontal Yokoya factor to 0, or
  2. use horizontal parallel plates BB model where horizontal symmetry eliminates horizontal TMCI (horizontal dip. and quadr. kick compensate each other)



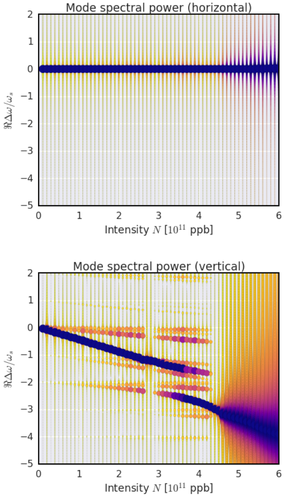


dip. X	dip. Y	quadrup. X	quadrup. Y
1	1	0	0

Table: Yokoya factors

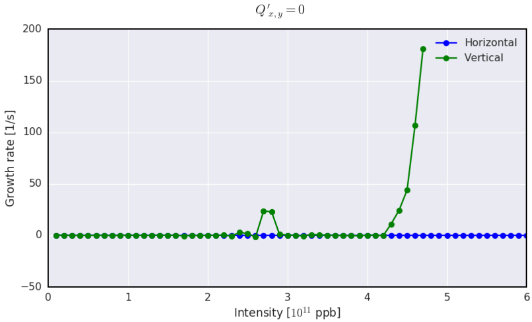


Circular Broad-band Resonator ONLY Vertical!

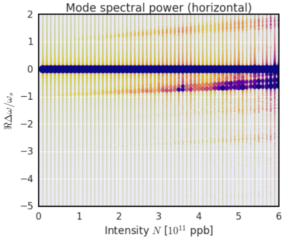


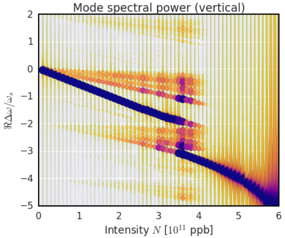
dip. X	dip. Y	quadrup. X	quadrup. Y
0	1	0	0

Table: Yokoya factors



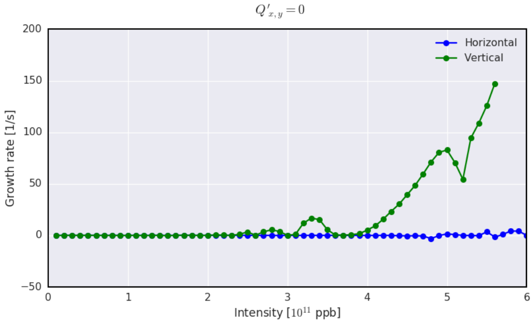
Parallel Horizontal Plates Broad-band Resonator





dip. X	dip. Y	quadrup. X	quadrup. Y
$+\frac{\pi^2}{24}$	$\frac{\pi^2}{12}$	$-\frac{\pi^2}{24}$	$\frac{\pi^2}{24}$

Table: Yokoya factors



Conclusion from Resonator Model Study

Comparing broad-band resonator models:

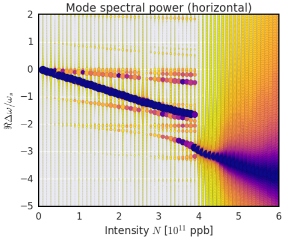
⟶ circular model with dip. horizontal kick removed (Yokoya $X_1 = 0$) seems better model to understand space charge impact:

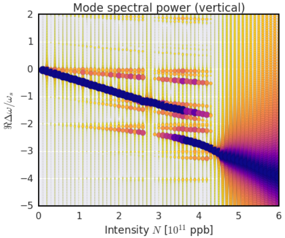
- no impact whatsoever on horizontal plane (as opposed to parallel plates)

⟹ clean vertical set-up (although not strictly realistic)

- vertical growth rates clearly show 2 features:
  1. mode 0&-1 coupling around $N = 2.6 \times 10^{11}$ ppb (and subsequent decoupling)
  2. mode -2&-3 coupling above $N > 4.3 \times 10^{11}$ ppb

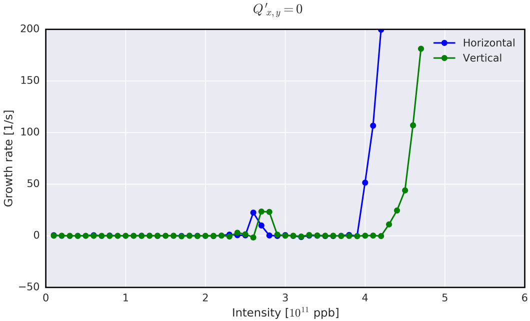
⟹ large distance between 2 TMCI regimes might allow to follow both features unambiguously when space charge is included!

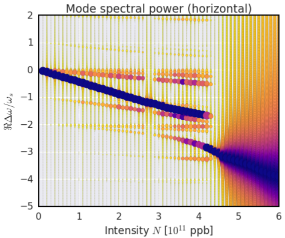


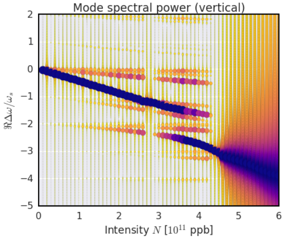


Q_x	Q_y	β_x	β_y
20.13	20.18	54.5 m	54.5 m

Table: optics parameters







Q_x	Q_y	β_x	β_y
20.18	20.18	54.5 m	54.5 m

Table: optics parameters