EFFECT OF DETUNING IMPEDANCE ON STABILITY

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MACHINE USED

- The machine used for all simulations is the SPS

01

TWO PARTICLE MODEL

Including non-zero chromaticity and resistive wall wakes in PyHEADTAIL

RHO – A PARAMETER FOR THE WAKES

- Rho defined as a measure of the detuning wake w.r.t the driving wake

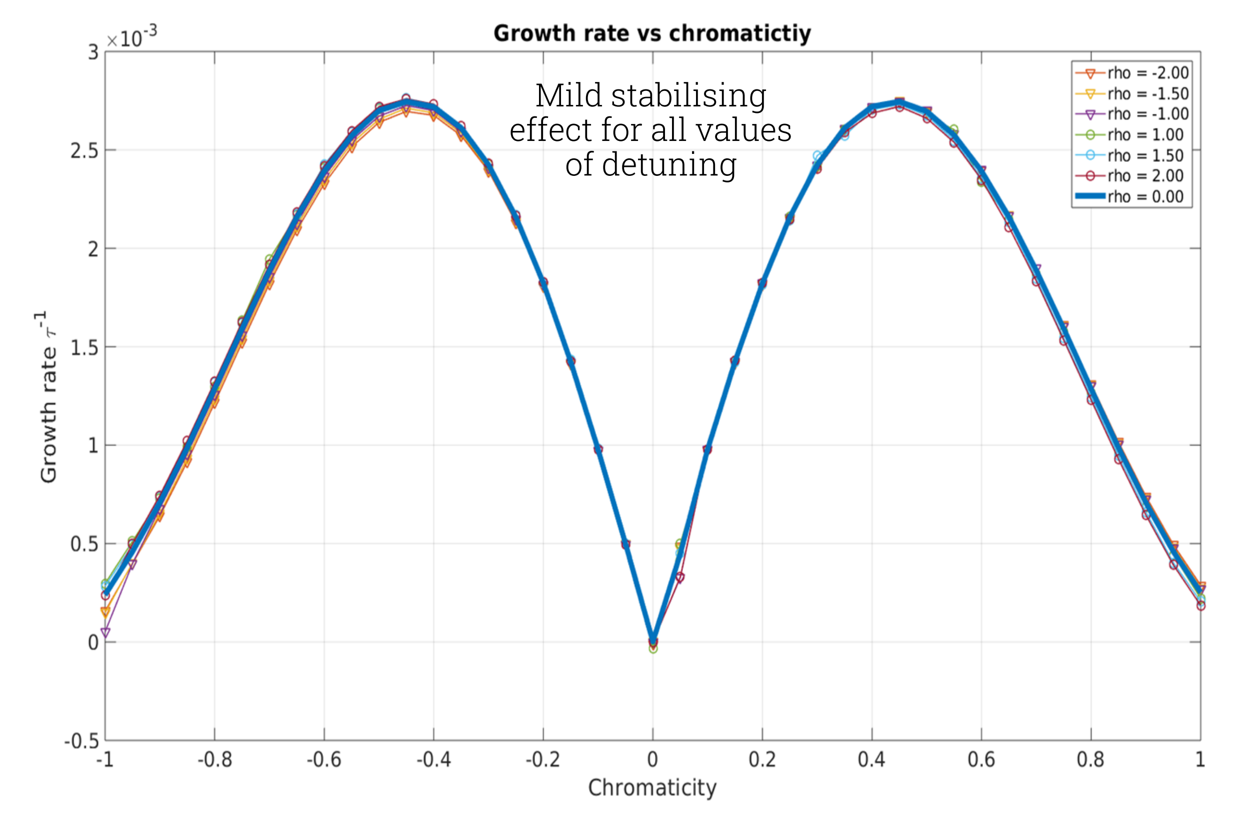
$$\rho = \frac{k_Q}{k_D}$$

  where k_Q is detuning wake and k_D is driving wake
- k_D always kept constant

TWO PARTICLE MODEL

HEAD–TAIL REGIME

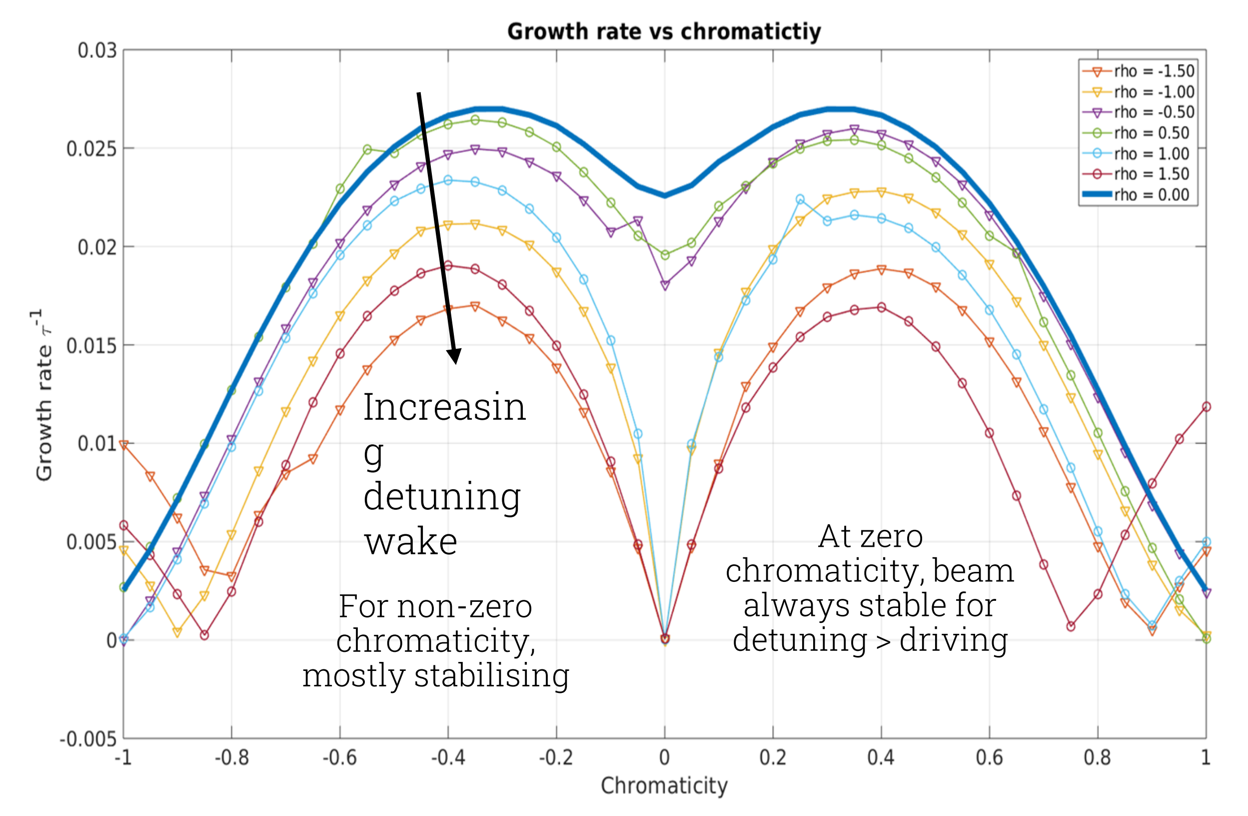
- Impedance: resistive wall
- Non-linear synchrotron motion



TWO PARTICLE MODEL

TMCI REGIME

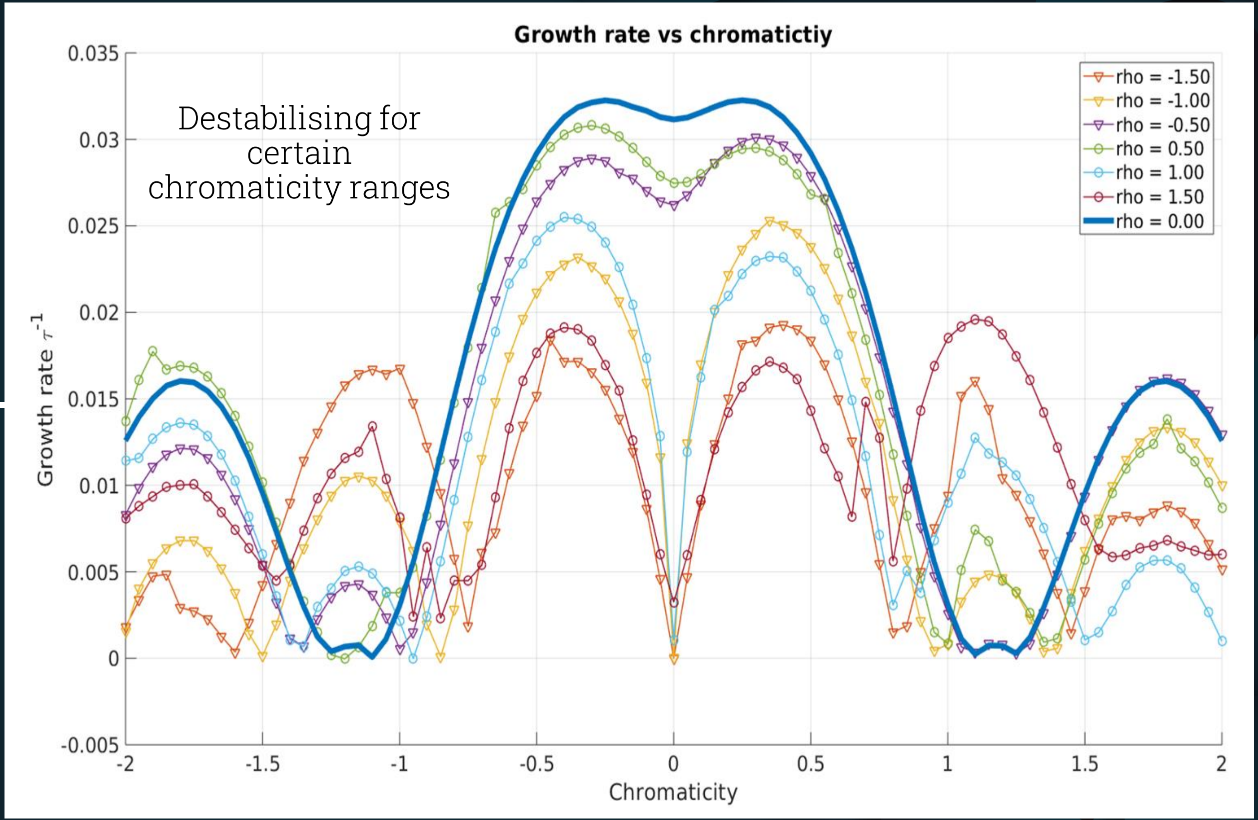
- Impedance: resistive wall
- Non-linear synchrotron motion



TWO PARTICLE MODEL

EXPANDED SWEEP

- Sweep with higher chromaticity range
- Impedance: resistive wall
- Non-linear synchrotron motion



RESULTS

- Very low effect in Head-Tail regime
- In the TMCI regime
  - Always stabilising at zero chromaticity
  - Destabilises in some chromaticity ranges
- Effect depends on the chromaticity and the relative magnitude of driving and detuning wakes
  - Greater impact for detuning > driving
- Matches the expectation of analytical two particle model

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02

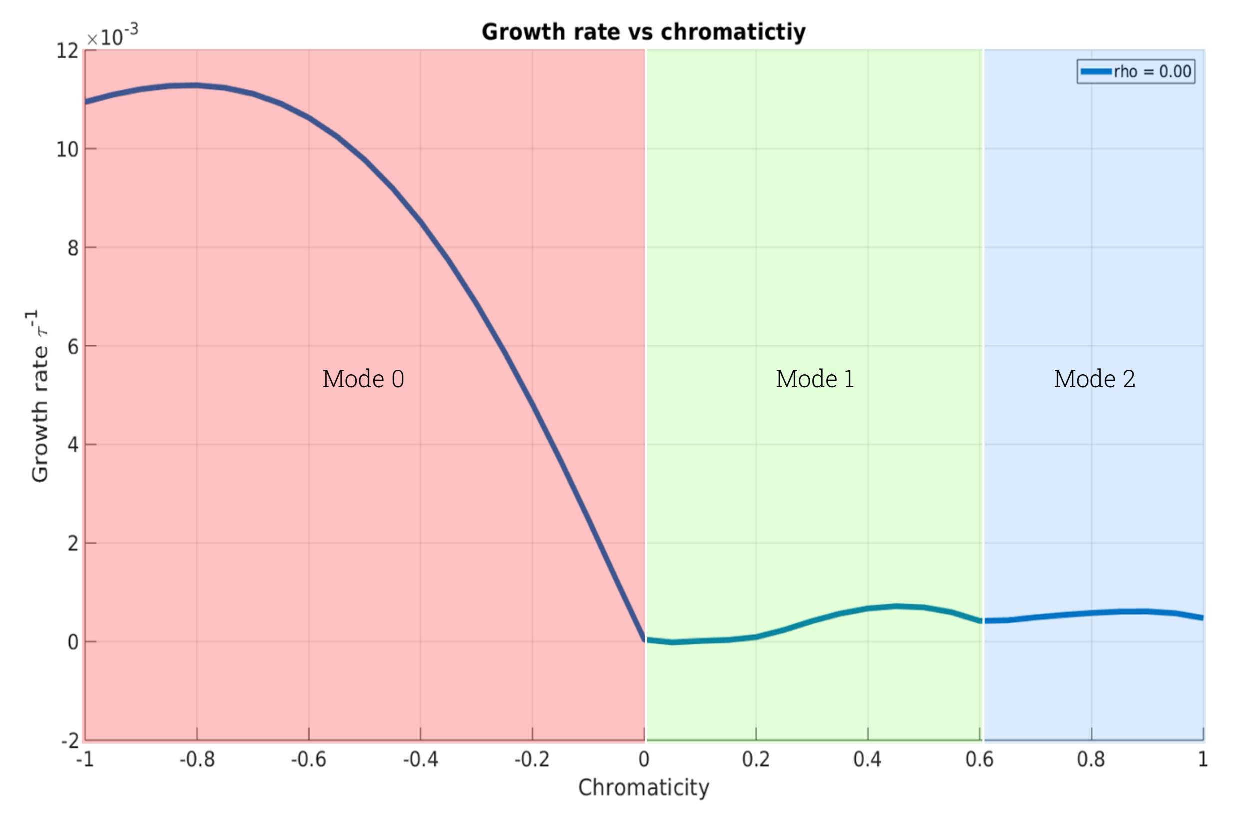
MANY PARTICLE MODEL

Extending previous simulations to consider large number of macroparticles and benchmarking with EDELPHI

MANY PARTICLE MODEL

DIFFERENT MODES

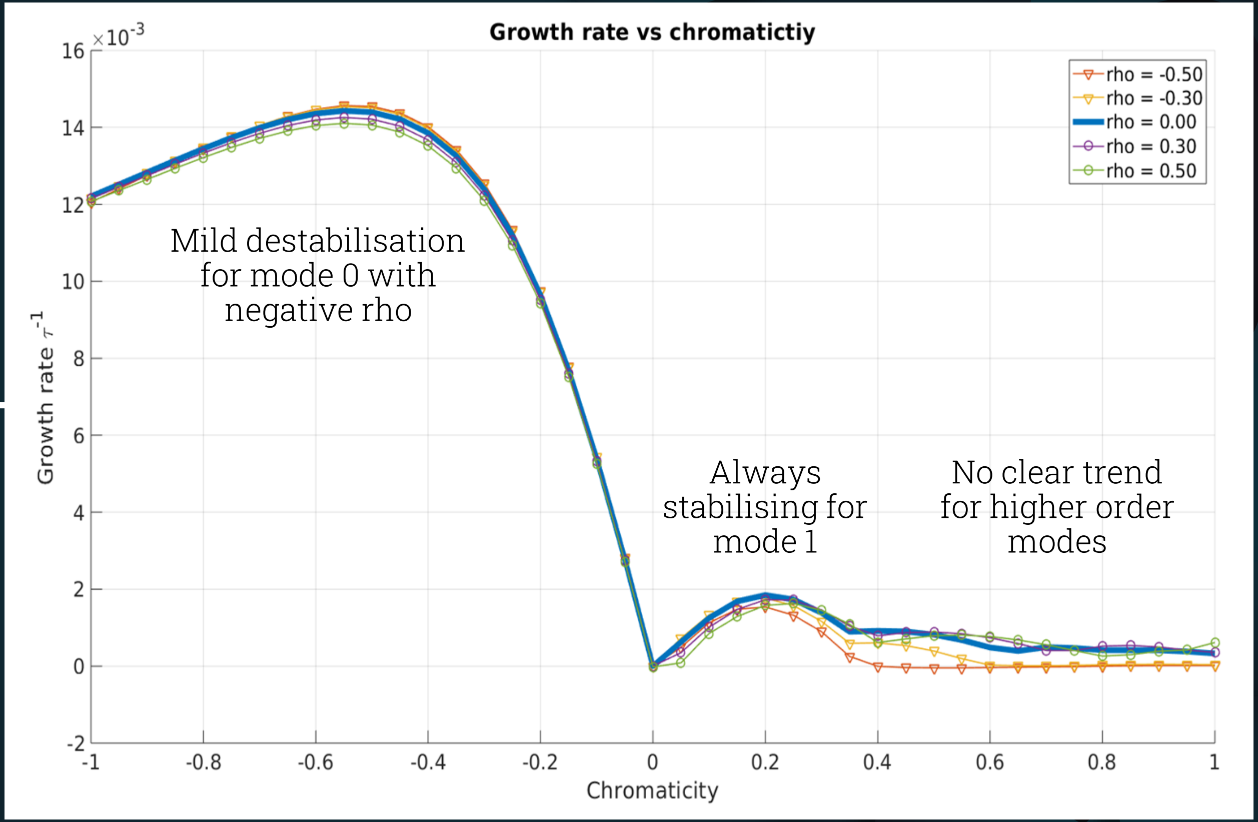
- Three modes expected
- Identified by observing intra-bunch motion



MANY PARTICLE MODEL

EFFECT W.R.T CHROMATICITY

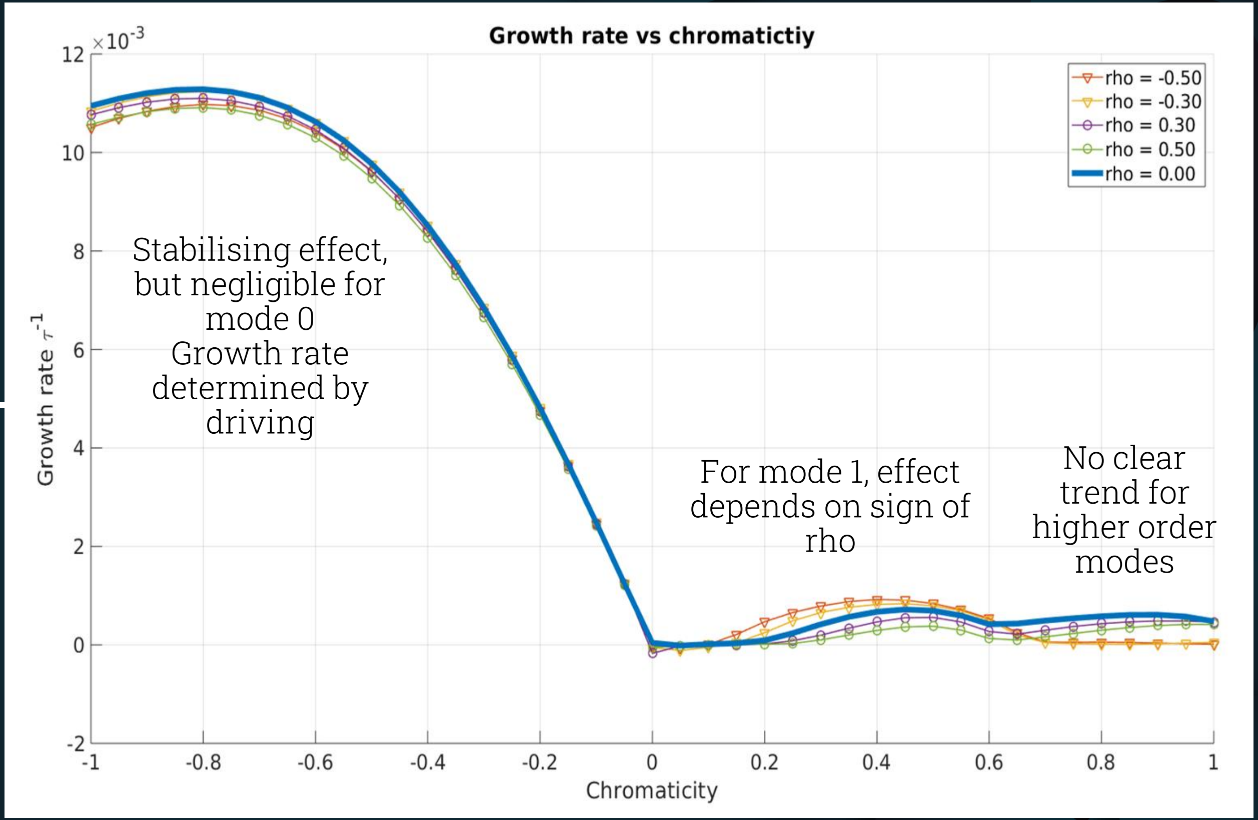
- Impedance: Resistive wall
- Linear synchrotron motion



MANY PARTICLE MODEL

EFFECT W.R.T CHROMATICITY

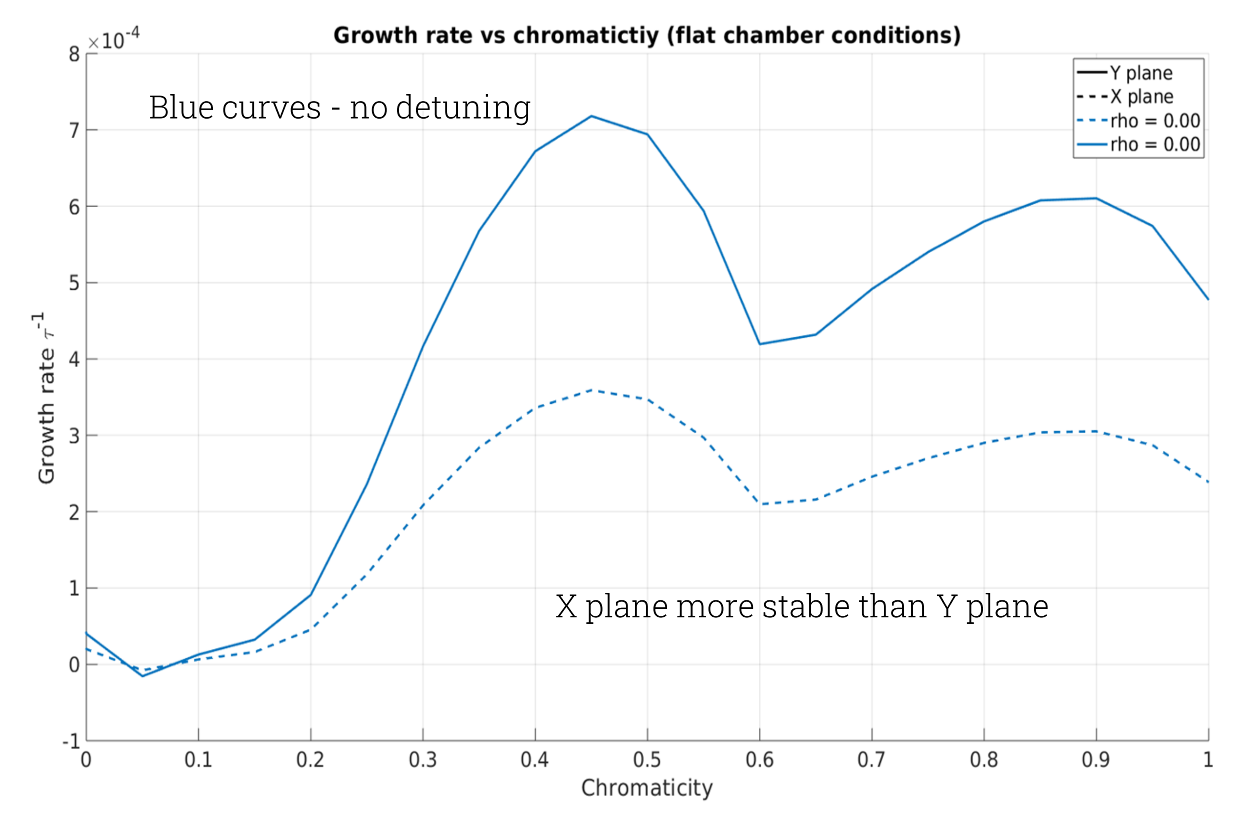
- Impedance: resistive wall
- Non-linear synchrotron motion
- Single harmonic RF voltage



MANY PARTICLE MODEL

FLAT CHAMBER CONDITIONS

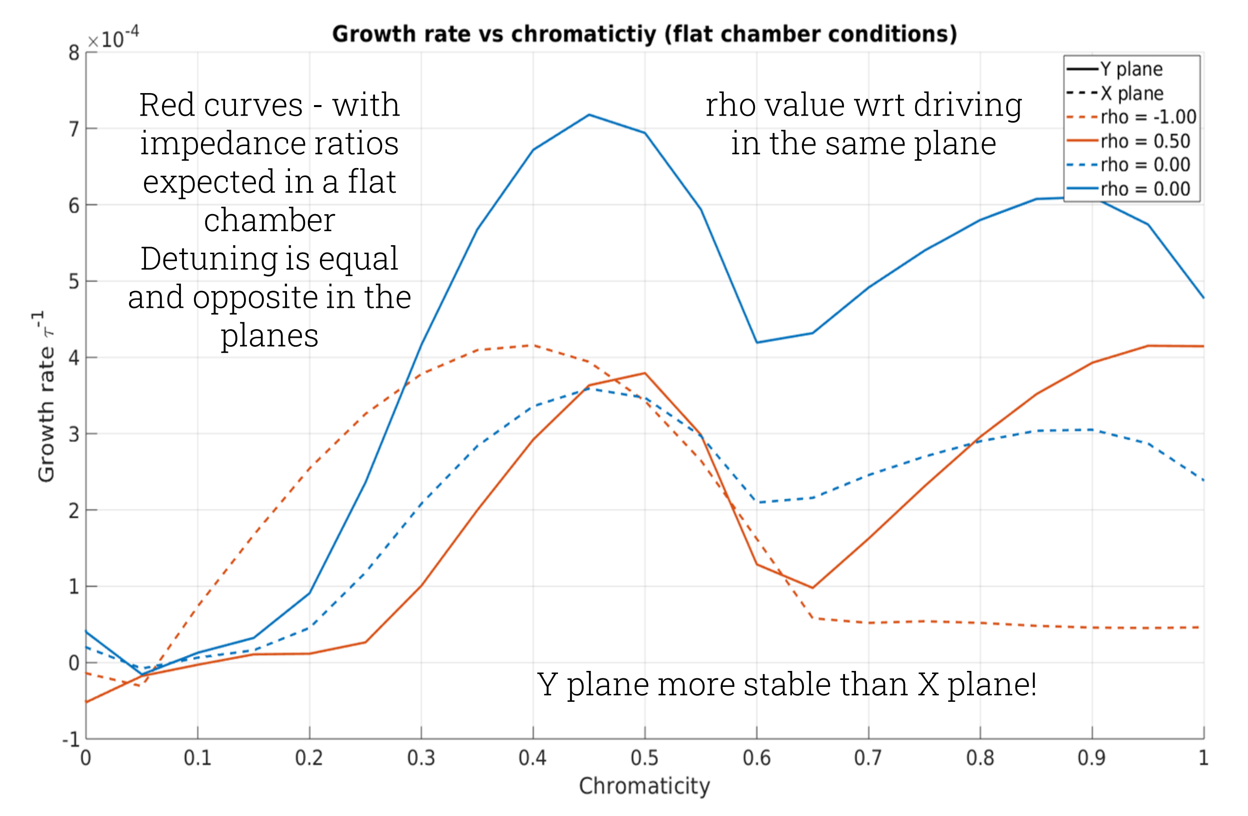
- Impedance: resistive wall
- Non-linear synchrotron motion
- Single harmonic RF voltage



MANY PARTICLE MODEL

FLAT CHAMBER CONDITIONS

- Impedance: resistive wall
- Non-linear synchrotron motion
- Single harmonic RF voltage



RESULTS

- Impact depends on the sign of the detuning impedance and chromaticity
  - For a flat chamber, a situation where the vertical plane is more stable than the horizontal plane is possible
- Second harmonic RF voltage also has an impact
  - Low second harmonic RF voltage - destabilises mode 1
  - High second harmonic RF voltage - stabilises mode 1
- Interesting to study this effect further

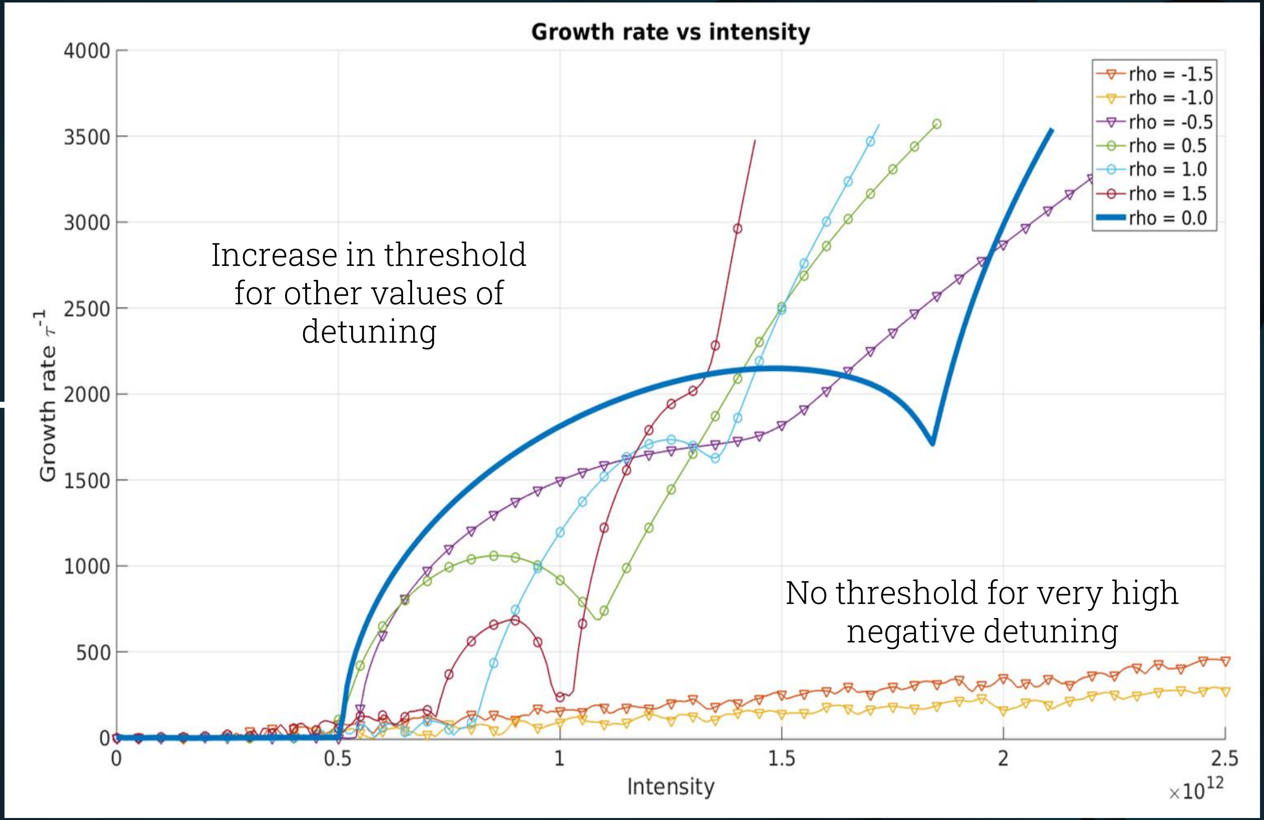
EFFECT ON TMCI THRESHOLD

- Detuning also expected to impact TMCI threshold
- Intensity sweeps carried out with different impedances

MANY PARTICLE MODEL

RESISTIVE WALL

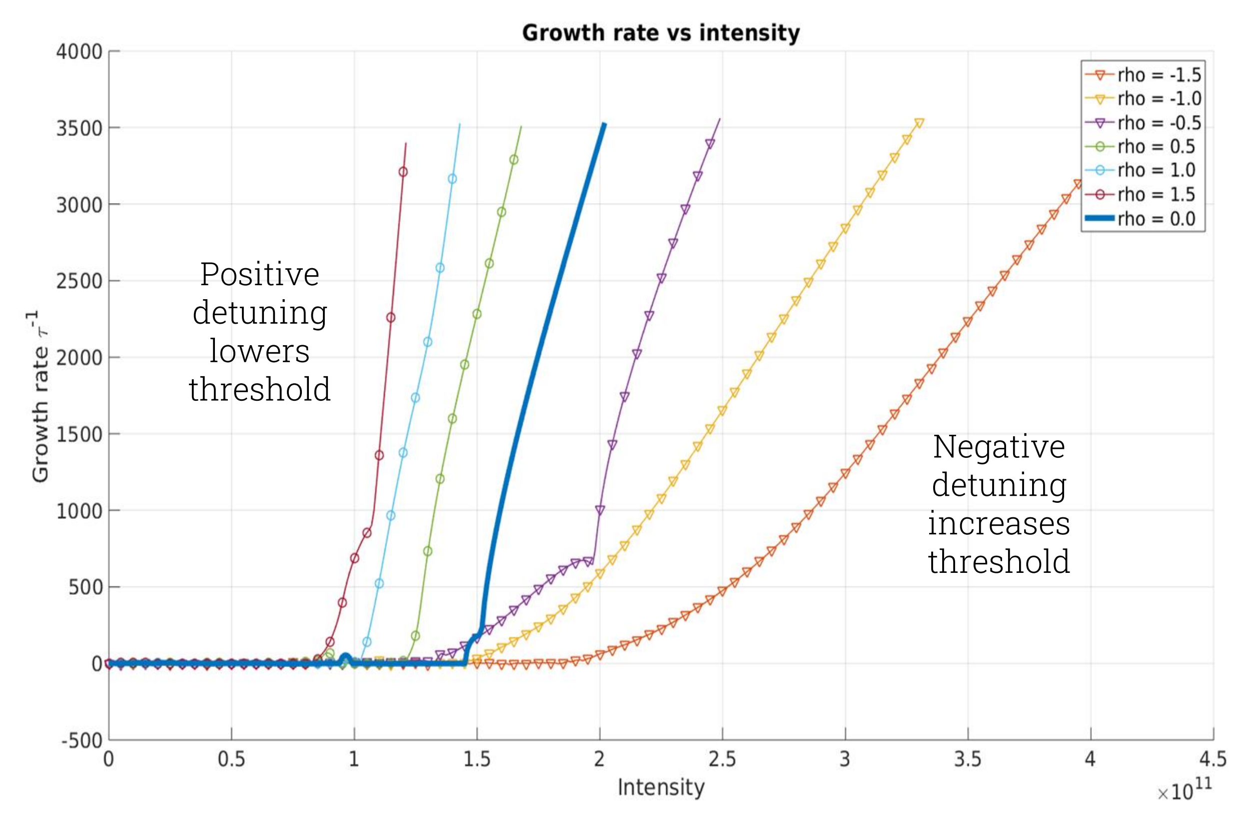
- Impedance: resistive wall
- Linear synchrotron motion



MANY PARTICLE MODEL

BROADBAND RESONATOR – SPS LIKE PARAMETERS

- Impedance: broadband resonator with Q = 1, f = 1 GHz and R = 7 M Ohm
- Linear synchrotron motion



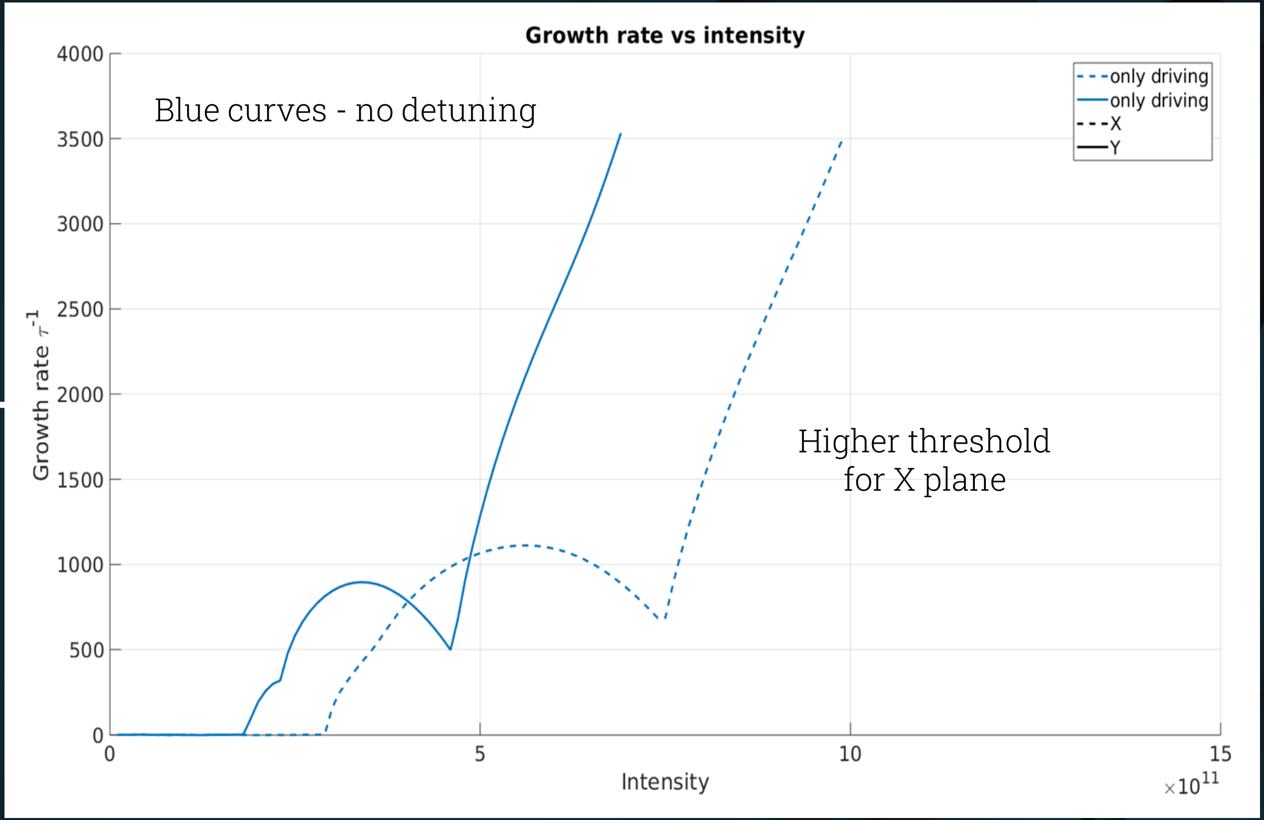
USING REALISTIC SPS WAKES

- Realistic SPS impedance model available as a wake table with values for driving and detuning in X and Y planes
- Post LS2 model used
- 2 conditions considered
    - Only driving wakes
    - Driving + detuning wakes

MANY PARTICLE MODEL

SPS IMPEDANCE

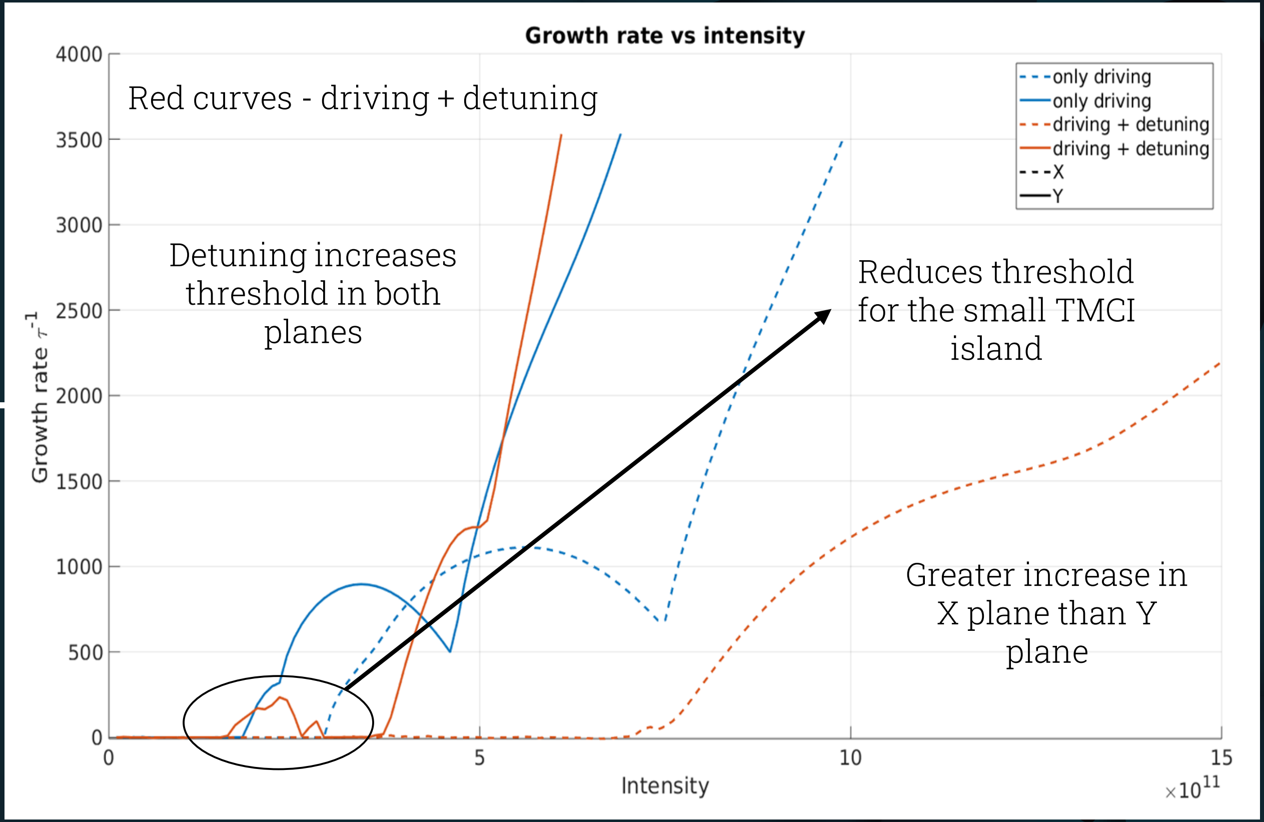
- Impedance: SPS wake model
- Linear synchrotron motion



MANY PARTICLE MODEL

SPS IMPEDANCE

- Higher threshold for X plane
- Threshold for X increased more by detuning than for Y



RESULTS

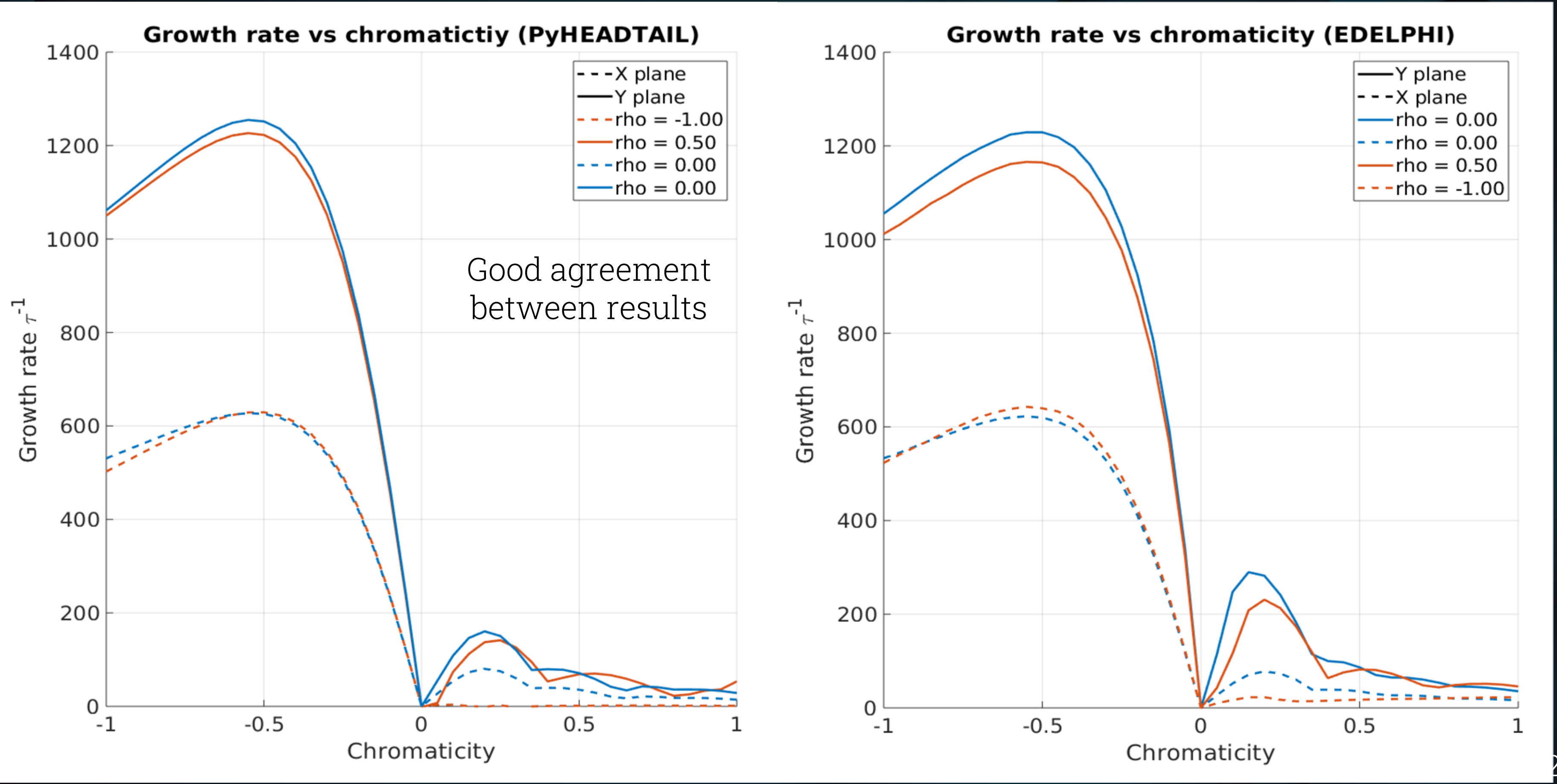
- Detuning impedance affects the TMCI threshold
  - The threshold for the horizontal plane is pushed farther than the threshold for the vertical plane in the SPS
- Different impact depending on kind of impedance considered

BENCHMARKING WITH EDELPHI

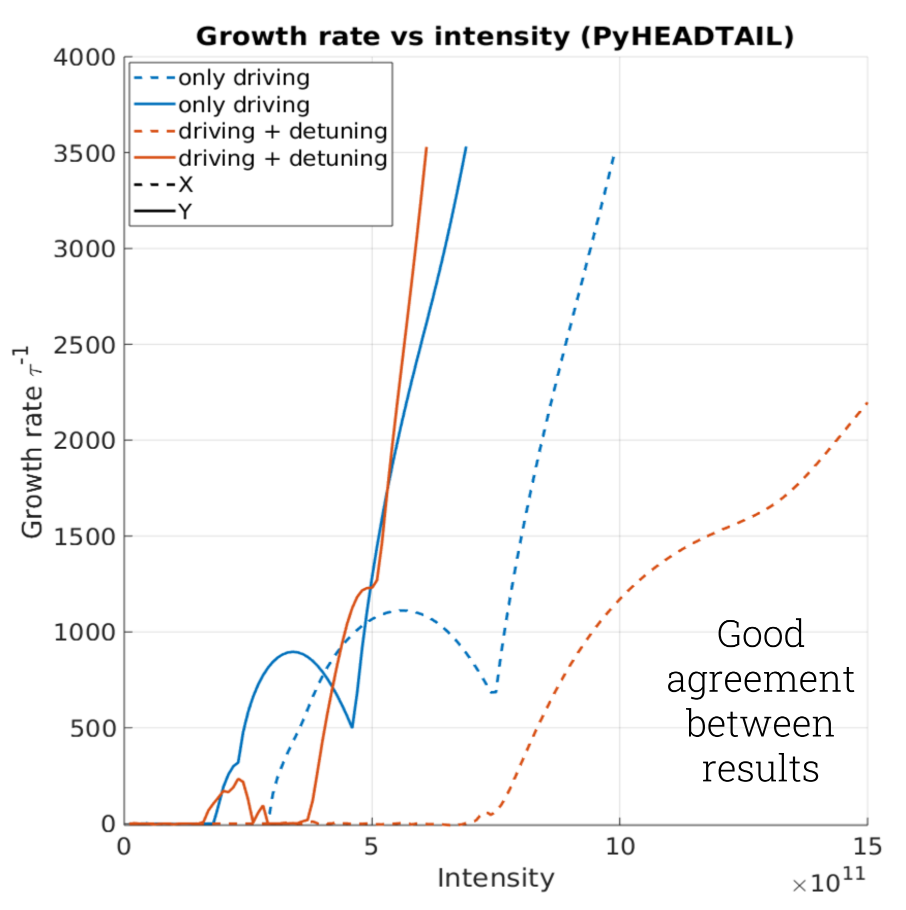
- Vlasov solver based approach
- Allows more detailed tune analysis than PyHEADTAIL

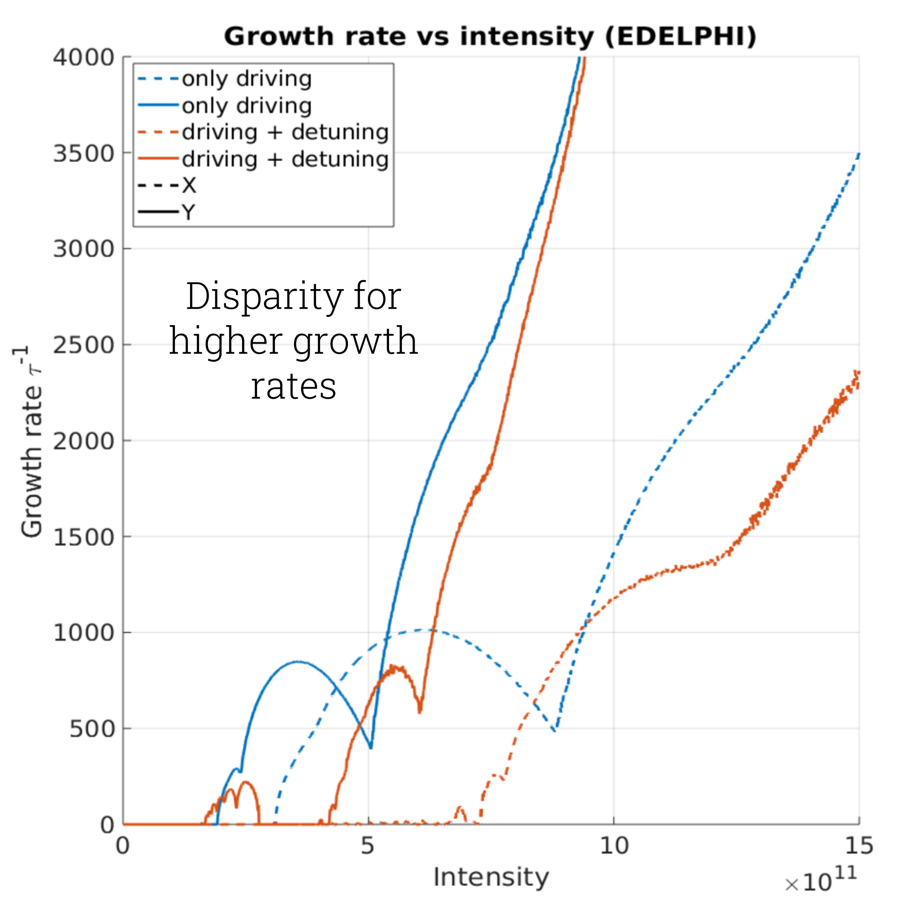
MANY PARTICLE MODEL

FLAT CHAMBER CONDITIONS, RESISTIVE WALL

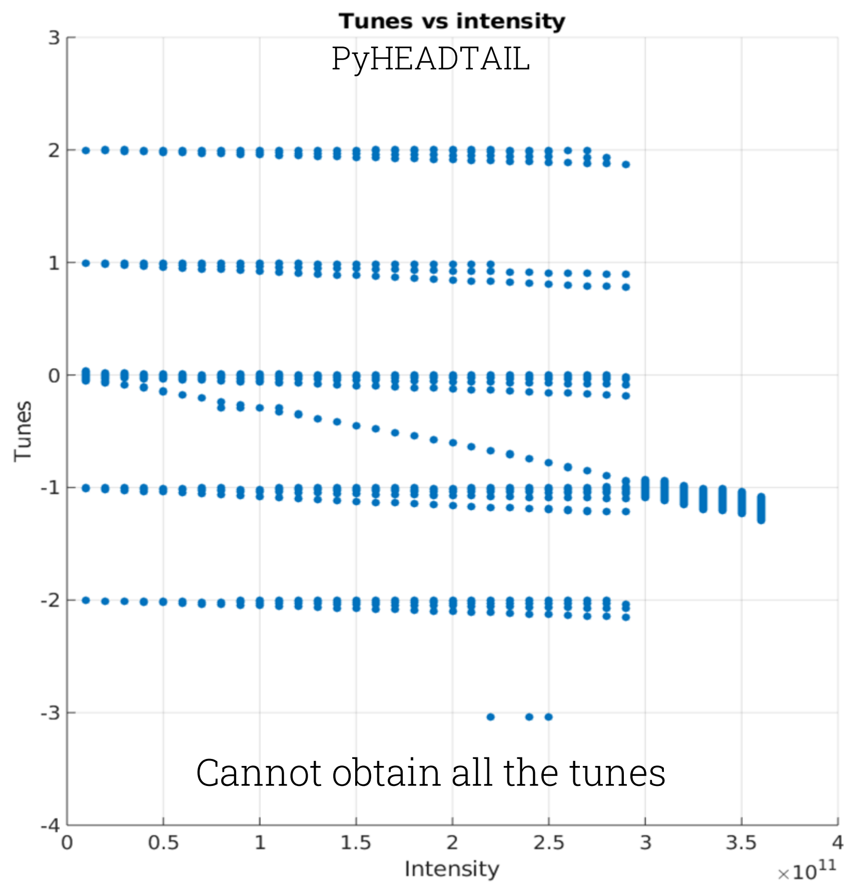


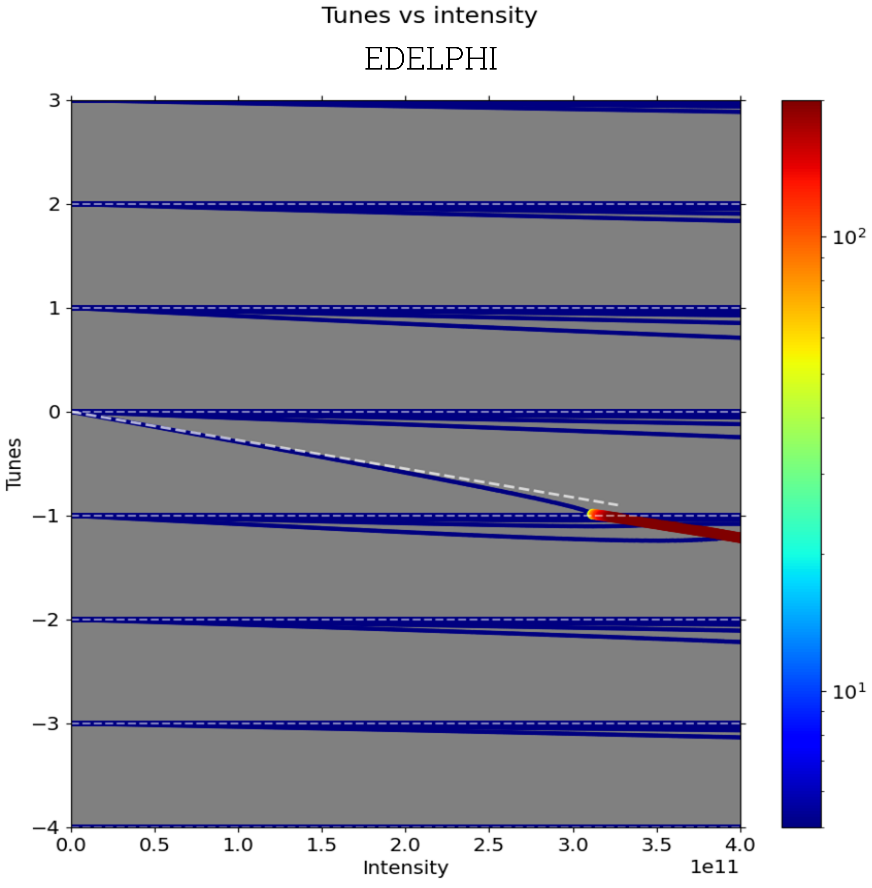
COMPARING GROWTH RATES, REAL WAKES





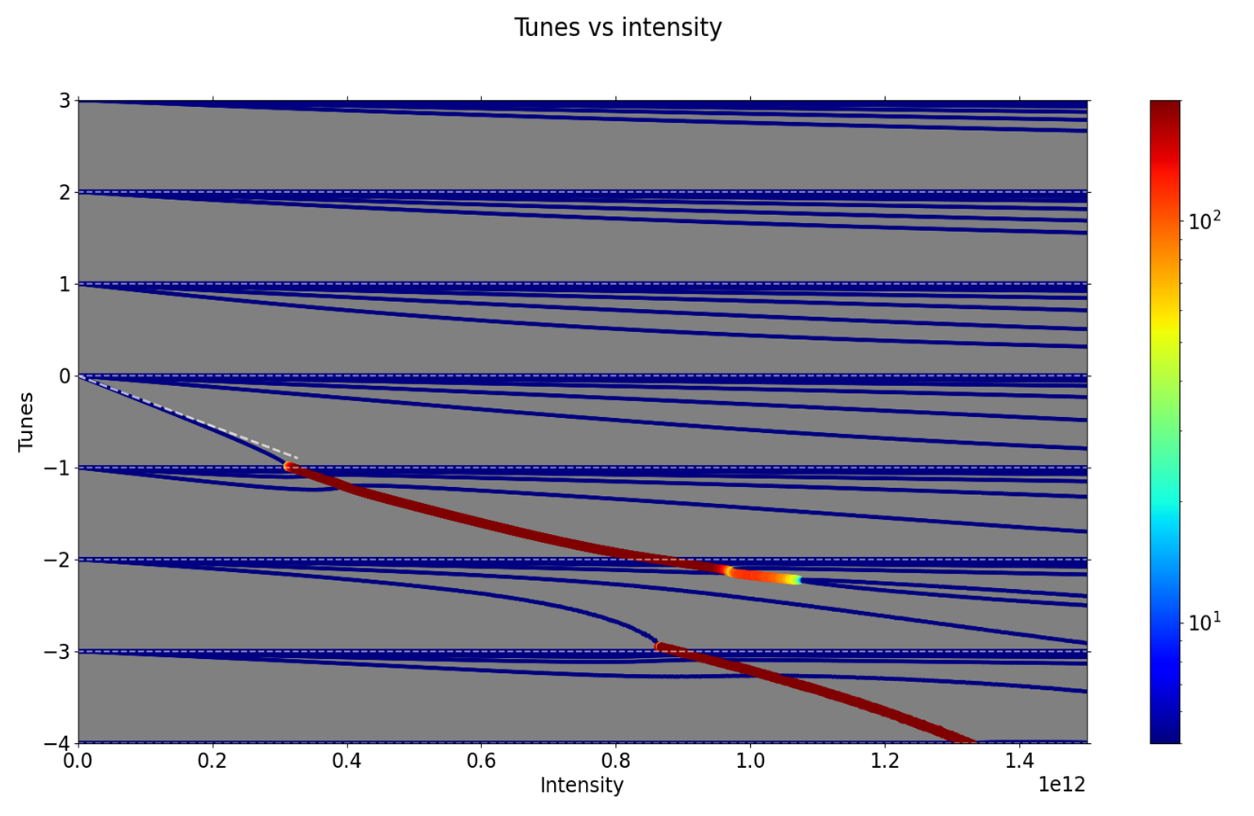
COMPARING X TUNES – WITHOUT DETUNING



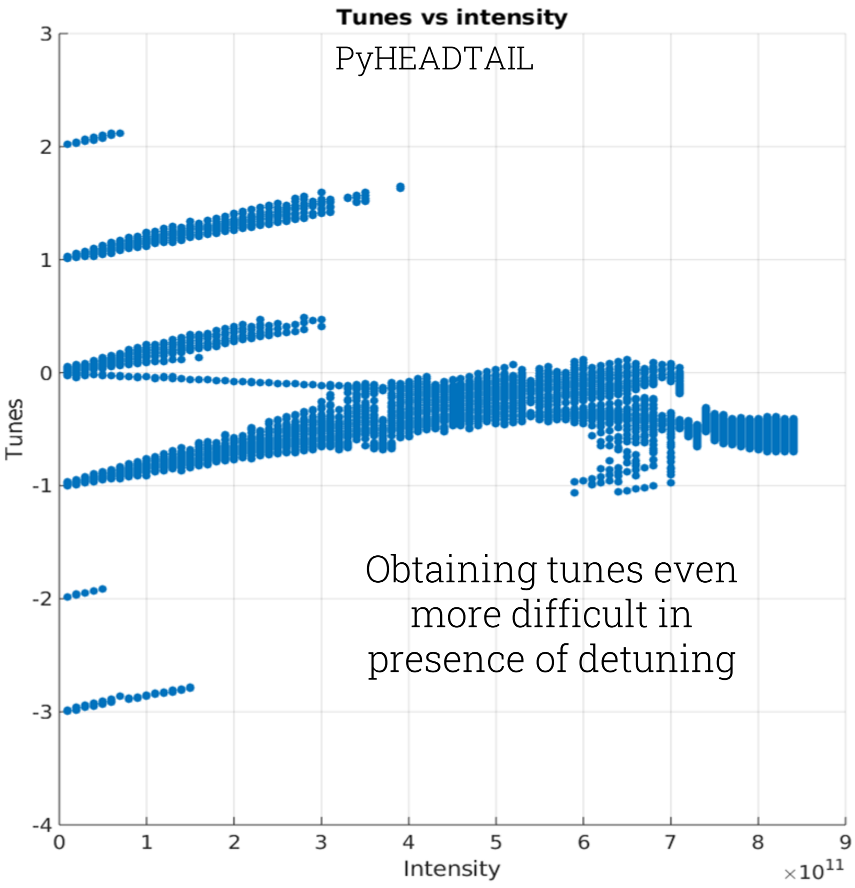


TUNE ANALYSIS – X WITHOUT DETUNING

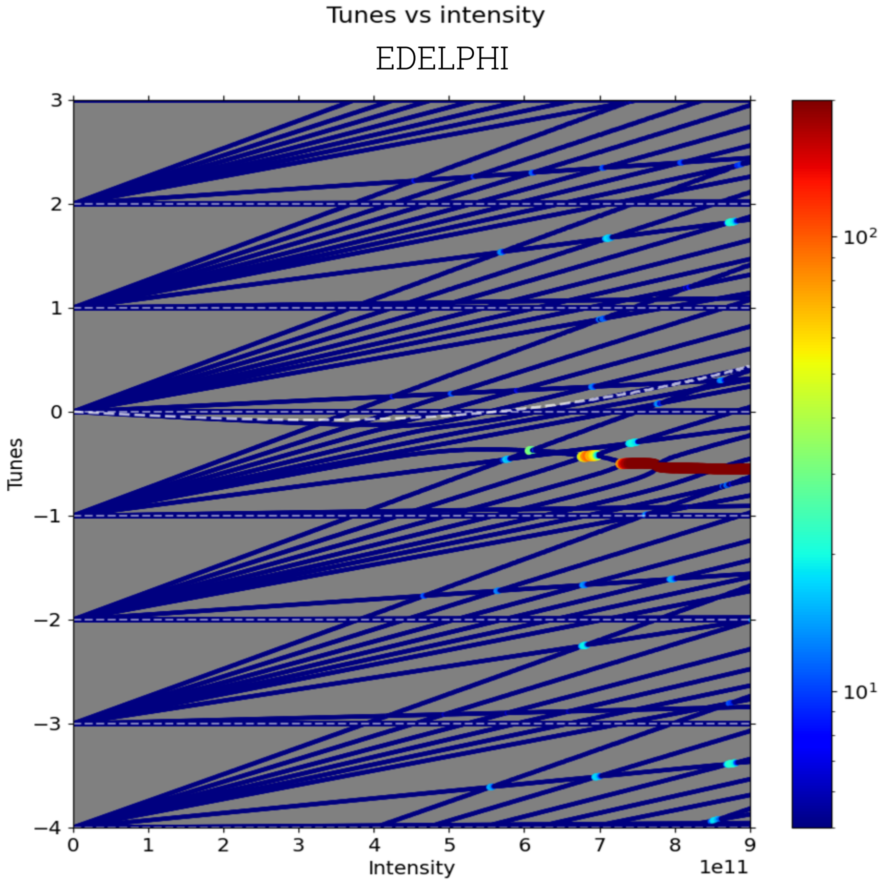
- Zooming out
- Complete tune picture possible



COMPARING X TUNES – WITH DETUNING



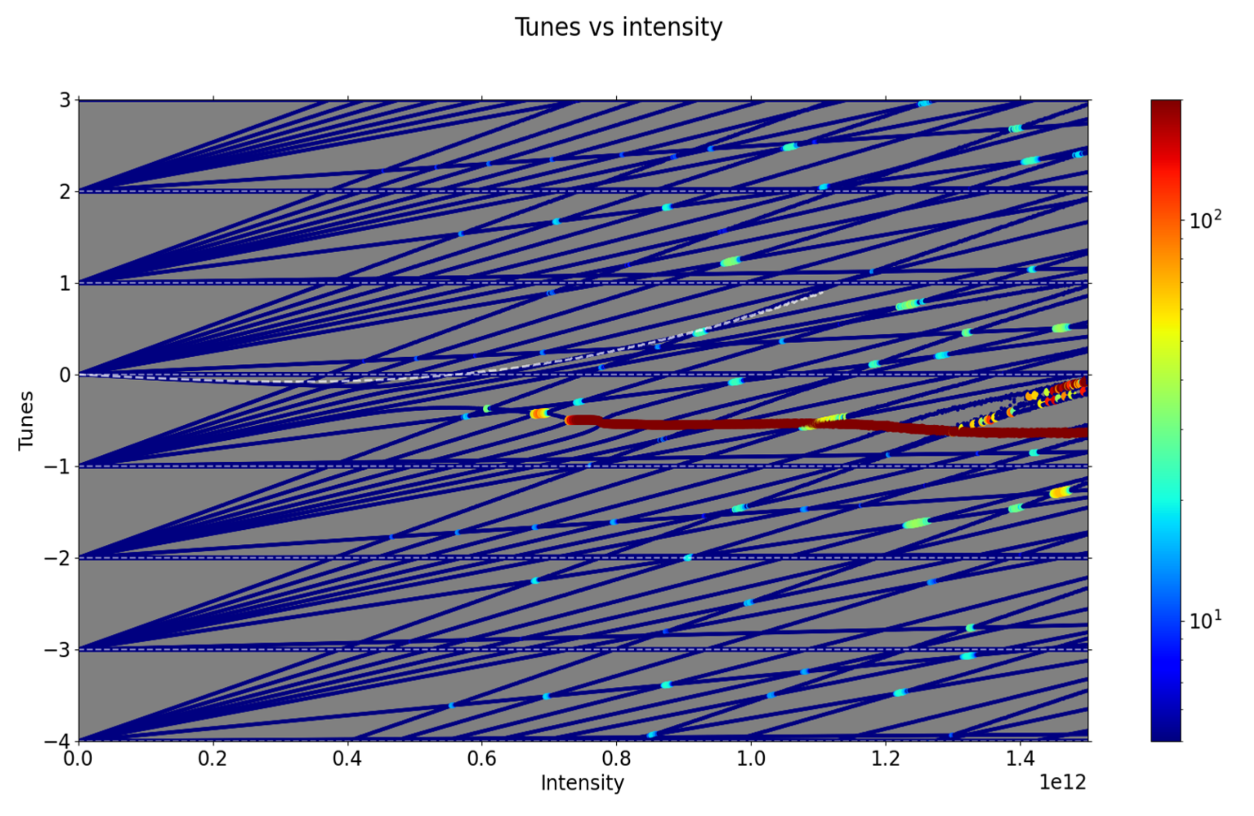
Obtaining tunes even more difficult in presence of detuning



MANY PARTICLE MODEL

TUNE ANALYSIS – X WITH DETUNING

- Zooming out
- Complete tune analysis possible even with detuning



RESULTS

- Good agreement between PyHEADTAIL and EDELPHI for intensity sweeps to a certain extent
  - Same threshold observed with both tools
  - Growth rates differ after ~500 for intensity sweep
- Response is in better agreement for chromaticity sweep

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03

DETUNING IN REAL MACHINE

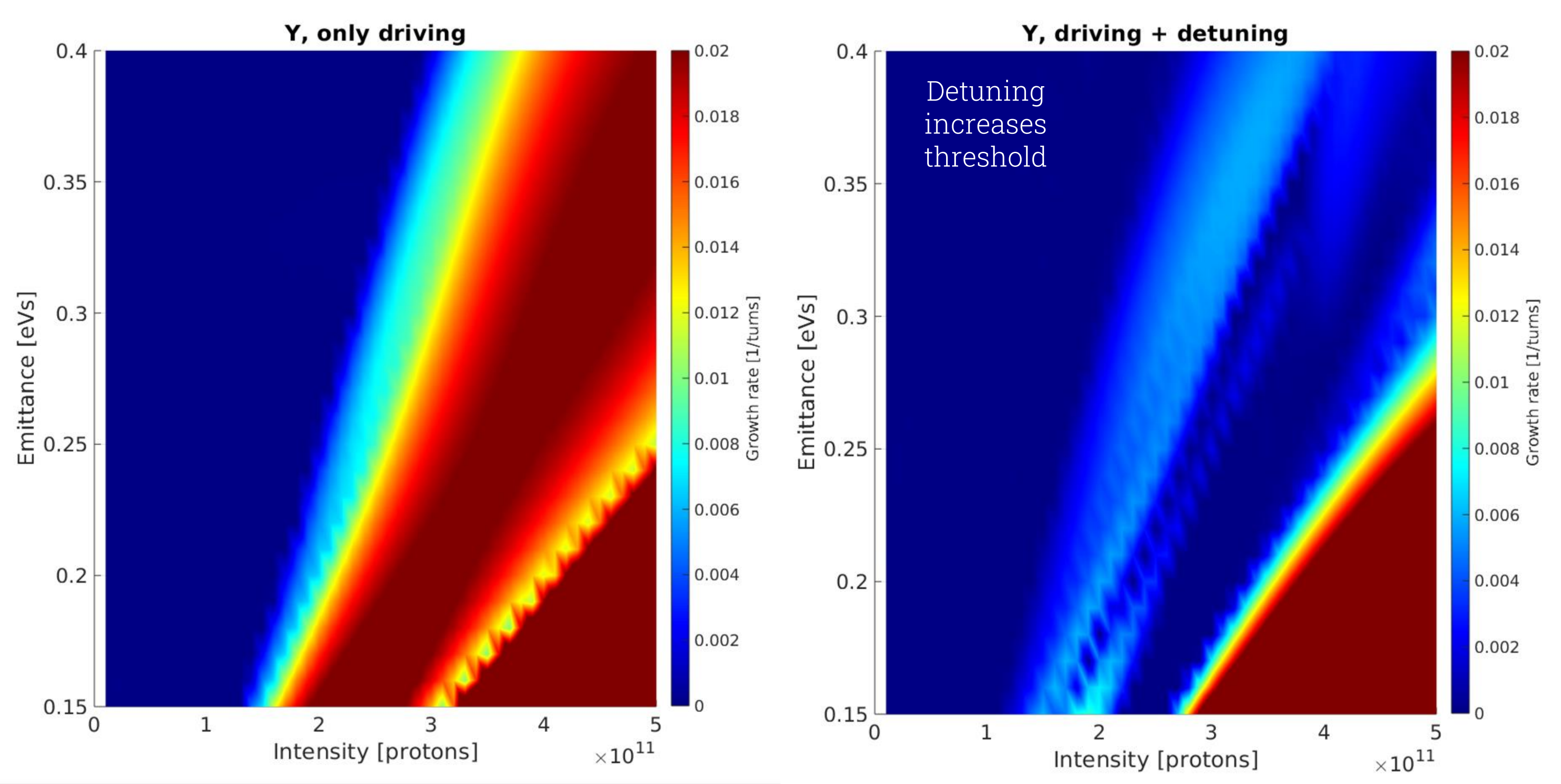
Including specific SPS parameters like higher order chromaticity and optics

EFFECT OF LONGITUDINAL EMITTANCE

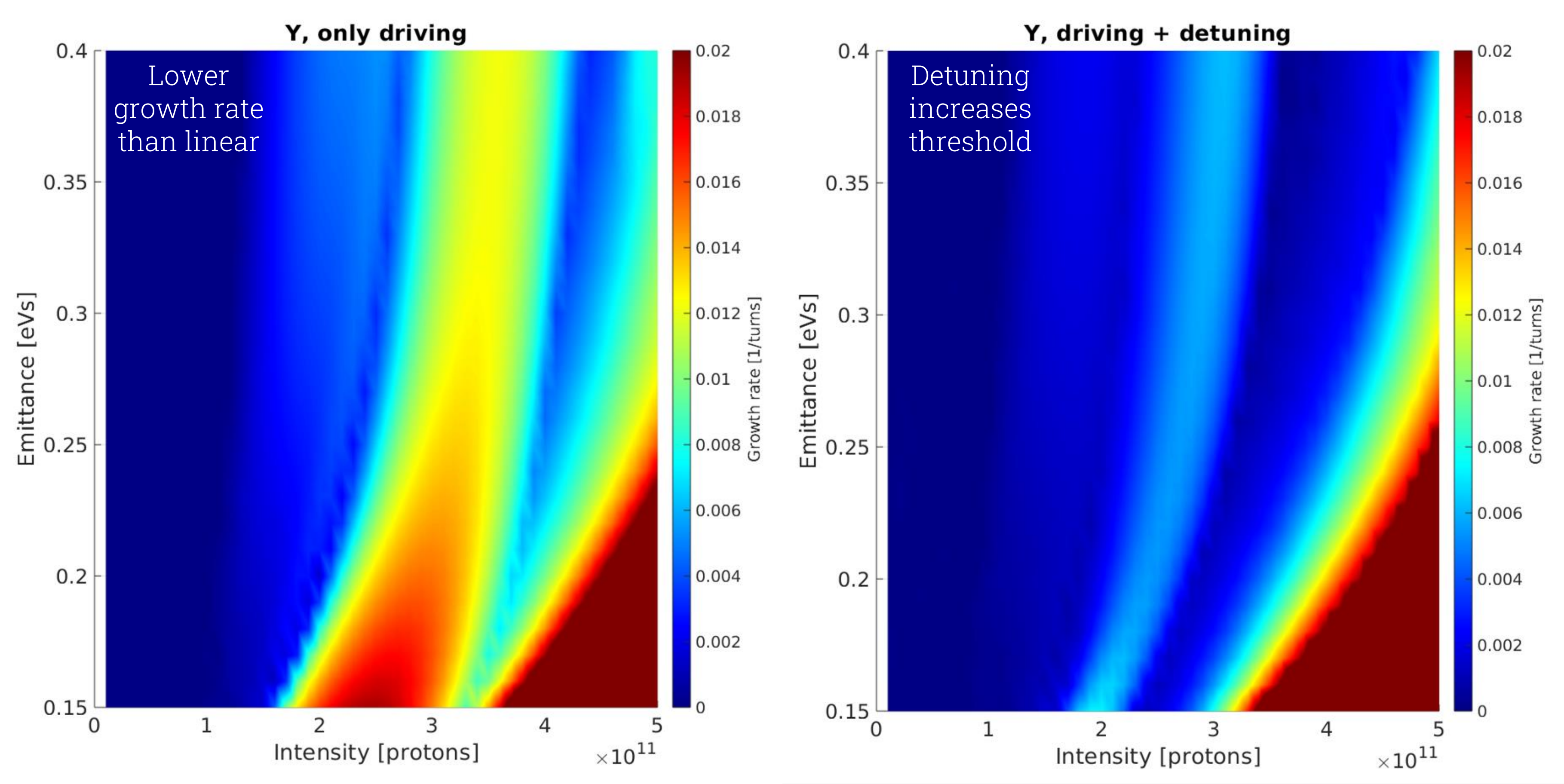
- Longitudinal emittance expected to impact the TMCI threshold
- Higher order chromaticity and non-linearities are considered as well
  - First order chromaticity is zero
- An overview of the effect of detuning is possible by considering the longitudinal emittance

SPS EXAMPLE

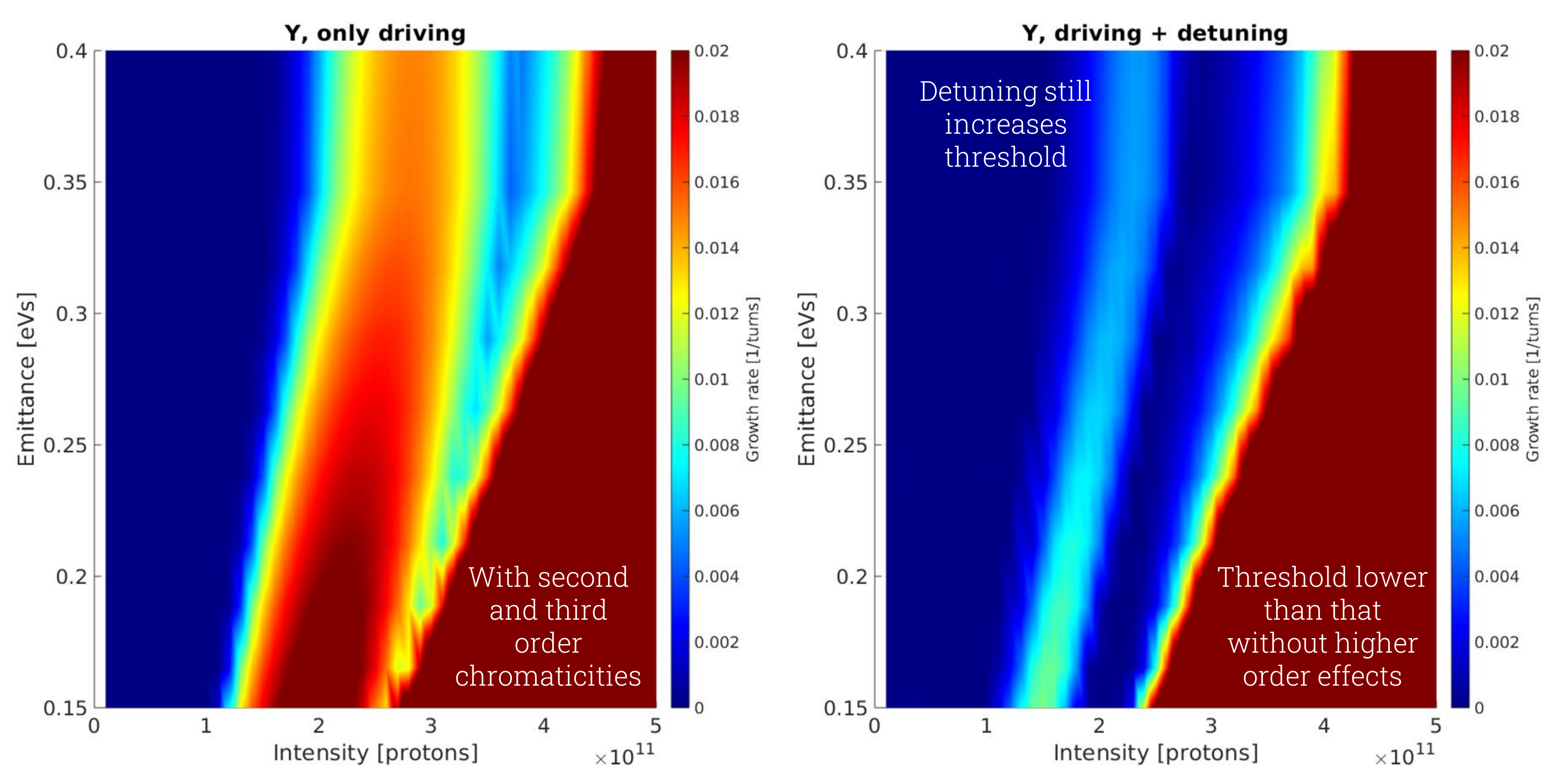
CONSIDERING EMITTANCE, LINEAR



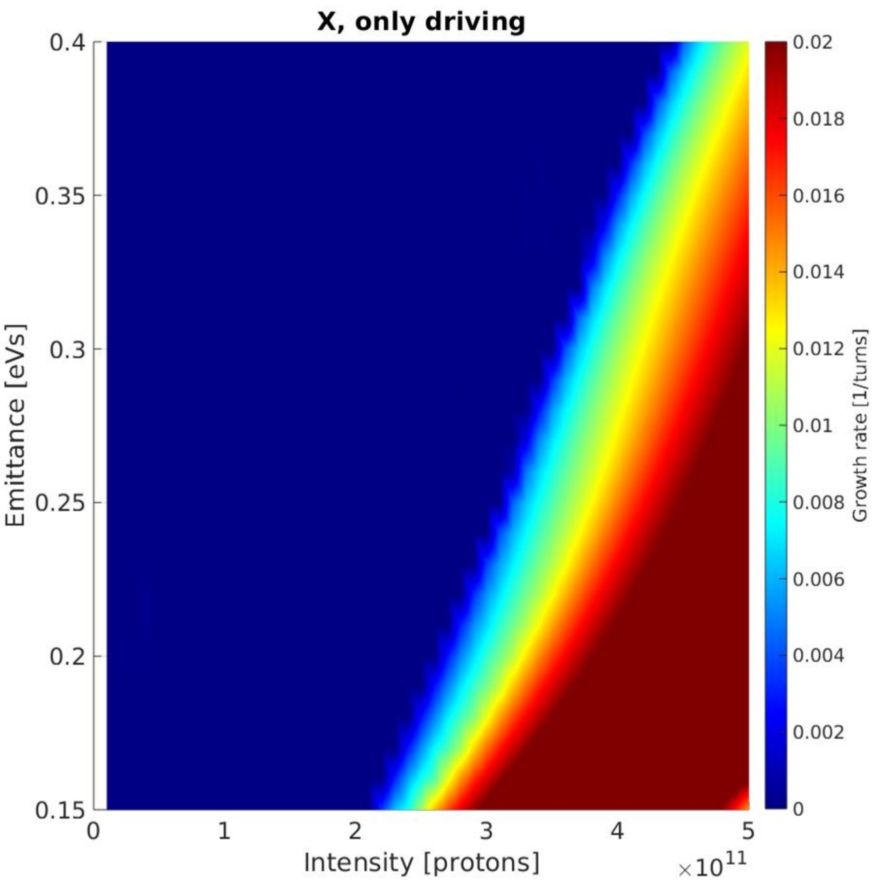
CONSIDERING EMITTANCE, NON LINEAR

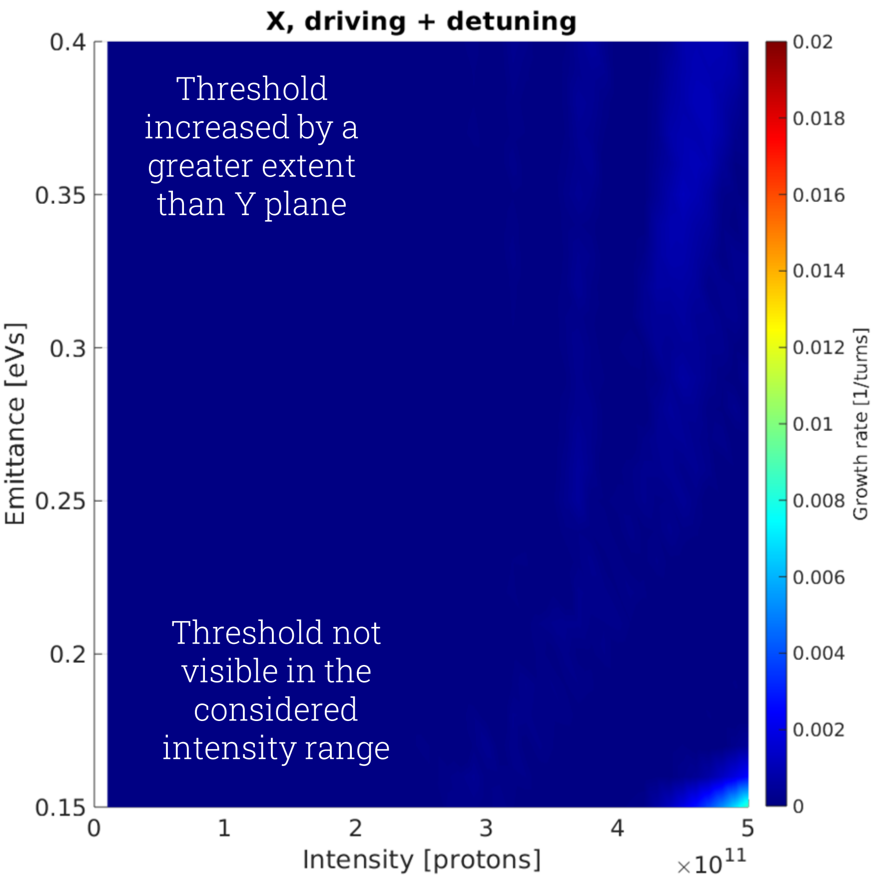


CONSIDERING EMITTANCE, NON LINEAR WITH HIGH ORDER CHROMATICITIES

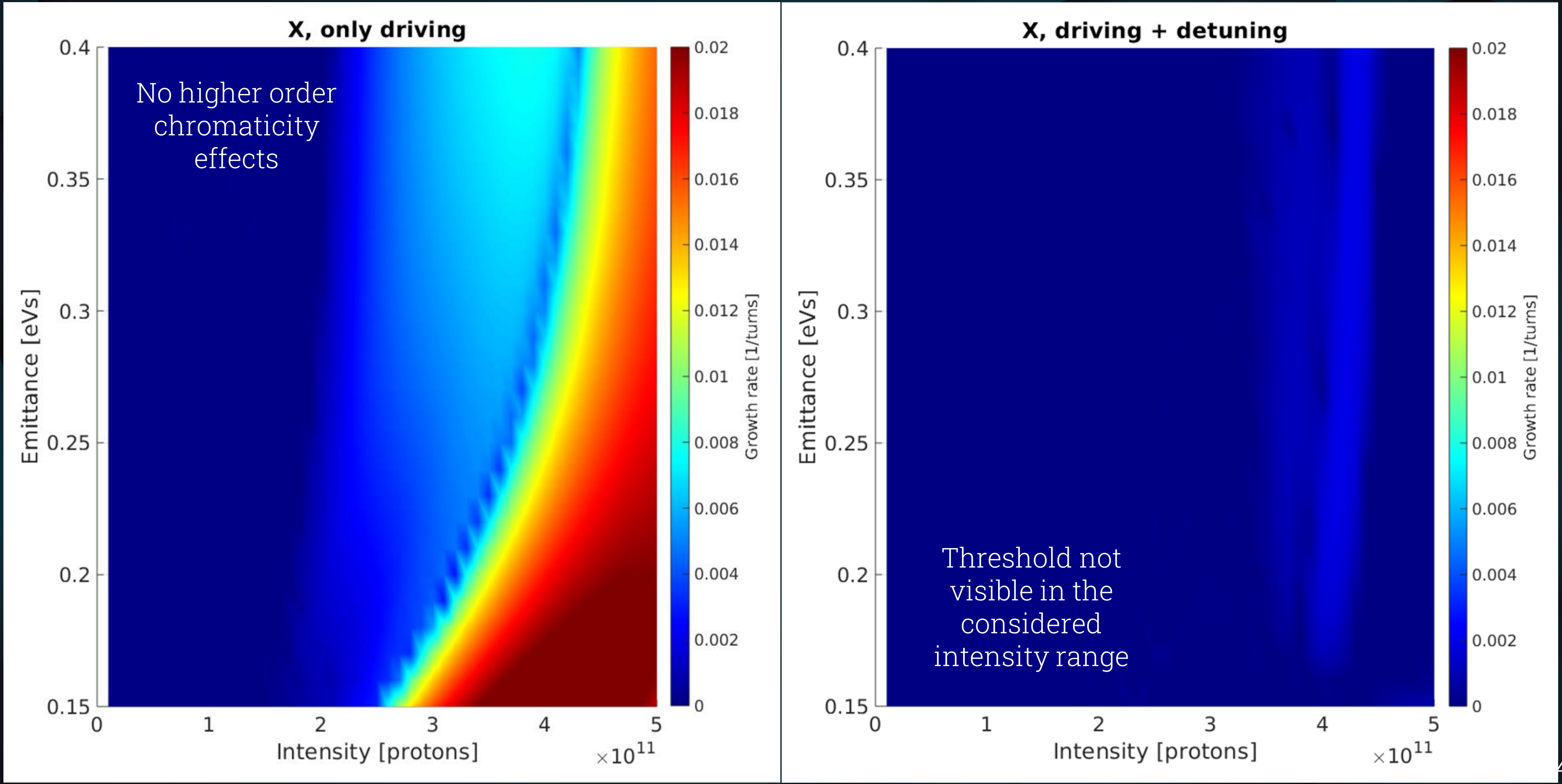


CONSIDERING EMITTANCE, LINEAR

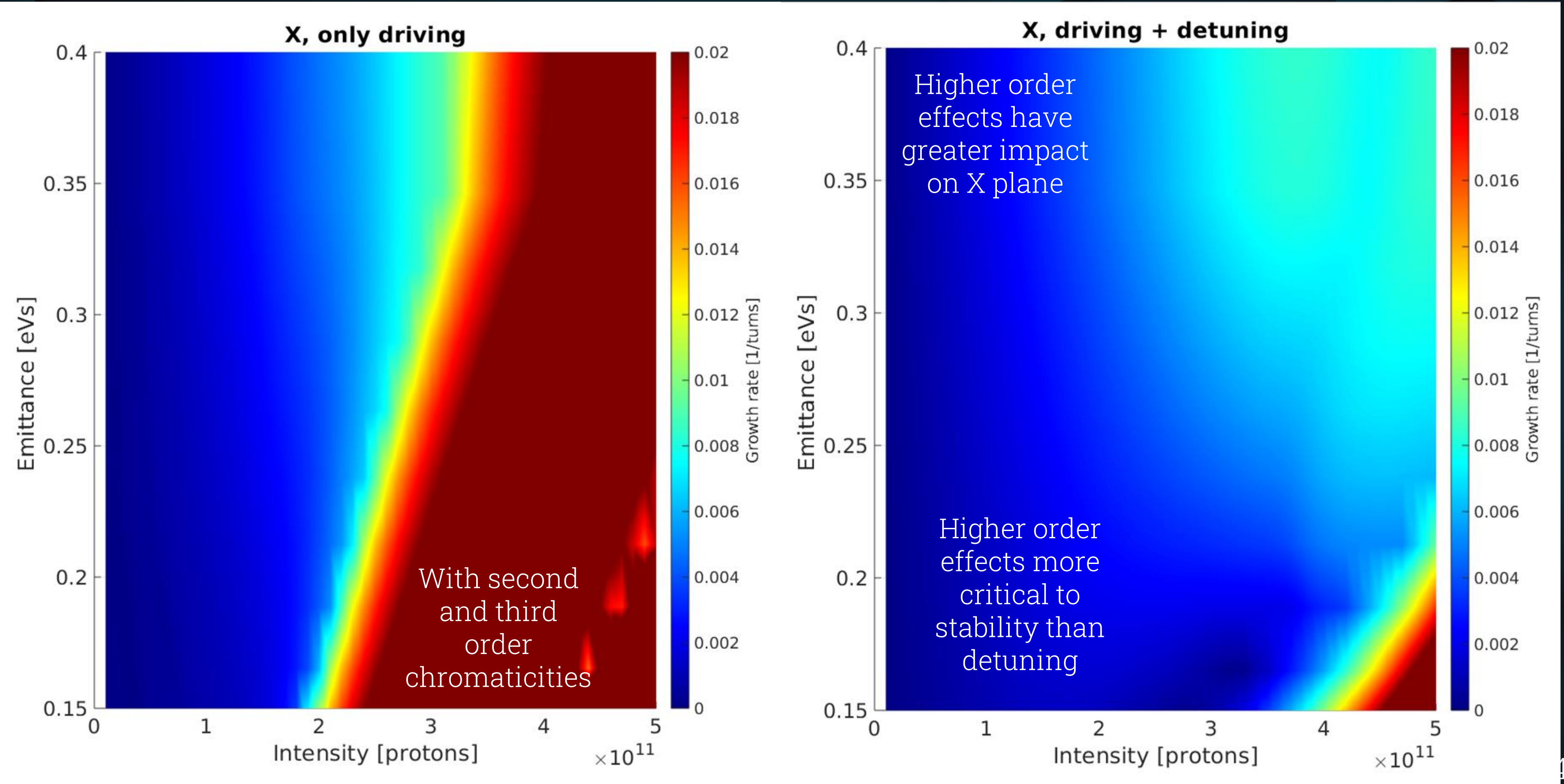




CONSIDERING EMITTANCE, NON LINEAR



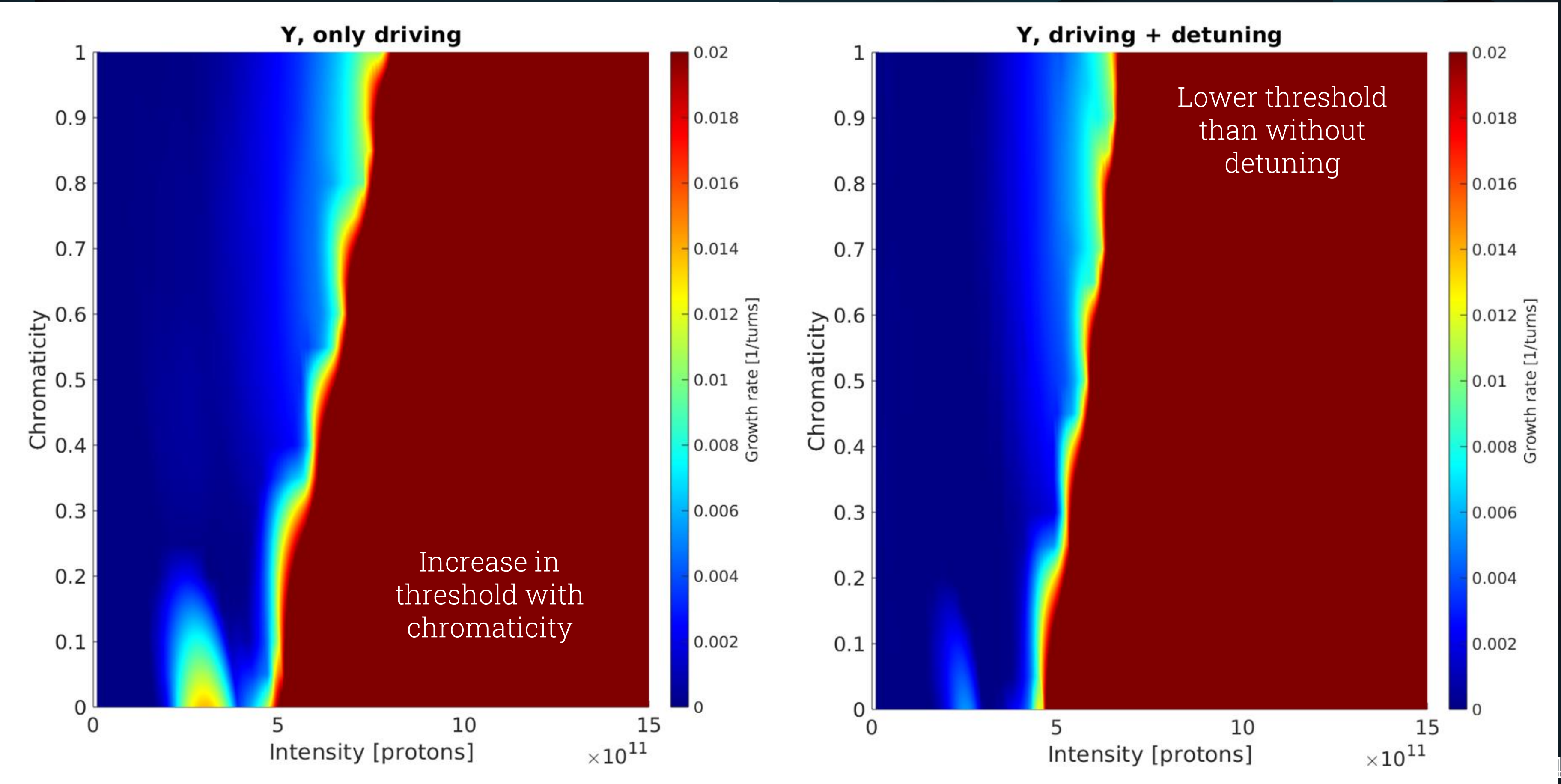
CONSIDERING EMITTANCE, NON LINEAR WITH HIGH ORDER CHROMATICITIES



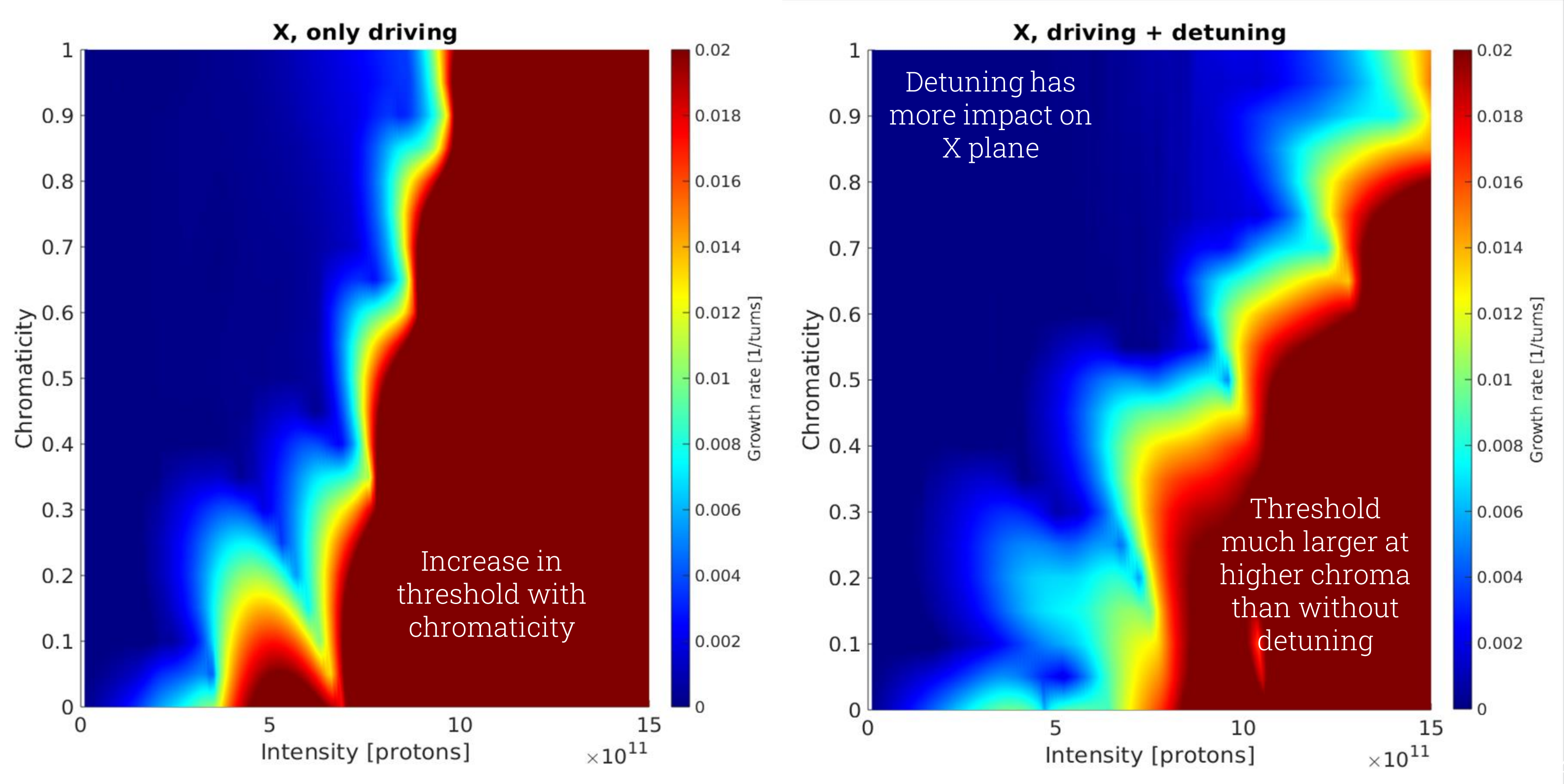
EFFECT OF CHROMATICITY

- The chromaticity of operation also expected to affect the threshold
- Positive chromaticity considered for study
    - Results for two different optics

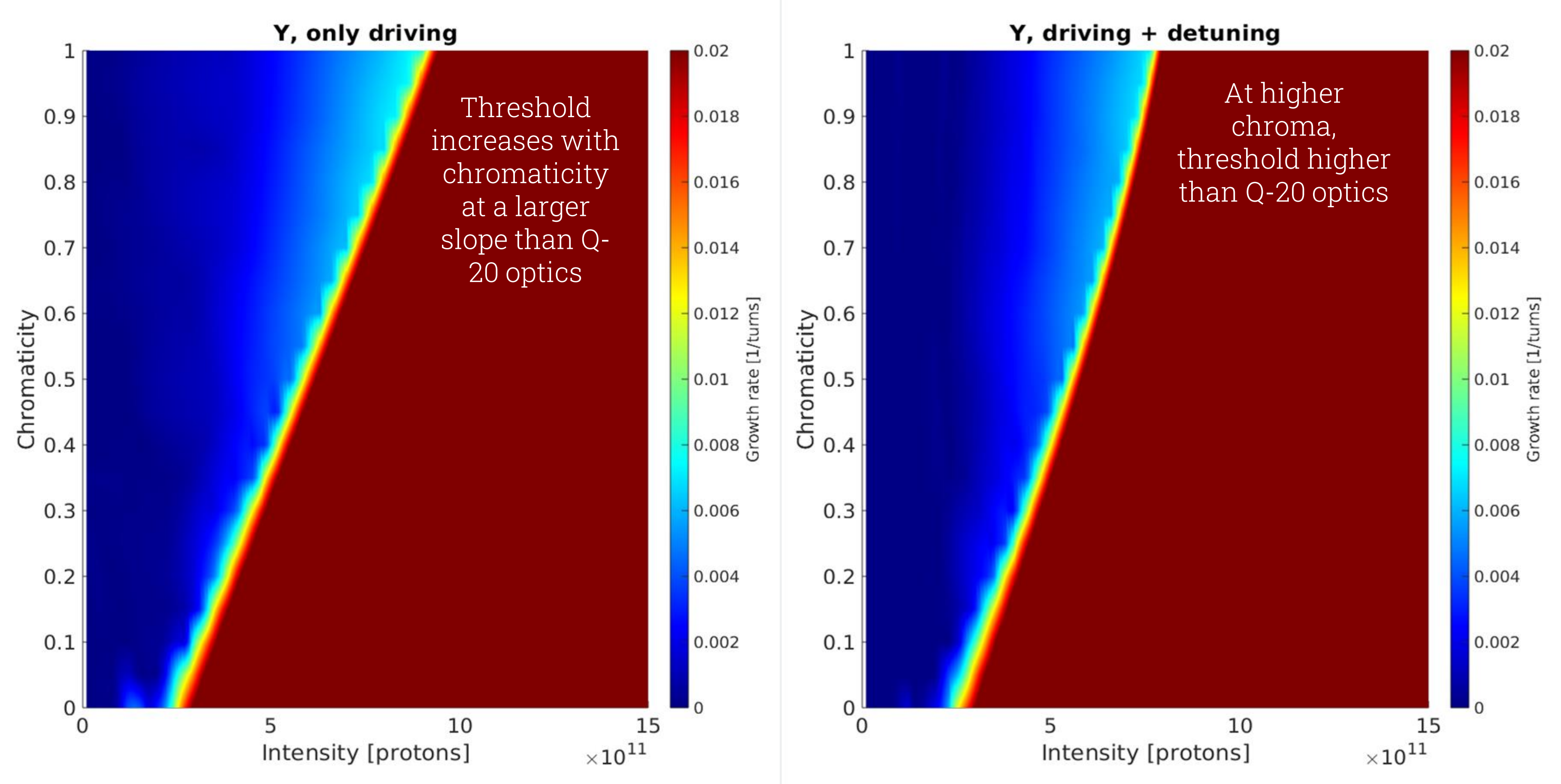
CONSIDERING CHROMATICITY, Q20 OPTICS



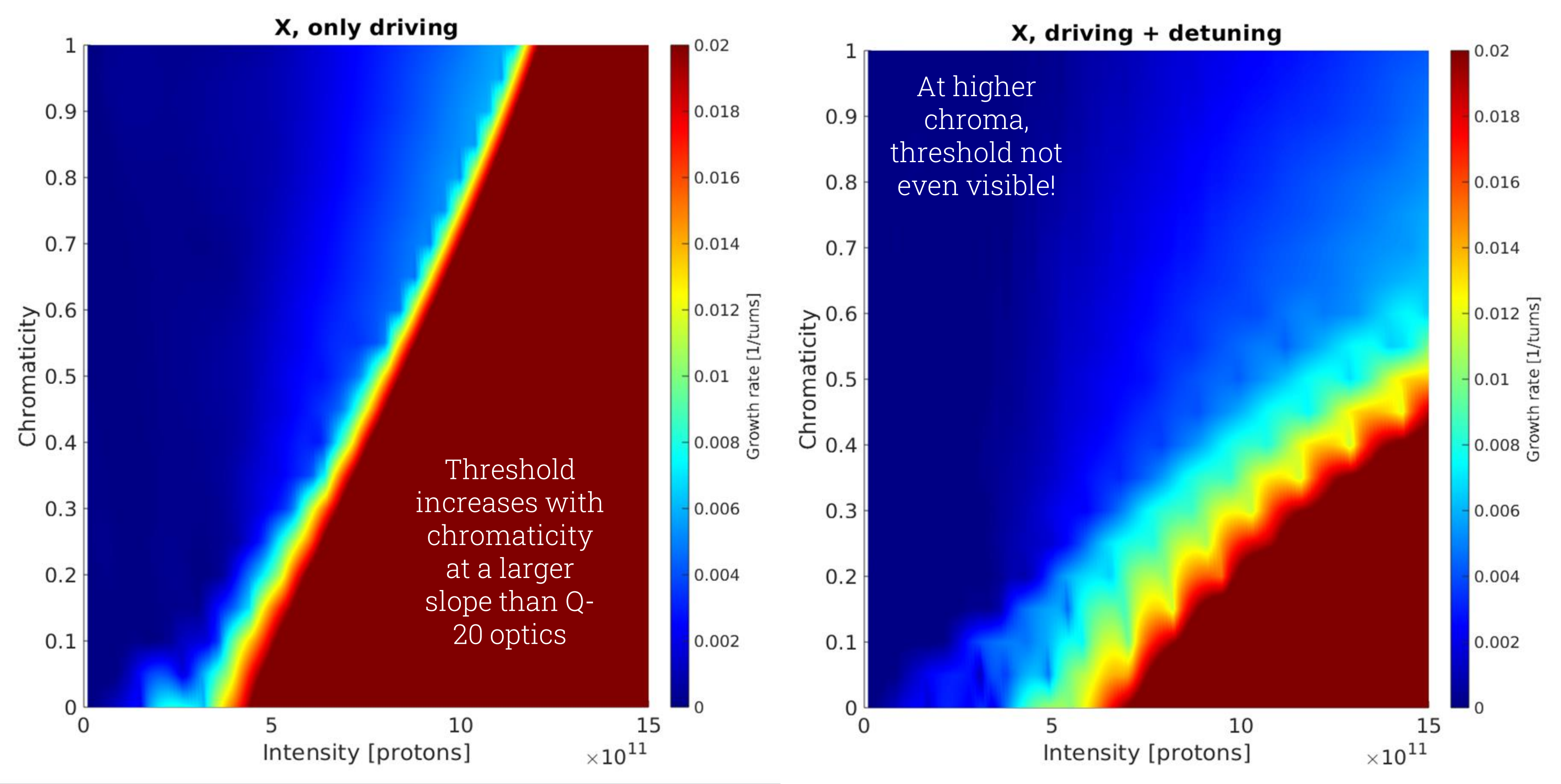
CONSIDERING CHROMATICITY, Q20 OPTICS



CONSIDERING CHROMATICITY, Q26 OPTICS



CONSIDERING CHROMATICITY, Q26 OPTICS



RESULTS

- Higher order chromaticities play a role in threshold especially at higher longitudinal emittances
- At higher chromaticities detuning reduces the threshold for the vertical plane and increases for the horizontal plane
- Q-20 optics is more critical than Q-26 wrt to TMCI threshold at higher chromaticities
  - For Y plane, Q-26 has higher threshold for chromaticity > 0.4
  - Due to different chromatic frequency shifts in different optics

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03

ANALYTICAL MULTI-BUNCH MODEL

Transfer matrix based approach for rigid bunches with wakes

ANALYTICAL APPROACH

- Transfer matrix approach for a multi-bunch model assuming
  - Rigid bunches
  - Single turn wakes
  - Decoupled transverse planes
  - No longitudnal motion
- Obtained a matrix relating the coordinates of all bunches from one turn to the next
  - Written as a function of transfer matrix and wake matrix

GENERAL EQUATION

- The general equation for n bunches is given by

$$\begin{pmatrix} x_0 \\ x'_0 \\ \vdots \\ x_{n-1} \\ x'_{n-1} \end{pmatrix}_j = \{I + W_{2n\times 2n}\}\{T_{n\times n}\} \begin{pmatrix} x_0 \\ x'_0 \\ \vdots \\ x_{n-1} \\ x'_{n-1} \end{pmatrix}_{j-1}$$

ANALYTICAL MULTI-BUNCH MODEL

TRANSFER MATRIX

- T is nxn block diagonal transfer matrix for n bunches where M is 2x2 matrix

$$T_{n\times n} = \begin{pmatrix} M & O & \dots & O \\ O & M & \dots & O \\ \vdots & \vdots & \ddots & \vdots \\ O & O & \dots & M \end{pmatrix}$$

- M is given by

$$M = \begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix}$$

WAKE MATRIX

- W_{2nx2n} is the sparse wake matrix for *n* bunches that generates the wake kick

$$W_{2n\times 2n} = \begin{pmatrix} 0 & 0 & \dots & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 \\ CW_x^{dip}(z_1) & 0 & CW_x^{quad}(z_1) & 0 & \dots & 0 \\ 0 & 0 & \vdots & \ddots & \dots & 0 \\ \vdots & & & & & \vdots \\ CW_x^{dip}(z_n) & 0 & CW_x^{dip}(z_n - z_1) & \dots & C\sum_{z_k<z_n} W_x^{quad}(z_n - z_k) & 0 \end{pmatrix}$$

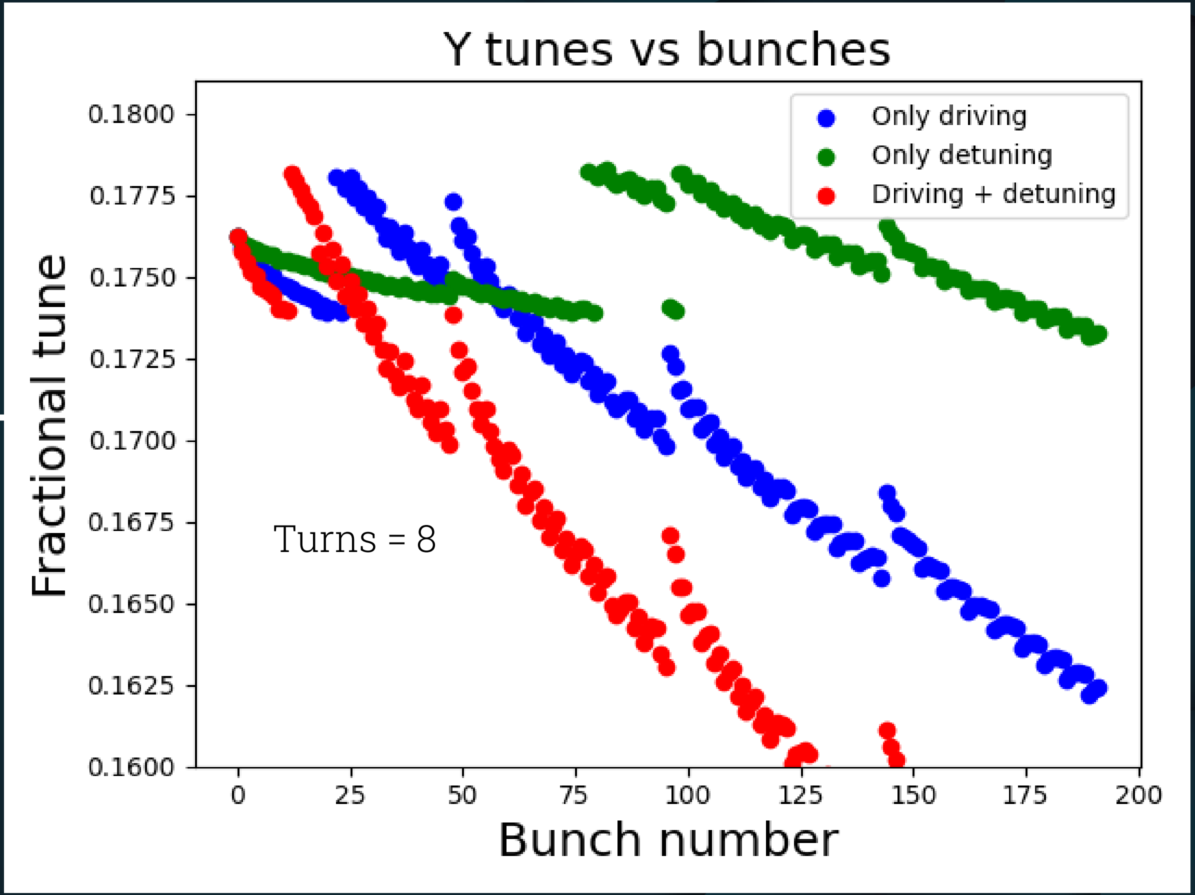
TIME DOMAIN TRACKING

- The obtained matrix used for time-domain tracking over a certain number of turns
- Bunch by bunch tunes obtained from this data using HarPy

ANALYTICAL MULTI-BUNCH MODEL

8 TURNS

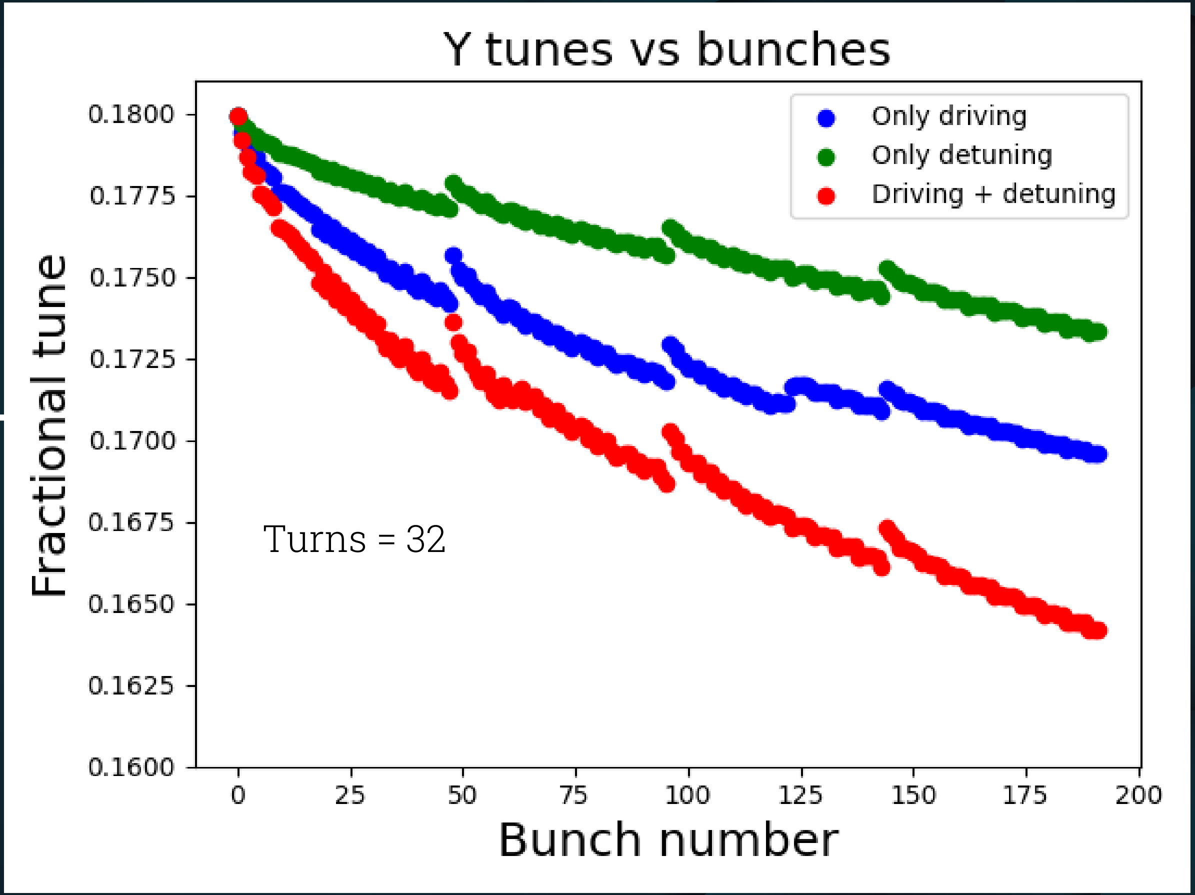
- Number of turns too low for detetcting tunes correctly



ANALYTICAL MULTI-BUNCH MODEL

32 TURNS

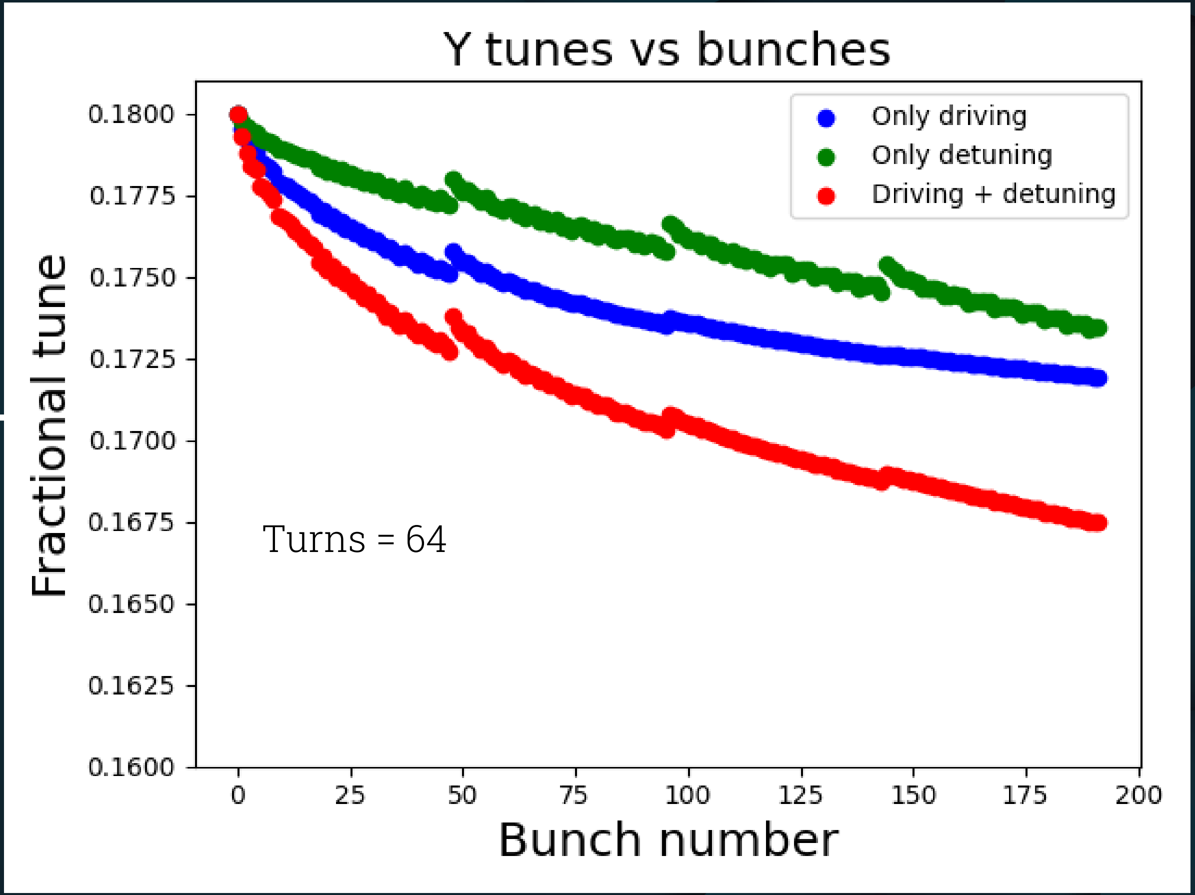
- Better picture seen



ANALYTICAL MULTI-BUNCH MODEL

64 TURNS

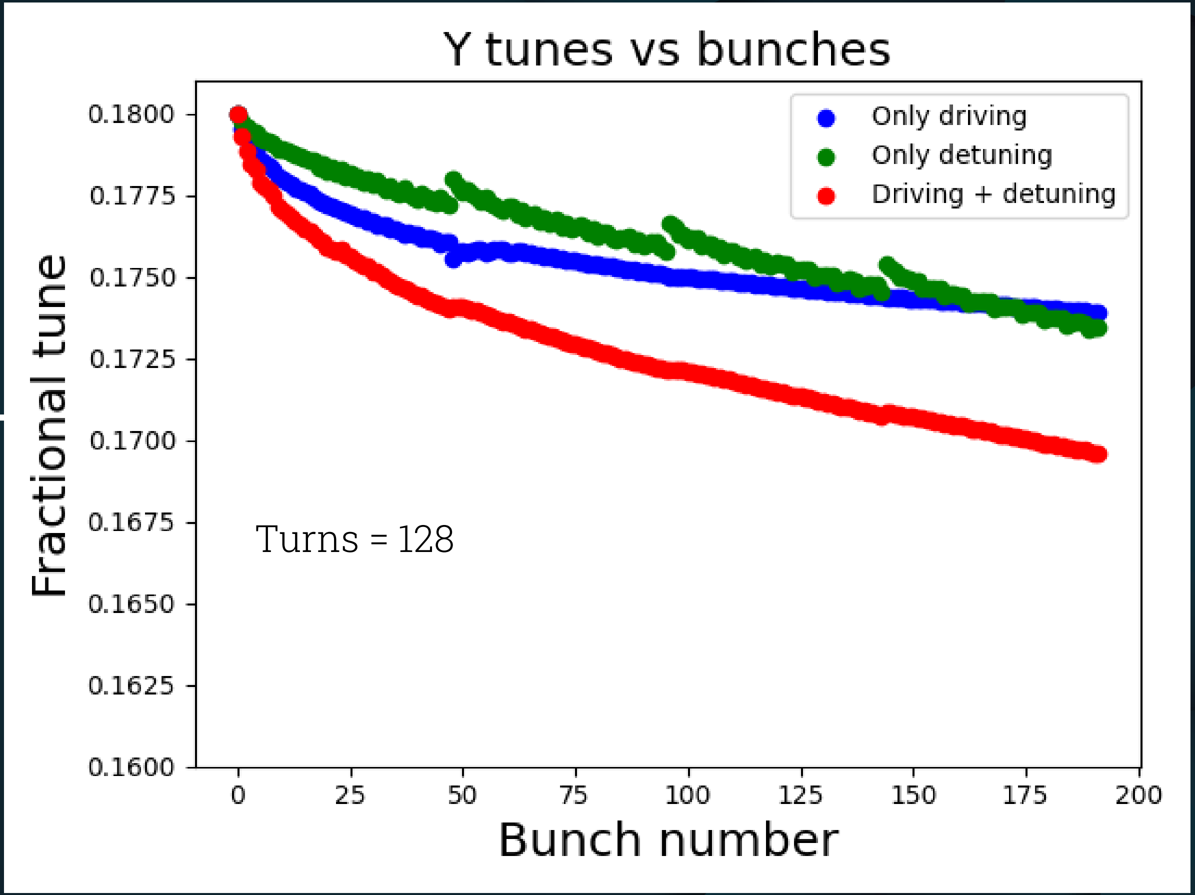
- Tune shift from detuning has converged
- Tunes from only driving still change



ANALYTICAL MULTI-BUNCH MODEL

128 TURNS

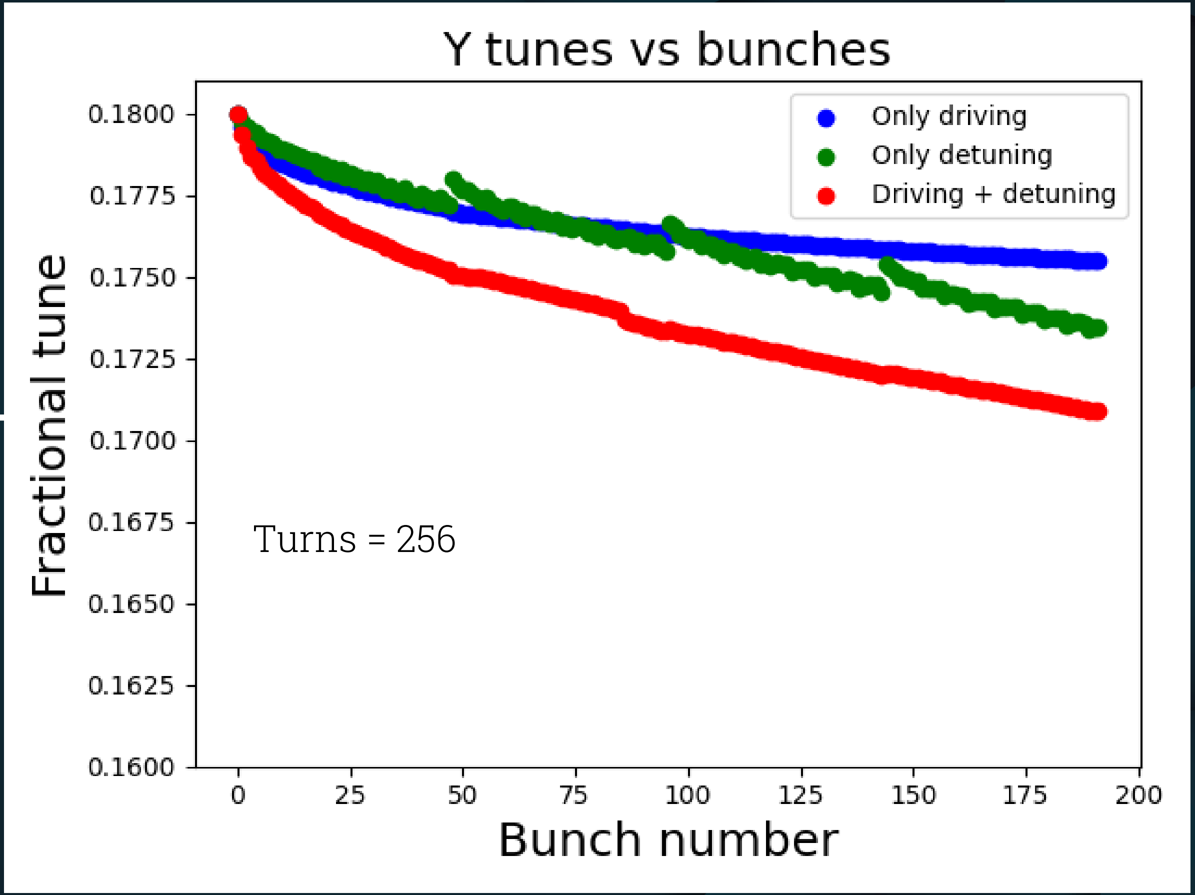
- Tune shift from detuning has converged
- Tunes from only driving still change



ANALYTICAL MULTI-BUNCH MODEL

256 TURNS

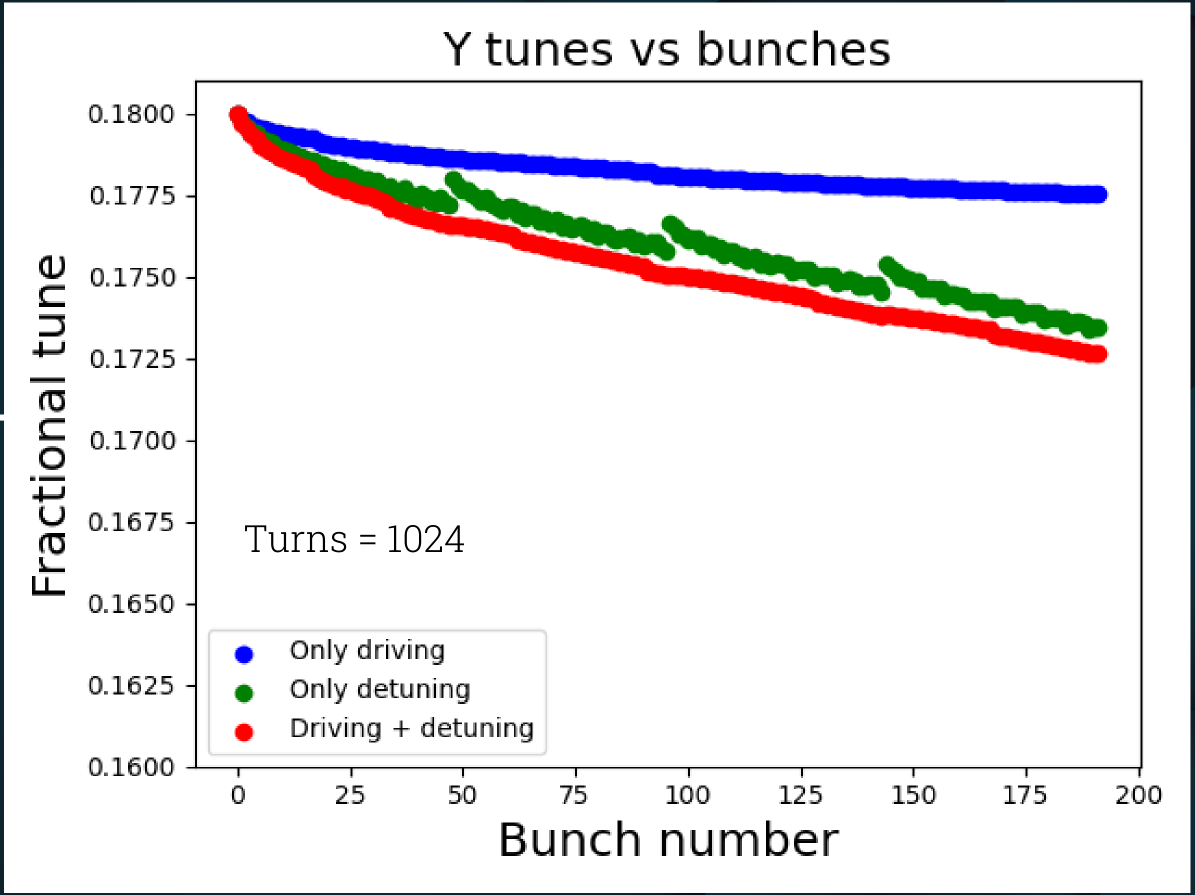
- Tune shift from detuning has converged
- Tunes from only driving still change



ANALYTICAL MULTI-BUNCH MODEL

1024 TURNS

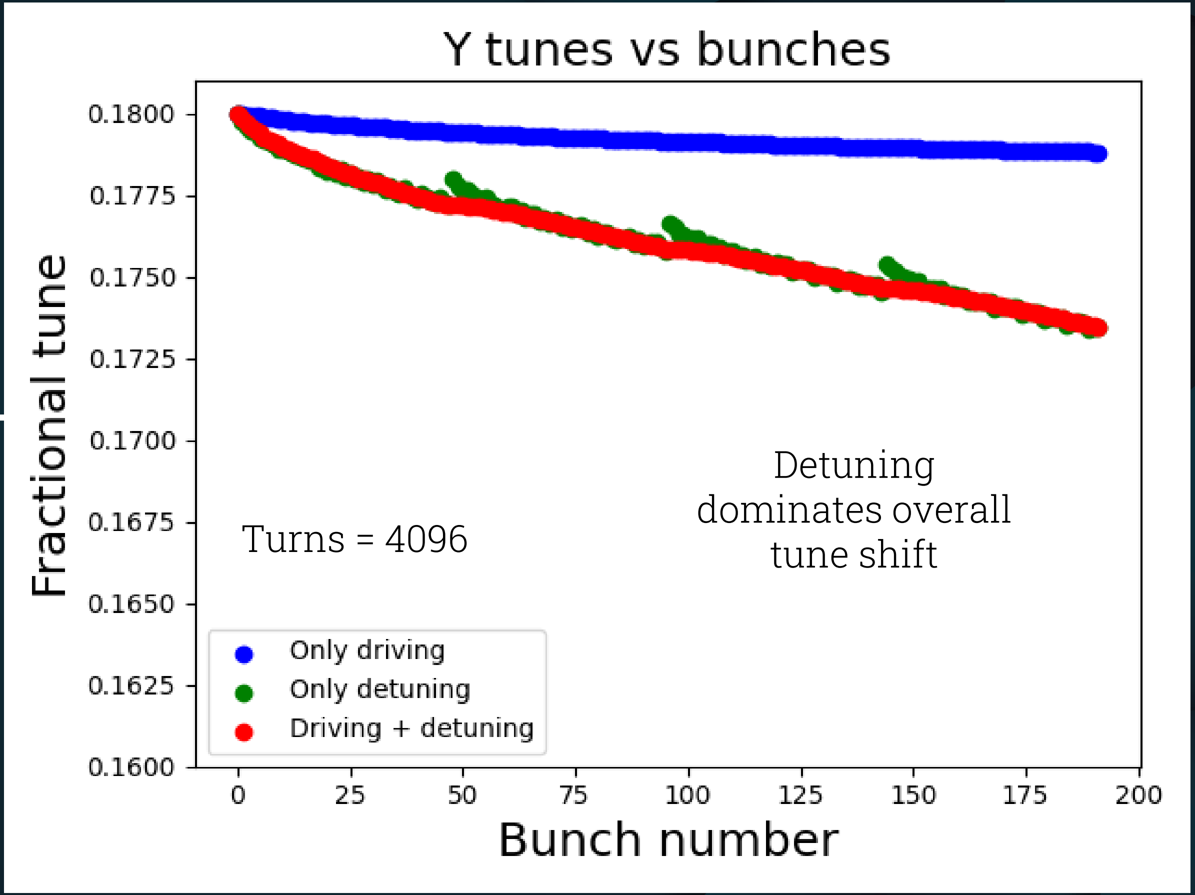
- Tune shift from detuning has converged
- Tunes from only driving still change



ANALYTICAL MULTI-BUNCH MODEL

4096 TURNS

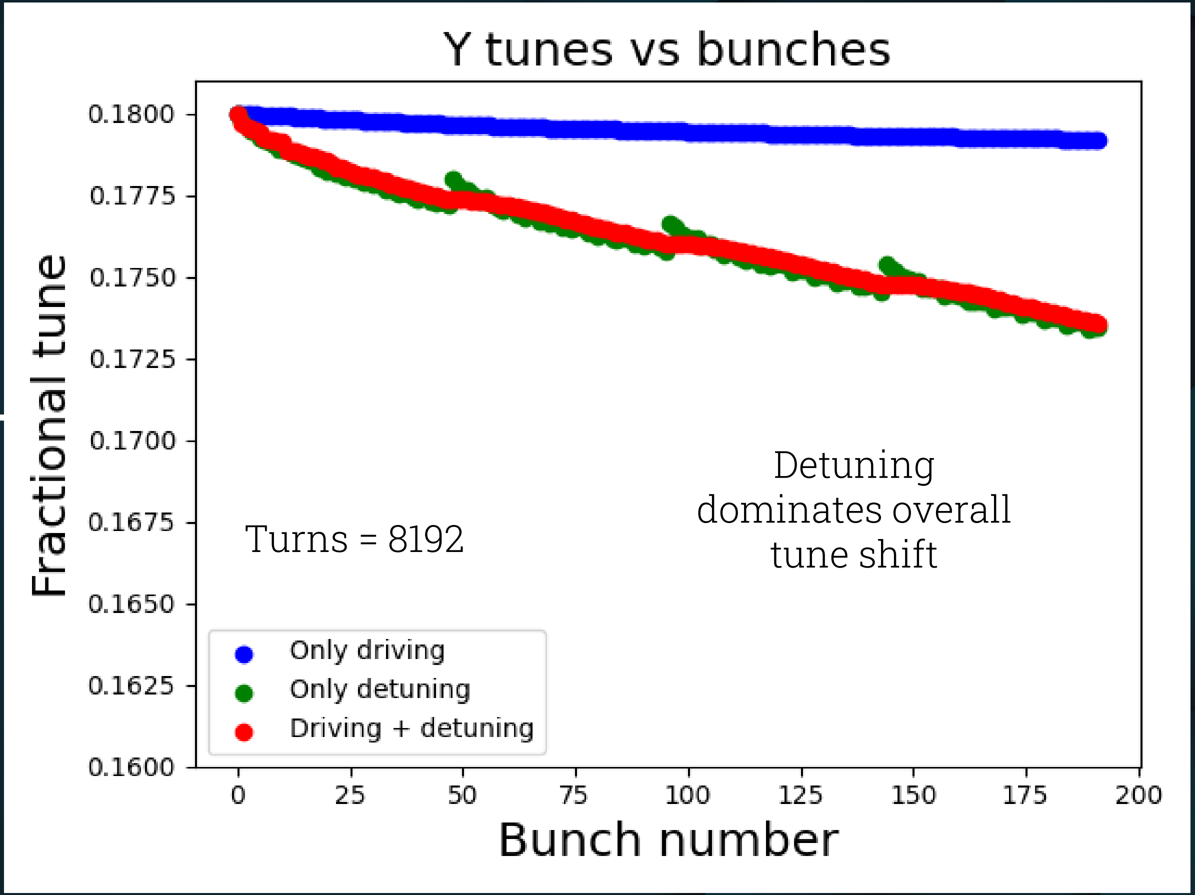
- Tune shift from detuning has converged
- Tunes from only driving still change



ANALYTICAL MULTI-BUNCH MODEL

8192 TURNS

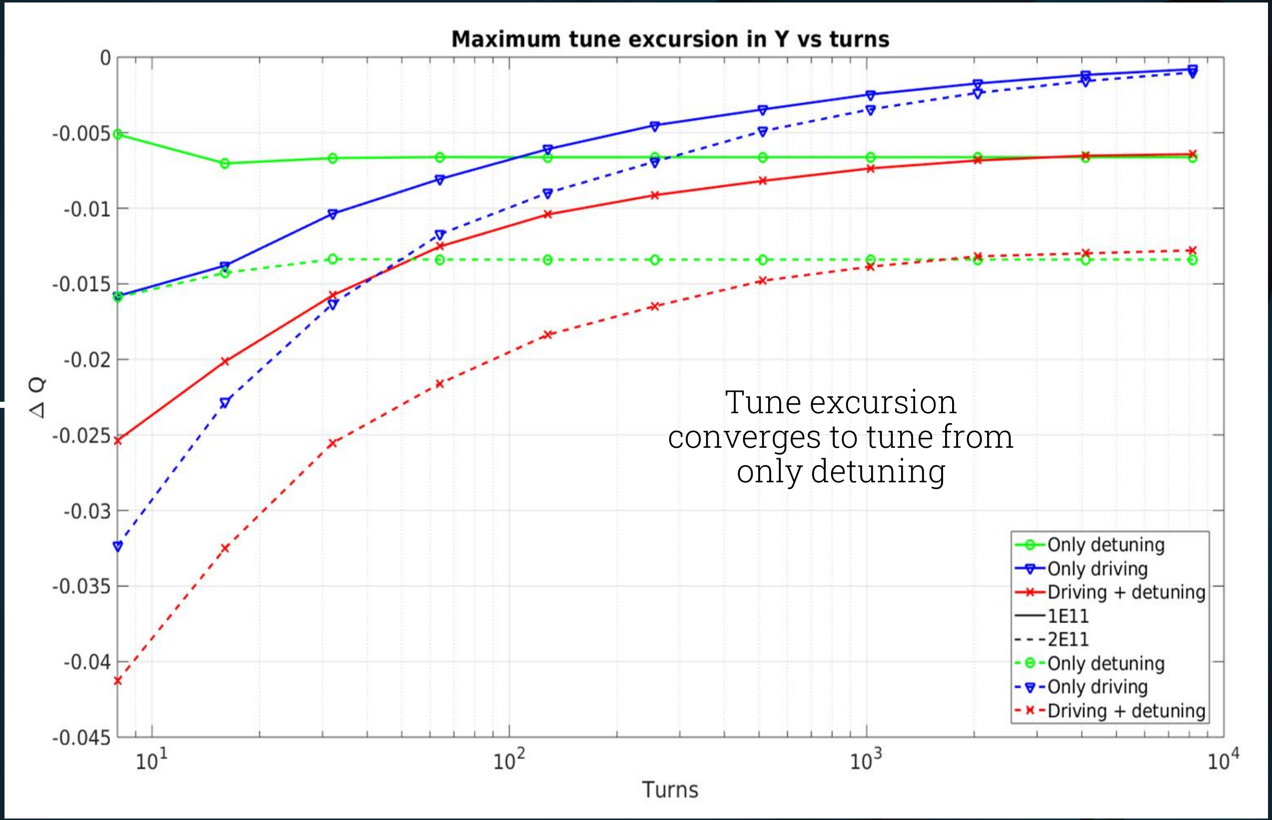
- Tune shifts have converged
- Small change with turns
- Smooth tunes as expected



ANALYTICAL MULTI-BUNCH MODEL

TUNE CONVERGENCE

- Plot of maximum tune excursion against the number of turns



RESULTS

- Driving averages out over a large number of turns
- Detuning dominates the tune shifts
- Multi-turn wake model also developed
    - Included in report

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SUMMARY

- Detuning impedance affects the growth rate and the extent of the effect depends on the chromaticity and the RF voltages
- It also has an appreciable impact on the TMCI threshold and tune shifts
- Good agreement between tracking simulations and Vlasov solver approach to a certain extent
- Rigid bunch analytical model developed for multi-bunch beams to study the effect of detuning impedance

THANKS!

Questions?

APPENDIX A

SIMULATION PARAMETERS

MACHINE PARAMETERS

- Number of macroparticles: 5e5
- Machine: SPS at Q-20 injection
- Number of slices: 500
- Chromaticities
  - Qp_x = Qp_y = 0 (for intensity sweep)
  - Qpp_x = 272; Qpp_y = 662
  - Qppp_x = -1869000; Qppp_y = 1449600
- Intensity: 2e11 protons (for chromaticity sweep)
- Number of turns: 8192
- Number of segments: 1
- RF voltages: 5.75 MV, 0.8625 MV
- Bunch length: 0.23 m
- Bucket length: 2.5 ns

WAKE PARAMETERS

RESISTIVE WALL

- Pipe radius: 3 cm
- Conductivity: 1E6

RESONATOR

- R: 7 M Ohm
- f: 1 GHz
- Q: 1

SPS MODELS

- Post LS2 Q20
- Post LS2 Q22
- Post LS2 Q26

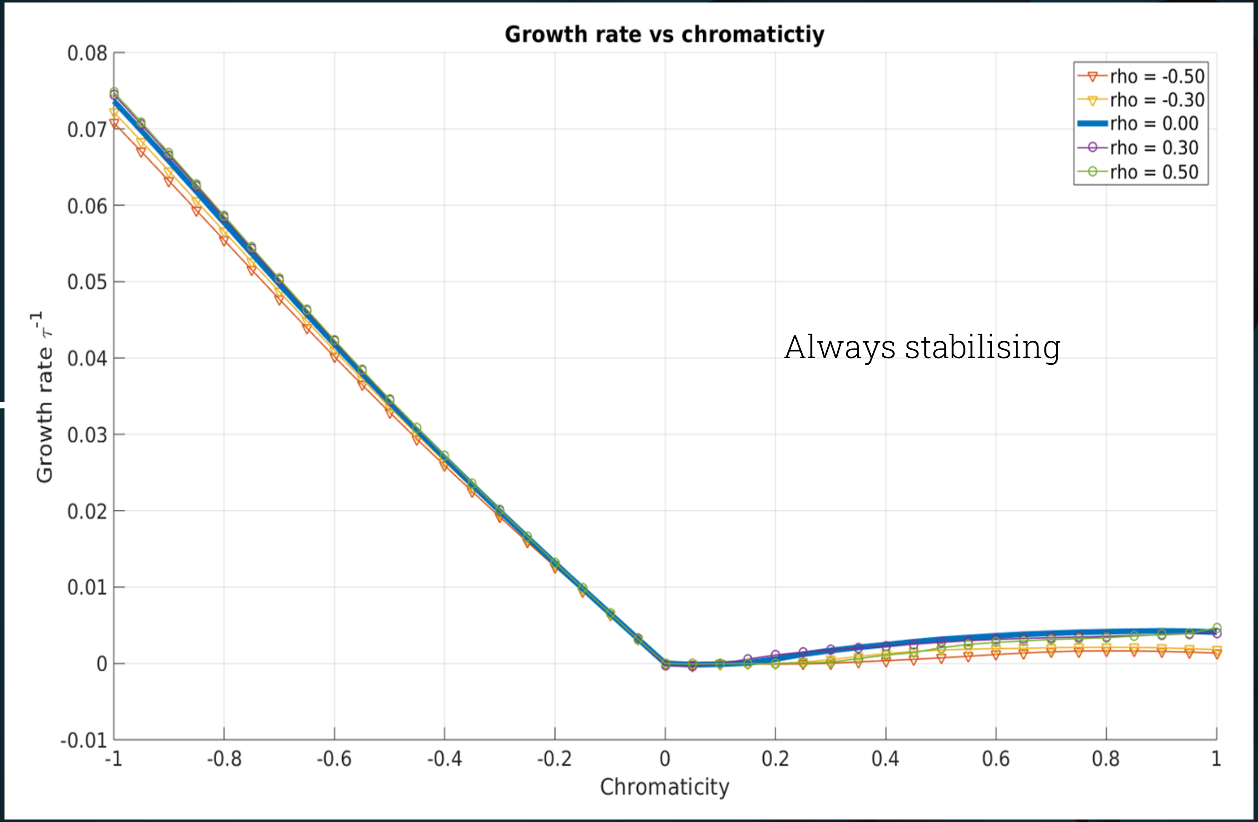
APPENDIX B

ADDITIONAL SLIDES

MANY PARTICLE MODEL

EFFECT W.R.T CHROMATICITY

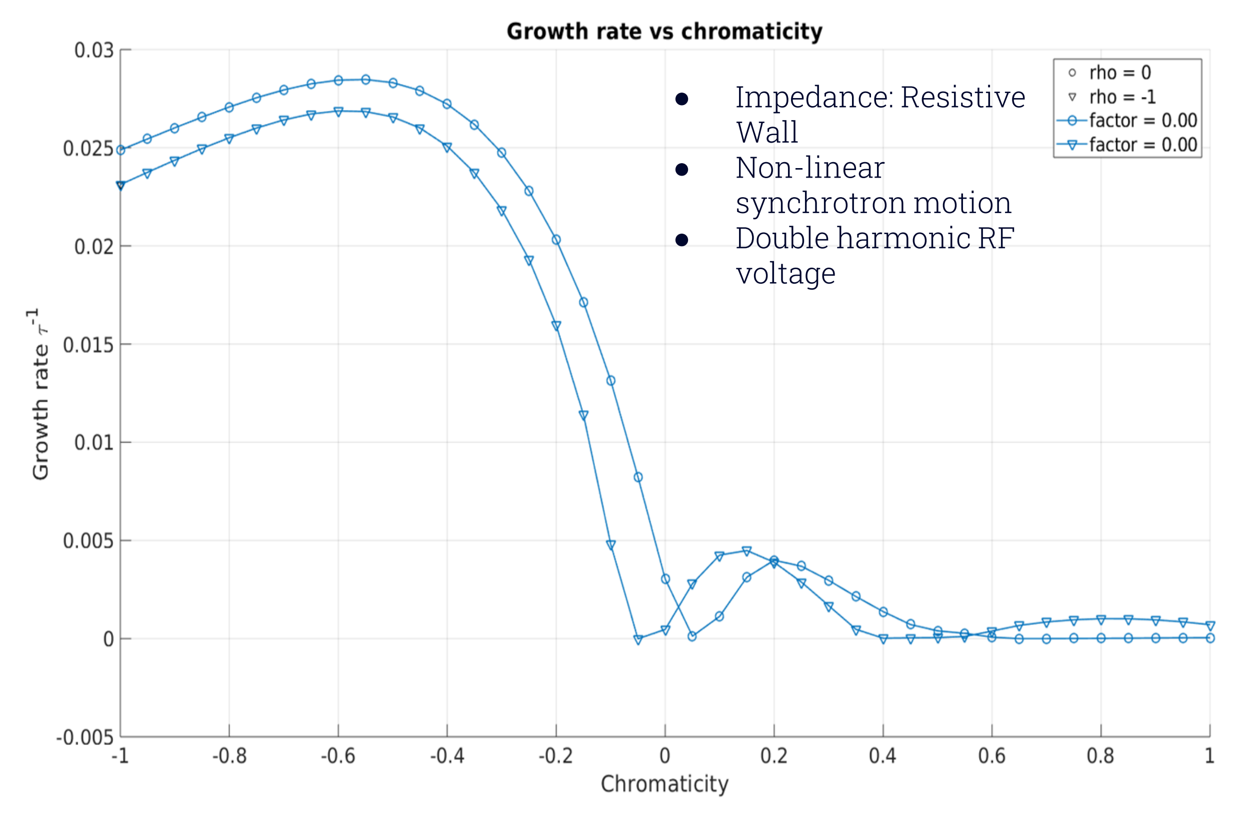
- Impedance: Broadband resonator
- Linear synchrotron motion



MANY PARTICLE MODEL

INCLUDING SECOND HARMONIC

- Only rho = 0 and -1 considered
- Second harmonic voltage varied as a percentage first
- For higher second harmonic, detuning is stabilising



- Impedance: Resistive Wall
- Non-linear synchrotron motion
- Double harmonic RF voltage

INCLUDING SECOND HARMONIC

- Only rho = 0 and -1 considered
- Second harmonic voltage varied as a percentage first
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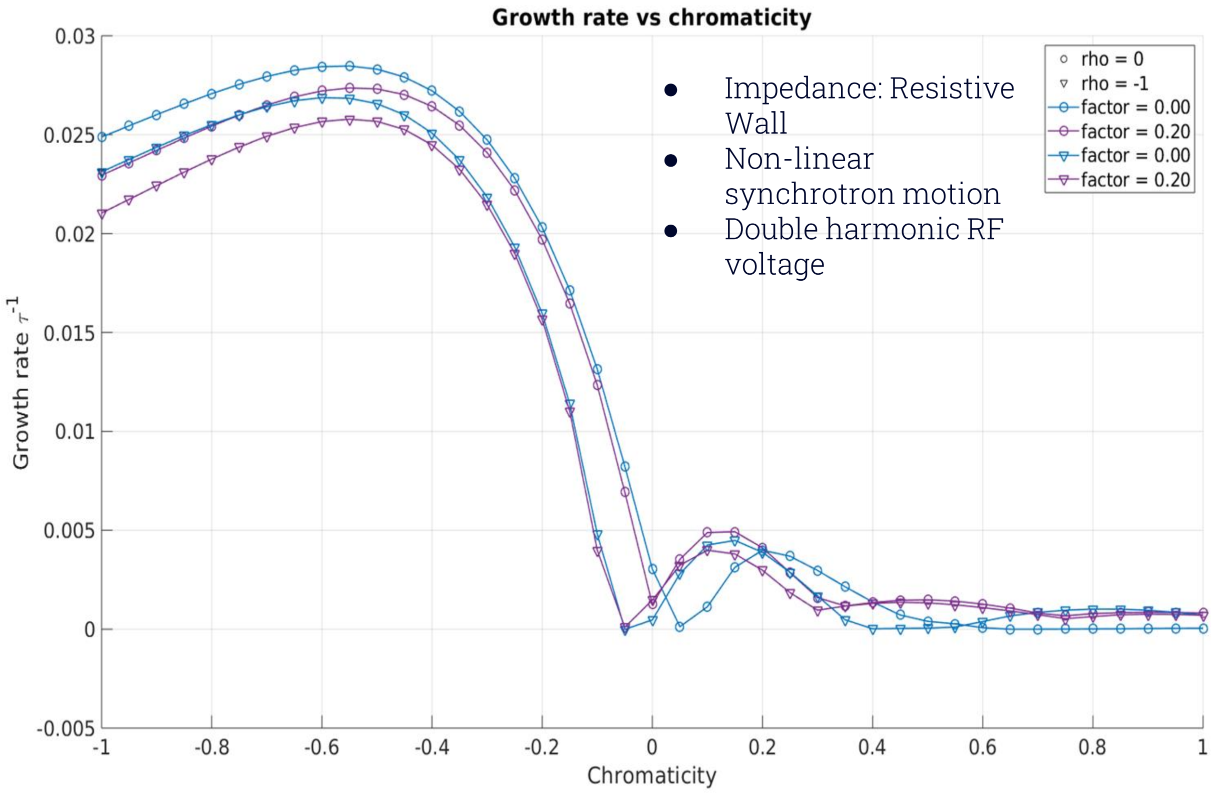


- Impedance: Resistive Wall
- Non-linear synchrotron motion
- Double harmonic RF voltage

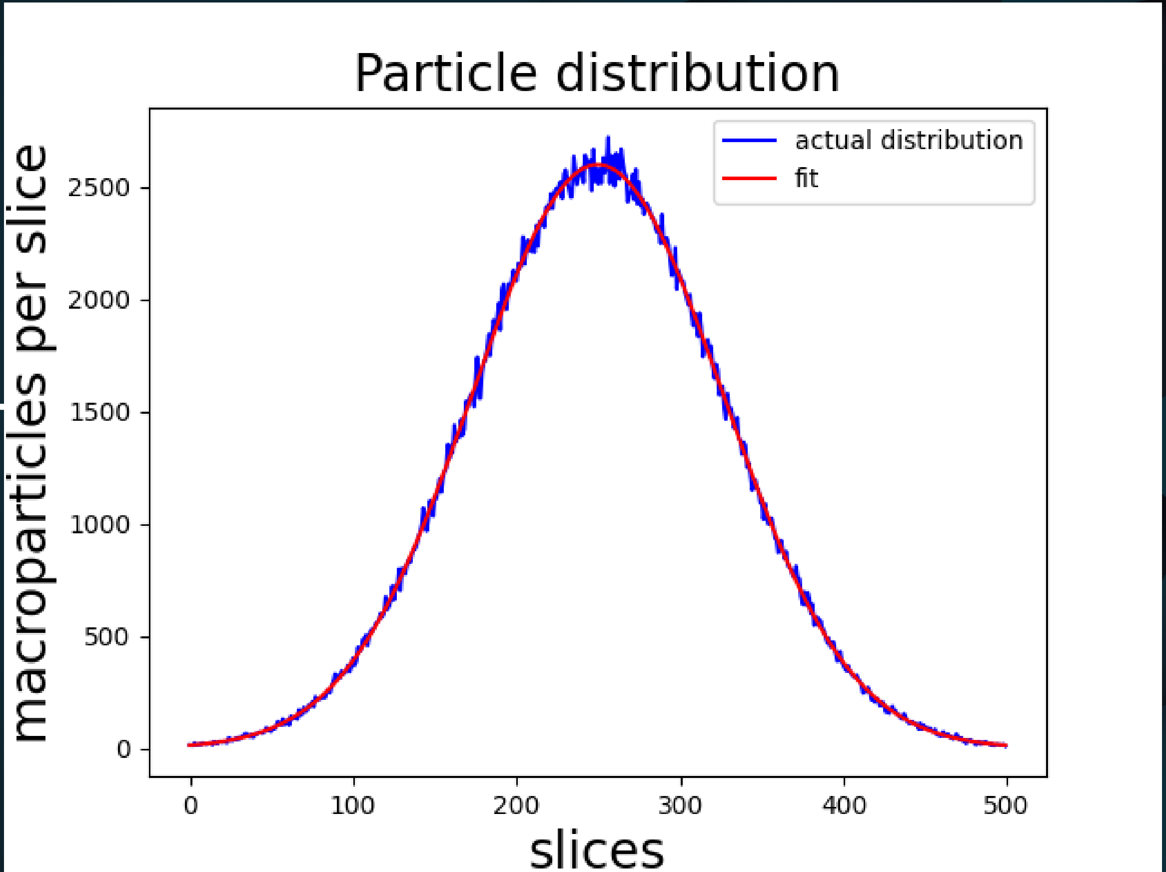
EFFECT OF ACTUAL DISTRIBUTION

- Dependence on the second harmonic implies effect influenced by the actual distribution
- Distribution profiles examined for different conditions

MANY PARTICLE MODEL

LINEAR

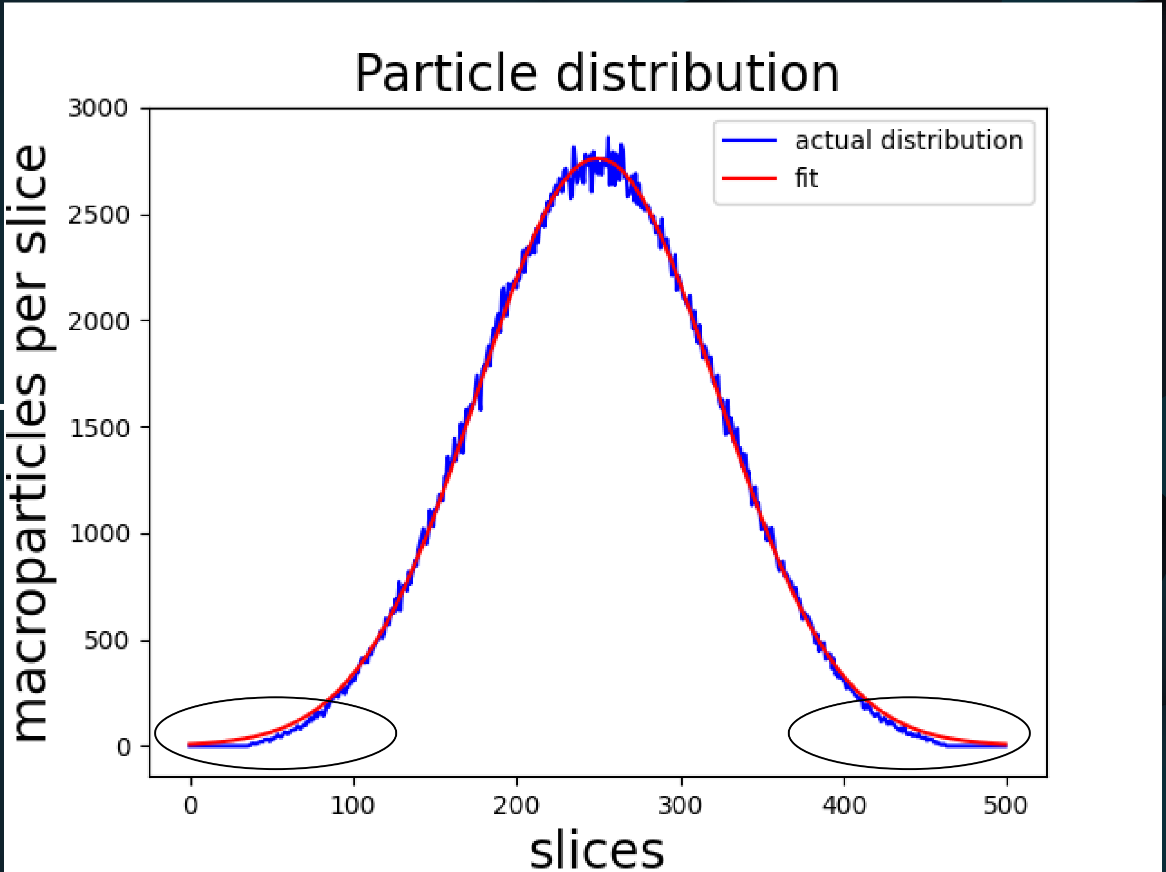
- Perfect gaussian
- No destabilisng effect



MANY PARTICLE MODEL

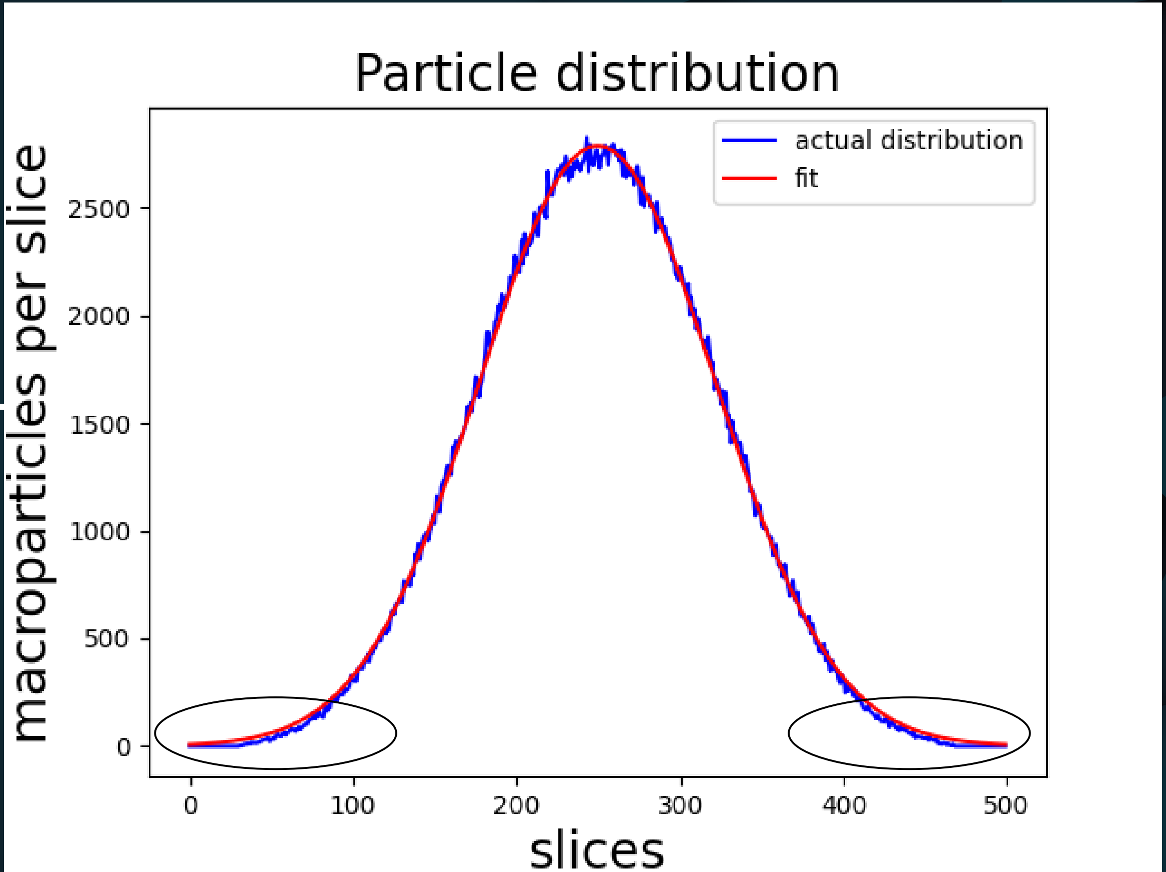
NON-LINEAR WITH SINGLE HARMONIC

- Imperfect gaussian
- Destabilising effect seen



INTRODUCING SECOND HARMONIC

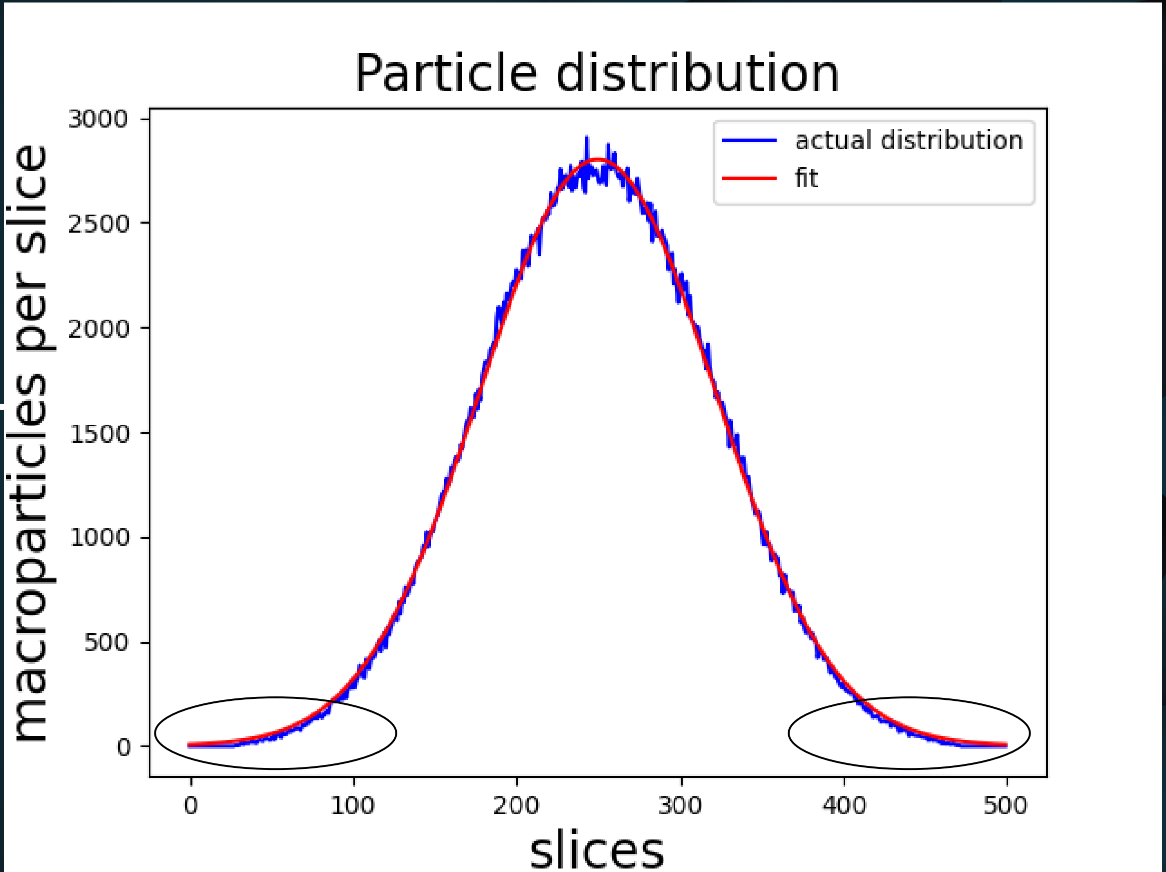
- Second harmonic 10% of first
- Distribution closer to gaussian than single harmonic



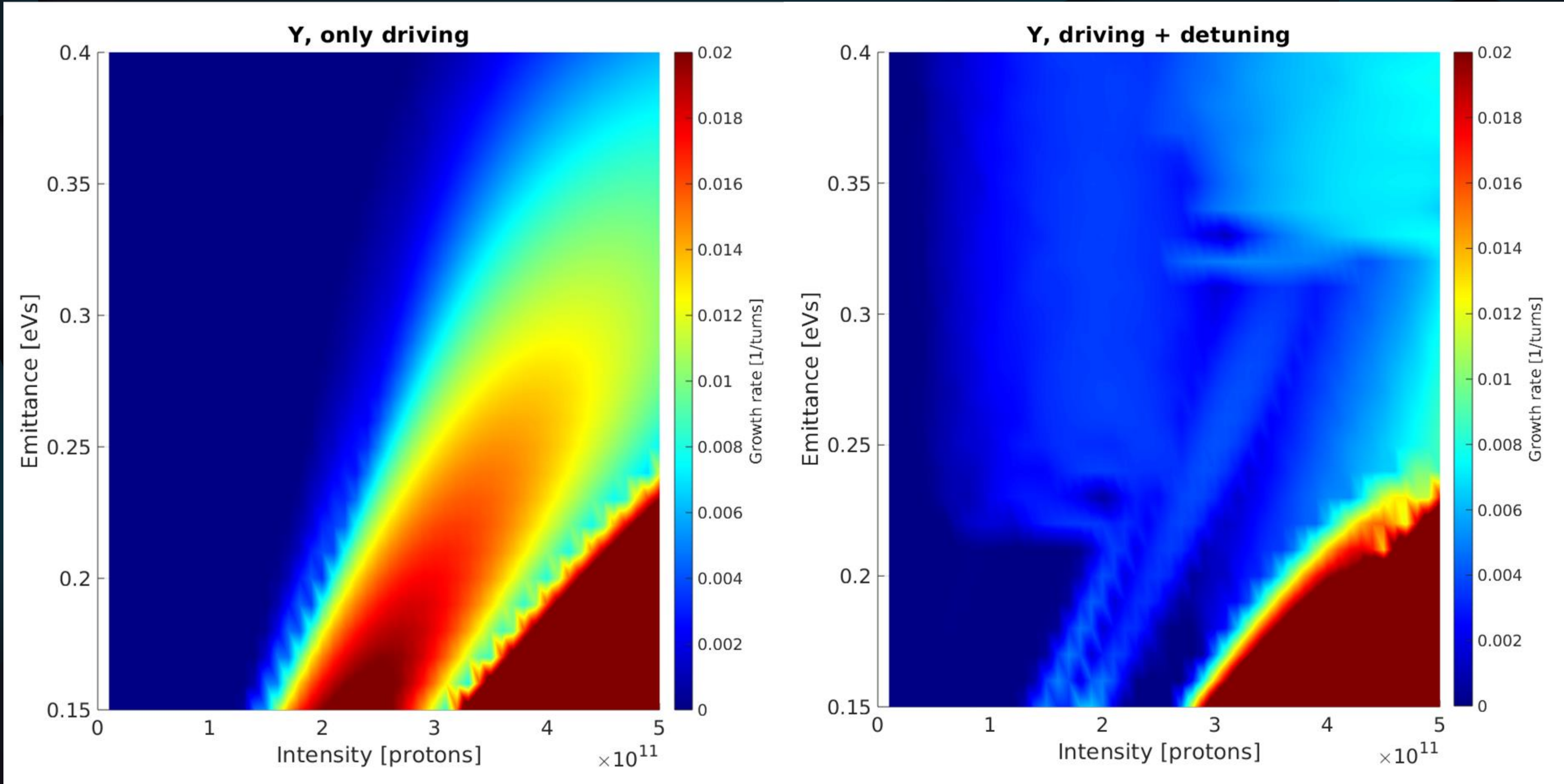
MANY PARTICLE MODEL

INTRODUCING SECOND HARMONIC

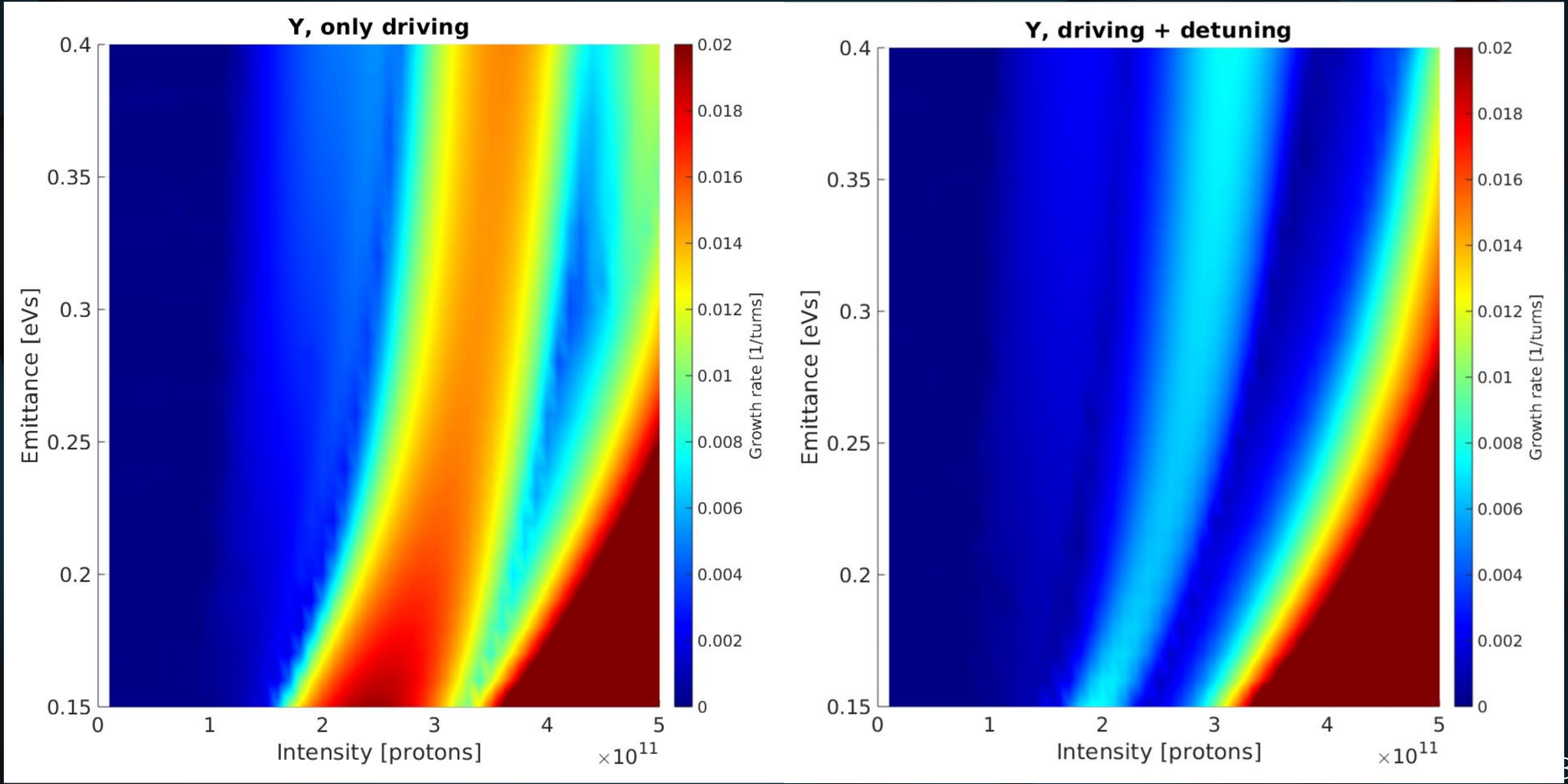
- Second harmonic 20% of first
- Distribution tends to ideal gaussian



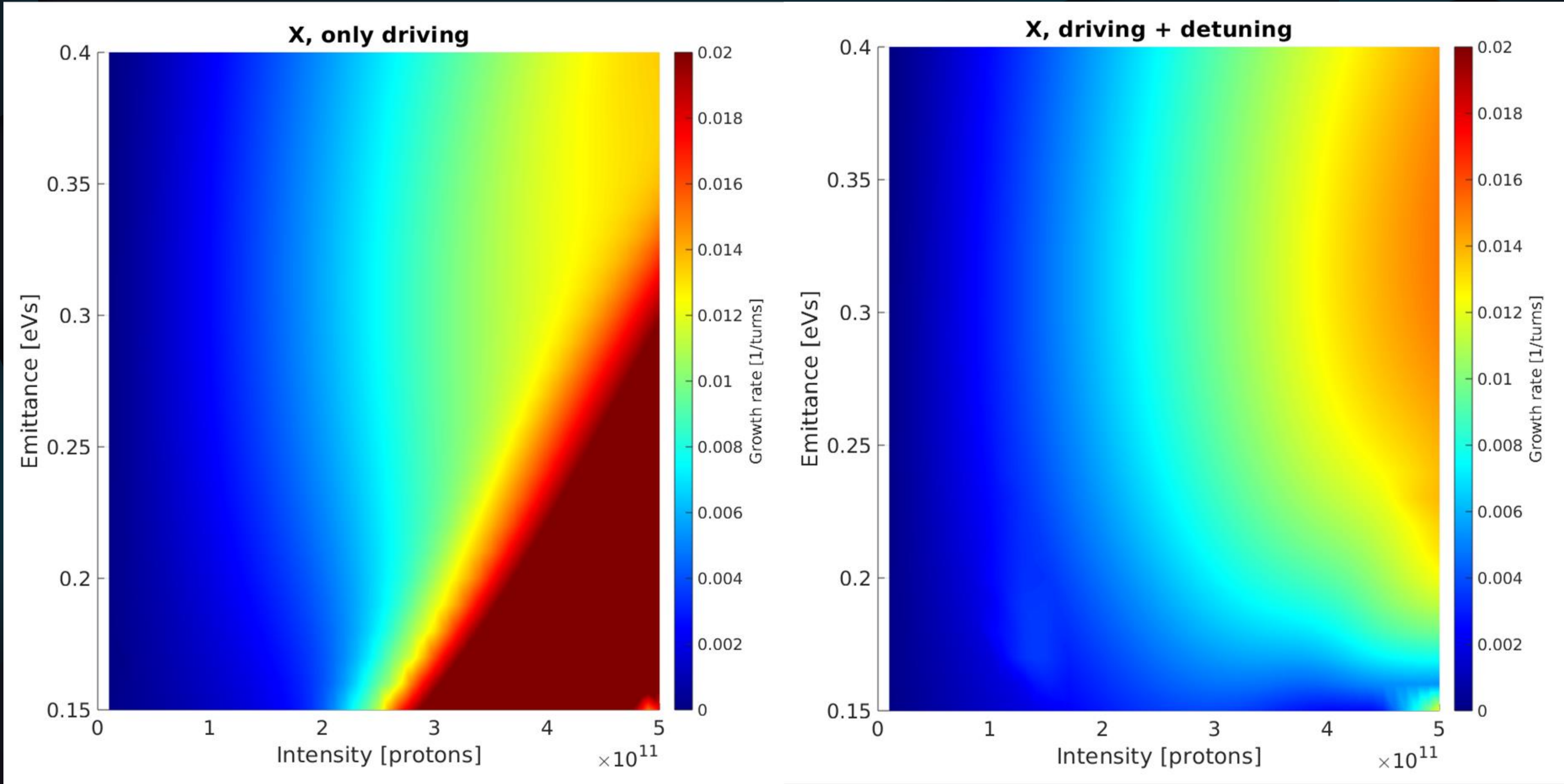
CONSIDERING EMITTANCE, LINEAR WITH HIGH ORDER CHROMATICITIES



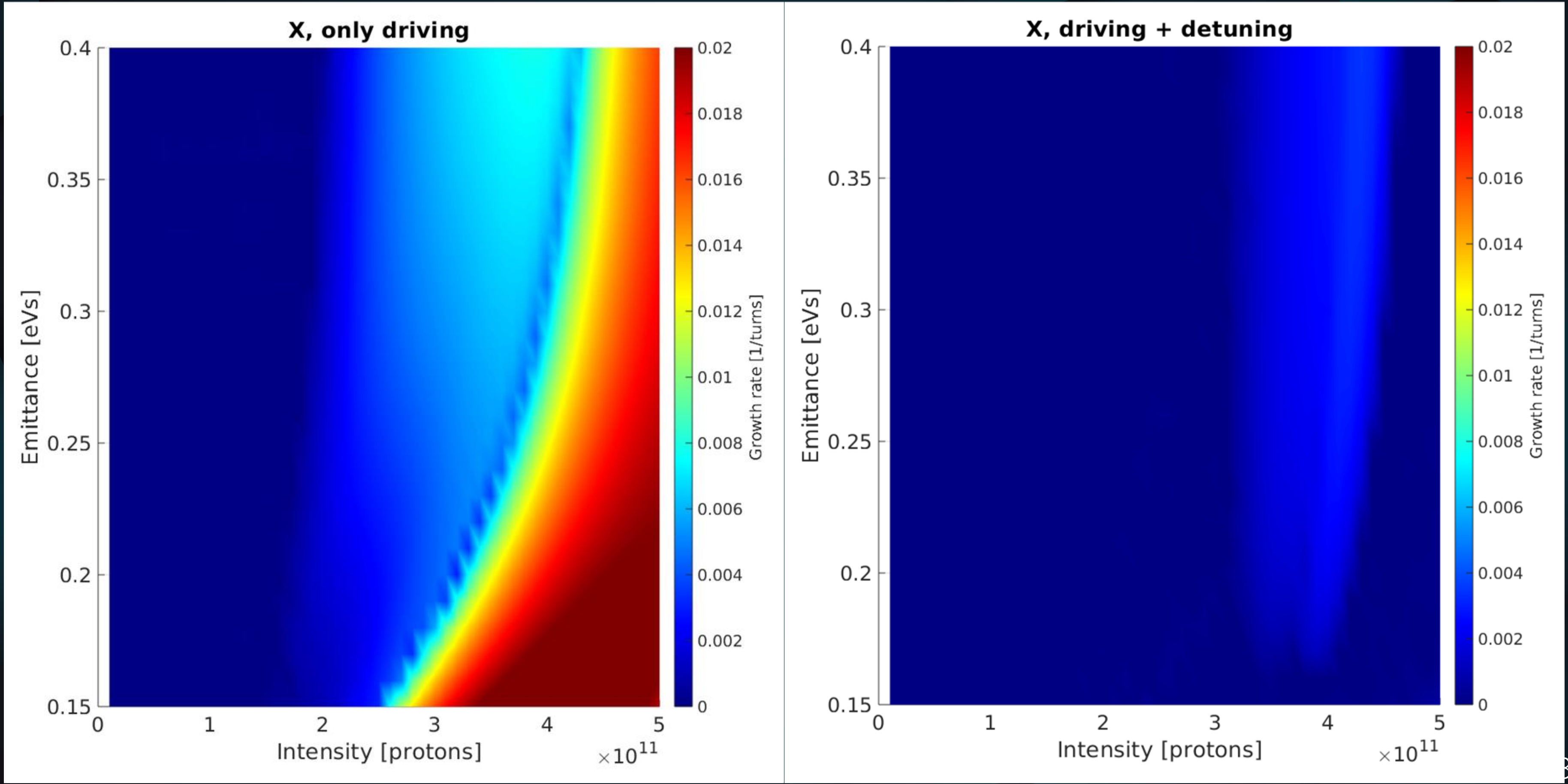
CONSIDERING EMITTANCE, NON LINEAR WITH SECOND ORDER CHROMATICITY



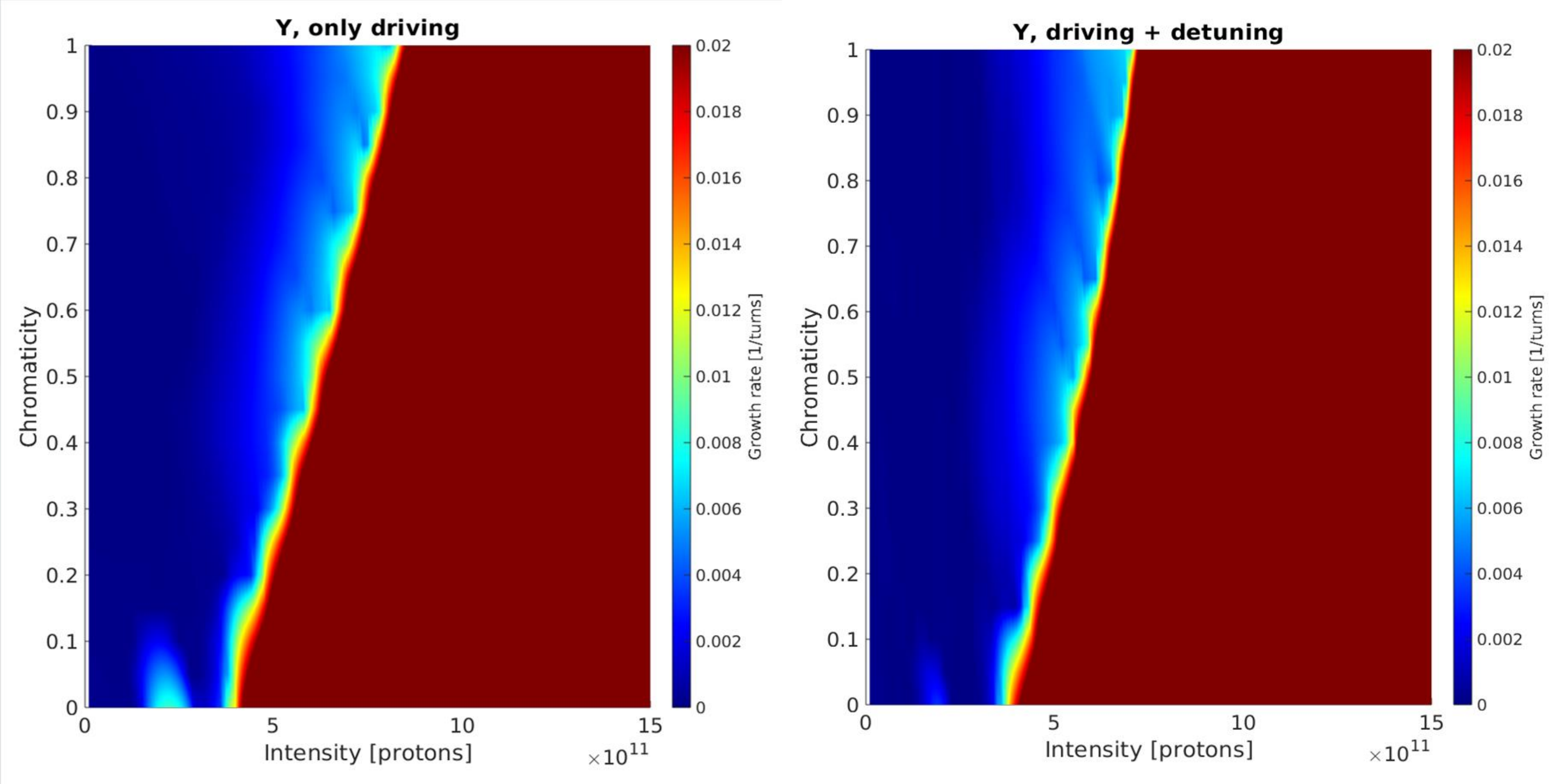
CONSIDERING EMITTANCE, LINEAR WITH HIGH ORDER CHROMATICITIES



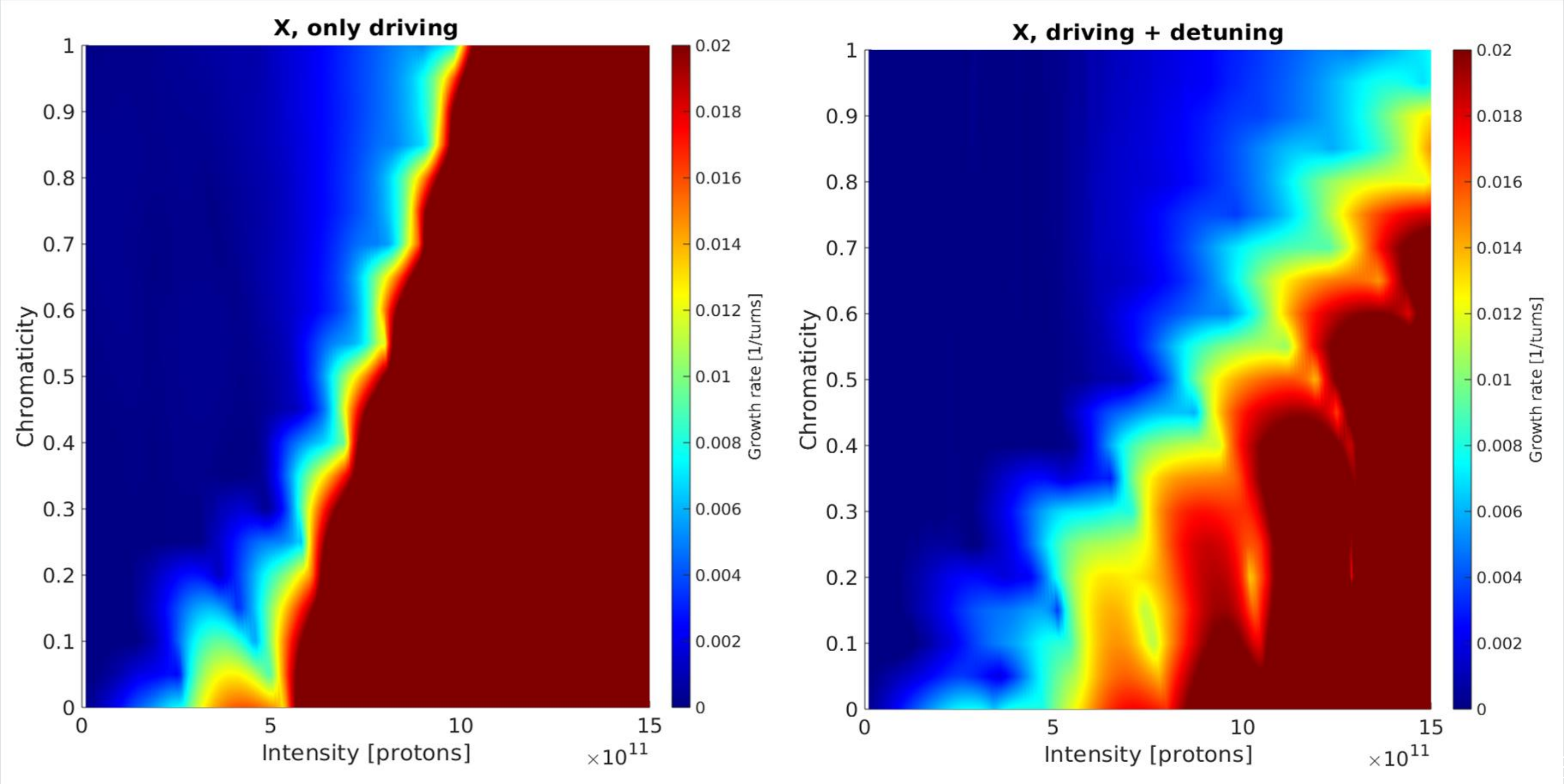
CONSIDERING EMITTANCE, NON LINEAR WITH SECOND ORDER CHROMATICITY



CONSIDERING CHROMATICITY, Q22 OPTICS



CONSIDERING CHROMATICITY, Q22 OPTICS



WAKE KICK

- Wakes generate a kick acting on the momentum
  - Felt once each turn
- Wake kick is given by

$$\Delta x_i' = C \sum_{z_k<z_i} \left\{ W_x^{dip}(z_i - z_k)x_k + W_x^{quad}(z_i - z_k)x_i \right\}$$

depends on the positions of the same turn

ANALYTICAL MULTI-BUNCH MODEL

ONE TURN MAP

- Let M be the one-turn map
- The new coordinates of bunch 1 after the lattice and before the wake kick are

$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix}_{1,int} = M * \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}_0$$

EFFECT OF WAKE KICK

- For 2 bunch system, final coordinates after kick given by

$$\begin{pmatrix} x_0 \\ x'_0 \\ x_1 \\ x'_1 \end{pmatrix}_1 = \begin{pmatrix} x_0 \\ x'_0 \\ x_1 \\ x'_1 \end{pmatrix}_{1,int} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ CW_x^{dip}(z_1) & 0 & CW_x^{quad}(z_1) & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ x_1 \\ x'_1 \end{pmatrix}_{1,int}$$

$$= \left\{ I + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ CW_x^{dip}(z_1) & 0 & CW_x^{quad}(z_1) & 0 \end{pmatrix} \right\} \{T\} \begin{pmatrix} x_0 \\ x'_0 \\ x_1 \\ x'_1 \end{pmatrix}_0$$

EIGENVALUE ANALYSIS

- The eigenvalues for n modes are given by

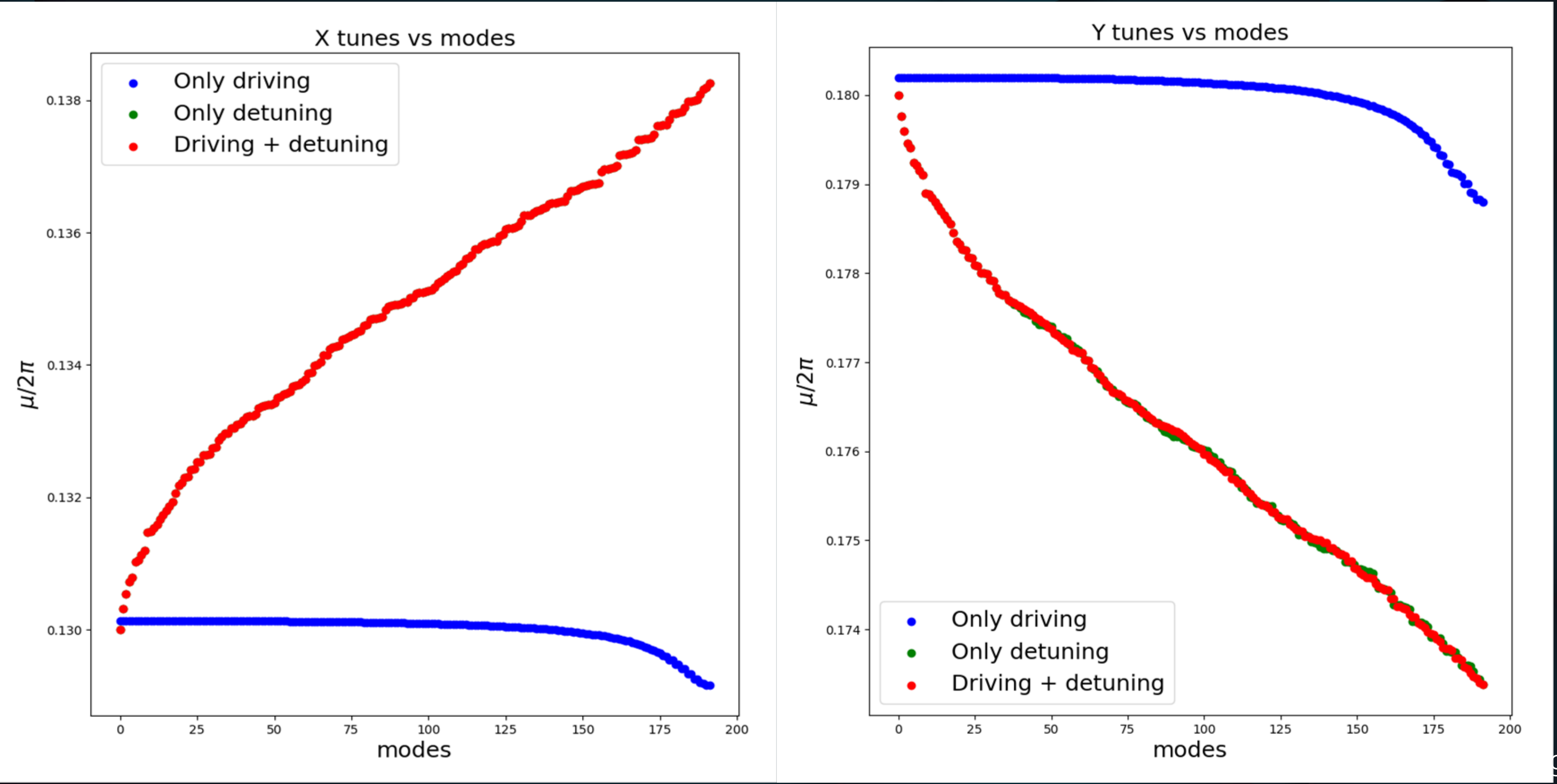
$$\lambda_{i_{1,2}} = r_i e^{\pm j\mu_i}$$

for mode i

- The tune μ_i of mode i is given by

$$\mu_i = \arccos \frac{\lambda_{i_1} + \lambda_{i_2}}{2\sqrt{\lambda_{i_1}\lambda_{i_2}}}$$

TUNES VS COUPLED BUNCH MODES



INTRODUCTION OF DAMPER

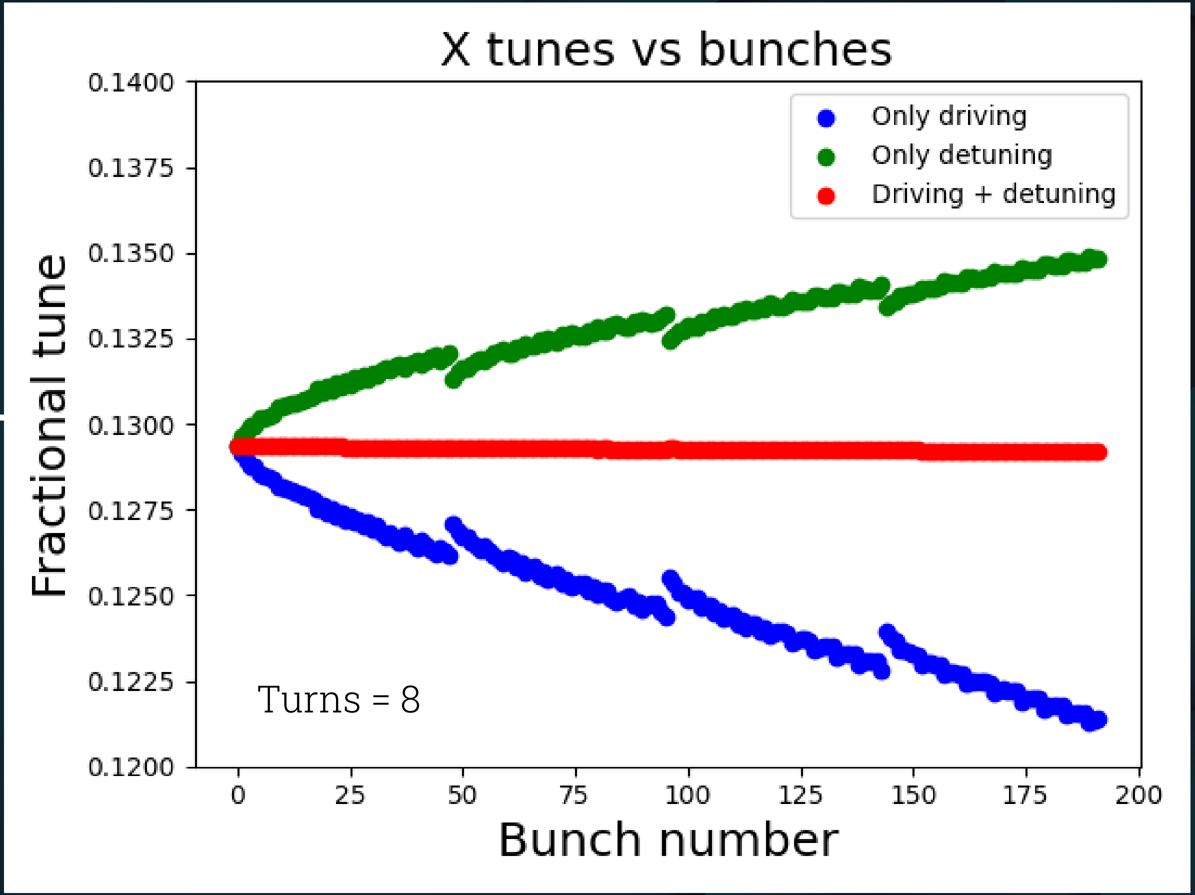
- Ideal damper with gain g acting on the position is considered
  - As damper is independent of wakes, additional term in M
- New matrix M is given by

$$M = \begin{pmatrix} \cos\mu + \alpha\sin\mu - g & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix}$$

ANALYTICAL MULTI-BUNCH MODEL

8 TURNS

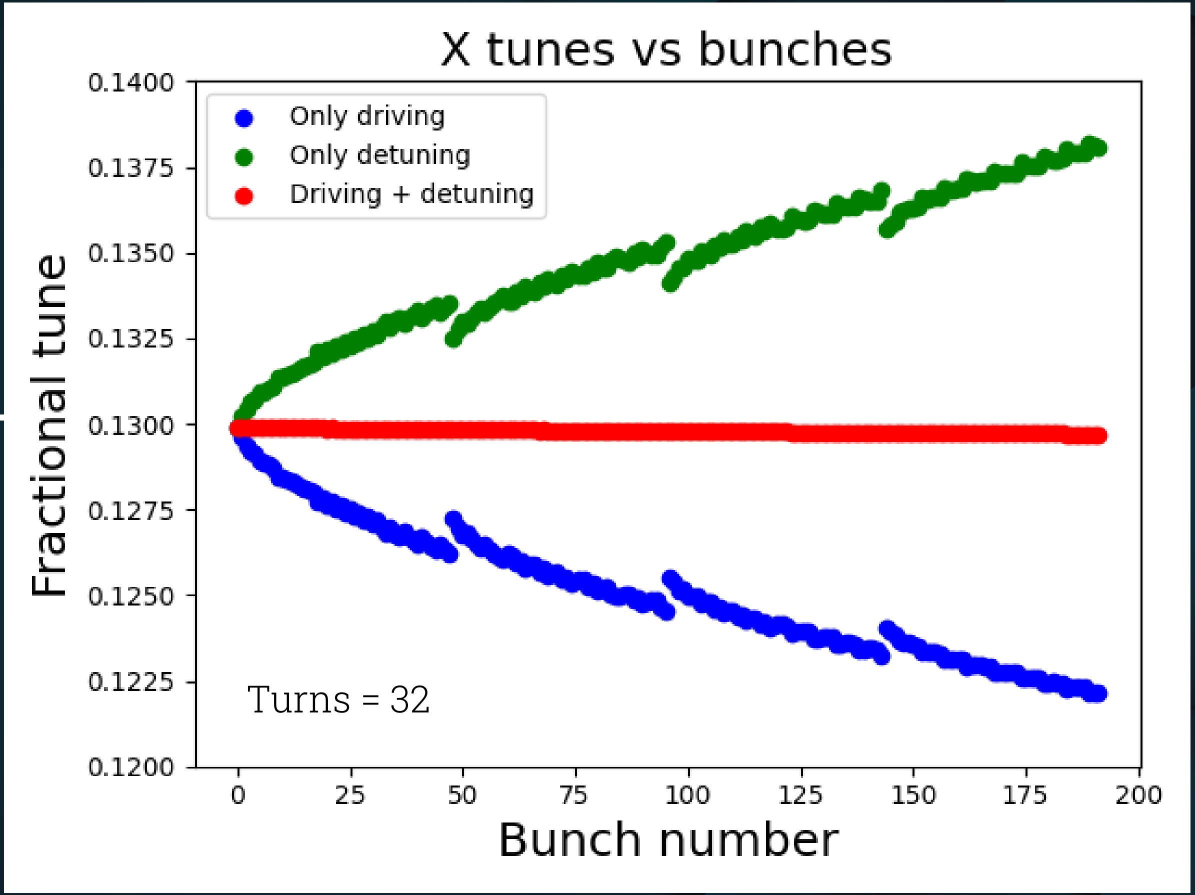
- Opposite shifts from driving and detuning
- Flat tune shift from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

32 TURNS

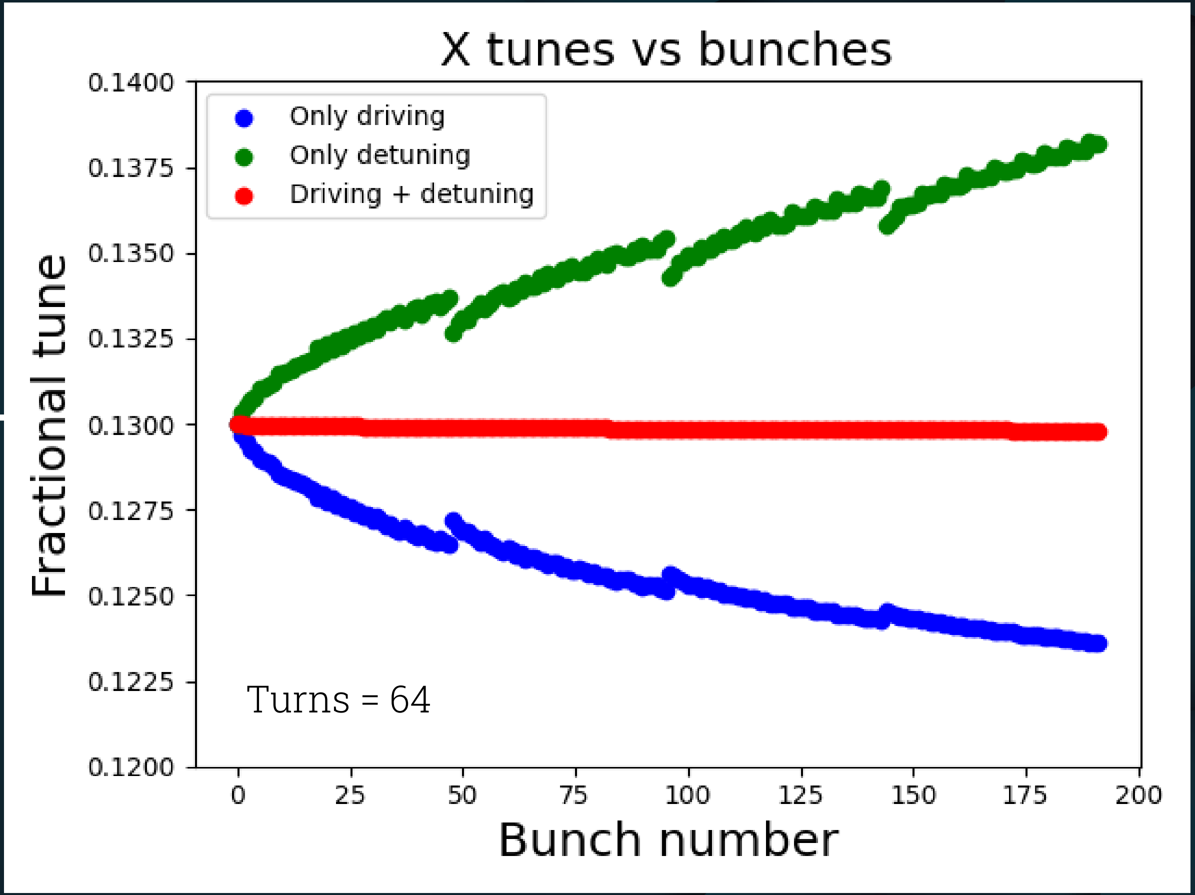
- Opposite shifts from driving and detuning
- Flat tune shift from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

64 TURNS

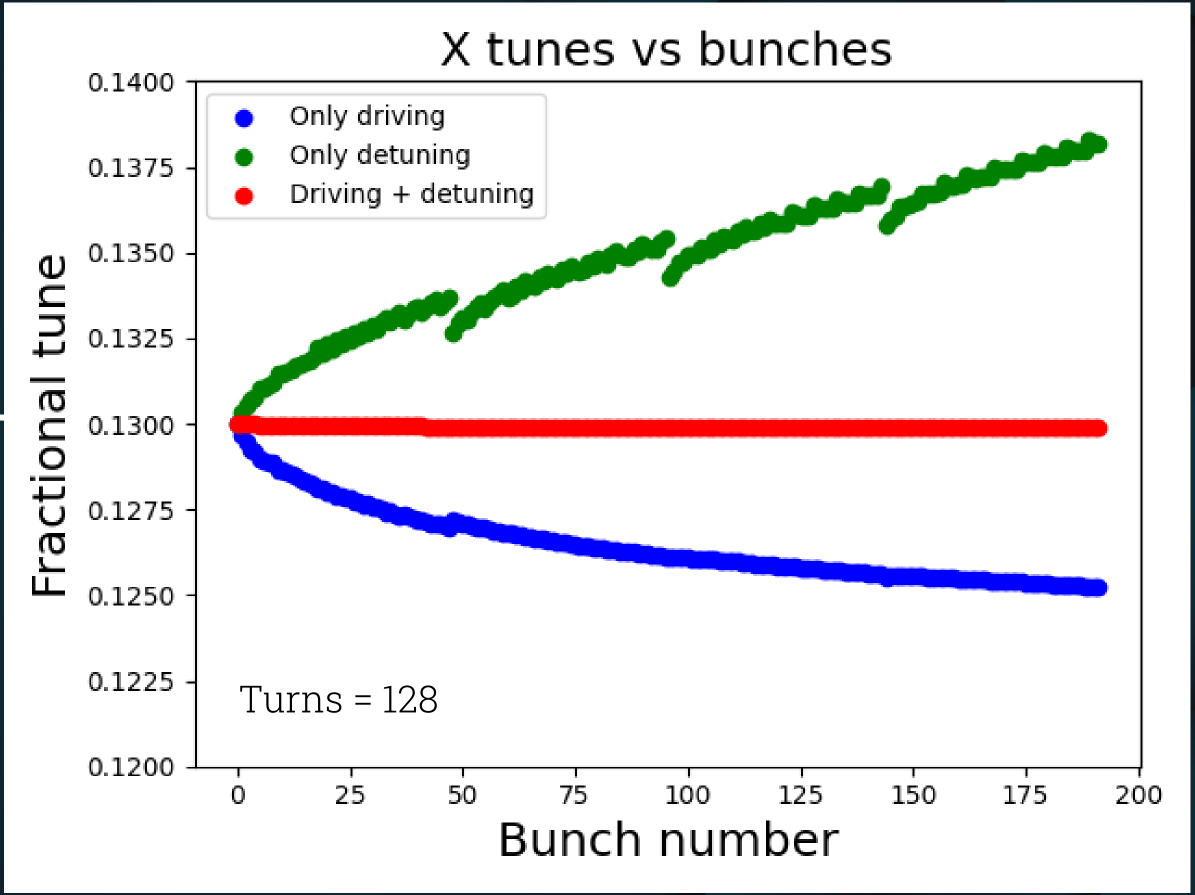
- Tune shift from detuning has converged
- Flat tune shift from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

128 TURNS

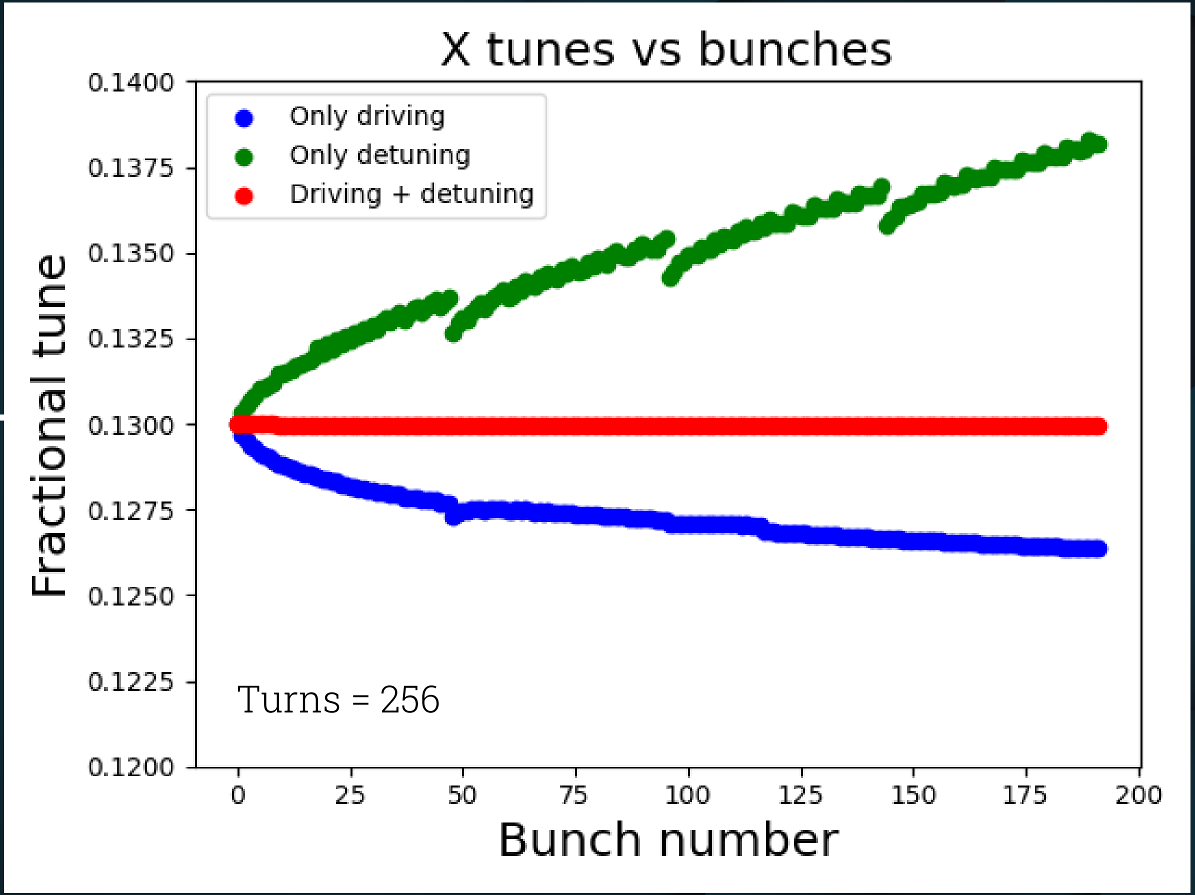
- Tune shift from detuning has converged
- Flat tune shift from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

256 TURNS

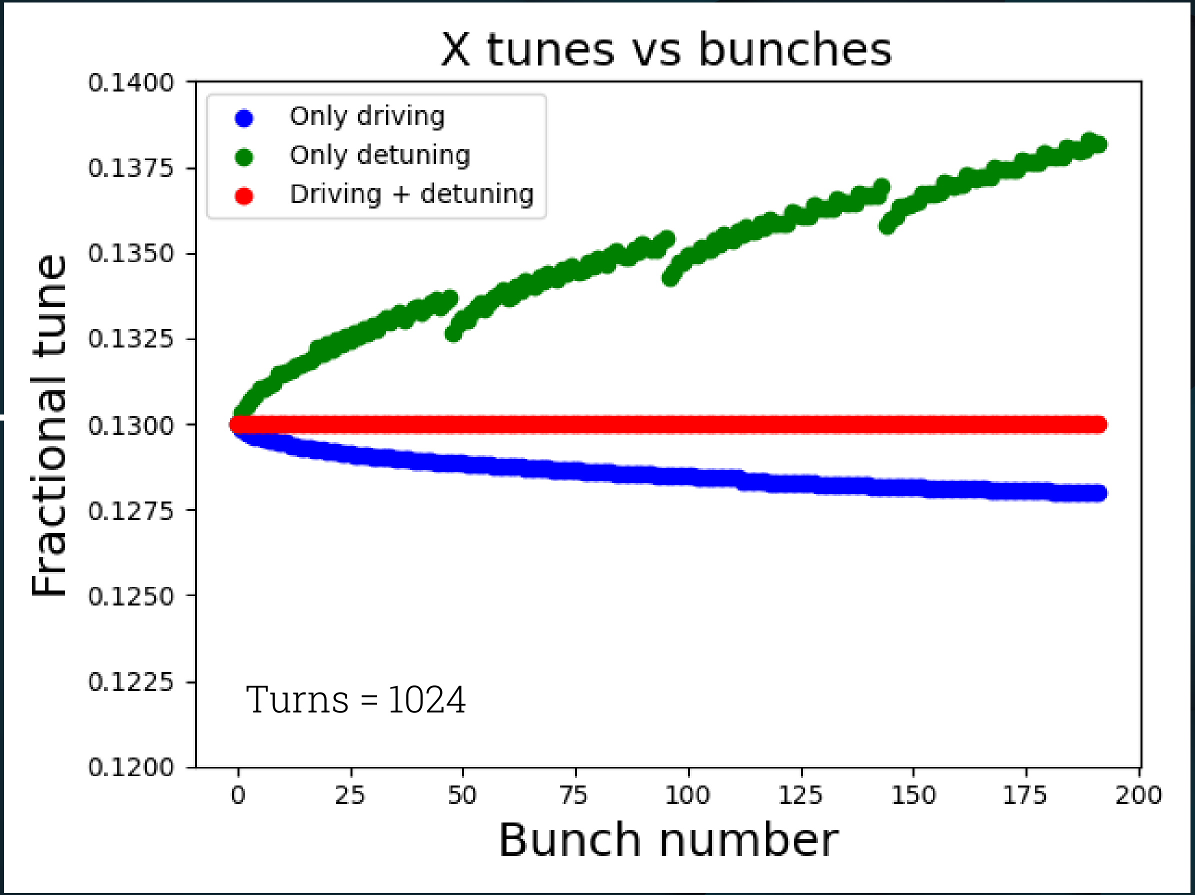
- Tune shift from detuning has converged
- Flat tune shift from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

1024 TURNS

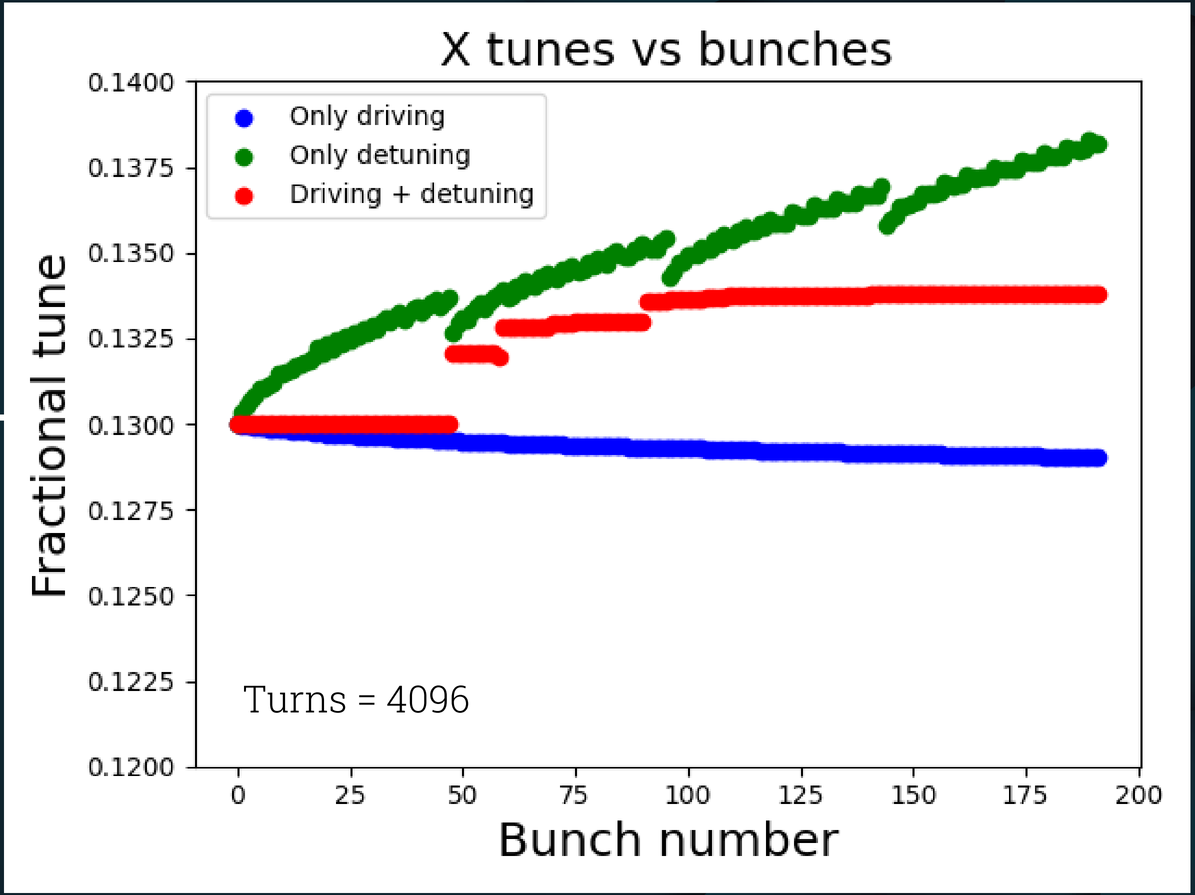
- Tune shift from detuning has converged
- Flat tune shift from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

4096 TURNS

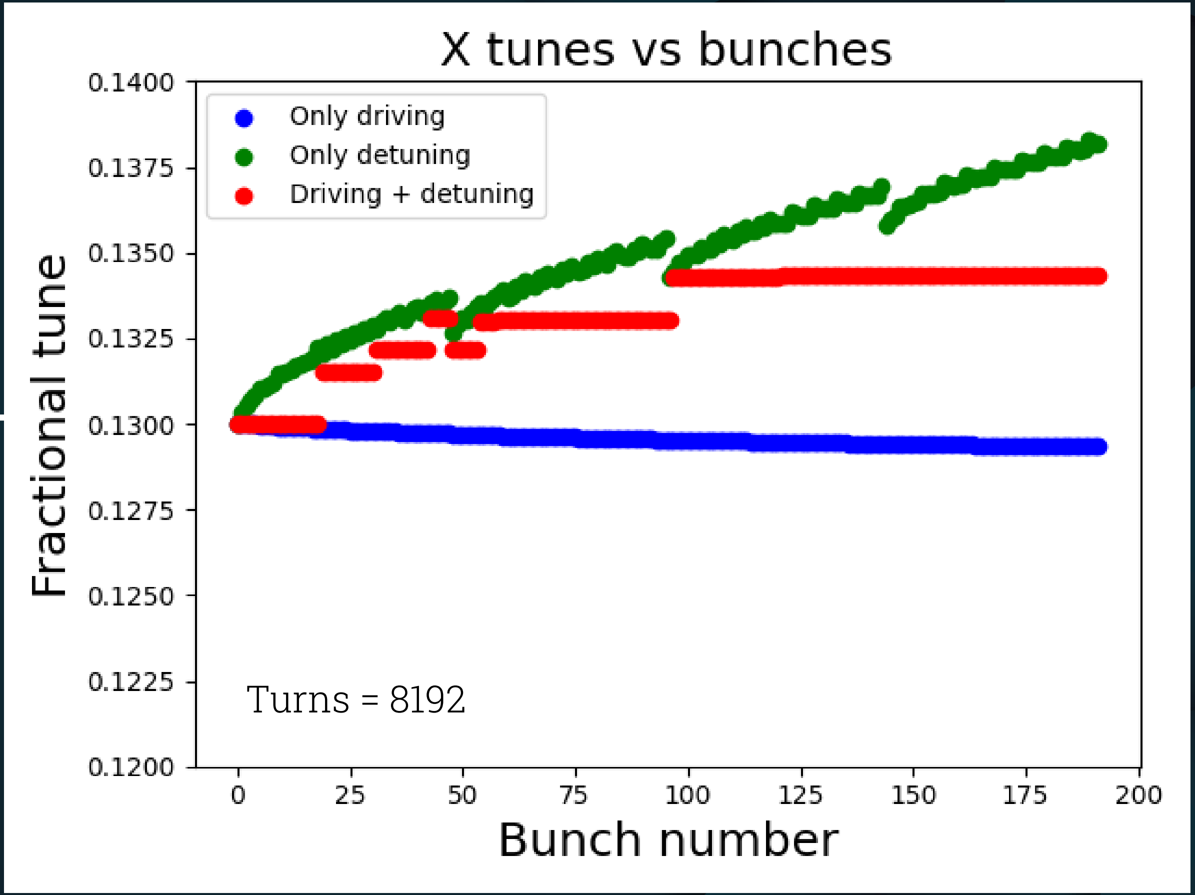
- Tune shift from detuning has converged
- Tune shift in steps from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

8192 TURNS

- Tune shift from detuning has converged
- Tune shift in steps from driving + detuning



ANALYTICAL MULTI-BUNCH MODEL

TUNE CONVERGENCE

- Plot of maximum tune excursion against the number of turns