TMCI in the presence of detuning impedance

E. Métral, X. Buffat and G. Rumolo

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- **Motivation**: recent pyHEADTAIL simulations for the CERN PS (by M. Migliorati, 2019) revealed that the detuning impedance can have a destabilising effect

=> Started to review in detail the theory of all transverse instabilities with detuning impedance

(see https://cds.cern.ch/record/2714848/files/CERN-ACC-NOTE-2020-0019.pdf)

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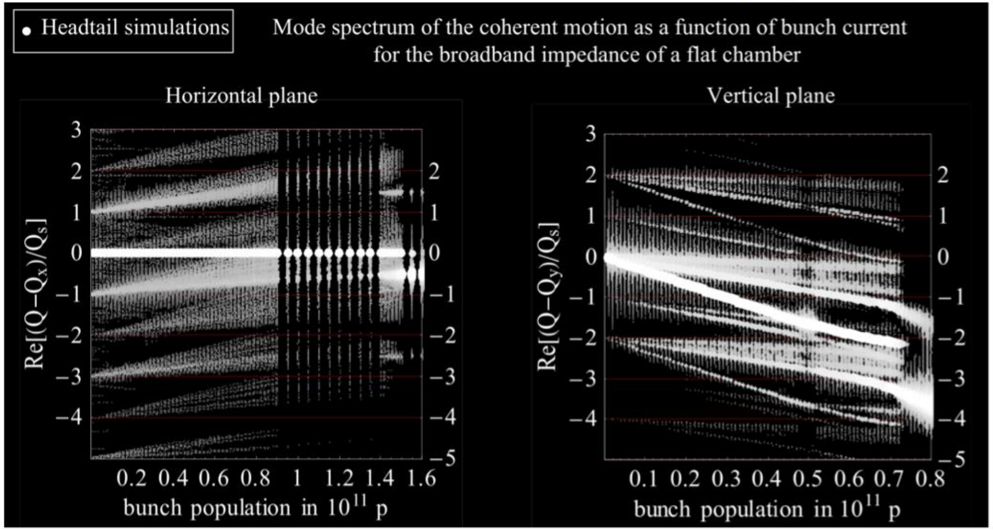
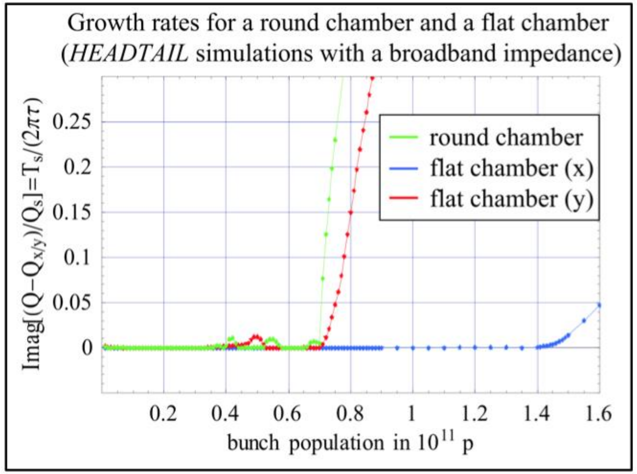
- TMCI for a single bunch ($Q' = 0$)
  - *Theory with 2-particle model => See next talk by G. Rumolo with all the detailed computations*
  - Theory of circulant matrix formalism with 2 or more azimuthal modes but still 1 radial mode
  - Comparison with simulation of circulant matrix formalism with many azimuthal modes but still 1 radial mode (from BimBim code)
  - Full BimBim simulation of circulant matrix formalism with many azimuthal modes and many radial modes
- *Coasting-beams => See next talk by N. Biancacci with a new instability mechanism identified*
- Conclusion and outlook

Intro: Past simulations for SPS TMCI

$$f_r \tau_b = 2.8$$





B. Salvant

=> $N_b^{th,x} / N_b^{th,round} \approx 2$ $\quad N_b^{th,y} / N_b^{th,round} \approx 1$

=> Can we fully understand them?

Intro: Past simulations for SPS TMCI

- As we will see, it is important to differentiate between the **“short-bunch” regime** (TMCI between modes 0 and -1) and the **“long-bunch” regime** (TMCI between higher-order modes)

Intro: Past simulations for SPS TMCI

- As we will see, it is important to differentiate between the **“short-bunch” regime** (TMCI between modes 0 and -1) and the **“long-bunch” regime** (TMCI between higher-order modes)

- Furthermore, one has to be careful when we mention the beneficial or detrimental effect of the detuning impedance, depending on what we compare it to => As can be seen already in the past HEADTAIL simulations for the x-plane
  - **Beneficial effect of the asymmetry** => Threshold ~ 2 times higher
  - But (slight) **detrimental effect of the detuning impedance wrt to the driving impedance** as the gain from the driving impedance only would have been $24/\pi^2 \approx 2.4$

Circulant matrix formalism (1 radial mode)

- See A. Burov and V. Danilov, “Suppression of transverse bunch instabilities by asymmetries in the chamber geometry”, Phys. Rev. Lett. 82, 2286 (1999) => Followed the formalism from Danilov-Perevedentsev_1997 (Feedback system for elimination of the TMCI, Nucl. Instr. and Methods, A391, 77)

$$\int_L F_x ds = -q^2 x_0 W_x(z) + q^2 x D(z)$$

$$\int_L F_y ds = -q^2 y_0 W_y(z) - q^2 y D(z)$$

$$\frac{d^2 x(\phi)}{dt^2} + \omega_b^2 x(\phi) = F_x(\phi)$$

$$F_x(\phi) = -\frac{Nq^2}{2\pi\gamma m L}\int_{-|\phi|}^{|\phi|}(W(z)x(\phi') - D(z)x(\phi))d\phi'$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \omega_s \frac{\partial}{\partial \phi}, \qquad z = a\cos\phi - a\cos\phi'$$

Circulant matrix formalism (1 radial mode)

- Using the **"air-bag" model** with a **constant wake** (given below as the constant term of a resonator wake, which will be used after) and considering first only **2 modes (0 and -1)**, the system is fully described by the following matrix to be diagonalized

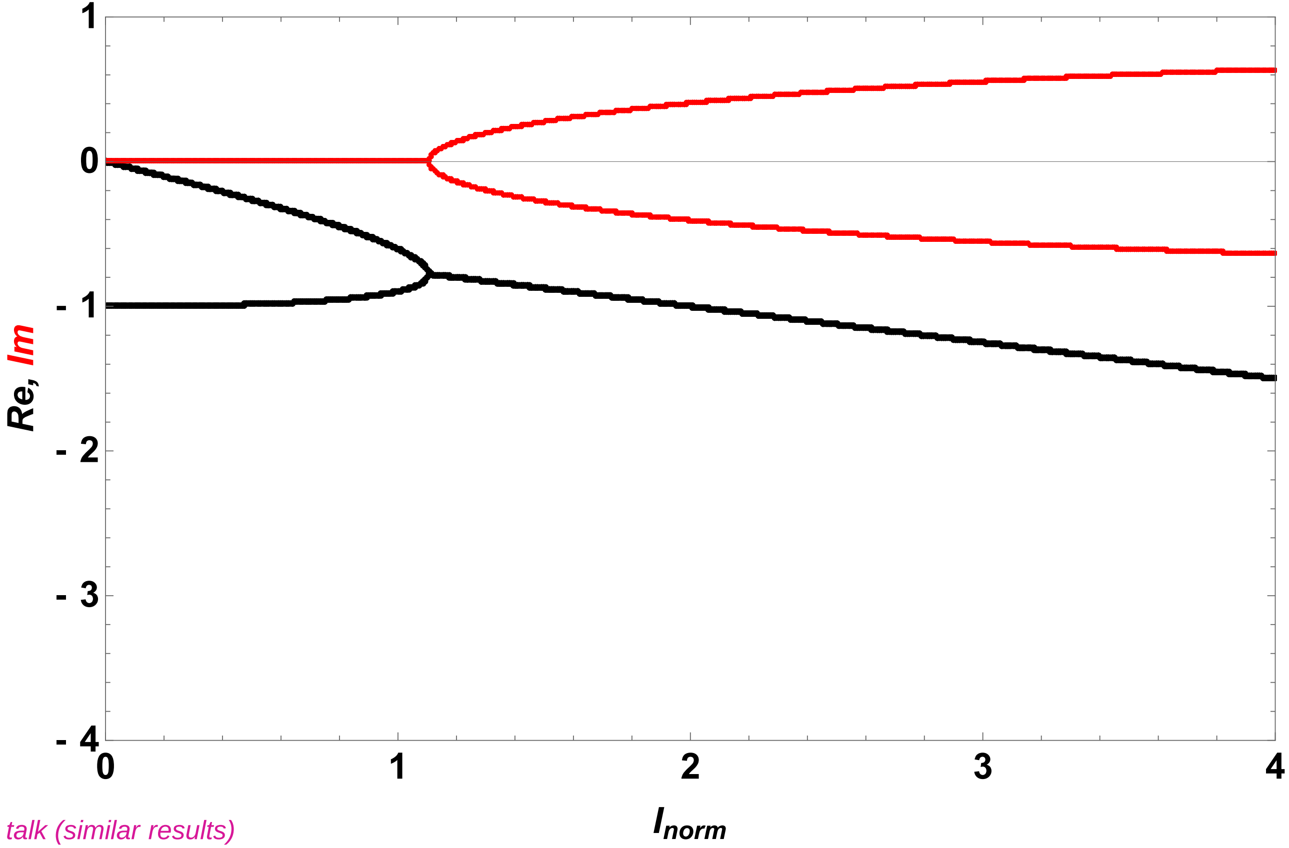
$$\begin{bmatrix} -1+\frac{\kappa}{2}\, I_{norm} & \frac{2\, I_{norm}}{\pi^2}\,(1-\kappa) \\ \frac{2\, I_{norm}}{\pi^2}\,(-1-\kappa) & \frac{I_{norm}}{2}\,(-1+\kappa) \end{bmatrix}$$

$$I_{norm} = \frac{N\, e^2}{2\, \gamma\, m_0\, \omega_\beta\, \omega_s\, C} \times \frac{\omega_r^2\, R_t}{Q\, \overline{\omega_r}} \qquad \kappa = \frac{D(z)}{W_x\,(z)}$$

+ 1 in x for CRW flat chamber
- 1/2 in y for CRW flat chamber

Circulant matrix formalism (1 radial mode)

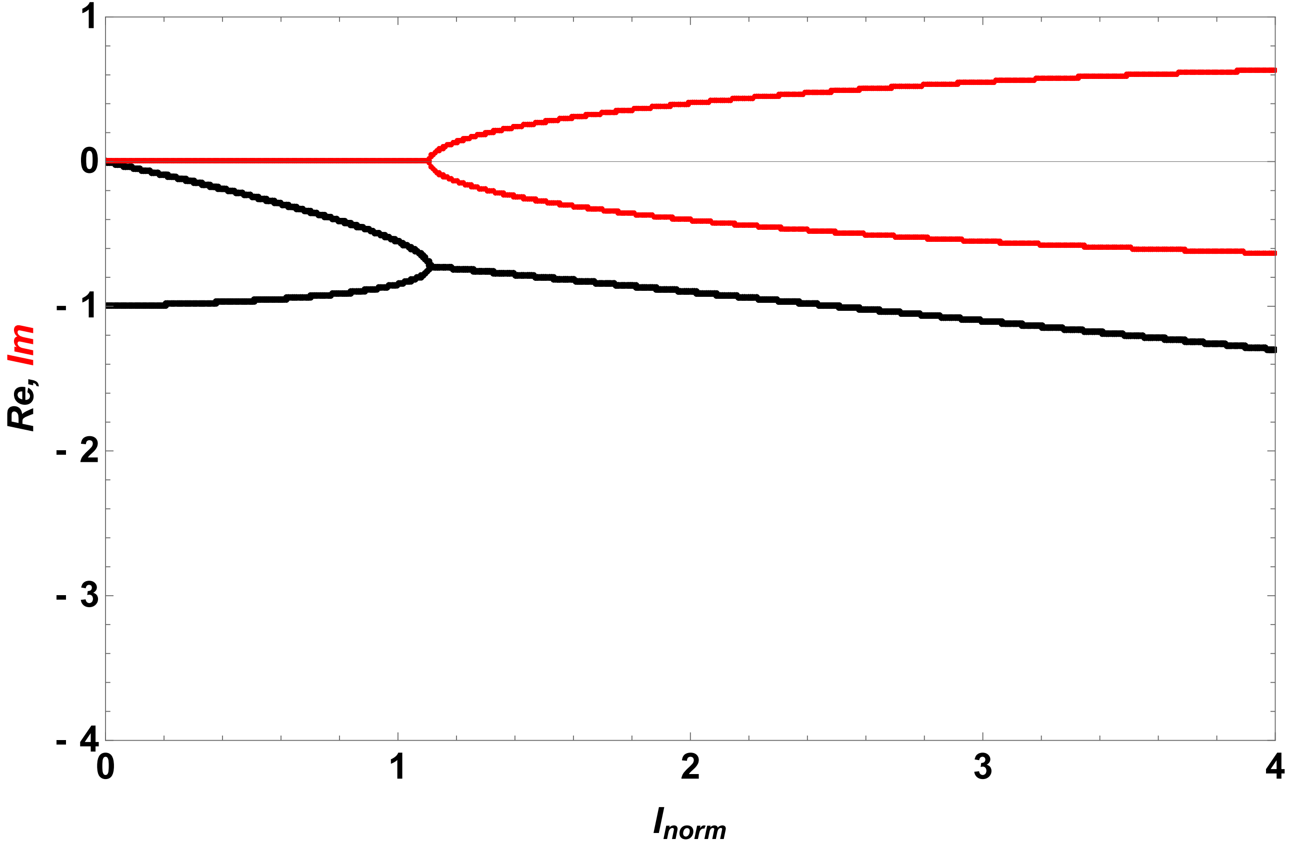
$\kappa = 0.0$



See aslo G. Rumolo's talk (similar results)

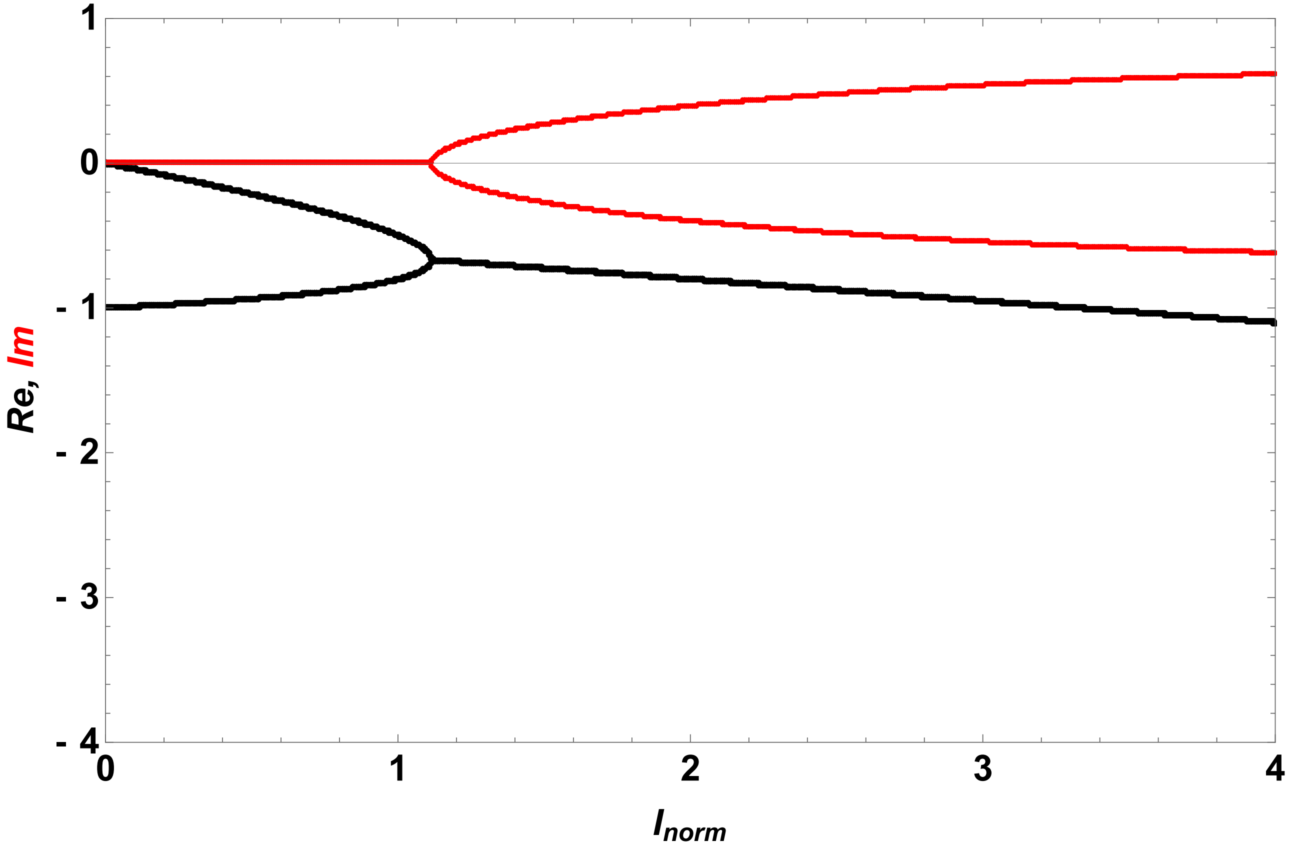
Circulant matrix formalism (1 radial mode)

$\kappa = 0.1$



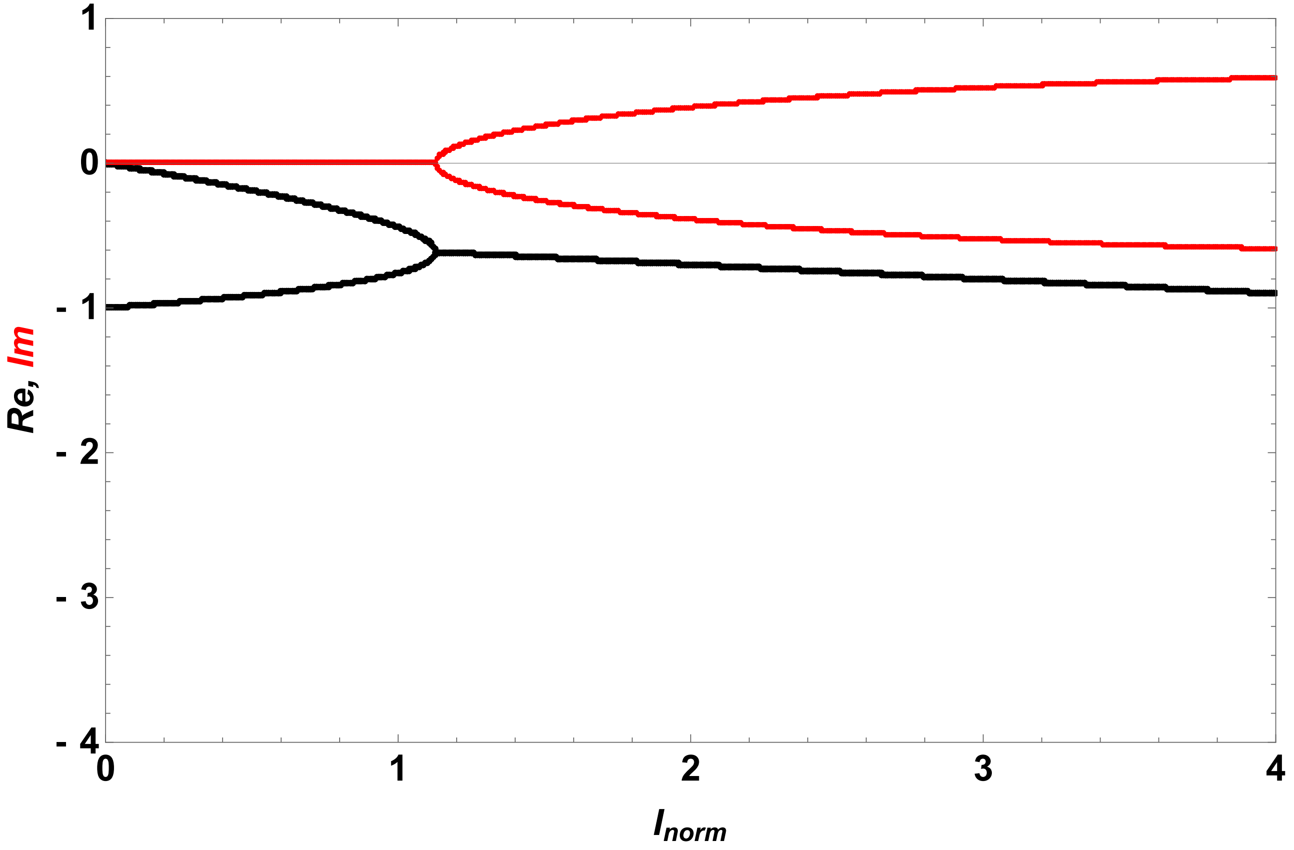
Circulant matrix formalism (1 radial mode)

$\kappa = 0.2$



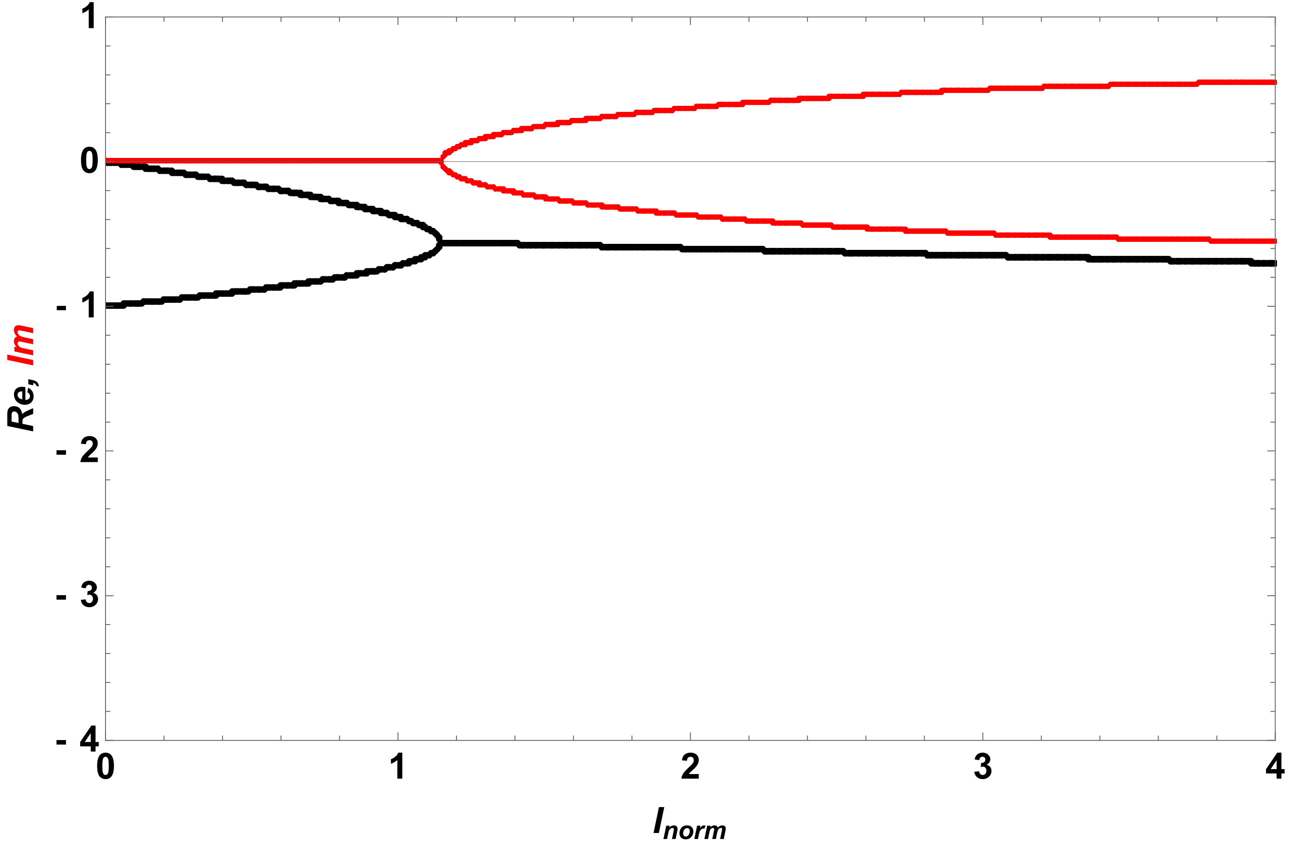
Circulant matrix formalism (1 radial mode)

$\kappa = 0.3$



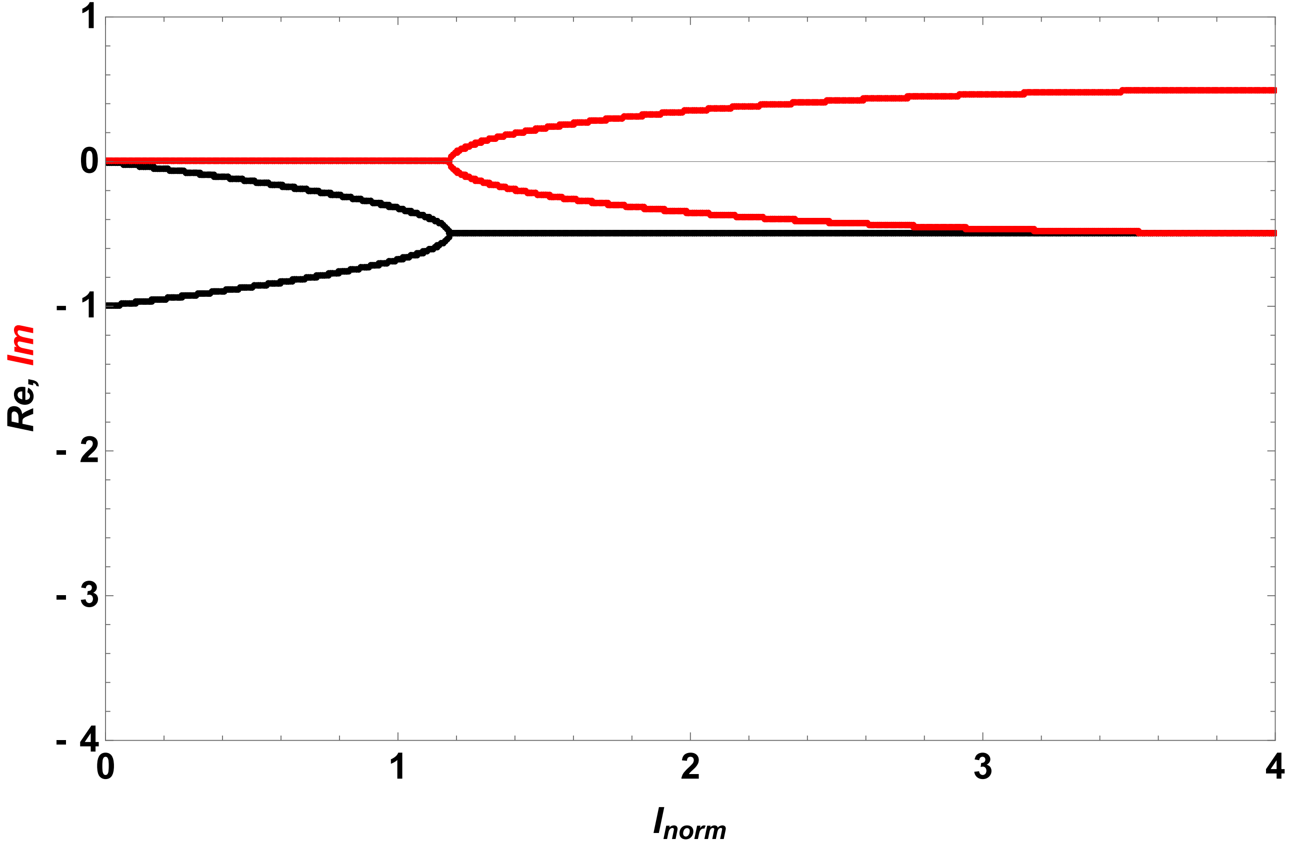
Circulant matrix formalism (1 radial mode)

$\kappa = 0.4$



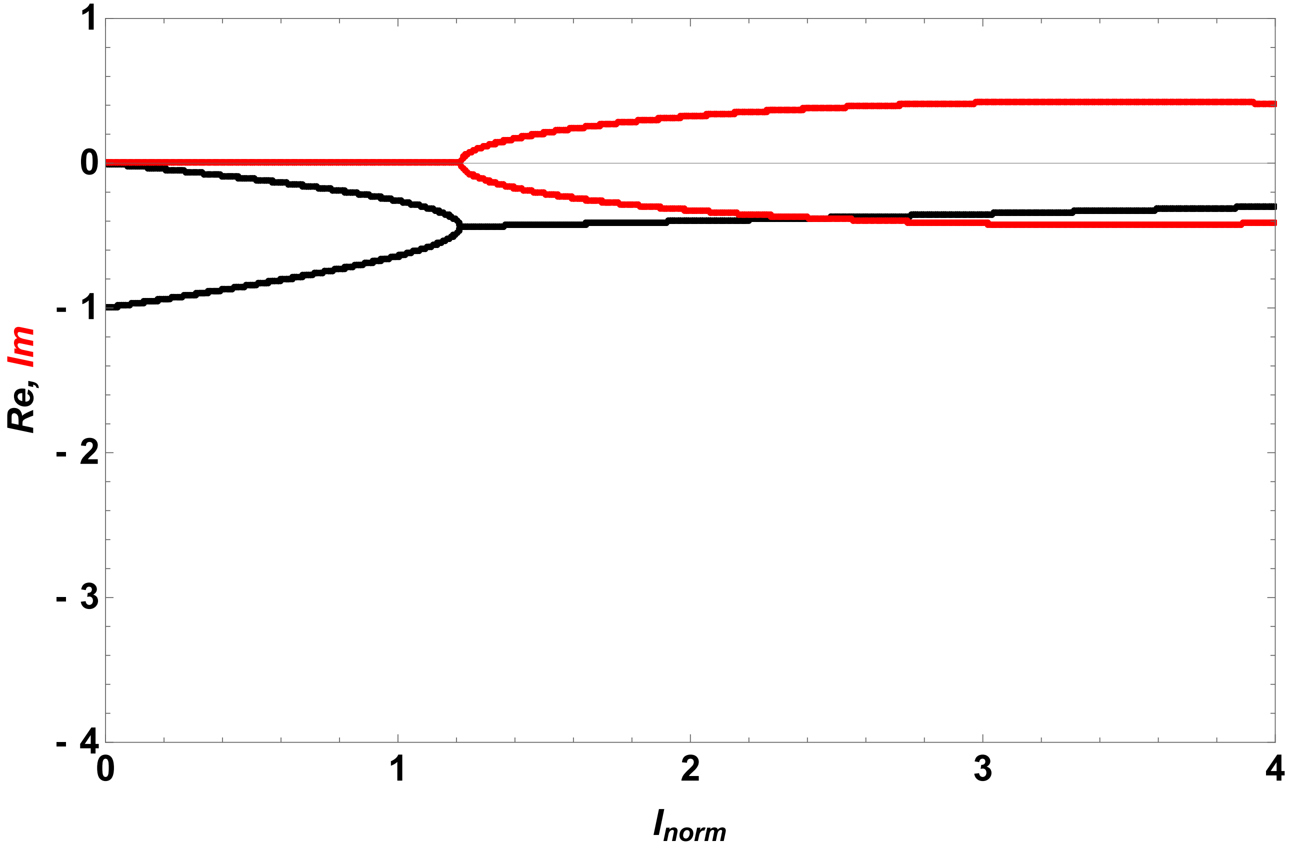
Circulant matrix formalism (1 radial mode)

$\kappa = 0.5$



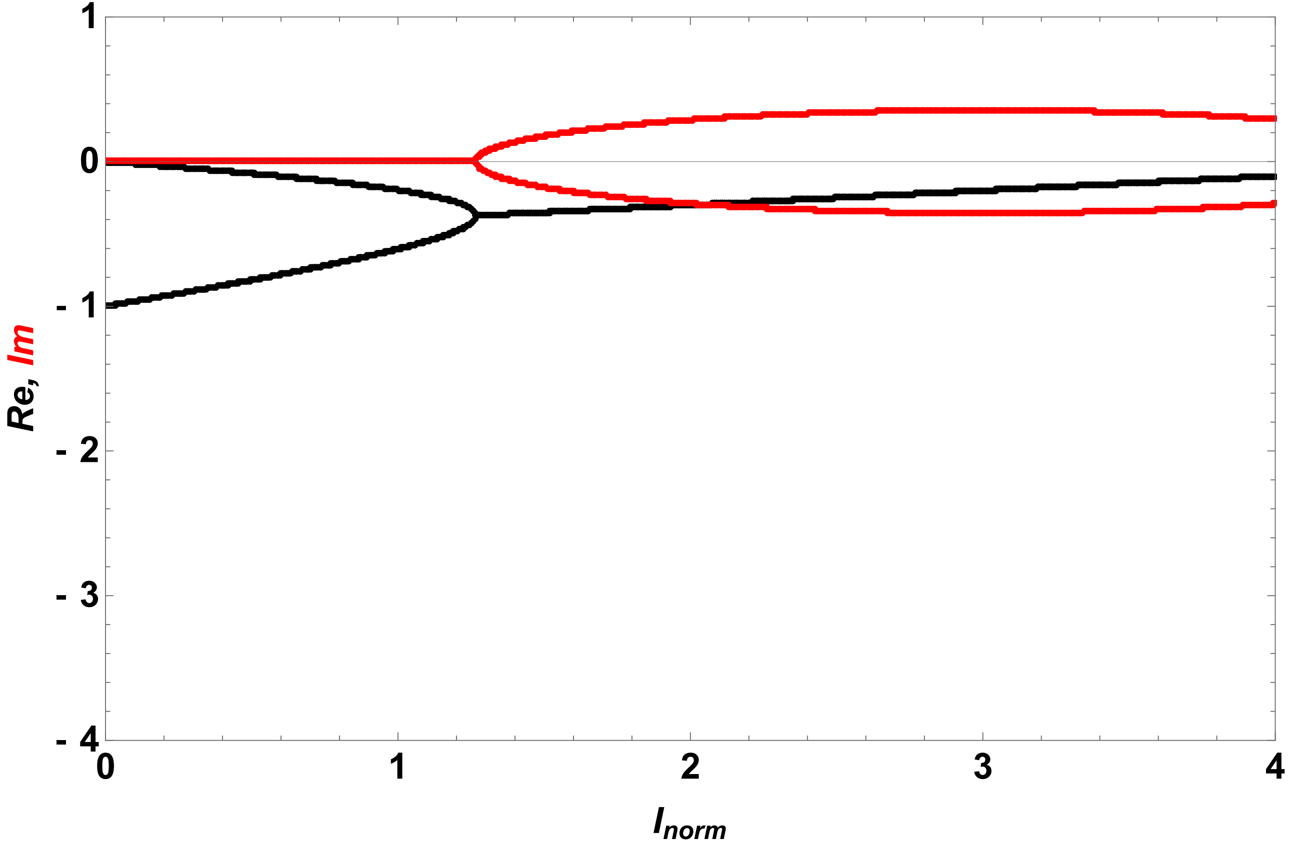
Circulant matrix formalism (1 radial mode)

$\kappa = 0.6$



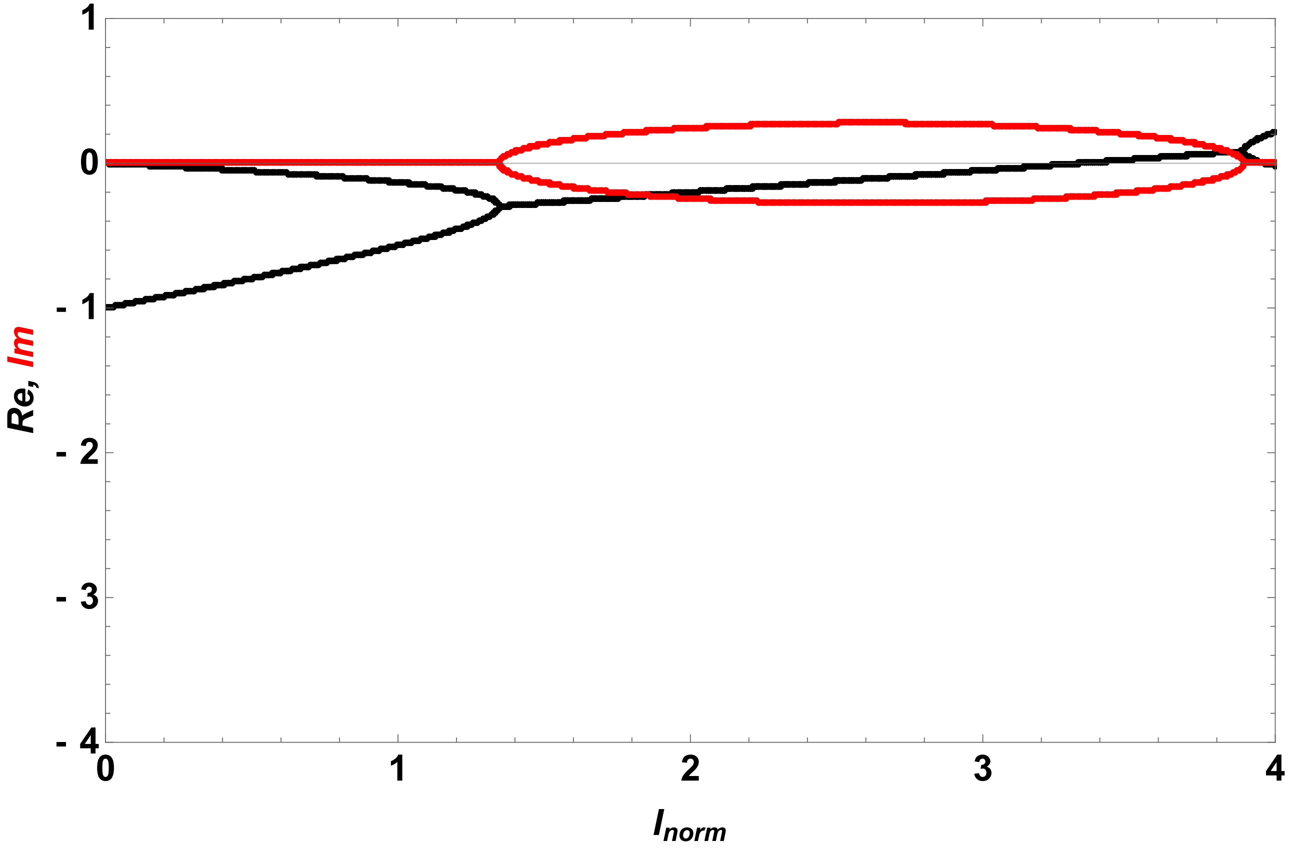
Circulant matrix formalism (1 radial mode)

$\kappa = 0.7$



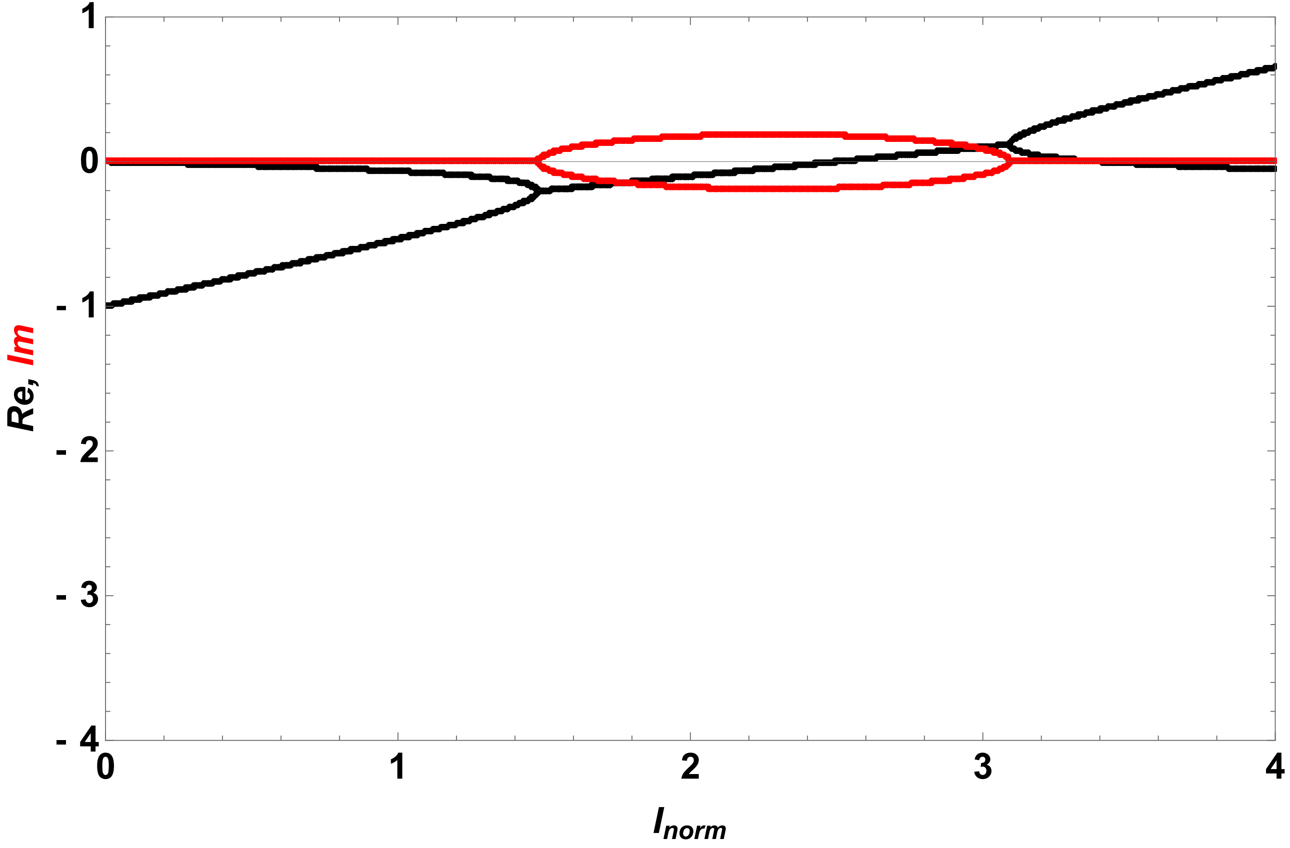
Circulant matrix formalism (1 radial mode)

$\kappa = 0.8$



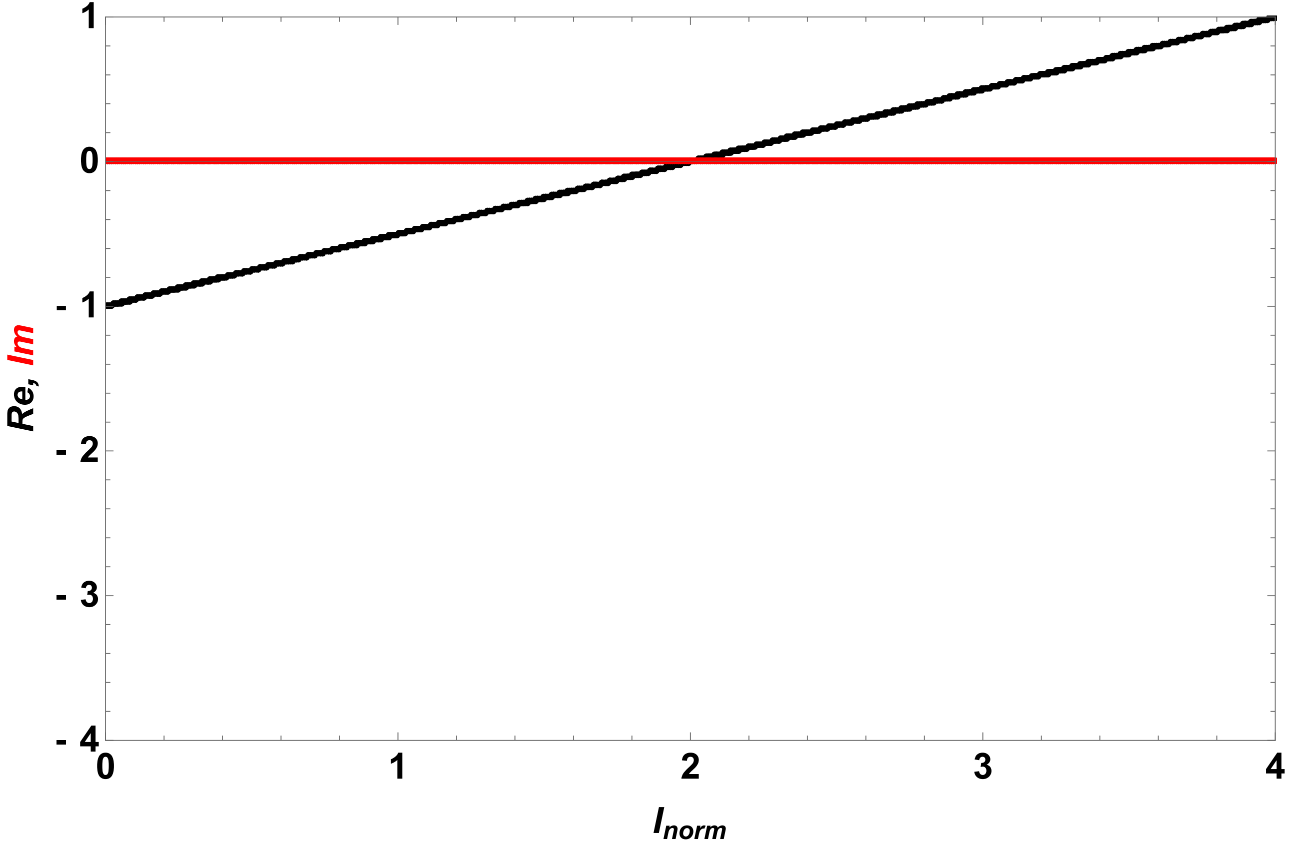
Circulant matrix formalism (1 radial mode)

$\kappa = 0.9$



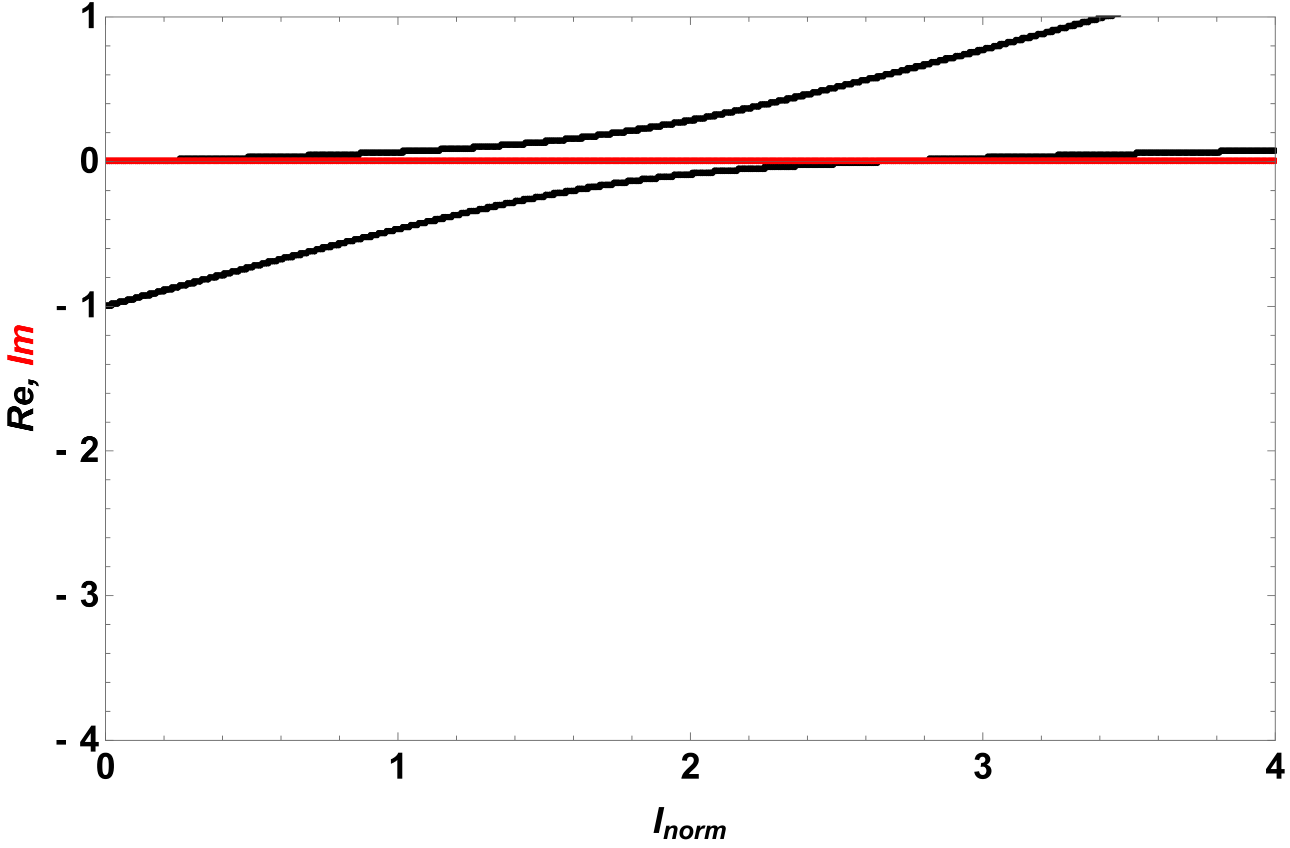
Circulant matrix formalism (1 radial mode)

$\kappa = 1.0$



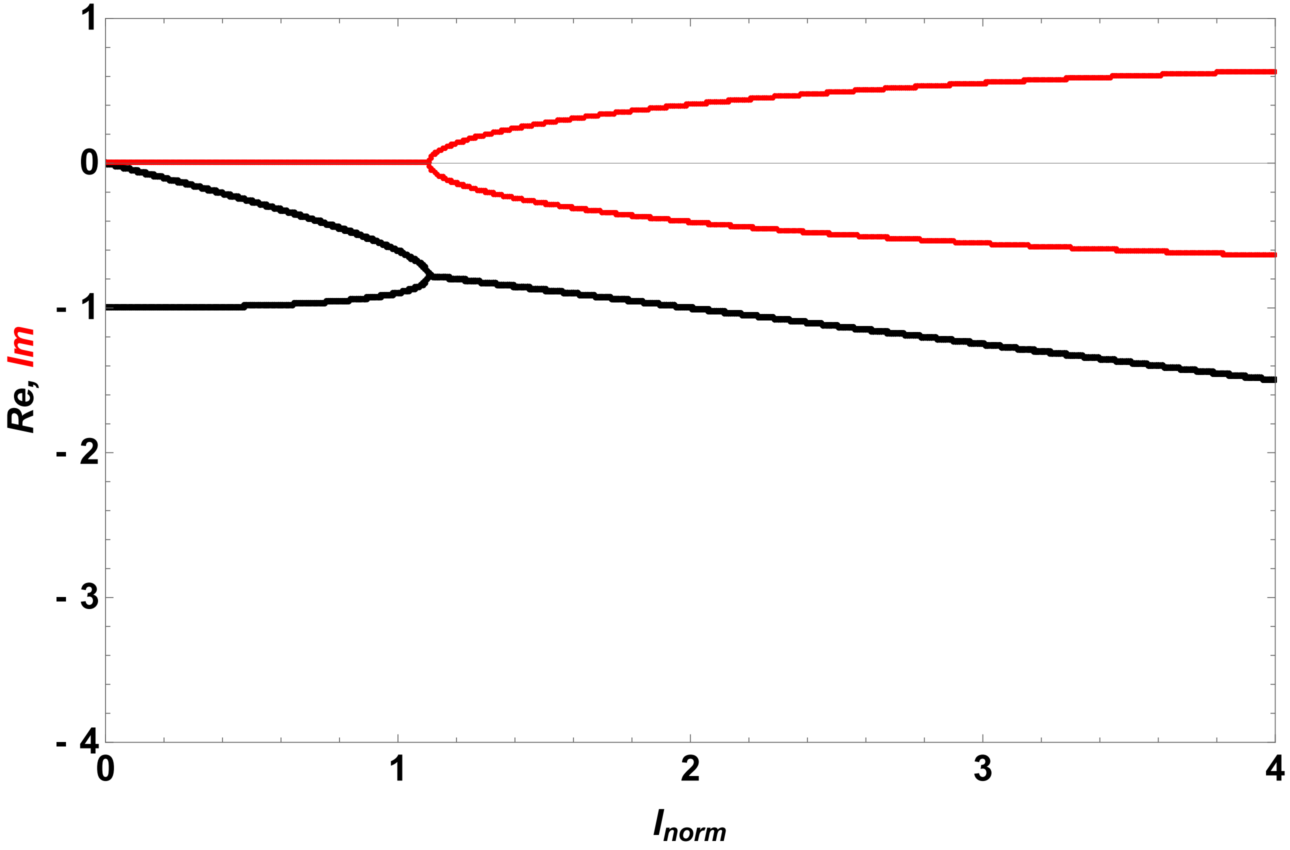
Circulant matrix formalism (1 radial mode)

$\kappa = 1.1$



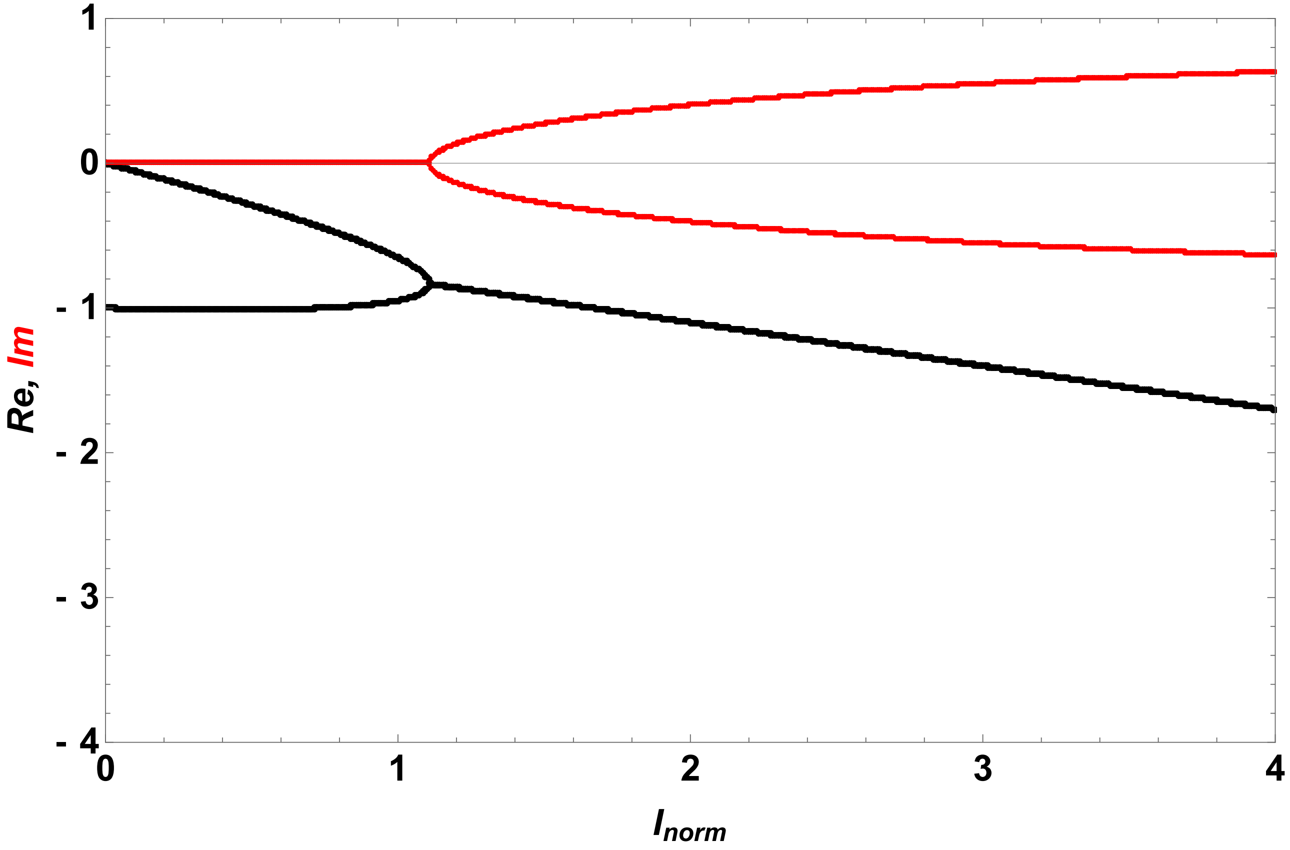
Circulant matrix formalism (1 radial mode)

$\kappa = 0.0$



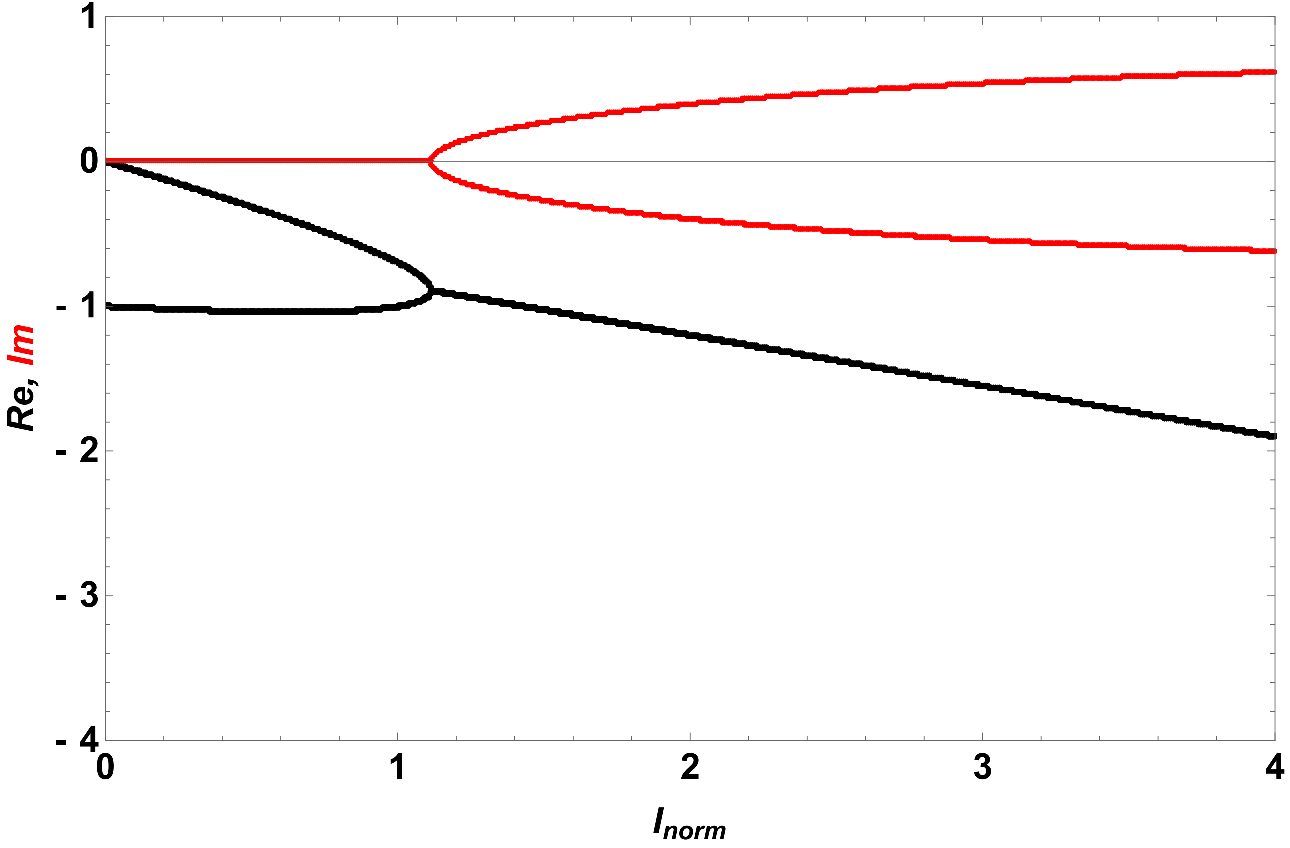
Circulant matrix formalism (1 radial mode)

$\kappa = -0.1$



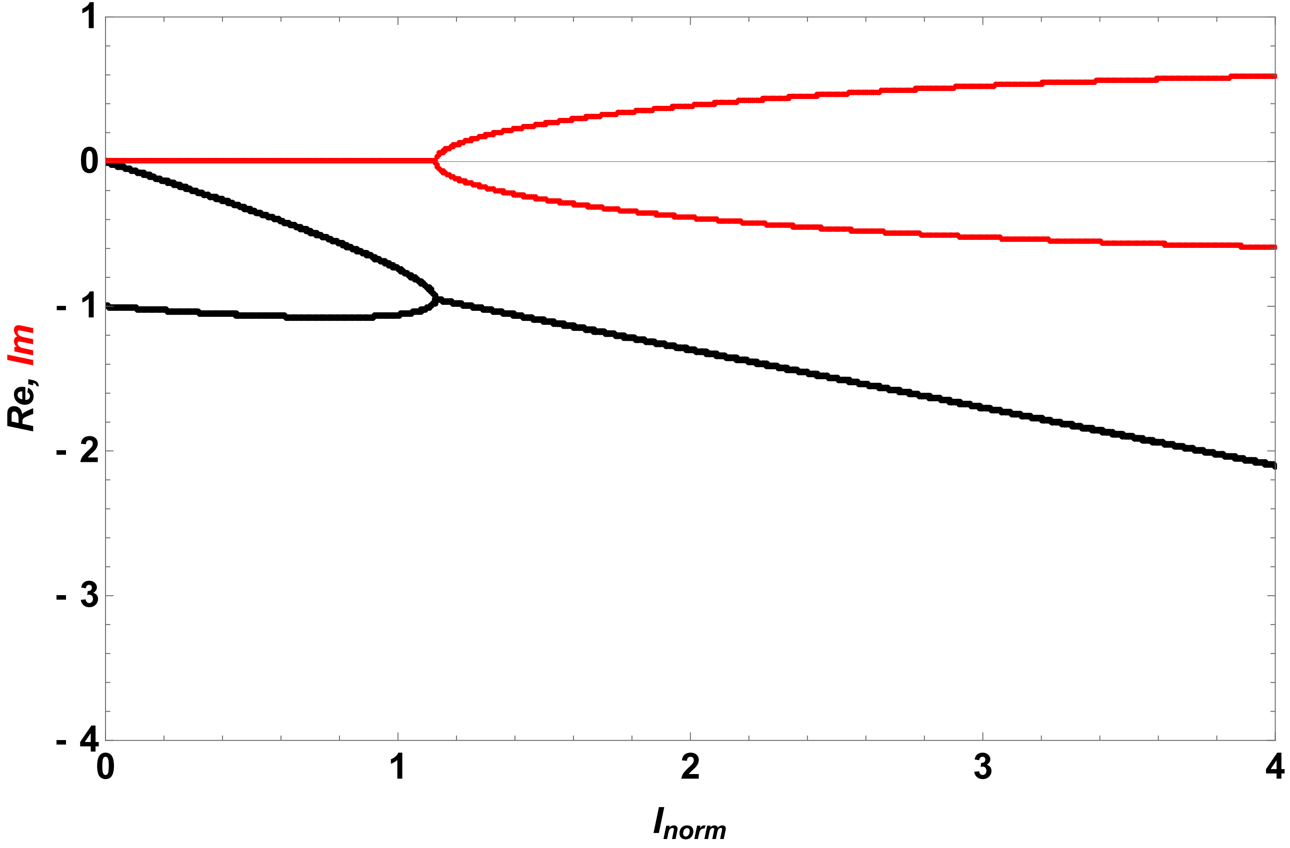
Circulant matrix formalism (1 radial mode)

$\kappa = -0.2$



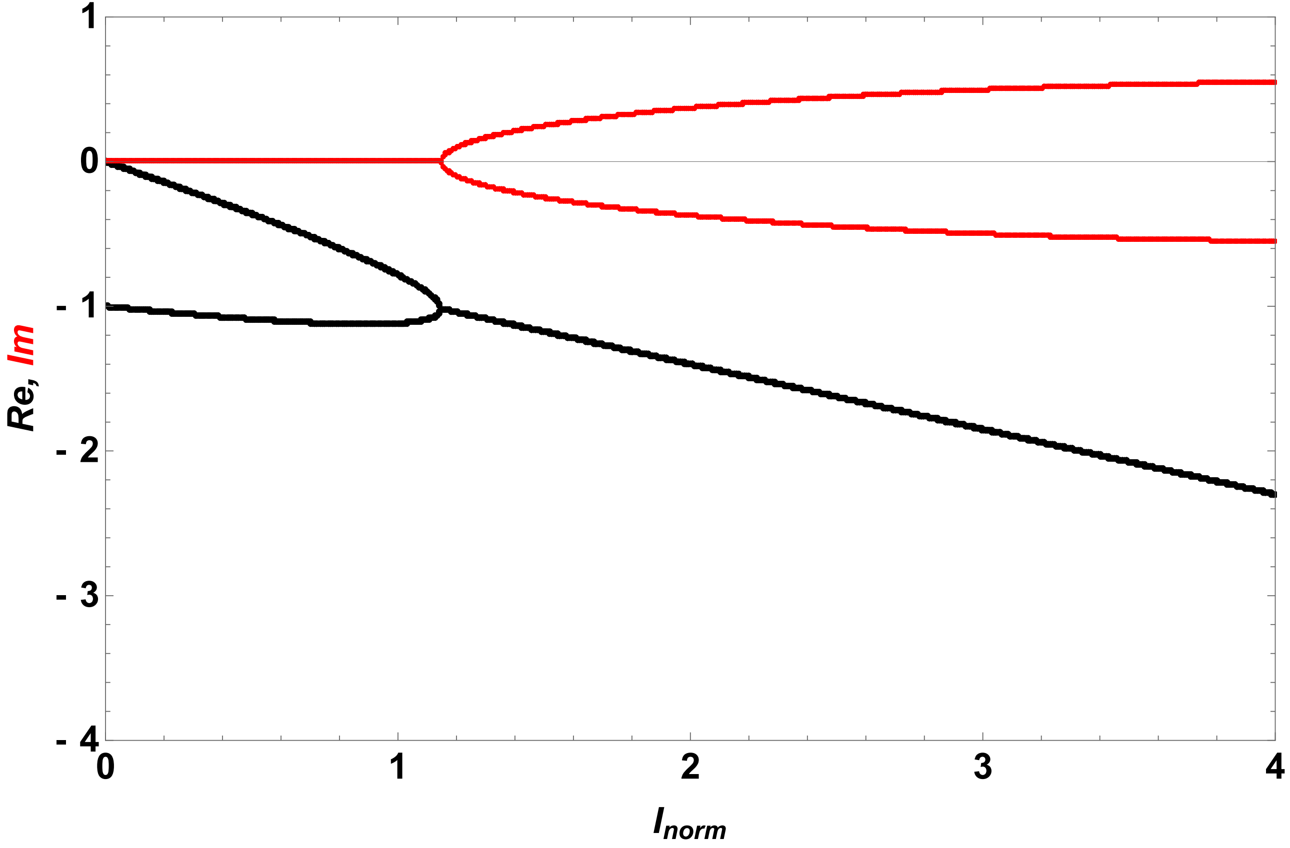
Circulant matrix formalism (1 radial mode)

$\kappa = -0.3$



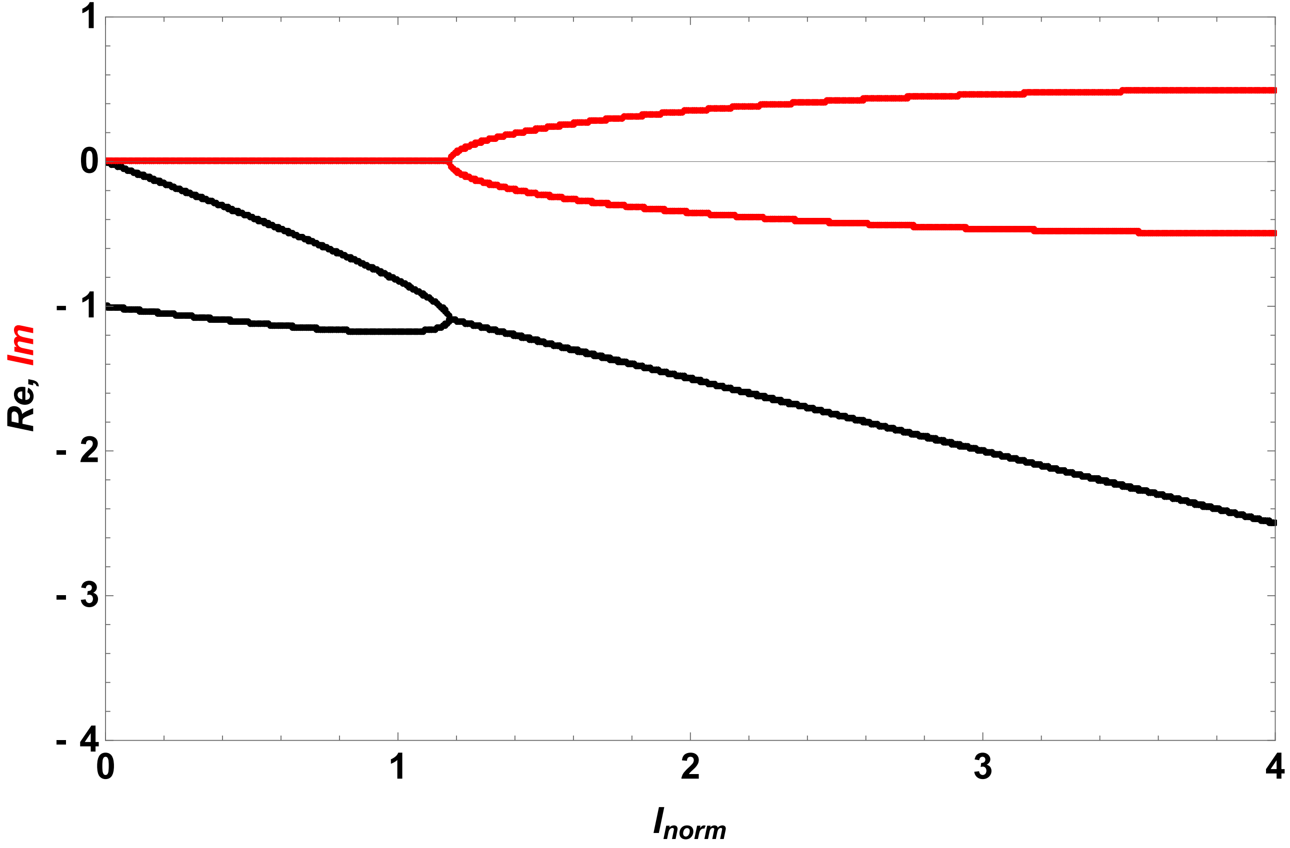
Circulant matrix formalism (1 radial mode)

$\kappa = -0.4$



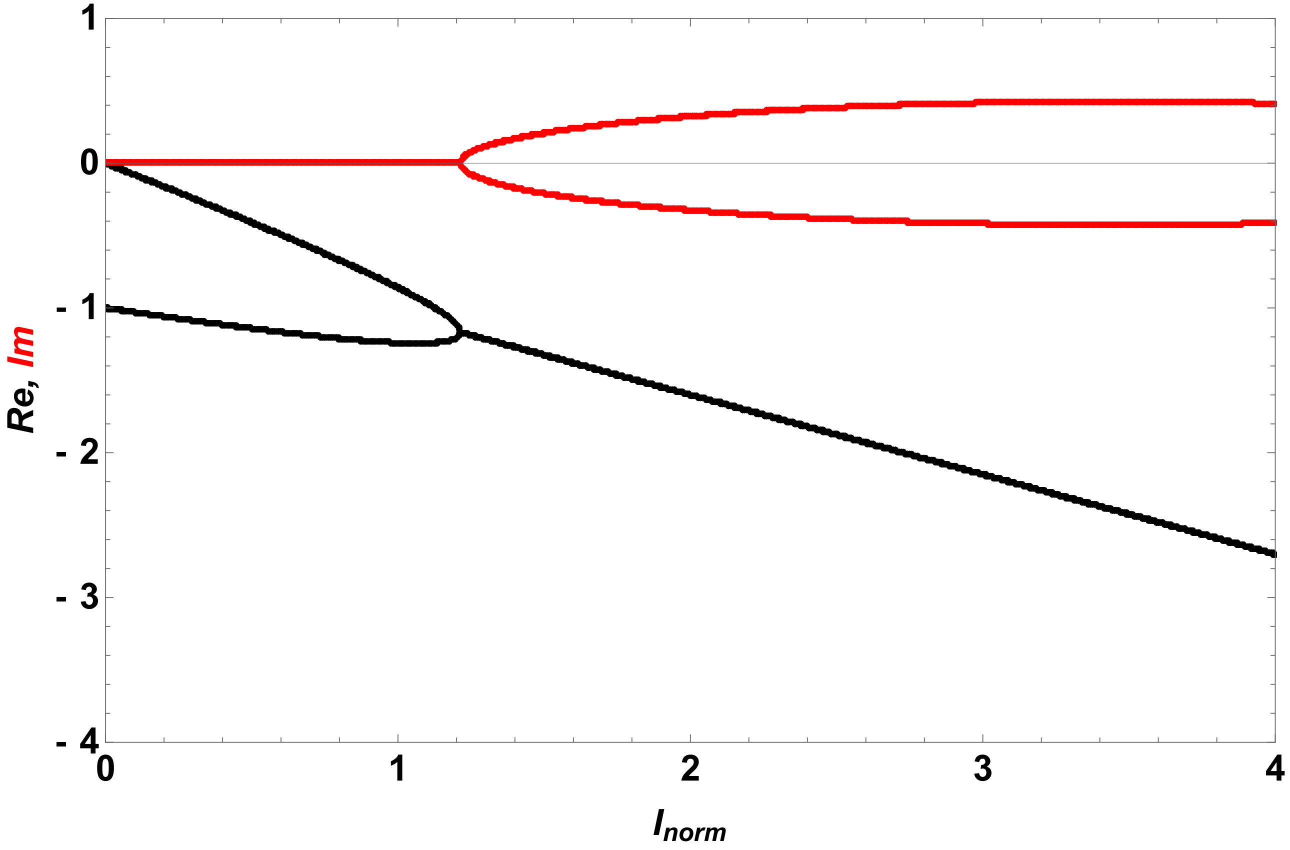
Circulant matrix formalism (1 radial mode)

$\boldsymbol{\kappa = -0.5}$



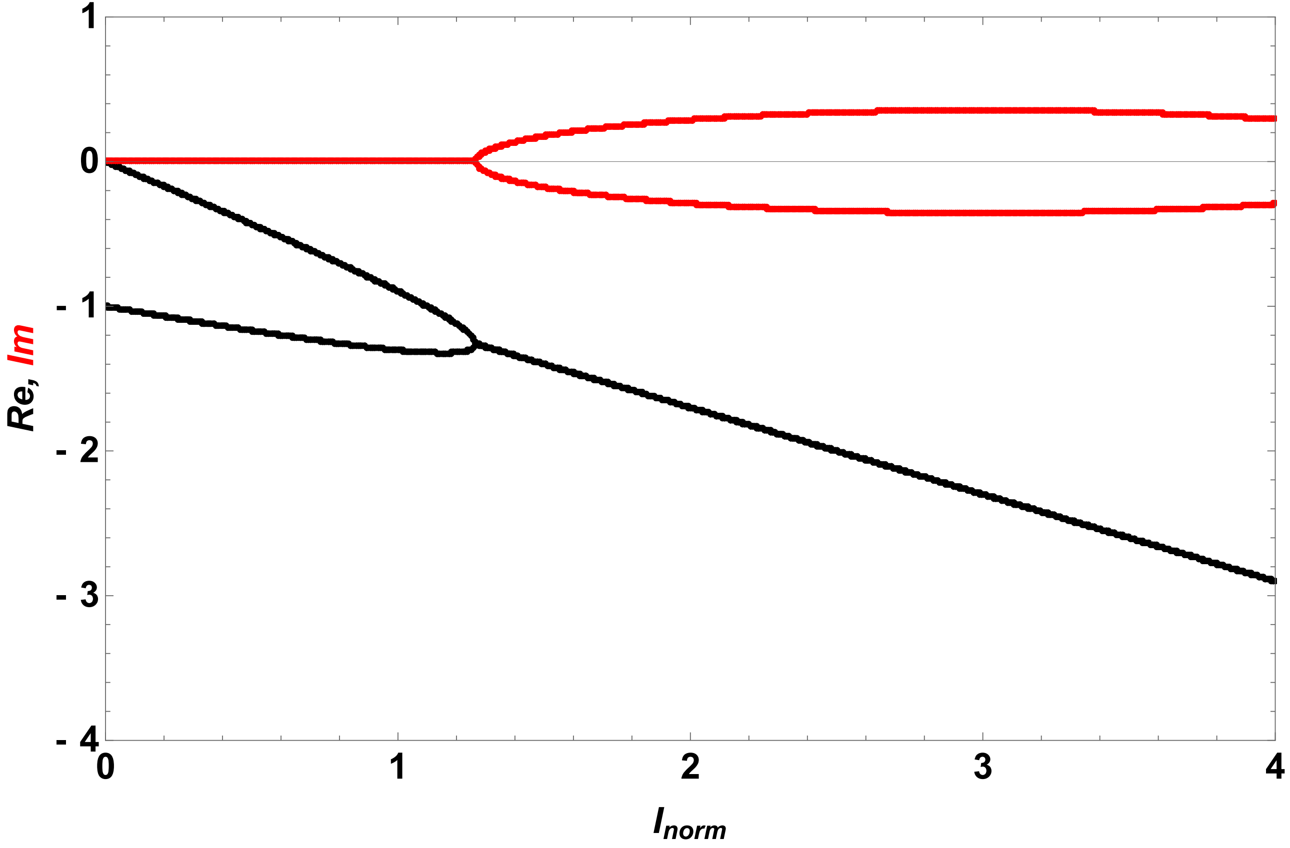
Circulant matrix formalism (1 radial mode)

$\kappa = -0.6$



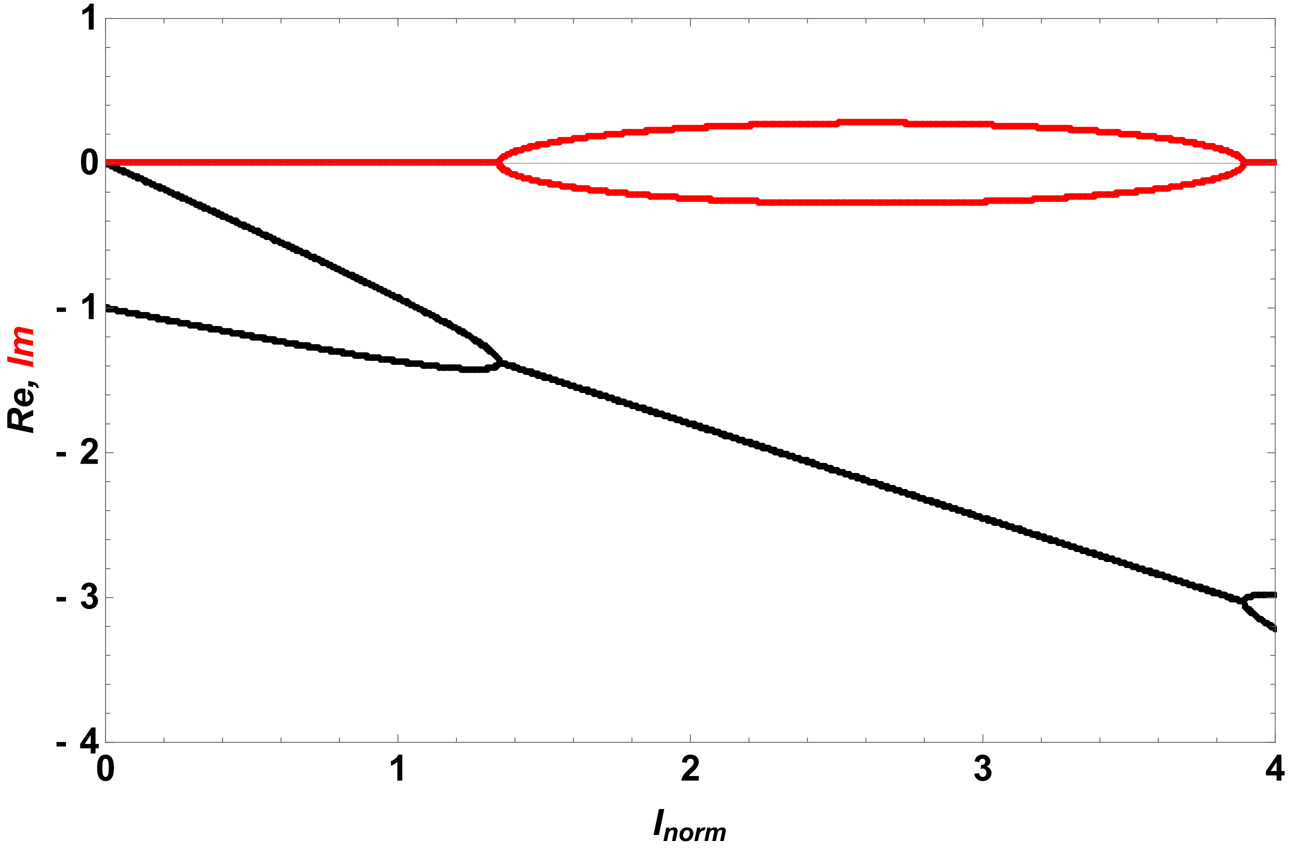
Circulant matrix formalism (1 radial mode)

$\kappa = -0.7$



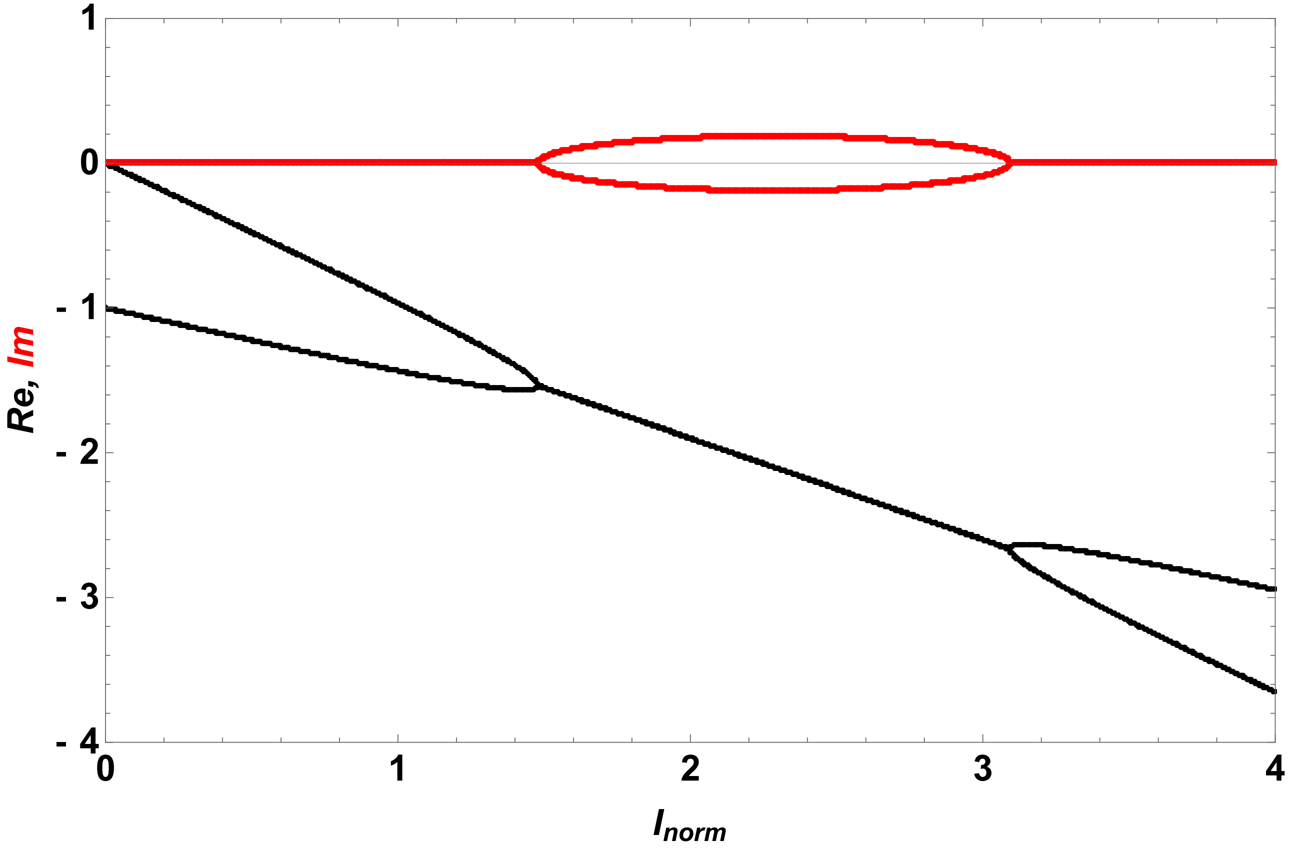
Circulant matrix formalism (1 radial mode)

$\kappa = -0.8$



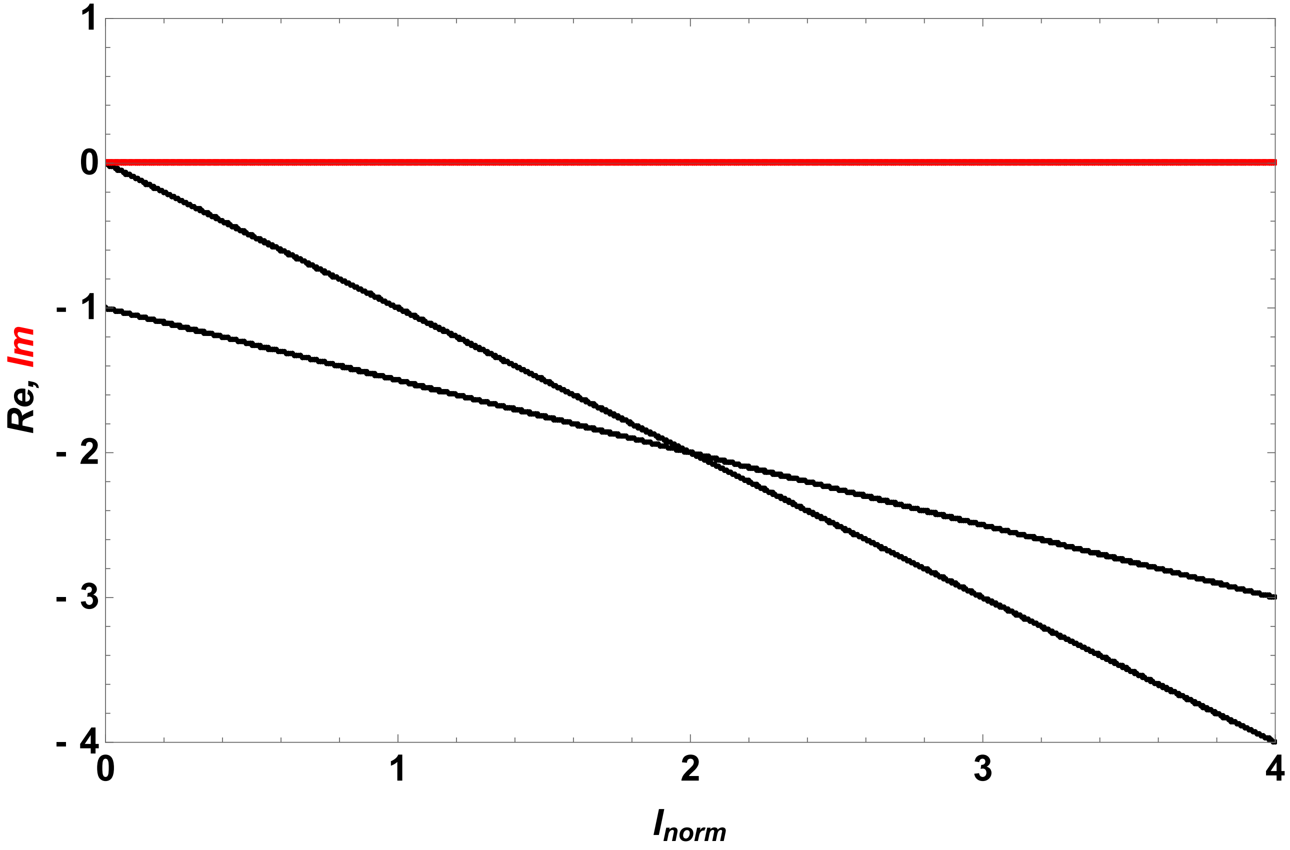
Circulant matrix formalism (1 radial mode)

$\kappa = -0.9$



Circulant matrix formalism (1 radial mode)

$\kappa = -1.0$



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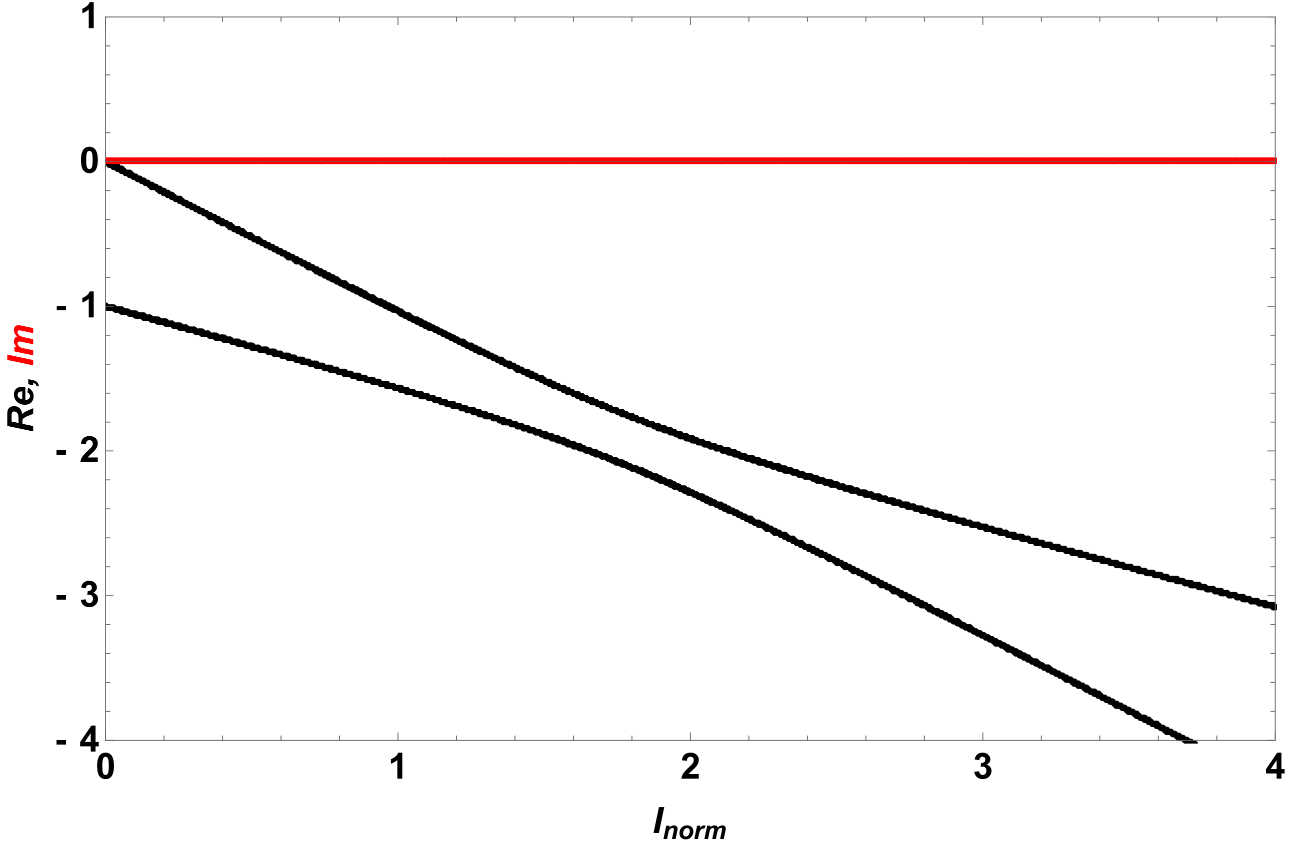

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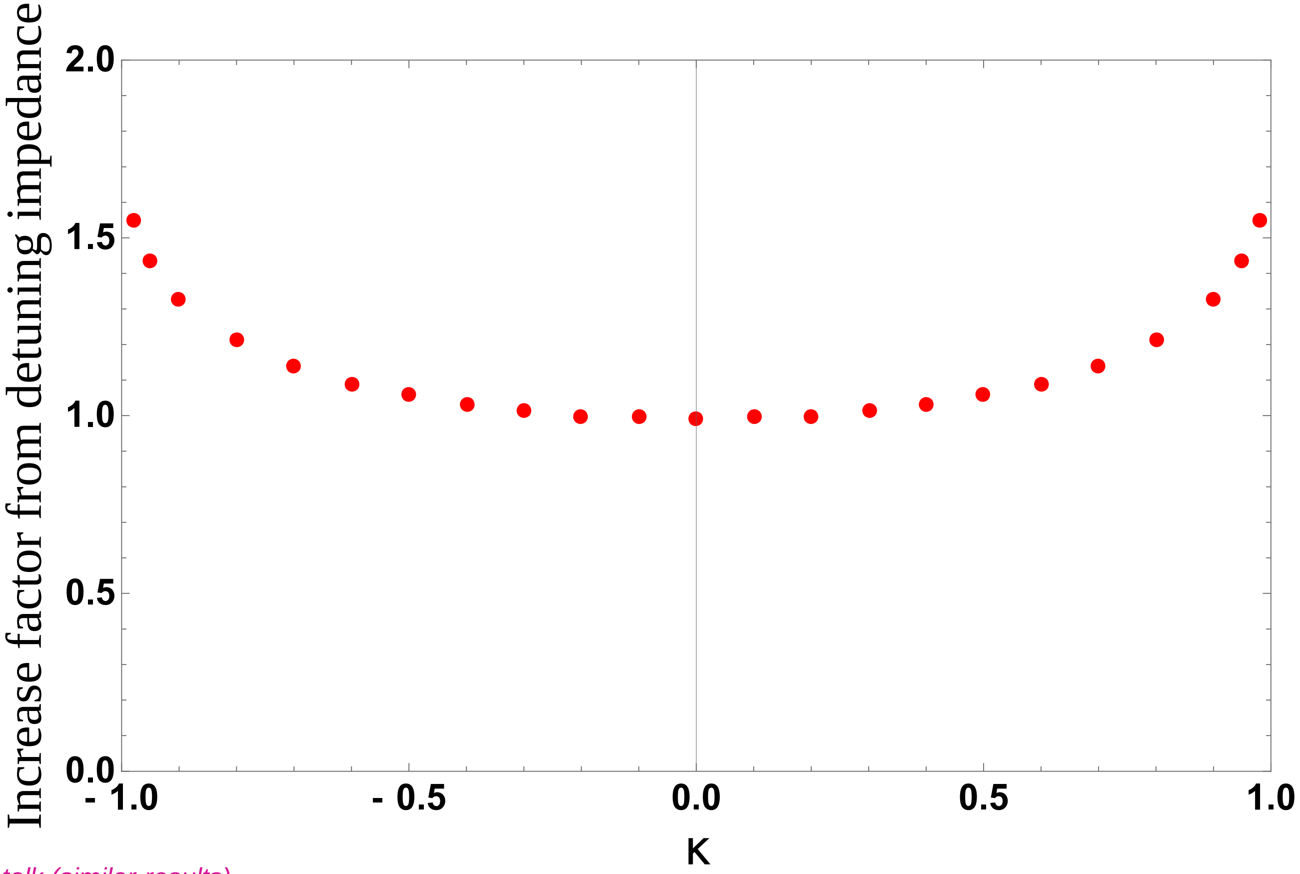

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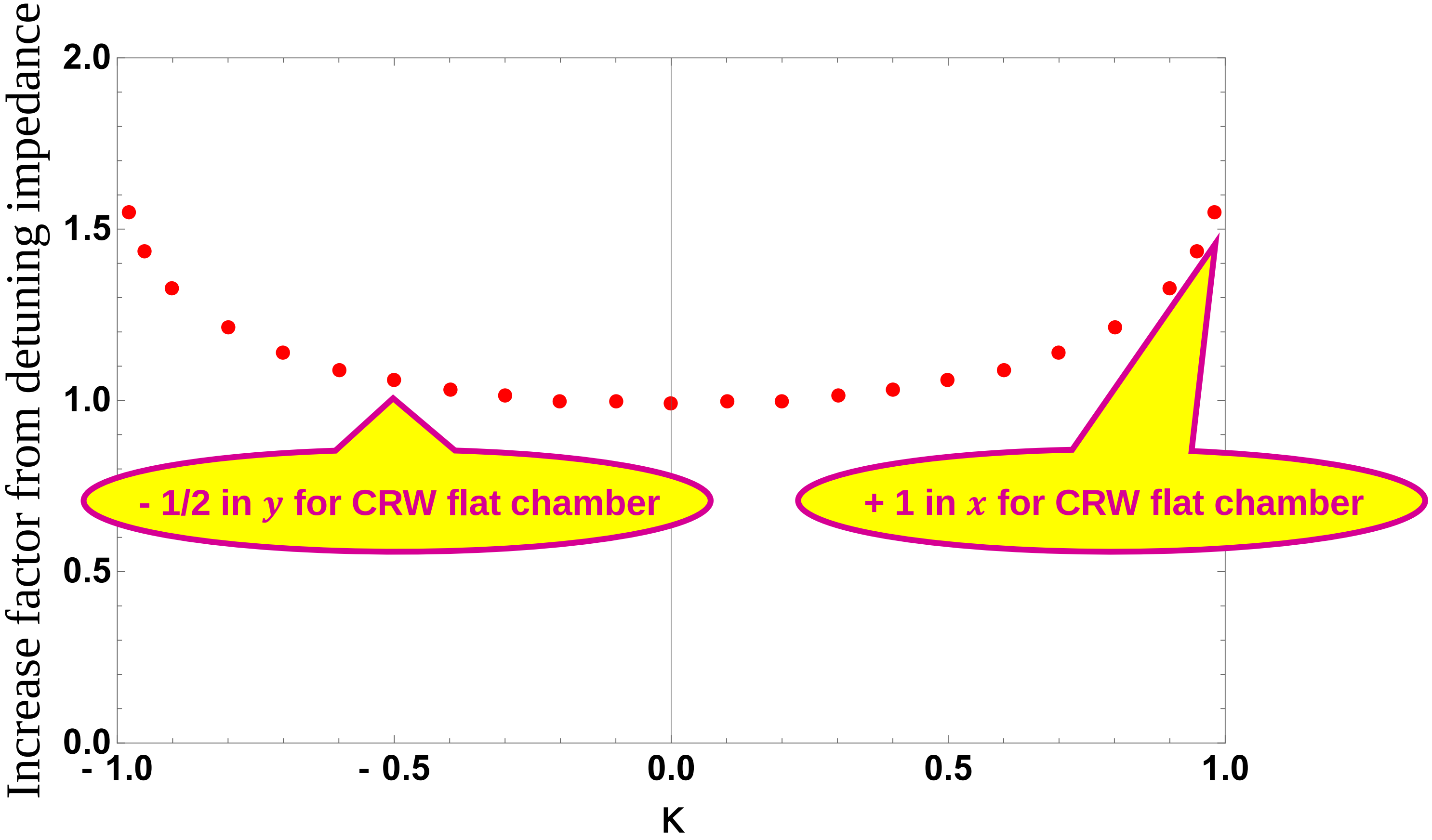

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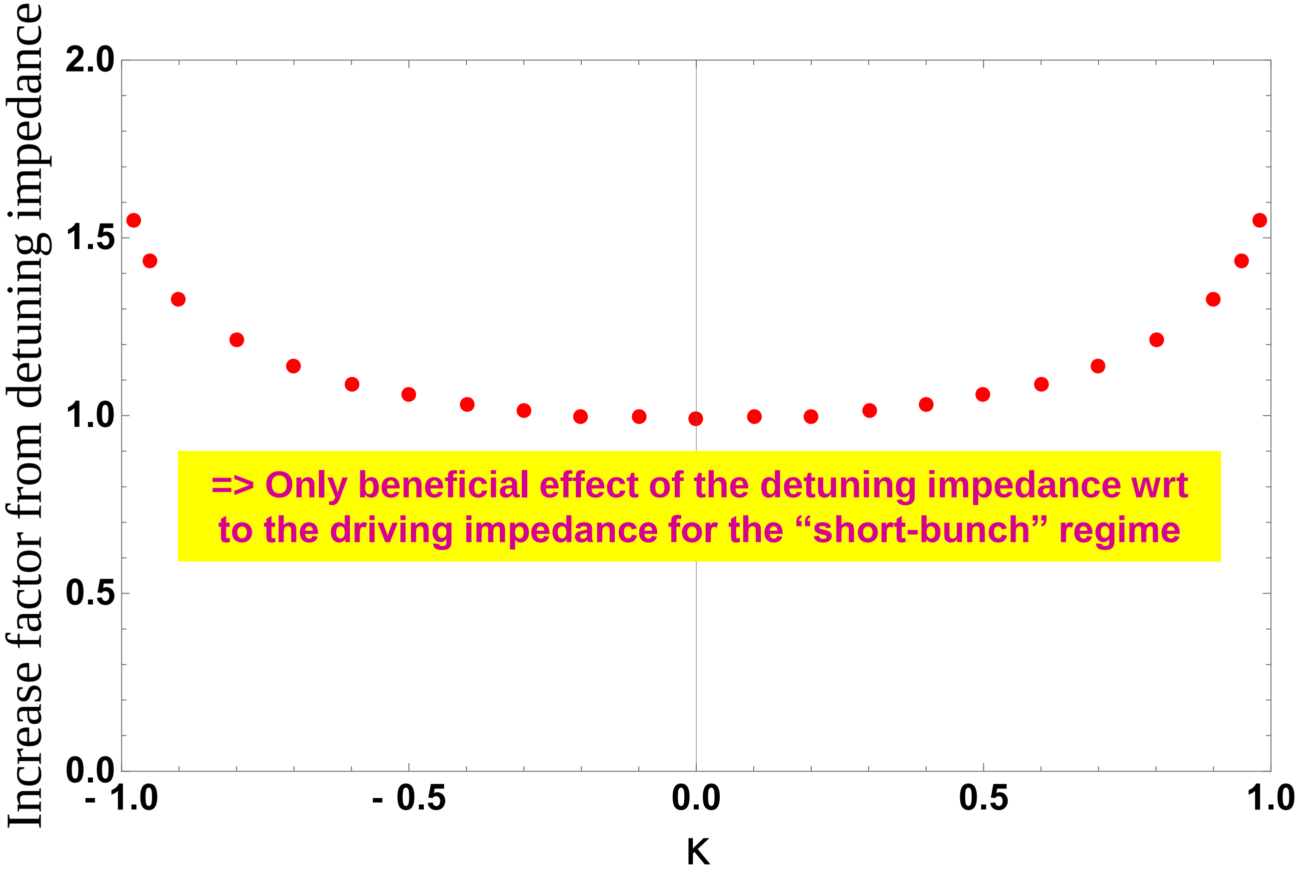

Circulant matrix formalism (1 radial mode)

- Considering now a **BBR impedance** and **many azimuthal modes** (but still 1 radial mode), an excellent agreement is obtained between theory and simulation (vs. the bunch length)

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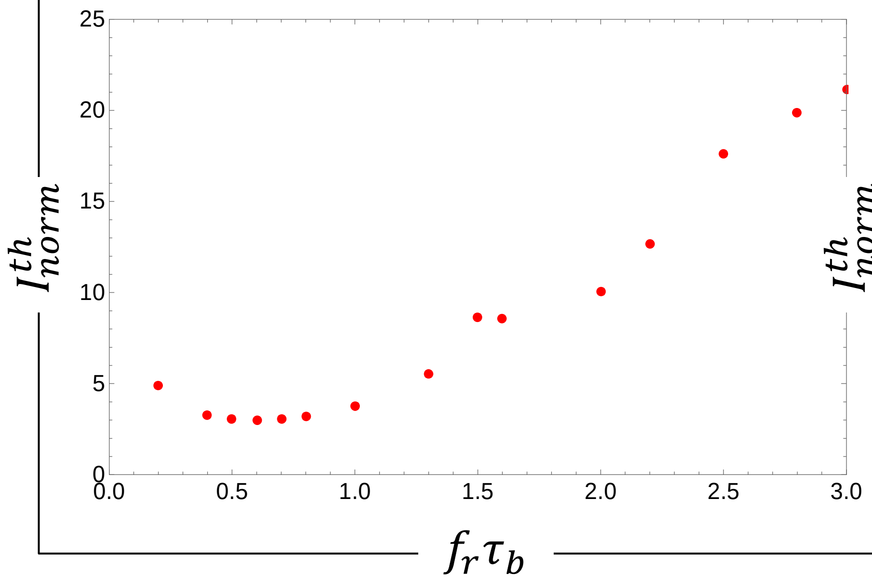
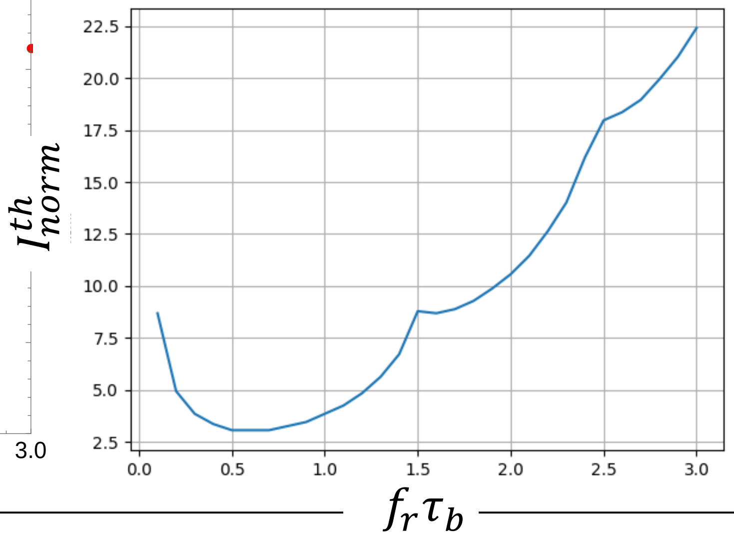
Theory



BimBim simulation (X. Buffat)



“Long-bunch” regime

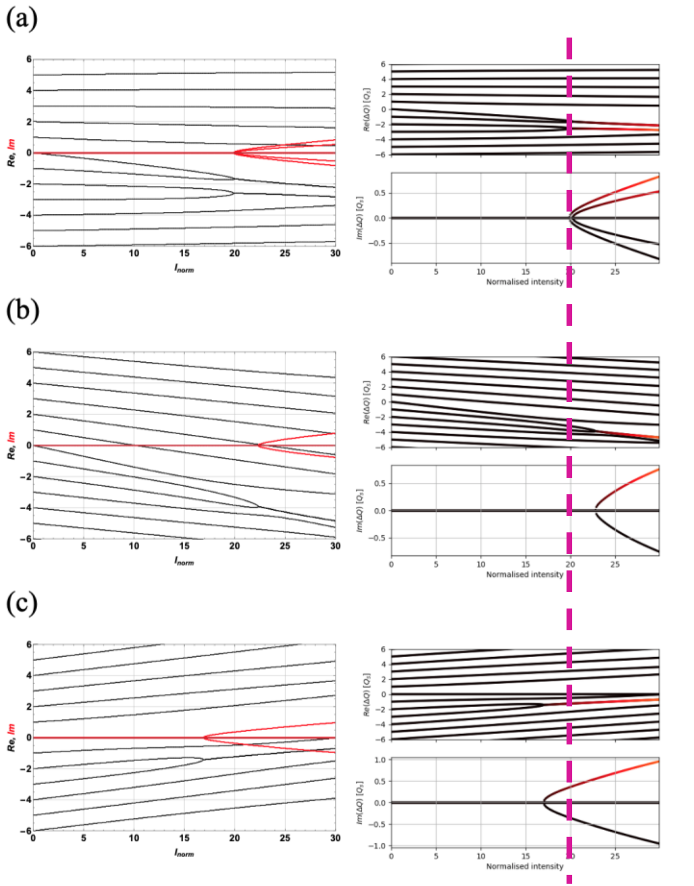
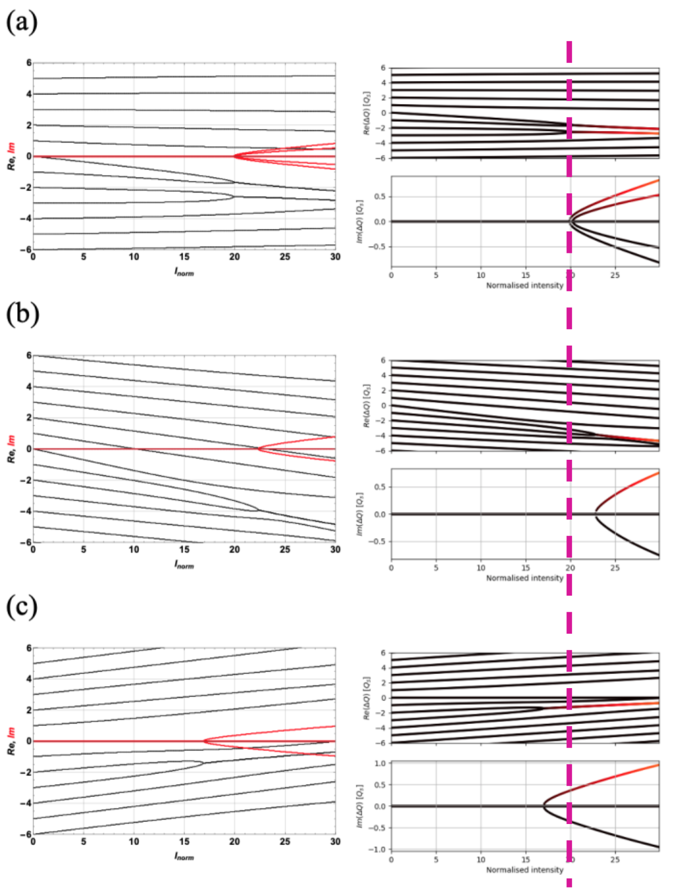


Figure 6: Comparison between theory (left) and the BimBim code (right) for the case of a broad-band resonator impedance with $f_r \tau_b = 2.8$ (a) $\kappa = 0$; (b) $\kappa = -1$; (c) $\kappa = +1$.

"Long-bunch" regime



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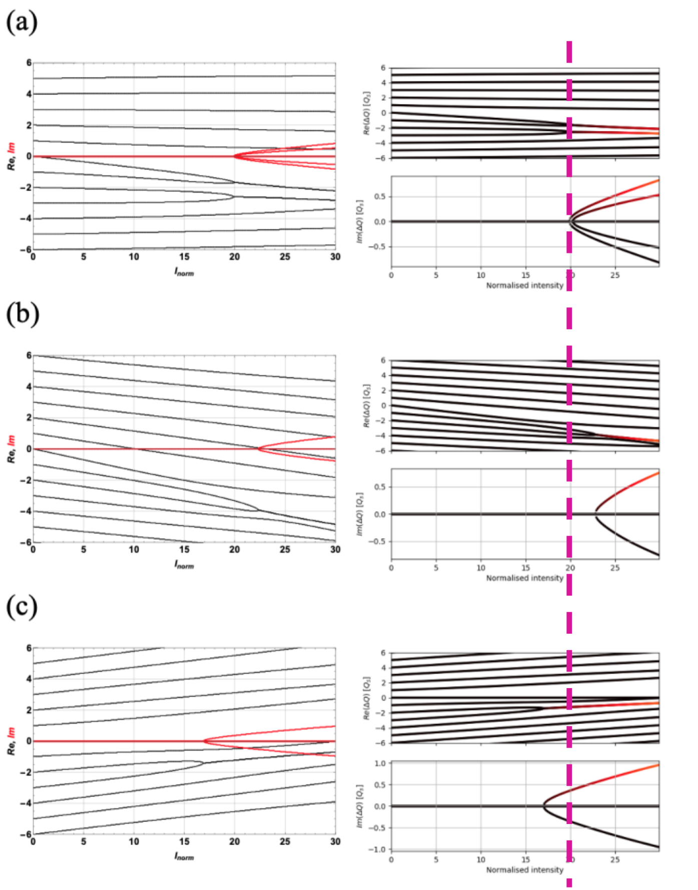
$\Rightarrow$ Detrimental effect of the detuning impedance wrt to the driving impedance for the horizontal plane ($\kappa = +1$)

"Long-bunch" regime



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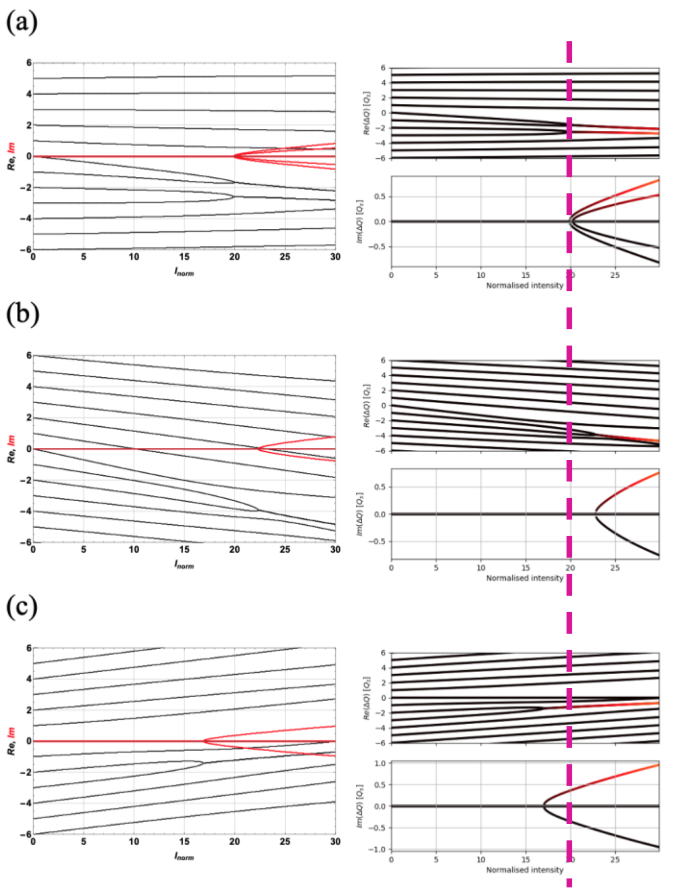
⇒ Detrimental effect of the detuning impedance wrt to the driving impedance for the horizontal plane ($\kappa = +1$)

⇒ But beneficial effect of the detuning impedance / asymmetry wrt symmetric case (as the driving impedance is much smaller)!



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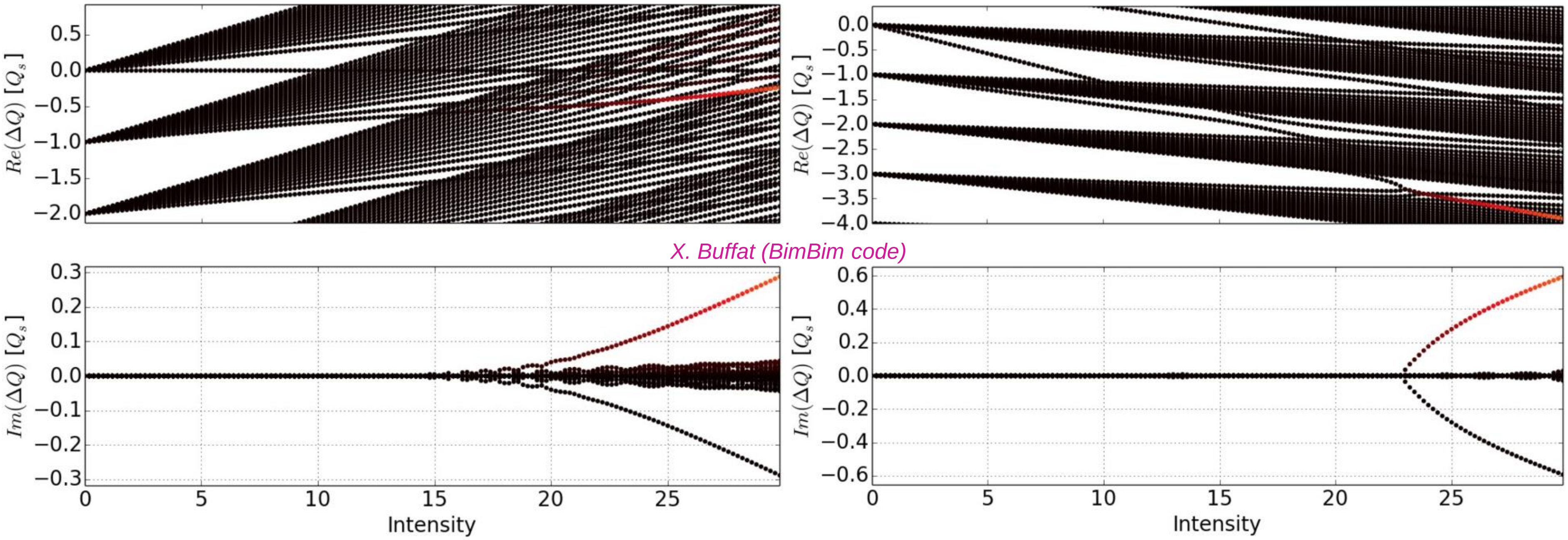
“Long-bunch” regime

⇒ Detrimental effect of the detuning impedance wrt to the driving impedance for the horizontal plane ($\kappa = +1$)

⇒ But beneficial effect of the detuning impedance / asymmetry wrt symmetric case (as the driving impedance is much smaller)!

One should be careful when comparing the different κ −cases, as for each case I_{norm} is normalised by the dipolar impedance (which includes a Yokoya dipolar factor [13]): 1 for round ($\kappa = 0$), $\pi^2/24$ for flat x ($\kappa = 1$) and $\pi^2/12$ for flat y ($\kappa = -1/2$). Applying this to the

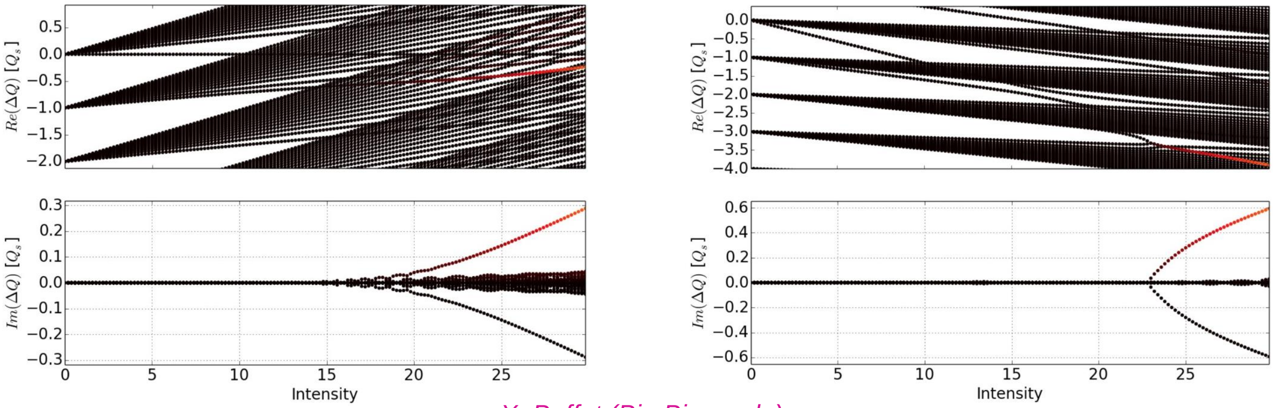
Circulant matrix formalism (>1 radial modes)



X. Buffat (BimBim code)

=> Similar intensity thresholds as before (with change of modes which couple), similar to past HEADTAIL simulations

Circulant matrix formalism (>1 radial modes)



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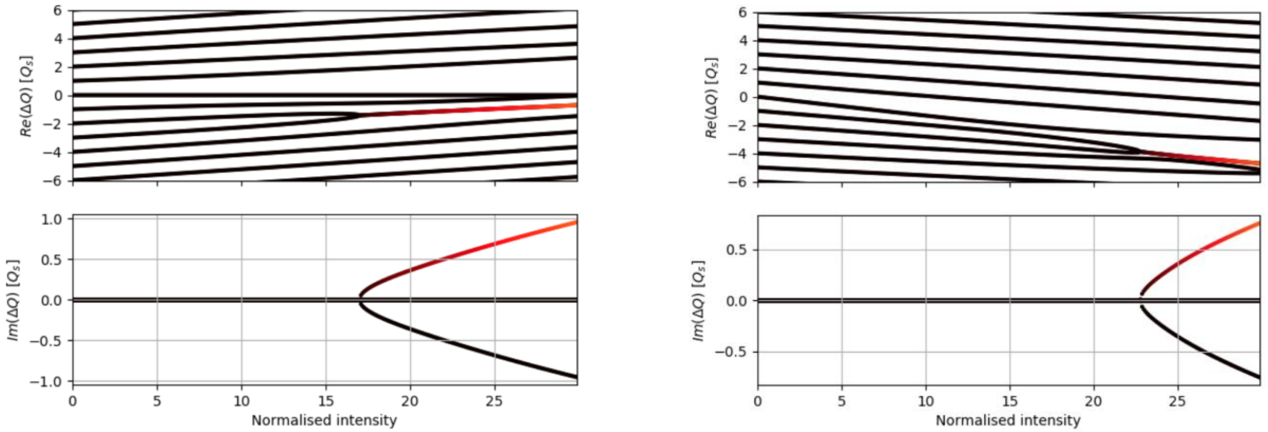

Conclusion and outlook

- Huge effort started in the CERN HSC section since ~ 1 year to try and fully understand the effect of the detuning impedance on beam stability

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  - **“Long-bunch” regime with a BBR impedance**: a **detrimental effect** is predicted wrt to the driving impedance (as it was in fact already observed in past HEADTAIL simulations)

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- Meanwhile, a general theory for bunched beams has been developed by G. Iadarola et al.: "Linearized method for the study of transverse instabilities driven by electron clouds", PRAB 23, 081002, 2020 (https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.23.081002)