MD Days 2025
Coupled-bunch instabilities in SPS

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Acknowledgements: PS & SPS OP, MD Coordinators

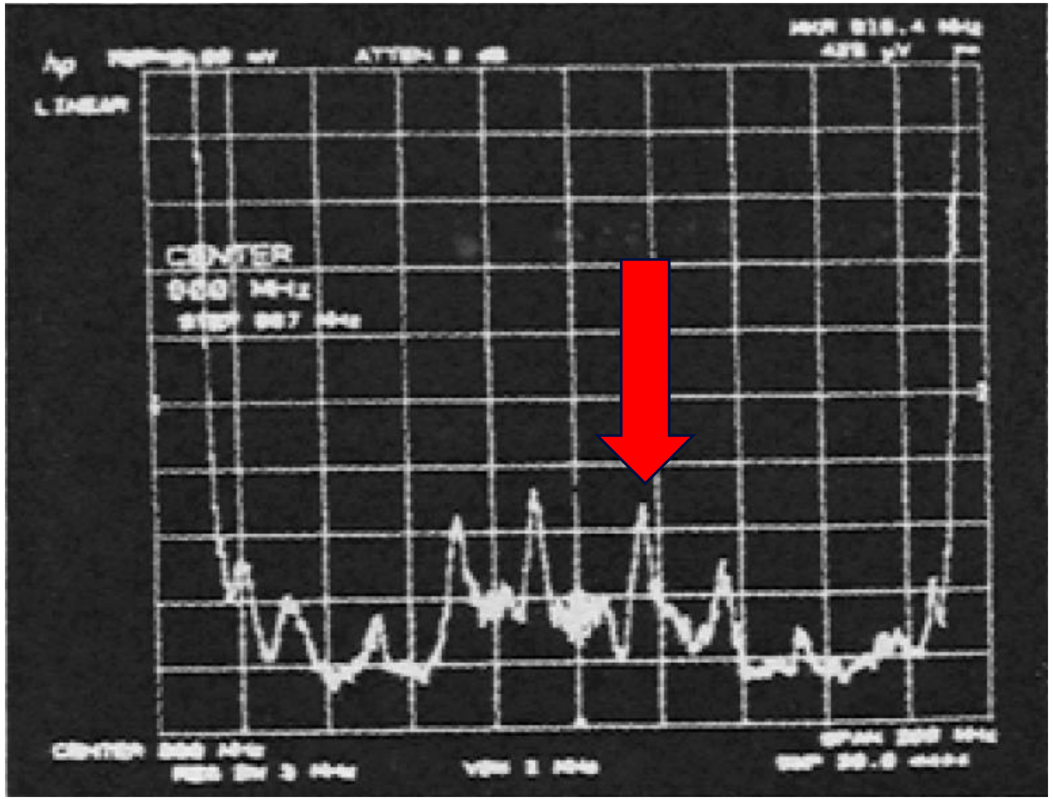
4^{th} February 2025

Motivation

1. Higher-Order-Modes (HOM) in the 200 MHz cavities:
- Defining factor for intensity threshold in the SPS
- Effect LHC-type & fixed target beam

Characteristics (SPS impedance model):
- f_r = 914 MHz & 914.7 MHz
- R_{sh} = 1.7 MΩ
- Q ~ 3000 & 5000

2. Intensity threshold for high voltage ratios (V_R):
- Non-monotonic synchrotron frequency distribution
- Expanded calculation with Lebedev suggests stabilizing mechanisms



E. Shaposhnikova: Analysis of coupled bunch instability spectra, AIP 1999
Beam spectrum from 0.8 to 1 GHz of fixed target proton cycle in SPS

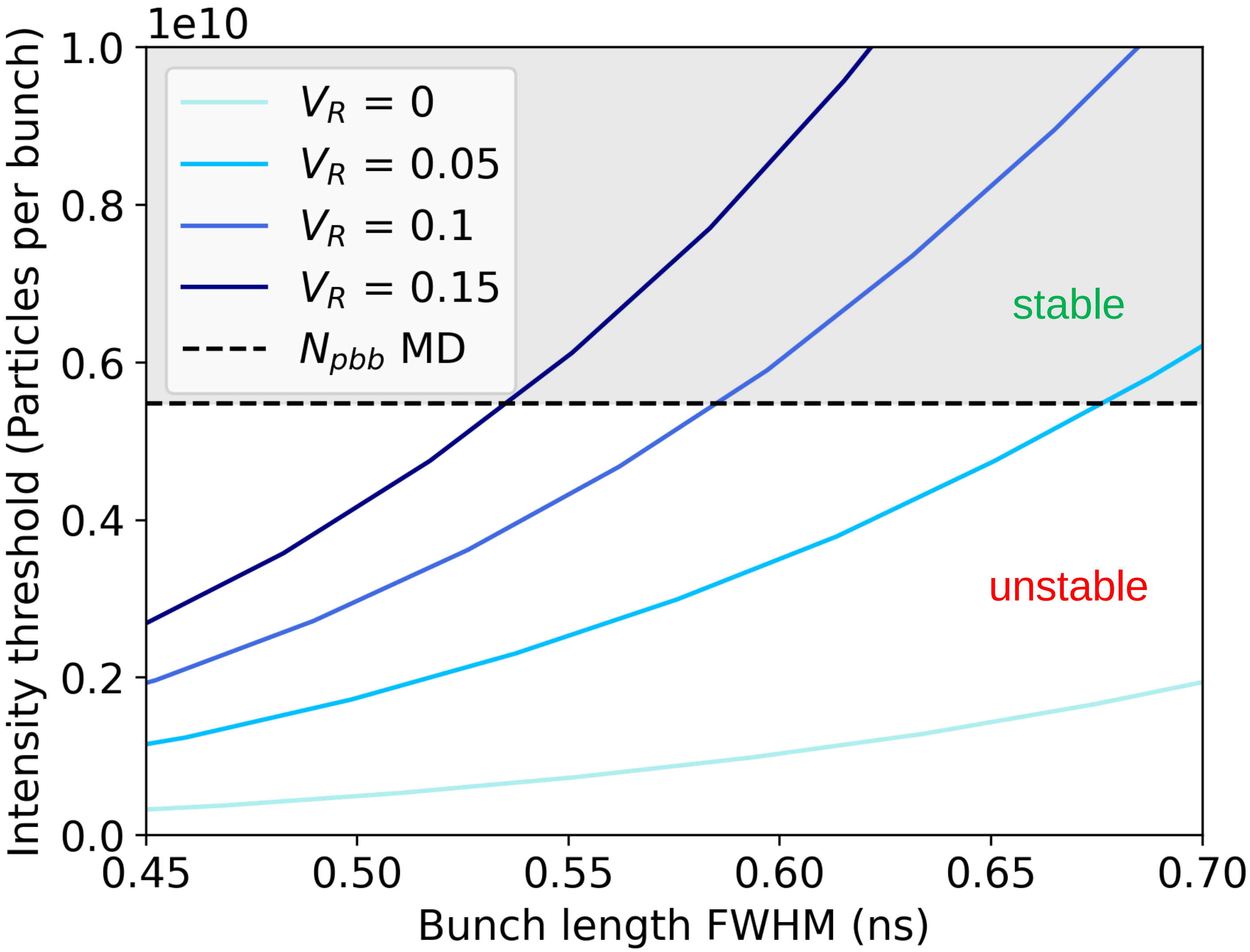
MDs 2024 – 914 MHz HOM

Copy operational settings:
- SFTPro (Higher filling factor)
- Disabled: barrier bucket, phase loop

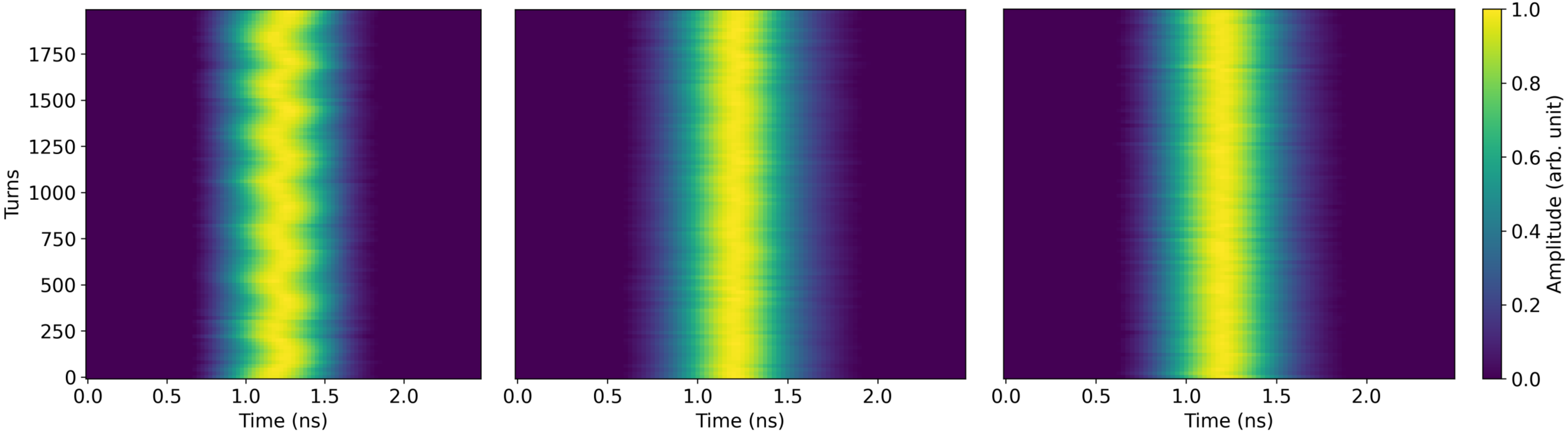
1. Adiabatically decrease 800 MHz to target voltage ratio
2. Searching for instability
3. Repeat with different voltage ratio

Time Domain	Frequency Domain
MD Scope	**Spectrum Analyzer**
(Dipole) Oscillation	**Interaction with mode**

Threshold prediction for $R_{sh} = 1.7\ \mathrm{M\Omega}$



Dipole oscillation during flat top

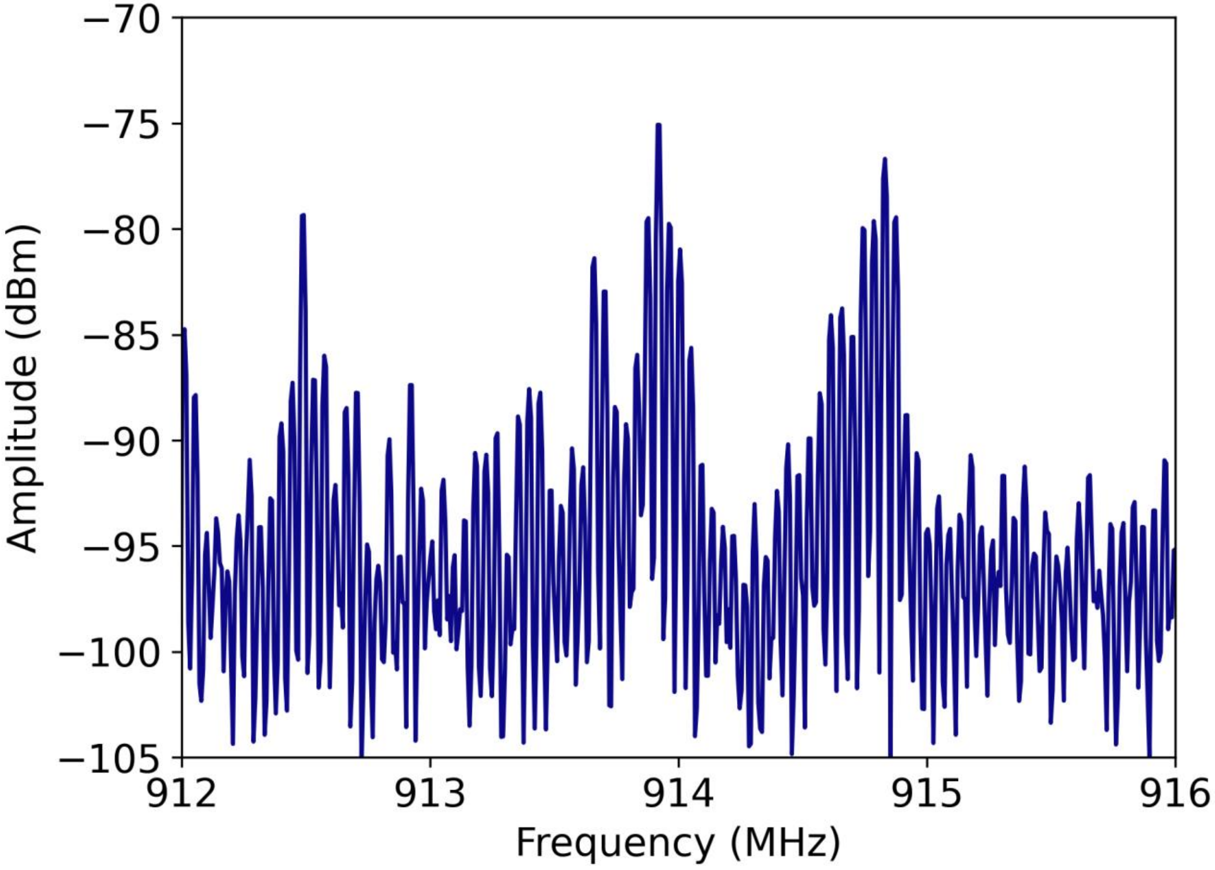


Voltage Ratio = 4%

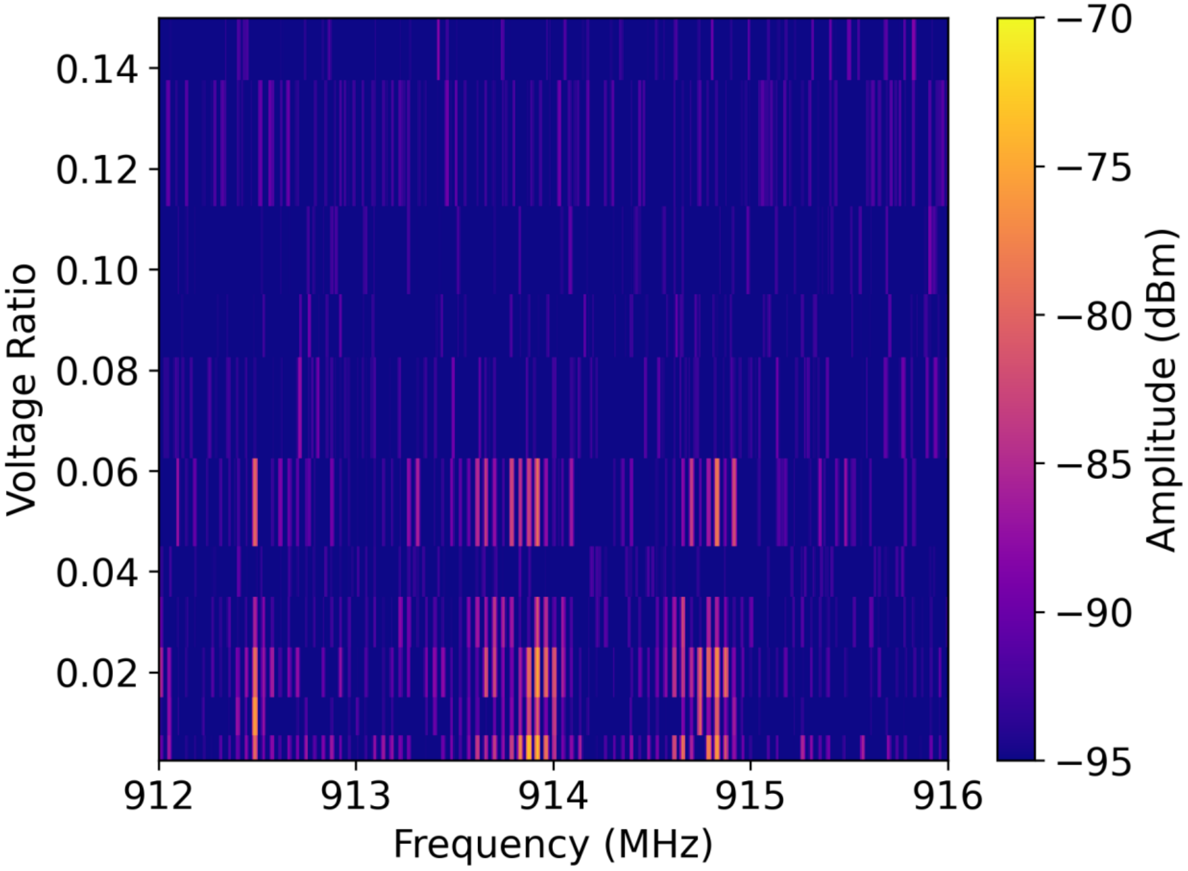
Voltage Ratio = 9%

Voltage Ratio = 12.5%

Interaction with the two modes around 914 MHz



Beam spectrum for voltage ratio = 2 %

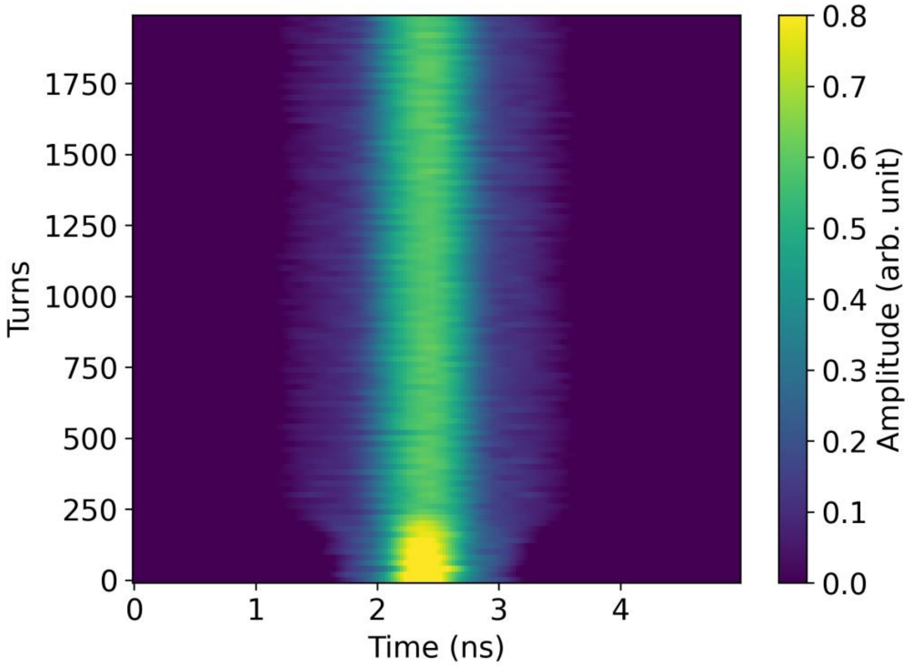


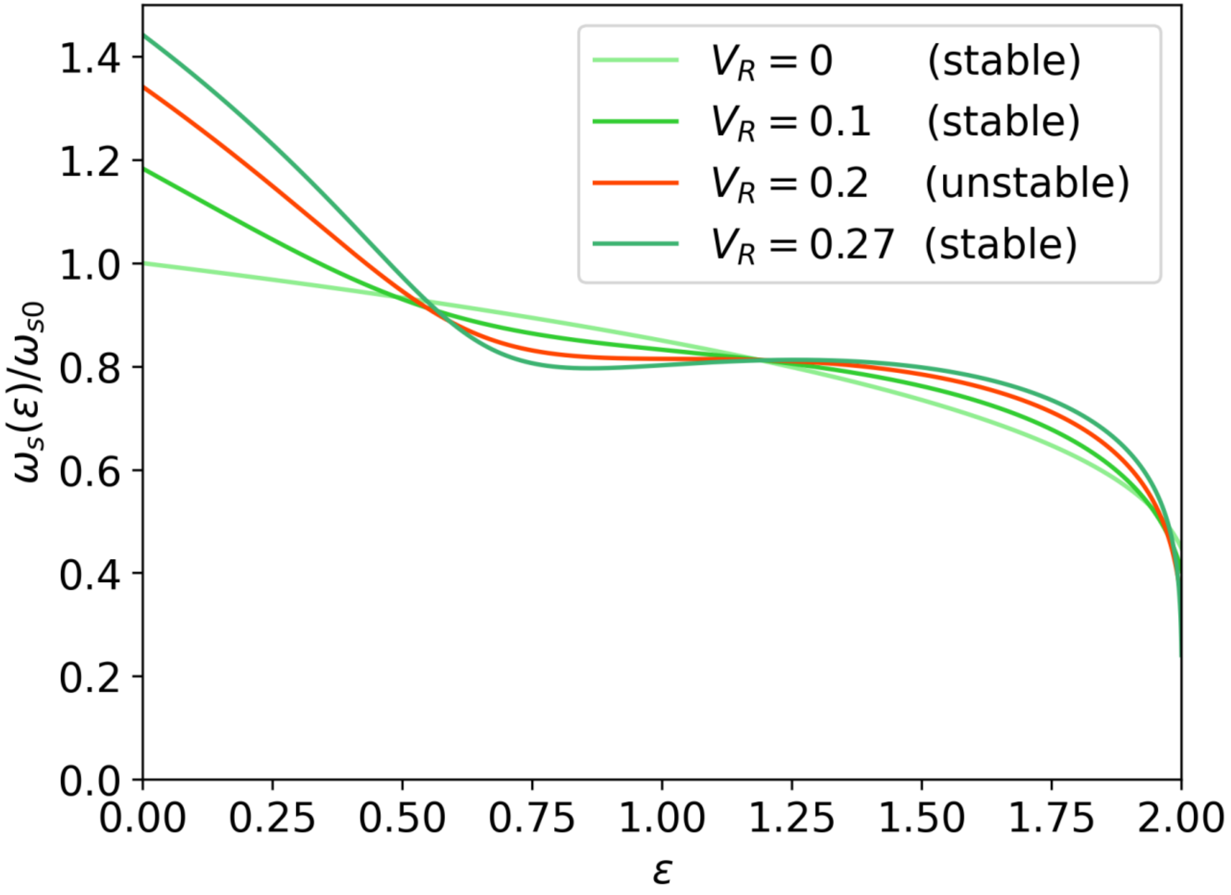
Beam spectrum for different voltage ratios

Non-monotonic frequency distribution

Calculation with stability diagram (based on Lebedev) suggest stabilizing mechanism for $V_R > 0.205$
Needed:

- Bunch length past critical point
- ➢ Adiabatic decrease of voltage to 1MV
- ➢ Adiabatic increase of V_R up to 0.5





Recap of 2024

914 MHz HOM

- MDs match theoretical calculations based on impedance model

Non-monotonic synchrotron freq.

- Beam unaffected by unstable regime

Availability:

- Overall, very good
- Minor hick ups (Difficulties of copying operational settings)

MDs in 2025

914 MHz HOM

- Check reproducibility
- Contribution of the phase loop
- Finer scan, more detailed

➢ Number of slots: 3-4

Non-monotonic synchrotron freq.

- Test impact of unstable area
- Validate threshold calculations from Lebedev

➢ Number of slots: 3-4

Thank you for your attention

Back-up slides for MD Days 2025 Coupled-bunch instabilities in SPS

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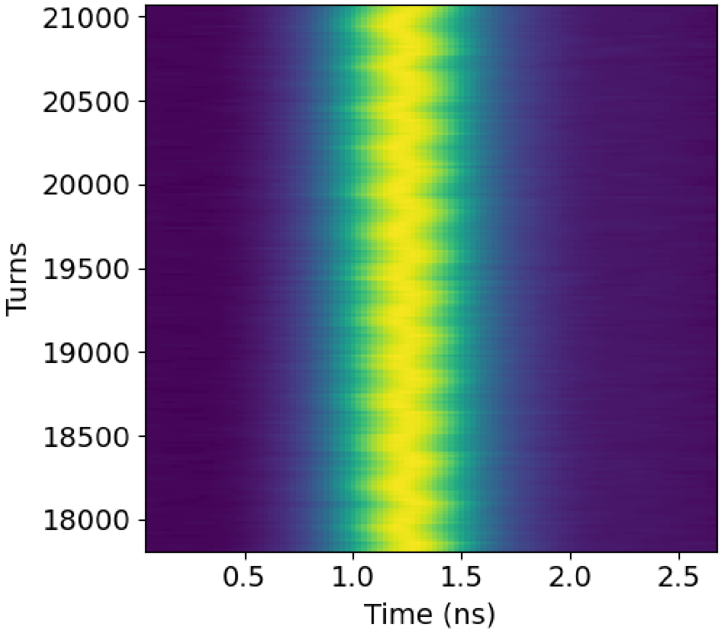
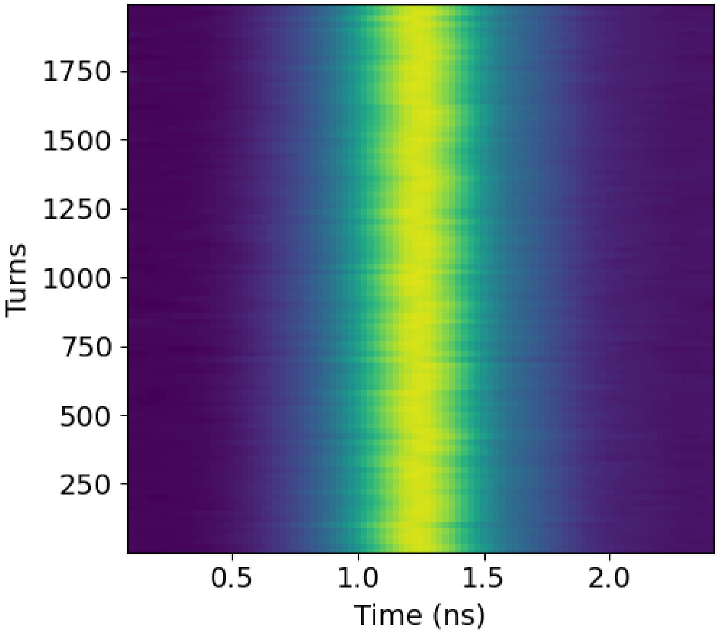
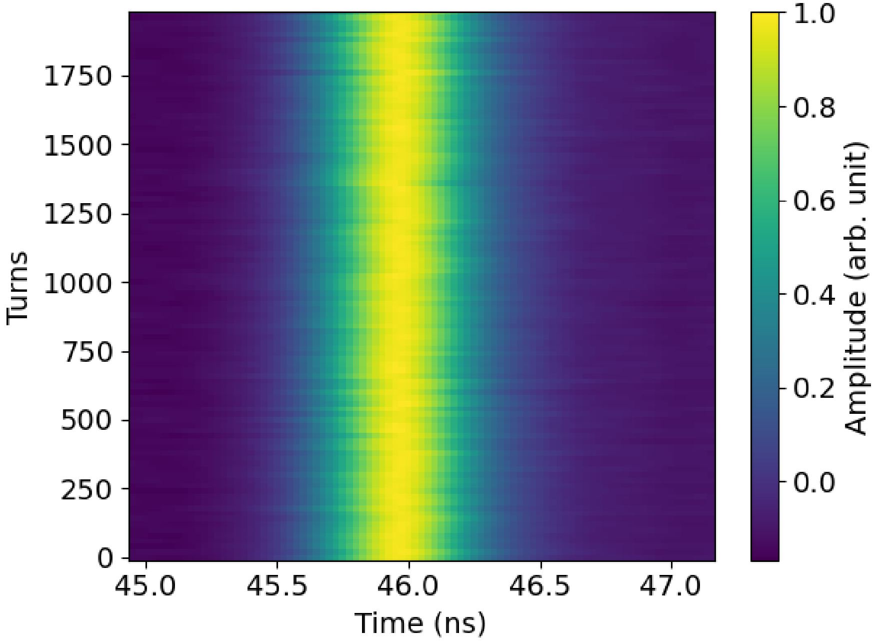
Dipole oscillation during flat top for higher V_R



Voltage Ratio = 10%



Voltage Ratio = 15%



Voltage Ratio = 17.5%

Lebedev equation for the G_{pk} matrix values

$$\tilde{\lambda}_p(\Omega) = -\frac{\zeta}{h}\sum_{k=-\infty}^{\infty} G_{pk}(\Omega)\frac{Z_k(\Omega)/k}{\mathrm{Im}Z/k}\tilde{\lambda}_k(\Omega)$$

$$\zeta = -\frac{qN_p h^2 \omega_0 \mathrm{Im}Z/k}{V_0 \cos\phi_{s0}}$$

$$G_{pk}(\Omega) = -i\frac{\omega_{s0}}{\pi A_N}\sum_{m=1}^{\infty}\int_0^{\mathcal{E}_{\max}} d\mathcal{E}\frac{dg(\mathcal{E})}{d\mathcal{E}}\frac{I_{mk}(\mathcal{E})I^*_{mp}(\mathcal{E})\omega_s(\mathcal{E})}{\Omega^2/m^2 - \omega_s^2(\mathcal{E})}$$

$$\int_{\varepsilon_0}^{\varepsilon_{max}} \frac{f(\varepsilon)}{\Omega - \omega_s(\varepsilon)} d\varepsilon = \int_{\omega_s(\varepsilon_0)}^{\omega_s(\varepsilon_{max})} \frac{f(\varepsilon(\omega_s))}{\Omega - \omega_s}\frac{1}{\frac{d\omega_s}{d\varepsilon}} d\omega_s$$

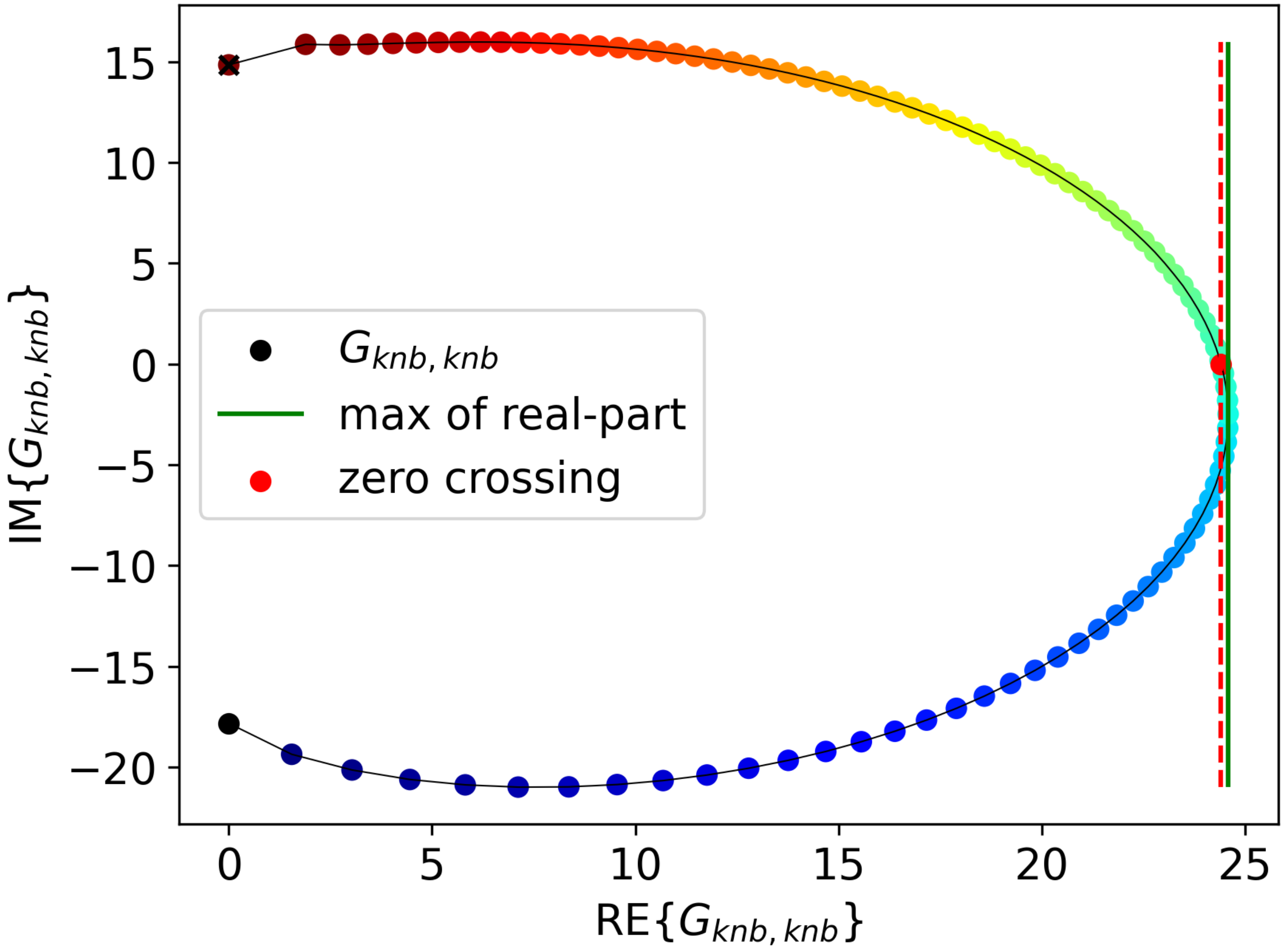
Expanding the Lebedev equation

$$\int_0^{\varepsilon_{max}} \frac{f(\varepsilon)}{\Omega - \omega_s(\varepsilon)} d\varepsilon = \int_0^{\varepsilon^* - \delta} \frac{f(\varepsilon)}{\Omega - \omega_s(\varepsilon)} d\varepsilon + \int_{\varepsilon^* - \delta}^{\varepsilon^* + \delta} \frac{f(\varepsilon)}{\Omega - \omega_s(\varepsilon)} d\varepsilon + \int_{\varepsilon^* + \delta}^{\varepsilon_{max}} \frac{f(\varepsilon)}{\Omega - \omega_s(\varepsilon)} d\varepsilon$$

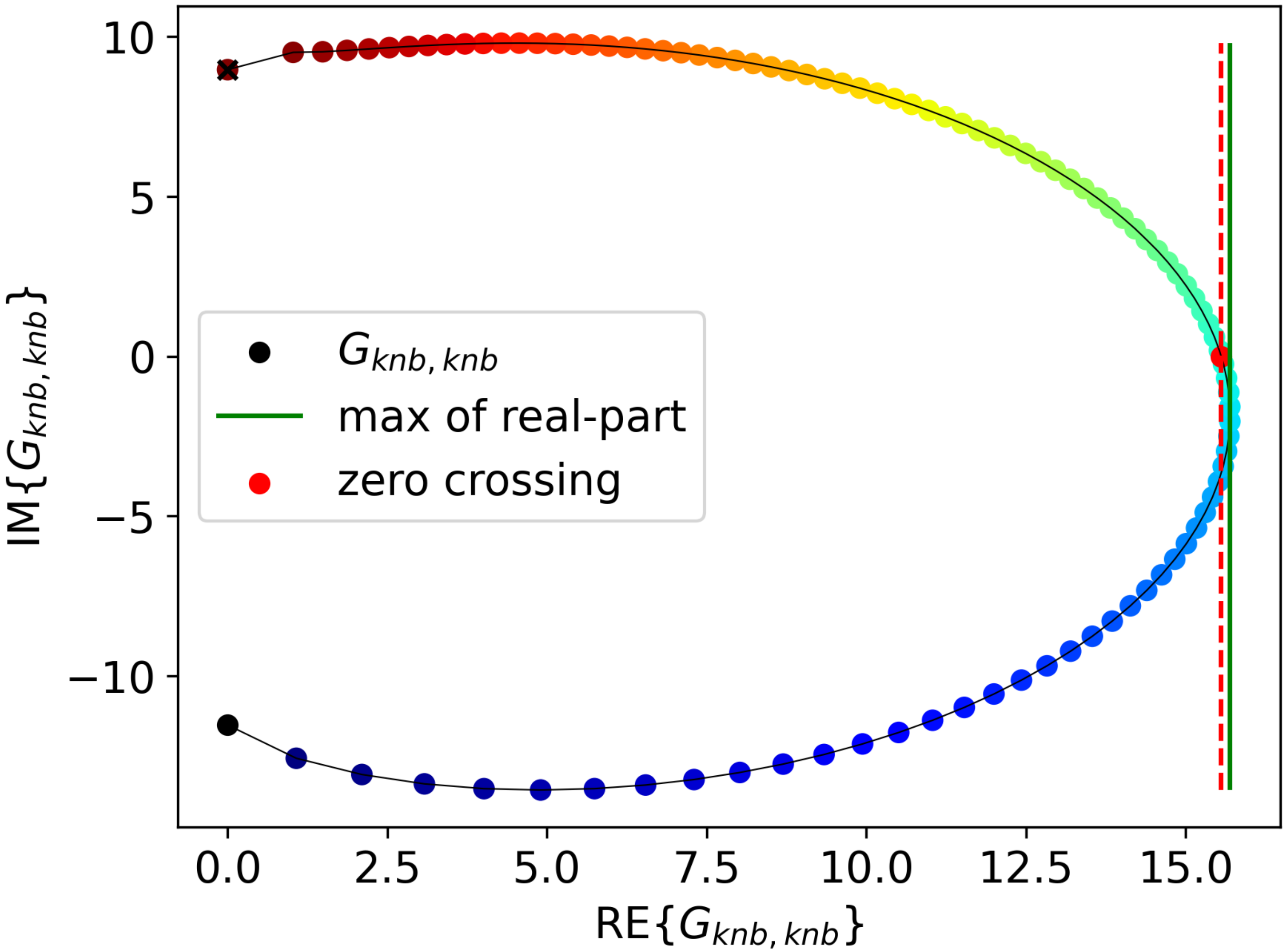
$$\int_0^{\varepsilon_{max}} \frac{f(\varepsilon)}{\Omega - \omega_s(\varepsilon)} d\varepsilon = \int_{\omega_s(0)}^{\omega_s(\varepsilon^* - \delta)} \frac{f(\varepsilon(\omega_s))}{\Omega - \omega_s} \frac{1}{\frac{d\omega_s(\varepsilon(\omega_s))}{d\varepsilon}} d\omega_s + \int_{\varepsilon^* - \delta}^{\varepsilon^* + \delta} \frac{f(\varepsilon)}{\Omega - \omega_s(\varepsilon)} d\varepsilon + \int_{\omega_s(0)}^{\omega_s(\varepsilon^* + \delta)} \frac{f(\varepsilon(\omega_s))}{\Omega - \omega_s} \frac{1}{\frac{d\omega_s(\varepsilon(\omega_s))}{d\varepsilon}} d\omega_s$$

Condition for integral part 2: $\Omega \notin [\omega_s(\varepsilon^* - \delta), \omega_s(\varepsilon^* + \delta)]$

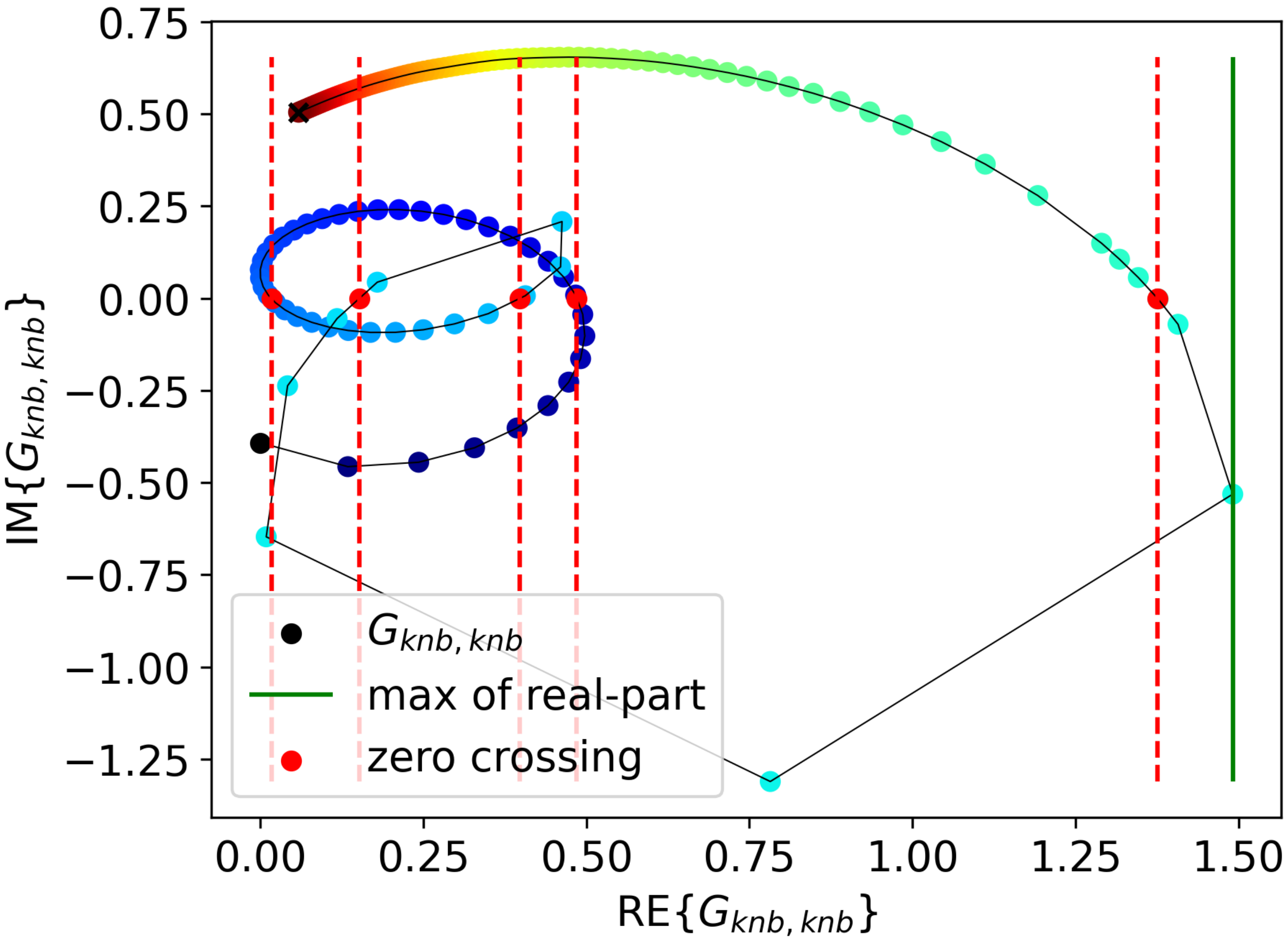
Stability diagram: short bunch, single RF



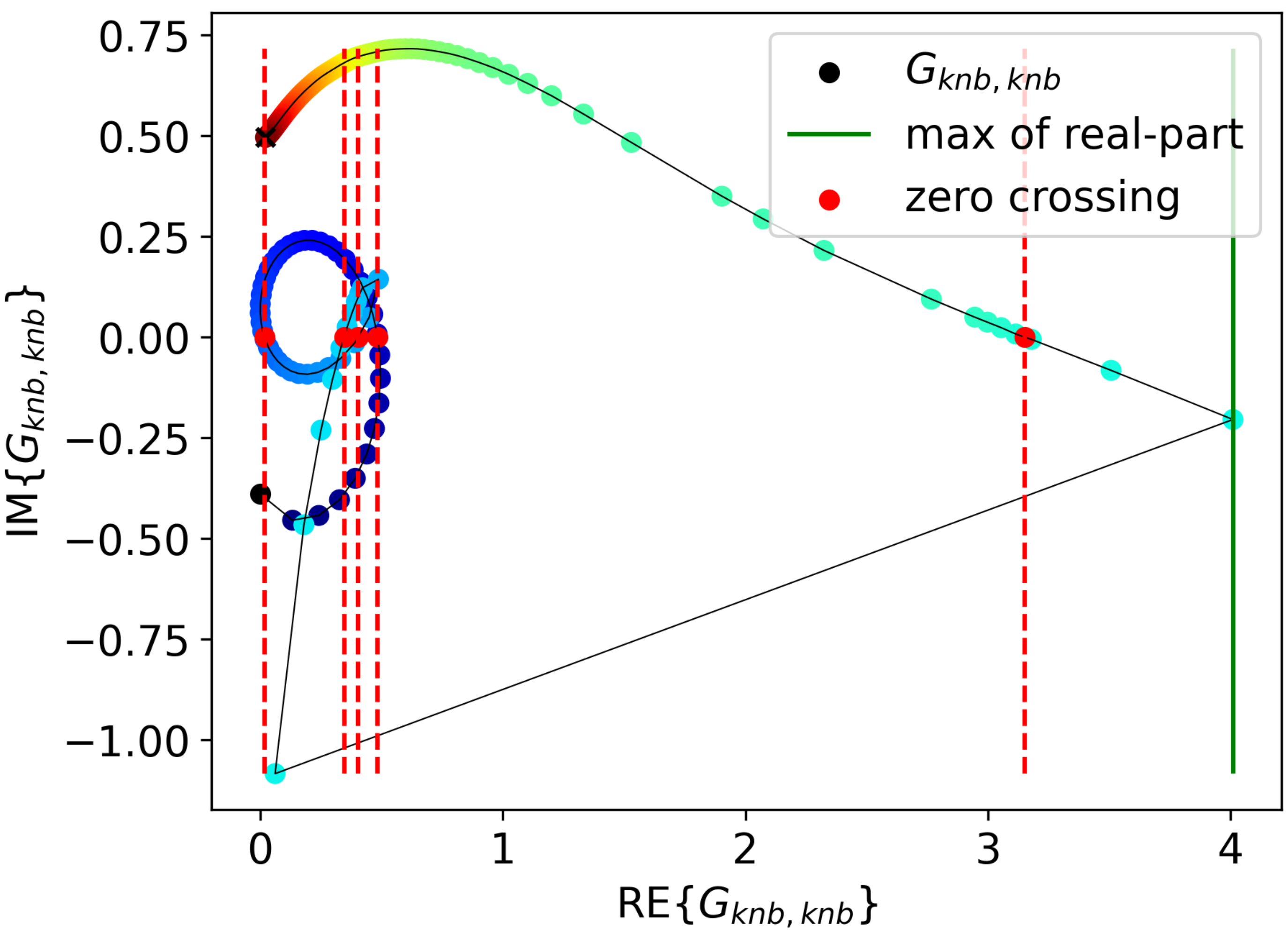
Stability diagram: short bunch, V_R = 0.2



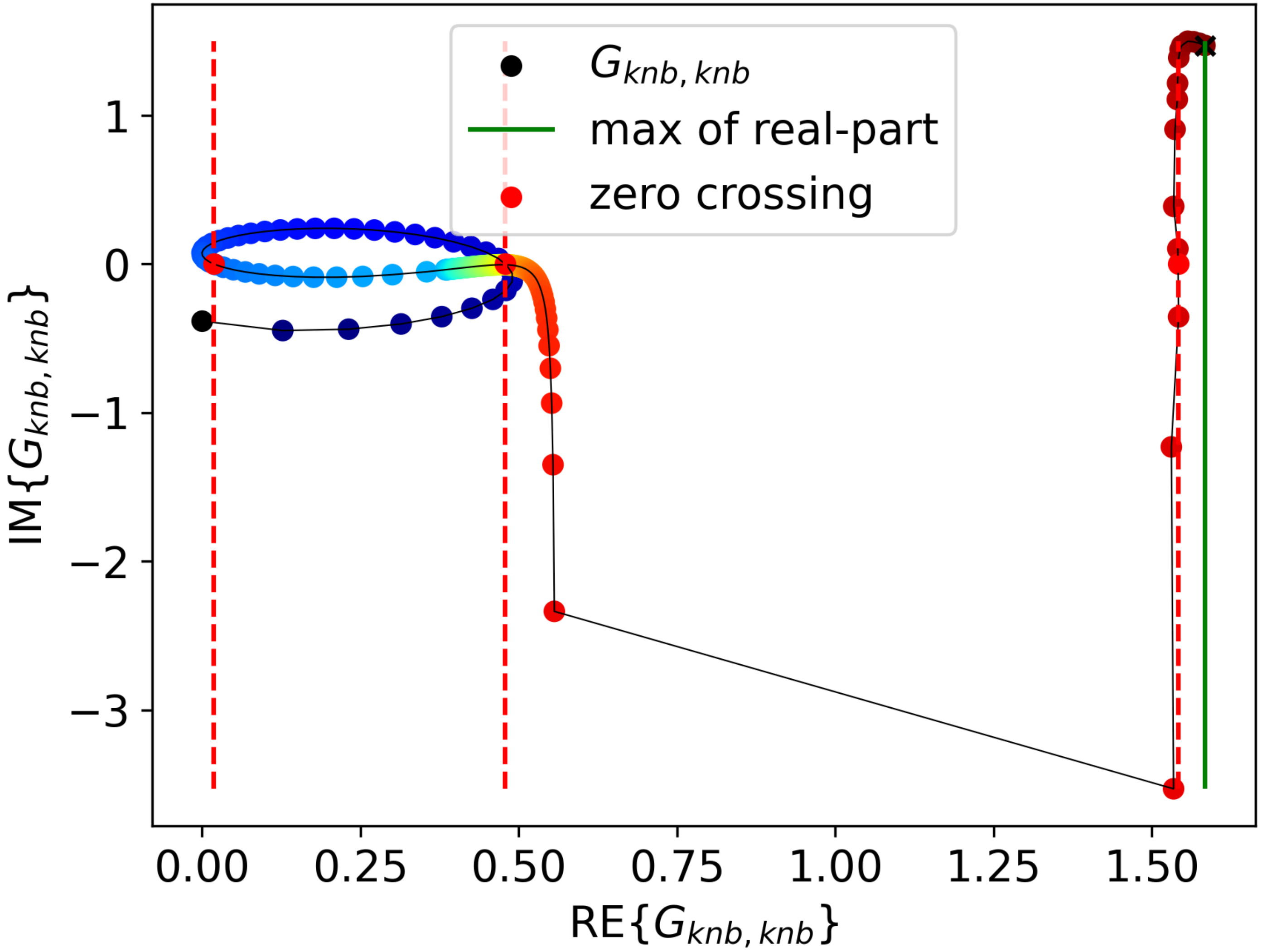
Stability diagram: long bunch, V_R = 0.202



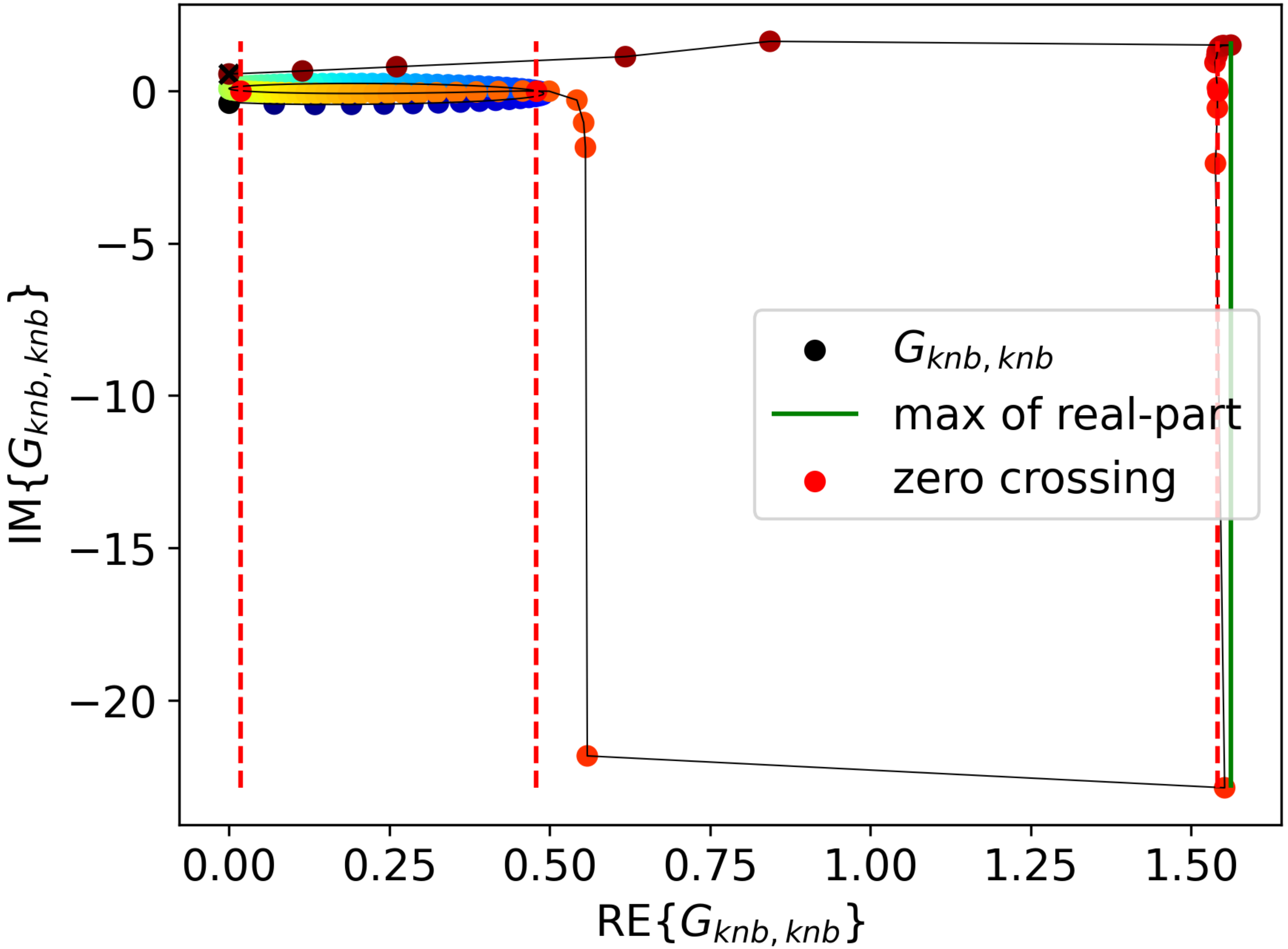
Stability diagram: long bunch, V_R = 0.204



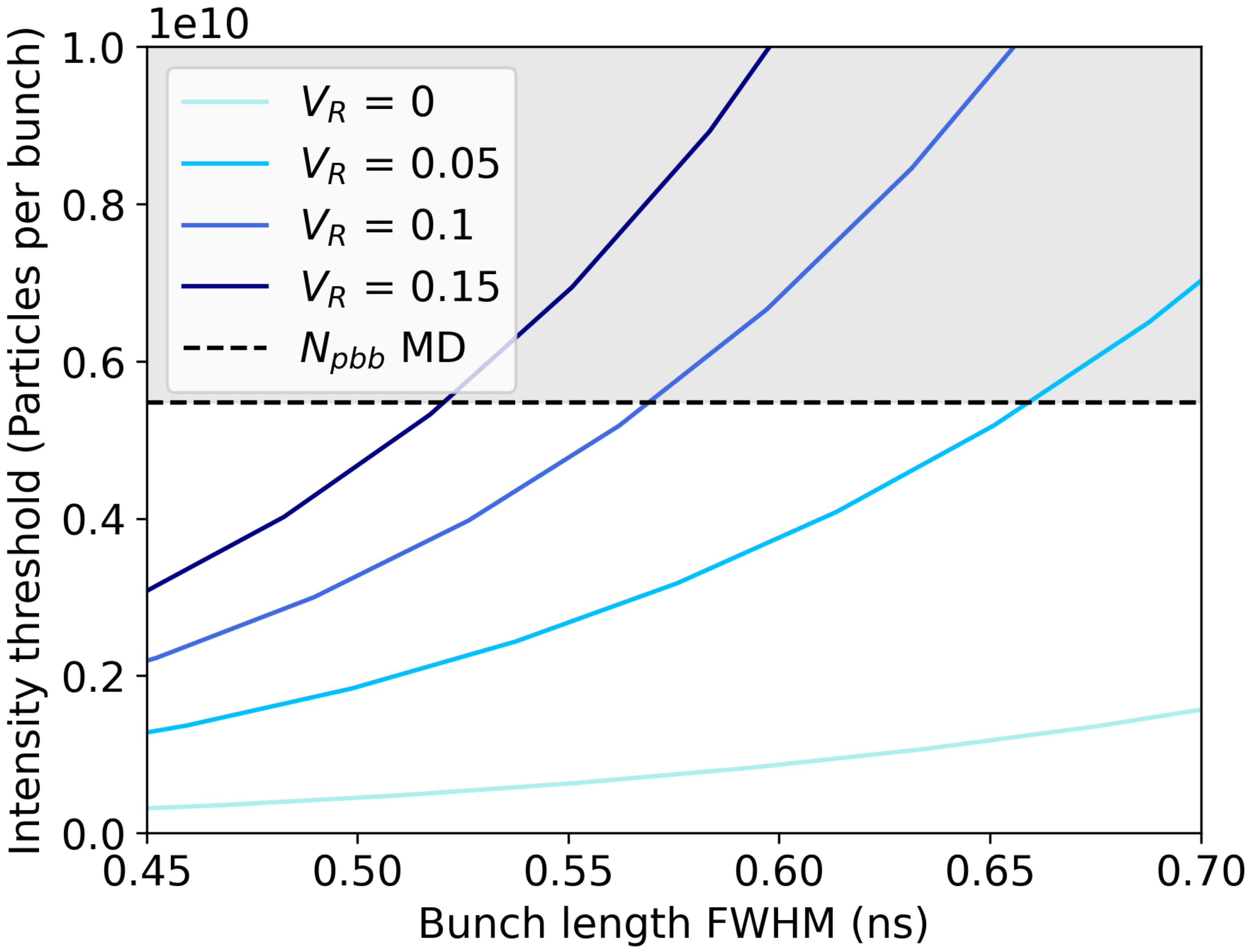
Stability diagram: long bunch, V_R = 0.22



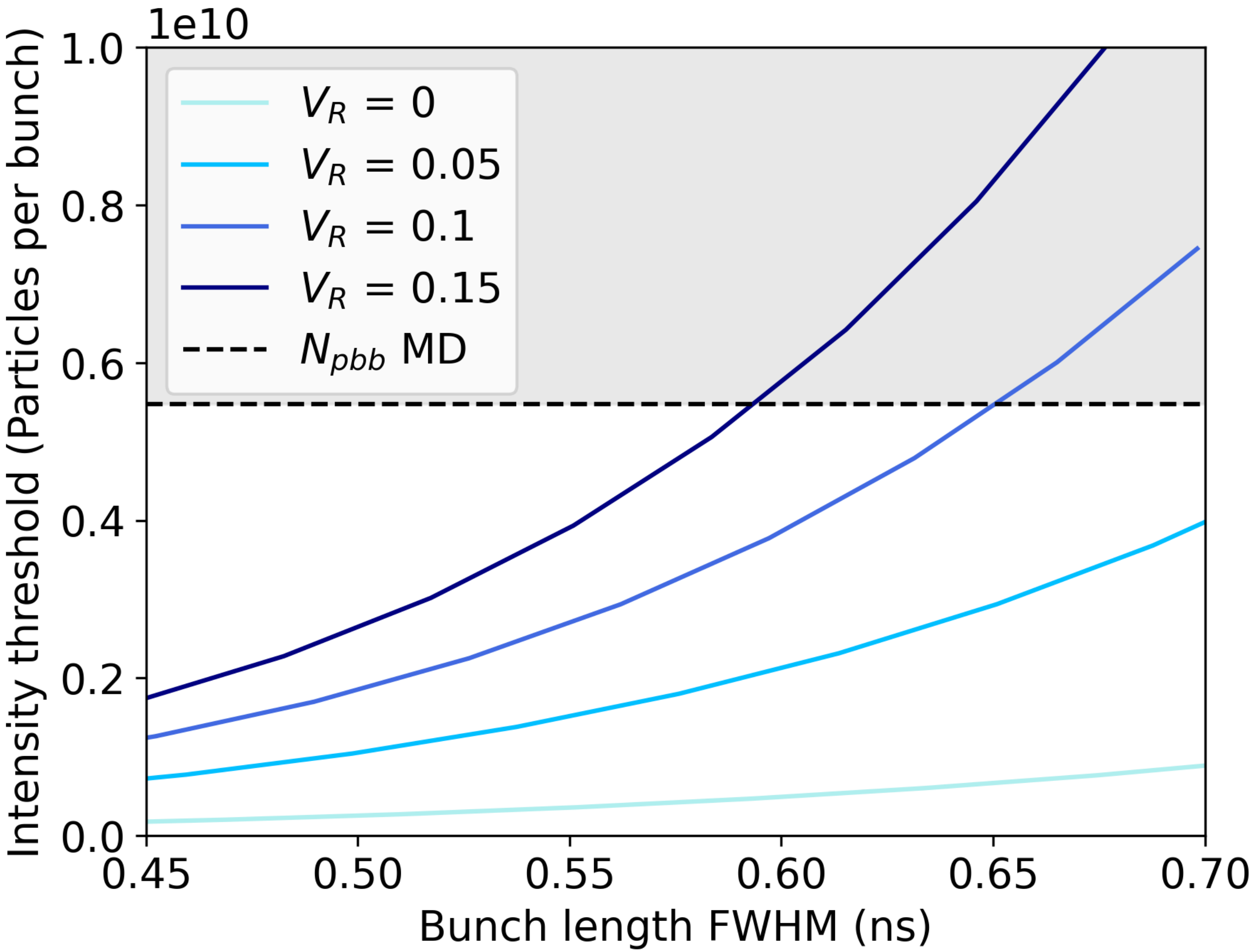
Stability diagram: long bunch, V_R = 0.22



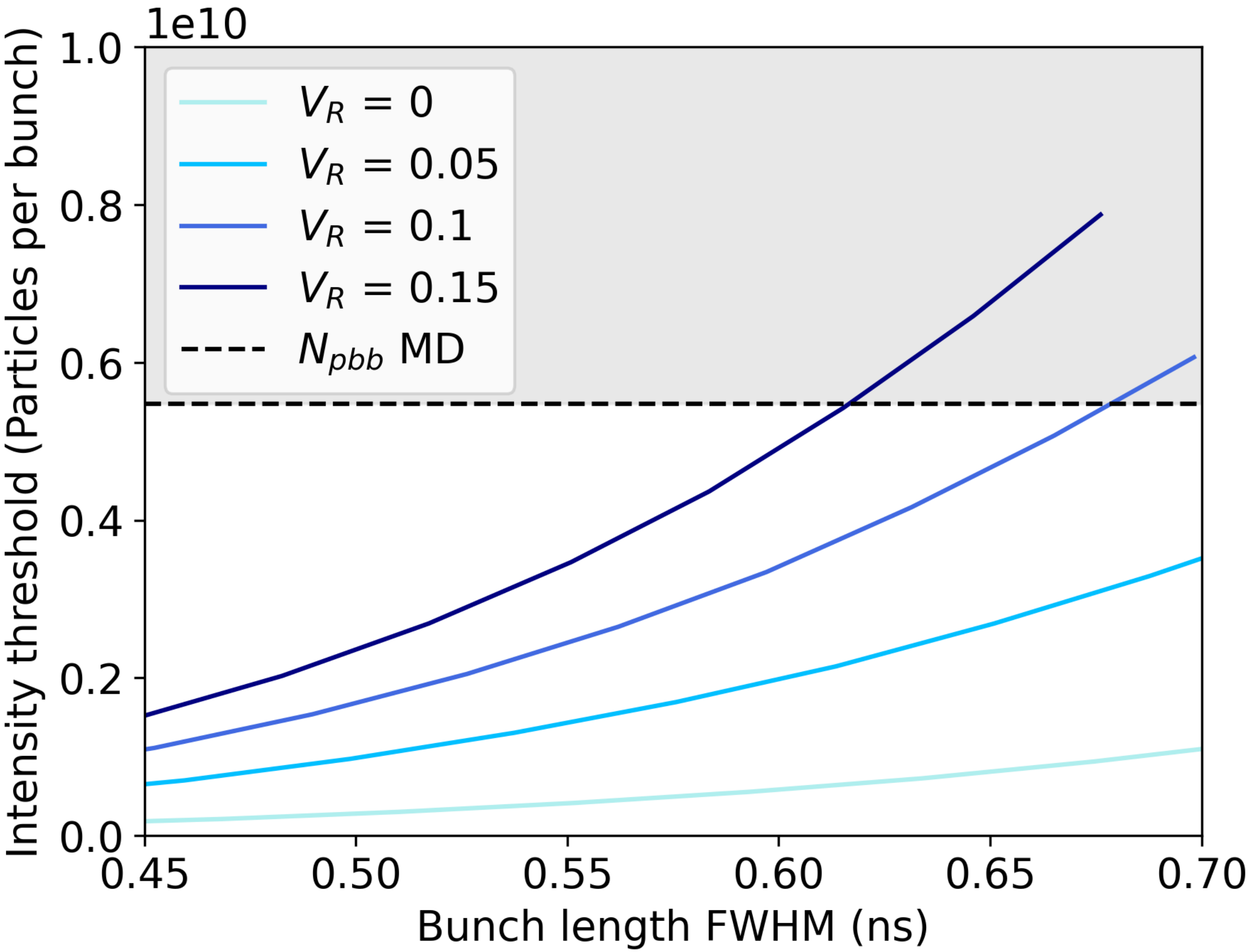
Analytical threshold prediction for $R_{\mathrm{sh}} = 1.7\ \mathrm{M\Omega}$



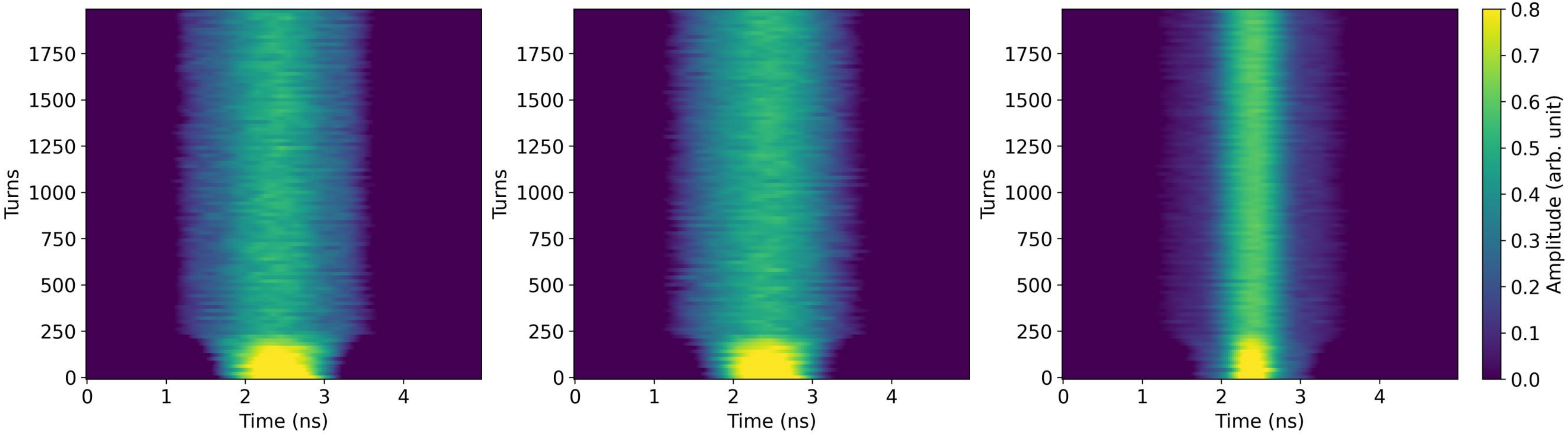
Analytical threshold prediction for $R_{\mathrm{sh}} = 3\ \mathrm{M\Omega}$



Numerical threshold prediction for $R_{\mathrm{sh}} = 3\ \mathrm{M\Omega}$



Bunch evolution for non-monotonic synchrotron frequency distributions



V = 0.75 MV and V_R = 0.5

V = 1 MV and V_R = 0.5

V = 2 MV and V_R = 0.23