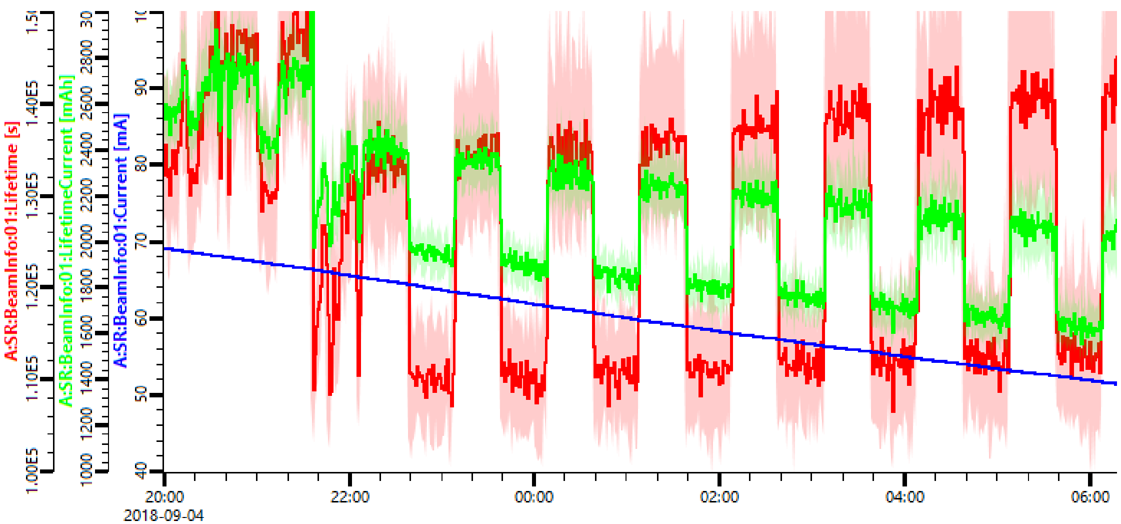
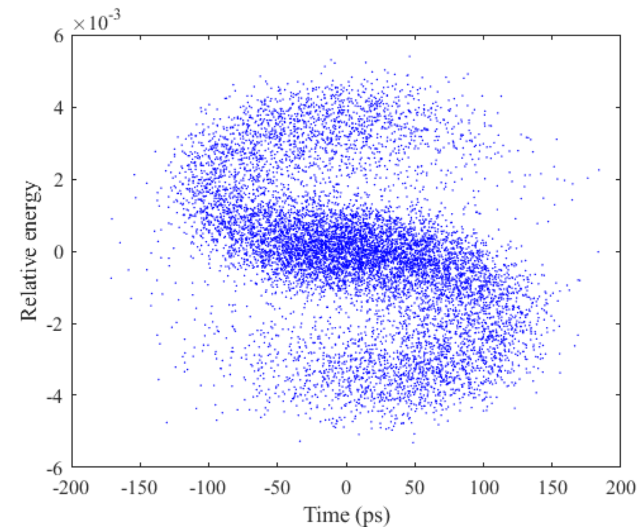
Numerical calculation of RF modulation for application to KARA storage ring

Akira Mochihashi   On Behalf of the KARA Accelerator Group

The Laboratory for applications of synchrotron radiation (LAS), Karlsruhe Institute of Technology (KIT)





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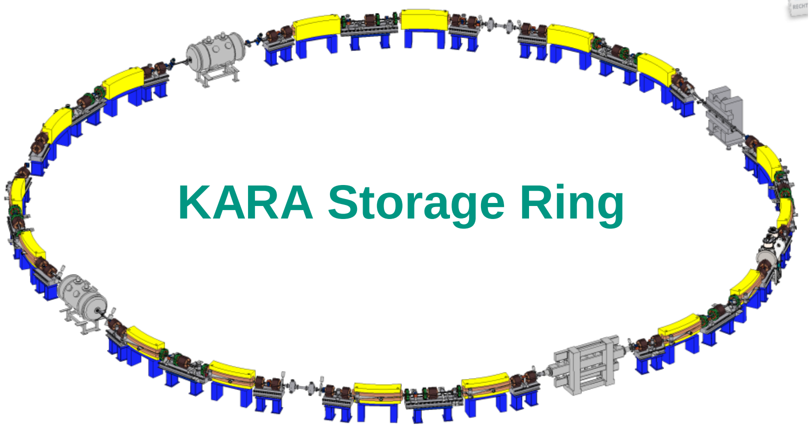

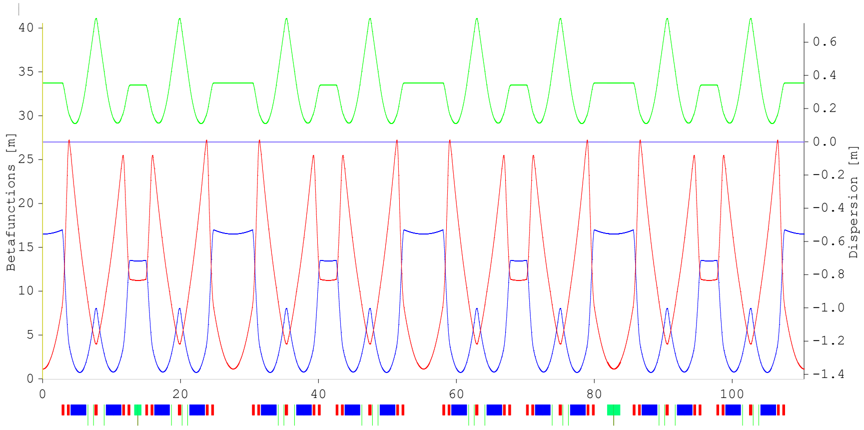

Extended DBA Lattice
(Dispersion>0 in straight section)
Designed Emittance = 59 nm-rad

Beam Energy	< 2.5 GeV
Circumference	110 m
RF Frequency	499.7 MHz
Harmonic Number	184
Number of RF Station	2
Number of Cavity in 1-Station	2
Acc. Voltage	1.4 MV (2.5 GeV)
Ring Lattice	DBA

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RF System in KARA Storage Ring (1)

Parameters	500 MeV (Injection)	2.5 GeV (User Operation)
RF / Revolution Freq.	499.7 MHz / 2.72 MHz	
Harmonic Number	184	
Total RF Voltage	300 kV (Typ.)	1.4 MV (Typ.)
Energy Loss per Turn	995.9 eV	622.4 keV
Synchronous Angle	0.05 deg.	6.38 deg.
Momentum Compaction	0.0105	0.00867
Synchrotron Frequency	35.0 kHz	34.0 kHz
Energy Spread (rms)	1.82×10^{-4}	9.08×10^{-4}
Bunch Length (rms)	8.67 ps	36.9 ps
Total Klystron Output	5.2 kW (150 mA)	140 kW (140 mA)
Ramping Time	-	3 minutes
Tuner Dead Band	0.1~0.5 deg.	0.1~0.5 deg.
Filling Pattern	Partical (30~33x3 bunches) or (30~33x4 bunches)	

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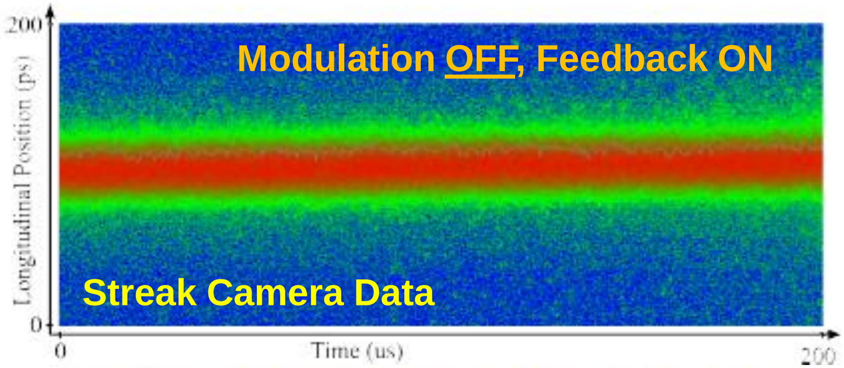
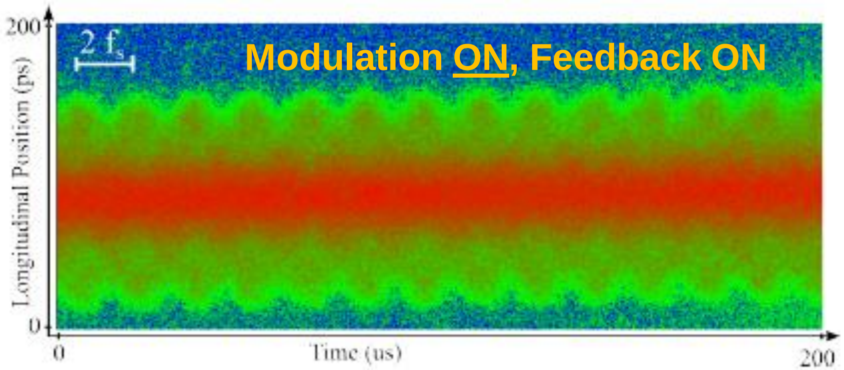
RF System in KARA Storage Ring (2)

- RF Modulation Systems

Injection Energy (500 MeV):
<u>RF Amplitude Modulation by Kicker Cavity</u>





By 2fs modulation, the bunch lengthening occurs and we can stabilize the injection rate from the booster to the storage ring.

E. Blomley, M. Schedler and A-S. Müller, Proceedings of IPAC2016, p.2658-2660

User Operation Energy (2.5 GeV):
<u>RF Phase Modulation by Main Cavities</u>

LLRF Controller: DIMTEL LLRF9/500

- We cannot excite the oscillation with enough amplitude by the kicker cavity at 2.5 GeV.
- On September 2018, we have improved the phase modulation function of our LLRF modules.
- We can excite the beam oscillation by the phase modulation in 2 RF stations independently.

- Now the experiments are under way and it is expected that an improvement of the beam lifetime, suppression of the coupled bunch instaility and an additional interesting beam dynamics will happen.

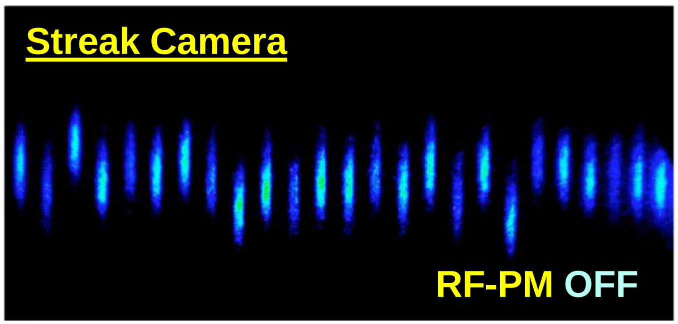
Today, only the calculation!

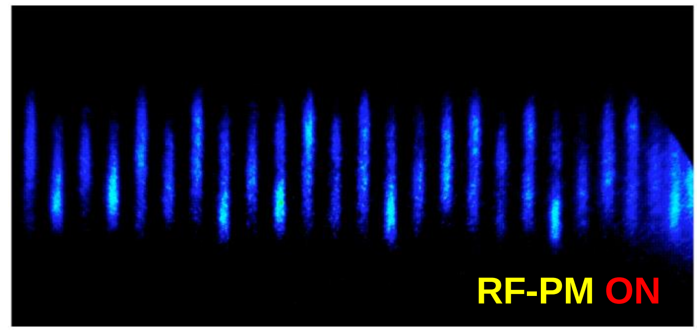
RF Phase Modulation: Preceding Study (1)

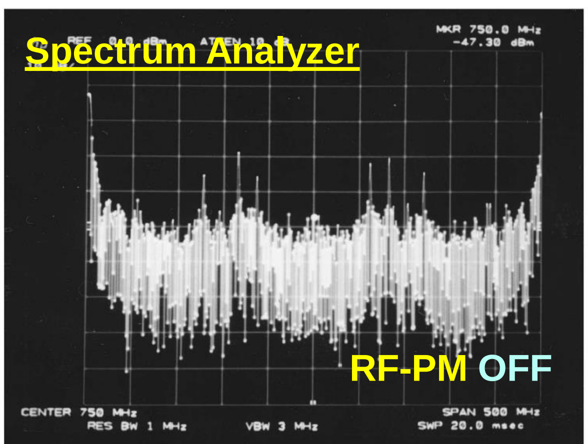
S. Sakanaka et al., in KEK-PF

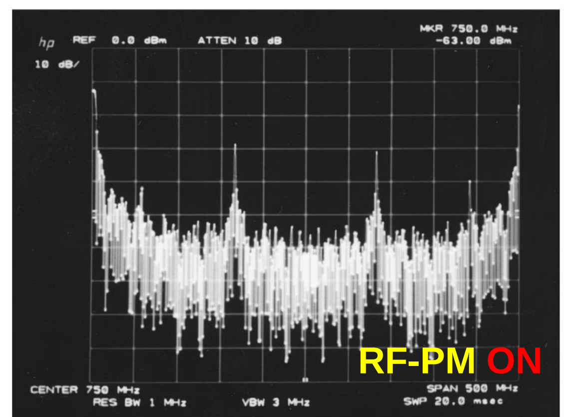
- Can excite longitudinal quadrupole mode oscillation
- Can increase the bunch length (and energy spread)
- Can change (modulate) behavior of the longitudinal coupled bunch instability

Example in KEK Photon Factory (2.5 GeV)







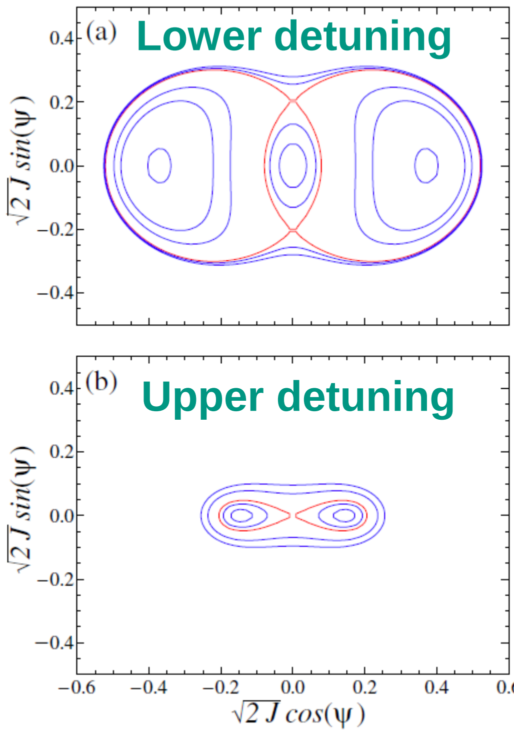


S.Sakanaka et al., PRST-AB 3 050701 (2001)

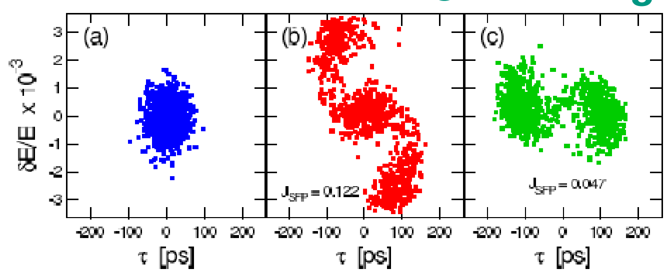
RF Phase Modulation: Preceding Study (2)

N. P. Abreu et al., in Brazilian electron storage ring

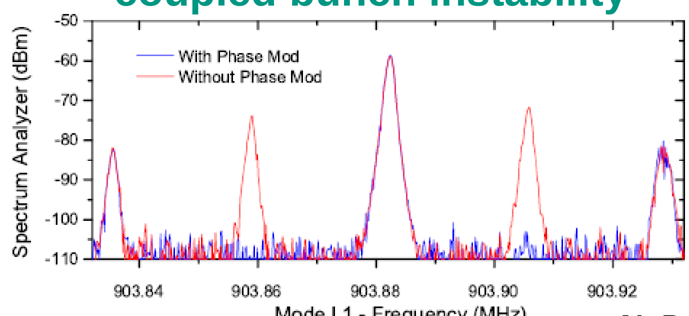
- Theoretical model for the RF phase modulation
- Existence of central & island bunch
- Suppression of coupled bunch intability by Landau damping
- Measurement of BTF & stability diagram



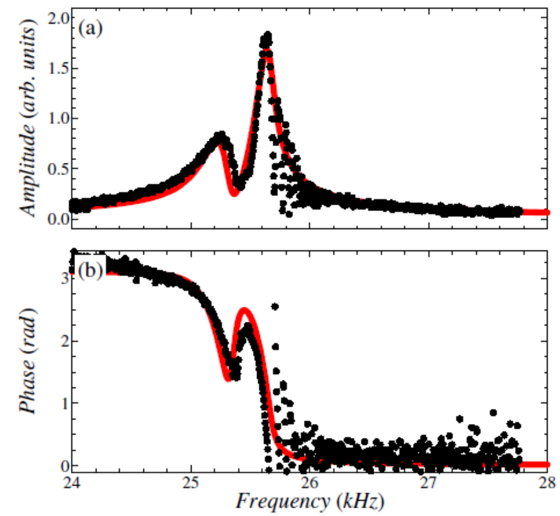
No mod.
Lower detuning
Upper detuning

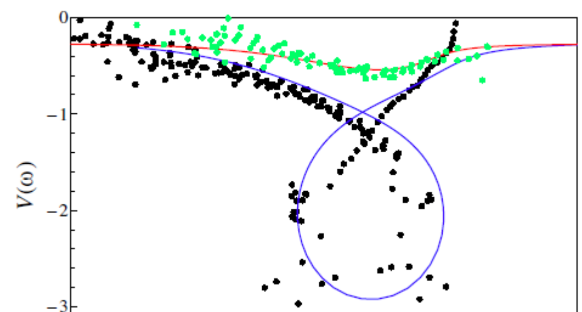


Suppression of longitudinal coupled bunch instability



BTF measurement





Stability diagram measurement

N. P. Abreu et al., PRST-AB 9 124401 (2006)

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Simulation (1): How to Treat the Beam

- To be considered for RF system
  - Phase modulation with sinusoidal pattern
  - Generator voltage with phase modulation
  - Beam induced voltage in each cavity with nonzero bunch length
  - Cavity voltage from vector sum of (generator, beam induced) voltage
  - (Phase advance, Amplitude decreasing) of the beam induced voltage during the bunch spacing
  - Loss factor in each cavity with nonzero bunch length

We calculate RF phase modulation with transient beam loading effect.

- The equation of motion
  - Radiation damping, radiation excitation
  - EoM has been separated into 2 parts because of 2 RF sectors in KARA.

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Simulation(2): Condition of the Calculation

- Physical Conditions:

Issues	Value, Condition
Accelerator	KARA storage ring, 2.5 GeV
Number of RF-Sections & Cavities	2 RF-sections, 2 cavities per each section
Loading Angle	0 degree (optimum tuning)
Filling Pattern	(44 bunches + 4 empties)x3 + (40 empties)

- Cavities: *the parameters come from the measurement for the delivery data sheet*

Parameters	Cav. 1	Cav. 2	Cav. 3	Cav.4
Shunt Impedance (MΩ)	3.32	3.52	3.50	3.01
Unloaded Q	38900	42100	41300	37600
Input Coupling	2.7			
Phase Modulation Amplitude	**100 mrad (Fixed)**			

- Calculation:

Issues	Value, Condition
Number of Particles	10000
Number of Turns	2 x (longitudinal damping time)

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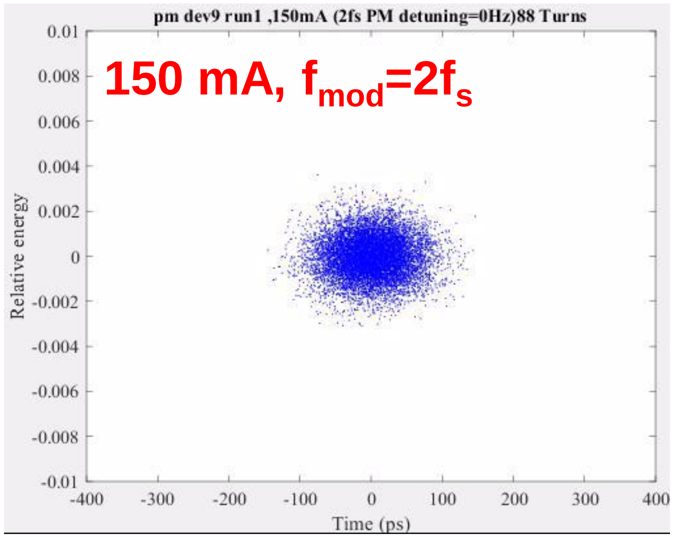
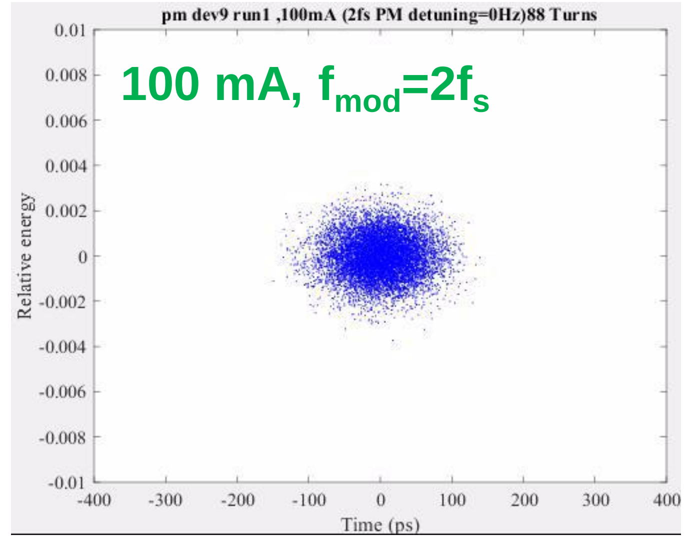
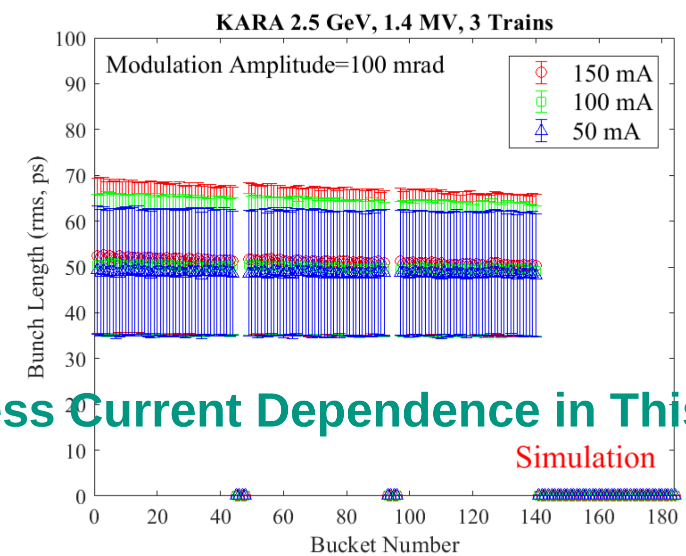
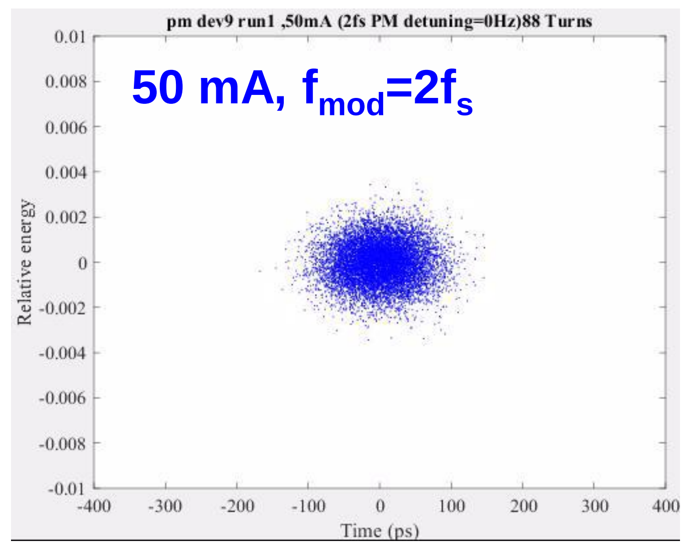
Simulation: Longitudinal Phase Space (1)







Less Current Dependence in This Case.



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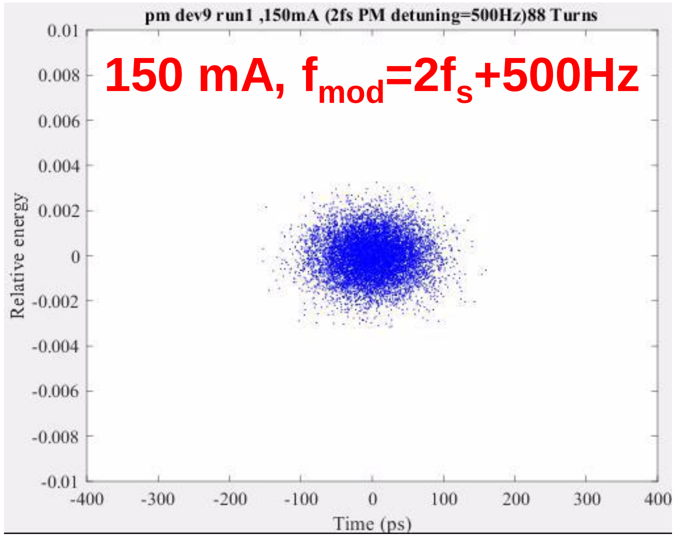
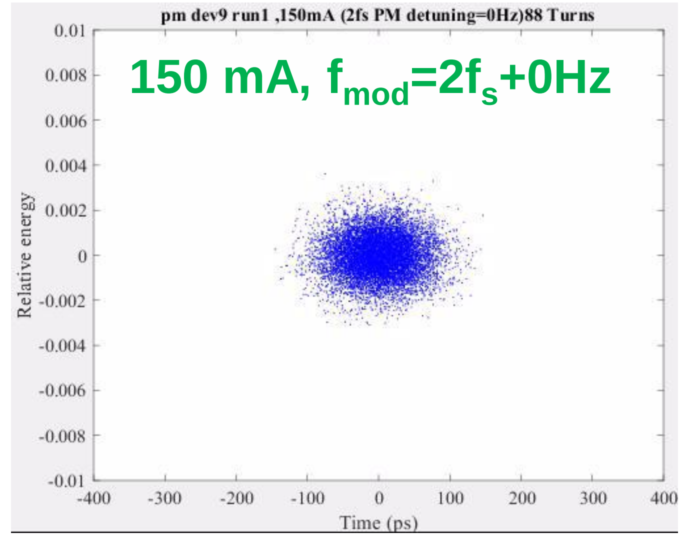
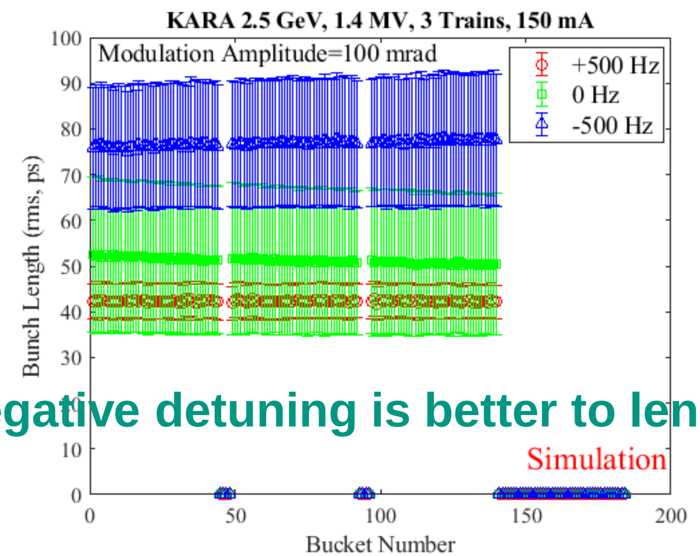
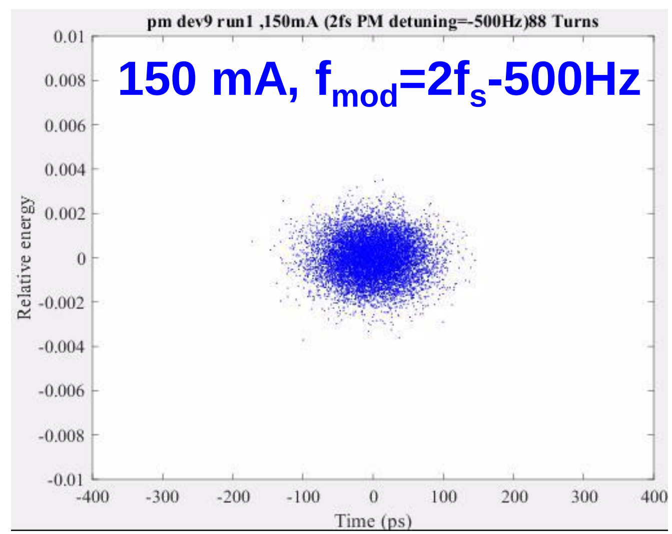
Simulation: Longitudinal Phase Space (2)







Negative detuning is better to lengthen.



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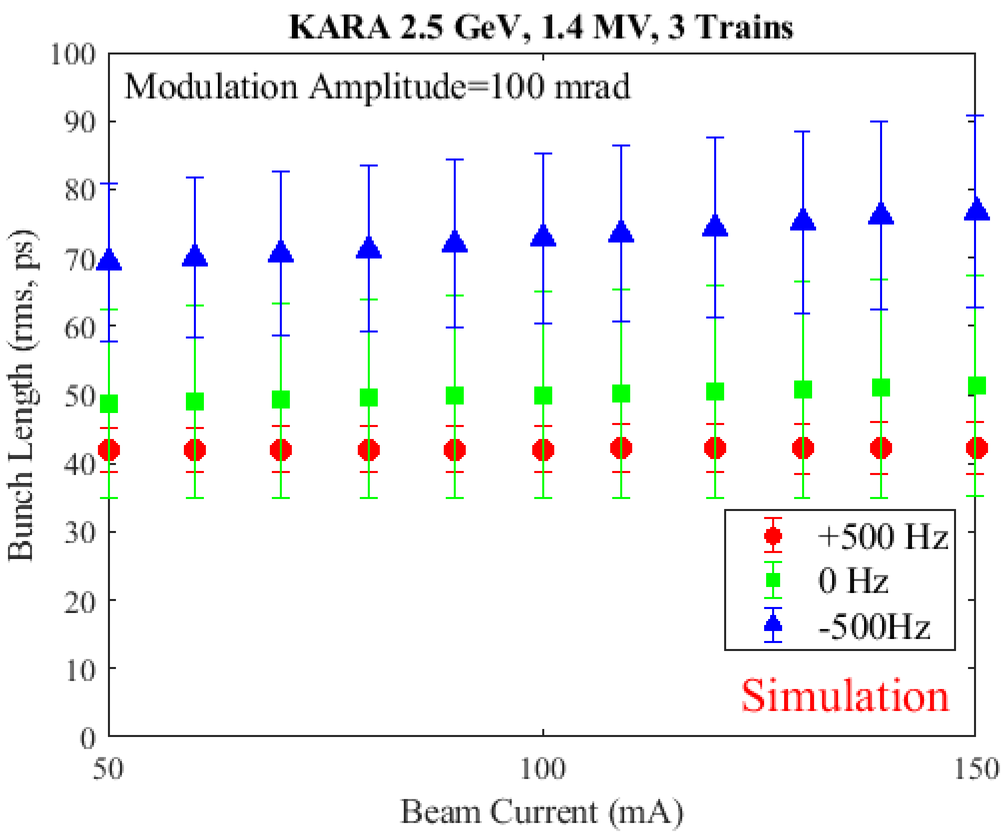
Simulation: Beam Current Dependence



- The beam current dependence on the bunch lengthening is not so large.
- That means the bunch can be lengthened in the wide beam current range.
- The optimum tuning condition has been always kept in different beam current condition in this simulation.
- The maximum achievable bunch length tends to be determined by **the detuning condition** of the modulation frequency.

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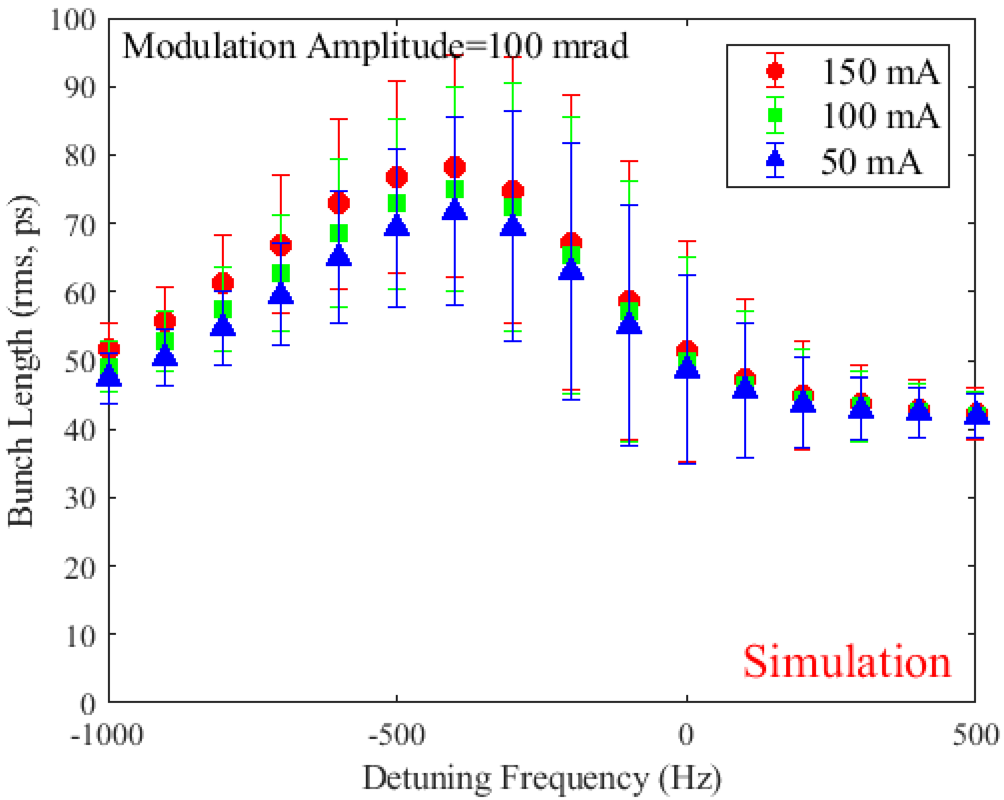
Simulation: Detuning Condition



- The detuning condition strongly affects the bunch lengthening.
- **A negative detuning** from 2fs tends to be much effective than without detuning and positive tuning condition.
- The frequency detuning effect does not have larger dependence on the beam current.

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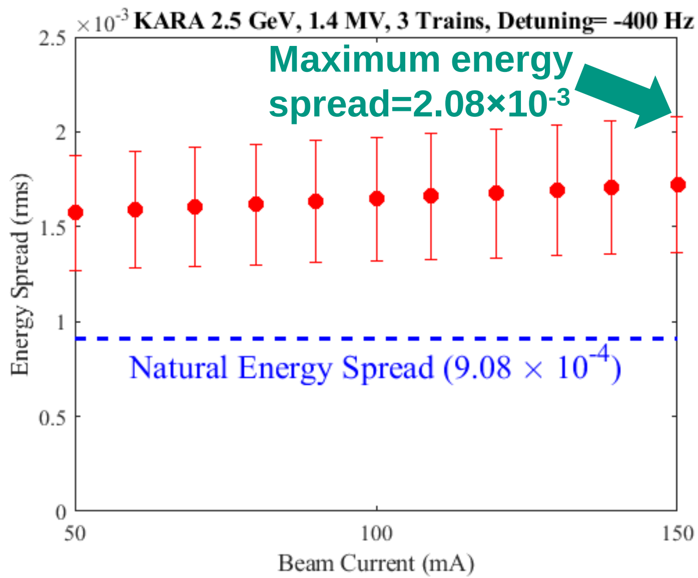
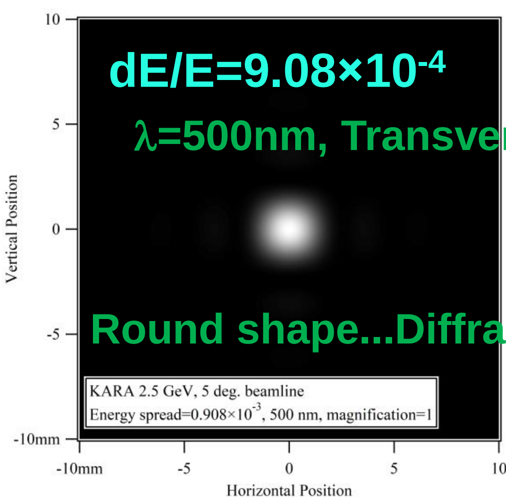
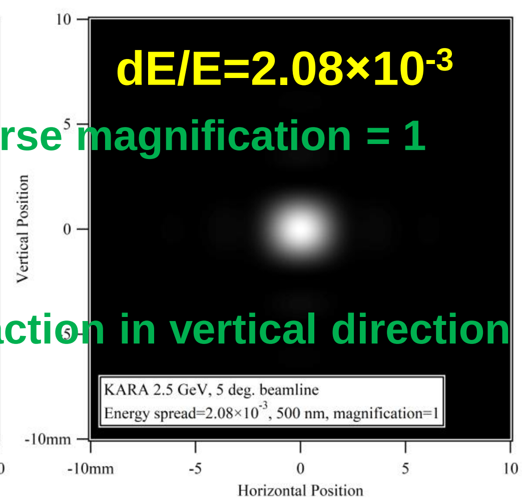
Beam Quality: Energy Spread (1) Bending Magnet

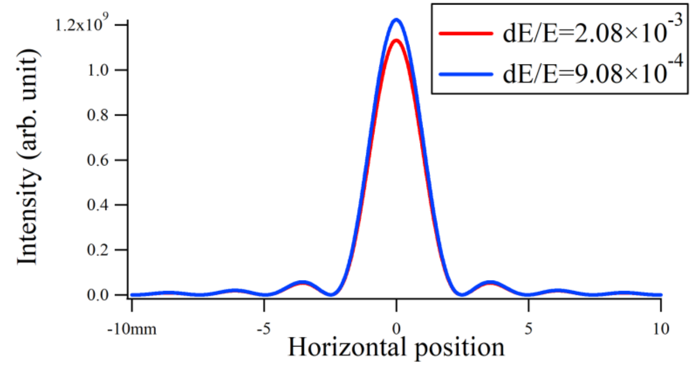


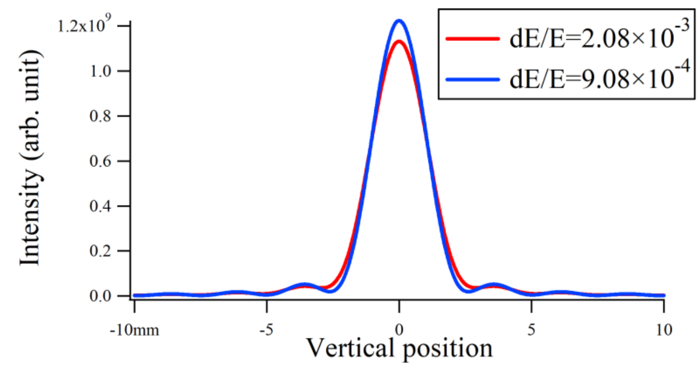




λ=500nm, Transverse magnification = 1

Round shape...Diffraction in vertical direction





Calculated by SRW

Name	Values
β_x / β_y	1.1590 m / 13.242 m
η_x / η_x'	0.2187 m / -0.2328
Emittance, coupling	59 nm-rad, κ_{xy}=0.1%

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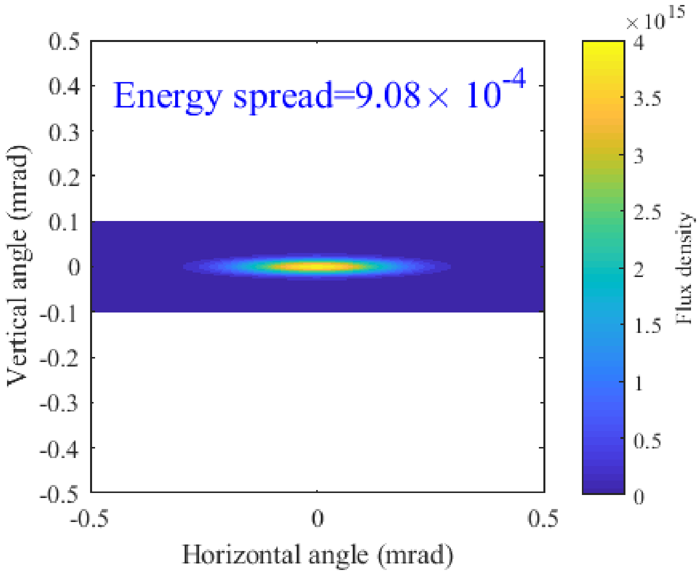
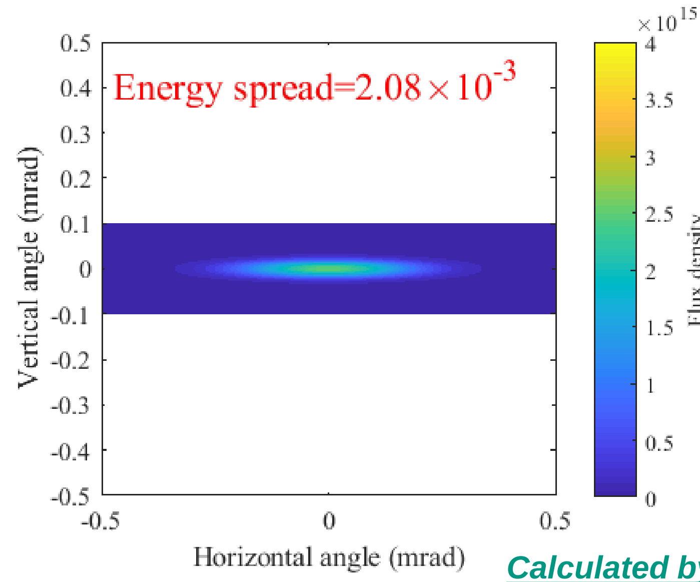
Beam Quality: Energy Spread (2) Undulator

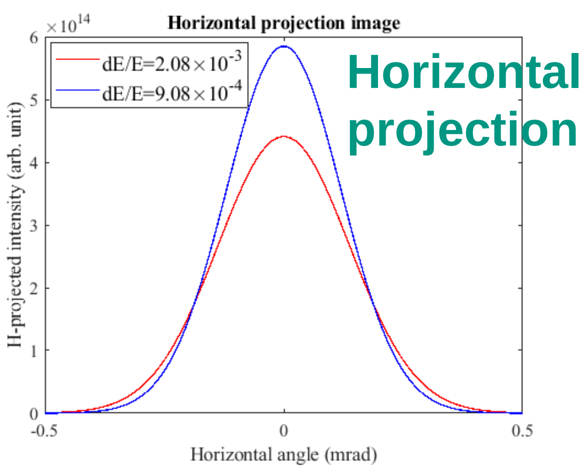
λ_u=20mm, N_p=75, K=0.1, κ_{xy}=0.1%, 1st harmonics=2.96 keV

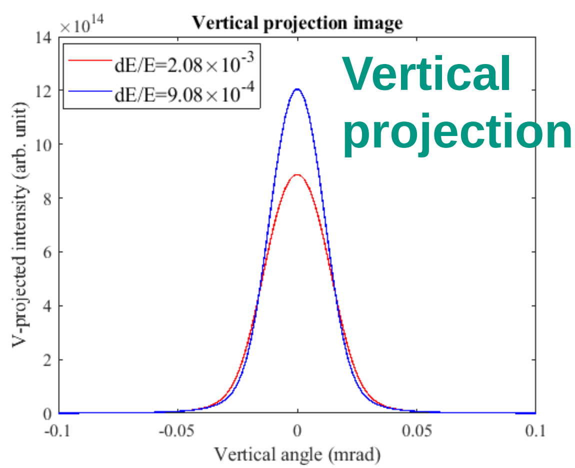


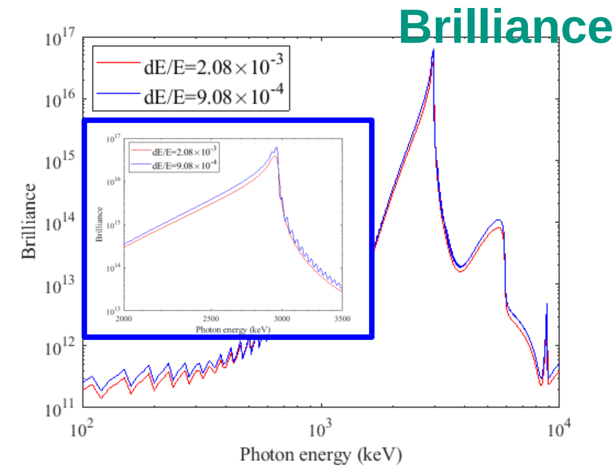


Name	Values
β_x	16.51 m
β_y	1.12 m
η_x	0.35 m
η_x'	0 m
Emittance	59 nm-rad
Coupling	0.1%

Calculated by SPECTRA







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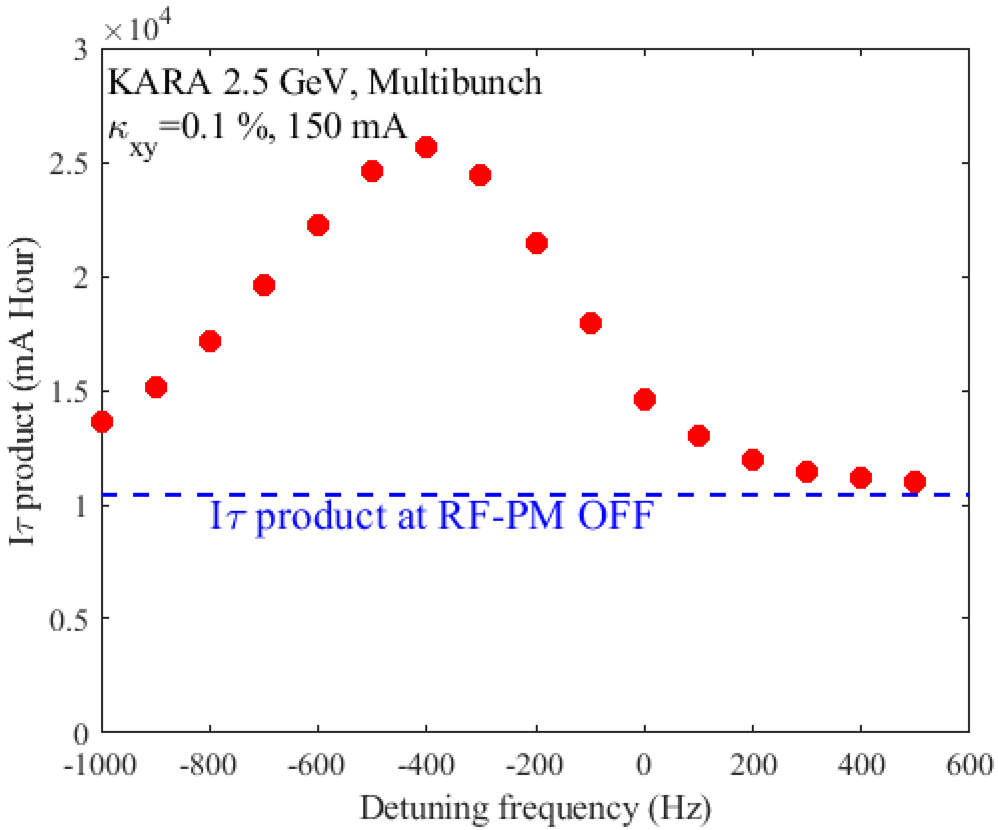
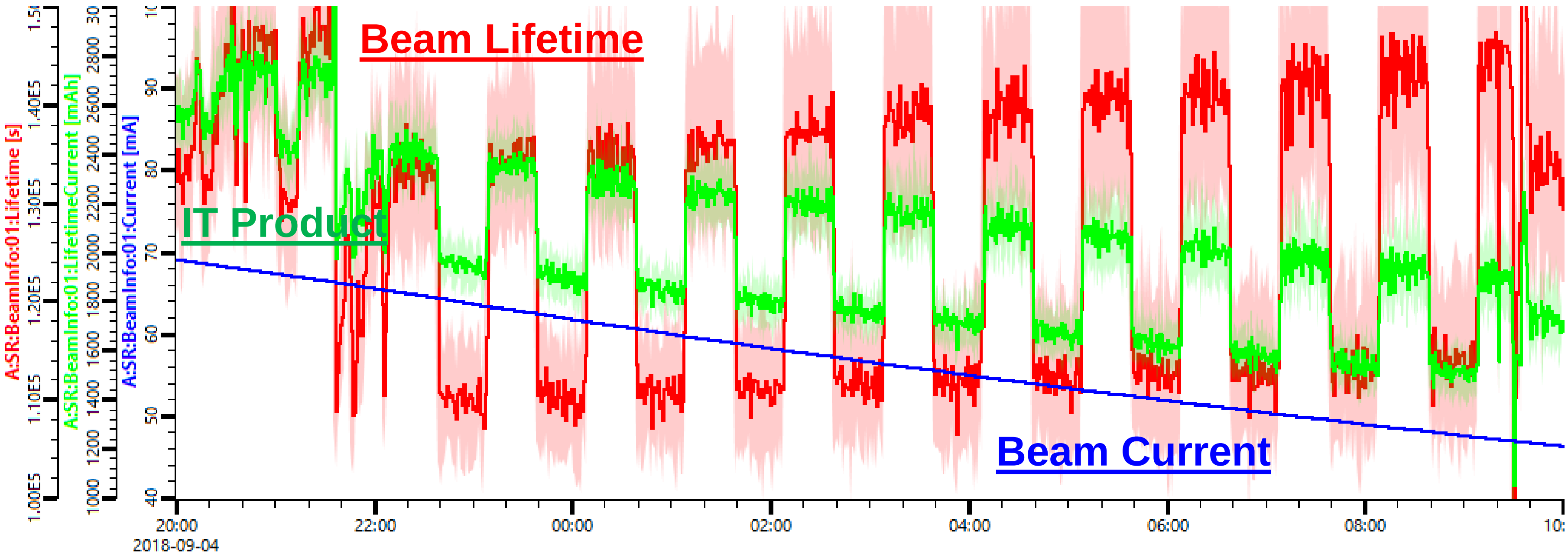
Beam Quality: Touschek lifetime



- Touschek lifetime can increase because of increase of both the bunch length and the horizontal beam size.
- The effect strongly depends on the detuning condition; we can lose the phase modulation effect completely if we are on the wrong detuning condition.
- In KARA 2.5 GeV case, more than twice of Touschek lifetime than that in the normal condition could be expected in proper detuning condition.

First Beam Trial: Control of Beam Lifetime

- 2fs phase modulation with the main cavity system at 2.5 GeV, multibunch condition in KARA (September, 2018)



- By deactivating/activating the RF phaser modulation, we could change/increase the beam lifetime in 2.5 GeV KARA storage ring.
- Optimization of the operating condition, beam diagnostics and additional beam dynamics issues are now under way experimentally and theoretically.

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Summary

- We have installed the RF phase modulation function into the LLRF system in KARA storage ring.
- The RF phase modulation in 2.5 GeV KARA is possible now.
- It is expected that the modulation scheme could improve the beam lifetime issue in KARA 2.5 GeV operation.
- Some influences could happen on the SR light in the beamline. We will have to estimate/evaluate the degradation experimentally in the near future.
- Additional topics such as beam diagnostics and beam dynamics are now under consideration. Very interesting, hopefully.

Thank you for your attention!

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Backup Slides

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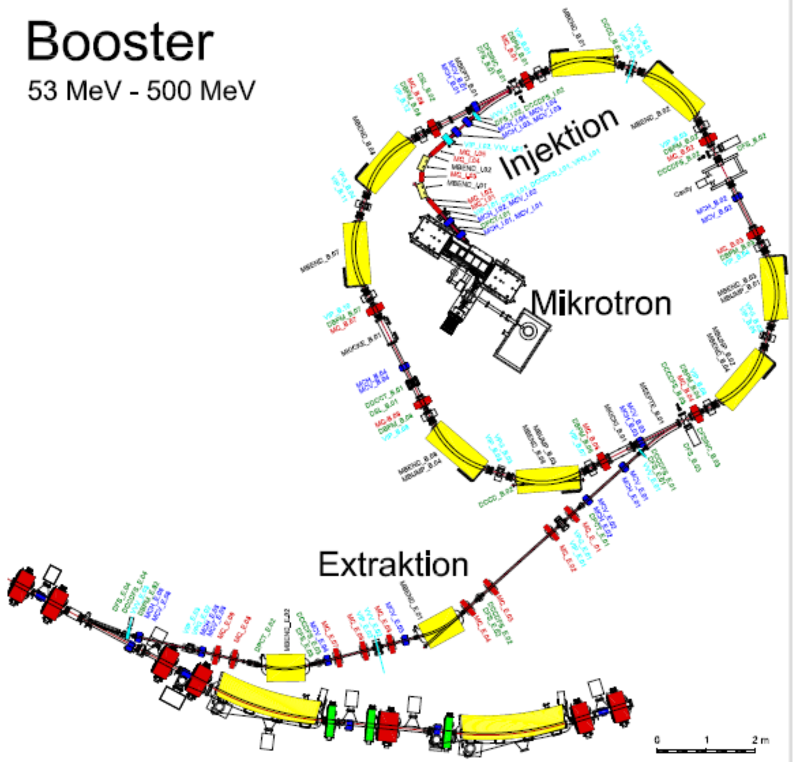
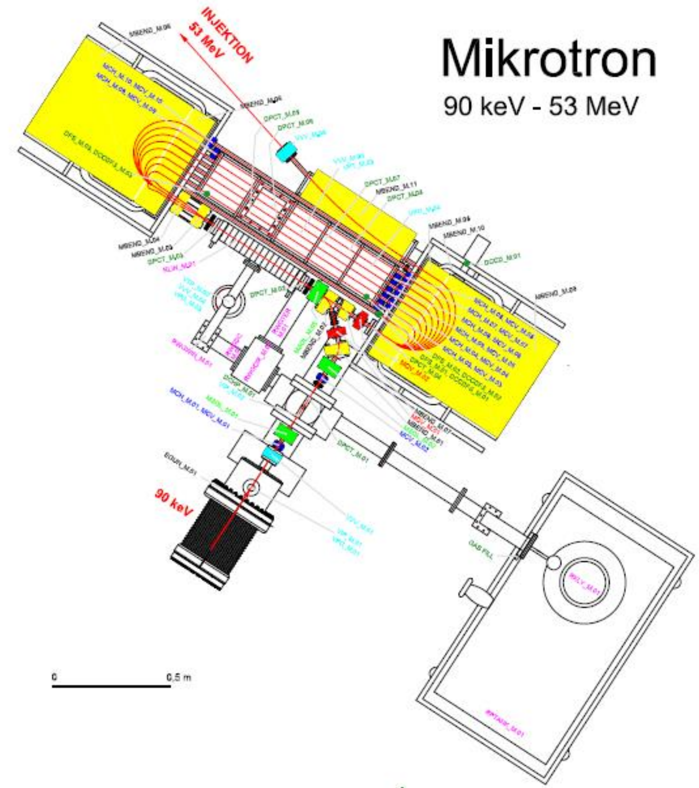
Introduction(2) Karlsuhe Research Accelerator





Beam Energy	< 500 MeV
Circumference	24 m
Harmonic Number	44
Number of RF Station	1
Operation Rep. Rate	1 Hz

Beam Energy	< 53 MeV
RF Frequency	2.999 GHz
Number of Turns	10 (up to 53 MeV)
Linac Structure	(1/2+7+1/2)Cells, Side Couple
Mode	$\Pi/2$ mode

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Phase Modulation & Beam – Cavity Interaction

Karlsruhe Institute of Technology

- Phase Modulation: $\phi_m(t) = \phi_{m0} \cos \omega_m t$
- Generator Voltage with P.M.: $\tilde{V}_g = \frac{i_{g0}}{2} e^{i\theta} \sum_{n=-\infty}^{\infty} i^n J_n(\phi_{m0}) \tilde{Z}(\omega + n\omega_m) e^{i(\omega + n\omega_m)t}$
  - Generator Current: $i_{g0} = \sqrt{\frac{16\beta P_g}{R_{sh}}}$, where $R_{sh} \equiv \frac{V_c^2}{P_c}$
  - Phase Offset: $\theta = \frac{\pi}{2} - \psi_s$, $\quad U_0 = \mathrm{q} V_c \sin \psi_s$
- Beam Induced Voltage:

$$\rho(z) = \frac{q}{\sqrt{2\pi}\sigma_z} e^{-\frac{z^2}{2\sigma_z^2}}$$

$$Z_0^{\parallel}(\omega) = \frac{1}{1+\beta} \frac{R_{sh}}{1 + iQ_L\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)}$$

$$V(z) = -\int_z^{\infty} dz' \rho(z') W_0'(z - z')$$

$$= -\frac{q}{2\pi} \int_{-\infty}^{\infty} d\omega Z_0^{\parallel}(\omega) e^{-\frac{\sigma_z^2 \omega^2}{2c^2}} e^{i\frac{\omega z}{c}}$$

$$= -q \frac{R_{sh}\omega_0}{2Q_0} e^{-\frac{\sigma_z^2 \omega_0^2}{2c^2}} e^{i\frac{\omega_0 z}{c}}$$

- 1-Bunch Passing: $V_b \to V_b - q \frac{R_{sh}\omega_0}{2Q_0} e^{-\frac{\sigma_z^2 \omega_0^2}{2c^2}}$
- Bunch Spacing: $V_b \to V_b e^{\left(i\omega_0 - \frac{\omega_0}{2Q_L}\right)\Delta t}$

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RF Phase Modulation: Equation of Motion

Half of the Ring with RF Cavity 1&2

$$\Delta\delta_1 = q\frac{\mathcal{R}\left[\left(\widetilde{V_1}+\widetilde{V_2}\right)e^{i\omega\tau_1}\right]-\frac{U_0}{2}}{E_0} - \frac{J_e U_0}{2E_0}\delta_1 - [\text{Additional Loss 1}]$$

$$\Delta\tau_1 = \frac{\alpha_c T_0}{2}\delta_2$$

$$\delta_1 \to \delta_1 + \Delta\delta_1 \stackrel{\text{def}}{=} \delta_2$$

$$\tau_1 \to \tau_1 + \Delta\tau_1 \stackrel{\text{def}}{=} \tau_2$$

Half of the Ring with RF Cavity 3&4

$$\Delta\delta_2 = q\frac{\mathcal{R}\left[\left(\widetilde{V_3}+\widetilde{V_4}\right)e^{i\omega\tau_2}\right]-\frac{U_0}{2}}{E_0} - \frac{J_e U_0}{2E_0}\delta_2 - [\text{Additional Loss 2}]$$

$$\Delta\tau_2 = \frac{\alpha_c T_0}{2}\delta_1$$

$$\delta_2 \to \delta_2 + \Delta\delta_2 + [\text{Radiation Excitation}] \stackrel{\text{def}}{=} \delta_1$$

$$\tau_2 \to \tau_2 + \Delta\tau_2 \stackrel{\text{def}}{=} \tau_1$$

$$[\text{Additional Loss}] = \left(\frac{R_{sh1,3}\,\omega_{res1,3}}{4E_0 Q_{1,3}} + \frac{R_{sh2,4}\,\omega_{res2,4}}{4E_0 Q_{2,4}}\right) q^2 e^{-\left(2\pi f_{rf}\sigma_t\right)^2}$$

$$[\text{Radiation Excitation}] = \sqrt{\frac{2J_e U_0}{E_0}} \times \left[\text{Gaussian RND with } \sigma = \frac{\sigma_E}{E_0}\right]$$

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Simulation method (according to RF theory...)

- Phase modulation : $\phi_m(t) = \phi_{m0}\cos(\omega_m t)$

- Generator current : $\widetilde{i_g} = i_{g0} e^{i(\omega t+\theta+\phi_m)} = i_{g0} e^{i\theta} \sum_{n=-\infty}^{\infty} i^n J_n(\phi_{m0})\, e^{i(\omega+n\omega_m)t}$
- $i_{g0} = \sqrt{\frac{16\beta P_g}{R_{sh}}}$, where $R_{sh} \equiv \frac{V_c^2}{P_c}$
- Phase offset ... $\theta = \frac{\pi}{2} - \psi_s,\ U_0 = \mathrm{q} V_c \sin\psi_s$

- Cavity impedance : $\tilde{Z}(\omega) = \dfrac{\frac{R_{sh}}{1+\beta}}{1+iQ_L\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)}$
- Generator voltage : $\widetilde{V_g} = \frac{i_{g0}}{2} e^{i\theta} \sum_{n=-\infty}^{\infty} i^n J_n(\phi_{m0})\, \tilde{Z}(\omega + n\omega_m) e^{i(\omega+n\omega_m)t}$

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Beam induced voltage

- 1-bunch passing through 1-cavity :

$$V(z) = -\int_{z}^{\infty} dz'\rho(z')W_0'(z-z')$$

$$= -\frac{q}{2\pi}\int_{-\infty}^{\infty} d\omega Z_0^{\parallel}(\omega)e^{-\frac{\sigma_z^2\omega^2}{2c^2}}e^{i\frac{\omega z}{c}}$$

$$= -q\frac{R_{sh}\omega_0}{2Q_0}e^{-\frac{\sigma_z^2\omega_0^2}{2c^2}}e^{i\frac{\omega_0 z}{c}}$$

$$\rho(z) = \frac{q}{\sqrt{2\pi}\sigma_z}e^{-\frac{z^2}{2\sigma_z^2}}$$

$$Z_0^{\parallel}(\omega) = \frac{1}{1+\beta}\frac{R_{sh}}{1+iQ_L\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)}$$

1-bunch passing : $V_b \to V_b - q\frac{R_{sh}\omega_0}{2Q_0}e^{-\frac{\sigma_z^2\omega_0^2}{2c^2}}$

Bunch-spacing : $V_b \to V_b e^{\left(i\omega_0-\frac{\omega_0}{2Q_L}\right)\Delta t}$

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Energy loss in the cavity

- 1-bunch passing through 1-cavity :

$$\Delta E = -\frac{1}{2\pi}\int_{-\infty}^{\infty} d\omega |\tilde{\rho}(\omega)|^2 \mathrm{Re} Z_0^{\parallel}(\omega)$$

$$= -q^2 \frac{R_{sh}\omega_0}{4Q_0} e^{-\omega_0^2\sigma_t^2}$$

Energy loss of the beam = (radiation loss)+(loss in the cavity)

Beam induced voltage & energy loss in the cavity depend on the bunch length.

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Phasor diagram (1)

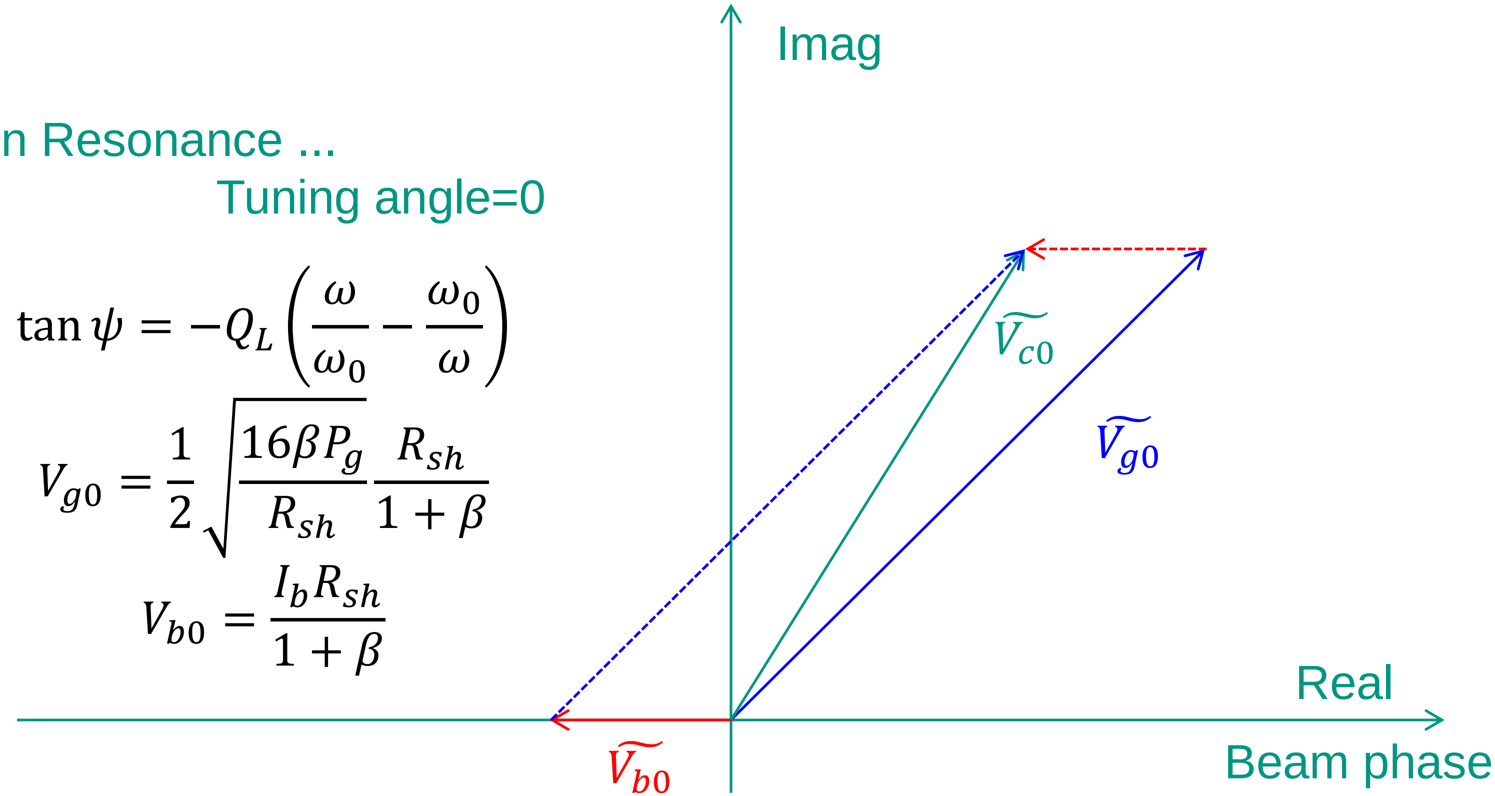
On Resonance ...

Tuning angle=0

$$\tan\psi = -Q_L\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$$

$$V_{g0} = \frac{1}{2}\sqrt{\frac{16\beta P_g}{R_{sh}}}\frac{R_{sh}}{1+\beta}$$

$$V_{b0} = \frac{I_b R_{sh}}{1+\beta}$$



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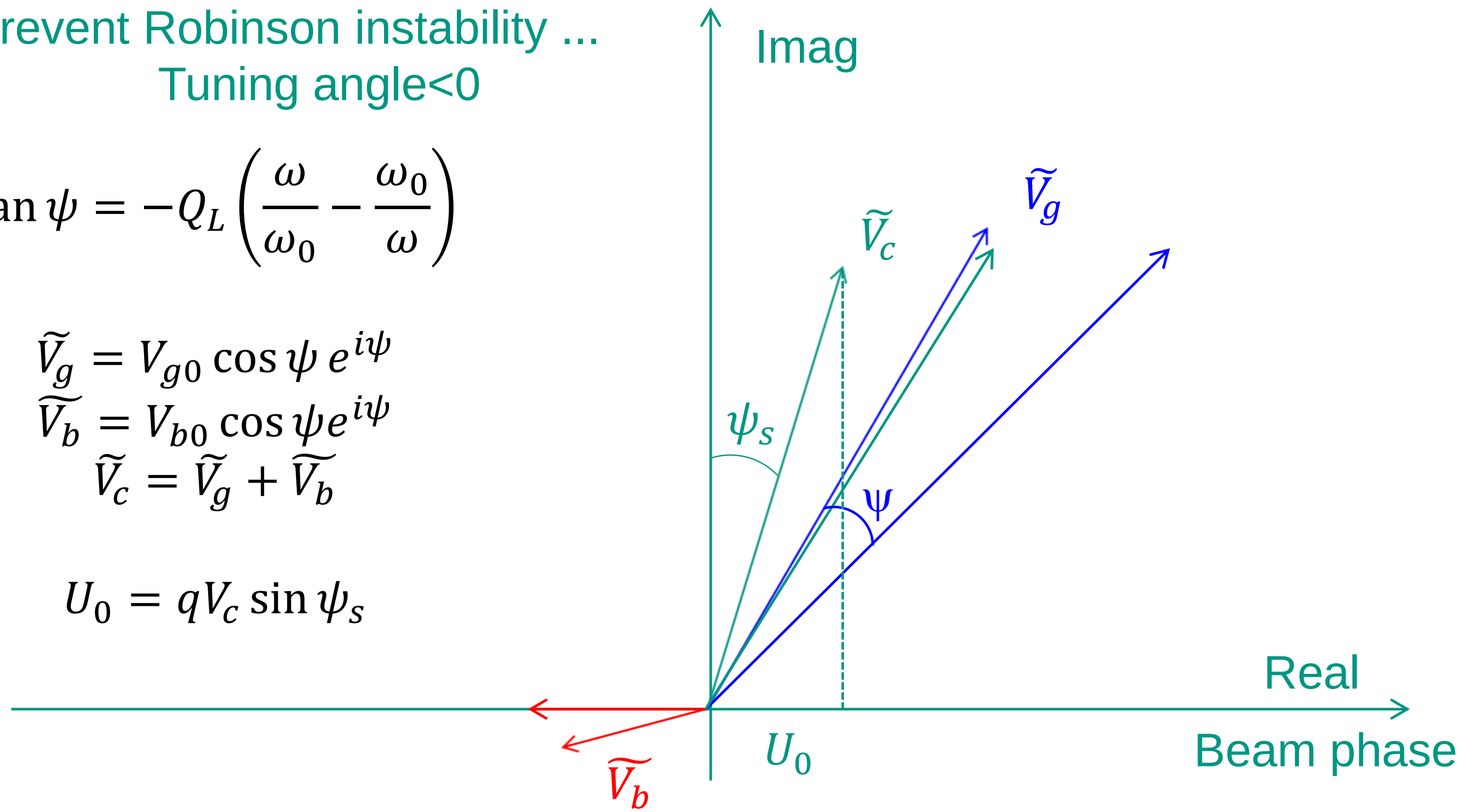
Phasor diagram (2)

To prevent Robinson instability ...
Tuning angle<0

$$\tan\psi = -Q_L\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$$

$$\widetilde{V_g} = V_{g0}\cos\psi\, e^{i\psi}$$
$$\widetilde{V_b} = V_{b0}\cos\psi e^{i\psi}$$
$$\widetilde{V_c} = \widetilde{V_g} + \widetilde{V_b}$$

$$U_0 = qV_c\sin\psi_s$$



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Cavity (de)tuning condition

- In case of optimum tunning (loading angle=0)

$$f_0 = f_{rf} - \frac{I_b \cos\psi_s}{2V_c}\frac{R_{sh}}{Q_0} f_{rf}$$

(in definition of $U_0 = qV_c \sin\psi_s$)

Tuning angle of the cavity :

$$\tan\psi = -Q_L\left(\frac{f_{rf}}{f_0} - \frac{f_0}{f_{rf}}\right)$$

Tuning angle depends on the beam current (move the tuner!)

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