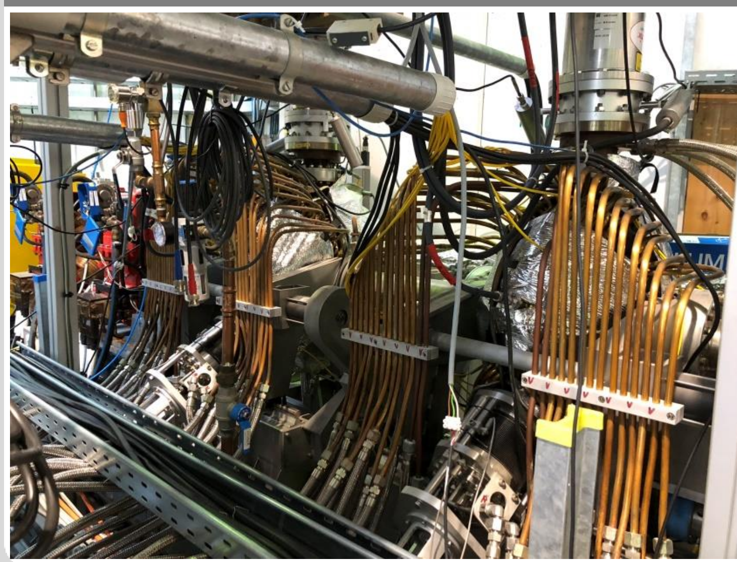
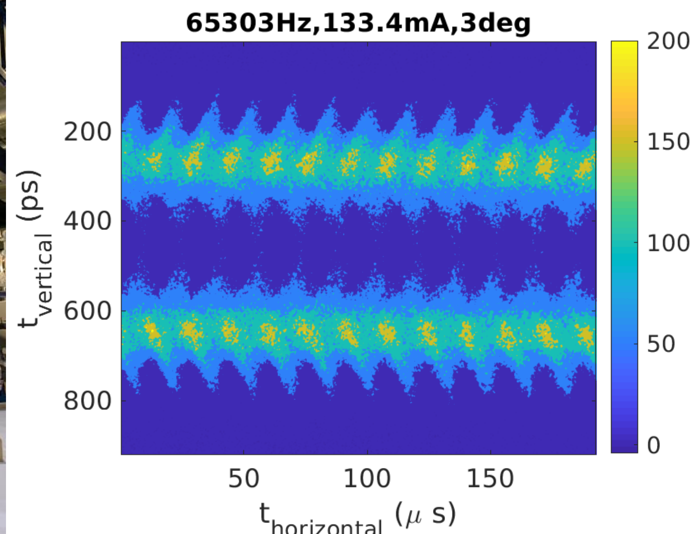
Karlsruhe Institute of Technology

Present Status of KARA RF System

Akira Mochihashi
On behalf of Institute for Beam Physics and Technology (IBPT)
and Laboratory for Applications of Synchrotron Radiation (LAS) team at KIT

Institute for Beam Physics and Technology (IBPT),
Karslsruhe Institute of Technology (KIT)





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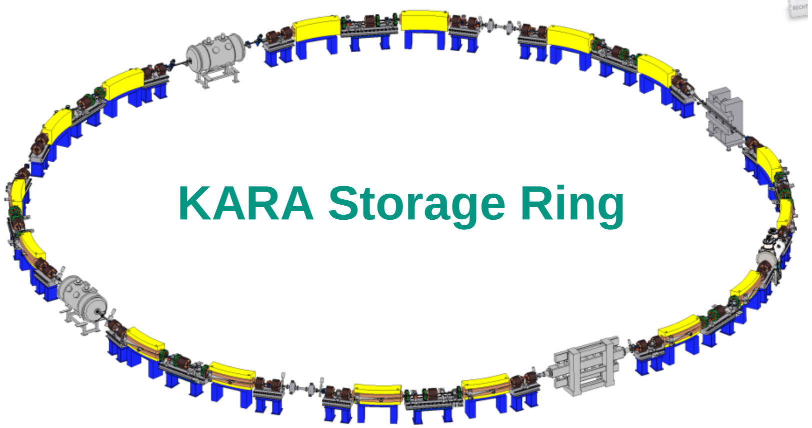
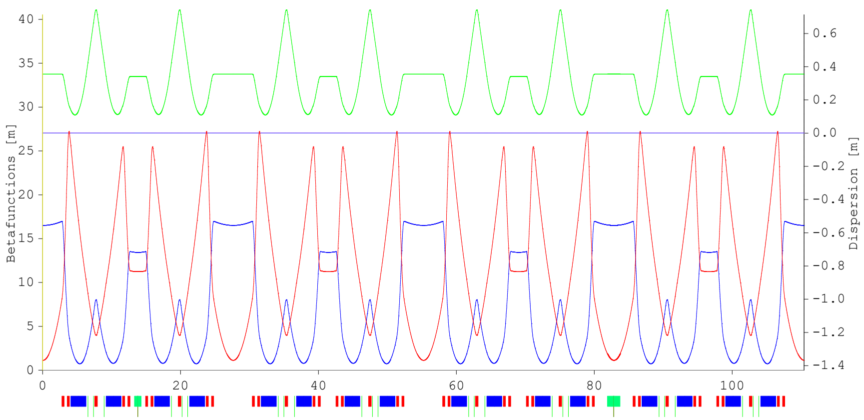
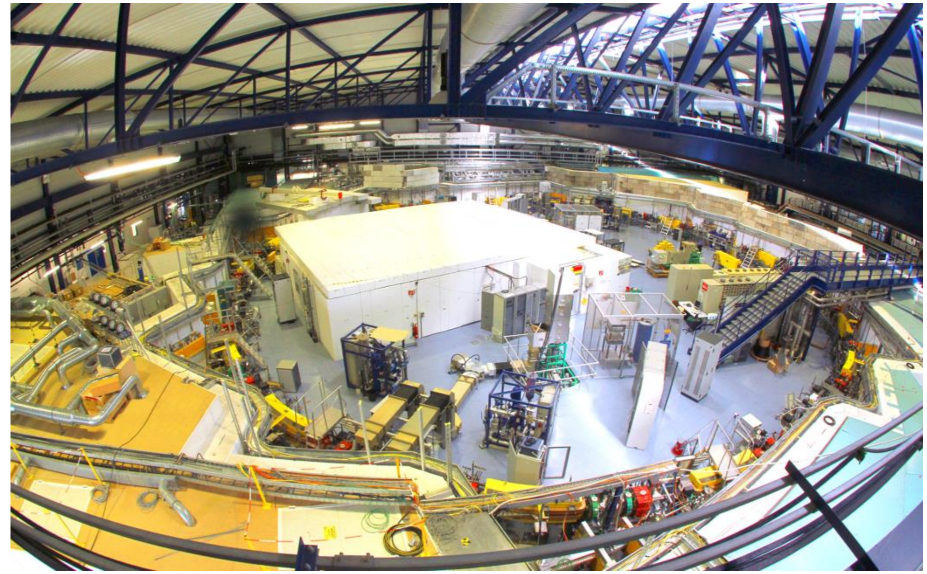




Extended DBA Lattice
(Dispersion>0 in straight section)
Designed Emittance = 59 nm-rad



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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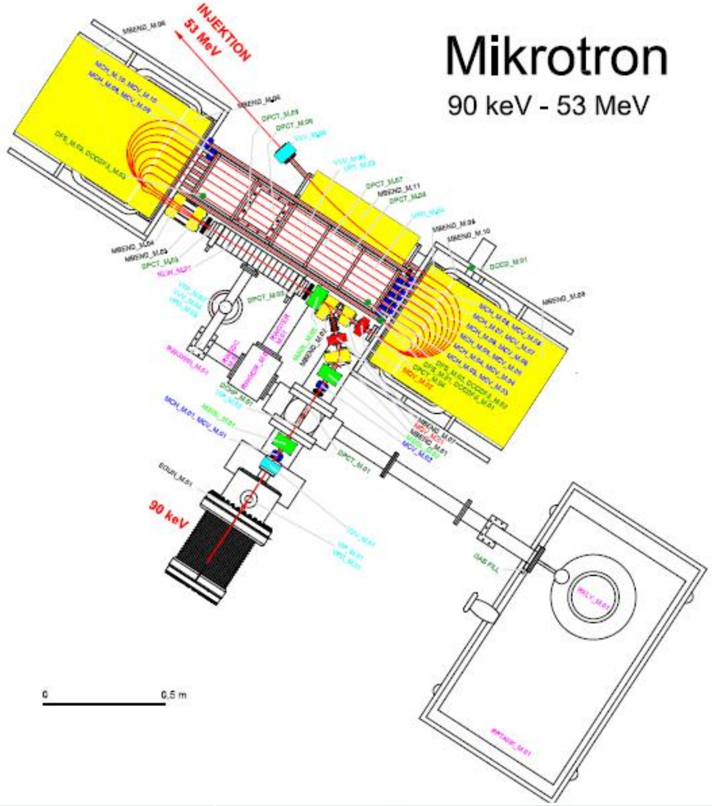
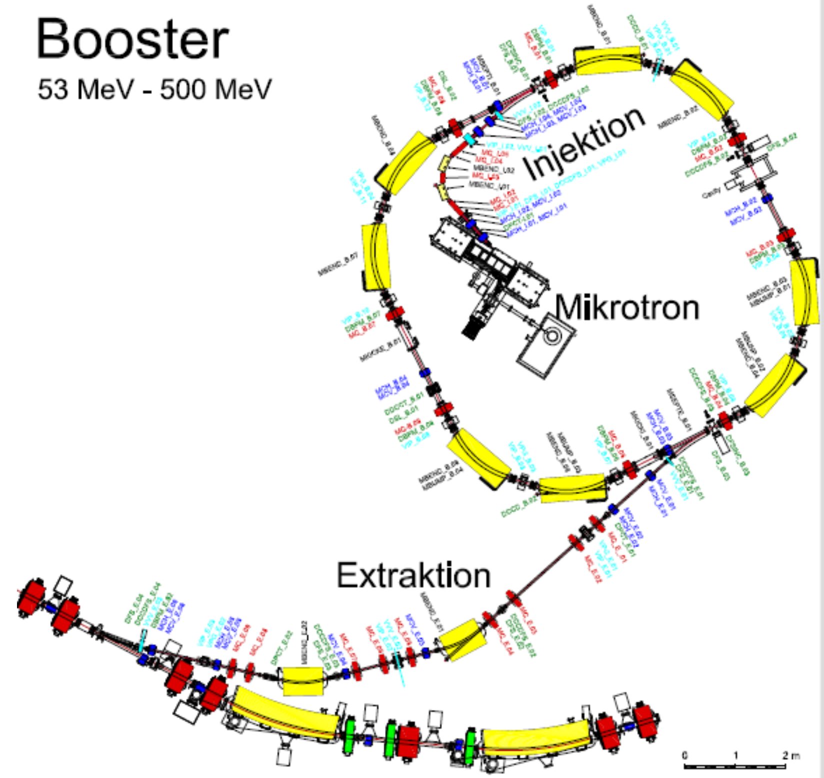
Introduction (2) KArlsruhe Research Accelerator





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

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

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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.
Typical Filling Pattern	Partial (30~33x3 bunches) or (30~33x4 bunches)	

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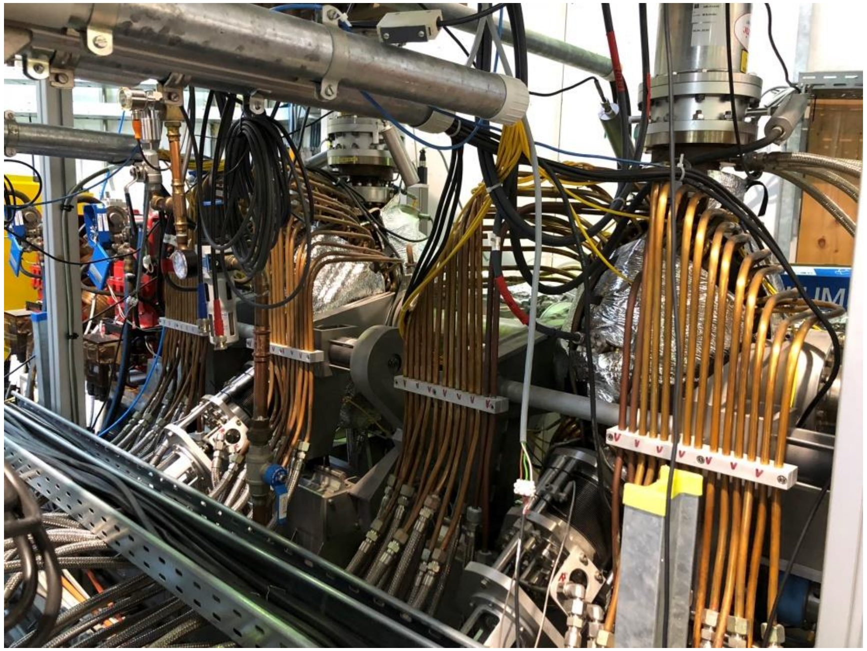
RF System in KARA Storage Ring (2)



- RF Cavity (2Cavs/Station)
  - ELETTRA Type Cavity
  - Q_0~40000, R_{sh}~3.3MΩ
  - Vc = 350kV/Cavity (@2.5GeV)

- Cavity Cooling System
  - 1-Chiller for each Cavity
  - Settled Temp. = 40~60degree
  - Controllable for each Cavity independently

Several times per one year, we have to change the cavity temperature to suppress longtitudinal coupled bunch instability at 500 MeV.

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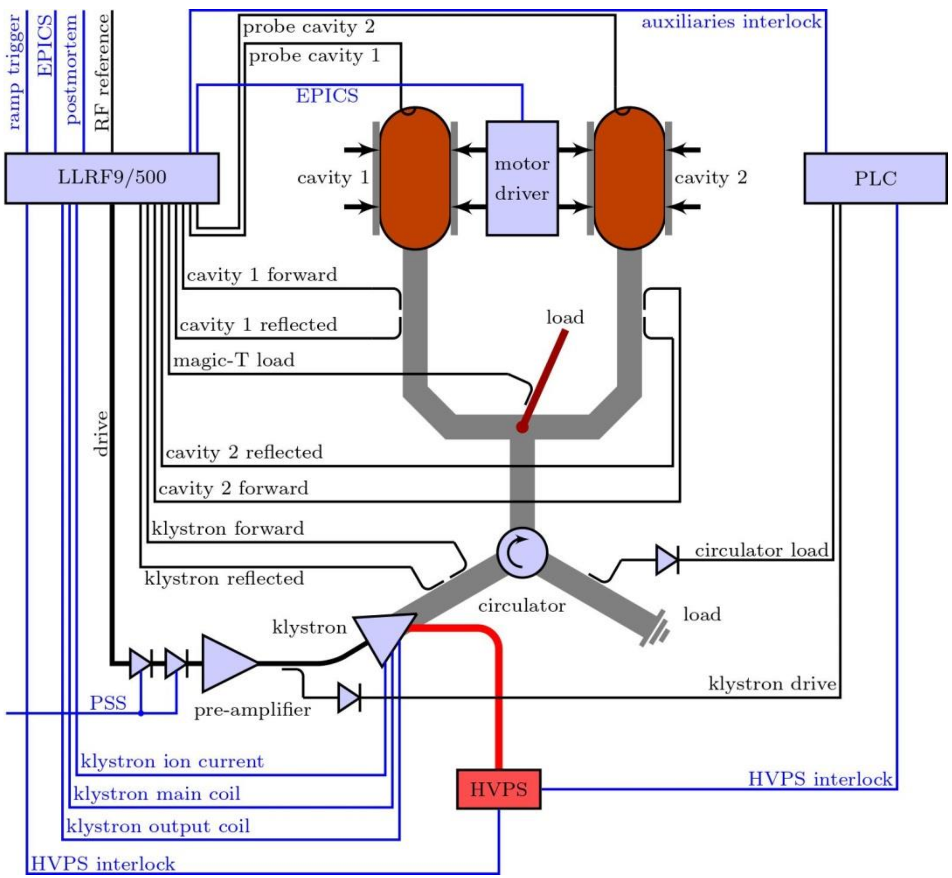
RF System in KARA Storage Ring (3)

- RF Control System in KARA

Setup for One RF Sector



LLRF Control Module

DIMTEL LLRF 9/500

- 1-Module per 1-Station (2 Cavities)
  - The cavity pickup signals are vector-summed and processed in LLRF.
  - The phase adjustment between 2 station are necessary.
  - **Option: modulations for output signal are available.**

Signal	Symbol	Ratio to f_{rf}	Frequency (MHz)
Reference	f_{rf}	1	499.654
IF	f_{IF}	$\frac{1}{12}$	41.6378
Local oscillator	f_{LO}	$\frac{11}{12}$	458.0162
ADC clock	f_{ADC}	$\frac{11}{48}$	114.5040
DAC clock	f_{DAC}	$\frac{11}{24}$	229.0081

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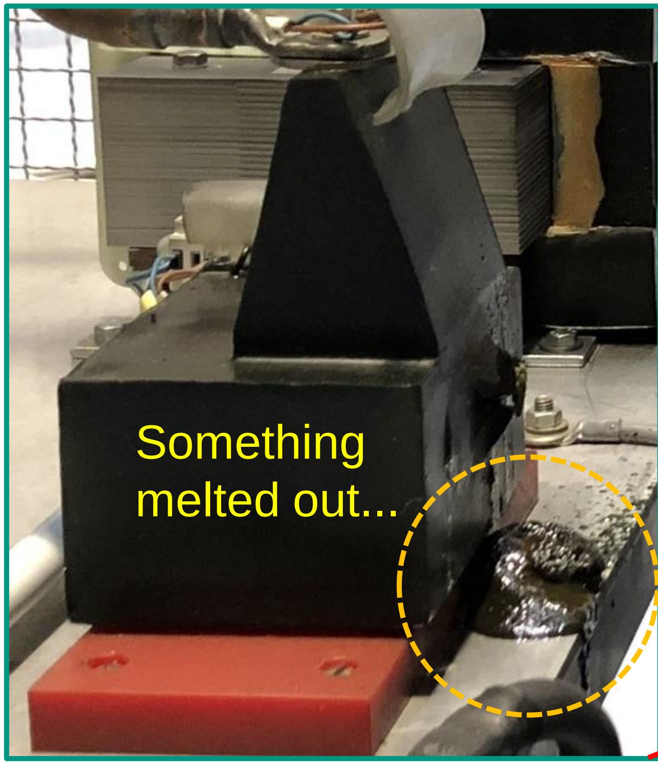
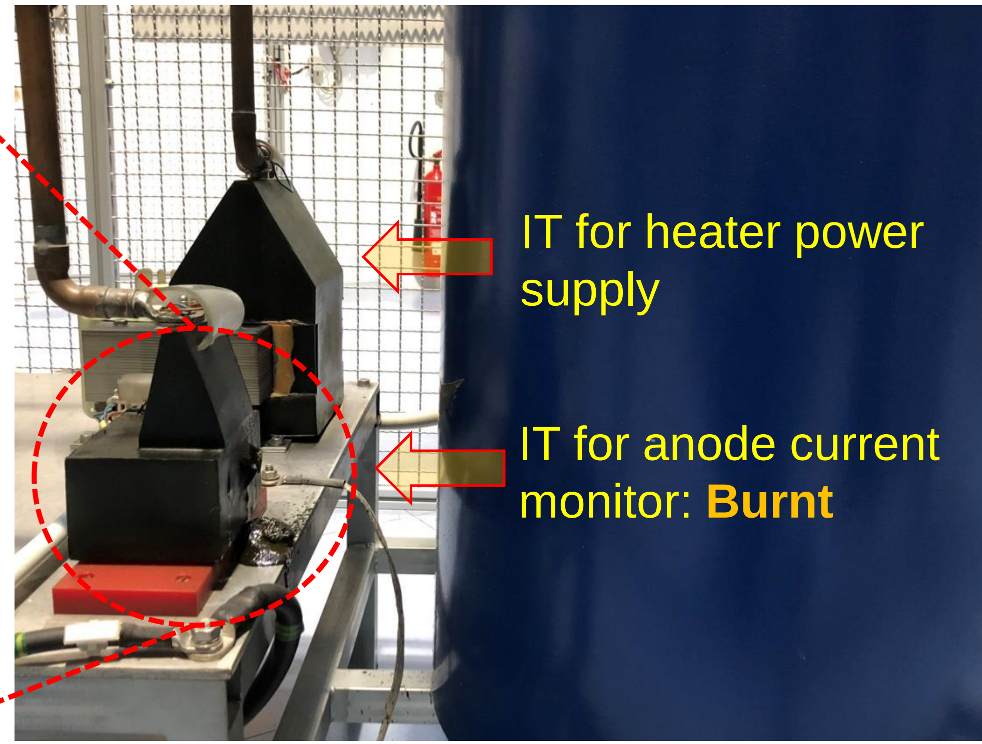
Trouble Report in 2019 (1)

- Trouble at **I**solation **T**ransformer (**IT**) on high volgate deck for klystron power supply at one of the 2 RF-sectors (10.01.2019)





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Trouble Report in 2019 (2)

- High voltage deck for klystron

High voltage deck for power supply and monitor

Resistance for cathode voltage adjustment

DC power supply for klystron heater

Anode current monitor

The trouble happend because of failure of the anode current monitor.

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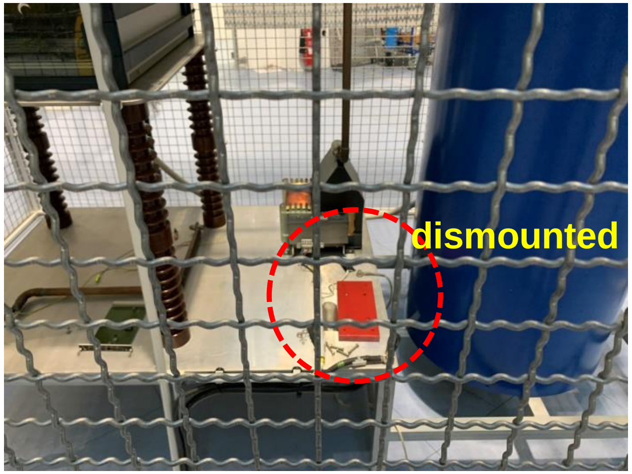
Trouble Report in 2019 (3)

- The way to the recovery
  - Attempt to operate the storage ring with one RF-sector
    - It was possible, but we could not store enough beam current.
  - Dismounted the transformer and the anode current monitor
    - The anode current interlock has never happened for 20 years.
    - We can check the anode condition by monitoring temperature of the klystron body which comes from near to the anode part.

We spent 8 days to recover from this failure.



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Research and Development (1) : Cavity HOM

- Probable Modes of Longitudinal Coupled Bunch Instability

From CST studio simulation with simplified 3D model

Modes	Frequency (GHz)	Q	R_{sh}/Q (Ω)	R_{sh} (Ω)
TM011	0.946751	45583	5.28×10^{-5}	2.40657
TM210	0.991593	57797	1.41×10^{-6}	0.08175
TM020	1.06244	60660	357	21679826
TM021	1.420783	52894	3.724×10^{-5}	1.9697
TM022	1.514722	61113	94	5718466
TM030	1.617131	73132	355	25971120
TM031	1.876905	53580	$9,10\times10^{-7}$	0.04868
TM032	1.948799	75495	11	839384
TM040	2.092726	58366	620	36201862

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Research and Development (2) : Cavity HOM

- Threshold Currents and Dangerous Modes at 500 MeV

Radiation damping time at 500 MeV = 180.4 ms

Modes	Frequency (GHz)	R_{sh}/Q (Ω)	I_{th} (mA)	Mode
TM011	0.946751	5.28×10^{-5}	-	-
TM210	0.991593	1.41×10^{-6}		-
TM020	1.06244	357	3	23
TM021	1.420783	3.724×10^{-5}	-	-
TM022	1.514722	94	8	6
TM030	1.617131	355	5	43
TM031	1.876905	9.10×10^{-7}	-	-
TM032	1.948799	11	88	166
TM040	2.092726	620	2	34

Very low threshold current

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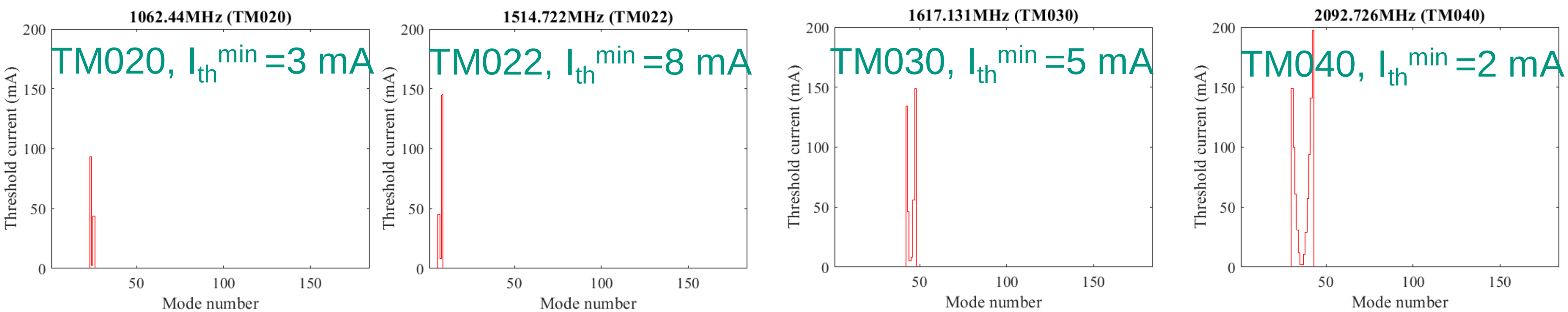
Research and Development (3) : Cavity HOM

Threshold currents for each HOM



- Longitudinal coupled bunch instability at 500 MeV
  - The instabilities happen daily from lower beam current (~ 1 mA) at 500 MeV
  - The instabilities limit the maximum injection current at present KARA
- How to supress
  - Bunch-by-Bunch feedback system is in operation, but difficult to suppress in higher beam current
  - Changing the cavity temperature, synchrotron frequency, horizontal beam orbit at cavity section etc.

Some additional ways to fight against the instabilities would be necesary.

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Research and Development (4) : Phase Modulation

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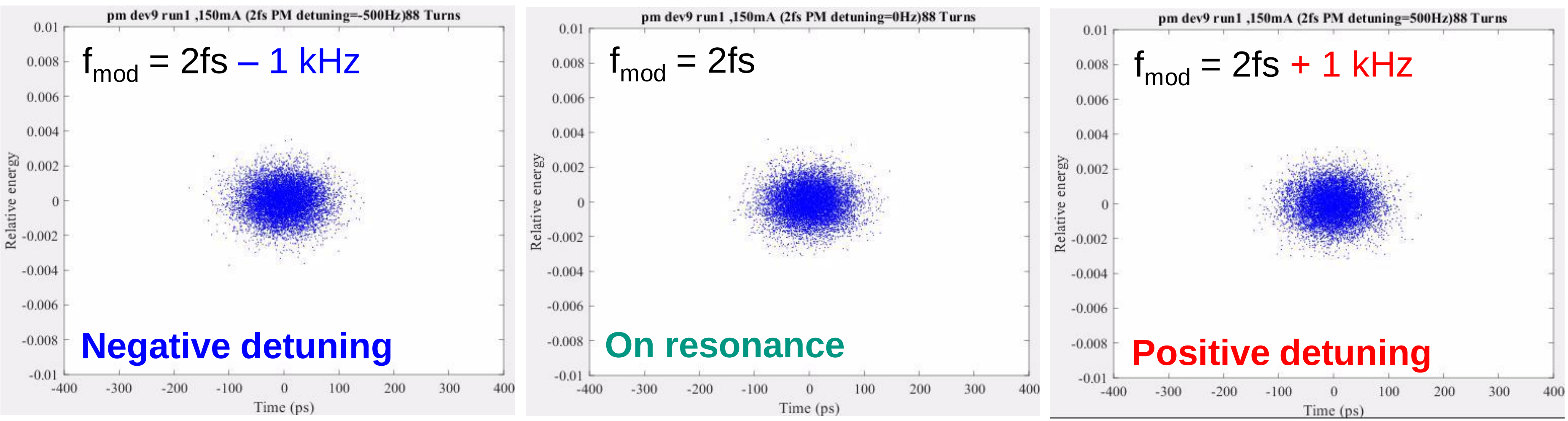
- Beam Manipulation by RF Phase Modulation
  - Tuning knobs: modulation frequency and amplitude
  - Using twice of synchrotron frequency to excite quadrupole mode on the longitudinal phase space

Simulation: amplitude = 100 mrad at 150 mA



- Interests:
  - Characteristics of frequency detuing condition
  - Depencence of bunch length on the excitation amplitude
  - Beam current dependence
  - etc.

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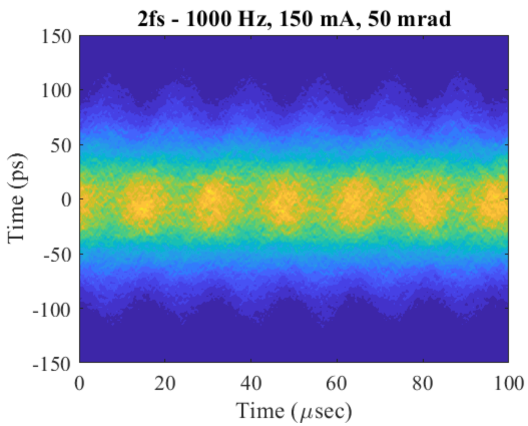
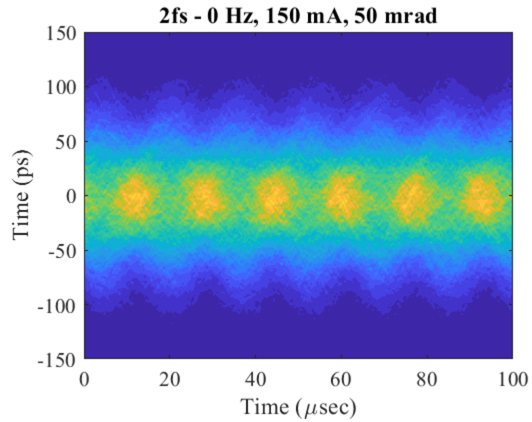
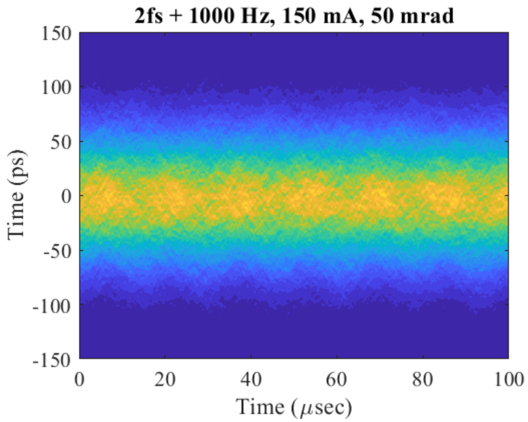
Research and Development (5) : Phase Modulation

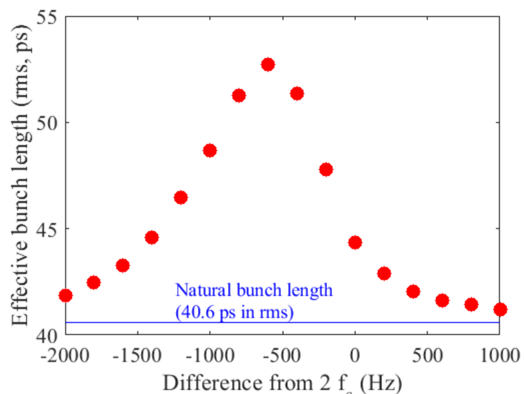
- Systematic Measurement of RF Phase Modulation: Detuning condition

Simulation





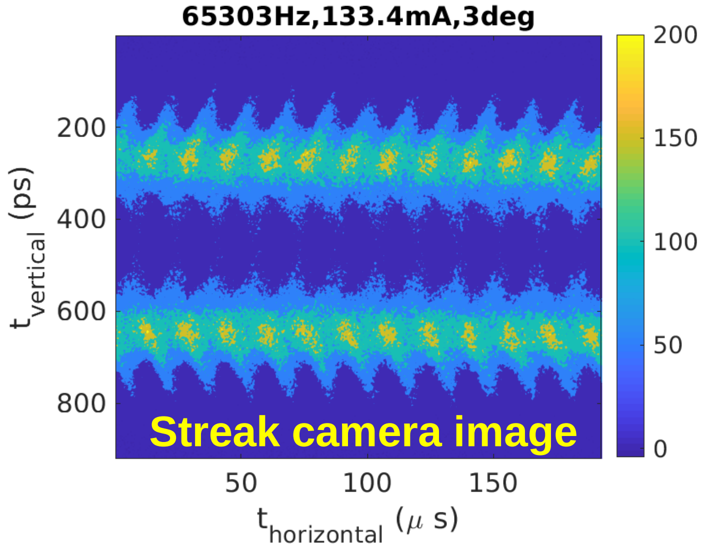


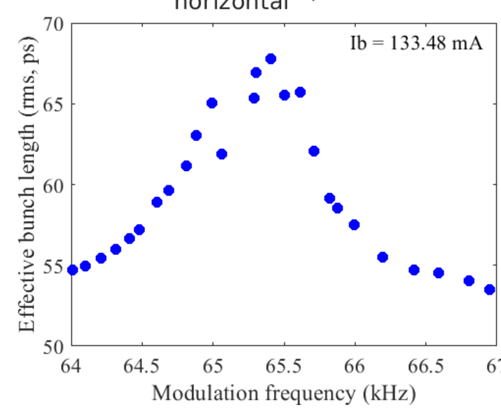


A. Mochihashi et. al., IPAC 2019 Proceedings, p.3123

Detuning curve

Experiment





Detuning curve

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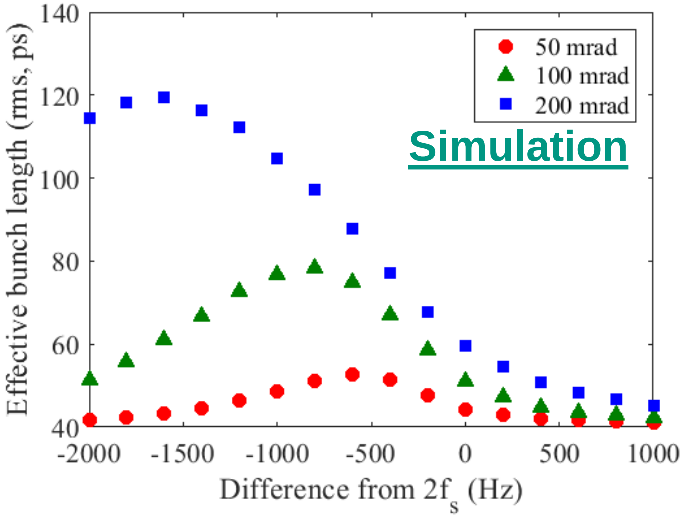
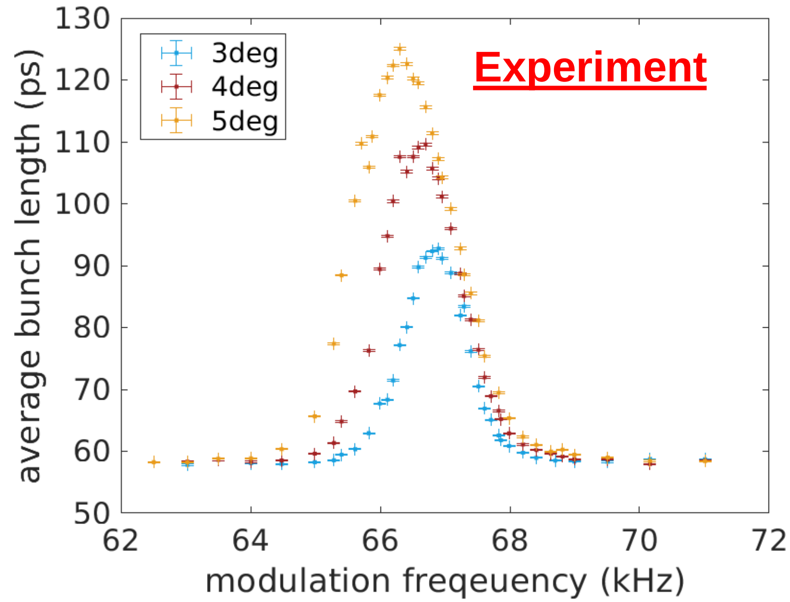
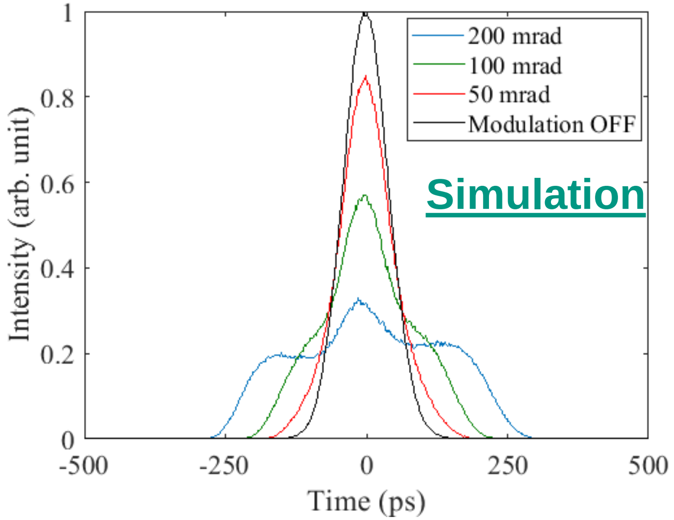
Research and Development (6) : Phase Modulation

- Systematic Measurement of RF Phase Modulation: Amplitude dependence







- Characteristics of bunch lengthening by phase modulation
  - Frequency detuning: slightly asymmetric
  - Amplitude dependence: detuning curves change with different amplitudes

A. Mochihashi et. al., IPAC 2019 Proceedings, p.3123

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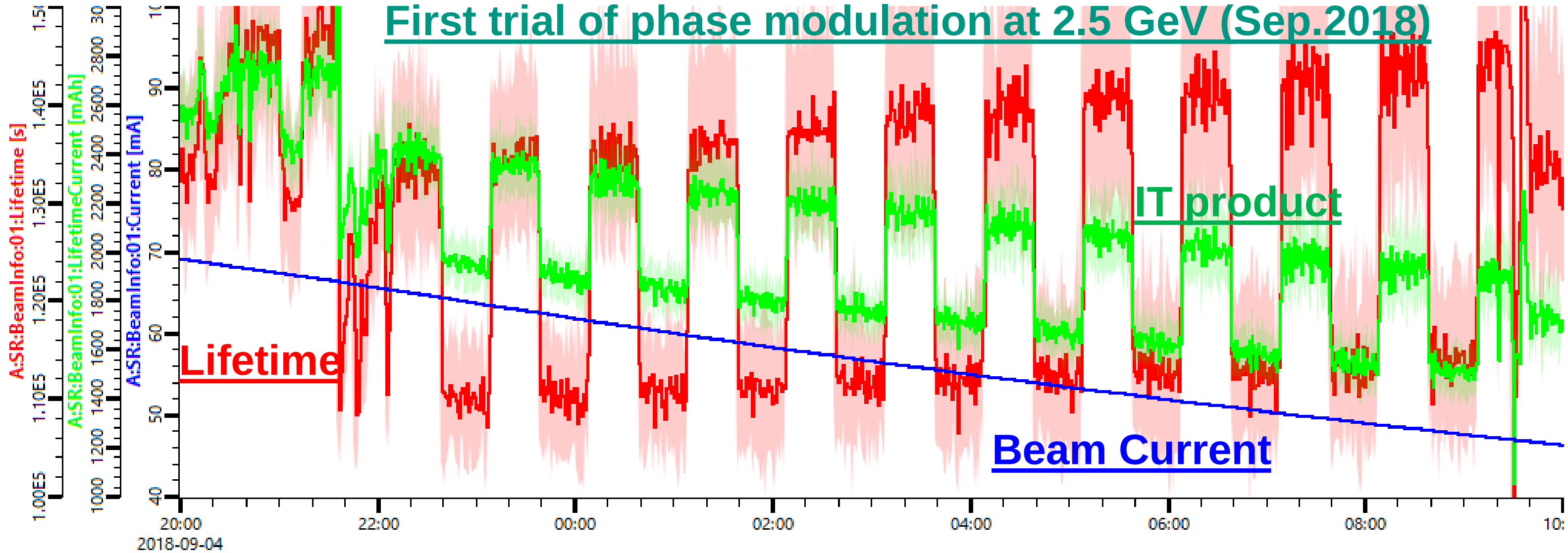
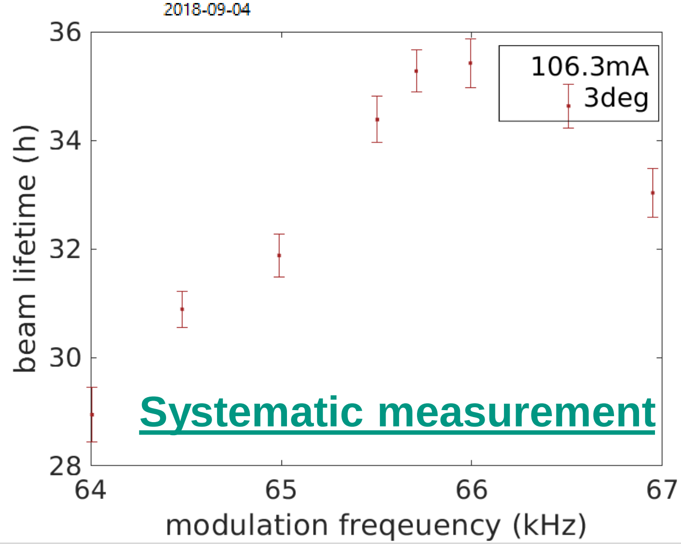
Research and Development (7) : Phase Modulation

- Improvement of beam life time by RF phase modulation





Because KARA is not a top-up machine, the beam lifetime is very essential for its operation.

- Ongoing and to be done:
  - To find an optimized operation method of the phase modulation
  - To check the influence of the modulation on the undulator spectrum
  - etc.

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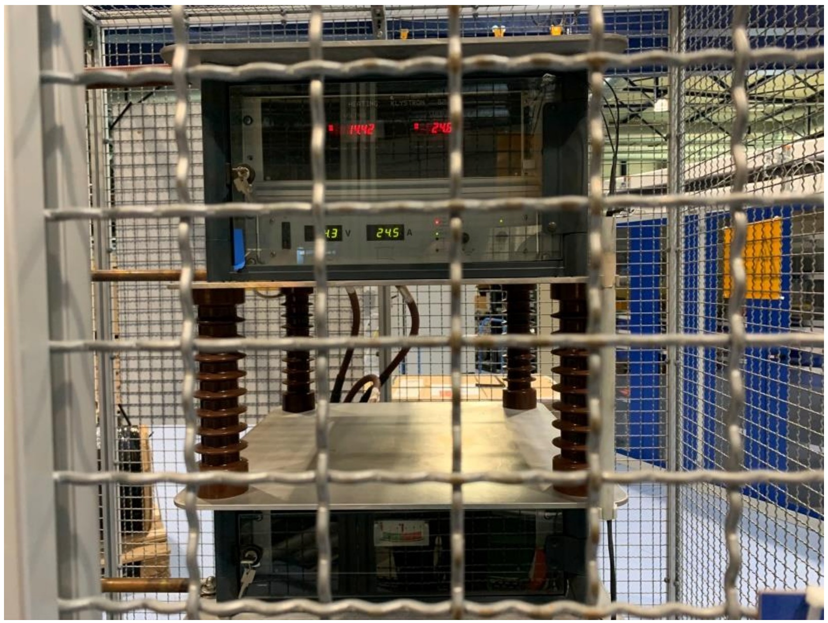
Improvements and Updates (1)

- Renewal of klystron heater power supply
  - The power supply has been renewed when the klystron interlock system has been changed because of its trouble.



Old setup (sector-2) :
Power supply + monitoring device

New setup (sector-4) :
Power supply + PLC

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Improvements and Updates (2)

- Ongoing Project
  - Renewal of master oscillator
    - Lower phase noise and sufficient stability for long term drift
    - The new master oscillator has been already at hand. Integration into the control system is going on now.
  - Renewal of pre-amplifiers
    - (3 GHz, 250 W, pulse) for microtron linac
    - (500 MHz, 50 W, CW) for storage ring
    - The production is going on. The new ones are comming next year.
  - Refurbishment of klystron interlock system
    - From self-made system to PLC system (already done in 1 RF sector)
  - Renewal of temperature compensation system of 500 MHz circulator for storage ring
    - Temperature compensation unit and cabes plan to be renewed in next year.

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Thank you very much for your attention!

Ricky´s Lengthening .....

Lengthening Condition
Not Good...

Lengthening Condition
Very Nice!

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Backup Slides

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Beam Quality: Energy Spread (1) Bending Magnet

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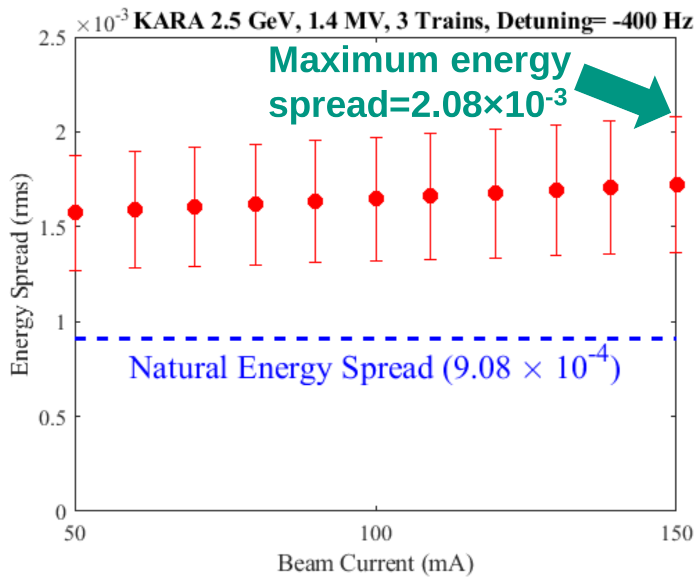

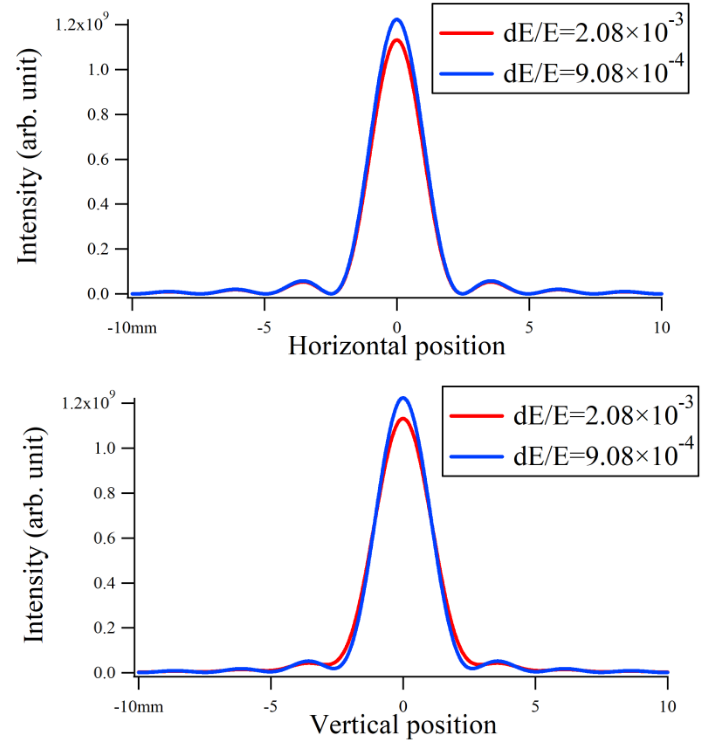

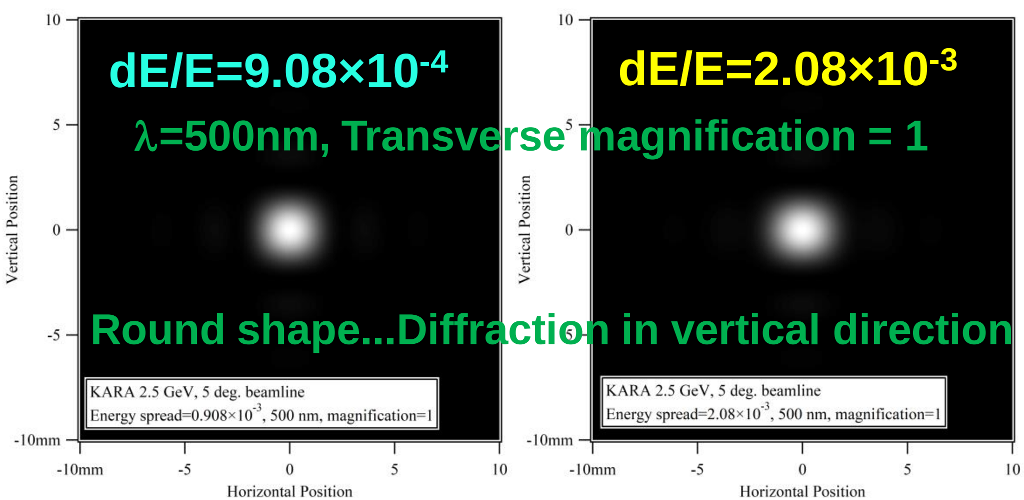

Calculated by SRW

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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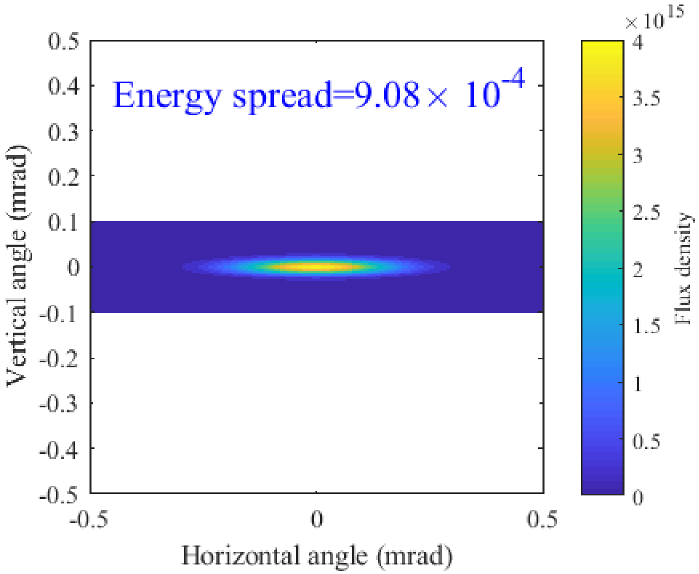
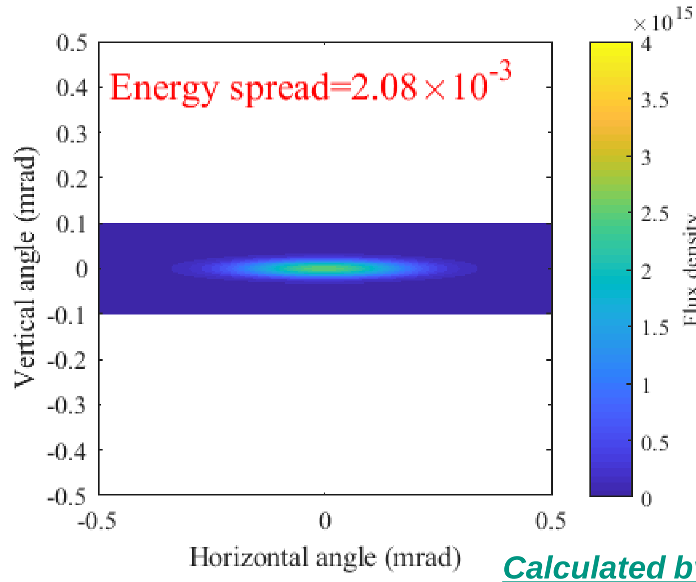
Beam Quality: Energy Spread (2) Undulator

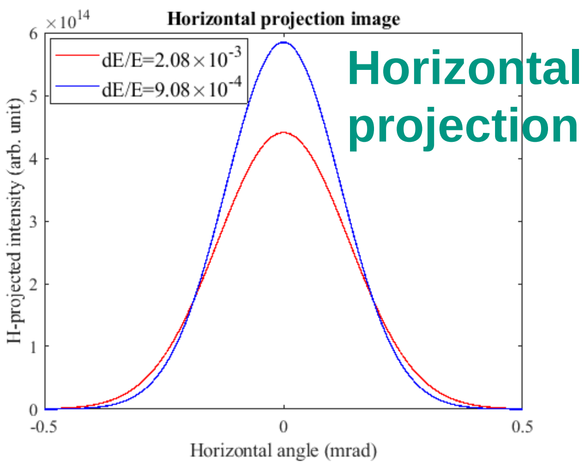
λ_u=20mm, N_p=75, K=0.1, κ_{xy}=0.1%, 1st harmonics=2.96 keV

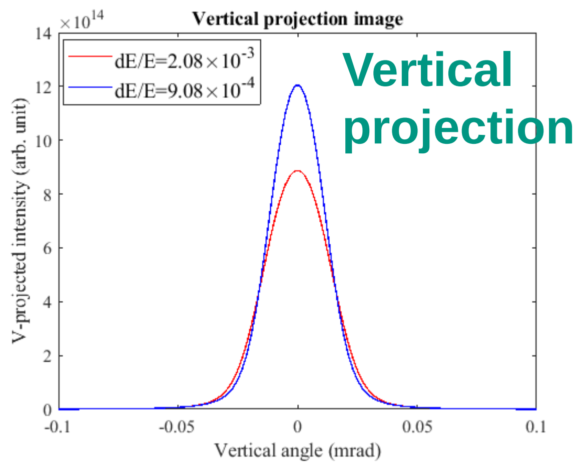




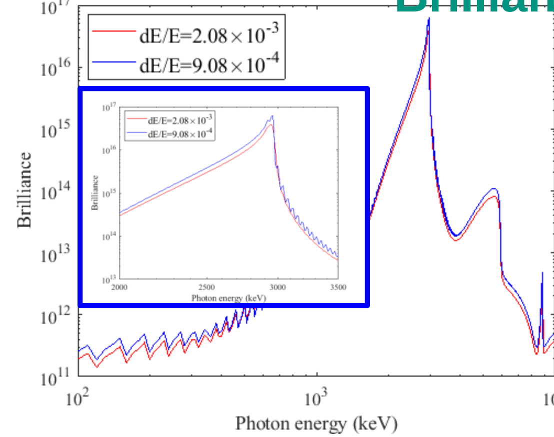
Name	Values
β_x	16.51 m
β_y	1.12 m
η_x	0.35 m
η_x'	0 m
Emittance	59 nm-rad
Coupling	0.1%

Calculated by SPECTRA





Brilliance



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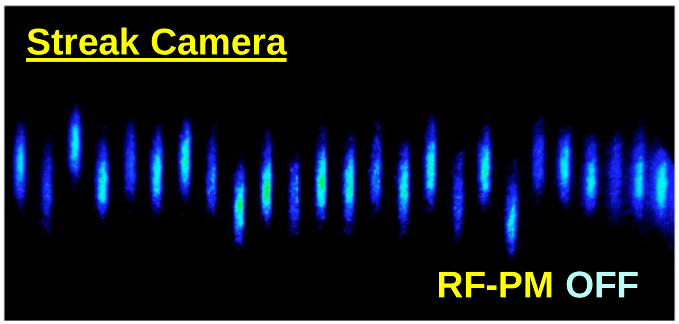
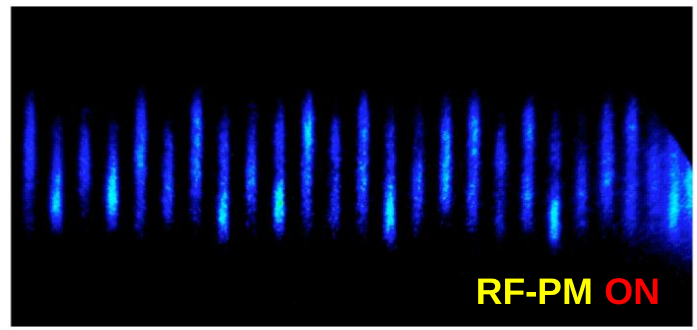
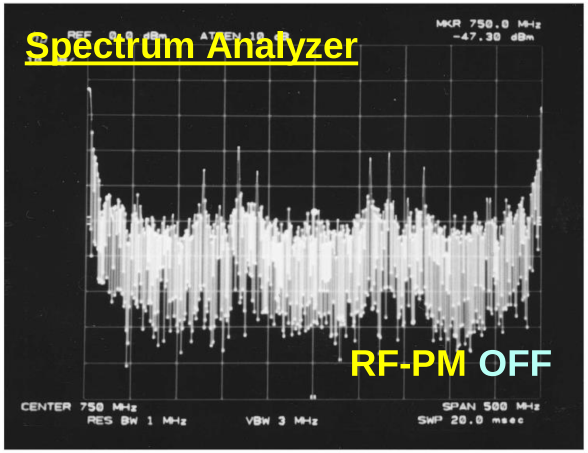
RF Phase Modulation: Preceding Study

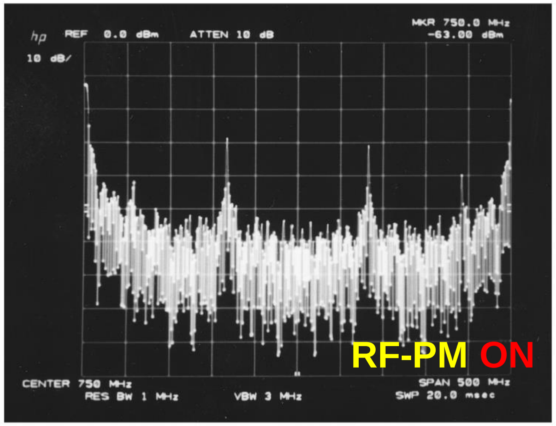
- Can excite longitudinal quadrupole mode oscillation
- Can increase the bunch length (and energy spread)
- Can change (modulate) behavior of the longitudinal coupled bunch instability

Example in KEK (in Japan) Photon Factory (2.5 GeV)









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

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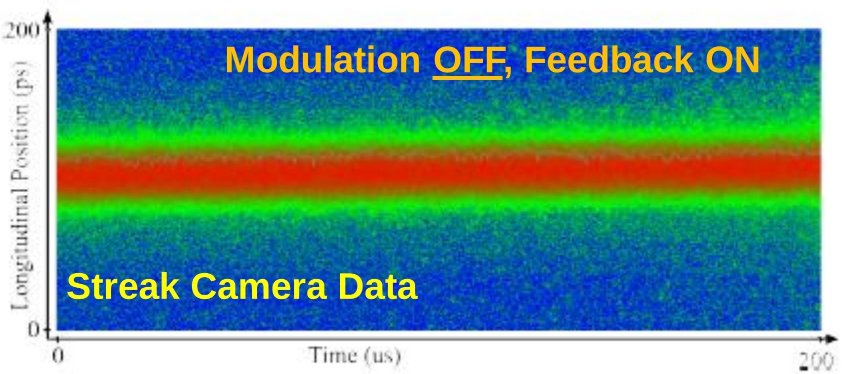
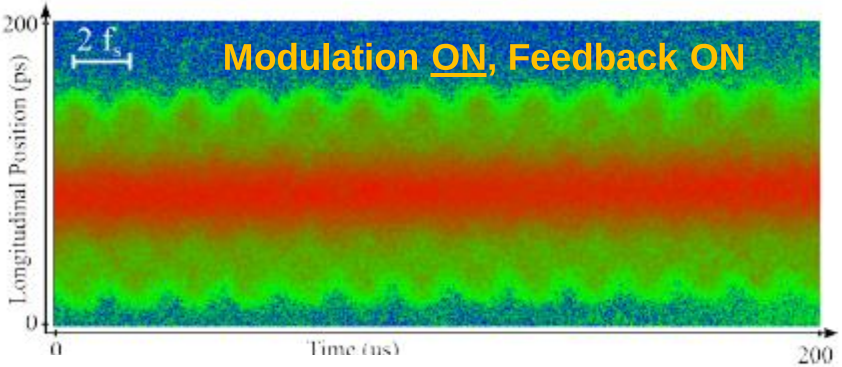
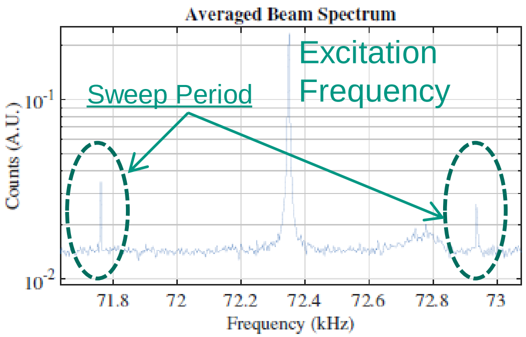
RF System in KARA Storage Ring: Operation(1)

- 2 Longitudinal Modulation Schemes
  - Modulation by Kicker Cavity
  - Phase Modulation by Main Cavities

- At the beam injection **(500MeV),** the kicker cavity is driven to excite quadrupole mode on the beam.
- The bunch lengthening occurs and the injection rate tends to be stabilized/improved.







Additional simulation would be necessary.

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

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Phase Modulation & Beam – Cavity Interaction

- 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:

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

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

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

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

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

- 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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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

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

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

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

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

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

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

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Karlsruhe Institute of Technology

RF System in KARA Storage Ring

- Low Level RF System (19inch,1-rack)
  - Based on DIMTEL LLRF System
  - (Klystron, Cavity tuner) control
- Klystron, Circulator and Waveguides
  - 250kW Klystron (EEV), 1Klystron/Station
  - Circulator (AFT), Magic-T ... Split into 2 ports

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