Experience with RF systems at DELTA

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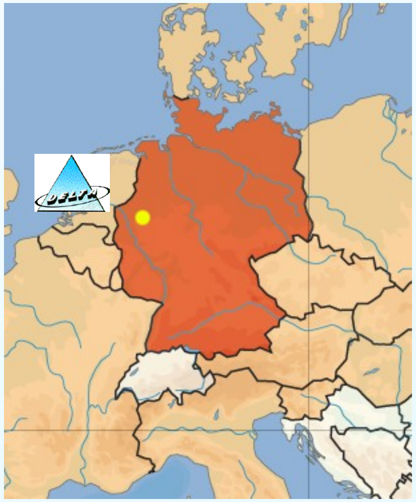
DELTA, TU Dortmund



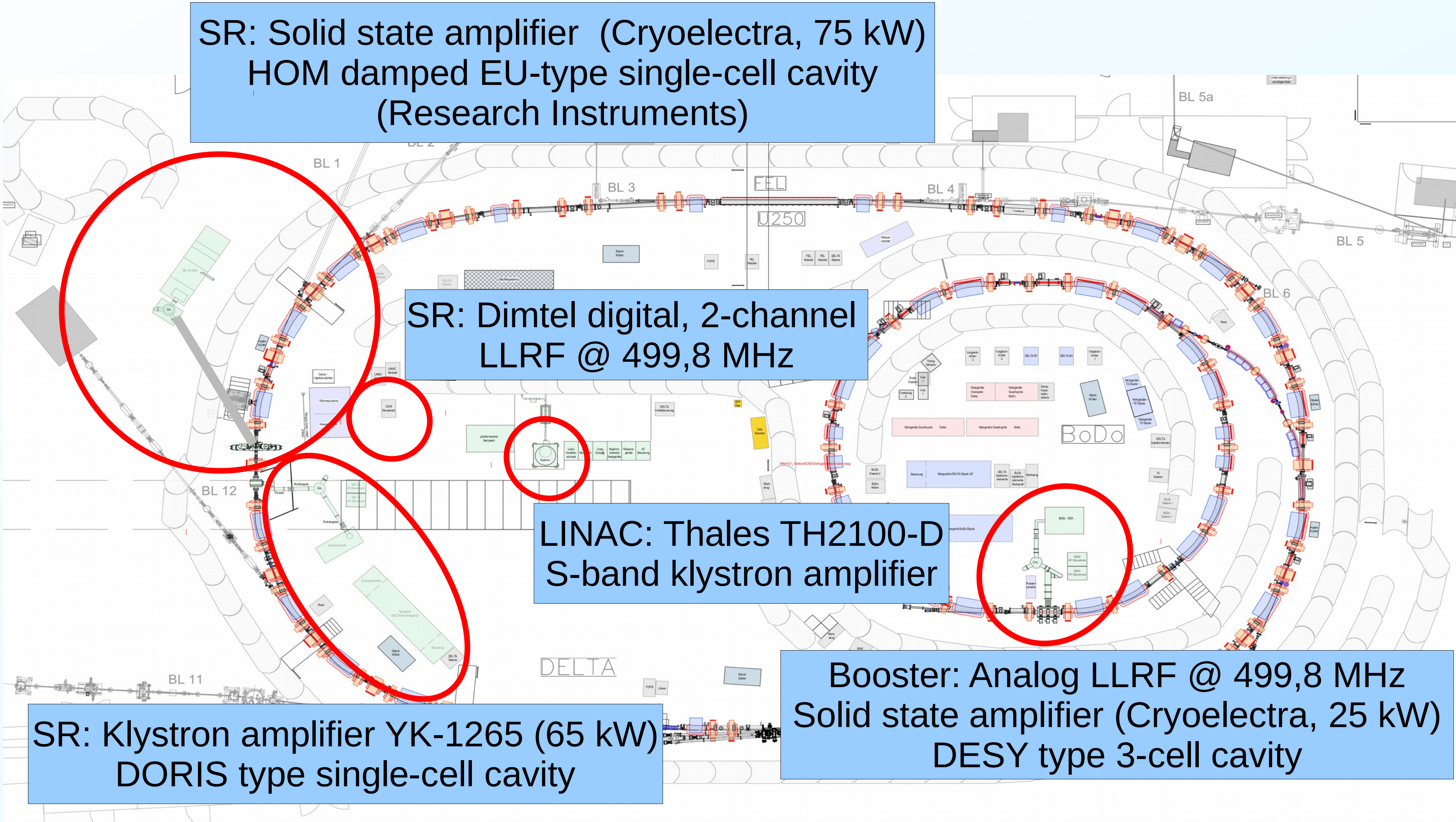
DELTA parameters:

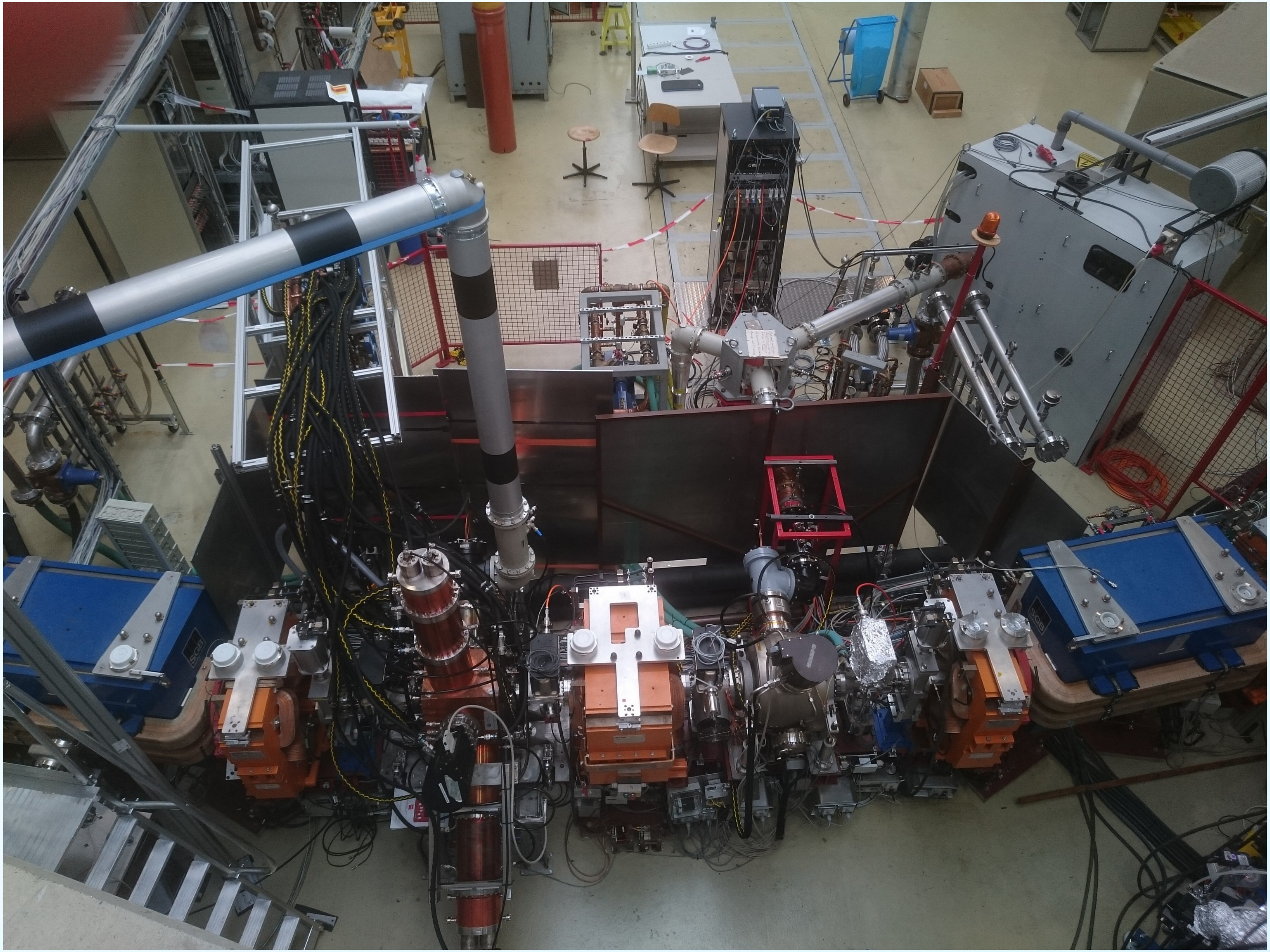
Beam energy: 550 MeV – 1.5 GeV
Beam current: 130mA @ 1.5GeV
Beam lifetime: 16h @ 130 mA
Availability: 95 %
Operational: 3000 h / year

RF Group:

P. Hartmann
V. Kniss
A. Leinweber

DELTA's RF systems





Work done on RF systems:

03/2021: LINAC S-Band Klystron replaced

03/2021: Defective module in Booster-SSA after power outage

08/2020: DELTA phase modulation scheme transferred to LLRF

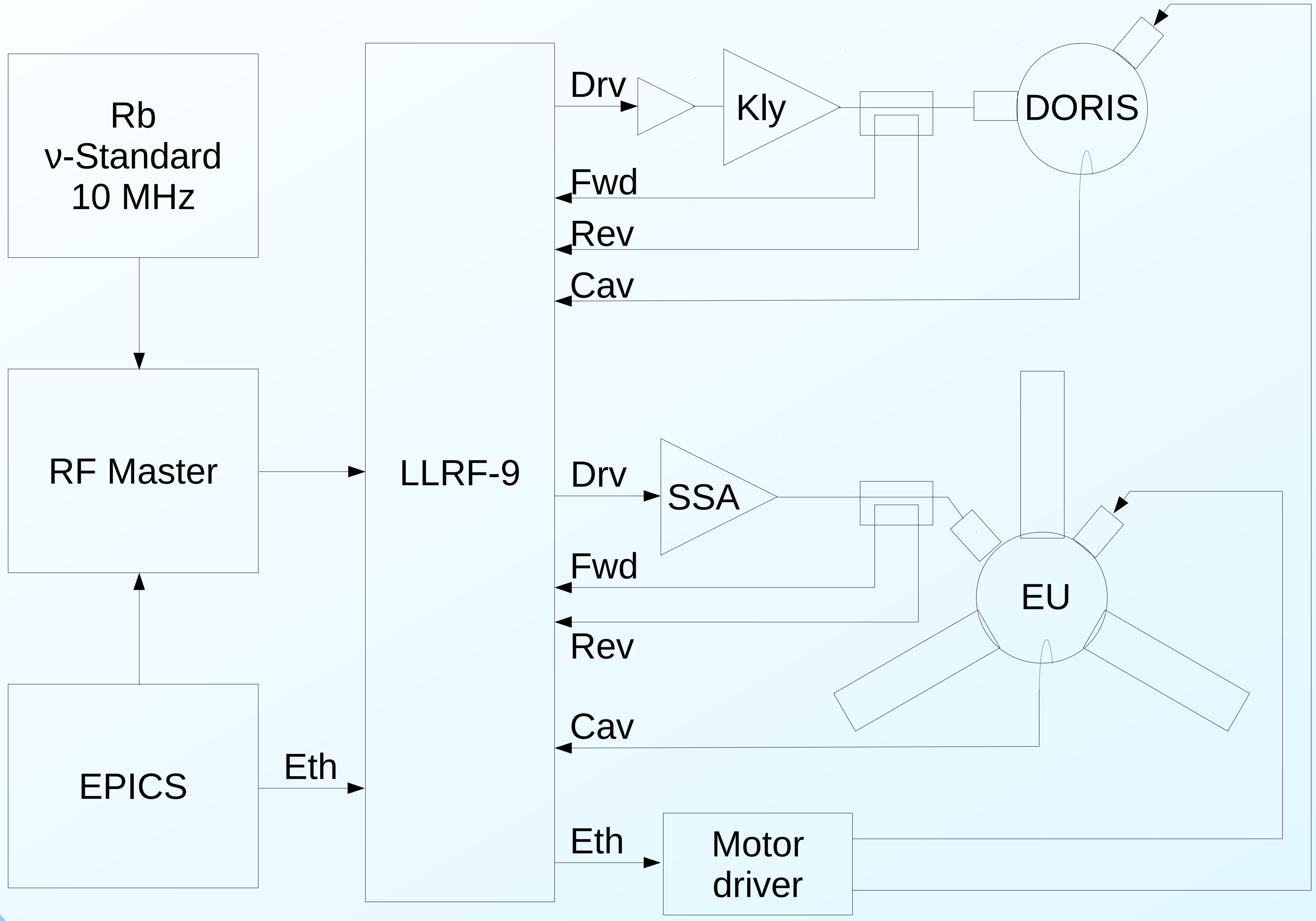
02/2020: RF GUI: Cavity phasing changed

10/2019: SR: RF Interlock scheme changed due to insufficient damping of LLRF internal PIN Diode for rad. prot. purpose

08/2019: Booster SSA: Broken PLC changed

Storage Ring LLRF calibration

Storage Ring RF



LLRF calibration check with beam

Synchrotron frequency: $f_S = f_{rev}\sqrt{\frac{\alpha h}{2\pi}\frac{e U_C}{E}\sin(\phi_S)}$, $\sin(\phi_S) = \sqrt{1-\left(\frac{U_{rev}}{U_C}\right)^2}$

$$U_C = \sqrt{\underbrace{\left(\frac{2\pi E}{f_{rev}^2 \alpha h e}\right)^2}_{k} f_S^4 + U_{rev}^2}$$

Reference parameters:

$(E = 1492\,\text{MeV}, \alpha = 0.0050)$

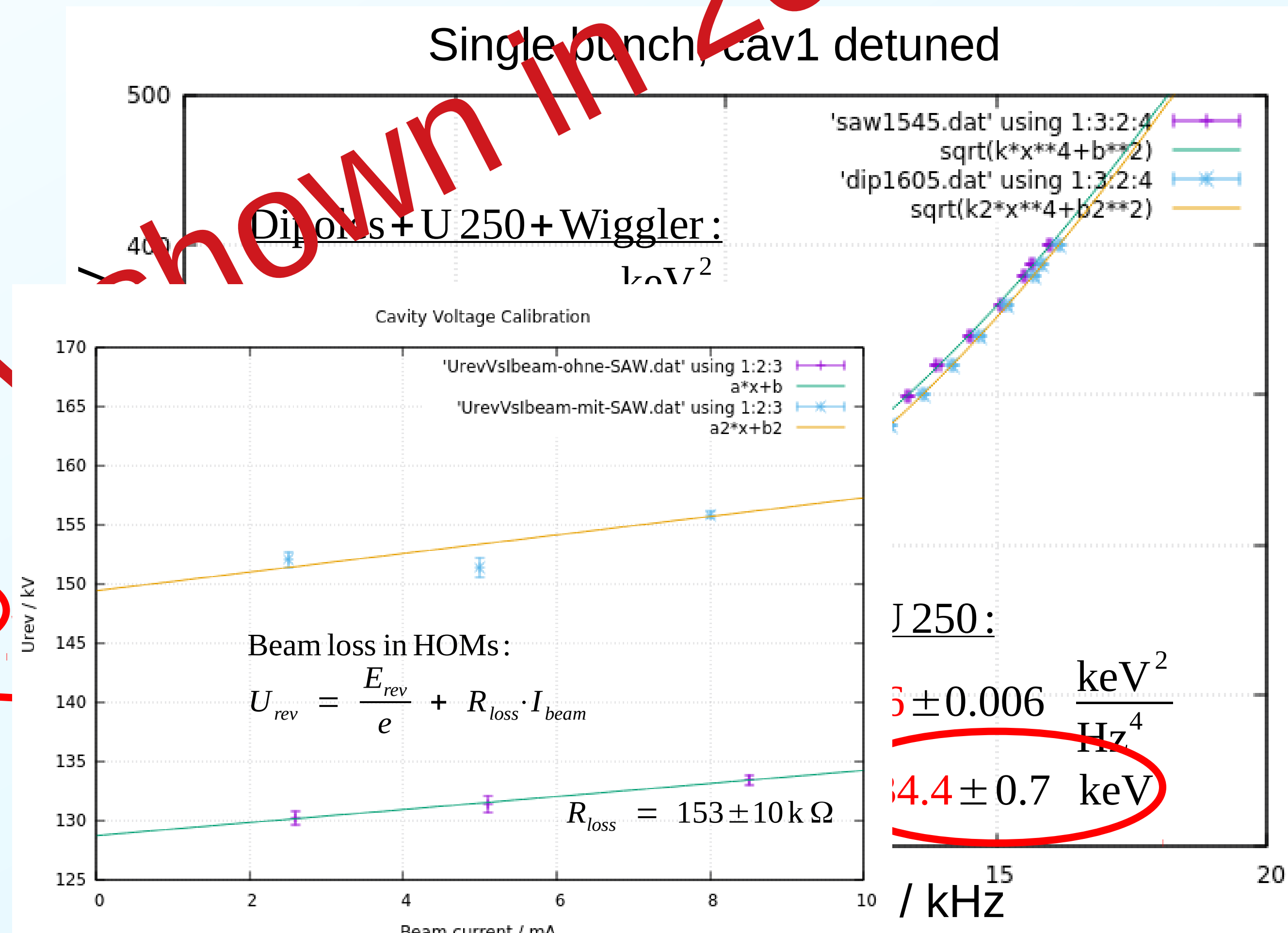
$\rightarrow k^{calc} = 2.076 \ \frac{\text{keV}^2}{\text{Hz}^4}$

Calculated and from Simulation:

$U_{rev}^{Dipoles+U250+Wiggler} = 150 \ \text{keV}$

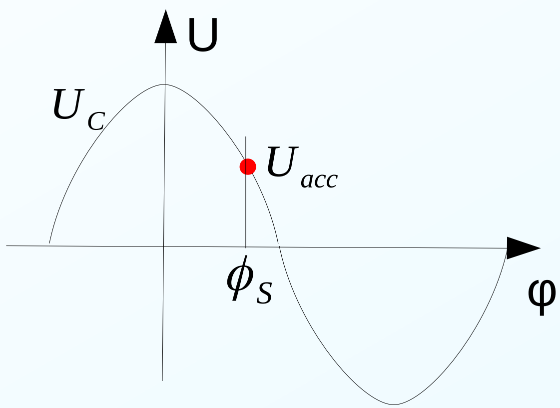
$U_{rev}^{Dipoles+U250} = 128 \ \text{keV}$

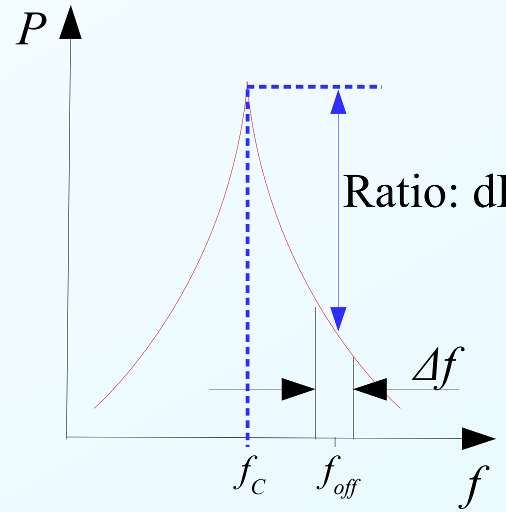
Already shown in 2019



Phase Noise

Phase Noise

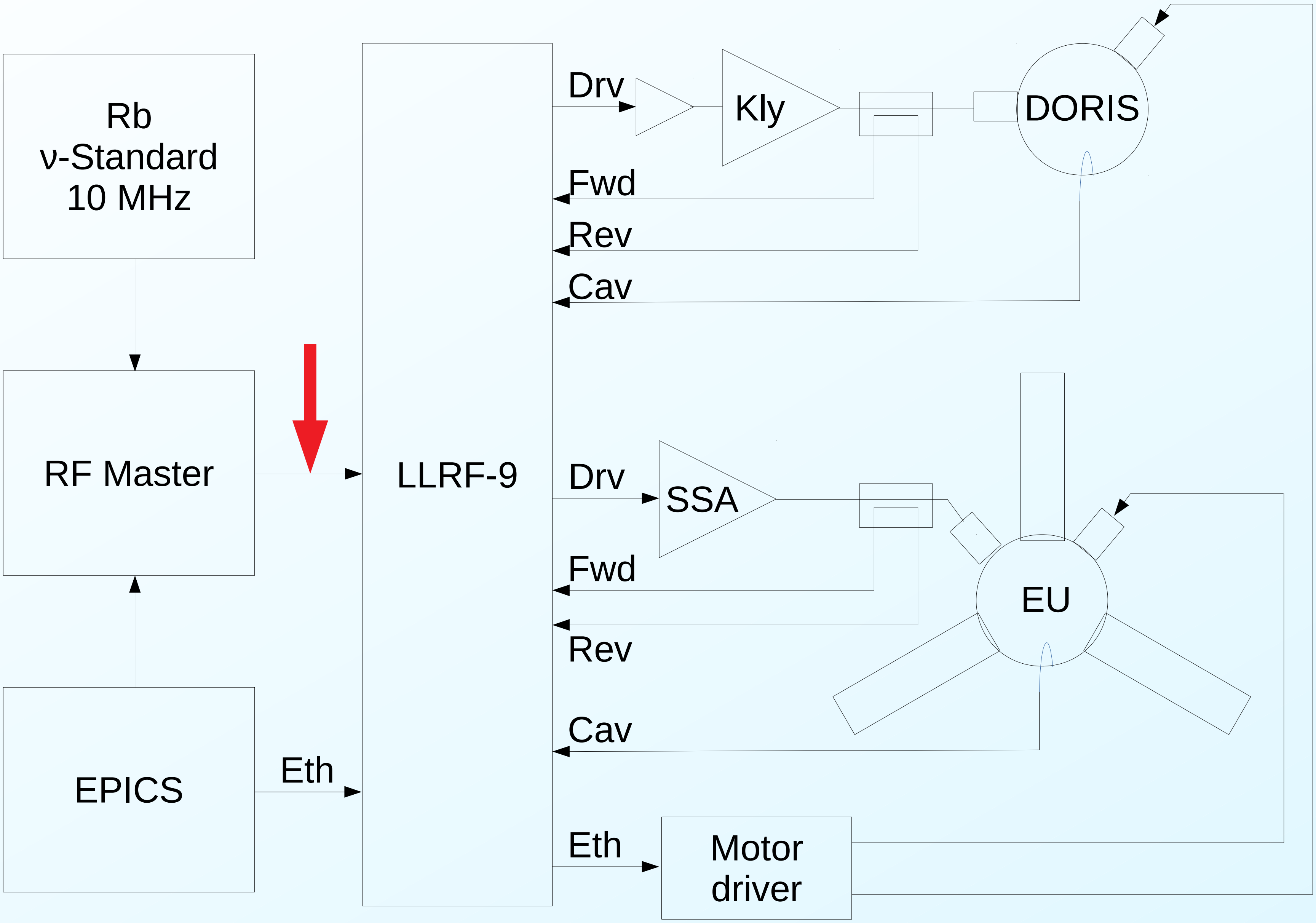




Noise power density: $$\mathscr{L}(f) = \frac{\text{Power density}}{\text{Carrier power}}\left[\frac{dBc}{Hz}\right] = \frac{1}{2}S_\phi(f)$$

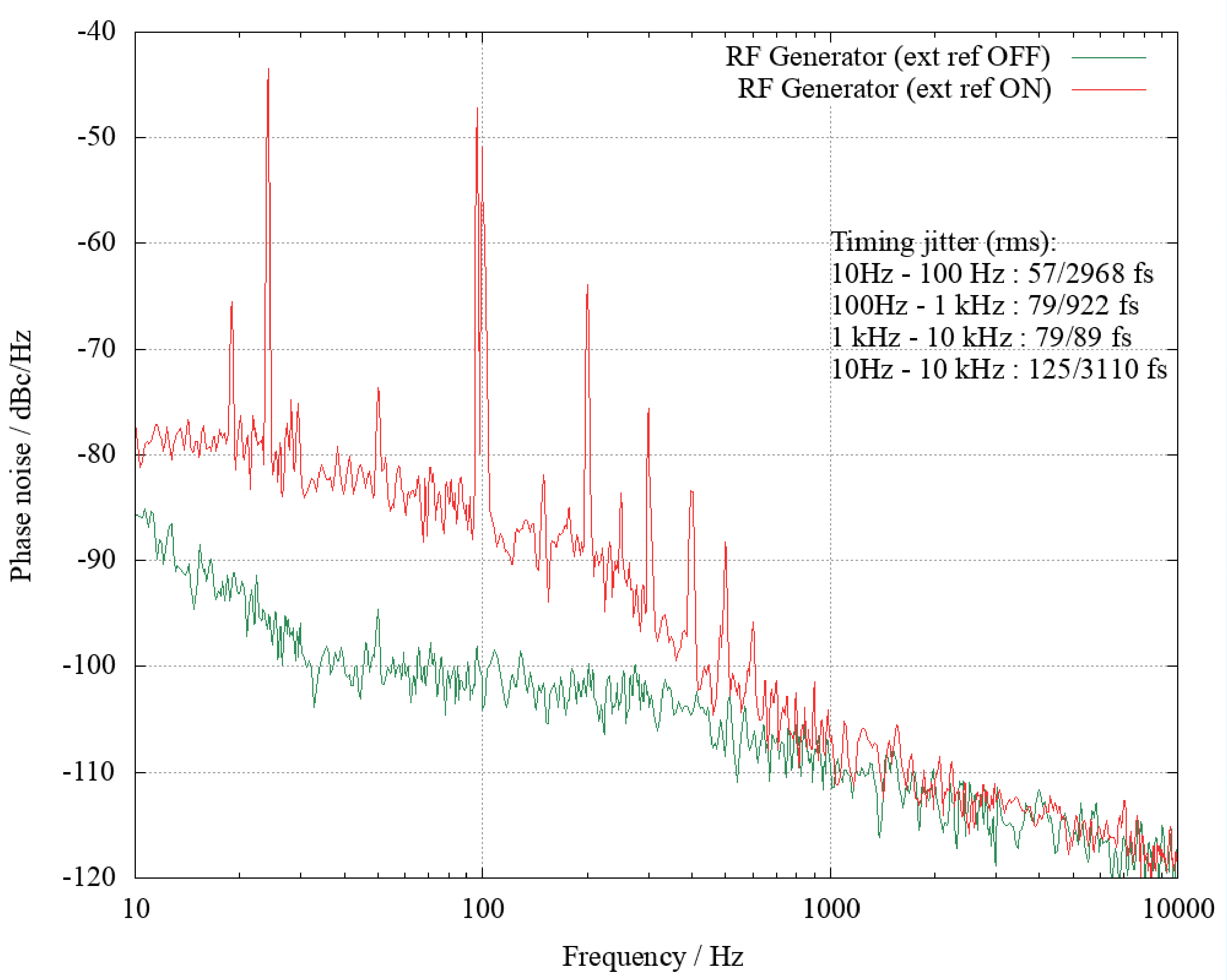
Timing Jitter: $$\sigma_t = \frac{1}{2\pi f_C}\sqrt{\int_{f_1}^{f_2} S_\phi(f)\,df}$$

Storage Ring RF

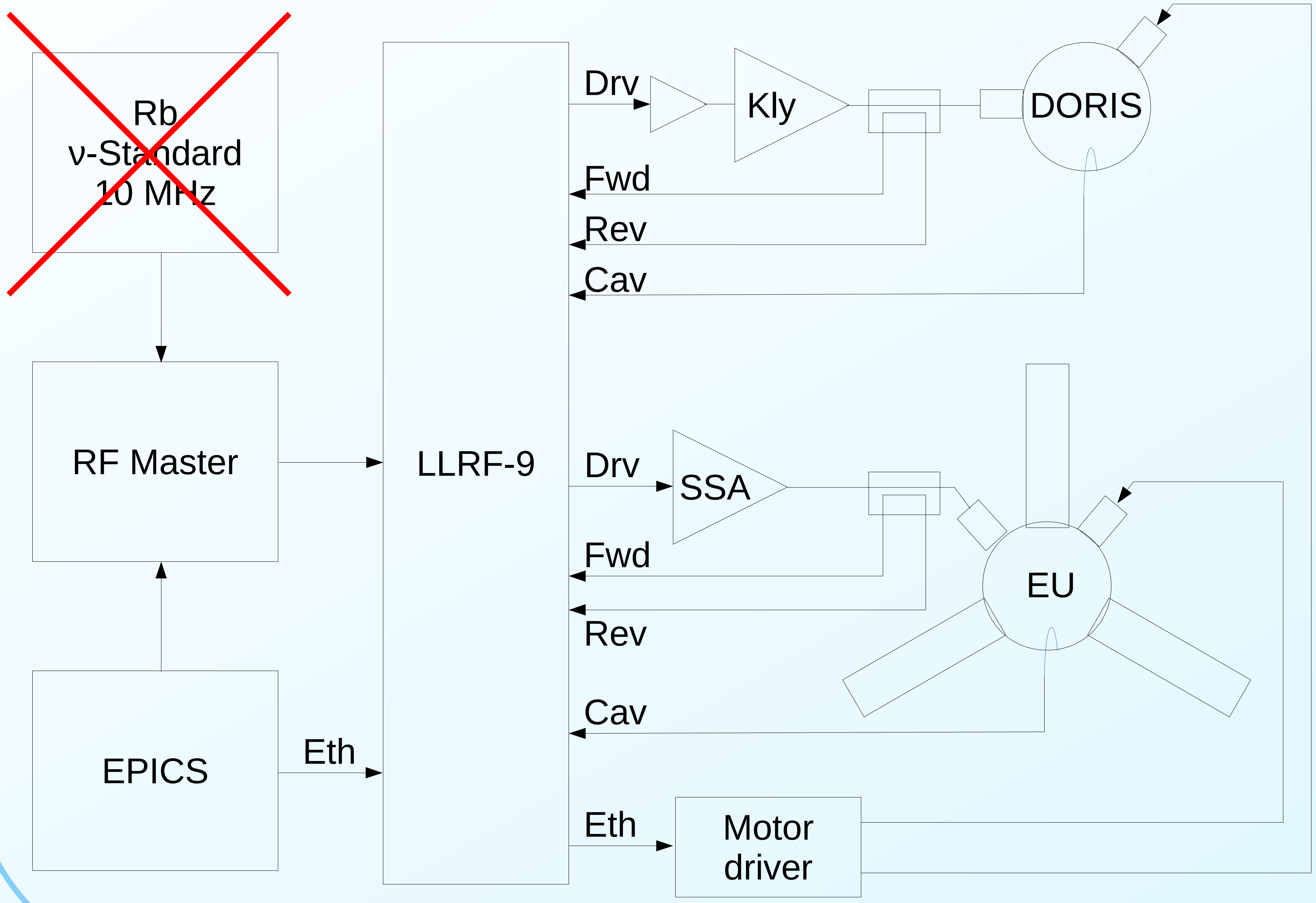


Phase Noise

(Analyzer and Master generator)

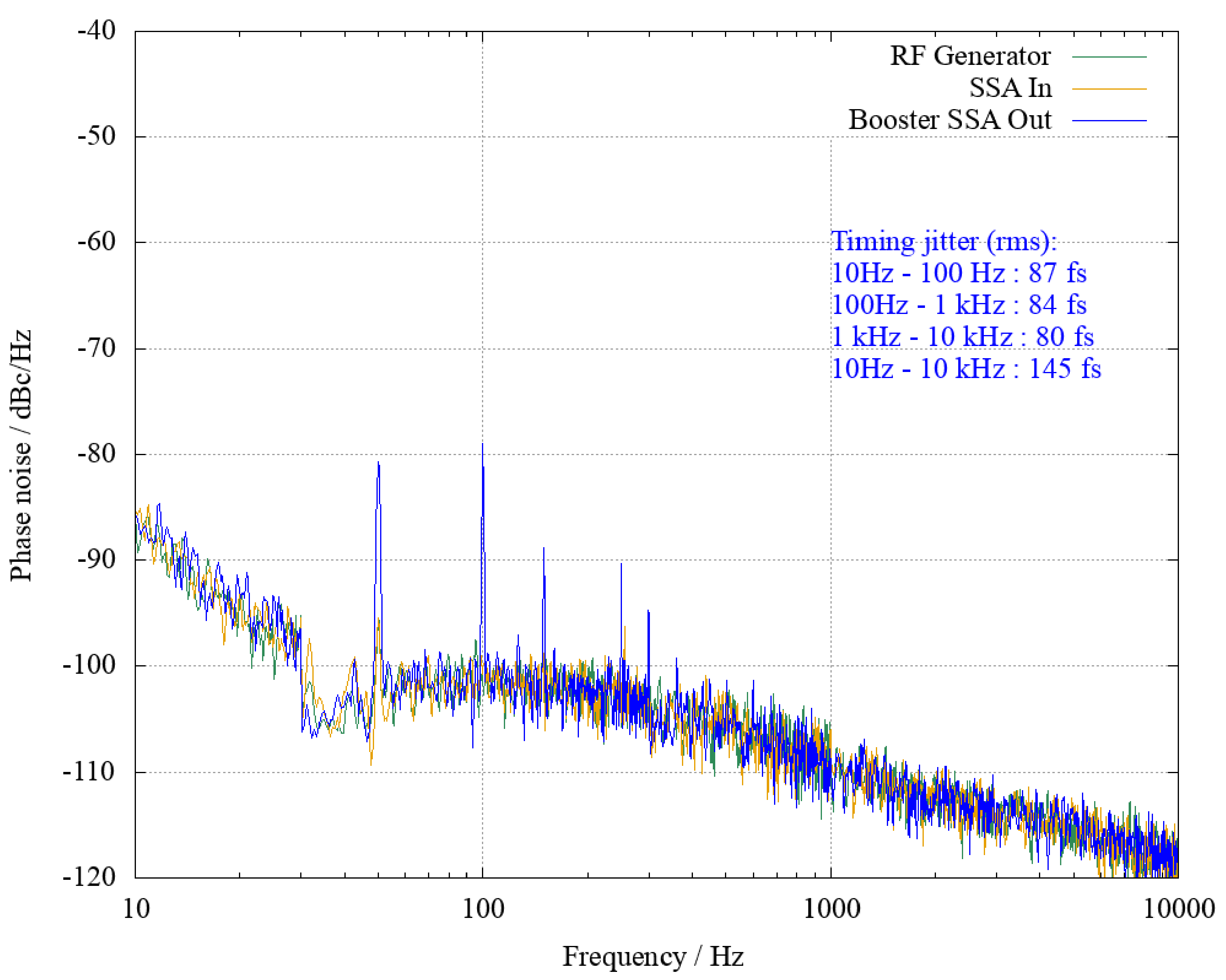


Storage Ring RF

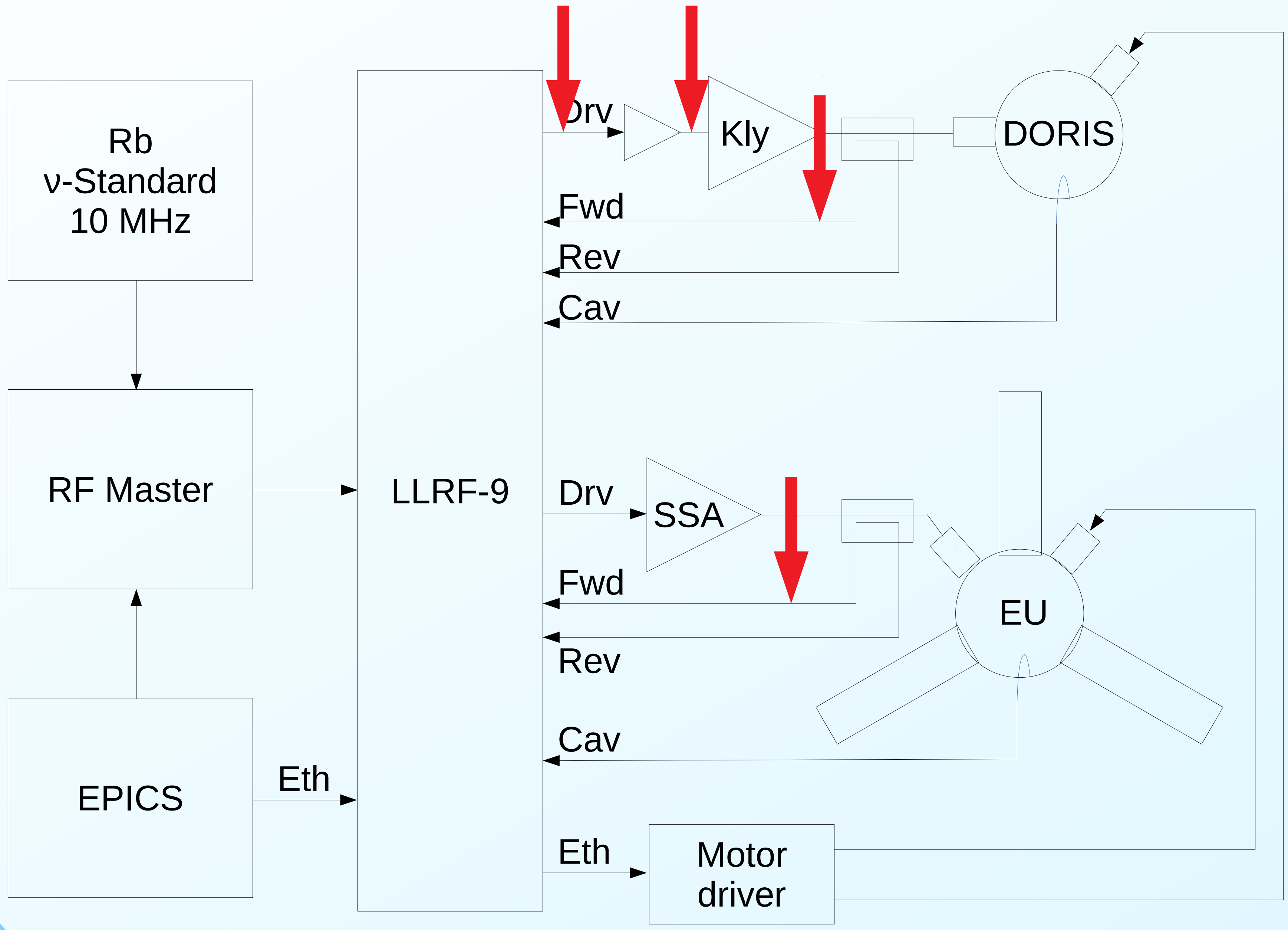


Phase Noise

(Booster)

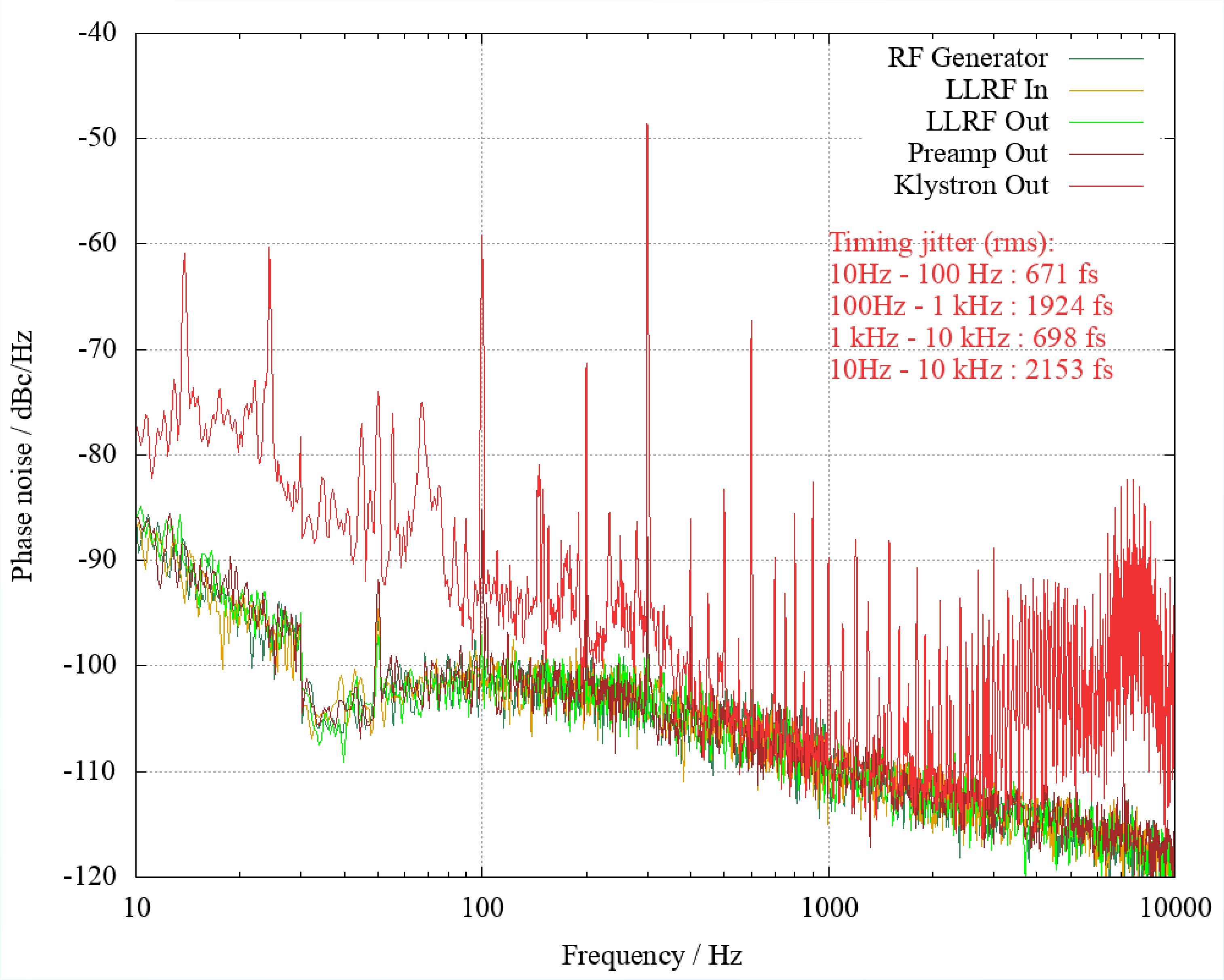


Storage Ring RF



Phase Noise

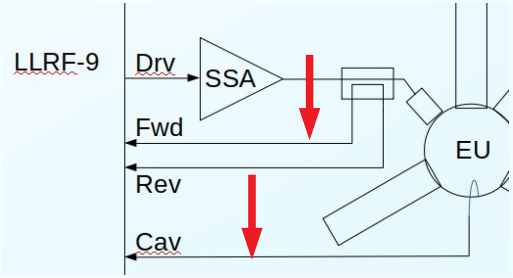
(Storage Ring)



Cavity Shunt Impedance

Measure Shunt Impedance

Method 1: Measure cavity voltage and fwd power



$$R_S = \frac{U_{cav}^2}{2\,P_{fwd}}$$

U_{NRVS} / V	U_{cav} / kV	P_{fwd} / kW	R_S / MΩ
1,937	307,0	11,91	3,96
2,259	358,0	16,25	3,94
2,517	398,9	20,25	3,93
1,614	255,8	8,25	3,97
1,291	204,6	5,27	3,97

$$R_S = 3.954 \pm 0.034\,\mathrm{M\Omega}$$

Cavity Shunt Impedance

Beam based measurements

Cavity impedance without beam loading

$$Z_C(\omega_r+\Delta\omega) = \frac{R_S}{1 + iQ\left(\frac{\omega_r+\Delta\omega}{\omega_r} - \frac{\omega_r}{\omega_r+\Delta\omega}\right)}$$

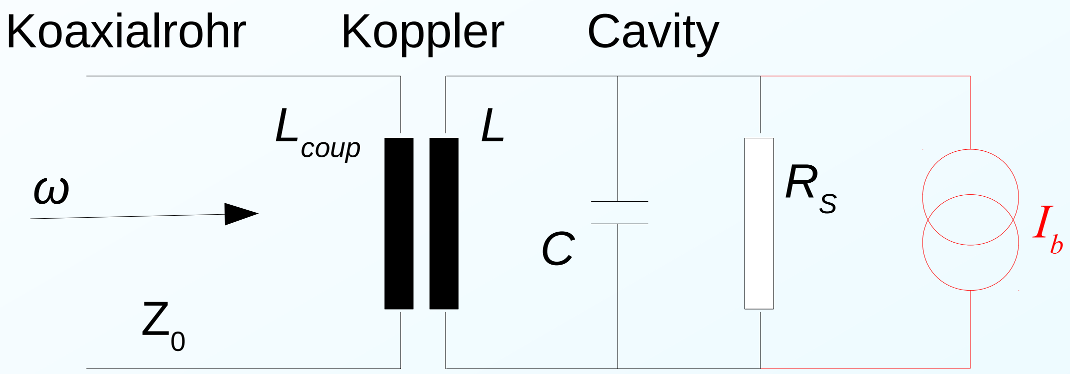
$$\overset{\Delta\omega\ll\omega_r}{=} \frac{R_S}{1 + iQ\left(\frac{2\Delta\omega}{\omega_r}\right)}$$

$$= \frac{R_S}{1+Q^2\left(\frac{2\Delta\omega}{\omega_r}\right)^2} - i\,\frac{R_S Q\left(\frac{2\Delta\omega}{\omega_r}\right)}{1+Q^2\left(\frac{2\Delta\omega}{\omega_r}\right)^2}$$

→ Cavity phase: $\tan(\phi_C(\omega_r+\Delta\omega)) = \frac{\Im(Z_C)}{\Re(Z_C)}$

$$= -Q\cdot\frac{2\Delta\omega}{\omega_r}$$

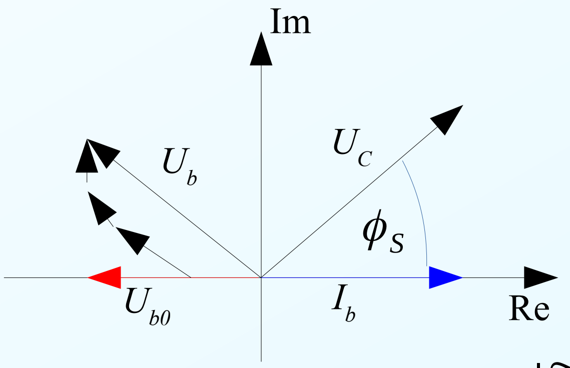
Beam loaded cavity impedance



$$Z_C = \frac{R_S}{1 + i\,Q_0\,\xi}$$

$$\beta = \frac{R_S}{Z_0} \cdot \frac{L_{coup}}{L}$$

$$Z = \frac{L_{coup}}{L}\left(Z_C \parallel \frac{\tilde{U}_C}{\tilde{I}_b}\right) = \frac{\beta Z_0}{R_S}\,\frac{1}{\frac{1}{Z_C} + \frac{\tilde{I}_b}{\tilde{U}_C}} = \frac{\beta Z_0}{1 + iQ_0\,\xi + R_S\frac{\tilde{I}_b}{\tilde{U}_C}}$$



$$\tilde{U}_C \propto \tilde{I}_b e^{i\,\phi_S} \Rightarrow R_S\frac{\tilde{I}_b}{\tilde{U}_C} = R_S\frac{|\tilde{I}_b|}{|\tilde{U}_C|}\cdot e^{-i\,\phi_S}$$

$|\tilde{I}_b|$: Leading fourier component $2I_{DC}$ of the base frequency ω,
Generated by an infinite row of short bunches with a temporal
Distance of $T_b = 2\pi/\omega$.

Beam Loaded cavity impedance

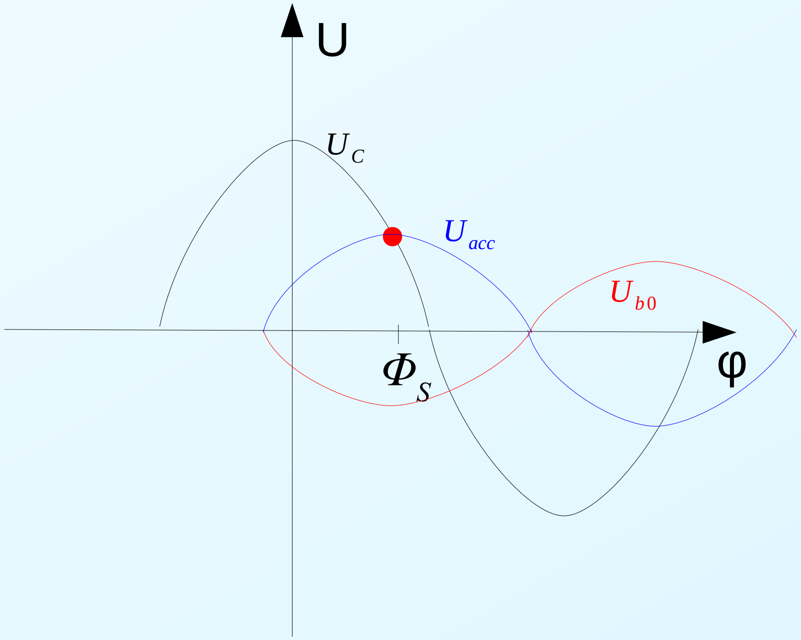
$$Z = \frac{\beta Z_0}{1 + iQ_0\xi + R_S \frac{\widetilde{I}_b}{\widetilde{U}_C}} = \frac{\beta Z_0}{1 + iQ_0\xi + \frac{2 I_{DC} R_S}{U_C} e^{-i\phi_S}}$$

$$Z = \frac{\beta Z_0}{1 + \frac{2 I_{DC} R_S}{U_C}\cos(\phi_S) + i\left(Q_0\xi - \frac{2 I_{DC} R_S}{U_C}\sin(\phi_S)\right)}$$

In case of match ($Z = Z_0$):

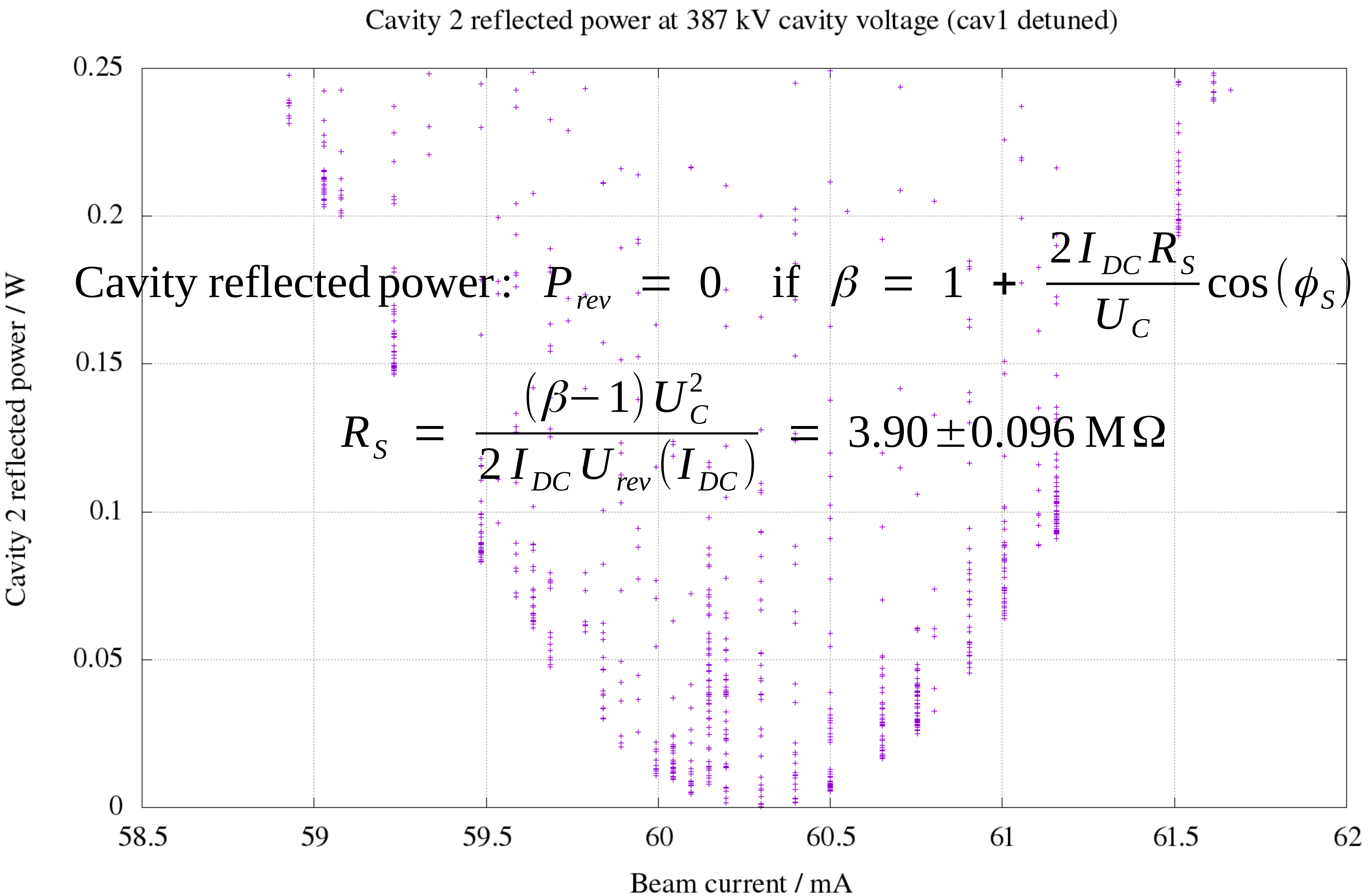
1. $\beta = 1 + \frac{2 I_{DC} R_S}{U_C}\cos(\phi_S)$

2. $0 = Q_0\xi - \frac{2 I_{DC} R_S}{U_C}\sin(\phi_S)$



Measure Shunt Impedance

(Method 2: Use real part of Z)

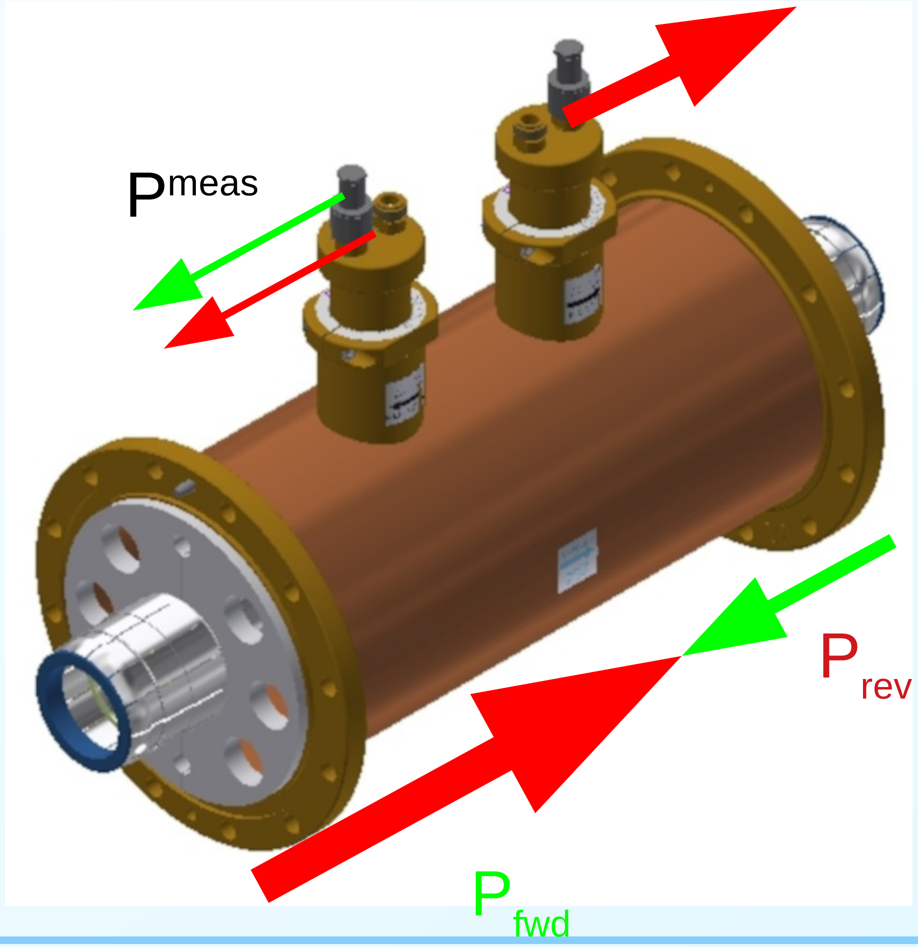


Cavity reflected power: $P_{rev} = 0 \quad \text{if} \quad \beta = 1 + \frac{2 I_{DC} R_S}{U_C} \cos(\phi_S)$

$$R_S = \frac{(\beta - 1) U_C^2}{2 I_{DC} U_{rev}(I_{DC})} = 3.90 \pm 0.096 \, \mathrm{M}\Omega$$

The measurement of the minimum reflected power vs. beam current is disputable, because of the limited directivity (typ: -30dB, ours: < -42dB) of the directional coupler used to measure the reflected power:

A large forward power generates a false signal of the order of magnitude of the measured returned power in the reflected power line.



Shunt Impedance
(Method 3: Use imaginary part of Z)

Imaginary part condition: $$0 = Q_0 \xi - \frac{2 I_{DC} R_S}{U_C} \sin(\phi_S)$$

with $$Q_0 \xi \overset{\Delta\omega \ll \omega_r}{=} (1+\beta) Q_L \cdot \frac{2 \Delta\omega}{\omega_r} = -(1+\beta) \tan(\phi_C)$$

$$\text{Cavity detuning angle:} \quad \tan(\phi_C) = -\frac{2 I_{DC} R_S}{(1+\beta) U_C} \sin(\phi_S)$$

Beam current dependent inductance of cavity, compensated by tuner loop.

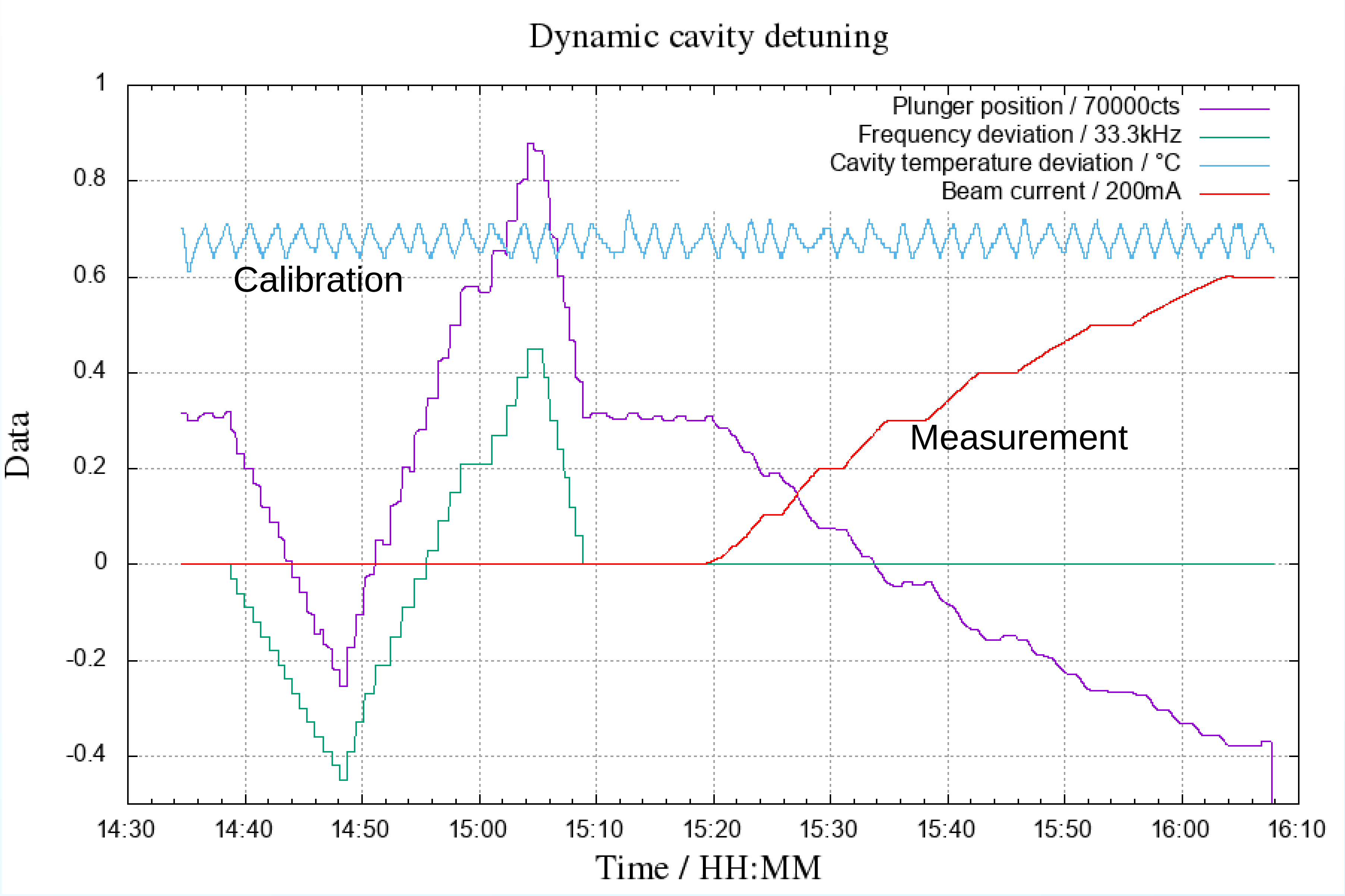
Measurement procedure

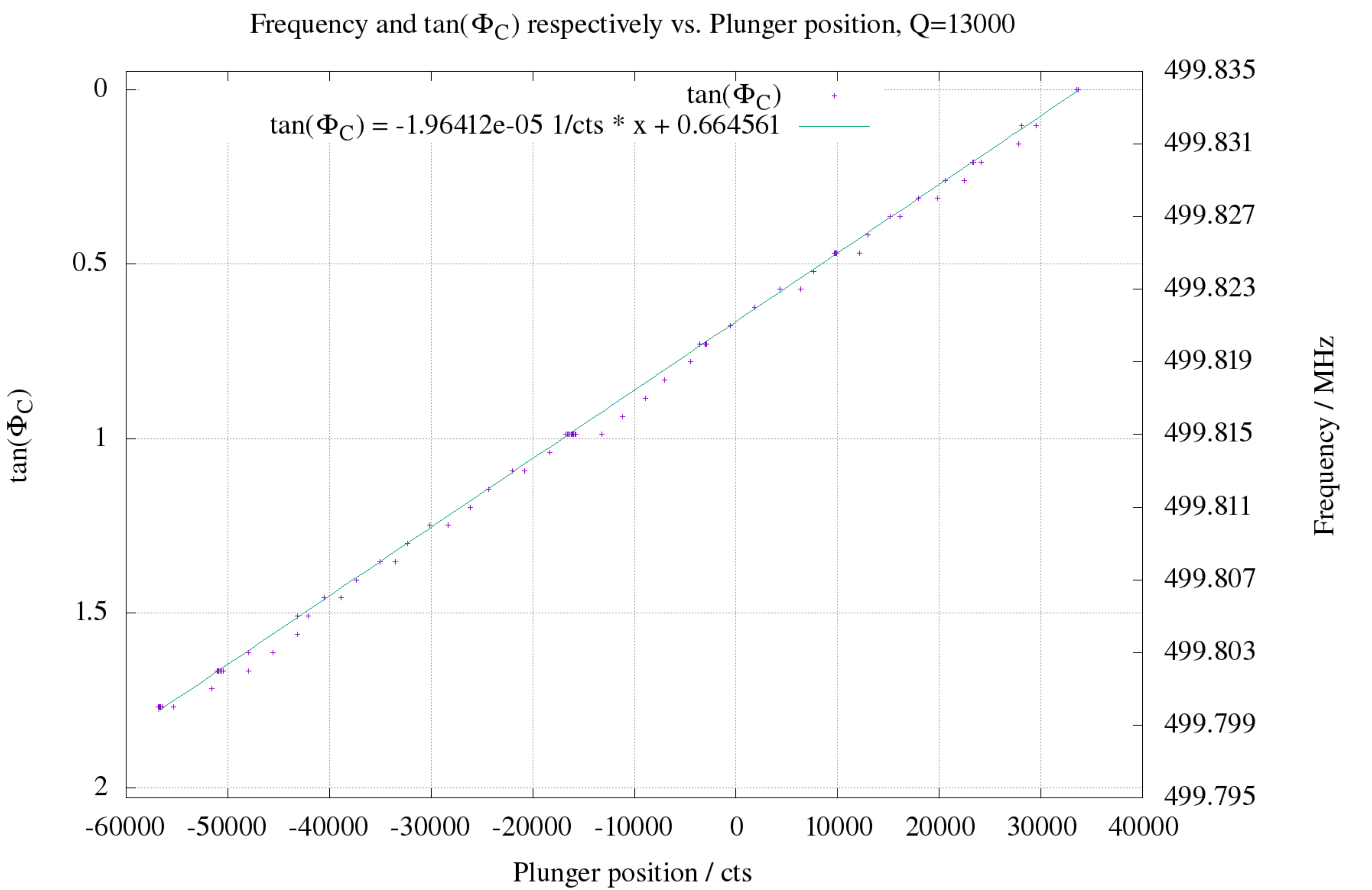
1. Prerequisites:
   - Good measurement of loaded Quality factor Q_L
   - Constant cavity temperature

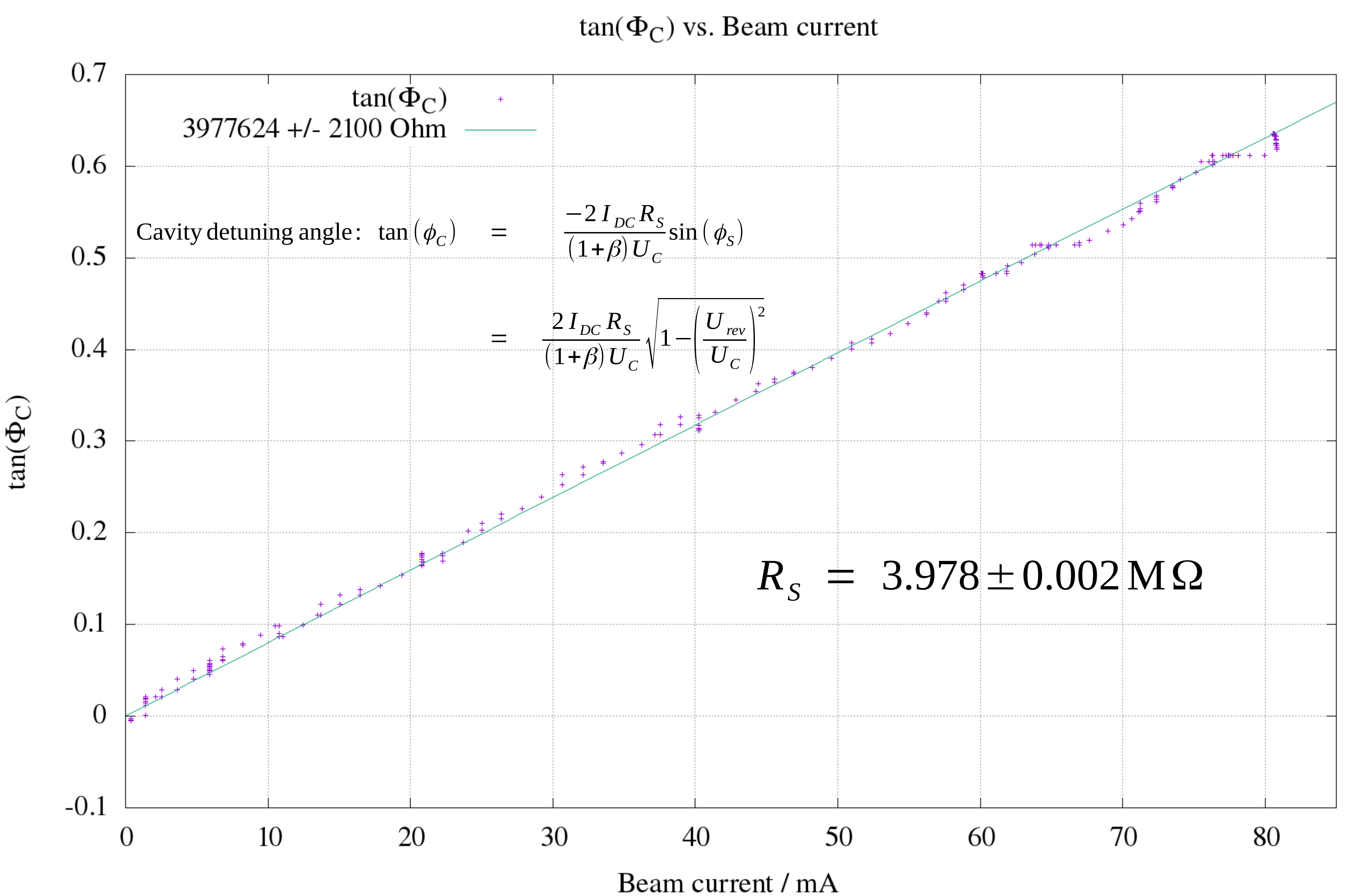
2. Calibrate plunger stepper motor steps with frequency deviation
   From measured Q_L → Relation btw. psm-steps and cavity phase Φ_C

3. Measure psm-Steps with increasing beam current
   - Slope gives measured cavity shunt impedance R_S

Typical measurement




Frequency and tan(ΦC) respectively vs. Plunger position, Q=13000
tan(ΦC)
tan(ΦC) = -1.96412e-05 1/cts * x + 0.664561
0
0.5
1
1.5
2
tan(ΦC)
499.835
499.831
499.827
499.823
499.819
499.815
499.811
499.807
499.803
499.799
499.795
Frequency / MHz
-60000
-50000
-40000
-30000
-20000
-10000
0
10000
20000
30000
40000
Plunger position / cts


tan(ΦC) vs. Beam current
tan(ΦC)
3977624 +/- 2100 Ohm
Cavity detuning angle: tan(φC) = −2 I_DC R_S / ((1+β) U_C) sin(φS)
= 2 I_DC R_S / ((1+β) U_C) √(1 − (U_rev / U_C)^2)
R_S = 3.978 ± 0.002 MΩ
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
10
20
30
40
50
60
70
80
tan(ΦC)
Beam current / mA

Summary & Outlook

- The LLRF, SSA and EU cavity run with only minor hickups for more than 2 years

- LLRF FPGA software changed by manufacturer to fulfill rad. prot. demands

- The LLRF voltage and power mesurement calibration is good

- Phase noise is generated by the externel reference (already uninstalled) and by the klystron (power supply?!)

- The shunt impedance R_S of the EU-type cavity was measured to be 3,97 MΩ

- Next step: Install second LLRF in booster

- If funded: Replace storage ring klystron with SSA

Acknowledgements

Vadim Kniss, Andreas Leinweber

DELTA Team

University electronics workshop

University mech. workshop

Literature:

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D. Boussard: *Beam Loading*, Cern Accelerator School, CERN, Geneva, Switzerland

A. Hofmann: *Beam Instabilities*, CERN, Geneva, Switzerland

M.G Minty, F. Zimmermann: Measurement and Control of Charged Particle Beams

Thank you
for your attention