TRIUMF

Achieving stable CW operation in vector sum

Ramona Leewe, Ken Fong, Yanyun Ma

Outline (Roadmap)

- Introduction to ARIEL
- Operating two cavities in vector sum and CW – starting conditions
- Challenges and Issues and Solutions
- Stable operation

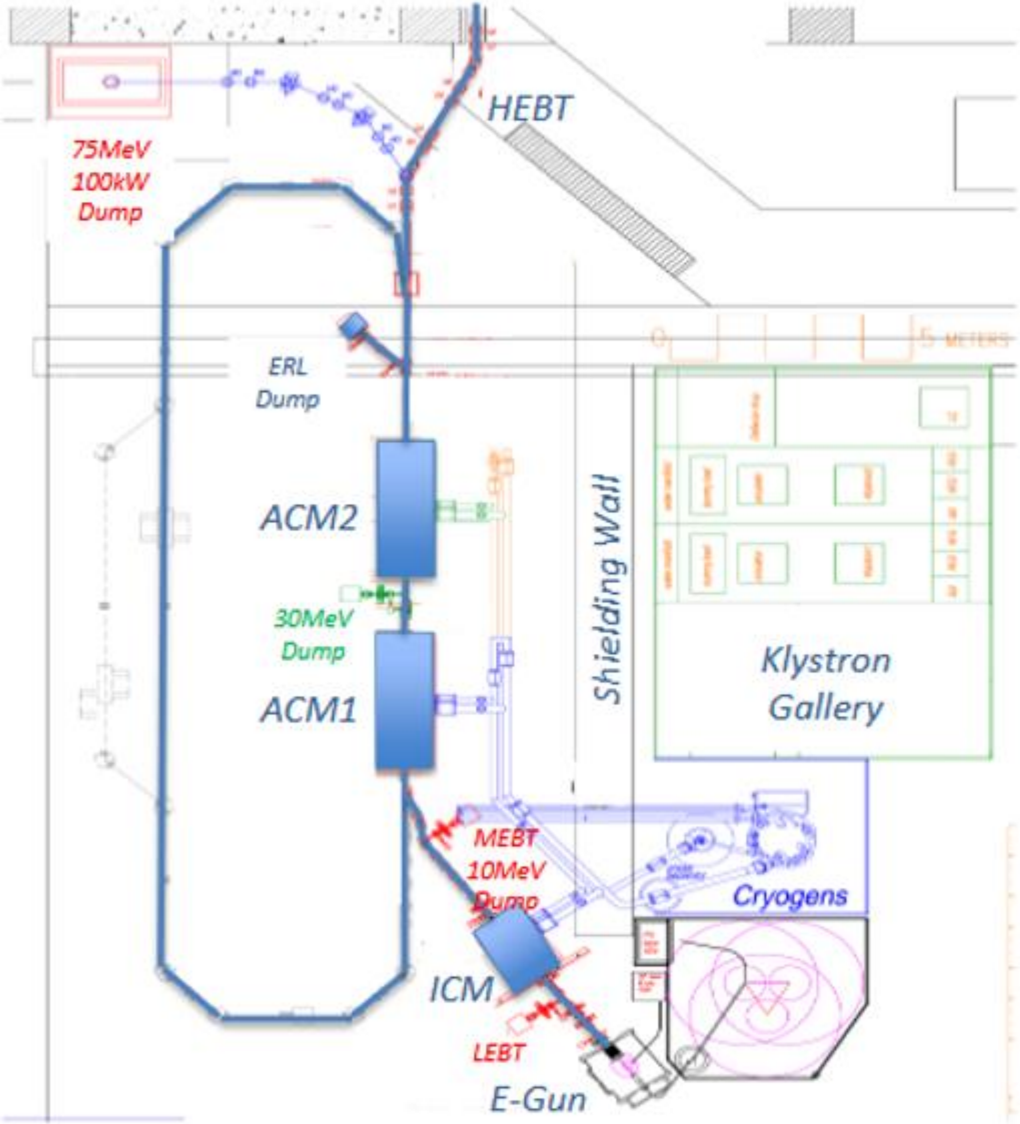
TRIUMF is Canada's Particle Accelerator Centre

Owned & operated by a consortium of 20 universities

- University of Alberta
- University of Calgary
- University of Manitoba
- McGill
- Queen's
- University of Regina
- Saint Mary's University
- University of Toronto
- University of Victoria
- Western
- Carleton University — Canada's Capital University
- University of Guelph
- McMaster University
- Université de Montréal
- SFU Simon Fraser University
- Université de Sherbrooke
- The University of British Columbia
- UNBC University of Northern British Columbia
- The University of Winnipeg
- York U

Introduction to Advanced Rare Isotope Electron Linac (ARIEL)

- ARIEL will be the world's most powerful ISOL complex.
- It will provide three simultaneous RIBs to experiments and triple ISAC's present rare isotope capabilities.
- A 30 MeV superconducting electron linac
- 300 kW beam power in CW
- It's configured to allow operation as an energy recovery linac for accelerator studies and applications



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Introduction to ARIEL

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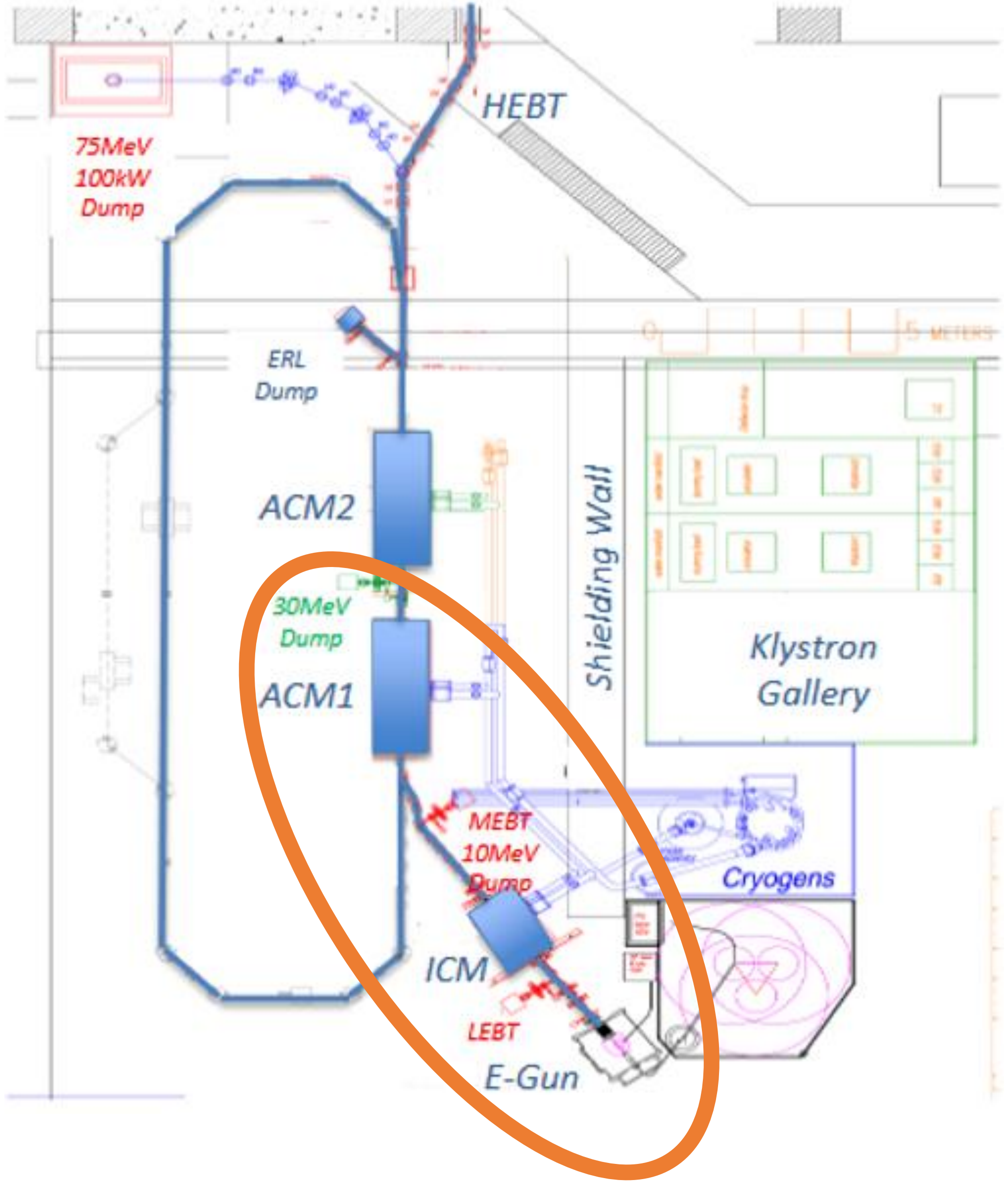

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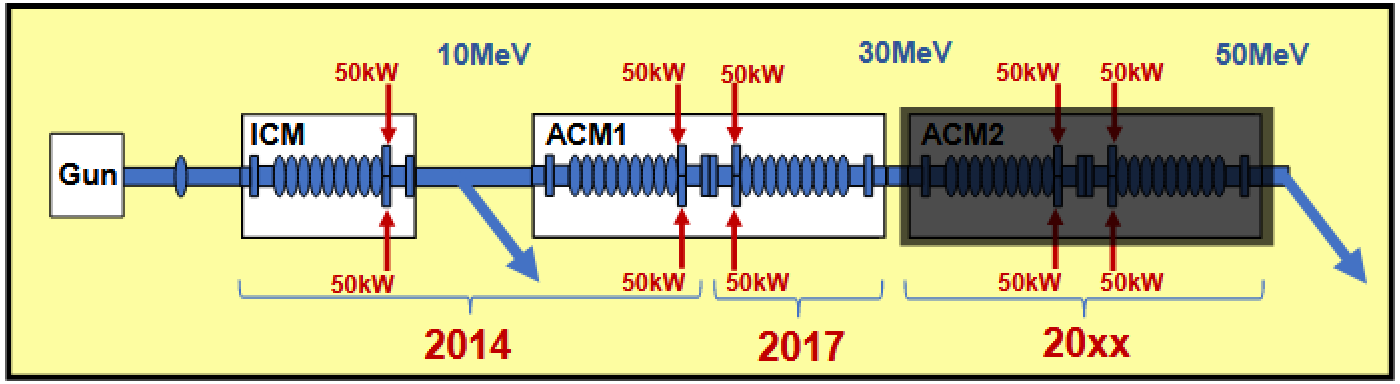
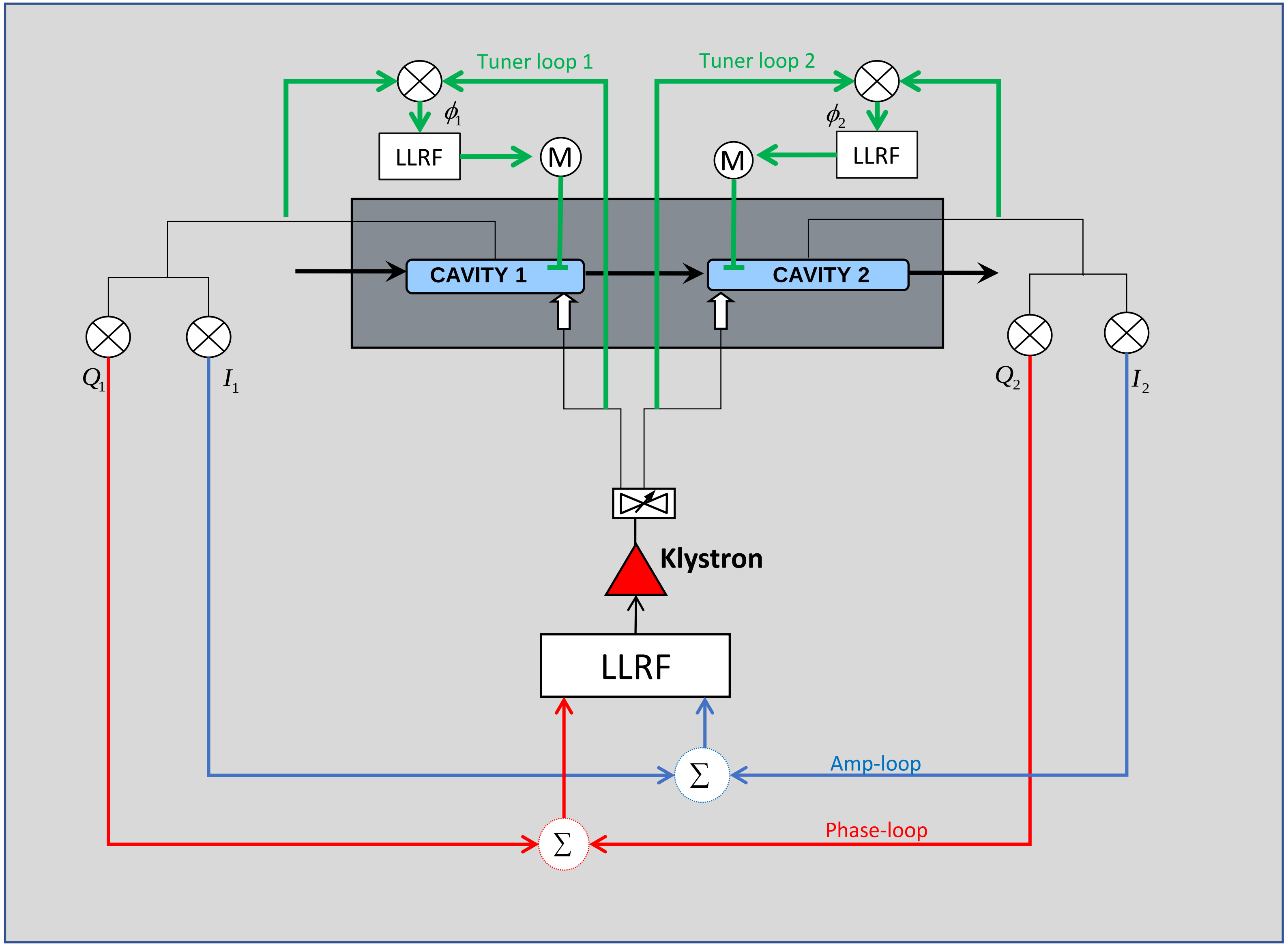
E-Linac Acceleration CryoModule

- ACM with two 9-cell cavities
- Two 50kW RF power couplers per cavity
- Scissor type frequency tuner with warm motor
- 4 K / 2 K heat exchanger with JT valve on board
- LN2 thermal shield and 4 K thermal interception via syphon
- 2 layers mu-metal shield
- WPM alignment system
- Performance meets specification



Acceleration cryomodule driving configuration, starting point

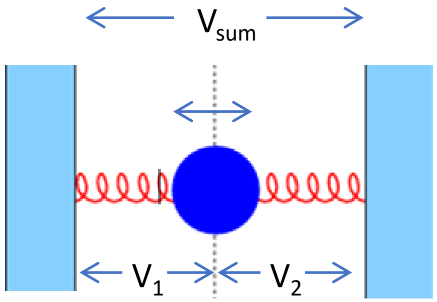
- 2 TESLA type cavities operated in vector sum
- Combined I and Q control
- 2 separate tuner loops tuned, correcting the phase error



First experiences and challenges with the initial setup

Amplitude of both cavities

- Amplitude oscillations in both cavities
- Counterphase, meaning the vector sum is stable
- Oscillation frequency roughly 160 Hz
- Cavity bandwidth roughly 300 Hz
- Takes several seconds for these oscillations to develop
- Oscillations are operational gradient dependent (>10MV)



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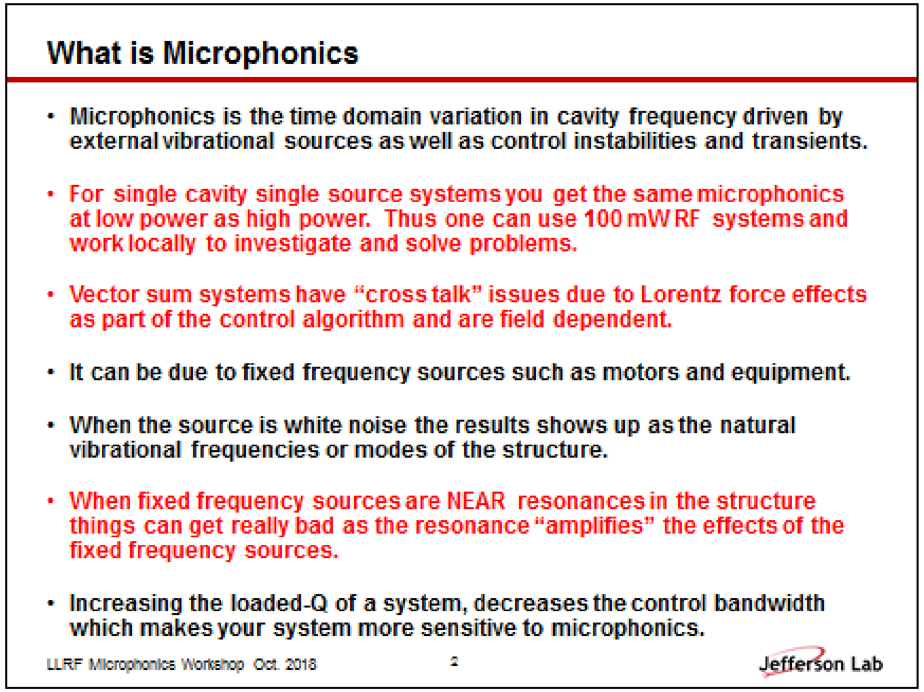
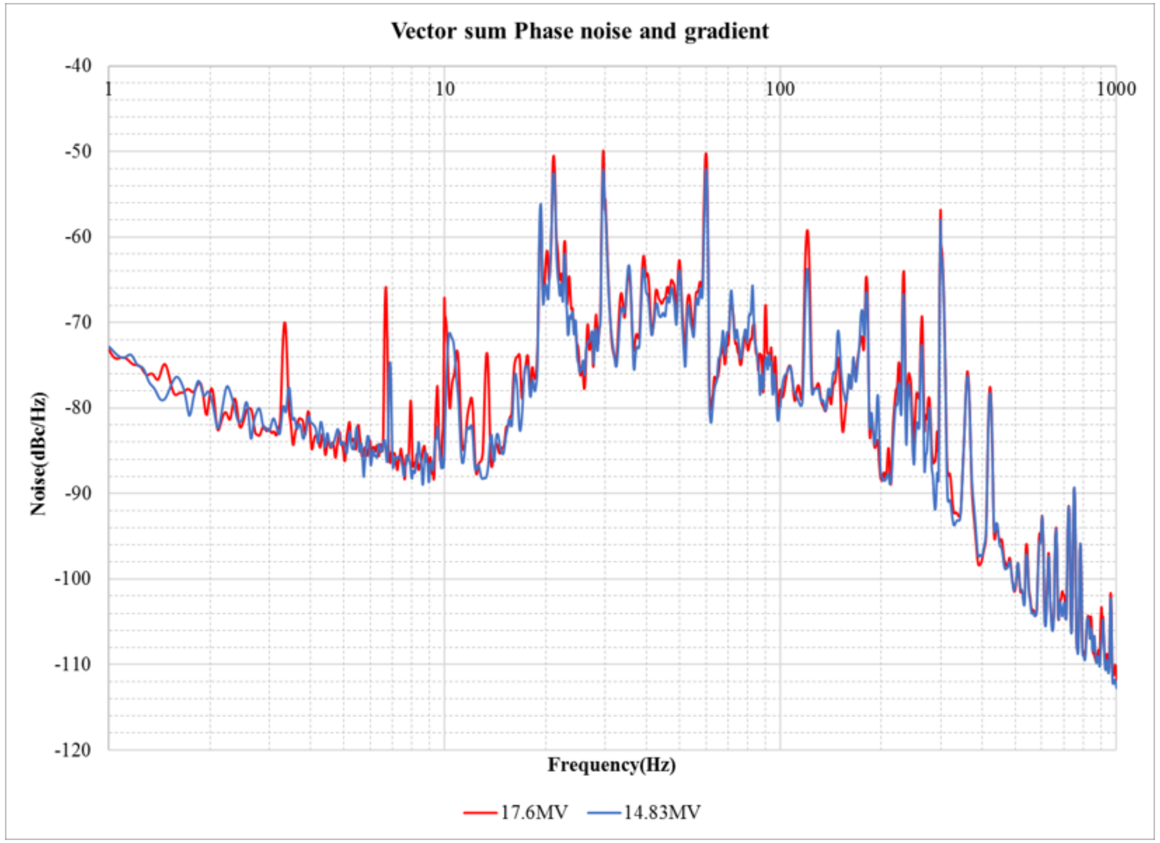
First thoughts: Vibration induced? Lorentz force induced oscillation?



"Tom Powers LLRF Microphonics workshop 2018"

- Vibration studies important before controller design
  - Is the mode actually in the cavity?
  - How does the cavity move?
  - Where to put a piezo?

- Vector sum phase noise measurements



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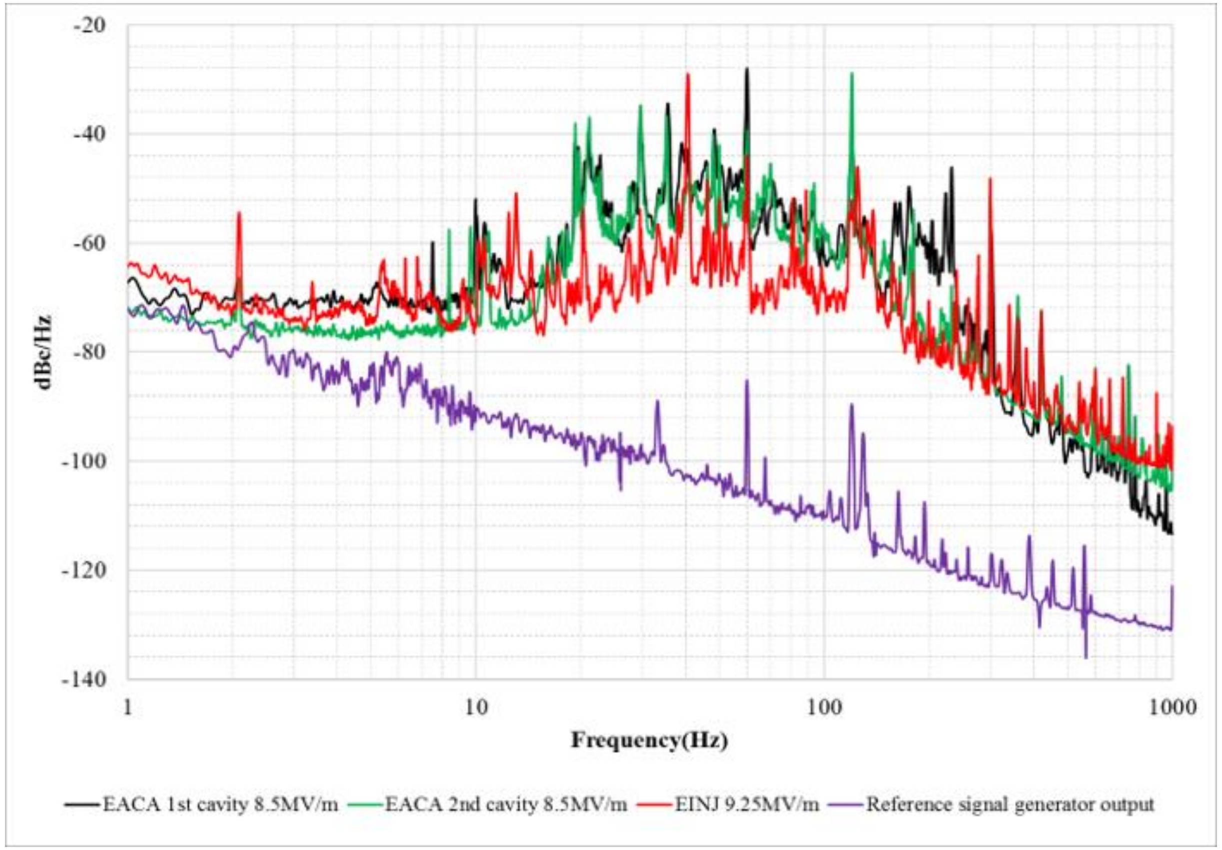
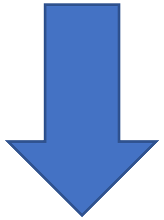
First thoughts: Vibration induced? Vibration triggering Lorentz force induced oscillation?

- Microphonics measurements in all cavities



Conclusion

- Similar peaks indicate that some of the noise sources are universal for all cavities



Microphonics source hunt

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Vibration sources identified and damping strategies applied

- Vibration sources and damping:
  - RF waveguide system
    - Anchored the waveguide support
    - Damped waveguide parts and dummy loads
    - Separated hoses and SS pipes from the waveguide support system
  - RF coupler cooling air
    - Added temperature sensor for each coupler warm window
    - Reduced the air flow rate
  - Cryomodule vacuum system
    - Turned off turbo pump
  - LN system
    - Added flow proportional valve for level regulation in phase separator

Analysis of the interaction between Lorentz force and vector sum operation

- Ponderomotive instabilities: Interaction between the mechanical and electromagnetic mode
- Dynamics of a mechanical mode driven by Lorentz force
- Delayen linearized the differential equation around its steady state and further stated the Lorentz force transfer function of the linearized system

Single cavity analysis

$$\Delta\ddot{\omega}_\mu + \frac{2}{\tau_\mu}\Delta\dot{\omega}_\mu + \Omega_\mu^2\Delta\omega_\mu = -k_\mu\Omega_\mu^2 V^2 + n(t)$$

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Ponderomotive instabilities and microphonics—a tutorial ☆

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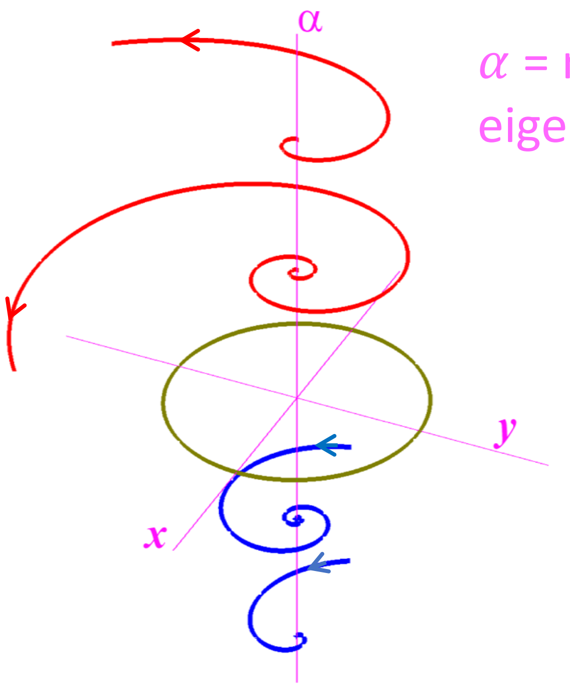
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Available online 4 May 2006

Single cavity analysis – linearized system

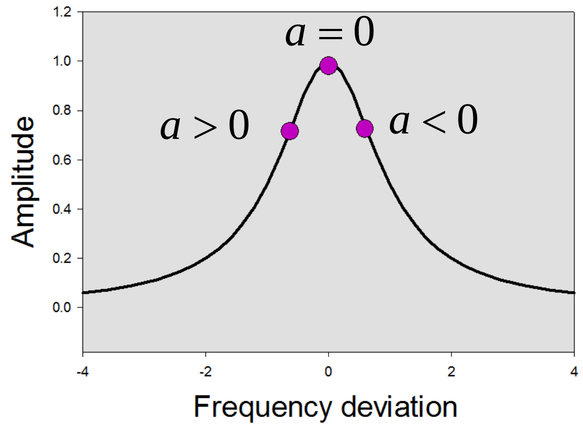
Graphical meaning of the linear analysis

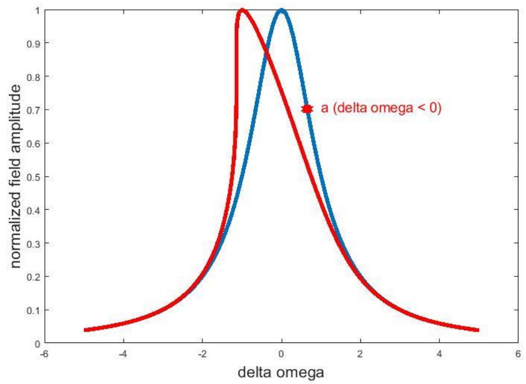


α = real part of the eigenvalue

Eigenvalues

$$\lambda_{1,2} \approx \underbrace{-4a\Lambda v_0^{\otimes} v_0 \frac{\tau}{\left(1+\tau^2\right)^2}}_{\alpha} \pm i$$





System stability depends on initial detuning parameter a

- Indicates a bifurcation in the system

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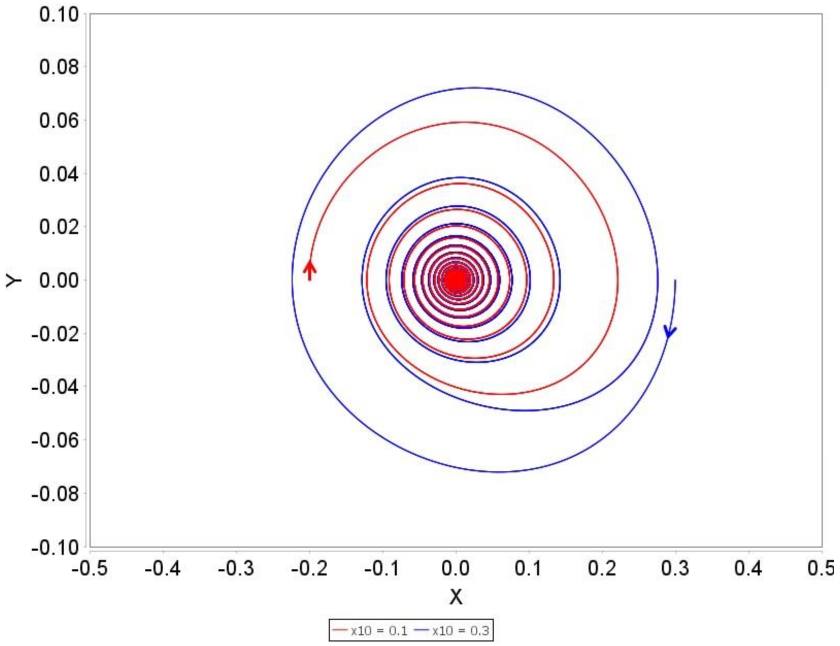
PARAMETRIC PUMPED OSCILLATION BY LORENTZ FORCE IN SUPERCONDUCTING RF CAVITY

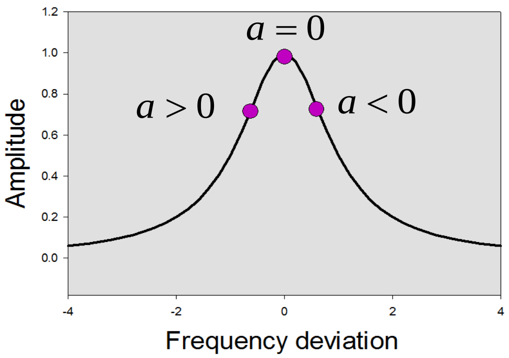
K. Fong†, R. Leewe, TRIUMF, Vancouver

Simulation results of the nonlinear system/ Phase space plots

Cavity initially detuned towards the stable side

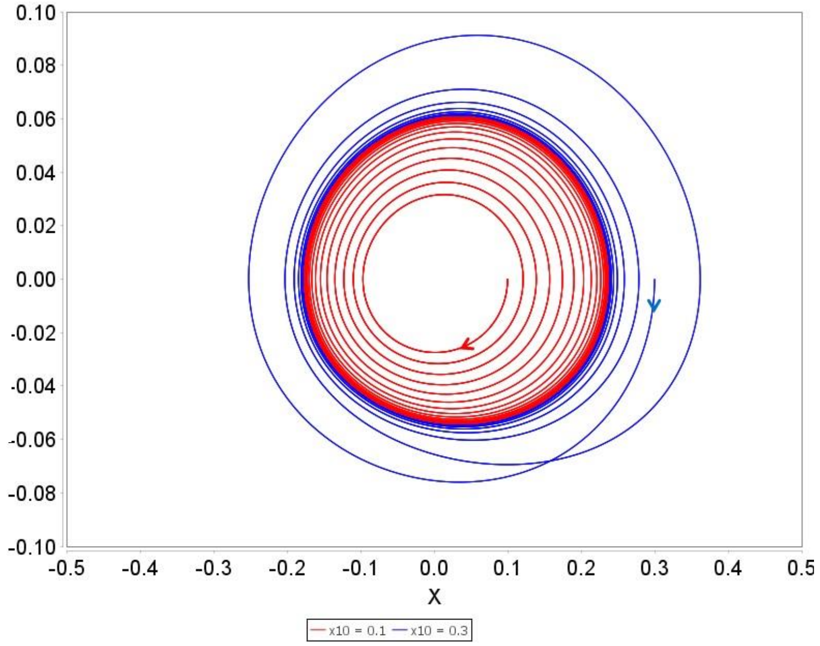
- Initial detuning $\approx 1.5^\circ$





Cavity initially detuned to the unstable/limit cycle side

- Initial detuning $\approx -1.5^\circ$



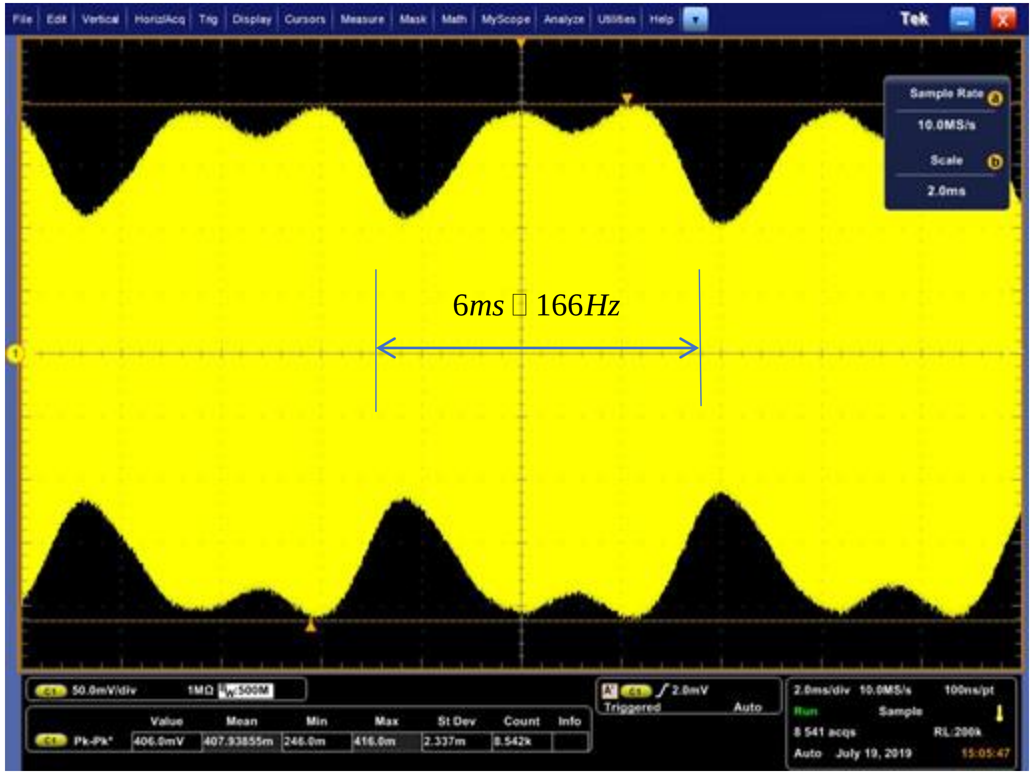
Limit cycle behavior

Simulation and measurement results/ model verification

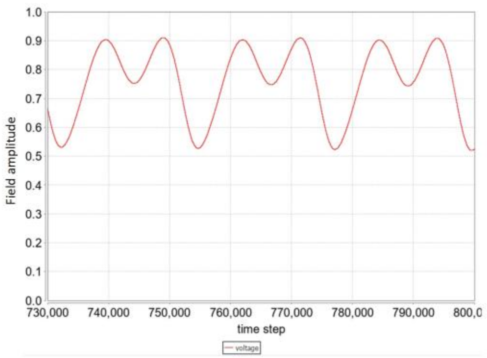
Limit cycle behavior in amplitude

Field envelope measurement on TRIUMF’s Injector cryomodule

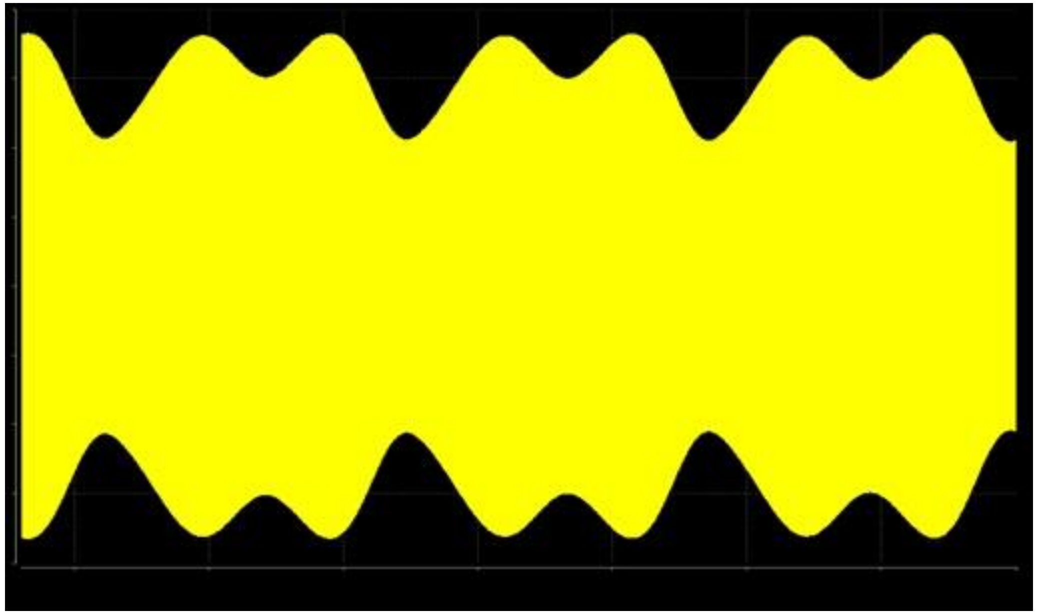
- Generator driven
- No feedback system
- Amplitude 10MV/m
- Cavity detuned to the oscillatory side



Simulation results



- Simulated envelope function of the nonlinear system



Double cavity simulation study with feedback in vector sum

SIMULATION ANALYSIS OF LORENTZ FORCE INDUCED OSCILLATIONS IN RF CAVITIES IN VECTOR SUM AND CW OPERATION

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V6T2A3 Vancouver, Canada

State equations

$$\dot{x}_1 = y_1$$
$$\dot{y}_1 = -\epsilon_1 y_1 - \Omega^2 x_1 - \Lambda\left(v_{i1}^2 + v_{q1}^2 - v_0^2\right)$$
$$\dot{v}_{i1} = \bar{\omega}\left(-v_{i1} - (a_1 + x_1)v_{q1} + v_{fi1}\right)$$
$$\dot{v}_{q1} = \bar{\omega}\left((a_1 + x_1)v_{i1} - v_{q1} + v_{fq1}\right)$$
$$\dot{x}_2 = y_2$$
$$\dot{y}_2 = -\epsilon_2 y_2 - \Omega^2 x_2 - \Lambda\left(v_{i2}^2 + v_{q2}^2 - v_0^2\right)$$
$$\dot{v}_{i2} = \bar{\omega}\left(-v_{i2} - (a_2 + x_2)v_{q2} + v_{fi2}\right)$$
$$\dot{v}_{q2} = \bar{\omega}\left((a_2 + x_2)v_{i2} - v_{q2} + v_{fq2}\right)$$
$$v_{fi1} = v_{i1} + K_p\left(\frac{(v_{i1} + v_{i2})}{2} - v_{iref}\right)$$
$$v_{fq1} = v_{q1} + K_p\left(\frac{(v_{q1} + v_{q2})}{2} - v_{qref}\right)$$
$$v_{fi2} = v_{i2} + K_p\left(\frac{(v_{i1} + v_{i2})}{2} - v_{iref}\right)$$
$$v_{fq1} = v_{q2} + K_p\left(\frac{(v_{q1} + v_{q2})}{2} - v_{qref}\right)$$

$$a = \frac{\omega_0 - \omega}{\bar{\omega}}$$

$\omega_0 = natural\ resonance\ frequency$

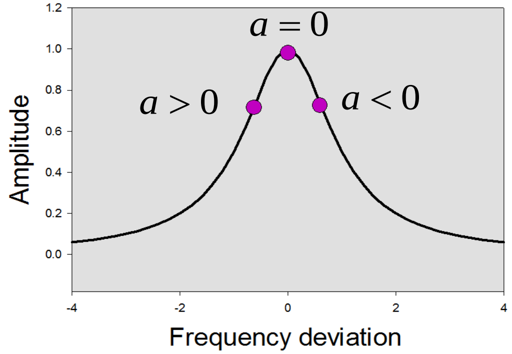
$\omega = operating\ frequency$

$\bar{\omega} = ratio\ of\ RF\ bandwidth\ \ over\ mechanical\ resonance$

$$v_0 = \left(\frac{1}{1 + a}\right) v_f^2$$

$v_{fi}, v_{fq} = feedback\ voltages$

$v_i + jv_q = v$



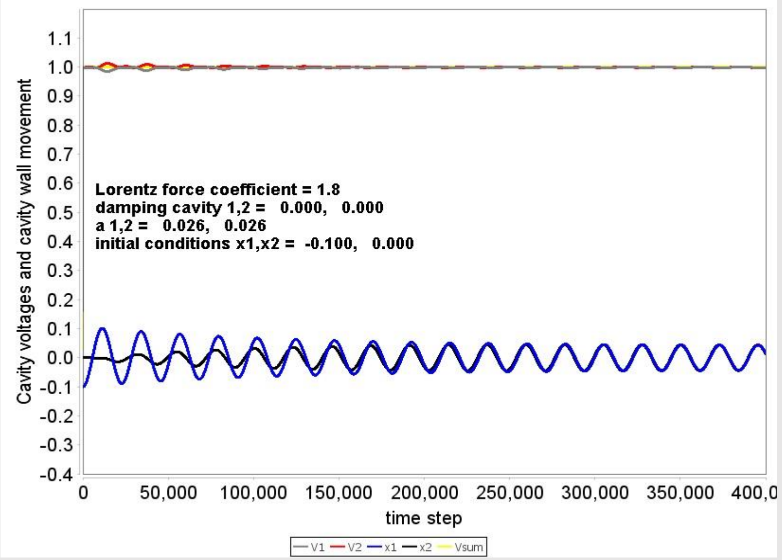
$a_{1,2}$ = initial misalignment for each cavity

$\epsilon_{1,2}$ = cavity damping (e.g active piezo feedback)

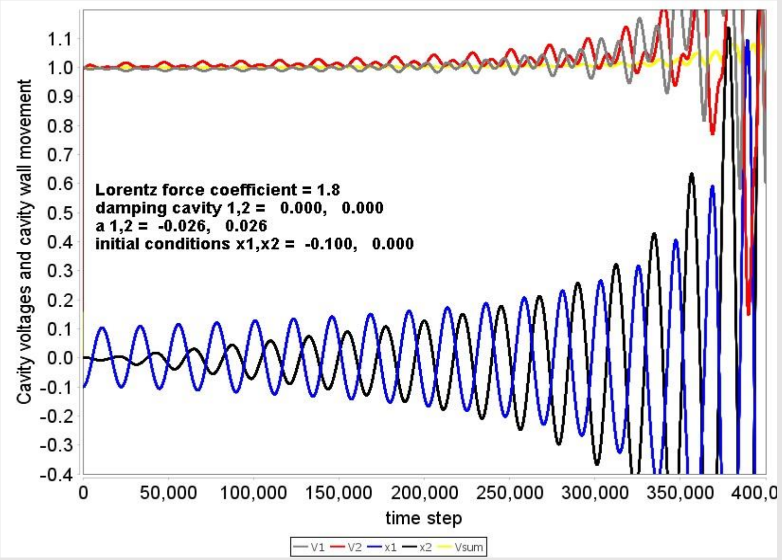
$x_{1,2}$= initial conditions for each cavity

Simulation results, CW vector sum operation

Undamped

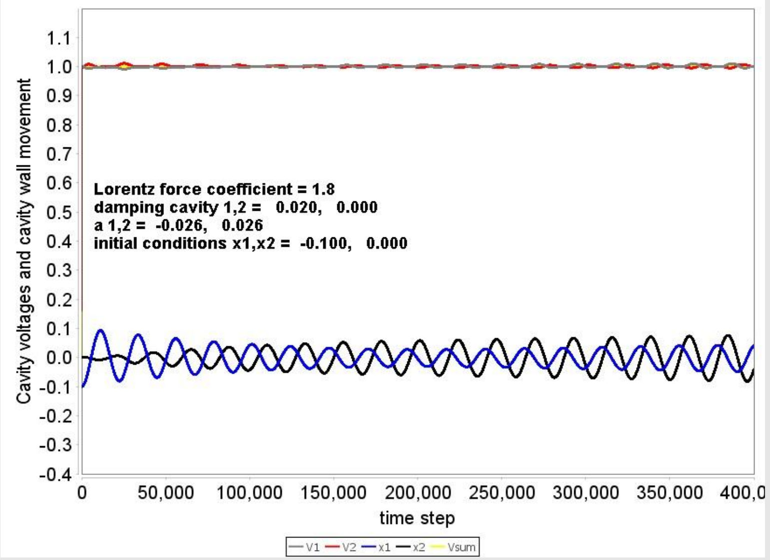


Only Stable if $a_{1,2} > 0$



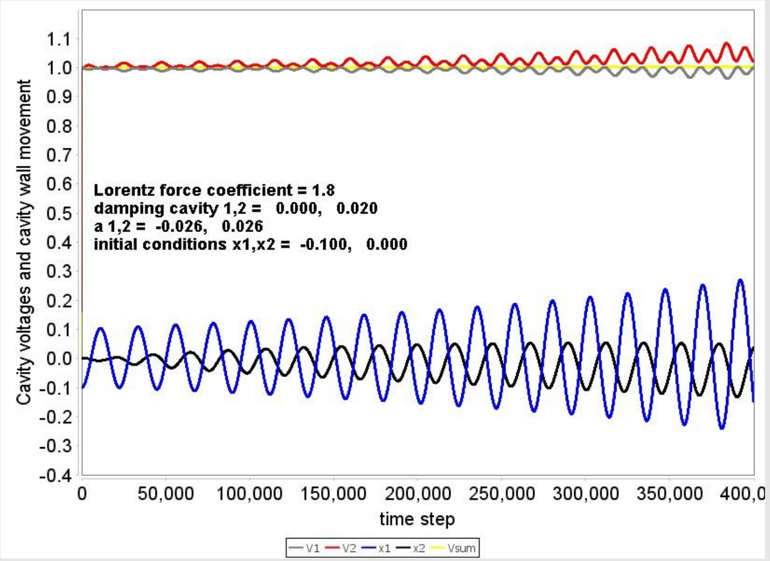
unstable

1 Cavity damped



unstable

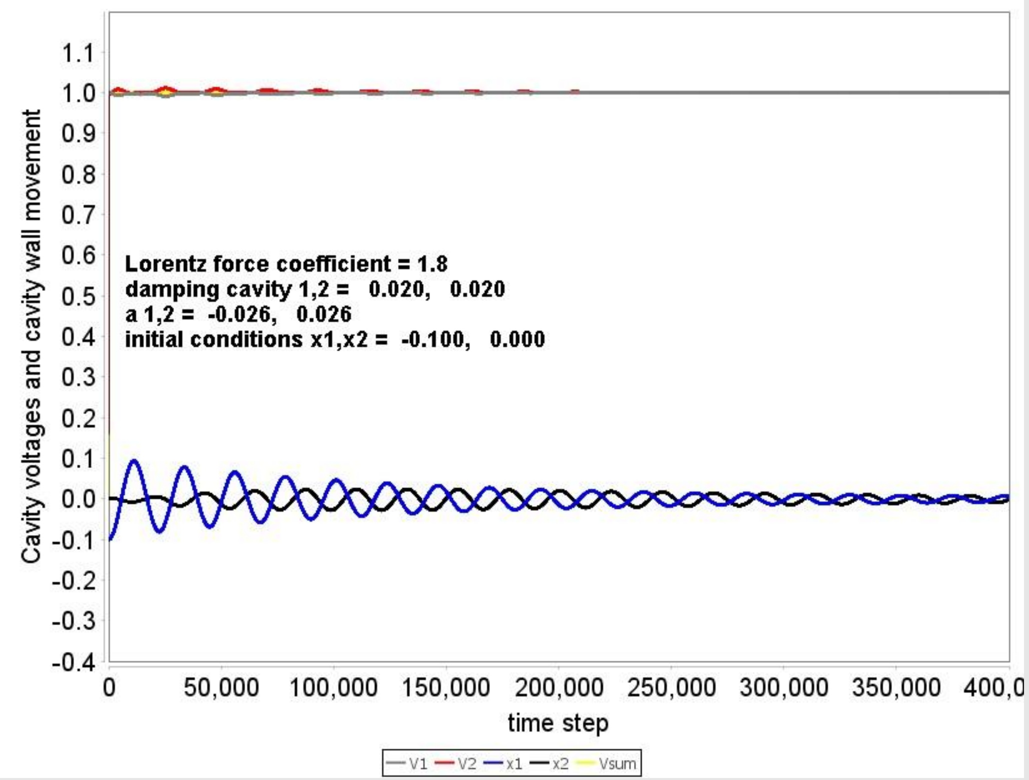
Only Stable if $a_{1,2} > 0$



unstable

Simulation results, CW vector sum operation

both Cavities damped



always stable

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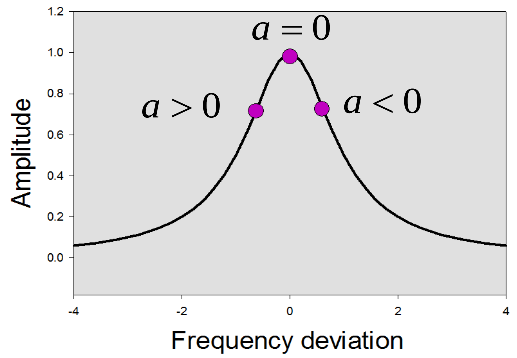
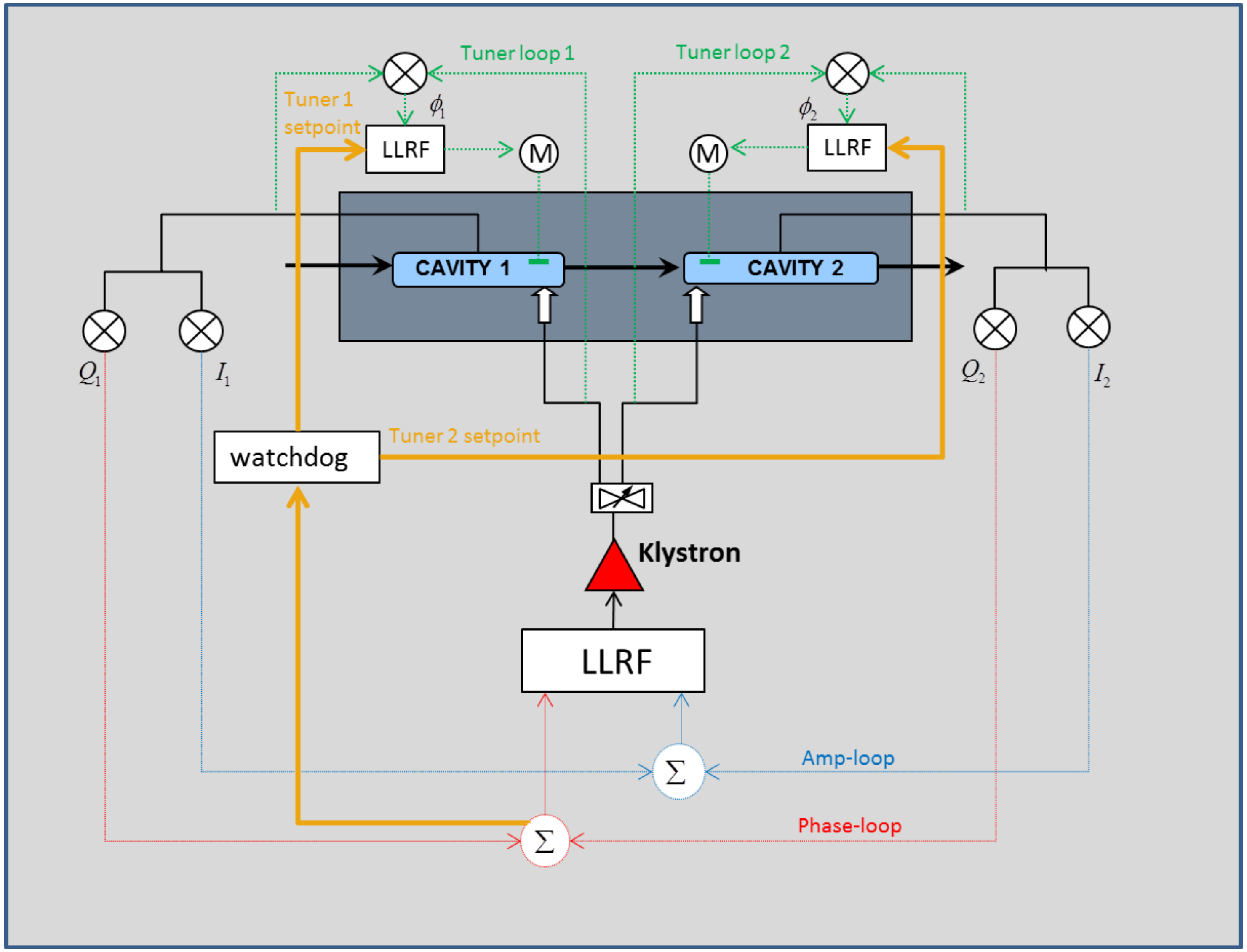
Added a piezo element to damp one resonance + adding a control loop to the LLRF

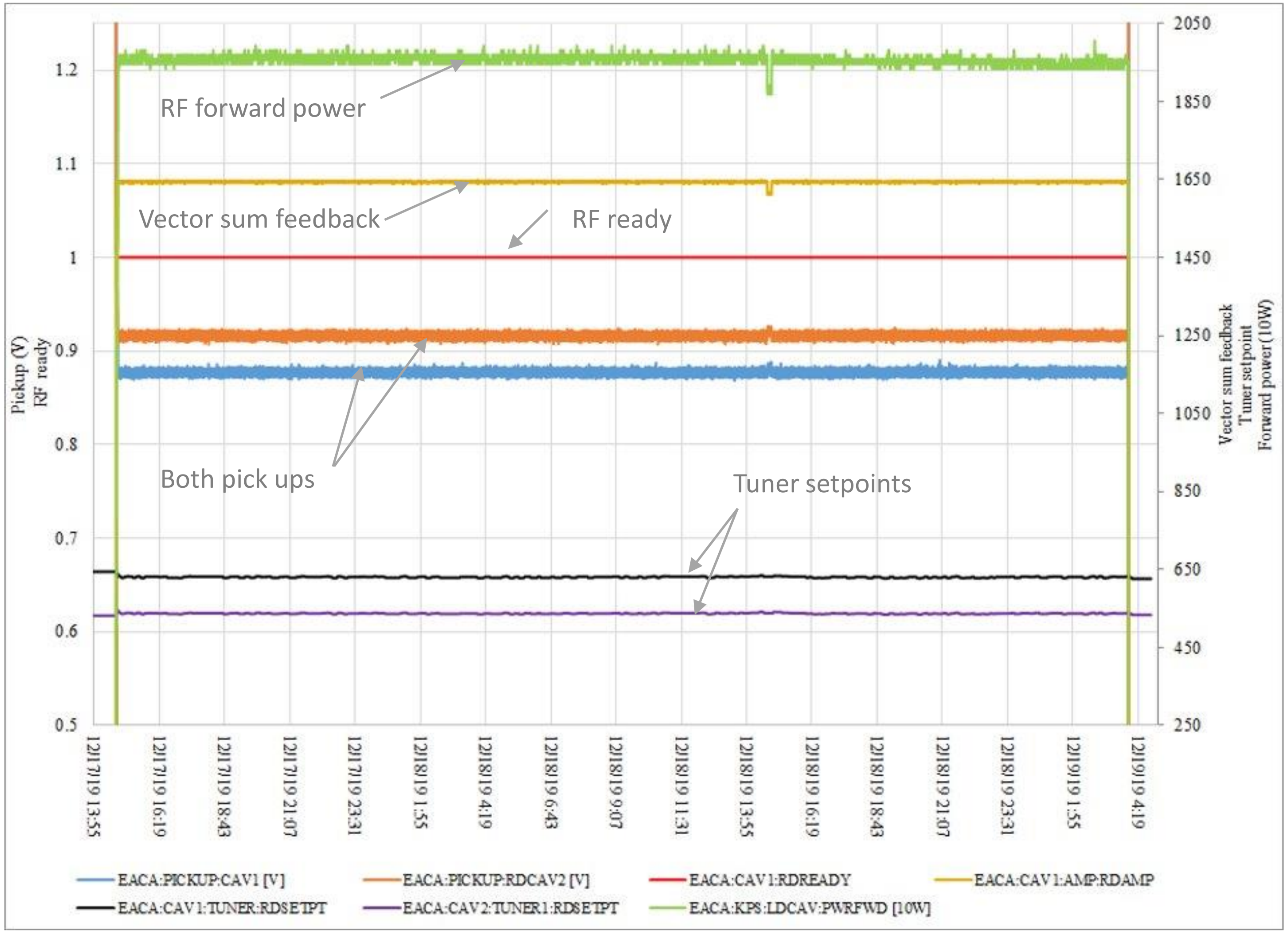
- Control loop watches on which side of the resonance the systems are operating and changes the tuner setpoints continuously to guarantees that both systems are operating on the right site of the curve





Summary: Achieving stable CW operation in vector sum

- Extensive vibration source analysis
- Damped every possibly transmitted vibration
- Added positive Q drive watchdog to guarantee that both cavities operate on the stable side of the resonance curve
- Added piezo to counteract strongest mechanical resonance
- Added an iterative learning controller for beam loading cancellation, talk on Thursday



37 hours of operation at 20 MV/m

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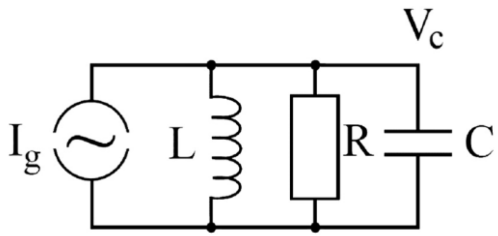
Thank you!

Backup slides - Single cavity analysis



Simplified differential equation

- Normalized differential equation w.r.t the mechanical mode frequency
- Damping neglected for simplicity

Find an expression for

$$\ddot{x} + x = -\Lambda\left(v^2 - {v_0}^2\right)$$

$$x \propto \Delta\omega$$

$$\Lambda \equiv Lorentz\_force\_coefficient$$

$$v = actual\_field\_amplitude$$

$$v_0 = initial\_field\_amplitude$$

Analytical expression for the cavity voltage with respect to it's deformation

- Change of current through resonator

$$\dot{I} = \frac{1}{R}\dot{V} + \ddot{C}V + 2\dot{C}\dot{V} + \ddot{V}C + \frac{1}{L}V = \frac{2}{Z_0}\dot{V}_f$$

Usually neglected

Approximate analytical expression obtained through:

- Parameter variation
- Assuming a Fourier series solution
- Reverting back to x,y - domain

$$\dot{x} = y$$

$$\dot{y} + x = -\Lambda 2 v_0 {}^{\otimes} v_0 * \left\{ \begin{array}{l} \frac{2a}{\left(1+\tau^2\right)^2}\left[\left(-1+\tau^2\right)x - 2\tau y\right] + \\ -\frac{1}{\left(1+\tau^2\right)\left(1+4\tau^2\right)}\left[\left(1-2\tau^2\right)\left(x^2-y^2\right) + 6\tau xy\right] \\ -\frac{4}{\left(1+\tau^2\right)}\left(x^2+y^2\right) \end{array} \right\}$$

Single cavity analysis - continued

Oscillation Growth and decay rates

- Eigenvalues $\lambda_{1,2} \approx -4a\Lambda v_0^{\otimes} v_0 \frac{\tau}{\left(1+\tau^2\right)^2} \pm i$

$$growth / decay \cong -4a\Lambda v_0^{\otimes} v_0 \frac{\tau}{\left(1+\tau^2\right)^2}$$

- Maximum growth rate

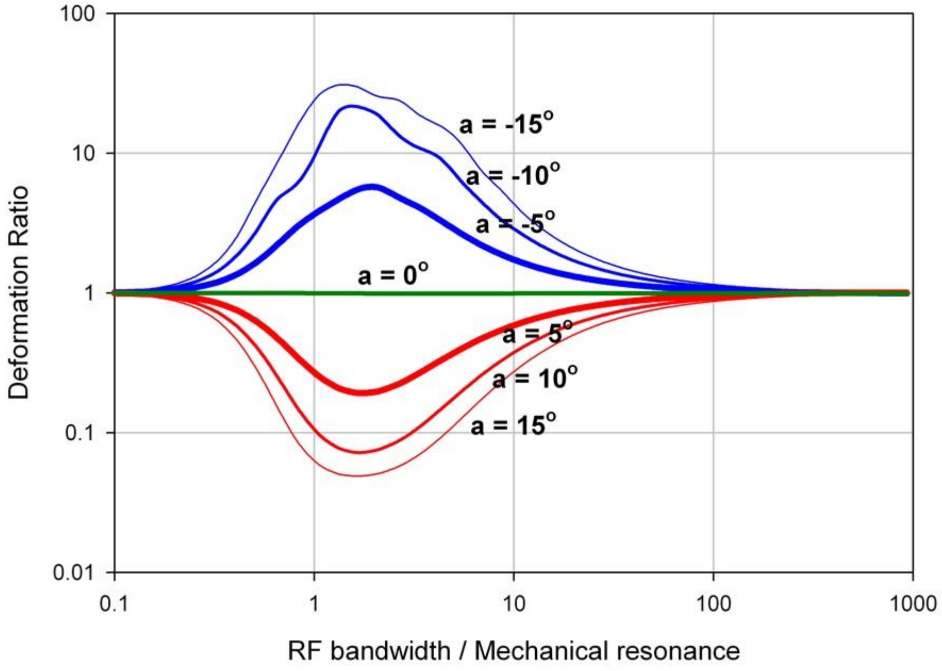
$$\frac{d}{d\tau} \frac{\tau}{\left(1+\tau^2\right)^2} = \frac{-3\tau^2+1}{\left(1+\tau^2\right)^3}$$

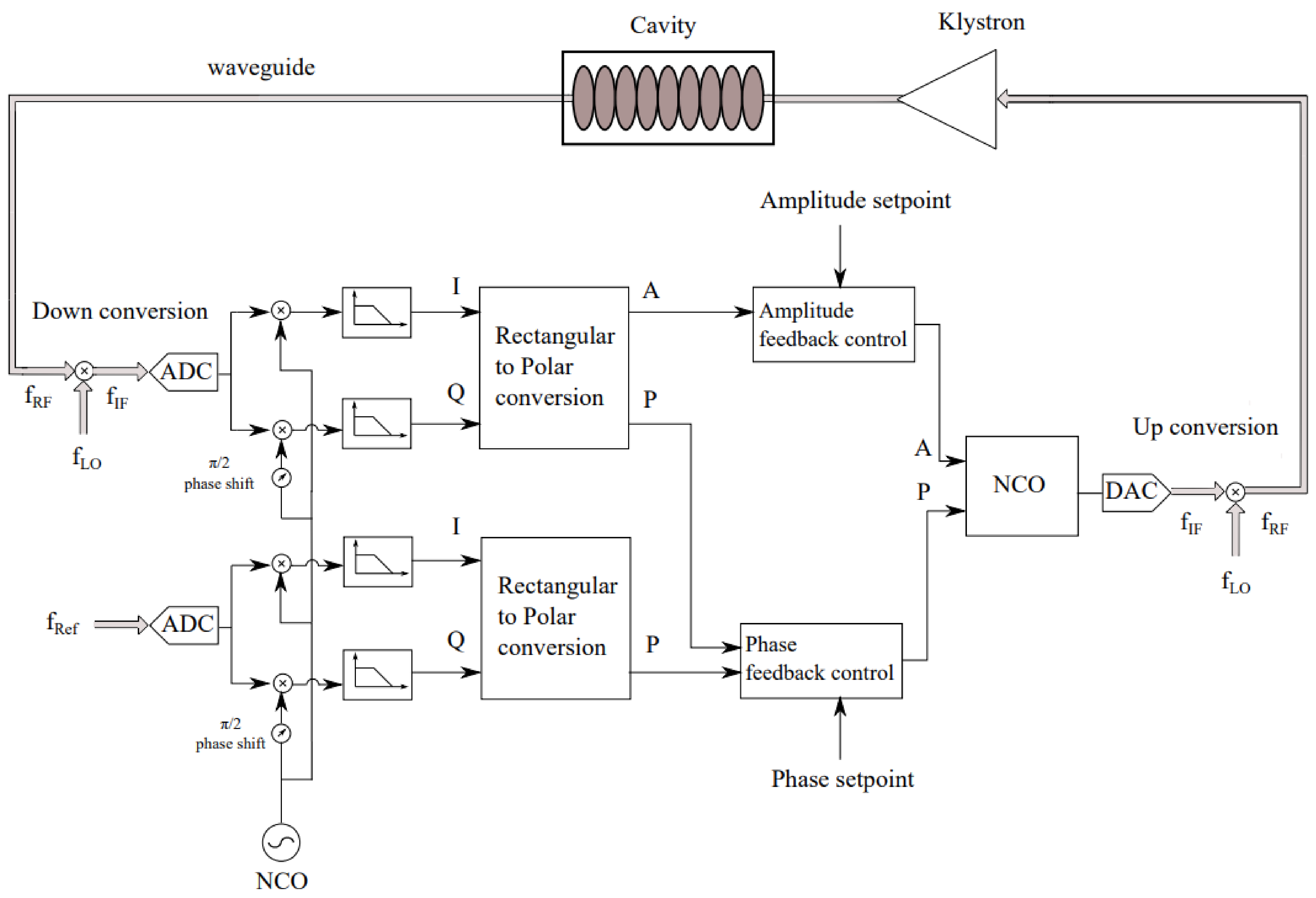
$$\tau = \frac{\sqrt{3}}{3} \approx 0.58$$

$$\varpi \approx 1.7$$

$\varpi = \frac{1}{\tau} =$ RF bandwidth over the mechanical resonance

Simulation of the deformation of the nonlinear system




Cavity
Klystron
waveguide
Amplitude setpoint
Down conversion
I
A
Amplitude
feedback control
Rectangular
to Polar
conversion
ADC
f_{RF}
f_{IF}
f_{LO}
Q
P
π/2
phase shift
A
P
NCO
Up conversion
DAC
f_{IF}
f_{RF}
f_{LO}
I
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