

RF Systems I



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CERN



Introduction to Accelerator Physics

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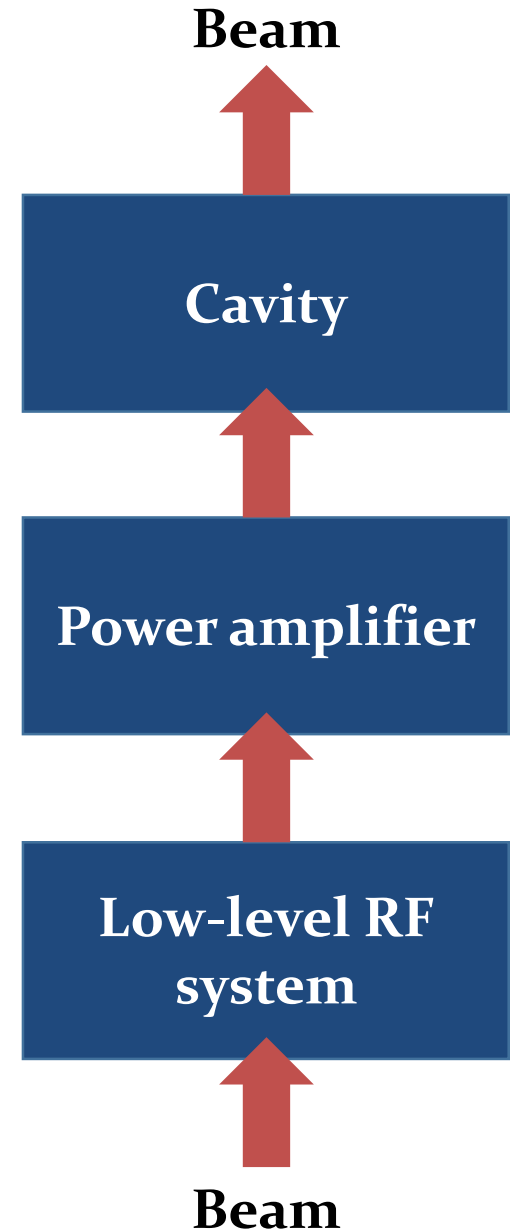
Outline

- **Introduction**
- **Choice of parameters**
 - Frequency and voltage
- **RF cavity parameters**
 - Shunt impedance, beam loading, power coupling
- **Power amplifiers**
 - Tube or solid state
 - Local feedbacks
- **Longitudinal beam control system**
 - Building blocks: RF source and receiver
 - Phase, radial and synchronization loops
- **Summary**

Introduction

Introduction

- The **radiofrequency (RF)** system transforms a string of magnets into an **accelerator**
 - Cavity most is the most visible part of an RF system
 - On top of the RF system **food chain**
 - Interacts directly with beam
- What is below?
- How are RF signals generated which make the beam feel comfortable?



Frequency and wavelength ranges



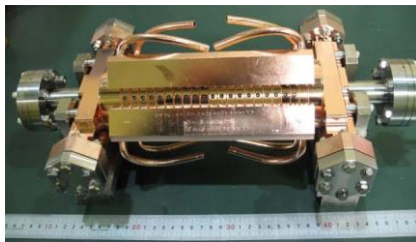
PS longitudinal damper



PS main RF system



SPS 200 MHz



CLIC 12 GHz

100 kHz
3 km

1 MHz
300 m

10 MHz
30 m

100 MHz
3 m

1 GHz
30 cm

10 GHz
3 cm

100 GHz
3 mm



Long wave

**Medium/
short wave**



VHF

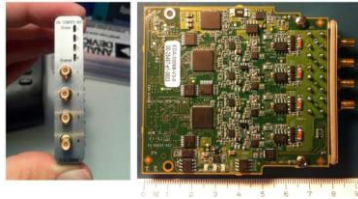


**Microwave
links**



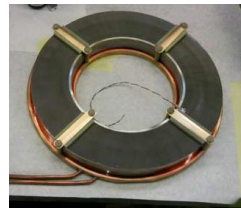
Amplitude ranges

Signals from beam
pick-ups

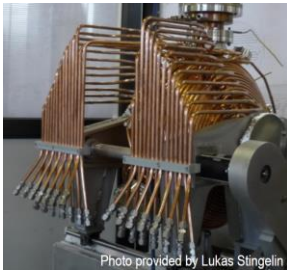


LLRF systems

Low/Medium
energy hadron RF



SLS



LHC: 16 MV



LEP: 3.6 GV total

1 μ V

1 mV

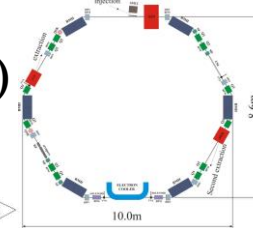
1 V

1 kV

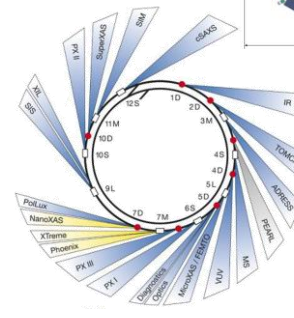
1 MV

1 GV

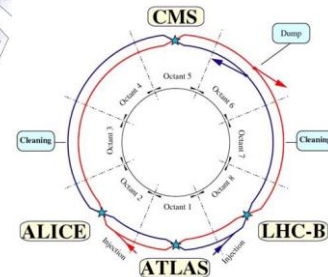
Cooled hadron
beams
(ELENA)



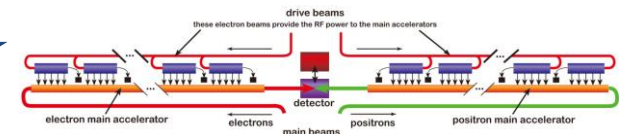
Electron light
sources



LHC

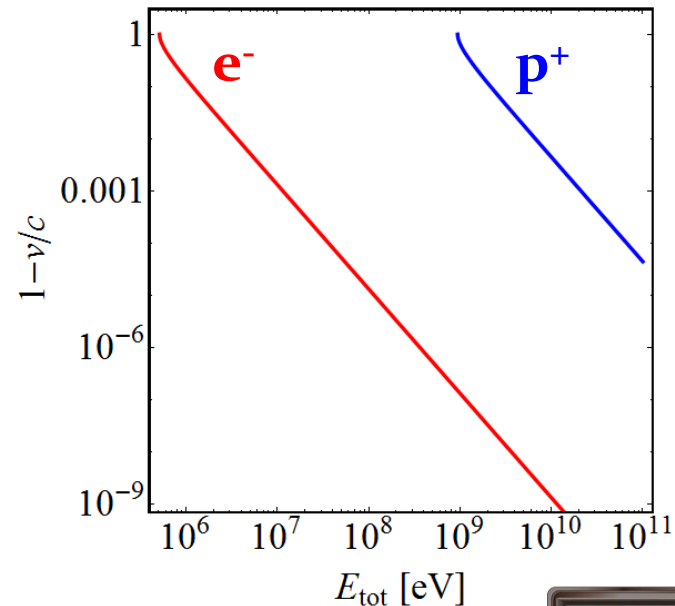
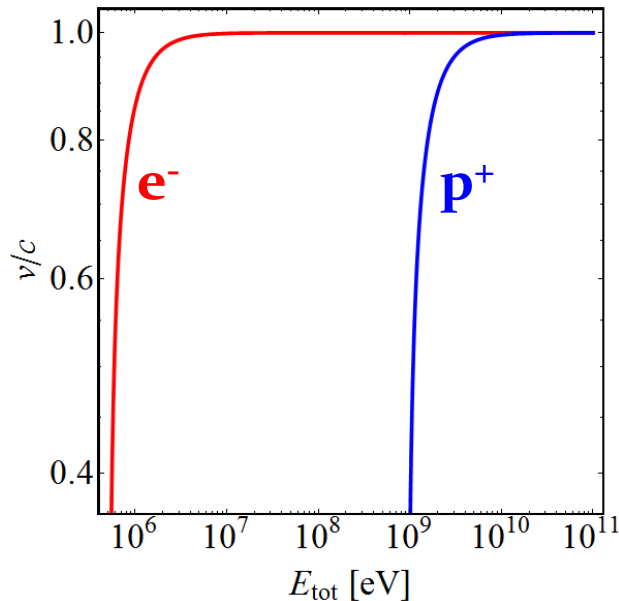


ILC and CLIC: several TV



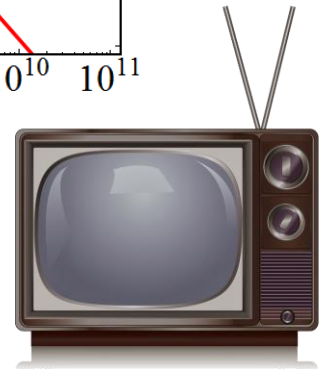
Particle velocity

- Particle velocity depends on its type: $\beta = v/c = \sqrt{1 - (E_0/E)^2}$



- Old television set (30 kV): **Electrons** at 30% of c_0
Protons just at 0.7%
- Small synchrotron (500 MeV): **Electrons** at 99.99995%
Protons at 75.8%

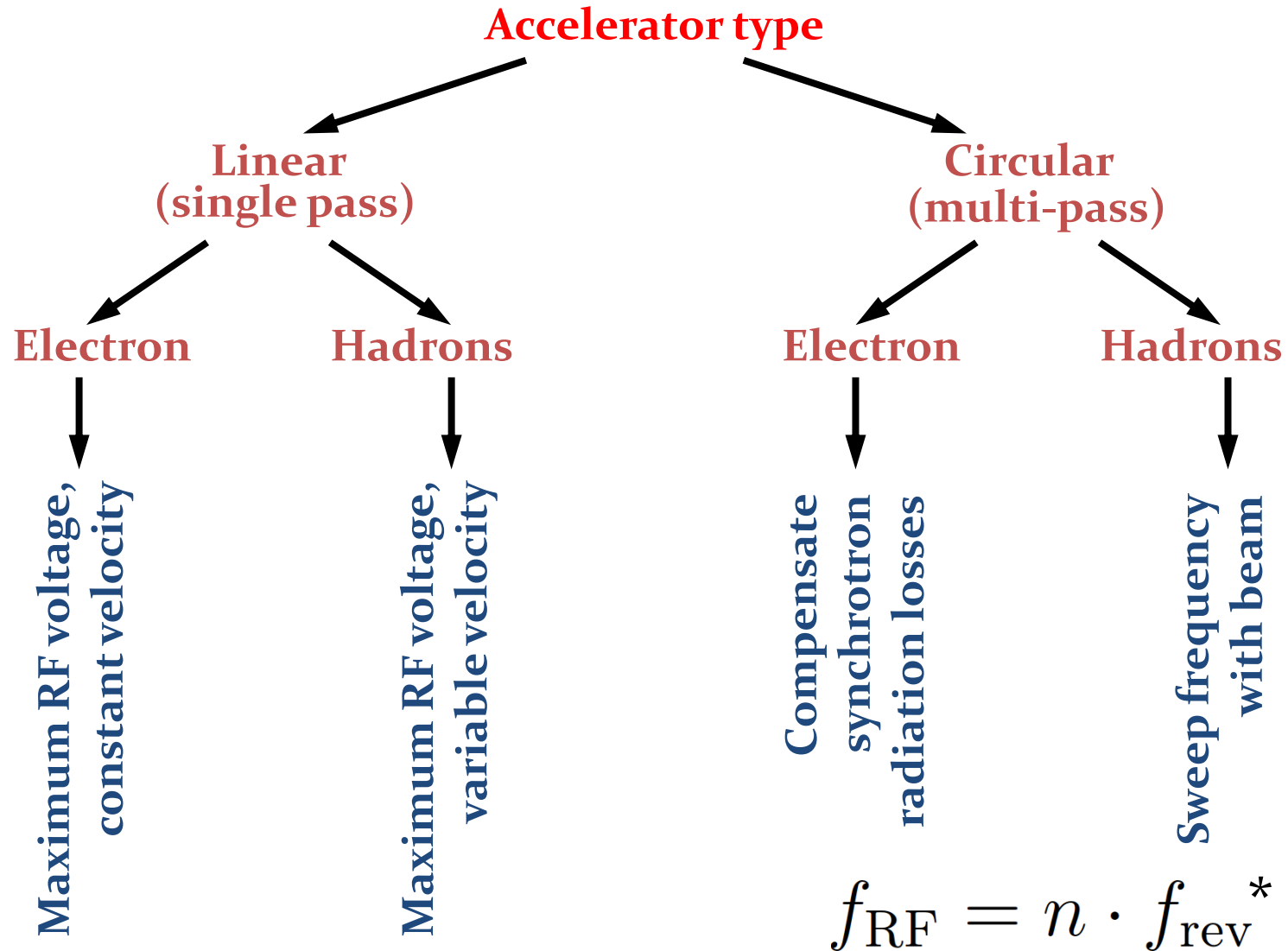
→ Most electron accelerators at 'fixed' frequency



Parameter choices

RF system for high-energy accelerators

9



$$f_{\text{RF}} = n \cdot f_{\text{rev}}^*$$

*Exceptions (rare) exist

Choice of frequency (range)

Why choose a **low** RF frequency?

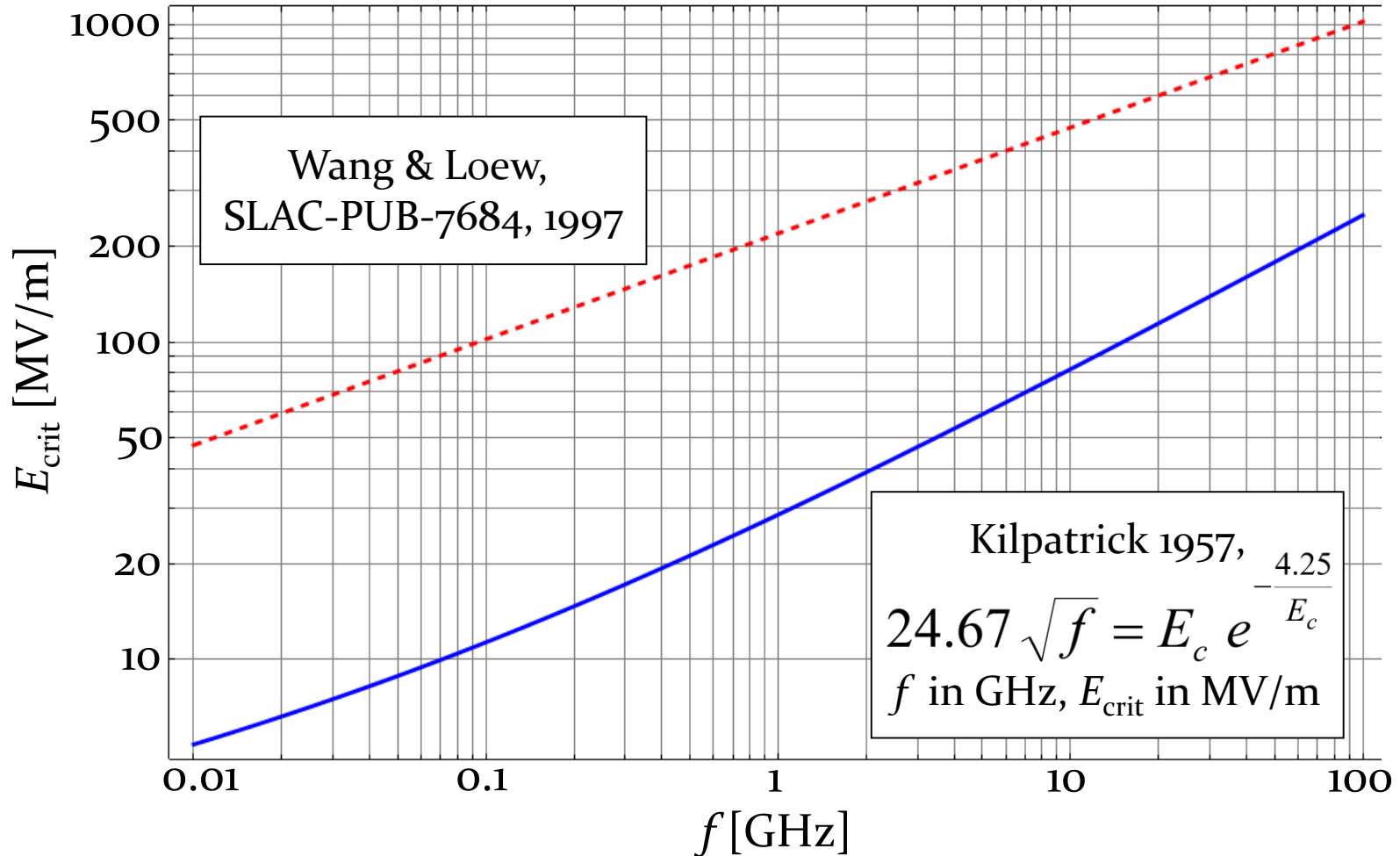
Advantages	Disadvantages
• Large beam aperture • Long RF buckets, large acceptance • Wide-band or wide range tunable cavities possible • Power amplification and transmission straightforward	• Bulky cavities, size scales $\propto 1/f$, volume $\propto 1/f^3$ • Lossy material to downsize cavities • Moderate or low acceleration gradient • Short particle bunches difficult to generate
RF frequencies below ~200 MHz for 	
→ Some hadron linear accelerators → Cyclotrons → Low- and medium energy hadron synchrotrons	

Why choose a **high** RF frequency?

Advantages	Disadvantages
• Cavity size scales $\propto 1/f$, volume $\propto 1/f^3$ • Break down voltage increases • High gradient per length • Particle bunches are short	• Maximum beam available aperture scales $\propto 1/f$ • No technology for wide-band or tunable cavities • Power amplifiers more difficult • Power transmission losses
RF frequencies above ~200 MHz used for 	
→ Linear accelerators → Electron storage rings → High energy hadron storage rings	

Limits to maximum gradient

- Surface electric field in vacuum



→ High frequencies preferred for large gradient

Some standard frequencies

If exact RF frequency not critical, choose standard value

Accelerator	Frequency
Hadron synchrotrons (PSB, PS, JPARC RCS, MR)	<10 MHz
Hadron accelerators and storage rings (RHIC, SPS)	~200 MHz
Electron storage rings (LEP, ESRF, Soleil)	352 MHz
Electron storage rings (DORIS, BESSY, SLS,...)	499.6...499.8 MHz
Superconducting electron linacs and FELs (X-FEL, ILC)	1300 MHz
Normal conducting electron linacs (SLAC)	2856 MHz
High-gradient electron linac (CLIC)	11.99 GHz

- Off-the-shelf **RF components easily available** in frequency ranges used by industry
- **Exchange of developments and equipment amongst research laboratories**

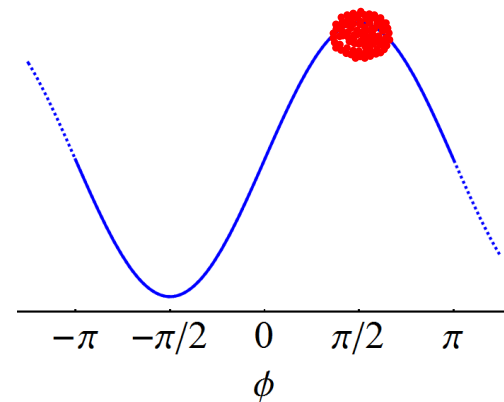
RF voltage

Minimum voltage requirement

- RF system expected to provide given energy gain

$$qV = \Delta E$$

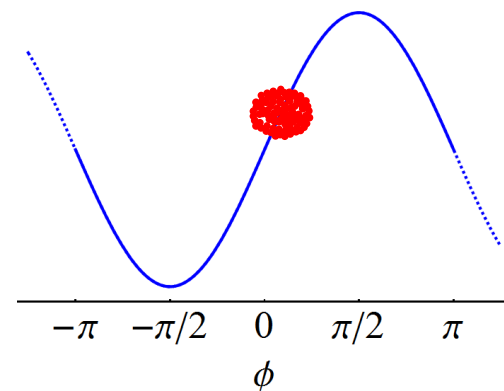
- On-crest acceleration
- Used in some linear accelerators
- Insufficient in a circular accelerator



- More voltage provided to avoid on-crest acceleration

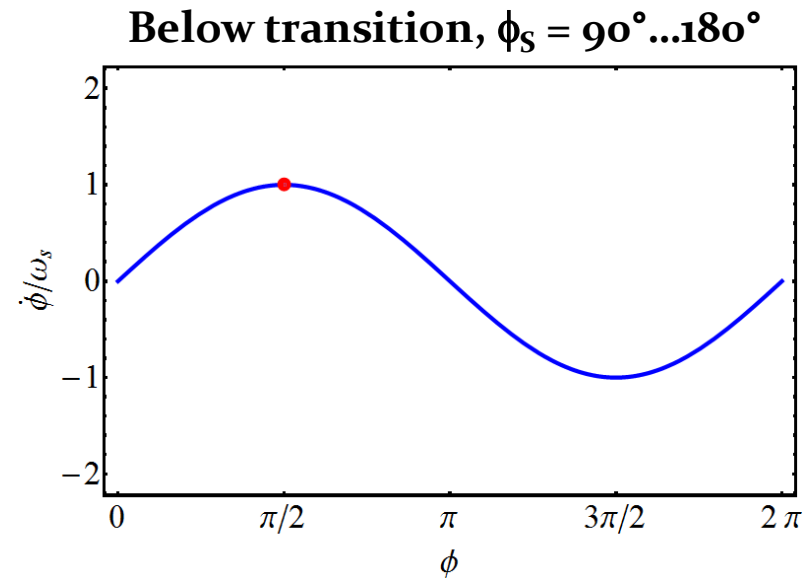
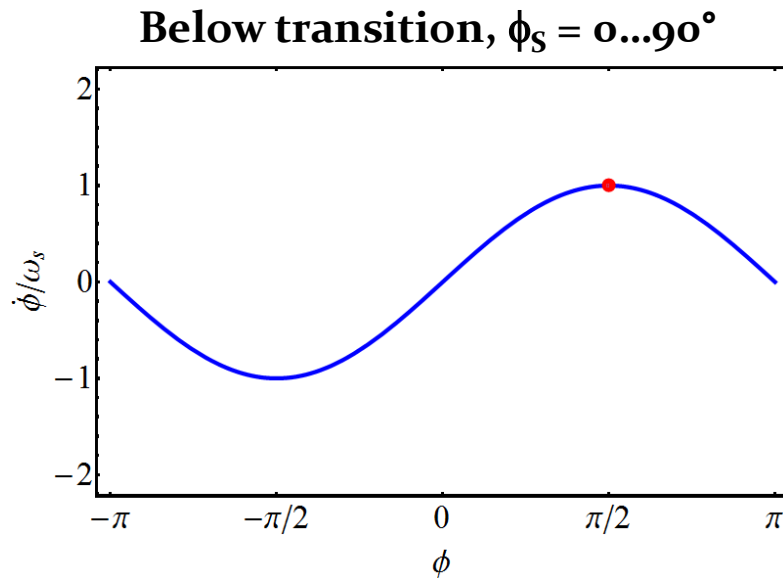
$$qV > \Delta E \rightarrow qV \sin(\phi_S) = \Delta E$$

- Off-crest acceleration
- Needed for circular accelerator
- Higher voltage for given energy gain



Bucket area dependence on stable phase

- In a circular accelerator the area in energy-time phase space (bucket area) depends on the stable phase



- Typical synchronous phase with respect to 0° or 180°
 - Hadron accelerators: $< 40^\circ$
 - Electron storage rings: $\sim 20^\circ$

Minimum voltage requirement (circular)

The RF system must compensate

1. Energy gain per turn due to changing magnetic field

$$F_Z = F_L \quad \rightarrow \quad \frac{p}{q} = \rho B \quad \rightarrow \quad \dot{p} = q\rho\dot{B}$$

$$\dot{p} = \frac{\Delta p}{\Delta t} = \frac{m_0 c^2 \beta}{2\pi R} (\beta \Delta \gamma + \gamma \Delta \beta) = \frac{\Delta E_{\text{turn}}}{2\pi R}$$

$$\Delta E_{\text{turn}} = 2\pi q \rho R \dot{B}$$

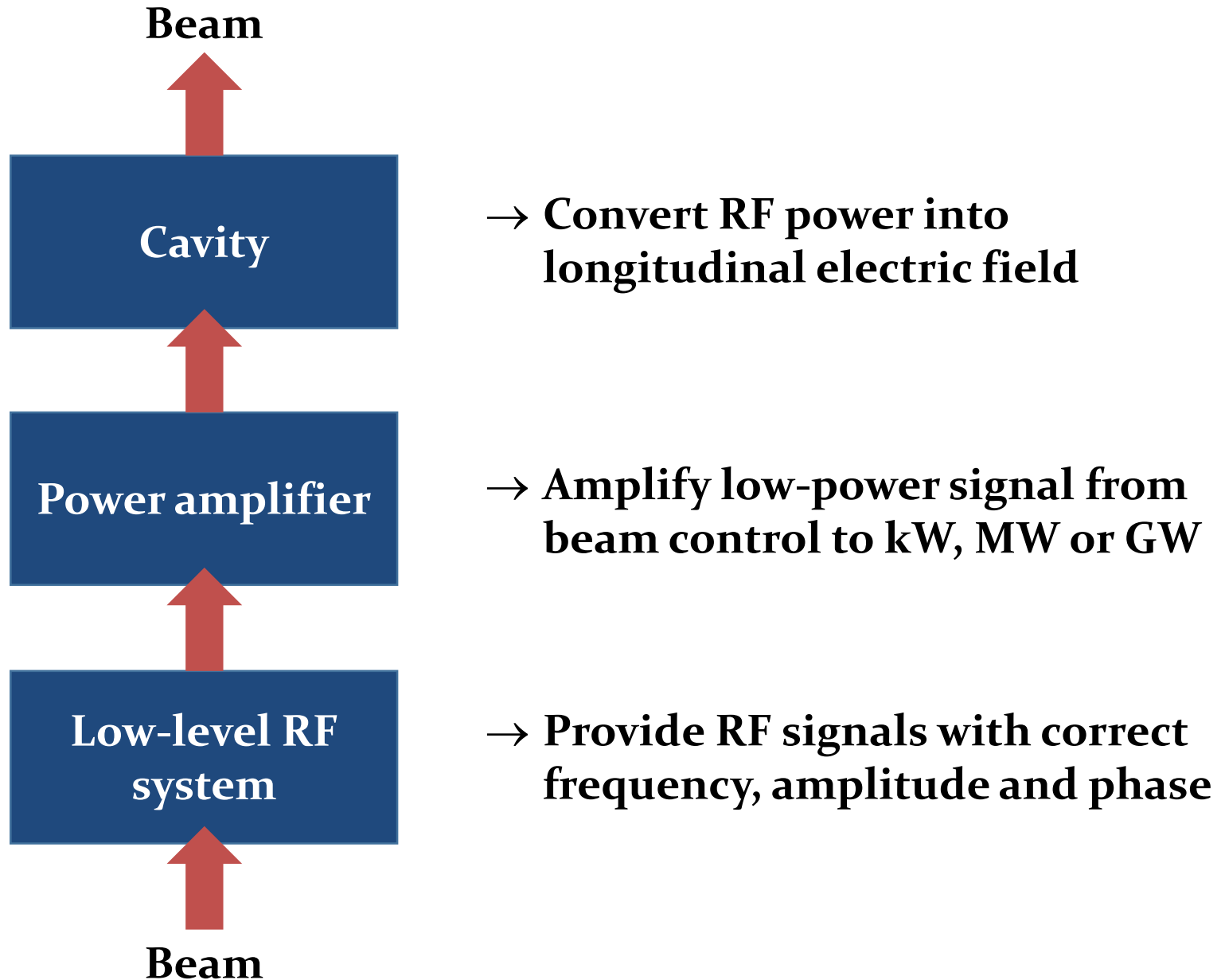
2. Energy loss, e.g., due to synchrotron radiation (electrons)

$$\Delta E_{\text{turn}} = \frac{e^2}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho}$$

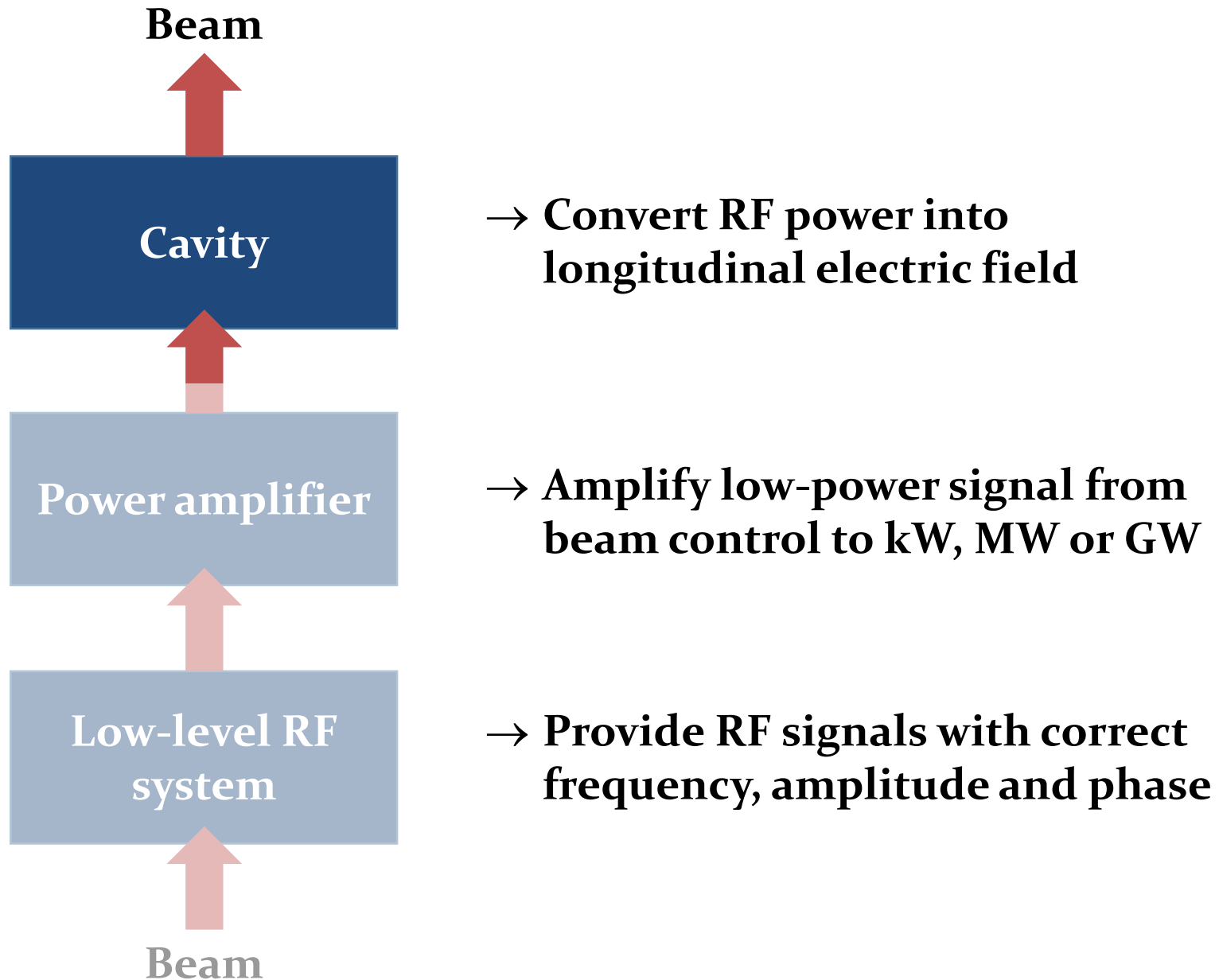
$$\Delta E_{\text{turn}}[\text{keV}] = 88.5 \cdot \frac{E^4[\text{GeV}]^4}{\rho[\text{m}]} \quad \Delta P_{\text{loss}}[\text{kW}] = 88.5 \cdot \frac{E^4[\text{GeV}]^4}{\rho[\text{m}]} \cdot I_B[\text{A}]$$

$$\rightarrow (m_p/m_e)^4 = 1836^4 \sim 1.1 \cdot 10^{13} \text{ times less for protons}$$

RF system overview



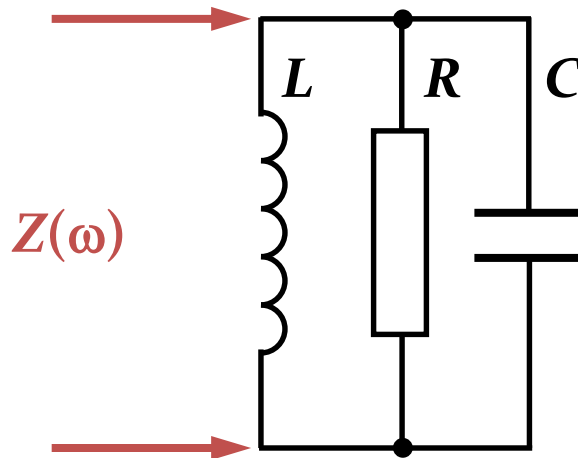
RF system overview



RF cavity

Cavity parameters

- The resonance of a cavity can be understood as simple parallel resonant circuit described by R , L , C



$$\frac{1}{Z(\omega)} = \frac{1}{R} + \frac{1}{i\omega L} + i\omega C$$

with $\omega_0 = \frac{1}{\sqrt{LC}}$

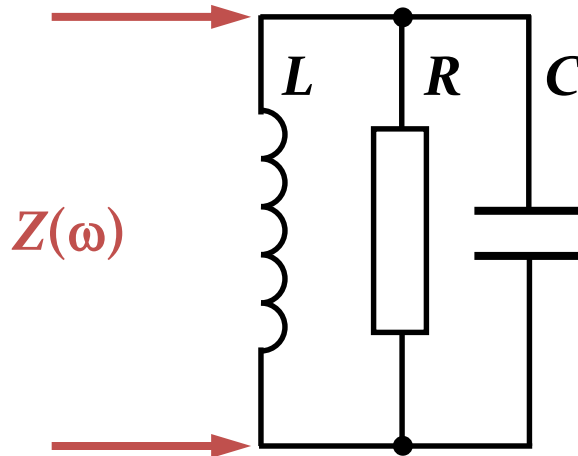
$$Q = \omega_0 \frac{\text{Stored energy}}{\text{Average power loss}} = \frac{\omega_0 E}{P}$$

$E = \frac{1}{2}CV^2 = \frac{1}{2}LI^2$
 $P = \frac{1}{2}\frac{U^2}{R} = \frac{1}{2}I^2R$

$$Q = \omega_0 RC = \frac{R}{\omega_0 L}$$

Cavity parameters

- The resonance of a cavity can be understood as simple parallel resonant circuit described by **R , L , C**



$$\frac{1}{Z(\omega)} = \frac{1}{R} + \frac{1}{i\omega L} + i\omega C$$

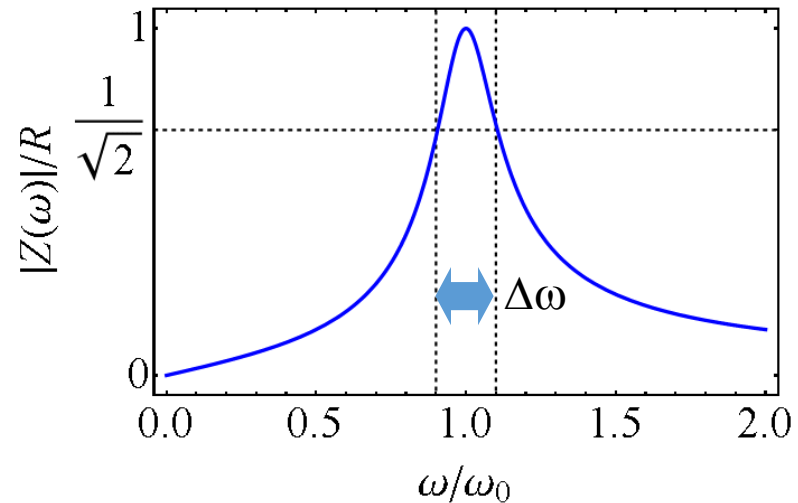
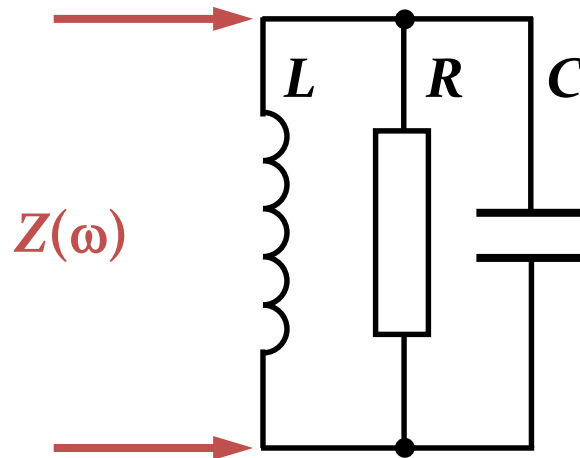
with $\omega_0 = \frac{1}{\sqrt{LC}}$

$$Q = \omega_0 RC = \frac{R}{\omega_0 L} \quad Z(\omega) = \frac{R}{1 + iQ \left(\frac{\omega^2 - \omega_0^2}{\omega\omega_0} \right)} \simeq \frac{R}{1 + 2iQ \frac{\Delta\omega}{\omega_0}}$$

→ Resonant circuit can also be described by **R , R/Q , ω_0** or any other set of three parameters

Cavity parameters

- The resonance of a cavity can be understood as simple parallel resonant circuit described by R, L, C



$$Q = \omega_0 RC = \frac{R}{\omega_0 L} \quad Z(\omega) = \frac{R}{1 + iQ \left(\frac{\omega^2 - \omega_0^2}{\omega \omega_0} \right)} \simeq \frac{R}{1 + 2iQ \frac{\Delta \omega}{\omega_0}}$$

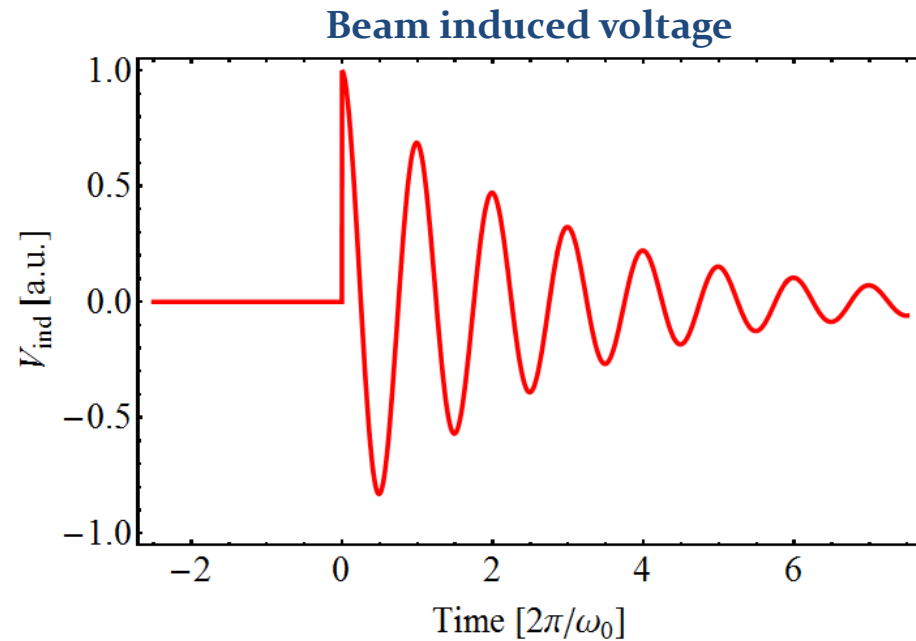
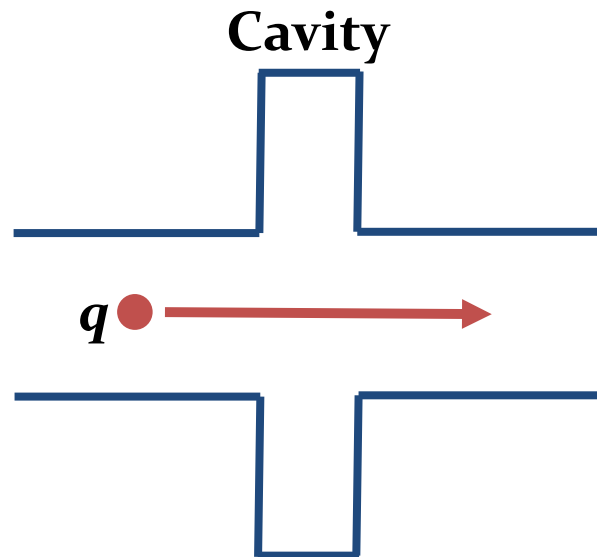
→ Resonant circuit can also be described by $R, R/Q, \omega_0$ or any other set of three parameters

Cavity parameters

- Most common choice by cavity designers ω_o , R , R/Q – why?
- **Resonance frequency, ω_o**
 - Exactly defined for given application, e.g. hf_{rev}
- **Shunt impedance, R**
 - Power required to produce a given voltage **without beam**
- **“R-upon-Q”, R/Q**
 - Defined only by the cavity geometry
 - Criterion to optimize a geometry
 - Detuning with beam proportional to R/Q

Why R/Q?

→ Charged particle experiences cavity gap as capacitor



$$q = V_{\text{ind}} C$$

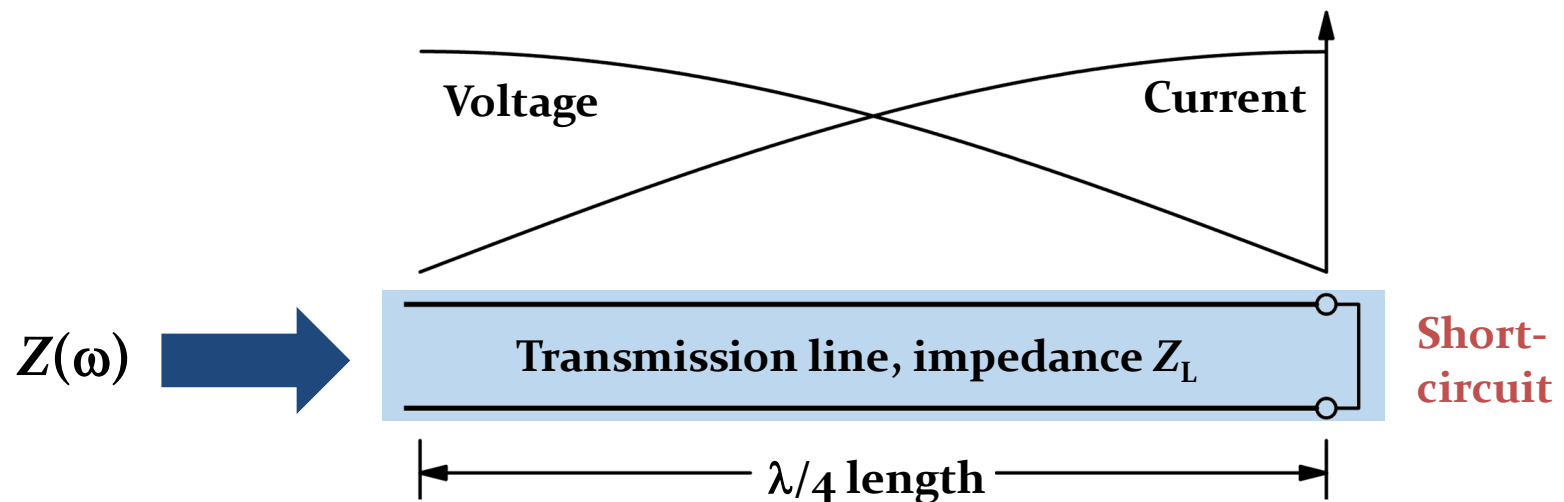
$$Q = \omega_0 RC \quad \rightarrow \quad \frac{1}{C} = \left(\frac{R}{Q} \right) \omega_0$$

$$V_{\text{ind}} = \frac{q}{C} \propto \frac{R}{Q}$$

→ Cavity geometry with small R/Q to reduce beam loading

RF cavities in low frequency range

- **RF wavelength large below ~10 MHz: >30 m**
- Would need huge cavities → too large for accelerators
- Line resonators: **$\lambda/4$ resonator**



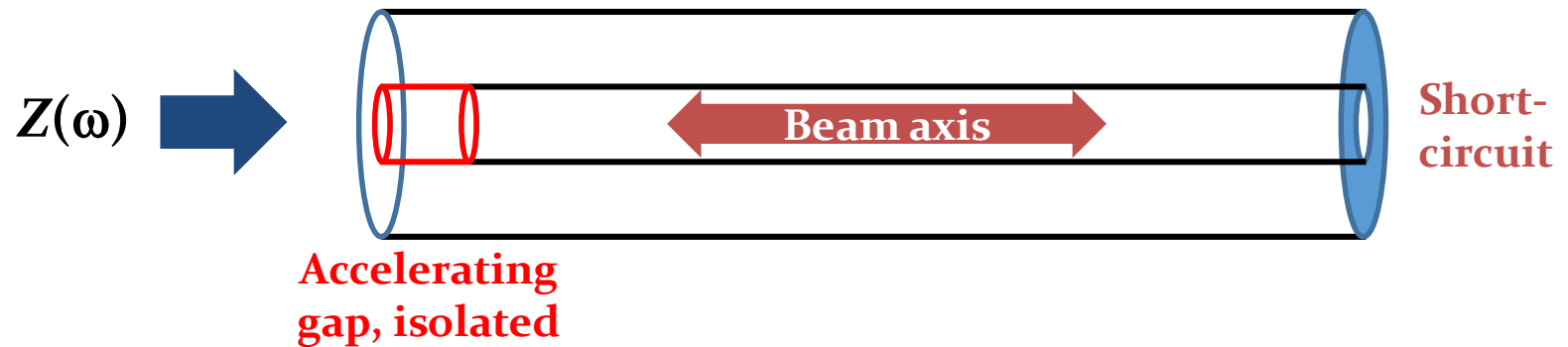
- Short circuit on one side
- Open end on other

- Voltage is zero
- No current but voltage

Why is this resonator so common in particle accelerators?

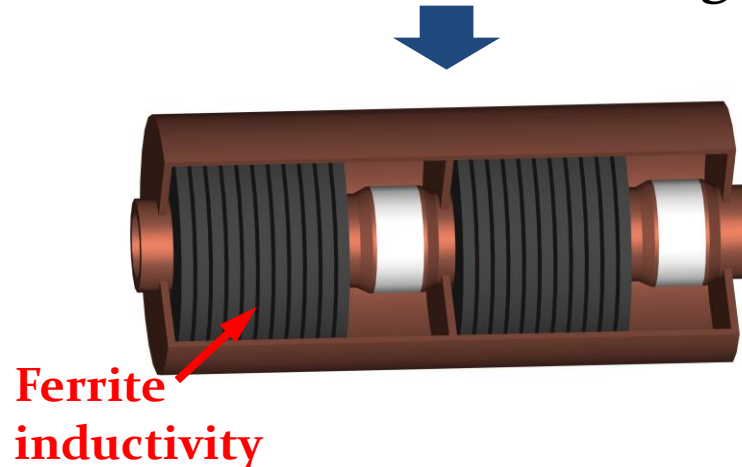
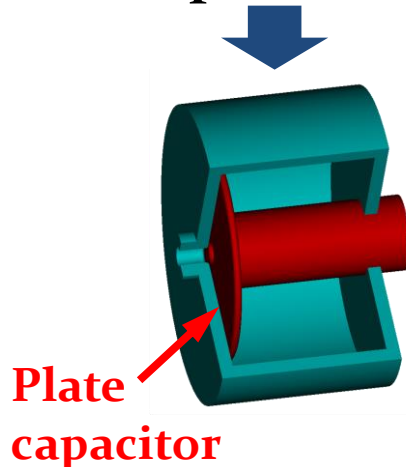
RF cavities in low frequency range

- Coaxial structure with inner conductor as beam pipe



→ Still rather long geometry, 7.5 m at 10 MHz

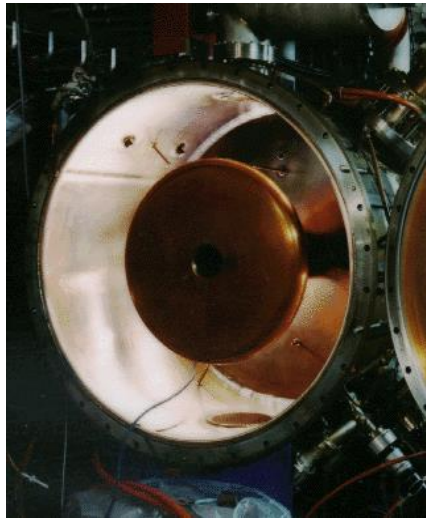
→ Add capacitive or inductive shortening



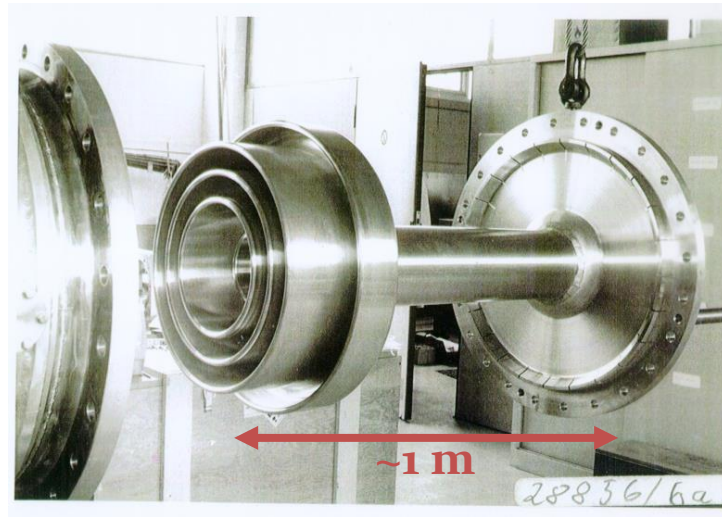
Capacitive loading

→ Add capacitor at gap of cavity to shorten the resonator

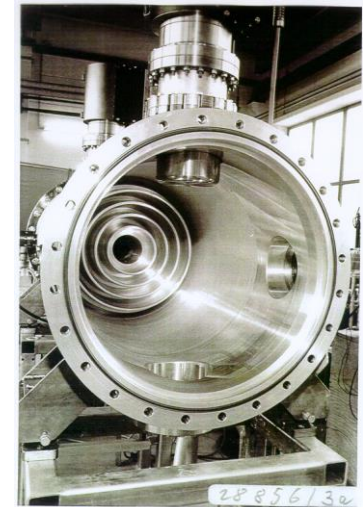
NSLS, 52.88 MHz



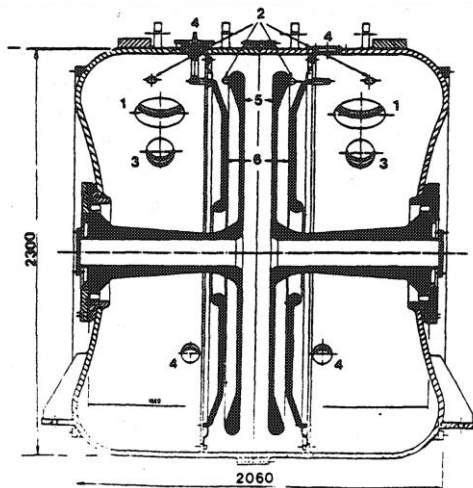
DESY PIA, 10.4 MHz, inner cond.



Outer cond.



ACOL, 9.53 MHz

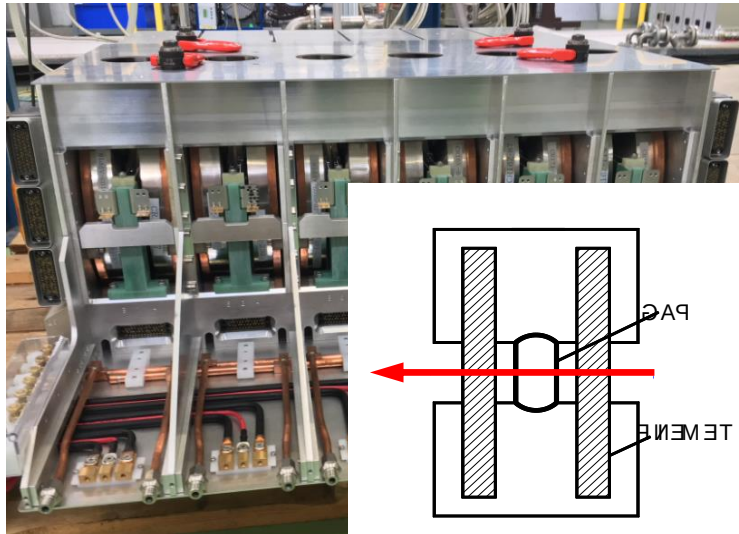


- Significantly reduces cavity size
- Fixed frequency only
- Small losses due to capacitor
- Cavity in vacuum

Inductive loading

- Inductive loading with magnetic material shortens resonator from tens of meters to a device, **lossy though**

CERN PSB Finemet cav., 0.6-18 MHz



CERN PS, double gap, 2.8-10 MHz

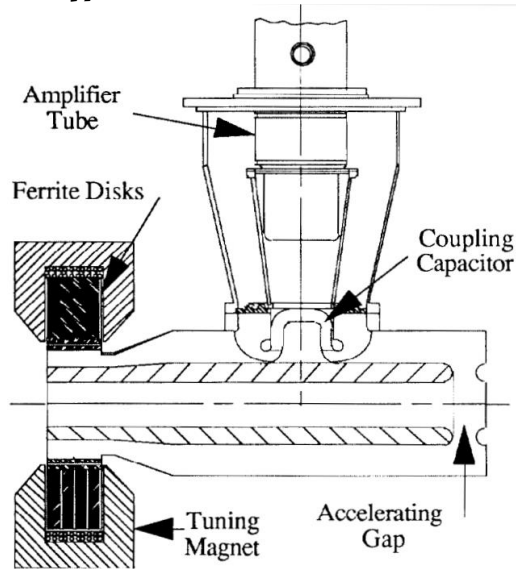


- Additional advantage: permeability of ferrite can be controlled by DC bias current → **variable inductivity**
 - Cavity with programmable resonance frequency
 - Essential for hadron acceleration in low-energy accelerators

Tunable cavities at higher frequencies

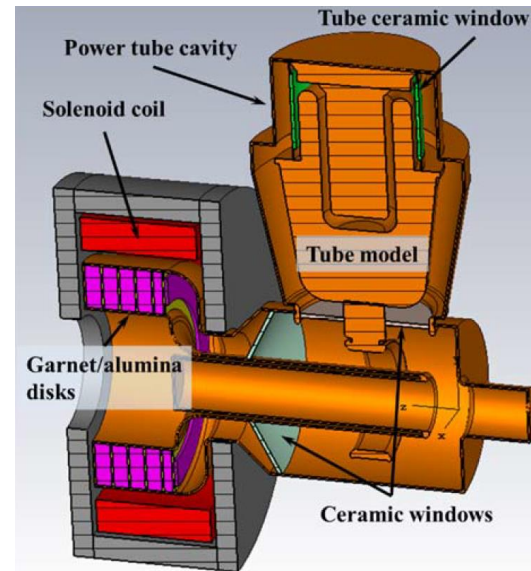
→ Remove inductive or capacitive loading

**SSC Low Energy Booster,
~47 MHz to 60 MHz**



C. C. Friedrichs et al., PAC91, p. 1020

**FNAL Booster 2nd harmonic,
76 MHz – 106 MHz, 100 kV**



R. L. Madrak, IPAC16, p. 130

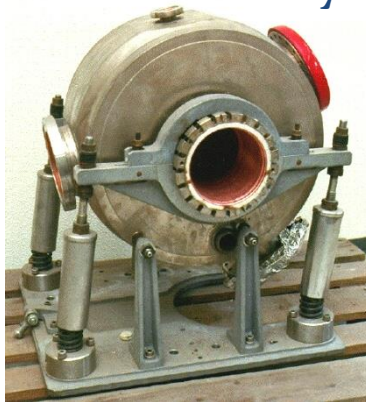
→ Upper frequency limit for cavities with large tuning range

Further increase frequency

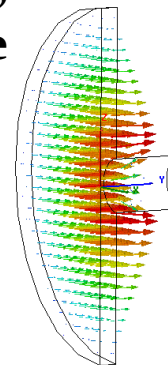
→ Remove inner conductor from coaxial set-up



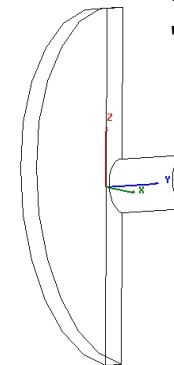
→ The resonator becomes a pill-box cavity
DORIS cavity



Electric field,
 TM_{010} -mode



Magnetic field,
 TM_{010} -mode

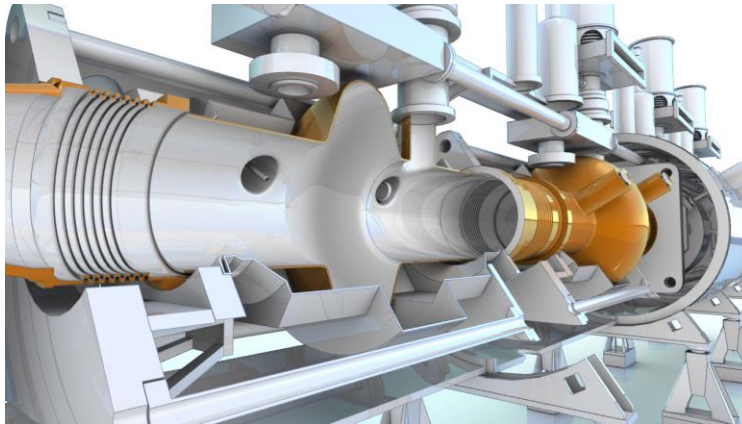


E. Jensen

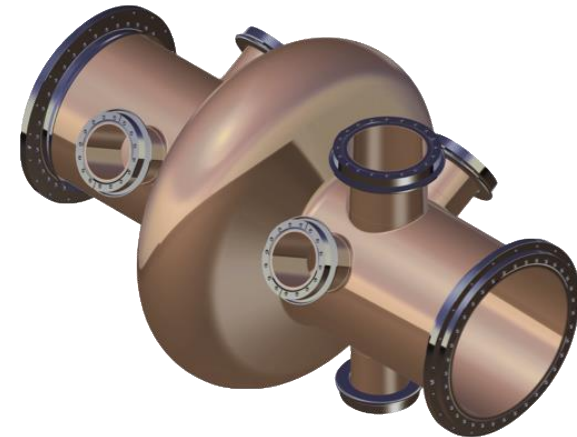
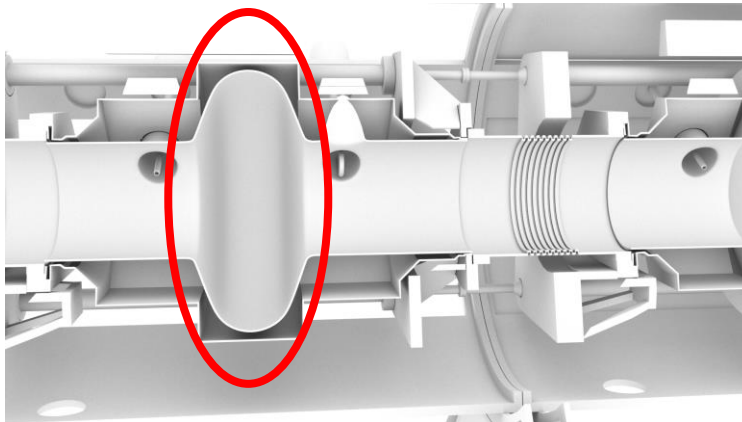
→ The basis for cavity resonators

Example: 400 MHz cavities in LHC

- Reduce beam loading in RF cavities
- Shunt impedance, R , low for small R/Q with normal conducting cavities → **superconducting cavities in LHC**



Bell shape: $R/Q \sim 44 \Omega$, 400 MHz



→ 2×8 cavities, 5.3 MV/m

$$\frac{1}{Q} = \frac{1}{Q_{\text{cav}}} + \frac{1}{Q_{\text{ext}}}$$

~0

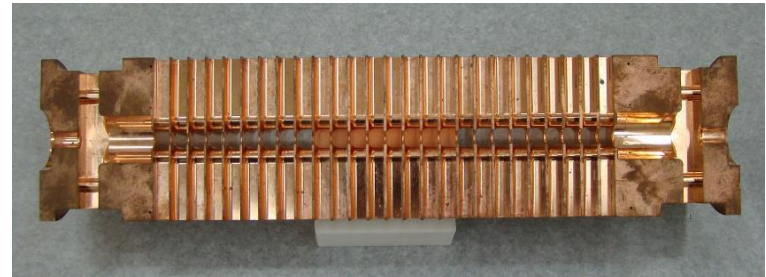
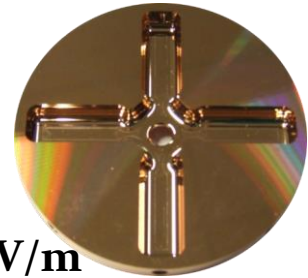
RF cavities in linear accelerators

- Beam only passes once → **Maximize gradient**
- Many accelerating cells to best reuse RF voltage

SuperHILAC, ~70 MHz, Berkley



CLIC, 12 GHz, ~100 MV/m

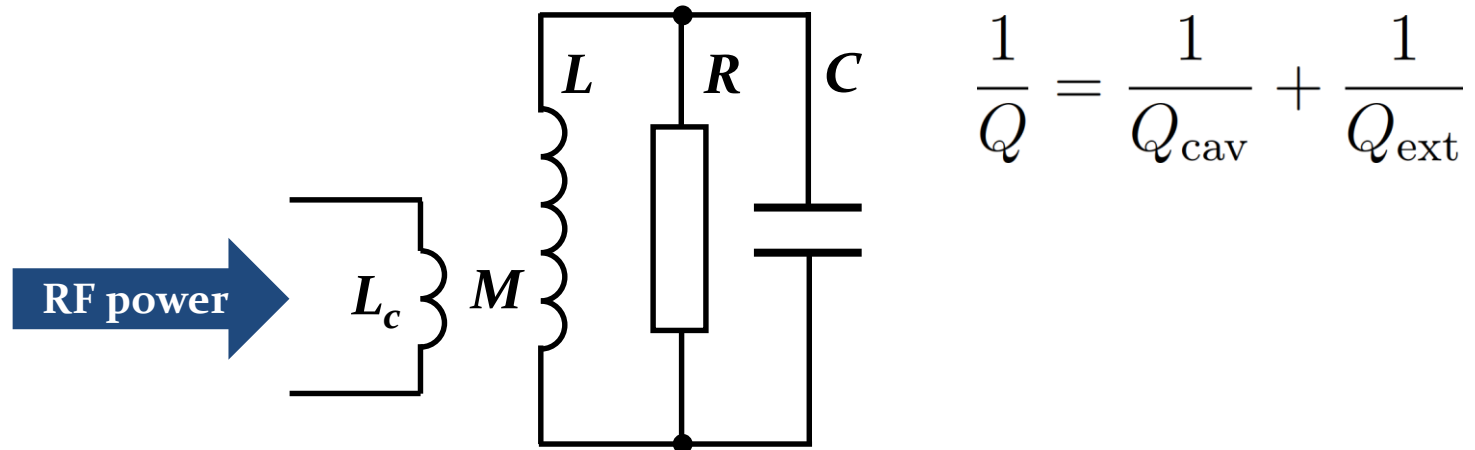


- Cavity is the **contrary** to 'one size fits all'
- Many, many more variants

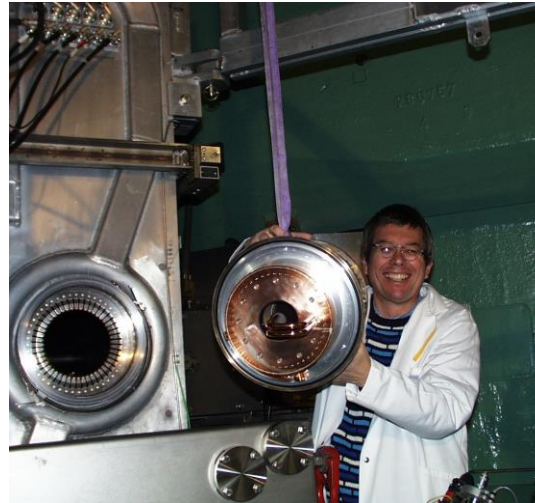
Coupling power into a cavity

Coupling power into a cavity

- Attack **inductivity** or capacitance of resonator, or combined



→ Coupling **loop** forms **transformer** with **resonator** inductivity



L. Stigelin

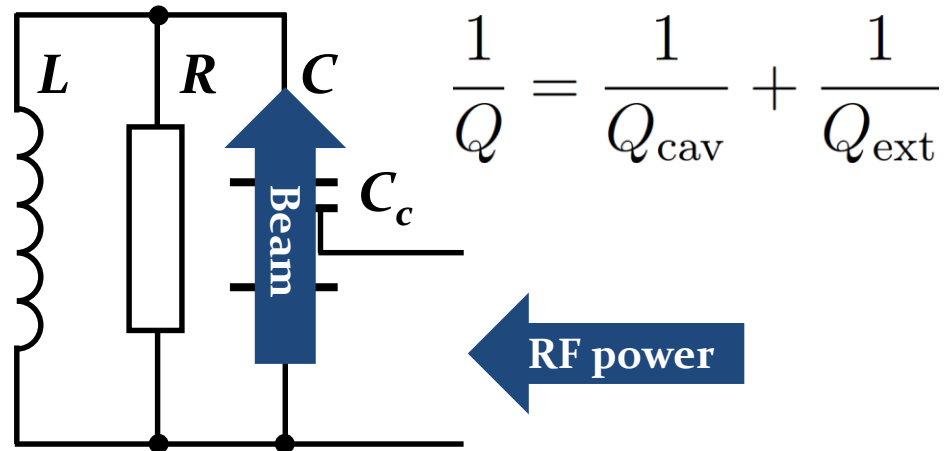
- Main coupler
PSI cyclotron
- **~1 MW at 50 MHz**



A. Rodchenko

Coupling power into a cavity

- Attack inductivity or **capacitance** of resonator, or combined



- **Capacitive divider** to gap to transform generator impedance to cavity shunt impedance
- Beam also **couples capacitively** via the gap

Coupler of CERN PS 40 MHz



- Coupler forms one **half of capacitor** with the gap

Capacitive (electric) coupling

- Coupling through an electric antenna

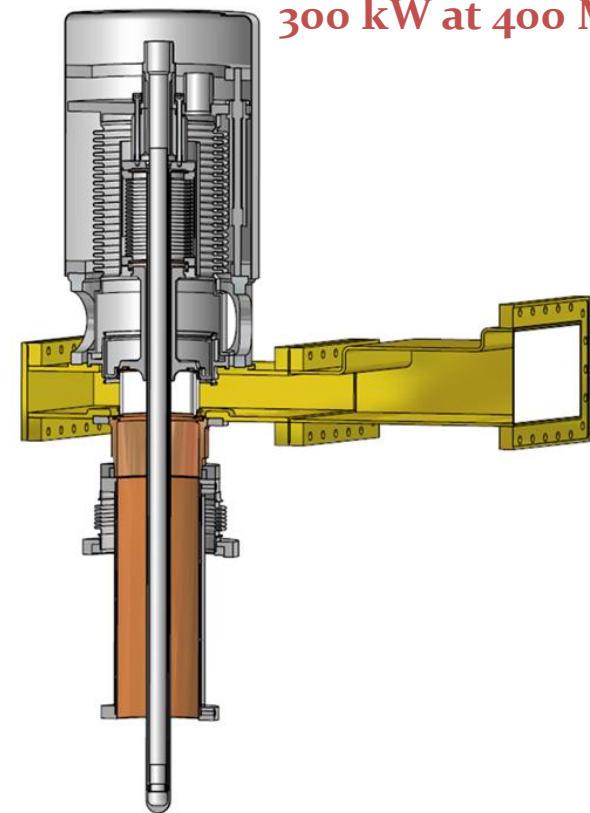
Electrical coupler to space



https://en.wikipedia.org/wiki/Transmitter_Solt

→ 2 MW at 540 kHz

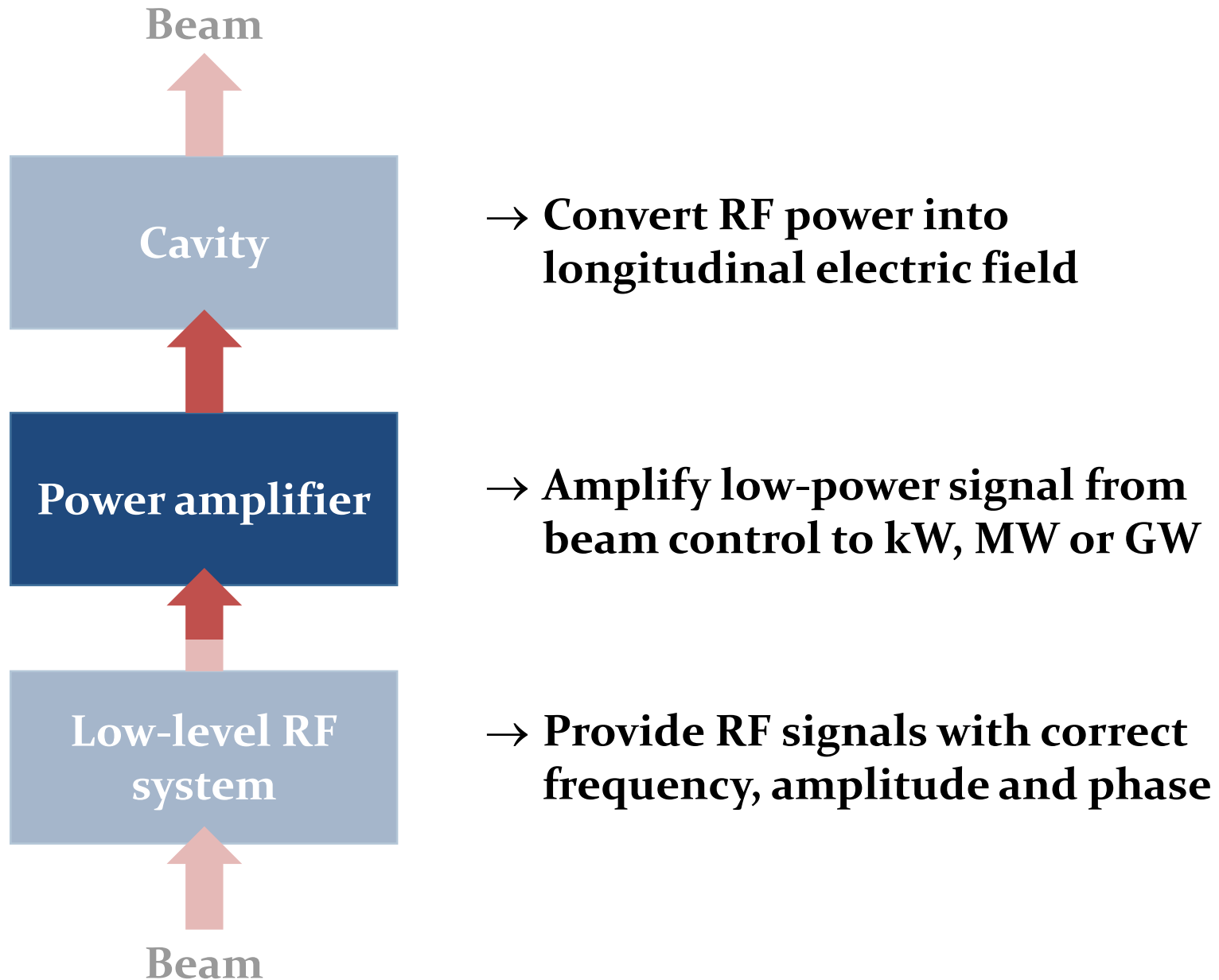
Power coupler of LHC cavities



300 kW at 400 MHz

→ Coupler antenna transmits directly into the cavity

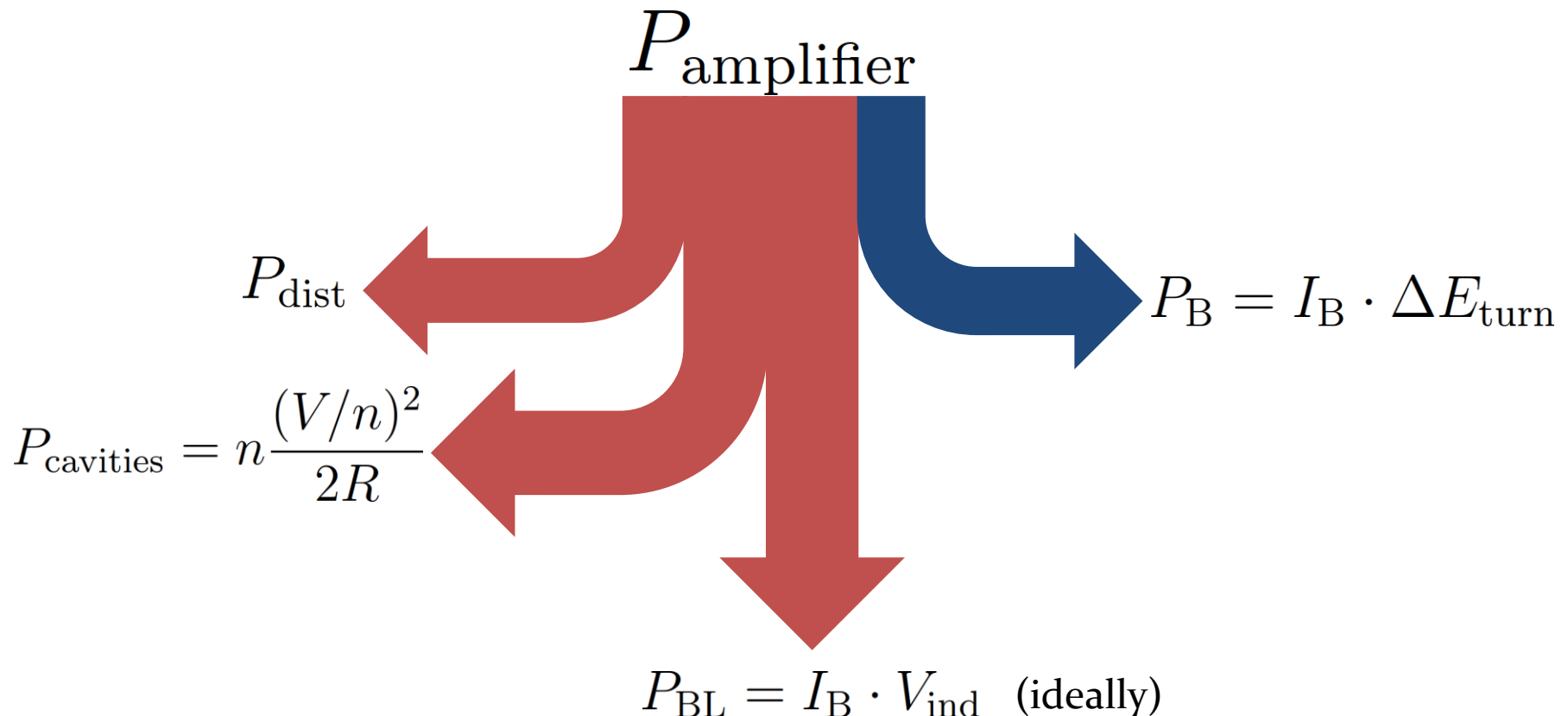
RF system overview



Power amplifiers

How much power is required?

1. Power to accelerate beam → **Wanted**
2. Compensate beam-induced voltage → **Refl. P**
3. Compensate electrical losses in cavity → **Heat**
4. Compensate electrical losses in distribution → **Heat**



Power amplifiers

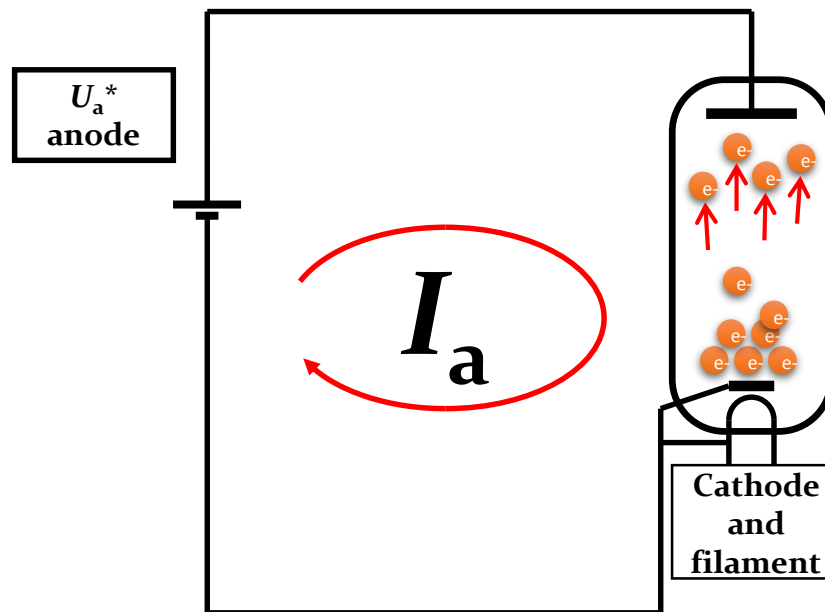
- Basically

$$P_{\text{out}} = g \cdot P_{\text{in}} \quad \text{or} \quad V_{\text{out}} = \sqrt{g} \cdot V_{\text{in}}$$

- The ideal power amplifier
 - Large bandwidth: amplifies all frequencies equally
 - No saturation, infinite power
 - Zero delay
 - No added noise
 - Unconditionally stable and resistant to reverse power
 - Radiation-hard
- Unfortunately such a device has not been invented yet
- Let us have a look at some real amplifiers

Basics of grid tube

- From diode to tetrode amplifier



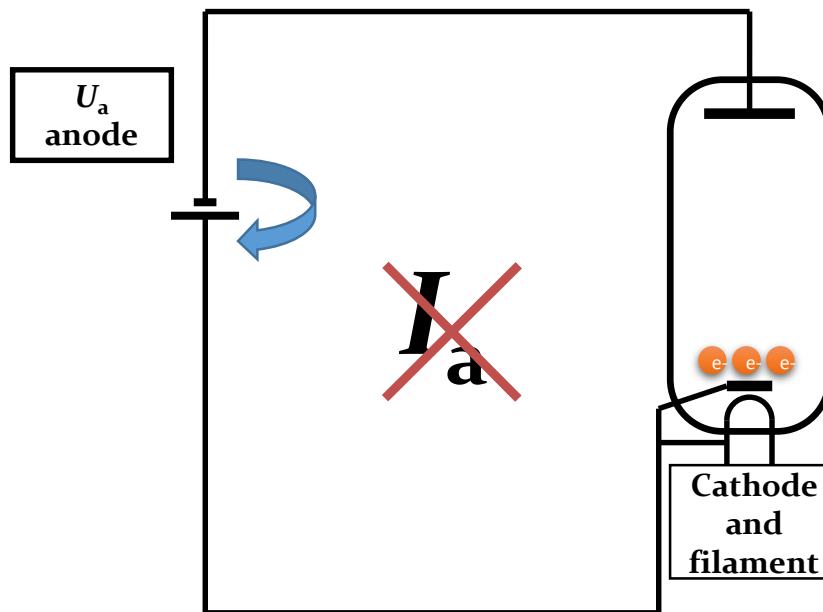
- Vacuum tube
- Heater + Cathode
- Heated cathode
 - Coated metal, carbides, borides,...
- thermionic emission
- Electron cloud
- Anode

→ Diode

*For tube amplifier designs
voltages are named U instead of V

Basics of grid tube

- From diode to tetrode amplifier

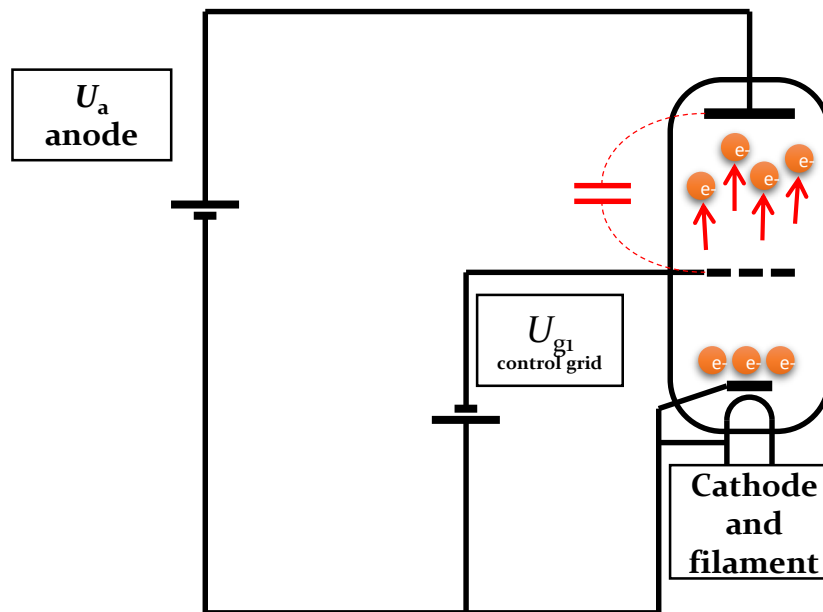


- Vacuum tube
- Heater + Cathode
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→ Diode

Basics of grid tube

- From diode to tetrode amplifier

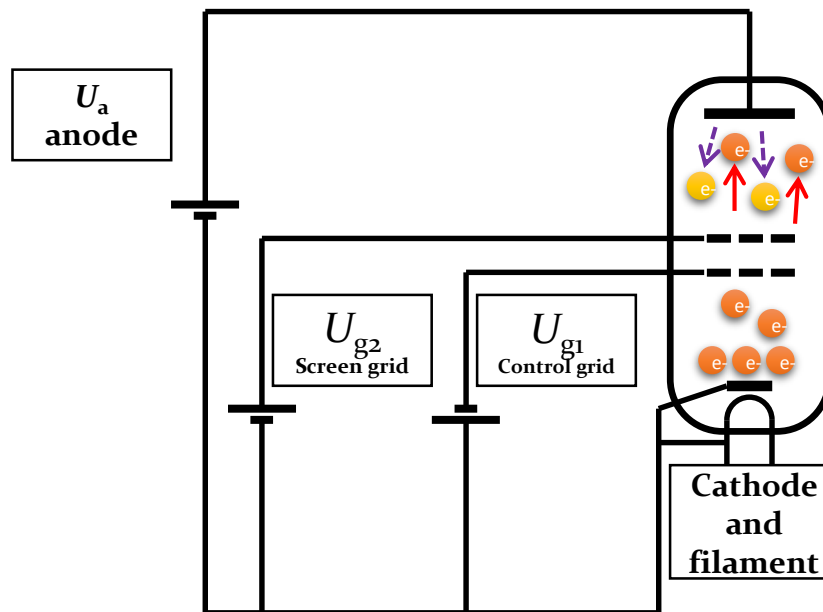


→ Triode

- Modulating the grid voltage proportionally modulates the anode current
- Transconductance
 - Voltage at grid
 - Current at anode
- Limitations
 - Parasitic capacitor from anode to control grid (g_1)
 - Tendency to oscillate

Basics of grid tube

- From diode to tetrode amplifier

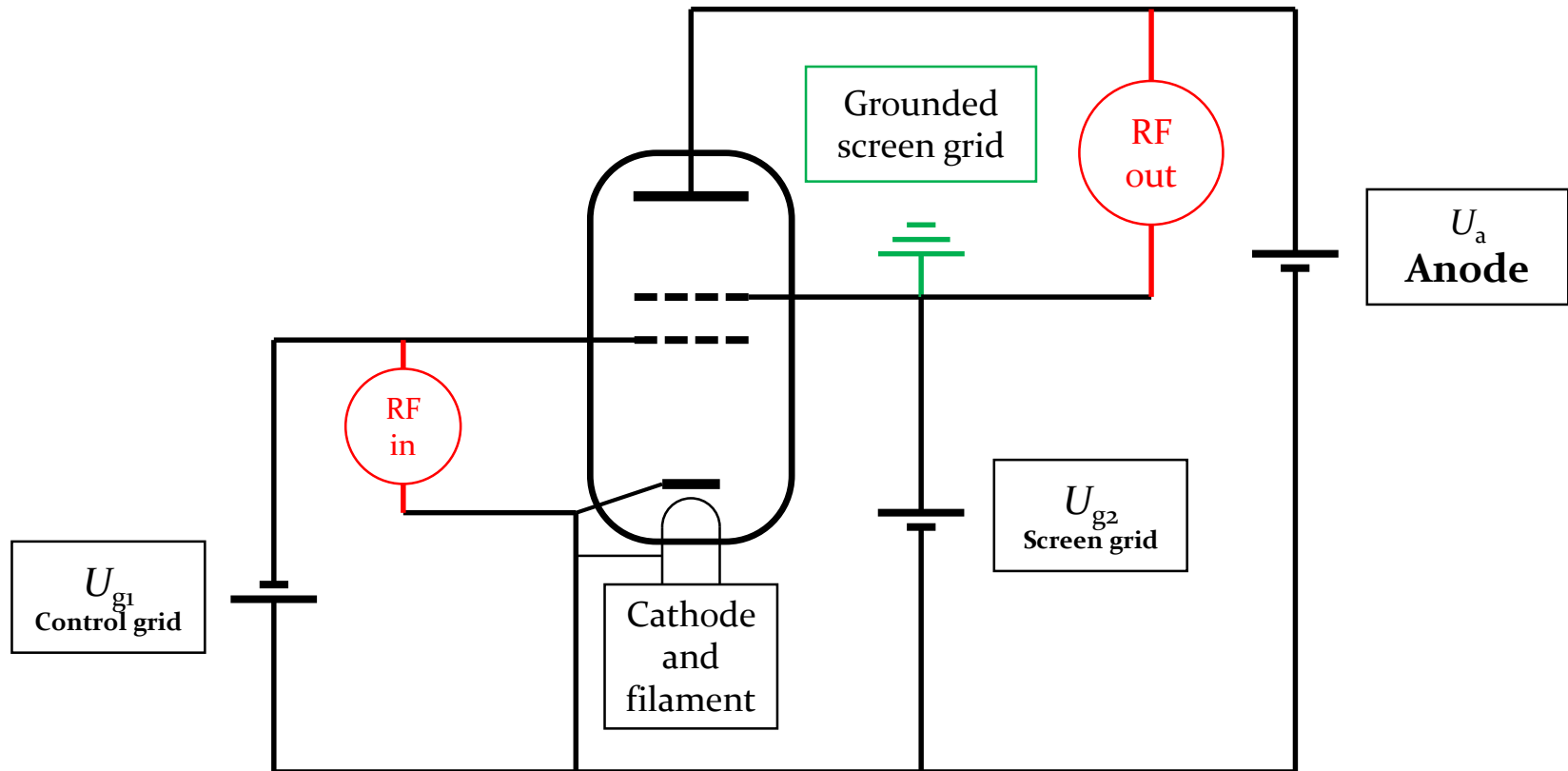


→Tetrode

- **Screen grid**
 - Positive (lower anode)
 - Decouple anode and g_1
 - Higher gain
- **Limitations**
 - Secondary electrons
 - Anode treated to reduce secondary emission

Tetrode based power amplifier

- Example of SPS 200 MHz amplifier, tetrode RS2004



→ Very simplified block diagram

Example: Tetrode amplifier driving SPS RF 48

- Two transmitters, 2×1 MW at 200 MHz (almost continuous)
- Eight tetrodes per amplifier

RS2004 tetrode



Amplifier trolley



Complete transmitter

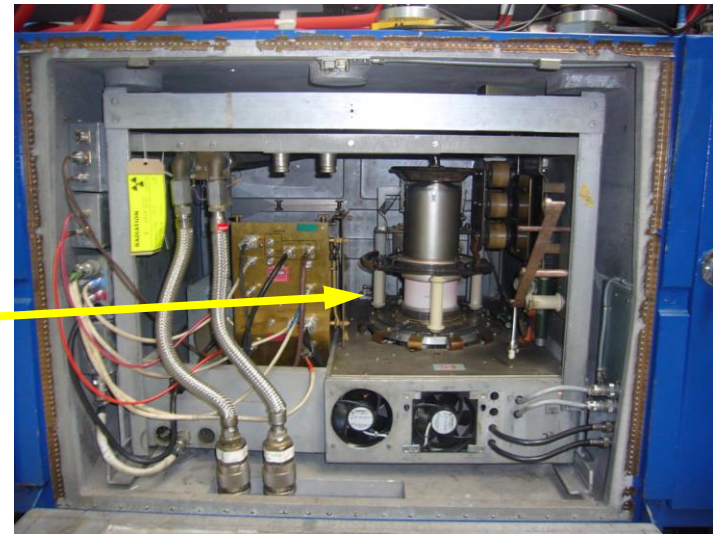
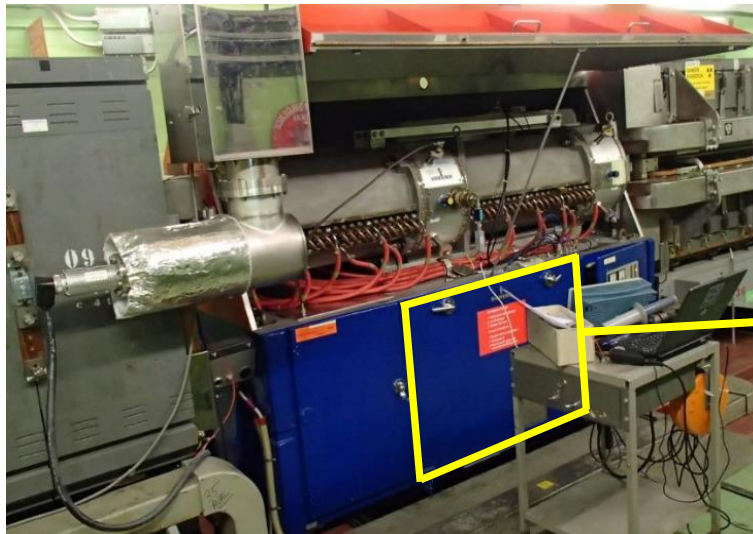


→ In operation since 1976

Tetrode amplifier driving PS RF

- Frequency range 2.8...10 MHz, ~60 kW per cavity, 11 units
- **Space constraints to have amplifier installed below cavity**

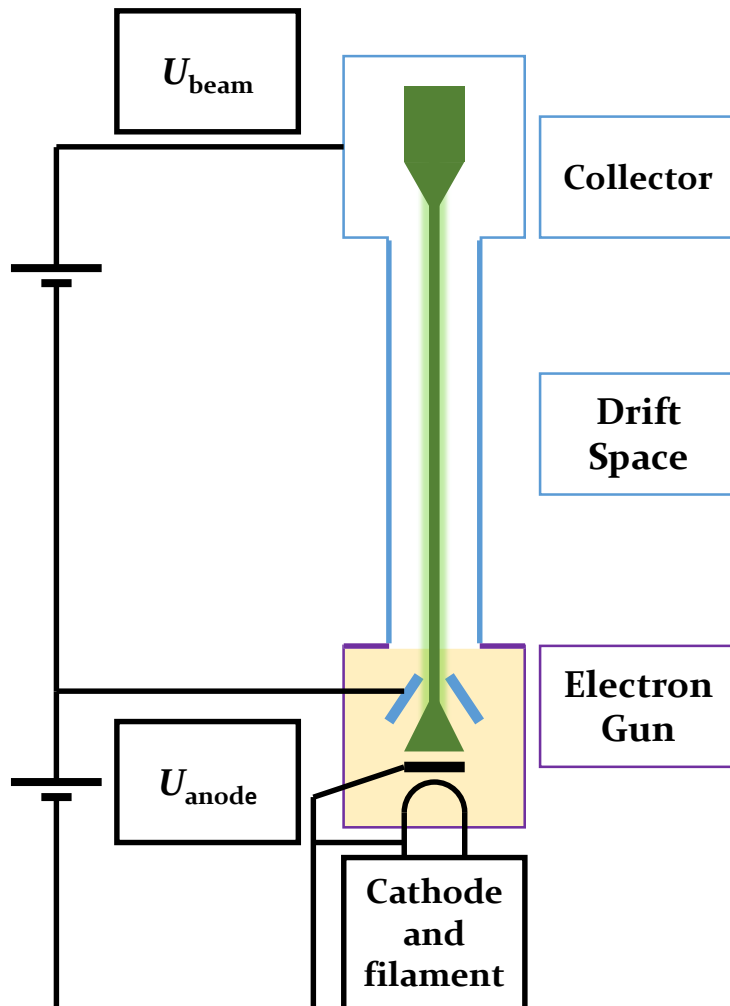
Amplifier trolley



- **Tetrode is obvious choice**
 - High power in small volume
 - Operates in radioactive environment

Basics of linear beam tube

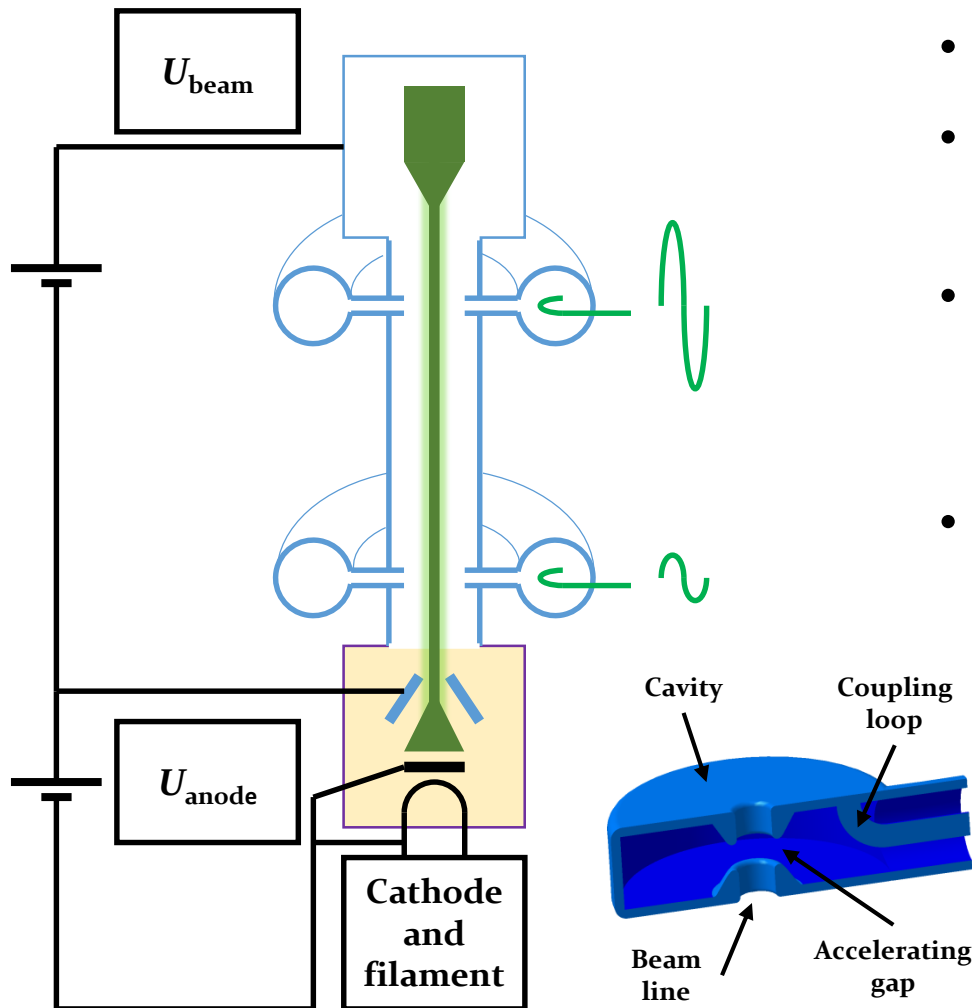
- **Klystron: a complete mini-accelerator**



- **Klystrons velocity modulation**
 - Converts the kinetic energy into RF power
- **Vacuum tube**
- **Electron gun**
 - Thermionic cathode
 - Anode
- **Electron beam**
- **Drift space**
- **Collector**
- **e- constant speed until the collector**

Basics of linear beam tube

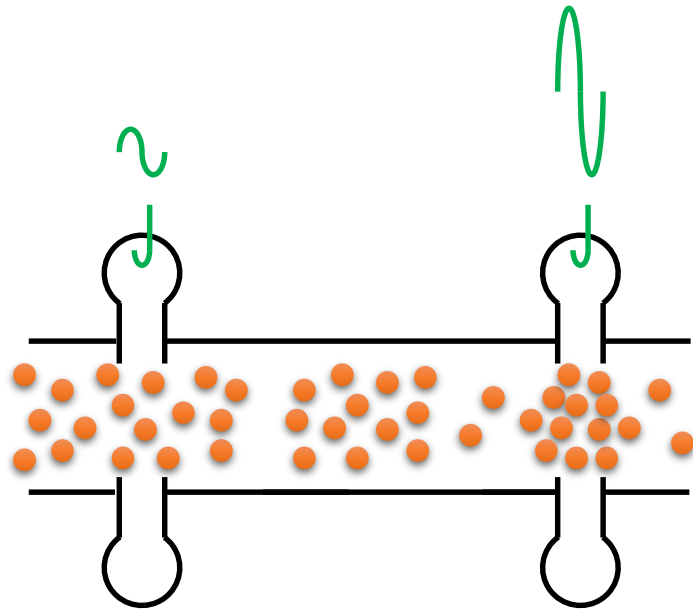
- Klystron: a **complete mini-accelerator**



- Cavity resonators and drift
- RF input cavity (Buncher)
 - Modulates electron velocity
- Drift space
 - Faster electrons catch up
 - Slower electrons fall behind
- RF output cavity (Catcher)
 - Resonating at same frequency as input cavity
 - At place where electrons are **maximally bunched**
 - Kinetic energy converted into voltage and extracted

Basics of linear beam tube

- **Klystron: a complete mini-accelerator**



- Cavity resonators and drift
- RF input cavity (Buncher)
 - Modulates electron velocity
- Drift space
 - Faster electrons catch up
 - Slower electrons fall behind
- RF output cavity (Catcher)
 - Resonating at same frequency as input cavity
 - At place where electrons are maximally bunched
 - Kinetic energy converted into voltage and extracted

Example: Klystrons driving accelerators

- **2×8 cavities**, each driven by separate 400 MHz klystron, **330 kW**
→ First klystron amplifiers powering a hadron collider



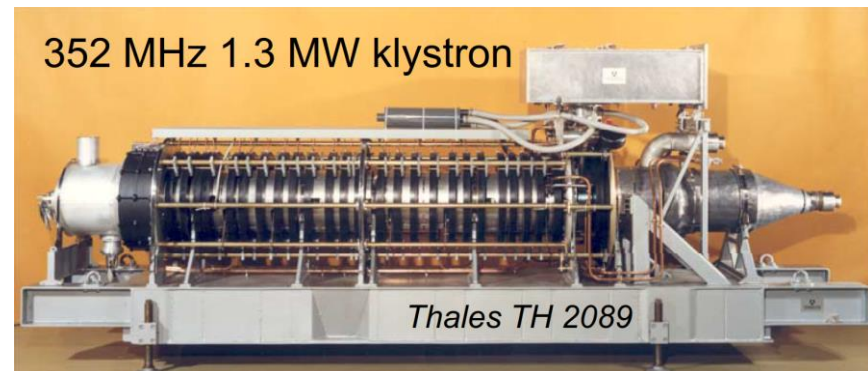
E. Montesinos

- 12 GHz pulsed klystron for CLIC
→ **50 MW in $1.5 \mu\text{s}$**

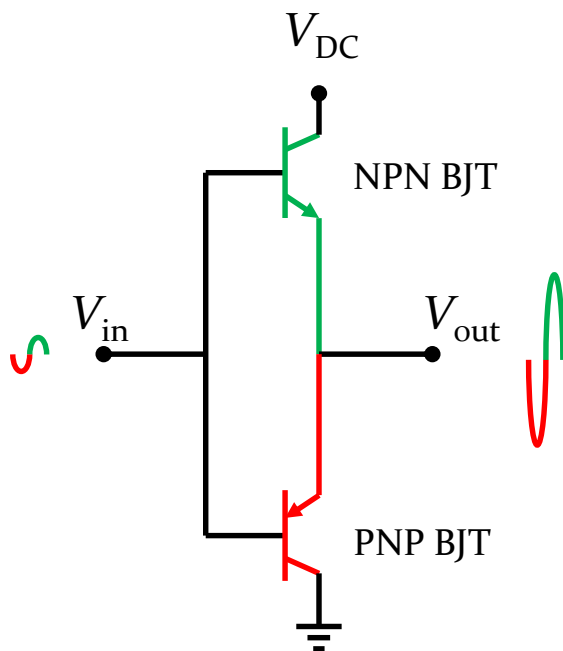


G. McMonagle

- Significantly more power was required to feed LEP (until 2000)
→ About **50 MW CW** was installed at 352 MHz



Basics of RF solid state amplifiers

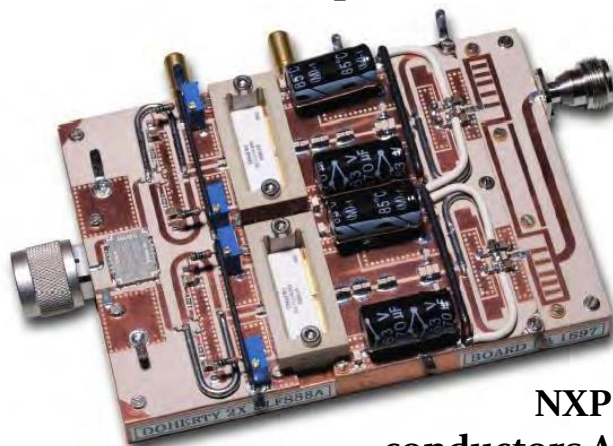
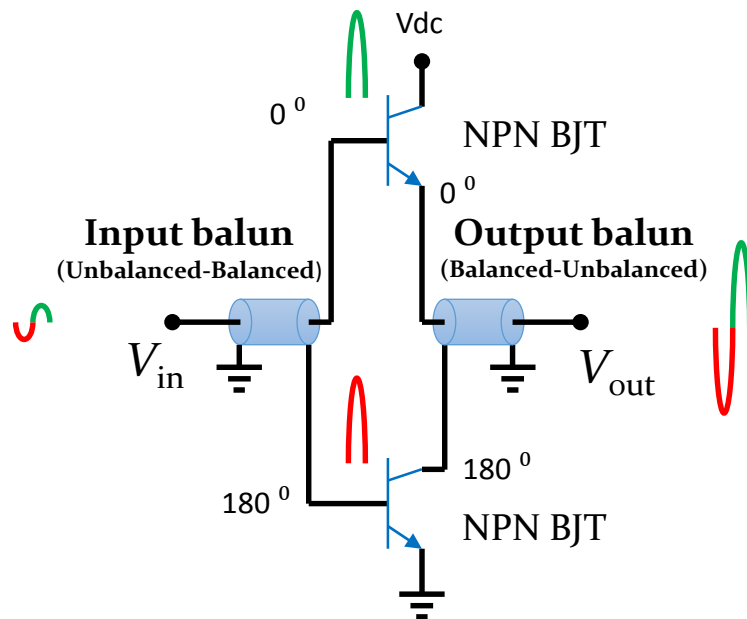


BJT: Bipolar Junction Transistor

- In a **push-pull** circuit the RF signal is applied to **two devices**
 - One of the devices is active on the positive voltage swing and off during the negative voltage swing
 - The other device works in the opposite manner so that the two devices conduct half the time
- The full RF signal is then amplified

→ Needs two different type of devices

Basics of RF solid state amplifiers

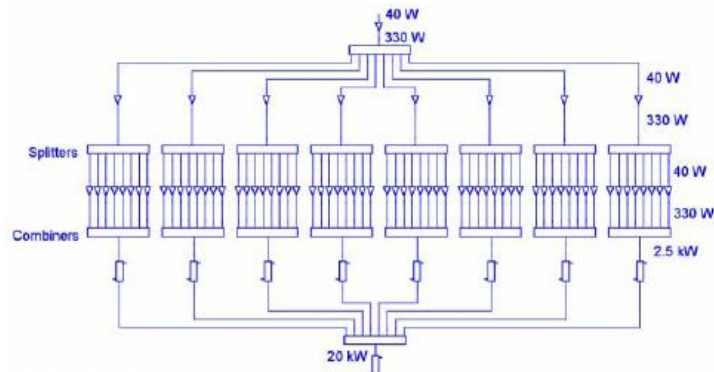


NXP Semi-
conductors AN11325
2-way Doherty amplifier with BLF888A

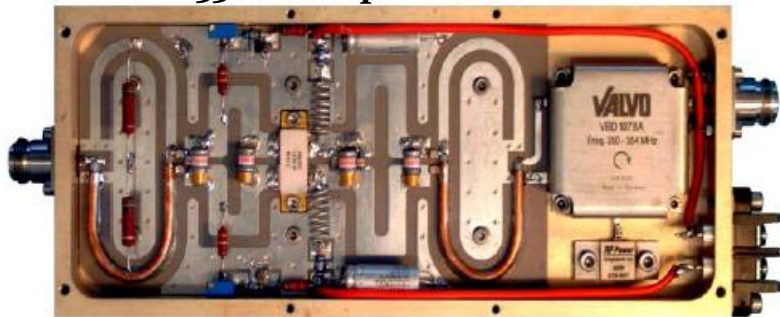
- Another **push-pull configuration** is to use a balun (balanced-unbalanced)
 - Power splitter, equally dividing the input power between the two transistors
 - Balun keeps one port in phase and inverts the second port in phase
 - Since the signals are out of phase only one device is On at a time
- This configuration is easier to manufacture since only one type of device is required

Example: Soleil 45 kW, 352 MHz

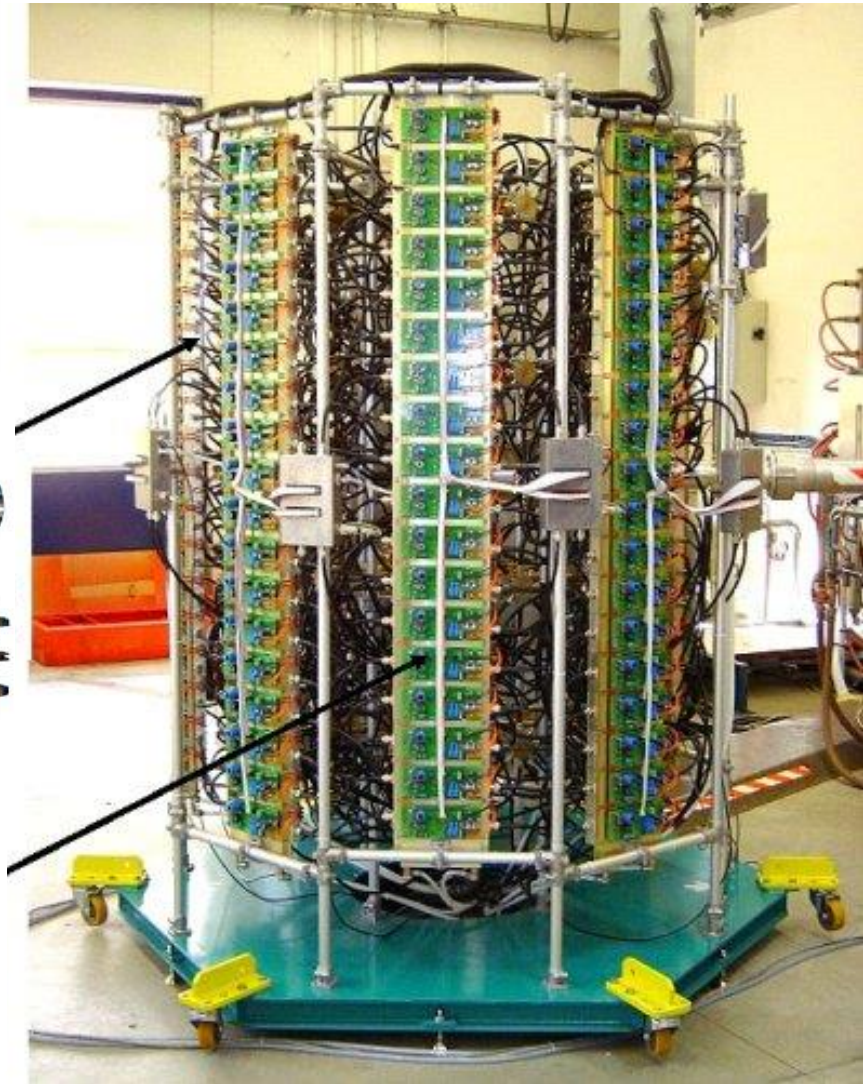
Electron storage ring running at 352 MHz



330 W amplifier module



600 W, 300 V_{DC}/30 V_{DC} converter



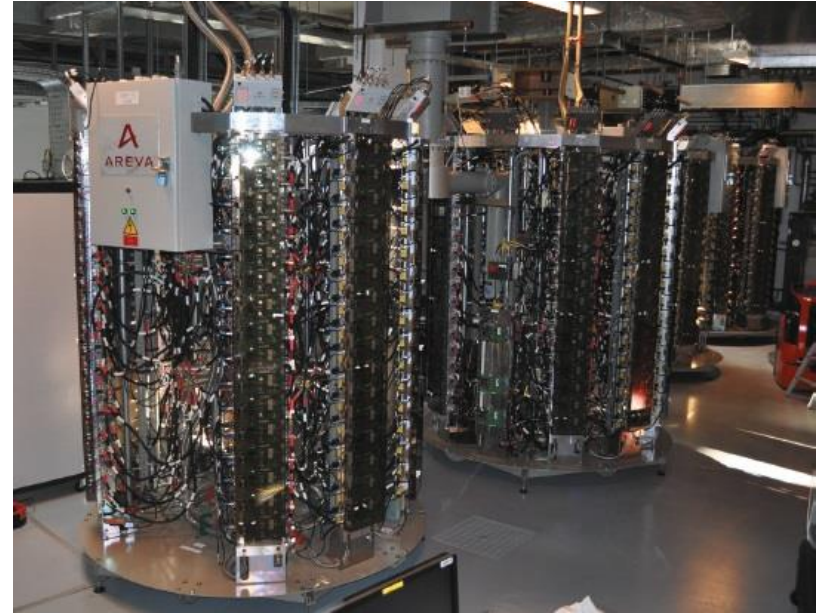
Example: Soleil 45 kW, 352 MHz

Large scale solid state amplifier installations

45 kW per tower (2004 and 2007)



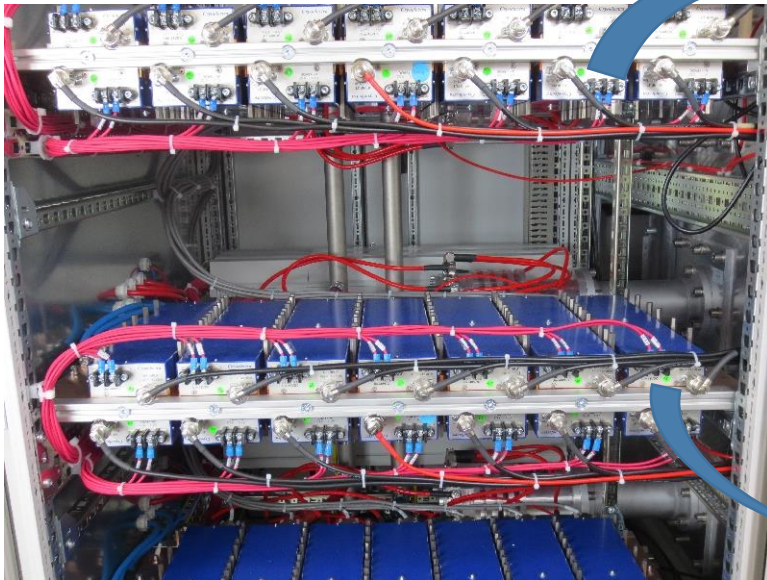
150 kW per tower (2012)



→ Requires a series of power combiners to moderate power per amplifier module to several tens of kilowatts

Example: BESSY II

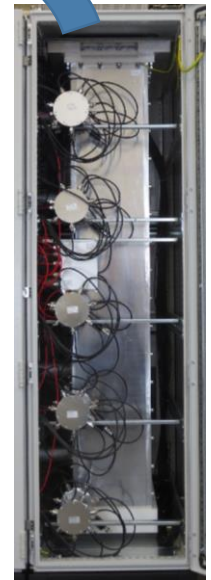
500 MHz solid state amplifiers: 4×80 kW for storage ring,
40 kW for booster synchrotron



Amplifier modules



80 kW unit

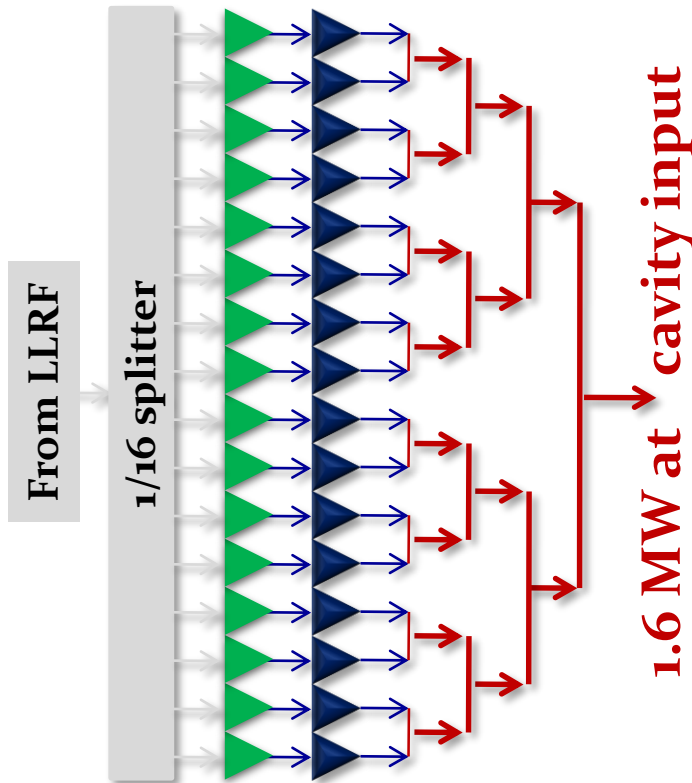


Combiner

- Power per module limited by RF transistors
- Increasing with modern semiconductor devices

Example: SPS

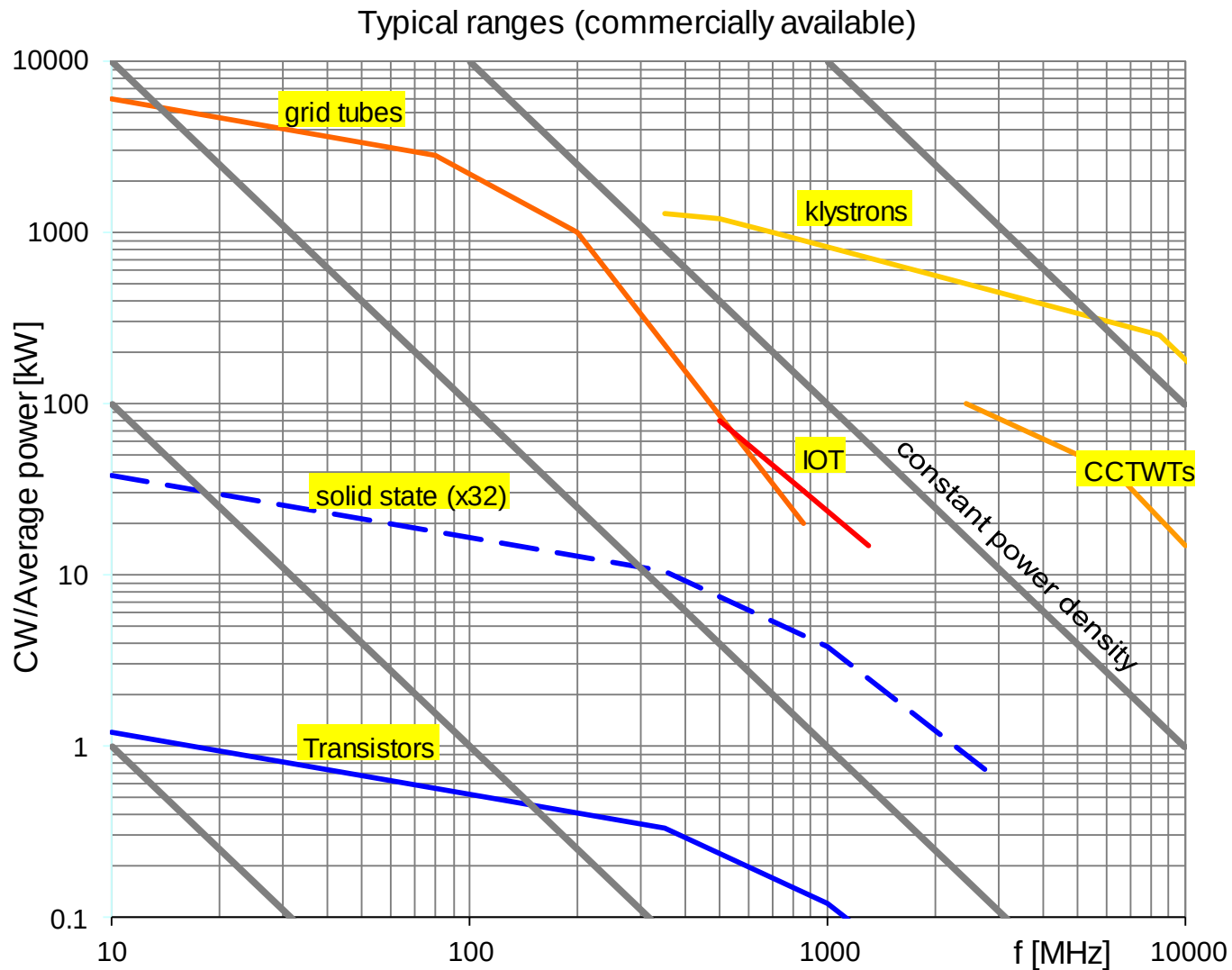
200 MHz solid state amplifiers: 2×1.6 MW peak power,
 2×16 towers per amplifier



- 80 modules per tower, 1280 modules with **5120 transistors per amplifier**
- Presently the **largest RF installation** in a particle accelerator

RF power amplifier

Power capability of commercially available amplifier types



How to choose the right RF amplifier?

Prefer tube amplifier, when	Prefer solid-state amplifier, when
• Amplifier must be installed in the accelerator tunnel • Expecting important spikes from beam induced voltage • Large output power of a single device is required, without combiners • Not much space is available • High peak power in pulsed mode • Amplifier must be compact and/or close to cavity	• Amplifier can be located in non-radioactive environment • Circulator can be installed to protect the amplifier • Delay due to unavoidable combiner stages is little issue • Sufficient space can be made available • Continuous operation • Amplifier can be separate from the cavity

→ Mostly no hard criteria → decide on case by case basis

Summary

- **RF system parameters**
 - Choose frequency and voltage wisely
- **Parameters of RF cavities**
 - R , R/Q
 - No 'one-size fits' all
- **Power amplifier**
 - Ideal amplifier does not (yet) exist
 - Tube or solid-state based
- **Feedbacks and longitudinal beam control**
 - Make the beam feel comfortable in bucket
 - Beam phase, radial and synchronization loops

RF Systems II



H. Damerau
CERN



Introduction to Accelerator Physics

4 October 2021



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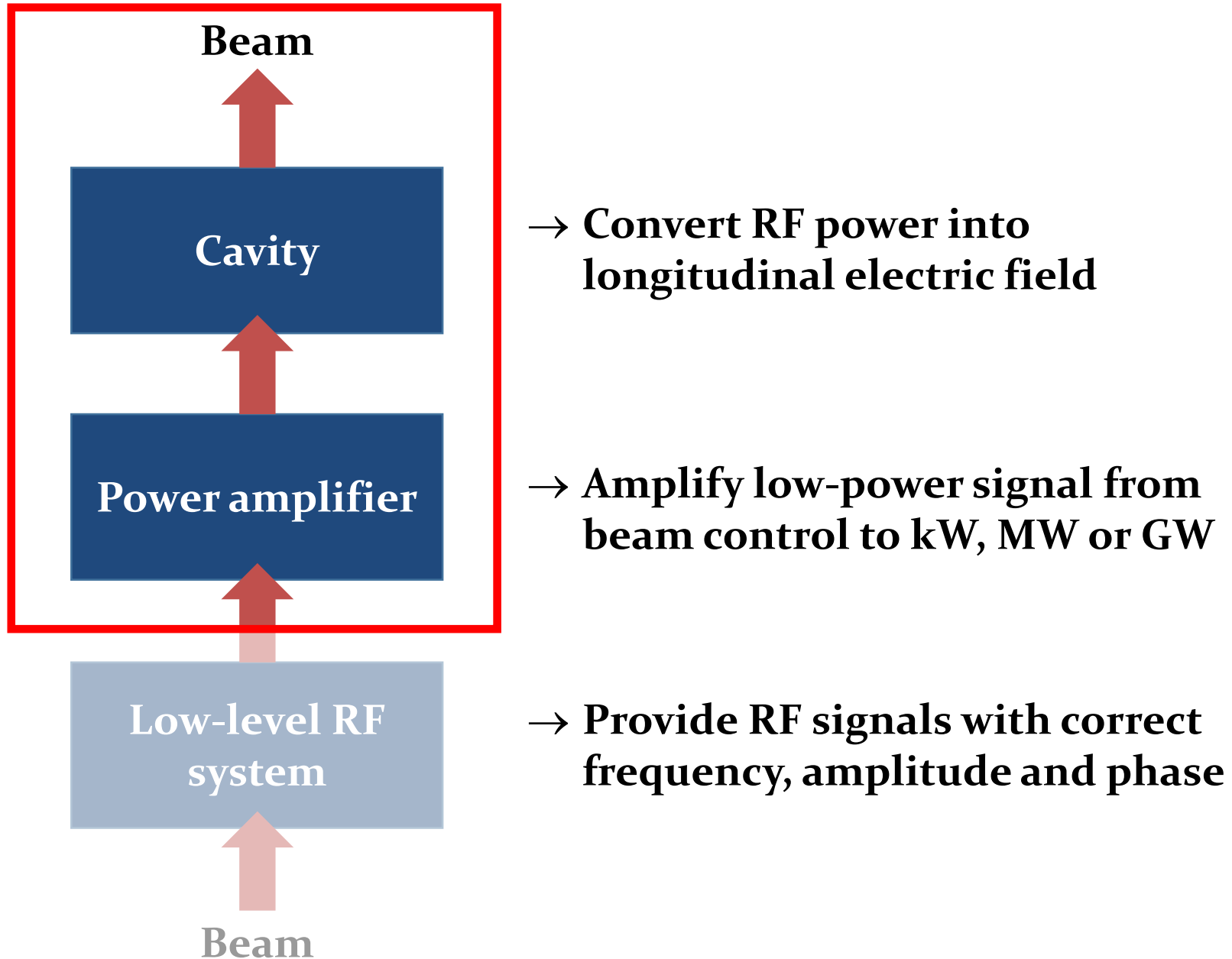
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Outline

- Introduction
- Choice of parameters
 - Frequency and voltage
- RF cavity parameters
 - Shunt impedance, beam loading, power coupling
- **Power amplifiers**
 - Tube or solid state
 - Local feedbacks
- **Longitudinal beam control system**
 - Building blocks: RF source and receiver
 - Phase, radial and synchronization loops
- **Summary**

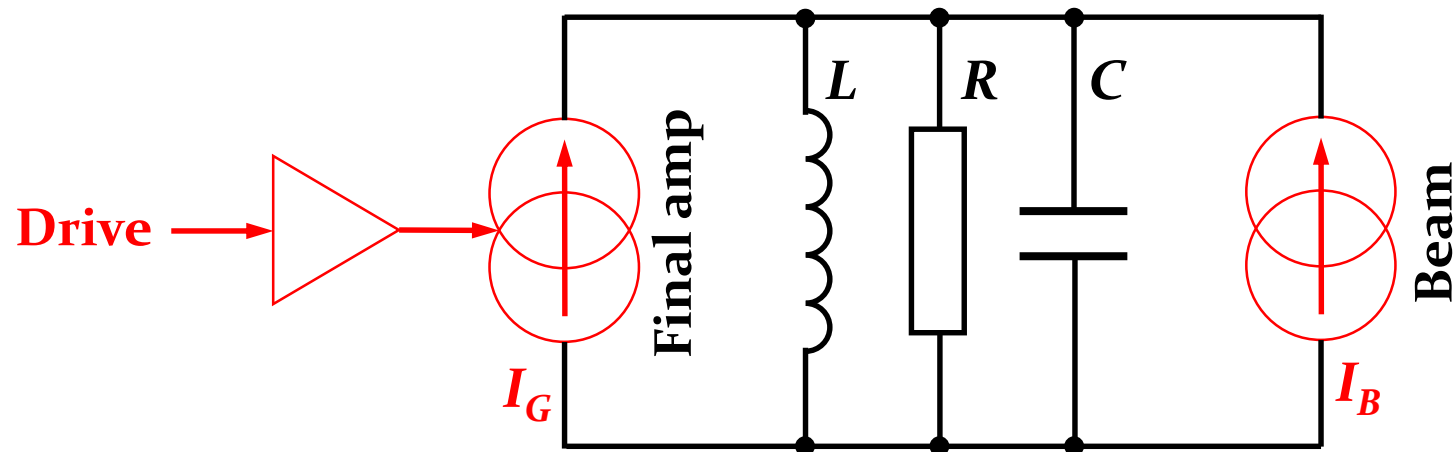
RF system overview



Local feedbacks

Reduction of cavity impedance

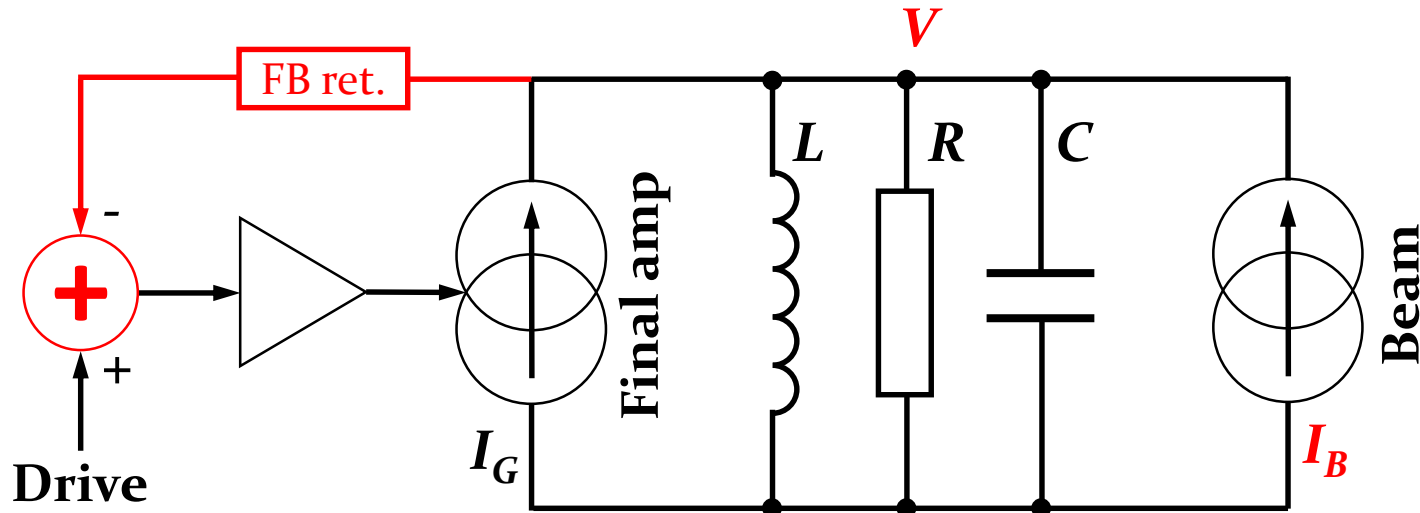
- Energy transfer from cavity to beam, but **from beam to cavity**
 → Both, RF generator and **beam can induced voltage** in cavity



1. Reduce beam induced voltage by reducing R , **but not efficient**
 → Obviously needs more power → \$\$\$
2. Feedback to decrease the apparent impedance for the beam
 → Use amplifier to counteract beam induced voltage

Reduction of cavity impedance

- Energy transfer from cavity to beam, but **from beam to cavity**
 → Both, RF generator and **beam can induced voltage** in cavity



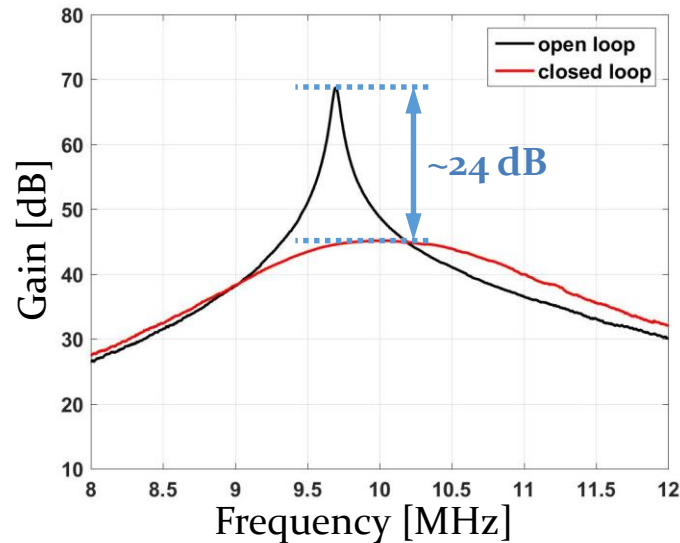
1. **Compare** drive signal (no beam) with gap (beam and generator)
2. **Amplify** inverted difference

$$Z_{\text{eq}}(\omega) = \frac{dV}{dI_B} = \frac{Z(\omega)}{1 + g_{\text{OL}}}$$

Example: 10 MHz RF system in CERN PS

70

Transfer function with and without feedback



- Feedback gain of 24 dB
- Equivalent impedance, $Z_{eq}(\omega)$ reduced
- Impedance for amplifier remains unchanged, $Z(\omega)$



Why not further reduction with more gain?

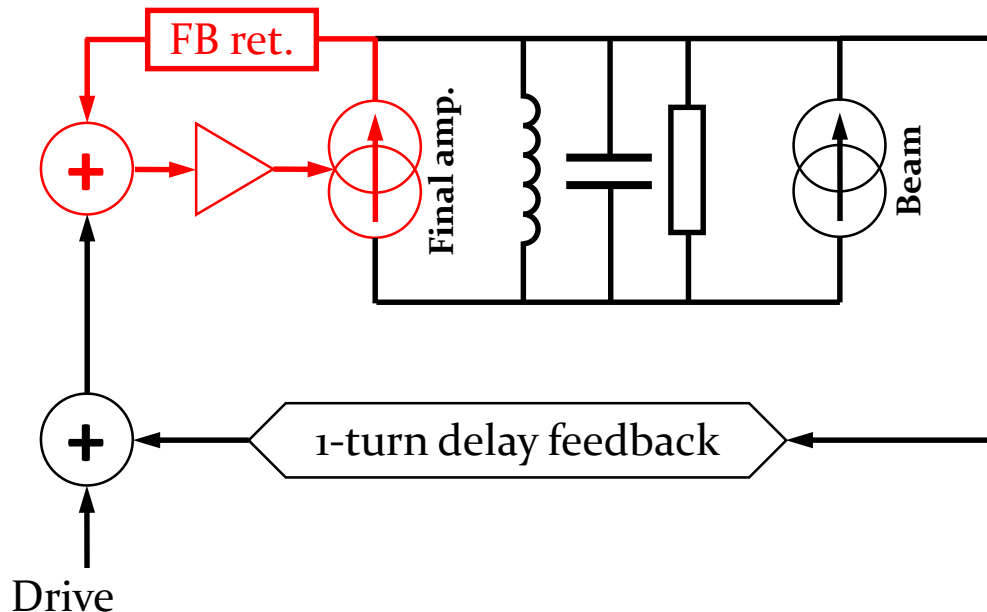
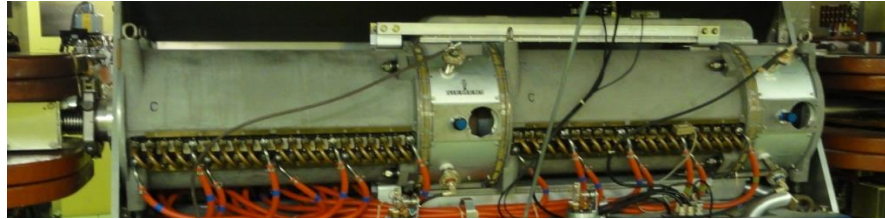
- Subtraction of gap voltage and drive signal imperfect due to
 1. Delay of cables and amplifier
 2. Parasitic resonances of amplifier and cavity system

Bandwidth $\uparrow$ $\leftrightarrow$ Achievable gain $\downarrow$

Example: 10 MHz RF system in CERN PS

71

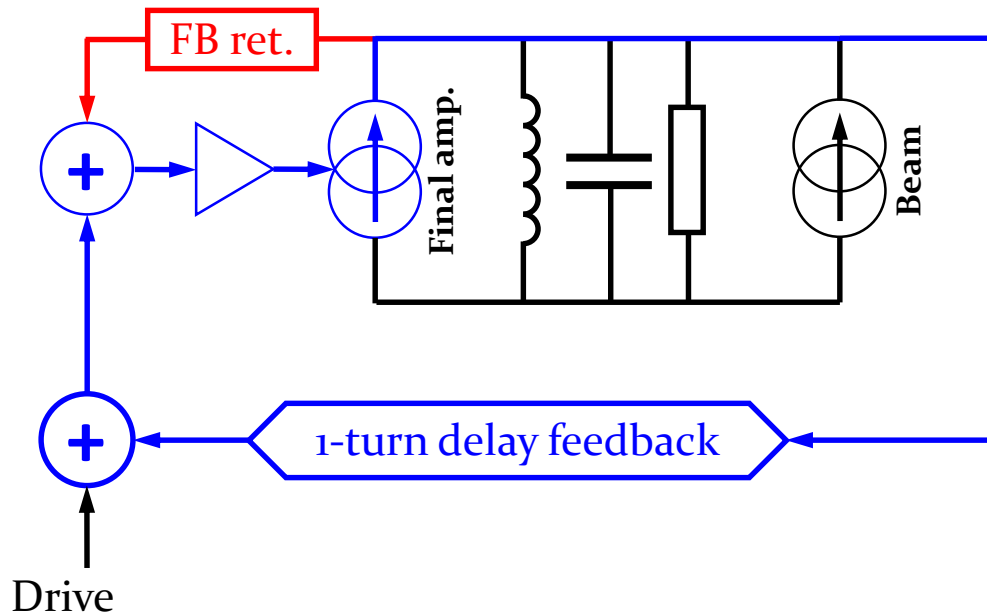
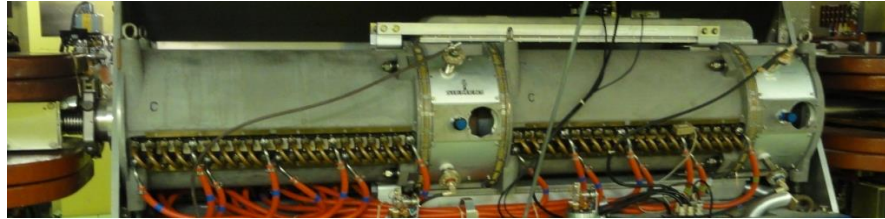
- 10 + 1 ferrite loaded cavities, tunable from 2.8...10 MHz



- Fast wide-band feedback around amplifier (internal)
→ Gain limited by delay

Example: RF feedback with 1-turn delay

- 10 + 1 ferrite loaded cavities, tunable from 2.8...10 MHz



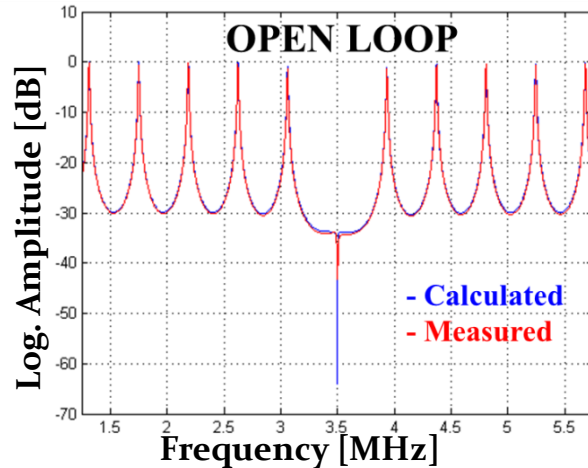
- Fast wide-band feedback around amplifier (internal)
→ Gain limited by delay

- 1-turn delay feedback
→ High gain at $n \times f_{\text{rev}}$

Example: RF feedback with 1-turn delay

→ Reduce cavity impedance beyond stability limit of wide-band FB

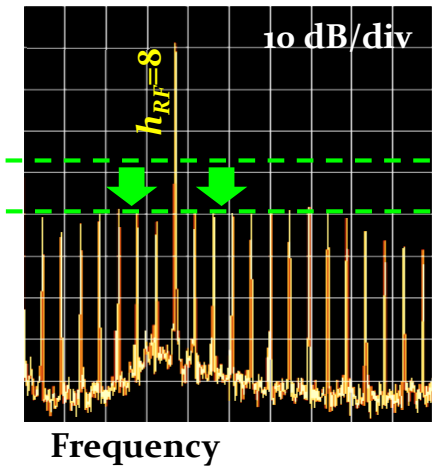
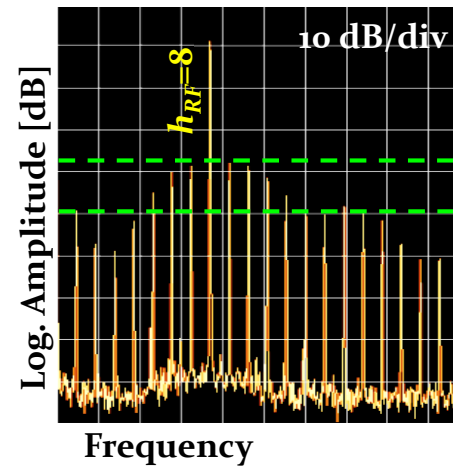
Open/closed loop
transfer functions



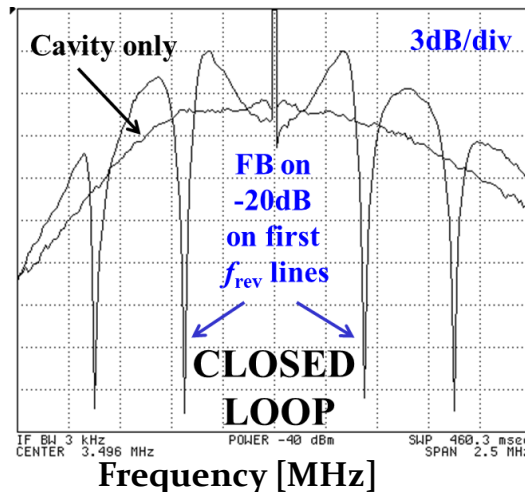
Spectrum at cavity gap return

Feedback **off**

Feedback **on**



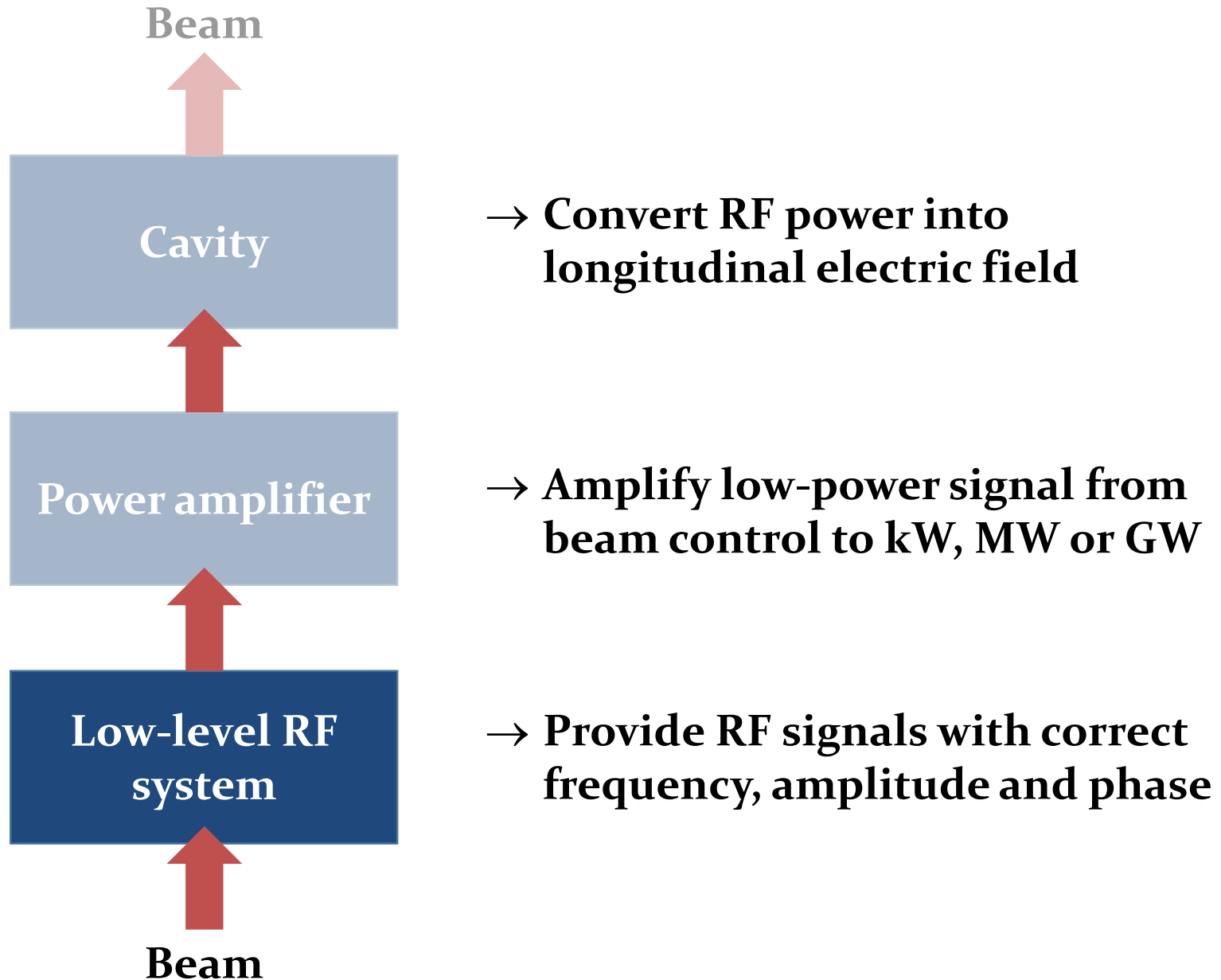
D. Perrelet



→ Important additional impedance reduction

→ Clever usage of beam periodicity in circular accelerator

RF system overview

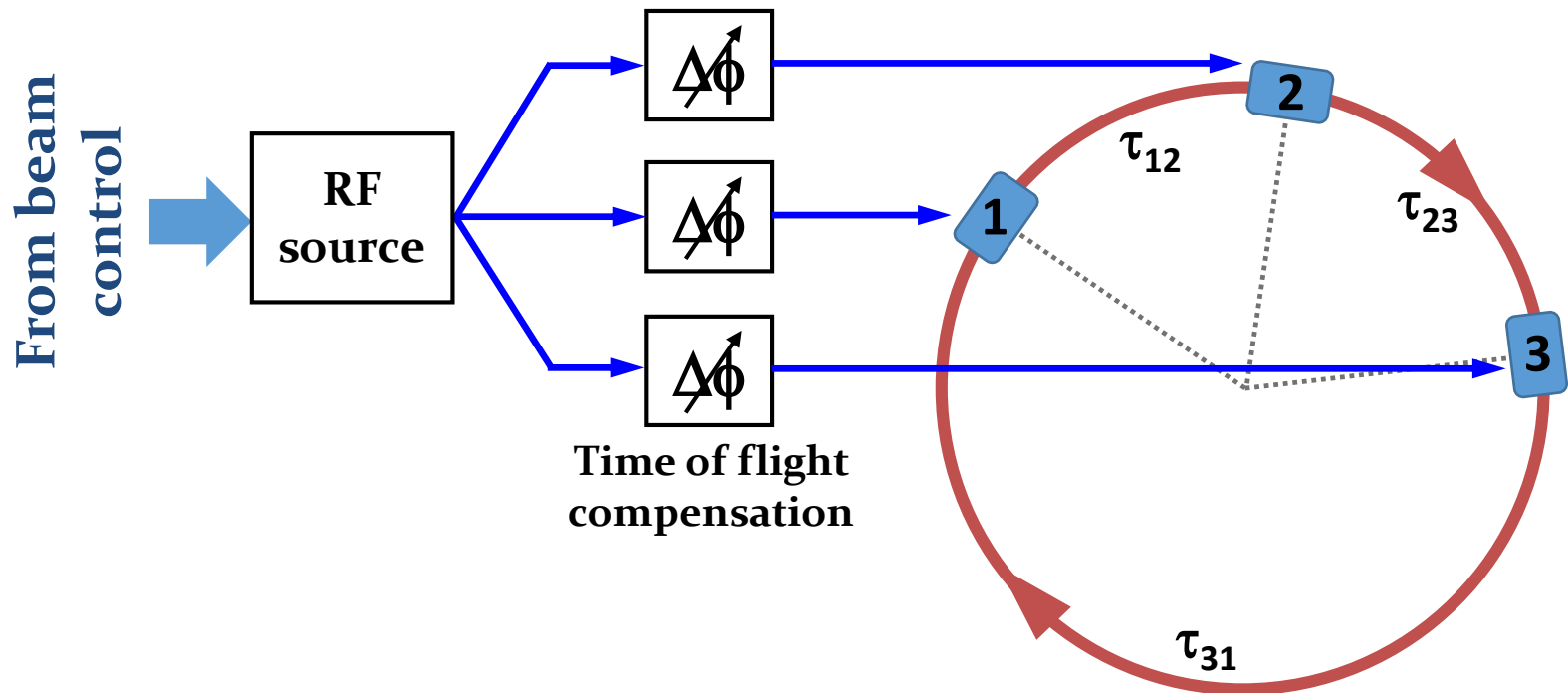


Global feedbacks

Low-level RF beam control

Longitudinal beam control

- **Local** feedbacks → Act on individual RF stations
- **Global** feedbacks → Act on all RF stations simultaneously

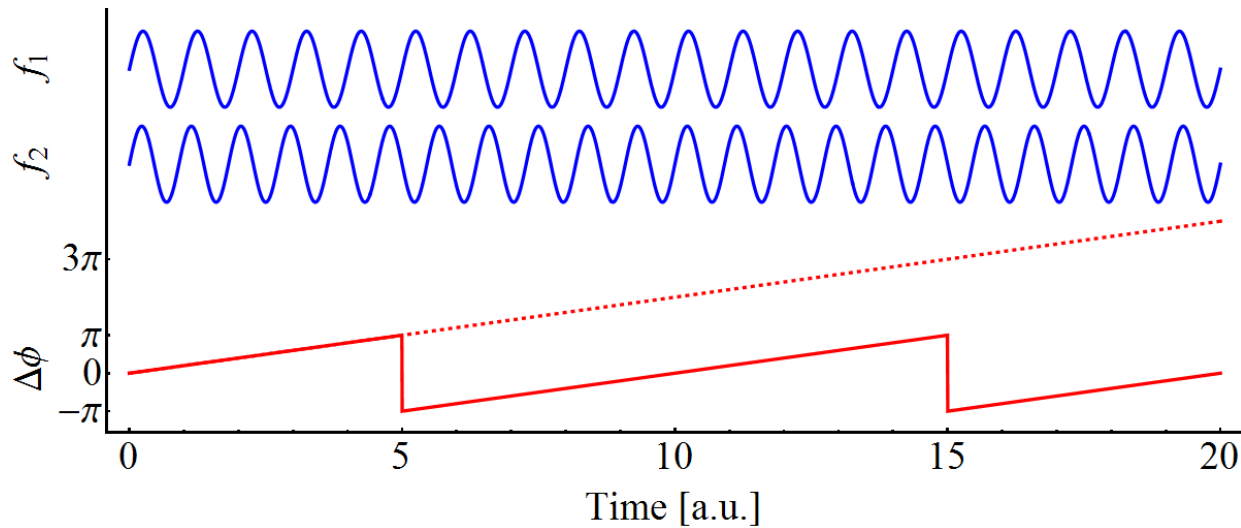


- RF distribution to compensate time of flight between stations
- Beam control drives all stations **like a single one**

Basic building blocks

Measure phase differences

- Two signals at different frequencies ω_1 and ω_2



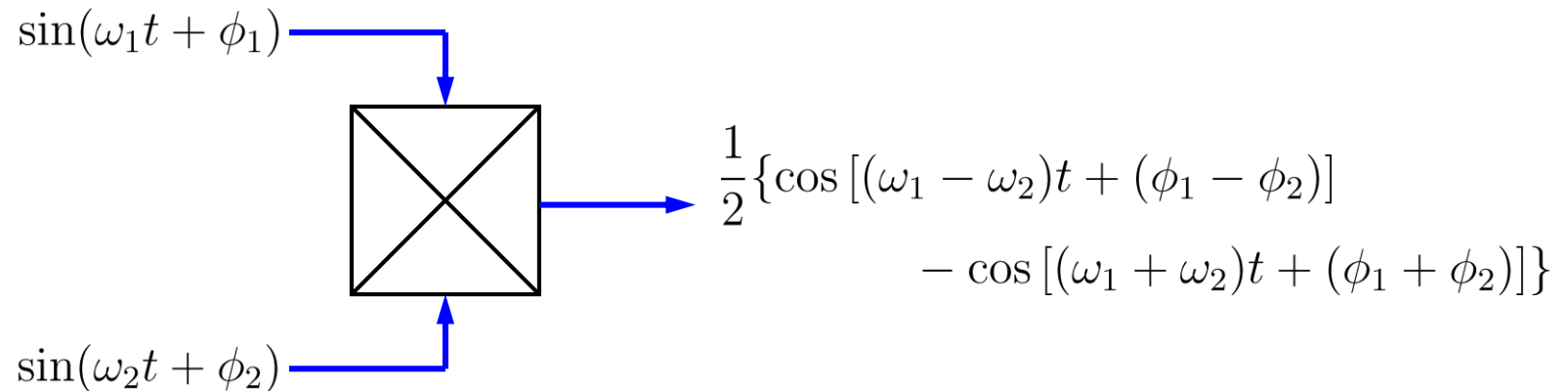
- Phase difference, $\Delta\phi$, between both signals changes linearly
- Ambiguity to distinguish between $\Delta\phi = -\pi, \pi, -3\pi, 3\pi, \dots$
- Saw-tooth in phase means constant frequency difference

→ Equivalence of frequency and phase

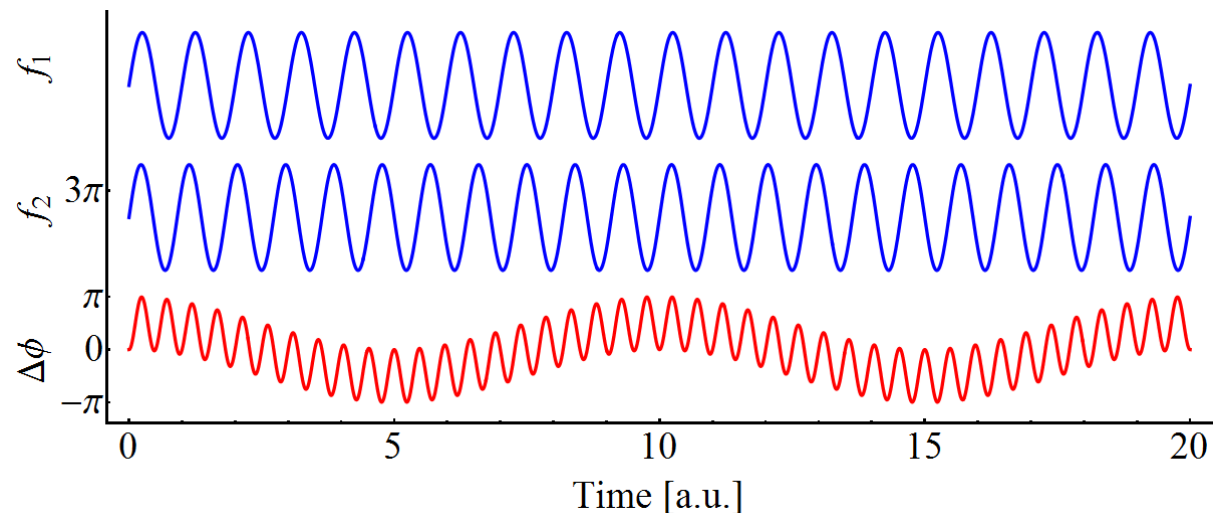
$$\omega = \frac{d\phi}{dt} \quad \Leftrightarrow \quad \phi = \int \omega dt$$

Mixer or multiplier

- Example: analogue 4 quadrant multiplier and low pass filter**

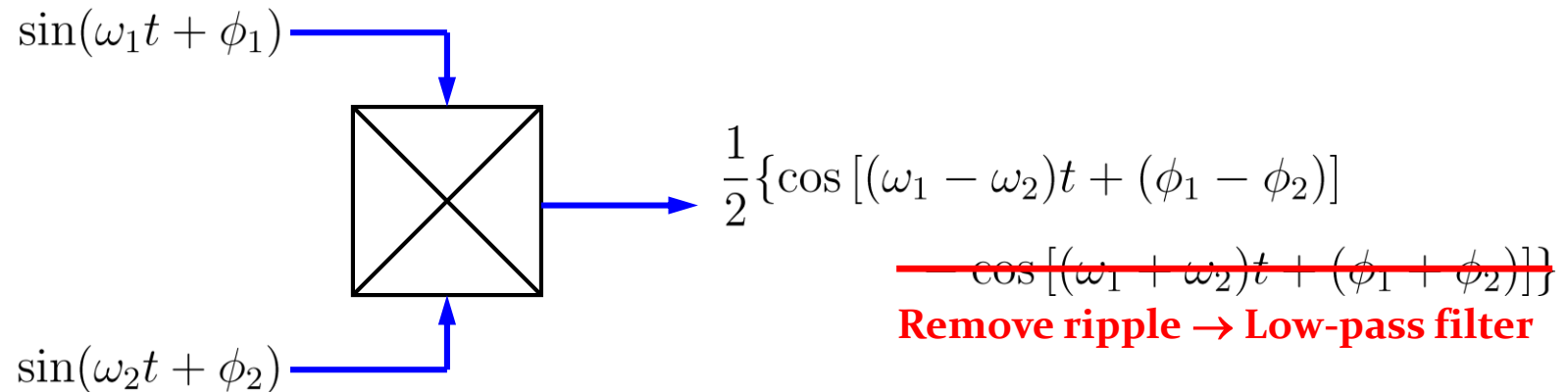


- Signals:**

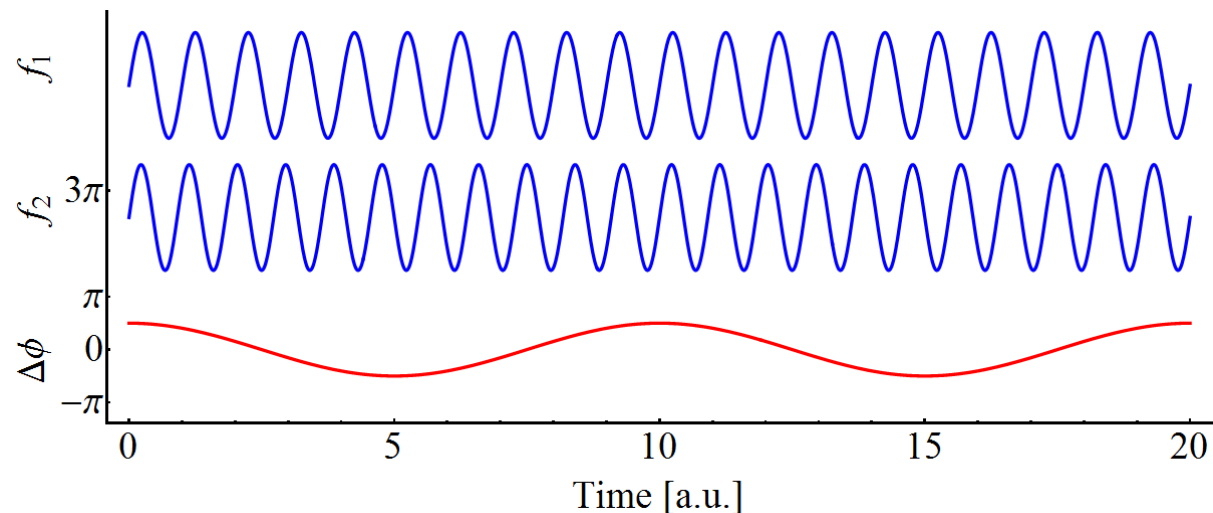


Mixer or multiplier

- **Example: analogue 4 quadrant multiplier and low pass filter**

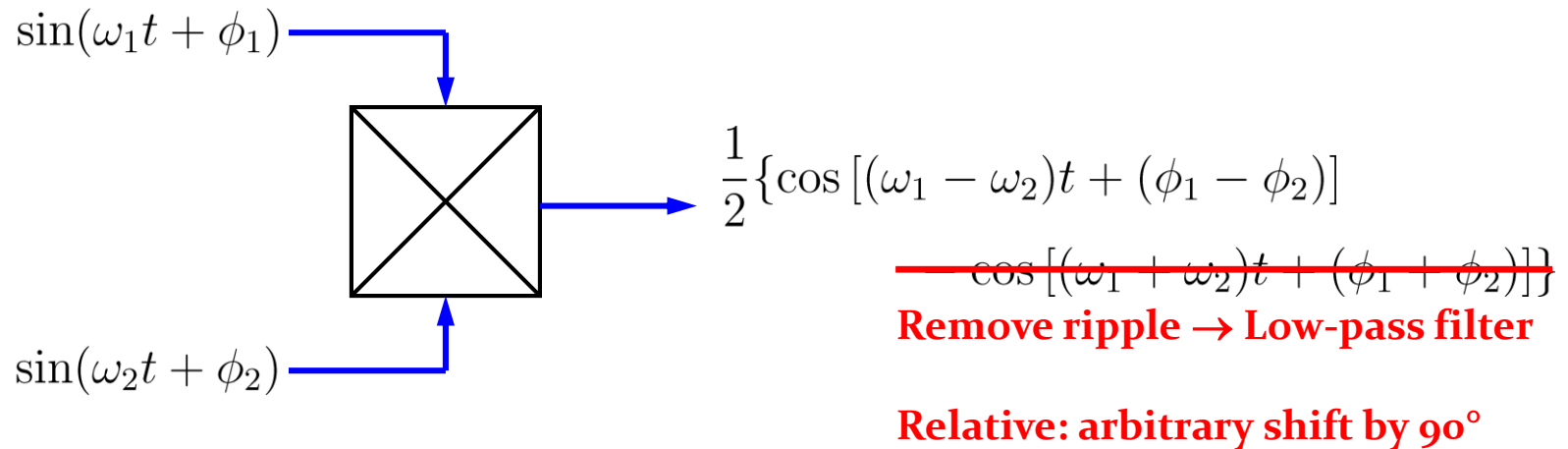


- **Signals:**

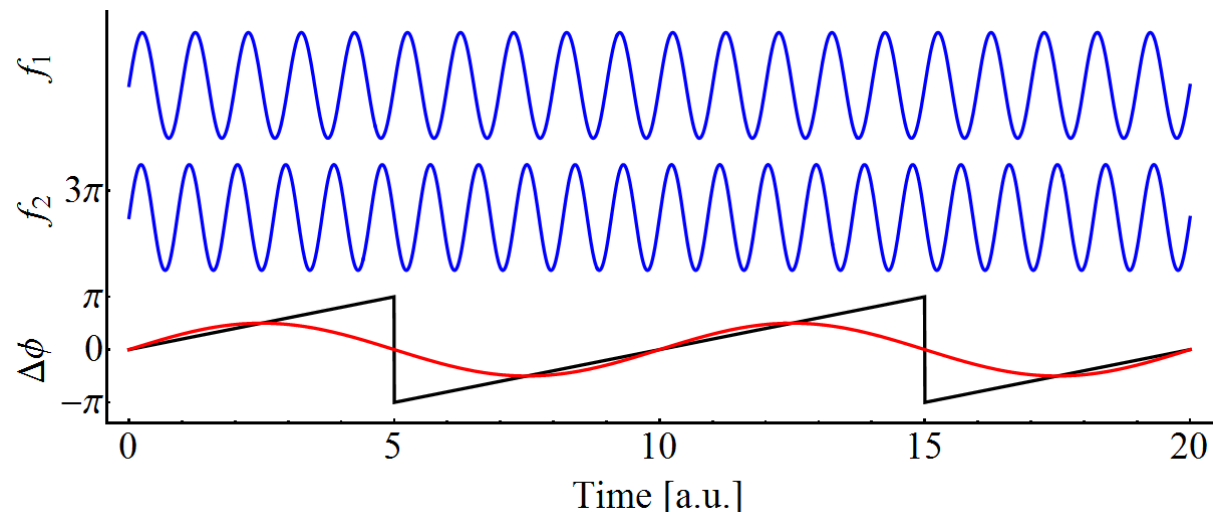


How to detect phase differences?

- **Example: analogue 4 quadrant multiplier and low pass filter**



- **Signals:**



- **Phase discriminator in approximately $\pm 90^\circ$ range**

RF sources

RF sources

What finally generates the RF signal to power amplifier and cavity?

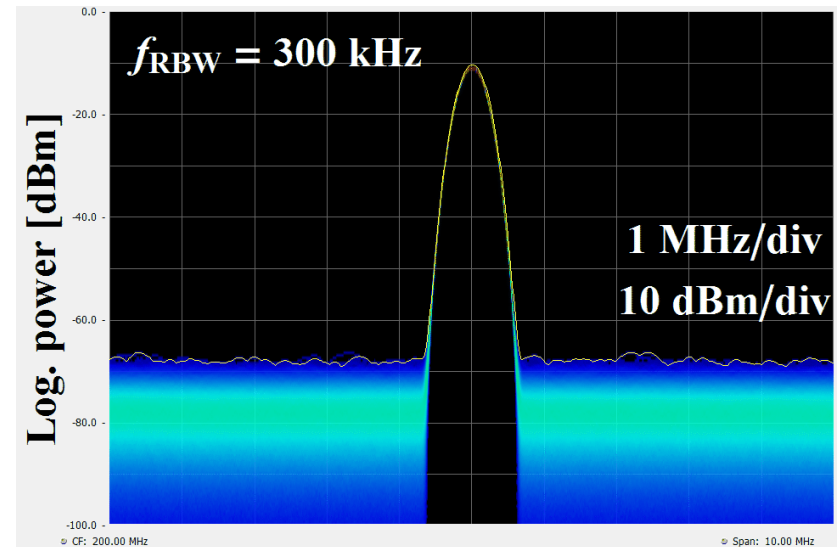
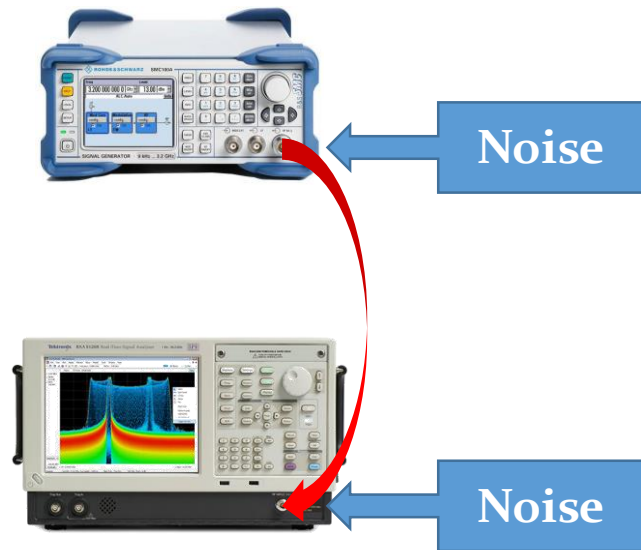
→ Need an RF source!



- **Electron accelerators**
 - Off-the-shelf high-performance laboratory generators as reference: **BESSY SR, CERN CTF₃**
 - Dedicated commercial fixed-frequency sources with low phase noise: **free electron lasers, CERN AWAKE**
- **Proton accelerators**
 - Special sweeping RF sources, controlled by beam-based loops: **mostly in-house developments**

Noisy RF signals

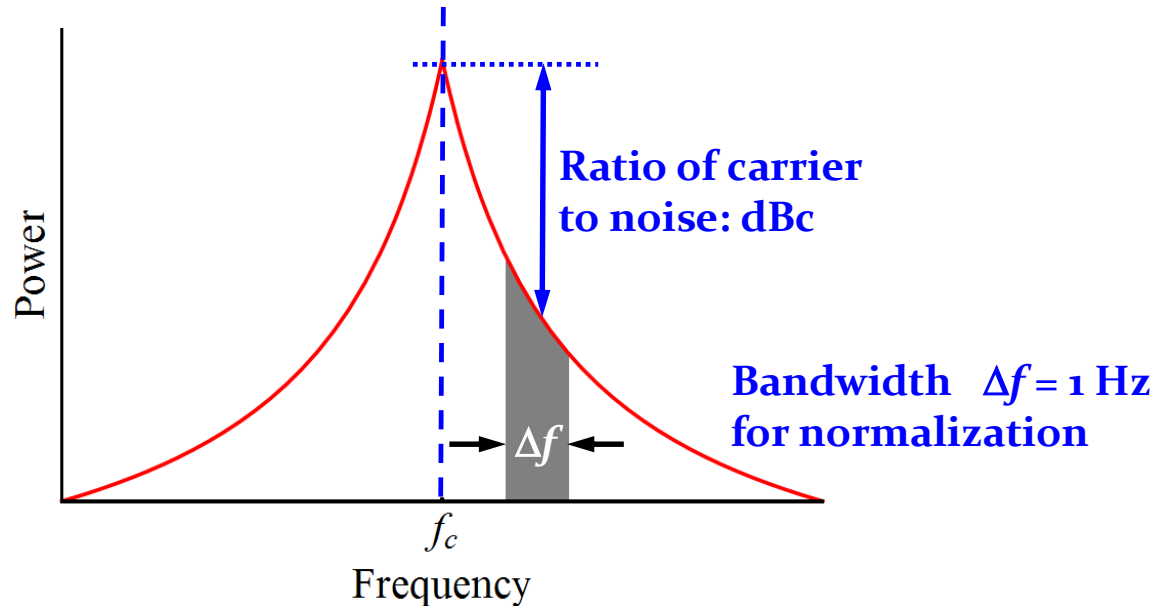
- Degradation of signal quality due to noise
 - Amplitude and/or phase jitter
- What is the difference between a coherent signal and noise?



- Amplitude of **coherent**, quasi **monochromatic** signal (at 200 MHz) is **independent of observation bandwidth**
- Incoherent **noise power** (dominated by spectrum analyzer front-end amplifier/mixer) is **proportional to bandwidth**
- Thermal noise power $\frac{P}{\Delta f} = k_B T = 1.38 \cdot 10^{-23} \text{ J/K} \cdot 296 \text{ K} \simeq -174 \text{ dBm/Hz}$

Analysis of phase noise

- Compare noise power with carrier power as reference



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

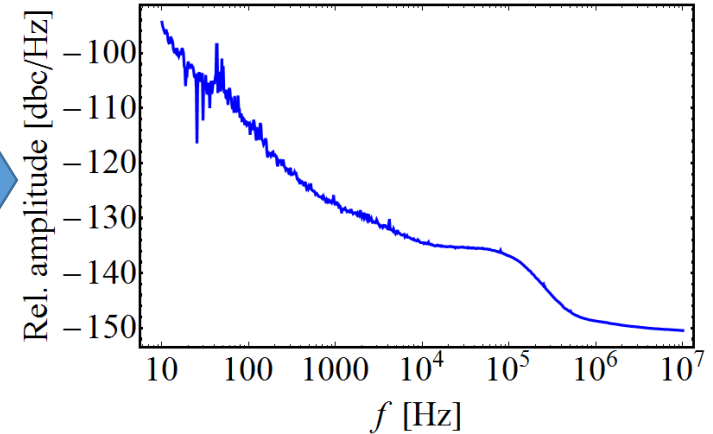
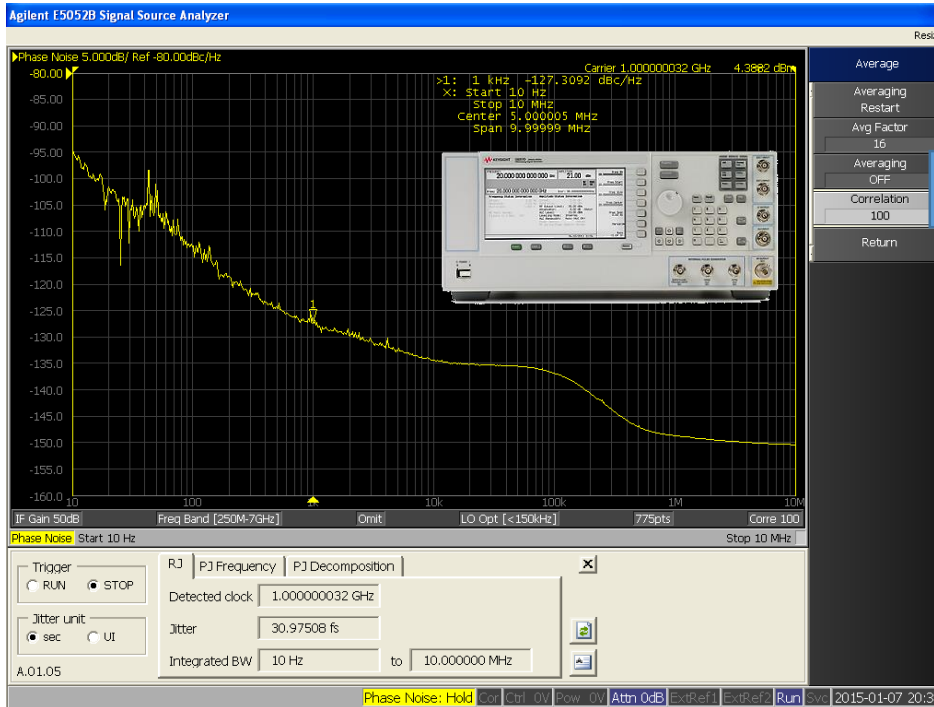
→ Its integral is the phase jitter and using $\Delta t = \frac{\Delta\phi}{2\pi f_c}$

the jitter in time becomes

$$\Delta t_{\text{rms}} = \frac{1}{2\pi f_c} \sqrt{\int_{f_1}^{f_2} S_\phi(f) df}$$

Typical phase noise plots

- Measure phase noise of a synthesized lab generator



→ **Note: jitter values can be added as square root of quadratic sum**

$$\Delta t_{\text{rms}} = \sqrt{\Delta t_{\text{rms},1}^2 + \Delta t_{\text{rms},2}^2 + \dots}$$

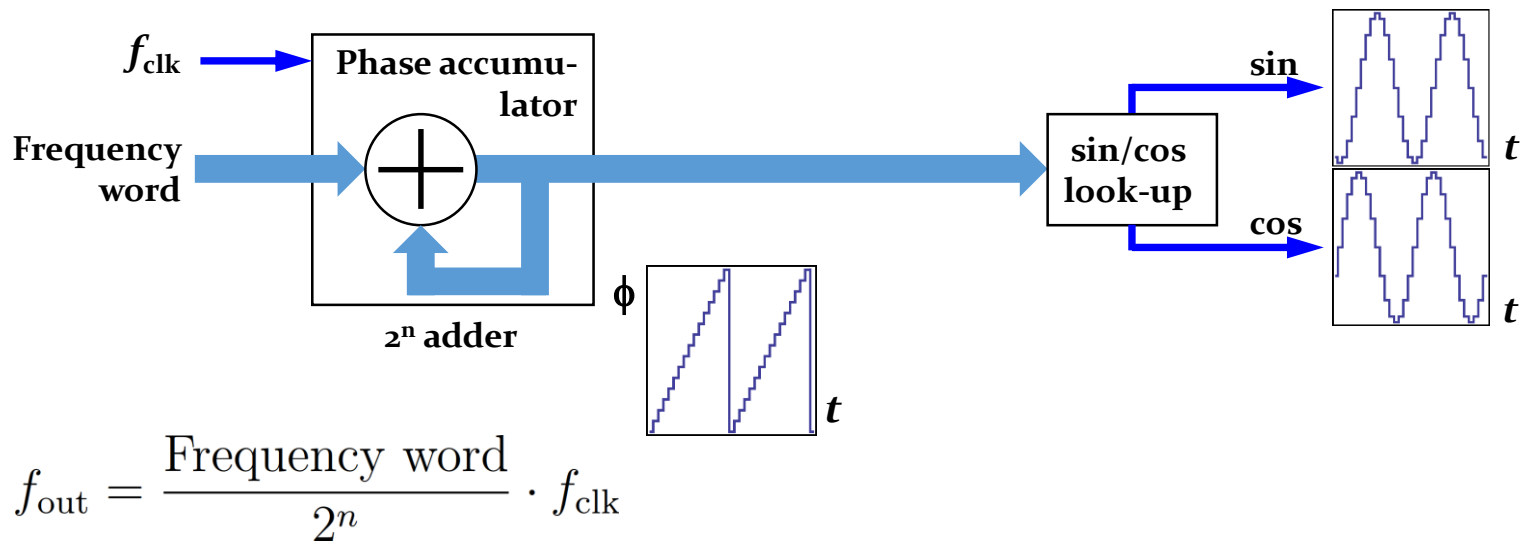
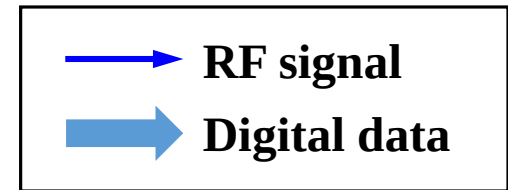
→ **Convenient split to relevant ranges**

Frequency range	Δt_{rms} [fs]
10...100 Hz	12.4
100 Hz ...1 kHz	5.4
1...10 kHz	5.4
10...100 kHz	11.1
100 kHz...1 MHz	13.0
Total	31.0

Variable frequency: direct digital synthesis

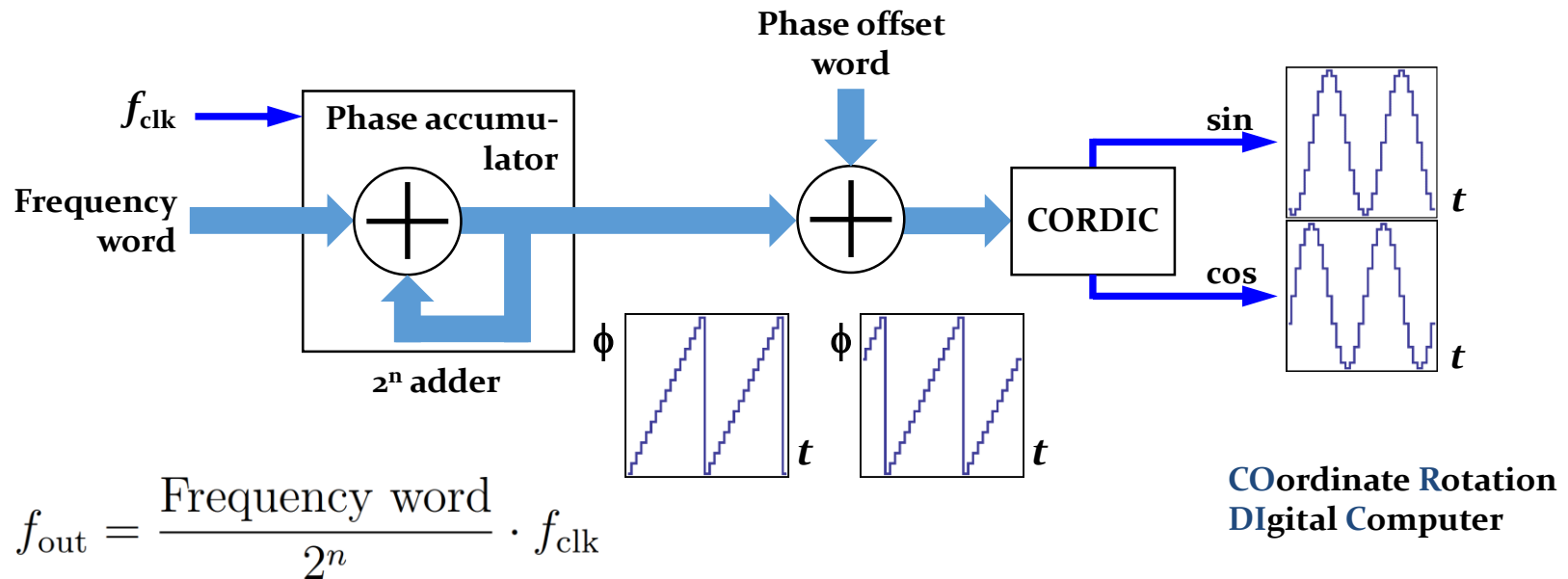
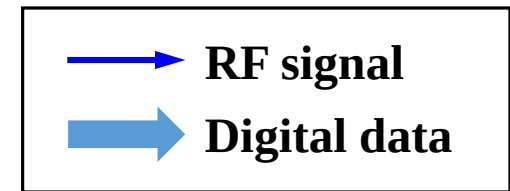
87

- Generate (almost) any frequency starting from a given clock frequency, f_{clk}
- Digitally programmable **in frequency**



Variable frequency: direct digital synthesis

- Generate (almost) any frequency starting from a given clock frequency, f_{clk}
- Digitally programmable **in frequency and phase**

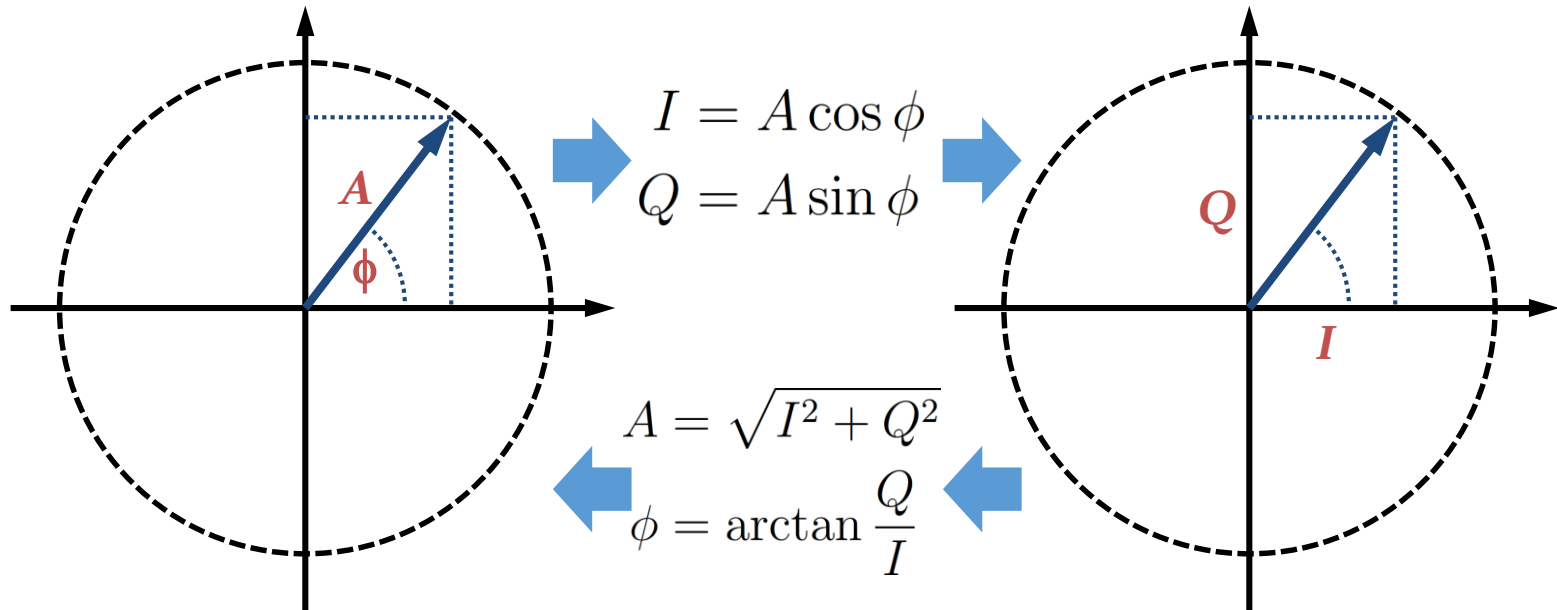


- Two output **signals with ideal 90° phase shift**
- Output signals are **digital data streams**

Receivers

I/Q representation of signals

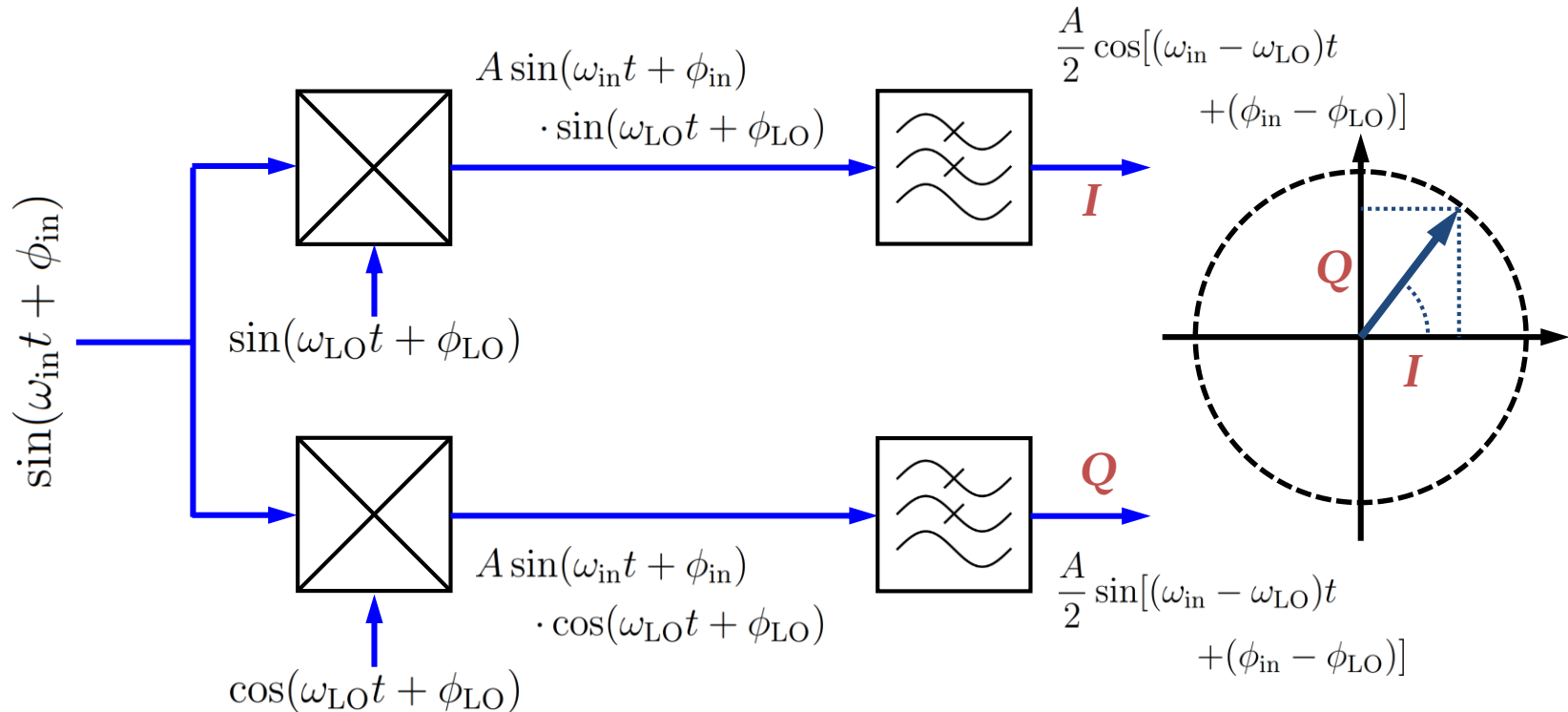
- Any signal can be represented by amplitude A and phase ϕ



- **In phase, I** and **quadrature, Q** describe the same signal
- **Avoids phase discontinuities** at $0, 2\pi, \dots$

Signal receivers

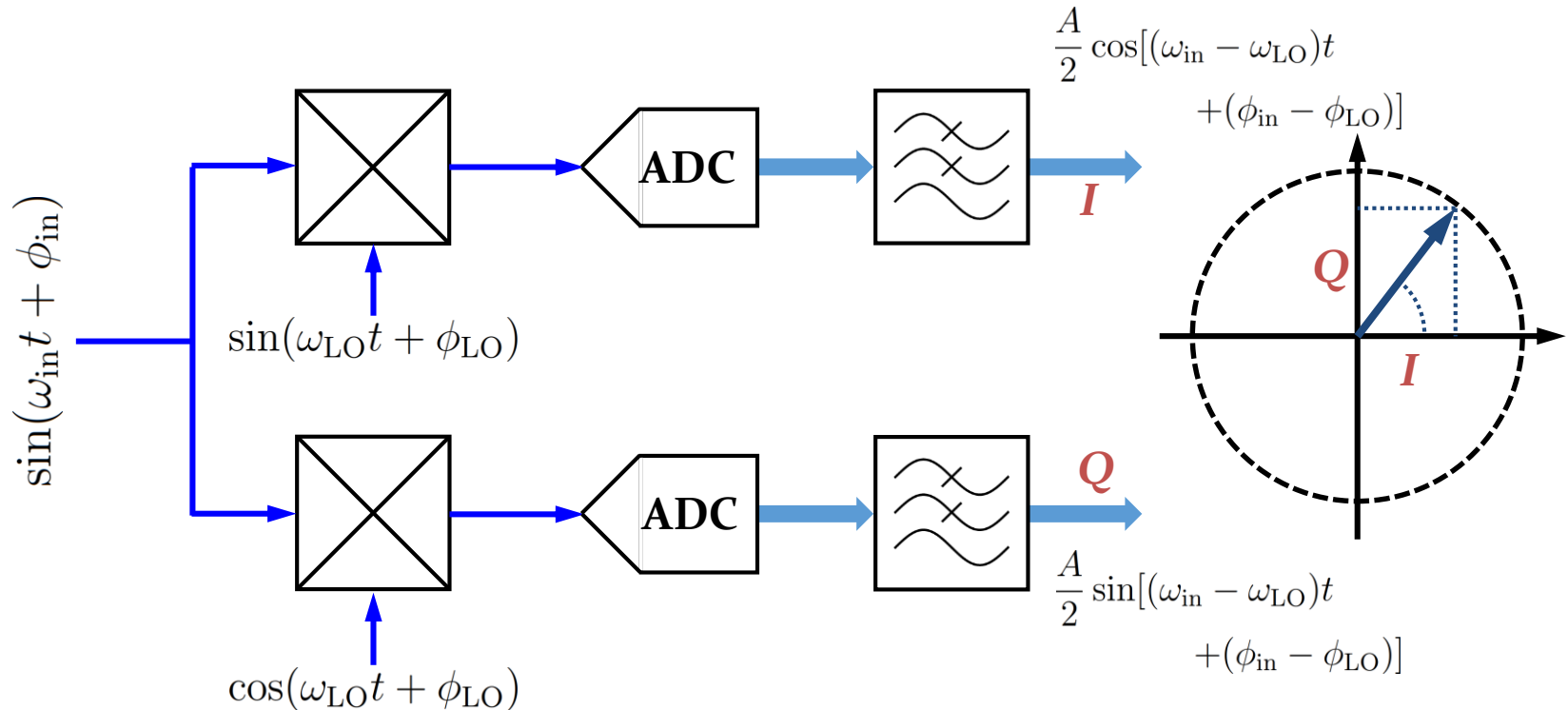
- Radio with listens to beam or cavity signals
- Listens to amplitude **and** phase



- With $\omega_{in} \approx \omega_{LO}$ input signal is **down-converted to base-band**
- Resulting **I/Q vector rotates slowly** with $\omega_{in} - \omega_{LO}$

Digital receivers

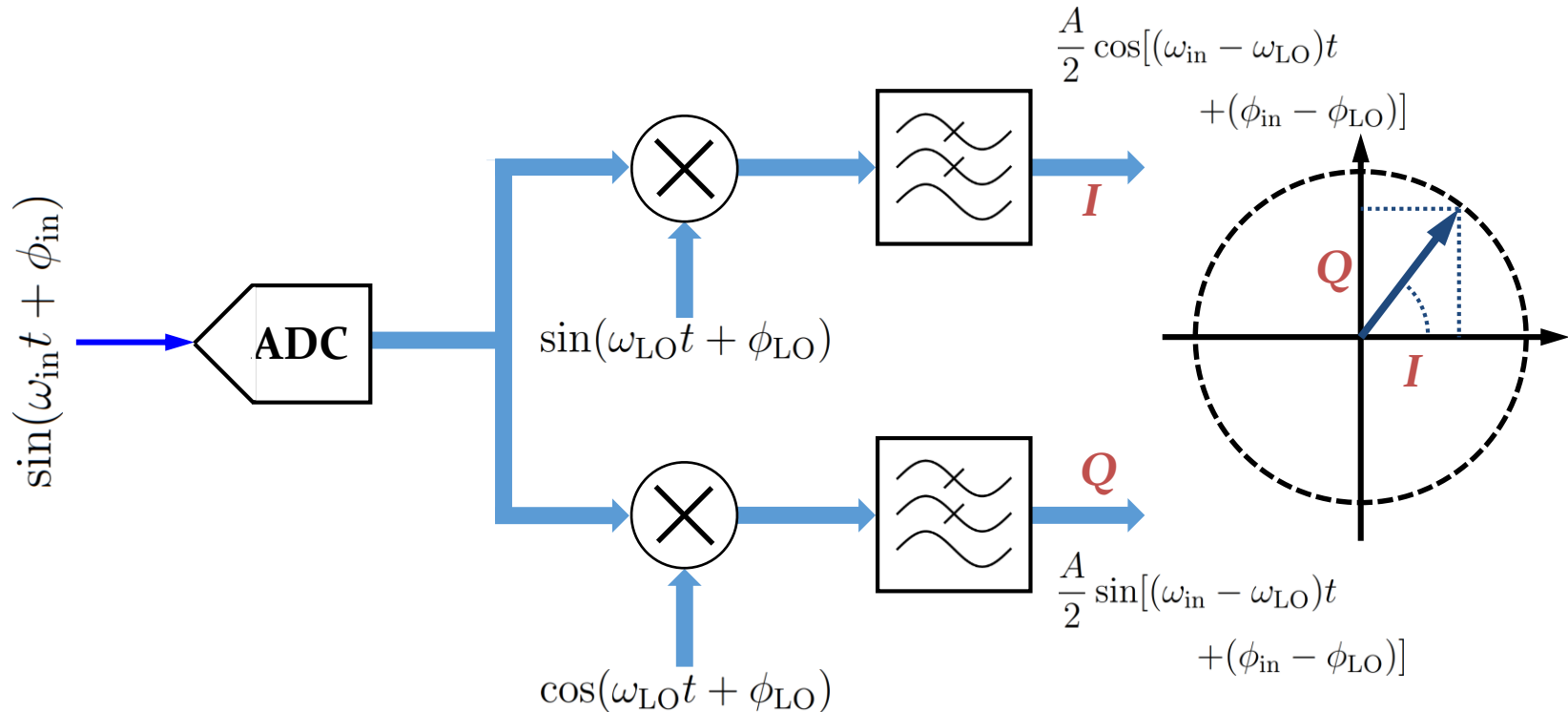
- No conceptual difference between analogue and digital
- Digitization can be performed at any level



- **Analog down-conversion** of I and Q, **then digital processing**
- High input frequencies beyond ADC sampling rates

Digital receivers

- No conceptual difference between analogue and digital
- Digitization can be performed at any level

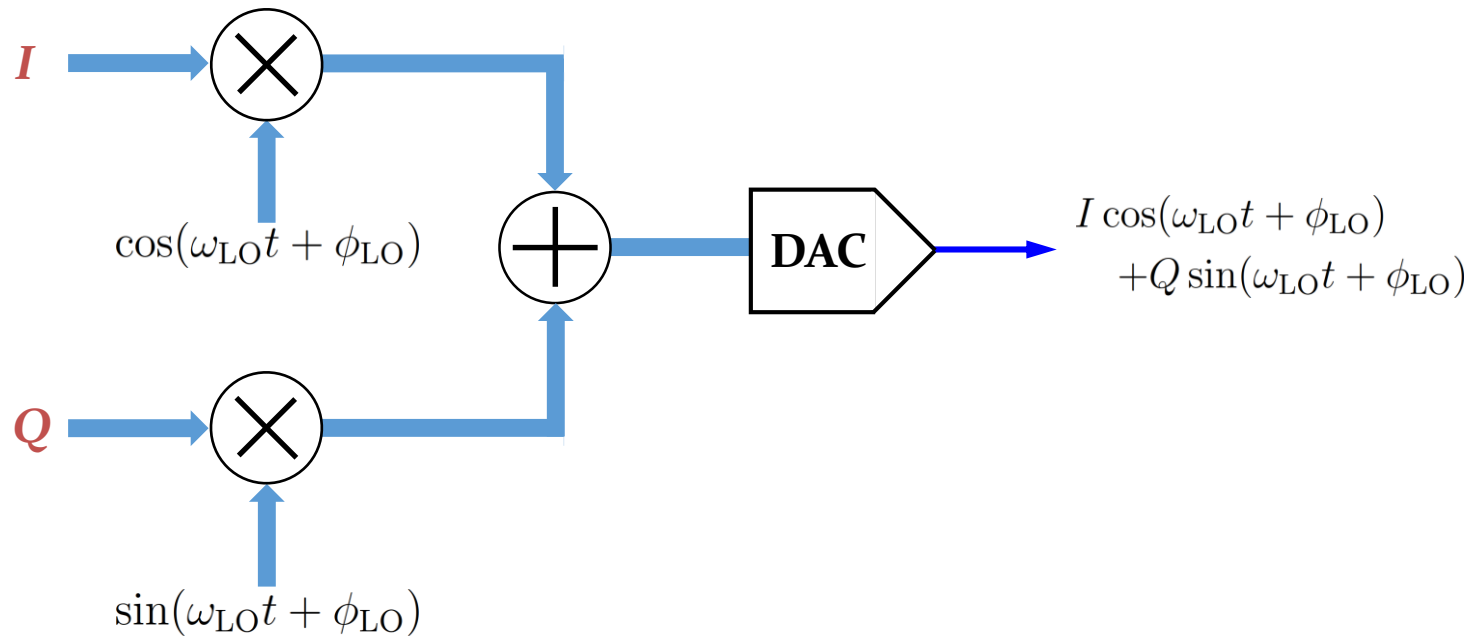


- Analogue mixers become digital multipliers
- All digital receiver
- Theoretically perfect I/Q symmetry

Vector modulator

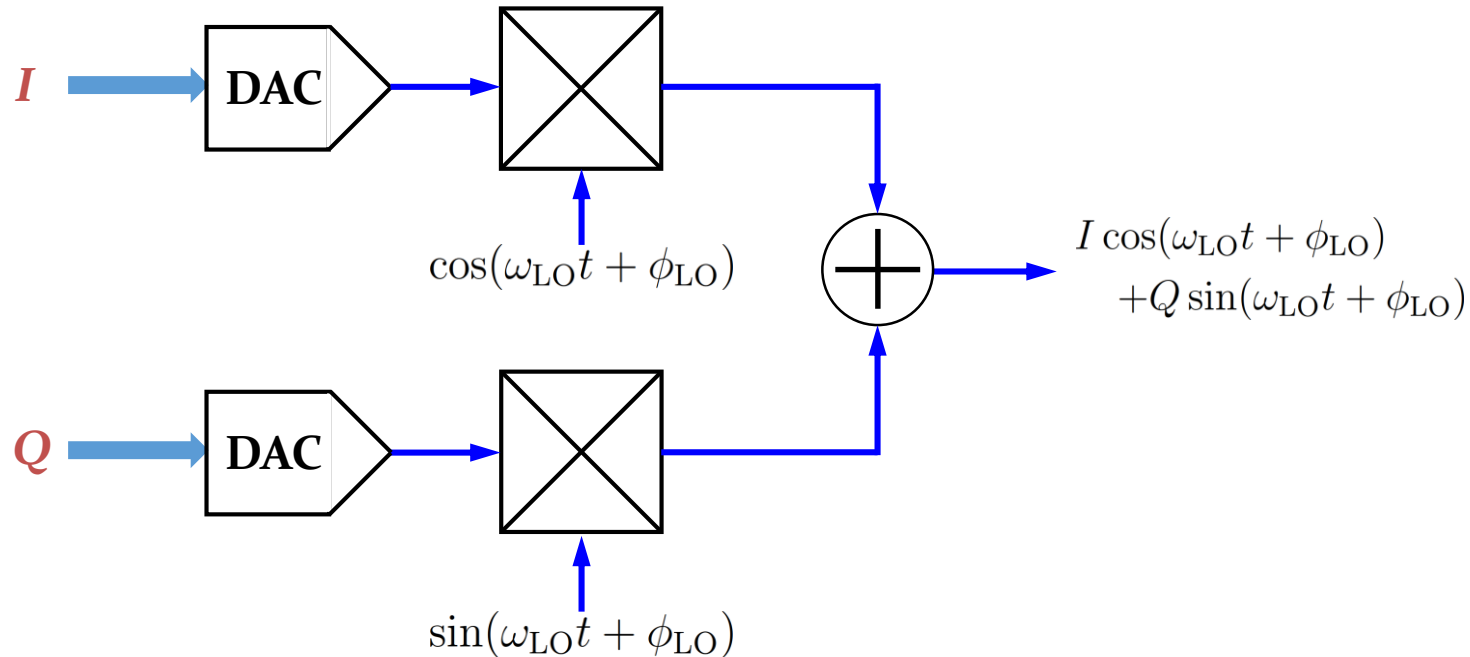
Invers receiver: vector modulator

- Convert I/Q data into modulated RF signal



Inverse receiver: vector modulator

- Convert I/Q data into modulated RF signal

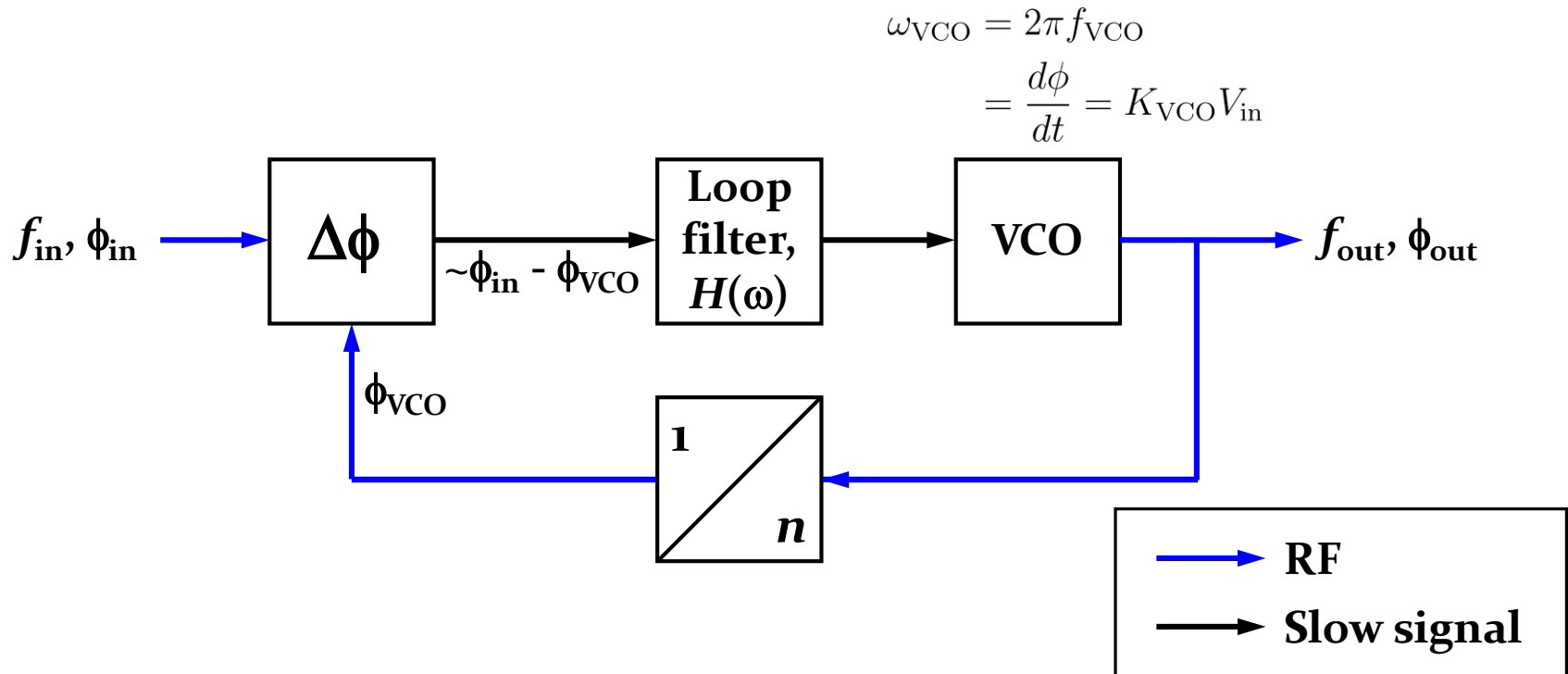


- Perfect **I/Q symmetry** difficult to achieve
- Up-conversion of digital signal to a high RF frequency

Beam phase loop

Electronic phase-locked loop

- Frequency re-generation and multiplication
- Voltage controlled oscillator (VCO) locked in phase to input



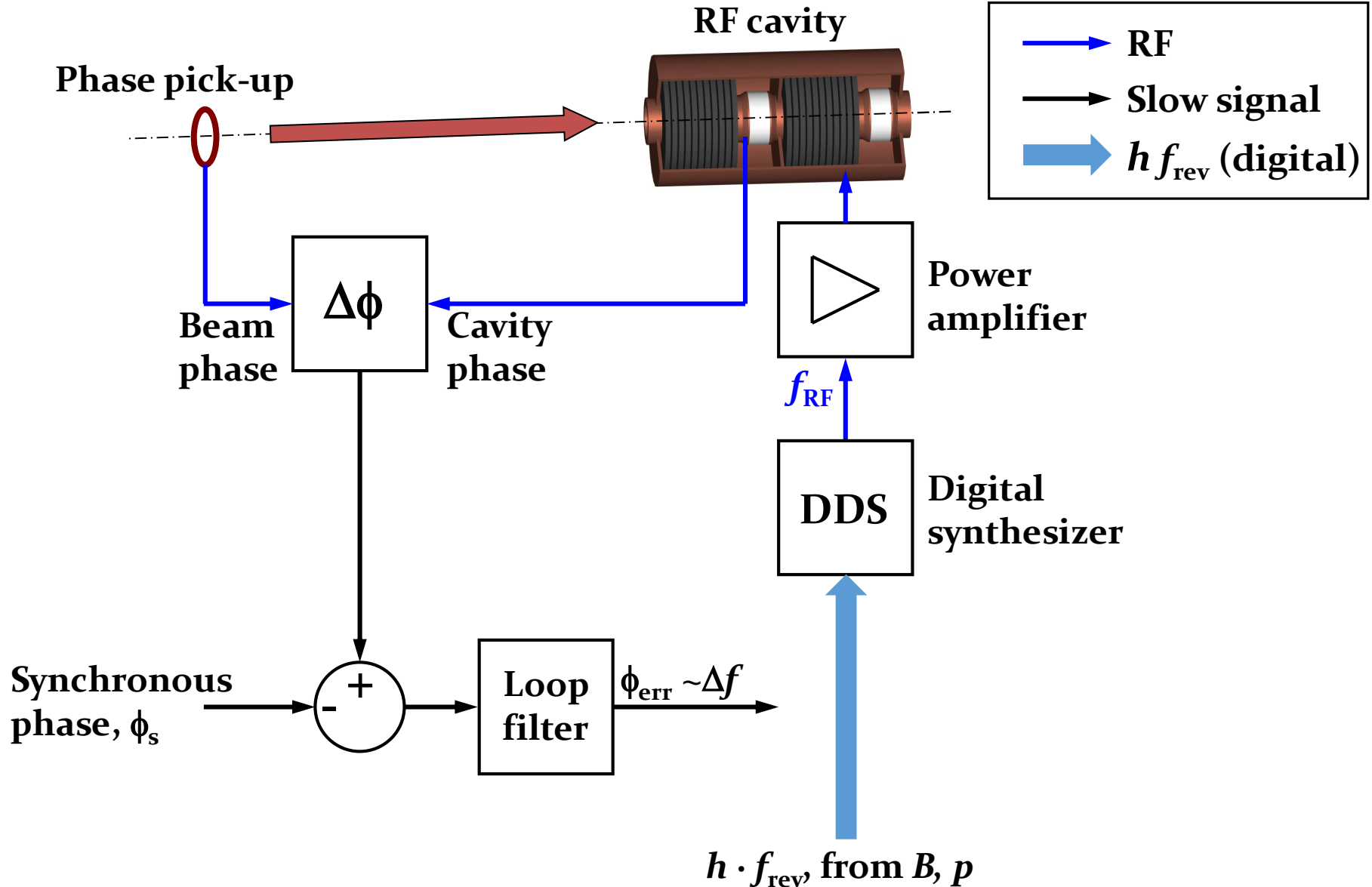
→ Fixed phase relationship:

$$\phi_{\text{out}}/n - \phi_{\text{in}} = \text{const.}$$

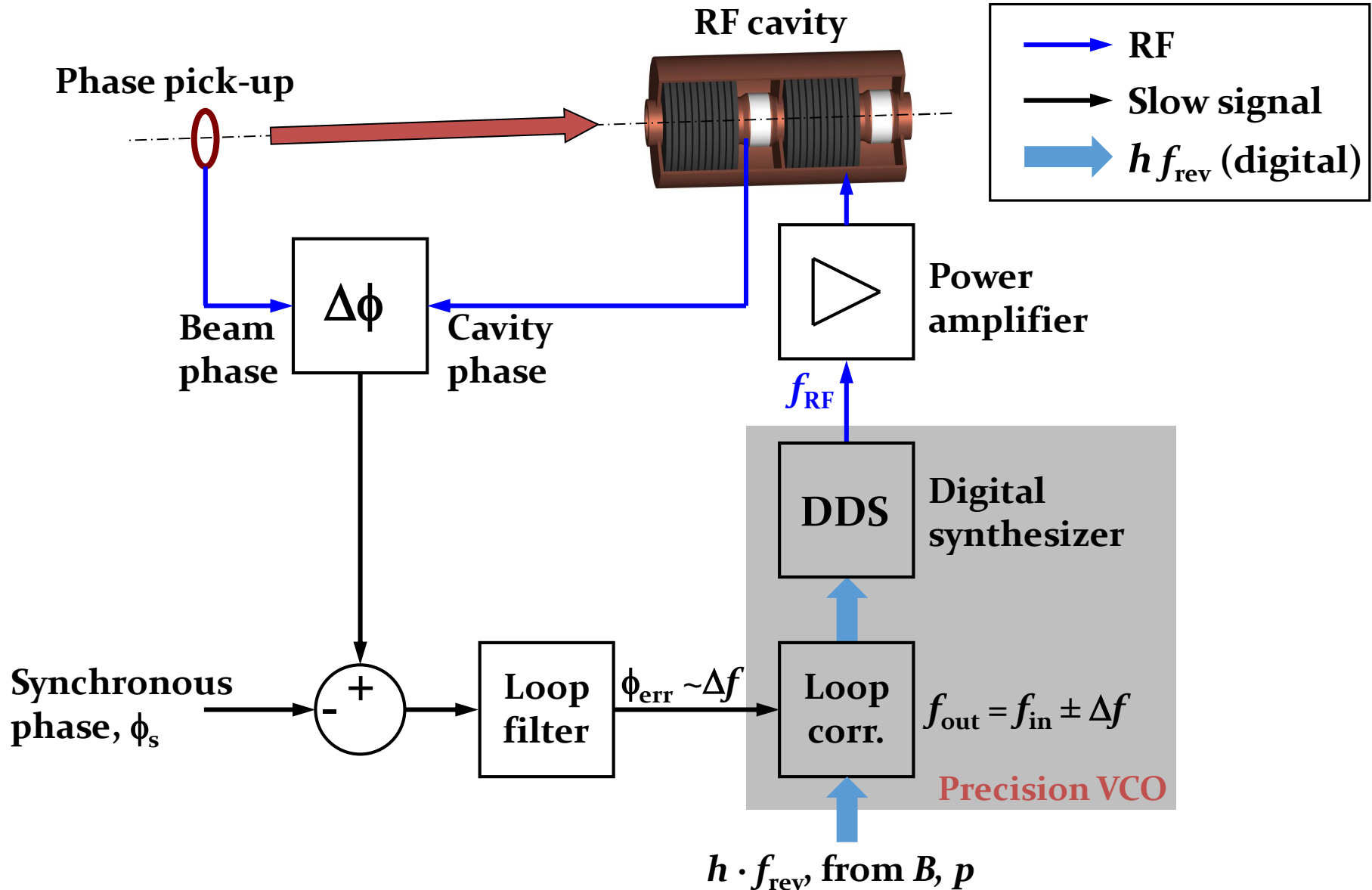
→ Optional divider:

$$f_{\text{out}} = n \cdot f_{\text{in}}$$

Beam phase loop

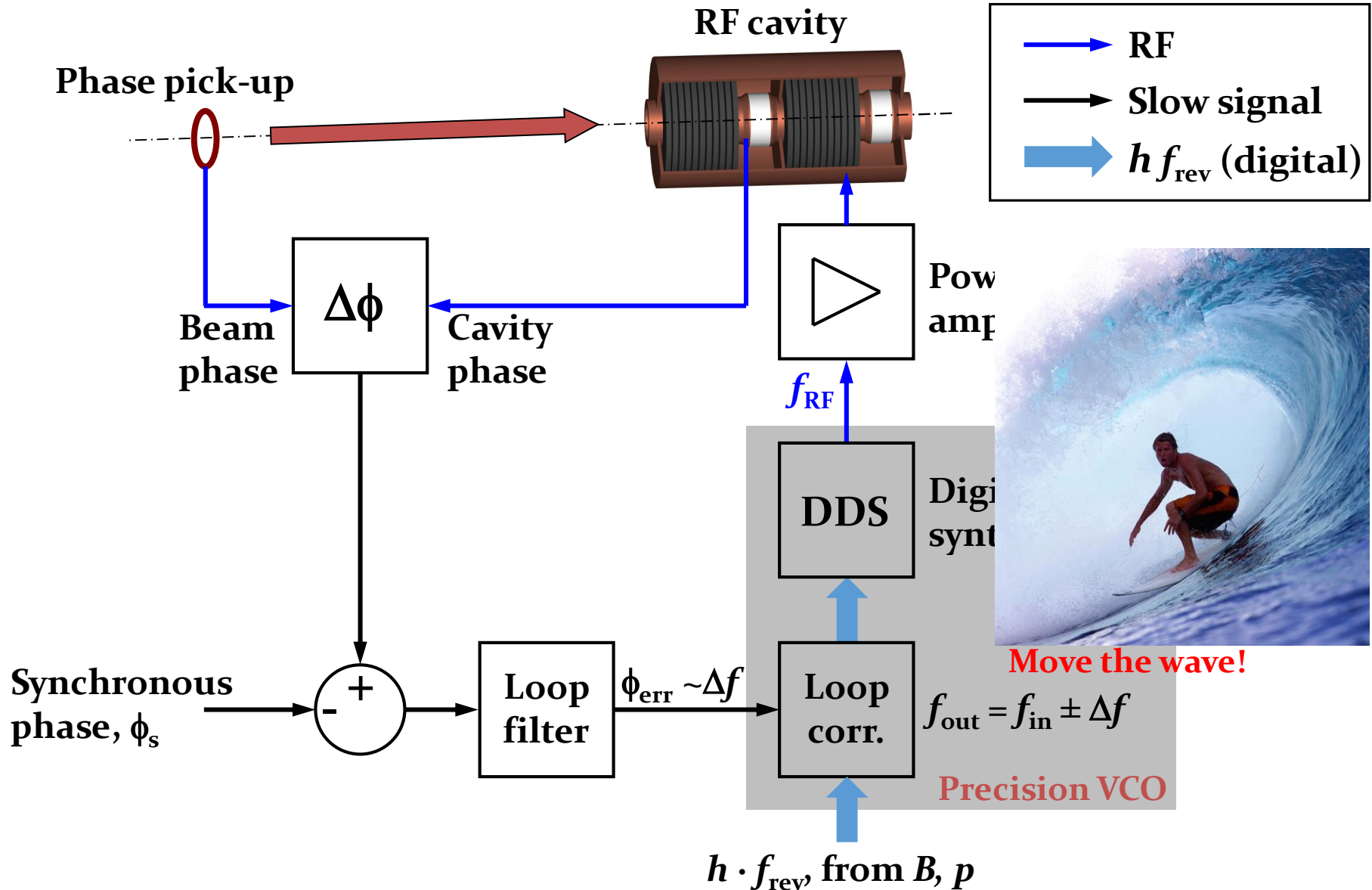


Beam phase loop



→ Phase-locked loop with beam phase as reference for RF system

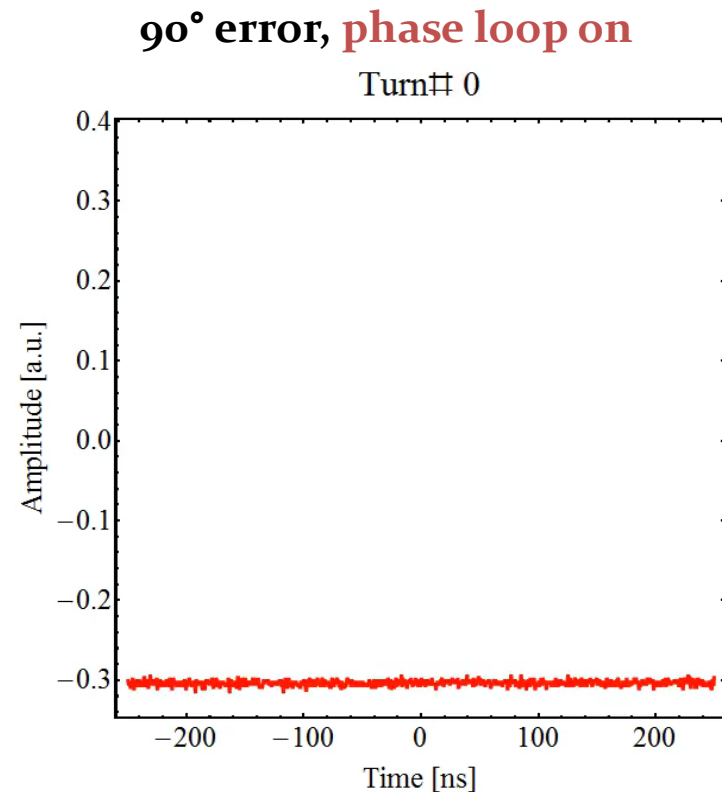
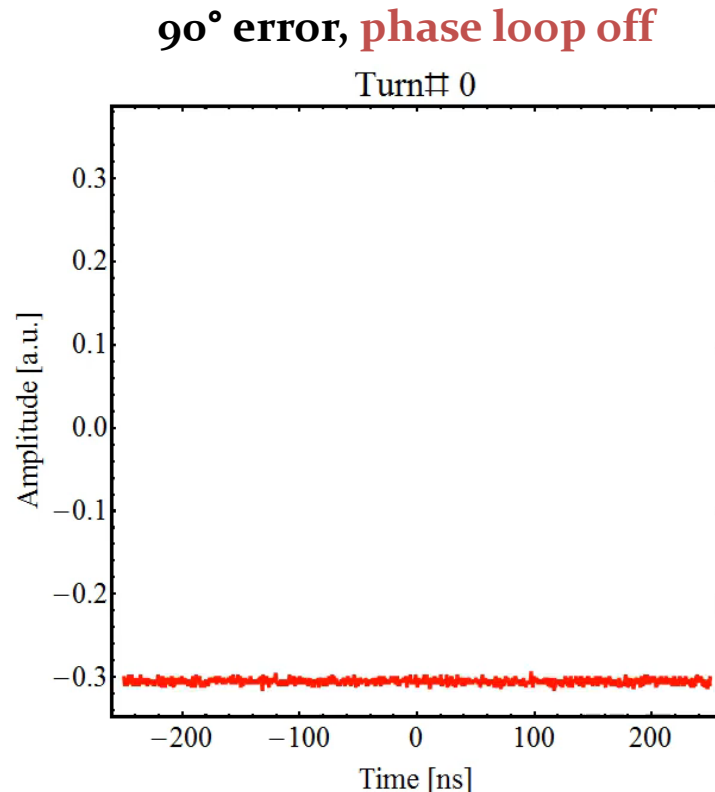
Beam phase loop



→ Fast control of RF frequency to cavities, **but no slow corrections**

Effect of beam phase loop at injection

- **Example: Injection of a bunch from PS Booster into PS**

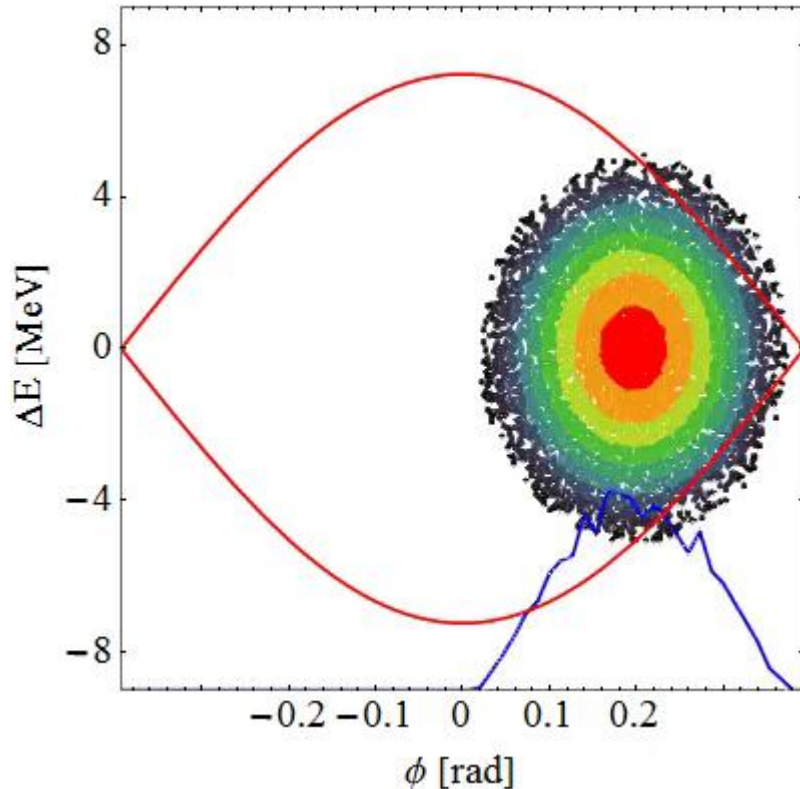


- **Essential in hadron accelerators** to keep RF locked to beam
- **How does this look like in longitudinal phase space?**

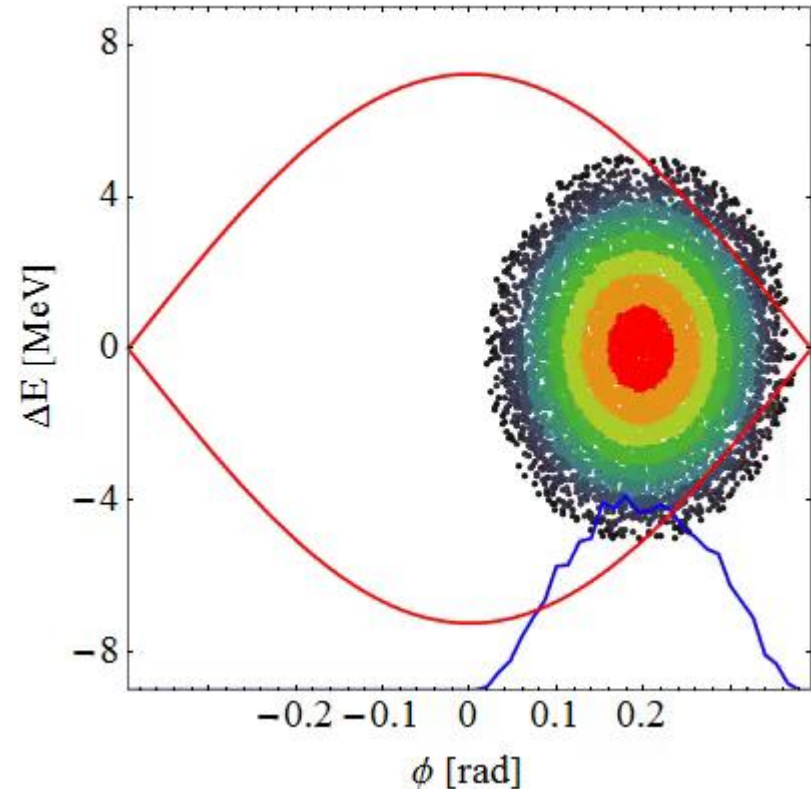
Effect of beam phase loop at injection

→ Essential in hadron accelerators to keep RF locked to beam

Bunch in rigid bucket, no loop



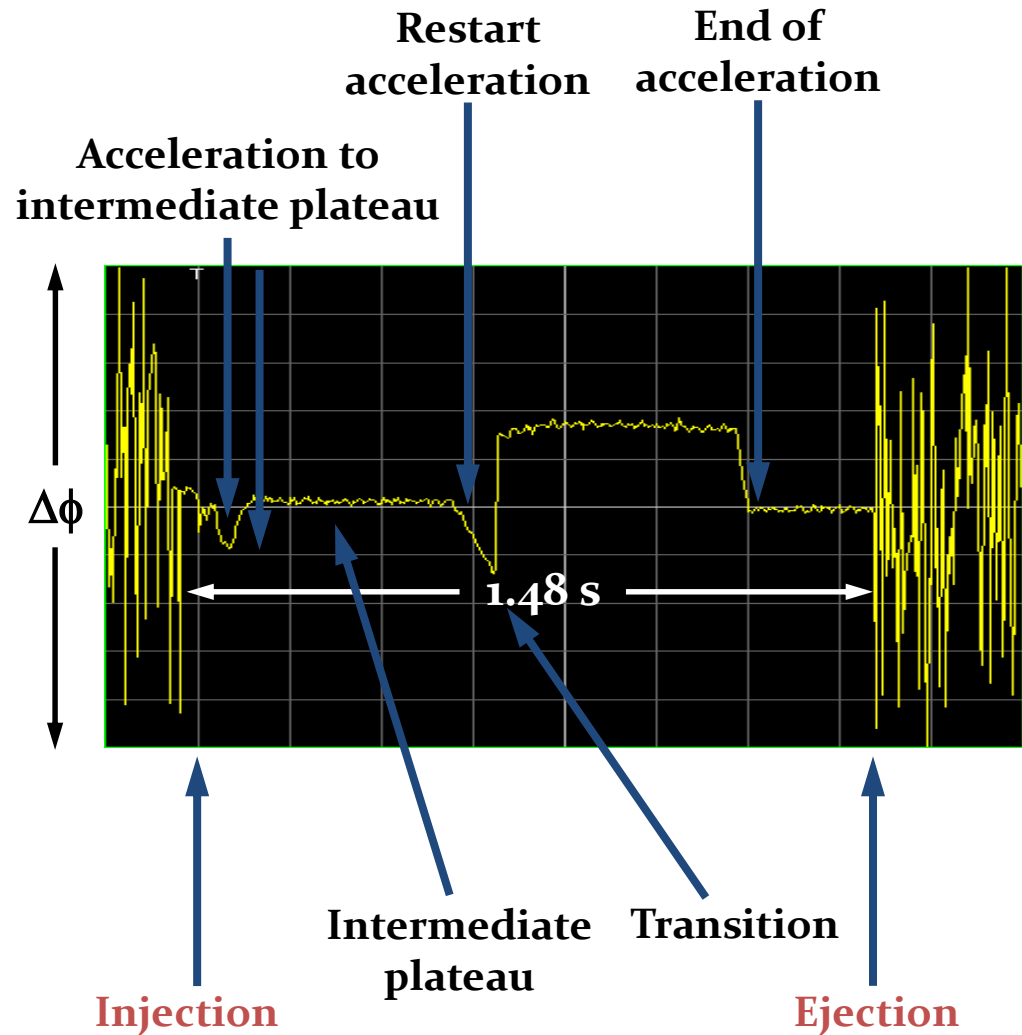
Injection with phase loop



- Even large transients (injection, transition) are controlled
- Only minor longitudinal perturbation

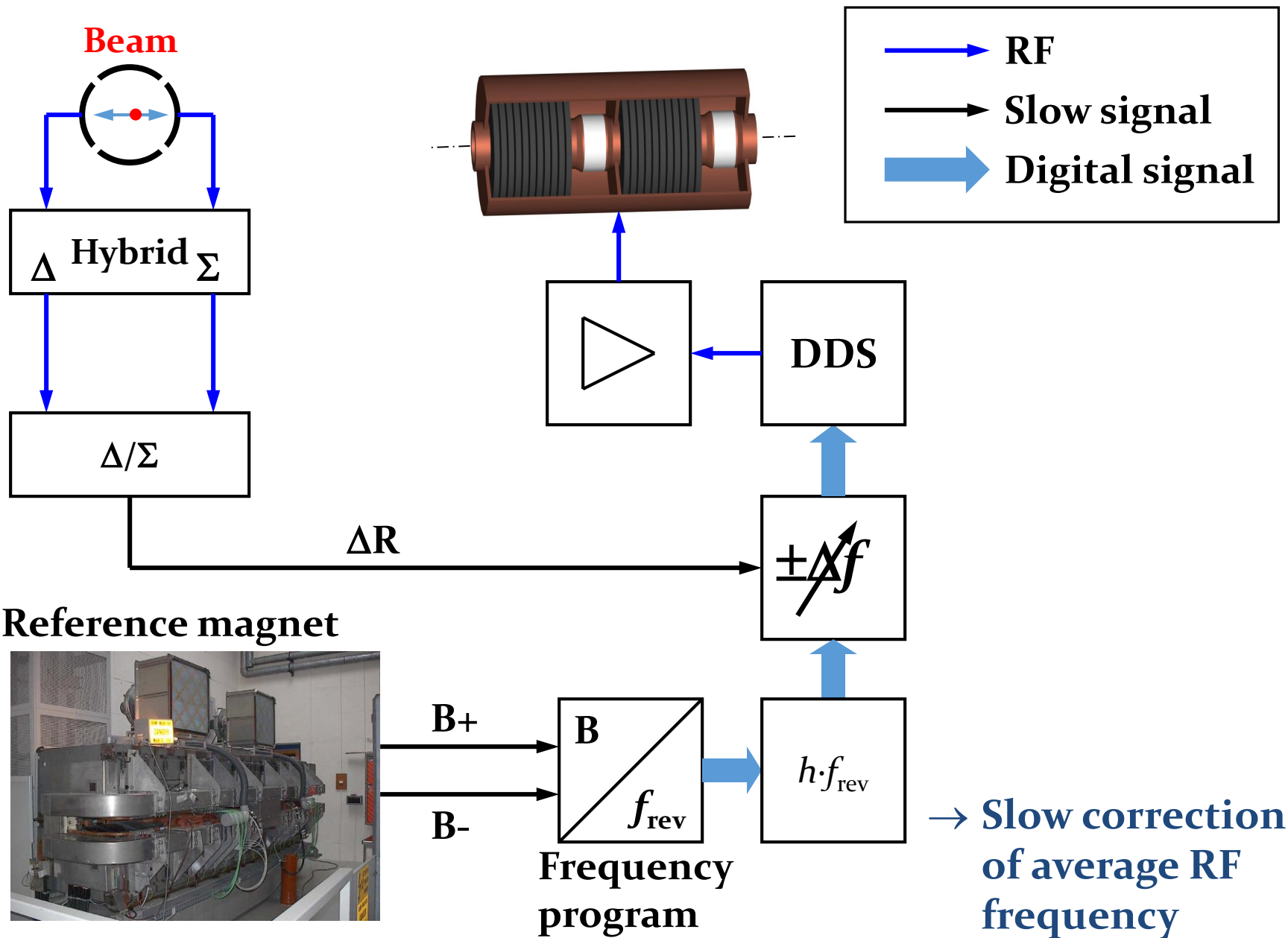
Beam phase loop during acceleration

- What happens with phase loop during acceleration?
- During plateaus the phase between RF and beam is either 0° or 180°
- Fast phase changes well handled, but **need slow frequency correction**
- **Radial** or **synchronization loop**



Radial loop

Radial loop



Radial loop

- Slow correction of RF frequency to keep beam centred

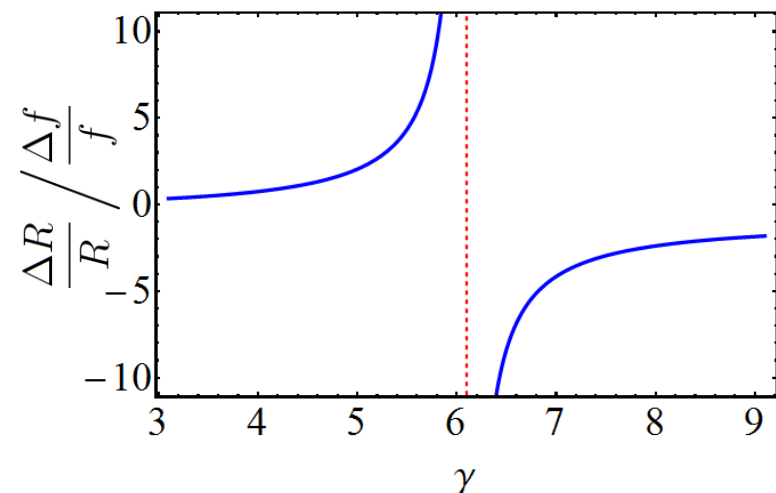
Why needed at all with arbitrary precision synthesizers driving the RF system?

→ At transition energy

- Longer path of higher energy particle compensated by higher velocity
- No revolution frequency change for energy offset

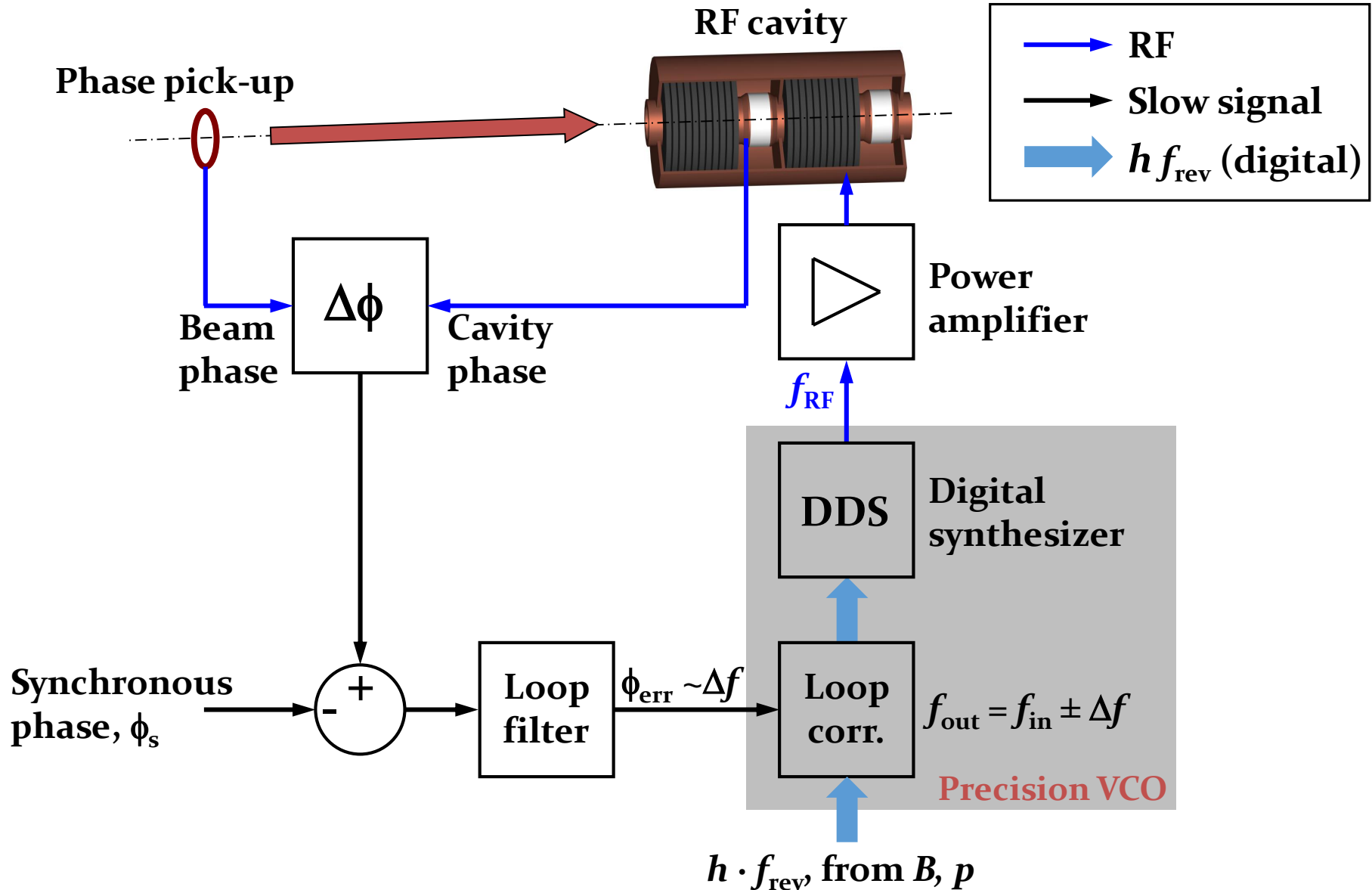
$$\frac{\Delta R}{R} = \frac{\gamma^2}{\gamma_{tr}^2 - \gamma^2} \frac{\Delta f}{f}$$

→ Need beam-based frequency correction



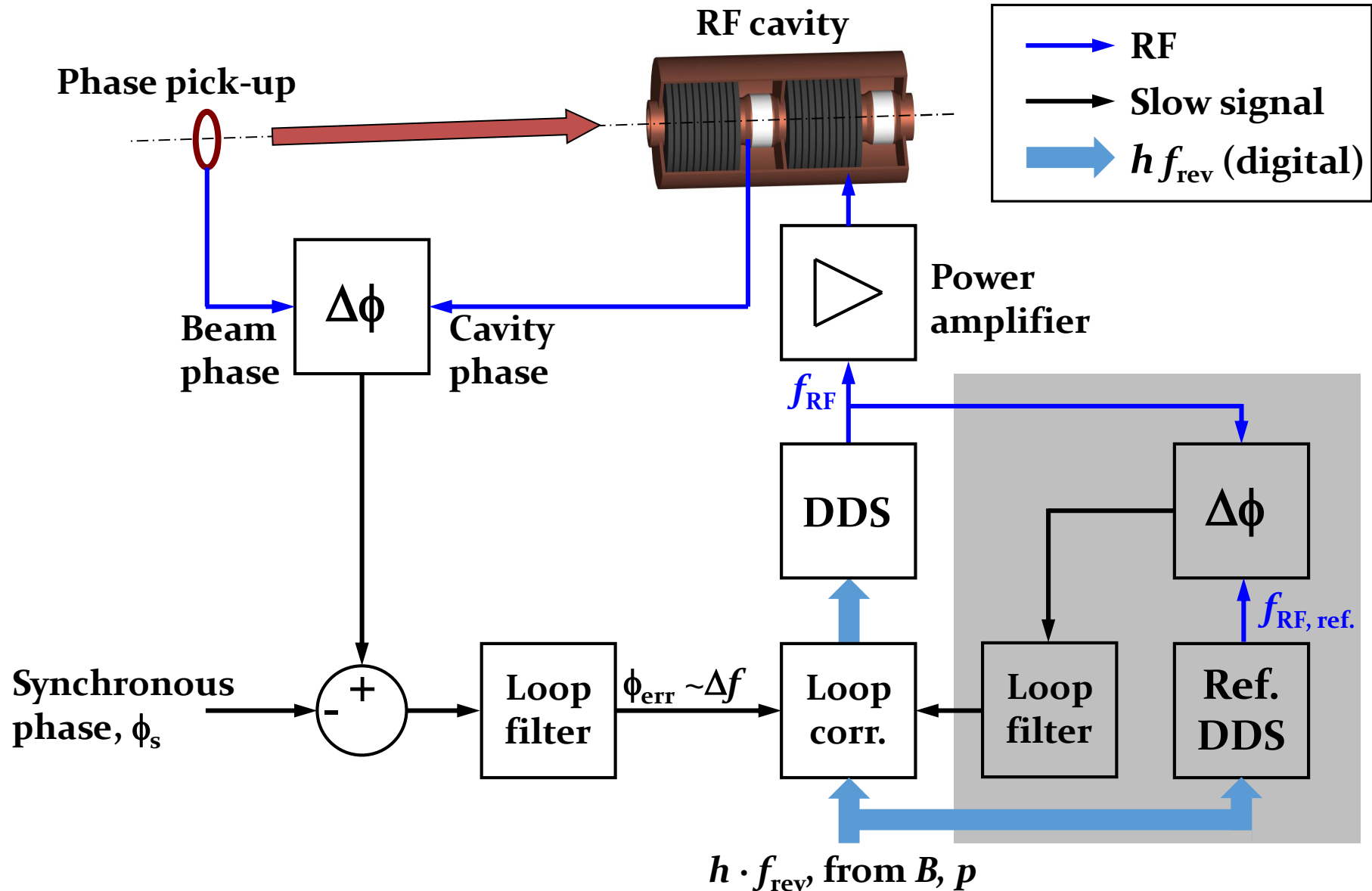
Synchro(nization) loop

Beam phase loop



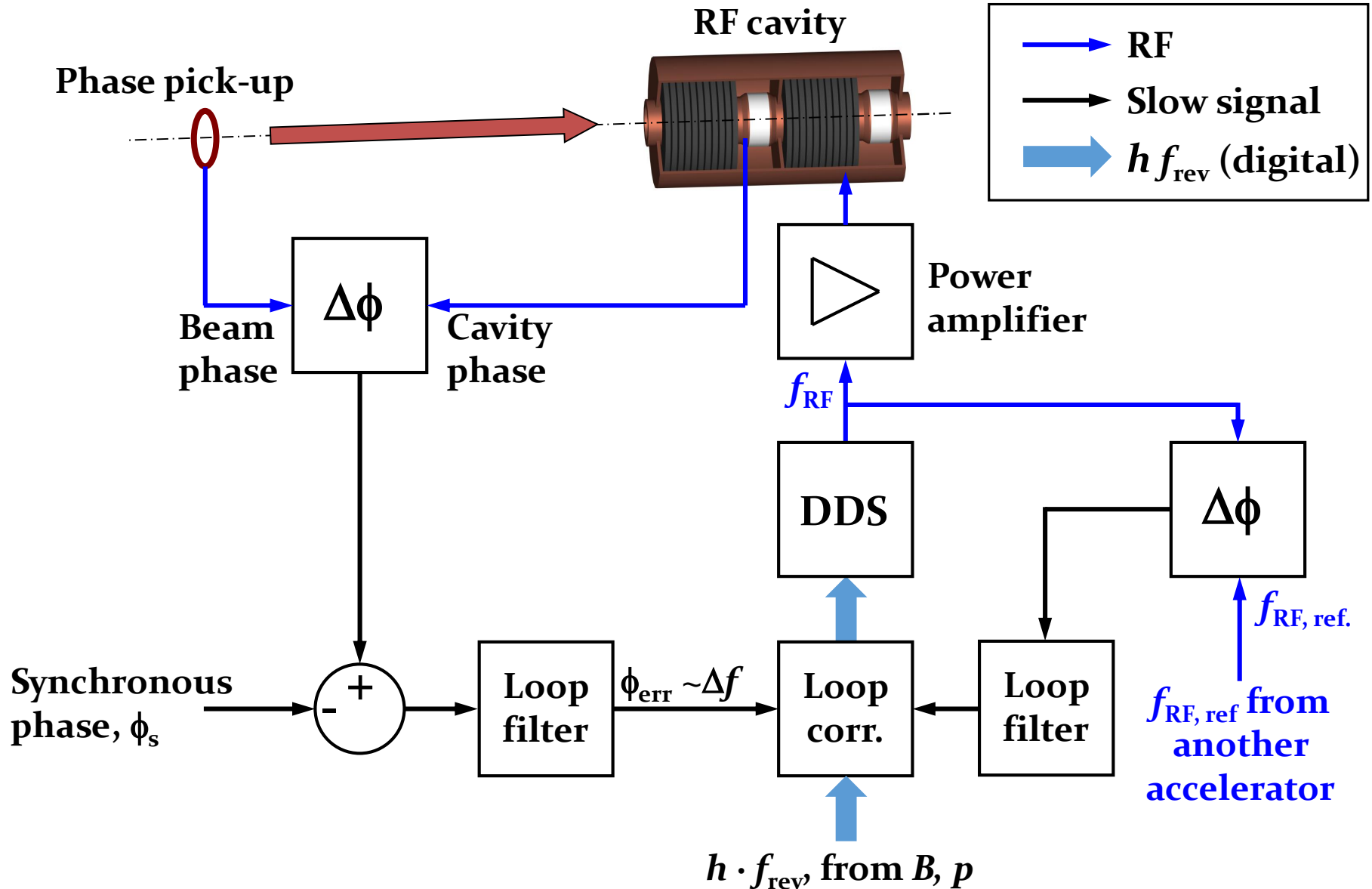
→ Fast control of RF frequency to cavities, **but no slow corrections**

Synchronization loop, **internal** reference



→ Avoids **noise from radial detection** when not crossing transition

Synchronization loop, **external** reference

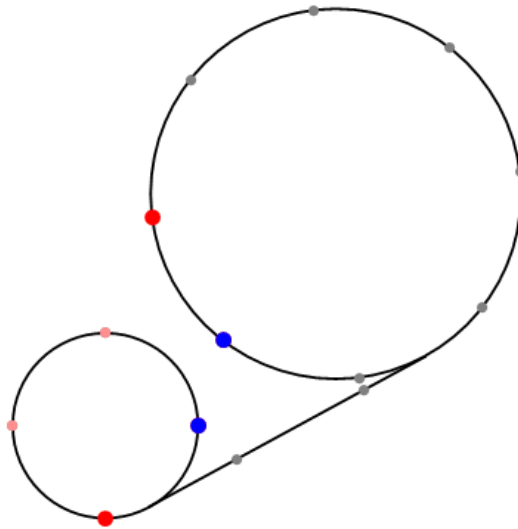


→ Synchronize between accelerators for **transfer**

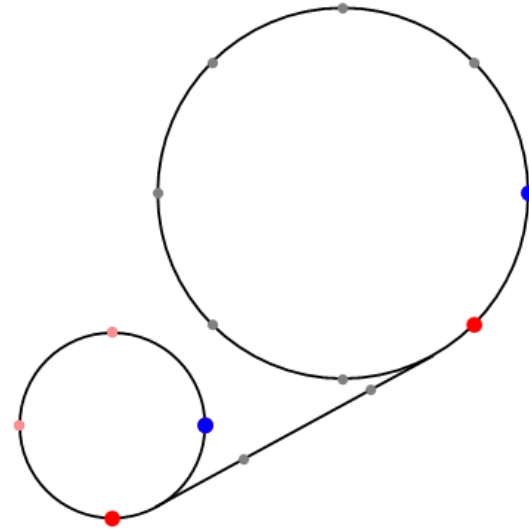
Before synchronization

- Simple test case of circumference ratio 2: $C_2 = 2C_1$

Target accelerator is
master at transfer



Target accelerator is
master at transfer

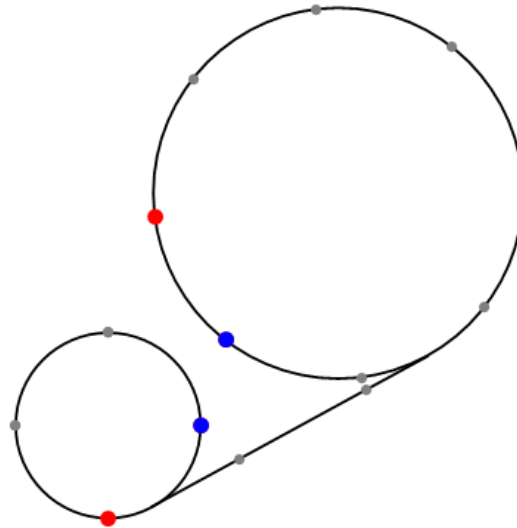


→ Synchronize both accelerator to force: $f_{\text{rev},1} = 2f_{\text{rev},2}$

After synchronization

- Simple test case of circumference ratio 2: $C_2 = 2C_1$

Source or target accelerator
is **master** at transfer



- Revolution frequencies coupled: $f_{\text{rev},1} = 2f_{\text{rev},2}$
- **Ready to extract during** every turn of the target accelerator

Summary

- RF system parameters
- Parameters of RF cavities
- Power amplifier
- **Local feedbacks**
 - **Direct and 1-turn delay feedback**
- **Building blocks of low-level RF systems**
 - **Phase comparison, RF sources and receivers**
- **Basic global feedback loops**
 - **Beam phase, radial and synchronization loops**
 - **Make the beam feel comfortable!**

A big Thank You

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Fumihiko Tamura, Frank Tecker, Daniel Valuch and many
more...**

**Thank you very much
for your attention!**

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- E. Montesinos, Accelerators for Medical Applications - Radio Frequency Powering, CERN-2017-004-SP, <http://cds.cern.ch/record/2315172/files/1804.08535.pdf>
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Normalized Hamiltonian representation

- For a single harmonic RF system

$$H(\phi, \dot{\phi}) = \frac{1}{2} \dot{\phi}^2 + \frac{\omega_s^2}{\cos \phi_S} [\cos \phi_S - \cos \phi + (\phi - \phi_S) \sin \phi_S]$$

with $\phi = \phi_S + \Delta\phi$ **it becomes**

$$H(\Delta\phi, \dot{\phi}) = \frac{1}{2} \dot{\phi}^2 + \frac{\omega_s^2}{\cos \phi_S} [\cos \phi_S - \cos(\phi_S + \Delta\phi) - \Delta\phi \sin \phi_S]$$

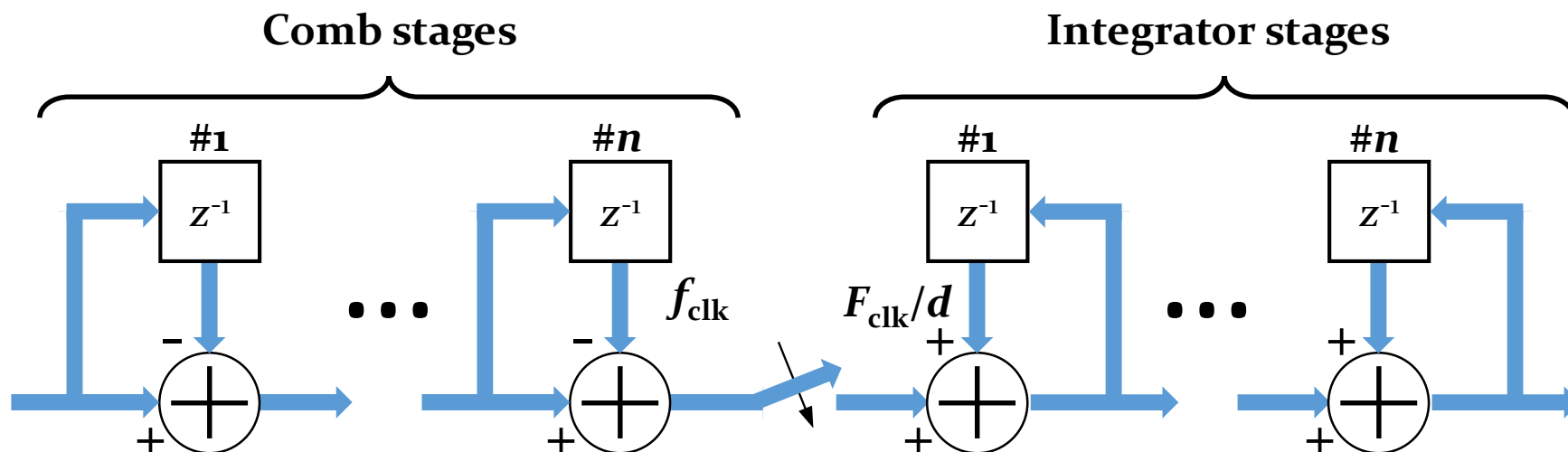
using $\cos(\phi_S + \Delta\phi) = \cos \phi_S \cos \Delta\phi - \sin \phi_S \sin \Delta\phi$

$$\simeq \cos \phi_S \left(1 - \frac{1}{2} \Delta\phi^2 \right) - \sin \phi_S \Delta\phi$$

this simplifies to $H(\Delta\phi, \dot{\phi}) \simeq \frac{1}{2} \dot{\phi}^2 + \frac{1}{2} \omega_s^2 \Delta\phi^2$

Cascaded integrator-comb filter (CIC)

- Efficient implementation of low pass filter
- Standard form with sampling rate decimation: $f_{\text{clk}} \rightarrow f_{\text{clk}}/d$



$$H(z) = \left(\frac{1 - z^{-d}}{1 - z^{-1}} \right)^n \quad \begin{array}{l} n: \text{filter order} \\ d: \text{decimation ratio} \end{array} \quad z = e^{2\pi i \cdot f / f_{\text{clk}}}$$

- Easy to implement in programmable logic: **no multipliers**
- **Only adders and shift registers**

Cascaded integrator-comb filter (CIC)

Why particularly interesting for circular accelerators?

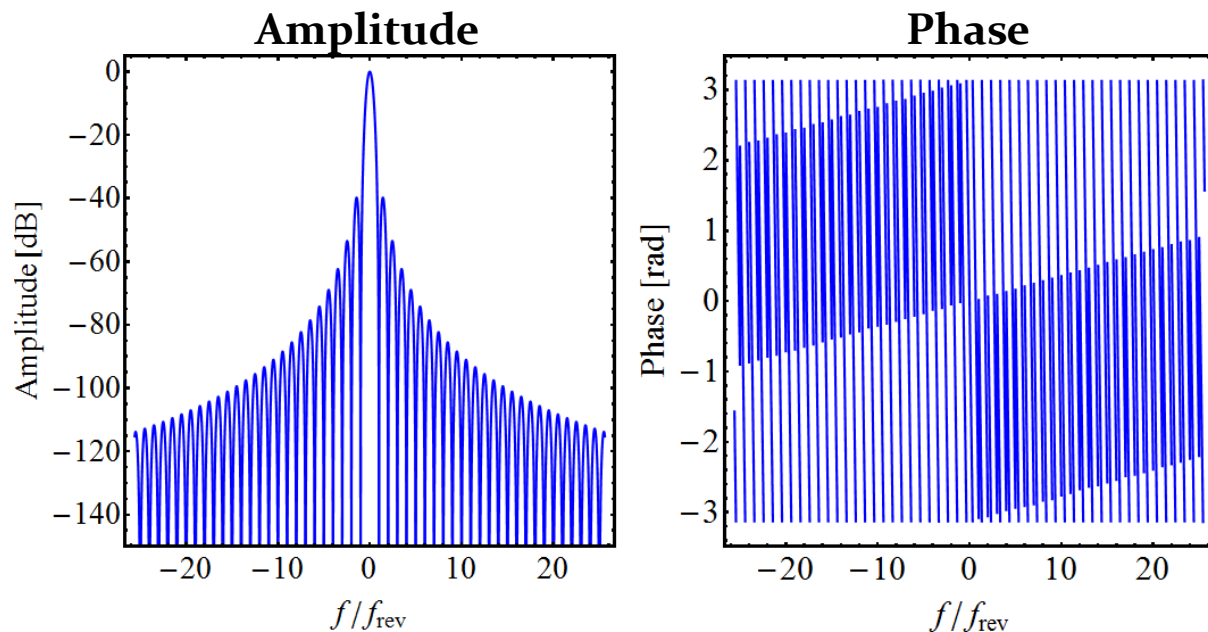
- Choose clock frequency, $f_{\text{clk}} = 2^m f_{\text{rev}}$ and decimation $d = 2^m$
- Notches at **all multiples of f_{rev} except zero**
- Linear phase $\phi(f) \rightarrow$ **filter behaves like a constant delay**

Example:

$$f_{\text{clk}} = 128 f_{\text{rev}},$$

$$d = 128,$$

$$n = 3$$



Ideal low-pass filter in digital receivers

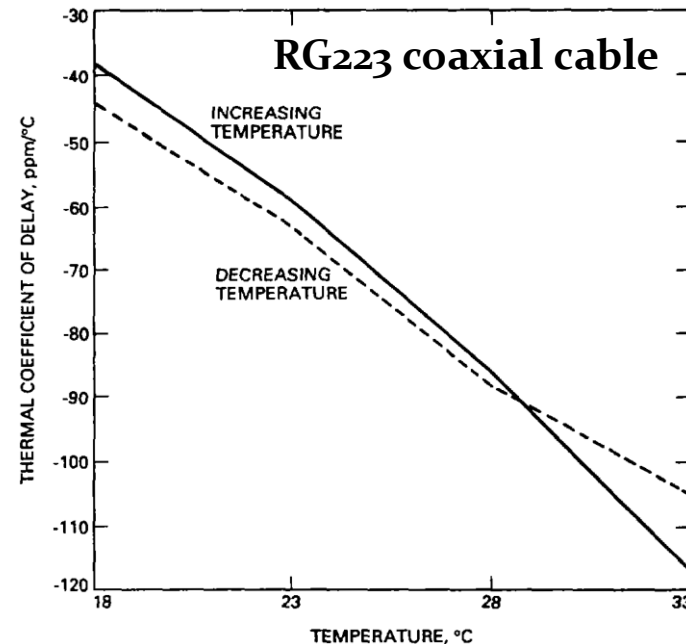
→ **Filter selected multiple of f_{rev} while suppressing all others**

Transmission of reference signals

- Thermal drift of long **coaxial cables** or optical fibres

- Thermal coefficient of delay:

$$\text{TCD} = \frac{\Delta\tau}{\tau} \cdot \frac{1}{\Delta T} = \frac{\Delta\phi}{\phi} \cdot \frac{1}{\Delta T}$$



- Example: **2 km long RG223 cable with ~10 μs delay**
 - ΔT of only 1° C (room temperature) changes delay by ~0.5 ns
 - 1.8° at 10 MHz (CERN PS), **but 73° at 400 MHz (LHC)**
- **Optical fibres are typically 10...100 times more stable**
- **What to do if this is still not sufficient?**

Simple synchronization process

1. Move beam to off-momentum (B const.): $\frac{df}{f} = \frac{\gamma_{tr}^2 - \gamma^2}{\gamma^2 \gamma_{tr}^2} \frac{dp}{p}$
 - Well defined frequency difference between accelerators
2. Measure azimuth error, when beam at correct azimuth
 - Close synchronization loop
 - Moves beam to ref. momentum

