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

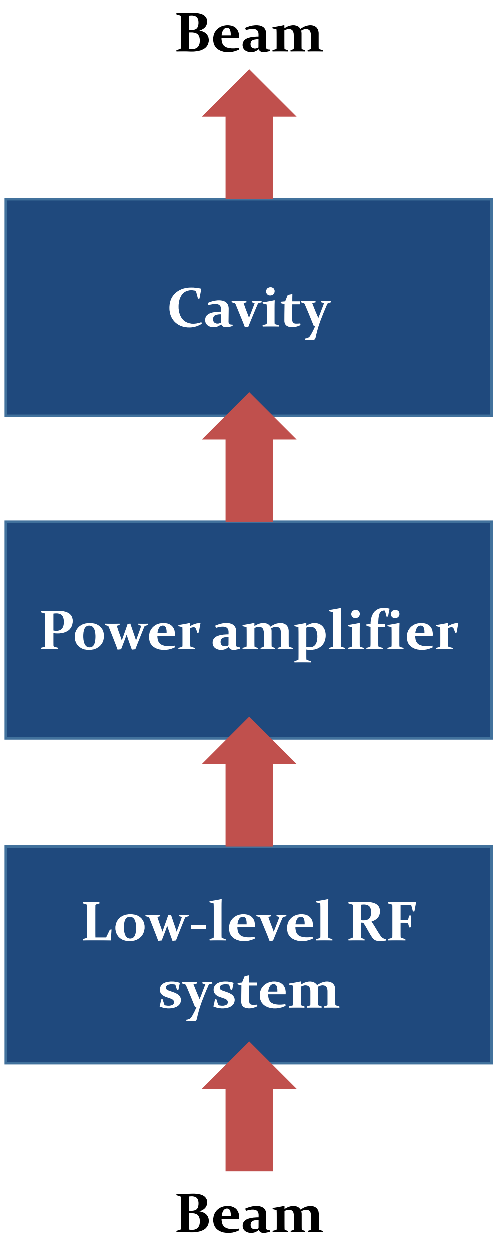
Introduction

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?



Beam

Cavity

Power amplifier

Low-level RF system

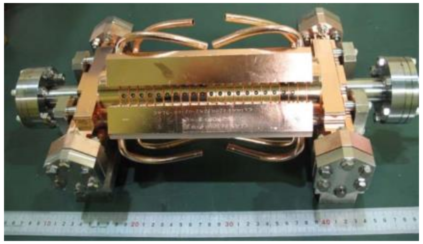
Beam

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

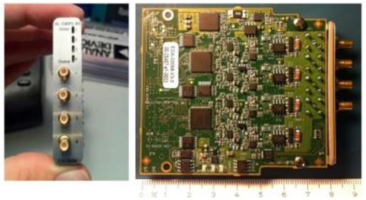
Medium/ short wave

VHF

Microwave links

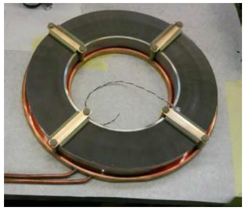
Amplitude ranges

Signals from beam pick-ups



LLRF systems

Low/Medium energy hadron RF



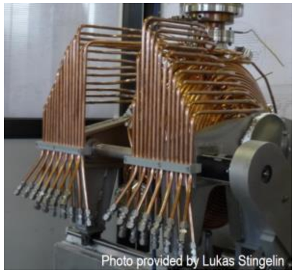


Photo provided by Lukas Stingelin

SLS

LHC: 16 MV

LEP: 3.6 GV total

1 µV

1 mV

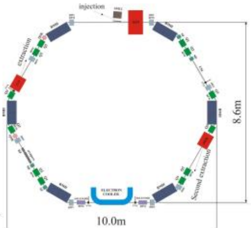
1 V

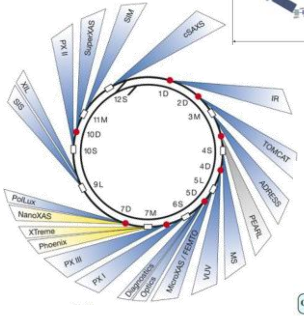
1 kV

1 MV

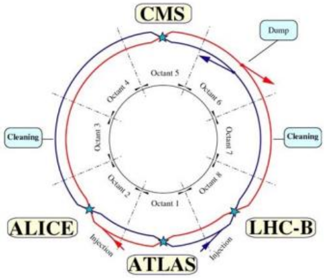
1 GV

Cooled hadron beams (ELENA)

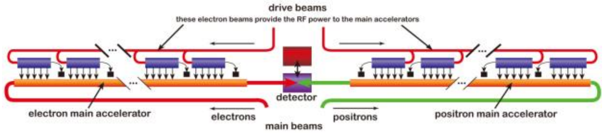




Electron light sources



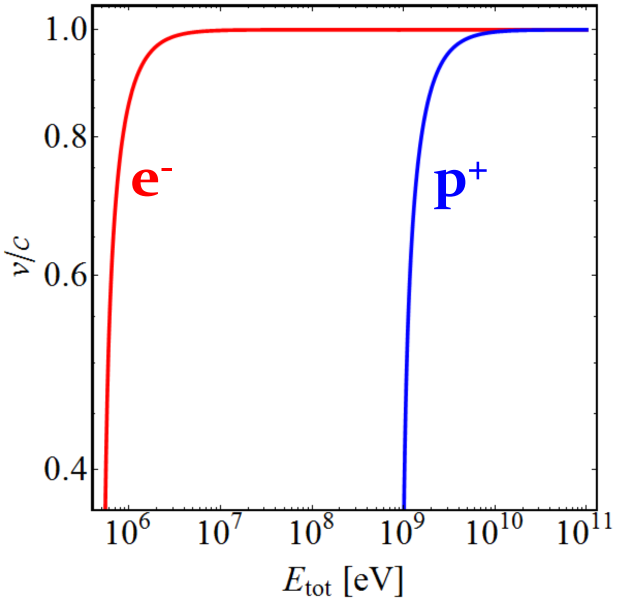
LHC

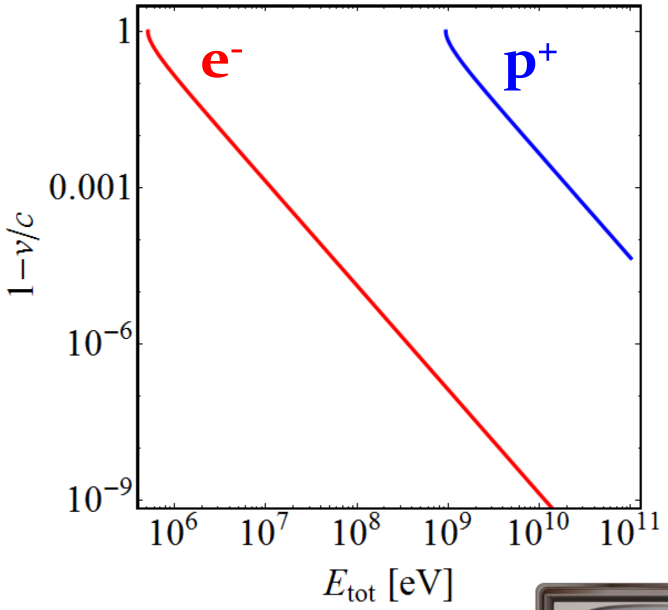


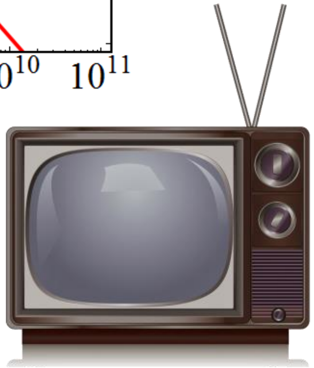
ILC and CLIC: several TV

Particle velocity

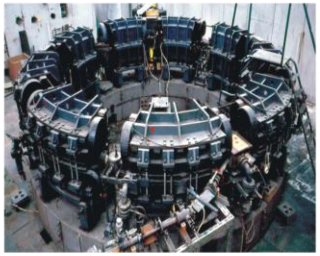
- **Particle velocity depends on its type:** $\beta = v/c = \sqrt{1-(E_0/E)^2}$







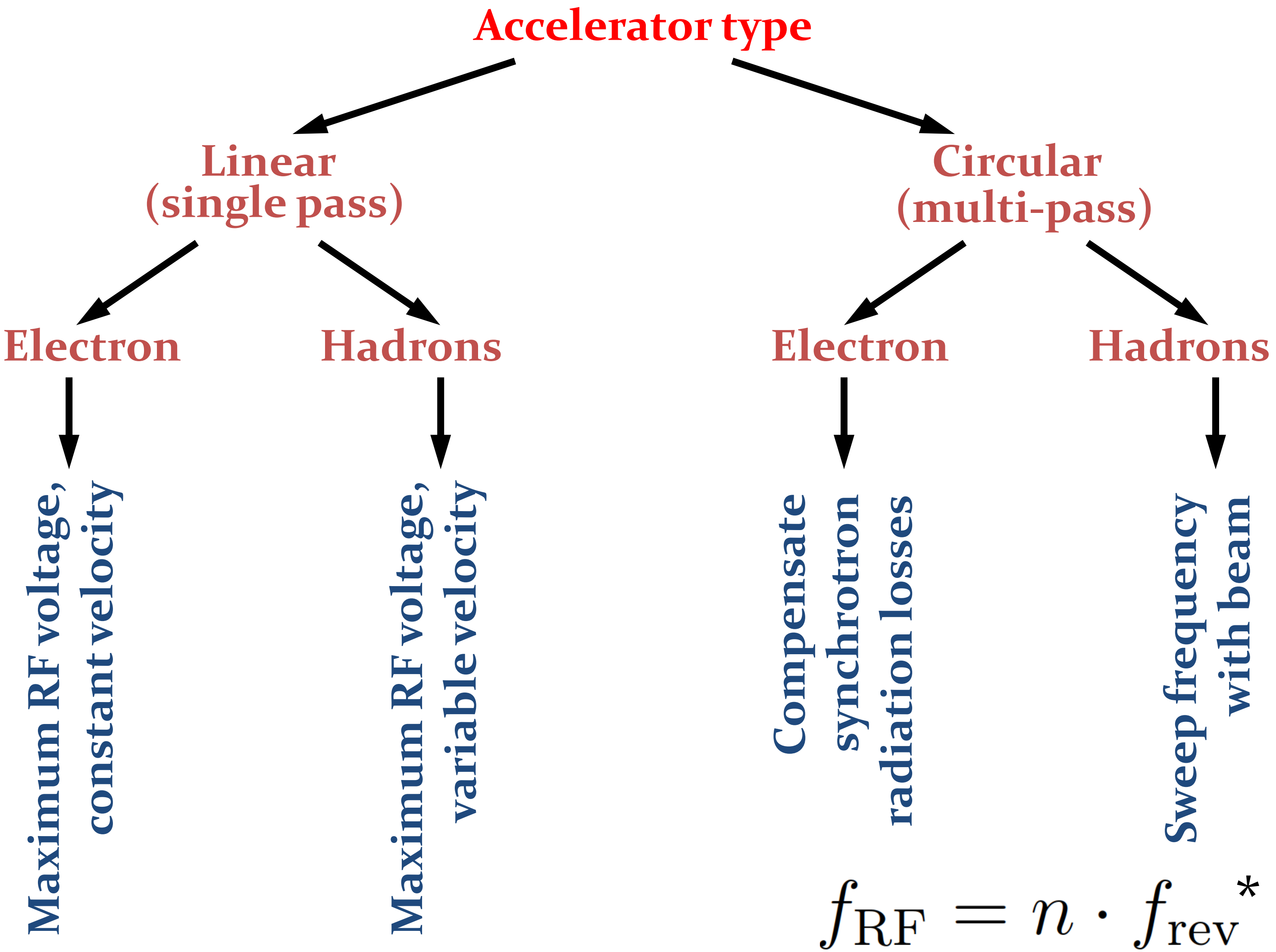
- **Old television set (30 kV):** **Electrons** at 30% of c_0
  Protons just at 0.7%
- **Small synchrotron (500 MeV):** **Electrons** at 99.99995%
  Protons at 75.8%



→ Most electron accelerators at 'fixed' frequency

Parameter choices

RF system for high-energy accelerators



Accelerator type

- Linear (single pass)
  - Electron
    - Maximum RF voltage, constant velocity
  - Hadrons
    - Maximum RF voltage, variable velocity
- Circular (multi-pass)
  - Electron
    - Compensate synchrotron radiation losses
  - Hadrons
    - Sweep frequency with beam

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

*Exceptions (rare) exist

Choice of frequency (range)

Why chose a low RF frequency?

Advantages	Disadvantages
Large beam aperture	Bulky cavities, size scales $\propto f$, volume $\propto f^3$
Long RF buckets, large acceptance	Lossy material to downsize cavities
Wide-band or wide range tunable cavities possible	Moderate or low acceleration gradient
Power amplification and transmission straightforward	Short particle bunches difficult to generate

RF frequencies below ~200 MHz for

→ Some hadron linear accelerators
→ Cyclotrons
→ Low- and medium energy hadron synchrotrons

Why chose a high RF frequency?

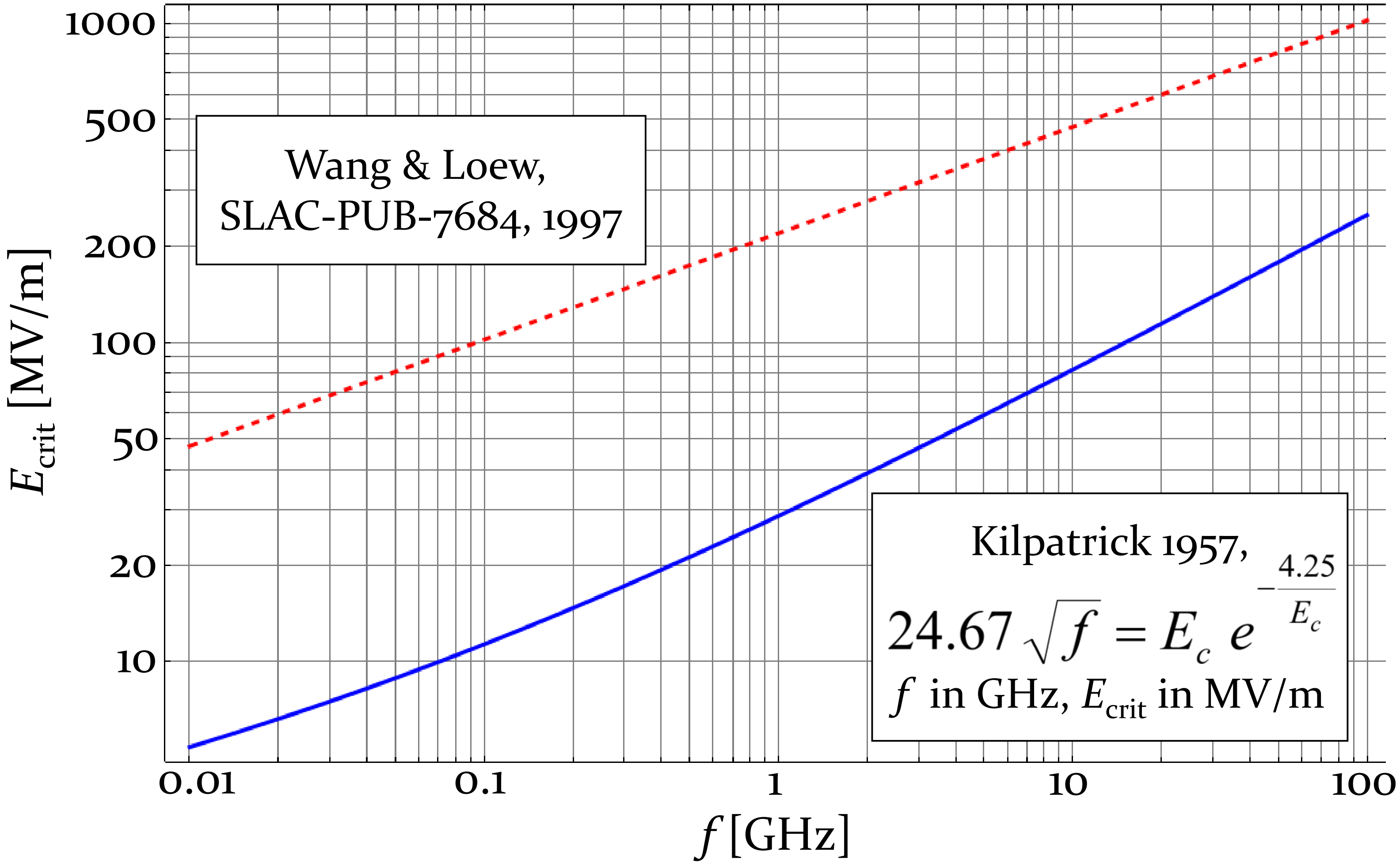
Advantages	Disadvantages
• Cavity size scales ∝ f, volume ∝ f^3 • Break down voltage increases • High gradient per length • Particle bunches are short	• Maximum beam available aperture scales ∝ $1/f$ • No technology for wide-band or tunable cavities • Power amplifiers more difficult • Power transmission 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**



$$24.67\sqrt{f} = E_c\, e^{-\frac{4.25}{E_c}}$$

f in GHz, E_{crit} in MV/m

→ High frequencies preferred for large gradient

E. Jensen

Some standard frequencies

If exact RF frequency not critical, chose standard value

Accelerator	Frequency
Hadron synchrotrons (PSB, PS, JPARC RCS, MR)	<10 MHs
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
Supraconducting 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

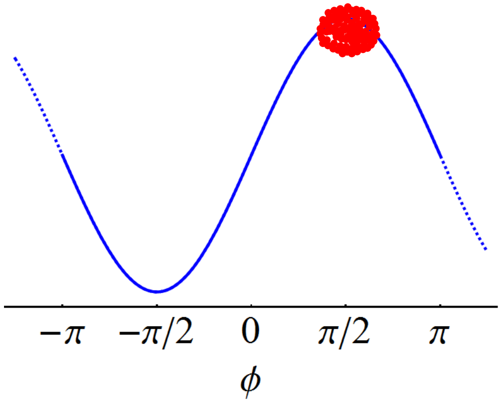
- **RF system expected to provide given energy gain**

$$qV = \Delta E$$

→ On-crest acceleration

→ Used in some linear accelerators

→ Insufficient in a circular accelerator



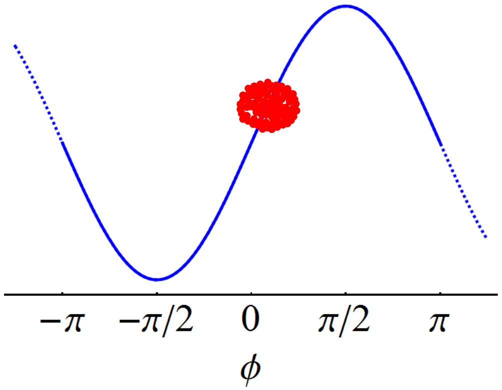
- **More voltage provided to avoid on-crest acceleration**

$$qV > \Delta E \;\rightarrow\; qV\sin(\phi_0) = E$$

→ Off-crest acceleration

→ Needed for circular accelerator

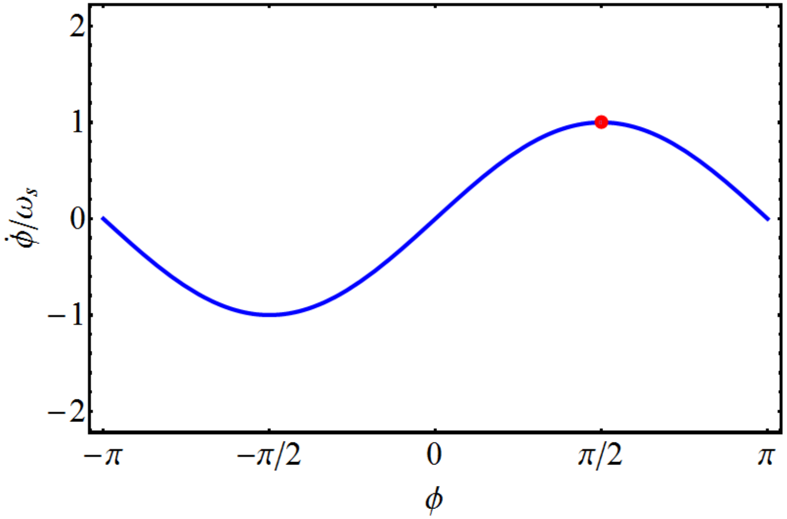
→ Higher voltage for given energy gain



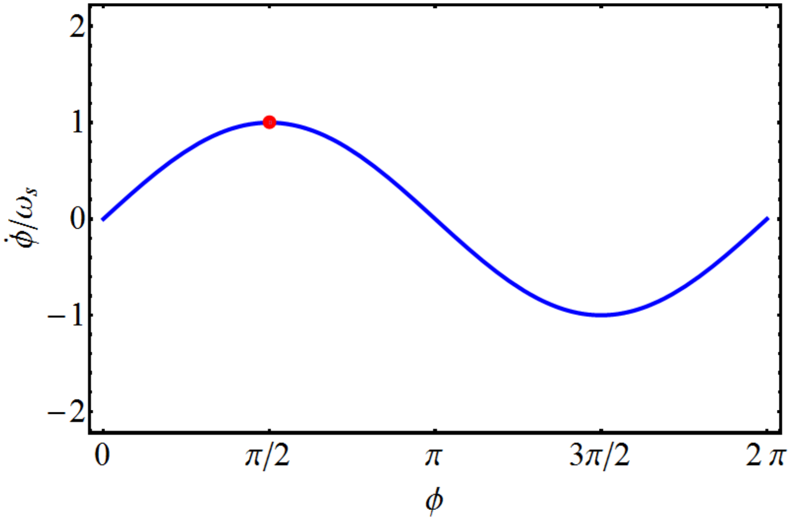
Bucket area dependence on stable phase

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

Below transition, ϕ_o = 0…90°



Below transition, ϕ_o = 90°…180°



- **Typical synchronous phase with respect to 0° or 180°**
  - **Hadron accelerators: < 40°**
  - **Electron storage rings: ~ 20°**

Minimum voltage requirement (circular)

The RF system must compensate

1. Energy gain per turn due to changing magnetic field

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

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

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

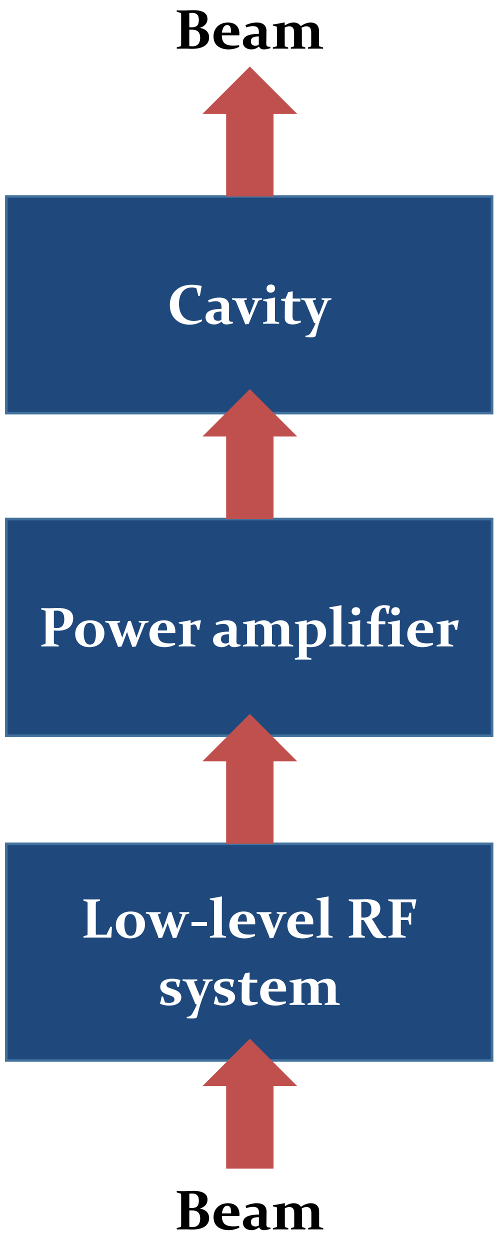
2. Energy loss, e.g., due to synchrotron radiation (electrons)

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

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

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

RF system overview



Beam

Cavity

Power amplifier

Low-level RF system

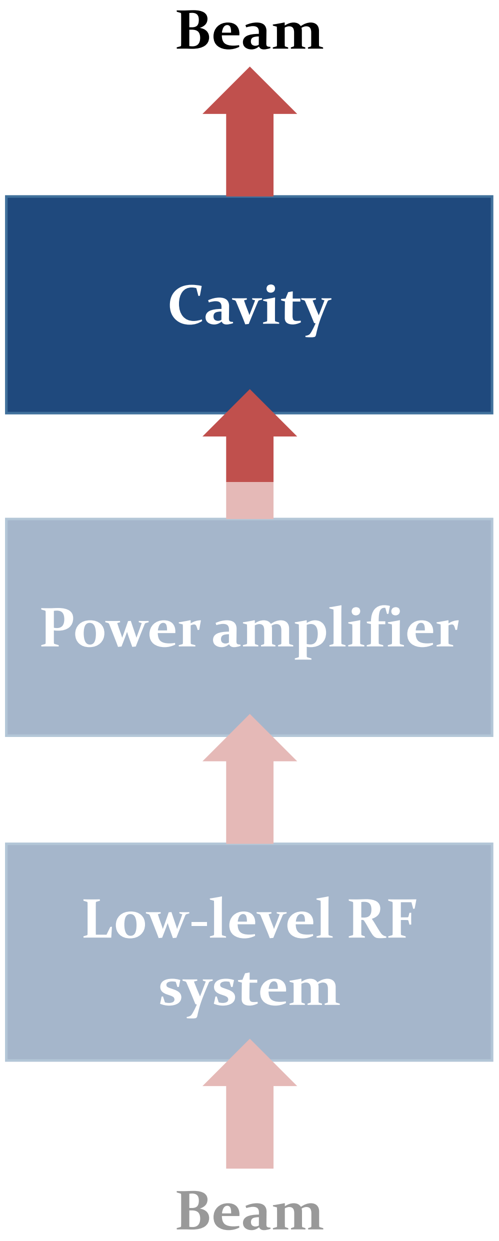
Beam

→ Convert RF power into longitudinal electric field

→ Amplify low-power signal from beam control to kW, MW or GW

→ Provide RF signals with correct frequency, amplitude and phase

RF system overview



→ Convert RF power into longitudinal electric field

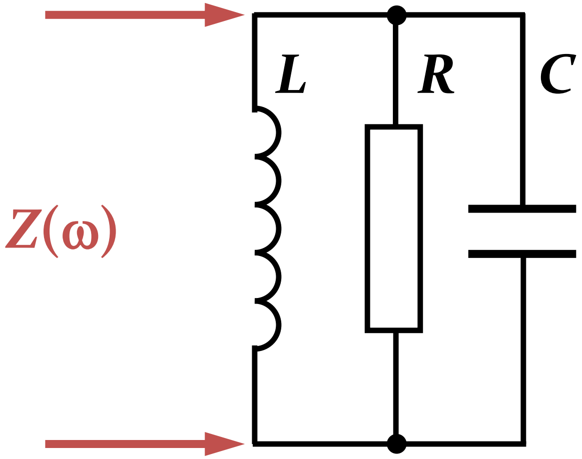
→ Amplify low-power signal from beam control to kW, MW or GW

→ Provide RF signals with correct frequency, amplitude and phase

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

$$E = \frac{1}{2}CV^2 = \frac{1}{2}LI^2$$

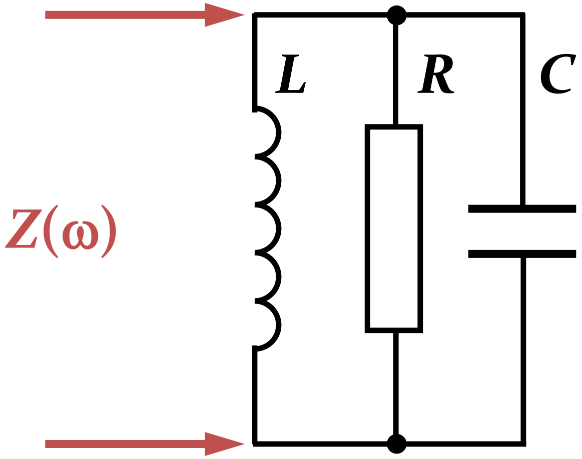
$$Q = \omega_0 \frac{\text{Stored energy}}{\text{Average power loss}} = \frac{\omega_0 E}{P}$$

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

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

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

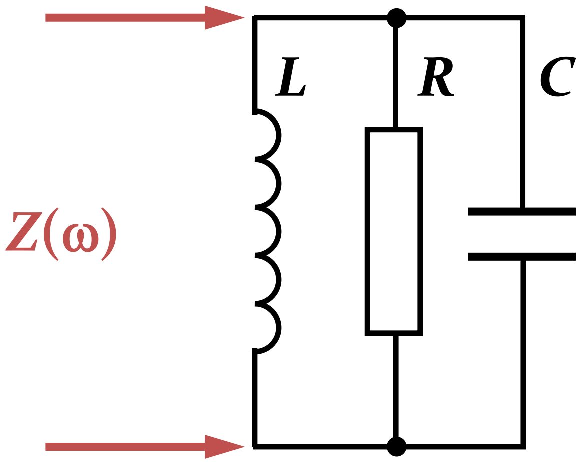
$$Q = \omega_0 RC = \frac{R}{\omega_0 L}$$

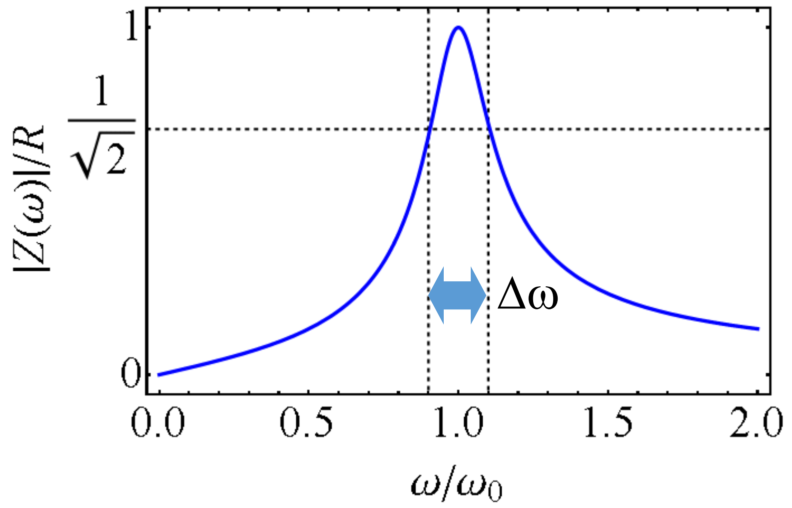
$$Z(\omega) = \frac{R}{1 + iQ\left(\frac{\omega^2 - \omega_0^2}{\omega\omega_0}\right)} \simeq \frac{R}{1 + 2iQ\frac{\Delta\omega}{\omega_0}}$$

→ **Resonant circuit can also be described by *R, R/Q, ω_o* 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***





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

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

Cavity parameters

- Most common choice by cavity designers ω_o, R, R/Q – why?

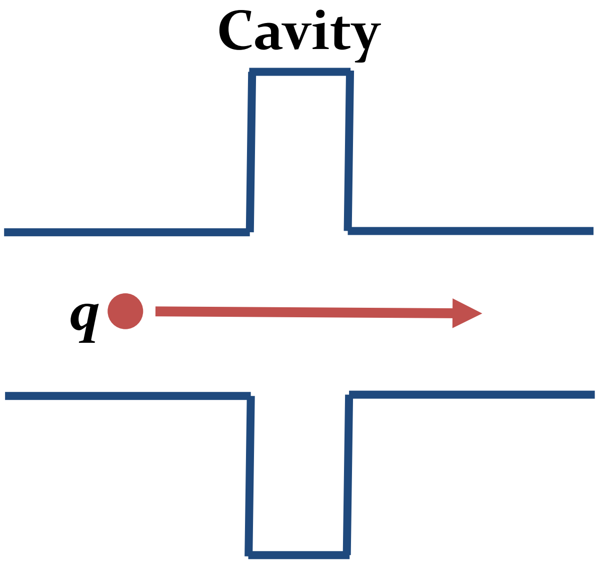
- Resonance frequency, ω_o
  - → Exactly defined for given application, e.g. hf_{rev}

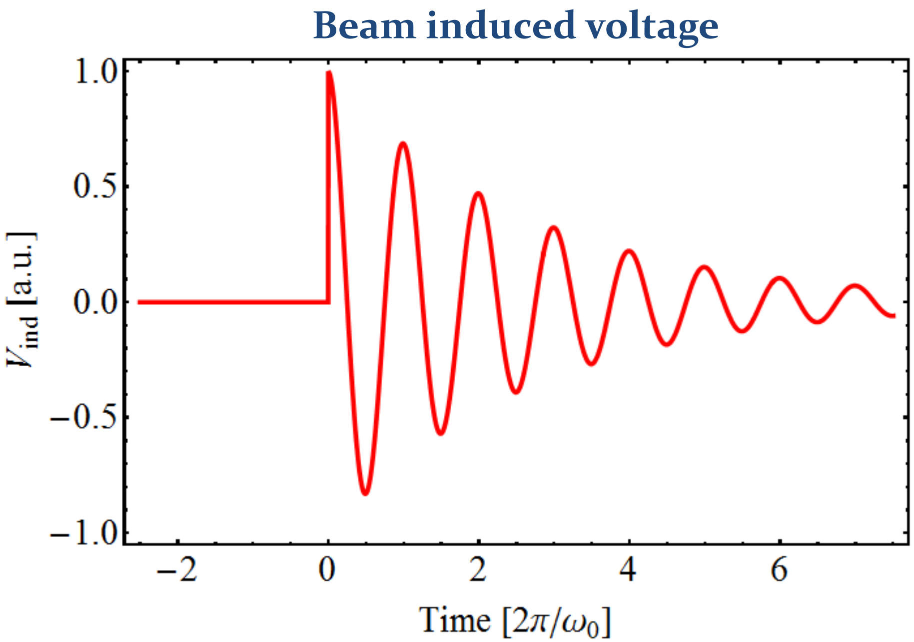
- Shunt impedance, R
  - → Power required to produce a given voltage without beam

- "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**


Cavity


Beam induced voltage

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

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

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

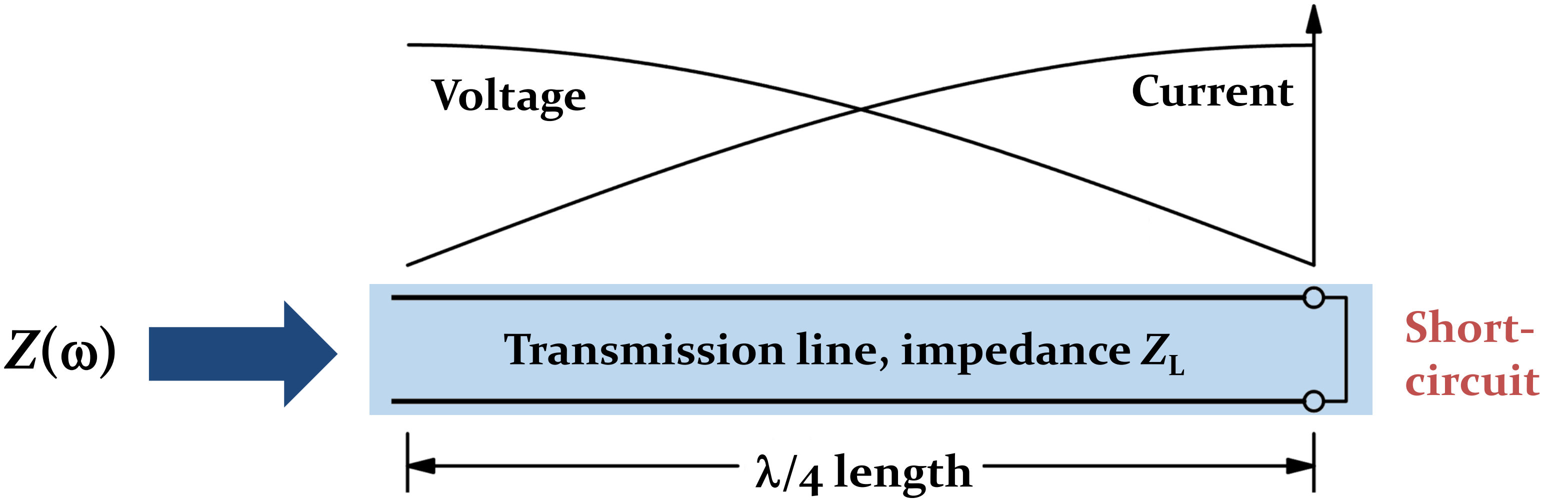
→ **Cavity geometry with small *R*/*Q* to reduce beam loading**

RF cavities in low frequency range

- RF wavelength large below ~10 MHz: >30 m

→ Would need huge cavities → too large for accelerators

→ Line resonators: λ/4 resonator



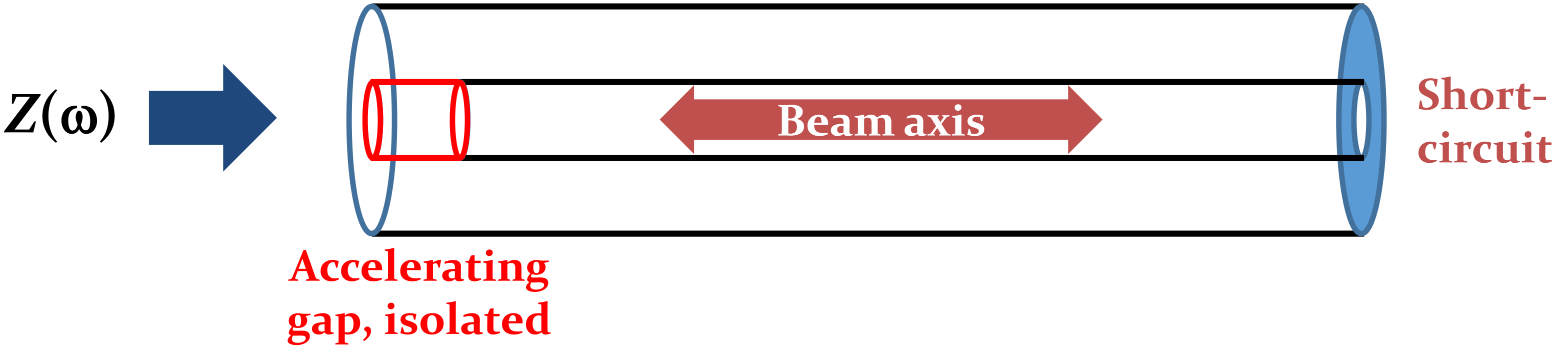
→ Short circuit on one side → Voltage is zero

→ Open end on other → 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

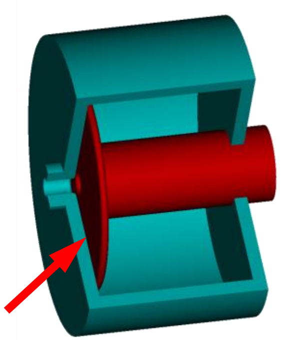
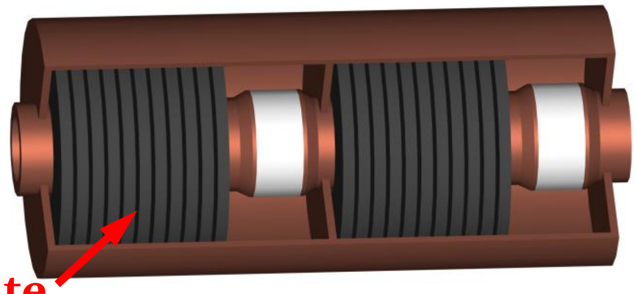


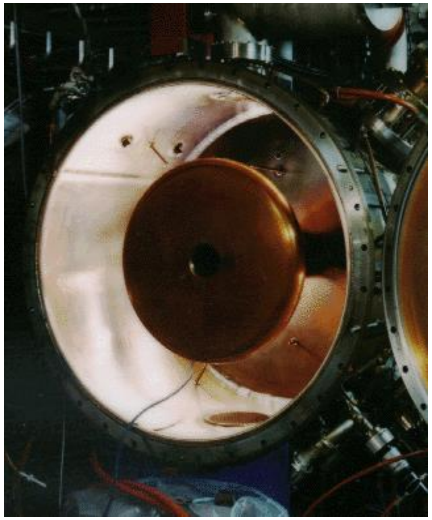
Plate capacitor


Ferrite inductivity

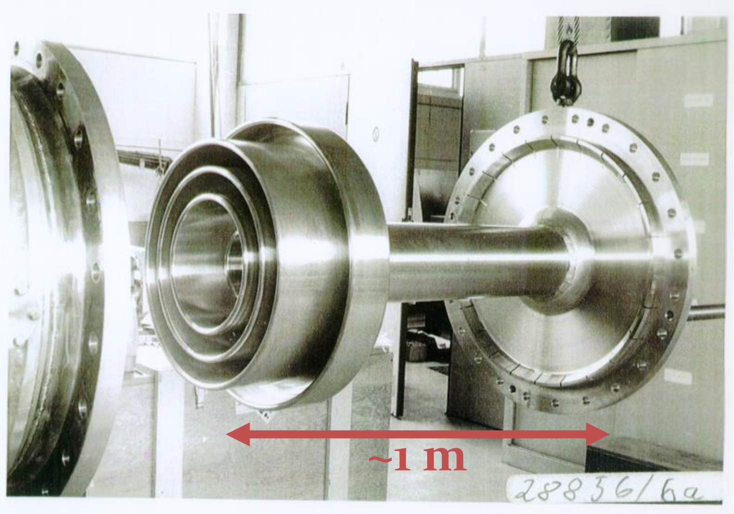
Capacitive loading

→ **Add capacitor at gap of cavity to shorten the resonator**

NSLS, 52.88 MHz



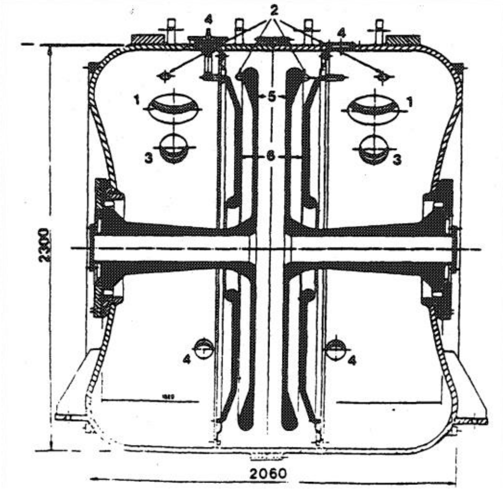
DESY PIA, 10.4 MHz, inner cond.



Outer cond.

M. Nagl

ACOL, 9.53 MHZ

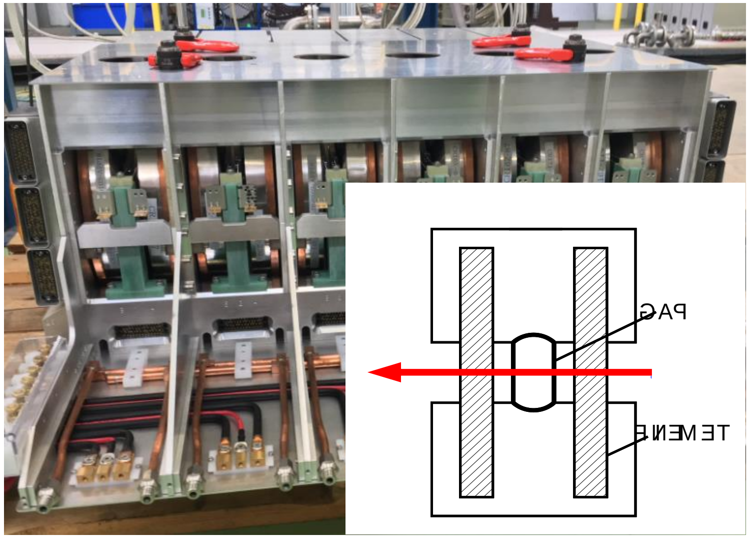


- → **Significantly reduces cavity size**
- → **Fixed frequency only**
- → **Small losses due to capacitor**
- → **Cavity in vacuum**

Inductive loading

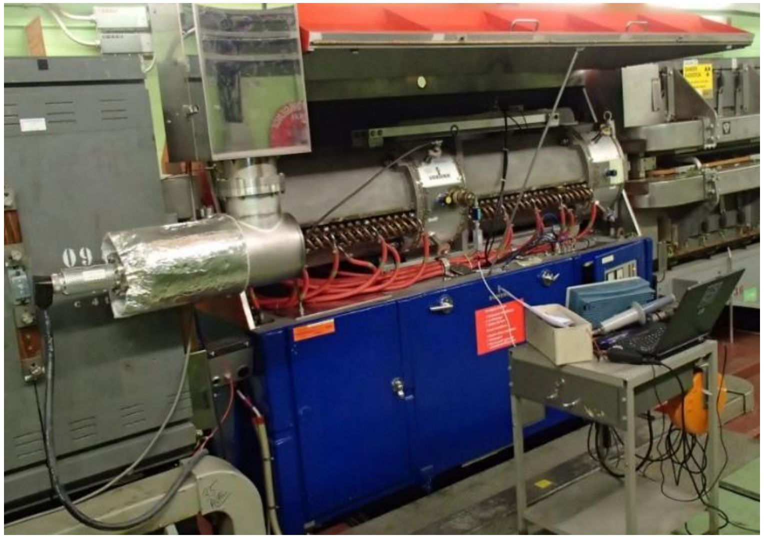
→ **Inductive loading with magnetic material shortens resonator from tens of meters to a device, lossy though**

CERN PSB Finemet cav., 0.6-18 MHz



M. Paoluzzi

CERN PS, double gap, 2.8-10 MHz

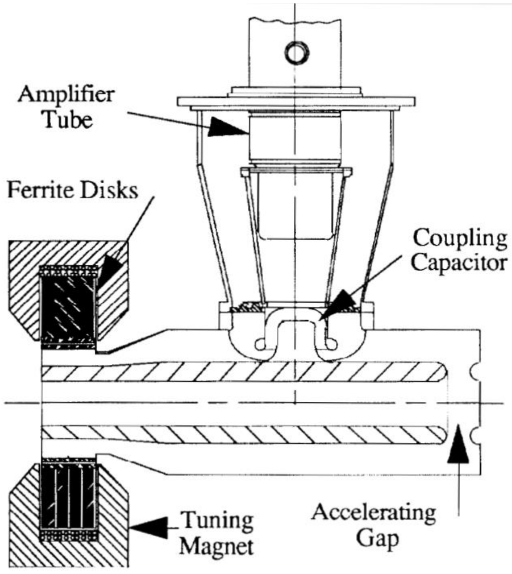


- **Additional advantage: permeability of ferrite can be controlled by DC bias current → variable inductivity**
  - → **Cavity with programmable resonance frequency**
  - → **Essential for hadron acceleration in low-energy accelerators**

Tunable cavities at higher frequencies

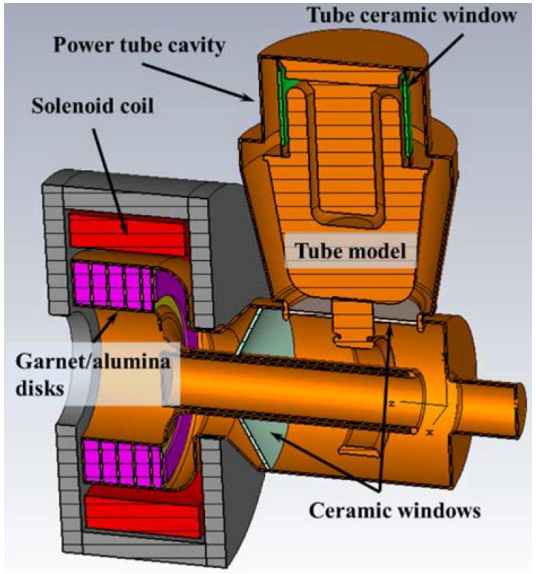
→ **Remove inductive or capacitive loading**

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

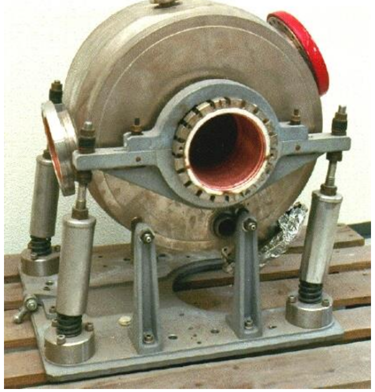
→ **Upper frequency limit for cavities with large tuning range**

Further increase frequency

→ **Remove inner conductor from coaxial set-up**

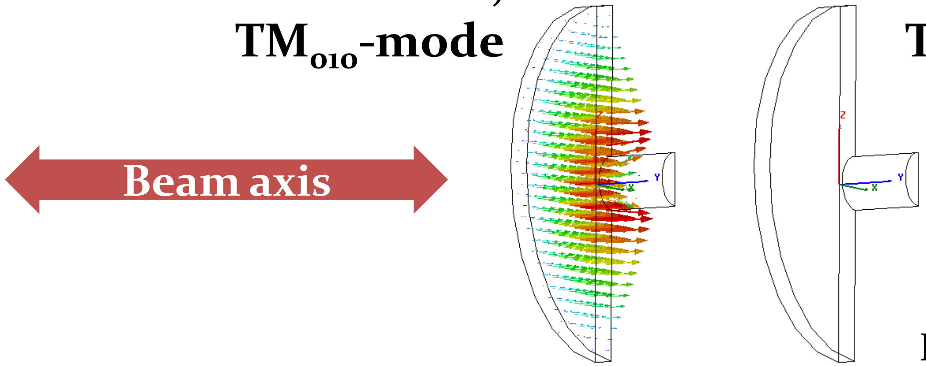
→ **The resonator becomes a pill-box cavity**

DORIS cavity



Electric field, TM$_{010}$-mode

Electric field, TM$_{010}$-mode

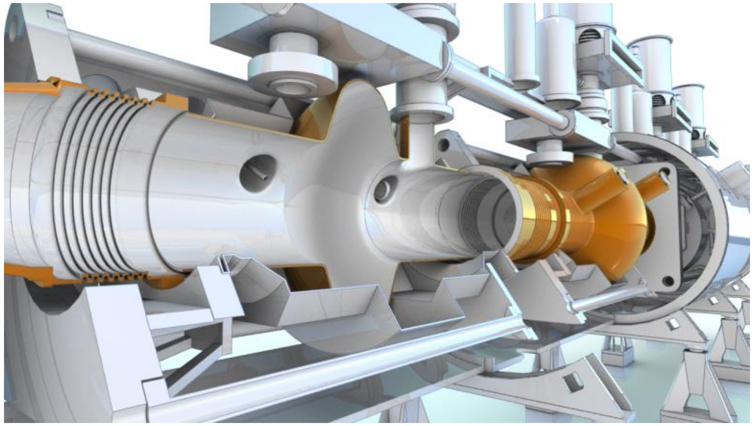


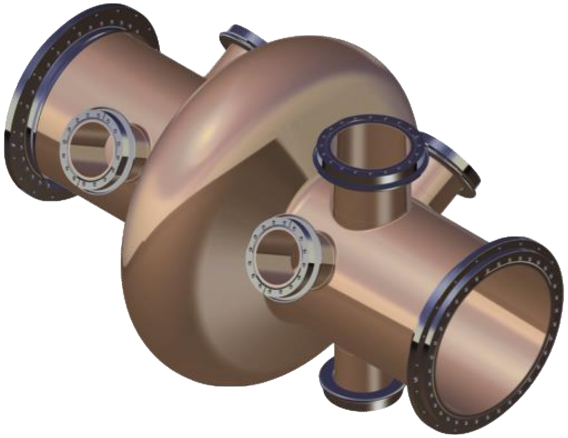
E. Jensen

→ **The basis for cavity resonators**

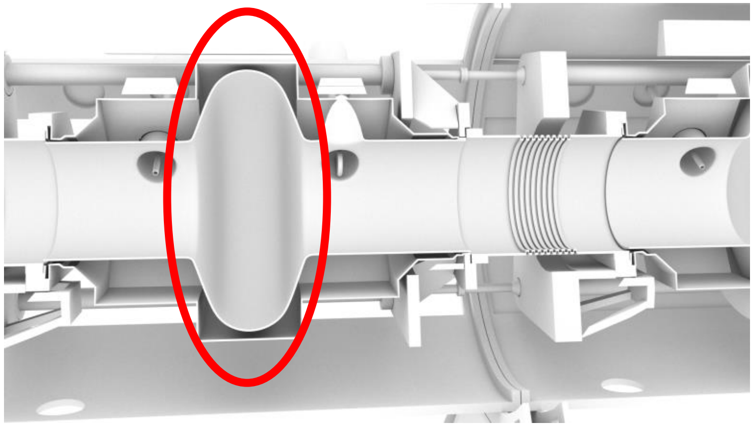
Example: 400 MHz cavities in LHC

- → 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 ~ 44 Ω, 400 MHz



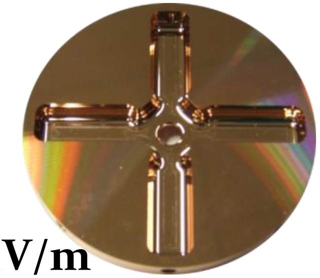
- → 2×8 cavities, 5.3 MV/m

$$\frac{1}{Q} = \cancelto{\sim 0}{\frac{1}{Q_{\text{cav}}}} + \frac{1}{Q_{\text{ext}}}$$

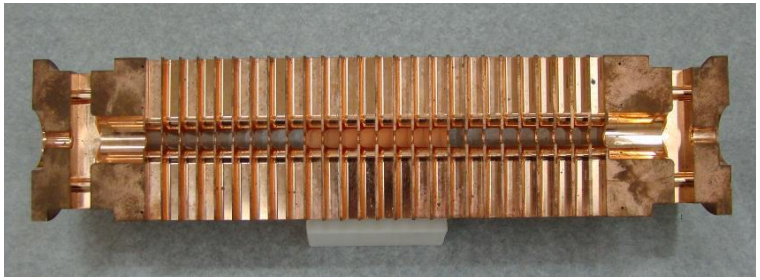
RF cavities in linear accelerators

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

SuperHILAC, ~70 MHz, Berkley



CLIC, 12 GHz, ~100 MV/m



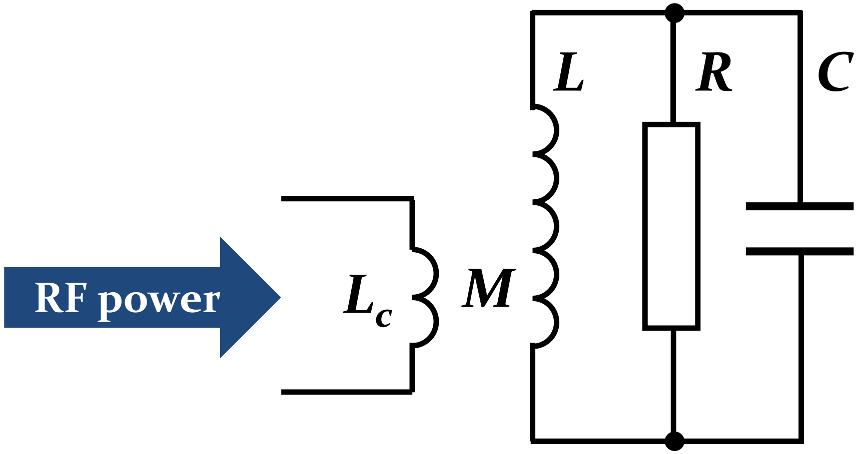
→ **Cavity is the contrary to 'one size fits all'**

→ **Many, many more variants**

Coupling power into a cavity

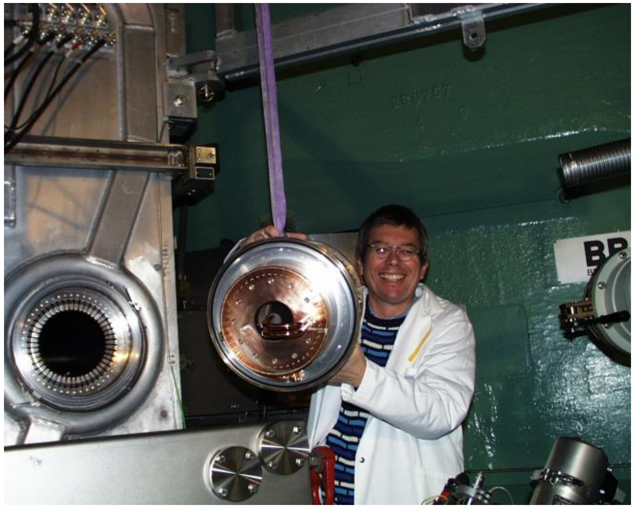
Coupling power into a cavity

- Attack inductivity or capacitance of resonator, or combined



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

→ Coupling loop forms transformer with resonator inductivity



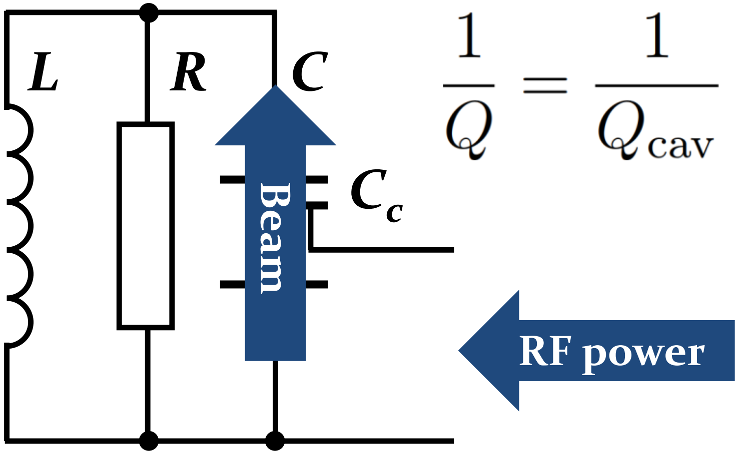
L. Stigelin

- Main coupler PSI cyclotron

→ ~1 MW at 50 MHz

Coupling power into a cavity

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



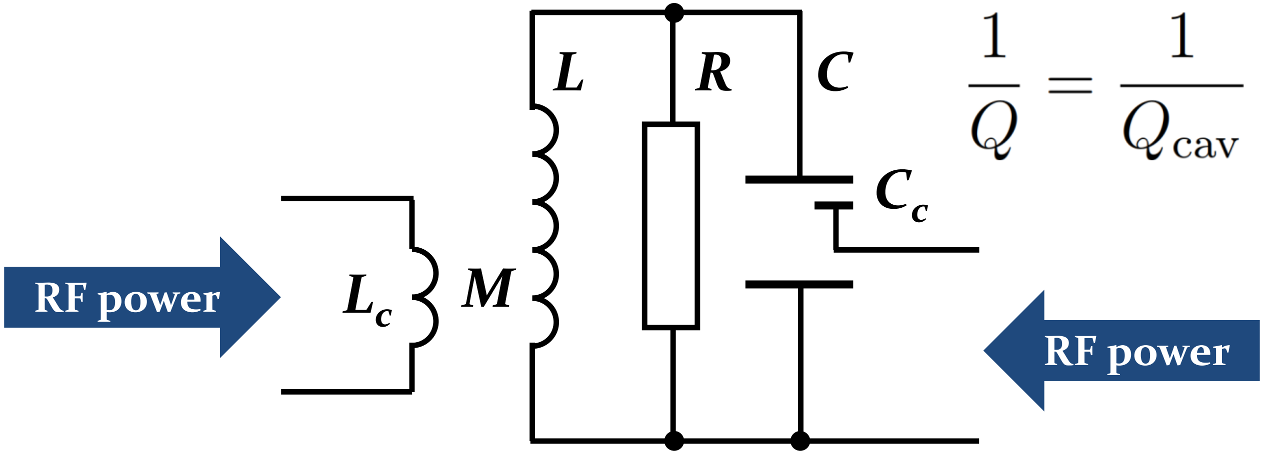
$$\frac{1}{Q} = \frac{1}{Q_{\mathrm{cav}}} + \frac{1}{Q_{\mathrm{ext}}}$$

→ **Capacitive divider to gap to transform generator impedance to cavity shunt impedance**

→ **Beam also couples capacitively via the gap**

Coupling power into a cavity

- Attack inductivity or capacitance of resonator, or combined



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

→ Combined electromagnetic coupling

→ Antenna radiating into cavity

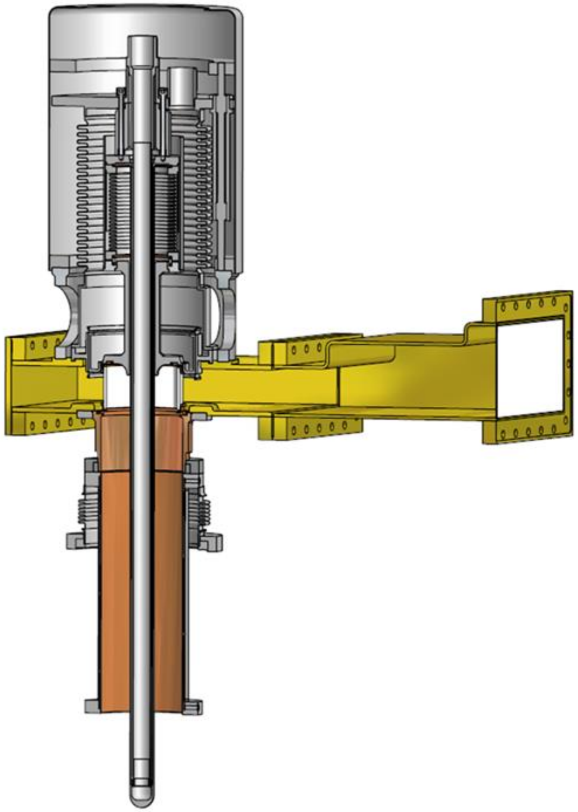
Capacitive or combined coupling

- **Some examples of capacitive and antenna couplers**

Capacitive coupler of CERN PS 40 MHz

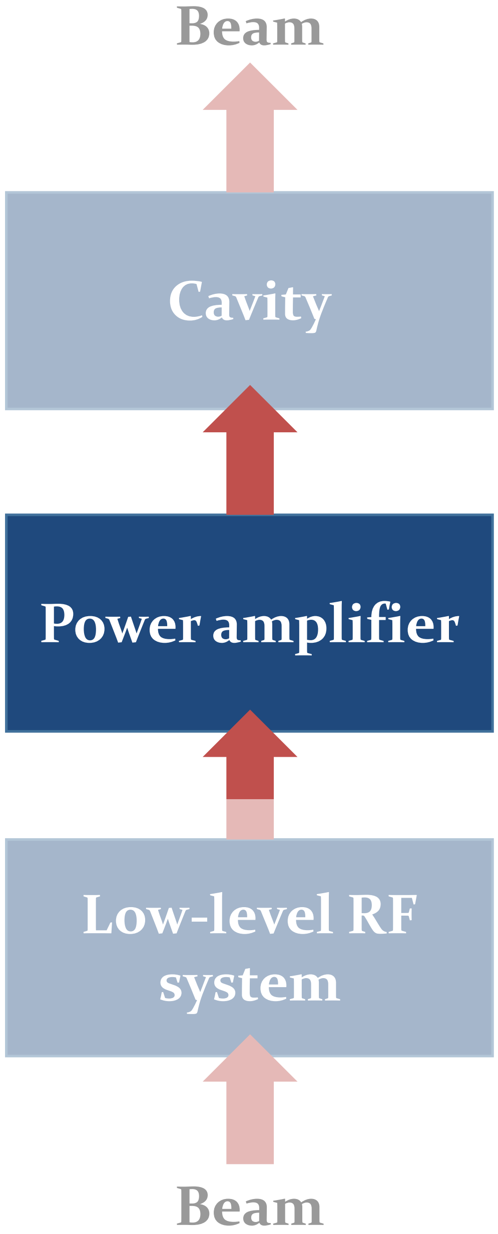
→ Coupler forms one half of capacitor with the gap

Antenna coupler of LHC cavities



→ Coupler antenna transmits directly into the cavity

RF system overview



Beam

Cavity

Power amplifier

Low-level RF system

Beam

→ **Convert RF power into longitudinal electric field**

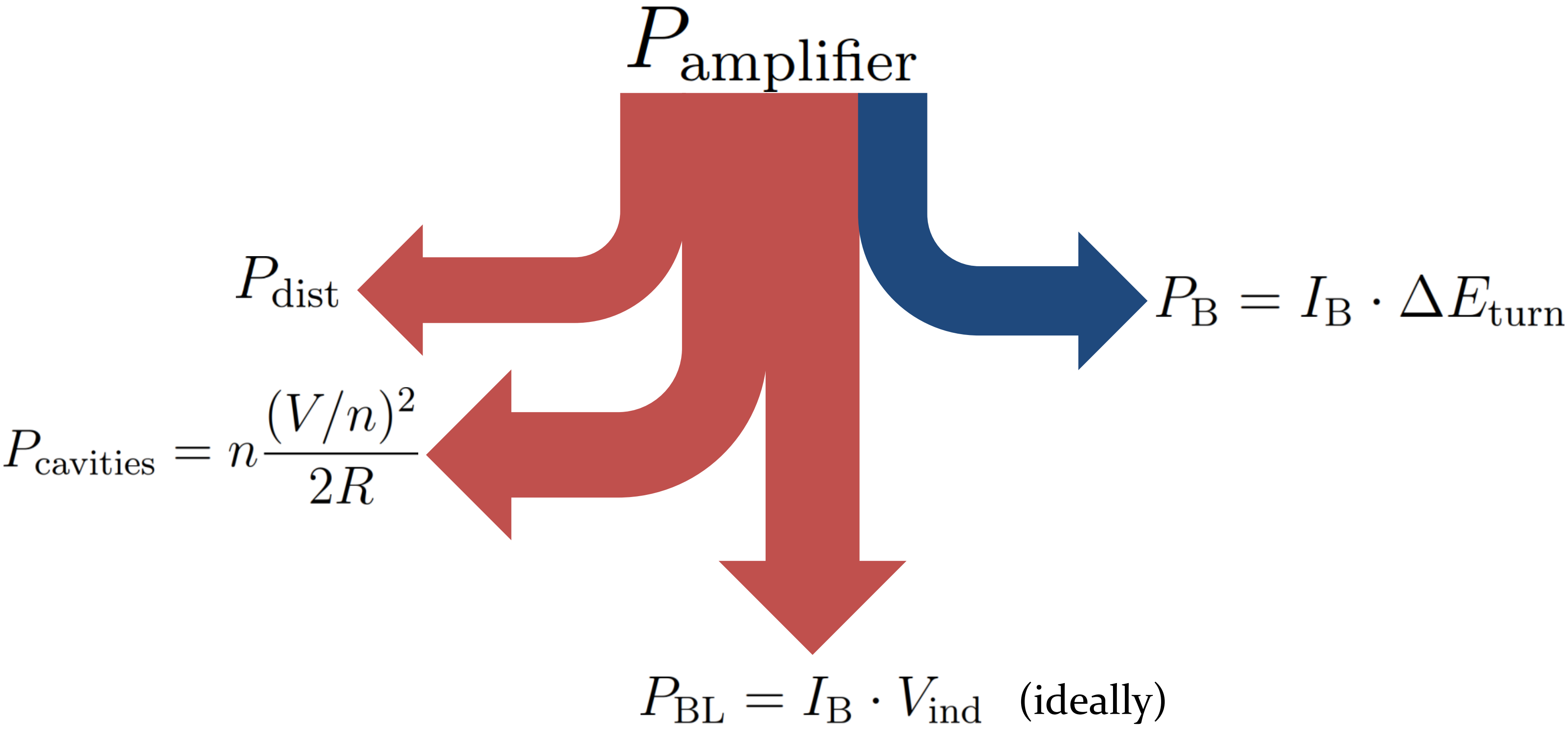
→ **Amplify low-power signal from beam control to kW, MW or GW**

→ **Provide RF signals with correct frequency, amplitude and phase**

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**



$$P_{\mathrm{amplifier}}$$

$$P_{\mathrm{dist}}$$

$$P_{\mathrm{B}} = I_{\mathrm{B}} \cdot \Delta E_{\mathrm{turn}}$$

$$P_{\mathrm{cavities}} = n\frac{(V/n)^2}{2R}$$

$$P_{\mathrm{BL}} = I_{\mathrm{B}} \cdot V_{\mathrm{ind}} \quad \text{(ideally)}$$

Power amplifiers

- Basically

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

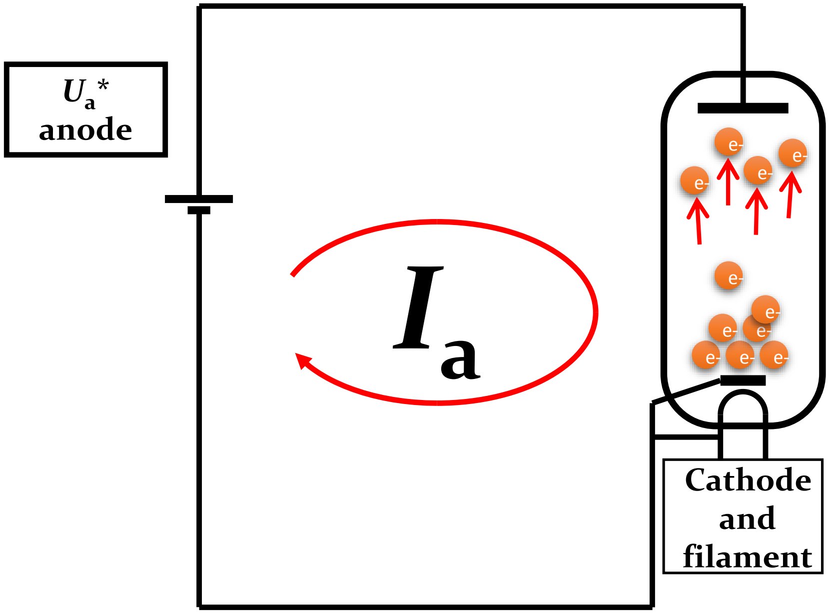
- The ideal power amplifier
  - → Large bandwidth: amplifies all frequencies equally
  - → No saturation, infinite power
  - → Zero delay
  - → No added noise
  - → Unconditionally stable and resistant to reverse power
  - → Radiation-hard

→ 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**

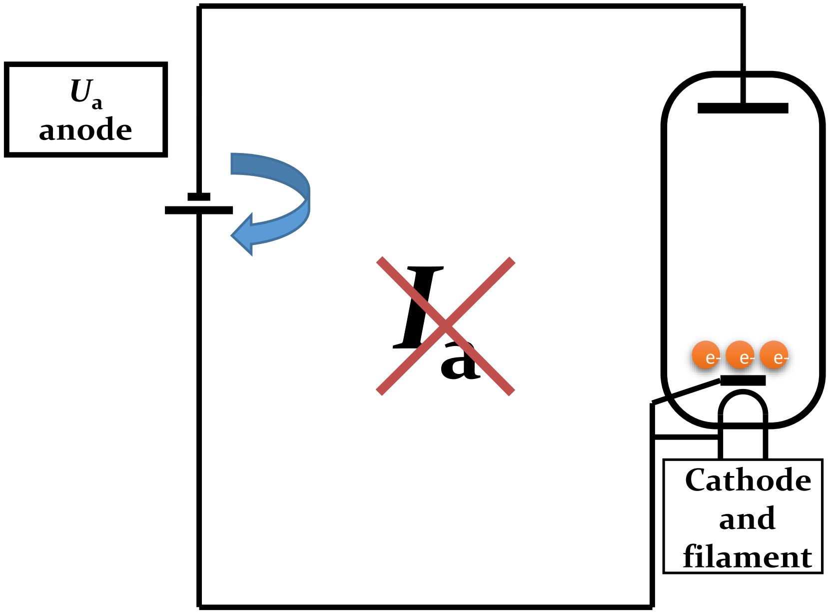
→Diode

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

E. Montesinos

Basics of grid tube

- **From diode to tetrode amplifier**



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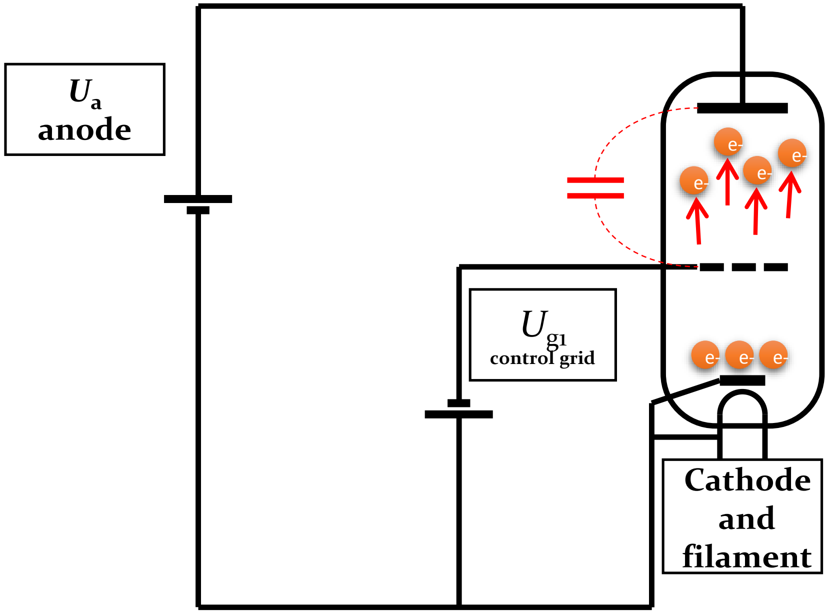
→Diode

Basics of grid tube

- From diode to tetrode amplifier



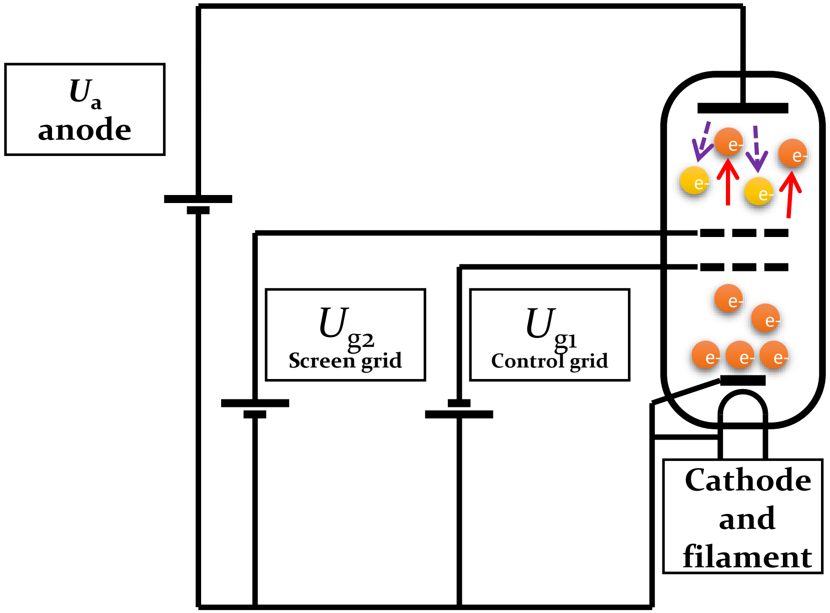
→Triode

- Modulating the grid voltage proportionally modulates the anode current
- Transconductance
  - Voltage at grid
  - → Current at anode
- Limitations
  - Parasitic capacitor from anode to control grid (g1)
  - Tendency to oscillate

E. Montesinos

Basics of grid tube

- **From diode to tetrode amplifier**



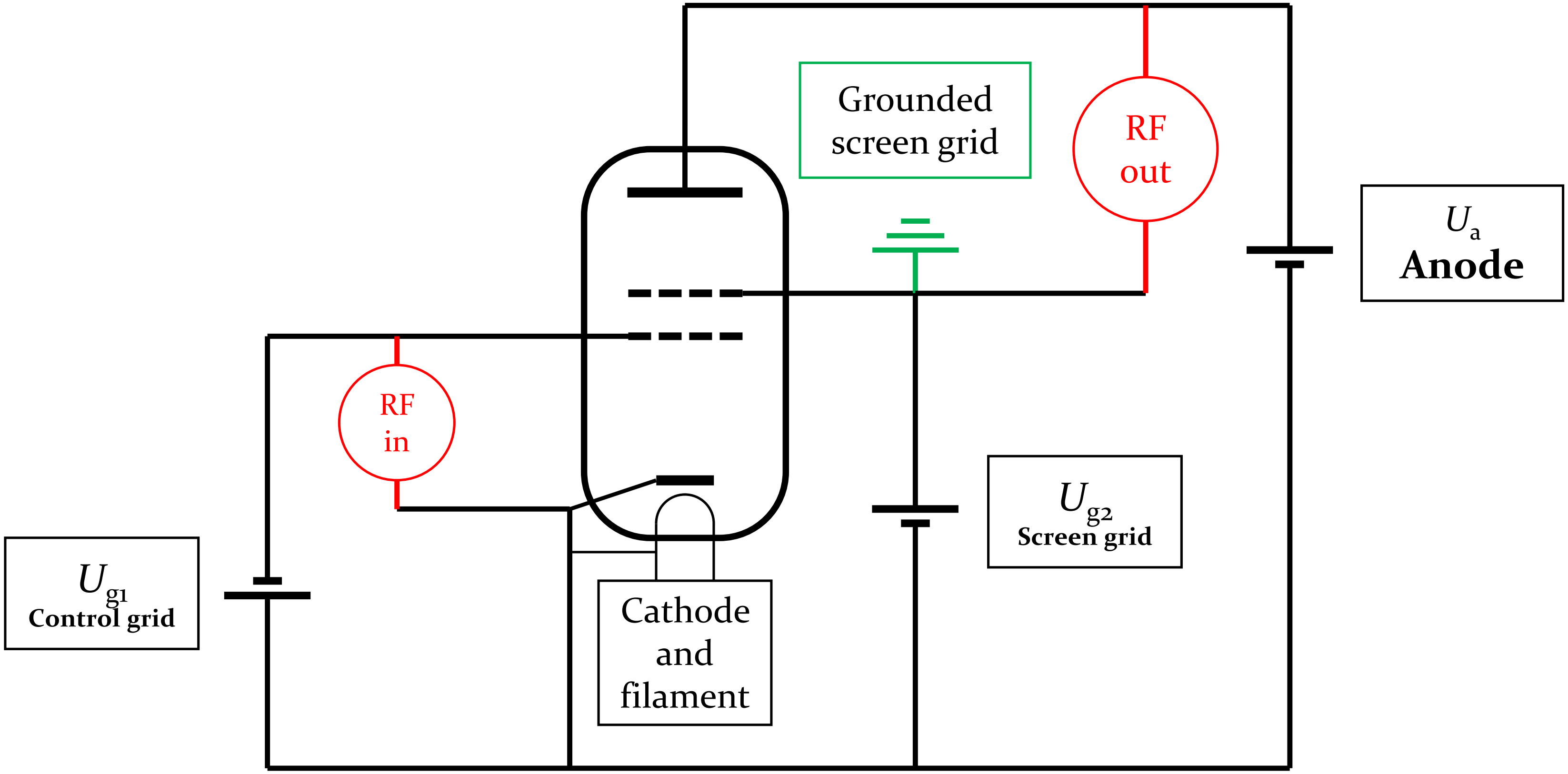
→Tetrode

- **Screen grid**
  - **Positive (lower anode)**
  - **Decouple anode and g1**
  - **Higher gain**
- **Limitations**
  - **Secondary electrons**
  - **Anode treated to reduce secondary emission**

E. Montesinos

Tetrode based power amplifier

- **Example of SPS 200 MHz amplifier, tetrode RS2004**



→ Very simplified block diagram

E. Montesinos

Example: Tetrode amplifier driving SPS RF

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

RS2004 tetrode

Amplifier trolley

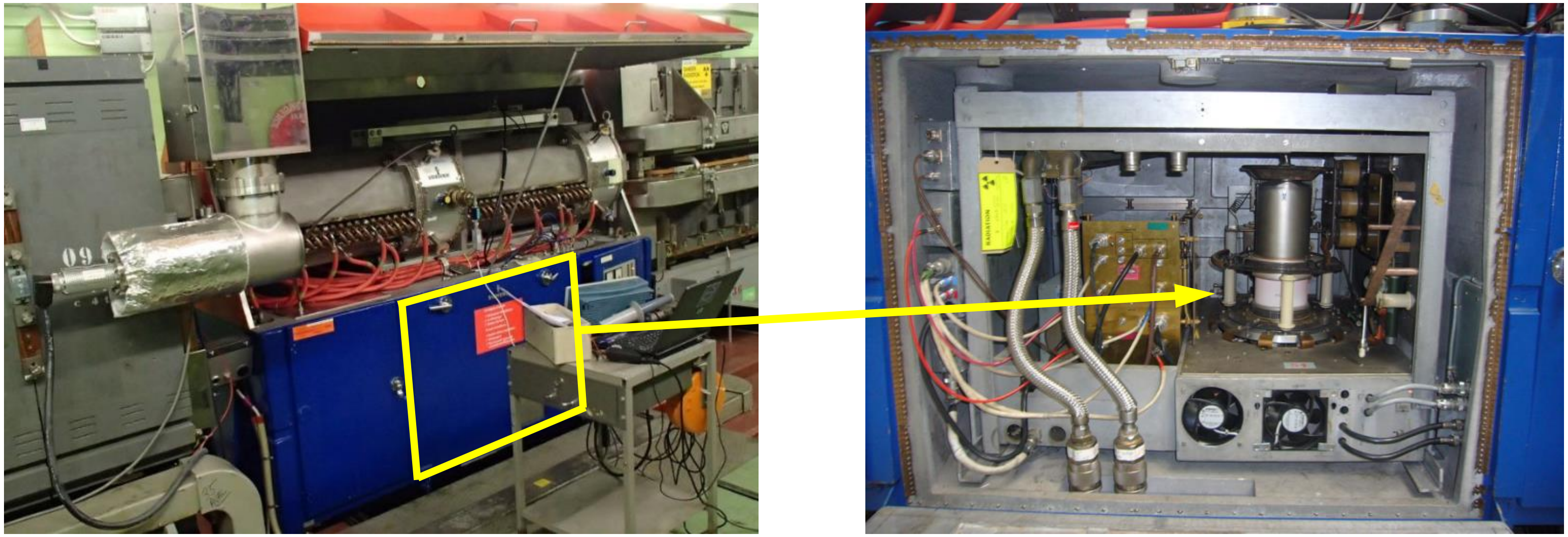
Complete transmitter

→ In operation since 1976

E. Montesinos

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

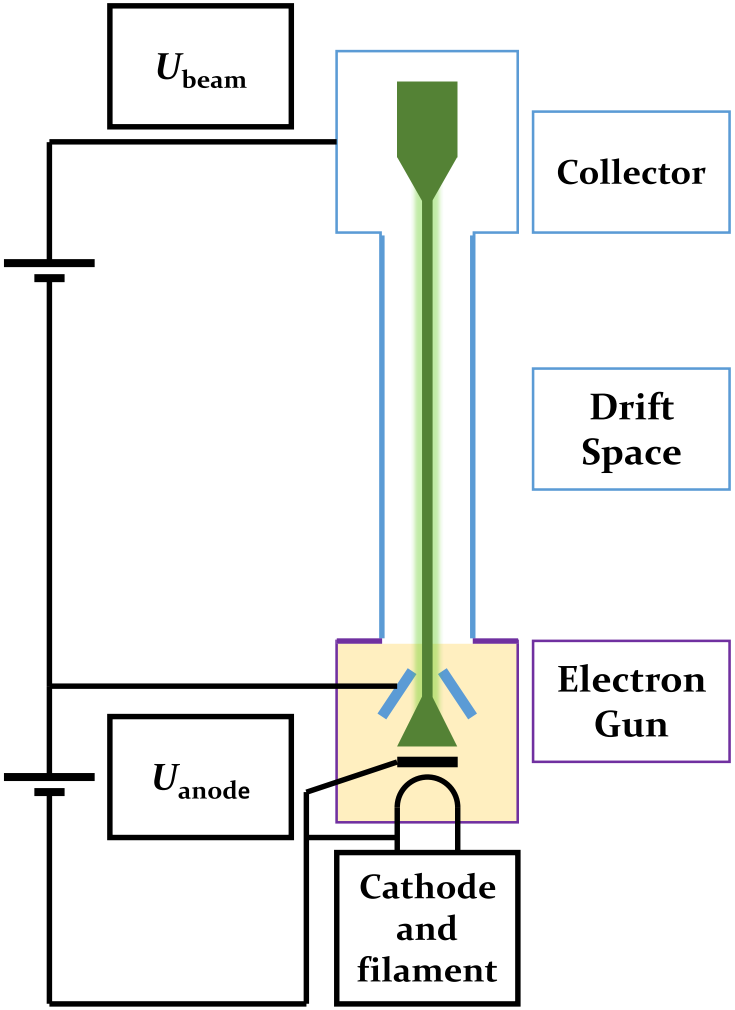


Amplifier trolley

- → 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**

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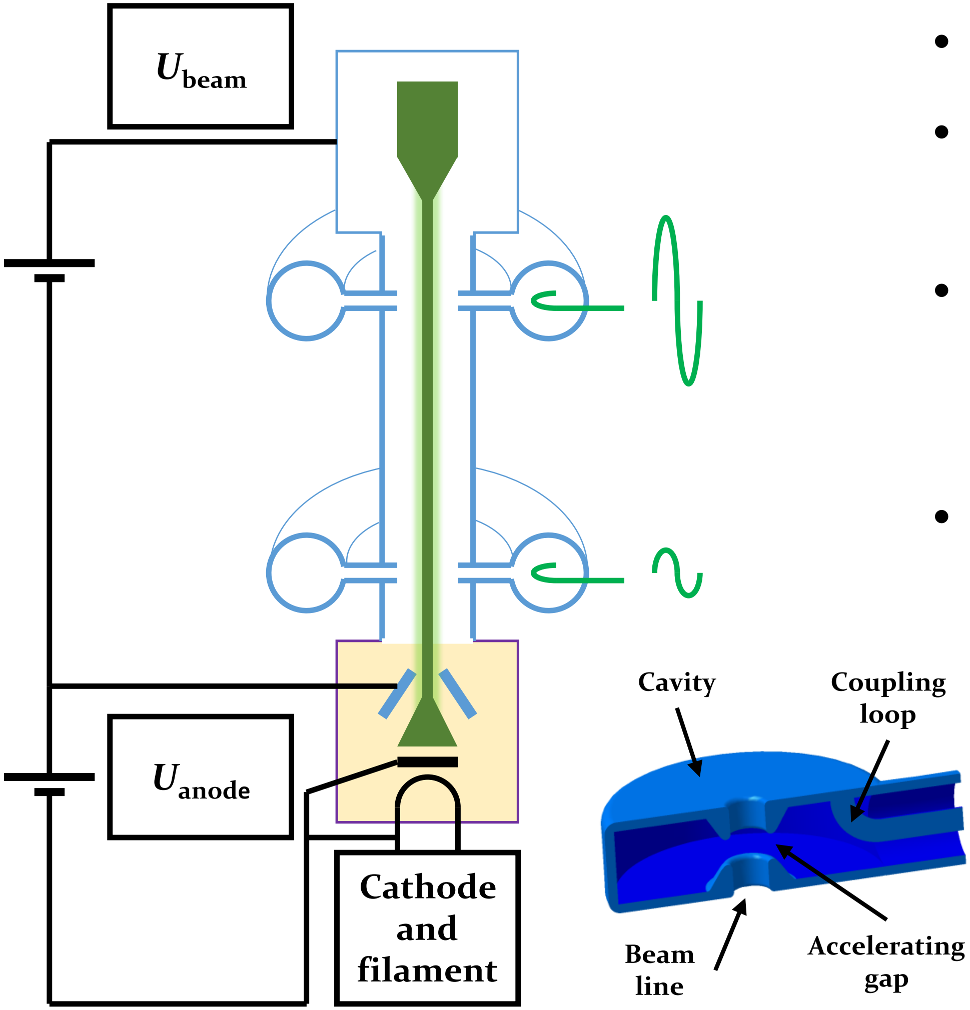
Basics of linear beam tube

- Klystron: a complete mini-accelerator

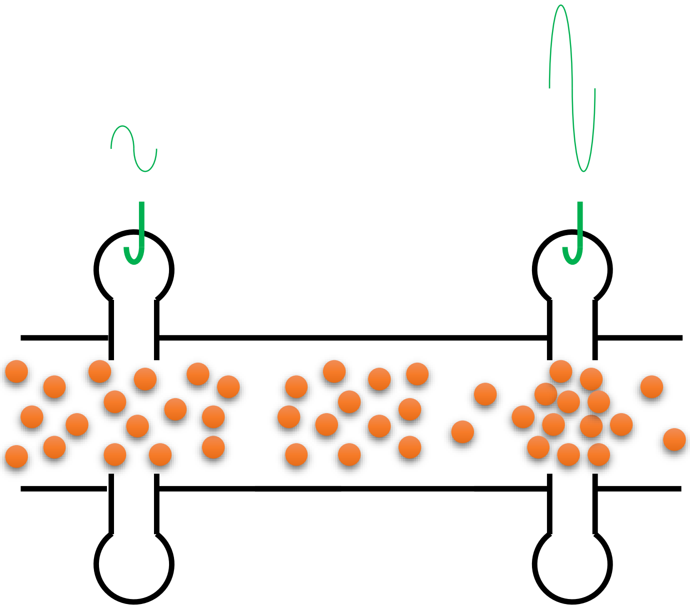


- Cavity resonators and drift
- RF input cavity (Buncher)
  → Modulates electron velocity
- Drift space
  → Faster electrons catch up
  → Slower electrons fall behind
- RF output cavity (Catcher)
  - Resonating atsame frequency as input cavity
  - At place where electrons are maximally bunched
  - Kinetic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

E. Montesinos

Basics of linear beam tube

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



- Cavity resonators and drift
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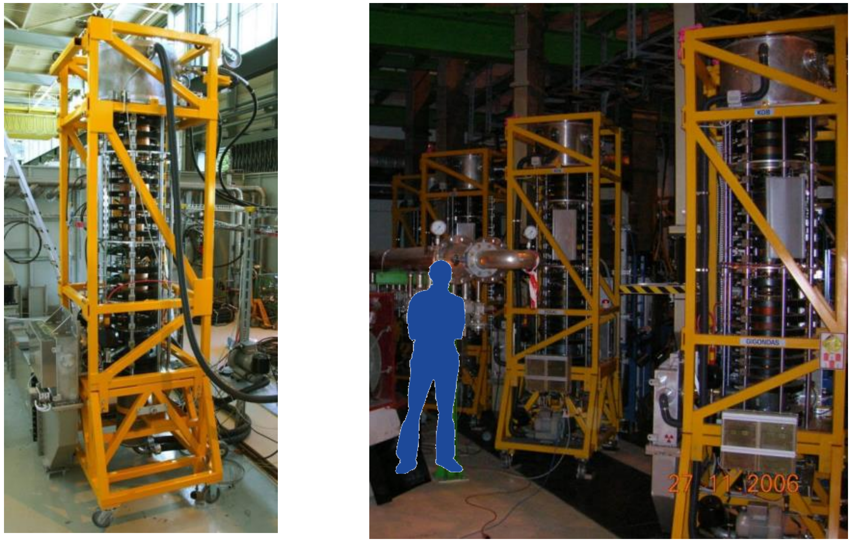
  - Resonating atsame frequency as input cavity
  - At place where electrons are maximally bunched
  - Kinetic energy converted into voltage and extracted

E. Montesinos

Example: Klystrons driving the LHC

- 2 × 8 cavities, each driven by separate 400 MHz klystron, 330 kW

→ First klystron amplifiers powering a hadron collider



E. Montesinos

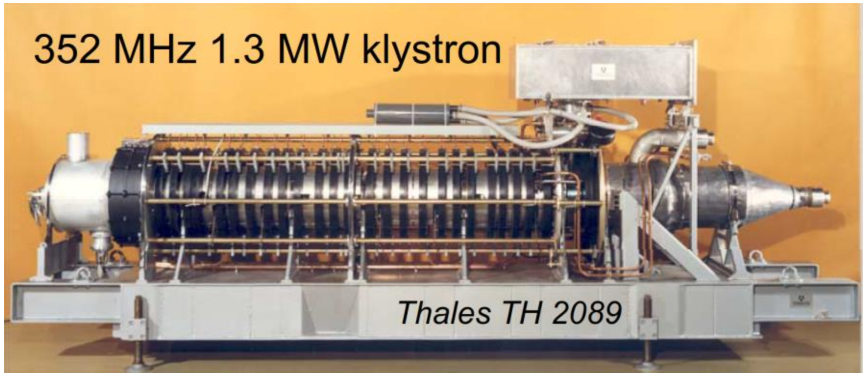
- 12 GHz pulsed klystron for CLIC

→ 50 MW in 1.5 μs

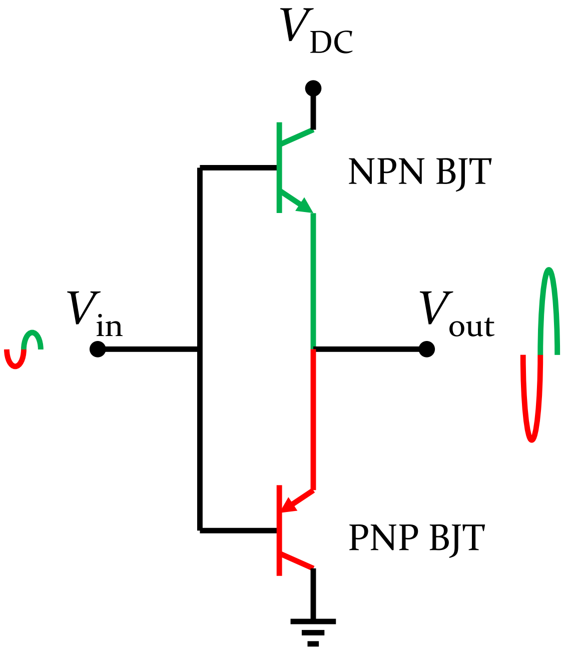
G. McMonagle

- 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

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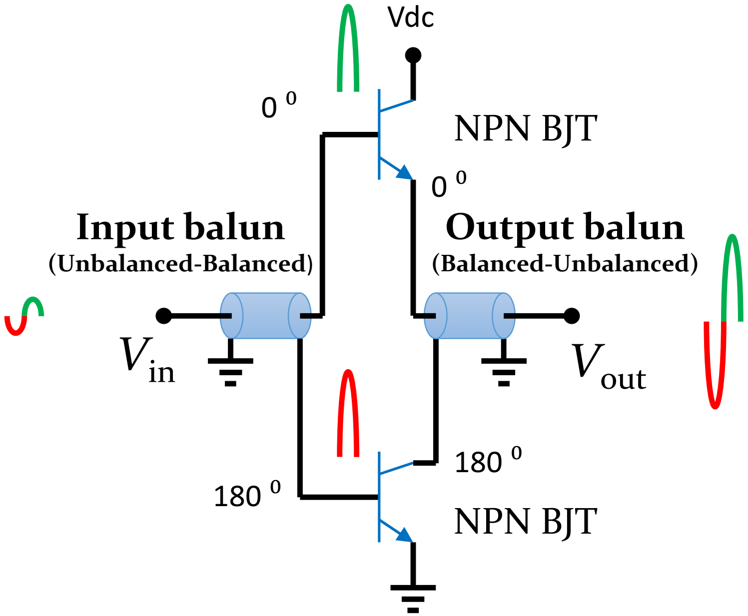
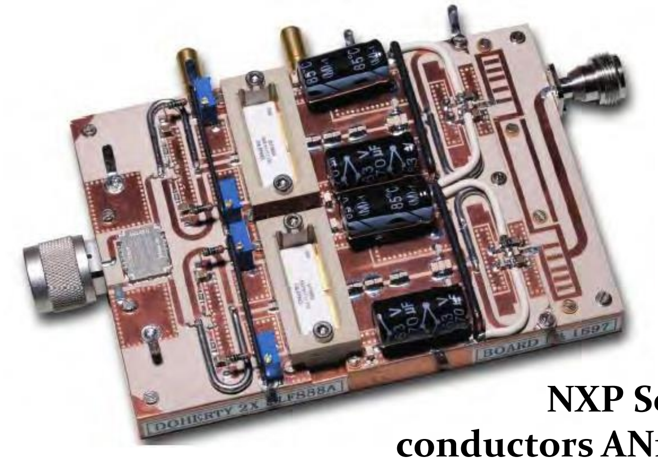
Basics of RF solid state amplifiers





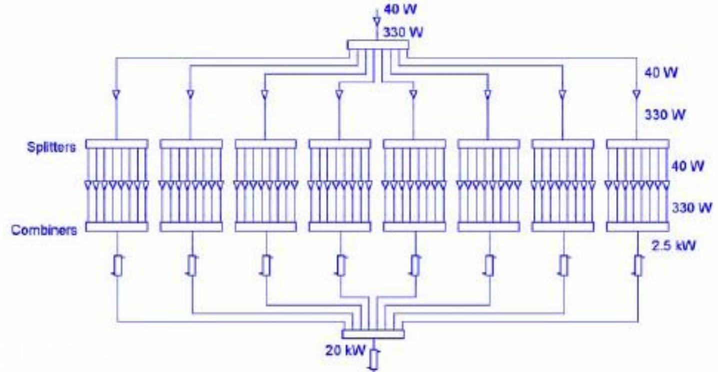
NXP Semiconductors AN11325
2-way Doherty amplifier with BLF888A

- **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**

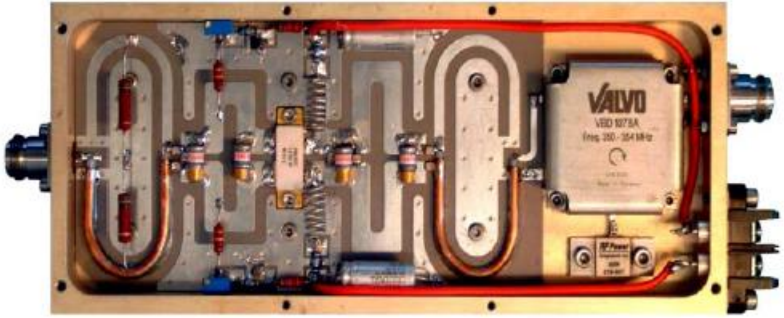
→This configuration is easier to manufacture since only one type of device is required

Example: Soleil 45 kW, 352 MHz

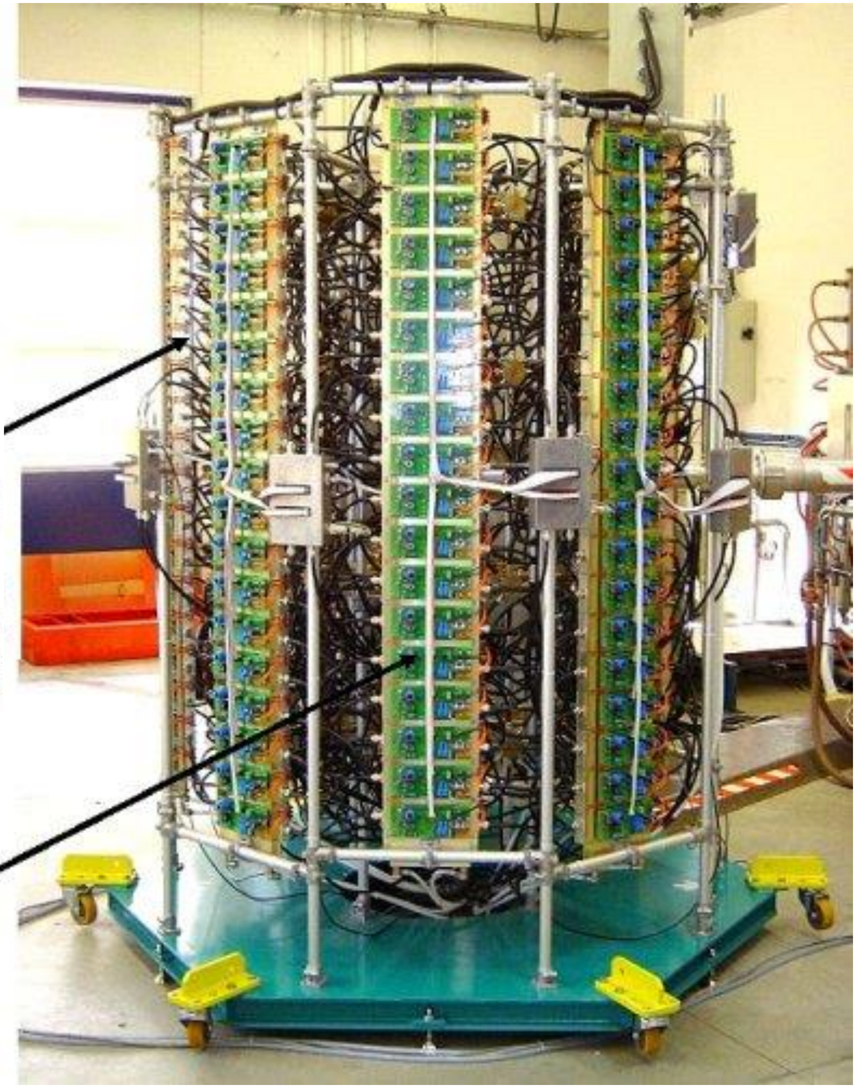
Electron storage ring running at 352 MHz



330 W amplifier module



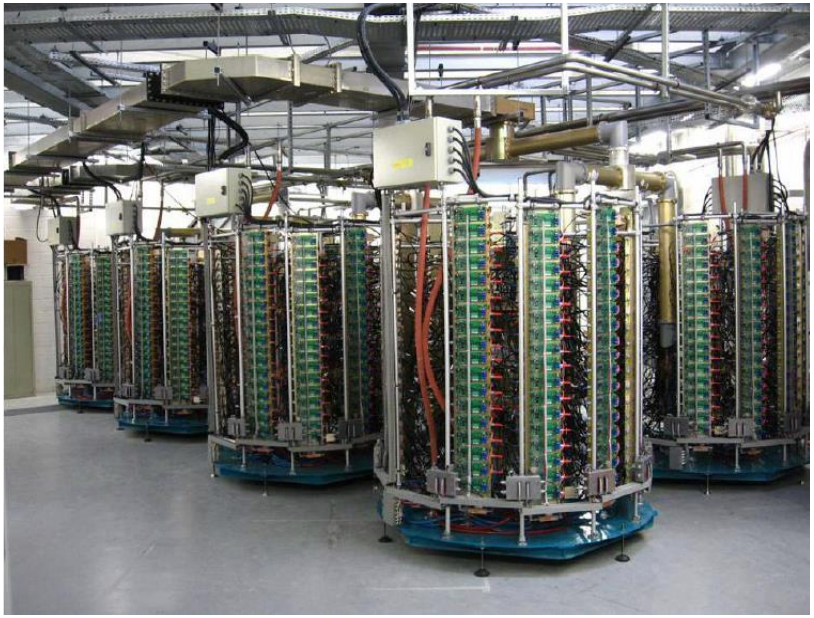
600 W, 300 V_{DC}/30 V_{DC} converter



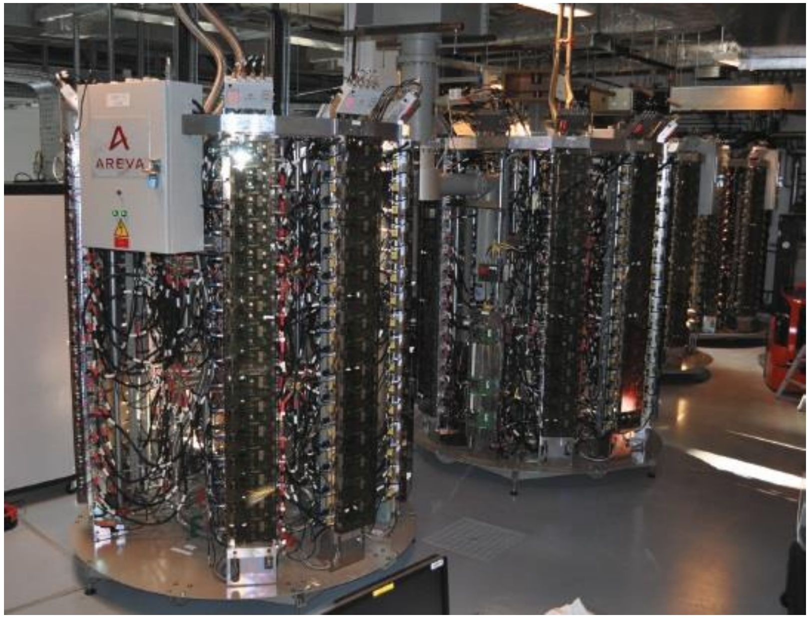
Example: Soleil 45 kW, 352 MHz

Large scale solid state amplifier installations

45 kW per tower (2004 and 2007)



150 kW per tower (2012)



SOLEIL SYNCHROTRON

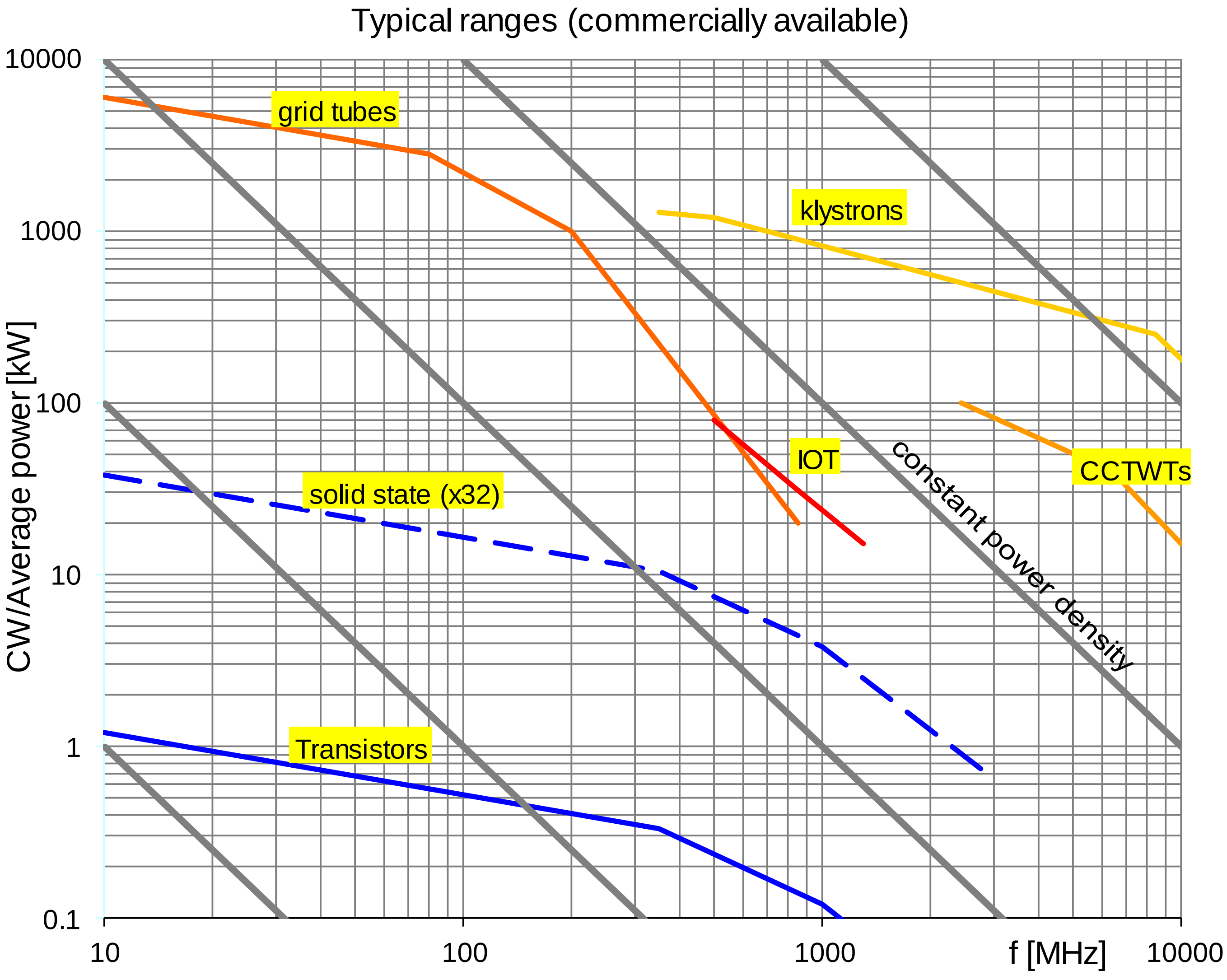
ESRF
The European Synchrotron

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

E. Montesinos

RF power amplifier

Power capability of commercially available amplifier types



E. Jensen

How to chose the right RF amplifier?

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

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

Summary

- **RF system parameters**
  → Chose 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

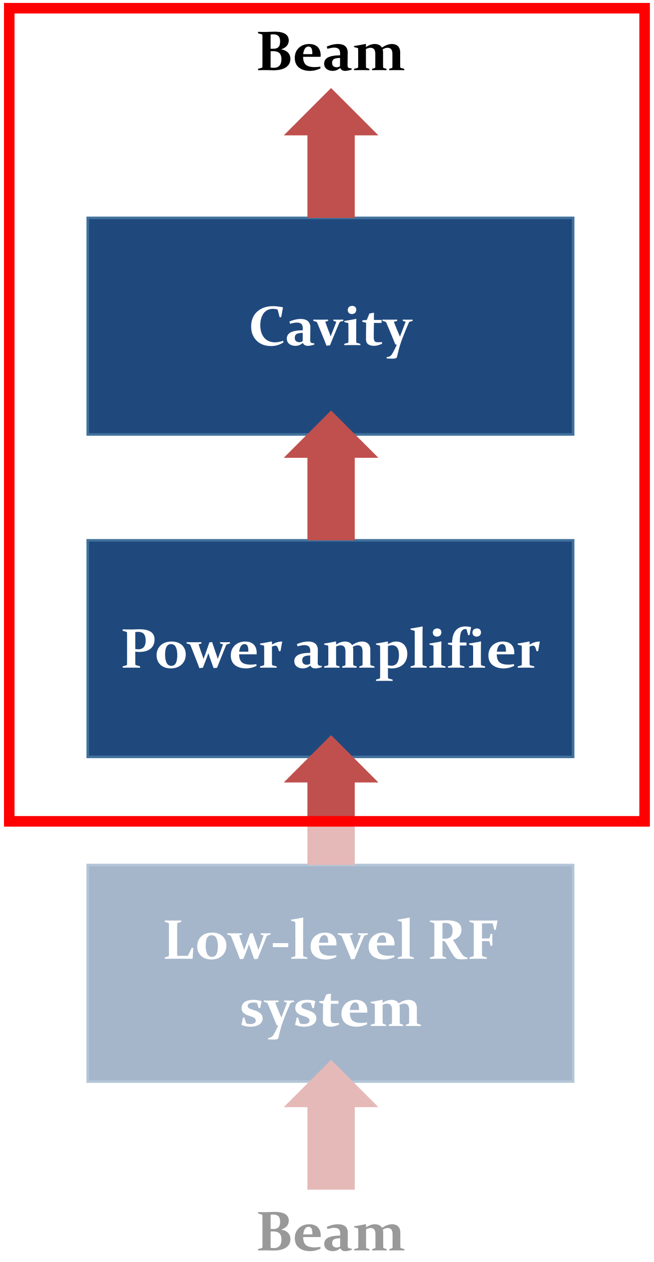
Introduction to Accelerator Physics

28 September 2018

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



→ **Convert RF power into longitudinal electric field**

→ **Amplify low-power signal from beam control to kW, MW or GW**

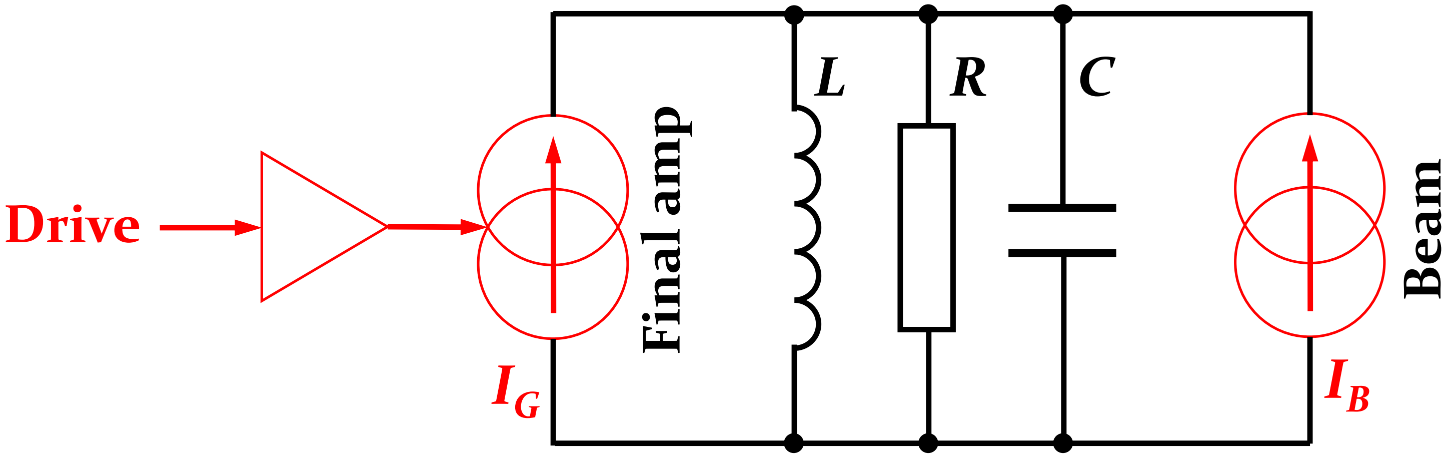
→ **Provide RF signals with correct frequency, amplitude and phase**

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 → $$$

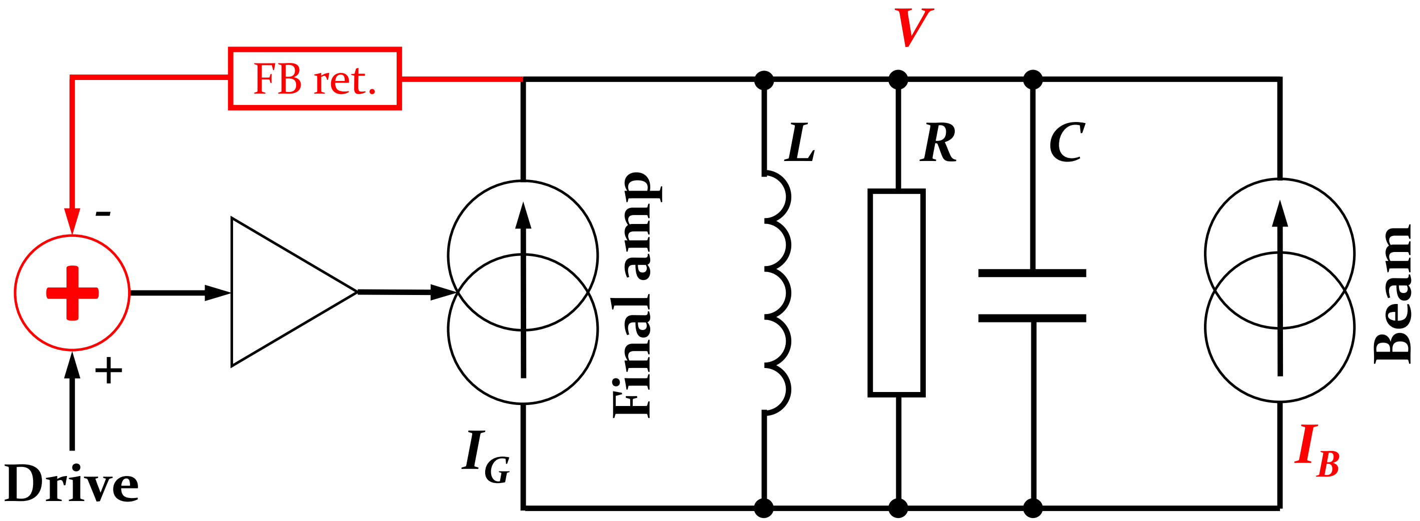
2. Feedback to decrease the apparent impedance for the beam

   → 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**

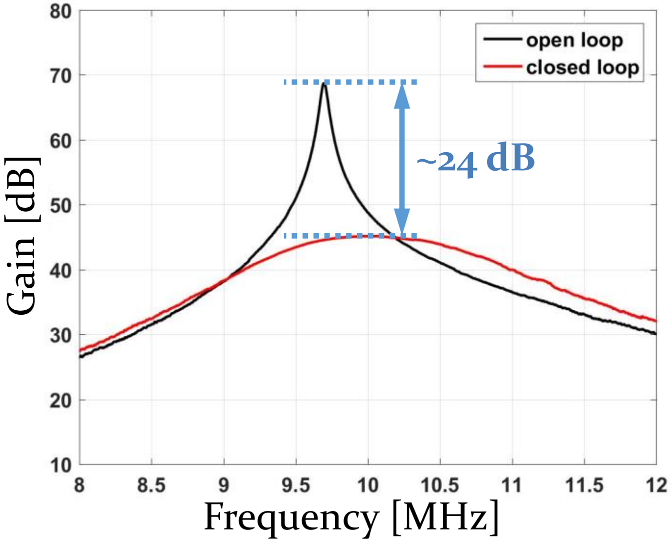


1. **Compare drive signal (no beam) with gap (beam and generator)**
2. **Amplify inverted difference**

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

Example: 10 MHz RF system in CERN PS

Transfer function with and without feedback



- **Feedback gain of 24 dB**

→ Equivalent impedance, $Z_{eq}(\omega)$reduced

→ Impedance for amplifier remains unchanged, $Z(\omega)$

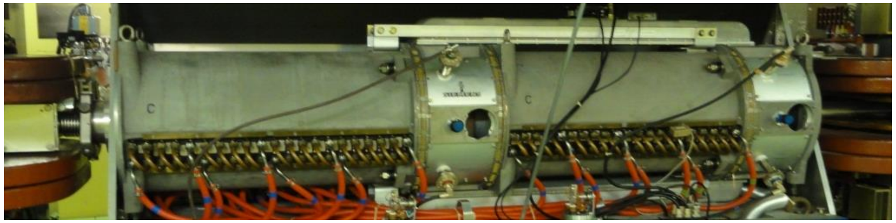
Why not further reduction with more gain?

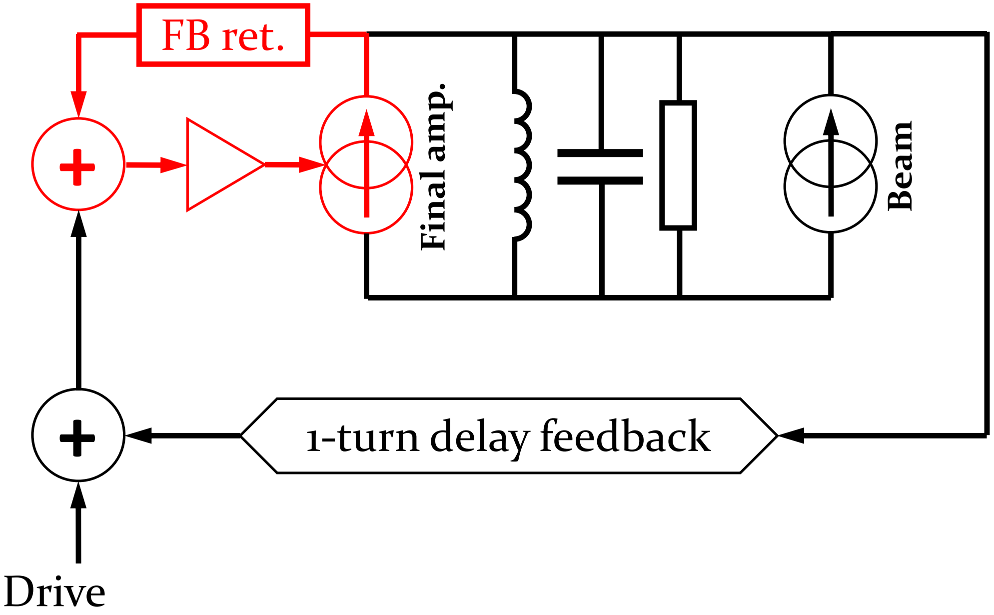
- **Subtraction of gap voltage and drive signal imperfect due to**
  1. **Delay of cables and amplifier**
  2. **Parasitic resonances of amplifier and cavity system**

Bandwidth ↑ ↔ Achievable gain ↓

Example: 10 MHz RF system in CERN PS

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

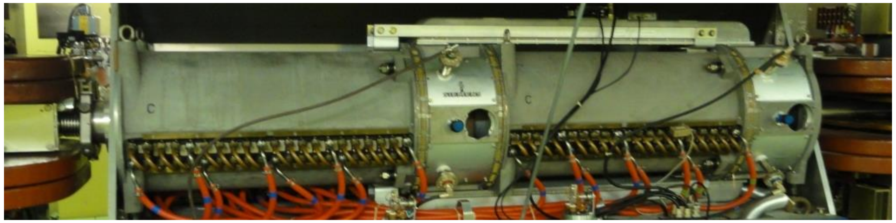


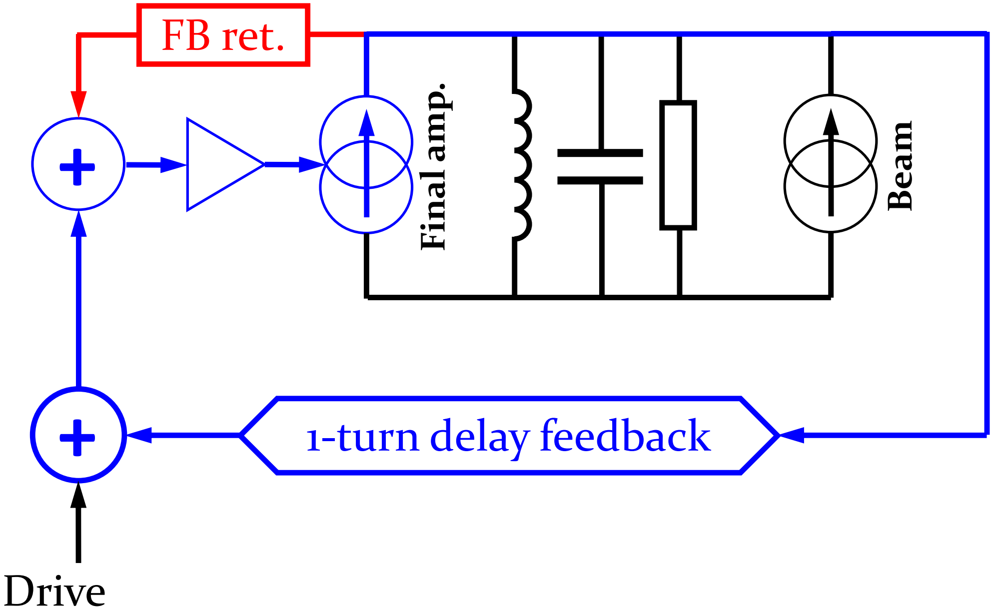


- Fast wide-band feedback
  around amplifier (internal)
  → Gain limited by delay

Example: RF feedback with 1-turn delay

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





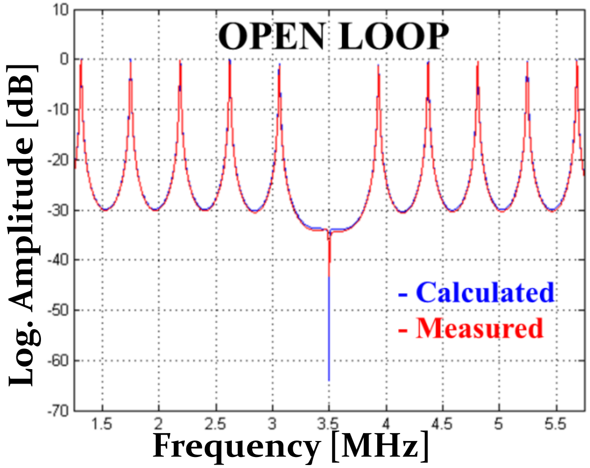
- **Fast wide-band feedback around amplifier (internal)**
  → Gain limited by delay

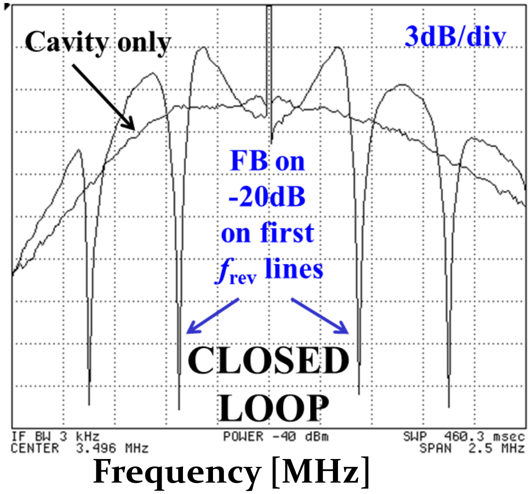
- **1-turn delay feedback**
  → High gain at n × f_{rev}

Example: RF feedback with 1-turn delay

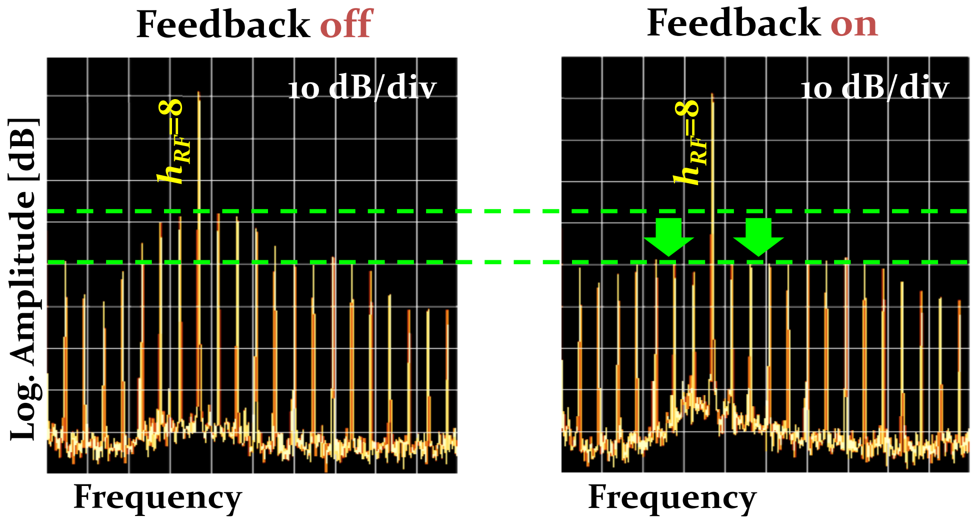
→ Reduce cavity impedance beyond stability limit of wide-band FB

Open/closed loop
transfer functions





Spectrum at cavity gap return

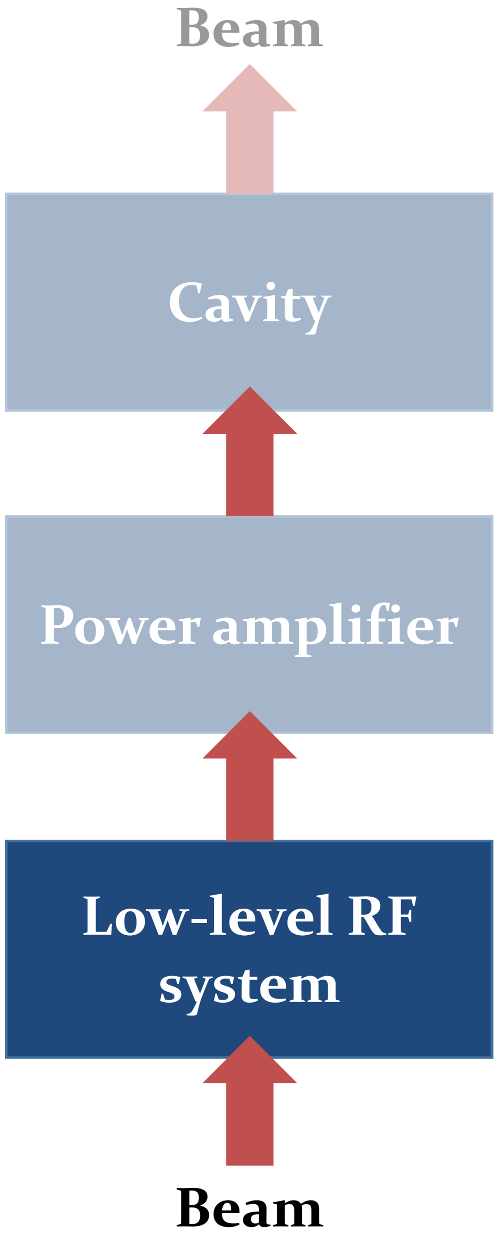


D. Perrelet

→ Important additional impedance reduction

→ Clever usage of beam periodicity in circular accelerator

RF system overview



→ **Convert RF power into longitudinal electric field**

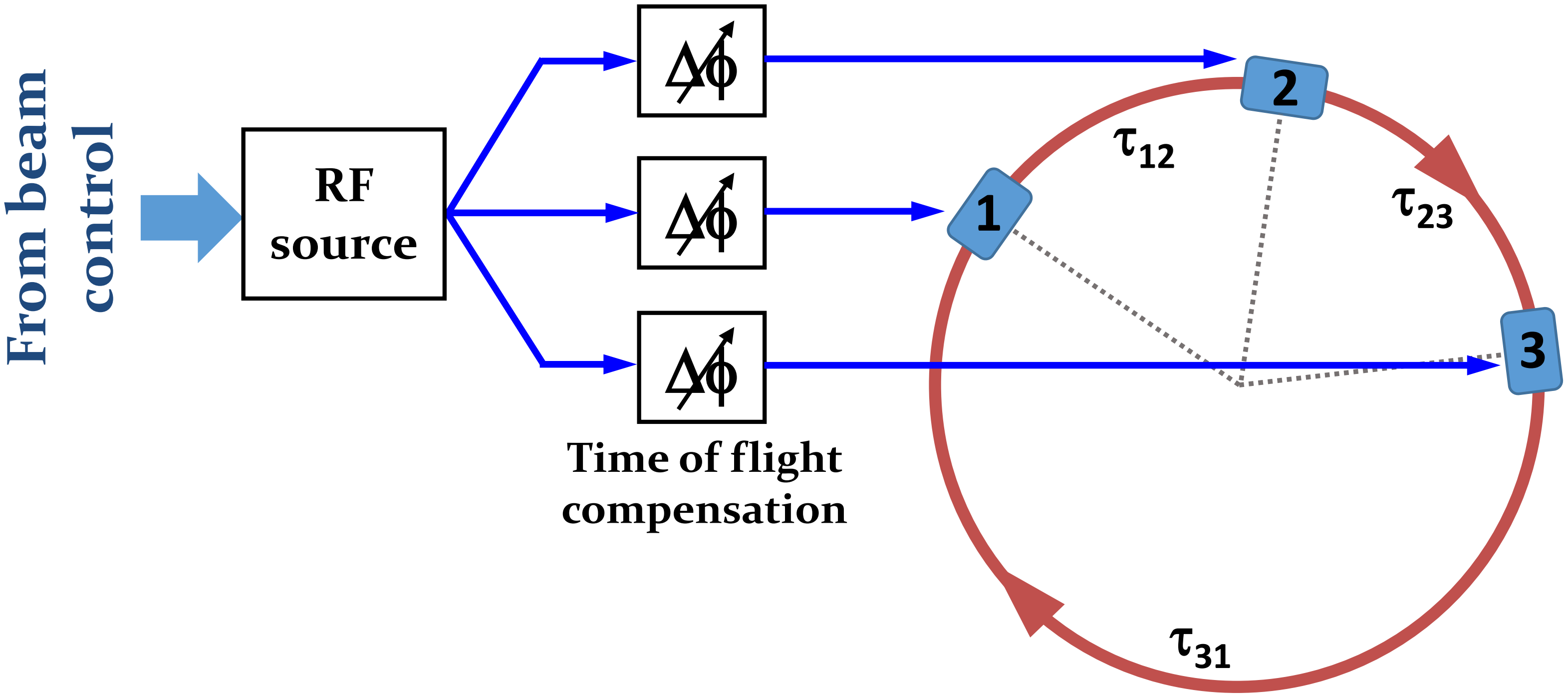
→ **Amplify low-power signal from beam control to kW, MW or GW**

→ **Provide RF signals with correct frequency, amplitude and phase**

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



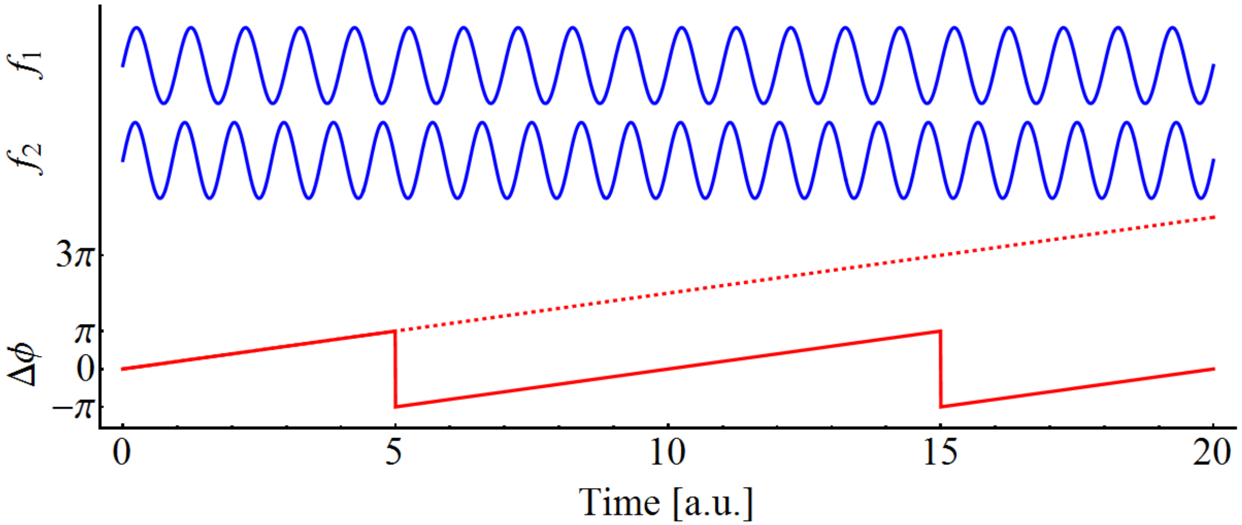
→ RF distribution to compensate time of flight between stations

→ 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, Δϕ, between both signals changes linearly

→ Ambiguity to distinguish between $\Delta\phi = -\pi, \pi, -3\pi, 3\pi, \ldots$

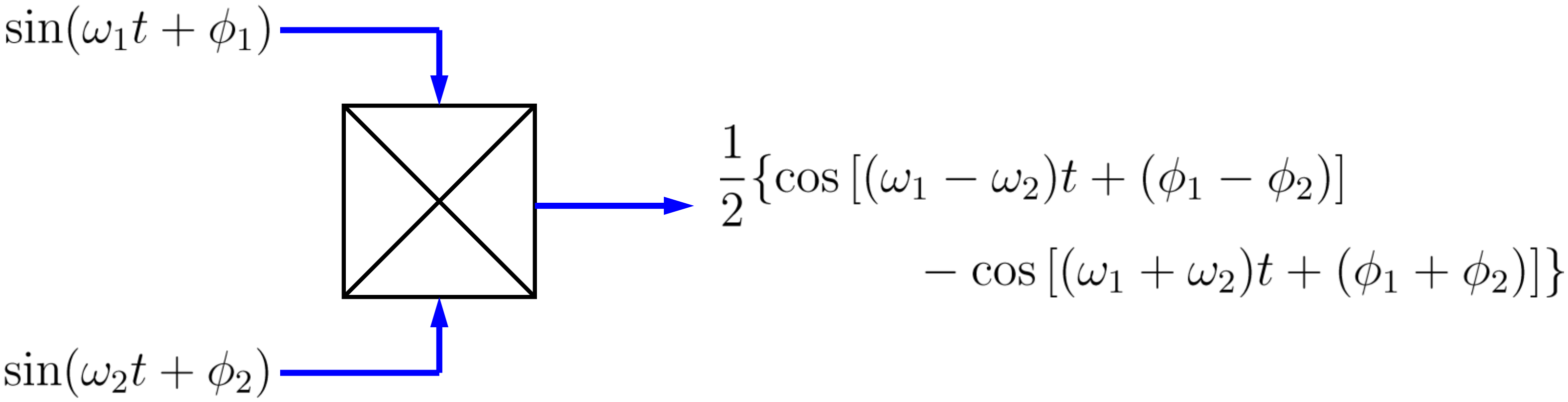
→ Saw-tooth in phase means constant frequency difference

→ 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**

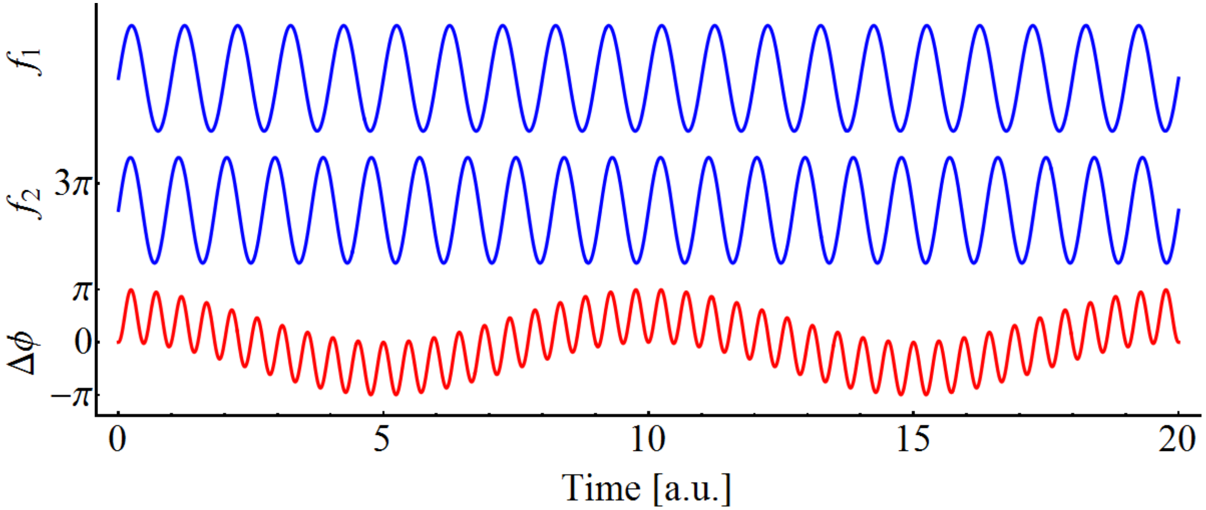


$\sin(\omega_1 t + \phi_1)$

$\sin(\omega_2 t + \phi_2)$

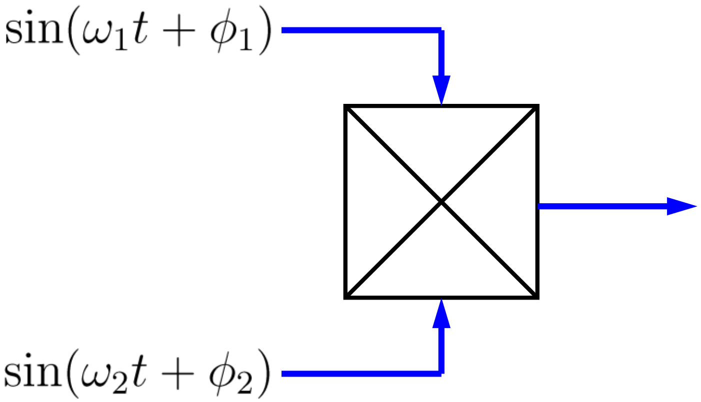
$$\frac{1}{2}\{\cos\left[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\right] \\ - \cos\left[(\omega_1 + \omega_2)t + (\phi_1 + \phi_2)\right]\}$$

- **Signals:**



Mixer or multiplier

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



$\sin(\omega_1 t + \phi_1)$

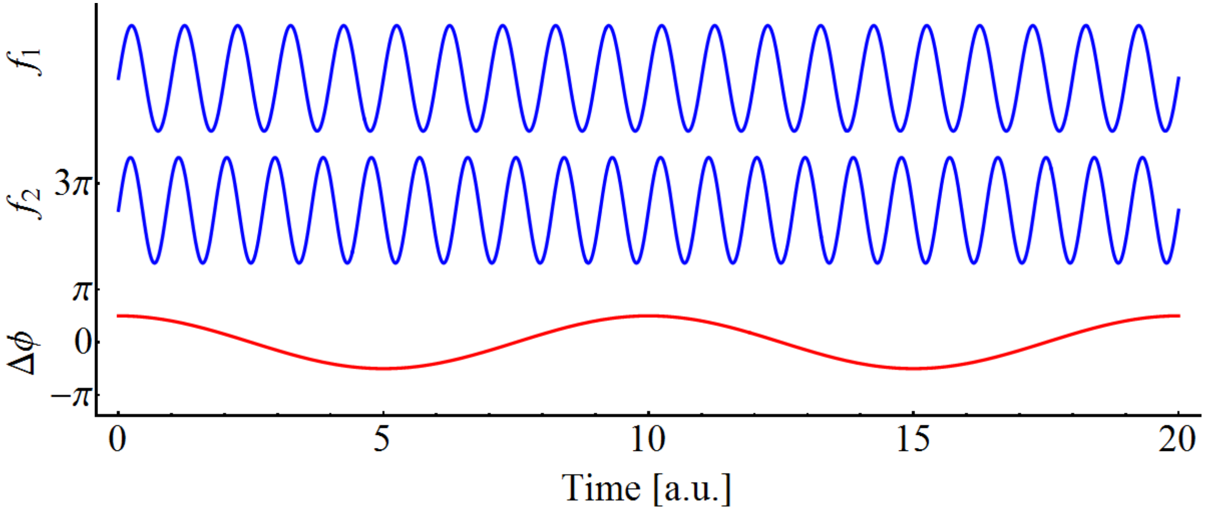
$\sin(\omega_2 t + \phi_2)$

$$\frac{1}{2}\{\cos\left[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\right]$$

$$\cancel{\cos\left[(\omega_1 + \omega_2)t + (\phi_1 + \phi_2)\right]}\}$$

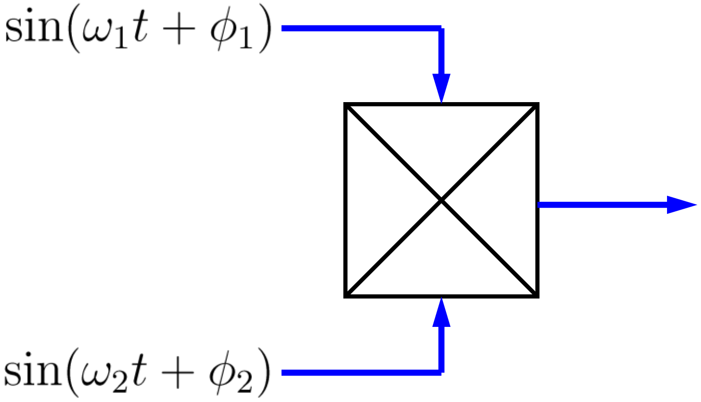
Remove ripple → Low-pass filter

- **Signals:**



How to detect phase differences?

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



$$\sin(\omega_1 t + \phi_1)$$

$$\sin(\omega_2 t + \phi_2)$$

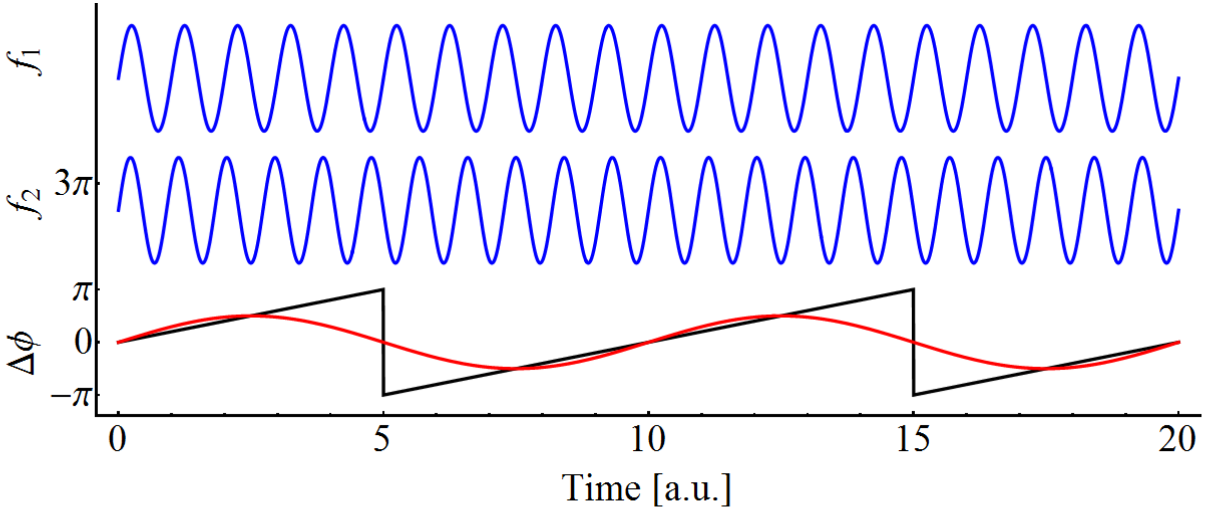
$$\frac{1}{2}\{\cos\left[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\right]$$

$$\cancel{\cos\left[(\omega_1 + \omega_2)t + (\phi_1 + \phi_2)\right]\}}$$

Remove ripple → Low-pass filter

Relative: arbitrary shift by 90°

- **Signals:**



- **Phase discriminator in approximately +/-90° range**

RF sources

RF sources

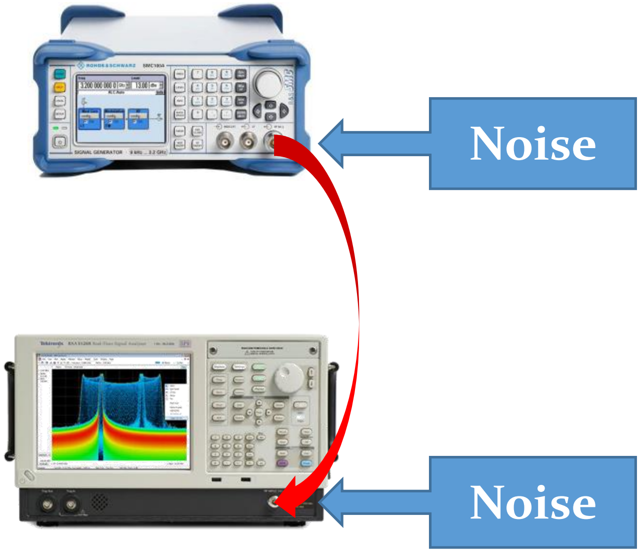
What finally generates the RF signal to power amplifier and cavity?

→ 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

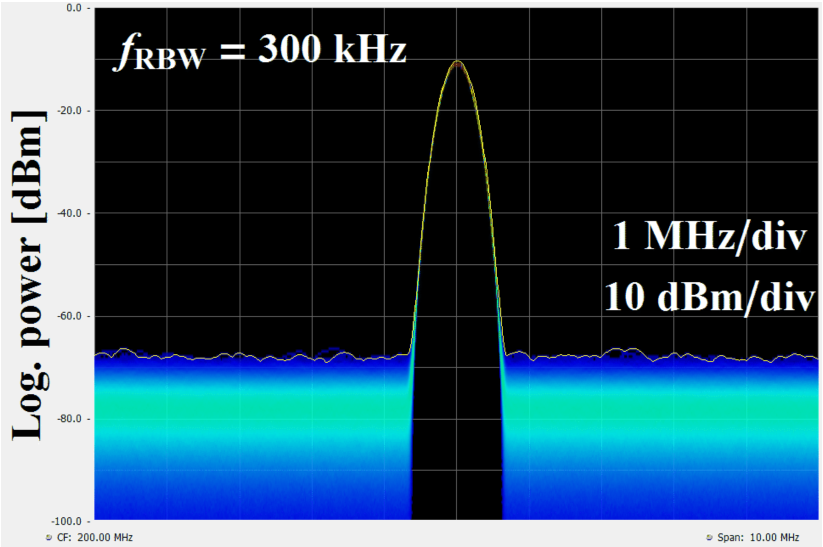
Noisy RF signals

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



Noise

Noise



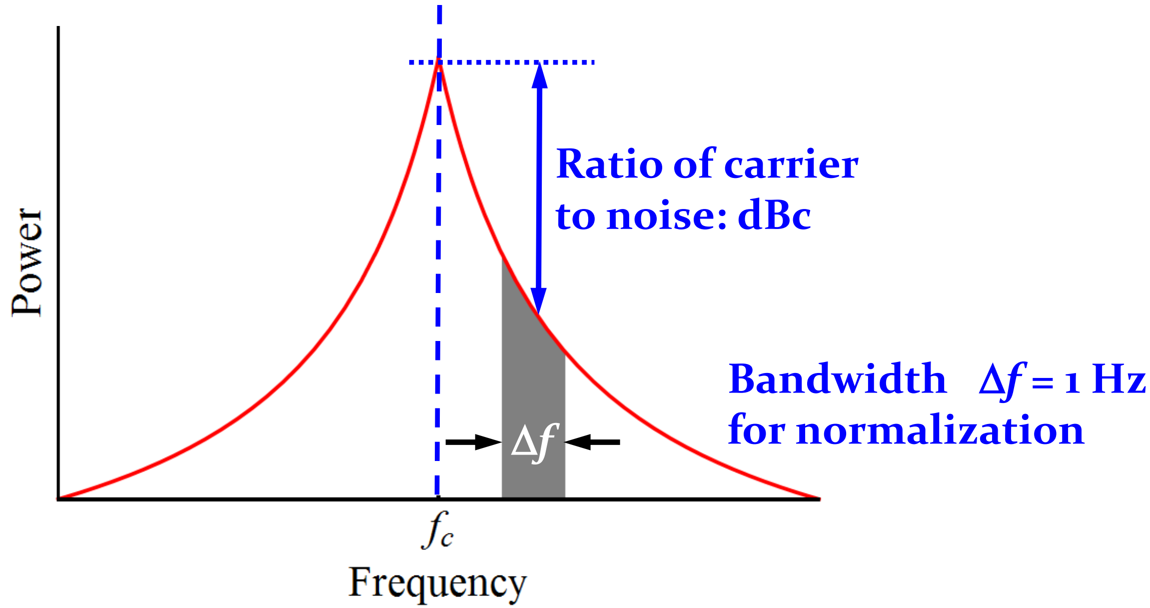
→ Amplitude of coherent, quasi monochromatic signal (at 200 MHz) is independent of observation bandwidth

→ Incoherent noise power (dominated by spectrum analyzer front-end amplifier/mixer) is proportional to bandwidth

→ Thermal noise power $\frac{P}{\Delta f} = k_{\mathrm{B}}T = 1.38 \cdot 10^{-23}\ \mathrm{J/K} \cdot 296\ \mathrm{K} \simeq -174\ \mathrm{dBm/Hz}$

Analysis of phase noise

- **Compare noise power with carrier power as reference**



- **Noise power density**

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

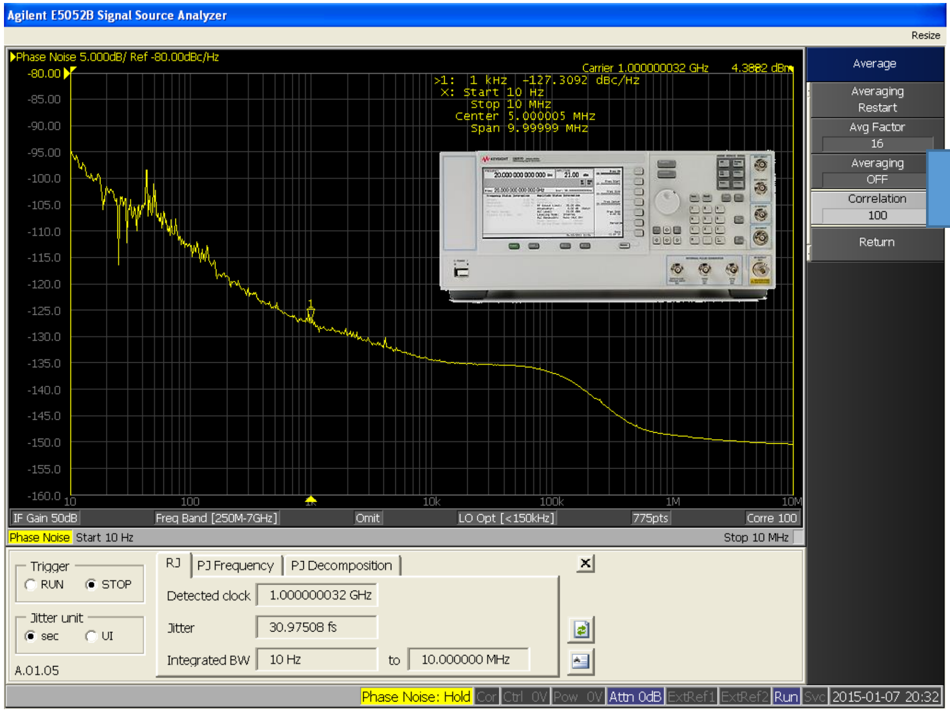
→ **Its integral is the phase jitter and using** $\Delta t = \dfrac{\Delta\phi}{2\pi f_\mathrm{c}}$

the jitter in time becomes

$$\Delta t_\mathrm{rms} = \frac{1}{2\pi f_\mathrm{c}} \sqrt{\int_{f_1}^{f_2} S_\phi(f)\, df}$$

Typical phase noise plots

- Measure phase noise of a synthesized lab generator



Carrier 1.000000032 GHz 4.3882 dBm

```
>1:  1 kHz  -127.3092 dBc/Hz
 X:  Start 10 Hz
     Stop 10 MHz
     Center 5.000005 MHz
     Span 9.99999 MHz
```

Avg Factor: 16

Averaging: OFF

Correlation: 100

Phase Noise Start 10 Hz Stop 10 MHz

Detected clock: 1.000000032 GHz

Jitter: 30.97508 fs

Integrated BW: 10 Hz to 10.000000 MHz

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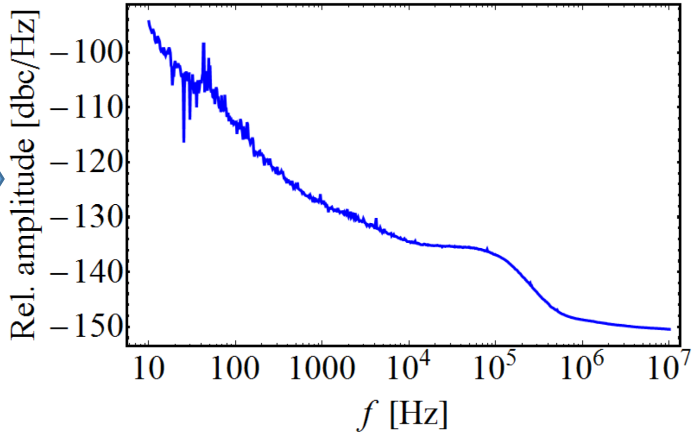


Frequency range	Δt_{rms} [fs]
10...100 Hz	12.4
100 Hz ...1 kHz	5.4
1...10 kHz	5.4
10...100 kHz	11.1
100 kHz...1 MHz	13.0
Total	31.0

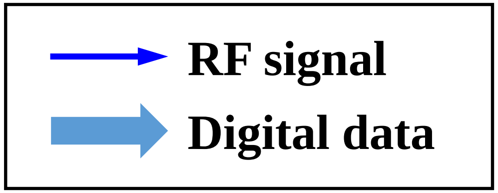
→ **Note: jitter values can be added as square root of quadratic sum**

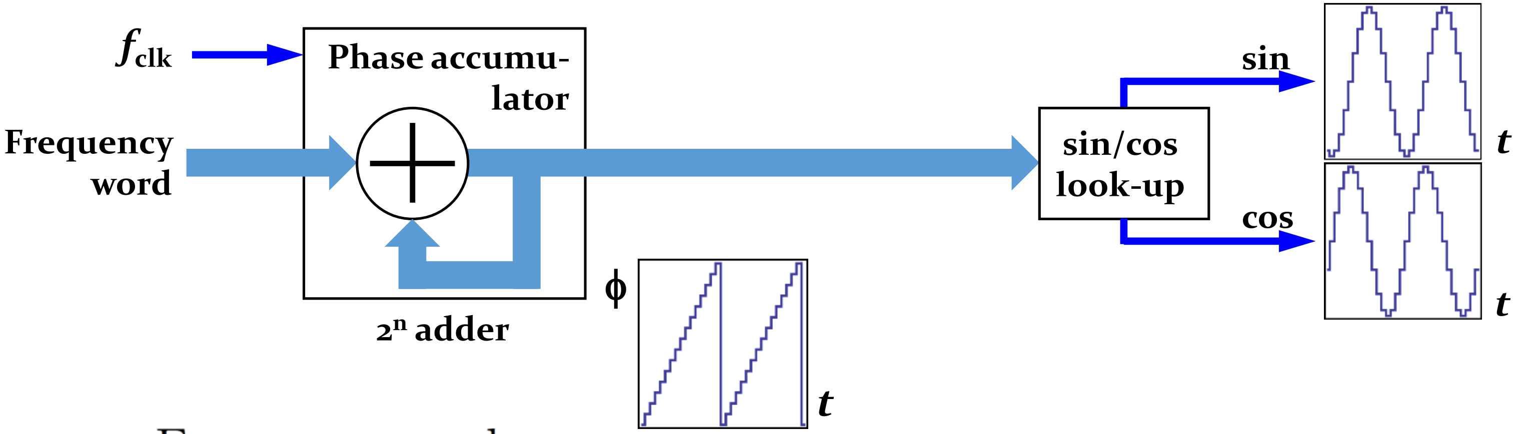
$$\Delta t_{\text{rms}} = \sqrt{\Delta t^2_{\text{rms},1} + \Delta t^2_{\text{rms},2} + \ldots}$$

→ **Convenient split to relevant ranges**

Variable frequency: direct digital synthesis

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



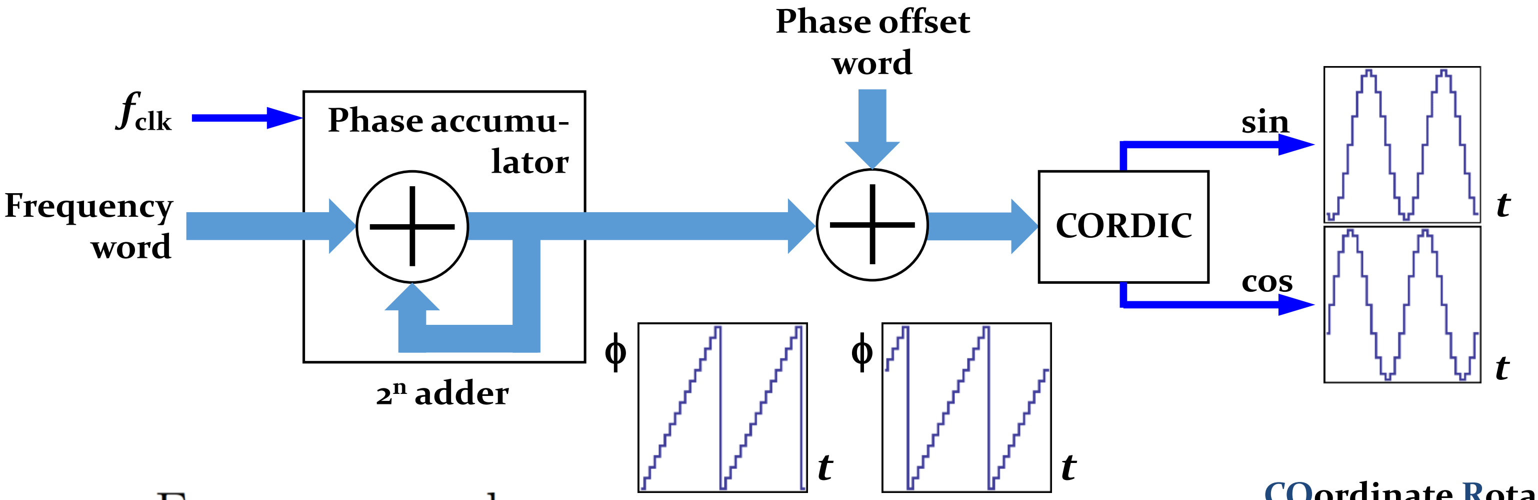


$$f_{\mathrm{out}} = \frac{\text{Frequency word}}{2^n} \cdot f_{\mathrm{clk}}$$

Variable frequency: direct digital synthesis

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

→ **RF signal**
⇒ **Digital data**



$$f_{\mathrm{out}} = \frac{\text{Frequency word}}{2^n} \cdot f_{\mathrm{clk}}$$

COordinate Rotation DIgital Computer

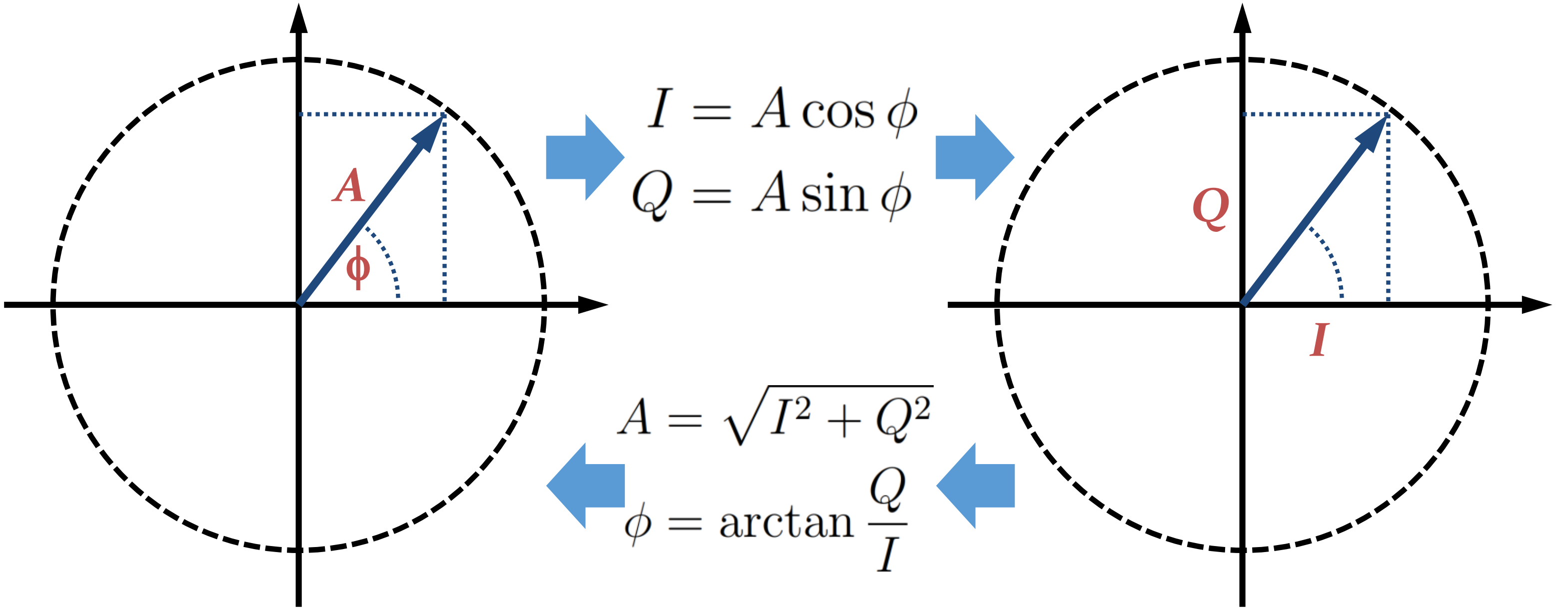
→ **Two output signals with ideal 90° phase shift**

→ **Output signals are digital data streams**

Receivers

I/Q representation of signals

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



$$I = A\cos\phi$$
$$Q = A\sin\phi$$

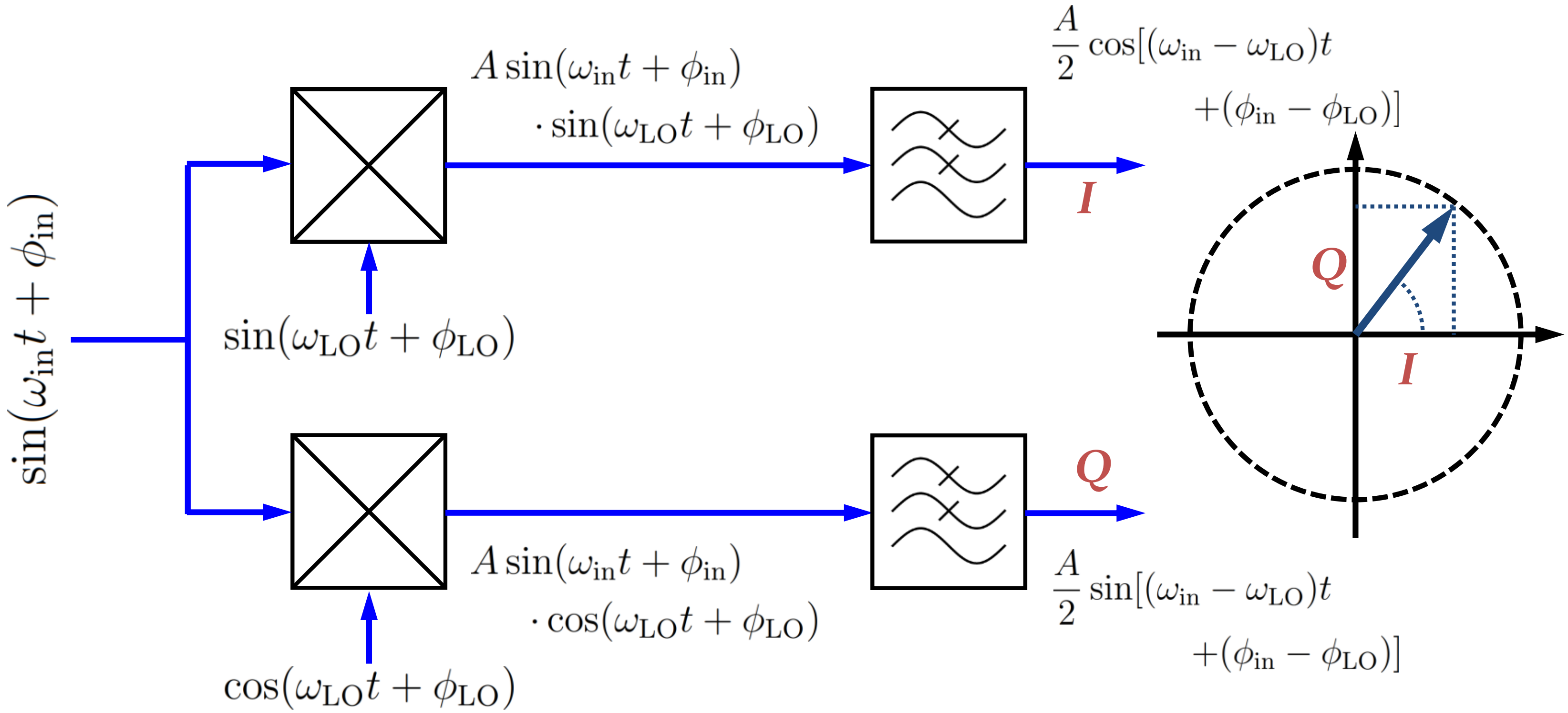
$$A = \sqrt{I^2 + Q^2}$$
$$\phi = \arctan\frac{Q}{I}$$

→ In phase, *I* and quadrature, *Q* describe the same signal

→ Avoids phase discontinuities at 0, 2π, …

Signal receivers

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



$\sin(\omega_{\text{in}} t + \phi_{\text{in}})$

$A \sin(\omega_{\text{in}} t + \phi_{\text{in}}) \cdot \sin(\omega_{\text{LO}} t + \phi_{\text{LO}})$

$\sin(\omega_{\text{LO}} t + \phi_{\text{LO}})$

$\frac{A}{2} \cos[(\omega_{\text{in}} - \omega_{\text{LO}})t + (\phi_{\text{in}} - \phi_{\text{LO}})]$

$A \sin(\omega_{\text{in}} t + \phi_{\text{in}}) \cdot \cos(\omega_{\text{LO}} t + \phi_{\text{LO}})$

$\cos(\omega_{\text{LO}} t + \phi_{\text{LO}})$

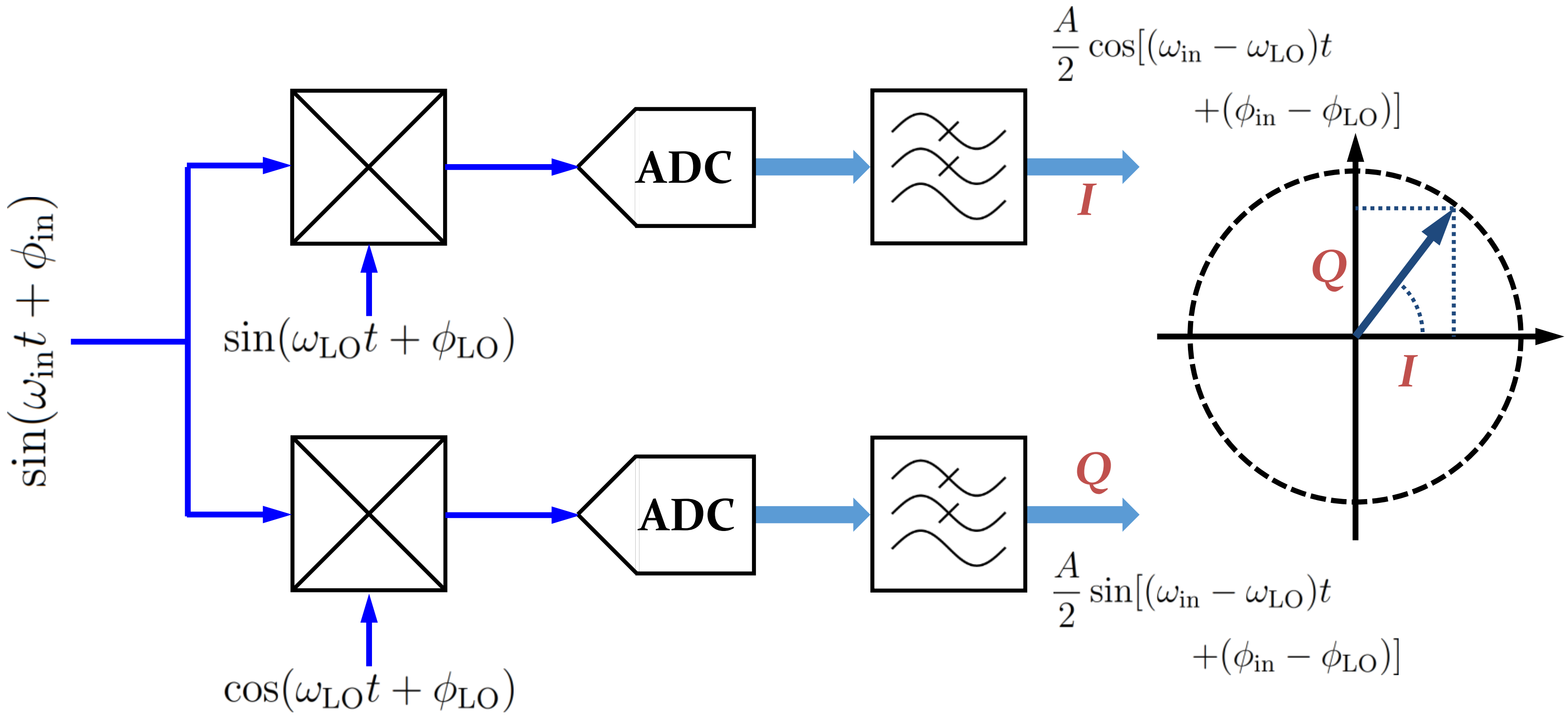
$\frac{A}{2} \sin[(\omega_{\text{in}} - \omega_{\text{LO}})t + (\phi_{\text{in}} - \phi_{\text{LO}})]$

→ **With $\omega_{in} \approx \omega_{LO}$ input signal is down-converted to base-band**

→ **Resulting I/Q vector rotates slowly with ω_{in} - ω_{LO}**

Digital receivers

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

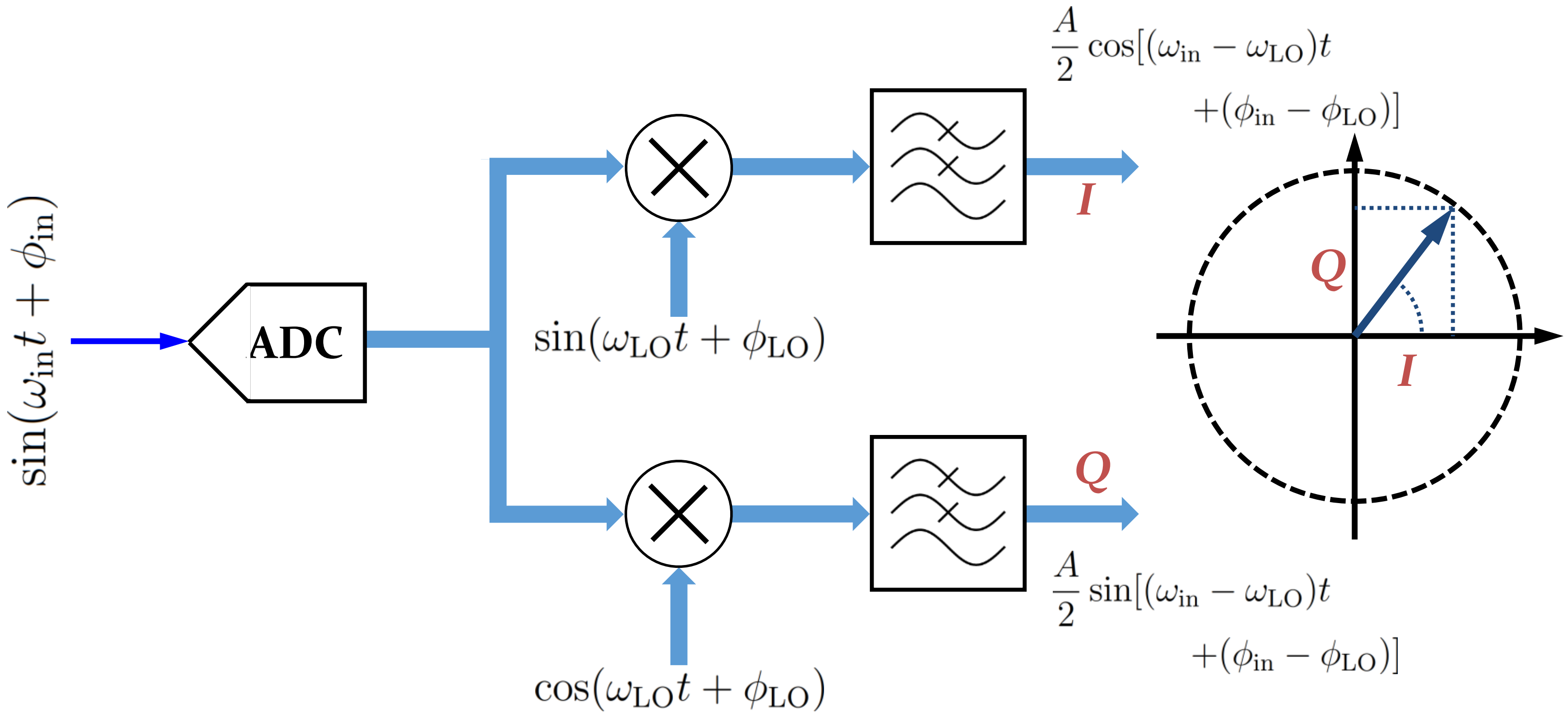


→ Analog down-conversion of I and Q, then digital processing

→ High input frequencies beyond ADC sampling rates

Digital receivers

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



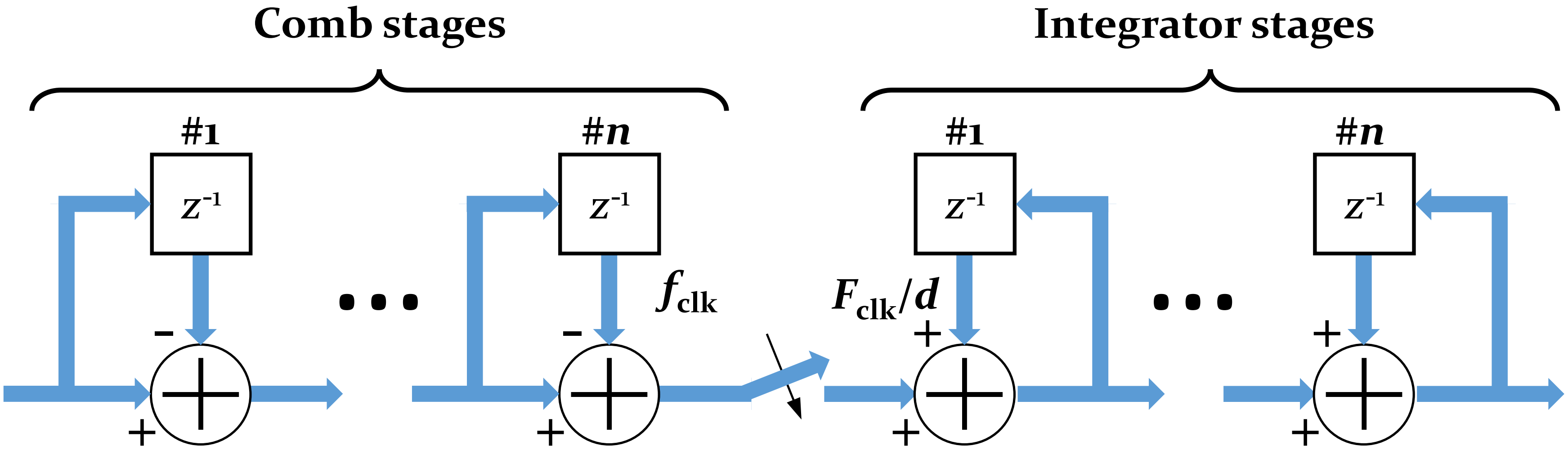
→ Analogue mixers become digital multipliers

→ All digital receiver

→ Theoretically perfect I/Q symmetry

Cascaded integrator-comb filter (CIC)

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



$$H(z) = \left(\frac{1-z^{-d}}{1-z^{-1}}\right)^n$$

***n*:** filter order
***d*:** decimation ratio

$$z = e^{2\pi i \cdot f/f_{\text{clk}}}$$

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

Cascaded integrator-comb filter (CIC)

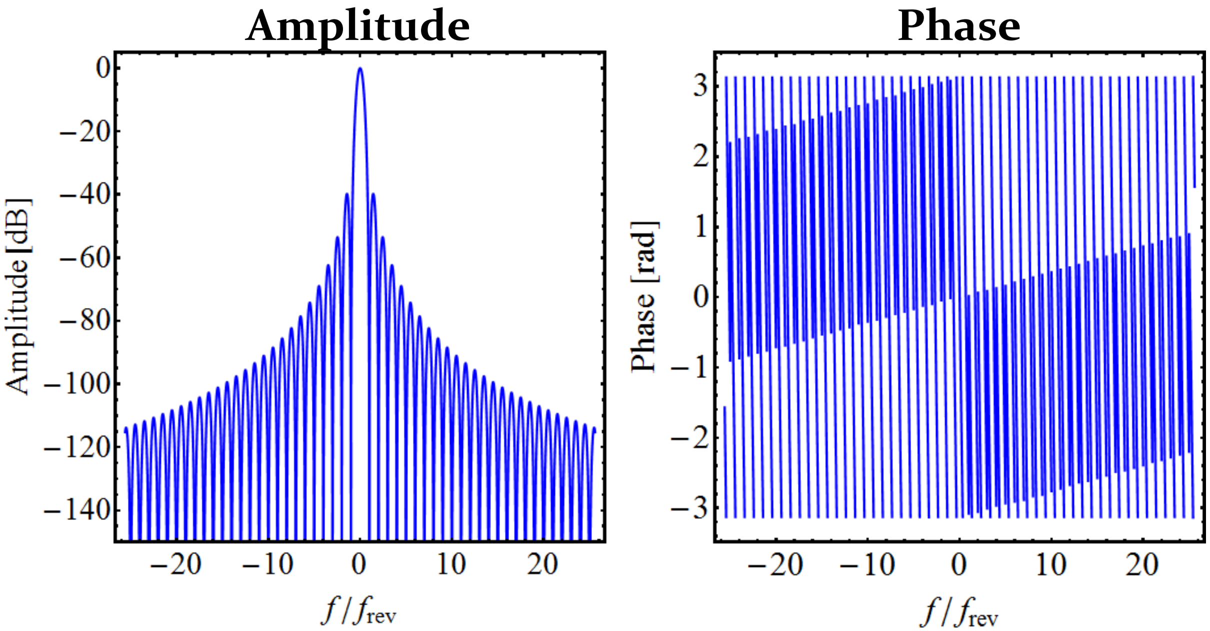
Why particularly interesting for circular accelerators?

- **Chose clock frequency, $f_{\mathrm{clk}} = 2^m f_{\mathrm{rev}}$ and decimation $d = 2^m$**

→ Notches at all multiples of f_{rev} except zero

→ Linear phase $\phi(f)$ → filter behaves like a constant delay

Example:
$f_{\mathrm{clk}} = 128 f_{\mathrm{rev}}$,
$d = 128$,
$n = 3$



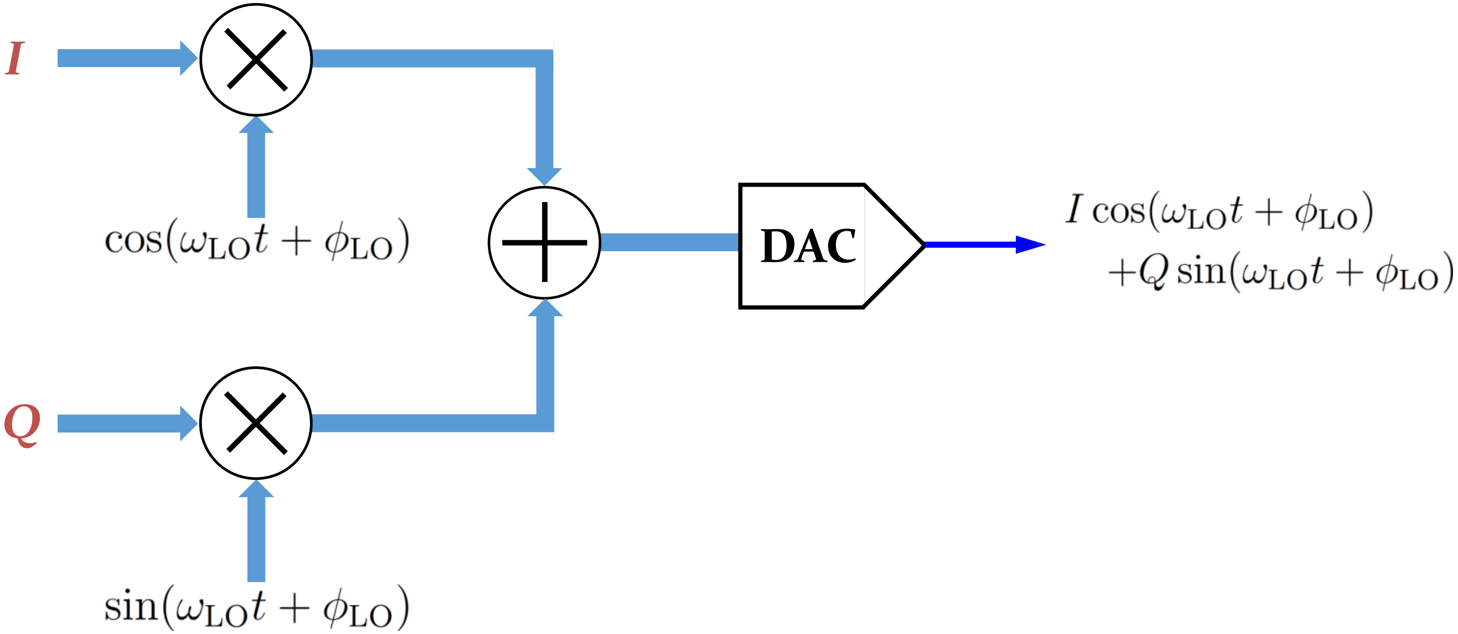
👍 **Ideal low-pass filter in digital receivers**

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

Vector modulator

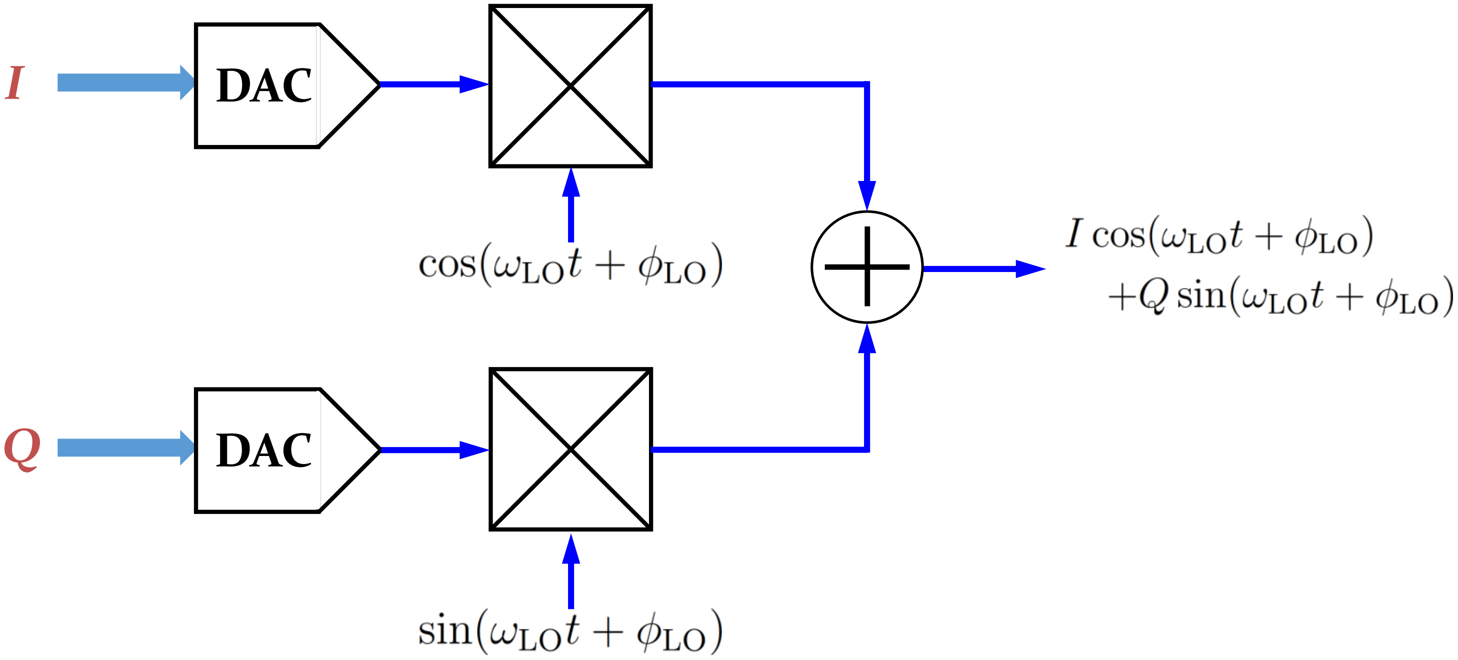
Invers receiver: vector modulator

- **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**

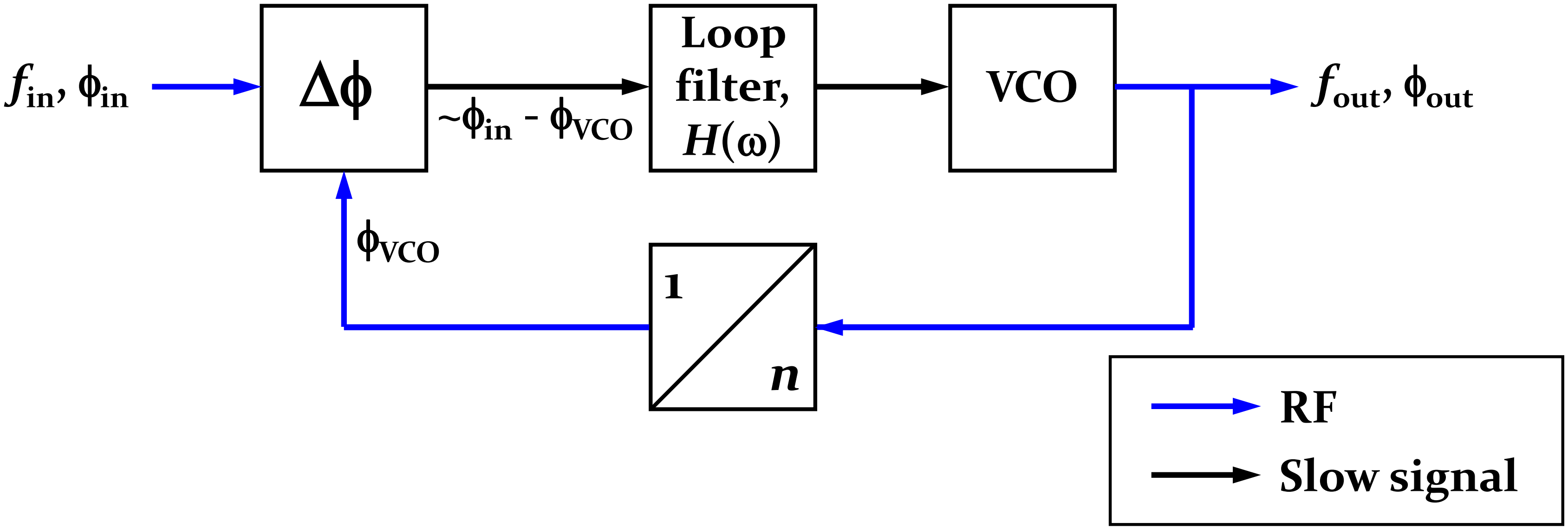
→ **Up-conversion of digital signal to a high RF frequency**

Beam phase loop

Electronic phase-locked loop

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

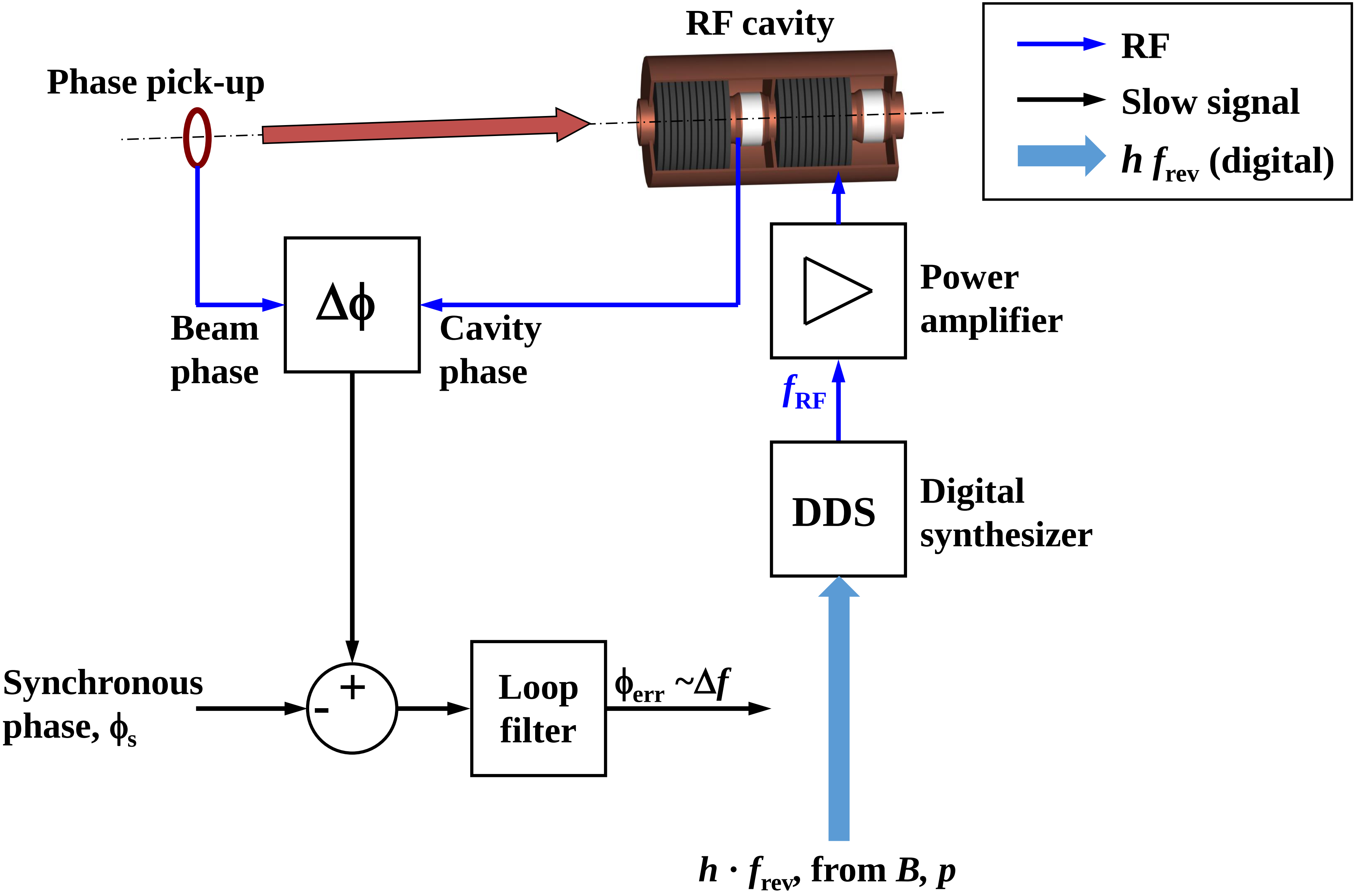
$$\omega_{\mathrm{VCO}} = 2\pi f_{\mathrm{VCO}} = \frac{d\phi}{dt} = K_{\mathrm{VCO}} V_{\mathrm{in}}$$



→ **Fixed phase relationship:** $\phi_{\mathrm{out}}/n - \phi_{\mathrm{in}} = \mathrm{const.}$

→ **Optional divider:** $f_{\mathrm{out}} = n \cdot f_{\mathrm{in}}$

Beam phase loop



RF cavity

Phase pick-up

RF

Slow signal

$h\,f_{rev}$ (digital)

$\Delta\phi$

Beam phase

Cavity phase

Power amplifier

f_{RF}

DDS

Digital synthesizer

Synchronous phase, ϕ_s

+

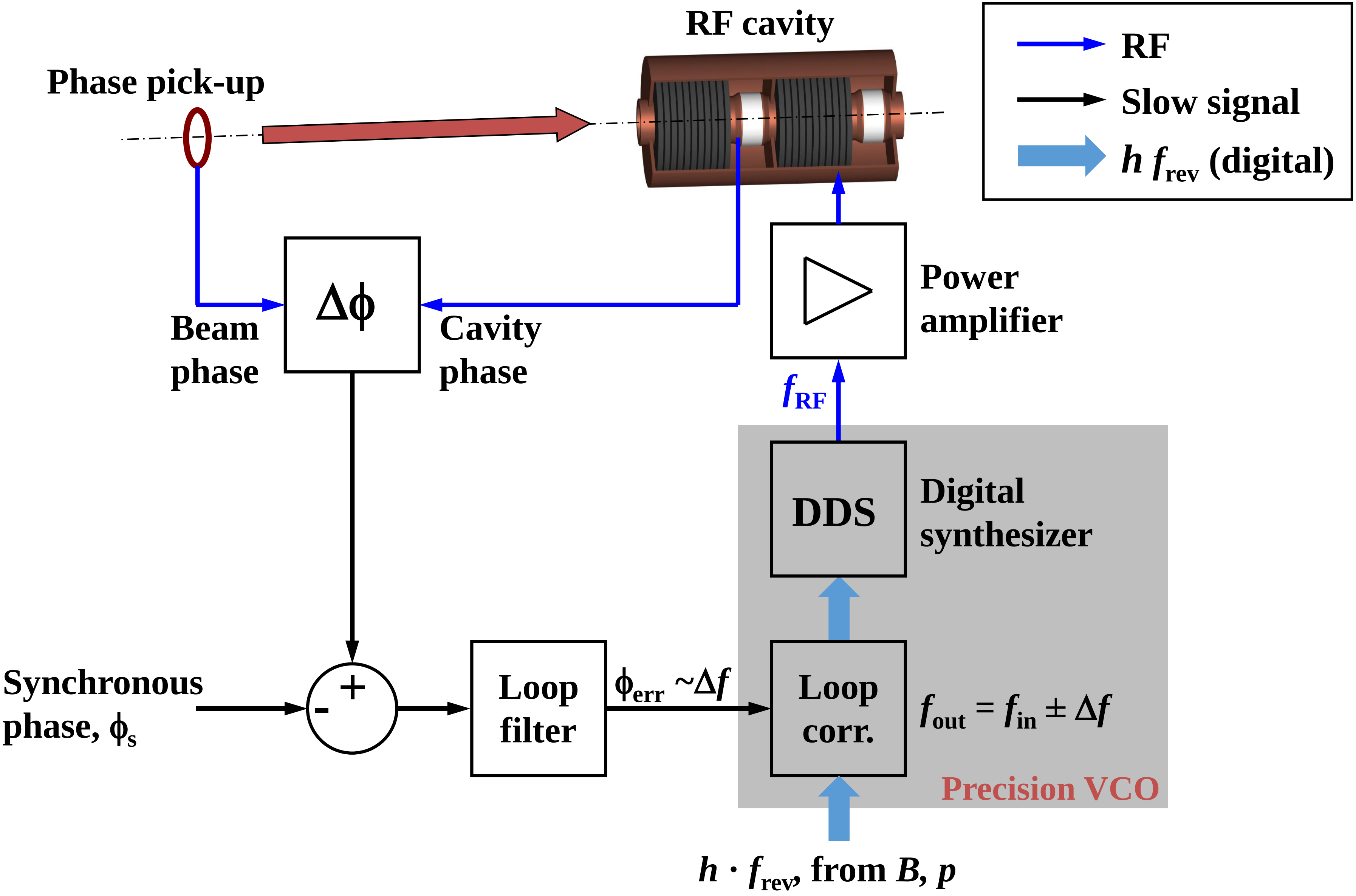
-

Loop filter

$\phi_{err} \sim \Delta f$

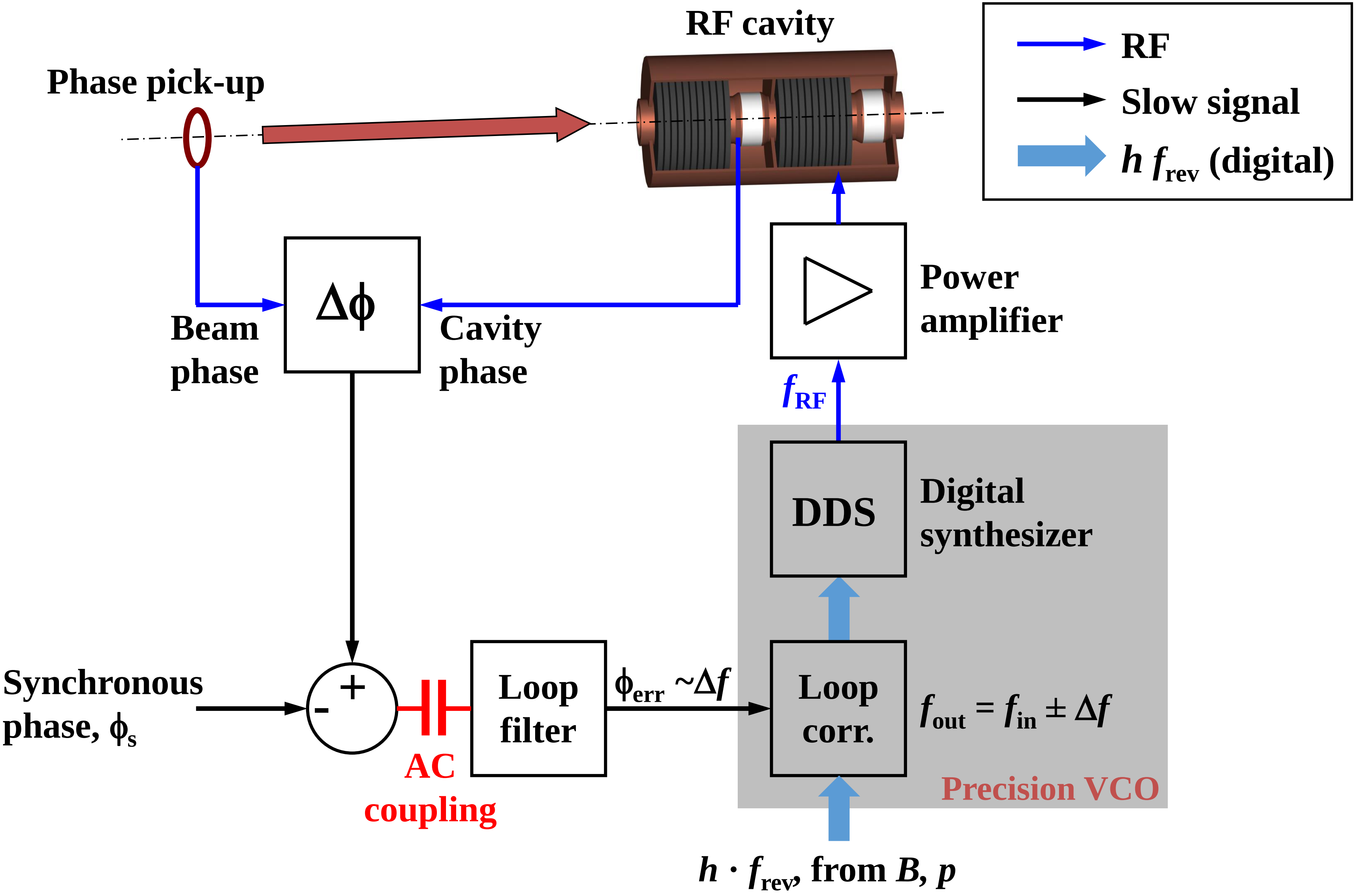
$h \cdot f_{rev}$, from B, p

Beam phase loop



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

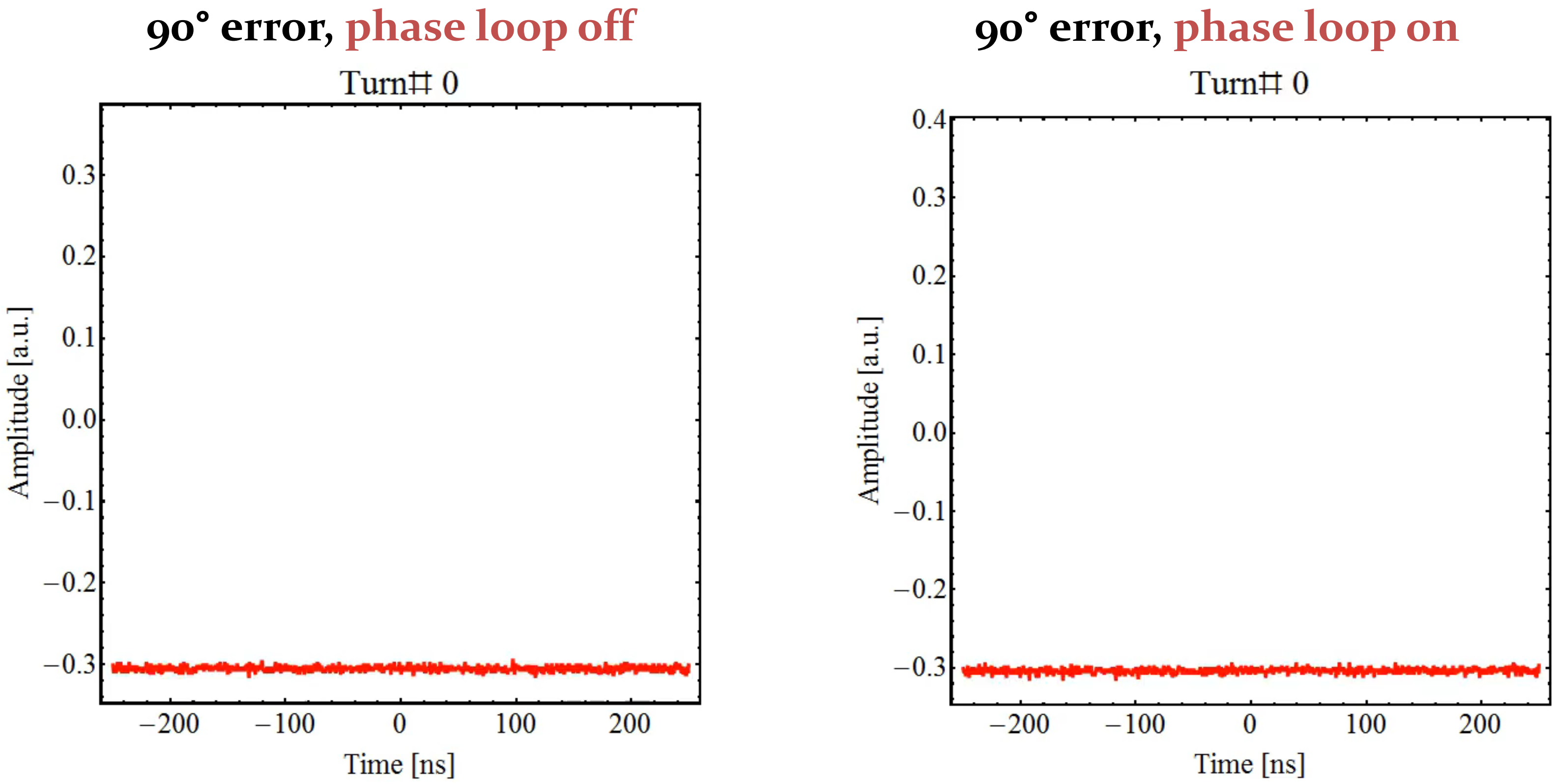
Beam phase loop



→ 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**

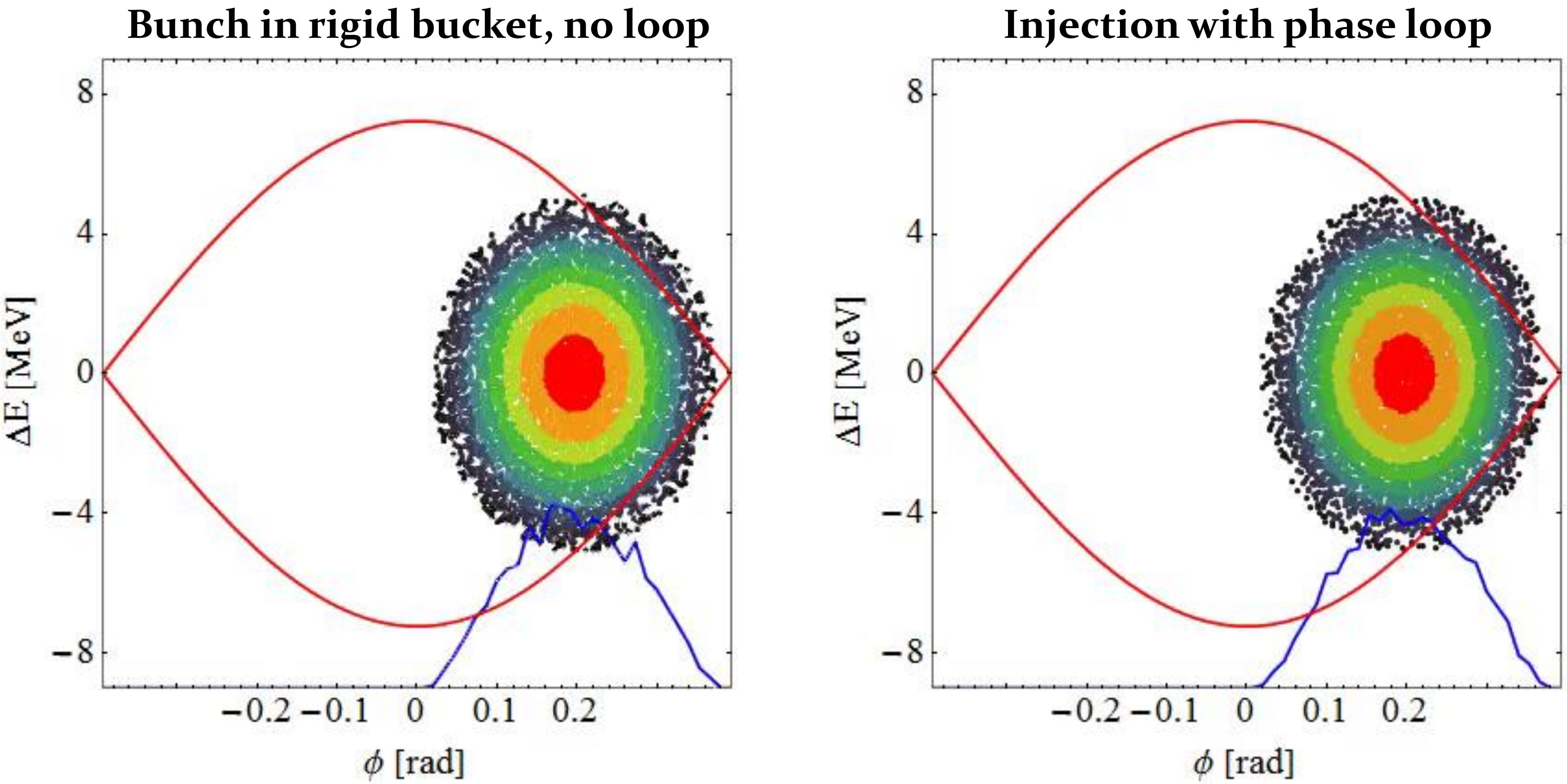


→ **Essential in hadron accelerators to keep RF locked to beam**

→ **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



→ Even large transients (injection, transition) are controlled

→ Only minor longitudinal perturbation

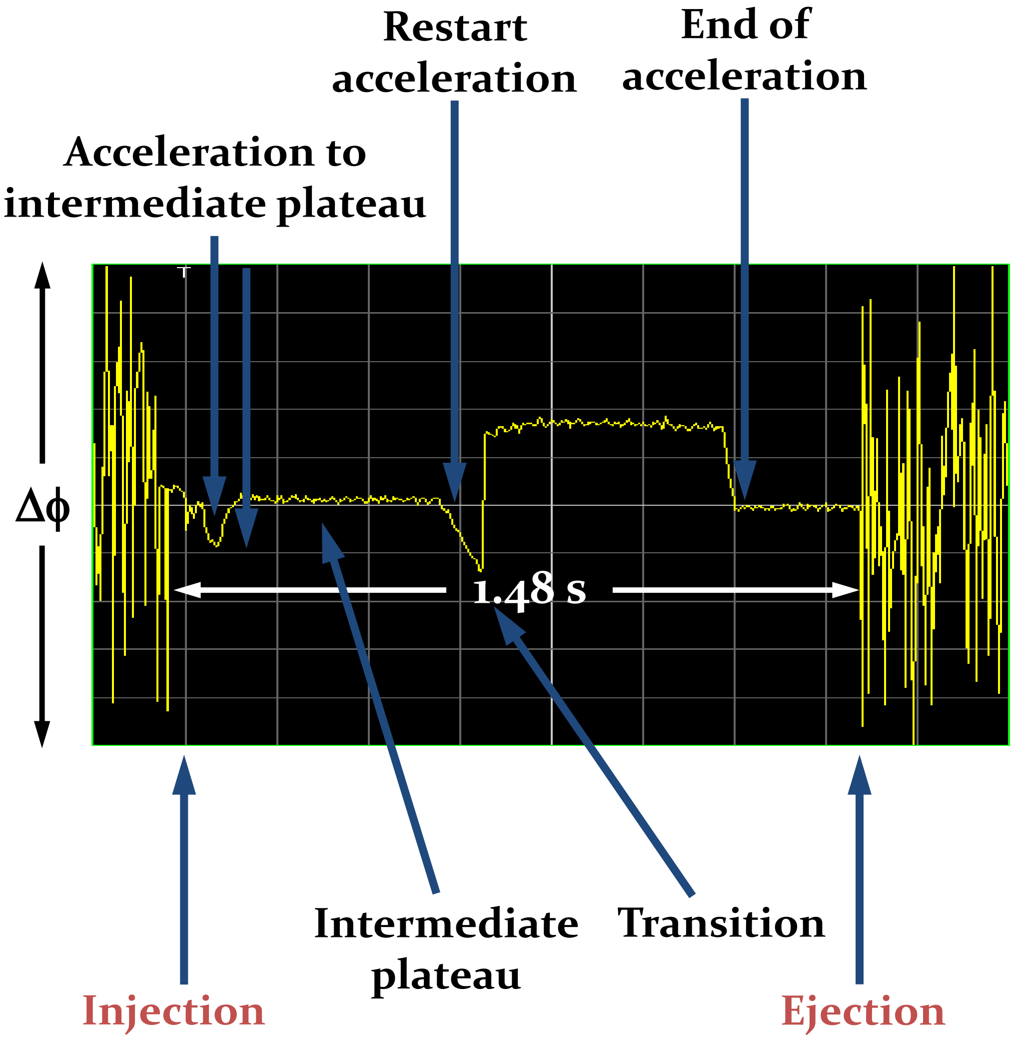
Beam phase loop during acceleration

→ What happens with phase loop during acceleration?

→ During plateaus the phase between RF and beam is either 0° or 180°

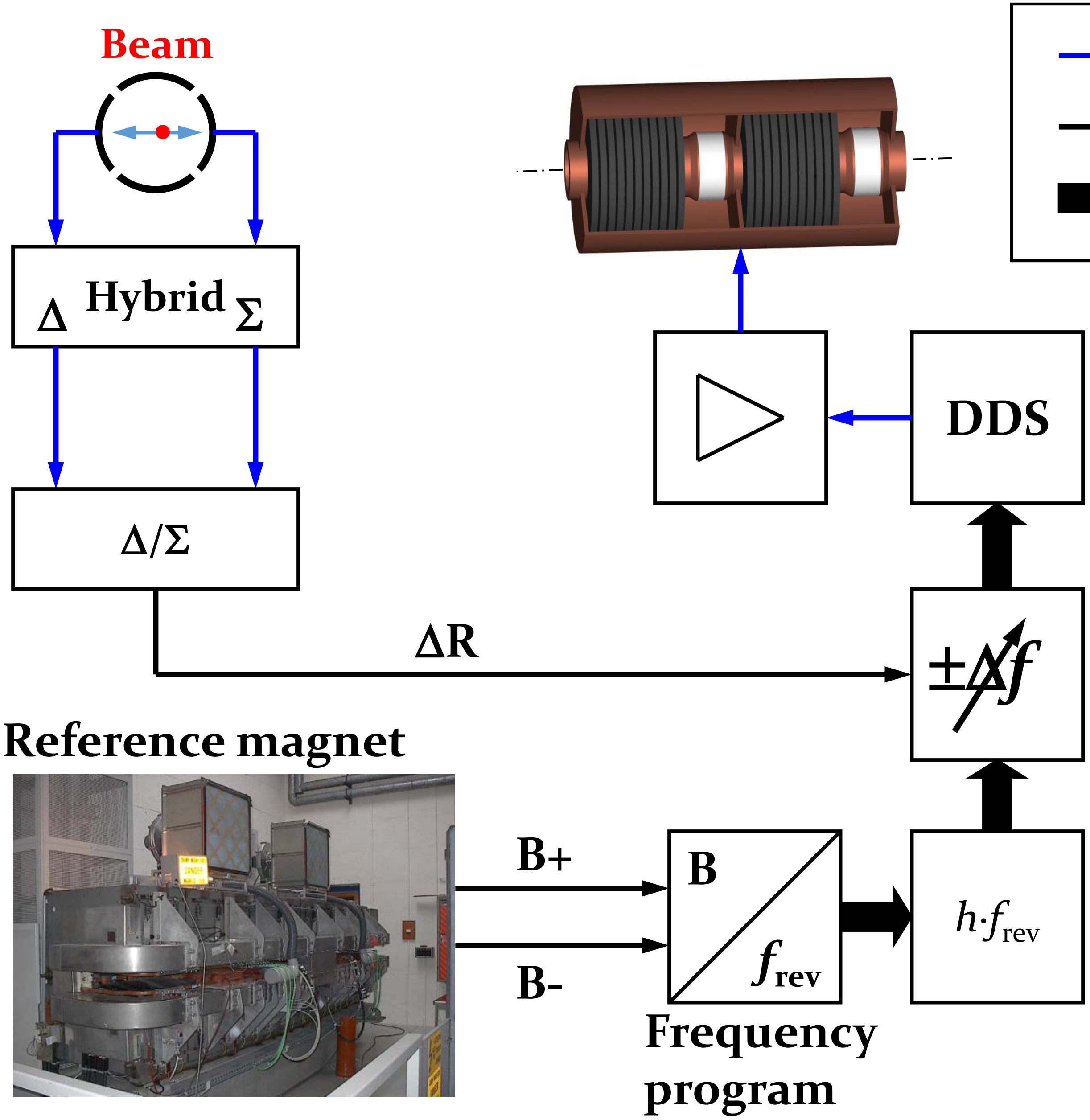
→ Fast phase changes well handled, but need slow frequency correction

→ Radial or synchronization loop



Radial loop

Radial loop



Beam

Δ **Hybrid** Σ

Δ/Σ

ΔR

$\pm\Delta f$

DDS

Reference magnet

B+

B-

B

f_{rev}

$h \cdot f_{rev}$

Frequency program

→ **RF**

→ **Slow signal**

➡ **Digital signal**

→ **Slow correction of average RF frequency**

Radial loop

- Slow correction of RF frequency to keep beam centred

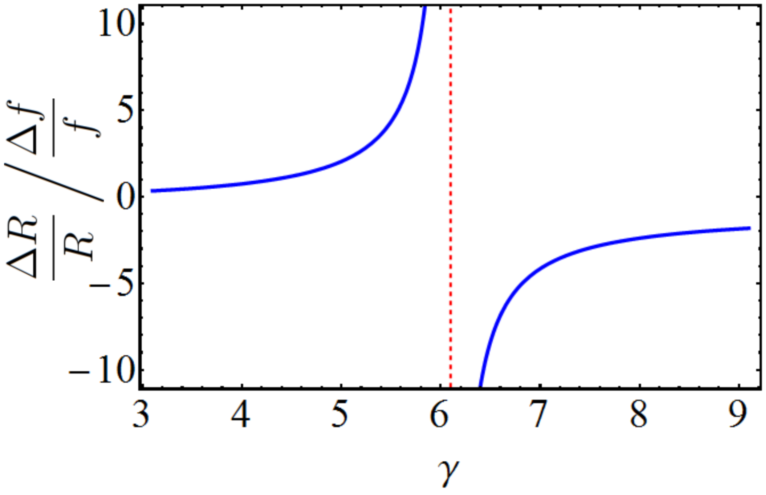
Why needed at all with arbitrary precision synthesizers driving the RF system?

→ **At transition energy**

  → **Longer path of higher energy particle compensated by higher velocity**

  → **No revolution frequency change for energy offset**

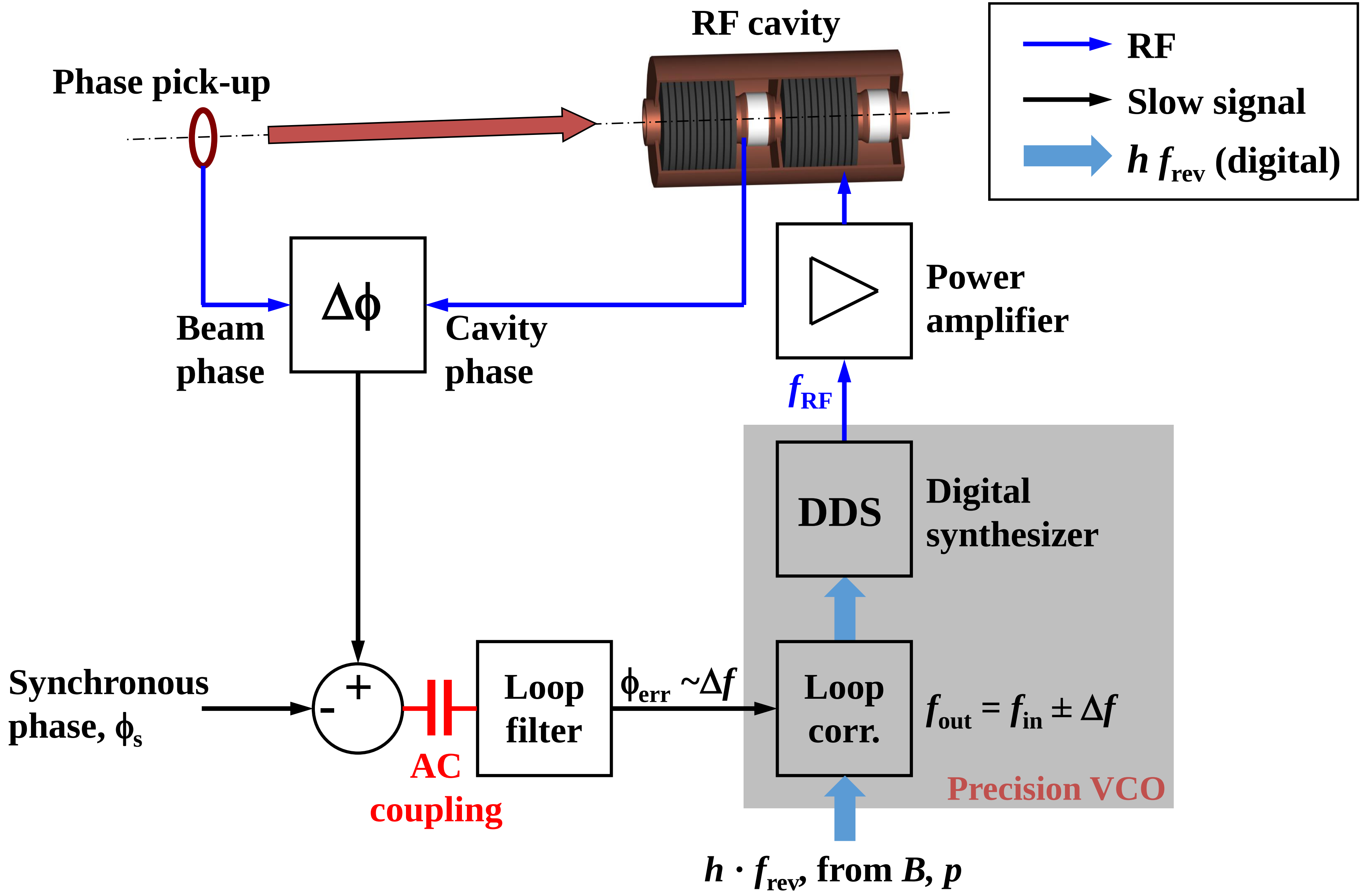
$$\boxed{\frac{\Delta R}{R} = \frac{\gamma^2}{\gamma_{\mathrm{tr}}^2 - \gamma^2}\frac{\Delta f}{f}}$$



→ **Need beam-based frequency correction**

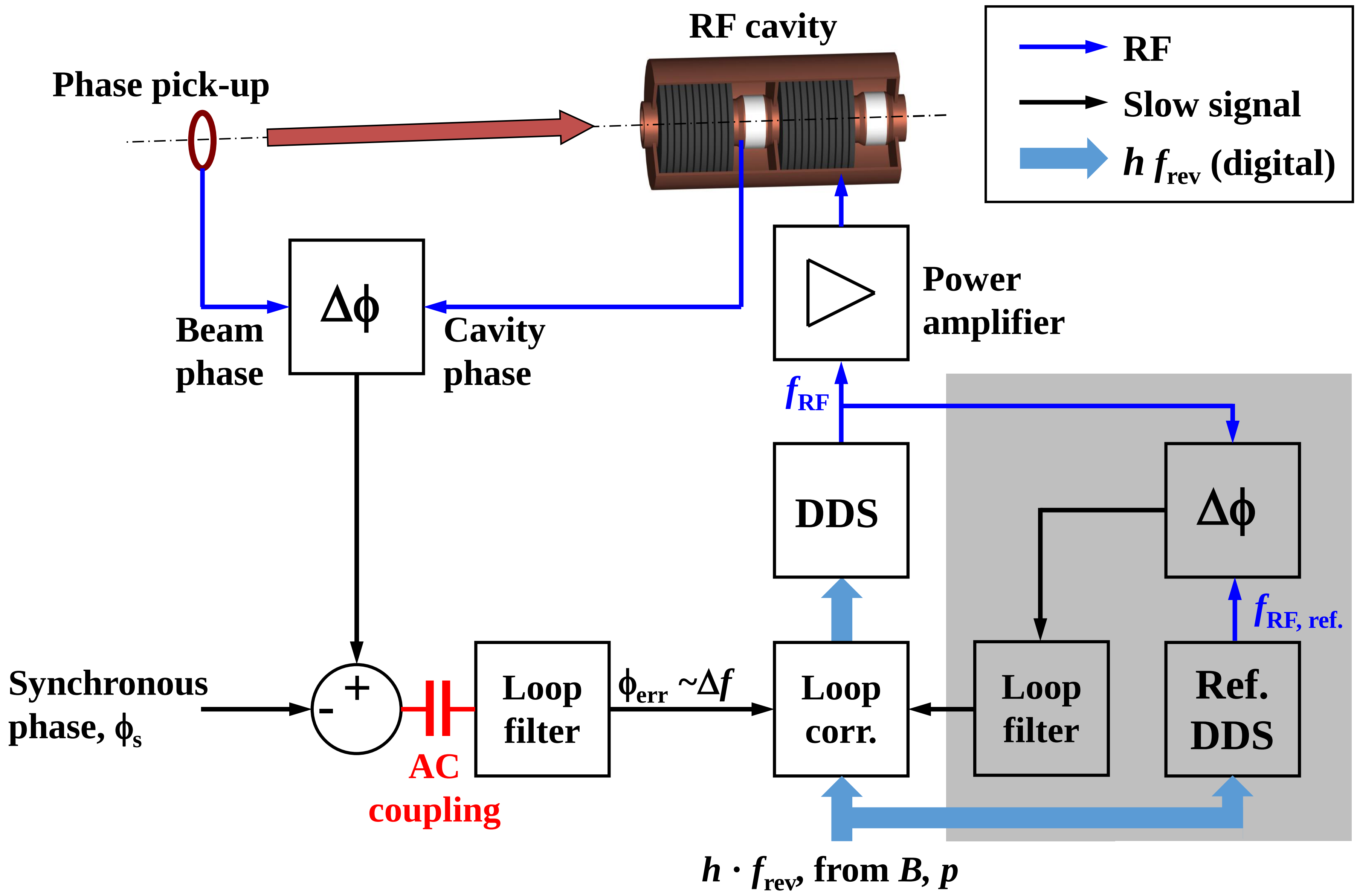
Synchro(nization) loop

Beam phase loop



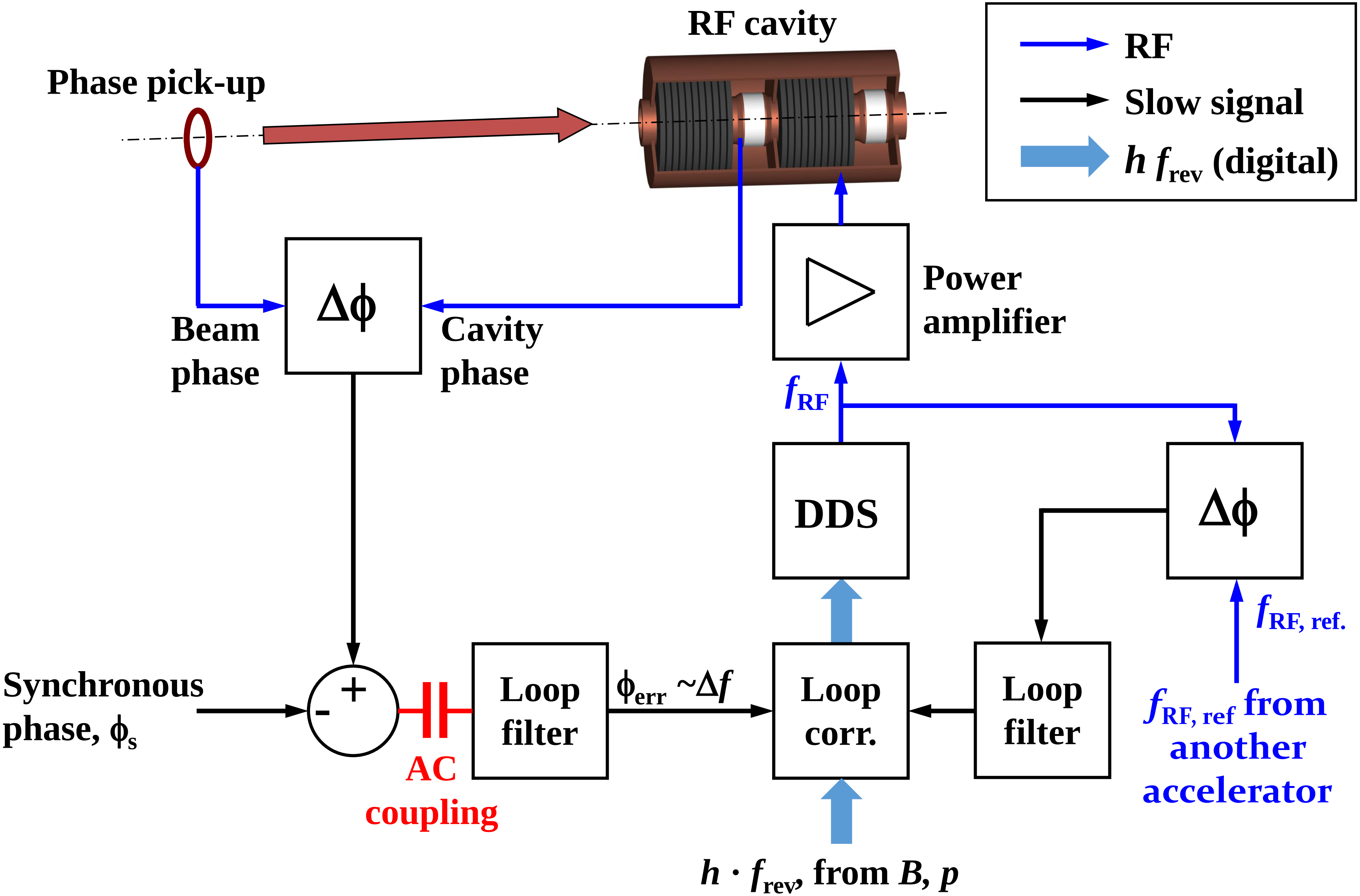
→ Fast control of RF frequency to cavities, but no slow corrections

Synchronization loop, internal reference



→ Avoids noise from radial detection when not crossing transition

Synchronization loop, external reference

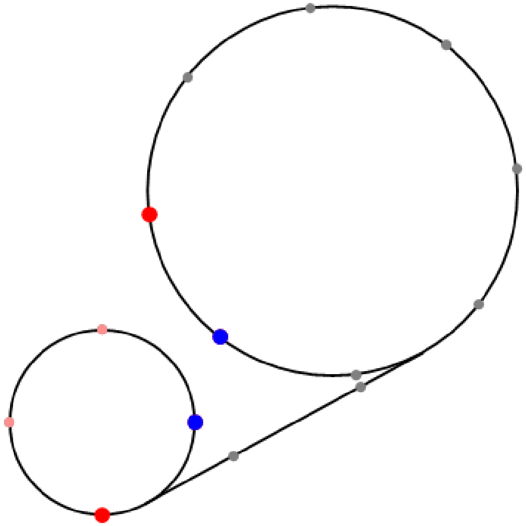


→ Synchronize between accelerators for transfer

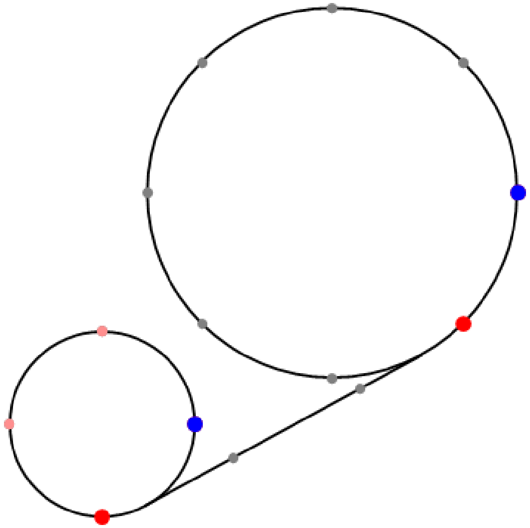
Before synchronization

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

Target accelerator is master at transfer



Target accelerator is master at transfer

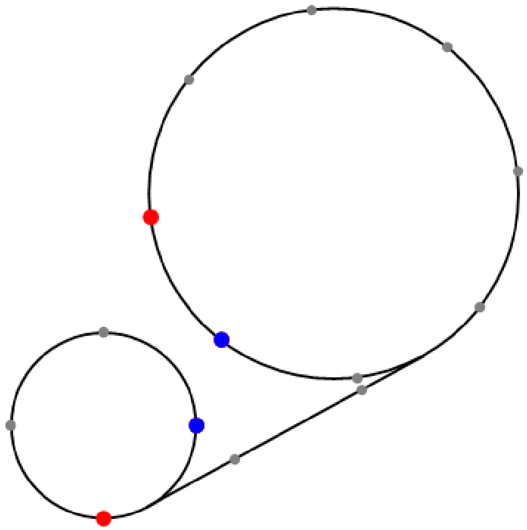


→ Synchronize both accelerator to force: $f_{\mathrm{rev},1} = 2f_{\mathrm{rev},2}$

After synchronization

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

Source or target accelerator
is master at transfer



→ Revolution frequencies coupled: $f_{\mathrm{rev},1} = 2f_{\mathrm{rev},2}$

→ 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

to all colleagues providing support, material and feedback

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Mauro Paoluzzi, Damien Perrelet, Lukas Stingelin,
Frank Tecker, Daniel Valuch and many more…**

Thank you very much for your attention!

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Normalized Hamiltonian representation

- **For a single harmonic RF system**

$$H(\phi,\dot{\phi}) = \frac{1}{2}\dot{\phi}^2 + \frac{\omega_s^2}{\cos\phi_0}\left[\cos\phi_0 - \cos\phi + (\phi-\phi_0)\sin\phi_0\right]$$

with $\phi = \phi_0 + \Delta\phi$ **it becomes**

$$H(\Delta\phi,\dot{\phi}) = \frac{1}{2}\dot{\phi}^2 + \frac{\omega_s^2}{\cos\phi_0}\left[\cos\phi_0 - \cos(\phi_0+\Delta\phi) - \Delta\phi\sin\phi_0\right]$$

using $\cos(\phi_0+\Delta\phi) = \cos\phi_0\cos\Delta\phi - \sin\phi_0\sin\Delta\phi$

$$\simeq \cos\phi_0\left(1-\frac{1}{2}\Delta\phi^2\right) - \sin\phi_0\Delta\phi$$

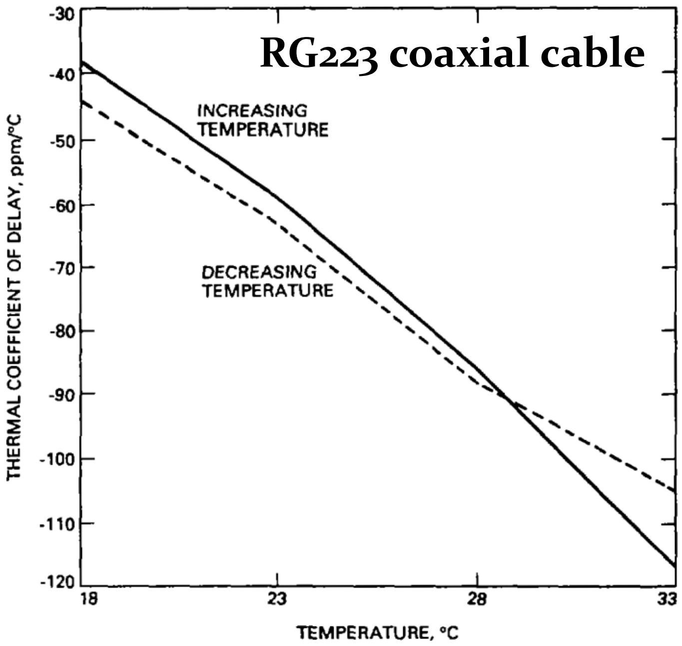
this simplifies to $H(\Delta\phi,\dot{\phi}) \simeq \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\omega_s^2\Delta\phi^2$

Transmission of reference signals

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

- **Thermal coefficient of delay:**

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



Lutes/Diener, NASA TDA Progress Report 42-99

- **Example: 2 km long RG223 cable with ~10 µs delay**

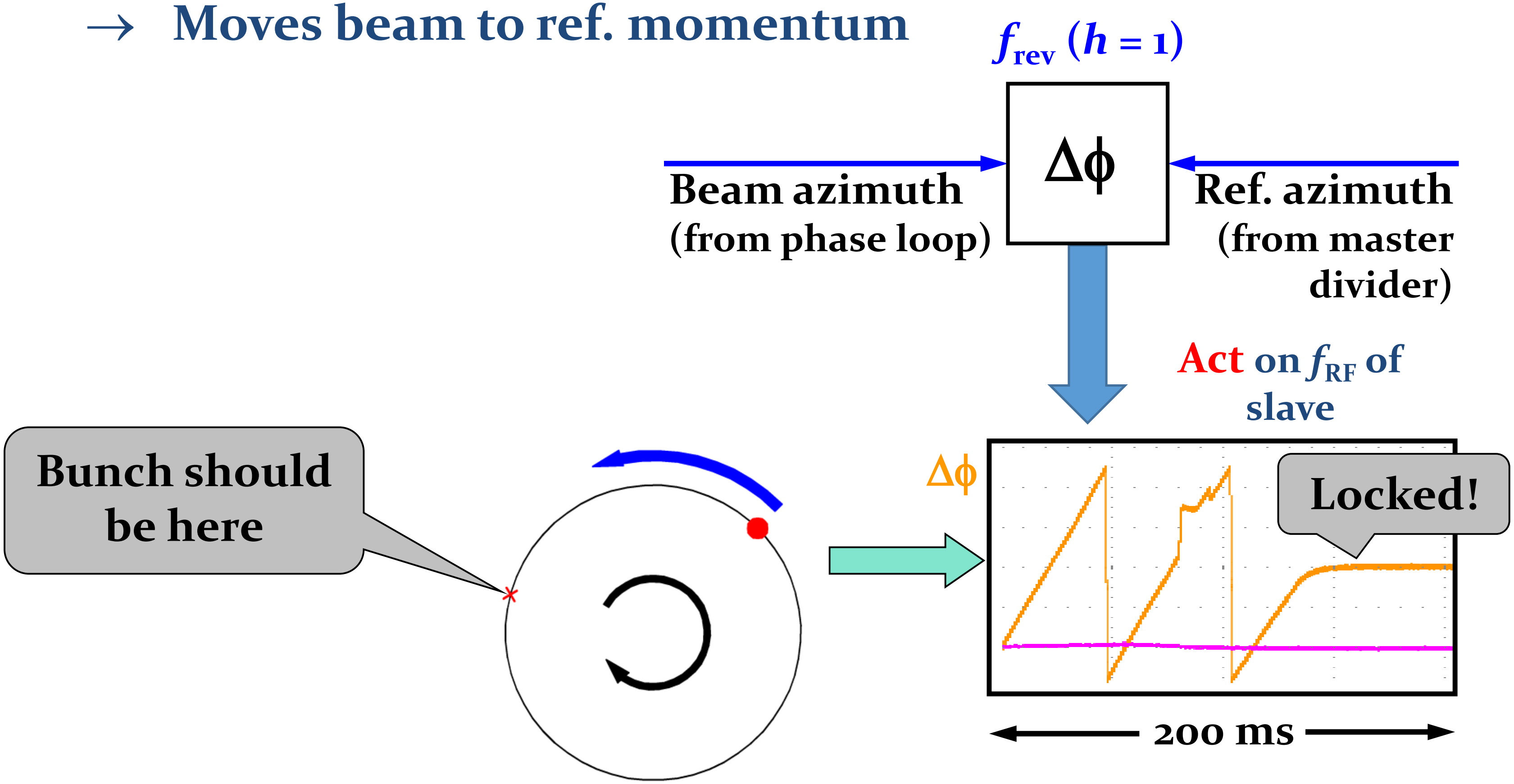
→ **ΔT of only 1° C (room temperature) changes delay by ~0.5 ns**

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



f_{rev} ($h = 1$)

Δϕ

Beam azimuth
(from phase loop)

Ref. azimuth
(from master divider)

Act on f_{RF} of slave

Bunch should be here

Locked!