RF Systems

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CERN

CAS Basics of Accelerator Physics and Technology

11 May 2022

The CERN Accelerator School

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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 feedback
- Longitudinal beam control system
  - Global feedback
  - Phase and radial loops
- Summary

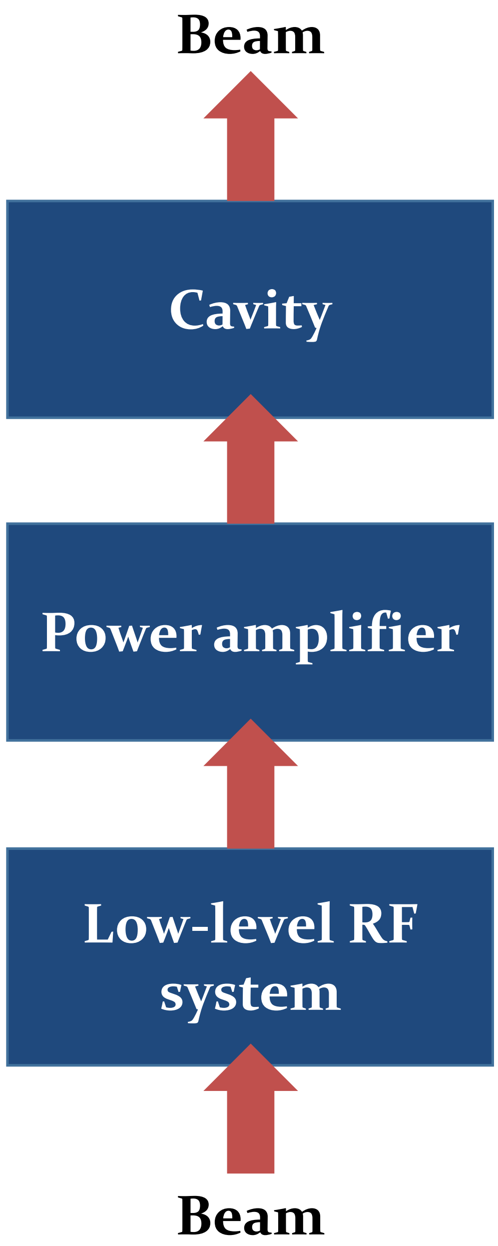
Introduction

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?

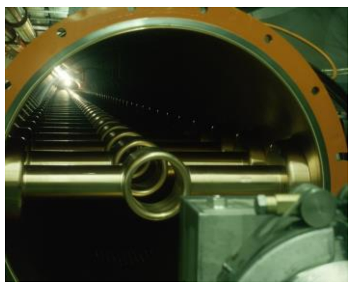
→ How are RF signals generated which make the beam feel comfortable?



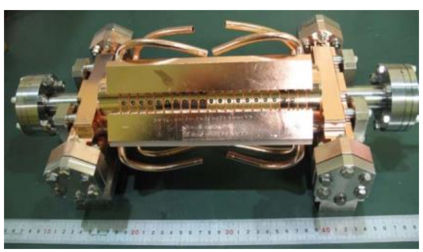
Frequency and wavelength ranges

PS longitudi-
nal 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

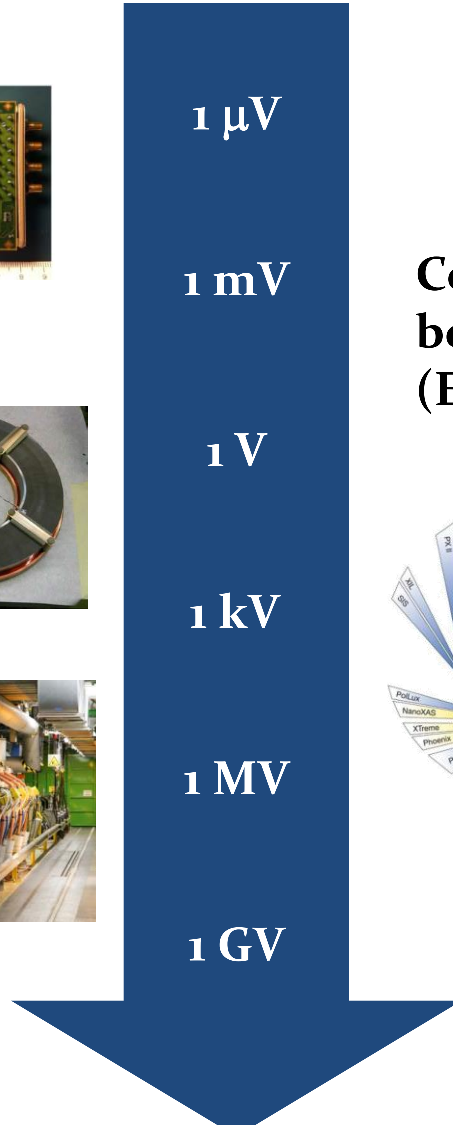
Long wave

Medium/
short wave

VHF

Microwave
links

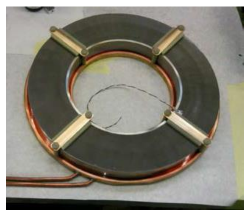
Amplitude ranges

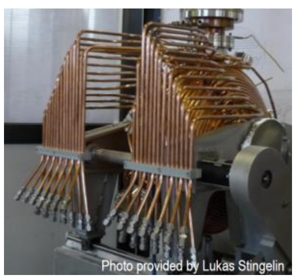


Signals from beam pick-ups

LLRF systems

Low/Medium energy hadron RF



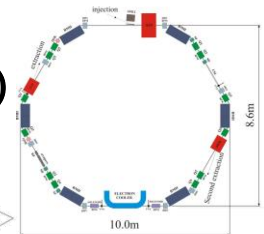


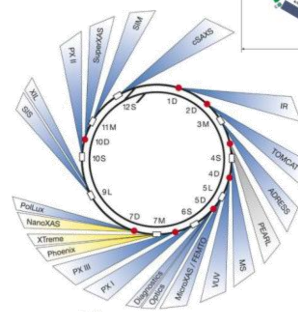
SLS

LHC: 16 MV

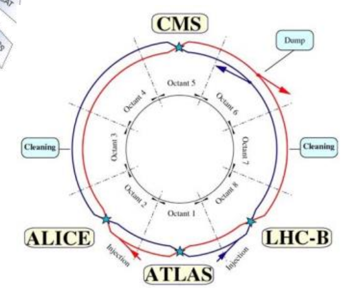
LEP: 3.6 GV total

Cooled hadron beams (ELENA)

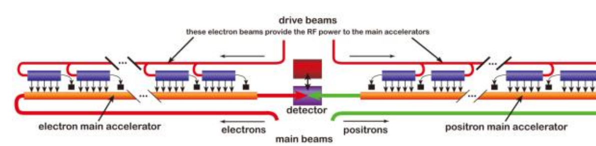




Electron light sources



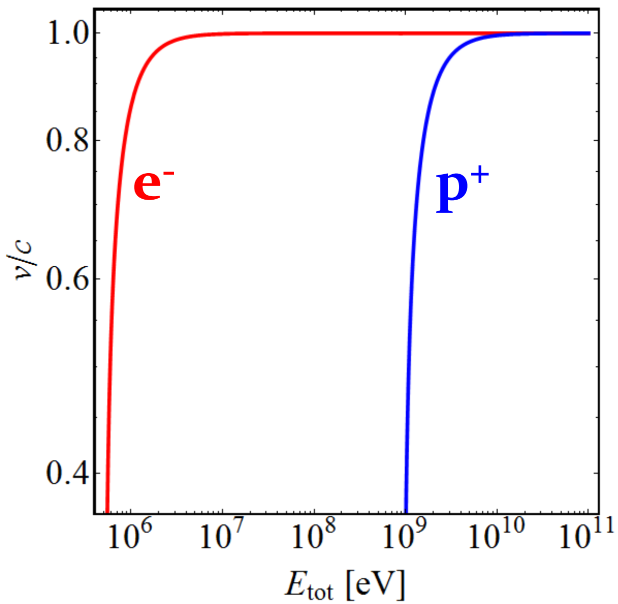
LHC

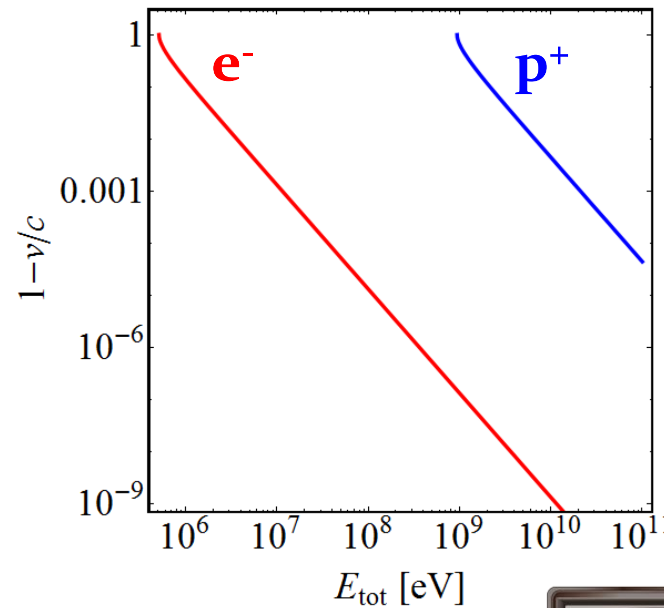


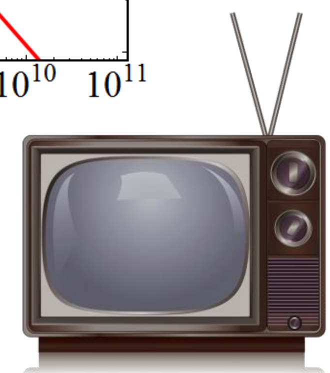
ILC and CLIC: several TV

Particle velocity

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





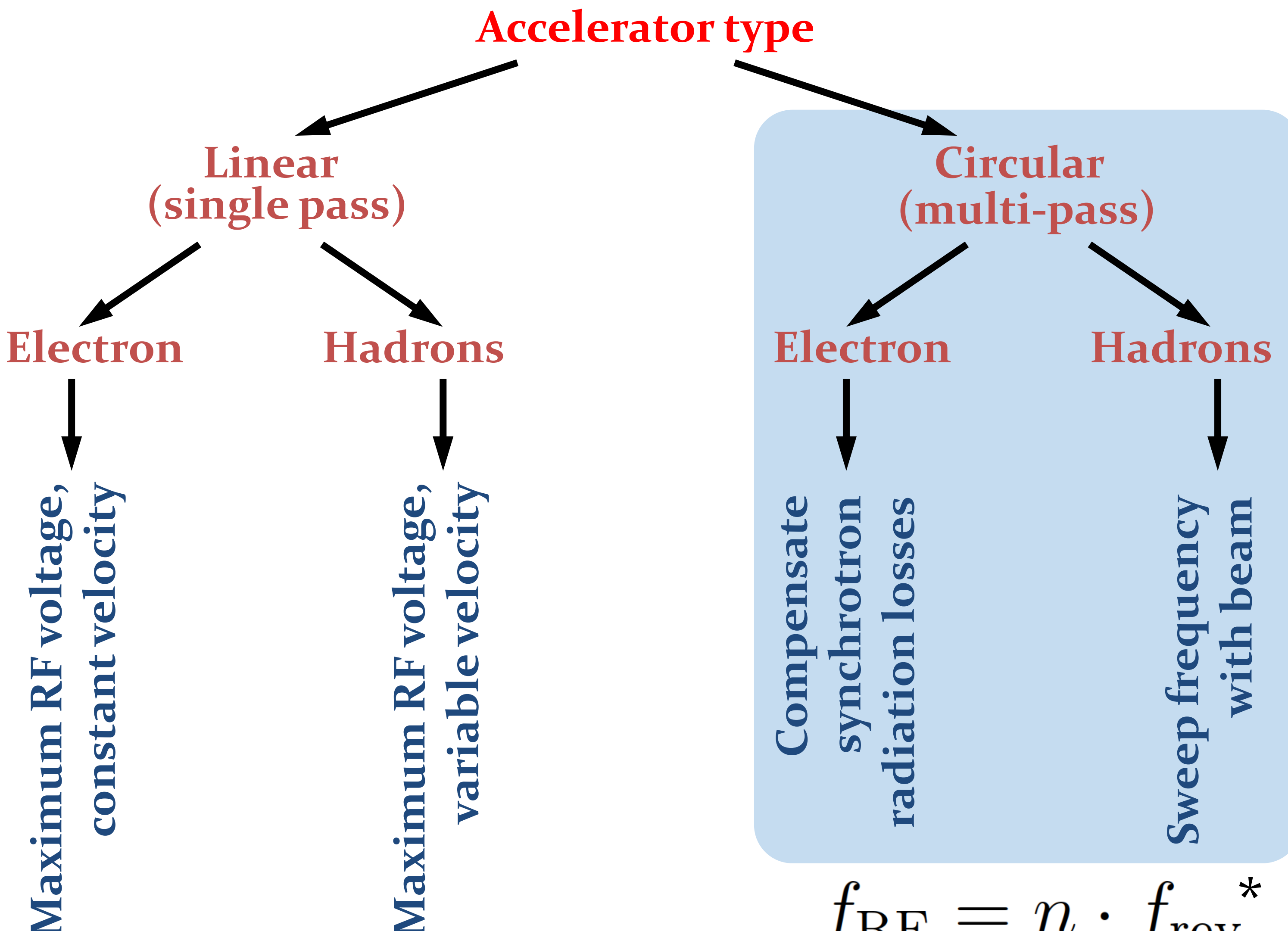


- **Old television set (30 kV):** **Electrons at 30% of c_0**
  Protons just at 0.7%
- **Small synchrotron (500 MeV): Electrons at 99.99995%**
  Protons at 75.8%

$\rightarrow$ **Most electron accelerators at 'fixed' frequency**

Parameter choices

RF system for high-energy accelerators



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

*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?

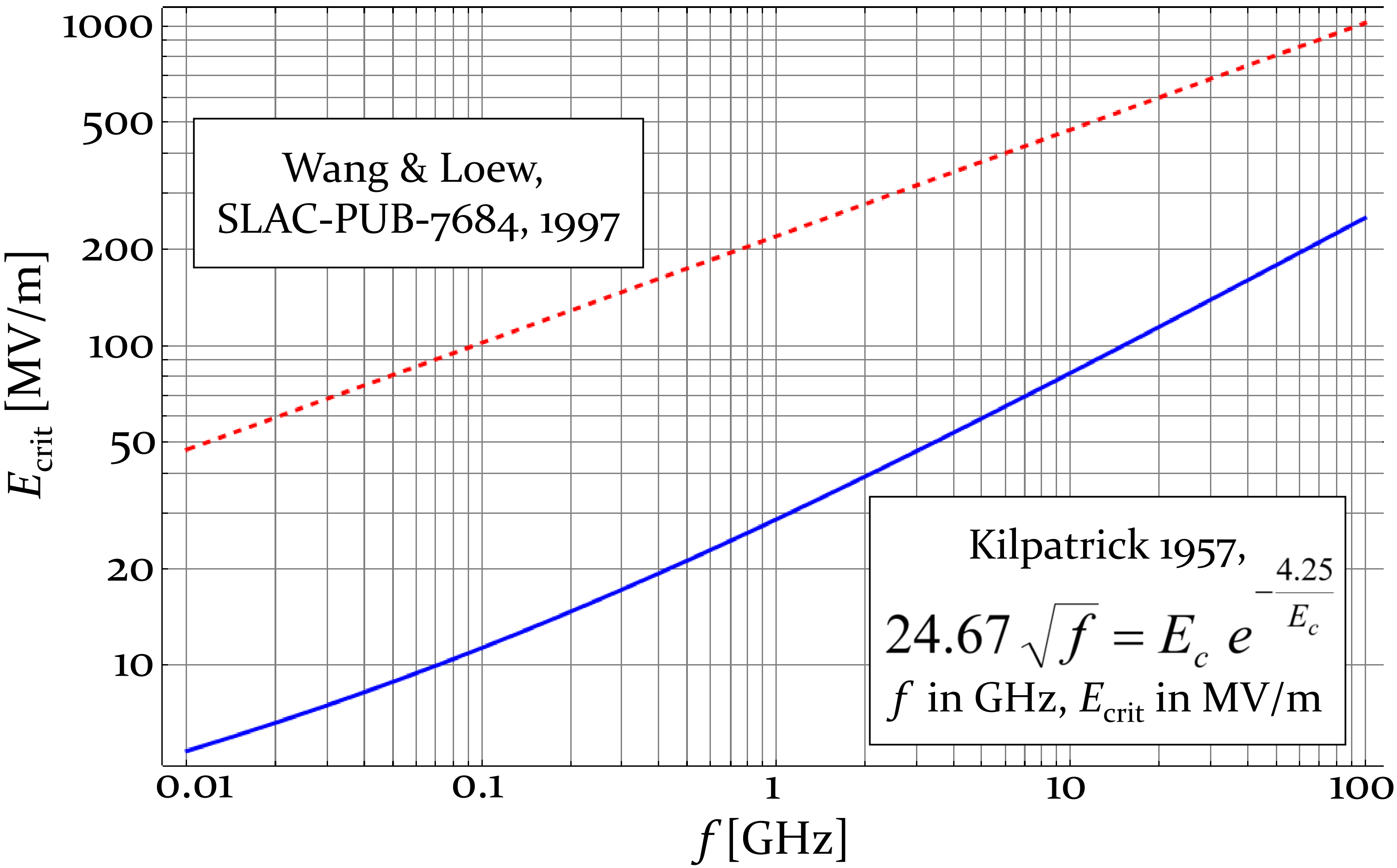
Advantages	Disadvantages
• Cavity size scales $\propto 1/f$, volume $\propto 1/f^3$ • Break down voltage increases • High gradient per length • Particle bunches are short	• Maximum beam available aperture scales $\propto 1/f$ • No technology for wide-band or tunable cavities • Power amplifiers more difficult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

E. Jensen

RF voltage

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)**

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

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

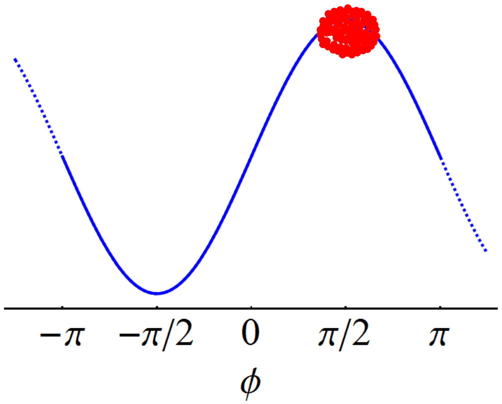
$\rightarrow (m_p/m_e)^4 = 1836^4 \sim 1.1 \cdot 10^{13}$ times less for protons

Minimum voltage requirement

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

$$qV = \Delta E$$

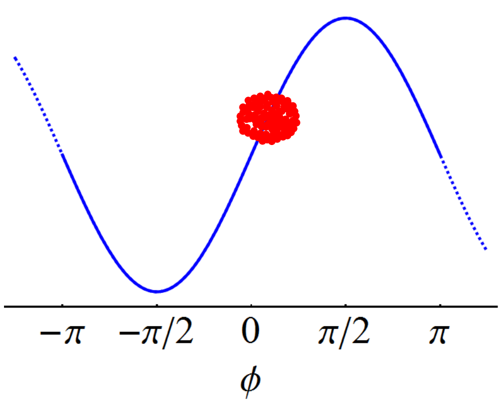
→ On-crest acceleration
→ Used in some linear accelerators
→ Insufficient in a circular accelerator



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

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

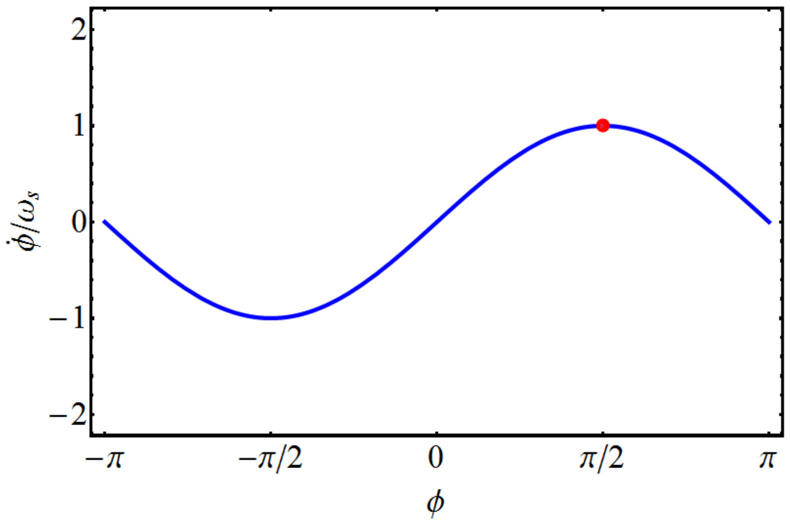
→ Off-crest acceleration
→ Needed for circular accelerator
→ Higher voltage for given energy gain



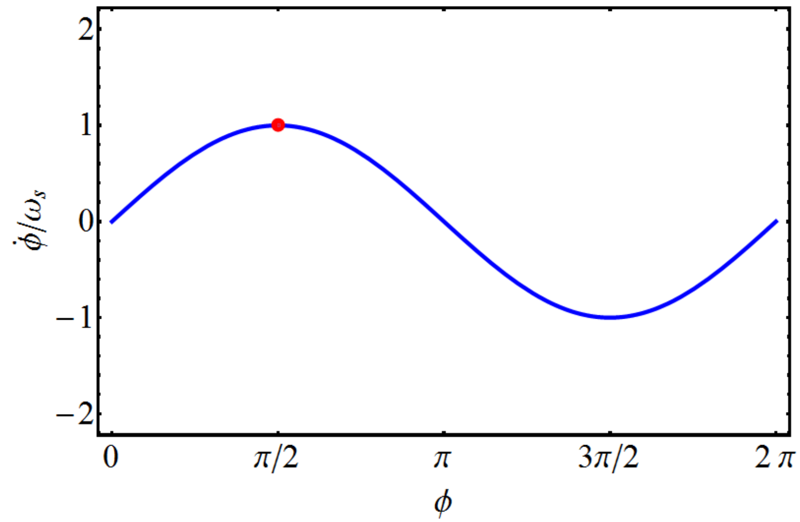
Bucket area dependence on stable phase

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

Below transition, ϕ_S = 0…90°

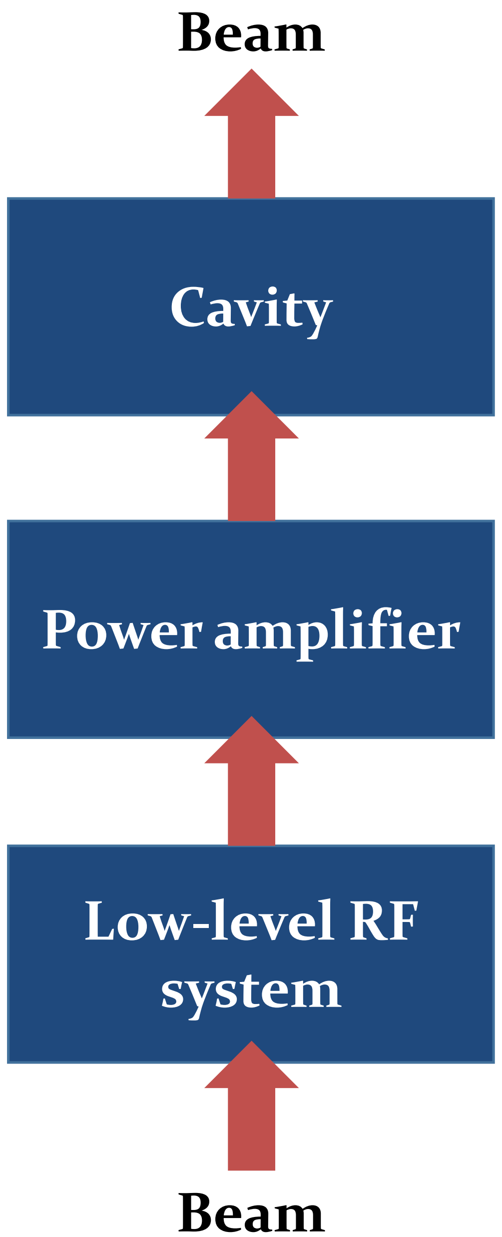


Above transition, ϕ_S = 90°…180°



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

RF system overview

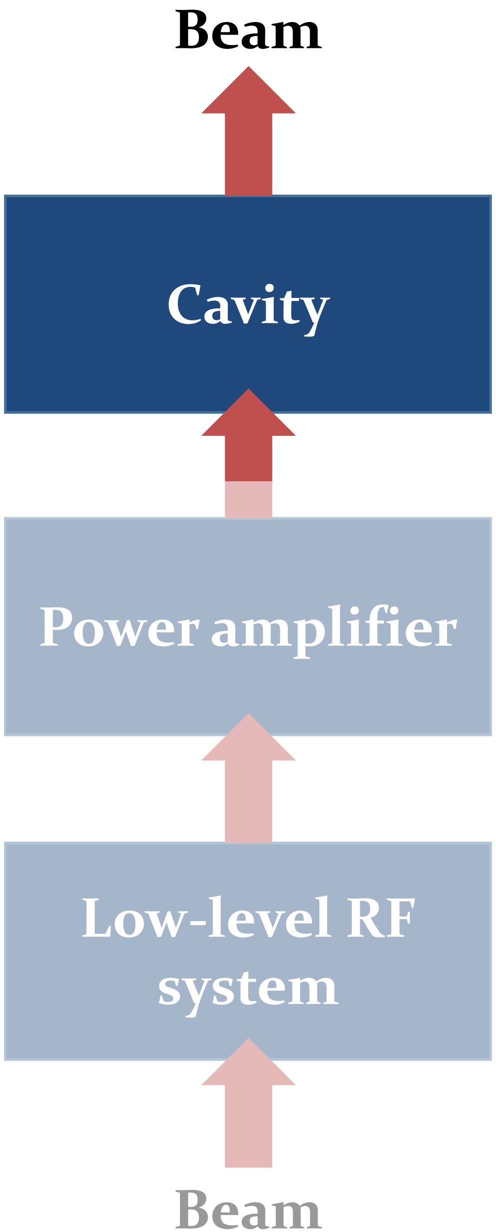


→ Convert RF power into longitudinal electric field

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

→ Provide RF signals with correct frequency, amplitude and phase

RF system overview



→ Convert RF power into longitudinal electric field

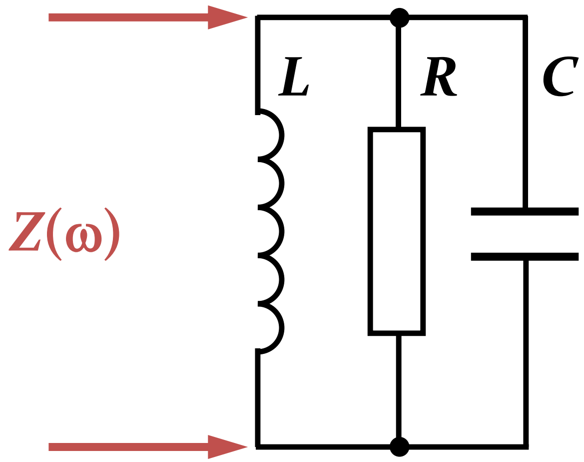
→ Amplify low-power signal from beam control to kW, MW or GW

→ 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 $$\omega_0 = \frac{1}{\sqrt{LC}}$$

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

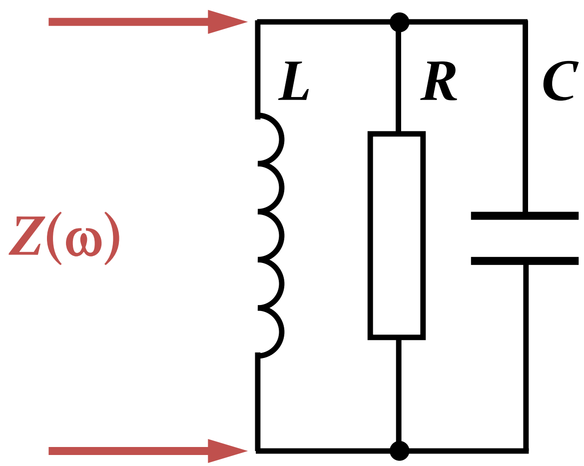
$$E = \frac{1}{2} C V^2 = \frac{1}{2} L I^2$$

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

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

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

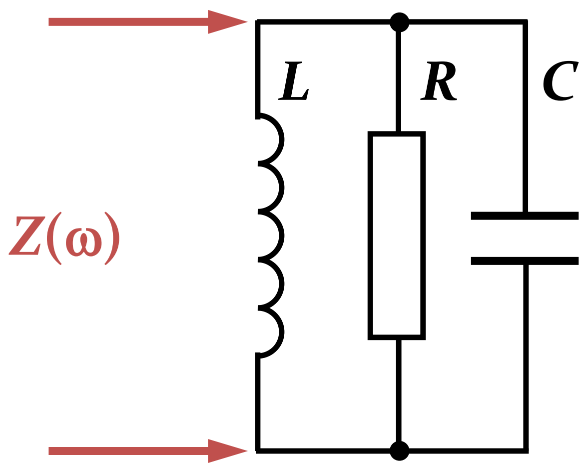
$$Q = \omega_0 RC = \frac{R}{\omega_0 L}$$

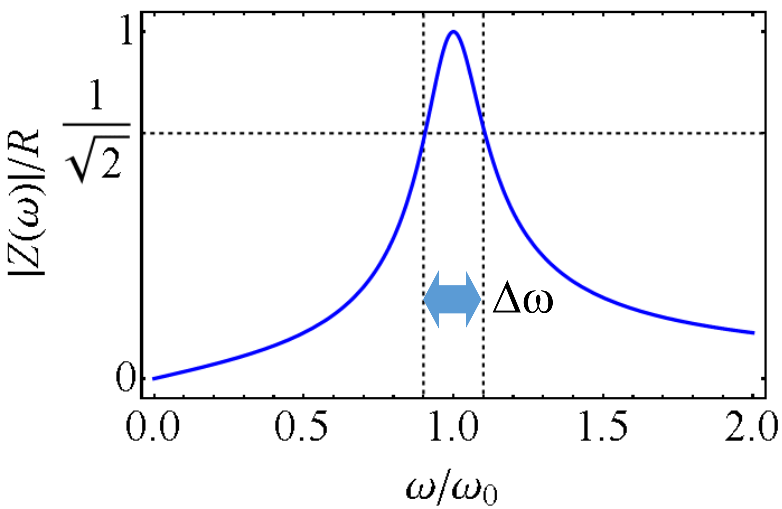
$$Z(\omega) = \frac{R}{1 + iQ\left(\frac{\omega^2 - \omega_0^2}{\omega\omega_0}\right)} \simeq \frac{R}{1 + 2iQ\frac{\Delta\omega}{\omega_0}}$$

→ **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***





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

→ **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?**

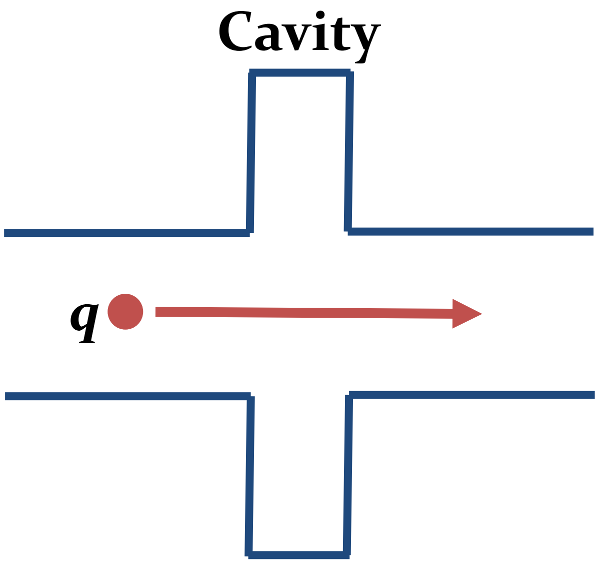
- **Resonance frequency, ω_o**
  - → **Exactly defined for given application, e.g. hf_{rev}**

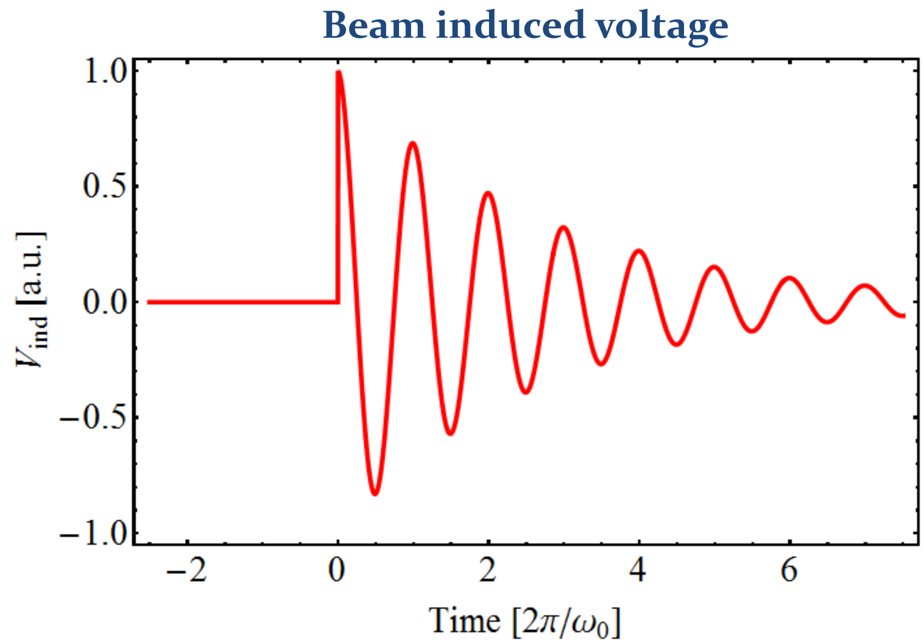
- **Shunt impedance, R**
  - → **Power required to produce a given voltage without beam**

- **"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**





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

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

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

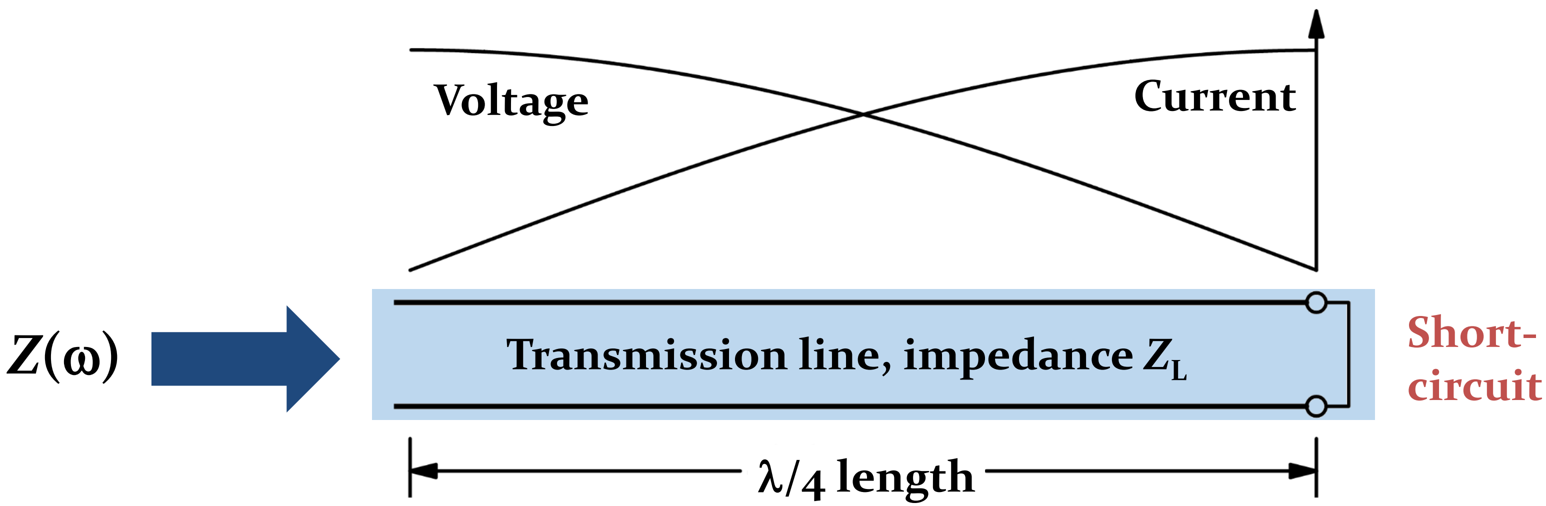
→ **Cavity geometry with small *R*/*Q* to reduce beam loading**

RF cavities in low frequency range

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

→ Would need huge cavities → too large for accelerators

→ Line resonators: λ/4 resonator



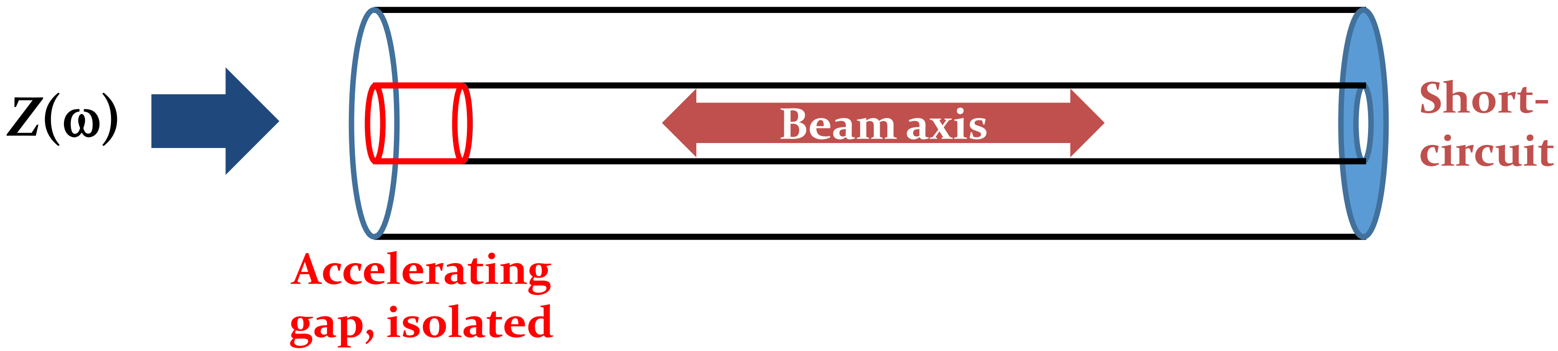
→ Short circuit on one side → Voltage is zero

→ Open end on other → No current but voltage

Why is this resonator so common in particle accelerators?

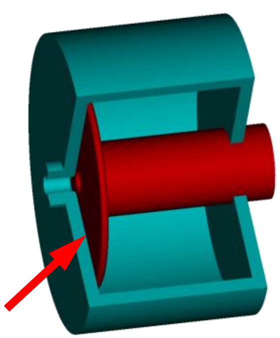
RF cavities in low frequency range

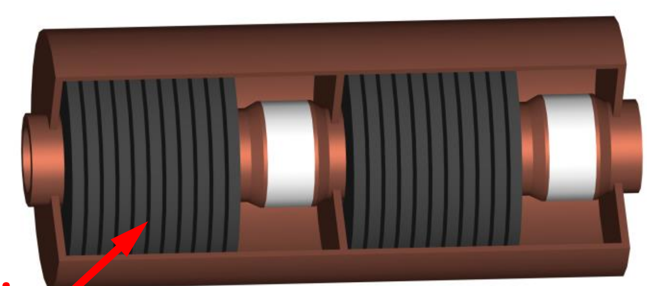
- Coaxial structure with inner conductor as beam pipe



→ Still rather long geometry, 7.5 m at 10 MHz

→ Add capacitive or inductive shortening

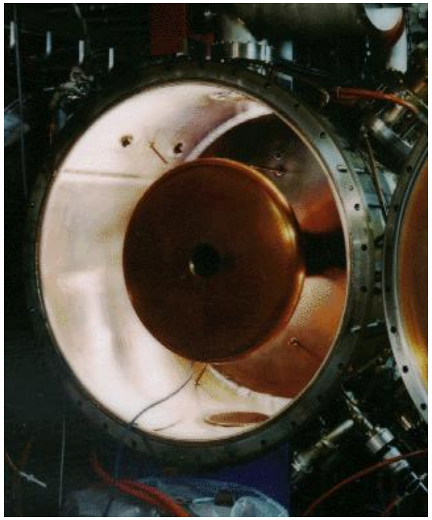




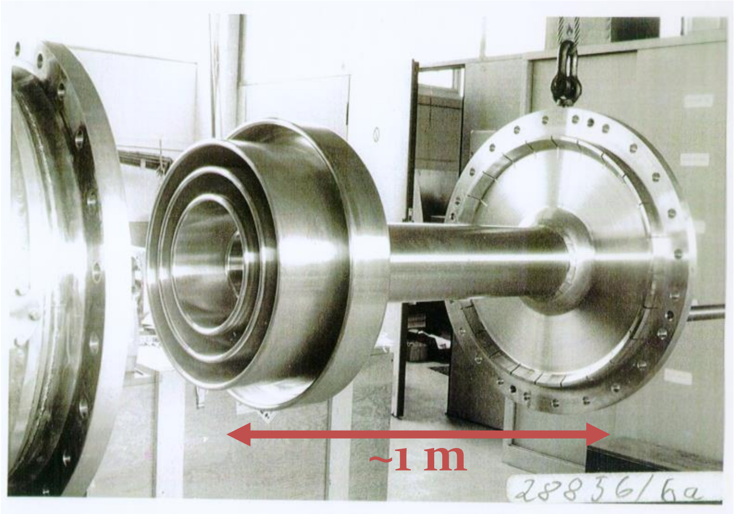
Capacitive loading

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

NSLS, 52.88 MHz



DESY PIA, 10.4 MHz, inner cond.



Outer cond.

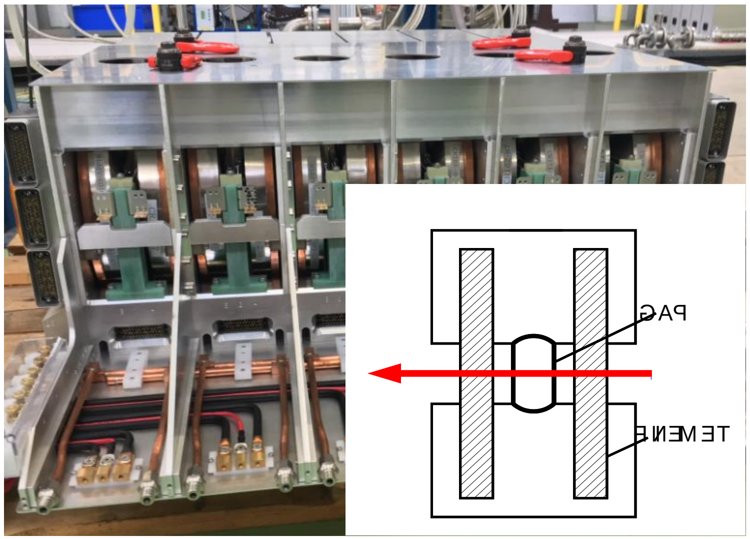
M. Nagl

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

Inductive loading

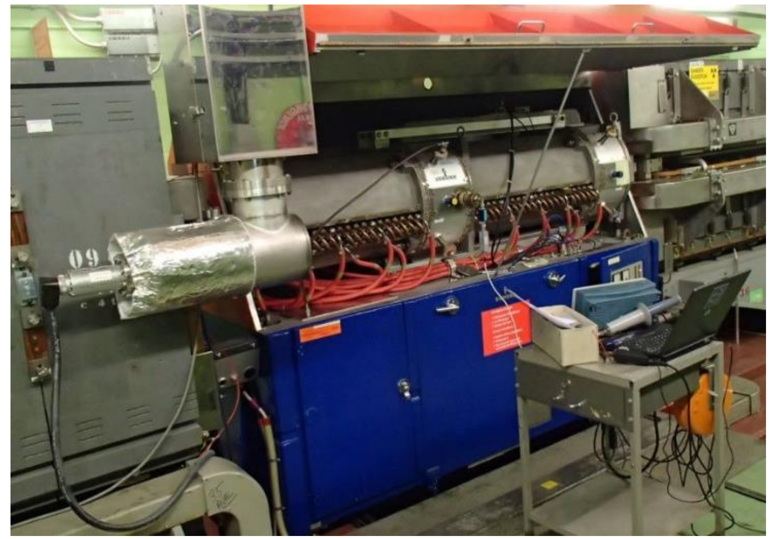
→ **Inductive loading with magnetic material shortens resonator from tens of meters to a device, lossy though**

CERN PSB Finemet cav., 0.6-18 MHz



M. Paoluzzi

CERN PS, double gap, 2.8-10 MHz



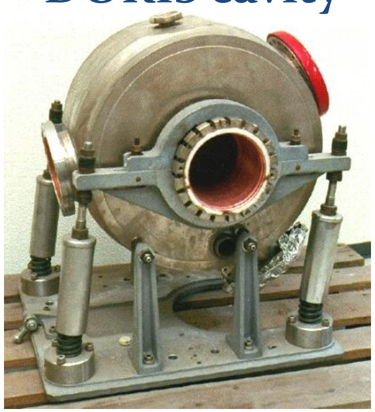
- **Additional advantage: permeability of ferrite can be controlled by DC bias current → variable inductivity**
  - → **Cavity with programmable resonance frequency**
  - → **Essential for hadron acceleration in low-energy accelerators**

Further increase frequency

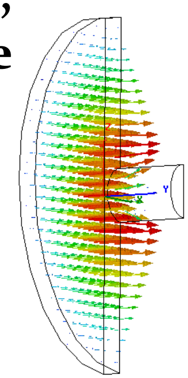
→ **Remove inner conductor from coaxial set-up**

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

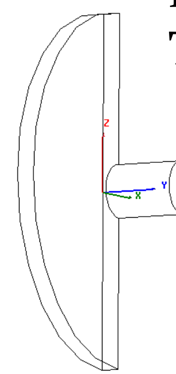
DORIS cavity



Electric field, TM_{010}-mode



Magnetic field, TM_{010}-mode



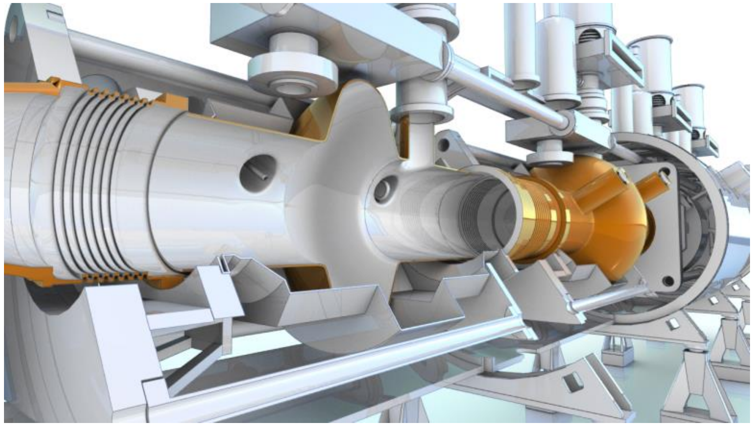
E. Jensen

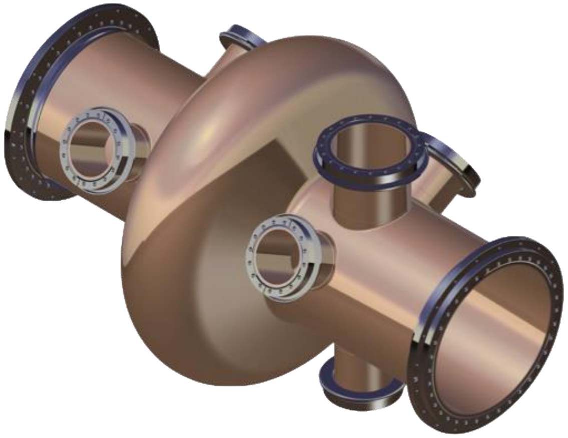
→ **The basis for cavity resonators**

Example: 400 MHz cavities in LHC

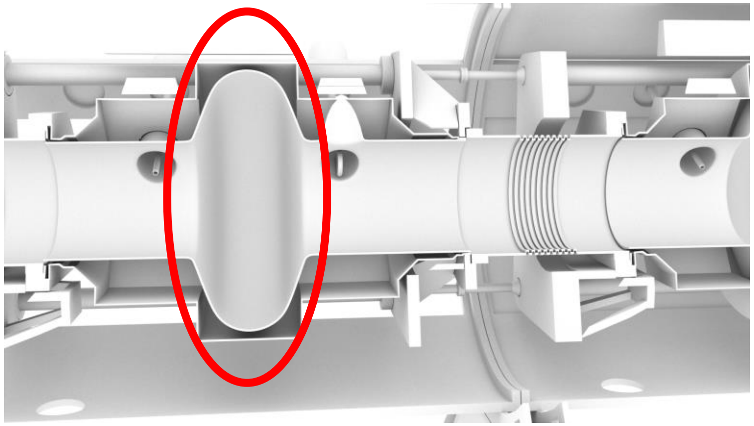
→ Reduce beam loading in RF cavities

→ Shunt impedance, *R*, low for small *R*/*Q* with normal conducting cavities → superconducting cavities in LHC





Bell shape: *R*/*Q* ~ 44 Ω, 400 MHz



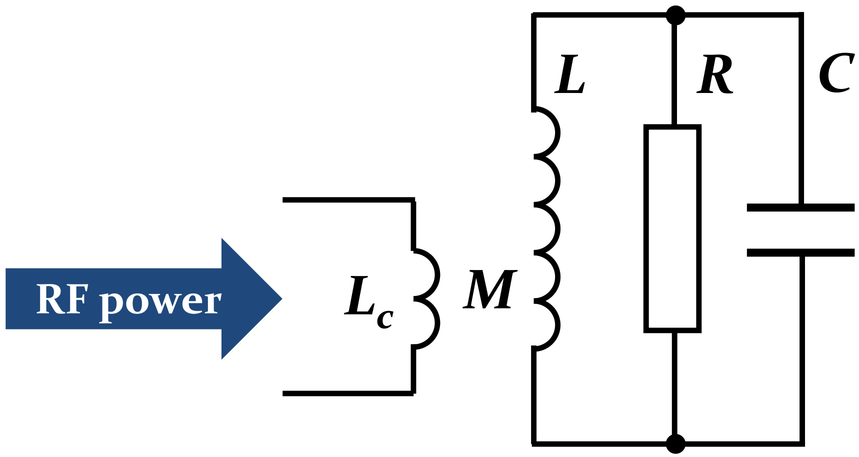
→ 2×8 cavities, 5.3 MV/m

→ 16 MV/beam

Coupling power into a cavity

Coupling power into a cavity magnetically

- Attack inductivity or capacitance of resonator, or combined



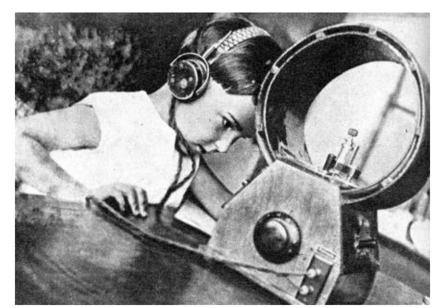
$$\frac{1}{Q} = \frac{1}{Q_{\mathrm{cav}}} + \frac{1}{Q_{\mathrm{ext}}}$$

→ Coupling loop forms transformer with resonator inductivity

L. Stigelin

- Main coupler PSI cyclotron

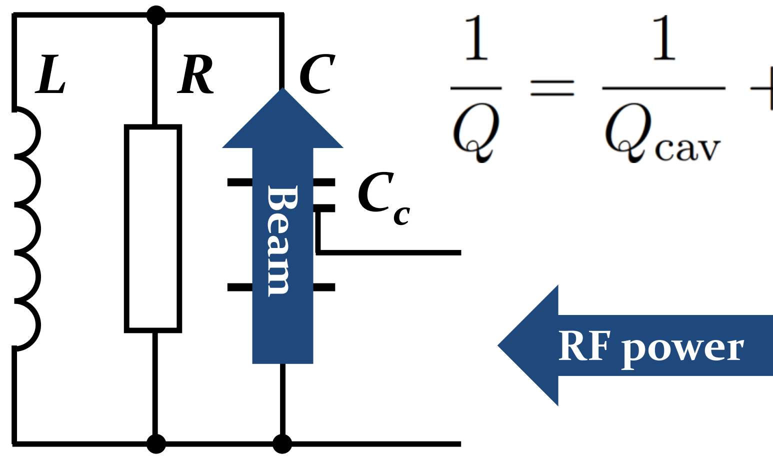
→ ~1 MW at 50 MHz



A. Rodchenko

Coupling power into a cavity electrically

- 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

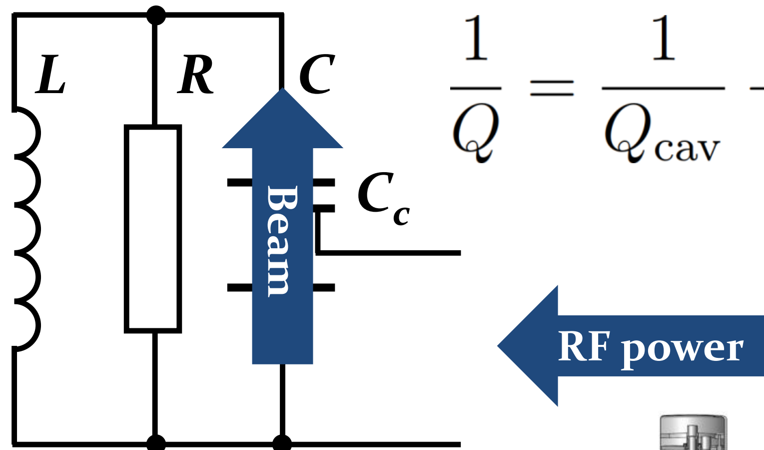
→ Beam also couples capacitively via the gap

Coupler of CERN PS 40 MHz

→ Coupler forms one half of capacitor with the gap

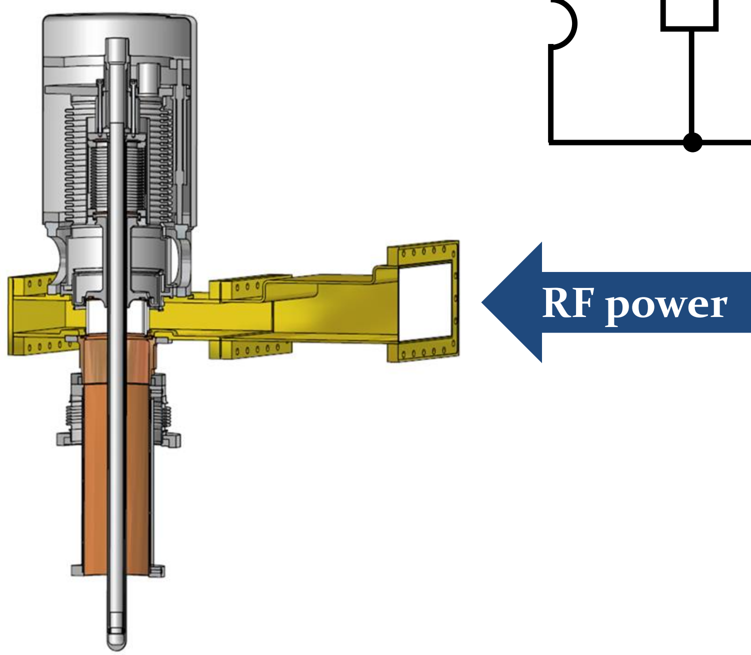
Coupling power into a cavity electrically

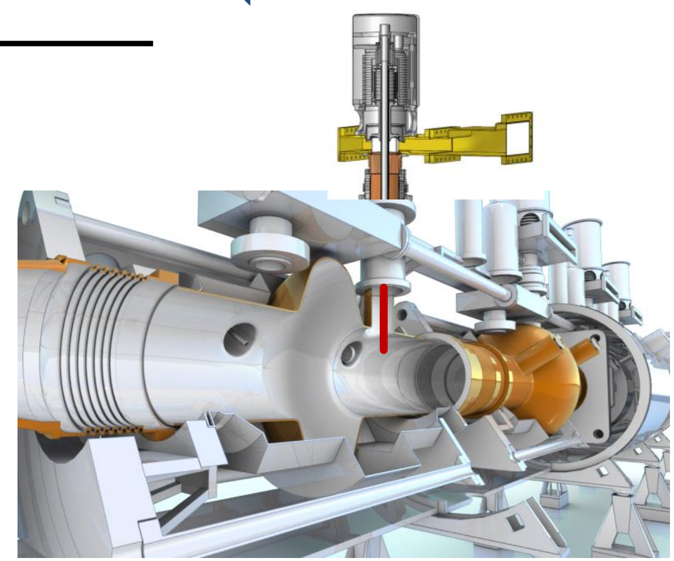
- **Attack inductivity or capacitance of resonator, or combined**



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

300 kW power coupler of LHC 400 MHz cavities

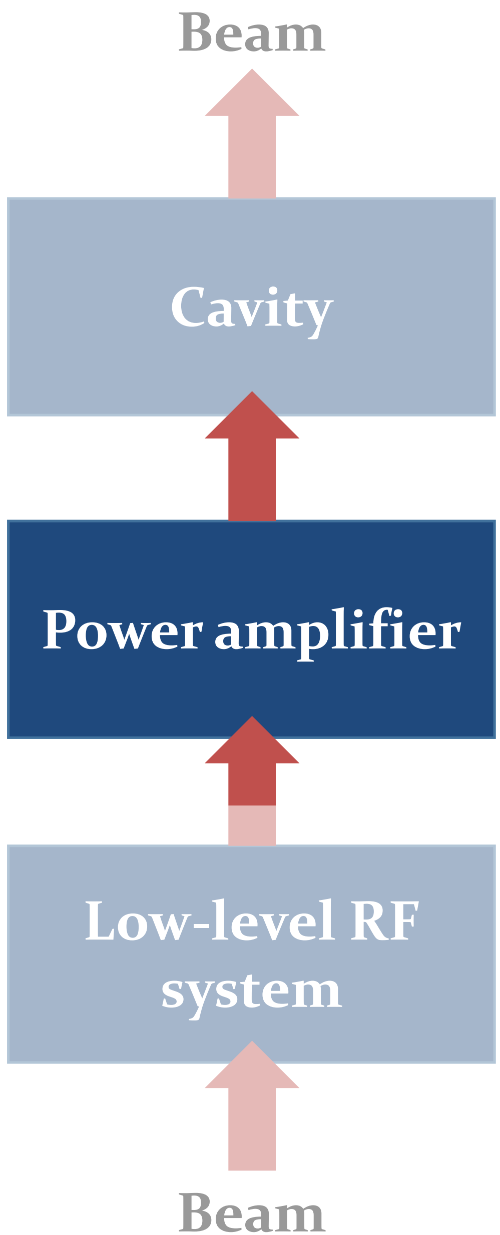




→ **Coupler antenna transmits directly into the cavity**

→ **Most common electrical coupler**

RF system overview



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

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

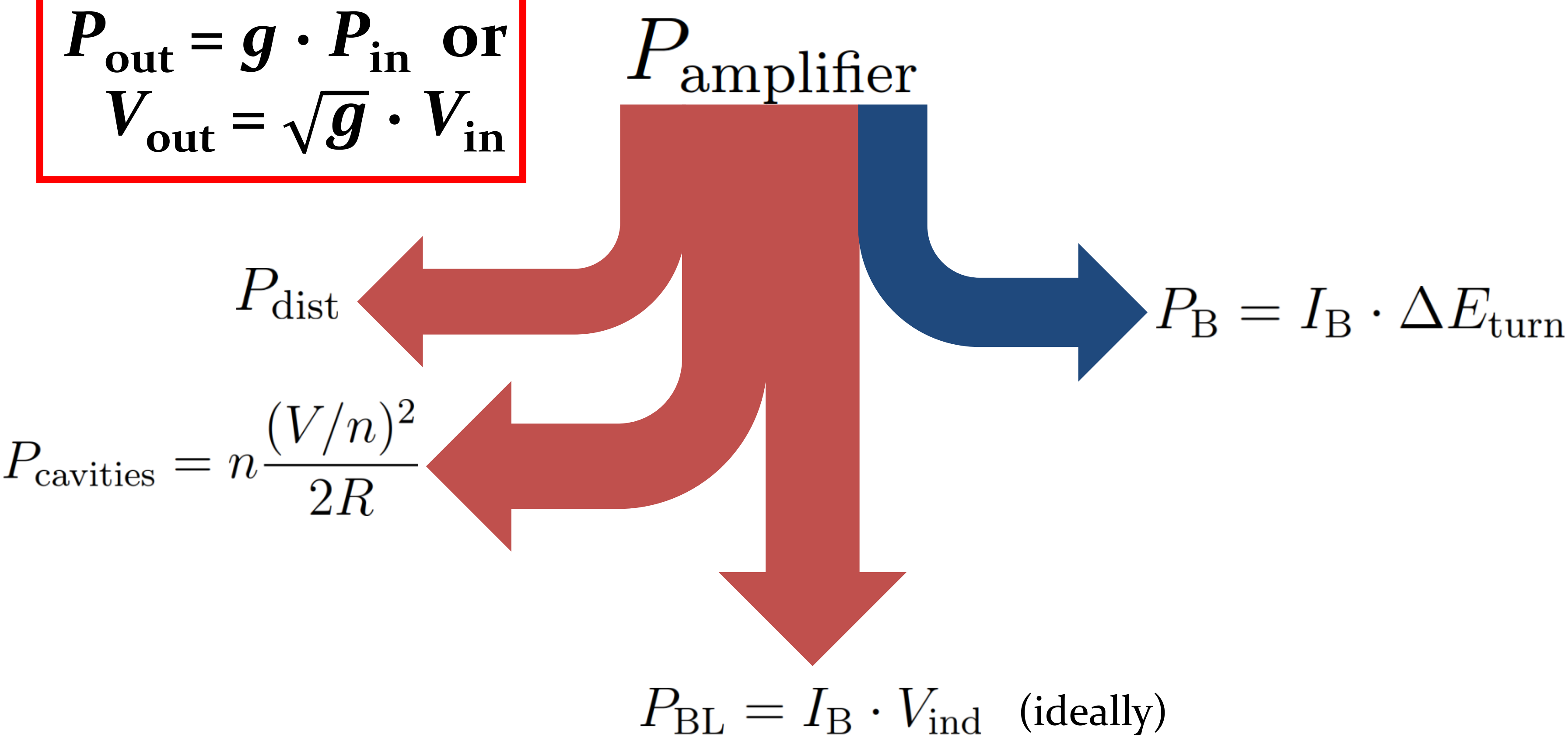
→ **Provide RF signals with correct frequency, amplitude and phase**

Power amplifiers

How much power is required?

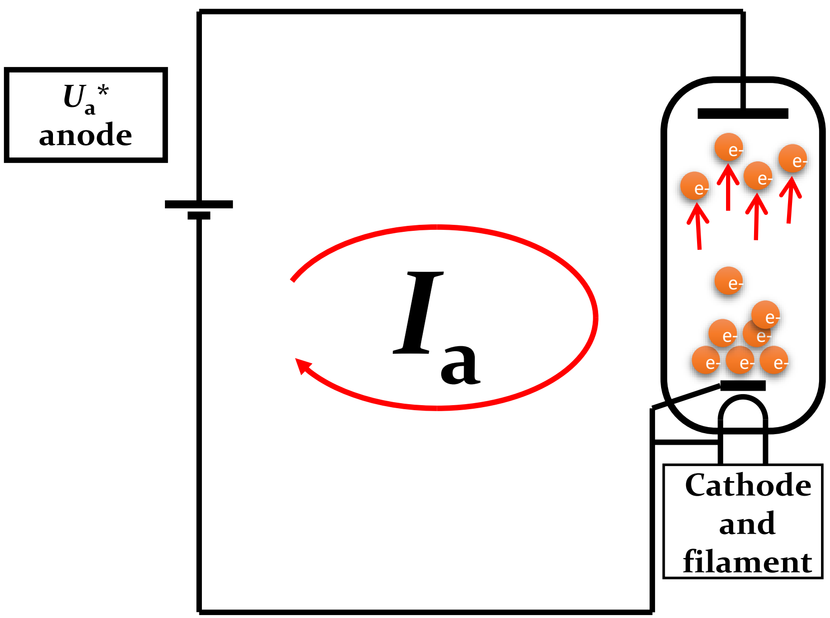
1. **Power to accelerate beam** → Wanted
2. **Compensate beam-induced voltage** → Refl. P
3. **Compensate electrical losses in cavity** → Heat
4. **Compensate electrical losses in distribution** → Heat

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



Basics of grid tube

- **From diode to tetrode amplifier**



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

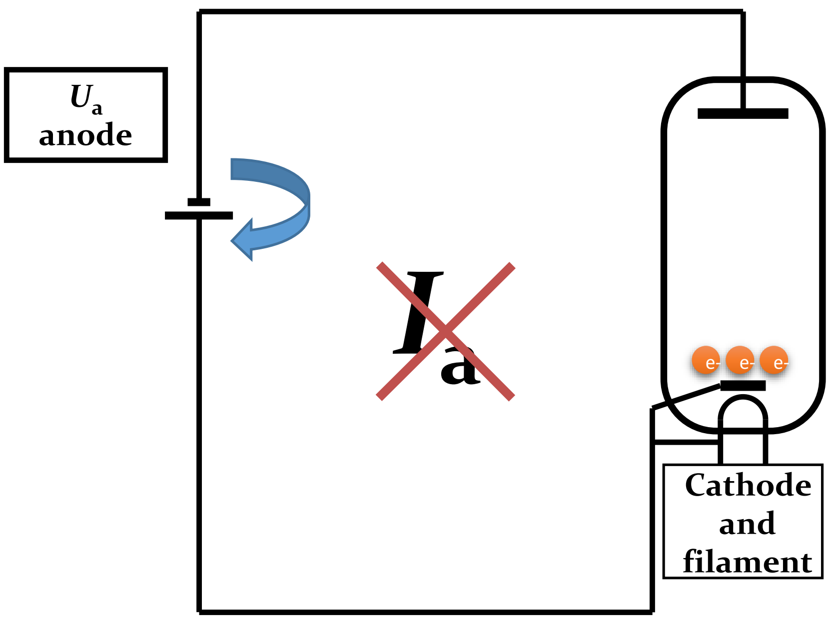
→Diode

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

E. Montesinos

Basics of grid tube

- From diode to tetrode amplifier



- Vacuum tube
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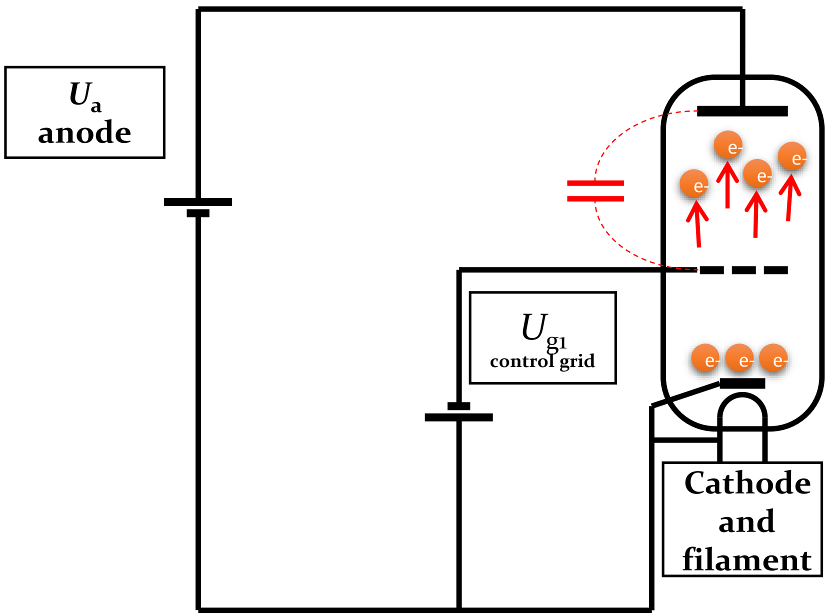
→ Diode

Basics of grid tube

- From diode to tetrode amplifier



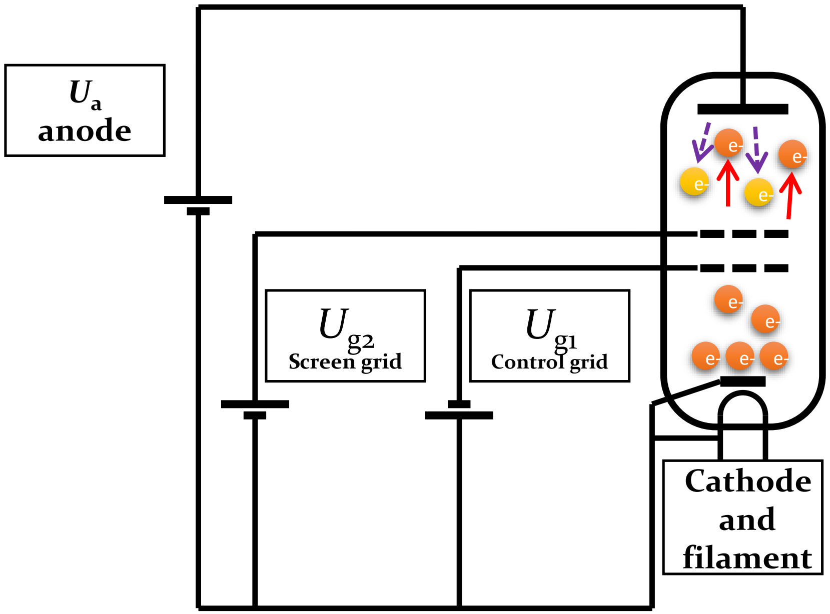
→Triode

- 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

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

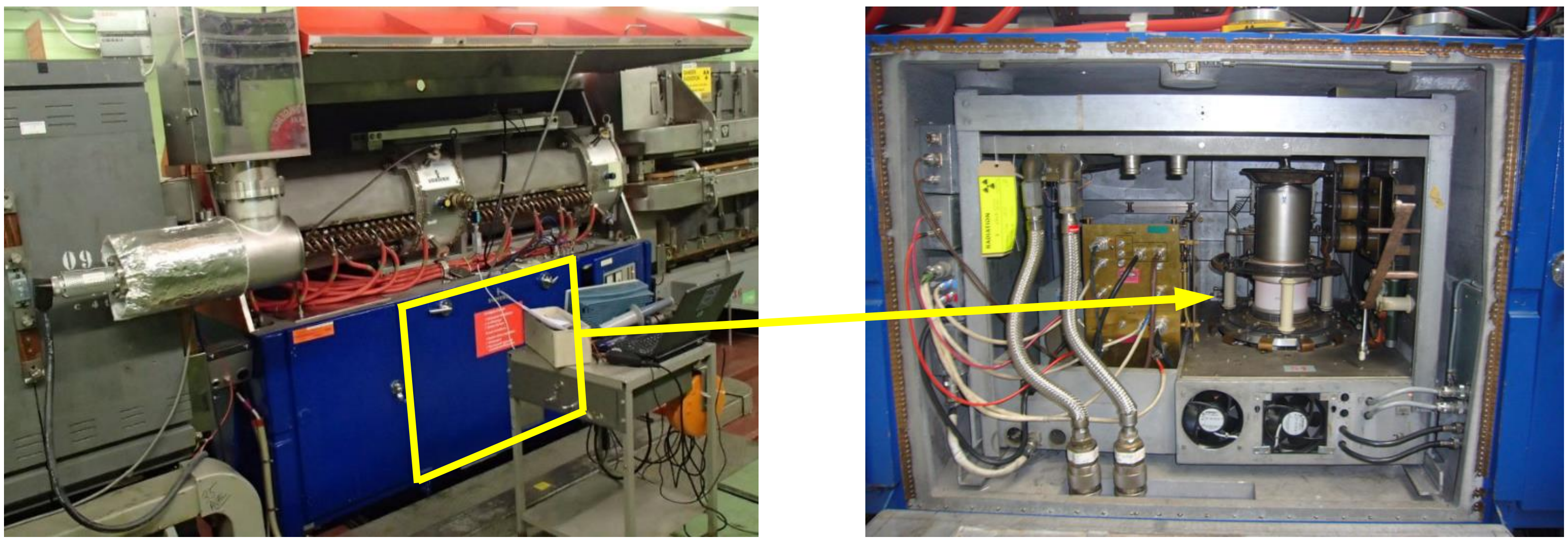
→ In operation since 1976

E. Montesinos

Tetrode amplifier driving PS RF

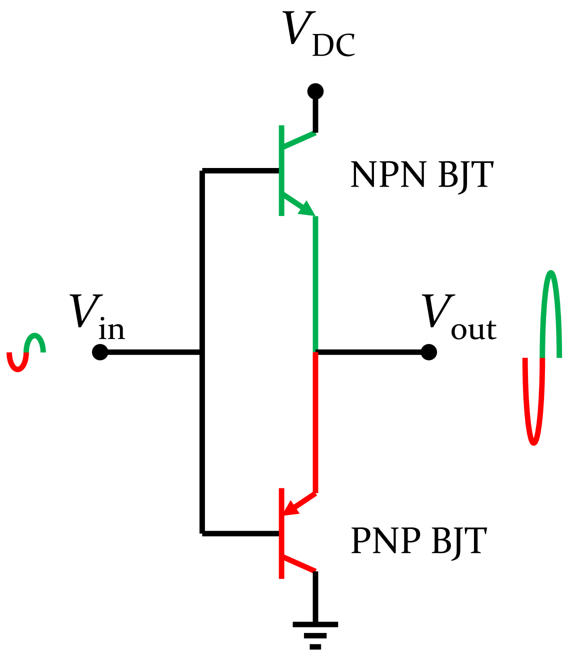
- → **Frequency range 2.8…10 MHz, ~60 kW per cavity, 11 units**
- → **Space constraints to have amplifier installed below cavity**

Amplifier trolley



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

Basics of RF solid state amplifiers



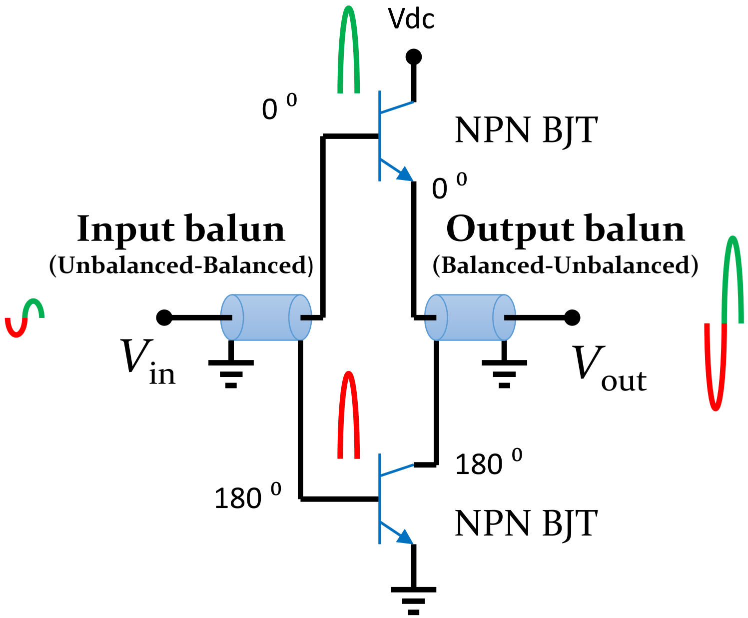
BJT: Bipolar Junction Transistor

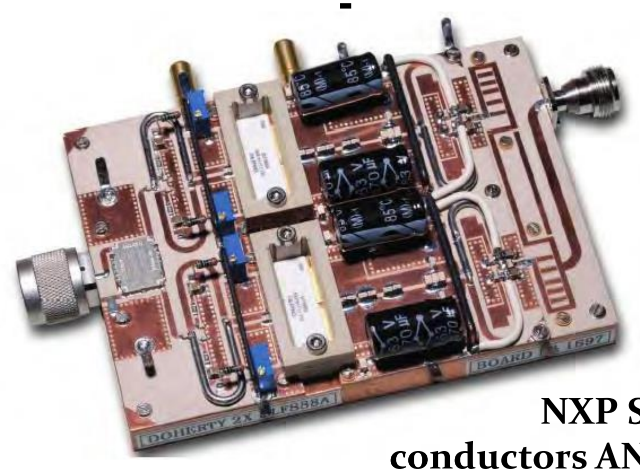
- **In a push-pull circuit the RF signal is applied to two devices**
  - **One of the devices is active on the positive voltage swing and off during the negative voltage swing**
  - **The other device works in the opposite manner so that the two devices conduct half the time**

  →The full RF signal is then amplified

→Needs two different type of devices

Basics of RF solid state amplifiers





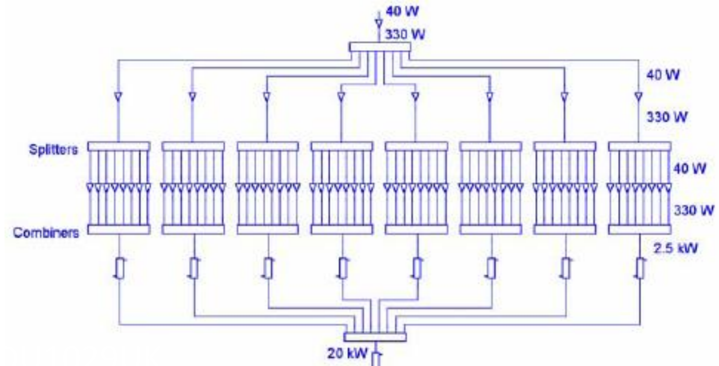
NXP Semi-
conductors AN11325
2-way Doherty amplifier with BLF888A

- **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**

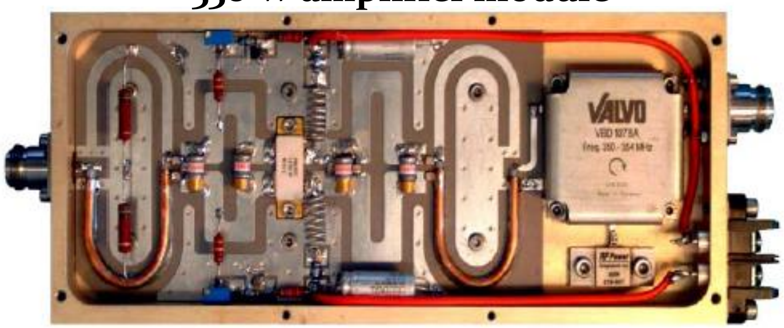
→This configuration is easier to manufacture since only one type of device is required

Example: Soleil 45 kW, 352 MHz

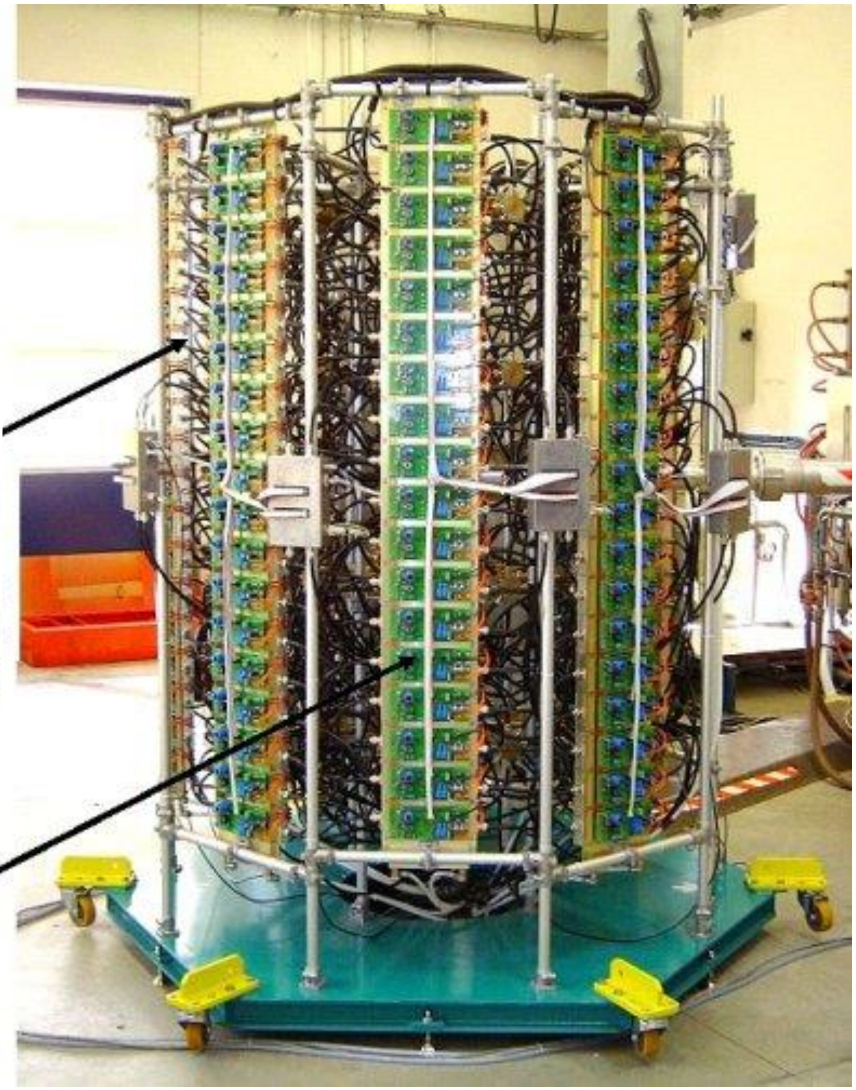
Electron storage ring running at 352 MHz



330 W amplifier module

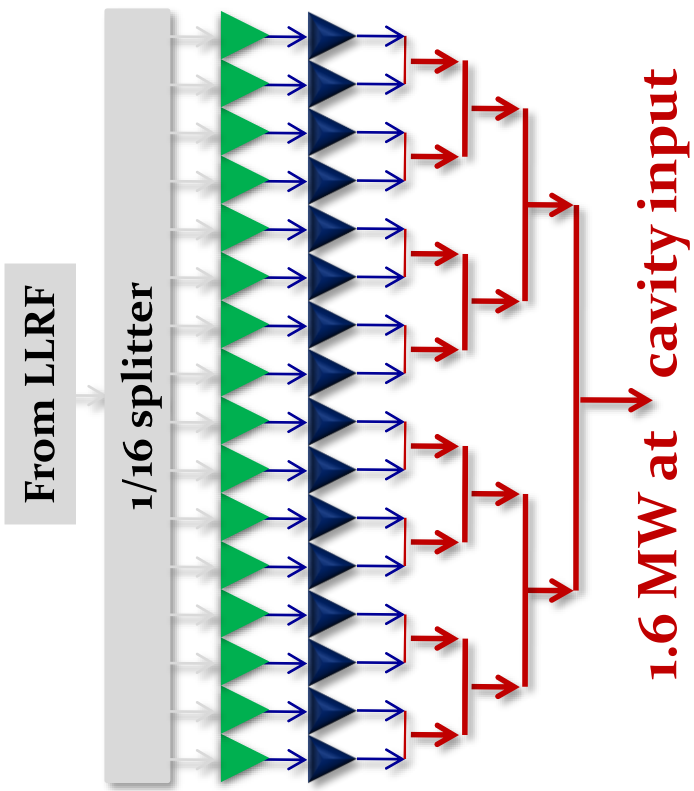


600 W, 300 V_{DC}/30 V_{DC} converter



Example: 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**

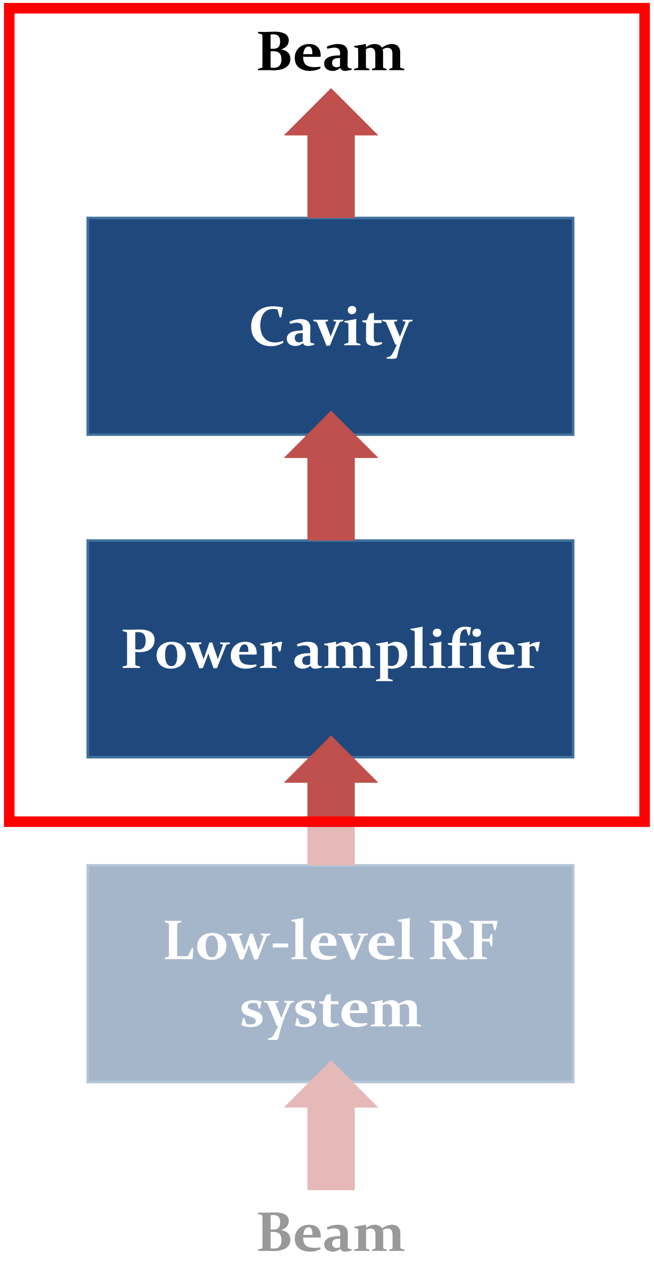
E. Montesinos

How to choose the right RF amplifier?

Prefer tube amplifier, when	Prefer solid-state amplifier, when
• 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

RF system overview



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

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

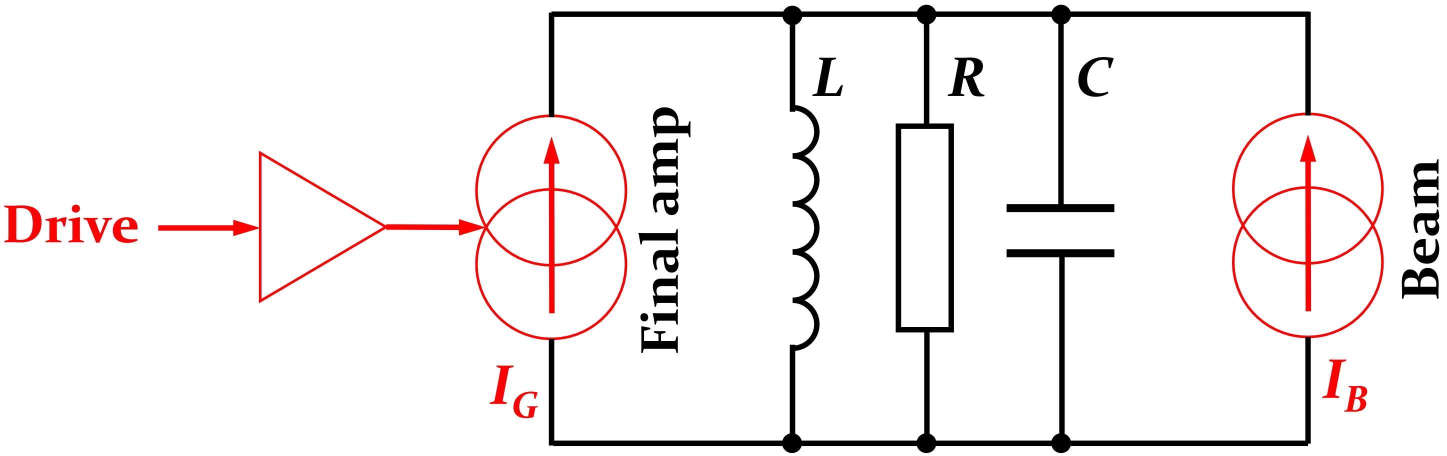
→ **Provide RF signals with correct frequency, amplitude and phase**

Local feedback

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 → 

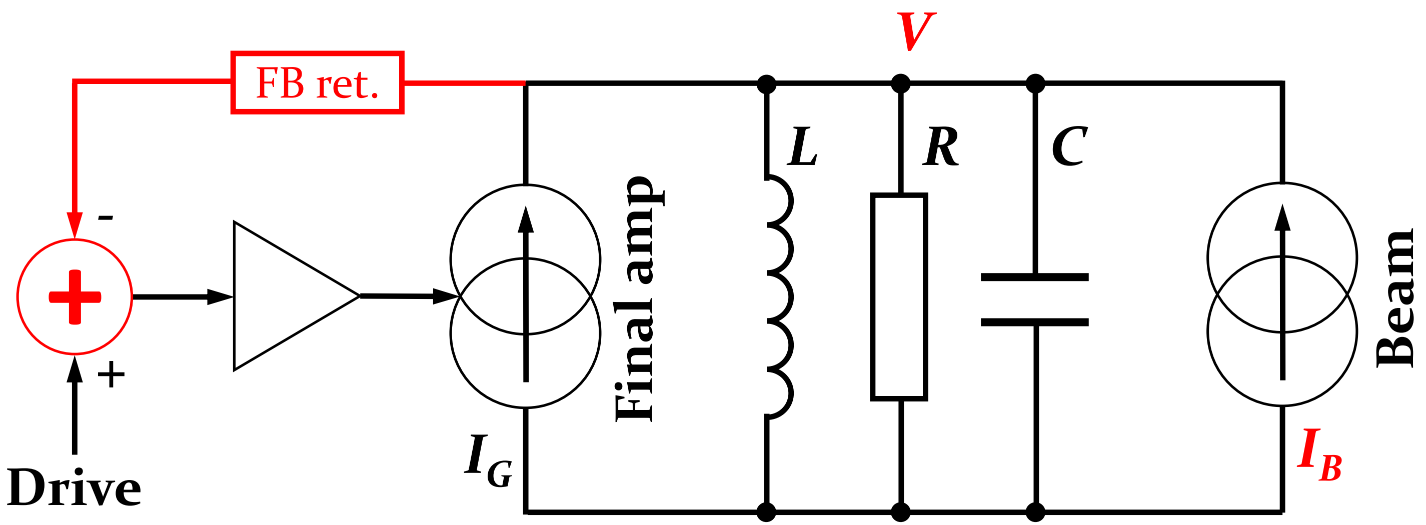
2. Feedback to decrease the apparent impedance for the beam

   → 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

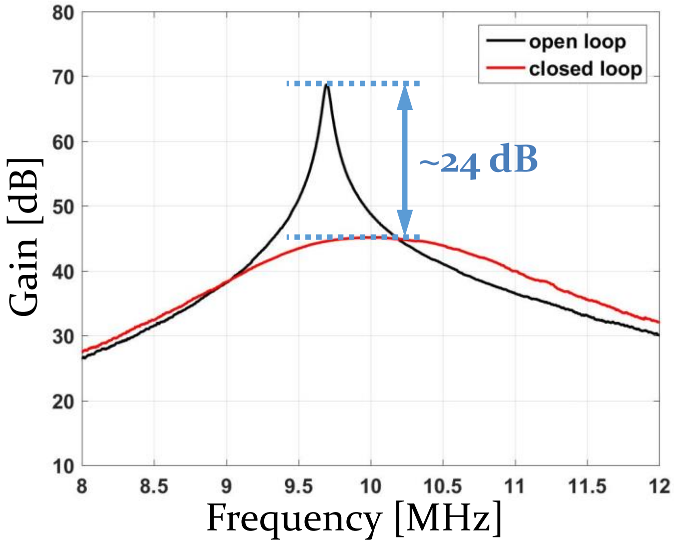


1. Compare drive signal (no beam) with gap (beam and generator)
2. Amplify inverted difference

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

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, $Z(\omega)$**

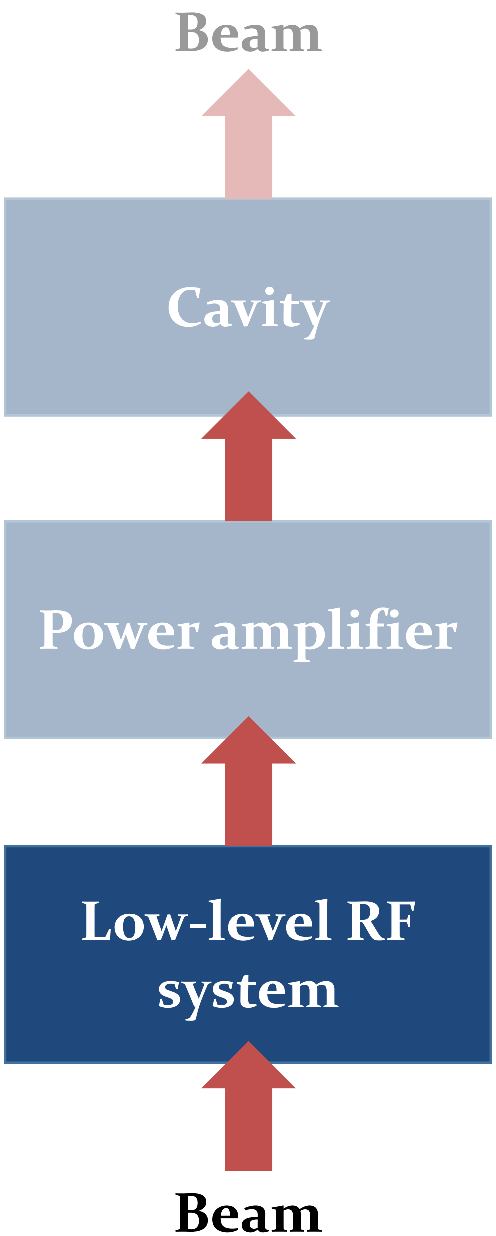
Why not further reduction with more gain?

- **Subtraction of gap voltage and drive signal imperfect due to**
  1. **Delay of cables and amplifier**
  2. **Resonances**

Bandwidth ↑ ↔ Achievable gain ↓

→ **Additional narrow-band filter feedback at $n \cdot f_{rev}$**

RF system overview



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

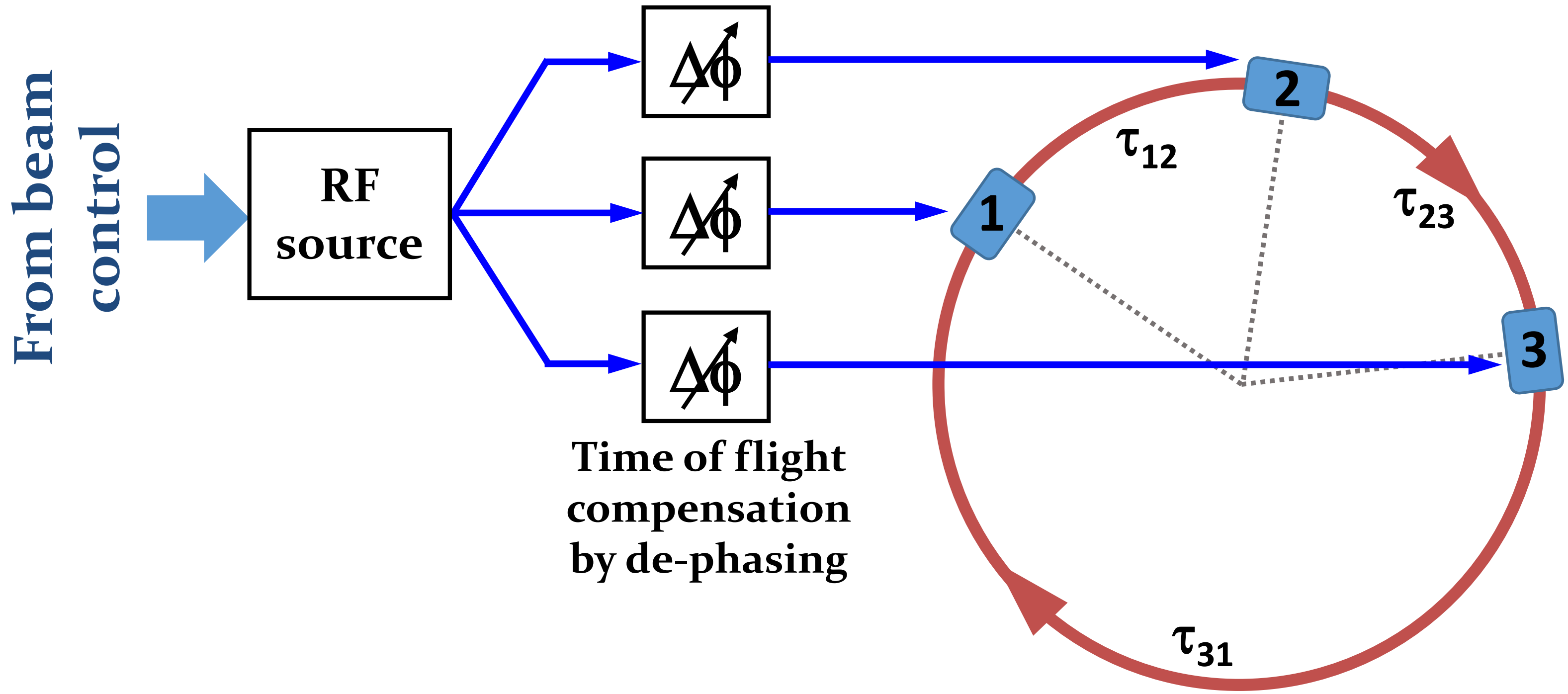
→ **Amplify low-power signal from beam control to kW, MW or GW**

→ **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

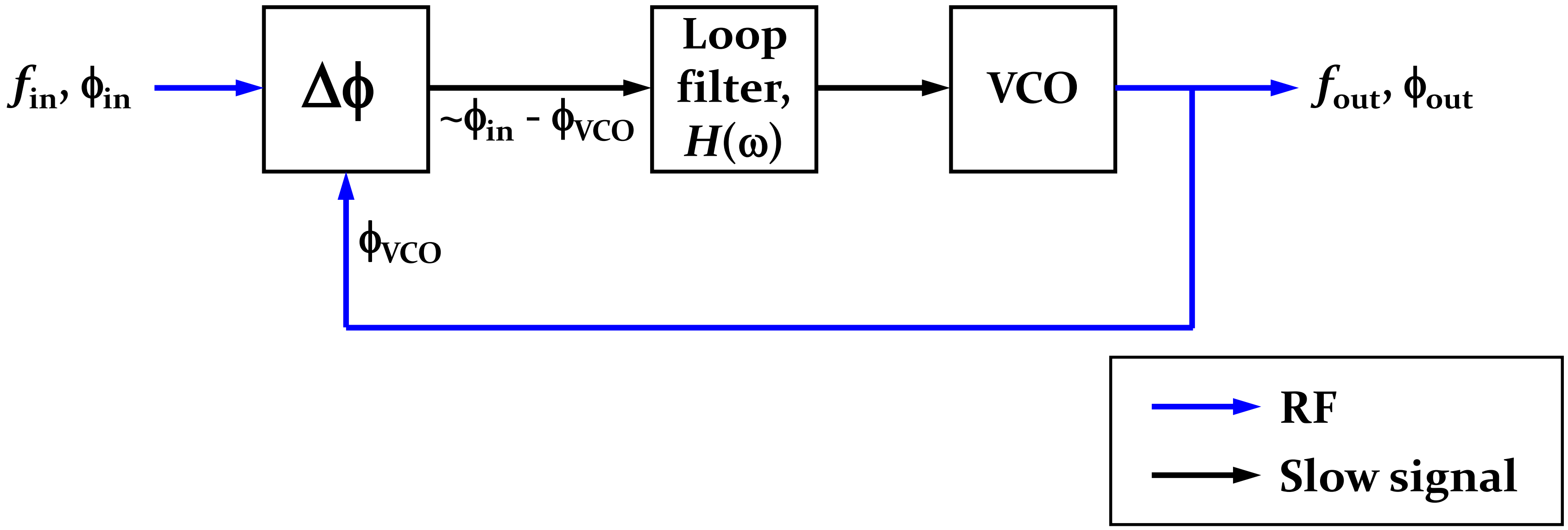
→ Beam control drives all stations like a single one

Fast bunch tracking: Beam phase loop

Electronic phase-locked loop

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

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



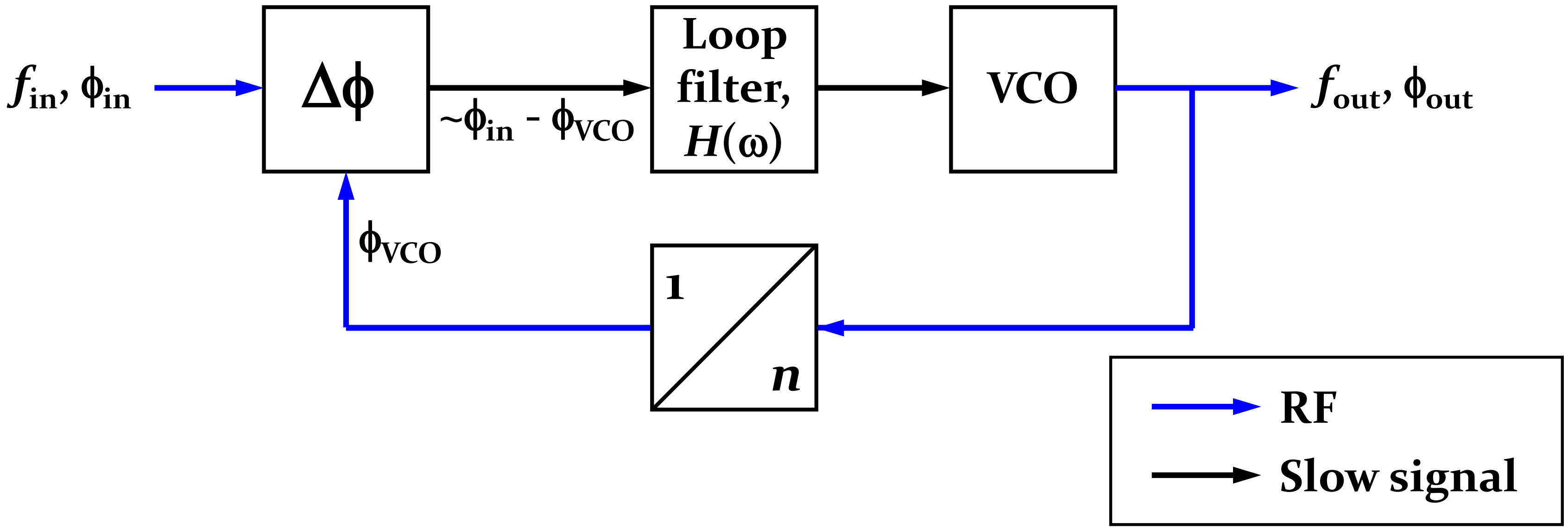
→ **Fixed phase relationship:** $\phi_{out} - \phi_{in} = \text{const.}$

→ **Locked frequencies:** $f_{out} = f_{in}$

Electronic phase-locked loop

- **Lock two signals: frequency re-generation and multiplication**
- **Voltage controlled oscillator (VCO) locked in phase to input**

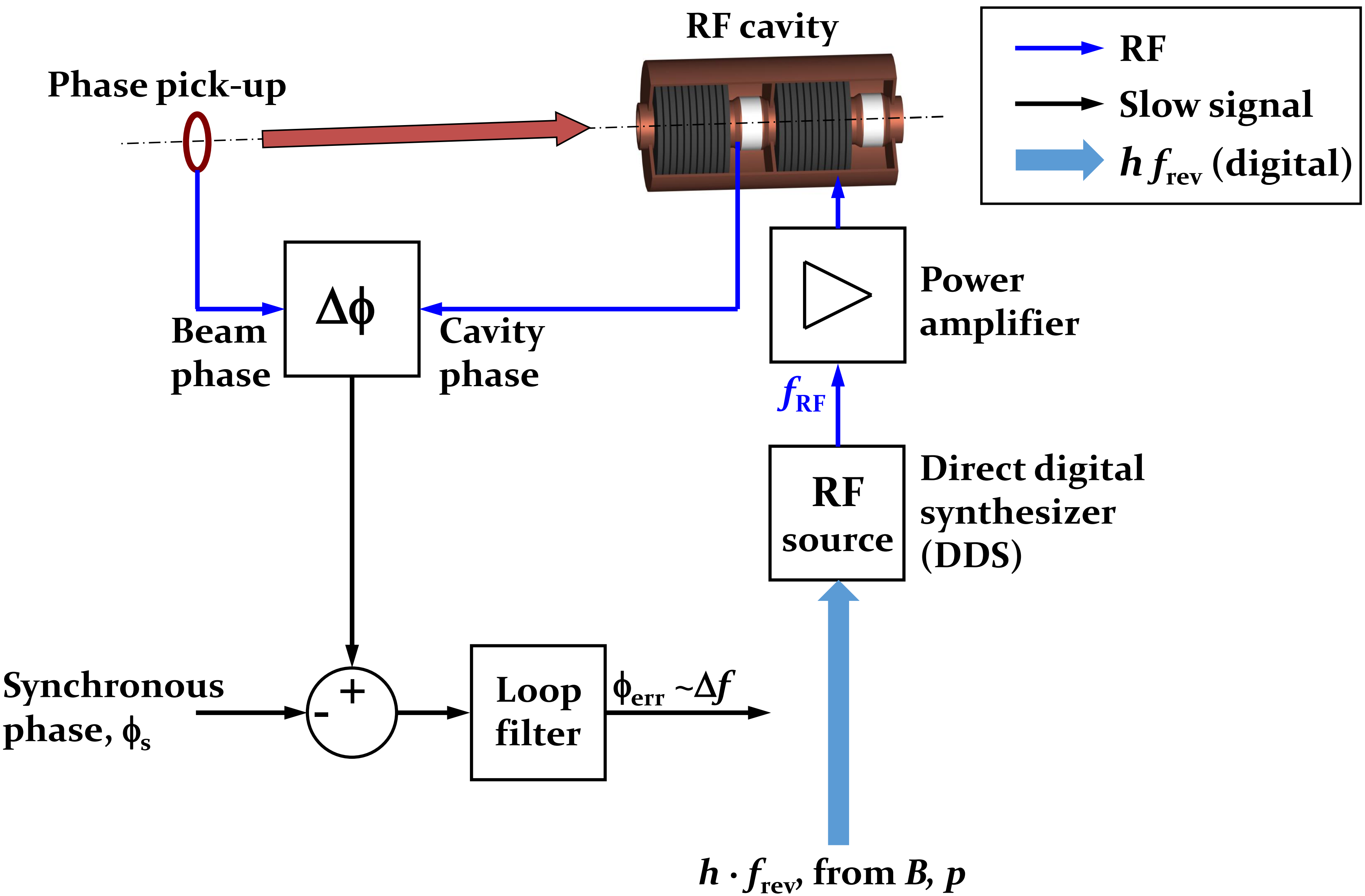
$$\omega_{\mathrm{VCO}} = 2\pi f_{\mathrm{VCO}} = \frac{d\phi}{dt} = K_{\mathrm{VCO}} V_{\mathrm{in}}$$



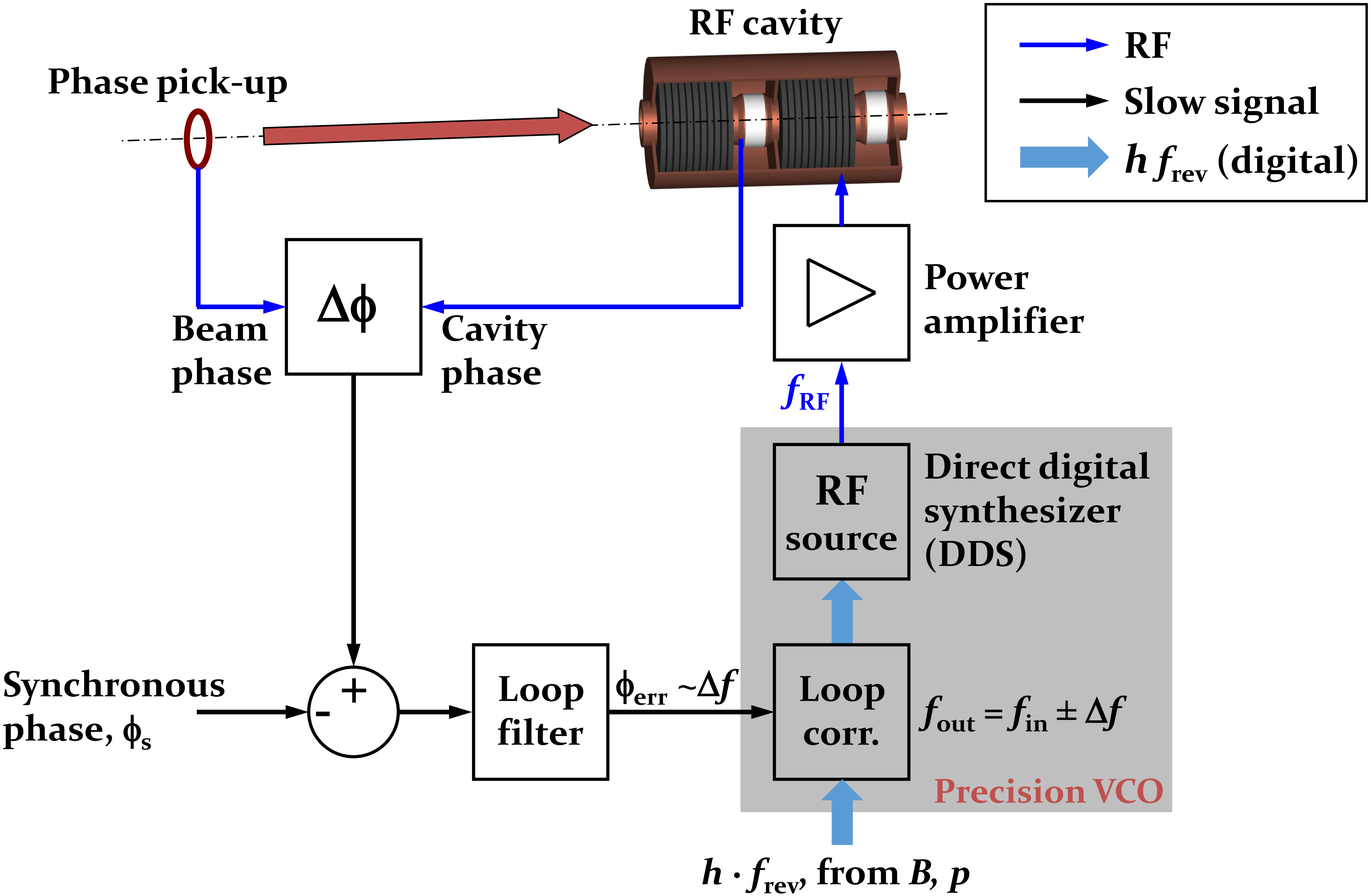
→ **Fixed phase relationship:** $\phi_{\mathrm{out}}/n - \phi_{\mathrm{in}} = \mathrm{const.}$

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

Beam phase loop

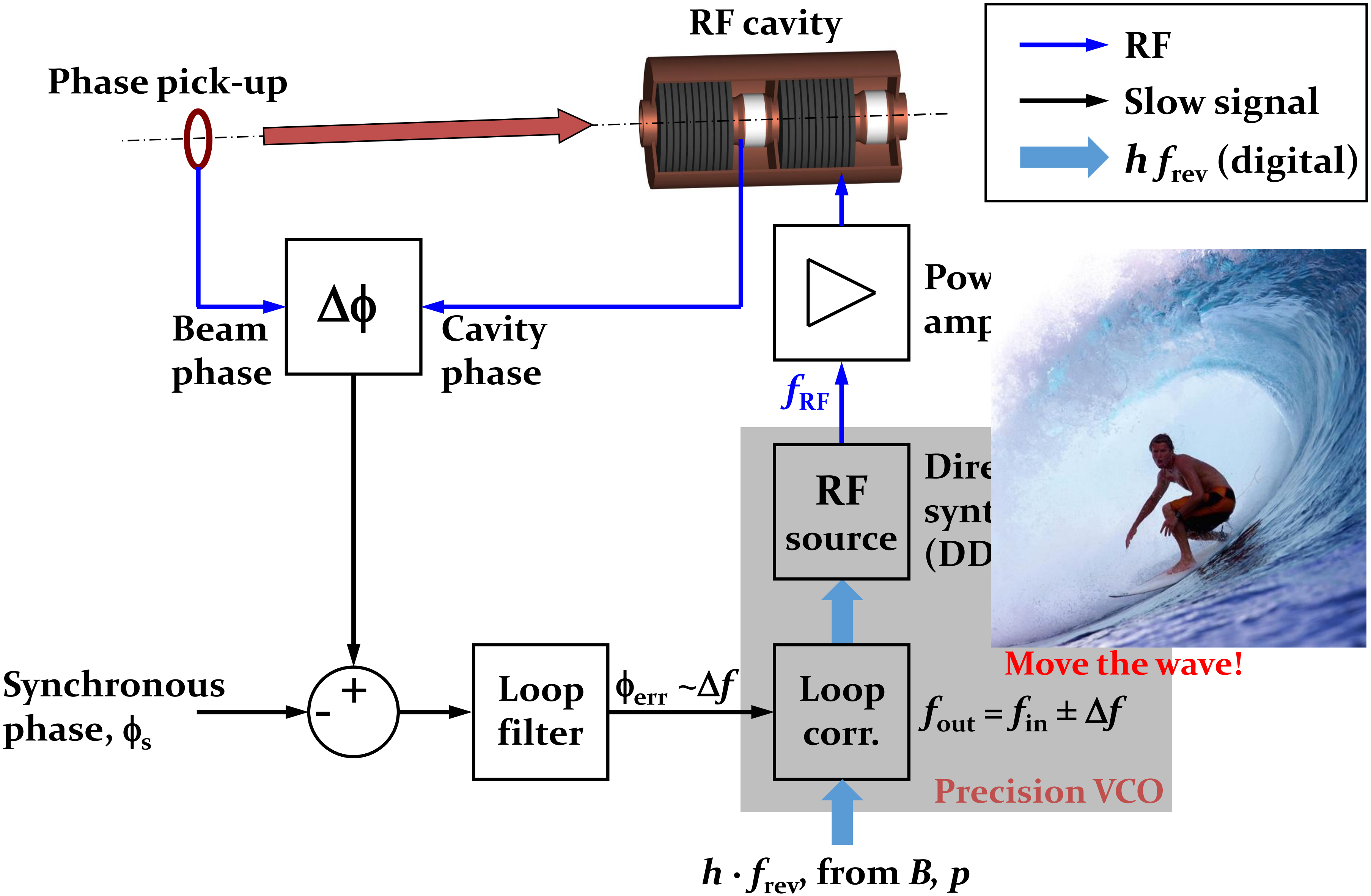


Beam phase loop



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

Beam phase loop

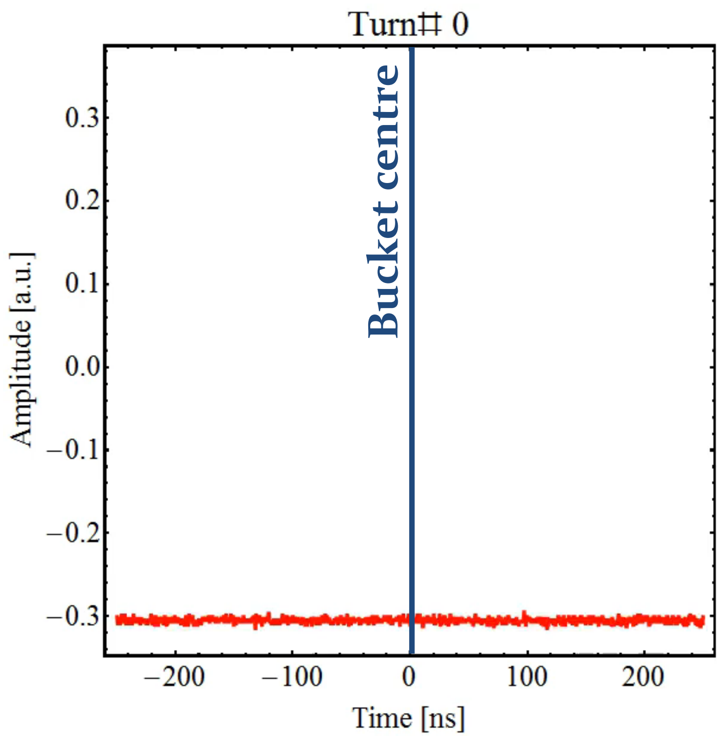


→ Fast control of RF frequency to cavities, but no slow corrections

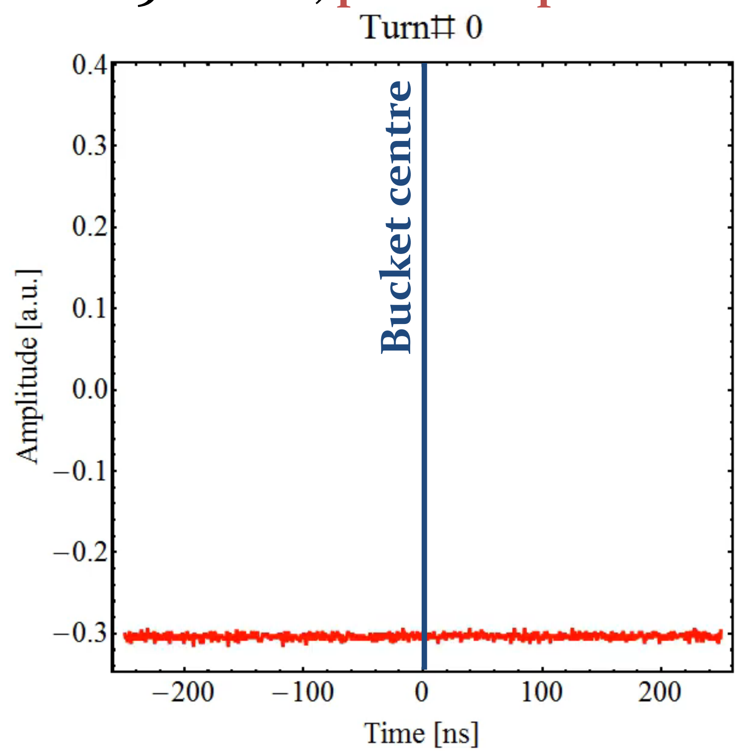
Effect of beam phase loop at injection

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

90° error, phase loop off



90° error, phase loop on



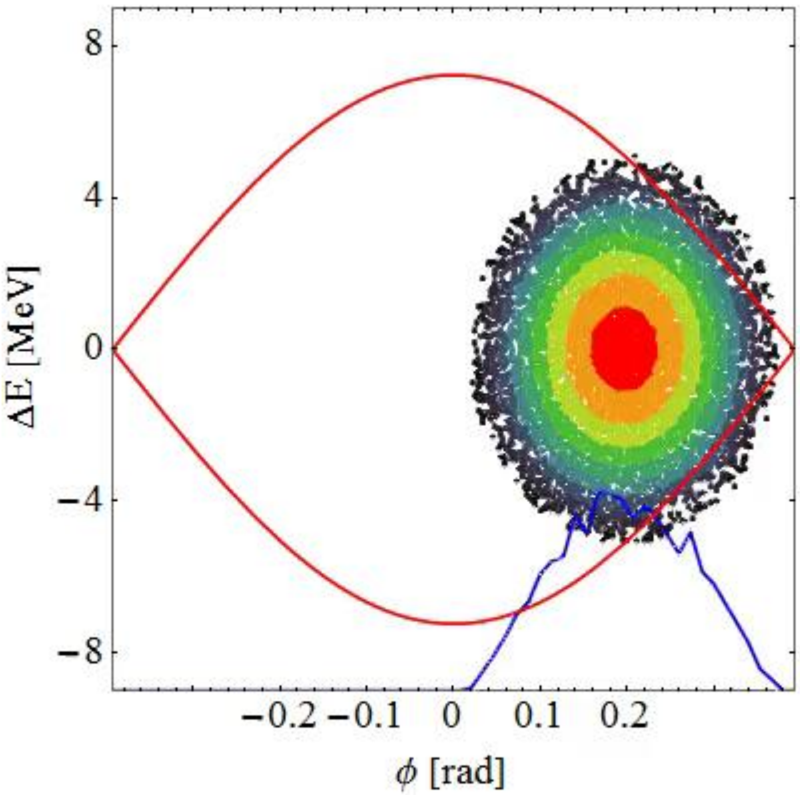
→ **Essential in hadron accelerators to keep RF locked to beam**

→ **How does this look like in longitudinal phase space?**

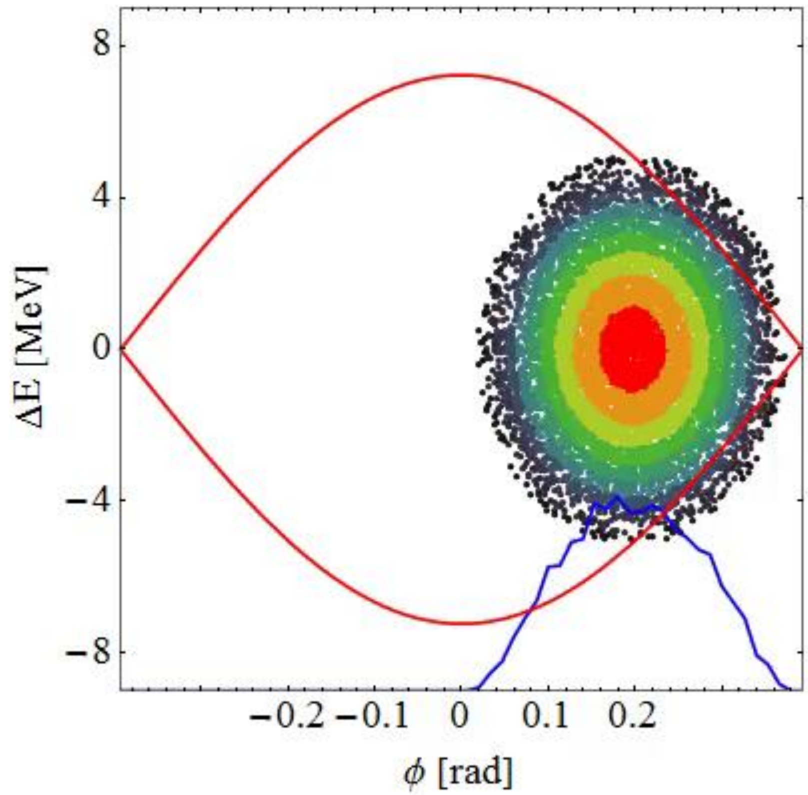
Effect of beam phase loop at injection

→ **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**

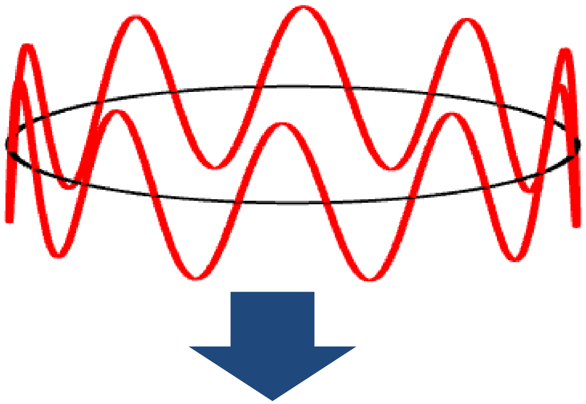
→ **Only minor longitudinal perturbation**

Slow RF frequency control: Radial loop

Radial loop

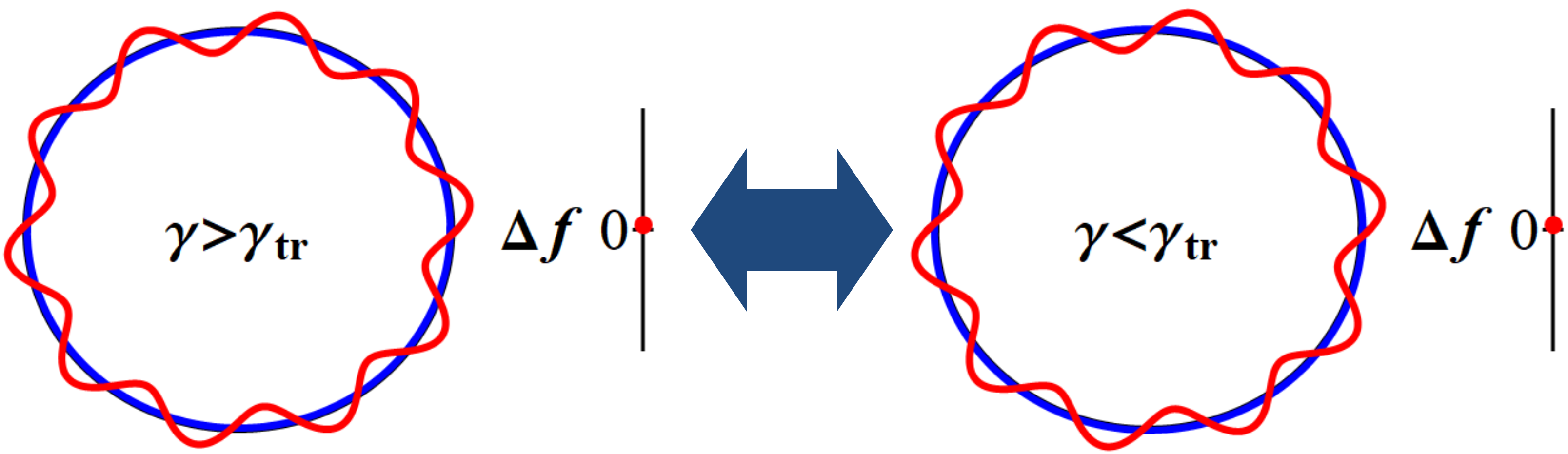
→ **Slow correction of average RF frequency**

Beam path length: $h \cdot \lambda_{RF} \cdot \beta$

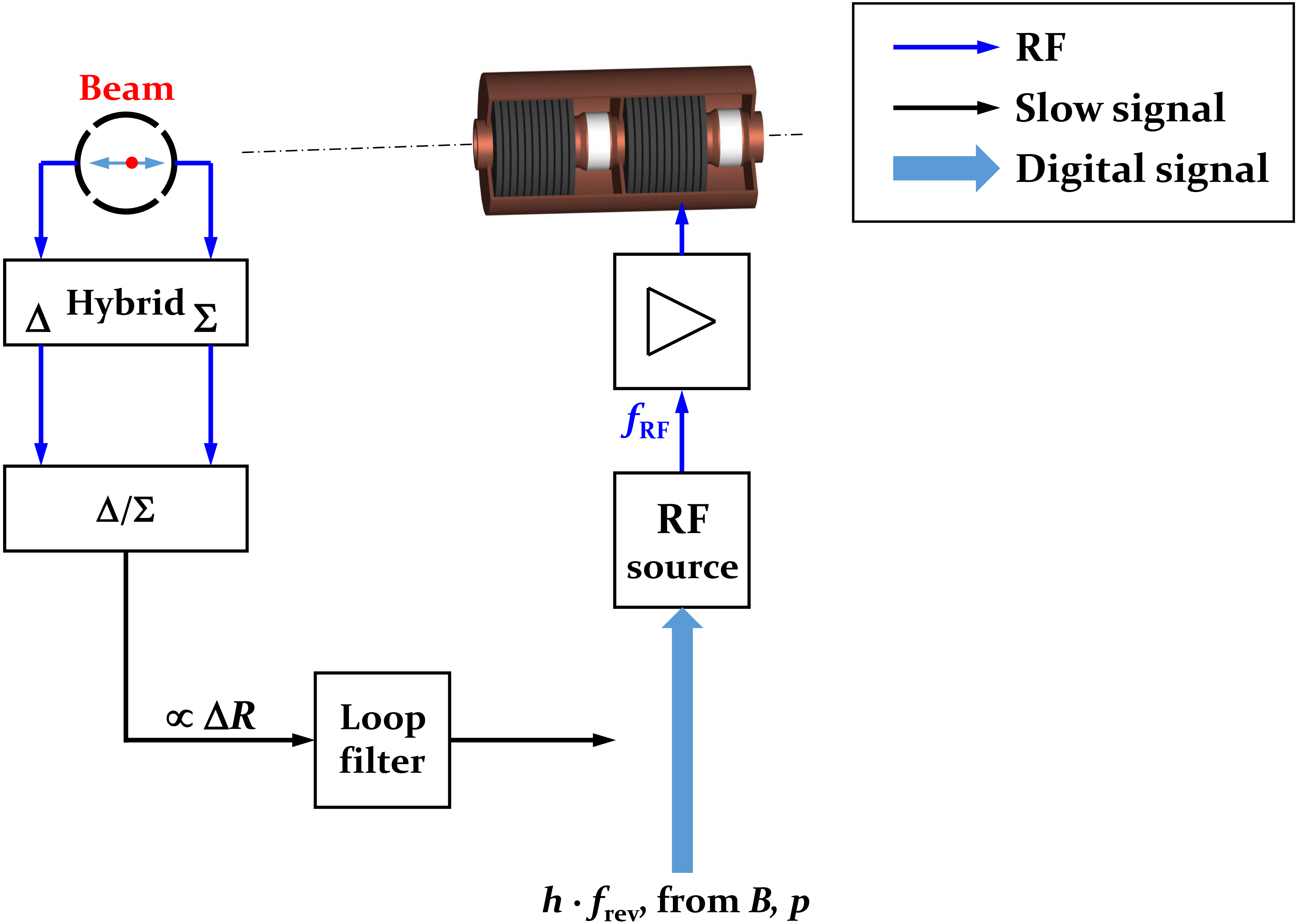


Above transition energy: $\beta \approx 1$

Below transition energy: β variable

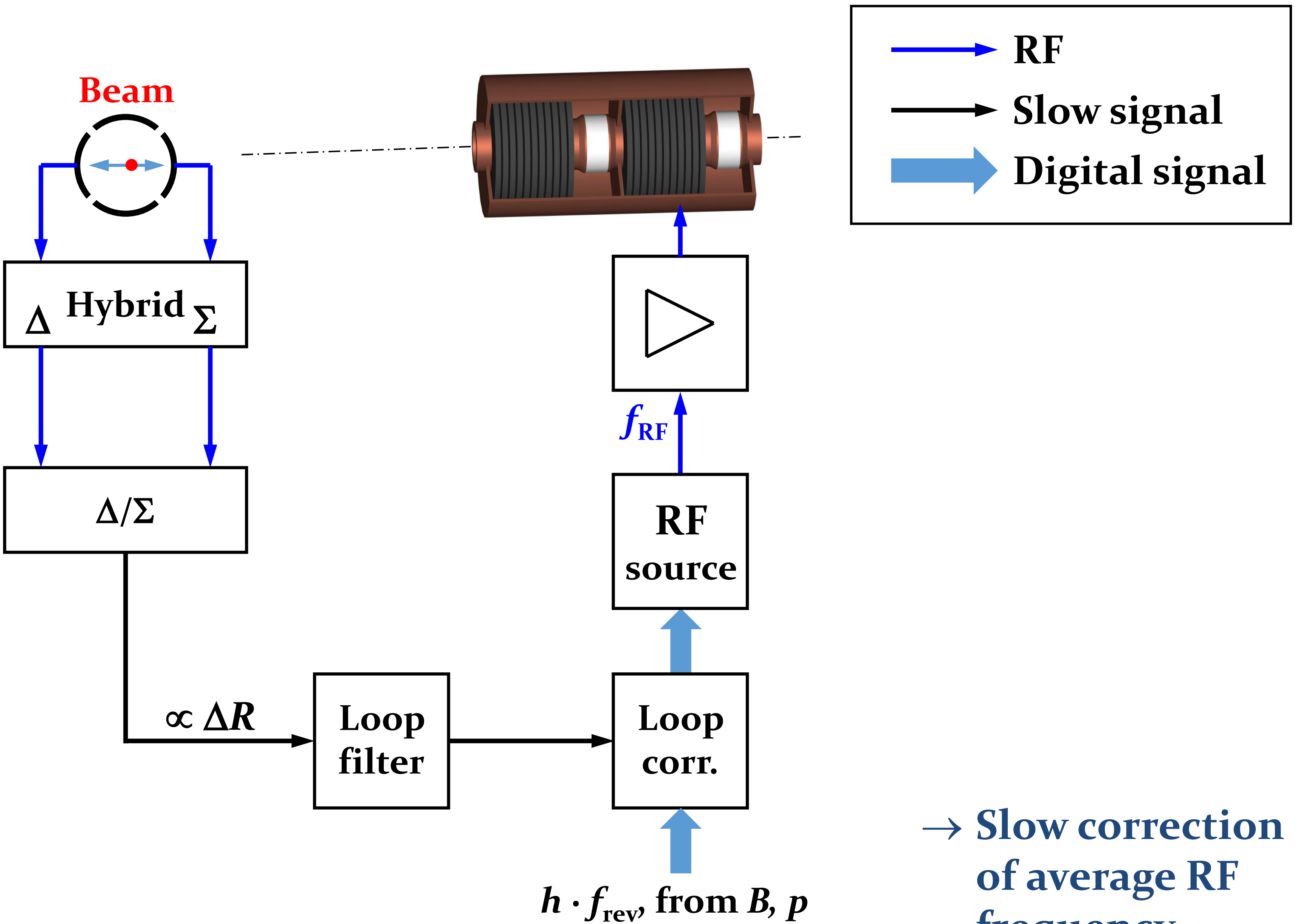


Radial loop



Beam
Hybrid
Δ
Σ
Δ/Σ
∝ ΔR
Loop filter
f_{RF}
RF source
$h \cdot f_{rev}$, from B, p
RF
Slow signal
Digital signal

Radial loop



→ Slow correction of average RF frequency

Radial loop at transition

- Slow correction of RF frequency to keep beam centred

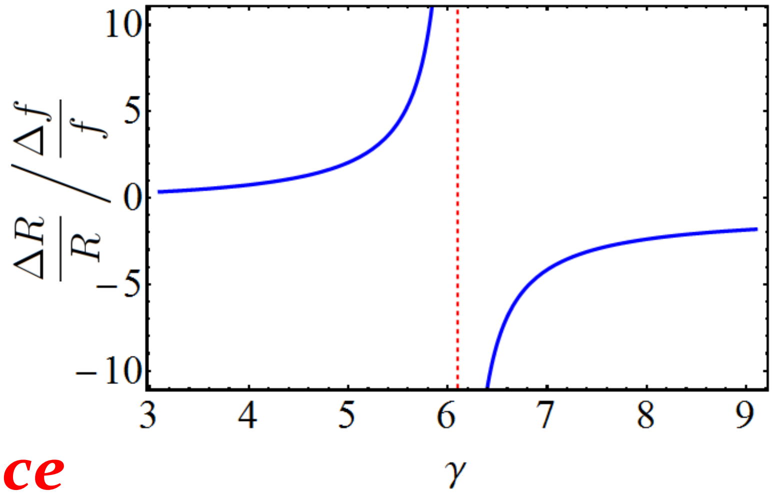
Why needed at all with arbitrary precision synthesizers driving the RF system?

→ At transition energy

→ Longer path of higher energy particle compensated by higher velocity

→ No revolution frequency change for energy offset

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



→ Beam-based frequency correction essential

→ Take beam as *the reference*

Summary

- **RF system parameters**
  - **$\rightarrow$ Choose frequency and voltage wisely**
- **Parameters of RF cavities**
  - **$\rightarrow$ R, R/Q**
  - **$\rightarrow$ No 'one-size fits' all**
- **Power amplifier**
  - **$\rightarrow$ Tube or solid-state based**
- **Local feedback**
- **Beam control as global feedback**
  - **$\rightarrow$ Beam phase and radial loops**

$\rightarrow$ The beam is *the reference* - make it feel comfortable!

Thank you very much for your attention!

A big Thank You

to all colleagues providing support, material and feedback

Maria-Elena Angoletta, Philippe Baudrenghien, Thomas Bohl, Giorgia Favia, Jörn Jacob, Erk Jensen, John Molendijk, Eric Montesinos, Gerry McMonagle, Mauro Paoluzzi, Damien Perrelet, Bernhard Schriefer, Lukas Stingelin, Fumihiko Tamura, Frank Tecker, Daniel Valuch and many more…

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Some standard frequencies

If exact RF frequency not critical, choose standard value

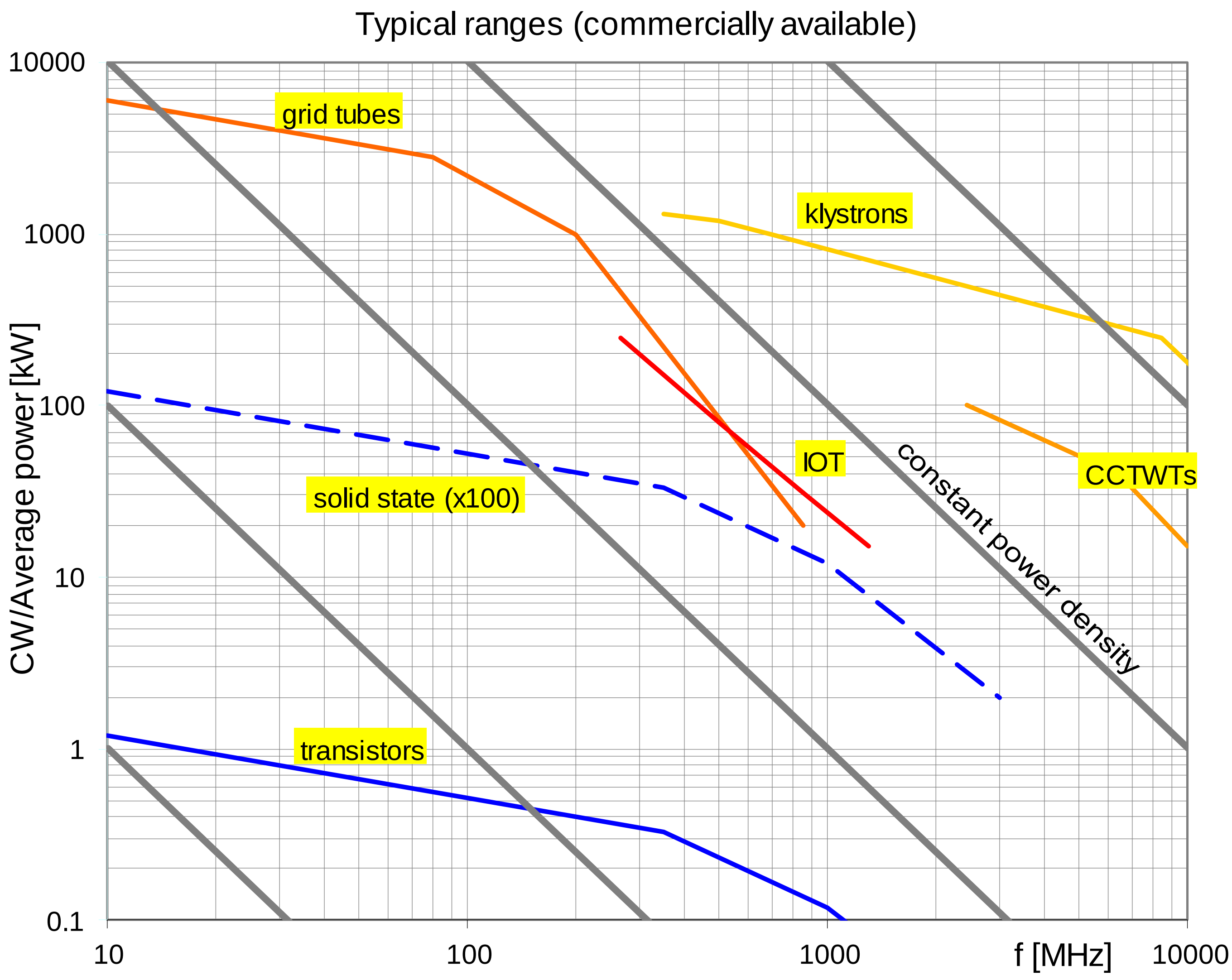
Accelerator	Frequency
Hadron synchrotrons (PSB, PS, JPARC RCS, MR)	<10 MHz
Hadron accelerators and storage rings (RHIC, SPS)	~200 MHz
Electron storage rings (LEP, ESRF, Soleil)	352 MHz
Electron storage rings (DORIS, BESSY, SLS,…)	499.6…499.8 MHz
Superconducting electron linacs and FELs (X-FEL, ILC)	1300 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 power amplifier

Power capability of commercially available amplifier types



E. Jensen