RF Systems I

H. Damerau
CERN

Introduction to Accelerator Physics

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Outline

• Introduction

• Choice of parameters
  • Frequency and voltage

• RF cavity parameters
  • Shunt impedance, beam loading, power coupling

• Power amplifiers
  • Tube or solid state
  • Local feedbacks

• Longitudinal beam control system
  • Building blocks: RF source and receiver
  • Phase, radial and synchronization loops

• Summary
Introduction
Introduction

• The radiofrequency (RF) system transforms a string of magnets into an accelerator

• Cavity most is the most visible part of an RF system
  → On top of the RF system food chain
  → Interacts directly with beam

→ What is below?
→ How are RF signals generated which make the beam feel comfortable?
Frequency and wavelength ranges

- **PS longitudinal damper**
- **PS main RF system**
- **SPS 200 MHz**
- **CLIC 12 GHz**
- **100 kHz**
  - 3 km
- **1 MHz**
  - 300 m
- **10 MHz**
  - 30 m
- **100 MHz**
  - 3 m
- **1 GHz**
  - 30 cm
- **10 GHz**
  - 3 cm
- **100 GHz**
  - 3 mm

- **Long wave**
- **Medium/short wave**
- **VHF**
- **Microwave links**
- **WiFi**
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: \[ \beta = \frac{v}{c} = \sqrt{1 - \left(\frac{E_0}{E}\right)^2} \]

- 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

\[ f_{RF} = n \cdot f_{rev} \]

*Exceptions (rare) exist
Choice of frequency (range)
## Why choose a low RF frequency?

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Large beam aperture</td>
<td>• Bulky cavities, size scales $\propto 1/f$, volume $\propto 1/f^3$</td>
</tr>
<tr>
<td>• Long RF buckets, large acceptance</td>
<td>• Lossy material to downsize cavities</td>
</tr>
<tr>
<td>• <strong>Wide-band or wide range tunable cavities possible</strong></td>
<td>• Moderate or low acceleration gradient</td>
</tr>
<tr>
<td>• Power amplification and transmission straightforward</td>
<td>• Short particle bunches difficult to generate</td>
</tr>
</tbody>
</table>

RF frequencies **below** ~200 MHz for

→ Some hadron linear accelerators
→ Cyclotrons
→ Low- and medium energy hadron synchrotrons
# Why choose a high RF frequency?

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

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

\[ 24.67 \sqrt{f} = E_c e^{\frac{E_c}{4.25}} \]

\( f \) in GHz, \( E_{\text{crit}} \) in MV/m

→ High frequencies preferred for large gradient

Kilpatrick 1957,

Wang & Loew, SLAC-PUB-7684, 1997
Some standard frequencies

If exact RF frequency not critical, choose standard value

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

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

• RF system expected to provide given energy gain

\[ qV = \Delta E \]

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

• More voltage provided to avoid on-crest acceleration

\[ qV > \Delta E \rightarrow qV \sin(\phi_S) = \Delta E \]

→ Off-crest acceleration
→ Needed for circular accelerator
→ Higher voltage for given energy gain
Bucket area dependence on stable phase

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

  - Below transition, $\phi_s = 0 \ldots 90^\circ$
  - Above transition, $\phi_s = 90^\circ \ldots 180^\circ$

- Typical synchronous phase with respect to $0^\circ$ or $180^\circ$
  - Hadron accelerators: $< 40^\circ$
  - Electron storage rings: $\sim 20^\circ$
Minimum voltage requirement (circular)

The RF system must compensate

1. Energy gain per turn due to changing magnetic field

\[ F_Z = F_L \rightarrow \frac{\dot{p}}{q} = \rho B \rightarrow \dot{p} = q \rho \dot{B} \]

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

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

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

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

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

\[ \rightarrow (m_p/m_e)^4 = 1836^4 \sim 1.1 \cdot 10^{13} \text{ times less for protons} \]
RF system overview

Beam → Cavity

→ Convert RF power into longitudinal electric field

Cavity → Power amplifier

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

Power amplifier → Low-level RF system

→ Provide RF signals with correct frequency, amplitude and phase

Low-level RF system → Beam
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
The resonance of a cavity can be understood as simple parallel resonant circuit described by $R$, $L$, and $C$

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

with

\[ \omega_0 = \frac{1}{\sqrt{LC}} \]

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

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

\[ Q = \omega_0 RC = \frac{R}{\omega_0 L} \]
Cavity parameters

- The resonance of a cavity can be understood as a 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 $\omega_0 = \frac{1}{\sqrt{LC}}$

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

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

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

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

• Most common choice by cavity designers $\omega_o, R, R/Q$ – why?

• Resonance frequency, $\omega_o$
  → Exactly defined for given application, e.g. $hf_{rev}$

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

• “R-upon-Q”, $R/Q$
  → Defined only by the cavity geometry
  → Criterion to optimize a geometry
  → Detuning with beam proportional to $R/Q$
Why R/Q?

→ Charged particle experiences cavity gap as capacitor

\[ q = V_{\text{ind}} C \]

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

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

→ Cavity geometry with small $R/Q$ to reduce beam loading
RF cavities in low frequency range

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

Why is this resonator so common in particle accelerators?
RF cavities in low frequency range

- Coaxial structure with inner conductor as beam pipe

\[ Z(\omega) \rightarrow \text{Beam axis} \rightarrow \text{Short-circuit} \]

→ 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.

ACOL, 9.53 MHz

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

M. Nagl
Inductive loading

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

CERN PSB Finemet cav., 0.6-18 MHz
CERN PS, double gap, 2.8-10 MHz

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

→ Remove inductive or capacitive loading

SSC Low Energy Booster, 
~47 MHz to 60 MHz

FNAL Booster 2\textsuperscript{nd} harmonic, 
76 MHz – 106 MHz, 100 kV

→ Upper frequency limit for cavities with large tuning range
Further increase frequency

→ Remove inner conductor from coaxial set-up

→ The resonator becomes a pill-box cavity

DORIS cavity

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

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

→ The basis for cavity resonators
Example: 400 MHz cavities in LHC

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

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

→ 2×8 cavities, 5.3 MV/m

$$\frac{1}{Q} = \frac{1}{Q_{\text{cav}}} + \frac{1}{Q_{\text{ext}}}$$
RF cavities in linear accelerators

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

SuperHILAC, ~70 MHz, Berkley

→ 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*

- Main coupler
  PSI cyclotron
  → ~1 MW at 50 MHz
Coupling power into a cavity

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

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

→ **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**
Capacitive (electric) coupling

- Coupling through an electric antenna

**Electrical coupler to space**

- 2 MW at 540 kHz

**Power coupler of LHC cavities**

- 300 kW at 400 MHz

→ Coupler antenna transmits directly into the cavity
RF system overview

 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

\[
P_{\text{amplifier}} = P_{\text{dist}} + P_{\text{cavities}} + P_B = I_B \cdot \Delta E_{\text{turn}}
\]

\[
P_{\text{cavities}} = n \frac{(V/n)^2}{2R}
\]

\[
P_{\text{BL}} = I_B \cdot V_{\text{ind}} \quad \text{(ideally)}
\]
Power amplifiers

- Basically

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

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

- Unfortunately such a device has not been invented yet
- Let us have a look at some real amplifiers
Basics of grid tube

- From diode to tetrode amplifier

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

→ Diode

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

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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

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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
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
Tetrode based power amplifier

- Example of SPS 200 MHz amplifier, tetrode RS2004

→ Very simplified block diagram

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Example: Tetrode amplifier driving SPS RF

- Two transmitters, $2 \times 1 \text{ MW at 200 MHz (almost continuous)}$
- Eight tetrodes per amplifier

$\rightarrow$ In operation since 1976

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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

→ 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 at same frequency as input cavity
  - At place where electrons are maximally bunched
  - Kinetic energy converted into voltage and extracted
Basics of linear beam tube

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

- **Cavity resonators and drift**

- **RF input cavity (Buncher)**
  → Modulates electron velocity

- **Drift space**
  → Faster electrons catch up
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- **RF output cavity (Catcher)**
  - Resonating at same frequency as input cavity
  - At place where electrons are maximally bunched
  - Kinetic energy converted into voltage and extracted

E. Montesinos
Example: Klystrons driving accelerators

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

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

- 12 GHz pulsed klystron for CLIC
  → 50 MW in 1.5 μs
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.

BJT: Bipolar Junction Transistor

Basics of RF solid state amplifiers

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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

NXP Semiconductors AN11325
2-way Doherty amplifier with BLF888A

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Example: Soleil 45 kW, 352 MHz

Electron storage ring running at 352 MHz

330 W amplifier module

600 W, 300 V\textsubscript{DC}/30 V\textsubscript{DC} converter
Example: Soleil 45 kW, 352 MHz

Large scale solid state amplifier installations

45 kW per tower (2004 and 2007)  
150 kW per tower (2012)

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

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Example: BESSY II

500 MHz solid state amplifiers: \(4 \times 80 \text{ kW}\) for storage ring, \(40 \text{ kW}\) for booster synchrotron

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

B. Schriefer
Example: SPS

200 MHz solid state amplifiers: $2 \times 1.6 \text{ MW}$ peak power,
$2 \times 16$ towers per amplifier

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

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RF power amplifier

Power capability of commercially available amplifier types

Typical ranges (commercially available)

- Transistors
  - solid state (x32)
- grid tubes
- klystrons
- IOT
- CCTWTs

E. Jensen
### How to choose the right RF amplifier?

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

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

• RF system parameters
  → Choose frequency and voltage wisely

• Parameters of RF cavities
  → $R$, $R/Q$
  → No ‘one-size fits’ all

• Power amplifier
  → Ideal amplifier does not (yet) exist
  → Tube or solid-state based

• Feedbacks and longitudinal beam control
  → Make the beam feel comfortable in bucket
  → Beam phase, radial and synchronization loops
RF Systems II

H. Damerau
CERN

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3 October 2023
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• 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 induce voltage in cavity

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

\[ Z_{eq}(\omega) = \frac{dV}{dI_B} = \frac{Z(\omega)}{1 + g_{OL}} \]
Example: 10 MHz RF system in CERN PS

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

Why not further reduction with more gain?

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

Bandwidth $\uparrow$ $\iff$ Achievable gain $\downarrow$
Example: 10 MHz RF system in CERN PS

- Fast wide-band feedback around amplifier (internal)

- Gain limited by delay

• 10 + 1 ferrite loaded cavities, tunable from 2.8...10 MHz
Example: RF feedback with 1-turn delay

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

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

• 10 + 1 ferrite loaded cavities, tunable from 2.8…10 MHz
Example: RF feedback with 1-turn delay

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

Open/closed loop transfer functions

Spectrum at cavity gap return

Feedback off

Feedback on

→ Important additional impedance reduction

→ Clever usage of beam periodicity in circular accelerator
RF system overview

- Beam → Cavity
  - Convert RF power into longitudinal electric field

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

- Power amplifier → Low-level RF system
  - Provide RF signals with correct frequency, amplitude and phase

- Low-level RF system → Beam
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 $\omega_1$ and $\omega_2$

$\Delta \phi$, between both signals changes linearly

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

Saw-tooth in phase means constant frequency difference

Equivalence of frequency and phase

$$\omega = \frac{d\phi}{dt} \leftrightarrow \phi = \int \omega \, dt$$
Example: analogue 4 quadrant multiplier and low pass filter

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

Signals:
Mixer or multiplier

• Example: analogue 4 quadrant multiplier and low pass filter

\[
\sin(\omega_1 t + \phi_1) \rightarrow \frac{1}{2} \{\cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)]
\]

\[
\cos[(\omega_1 + \omega_2)t + (\phi_1 + \phi_2)]
\]

Remove ripple → Low-pass filter

• Signals:
How to detect phase differences?

• Example: analogue 4 quadrant multiplier and low pass filter

\[
\sin(\omega_1 t + \phi_1) \rightarrow \frac{1}{2} \{\cos[(\omega_1 - \omega_2) t + (\phi_1 - \phi_2)] - \cos[(\omega_1 + \omega_2) t + (\phi_1 + \phi_2)]\}
\]

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?

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

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

→ Thermal noise power $\frac{P}{\Delta f} = k_B T = 1.38 \cdot 10^{-23} \text{ J/K} \cdot 296 \text{ K} \approx -174 \text{ dBm/Hz}$
Analysis of phase noise

- Compare noise power with carrier power as reference

\[ \Delta f = 1 \text{ Hz} \] for normalization

- Noise power density

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

→ Its integral is the phase jitter and using

\[ \Delta t = \frac{\Delta \phi}{2\pi f_c} \]

the jitter in time becomes

\[ \Delta t_{\text{rms}} = \frac{1}{2\pi f_c} \sqrt{\int_{f_1}^{f_2} S_\phi(f) \, df} \]
Typical phase noise plots

- Measure phase noise of a synthesized lab generator

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

\[ \Delta t_{\text{rms}} = \sqrt{\Delta t_{\text{rms,1}}^2 + \Delta t_{\text{rms,2}}^2 + \cdots} \]

→ Convenient split to relevant ranges

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>( \Delta t_{\text{rms}} ) [fs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10...100 Hz</td>
<td>12.4</td>
</tr>
<tr>
<td>100 Hz ...1 kHz</td>
<td>5.4</td>
</tr>
<tr>
<td>1...10 kHz</td>
<td>5.4</td>
</tr>
<tr>
<td>10...100 kHz</td>
<td>11.1</td>
</tr>
<tr>
<td>100 kHz...1 MHz</td>
<td>13.0</td>
</tr>
<tr>
<td>Total</td>
<td>31.0</td>
</tr>
</tbody>
</table>
Variable frequency: direct digital synthesis

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

$$f_{out} = \frac{\text{Frequency word}}{2^n} \cdot f_{clk}$$
Variable frequency: direct digital synthesis

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

\[ f_{out} = \frac{\text{Frequency word}}{2^n} \cdot f_{clk} \]

→ 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 $\phi$

$$I = A \cos \phi$$

$$Q = A \sin \phi$$

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

$$\phi = \arctan \frac{Q}{I}$$

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

→ Avoids phase discontinuities at 0, $2\pi$, ...
Signal receivers

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

\[
\begin{align*}
A \sin(\omega_{in}t + \phi_{in}) \cdot \sin(\omega_{LO}t + \phi_{LO}) \\
\cos(\omega_{LO}t + \phi_{LO})
\end{align*}
\]

\[
\begin{align*}
\frac{A}{2} \cos[(\omega_{in} - \omega_{LO})t + (\phi_{in} - \phi_{LO})] \\
\frac{A}{2} \sin[(\omega_{in} - \omega_{LO})t + (\phi_{in} - \phi_{LO})]
\end{align*}
\]

→ With \( \omega_{in} \approx \omega_{LO} \) input signal is down-converted to base-band
→ Resulting I/Q vector rotates slowly with \( \omega_{in} - \omega_{LO} \)
Digital receivers

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

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

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

→ Analogue mixers become digital multipliers
→ All digital receiver
→ Theoretically perfect I/Q symmetry
Vector modulator
Invers receiver: vector modulator

- Convert I/Q data into modulated RF signal

\[ I \cos(\omega_{LO}t + \phi_{LO}) + Q \sin(\omega_{LO}t + \phi_{LO}) \]
Inverse receiver: vector modulator

- Convert I/Q data into modulated RF signal

\[ I \xrightarrow{\text{DAC}} \cos(\omega_{\text{LO}} t + \phi_{\text{LO}}) \]

\[ Q \xrightarrow{\text{DAC}} \sin(\omega_{\text{LO}} t + \phi_{\text{LO}}) \]

\[ I \cos(\omega_{\text{LO}} t + \phi_{\text{LO}}) + Q \sin(\omega_{\text{LO}} t + \phi_{\text{LO}}) \]

→ 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

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

\[ f_{in}, \phi_{in} \rightarrow \Delta\phi \rightarrow \sim\phi_{in} - \phi_{VCO} \rightarrow \text{Loop filter, } H(\omega) \rightarrow \text{VCO} \rightarrow f_{out}, \phi_{out} \]

\[ \phi_{VCO} \]
1
\[ \frac{1}{n} \]

→ Fixed phase relationship: \[ \phi_{out}/n - \phi_{in} = \text{const.} \]
→ Optional divider: \[ f_{out} = n \cdot f_{in} \]
Beam phase loop

Phase pick-up

\[ \Delta \phi \]

Beam phase

Cavity phase

RF cavity

Power amplifier

Digital synthesizer

Synchronous phase, \( \phi_s \)

\[ \phi_{err} \sim \Delta f \]

Loop filter

\[ h \cdot f_{rev}, \text{ from } B, p \]
Beam phase loop

Phase pick-up

Beam phase

Δφ

Loop phase

RF cavity

Cavity phase

Power amplifier

Digital synthesizer

DDS

φ_{err} \sim Δf

f_{out} = f_{in} \pm Δf

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

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

Phase pick-up

Beam phase loop

RF cavity

Power amplifier

Digital synthesizer

 DDS

Loop filter

Loop corr.

Synchronous phase, $\phi_s$

$\Delta \phi$

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

$f_{RF}$

$f_{out} = f_{in} \pm \Delta f$

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

Move the wave!

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

→ 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

→ 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 synchro-nization loop
Radial loop
Radial loop

Beam

Δ Hybrid Σ

Δ/Σ

ΔR

Reference magnet

RF

Slow signal

Digital signal

DDS

Δf

B \frac{f_{rev}}{f_{rev}}

h f_{rev}

→ Slow correction of average RF frequency

Frequency program

→ Slow signal

Digital signal
Radial loop

• Slow correction of RF frequency to keep beam centred

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

→ At transition energy
  → Longer path of higher energy particle compensated by higher velocity
  → No revolution frequency change for energy offset

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

→ Need beam-based frequency correction
Synchro(nization) loop
Beam phase loop

Phase pick-up

Beam phase loop

RF cavity

Power amplifier

Digital synthesizer

Loop filter

Loop corr.

DDS

Precision VCO

Synchronous phase, $\phi_s$

$\Delta \phi$

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

$f_{out} = f_{in} \pm \Delta f$

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

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

$h \cdot f_{rev}$ (digital)
Synchronization loop, internal reference

Phase pick-up

Beam phase

Cavity phase

Beam phase, $\phi_s$

Synchronous phase, $\phi_s$

Loop filter

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

Loop corr.

Power amplifier

$\Delta \phi$

DDS

Ref. DDS

Ref. DDS

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

→ Avoids noise from radial detection when not crossing transition
Synchronization loop, external reference

Phase pick-up

Beam phase

$\Delta \phi$

Cavity phase

RF cavity

Power amplifier

Synchronous phase, $\phi_s$

Loop filter

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

Loop corr.

DDS

$\Delta \phi$

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

$\rightarrow$ Synchronize between accelerators for transfer
Before synchronization

• Simple test case of circumference ratio 2: \( C_2 = 2C_1 \)

\[
\rightarrow \text{Synchronize both accelerator to force: } f_{\text{rev,1}} = 2f_{\text{rev,2}}
\]
After synchronization

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

Source or target accelerator is master at transfer

$\rightarrow$ Revolution frequencies coupled: $f_{\text{rev},1} = 2f_{\text{rev},2}$

$\rightarrow$ 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!
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References

- W. D. Kilpatrick, Criterion for vacuum sparking designed to include both rf and dc, Rev. Sci. Instrum. 28 (1957), 1957, http://inspirehep.net/record/44645
Normalized Hamiltonian representation

- For a single harmonic RF system

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

with \( \phi = \phi_S + \Delta \phi \) it becomes

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

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

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

this simplifies to

\[ H(\Delta \phi, \dot{\phi}) \simeq \frac{1}{2} \dot{\phi}^2 + \frac{1}{2} \omega_s^2 \Delta \phi^2 \]
Cascaded integrator-comb filter (CIC)

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

\[
H(z) = \left( \frac{1 - z^{-d}}{1 - z^{-1}} \right)^n \quad n: \text{filter order} \quad d: \text{decimation ratio}
\]

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

→ Easy to implement in programmable logic: no multipliers
→ Only adders and shift registers
Cascaded integrator-comb filter (CIC)

Why particularly interesting for circular accelerators?

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

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

Ideal low-pass filter in digital receivers
  - Filter selected multiple of $f_{\text{rev}}$ while suppressing all others
Transmission of reference signals

- Thermal drift of long coaxial cables or optical fibres

- Thermal coefficient of delay:
  \[ TCD = \frac{\Delta \tau}{\tau} \cdot \frac{1}{\Delta T} = \frac{\Delta \phi}{\phi} \cdot \frac{1}{\Delta T} \]

- Example: 2 km long RG223 cable with \(~10\ \mu s\) delay
  \(\Delta T\) of only 1° C (room temperature) changes delay by \(~0.5\ \text{ns}\)
  \(1.8\°\) at 10 MHz (CERN PS), \text{but} 73° at 400 MHz (LHC)

- Optical fibres are typically 10...100 times more stable
- What to do if this is still not sufficient?
Simple synchronization process

1. Move beam to off-momentum ($B$ const.):
   \[
   \frac{df}{f} = \frac{\gamma_{tr}^2 - \gamma^2}{\gamma^2 \gamma_{tr}^2} \frac{dp}{p}
   \]
   → Well defined frequency difference between accelerators

2. Measure azimuth error, when beam at correct azimuth
   → Close synchronization loop
   → Moves beam to ref. momentum

Beam azimuth (from phase loop) \[\Delta \phi\]
Ref. azimuth (from master divider) \[f_{rev} (h = 1)\]

Bunch should be here

Locked!

200 ms