# Longitudinal Hands-on Calculations

# RF System Design

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**CERN**

The CERN Accelerator School

**Introduction to Accelerator Physics**

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The CERN Accelerator School

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# Agenda of the afternoon

| | |
|---|---|
| 15h00 – 15h30<br>**Introduction to exercises** | |
| 15h30 – 16H00<br>**RF system design** | |
| **Coffee break** | |
| 16h30 – 17h45<br>**RF system design** | |
| 17h45 – 18h30<br>**Discussion on solutions of exercises** | |

# Outline

- **Introduction**
  - **Interaction between beam and RF system**
- **Design of RF systems**
  - **Design flow and constraints**
  - **Examples of RF systems at CERN**
- **Summary**

# Introduction

# Study interaction between beam and RF

## Complementary approaches for the same problem

| (Semi-)Analytical |
| --- |
| • Describe particle motion by differential equations<br>→ Continuous trajectories of particle motion<br>→ Deduce useful parameters for stable acceleration:<br>→ RF bucket<br>→ Synchrotron frequency<br>→ Stable phase<br>→ … |

# Study interaction between beam and RF

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| (Semi-)Analytical | Numerical: tracking |
|---|---|
| • Describe particle motion by differential equations<br><br>→ Continuous trajectories of particle motion<br>→ Deduce useful parameters for stable acceleration:<br>→ RF bucket<br>→ Synchrotron frequency<br>→ Stable phase<br>→ … | • Track particle parameters from turn to turn<br><br>→ Profit from discretization of motion: turn-by-turn, RF station-by-RF station<br>→ No notion of RF bucket, synchrotron frequency, stable phase, etc.<br>→ Follow ensemble of particles to study evolution of bunch |

# Study interaction between beam and RF

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| --- | --- |
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| → Classical […] of longitudinal beam dynamics<br>Today | → […]pproach<br>Tomorrow afternoon |

# Objectives of longitudinal hands-on

1. **Design RF system (upgrade)**

   `LongitudinalHandsOnRFSystemCalculations_empty.ipynb`

   - Study boundary constraints
   - Derive requirements for RF system
   - Choose main components
   - Compare with existing facilities

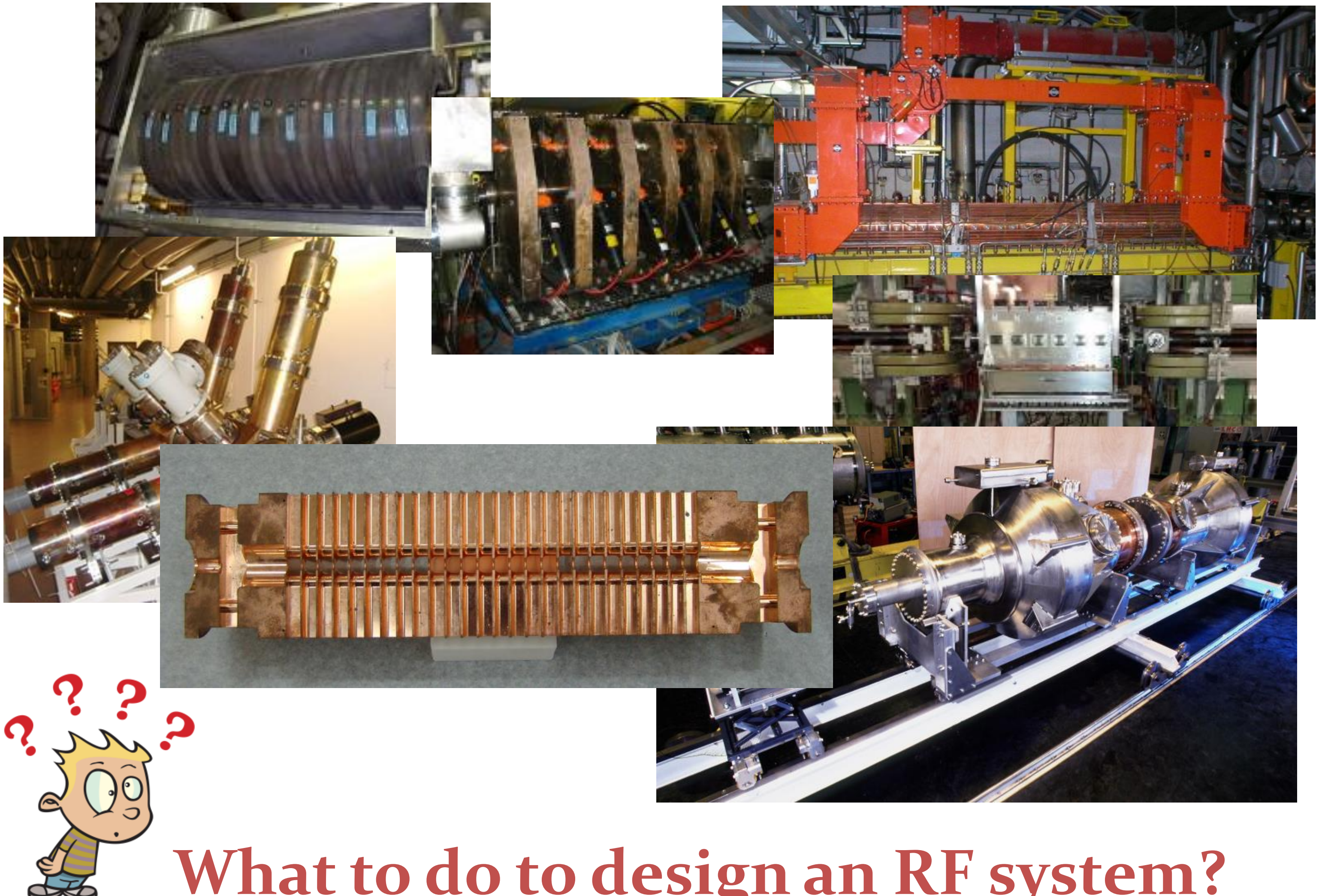
2. **Play with longitudinal beam dynamics**

   `LongitudinalHandsOnTracking_empty.ipynb`

   - Build your own particle tracker
   - Understand motion of particles in longitudinal phase space
   - Transition from single particle motion to evolution of an entire bunch

# RF system design

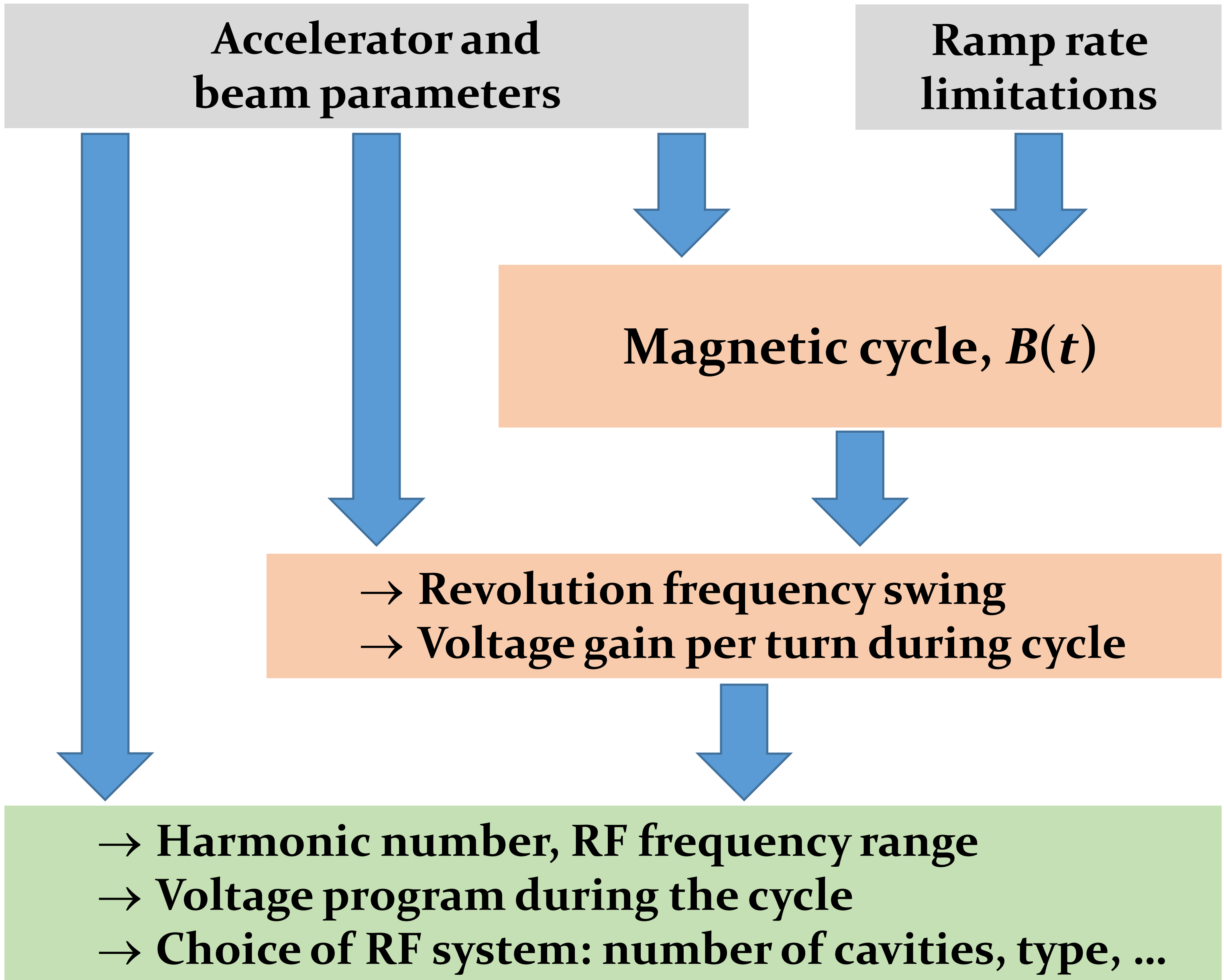
# Introduction



**What to do to design an RF system?**

**How to choose the right one?**

# Simplified design work flow

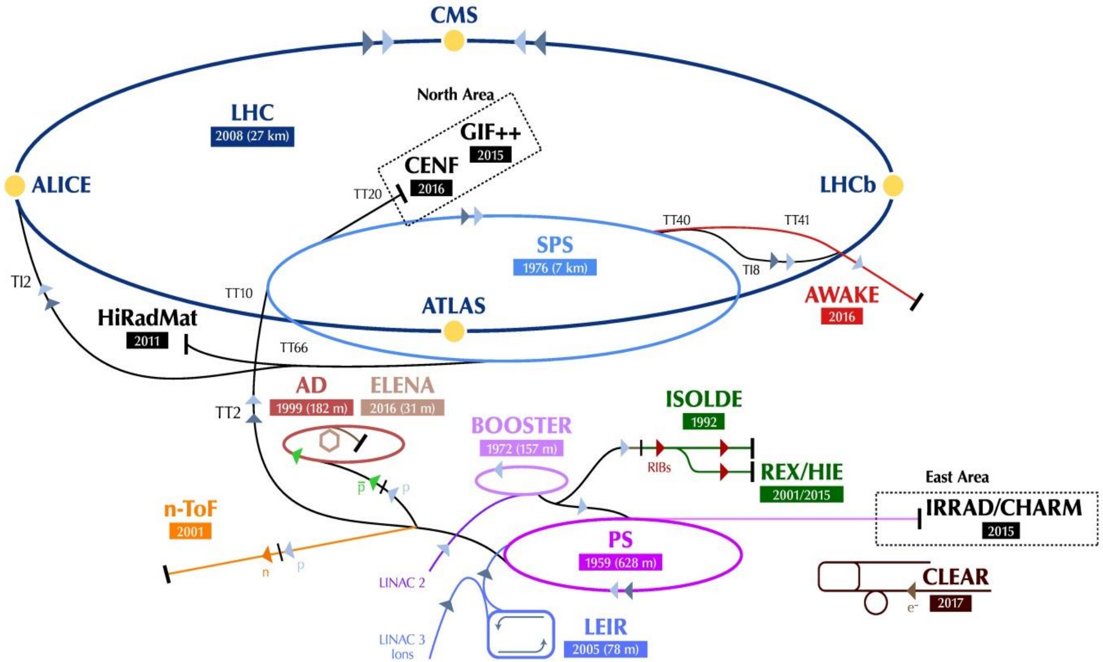


# RF parameters of existing accelerators

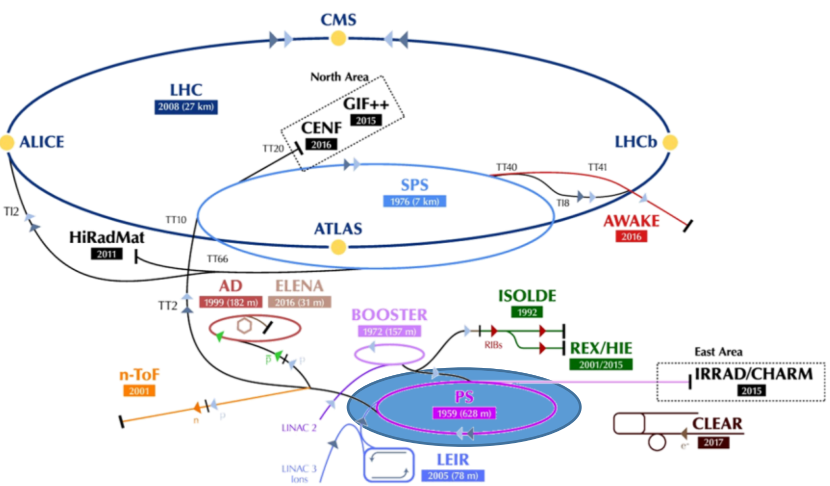
**Try to follow design choices of existing accelerator**

- **Can we understand the arguments?**
- **Are the choices reasonable?**

Good design?



# Proton Synchrotron



# Example: RF System for CERN PS

- **Attention**
  - → **Present RF system designed in ~1969**
  - → **Not the same energy range as today**

| **Parameter** | **Value** |
|---|---|
| Circumference, $2\pi R$ | $2\pi \cdot 100$ m = 628 m |
| Acceleration time, $t_{cycle}$ | 1 s |
| Maximum ramp rate, $dB/dt$ | **2.3 T/s** |
| Injection energy, $E_{kin}$ | **45 MeV** |
| Flat-top energy, $E_{tot}$ | initially **28 GeV** |
| **Revolution frequency at injection, $f_{rev,inj}$** | **143 kHz** |
| **at flat-top, $f_{rev,FT}$** | **477 kHz** |
| **Relative frequency swing** | **3.33** |

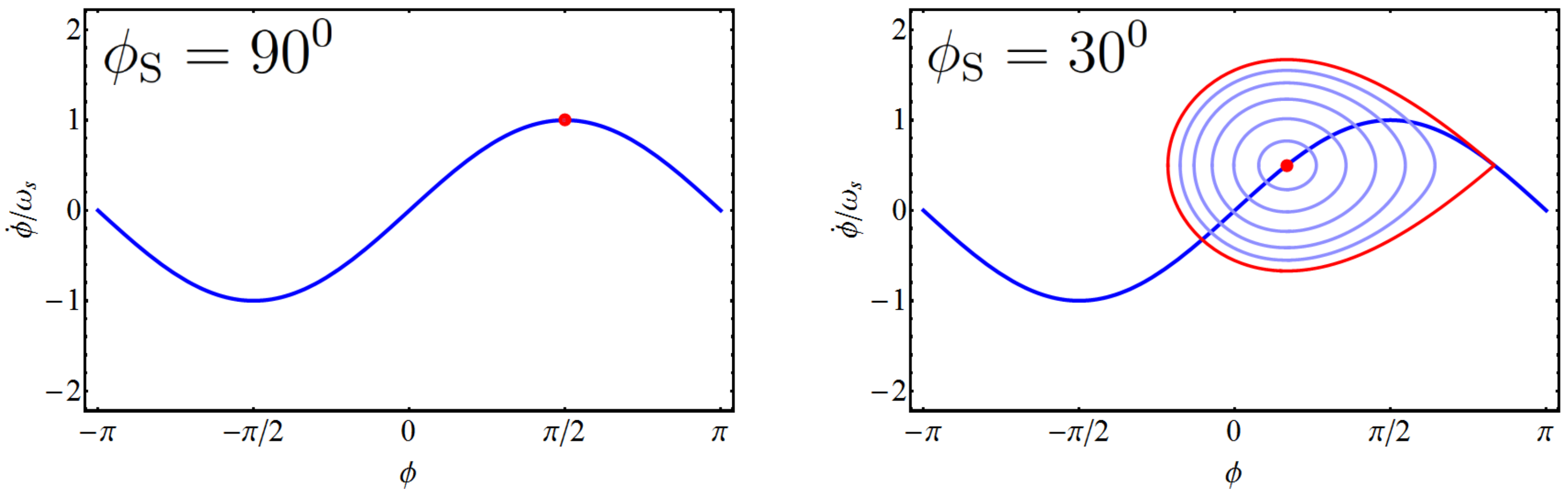
# Example: CERN PS - choice of RF voltage

→ **Energy gain per turn defined by size and ramp rate**

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

→ **At 2.3 T/s ramp rate: ~100 keV gain per turn**

→ **Just sufficient to accelerate synchronous particle**

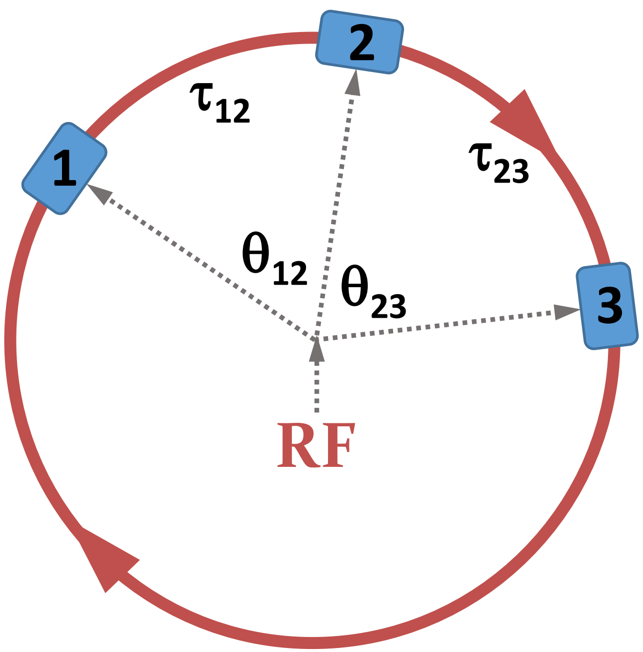



→ **Over-voltage for bucket area:** $V_{\text{RF}} = \frac{1}{\sin\phi_S}\frac{\Delta E}{q} \simeq 200 \text{ kV}$

# Example: CERN PS - choice of RF harmonic

→ **Operate RF stations in phase with respect to beam**

→ **Use common RF signal**




- **Time of flight, $\tau_{pq}$ between RF cavities:**

→ **Multiple of RF period**

→ $\tau_{\mathrm{pq}} = n \cdot T_{\mathrm{RF}} = n/hT_{\mathrm{rev}}$

$$\theta_{\mathrm{pq}} = n \cdot 2\pi/h$$

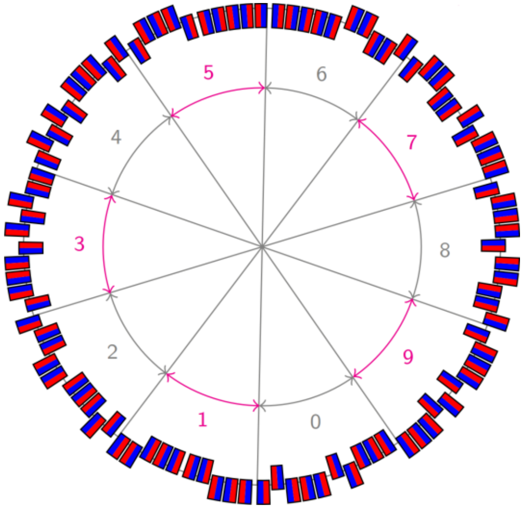
→ **RF stations must be located an multiples of $2\pi/h$**

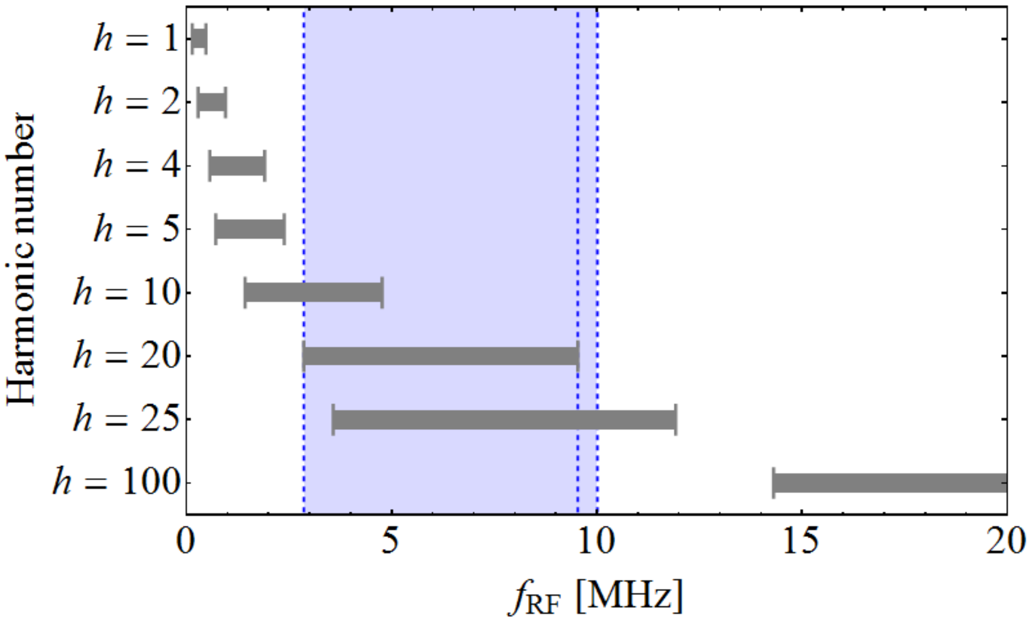
# Example: CERN PS - choice of harmonic

→ **Main elements: 100 bending magnets**

→ **100 possible location for RF stations in-between**

→ **100 = 2 · 2 · 5 · 5, hence divisible by 2, 4, 5, 10, 20, 25, 50**




→ **Distribute total RF voltage over many cavities**

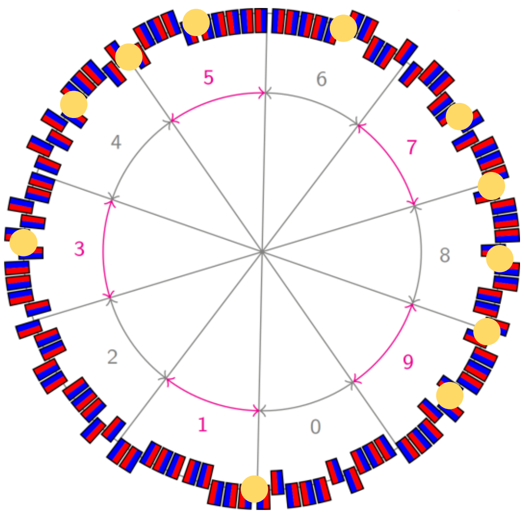
→ **Possible harmonic numbers 20 or 25 → *h* = 20 retained**

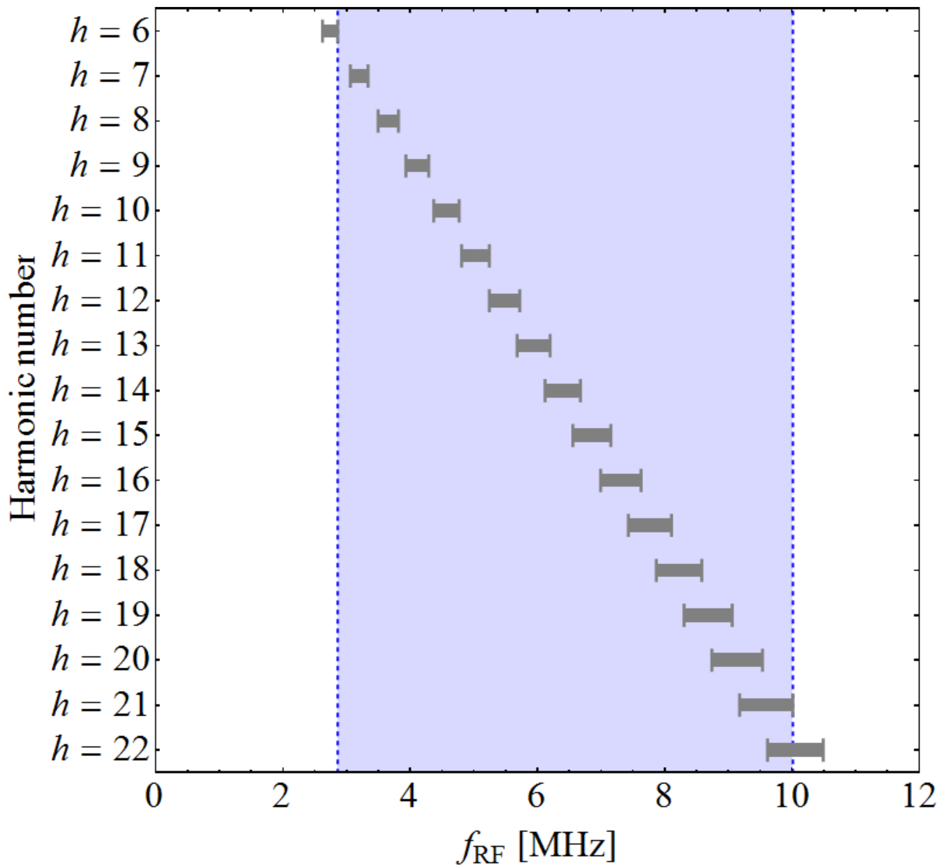
# Example: CERN PS choice of harmonic

→ **Distance between RF stations: multiples of 2π/20**

→ **No need to use common RF with todays technology**

→ **Injection energy at 1.4 GeV (2 GeV) → 10% (5%) swing**




→ **Early design choices based on *h* = 20**

→ **Today's flexibility**

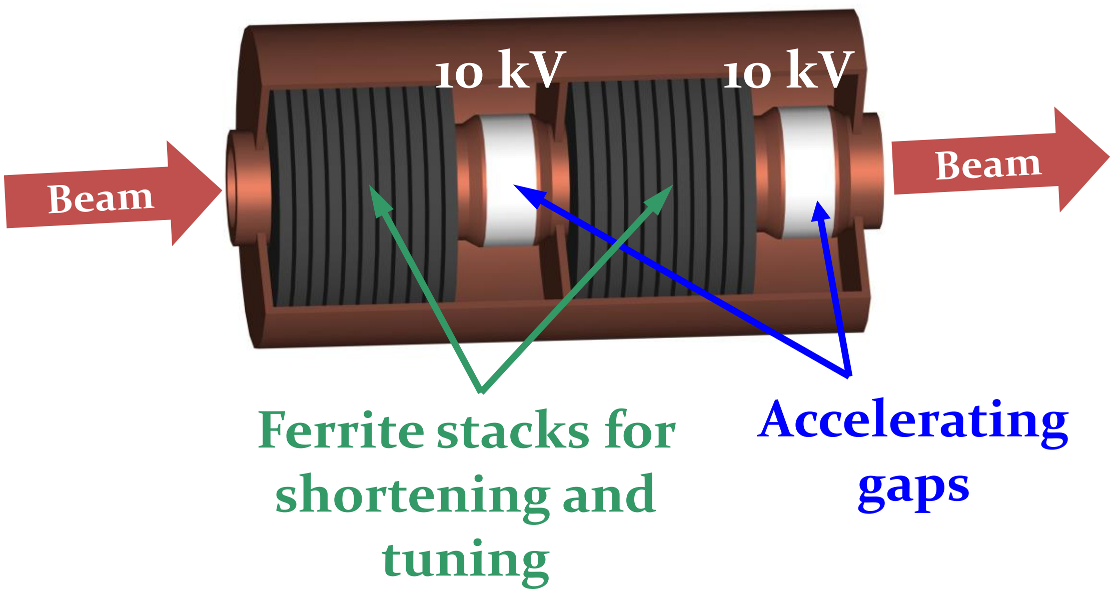
# Example: CERN PS choice of cavity

→ **RF system parameters:**

| Parameter | |
|---|---|
| Harmonic, $h$ | 7..., 20, 21 |
| Frequency, $f_{RF}$ | 2.8-10 MHz |
| Voltage, $V_{RF}$ | 10 (+1) × 20 kV |

→ **Distribute voltage over 10 RF stations: 20 kV/cavity**

**Shortened λ/4 coaxial resonators with ferrite tuning**




# Electrons in the PS

- **As an injector of LEP electrons were accelerated in the PS to *E* = 3.5 GeV**
- **Is the RF system for acceleration of protons usable?**

$$\Delta E_{\mathrm{turn}} = \frac{e^2}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho} \simeq 190\ \mathrm{keV/turn}$$

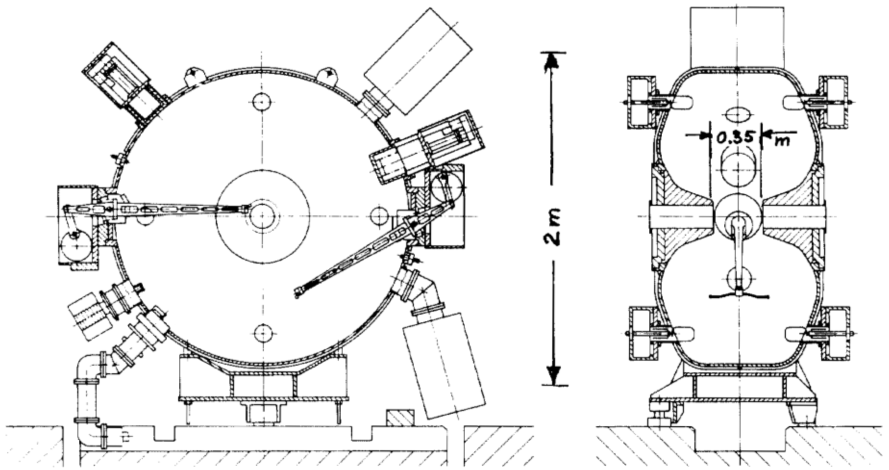
$\epsilon_0 \simeq 8.85 \cdot 10^{-12}\ \mathrm{As/Vm}$

→ **Bucket area too small and bunches too long at 3.5 GeV**

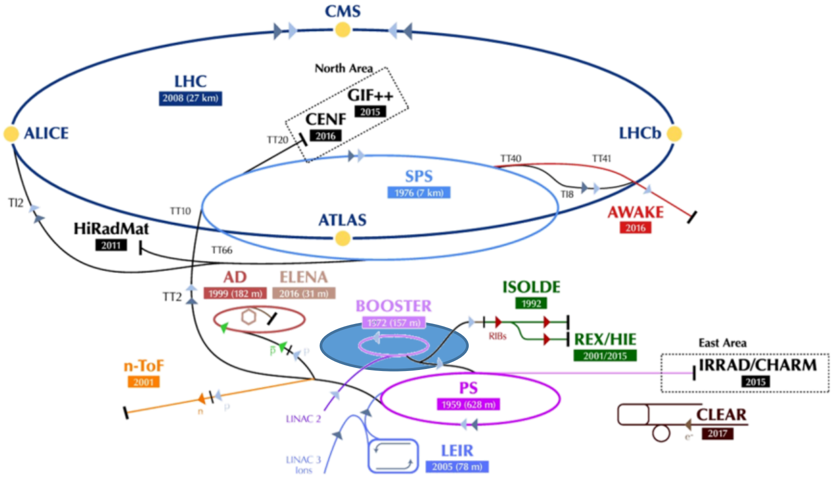
→ **Optimized RF system for electron acceleration**

| Parameter | |
|---|---|
| Harmonic, $h$ | 240 |
| Frequency, $f_{RF}$ | **114 MHz** |
| Voltage, $V_{RF}$ | **1 MV** |

**(5 × more than 10 MHz cavities)**

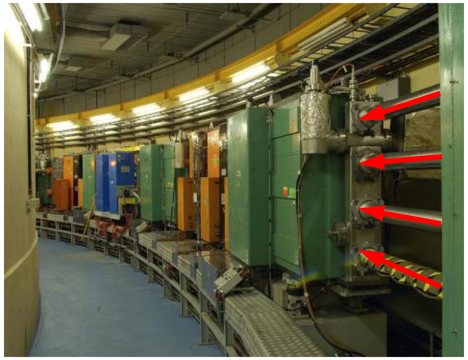


# PS Booster


CMS
LHC
2008 (27 km)
North Area
GIF++
2015
CENF
2016
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT66
AD
1999 (182 m)
ELENA
2016 (31 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1992
RIBs
REX/HIE
2001/2015
East Area
IRRAD/CHARM
2015
n-ToF
2001
PS
1959 (628 m)
LINAC 2
CLEAR
2017
LEIR
2005 (78 m)
LINAC 3
Ions

# Example: RF System for CERN PS Booster

- **PS injector synchrotron**
  - → $2\pi R_{PSB} = 2\pi R_{PS}/4$
  - → **Sandwich of 4 rings**
  - → **Total length as PS circumference**

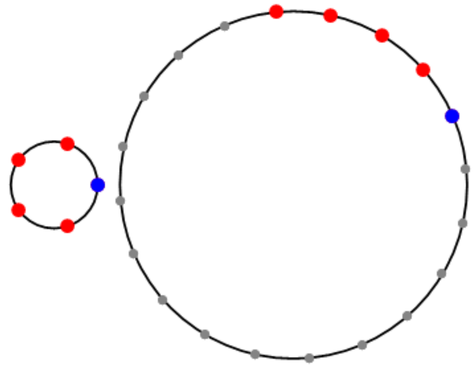


| Parameter | Value |
|---|---|
| Circumference, $2\pi R$ | $2\pi \cdot 25$ m = 157 m |
| Acceleration time, $t_{cycle}$ | ~0.5 s |
| Maximum ramp rate, $dB/dt$ | 2.3 T/s |
| Injection energy, $E_{kin}$ | **50/160 MeV** |
| Flat-top energy, $E_{kin}$ | **0.8/1.0/1.4/2.0 GeV** |

| | |
|---|---|
| **Revolution frequency at injection, $f_{rev,inj}$** | **0.6/1 MHz** |
| **at ejection, $f_{rev,ej}$** | **1.81 MHz** |
| **Relative frequency swing** | **3** |

# Example: CERN PS Booster (PSB)

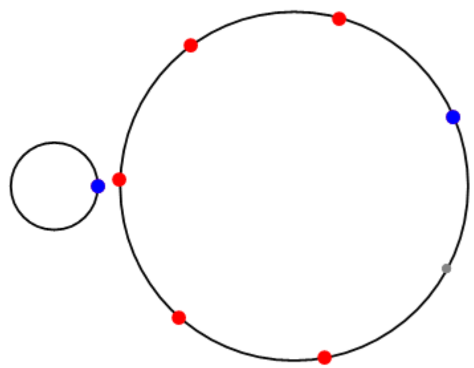
- **Circumference** $2\pi R_{\mathrm{PSB}} = 2\pi R_{\mathrm{PS}}/4 = 157$ m
- **Initial design as PS injector**



$$f_{\mathrm{RF,PSB}} = f_{\mathrm{RF,PS}}$$

$$h_{\mathrm{PSB}} = h_{\mathrm{PS}}/4 = 5$$

→ **Modifications as pre-injector to LHC:**



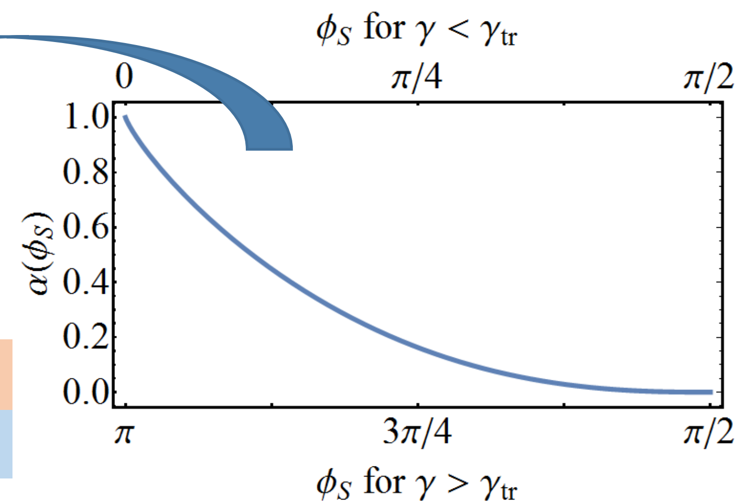
| Parameter | |
|---|---|
| Harmonic, $h$ | 1 or/and 2 |
| Frequency, $f_{\mathrm{RF}}$ | 0.6/1...1.8 MHz |
| Voltage, $V_{\mathrm{RF}}$ | 8...20 kV |

# Example: CERN PSB (single harmonic, $h = 1$)



**Bucket area:**

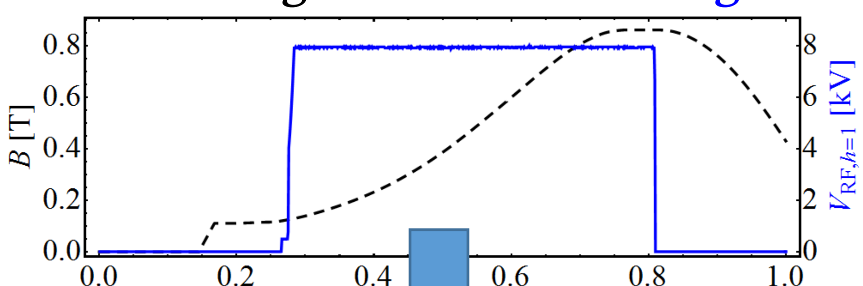
$$A_{\text{bucket}} = \frac{8\sqrt{2}}{h\omega_0}\sqrt{\frac{E\beta^2 qV}{\pi h|\eta|}} \cdot \alpha(\phi_S)$$

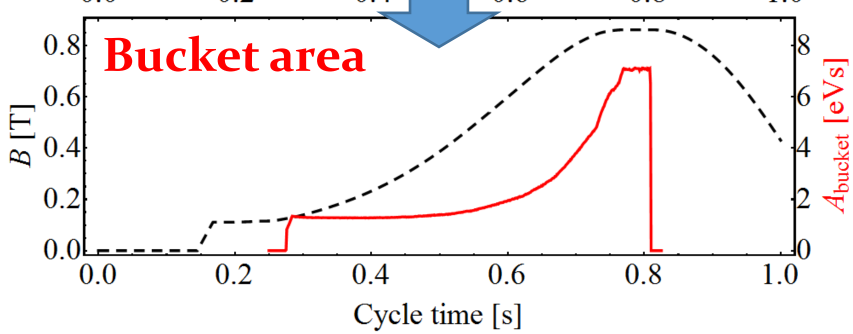



**Depends on:**

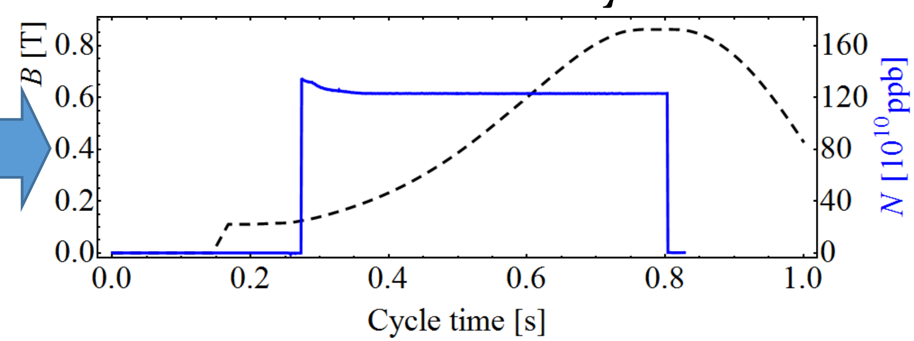
- **Bending field, *B* and ramp rate *dB/dt***
- **RF voltage, *V***

**Bending field and RF voltage**

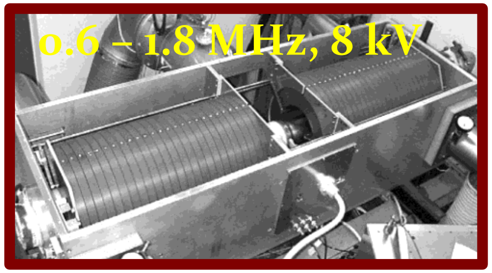


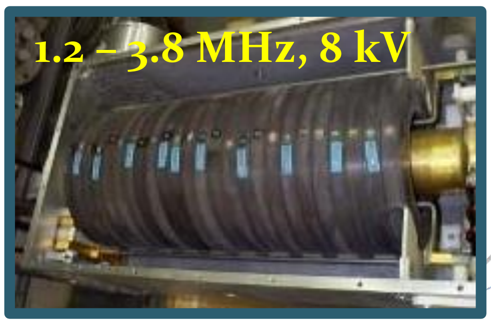

**Beam intensity**



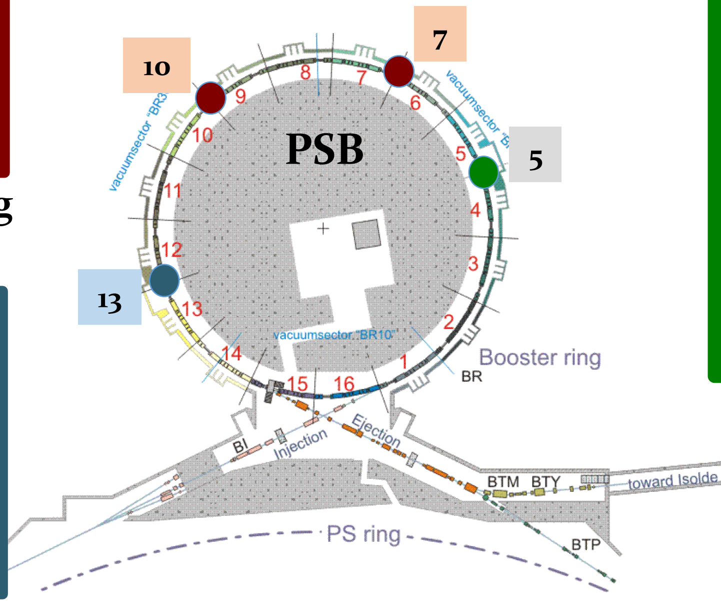
# RF systems in the PS Booster




Acceleration and splitting




Acceleration and splitting



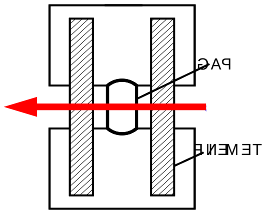


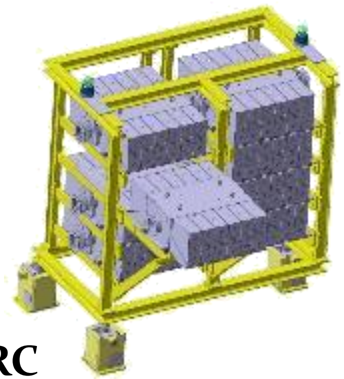
Controlled longitu-dinal blow-up

→ **4 rings** with **3 cavities**

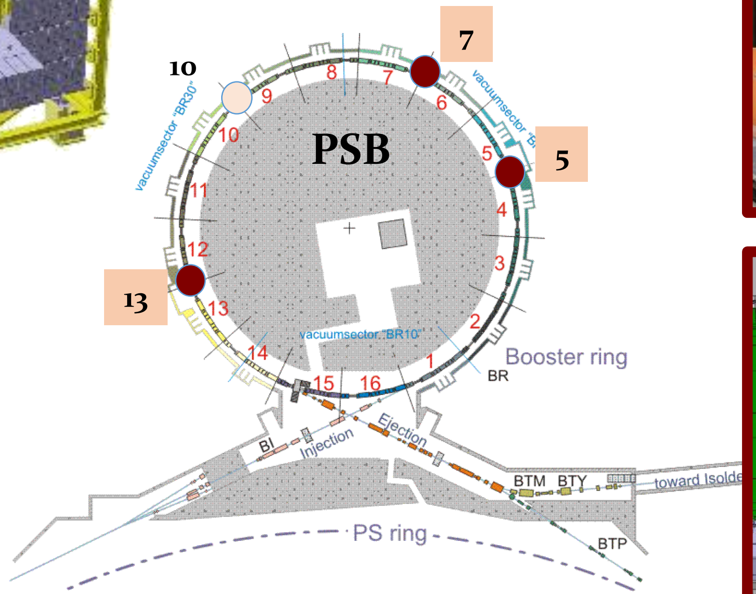
→ PS Booster RF systems based on tuned ferrite cavities

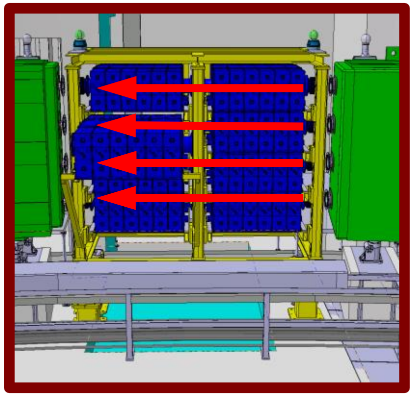
# RF systems in the PS Booster after upgrade

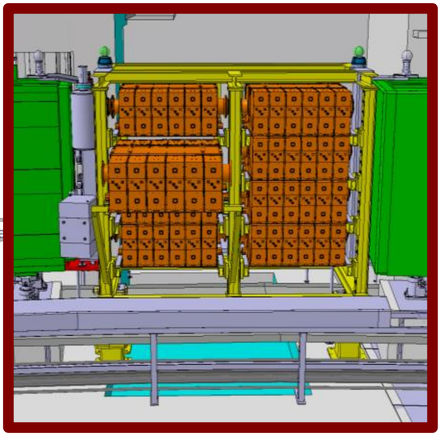




Collaboration with KEK/JPARC



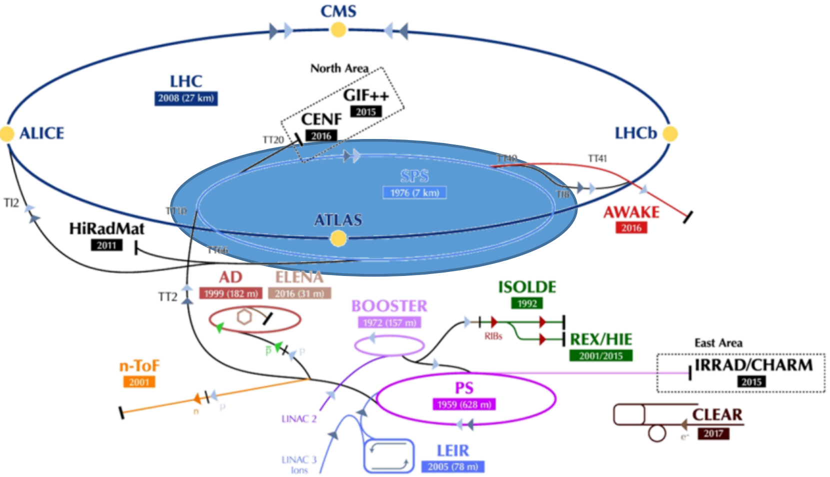


→ New wide-band cavities covering *h* = 1, 2, and higher

→ Based on innovative Finemet material

→ Much increased flexibility

# Super Proton Synchrotron



# Example: RF System for CERN SPS

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

→ **Needs significantly more RF voltage: several MV**

| Parameter | Value |
|---|---|
| Circumference, $2\pi R$ | $2\pi \cdot$ **1.1 km** = 6.91 km |
| Acceleration time, $t_{\text{cycle}}$ | ~4 s |
| Maximum ramp rate, $dB/dt$ | ~0.74 T/s |
| Injection Energy, $E_{\text{tot}}$ | initially **10 GeV** |
| Flat-top energy, $E_{\text{tot}}$ | **450 GeV** |

| | |
|---|---|
| **Relativistic beta, $\beta = v/c$ at injection** | **0.9955885** |
| **at flat-top** | **0.9999978** |
| **Relative frequency swing** | **0.44%** |

# Example: SPS - choice of RF harmonic

| Harmonic number should be multiple of | |
|---|---|
| Revolution frequency ratio of PS and SPS | 11 |
| Acceleration harmonic in the PS | 20 |
| Super-periodicity of SPS | 6 |

$\rightarrow$ **Looking for multiples of 660**

| $h$ | 660 | 1320 | 1980 | 2640 | 3300 | 3960 | 4620 | 5280 | 5940 |
|---|---|---|---|---|---|---|---|---|---|
| $f_{RF}$ [MHz] | 29 | 57 | 86 | 115 | 143 | 172 | 200 | 229 | 258 |

| Lower RF frequency | Higher RF frequency |
|---|---|
| • Total bucket area: $$hA_B \propto \sqrt{\frac{V}{h}}$$ $\rightarrow$ Insufficient at inj. for $h > 5500$ | • Mechanically smaller cavities<br>• Higher shunt impedance easier to achieve $\rightarrow$ power efficiency |
| • Magnetic tuning only possible at $f_{RF} < 100$ MHz) | • Higher breakdown voltages |

# Example: SPS choice of RF cavities

- **Requirements:**

| Parameter | |
|---|---|
| Harmonic, $h$ | 4620 |
| Frequency, $f_{RF}$ | **200 MHz** |
| Bandwidth, $\Delta f_{RF}$ | **0.44%** |
| Voltage, $V_{RF}$ | **Few MV** |

## How to build such an RF system?

→ **Cavity resonator would need tuning or low** $Q < 1/0.44\% \approx 230$

**Mechanically tuned cavity** ✗

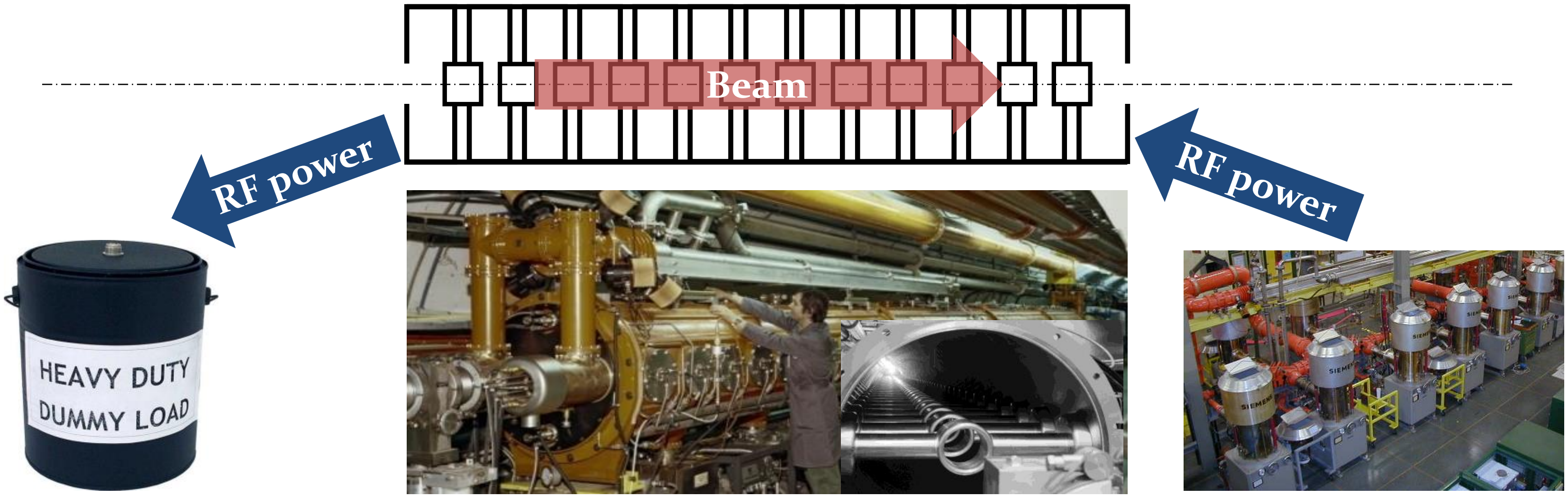
**Avoid cycling mechanics in vacuum** ✗

**Travelling wave structure**

**High voltage in moderate bandwidth**

# Example: SPS travelling wave cavities

→ **Multi-cell structure operated as a waveguide**



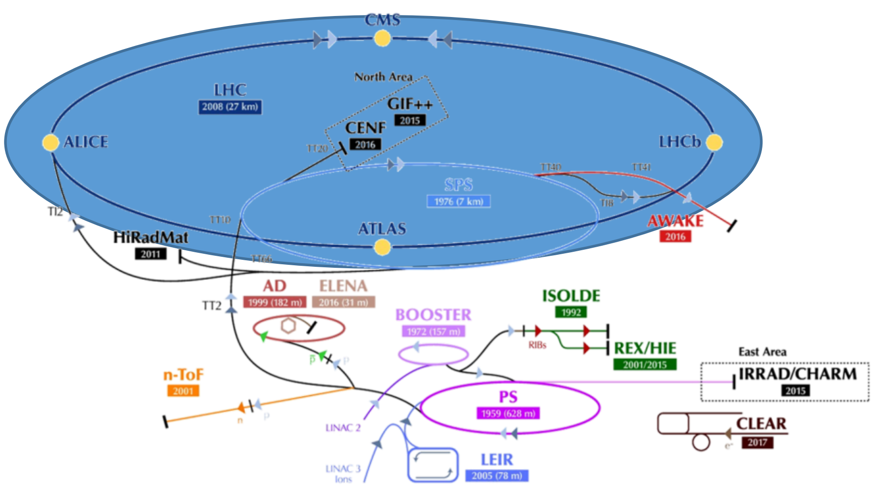

→ **Sufficient bandwidth without mechanically moving parts**

→ **Travelling wave structure always matched to amplifier**

→ **Beam takes power it needs from the waveguide**

$$P_{\text{load}} = P_{\text{in}} - P_{\text{beam}} - P_{\text{loss}}$$

# Large Electron Positron and Hadron Colliders



# Ex.: RF against synchrotron radiation in LEP



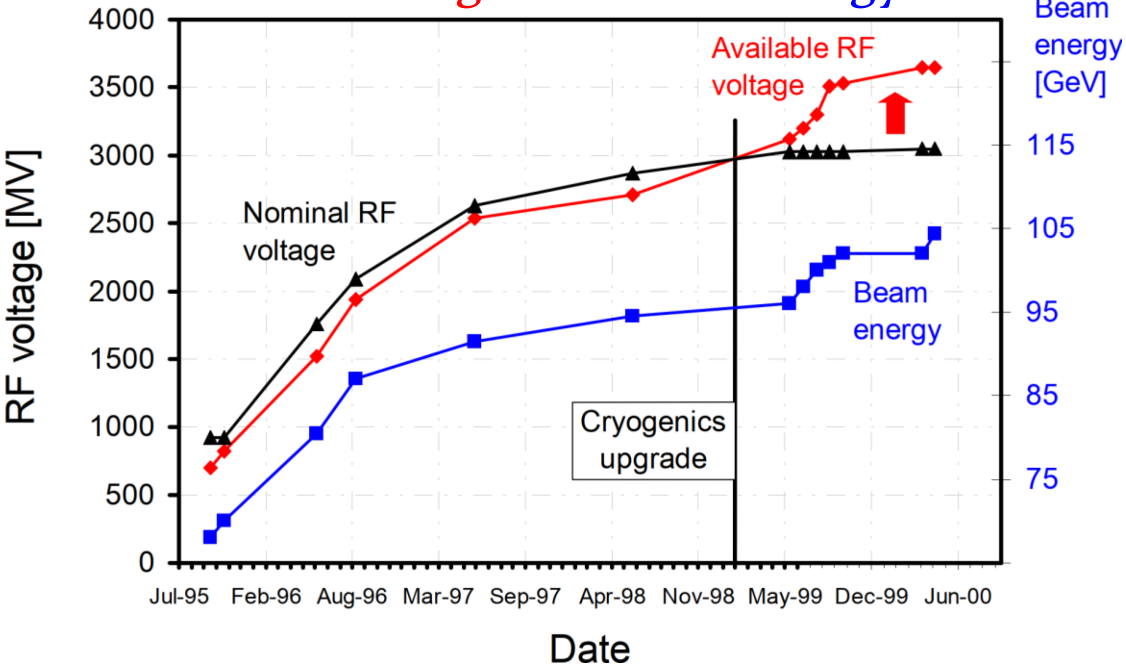
- **LEP energy was entirely dominated by synchrotron radiation**
- **At $E$ = 100 GeV:**

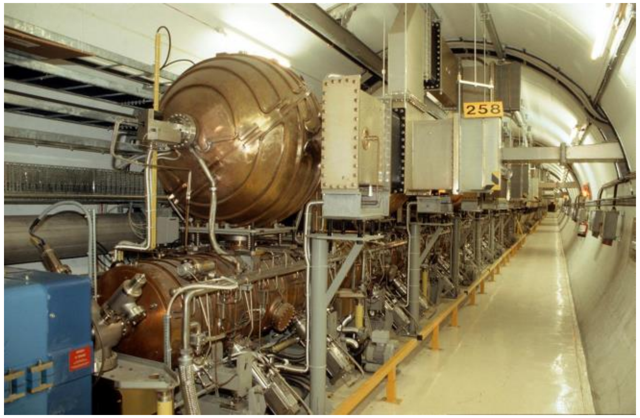
$$\Delta E_{\text{turn}} = \frac{e^2}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho} \simeq 3\ \text{GeV/turn}$$

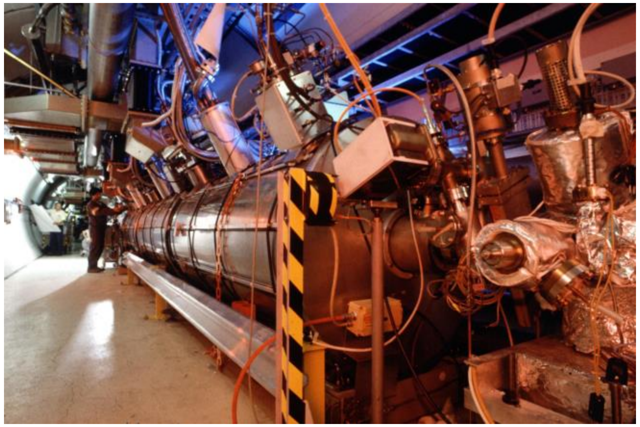
$$\epsilon_0 \simeq 8.85 \cdot 10^{-12}\ \text{As/Vm}$$

→ **About 3 % of beam energy lost each turn**

**RF voltage and beam energy**



# Example: LHC

- **LHC maximum energy and ramp rate limited by super-conducting bending magnets: 20 minutes ramp time**

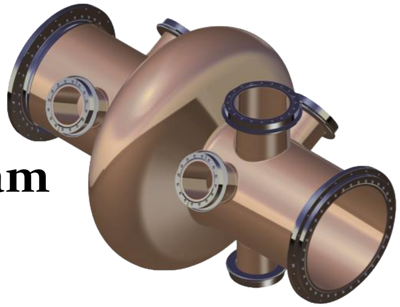
**→ Average energy gain per turn only $\Delta E_{turn} \approx 500$ keV/turn**

**→ Revolution frequency stays almost constant**

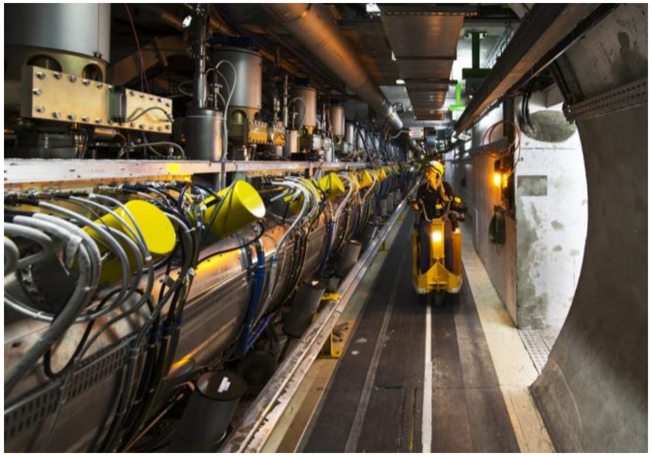
**→ RF voltage required to keep bunches short**

**→ Superconducting cavities chosen to reduce beam induced voltage (small R/Q)**

**8× per beam**



| Parameter (per beam) | |
|---|---|
| Harmonic, $h$ | 35640 |
| Frequency, $f_{RF}$ | 400.8 MHz |
| Voltage, $V_{RF}$ | 16 MV |



# Summary

- **Design of RF system for circular accelerator**
    1. **Start from accelerator parameters**
    2. **Define RF parameters based on beam requirements**
    3. **Chose RF system**

**→ Mostly several design options are possible**


Google

...is your friend!

# You will design an RF system (upgrade)

1. **Protons accelerator:** Upgrade of CERN SPS to 1.3 TeV
2. **Electron storage ring:** Energy and current upgrade of SOLEIL

# A big Thank You

**to all colleagues providing support, material and feedback**

**Simon Albright, Maria-Elena Angoletta, Philippe Baudrenghien, Thomas Bohl, Wolfgang Höfle, Erk Jensen, Alexandre Lasheen, Elena Shaposhnikova, Frank Tecker, Daniel Valuch, Manfred Wendt, Jörg Wenninger and many more…**

# Thank you very much for your attention!

# References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