Longitudinal Hands-on Calculations

RF System Design

H. Damerau, L. Intelisano,
F. Tecker, M. Zampetakis

CERN

The CERN Accelerator School

Introduction to Accelerator Physics

30 September 2024

Agenda of the afternoon

14h50 – 15h20	**Introduction to exercises**	
15h20 – 15h50	**RF system design**	
	Coffee break	
16h20 – 16h35	**Intermediate wrap-up**	
16h35 – 17h40	**RF system design**	
17h40 – 18h25	**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

→ Continuous trajectories of particle motion

→ Deduce useful parameters for stable acceleration:

  → RF bucket
  → Synchrotron frequency
  → Stable phase
  → …

Study interaction between beam and RF

Complementary approaches for the same problem

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

Study interaction between beam and RF

Complementary approaches for the same problem

(Semi-)Analytical	Numerical: tracking
• Describe particle motion by **differential equations** → **Continuous trajectories** of particle motion → Deduce useful parameters for stable acceleration: → RF bucket → Synchrotron frequency → Stable phase → …	• Track particle parameters from turn to turn → Profit from **discretization of motion**: turn-by-turn, RF station-by-RF station → **No notion** of RF bucket, synchrotron frequency, stable phase, etc. → Follow **ensemble of particles to study evoluti… of bunch**
→ Classical … of longitudinal beam dynamics **Today**	→ … pproach **Tomorrow afternoon**

Objectives of longitudinal hands-on

1. Design RF system (upgrade)

`LongitudinalHandsOnRFSystemCalculations_empty.ipynb`

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

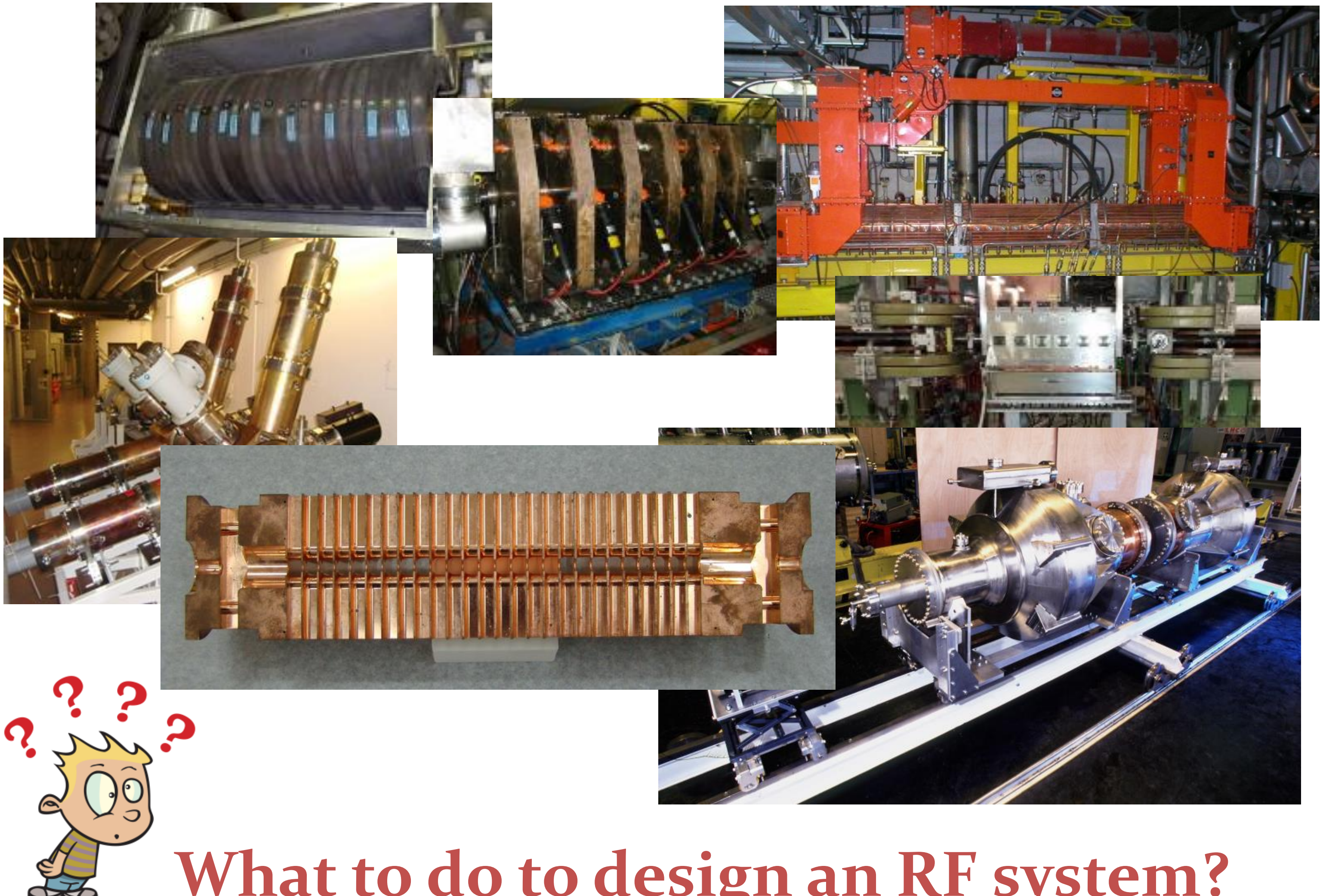
2. Play with longitudinal beam dynamics

`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

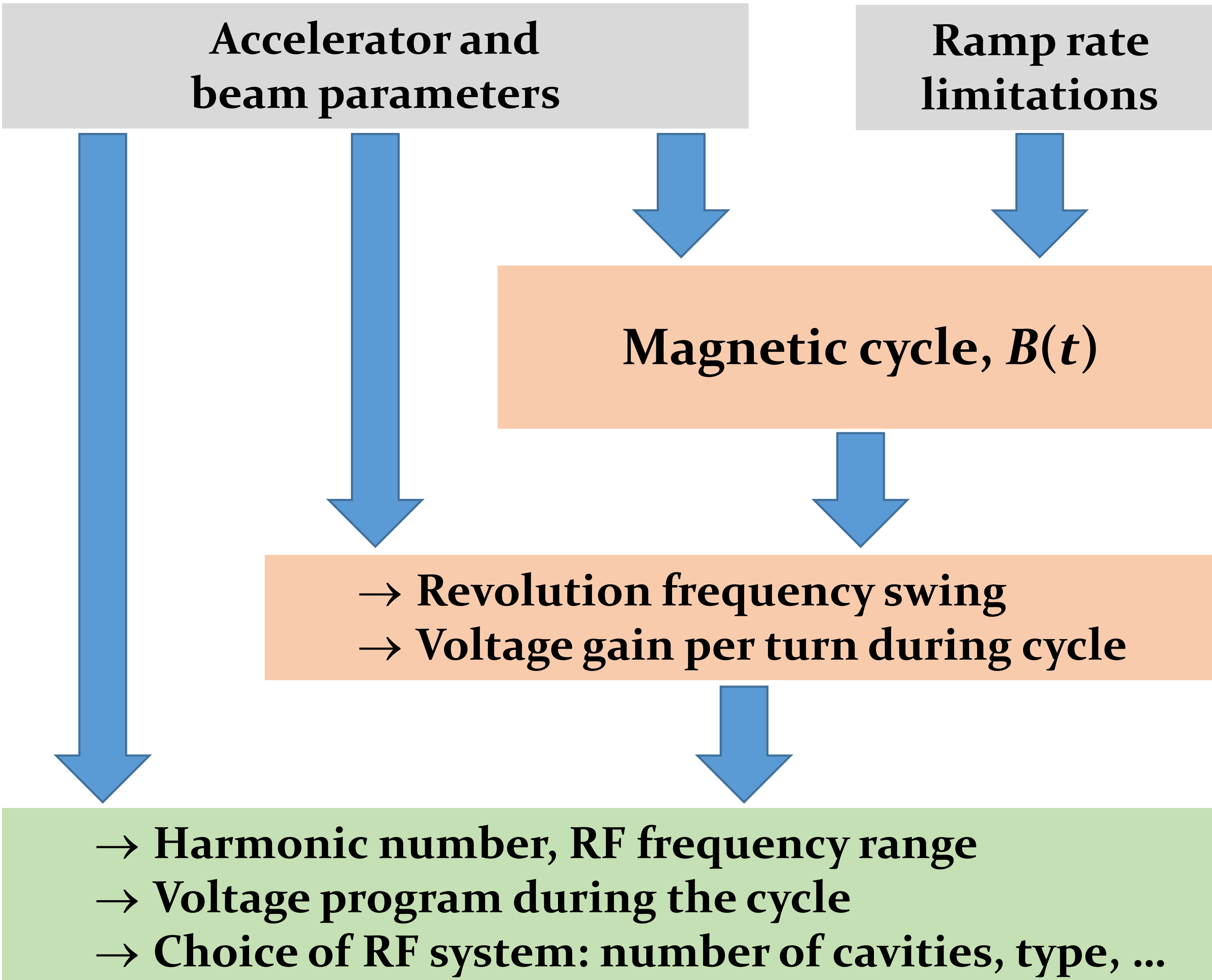
Introduction



What to do to design an RF system?

How to choose the right one?

Simplified design work flow

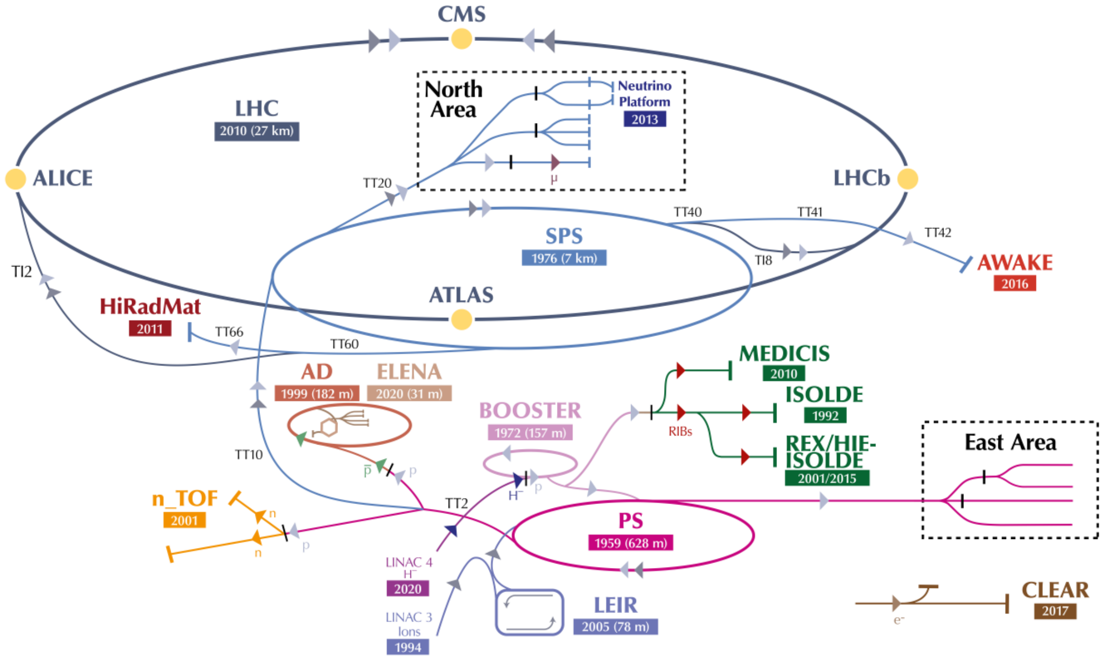


RF parameters of existing accelerators

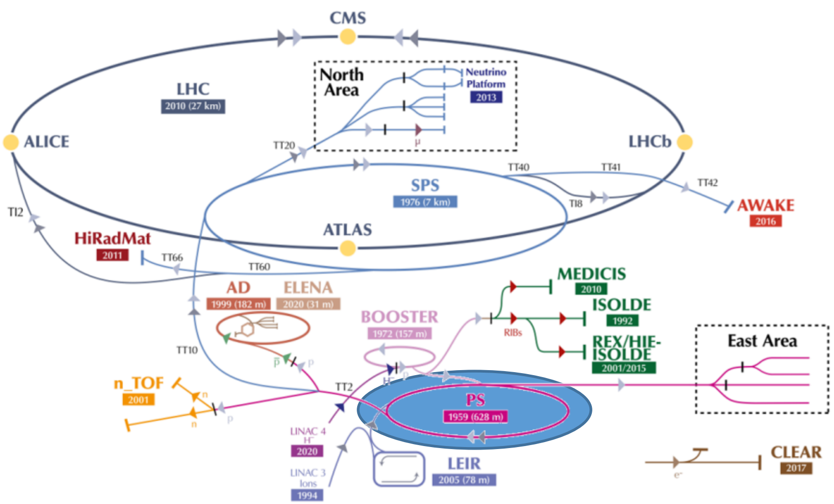
Try to follow design choices of existing accelerator

- **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**

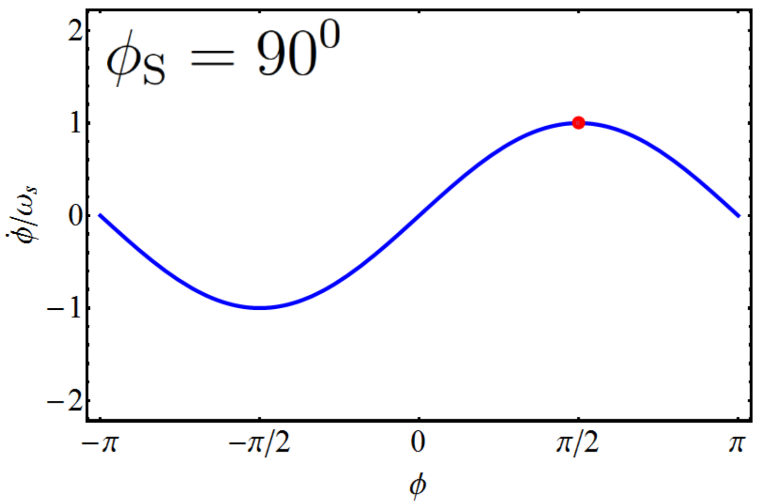
Example: CERN PS - choice of RF voltage

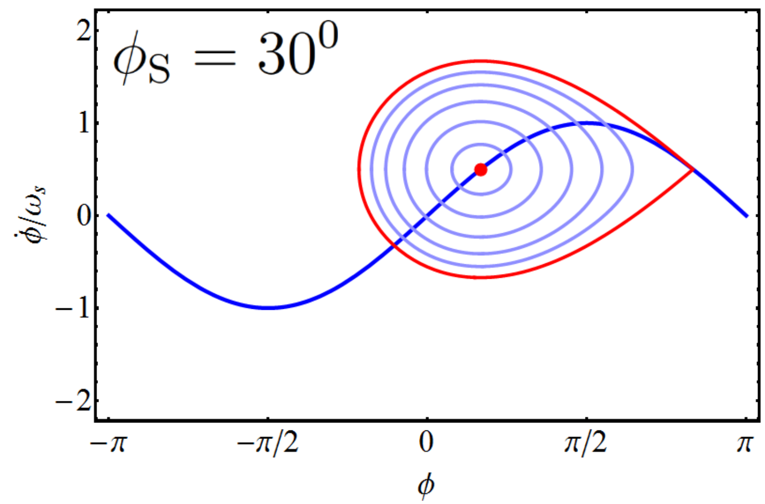
→ **Energy gain per turn defined by size and ramp rate**

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

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

→ **Just sufficient to accelerate synchronous particle**



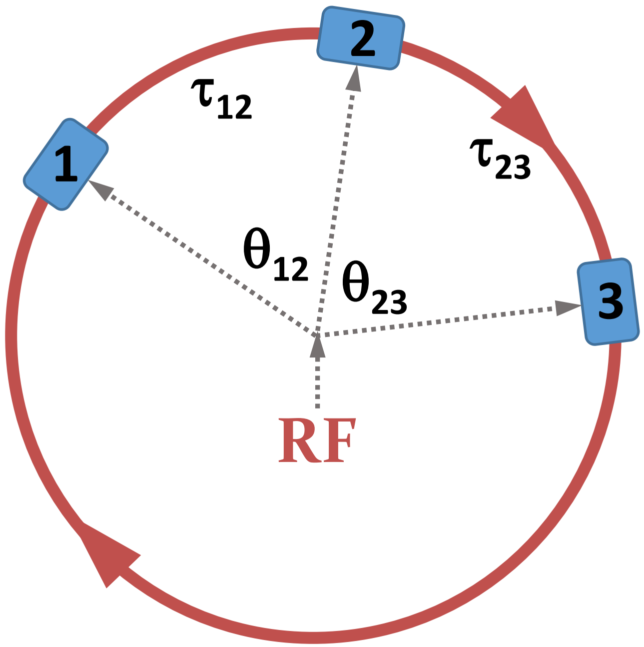


→ **Over-voltage for bucket area:** $V_{\text{RF}} = \frac{1}{\sin \phi_S} \frac{\Delta E}{q} \simeq 200 \text{ kV}$

Example: CERN PS - choice of RF harmonic

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

→ **Use common RF signal**



- **Time of flight, τ_{nm} between RF cavities:**

→ **Multiple of RF period**

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

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

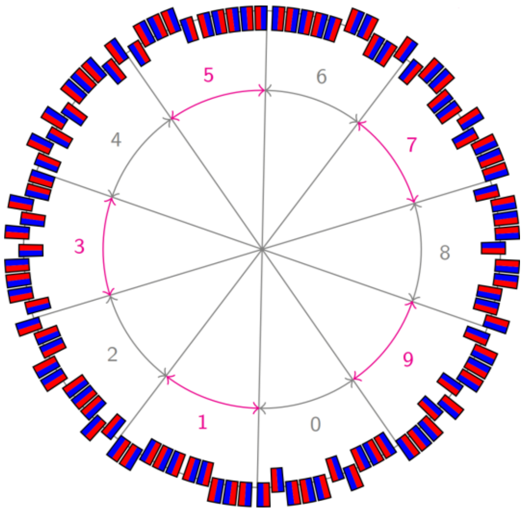
→ **RF stations must be located an multiples of 2π/*h***

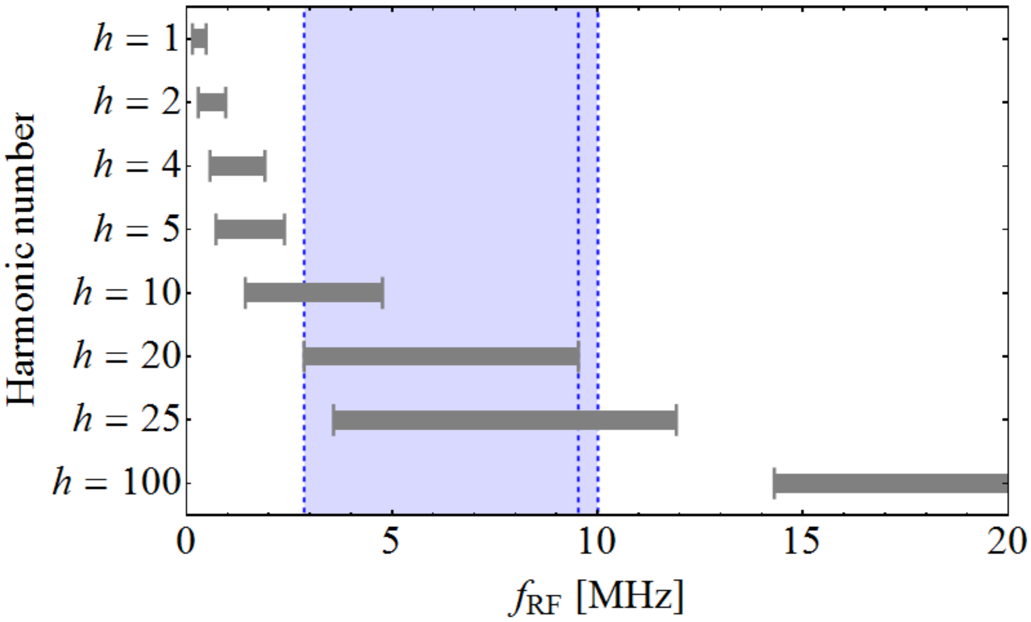
Example: CERN PS - choice of harmonic

→ **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**

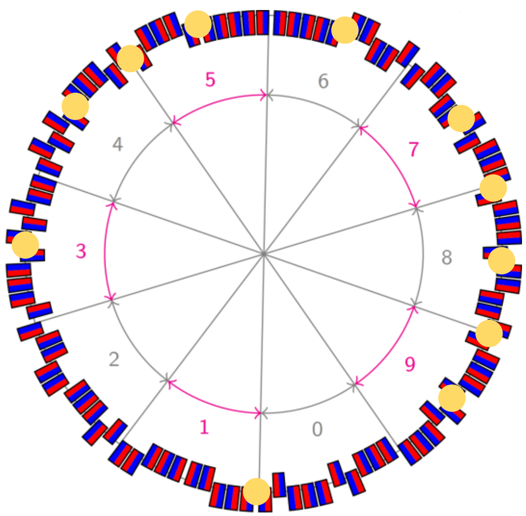
→ **Possible harmonic numbers 20 or 25 → *h* = 20 retained**

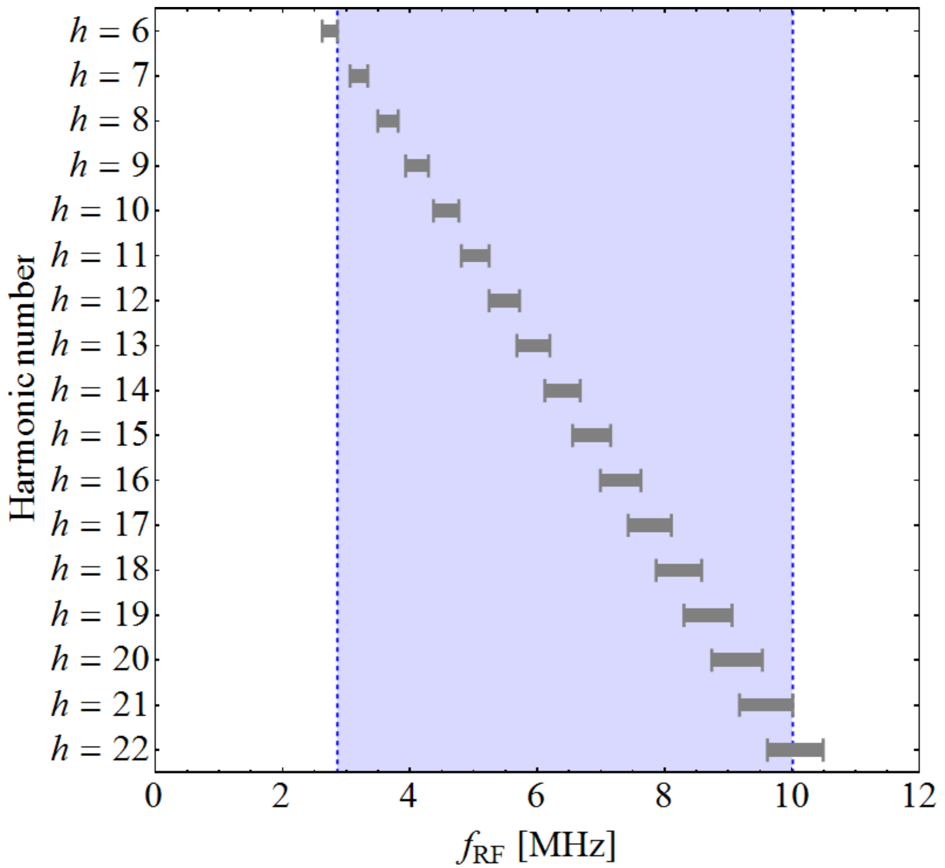
Example: CERN PS choice of harmonic

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

→ No need to use common RF with today's technology

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





→ Early design choices based on $h = 20$

→ Today's flexibility

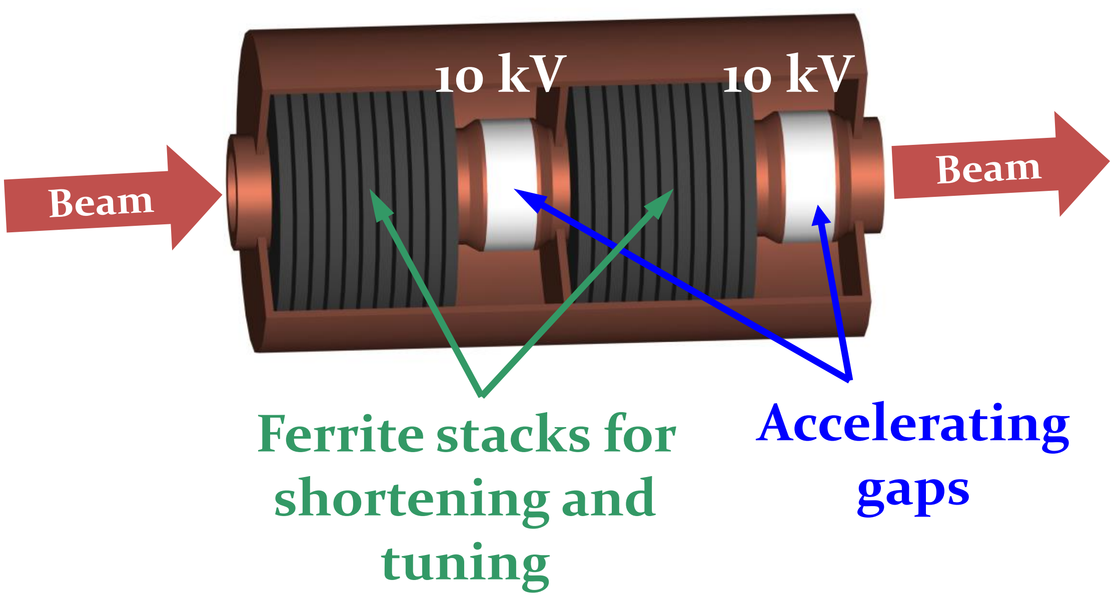
Example: CERN PS choice of cavity

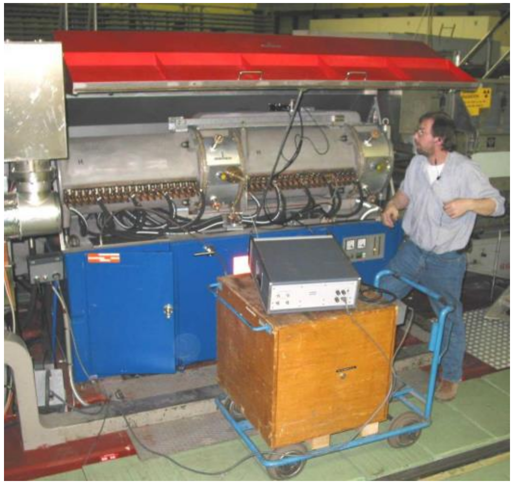
→ **RF system parameters:**

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?**

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

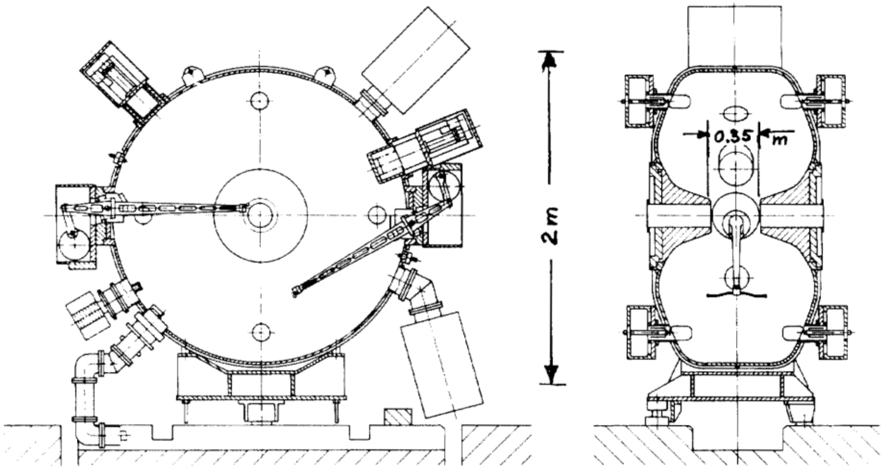
$$\epsilon_0 \simeq 8.85 \cdot 10^{-12} \text{ As/Vm}$$

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

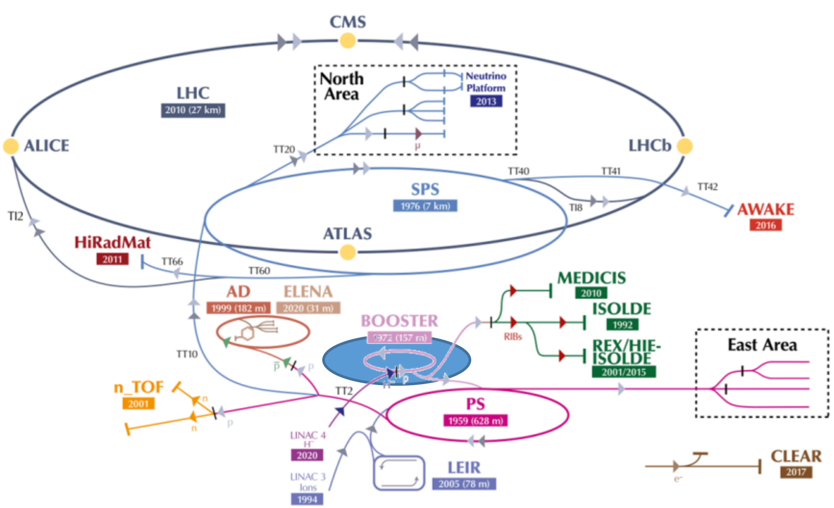
→ **Optimized RF system for electron acceleration**

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

(5 × more than 10 MHz cavities)

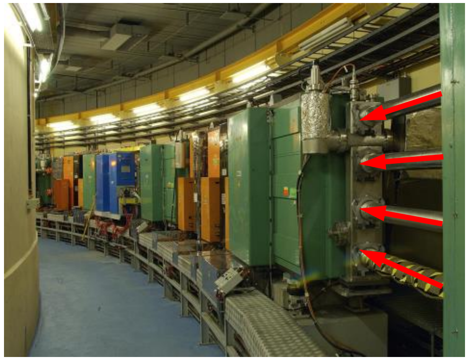


PS Booster


CMS
LHC
2010 (27 km)
North Area
Neutrino Platform
2013
ALICE
LHCb
TT20
TT40
TT41
TT42
AWAKE
2016
SPS
1976 (7 km)
TI8
TI2
ATLAS
HiRadMat
2011
TT66
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
MEDICIS
2010
ISOLDE
1992
REX/HIE-ISOLDE
2001/2015
RIBs
BOOSTER
TT10
East Area
n_TOF
2001
TT2
PS
1959 (628 m)
LINAC 4
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)
CLEAR
2017

Example: RF System for CERN PS Booster

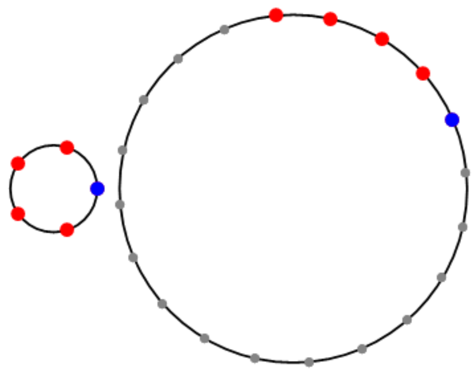
- **PS injector synchrotron**
  - **→ $2\pi R_{PSB} = 2\pi R_{PS}/4$**
  - **→ Sandwich of 4 rings**
  - **→ Total length as PS circumference**



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

Example: CERN PS Booster (PSB)

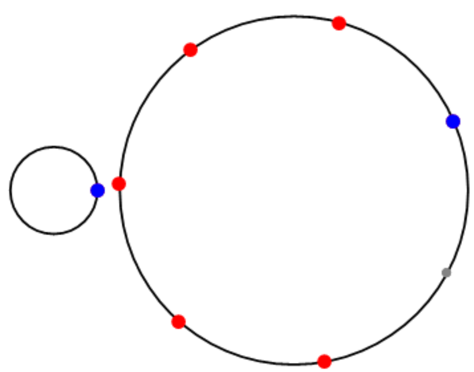
- **Circumference** $2\pi R_{\mathrm{PSB}} = 2\pi R_{\mathrm{PS}}/4 = 157$ m
- **Initial design as PS injector**



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

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

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

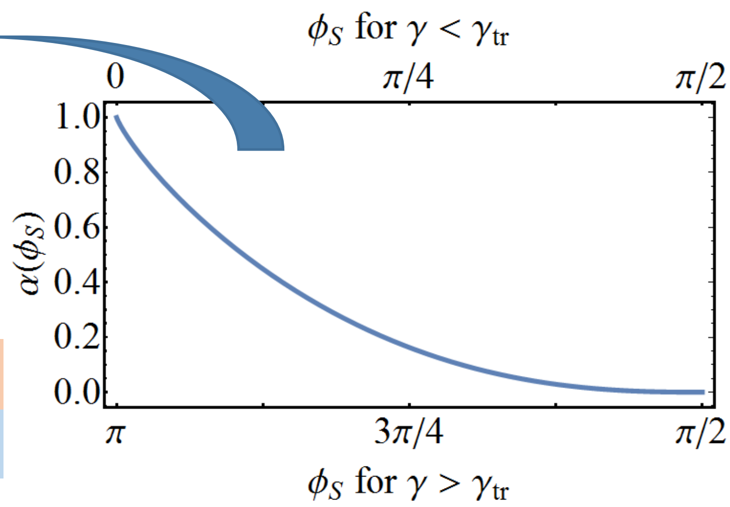


Parameter	
Harmonic, h	1 or/and 2
Frequency, f_{RF}	0.6/1...1.8 MHz
Voltage, V_{RF}	8...20 kV

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

Bucket area:

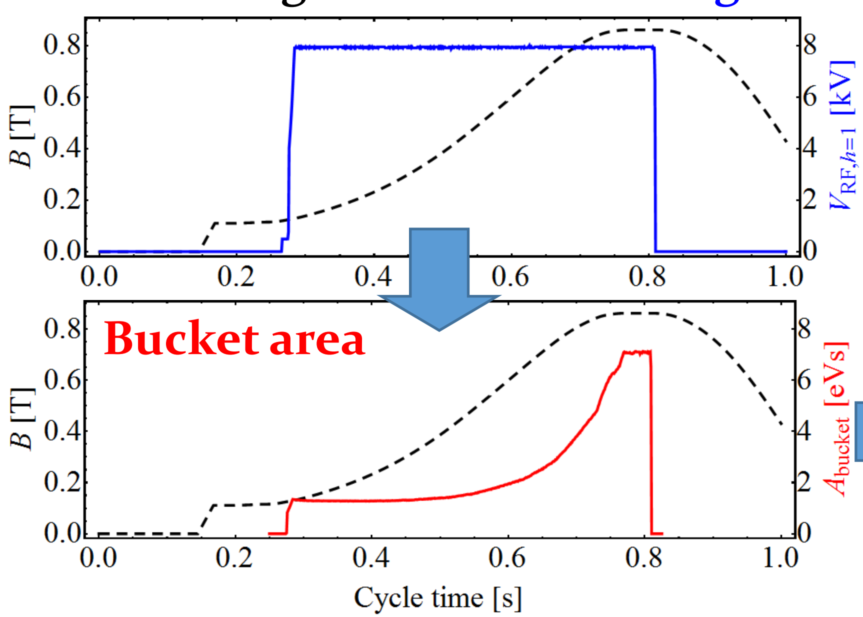
$$A_{\text{bucket}} = \frac{8\sqrt{2}}{h\omega_0}\sqrt{\frac{E\beta^2 qV}{\pi h|\eta|}} \cdot \alpha(\phi_S)$$



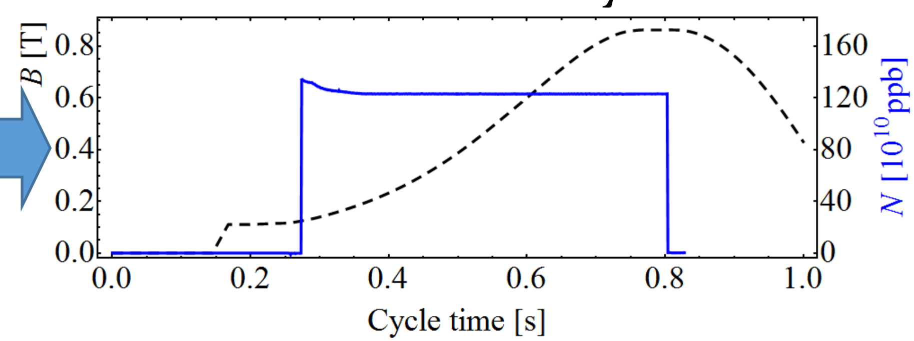
Depends on:

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

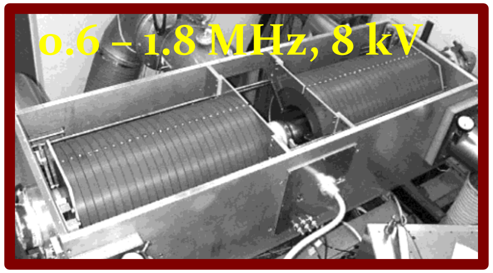
Bending field and RF voltage



Beam intensity

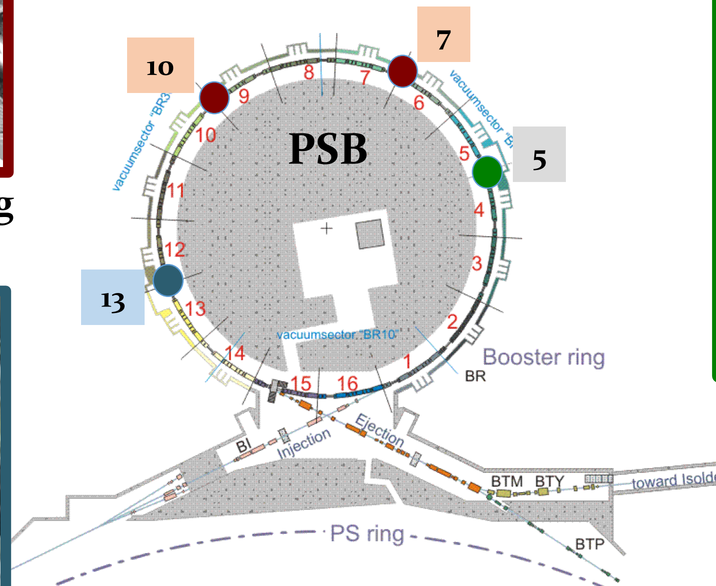


RF systems in the PS Booster



Acceleration and splitting

Acceleration and splitting

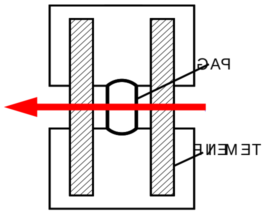


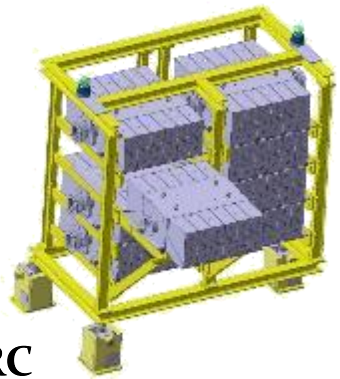
Controlled longitu-dinal blow-up

→ 4 rings with 3 cavities

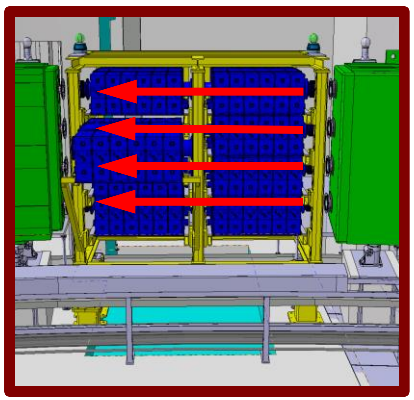
→ PS Booster RF systems based on tuned ferrite cavities

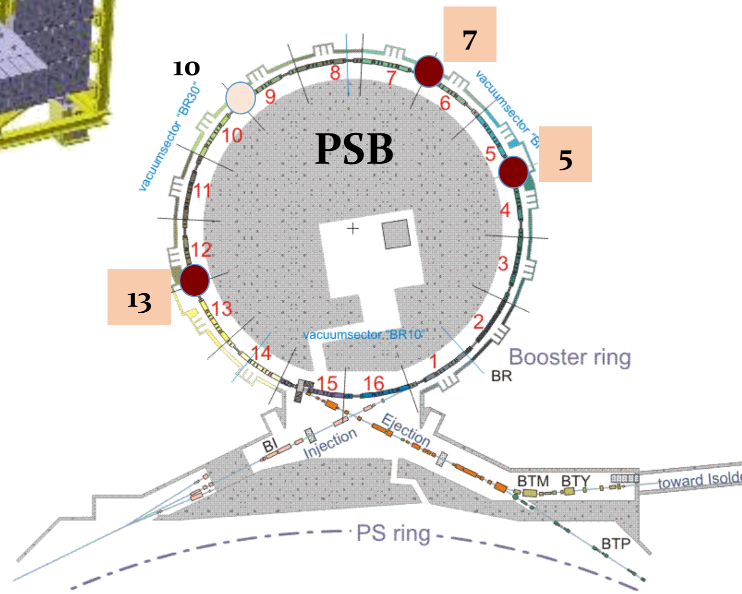
RF systems in the PS Booster after upgrade

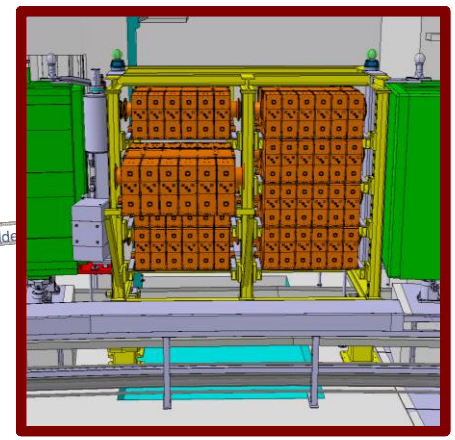




Collaboration with KEK/JPARC





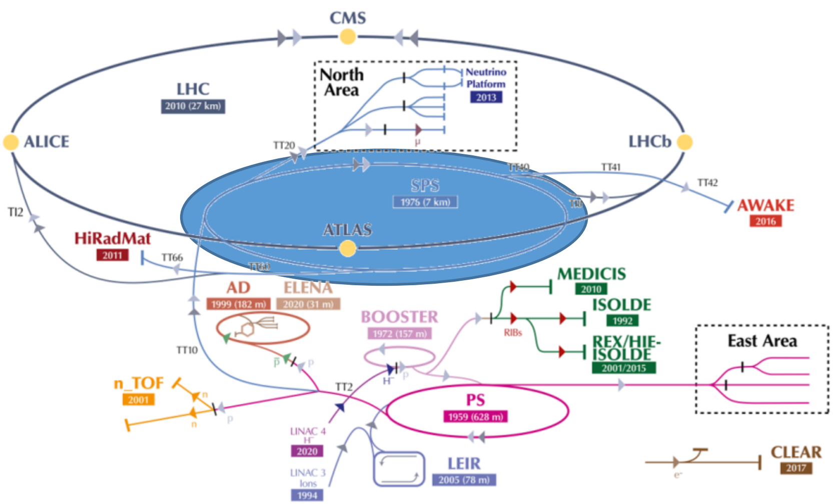


→ New wide-band cavities covering *h* = 1, 2, and higher

→ Based on innovative Finemet material

→ Much increased flexibility

Super Proton Synchrotron



Example: RF System for CERN SPS

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

→ **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_{cycle}	~4 s
Maximum ramp rate, dB/dt	~0.74 T/s
Injection Energy, E_{tot}	initially **10 GeV**
Flat-top energy, E_{tot}	**450 GeV**

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

→ **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

Example: SPS choice of RF cavities

- **Requirements:**

Parameter	
Harmonic, h	4620
Frequency, f_{RF}	**200 MHz**
Bandwidth, Δf_{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 ✗

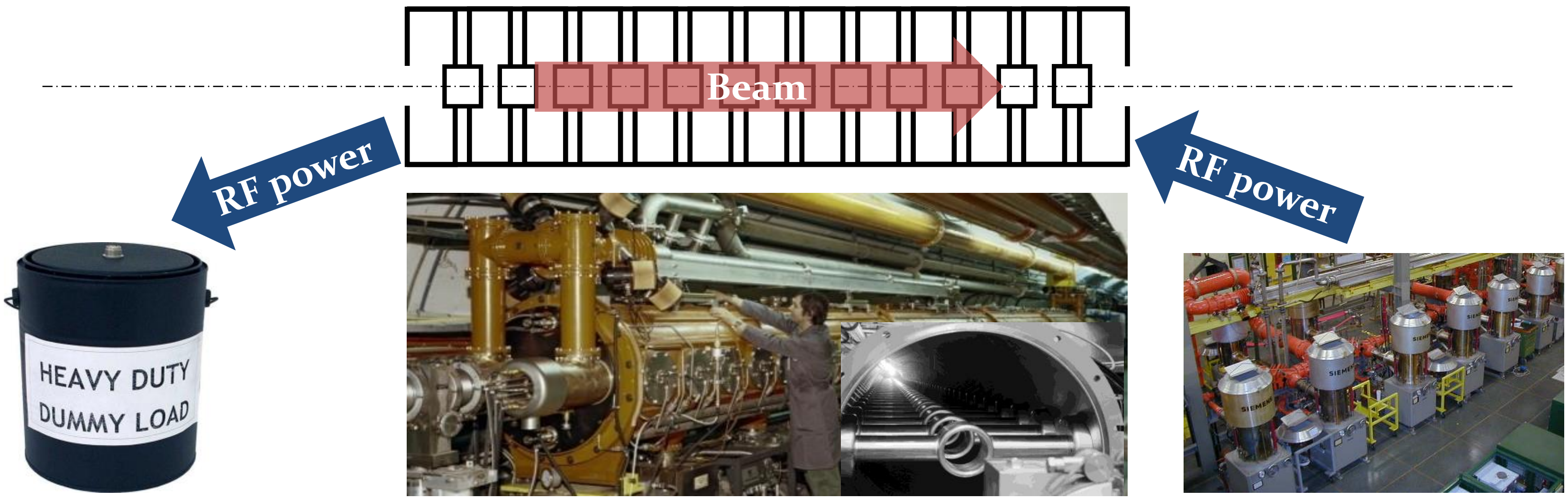
Avoid cycling mechanics in vacuum ✗

Travelling wave structure

High voltage in moderate bandwidth

Example: SPS travelling wave cavities

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



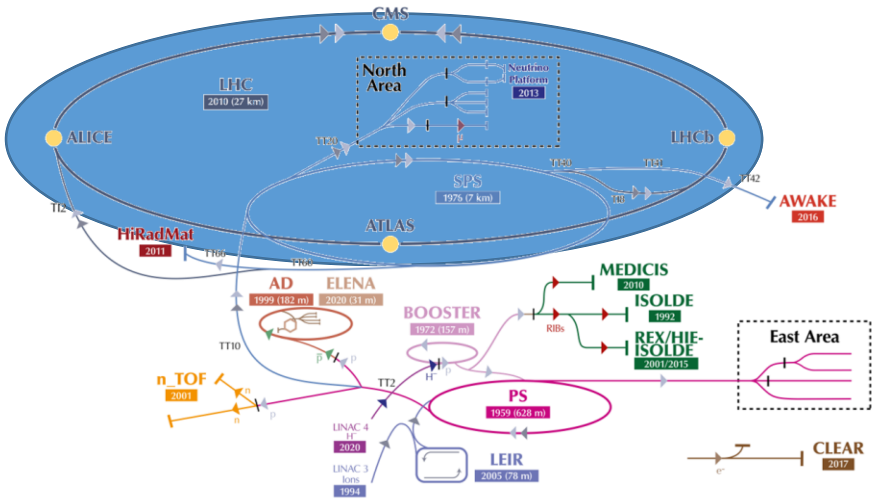
→ **Sufficient bandwidth without mechanically moving parts**

→ **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



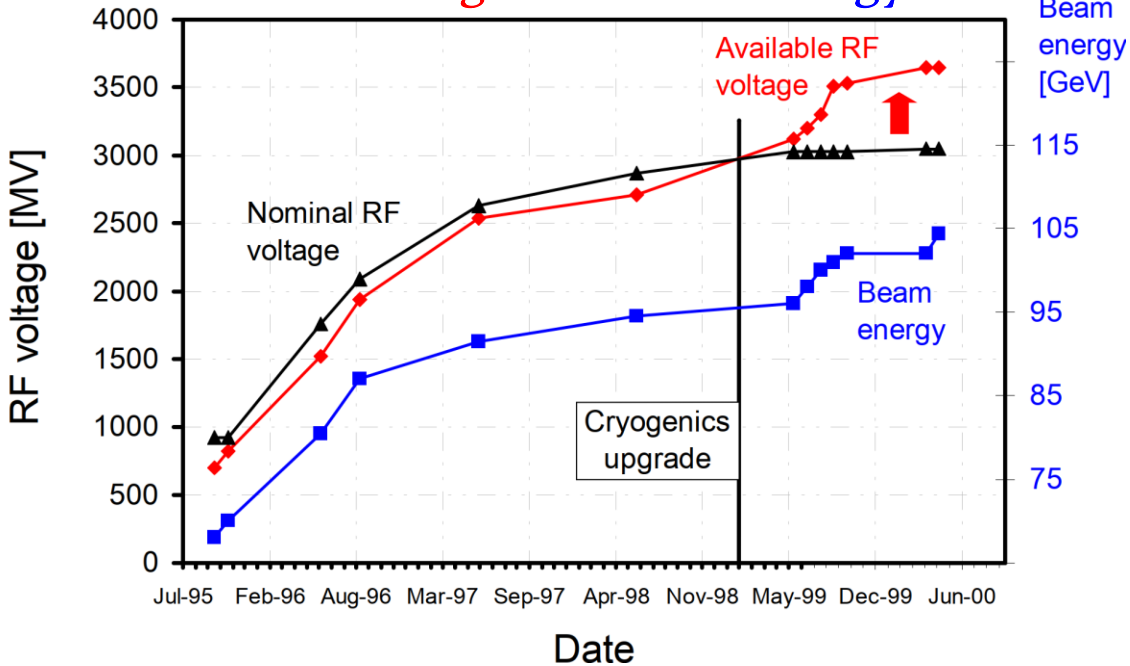
Ex.: RF against synchrotron radiation in LEP

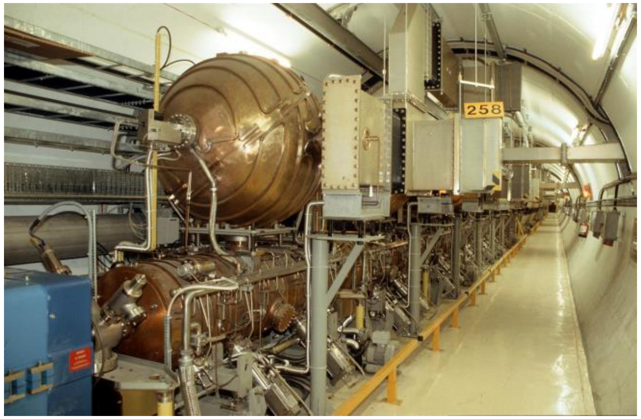
- **LEP energy was entirely dominated by synchrotron radiation**
- **At E = 100 GeV:** $$\Delta E_{\text{turn}} = \frac{e^2}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho} \simeq 3 \text{ GeV/turn}$$

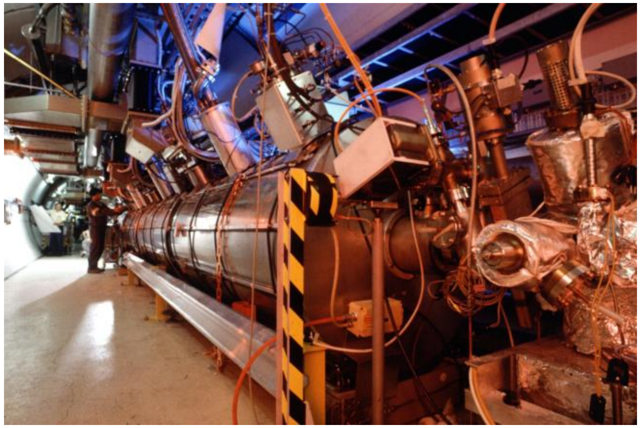
$\epsilon_0 \simeq 8.85 \cdot 10^{-12}$ As/Vm

→ **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**

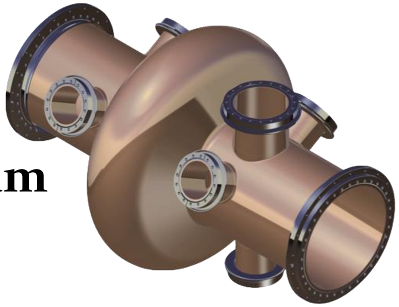
→ **Average energy gain per turn only $\Delta E_{\text{turn}} \approx 500$ keV/turn**

→ **Revolution frequency stays almost constant**

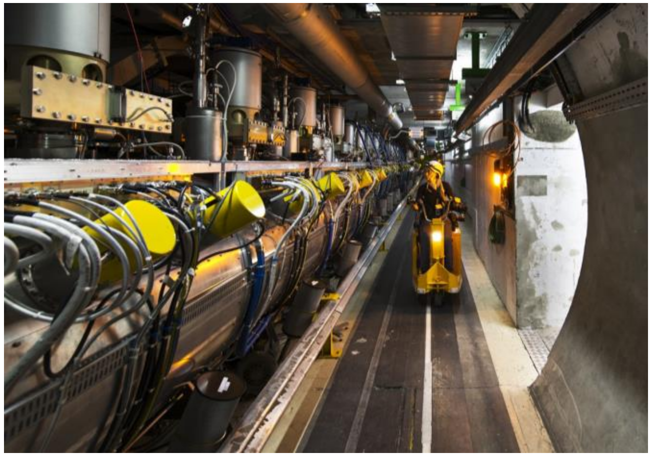
→ **RF voltage required to keep bunches short**

→ **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

Helpful hints

- **SI units for particle mass (kg), energy (J) and momentum (kg m/s) not very common**

→Accelerator physicists love electron volts (eV)

Mass and energy	Momentum
$E = mc^2 = m_0\gamma c^2$	$p = mv = m\beta\gamma c$
$m\,[\mathrm{eV}] = m\,[\mathrm{kg}] \cdot c^2/e_0$	$p\,[\mathrm{eV}] = p\,[\mathrm{kg\,m/s}] \cdot c/e_0$

	SI units	Electron volts
Proton rest mass	$1.67 \cdot 10^{-27}$ kg	938 MeV
Electron rest mass	$9.11 \cdot 10^{-31}$ kg	511 keV
Proton beam momentum at $\beta = 0.5$	$2.90 \cdot 10^{-19}$ kg m/s	542 MeV/c

$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}}$$

$$\gamma = \frac{m}{m_0} = \frac{1}{\sqrt{1-\beta^2}}$$

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**

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, Alexander Lasheen, Elena Shaposhnikova, Frank Tecker, Daniel Valuch, Manfred Wendt, Jörg Wenninger and many more…

Thank you very much for your attention!

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