Basic design of RF systems

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Links

- Introductory CAS website: https://indico.cern.ch/event/1394000/
- Introductory CAS Indico page: https://indico.cern.ch/event/1394000/contributions/6139223/
- Python software framework for transverse and longitudinal calculations: https://github.com/cern-accelerators-and-power/pyhellweh/tree/v_introductory-cas
- Longitudinal tracking code, to be cloned and built locally: https://gitlab.cern.ch/acwg/longitudinal-tracking/-/tree/v1.0.0

Introduction

In this first lecture we will cover:

- design the RF system of a proton synchrotron, the synchrotrons PS and SPS
- understand the RF system for a hypothetical linear energy and current upgrade of an electron storage ring (FCC)

Please make your choices according to your interest.

Useful formula for bucket area reduction factor depending on stable phase

- Bucket area reduction ratio depending on stable phase:

$$r_A = \frac{A_{bucket}}{A_{bucket,0}} = \frac{\sqrt{2}\cos\phi_s - \sin\phi_s - \frac{\pi}{2} + \phi_s}{\sqrt{2} - \frac{\pi}{2}}$$

- Low synchrotron $Q_s \ll 1$ and small stable phase $\phi_s \ll 1$:

$$r_A \approx 1 - \frac{\phi_s^2}{2}$$

Upgrade the CERN-SPS to higher energy as an injector for the Future Circular Collider (FCC)

Design an RF system optimized for the Superconducting Super Proton Synchrotron (ss-SPS)

see, e.g. T. Bohl et al., RF energy upgrade scenarios.pdf

In the hands on session we will design the RF system for a proton synchrotron.

The goal of the session is to calculate the required RF parameters.

The lattice is constructed with the following purpose in mind:

- Design a linear acceleration cycle to maintain a constant transverse average energy gain per turn and stable phase
- Working energy gain per turn and the number of particles accelerated, the average RF power for the beam is constant
- Design the RF system to provide the required voltage and phase for beam stability, the voltage is constant during the RF frequency range
- The acceleration cycle will be given, it is the established phase space, i.e. longitudinal emittance, neither is sufficient focusing yet. This phase defined by the RF system, the RF system must provide the required voltage and phase for beam stability.
- Shift the knowledge of frequency and voltage for fundamental requirements as ref. curve for existing RF systems in particle accelerators and suggest your design. No detailed design of components, just fundamental requirements and feasibility.
- The energy transfer does not take into account the losses, but also the losses, keep the beam stable, keep beam loading voltage low (no Pac-Man phenomenon, keep the beam current low, keep the RF power low).
- The RF systems for particle accelerators are rarely designed from scratch, but required by existing installations. Compare your RF system design with the existing one of the CERN-SPS, as one of the RF system of the new decelerator Antiproton Facility, or any other RF system.

Basic parameters of the superconducting Proton Synchrotron (ss-SPS) as ORBE

	Value	Unit
Kinetic energy	E_{kin}	14 / 157.987 / 1000 GeV
Circumference	C	1.11 km
Bending radius	ρ	174.79 m
Momentum compaction	α_p	$1.\cdot10^{-3}$
Transition energy	γ_t	22.36
Longitudinal emittance (rms)	ε_{rms}	0.35 / 0.35 / 0.35 eVs
Maximum Gaussian Peak current	$\hat{I}$	I_{Peak} = 10 A
Average beam current	I_{avg}	I_{avg} = 0.4 A
Harmonic number (working)	h	924
Average beam pipe radius	r_{pipe}	0.05 m

Exercise 1: Average energy gain and stable phase

Here we will design the RF system for the ramp, the ramp is a linear ramp with a bending field, B!

- Assume a linear acceleration and $\dot{B} = \text{const.}$

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** Helpful Hints **
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- Assume constant average, E_{kin}^{avg}, or sequence and exercise to monitoring, ϕ or $E_{kin}(t)$. Note that the common unit for energy is GeV, and the unit for momentum is eVs/c. Hence also the proposed code is made flexibly to work with both units.
- Use the attached code to calculate the required bending field or acceleration and exercise.
- Calculate the required average energy gain per turn, ΔE_{avg}, and the required voltage, $\hat{U}$, for stability by the acceleration time.

```
import numpy as np
import matplotlib as mpl
import matplotlib.pyplot as plt

# Ring parameters
C = 1110.0 # [m] circumference
rho = 174.79 # [m] bending radius
alpha_p = 1.0e-3 # [-] momentum compaction factor
gamma_t = 1/np.sqrt(alpha_p) # [-] transition gamma
h = 924 # [-] harmonic number
r_pipe = 0.05 # [m] average beam pipe radius

# Injection and extraction energy
E_kin_inj = 14.0 # [GeV]
E_kin_ext = 157.987 # [GeV]

# Bending field
B_inj = 0.1 # [T]
B_ext = 1.0 # [T]

# Ramp rate
dot_B = (B_ext - B_inj)/(E_kin_ext - E_kin_inj)*(np.sqrt(E_kin_ext*(E_kin_ext+2*E_0)) - np.sqrt(E_kin_inj*(E_kin_inj+2*E_0)))/(E_kin_ext - E_kin_inj) # [T/s]

# Average energy gain per turn
DeltaE_avg = (E_kin_ext - E_kin_inj)/(t_ext - t_inj) # [GeV]

# Acceleration time
t_acc = (t_ext - t_inj) # [s]

# Average beam current
I_avg = 0.4 # [A]

# Average RF power
P_avg = DeltaE_avg*I_avg # [GW]

# Average RF voltage
U_avg = DeltaE_avg/(q*np.cos(phi_s)) # [GV]

# Peak RF voltage
U_hat = U_avg/(2*r_bar*(np.sqrt(2)*np.cos(phi_s) - np.sin(phi_s) - pi/2 + phi_s)) # [GV]

# Bucket area reduction factor
r_A = (np.sqrt(2)*np.cos(phi_s) - np.sin(phi_s) - pi/2 + phi_s)/(np.sqrt(2) - pi/2)

# Synchrotron tune
Q_s = np.sqrt(q*U_hat*h*gamma_t*np.sin(phi_s)/(2*pi*E_0*beta_0**2*gamma_0)) # [-]

# Synchrotron frequency
f_s = Q_s*f_0 # [Hz]

# Synchrotron angular frequency
omega_s = 2*pi*f_s # [rad/s]

# Synchrotron period
T_s = 1/f_s # [s]

# Longitudinal emittance (rms)
eps_rms = 0.35 # [eVs]

# Longitudinal emittance (rms) in [GeV*s]
eps_rms = eps_rms*q*U_hat/(h*omega_s) # [GeVs]

# Longitudinal emittance (rms) in [GeV/c]
eps_rms = eps_rms/(beta_0*c) # [GeV/c]

# Longitudinal emittance (rms) in [m]
eps_rms = eps_rms*eta_0/(p_0*beta_0) # [m]

# Longitudinal emittance (rms) in [m*rad]
eps_rms = eps_rms/p_0 # [m*rad]

# Longitudinal emittance (rms) in [m*m]
eps_rms = eps_rms*eta_0/(p_0*beta_0) # [m*m]

# Longitudinal emittance (rms) in [um*um]
eps_rms = eps_rms*1e6*1e6 # [um*um]

# Longitudinal emittance (rms) in [um]
eps_rms = eps_rms**0.5 # [um]

# Longitudinal emittance (rms) in [um*rad]
eps_rms = eps_rms/(p_0*beta_0*eta_0) # [um*rad]

# Longitudinal emittance (rms) in [um*um]
eps_rms = eps_rms*p_0*beta_0 # [um*um]

# Longitudinal emittance (rms) in [um]
eps_rms = eps_rms**0.5 # [um]

# Longitudinal emittance (rms) in [um*rad]
eps_rms = eps_rms/(p_0*be
```

```
print("D = "+str(dampingIntegralD)+" (well below one, 2+D can be approximate to 2)")

dampingTimeBefore = beamEnergyBefore*revolutionTime/energyLossPerTurnBefore  #not radiationPowerBefore (which is for the whole beam)
dampingTimeAfter  = beamEnergyAfter*revolutionTime/energyLossPerTurnAfter   #not radiationPowerAfter

print("SR Damping time before: "+str(dampingTimeBefore*1E3)+" ms")
print("SR Damping time after:  "+str(dampingTimeAfter*1E3)+" ms")
```

```
D = 0.004373920850699349 (well below one, 2+D can be approximate to 2)
SR Damping time before: 3.441183837581627 ms
SR Damping time after:  1.6691748133458983 ms
```

Exercise 8: Comparison with RF system at ESRF

- Compare the parameters of the (additional) RF system with the one of the storage ring at ESRF.

Parameter	Unit	ESRF	Soleil	Soleil (CAS upgrade)
Beam energy, E	GeV	6	2.75	3.5
Beam current, I_{beam}	mA	200	500	800
Circumference, $2\pi R$	m	844	354	354
Bending radius, ρ	m	23.37	5.36	5.36
RF harmonic, h		992	416	416 and 832
RF frequency, f_{RF}	MHz	352	352	352 and 704
RF voltage, V_{RF}	MV	6.5	3	3 + >1.5
Number of cavities		14	4	4 + ~4

In [ ]: