Radio frequency systems of the CERN synchrotron accelerators

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Abstract. *CERN – the European Organization for Nuclear Research – is the largest particle physics laboratory and one of the world's most respected scientific institutes. Currently it operates ten particle accelerators, a new linear injector for H⁻ acceleration is under construction and two future machines are in the study and research phase.*

Radio frequency systems are a vital part of almost all particle accelerators. The RF systems at CERN cover a frequency range from a few kHz up to 30 GHz, and a power range from the noise levels up to hundreds of MW in a single structure. The Low-Level loops of the RF systems accommodate a wide range of electronics from purely analogue circuitry dating back to the 60's up to state of the art remotely operated digital systems based on the most recent FPGA and DSP technology. This paper provides a short overview of the RF systems of the CERN synchrotron particle accelerators with emphasis on the specific problems and issues typical for each accelerating stage in the chain.

Keywords

CERN, particle accelerator, synchrotron, ferrite loaded cavity, travelling wave cavity, normal conducting cavity, super conducting cavity, tetrode, klystron, high power RF

1. Introduction

This paper gives a short introduction to the use of RF systems in accelerator technology with focus on the operating CERN synchrotron machines. It was written on behalf of the Radio-Frequency Group, which is in charge of the RF systems at CERN. The author is an engineer and member of the Low-Level/Feed-back section of the RF group.

Radio frequency systems are a vital part of all particle accelerators (except those of the special electrostatic type) as they are used to control momentum of the particles in the longitudinal and transverse planes or for beam diagnostics.

In the longitudinal plane, electromagnetic fields create the "RF buckets" which allow to capture the injected beam, keep it bunched[1], provide the acceleration, deceleration, or keep the beam circulating at a constant energy in storage ring [1]. Radio frequency fields are also used to manipulate the beams in the phase space e.g. bunch rotation or emittance blow-up [2]. In the transverse plane, the radio frequency fields are used to damp beam oscillations and suppress certain types of instabilities [3]. At the same time the RF system is also able to excite beam oscillations, which is useful e.g. for machine tune measurements or for beam "cleaning" [4].

The particle beams, composed of moving charges, emit electromagnetic energy so the RF systems are also widely used to measure the beam parameters and beam diagnostics [5] [6].

Each type of the particle accelerator deals with specific problems putting constraints on the RF system and type of technology used.

The linear injectors (linacs) and smaller circular machines (synchrotrons PSB[2], PS[3]) accelerate particles from very low energies where the beams are not yet relativistic (particle velocity is much lower than the speed of light) and the relative change of the velocity is large. Therefore in case of linacs the accelerating structures must follow the gradually increasing velocity as the RF frequency is usually constant (e.g. spacing between the elements or proper phasing of the accelerating cavities). In case of synchrotrons the RF system must deal with large frequency spans, covering often several octaves, until the beam velocity approaches the speed of light.

Larger synchrotrons (SPS[4], LHC[5]) work with almost- or highly-relativistic beams relieving the

[1] If the beam of particles is accelerated in synchrotrons (i.e. by alternating fields) it gets bunched. The bunch presents a "cloud" of particles, thin transversally (typ. μm-cm), and long longitudinally (typ. mm-m) typically with Gaussian charge distribution in both planes.

[2] PSB – Proton Synchrotron Booster [7]

[3] PS – Proton Synchrotron [8]

[4] SPS – Super Proton Synchrotron [9]

[5] LHC – Large Hadron Collider [10]

bandwidth constraints, but the high-energy beams require significantly higher RF voltages (than the small machines) in order to capture and accelerate the beam or keep it circulating for several hours for the physics experiments.

Finally, the future very long linear colliders (~TeV range) in which the beam passes through the machine only once, require very high accelerating gradients in the RF structures to obtain the full energy while keeping the length of the machine reasonable. Presently, with current state of the art technology it still will be tens of kilometers. Apart from very high RF power (per unit of length) these machines also require extremely high precision and field quality, and to absolute phasing and timing precision in the femtosecond range distributed to thousands of RF stations geographically spaced over machines that are tens of kilometers long.

The RF systems of the currently running and future accelerators being studied at CERN cover a frequency range from a few kHz up to 30 GHz. The power levels range from the noise level for some observation and diagnostic systems up to hundreds of MW per accelerating structure. The RF power amplifiers typically employ vacuum tubes (tetrodes, diacrodes, IOTs, klystrons) but some new developments are also making use of high power solid-state amplifiers. Accelerators are one of the driving forces for research and development activities in the field of high power microwave tubes.

The Low-Level RF control systems installed on the CERN accelerators accommodate a wide range of electronics from purely analogue circuitry dating back to the 60’s to state of the art remotely operated digital systems based on the most recent FPGA and DSP technology running advanced control algorithms and signal processing techniques.

Going through the accelerating chain, requirements differ on the type of accelerating RF structures – from ferrite loaded resonant cavities tuneable over several octaves, travelling wave structures, single or multi-cell standing wave normal conducting cavities, to single and multi-cell super conducting standing wave cavities.

This paper provides a short overview of the RF systems of the CERN particle accelerators with focus on the synchrotrons, showing specific RF hardware problems typical for each accelerating stage in the chain.

2. The CERN accelerator chain

As the range of energy between the injected and extracted beam of each accelerator is limited, the particles generated by the source are accelerated to the final energy in several successive stages. A schematic drawing of the present CERN accelerator chain is shown in the Figure 1.

The protons generated in the source are accelerated by Linac 2 to a kinetic energy of 50 MeV [11], injected into the PSB and accelerated to 1.5 GeV. The following PS machine, originally designed to accelerate up to 10 GeV now covers the energy range 14-26 GeV. This beam can be used in the East Experimental Area, sent to the target for antiproton production for the AD[6] or can be injected at 14 GeV into the SPS. The SPS accelerates protons to 450 GeV. SPS beams are used for fixed target experiments in the North Area, CNGS[7] or for injection into the LHC. The LHC is a collider accelerating two counter rotating proton beams from 450 GeV and bringing them into collisions at up to 7 TeV. The LHC is also designed to accelerate heavy ion beams.

Lead ions are generated and accelerated by the Linac 3, accumulated and accelerated in LEIR[8] and then follow a similar path as the proton beams.

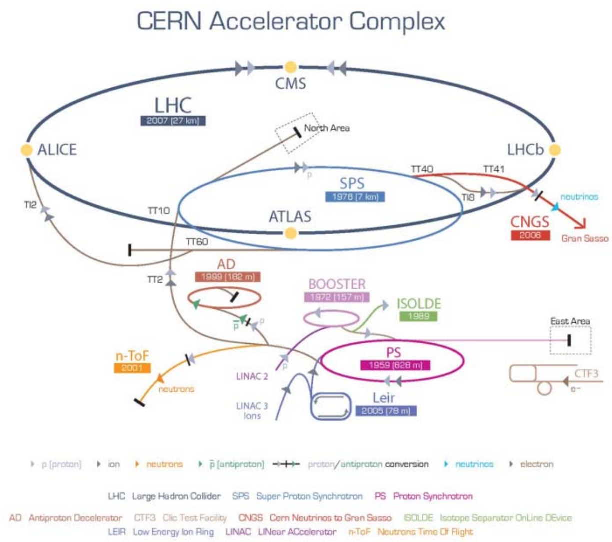

Fig. 1: CERN accelerator complex [12]

3. Small synchrotrons (PSB, PS)

The RF systems of the small circular synchrotrons are probably the most versatile ones within the whole CERN complex. The first in the chain, the PS Booster has four superimposed rings each with its own independent RF system. The beams from the four rings can be ejected towards the Isolde experimental zone (isotope studies) or towards the PS accelerator. The PSB RF system can shape the beam as required in terms of bunch length: 60 ns -> 200 ns, number of particles per bunch: 10^{10} -> 10^{13} and filling pattern within the PS circumference. As a part of the injector chain these machines must deliver different types of beams of different particle species on a pulse-to-pulse basis (PPM operation). The machines must be able to completely re-tune for the new type of beam each 1200 ms, which is the typical acceleration cycle length.

[6] AD – Antiproton Decelerator [13]
[7] CNGS – CERN Neutrinos for Grand Sasso experiment [14]
[8] LEIR – Low Energy Ion Ring [15]

The CERN PS complex accelerates beams which are not “relativistic”. This means a relatively large change of velocity and implicit RF frequency variation (~300 % in the PSB and 10% in the PS (260% in case of Pb ions)). Apart from the acceleration, the RF systems also perform complex beam operations like bunch splitting [29], bunch shaping using higher harmonic RF systems, bunch rotation and longitudinal emittance blow-up. These beam manipulations and the acceleration require large frequency swings. The PSB and PS machines use tuneable, ferrite-loaded cavities and several fixed frequency cavities [16] [17]. See Table 1 for details.

	Cavity	Count	Harmonic number	Freq. range (MHz)	Peak voltage (kV)
PSB	C02	1 per ring	1	0.6 - 1.8	8
	C04	1 per ring	2	1.2 - 3.9	8
	C16	1 per ring	8 - 24	6 -17	6
PS	C10	10+1	7 - 21	2.7 - 10	1 - 20
	C20	1+1	28, 42	13 or 20	15
	C40	1+1	84	40	3 - 350
	C80	2+1	168, 169	80	350
	C200	4+2	420 - 433	200	30

Table 1: Summary of PSB and PS RF systems/cavities

The RF power amplifiers for the tunable cavities in both machines are implemented directly in the RF cavity assembly installed in the machine tunnel as shown in Fig. 2 [18][39].

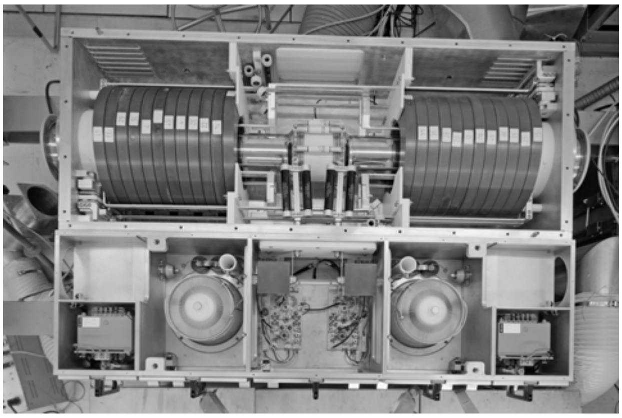

Fig. 2: Ferrite loaded accelerating cavity used in the PSB (picture taken in 1983). The beam passes in the horizontal direction inside the vacuum chamber surrounded by massive ferrite rings. The two tetrodes are located at the bottom of the metallic chassis that includes the ensemble.

Amplifiers use coaxial tetrodes delivering power in the order of 5-20 kW. The resonant frequency of these cavities is tuned by DC biased ferrite rings. For illustration, a typical value of the DC bias current for the PS cavities is up to 2.8 kA.

A block diagram of the cavity assembly with its main control loops is shown in Fig. 3.

The Fig. 4 shows a typical acceleration cycle for an LHC type of beam in the PS machine. The beam injected from the PSB is captured by the tunable cavities numbered 1-2 and pre-set to harmonic[9] *h*=7. Triple bunch splitting[10] is performed by raising the field in the cavities 3-4 (*h*=14) and then 5-10 (*h*=21). In the mean-time the cavities 1-4 retune to *h*=21. After about 40 ms all cavities start acceleration at *h*=21. The cavity retuning typically takes about 30 ms. After acceleration the beam is handed over to the *h*=42 and *h*=84 fixed frequency cavities to perform another bunch splitting. From six 160 ns long injected bunches, 72 bunches, <5 ns long, are created and sent to the following SPS accelerator.

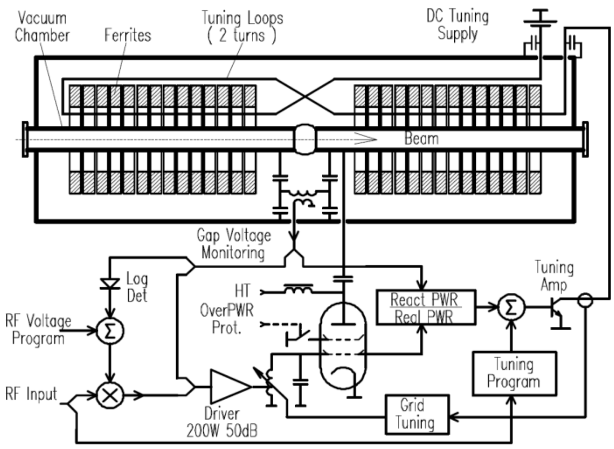

Fig. 3: Principal diagram of the tuneable ferrite cavity assembly and control [16].

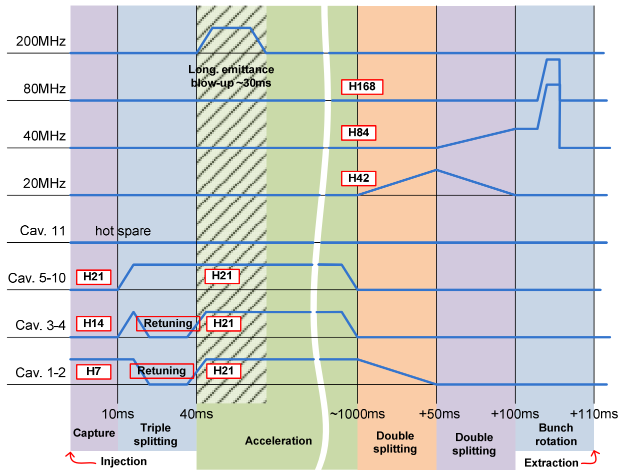

Fig. 4: Typ. acceleration cycle for an LHC beam in the PS machine. The blue curve represents the voltage in the RF cavities mentioned on the vertical axis.

The low-level RF part of the accelerator is designed to allow the creation of the different type of beams

[9] *h* stands for “harmonic number”. The frequency of the RF accelerating field is usually an integer multiple of the particle revolution frequency in the machine. In case of protons in the PS f_{rev} = 436 kHz (at injection) to 477 kHz (at extraction) [19].

[10] Bunch splitting – one long bunch is split into several shorter bunches, maintaining the original number of particles. Reference e.g. [29]

summarized above. Several feed-back loops, closing around the beam must be used to maintain a stable beam and lock the RF phase with the beam (phase loop, radial loop, coupled-mode and multi-harmonic instabilities). For this purpose, signal processing circuits treat the cavity and beam signals. By means of specific filters they calculate a correction value which is sent to the system as a phase, frequency or amplitude modulation. Thanks to the high operating frequency of modern digital circuits, the previous analogue signal processing electronics tend to be replaced by FPGAs and DSPs with full remote programmability [20][37].

4. Large synchrotrons – SPS, LHC

Large synchrotrons such as the SPS, former LEP and present LHC work with relativistic beams relieving bandwidth constrains on the RF system. However significantly higher RF voltages are needed to capture and accelerate the beam. A summary of the SPS and LHC systems is in the Table 2.

	Cavity	Count	Typ. harm. number	Freq. (MHz)	Band-width	Peak voltage (MV)
SPS	TWC 200 4 sections	2	4620	200.2	1.7 MHz	2.3
SPS	TWC 200 5 sections	2	4620	200.2	1.4 MHz	2.8
SPS	TWC 800	2	18480	800.8		0.7
LHC	ACS	8 per ring	35640	400.8	20 kHz @inj. 2 kHz @flat top	8 x 2

Table 2: Summary of the SPS and LHC RF systems

4.1 SPS

The relative frequency change in the SPS during the proton acceleration cycle (from 14 GeV to 450 GeV), which is a typical SPS mode of operation today, is <0.3%. The bandwidth is narrower than in the PS complex but still too large for a non-tunable standing wave cavity. Therefore a set of four, fixed frequency, normal conducting travelling wave cavities (TWC) is used [21]. Two cavities comprise four sections each providing a total accelerating voltage 2.3 MV when driven by 700 kW of RF power[11]. The other two cavities have five sections, each providing more total RF voltage at the same drive power (2.8 MV @ 700 kW[12]) [21][22]. Figure 5 shows the internal structure of the SPS travelling wave cavity [23]. The cavities are installed in the SPS accelerator tunnel, about 80 meters underground.

Each cavity is driven by a separate power amplifier located in the surface building. Two types of amplifiers are used – the “Siemens” amplifier uses 8 x 135 kW RS2004 tetrodes for the final stage and the “Philips” amplifier 32 x 35 kW YL1530 tetrodes for the final stage. The “Siemens” amplifier delivers 650 kW and “Philips” 700 kW of CW power (each) at a frequency of 200.2 MHz with 2.5 MHz (3.1 MHz) bandwidth [24].

Under normal operation, the cavities are impedance matched, so no circulators are needed to protect the amplifiers from the reflected wave.

Fig. 5: Internal structure of the SPS travelling wave cavity

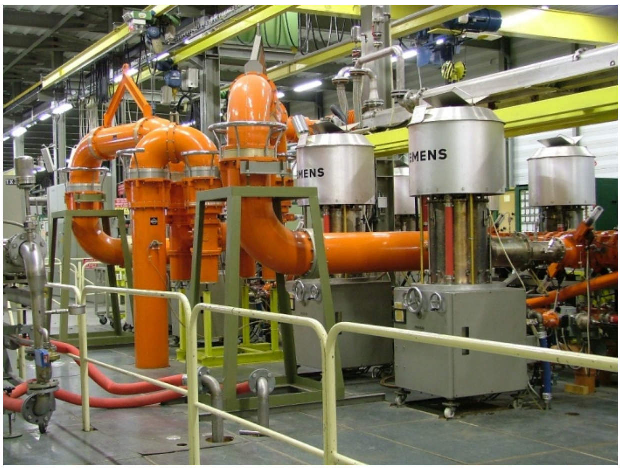

Fig. 6: Part of the “Siemens” RF power plant (tetrode amplifier blocks and the coaxial transmission line system (in orange)).

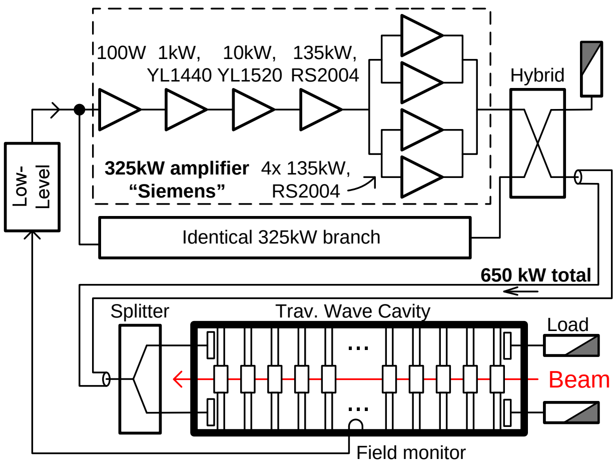

Fig. 7: A block diagram of the “Siemens” 200 MHz system.

[11] Four section cavity V = 84 kV per sqrt (P [kW])
[12] Five section cavity V = 105 kV per sqrt (P [kW])

Power from the surface is transferred to the cavities located in the tunnel by 345 mm diameter 50 Ohm coaxial lines. With only natural cooling, these can sustain 750 kW of CW signal at 200 MHz.

A principal block diagram of the "Siemens" 200 MHz system is shown in Fig. 7. The "Philips" branch is identical except for the power part where a larger number of lower power tubes generate the required output power.

The SPS has a second, 800 MHz, system which is currently used for Landau damping of the LHC beams [25][38]. Klystron based amplifiers, 2x 225 kW feed two travelling wave cavities. The SPS 800 MHz system is vital for the LHC operation. The system is currently at the end of its life-time and presently undergoes a substantial consolidation program. The klystron amplifiers and power supplies from the 70's will be replaced by modern IOT based amplifiers. The low-level system will be replaced with a digital one based on FPGA technology.

The layout of the 800 MHz and 200 MHz cavities in the SPS tunnel is shown in the Fig. 8.

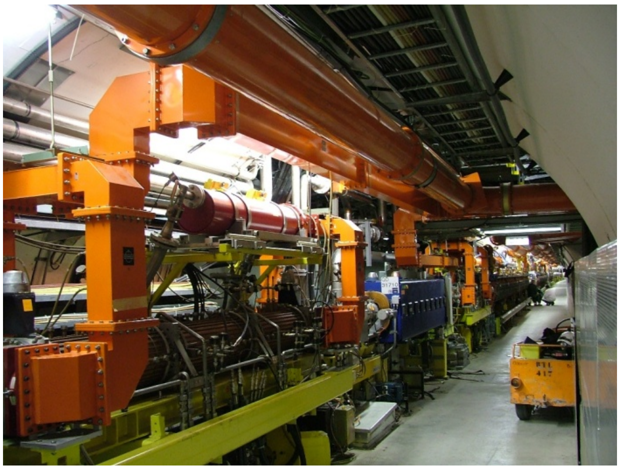

Fig. 8: The SPS RF cavities in the SPS tunnel. Front 800 MHz system (supplied by waveguides), further in the tunnel 200 MHz system (supplied by the coaxial lines)

The low-level system of the SPS is located completely in a Faraday Cage next to the RF power plants. It is based on a mix of analogue circuitry together with less complex digital systems. Recently introduced new functionality (mainly LHC related such as re-phasing and synchronization with the LHC [26]) is implemented on fully remote controlled digital hardware. A complete migration to a digital beam control system is foreseen in coming years.

4.2 LHC

The LHC is a new machine which was put into operation in 2008. It is presently the largest and the most powerful particle accelerator ever built. The LHC accelerates two counter-rotating proton or ion beams up to the energy of 7 TeV (for Pb ions 2.76 TeV/nucleon, or 1.15 PeV centre of mass energy).

Beams accelerated in the LHC are already highly relativistic. Change of the revolution and RF frequency during the acceleration is very small (~2.5 ppm for protons). Standing wave accelerating cavities are used. For each ring, the LHC has 8 superconducting, single cell, niobium coated copper cavities, installed in groups of four in a common cryostat [27] [30]. Cavities are cooled to 4.5 K by liquid helium. Each cavity is designed to provide 2 MV of accelerating voltage; together providing 16 MV per beam.

The cavity has a variable, motor controlled main coupler allowing to adjust the cavity Q_{ext} in a range of 10 000 (used at injection) to 200 000 (used at top energy). The "low-Q" setting provides more bandwidth to capture the beam after the injection. When the acceleration starts, the coupler will gradually be pulled out, increasing the Q_{ext}, lowering the bandwidth but providing more RF voltage with a given input power. The resonant frequency of the LHC cavities can be tuned within a range of 100 kHz by a mechanical tuner.

Fig. 9: Accelerating cavities at LHC Point 4. The cryomodule contains 4 cavities. The power coupler of each cavity with the waveguide feeder line is visible on top of the module [30].

Fig. 10: LHC klystron gallery. TH2167 klystrons (in yellow support frames), WR2300 size waveguide system and racks with electronics are visible.

Each cavity is powered by a dedicated 300 kW klystron amplifier (Thales TH2167). Most of the RF power is needed to keep up the cavity field and to compensate for the high beam loading (voltage induced in the cavity by the beam) and during the acceleration only small fraction of power goes to the beam (less than 275 kW out of installed 2.4 MW [27]). The unused power is reflected from the cavity back to the amplifier. The klystron is protected by a circulator with a water cooled ferrite load. A view of the klystron gallery at Point 4 of the LHC is shown in Fig. 10.

A block diagram of one "RF line" (low-level – klystron – circulator – cavity) is shown in the Fig. 11.

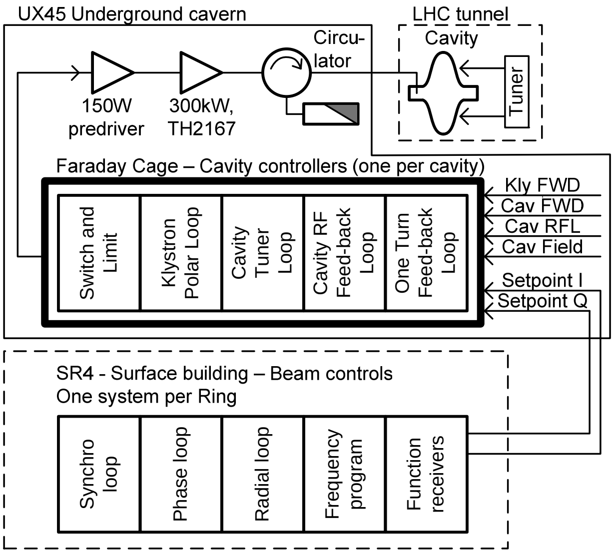

Fig. 11: Block diagram of LHC RF system (one "line").

The power part of the RF system, containing only one klystron per cavity, is relatively simple with respect to the previously described smaller machines. The system uses "standard" power components without big technological challenges.

However, the challenge for the LHC RF system is the RF related noise. The synchrotron radiation losses of the LHC proton beams are very low, too low to provide sufficient damping for excessive noise introduced by the RF system [28]. Many measures were implemented to minimize these effects (e.g. careful analysis of noise sources in the low-level systems, a klystron polar loop to compensate the high voltage power supply related noise and interference etc.). The LHC is the first proton collider using klystrons. The first beam life time measurements taken during the LHC start-up in September 2008 showed promising results, however more detailed measurements will be done when the machine is back in operation in 2009.

5. Transverse damping systems

Transverse damping systems help to damp transverse beam oscillations. When the beam is injected into the machine with a transverse offset with respect to the ideal closed orbit it will perform perturbing betatron oscillations. If these are not sufficiently damped the transverse beam size will increase, what degrades the beam quality delivered to the experiments [31]. At the same time, when the beam intensity is above a certain threshold the transverse instabilities caused e.g. by high machine impedance[13] can drive coupled bunch coherent oscillations [32] [33]. The beam can become unstable and the accelerator suffers of high losses when particles reach the machine aperture. The transverse damping system counteracts these oscillations by means of a feed-back loop.

The transverse beam position is measured by beam position monitors installed in the vacuum chamber along the machine. The transverse position information is used to calculate the deviation from the equilibrium orbit. The trajectory of the beam is then corrected proportionally to its deviation by deflectors [34]. The deflector plates are driven by broadband power amplifiers (see Fig. 12). The low frequency range is defined by the fractional machine tune (for SPS and LHC machines typ. ~kHz range) whereas the upper frequency range is defined by the circulating bunch spacing (e.g. 20 MHz for 25 ns bunch spacing in the LHC).

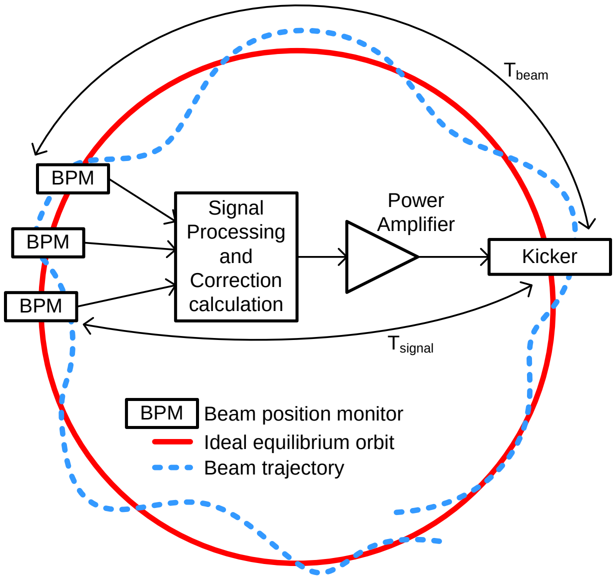

Fig. 12: Block diagram of a Transverse damping system

Typically the transverse position is sampled and calculated synchronously for each individual bunch at the full rate (e.g. 40 MHz @ LHC). The correction of the transverse beam momentum (kick) needs to be applied to the very same bunch of which the position was measured within the same machine turn, or if the group delay of the electronic system is long with respect to the time of flight between the position monitor and the deflector, the kick could be applied at a corresponding time in any consecutive turn.

[13] Machine impedance: Electromagnetic fields emitted by the moving charges (beam) interact with the surrounding environment (e.g. vacuum chambers). The trailing fields interact with the subsequent particles in the bunch train.

The deflector and the power system can later also be used to excite oscillations of the beam. A controlled excitation is used for instance to measure the machine tune [35]. Another application is to excite the unwanted portions of the beam e.g. in the abort gap such that the particles will hit the collimators keeping the abort gap free of particles [36].

6. Acknowledgements

This paper gives an introduction to the use of RF systems in accelerator technology with focus on the operating CERN synchrotron machines. It was written on behalf of the Radio-Frequency Group, which is responsible for all of the RF systems at CERN. The author would like to thank all members of the RF group who gave valuable input and contributed to the paper. Special thanks to my colleagues D. Belohrad, A. Blas, T. Bohl, E. Ciapala, W. Hofle, O. Holme, E. Jensen, G. Kotzian, E. Montesinos, M. Paoluzzi, M. Schokker, M. Vretenar.

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