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COOLED BEAM DIAGNOSTICS

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Cooled beam diagnostics

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1. Introduction

People working at a cooler ring talk about high beam density, low emittance and low momentum spread. The difference comes from the current circulating in the ring which together with the cooling rate give the limited density which is obtainable. The instrumentation characteristics depend on the resolution needs. For high beam current, the electromagnetic detectors show much information on the beam impedance and distribution. The methods used to disentangle the different effects are reported. An important issue is the knowledge of the cooling forces. Some tools developed will be reviewed.

2. Electromagnetic instrumentation

Current measurement

For the coasting beams, the DC current transformers [1] are used in the cooler rings. To reach a 1 μa resolution and stability in the harsh electromagnetic environment of an accelerator, the external loop current must be well connected to vacuum chamber, a sophisticated shielding has to be arranged around the transformer which itself has to be suspended by anti-vibration systems. Nevertheless, measurement drift can be observed due to temperature variation. Improved resolution is obtainable by averaging the measurement and by ripple suppressors. The cut-off is of the order of a few hundreds of Hz. Recently, a cryogenic current measurement device using SQUID[1] [2] was able to measure a 1 nA beam

For the bunched beam, AC transformers resolution of some nA [3] can be contemplated with the advantage of higher peak current due to short bunches and the disadvantage that the transformer measurement has to be synchronised with the bunch. The integration of the bunch signal observed with a position pick-up is sometimes used providing the capacitance of the pick-up has been calibrated.

The current measurement gives an absolute value of the number of particles circulating into the machine which is then the reference for all the other measurements. It is very useful for the lifetime measurement of very short-lived ions.

Position measurement

Generally, electrostatic pick-ups [4] are used for the beam position measurement. A frequency bandwidth from 1 kHz to 50 MHz is sufficient. The best sensitivity is obtained when the active and ground electrodes are separated by vacuum instead of being coated onto the inner and outer surface of a cylindrical ceramics. But the capacity of the connections has to be minimised. Low noise amplifiers are used which provide the sum (Σ) and difference (Δ) signals. On line calibration of the electronic chain is

[1] SQUID is the acronym for Superconducting Quantum Interference Device

needed for the routine operation. Many systems are used to extract the position:

- Turn by turn trajectory measurement by integrating the signals Δ and Σ, digitising the result and computing the ratio.

- Direct digitising of the signals. After some computation, the position is obtained. A lot of data has to be treated locally by the Digital Signal Processor [30] and this can give the beam position as an average over some turns.

- The Δ and Σ signals are treated through a network analyser which gives the ratio and the phase of these two signals. The measurement takes a longer time as the averaging takes about 1 ms per pick-up. A 1 mm precision is obtained for some 10^8 charges circulating in the ring

Once the position is known, many correction or modifications of the orbit are possible: correction by a least square fit method; creation of bumps around the machine for injection and ejection; alignment between circulating ion beam and electron beam of the cooler or with laser beam; search for machine acceptance by moving a bump around the machine.

By modulating at some kHz the current of the electron cooling system, the position of the electron beam can be measured with electrostatic pick-ups. This permits the adjustment of its trajectory to the centre of the vacuum chamber. The same pick-ups are then used for the circulating bunched ion beam, so making easier to align the two beams.

The Δ signal is also used for tune measurement by digitising it on a turn-by-turn basis (synchronisation on bunch needed) followed by a Fast Fourier Transform (FFT) of the signal. Algorithms developed by E. Asseo [5] improve greatly the precision of the measurement (down to ΔQ=0.0001) which make itpossible to measure within one degree the phase advance between two pick-ups. This leads to a better adjustment of the lattice mainly when many quadrupole families are used. This technique is also used to evaluate the strength of low order resonances [6]. The construction of the beam trajectory in phase space by recording the position of the beam at two pick-ups having a phase advance difference of 90 degrees is a nice tool for understanding the effect of many machine imperfections [7], [8].

Electrostatic pick-ups are also the heart of the low-frequency transverse feedback systems required to counteract the instability of the high-density beams. Using long pick-ups and very low-noise amplifier increases the sensitivity to coherent signals. The bandwidth with electrostatic pick-ups is limited to less a hundred MHz [9].

Schottky signals

The Schottky noise signal provides a measurement of the temperature of the beam, which is nothing else that the aggregate of the incoherent motion of the particles in the beam even if this motion is well determined. These signals are visualised in the frequency domain [10]. The longitudinal signal shows a spectrum line around frequencies corresponding to all harmonics of the revolution frequency. For each spectrum line, the integrated power is proportional to the circulating current, the width is proportional to the momentum spread of the beam. The transverse signal spectrum is an infinite series of spectral line at $(n\pm q)f_{rev}$ where n is the mode number, q the decimal part of the machine tune and f_{rev} the revolution frequency of the particles. The width of each spectral line depends mainly on the chromaticity and the momentum spread. The chromaticity can be derived comparing the $(n+q)$ and $(n-q)$ lines using a low mode number. The total power of one mode is proportional to the RMS emittance and the current of the beam. On a spectrum analyser there are two modes seen per interval of f_{rev} (the $n+q$ and $n-q$ modes), and they are mirrored by $(n+0.5)f_{rev}$.

To observe coasting beams containing some 10^6 charges the following techniques are used:

- Wide band pick-ups of loop couplers type with one side connected to a 50 Ω resistor cooled to 20K the other side connected to a 50 Ω large bandwidth, low noise and high gain amplifier. The individual signals from many loop couplers are summed with the correct time delay for the flight time of the particles. The number of couplers multiplies the final signal power.

- Alternatively, at low enough particle velocity, the exit of one loop coupler is connected with the correct time delay to the entrance of the next one and so on. The signal power is multiplied by the square of the number of couplers.

- As a third possibility, a longer pick-up is made resonant at an appropriate Schottky line frequency.

- In all cases, using appropriate cabling, cryogenic amplifiers or feedback reduces the noise level.

The high level of the coherent signal complicates the case of bunched beam Schottky noise observation. Attempts have been made to observe signals at frequencies at least 6 times the bunch frequency [11] but problems have been encountered linked to some coherent effect probably due to the impedance of elements of the machine.

The high density of the beam obtained by cooling leads to important modifications of the Schottky signals. The space-charge impedance, the damping due to the cooling itself and the machine impedance have the following trends:

- Two coherent waves [12] are observed one on each side of the Schottky lines of the longitudinal beam signal. They are even more pronounced if the beam distribution tends to be uniform [13] (as observed with laser cooling) instead of being Gaussian. They disappear if the damping rate due to cooling is very large [14]. One wave is usually larger than the other one. This is due to the influence of the real part of the ring impedance.

- For the transverse mode *(n+q)*, a large peak appears at a frequency slightly lower than *(n+q)*, *q* being the decimal part of the tune obtained for the low-density beam. The frequency shift corresponds to the coherent tune shift due to space charge. With the low emittance of the cooled beam, the incoherent tune distribution can be seen at still lower frequencies, i.e. to the left of the large coherent peak. A similar remark applies for the *(n-q)* sideband but the situation is mirrored.

The large peaks observed are a sign that the beam is close to instability. When this happens, the coherent signals becomes very large and then the head amplifiers are usually saturating and the information is lost. The active feedback used to stabilise the beam acts on the coherent signals, decreasing their strength. Observation of the coherent signal is useful to fine-tune the gain and delays of the feedback systems.

To disentangle all these ingredients the Beam Transfer Function method (BTF) has been developed [14,15]. By recording the spectrum of the longitudinal Schottky signal and the response of the beam to an excitation (BTF), it is possible to find [14,16] the real momentum distribution of the beam and the longitudinal impedance. In the transverse plane the BTF of two sidebands permits to measure the coherent tune and the effect of the active feedback systems. At low density, comparing the (n+q) and (n-q) sidebands, the transverse BTF gives also the chromaticity. The signal over noise ratio obtained by BTF is N times better than for the Schottky signals, N being the number of particles circulating in the machine, if the excitation causes a coherent oscillation of the order of the beam size.

The observation of the Schottky signals made by a spectrum analyser is often too slow to follow the cooling processes. This is also true for the BTF when using a network analyser. To improve the speed, the down mixing technique is used followed by digitising and Fourier transform. In that way, a time resolution of some ms is obtainable but signal to noise ratio and frequency resolution are somewhat degraded. Single Side Band Mixers (SSBM) have been developed [17] with frequency bandwidth of 100 kHz that are well adapted to systems commercially available (high-resolution digitiser, large memory, Fast Fourier Transform…). The three Schottky signals (momentum spread, horizontal and vertical emittances) can then be observed at the same time. Another choice is to run the spectrum analyser in receiver mode and to use the intermediate frequency output prior the SSBM. Instead of using SSBMs, it is possible to perform an under sampling of the intermediate frequency output of the spectrum analyser [18] but with proper choice of the digitising frequency.

The latter systems makes it possible to measure one mode per channel. Modern digital network analysers allow the measurement of one point per mode. The open loop transfer function of the feedback systems is then made easier. A particular application is the measurement of the phase advance between position pick-ups [19].

<u>Quadrupole pick-ups</u>

It has been proposed to use the Quadrupole BTF(ie excitation and observation of the beam with quadrupolar pick-ups and kickers) to measure the incoherent tune shift of the high-density beam [20]. This has proved to be a nice tool to evaluate the incoherent tune shift, the ratio of beam sizes and to test the effect of resonances on cooling.

<u>Longitudinal cooling force measurement</u>

Two ways have been used to measure the longitudinal cooling force:

- To counteract the cooling force, a constant acceleration force is given to the beam by an induction accelerator [21]. At the equilibrium, the circulating beam energy is recorded. This method is best suited for speed difference in the centre of mass between the ions and electrons larger than 10^4 m/s.

- A uniform or especially shaped white noise [22] is applied around a harmonic of the revolution frequency to the beam through a longitudinal kicker. The final beam distribution is the equilibrium between the energy diffusion provoked by the noise and the cooling force of the cooler. The force versus speed difference in the centre of mass is computed applying the Fokker-Planck equation. The force is proportional to the ratio of the derivative of the speed distribution of the particles and the applied noise. This derivative is also obtained taking the imaginary part of the BTF at the excitation frequency. This method gives access the low ion velocity in the centre of mass. Too large space charge should be avoided for this measurement.

3. Ionisation profile monitors

The circulating particles interact with the residual gas of the machine creating pairs of ions and electrons. The idea is to collect one of these two species or even both to measure the beam profile [23]. In a simple detector the ions are preferably used, as their transverse speed is smaller. The ultra high vacuum (less than 10^{-11} mbar) needed in the low-energy machines limits the ionisation rate to some 10^4 s^{-1} in a monitor of 50 mm length. One way to amplify the signal consists of accelerating the ions to a Micro Channel Plate systems (two MCPs in chevron to increase the gain) where electrons are created, their number amplified and then collected on the detector. The detector can be of many types:

- A resistive plate, which measures electronically [24] the transverse position of the electron beam exited from the MCPs. The resolution is of the order of 0.2 mm. The counting rate is limited to some kHz, which limits the observable circulating current. A lot of averaging needs to be done to have good distribution during the cooling process and a time resolution of 100 ms.

- Many conductive strips with a pitch of 0.5 or 1 mm are deposited on a ceramic substrate. The analog signal of each strip is then integrated and recorded. This is particularly useful when the size of the beam is large after a multiturn injection.

- A scintillating material is deposited on a transparent substrate and a CCD camera is looks at this detector.

To increase the sensitivity, a thin magnesium-jet (0.3 mm) is swept through the beam [25] at a speed of 10 mm/s. Magnesium atoms are ionised and the electrons are recorded with a photo-multiplier as a function of the jet position. This gives the profile of the beam. An alternative method is to record the total electron current when the jet is stationary in the centre of the beam. The maximum density of the beam is then recorded. The method of an atomic curtain produced by the evaporation of the carbon initiated by a laser pulse was discontinued due to a lot of carbon ions masking the measurement.

Recently it was proposed [26] to create a very small neutral ion cloud maintained in levitation in a Magneto Optical Trap (MOT) created at the intersection of many lasers. Thae trap is moved across the circulating beam and the electrons that are produced are recorded as for the magnesium jet.

Nevertheless, the ion trajectories are influence by the space charge of the high-density circulating beam and then the space resolution of these detectors is limited.

4. Recombination monitors

The electron beam and the ion beam are travelling together for some meters. Since their energy difference is very small in the centre of mass, the ions can capture an electron by radiative or di-electronic processes. In the next bending magnet, their trajectory becomes very different from the circulating ions. In the case of protons and deuterons, the H_0 and D_0 that are created leave the machine at the end of the straight section. Most of the time, there is an interest in counting rate of the recombination processes and an assembly composed of a phosphor detector or a glass scintillator followed by a photomultiplier is sufficient. The horizontal and vertical profiles of the beam can be recorded after the phosphor detector by a camera. MCPs[23] or silicon strip detectors can also be used to amplify the signal [27].

5. Transverse cooling force measurements

Once the horizontal and vertical profiles have been recorded versus time, it is possible to transform them in amplitude density distributions by applying an Abel transformation. Amplitude means the amplitude of oscillation expressed in speed of the particle in phase space. To evaluate the transverse cooling force as function of the transverse speed, some assumption is made on the amount of coupling between the horizontal and vertical motion. The density distributions versus transverse amplitude of oscillation can then be computed. The variation in time between two consecutive integrated density distributions divided by the mean value of the density distributions is proportional to the mean cooling force exerted onto the particles while they perform betatronic oscillations [28].

6. Laser light monitors

The fluorescence light emitted by some ions irradiated by a laser beam is used when doing laser cooling. Sophisticated methods have been developed which will be explained in a different talk [29].

7. Conclusions

A lot of specific measurement devices and techniques have been developed to analyse the cooling process and the limits of beam dimensions. They are used in many machines [30] depending on the needs. New instrumentation is still under developments.

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