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TECHNIQUES OF ENERGY CHANGING AND ENERGY MONITORING
OF COOLED STORED BEAMS

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ABSTRACT

It can be desirable - both for machine operation and for machine and particle physics experiments - to change the energy of a beam, circulating in a storage ring, by small and well controlled amounts. This paper compares six different methods of energy changing and five methods of non destructive energy monitoring.

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It can be desirable - both for machine operation and for machine and particle physics experiments - to change the energy of a beam, circulating in a storage ring, by small and well controlled amounts. This paper compares six different methods of energy changing and five methods of non destructive energy monitoring.

INTRODUCTION

Due to the nature of the Lorentz force, the energy of a circulating charge particle can best (or only) be changed by a longitudinal electric field. The methods to be discussed differ by the way in which this electric field is created.

If the storage ring guide fields are kept constant, the beam changes its radial position with momentum $\Delta x(s) = D(s)(\Delta p/p)$ where the "dispersion function" $D(s)$ [frequently also called $\eta(s)$ or $x_p(s)$ or $\varphi_p(s)$] is a property of the magnetic lattice of the storage ring. It results from the equilibrium between the increased centrifugal force in the arcs as the energy increases and the "restoring" action due to the focusing fields. In general, $D(s)$ varies with the azimuthal position s around the ring.

To keep the radial position unchanged, all guide fields have to be changed by $\Delta B/B = \Delta p/p$.

1. TECHNIQUES OF ENERGY CHANGING

PROGRAMMED RF ACCELERATION

This is the method used to accelerate the beam in synchrotrons and cyclotrons : an RF field is applied with a frequency $f = h f_0$ at a harmonic h of the revolution frequency. On each traversal, the particles experience an accelerating kick due to the longitudinal electric field. As discussed in textbooks, the motion can be analysed in terms of a potential well ("bucket") travelling around with the particles.

To capture the coasting beam, the RF field has to be turned on slowly so that particles are trapped into the potential well ("adiabatic capture"). The well must be deep enough to hold the energy spread of the beam. This determines the required minimum RF voltage per turn $U = \int_0^{2\pi R} E ds$ which is

$$U = \frac{\pi}{2} h |\eta| \beta^2 \gamma \left(\frac{\Delta p}{p}\right)^2 U_0 \quad (1)$$

where $\eta = 1/\gamma^2_{\text{transition}} - 1/\gamma^2 = -\frac{\Delta f_0}{f_0} / \Delta p/p$

is the off energy function of the storage ring, which determines the change of revolution frequency with momentum; $U_0 = 938$ MV for protons and $\beta = v/c$; $\gamma^2 = (1 - \beta^2)^{-1}$

For the $\Delta p/p$ of cooled beams, the required voltage is very modest, see the example of Table 1, so that a simple RF system can be used.

Table 1

Example of the RF voltage required to hold a beam

Assumed beam and machine parameters :

RF harmonic number : $h = 1$
off energy function : $\eta = -1$
particle velocity v/c : $\beta = 0.3$

Momentum spread $\Delta p/p$	$\pm 10^{-4}$	$\pm 10^{-3}$	$\pm 10^{-2}$
RF voltage to hold the beam U (Volt)	1.3	130	13000

To change the beam energy, the potential is moved by changing the RF frequency. The concurrent momentum change is

$$\Delta p/p = -\eta^{-1} \frac{\Delta f}{f} \quad (2)$$

During energy change, the beam is bunched. However, after the change, the RF can be turned off adiabatically to redistribute particles uniformly around the circumference. If the capture, energy change and debunching are done sufficiently slowly, the blow-up of momentum spread and the residual density modulation can be kept small and the voltage required is only slightly larger than the minimum (1). Sufficiently slowly in this context means a few (2 to 5) synchrotron oscillation periods T_s for each of the 3 operations, where

$$T_s = \beta/f_0 \left(\frac{2 \pi \gamma U_0}{h |\eta| U} \right)^{1/2} \quad (3)$$

Usually, T_S is less than 10 ms, so that the procedure can be finished within 100 ms.

PHASE DISPLACEMENT ACCELERATION

This method was used in the CERN ISR to accelerate the beam from about 26 to 31 GeV/c. The procedure is to turn on an RF accelerating field at a frequency just below (or above) a revolution harmonic. In contrast to normal RF acceleration, the potential can have a depth smaller than the beam momentum spread, i.e. the voltage is smaller than (1). Sweeping the frequency slowly to a value above (below) hf_0 particles are pushed in the opposite direction, i.e. towards lower (higher) frequency. By virtue of (2), they are accelerated in a machine working above transition like the ISR and vice versa in a machine below transition.

The voltage is then turned off, the frequency restored to its initial value and the process of sweeping the RF potential well ("the RF bucket") across the range of beam frequencies is repeated (some 100 times in the ISR) until the desired total energy displacement is achieved.

The advantage of this method : the beam stays practically unbunched and very little RF voltage is needed. The price : phase displacement needs more time and tends to introduce more blow-up and distortion of the energy distribution than normal RF acceleration.

In the ISR, this method was used since the voltage (1) to hold a beam of one or several percent $\Delta p/p$ turned out excessive and also since the momentum spread of the bunched beam would have exceeded the acceptance.

BETATRON ACCELERATION

Imagine a torus (or a frame) of ferromagnetic material in which a magnetic flux is created enclosing the beam. From Maxwell's equation, the energy gain per turn of the particles due to a change of this flux is

$$U = \int E \, ds = - \int \dot{B} \, dF = - \dot{B} F \quad (4)$$

where F is the effective cross-section of the flux ring, i.e. the cross-sectional area of the ring or frame. The arrangement may be viewed as a transformer where the excitation coil is the primary and the beam the secondary winding. The advantage of this method : all particles are uniformly displaced in energy. The disadvantage : a large size magnet is required to give an appreciable energy change. In fact, the total energy change experienced by a particle with f_0 revolutions per second is by virtue of (4)

$$e\Delta U = e\Delta B F f_0$$

An example : For $f_0 = 1$ MHz, $B = 2$ Tesla, to provide an energy change $e\Delta U$ of 2 MeV, one needs a "frame" with a cross-section of $F = 1$ m². For a magnet which takes 1 m of straight section space, this means a volume of ≈ 4 m³ and a weight of ≈ 30 tons. For a cooled beam, the same energy change can easily be supplied in a fraction of a second using a very modest RF system, which supplies a few tens of Volts per turn.

ENERGY DISPLACEMENT BY OFFSET OF A MOMENTUM COOLING SYSTEM

When the energy of the cooling electrons is changed slowly or in small steps, the ion beam will follow due to the drag force which acts between the two beams. In the cooling experiments, this has been used to measure the cooling strength. As a rule of thumb, one can assume that the beam can be displaced by an amount equal to its initial energy width within one cooling time. This seems well suited for our present purpose.

Similar considerations also apply to stochastic cooling. Using the filter method, one can change the electric length of the filter line which defines the nominal revolution time and thereby the momentum. For the Palmer method, which detects momentum via the concurrent radial displacement, one can electronically change the "zero position setting" of the difference pick-up.

In the operation of LEAR, the change of beam energy by the stochastic cooling system is clearly observed when the beam is injected with a slightly displaced energy due to a synchronization error between the proton synchrotron (PS) and LEAR.

ENERGY DISPLACEMENT BY RF NOISE

Filtered noise applied on an RF cavity in a band near a harmonic of the revolution frequency causes a diffusion of particles over the corresponding momentum range. This is used in LEAR to transport particles into the extraction resonance. The same method looks interesting to "transport" particles for other applications, for instance to bring a small portion of beam onto an internal target.

Particles perform a random walk over the band covered by noise. The speed $v(\Delta p)$ of this "Brownian motion" is determined by the power level of the noise.

The particle density - which is determined by the inverse of $v(\Delta p)$ - is a smooth function which follows a diffusion type of equation. By displacing the edge of the noisy band into the stack, the number of particles participating in the random walk process can be controlled.

UNSTACKING RF BUCKETS

This is another method by which a small fraction of the beam can be displaced in energy. It is used in the antiproton accumulator (AA) at CERN to extract portions of the stack.

By slowly turning on an RF voltage at a harmonic of a frequency within the range of revolution frequencies of the stack, a fraction of the particles is trapped into the RF potential well ("buckets"). Changing the frequency, the trapped particles are displaced in energy and can be transported out of the stack. This method could also be used to carry small portions of beam onto an internal target. If desired, the small batch can be debunched by slowly turning off the RF.

In this way, a beam of tiny momentum spread can be separated from the main stack. This, together with selective cooling of the small beam, has been considered for special applications in LEAR.

2. MONITORING OF ENERGY CHANGE

MEASUREMENT OF ENERGY FROM RADIAL DISPLACEMENT OF THE BEAM

A position sensitive pick-up electrode can be used to monitor the radial position of the beam centre. For an unbunched beam, one can observe the "Schottky noise" signals due to the fluctuation of the number of particles in a beam sample of a given length. The resolution is limited by the beam size and by the accuracy of the pick-up to typically 1 mm for both Schottky noise and bunched beam pick-ups. It may be possible to gain some factor for cooled beams.

In the presence of guide field errors ($\Delta B/B$), the radial displacement is

$$\Delta x = D \left(\frac{\Delta p}{p} - \frac{\Delta B}{B} \right)$$

The value of the dispersion function $D(s)$, which for small cooling rings is typically in the range of 1 to 10 mm/per mille, is known from lattice calculations to a relative precision of, say, 10^{-2} . The field can be controlled to a precision of 10^{-3} or 10^{-4} . The most critical factor is thus the accuracy by which the beam position can be observed. It limits the method to momentum changes of, say, a per mille which can then be monitored with a relative error of typically 10%. A high precision pick-up is desirable, located at a position where $D(s)$ is large and the beam size due to betatron oscillation small.

CHROMATIC CHANGE OF BETATRON TUNE

The change of betatron tune Q can be measured with a precision of 10^{-2} to 10^{-4} in $\Delta Q/Q$, depending on the effort and on the beam

conditions. Once again, the resolution is limited by the beam tune spread and by the measurement device itself. The "chromaticity coefficients" ξ and ξ_B , which determine the Q change are defined by

$$\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p} - \xi_B \frac{\Delta B}{B}$$

For typical cooling rings with correction sextupoles, these coefficients are tunable in the range of, say, -5 to 1. Their value can be estimated from the storage ring lattice - including the sextupole lenses - to an accuracy $\Delta\xi$ of, say, 0.1. Measurement of energy change from the chromatic tune change is therefore mainly limited by the precision of the Q measurement and by drift and ripple of Q due to power supply imperfections. One can expect a resolution of $\Delta p/p$ of the order of 1 part in 10^3 . Large chromaticity $|\xi|$ is helpful in this context.

ENERGY MEASUREMENT FROM REVOLUTION FREQUENCY

Revolution frequency can be measured with high accuracy $\Delta f_0/f_0 = 10^{-5} - 10^{-6}$ by observing the Schottky noise signals of a coasting beam or the bunch signals in the case of a bunched beam. In both cases, a current sensitive (sum) pick-up is to be used - in contrast to the position sensitive (difference) pick-up considered above to detect radial displacement. The revolution frequency is simply $f_0 = \beta c/2\pi R$ and hence

$$\frac{\Delta f}{f} = \frac{\Delta \beta}{\beta} - \frac{\Delta R}{R} = \frac{1}{\gamma^2} \frac{\Delta p}{p} - \frac{1}{\gamma_{tr}^2} \left(\frac{\Delta p}{p} - \frac{\Delta B}{B} \right) - \frac{\Delta R_0}{R_0} \quad (5)$$

Estimated relative accuracies are:

$$\gamma_{tr} : 10^{-2} \quad (\text{transition energy})$$

$$B : 10^{-4} \quad (\text{magnetic guide field})$$

$$2\pi R_0 : 10^{-4} \quad (\text{circumference of central orbit}).$$

Hence, the method looks well suited to measure momentum changes of less than 1 part in 10^4 - perhaps 1 in 10^5 . This, especially in machines with a large value of transition energy, as in this case the orbit circumference $2\pi R$, is insensitive to field and momentum errors. In addition, an absolute momentum measurement is feasible to the precision by which the circumference $2\pi R_0$ of the "central orbit" is known. However, both the absolute and the relative measurement become imprecise when the machine works close to transition energy where by virtue of (5) f_0 is insensitive to a change of p. Sufficiently far from transition revolution frequency is a well suited "indicator" of momentum.

FURTHER METHODS OF ENERGY MONITORING

To conclude, we list further methods of energy monitoring and/or calibration:

- a) Excite depolarizing RF fields. Measure the frequency of resonant depolarization ("spin k.o."):

$$f_{\text{RF}} = (n \pm \nu_{\text{spin}}) \cdot f_0$$

where n is an integer, f_0 the revolution frequency and

$$\nu_{\text{spin}} = \left(\frac{g-2}{2}\right) \cdot \gamma$$

the number of spin precessions (per turn) around the magnetic guide field. This method works if the beam is polarized and the gyromagnetic anomaly $g-2$ of the ions is well known. Used at Novosibirsk for electrons and positrons, it permitted to determine the mass of the J/ψ particle with a precision of 90 eV (A. Skrinsky, Proc. 12 Intern. Acc. Conf., Fermilab 1983, p. 235).

- b) Observe known thresholds for reactions on internal target (K. Kilian, CERN EP 84-58 and Proc. of the 4th Workshop on pp collider Phys., Bern, March 1984).
- c) Observe energy of the cooling electron beam.
- d) Measure time of flight in a straight section using scattering of laser light or correlation of particle signals on pick-up electrodes.
- e) Extract beam onto spectrometer.

CONCLUSIONS

Several methods to change the energy of a circulating beam are well established. The choice depends on the application foreseen and the hardware available :

- RF acceleration (normal or phase displacement) seems easiest for a quick and/or large change.
- Use of the cooling system looks natural and well suited for energy sweeping in a cooler ring.
- Diffusion by RF noise or RF unstacking offer themselves to transport beam onto an extraction resonance or an internal target.

Energy can be monitored observing e.g.:

- radial beam displacement;
- betatron frequency;
- revolution frequency;
- "settings" of the cooling system.

Most of these "machine physics methods" are limited - amongst other factors - by the accuracy at which the guide field is known. Highest accuracy is probably possible by deducing momentum from the revolution frequency, especially if the machine has a large value of transition energy and works remote from transition,

Special "particle physics properties" (spin, threshold reactions, ...) look attractive for an absolute calibration.

Distribution (of abstract)

PS Scientific Staff

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