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RF-Resonance Beam Polarimeter

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Abstract

The possibility of an RF-resonance polarimeter (RFP) for fast non-destructive measurement of beam polarization in an accelerator ring is considered, using a passive superconducting cavity. The increase of collective voltage in the cavity (TM_{110} mode) with time, related to the free oscillating coherent spin of the beam is calculated.
The efficiency of the RFP does not decrease with particle energy and is proportional to the average beam current.
There are in the RFP dynamics different effects of the beam charge - cavity interaction , positive and negative.
The negative effects are the beam noises, while the positive ones are as follows:
- the possibility to enhance the spin-dependent beam - cavity interaction, via the spin-orbit coupling in the machine focusing lattice.
- the possibility to increase, if necessary, the effective quality of the superconducting resonator, via redistribution of decrements between the TM_{110} mode and the beam coherent oscillation.

A scheme of elimination of charge effects from the measurement is proposed, if needed, which is based on use of two cavities with a spin rotator (Siberian snake) between them. Finally, the RFP scheme is transformed to a Beam Spin Maser system, which is a spin feedback based on the superconducting cavities. This would allow one to create, to observe, and to use for polarization measurements the phenomenon of beam spontaneous coherent spin flip. Numerical exemples are given.

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RF-resonance Beam Polarimeter

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Abstract

The possibility of an RF-resonance polarimeter (RFP) for fast non-destructive measurement of beam polarization in an accelerator ring is considered. In order to accumulate the spin-dependent beam transition radiation, a passive superconducting cavity is proposed. The increase of effective voltage in the cavity (TM_{110} mode) with time, related to the free oscillating coherent spin of the beam, is calculated. The efficiency of the RFP does not decrease with particle energy and is proportional to the average beam current. Siberian snakes can be used in order to provide a sufficiently small value for the spin tune spread. Possible schemes of measurement of the accumulated voltage are presented. The noise limitations are taken into account and evaluated.

There are in the RFP dynamics different effects of the beam charge - cavity interaction, positive and negative. The negative effects are the beam noises, while the positive ones are as follows:

-the possibility to enhance the spin-dependent beam - cavity interaction, via the spin-orbit coupling in the machine focusing lattice;

-the possibility to increase, if necessary, the effective quality of the superconducting resonator, via redistribution of decrements between the TM_{110} mode and the beam coherent oscillation.

A scheme of elimination of charge effects from the measurement is proposed, if needed, which is based on use of two cavities with a spin rotator (Siberian snake) between them.

Finally, the RFP scheme is transformed to a Beam Spin Maser system, which is a spin feedback based on the superconducting cavities. This would allow one to create, to observe, and to use for polarization measurements the phenomenon of beam <u>spontaneous coherent spin flip</u>.

Numerical examples are given.

1. Fundamental concepts

1.1. RF-voltage accumulation rate

When a polarized beam is circulating in an accelerator ring, and the coherent spin of the beam is declined from the equilibrium direction, $\vec{n}$ (vertical or, in general case, periodical along the beam orbit), then the electromagnetic field of the beam, "observed" by a cavity located at a point of the orbit, has to have a modulation with periodicity of the free precession of the spin in the accelerator, which is different from the periodicity of the particle orbital motion. Apparently, this signal is very small. However, if the spin tune spread, $\Delta\nu$, is small enough, the beam current, J, is sufficiently high, and the quality Q_c of the cavity, tuned in resonance with the spin free precession, is also high enough, then the beam could excite the cavity resonance mode to a measurable level while an unpolarized beam would not be able to do this.

The most convenient cavity mode for the spin-cavity interaction is TM_{110} mode (see Fig. 1). The mode energy accumulation rate can be calculated starting from the Hamilton's approach driving the common coherent spin and cavity dynamics:

$$H_{int} = \sum_j \vec{W}(\vec{r}_j, \vec{p}_j)\vec{S}_j$$

where $\vec{W}$ function is taken from the BMT equation [1]

$$\dot{\vec{S}} = \vec{W} \times \vec{S},$$

$$\vec{W} \equiv -\frac{e}{mc}\left\{\left(G+\frac{1}{\gamma}\right)\vec{B}_\perp + \frac{1+G}{\gamma}\vec{B}_v + \left(G+\frac{1}{\gamma+1}\right)\vec{E}\times\frac{\vec{v}}{c}\right\},$$

where G≈1.79 for protons and ≈ 1/2π·137 for electrons, and $\gamma^{-2} = 1 - v^2/c^2$.

In our case, $\vec{B}_v$ and $\vec{E}\times\frac{\vec{v}}{c}$ can be neglected.

Solving the field equations in terms of energy E_c - phase φ_c of the eigen modes, we find the effective voltage rate [2]:

$$\frac{dV}{dt} \approx 33\left(G+\frac{1}{\gamma}\right)\frac{J\hbar}{mcr_c^2}\sin\left(\frac{1.9d}{\beta r_c}\right)\cdot\xi\sin\alpha\,,$$

$$\left(E_c \equiv \frac{1}{2}CV^2\,,\quad C = {r_c^2}/{4d}\right).$$

where ξ is the polarization degree.

Note, that the bunch length must be less than cavity radius r_c:

$$\ell_b \ll r_c\,.$$

Remark, that the accumulation rate does not drop with particle energy, γ, and it is proportional to the average beam current, J.

1.2. Maximum accumulated voltage

The maximum voltage that can be accumulated in the resonator is defined by an effective maximum time:

$$V_{max} = \dot{V}t_{max}\,,\quad t_{max} = \min(\tau_{sp}, \tau_c),$$

where $\tau_{sp} = (\omega_0\Delta\nu)^{-1}$, $\omega_0/2\pi$ is the particle's revolution frequency, and τ_c is the RF-voltage damping time due to the cavity wall resistance. It is related to the quality factor Q_c of the considered cavity mode as:

$$\tau_c = Q_c/\omega_c\,.$$

A typical Q_c value for TM_{110} mode of available superconducting resonators is 2×10^{10} [3]. At r_c=20 cm, τ_c value is about 5 s.

To provide τ_{sp} value compatible with τ_c, special measures for reduction of $\Delta\nu$ are required. For a bunched beam, $\Delta\nu$ is proportional to the beam emittances. It can be reduced by application of compensating sextupoles. The spin tune spread can be made especially small in rings with Siberian snakes. These possibilities should be investigated in detail separately.

1.3. RF-voltage measurement (noise criteria)

In view of the rather small value of possible accumulated voltage, one has to take into account noise limitations. There are two basic kinds of noise: thermal cavity noise and voltmeter input thermal noise.

1) The cavity noise effect is defined by the noise spectral density of the considered field mode, which is a single oscillator. When there is a state of thermodynamic equilibrium in the cavity walls, we can use a canonical formula for the oscillator energy distribution [4], which can be written for frequencies near resonance as follows:

$$\frac{dE_T}{d\omega} \approx \frac{T_c \tau_c}{1+(\omega-\omega_c)^2 \tau_c^2} \frac{1}{\pi},$$

where T_c is the cavity wall temperature (in units of energy). A voltmeter will integrate the frequencies in the interval $\Delta\omega \sim 1/t_m$, where t_m is the measurement time:

$$t_m = \max\{\tau_{sp}, \tau_c\}.$$

There are two characteristic cases:

a) $\tau_{sp} << \tau_c$, then

$$(E_c)_{max} = \frac{1}{2} C \dot{V}^2 \tau_{sp}, \quad t_m = \tau_c, \quad E_T \sim T_c$$

b) $\tau_{sp} >> \tau_c$, then

$$(E_c)_{max} = \frac{1}{2} C \dot{V}^2 \tau_c, \quad t_m = \tau_{sp}, \quad E_T \sim T_c(\tau_c/\tau_{sp}).$$

To measure the accumulated voltage with confidence, the following condition is necessary:

$$C \dot{V}^2 \tau_{sp} \min(\tau_{sp}, \tau_c) >> T_c.$$

2)The frequency bandwidth Δf of an applied RF-voltmeter should satisfy the requirement

$$2\pi t_m \Delta f >> 1;$$

on the other side, the Δf value should be small enough to eliminate the noise voltage due to the input resistance R_{in} of the voltmeter:

$$V_{in} = [2(TR_{in})\Delta f]^{1/2} << V_{max}$$

A possible voltmeter scheme is shown in Fig. 2 [5]. In the frequency region $f \sim 10^8 - 10^9$ Hz, the characteristic R_{in} value can be about 100 Ω or less. Assume that the preamplifier channel temperature $T_{in} = 300$ K, and an f-band value 10^3 Hz; then

$$V_{in} \sim 4 \times 10^{-8} \text{ V},$$

which is much less than the thermal noise effective voltage $V_T = \sqrt{2T_c/C} \sim 10^{-6}$ V. We can conclude that, in practice, the minimum value of accumulated voltage is defined by the resonator thermal noise.

1.4. Numerical examples

Table 1 illustrates the values of basic parameters and requirements for different machines, assuming:
$V_{max}/V_T = 5,\quad \xi = 1,\quad \alpha = 90^\circ,\quad d = \pi\beta c/\omega_c,\quad r_c = 20$ cm.
at a single resonator in a ring with $T_c = 1\,K$. With N superconducting resonators, the maximum total accumulated voltage would be N times larger, and then the requirements for the $\Delta\nu$ value would be $\sqrt{N}$ times weaker.

1.5. Possible operational scheme

An operational procedure of polarization measurement could include the following steps:

1)To swing spin coherent free oscillation, use an RF-driven voltage (perhaps a different superconducting cavity), then switch off this voltage.

2)Shunt polarimeter's superconducting cavity, in order to kill an initial RF-oscillation (exited by beam charge).

3)Turn-off the shunting resistance adiabatically.

4)Wait for spin-swing of the polarimeter superconducting cavity.

5)measure the accumulated RF-voltage.

2. Beam charge effects

There is a number of beam charge different contributions to the cavity field dynamics, which have to be taken into account and reduced, if necessary.

2.1. Cavity tune shift

This is an effect of the neutral kind. It can be attributed to the definition of the TM_{110} mode frequency at the beam transverse loading and calculated in usual approach.

2.2. Renormalization of the resonator quality

Beam coherent transverse damping (deliberately arranged) can be used for the reduction of the 110 mode decrement, i.e. to increase the resonator quality, if necessary. If there is a fast beam coherent damping with decrement λ_b, then the decrement of the resonator is changed by some value $\eta\lambda_b$, where

$$\eta>0,\ \text{at}\ \nu_c \approx k + \nu_y$$
$$\eta<0,\ \text{at}\ \nu_c \approx k - \nu_y,$$

where ν_y is betatron tune.

A necessary precise control of the reduced τ_c^{-1} value seems to be easy to realize in this way.

2.3. Renormalization of the spin-resonator interaction

This effect takes the origin from the spin-orbital force in the machine focusing field, which creates the particle orbit modulation with spin precession frequency. It is described by the equation as follows:

$$\ddot{Q} + 2\lambda\dot{Q} + \omega_c^2 Q = Neb\langle y\rangle_{sp},$$

where $\langle y\rangle_{sp}$ is the enforced solution of the equation

$$\langle\ddot{y}\rangle_{sp} + n\omega_0^2\langle y\rangle_{sp} = -\frac{\omega_0^2}{mc}\left(G+\frac{1}{\gamma}\right)n\langle S_x\rangle(t),$$

n is the focusing field index, and b is the normalized magnetic field in the cavity. Apparently, the coupling effect increases near the spin-orbit resonances. The gain in the effective spin-resonator interaction is of about

$$k_{(sp-orb)} \sim \frac{\nu_y}{\nu_y - k \pm \nu_{sp}}.$$

This influence complicates the coherent spin measurement, although its contribution can be precisely calculated for any given energy, γ. It may be also used for a reduction of the accumulation time, if necessary.

2.4. Beam overtonal resonance noise

Particle oscillations may get in resonance with TM_{110} mode because of nonlinearities of this field, as well as because of the overtonal modulation of particle's motion due to the nonlinearities of the lattice (including beam-beam effect). It should be noted, that, in fact, one meets here the same set of resonances as for the spin motion in a ring (with snakes) in view of the spin-resonance condition. Therefore, tuning-off the spin resonances is similar to tuning-off the orbit-resonator resonances. Estimation of dangerous high order resonances have to be made for definite situations. In practical aspects, these effects seem not to be of a dramatic meaning for the presented polarimetry concept.

2.5. Vacuum chamber-resonator beam link

A circulating beam will also transfer the vacuum chamber noise into the superconducting resonator. It has to be taken into account, in principle, because the chamber temperature (or temperature of the feedback elements, e.t.c.) frequently exceeds T_c. Nevertheless, and as a rule, the transferred noise must be relatively small, excluding situations of resonances between TM_{110} resonator mode and chamber eigen modes.

Note, that the resulting resonator noise spectrum has to be defined with taking into account the decrements redistribution as discussed in Sect.2.2.

2.6. Charge effects compensation

A modified sophisticated schemes of the RF-polarimeter may be used in order to avoid a complication in the polarization measurement due to the spin-orbit contribution and to reduce beam noise effect, if necessary. Fig.3 presents an example of this kind. It involves a spin rotator (Siberian snake) located between two superconducting resonators. Phase shift of value π between signals from these two resonators has to be provided to cancel charge contribution effect on the input of the resonator.

3. Beam spin maser

The next stage of the RF-polarimeter concept may be a spin feedback based on superconducting resonators. Fig.4 presents a simple principal scheme of this. If the above discussed noise limitations are fullfilled in the accumulating resonator, then the field in the resonator-kicker will be well correlated with coherent spin precession. The purpose of the feedback is to provide stability of spin coherent free precession against the spin tune spread, i.e., the condition $\Delta\omega_c >> \omega_0\Delta\nu$, where $\Delta\omega_c$ is spin tune shift by the RF-field of the kicker, should be satisfied. Then, if there would be no dissipation in the resonators, the coherent spin free precession would continue infinitely, although it may be complicated by beating as being a non-linear process. With the dissipation, the coherent spin damps to the equilibrium axis, $\vec{n}$ (periodical along the beam orbit). Since there are two possible signs of the equilibrium polarization, we can anticipate, that one of them is stable, while the other one is unstable with respect to the dissipation factor. This is the phenomenon that can be treated as beam spin maser.

Maser effect gives to the spin free precession a characteristic convenient for observations. The measurement procedure would become simple. Switching the feedback parameters, the initial equilibrium polarization of the beam can be made coherently unstable. After some characteristic time (a few resonator damping time) the excitation of the resonator-kicker will reach a maximum, when the polarization becomes transverse to $\vec{n}$, and then will vanish back to the noise level, with spin reversed to the new, stable polarization. This process can be repeated frequently, if needed. With the calibration of the involved parameters, the polarization degree can be calculated after measuring the maximum voltage of the resonator. No special RF spin kicker and hence resonator shunt would be required in here.

Note, that the noise limitation criteria have to be redefined, taking into account the tune shift, decrements redistribution and maser relaxation time.

4. Conclusion

The above consideration allows us to believe that the RF-polarimeter may become an efficient way of beam spin monitoring in high energy accelerators and storage rings.

The superconducting resonators of necessary quality value are available today. In addition, the beam transverse loading can be used to raise the resonator dynamic quality, if needed.

The RF-polarimeter principle matches well with the Siberian snakes technique, that makes the spin tune independent of energy and reduces the spin tune spread.

The RF-polarimeter efficiency grows with the beam current. At low current (low and middle energy range accelerators), the spin-resonator interaction can be enhanced using the spin-orbit coupling.

Finally, the RF-polarimeter becomes especially attractive and operationally simple when converted to a maser type system using the superconducting resonator feedback.

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References

1. L.D. Landau and E.M. Lifshits, Course of Theoretical Physics, vol. 4 Quantum Electrodynamics, 2nd ed. (Pergamon, 1982).
2. Ya.S. Derbenev, Nucl. Instr. & Meth., A336 (1993) 12-15.
3. H. Padamsee, private communication.
4. L.D. Landau and E.M. Lifshits, Course of Theoretical Physics, vol. 5, Statistical Physics, 3rd ed. (Pergamon, 1980).
5. V.V.Rykalin, private communication.

Table 1
Examples
For a number N of resonators, the total V value can be N times larger, the necessary accumulation time t_{max} can be $\sqrt{N}$ times smaller, and the requirement for $\Delta\nu_{min}$ is $\sqrt{N}$ times weaker.

Machine particles	Polarized beam current[mA]	Energy γ	$\dot{V}$ [V/s]	$t_{max} = \tau_{sp}[s]$ required	$\Delta\nu_{min}$ required
IUCF Cooler Ring, p	1	1.3	5×10^{-6}	2	5×10^{-7}
FNAL, Tevatron, p	100	10^{3}	3×10^{-4}	0.03	10^{-4}
RHIC, p	50	250	1.5×10^{-4}	0.06	3×10^{-5}
CESR, $e^{\pm}$	100	10^{4}	3.3×10^{-4}	0.03	1.2×10^{-5}
HERA, $e^{\pm}$	30	5×10^{4}	10^{-4}	0.1	4×10^{-5}
LEP, $e^{\pm}$	3	10^{5}	10^{-5}	1	1.6×10^{-5}
LHC, p	100	6×10^{3}	3×10^{-4}	0.03	4×10^{-4}

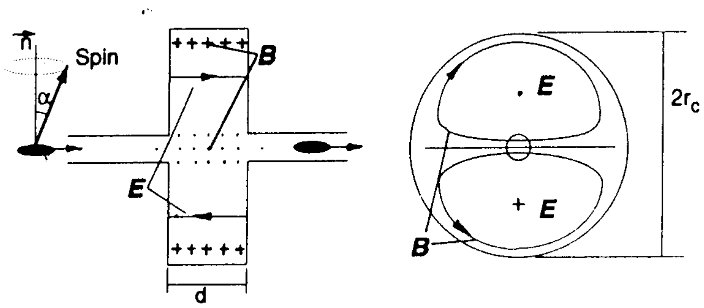

Fig. 1. Scheme of spin interaction with TM_{110} mode.

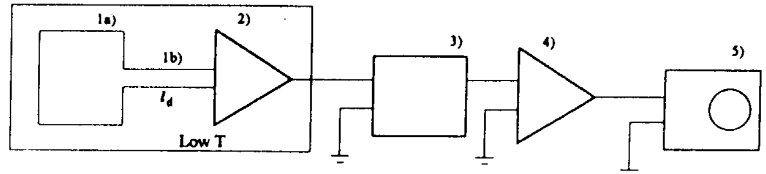

Fig. 2. RF voltage measurement scheme. 1a) A loop in the magnetic field of the superconducting RF-resonator. 1b) Waveguide (min. distance). 2) Preamplifier with narrow f-band. 3) Emitter follower. 4) Resonance circuit. 5) Scope.

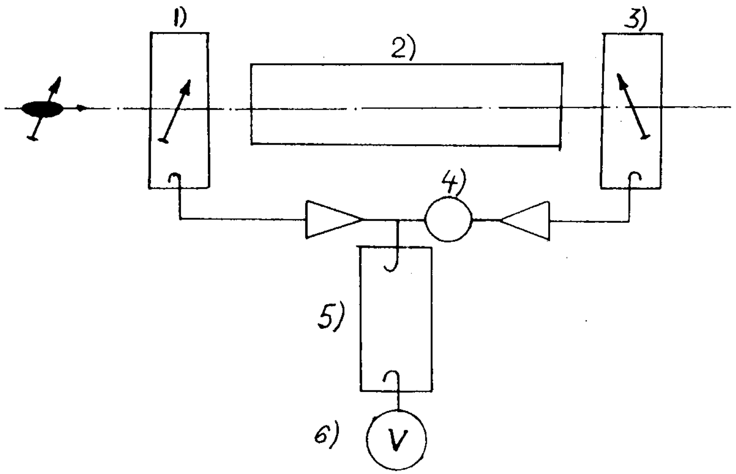

Fig. 3. Charge effect compensation scheme.
1), 3), 5) Superconducting resonators.
2) Spin rotator (Siberian snake)
4) Phase shift π circuit
6) Voltemeter

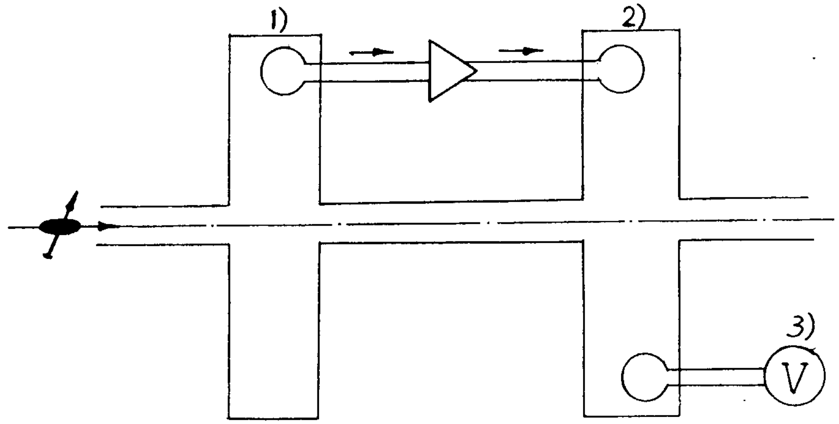

Fig 4. Spin feedback scheme
1) Superconducting resonator - accumulator
2) Superconducting resonator - kicker
3) Voltmeter