ON A POSSIBILITY OF USING A SUPERCONDUCTING CAVITY IN THE RF SYSTEM OF THE STORAGE RING LESR - N100

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In the Kharkov Institute of Physics and Technology the design project of the 200 MeV electron storage ring LESR-N100 is under development. The essential feature of this facility is the large beam energy spread (of about 1%). To ensure a reasonable beam lifetime the RF-system should provide the accelerating voltage of about 0.5 MV, while the total energy losses do not exceed ~700 eV/turn. The power dissipated in two 700 MHz normal-conducting (NC) cavities much exceeds the power transmitted to the beam. We considered a possibility to use in LESR-N100 a high-Q superconducting RF-cavity (SRF-cavity) in which the dissipated power is the same order of magnitude as the beam-transmitted power. The studies show that the system with SRF-cavity cannot operate in the standard mode when the cavity is matched to the power transmission line at some nominal beam current. The optimal operation mode with high overcoupling is proposed that requires the RF-power one order of magnitude less than in the case of NC-cavities.

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1. INTRODUCTION

The RF system of any electron storage ring is developed to provide both the compensation of total energy losses of the beam and the required energy acceptance.

The storage ring LESR-N100 [1] is intended for studies of the laser-beam cooling effect and feasibility of producing intensive X-ray beams through Compton scattering of a laser light on an electron beam [2]. The main parameters of the ring are presented in Table 1.

***Table 1**. Parameters of the LESR-N100*

Electron energy, E_0, *MeV*	200	
Beam current, I_b, *mA*	10	
Momentum compaction factor, α	0.021	
Number of bunches	1	
RF-frequency, f_{RF}, *MHz*	699.3	
Accelerating voltage, V_c, *MV*	0.5	
RF- bucket width, Δ_{RF}/E_0, %	5.3	
Radiation loss, U_{rad}, *eV*/turn	283	
Energy spread, $\Delta E/E_0$, %	0.8	
Accelerating cavities:	NC	SC
Number of cavities	2	1
Parasitic energy loss, *eV*/turn: -RF-cavities - vacuum chamber -total, U_{tot}	 330 140 750	 60 140 480
Synchronous phase, Φ_c, deg	89.913	89.945
Power transmitted to the beam, P_b, *W*	7.5	4.8
Dissipated power, P_c, *kW*/cell	11.5	0.0025
RF-generator power, P_g, *kW*	23	1.25

The essential feature of this facility is the large beam energy spread $\Delta E/E_0 \approx 1\%$ [3]. To ensure a reasonable beam lifetime, the accelerating system should provide the RF voltage V_c=0,5 *MV*, while the total energy losses U_{tot} do not exceed ~700 *eV*/turn. The result of such disproportion is the necessity to operate practically in a minimum of a wave of an accelerating voltage ($\Phi_s=\arccos(U_{tot}/V_c)\approx 90^{\circ}$). The power dissipated in two normal conducting (NC) cavities (P_c=11.5 *kW*/cavity) much exceeds the power transmitted to the beam (P_b~ 7*W*). In view of the above mentioned, it seems an inviting prospect to use in LESR-N100 a high *Q* superconducting RF cavity (SRF-cavity), in which the dissipated power is the same order of magnitude as P_b. Such a possibility is considered below.

2. OPERATION PARAMETERS

Let's consider a phase vector diagram for the cavity gap voltages, presented in Fig. 1. The accelerating voltage $\boldsymbol{V_c}$ is determined by a sum of voltages $\boldsymbol{V_g}$ and $\boldsymbol{V_b}$ induced by an RF-generator and a beam, accordingly.

For the projections of these vectors onto axes *X* (*X* is selected along the vector $-\boldsymbol{I_b}$) and *Y* the following relations are valid:

$$V_c \cdot \cos\Phi_s = V_g \cdot \cos(\theta + \psi) - V_b \cos\psi \qquad (1a)$$

$$V_c \cdot \sin\Phi_s = V_g \cdot \sin(\theta + \psi) + V_b \cdot \sin\psi , \qquad (1b)$$

The cavity tuning angle ψ is defined by the expression ($\omega_0 - \omega << \omega_0$):

$$tg\psi = -\frac{2 \cdot Q_0}{1+\beta} \cdot \frac{\omega - \omega_0}{\omega_0} = -2 \cdot Q_L \frac{\omega - \omega_0}{\omega_0} = -\frac{\omega - \omega_0}{\Gamma/2} , \qquad (2)$$

where Q_0 is an unloaded quality-factor of a cavity; β is a coupling coefficient of a cavity with a transmission line; Q_L is a loaded quality factor; ω_0 is a fundamental frequency of a cavity, ω is a generator frequency, Γ is a width of resonance curve of the loaded cavity at half its height in maximum. One can see from the relation (2) that $tg\psi$ is equal to the relative cavity detuning in terms of the resonance width.

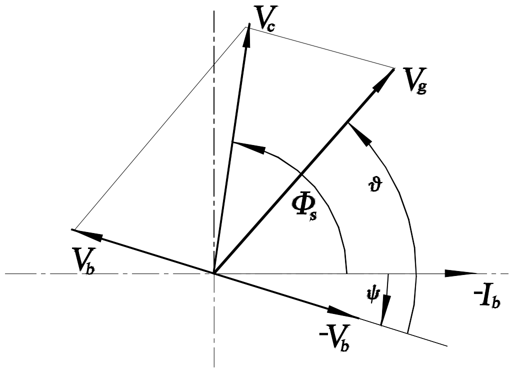

Fig. 1. *The phase-vector diagram for steady-state beam loading*

The voltages V_b and V_g are given by the relations [4]:

$$V_b = V_{br} \cdot \cos\psi = \frac{I_b\left(\frac{R}{Q}\right)Q_0}{1+\beta}\cos\psi \tag{3a}$$

$$V_g = V_{gr} \cdot \cos\psi = \frac{2\left(P_g\left(\frac{R}{Q}\right)Q_0\beta\right)^{\frac{1}{2}}}{1+\beta}\cos\psi\ , \tag{3b}$$

where V_{br} and V_{gr} represent the values V_b and V_g in the resonance, P_g is the generator power at the cavity input, and the factor R/Q is a figure of merit sometimes called "a geometrical shunt resistance" of a cavity.

By excluding θ from the relations (1a, 1b), substituting in the obtained equation V_g with (3b), and solving it with respect to P_g, one can get the following expression for the generator power:

$$P_g = \frac{V_c^2 \cdot (1+\beta)^2}{4\beta\left(\frac{R}{Q}\right)Q_0\cos^2\psi}\left\{\left[\cos\Phi_s + \frac{I_b\left(\frac{R}{Q}\right)Q_0}{V_c(1+\beta)}\cos^2\psi\right]^2 + \left[\sin\Phi_s + \frac{I_b\left(\frac{R}{Q}\right)Q_0}{V_c(1+\beta)}\cos\psi\cdot\sin\psi\right]^2\right\} \tag{4}$$

Usually, in the RF-systems of electron storage rings the fundamental frequency of the loaded cavity is tuned so that to compensate the reactive beam-loading component and reduce the power consumed from the generator. The corresponding expressions for P_g can be obtained by optimizing the equation (4) for a cavity tuning angle ψ:

$$tg\psi = -\frac{I_b R_{sh}}{V_c(1+\beta)}\cdot\sin\Phi_s\ , \tag{5a}$$

$$P_g = \frac{(1+\beta)^2}{4\beta\cdot R_{sh}}\cdot\left[V_c + \frac{I_b R_{sh}}{(1+\beta)}\cos\Phi_s\right]^2 . \tag{5b}$$

The optimization of the equation (5b) for a coupling coefficient β reduces the expressions (5) to:

$$\beta_0 = 1 + \frac{P_b}{P_c}\ , \tag{6a}$$

$$tg\psi_0 = -\frac{\beta_0 - 1}{\beta_0 + 1}\cdot tg\Phi_s\ , \tag{6b}$$

$$P_{g0} = P_b + P_c\ , \tag{6c}$$

where $P_b = I_b V_c \cos\Phi_s$ is the power transmitted to the beam, and $P_c = V_c^2/[(R/Q)Q_0]$ is the power dissipated in cavity walls. So, the equations $\beta = \beta_0$ and $\psi = \psi_0$ are the conditions of matching of a beam-loaded cavity to a transmission line, because no reflection takes place at a cavity input, and the required generator power is minimal.

Substituting in expressions (3) and (6) the values R/Q=100 and $Q_0=10^9$, typical for superconducting cavities, one obtains the following results:

P_{g0}=7.3 *W*; β_0=2.9; $\psi_0 \cong \Phi_s \cong 90^0$; $V_b >> V_g$;

that is a matched operation demands a complete detuning of a cavity ($\Delta\omega$=4.4 k*Hz*, while Γ=*8.8 Hz*), and the above considerations make no sense.

It should be noted that the control of the accelerating voltage parameters is carried through changing the phase and amplitude of $\mathbf{V_g}$, and the practical operation of the RF-system is possible when the dominant contribution to the total cavity voltage $\mathbf{V_c}$ gives this vector, i.e. when $V_b \le V_g$. Then, assuming that the reactive component of beam loading is compensated by a cavity detuning one can obtain the following relation:

$$I_b \cdot \left(\frac{R}{Q}\right)\cdot Q_0(1-\cos\Phi_s) \le V_c(1+\beta)\ . \tag{7}$$

Taking into account that in our case $\cos\Phi_s << 1$ we derive the relation restricting a magnitude of β:

$$\beta \ge \frac{I_b\cdot\left(\frac{R}{Q}\right)\cdot Q_0}{V_c} - 1\ . \tag{8}$$

Having substituted in expression (8) R/Q=100 and $Q_0=10^9$, we obtain $\beta \ge 2\text{x}10^3$, that is the system should operate under strongly overcoupled conditions. It returns us to the traditional operation of superconducting cavities at modern accelerating facilities, where overcoupling is stipulated by a high value of P_b, i.e. all RF-power is transmitted to the beam. In our case $P_b \sim P_c$, and practically all power will be reflected at the cavity input and should be dissipated in a circulator load. For the boundary case $\beta=\beta_{opt}$ the generator power P_g is given by the simple expression:

$$P_g = \frac{1}{4} I_b V_c \,. \tag{9}$$

From this expression one can see, that the power required from a generator does not depend on the cavity parameters. Using the above mentioned relations, we obtain the main parameters for the boundary case $\beta=\beta_{opt}=2000$:

$\psi=-45°$; $P_c=2.5\ W$; $P_b=4.8\ W$; $P_g=1.25\ kW$;

One can see that according to (2) $\Delta\omega = \Gamma/2$, *i.e.* the optimal coupling corresponds to the cavity detuning equal to the resonance half-width, and the required RF-power is one order of magnitude less than in the case of NC cavities (~20 *kW*). However, it should be noted, that in the first case the required RF-power grows proportionally to the beam current, while in the second case it practically does not depend on the beam current.

3. STABILITY OF PHASE OSCILLATIONS

As the result of a beam interaction with a fundamental mode of an accelerating cavity a growth rate of the rigid-bunch phase oscillations (Robinson instability) is possible. For the cavity voltage phase and amplitude control loops opened, and for the case of reactive beam loading compensation, the stability criteria is given by [4]:

$$V_c > V_{br} \cdot \cos\Phi_s \,, \tag{10}$$

In our case the synchronous phase Φ_s is defined by:

$$\cos\Phi_s = \frac{U_{tot}}{V_c} = \frac{U_{rad} + I_b \cdot R_{loss}}{V_c} \,, \tag{11}$$

where R_{loss} is a total loss resistance of the ring. Substituting the expressions (11) and (3a) in (10), we obtain the following limitation on the beam current:

$$I_b < V_c \cdot \left[\frac{1+\beta}{R_{loss} \cdot \left(R/Q \right) \cdot Q_0} \right]^{1/2} = 500\,mA \,. \tag{12}$$

This estimate far exceeds the designed value of the beam current.

4. THE SUPERCONDUCTING CAVITY

For the LESR-N100 accelerating cavity we consider a single-cell spherical cavity with wide beam pipes. The cavity cell geometry is shown in Fig. 2.

Cavity calculations were performed with SUPERFISH [5]. The cavity spectrum for monopole modes is presented in Table 2. Boundary conditions *E* or *M* correspond to Dirichlet or Neumann boundaries, accordingly, at the ends of the half-cell.

The cavity has beam pipes by a diameter of 170mm, and the cut-off frequencies are 1349 MHz for TM_{01}-like modes and 2150 MHz for TM_{11}-like modes. The calculated field topography for monopole cavity modes shows that only the fundamental mode is trapped in the spherical part of the cavity, all other modes propagate effectively into the beam pipes. It is supposed to reduce the *Q*-factors of these modes with a pair of coaxial antennas-dampers located on the cavity beam pipes.

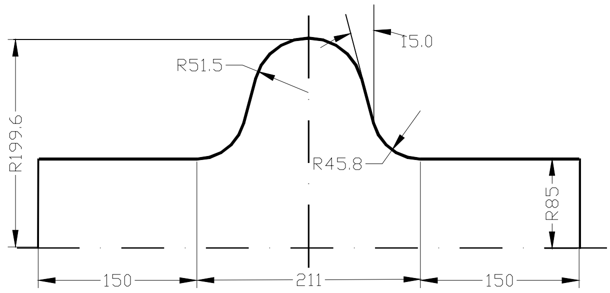

***Fig. 2**. The SRF cavity for the LESR – N100 storage ring*

***Table 2**. Cavity modes*

Frequency, MHz	Boundary conditions	$Q\cdot10^{10}$	*R/Q*, Ω
699.95	EM	1.57	82.8
1368.50	EM	1.90	23.0
1368.87	ME	1.68	236.0
1502.46	ME	1.59	78.2
1584.28	EM	1.65	375.8
1965.64	EM	1.60	122.8
2200.46	EM	1.50	112.4
2814.42	EM	1.22	12.4

5. CONCLUSIONS

The consideration presented above shows that the implementation of a SC-cavity in the RF-system of LESR-N100 is justifiable for the stored beam currents up to ~10mA. In the case of project upgrading for storing higher currents (multibunch mode), it seems reasonable to use conventional room-temperature RF-cavities.

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