OPERATION OF SUPERCONDUCTING CAVITIES IN A FAST RAMPING ELECTRON STORAGE RING*

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Abstract

The achievable maximum energy of a medium-sized electron accelerator is mainly limited by the accelerating voltage. Using superconducting (SC) cavities, the energy limitation can be shifted considerably. However, the operation of SC multi-cell cavities in a fast ramping storage ring causes additional problems which were investigated at the 3.5 GeV Electron Stretcher Accelerator ELSA. We studied the use of two 500 MHz SC cavities providing the necessary resonator voltage of up to 14 MV and replacing the normal conducting cavities of PETRA type. A large cavity coupling factor is required, so that, using the existing 260 kW klystron, an internal beam of 50 mA can be accelerated up to 5 GeV. In addition, a fast detuning of the resonance frequency of the cavities must be implemented during beam injection and the energy ramp of 4 GeV/s. An appropriate 500 MHz structure is given by a five-cell cavity constructed for the JAERI FEL LINAC. Based on this geometry, HOM have been calculated from a numerical simulation. Since all monopole and a large number of dipole HOM are well above the multi-bunch instabilities threshold, further studies about the damping of beam instabilities are essential.

ENERGIES OF UP TO 5 GEV AT ELSA

At the 3.5 GeV Electron Stretcher Accelerator ELSA [1] of Bonn University, an energy upgrade up to 5 GeV for the future external hadron physics experiments program was studied. It turned out that, using the existing RF system (260 kW klystron power, 500 MHz RF frequency) and by replacing the two currently installed five-cell normal conducting cavities of PETRA type with superconducting (SC) cavities, an internal beam of up to 50 mA beam current could be accelerated up to 5 GeV.

Acceleration with SC Cavities

The operation of the storage ring for the external experiments requires beam life times of at least one minute at the maximum energy of 5 GeV in order to avoid significant beam losses. This corresponds to an overvoltage factor of 2.69 at 5 GeV. The synchrotron radiation losses at this energy add up to 5.08 MeV per turn so that a large overall peak voltage of 13.67 MV is required, which considering the conditions at ELSA can only be provided by multi-cell SC cavities.

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An appropriate 500 MHz structure is given by the geometry of SC five-cell cavities (see Fig. 1) constructed for the JAERI FEL LINAC by the former company Accel Instruments in the early 90's [2]. Those SC acceleration modules

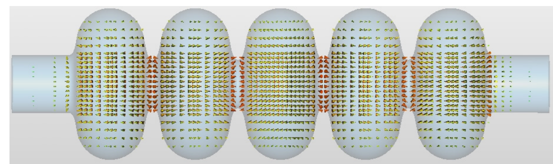

Figure 1: Elliptic geometry (cell length: 300 mm, cell diameter: 532.5 mm, beam pipe diameter: 202 mm) of the five-cell SC 500 MHz cavity with electric field distribution of the TM_{010} π-mode for beam acceleration. Simulated with the eigenmode solver of CST Microwave Studio®.

are characterized by an operating gradient of up to 5 MV/m with a cavity quality factor above 10^9. Using two of these five-cell cavities, the necessary overall cavity voltage of 13.67 MV can be provided. This setup corresponds to a total section of acceleration of 3 m and leads to a maximum electric field strength of 4.56 MV/m. The relevant parameters regarding beam acceleration at 5 GeV are summarized in Table 1.

Table 1: Beam Acceleration Parameters at 5 GeV

Overvoltage factor, q	2.69
Acceleration voltage to compensate for synchrotron radiation losses, U_a	5.08 MV
Peak voltage per module, U_c	6.84 MV
Total RF power for a beam current of $I_\mathrm{b} = 50\,\mathrm{mA}$	254 kW

ACCELERATOR CYCLE

The typical ELSA operation cycle ensuring a high duty cycle begins with the beam accumulation of up to 50 mA at 1.2 GeV in the storage ring. A fast energy ramp of 4 GeV/s follows, and at 5 GeV the beam is slowly extracted to the external experiments within 5 seconds. Therefore, most of the parameters relevant for beam acceleration must be changed significantly during this operation cycle.

Coupling Factor and Cavity Detuning

In order to investigate the operation with SC cavities for this scenario, at first, the coupling factor β of the RF input

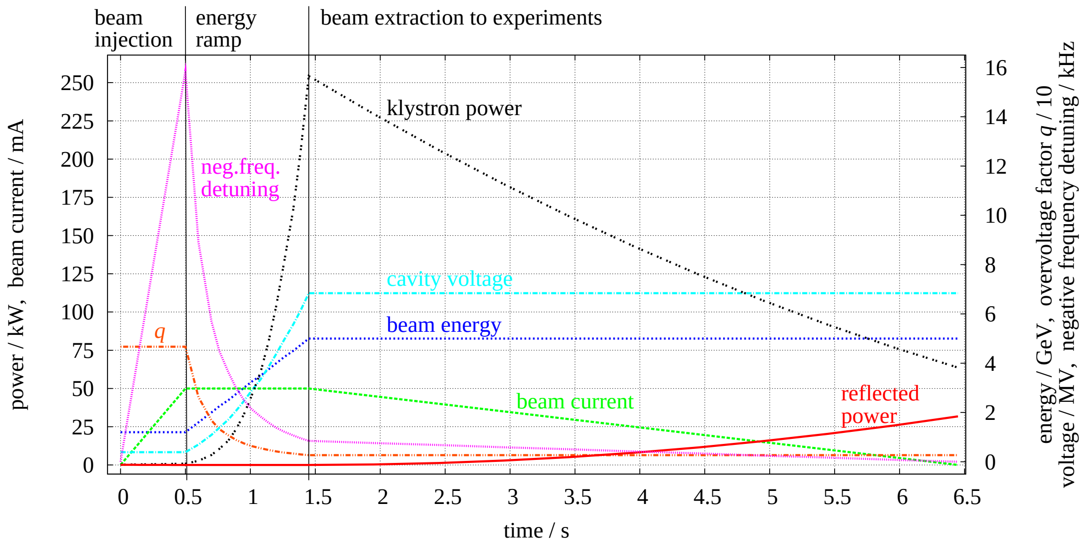

Figure 2: Accelerator cycle for a beam current of 50 mA up to an energy of 5 GeV using two SC cavities with a shunt impedance of $R_\mathrm{s} = 5 \cdot 10^{11}\,\Omega$ and an unloaded quality factor of $Q_0 = 2 \cdot 10^9$. Time dependence of cavity voltage and overvoltage factor, total klystron power as well as reflected power per cavity and negative frequency detuning per cavity.

coupler and the required detuning of the cavity's resonance frequency were calculated.

Assuming two SC cavities with a typical shunt impedance R_s of $5 \cdot 10^{11}\,\Omega$ for each cavity, β was adjusted to an optimal fixed coupling (no reflections at the RF input coupler) of 2720 by using [3]

$$\beta_0 = 1 + \frac{P_\mathrm{b}}{P_\mathrm{c}} = 1 + \frac{I_\mathrm{b}\,U_\mathrm{a}/2}{\frac{U_\mathrm{c}^2}{2R_\mathrm{s}}} \quad , \qquad (1)$$

where P_c is the cavity power, U_c the cavity voltage, U_a the overall acceleration voltage and $P_\mathrm{b}/2$ the beam power per cavity for acceleration of a current $I_\mathrm{b} = 50\,\mathrm{mA}$ at 5 GeV.

In addition, due to the heavy beam loading of SC cavities ($P_\mathrm{b} \gg P_\mathrm{c}$), it is necessary to detune the resonance frequency f_c of the cavities during the accelerator cycle, in particular during the phase of beam injection and energy ramping. As a function of I_b, the overvoltage factor q and U_c, the optimal frequency detuning $\Delta f = f_\mathrm{c} - f_\mathrm{RF}$ of the cavity is given by [4]

$$\Delta f = f_\mathrm{RF}\,\frac{I_\mathrm{b} R_\mathrm{s}}{U_\mathrm{c} Q_0}\sqrt{1 - \frac{1}{q^2}} \quad , \qquad (2)$$

where f_RF is the frequency of the ELSA RF system (500 MHz) and Q_0 is the unloaded cavity quality factor (assumed $2 \cdot 10^9$). Because of $f_\mathrm{c} < f_\mathrm{RF}$, this frequency detuning also fulfills the second Robinson stability criterion. Furthermore, in order to ensure beam stability for heavily beam loaded cavities, the cavity voltage (and therefore also the overvoltage factor) must be large enough to provide a restoring force which is able to damp the phase oscillations of the beam [4].

By choosing adequate large overvoltage factors, calculating U_c and Δf in dependence of the beam energy as well as the beam current and using $\beta_0 = 2719$, the required total klystron power and the reflected power per cavity can be determined for a complete accelerator cycle at ELSA. A typical cycle using two SC cavities was calculated and is illustrated in Fig. 2.

Results

Due to the optimized values for the coupling factor and the frequency detuning, the total klystron power and the reflected power could be reduced as low as possible. Only during the extraction phase, the reflected power reaches significant but manageable values smaller than 32 kW per cavity. Altogether, the existing RF power of maximum 260 kW provides sufficient power to accelerate a beam current of up to 50 mA up to 5 GeV. The maximum cavity frequency detuning adds up to less than 16 kHz per cavity during the injection and ramp phase corresponding to a maximum detuning speed of about 32 kHz/s. A dedicated low level RF system combined with fast and wide-band mechanical and piezoelectric cavity tuners have to provide the control of q (respectively the reference phase of the beam), U_c and Δf with sufficient bandwidth and velocity.

CAVITY SIMULATION

With the software package CST Microwave Studio® [5] (CST MWS) the geometry of the five-cell SC cavities constructed for the JAERI FEL was simulated. Using the eigenmode solver of CST MWS, the electric field distribution of the TM_{010} 500 MHz fundamental π-mode was computed (see Fig. 1). It is characterized by a shunt impedance of $R_\mathrm{s} = 6.88 \cdot 10^{11}\,\Omega$ as well as an unloaded quality factor of $Q_0 = 2.4 \cdot 10^9$. These results base upon a calculated surface resistance of niobium of $116\,\mathrm{n}\Omega$ (including a pessimistic temperature-independent residual resistance of $25\,\mathrm{n}\Omega$) at a liquid helium temperature of 4.2 K and an RF field of 500 MHz. Assuming a cavity voltage U_c of 6.84 MV, the maximum cavity wall losses P_c add up to 34 W.

HOM & Beam Instabilities

In order to investigate the impact of higher order modes (HOM) regarding the excitation of coupled-bunch instabilities (CBI), the field distribution of the relevant HOM were computed and the corresponding shunt impedances were determined with CST MWS. While longitudinal CBI are excited by the fields of monopole modes, the fields of dipole modes are mainly responsible for transverse CBI. Figure 3 shows the longitudinal shunt impedances $R_\parallel$ of the monopole HOM and Fig. 4 the transverse shunt impedances $R_\perp$ of the dipole HOM.

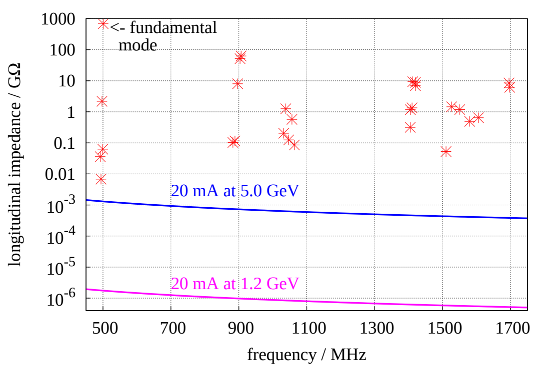

Figure 3: Longitudinal shunt impedances $R_\parallel$ of monopole HOM and typical threshold impedances for longitudinal CBI at a beam current of 20 mA at ELSA.

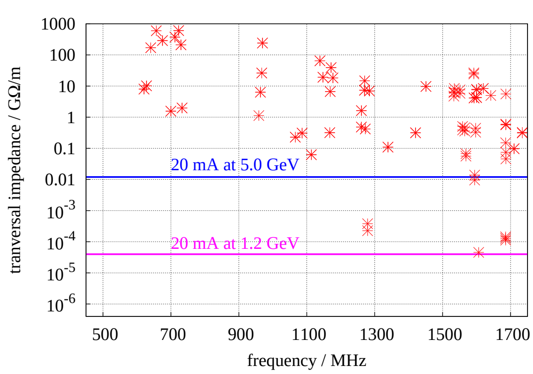

Figure 4: Transverse shunt impedances $R_\perp$ of dipole HOM and typical threshold impedances for transverse CBI at a beam current of 20 mA at ELSA.

Threshold Impedances

If the natural damping times $\tau_{s,x,y}$ due to synchrotron radiation are shorter than the growing times $\tau_{\parallel,\perp}$ of coupled-bunch modes excited by HOM, the bunch oscillations are damped sufficiently and the beam remains stable. $\tau_{\parallel,\perp}$ mainly depends on the beam current I_b, the beam energy E and the shunt impedances $R_{\parallel,\perp}$ of the HOM. Using standard expressions for $\tau_{\parallel,\perp}$ [6], longitudinal (depending on the frequency f) and transverse threshold impedances for the excitation of CBI can be calculated:

$$R_\parallel = \frac{2\,Q_s\,E/e\,f}{\alpha_\mathrm{c}\,I_\mathrm{b}\,\tau_s}\ , \tag{3}$$

$$R_\perp = \frac{2\,E/e}{\beta_{x,y}\,f_0\,I_\mathrm{b}\,\tau_{x,y}}\ , \tag{4}$$

where the following parameters of the ELSA storage ring have to be included: synchrotron tune Q_s of 0.03 at 1.2 GeV and 0.08 at 5.0 GeV, momentum compaction factor α_c of 0.063, betatron function at the cavity location $\beta_{x,y} \leq 10.7\,\mathrm{m}$ and revolution frequency f_0 of 1.824 MHz. Taking into account the beam energy E and the damping times τ_s (at 1.2 GeV: 36.2 ms, at 5.0 GeV: 0.5 ms) and $\tau_{x,y}$ (at 1.2 GeV $\leq 92.5\,\mathrm{ms}$, at 5.0 GeV $\leq 1.3\,\mathrm{ms}$), the thresholds $R_\parallel$ and $R_\perp$ were calculated for a beam current of 20 mA at 1.2 and 5.0 GeV (see Fig. 3 and Fig. 4). It is obvious that all monopole and a large number of dipole modes are well above the calculated thresholds for CBI.

CONCLUSION

Basically, we showed the feasibility of an operation of SC multi-cell cavities in a fast ramping storage ring using the example of an energy upgrade to 5 GeV at ELSA. However, due to undamped HOM of the described SC cavity structure, large problems with beam instabilities are to be expected. Therefore, before using the structure for a storage ring operation, the development of sophisticated HOM couplers as well as an improvement of the cavity geometry with respect to HOM suppression must be considered.

ACKNOWLEDGMENT

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REFERENCES

[1] W. Hillert, "The Bonn Electron Stretcher Accelerator ELSA: Past & Future", EPJ A28 s01 (2006) 139.

[2] M. Pekeler et al., "RF Activities of Accel Instruments in Asia-Pacific", APAC 2007, Indore, February 2007, THPMA104.

[3] P.B. Wilson, "Fundamental mode RF design in e+ e- storage ring factories", March 1993, SLAC-PUB-6062.

[4] H. Padamsee, J. Knobloch, T. Hays, "RF Superconductivity for Accelerators", Wiley-VCH, May 1998.

[5] CST Computer Simulation Technology AG, Darmstadt, Germany, `http://www.cst.com`.

[6] M. Svandrlik et al., "CBI Calculations for the ANKA Storage Ring", EPAC 1998, Stockholm, pp. 1011-1013.