THE HIGH HARMONICS CAVITY SYSTEM FOR THE NEW EXPERIMENTAL STORAGE RING AT FAIR

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Abstract

The ”Facility for Antiproton and Ion Research” (FAIR) will consist of several synchrotrons and storage rings dedicated to target experiments as well as in-situ experiments. One of the in-situ experiments is ELISe, a head-on collision of a heavy ion beam in the new experimental storage ring (NESR) [1, 2] with an electron beam prepared in the electron ring (ER). The vertex is placed in a bypass to the NESR where both rings have a common straight section. To prepare the heavy ion beam for collision with the bunched electron beam circulating at a fixed repetition rate a dedicated RF system called high harmonics cavity system (HHC) operating at a frequency of 44.7MHz is needed. The HHC will be realised as a disk-loaded coaxial quarter wave resonator. This paper deals with the actual development status of this RF-system, including analytically derived voltage demands, multipactor thresholds and considerations on input coupling and higher order mode (HOM) damping.

INTRODUCTION

The NESR is a heavy ion storage ring with a circumference of 222.9m and a momentum compaction $\alpha = 0.047$. The experiments are made using U $(A/Z = 2.7)$, with discrete kinetic energies between 118MeV/u and 740MeV/u. So the revolution frequencies are $f_0 = 0.62, \ldots, 1.12$MHz, while the electrons circulate at $f_{\mathrm{ER}} = 5.6$MHz. Before adiabatic bunching, the coasting-beam of up to $4 \cdot 10^8$ particles is electron cooled, so the relative momentum spread δ can be assumed to be gaussian with $\sigma_\delta = 5 \cdot 10^{-5}$ @ 740MeV/u in equilibrium between electron cooling and intra beam scattering according to BETACOOL simulations [3].

To have a fixed interaction point the ratio between both ring RF-frequencies has to be an integer. It was chosen to keep the RF-frequency of the NESR constant at 44.7MHz and to have a changing harmonic number h.

VOLTAGE DEMANDS

The maximum bunching voltage V_{RF} is determined by the bunch length, here σ_ϕ in RF coordinates, that has to be achieved and the longitudinal emittance $\epsilon_l = h\epsilon_b$ of the coasting beam [4, eq. 2.76].

$$V_{\mathrm{RF}} = \frac{2\pi h|\alpha - \gamma^{-2}|\omega_{\mathrm{RF}}^2 \epsilon_b^2}{Ze\gamma m_0 c^2 \beta^2 \sigma_\phi^4}, \qquad (1)$$

with m_0 being the particles rest mass and Ze its charge, γ the relativistic factor and $\beta = v/c$. The RMS-emittance of the beam is $\epsilon_l = \sigma_\delta \sigma_\theta$, with $\sigma_\theta = \frac{\pi}{\sqrt{3}}$ for a rectangular particle distribution along the accelerator circumference θ $(\Rightarrow \epsilon_l = 9.1 \cdot 10^{-5} \equiv 3.7\mathrm{eVs})$. The voltages to achieve an RMS bunch length of 30cm are listed in table 1. Simulations with BETACOOL showed, that application of electron cooling during adiabatic bunching can decrease the bunch length by a factor of 4 with those RF-voltages, but at the expense of transverse beam emittance, which is then up to $4 \cdot 10^{-2}$mm mrad according to the simulations.

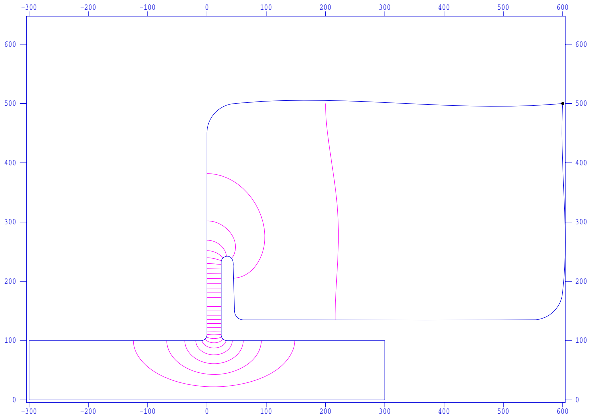

Figure 1: HHC profile with field contours of the accelerating mode at 44.7MHz, computed with Superfish

CAVITY DESIGN

The insertion space for the HHC is very limited, both in longitudinal and lateral dimension, so the most promising design possible is a disk-loaded quarter wavelength resonator (see figure 1). To have some margin to the maximum voltage needed (see table 1), the intended peak voltage is 200kV. The Kilpatrick Limit [5] at 44.7MHz is 8.57MV/m so a gap distance of $d = 24$mm is sufficient to maintain this peak voltage. The inner dimensions of the cavity body is in the current configuration 60cm between the endplates and 1m in diameter. The inner conductor has a diameter of 27cm. This results in a shunt impedance $R_s = 0.93\mathrm{M}\Omega$ (table 2). The cavity will dissipate about 21kW at 200kV, thereof about 16kW on the inner conductor, so cooling is a serious issue. The tuning mechanism currently under discussion is tuning by squeezing the cavity [6].

Multipactor Considerations

To avoid emittance growth, the process of adiabatic capture has to start at very low RF-voltages. Therefore the

Table 1: This table contains data of the NESR beam at the energies intended for the ELISe experiment together with the bunching voltage and the threshold impedances for a beam with 30cm bunch length.

E [MeV/u]	h	β	γ	f_0 [MHz]	U_{RF} [MV]	R_{th} [MΩ]
740	40	0.8303	1.7944	1.1167	0.129	0.3
358.7	48	0.6919	1.3851	0.9305	0.175	1.223
225.4	56	0.5930	1.2420	0.7976	0.155	2.251
158.2	64	0.5189	1.1698	0.6979	0.126	3.286
118.4	72	0.4613	1.1217	0.6204	0.099	4.304

gap region is prone to multipacting. This process generates by electron emission a resonant discharge, which causes a field break down. Hatch [7, 8] has derived resonance and phase focusing conditions, that determine RF-voltages where two-point multipacting happens:

$$U_n = 4\frac{m_e c^2}{e}\frac{d^2}{\lambda_{\text{RF}}^2}\frac{\pi^2}{(2n+1)\pi\cos\varphi + 2\sin\varphi} \tag{2}$$

with

$$0 \le \varphi \le \arctan\frac{2}{(2n+1)\pi} \tag{3}$$

The upper multipactor limit ($n = 0$, $\varphi = 0$) is the lowest voltage possible for starting the capture process. A further condition for multipactor to happen is that the secondary emission yield (SEY) of the surface material is > 1, so more than one electron is generated in each cycle. In our case the upper multipactor limit is 82.1V and the SEY for OFHC copper baked to $300°$C is < 1 for electron energies below 88eV and above 2.6keV [9]. So the current configuration of the HHC should not suffer from multipacting in the gap region.

Input Coupling

The most common way to couple RF power into a resonant cavity is to either couple capacitively or inductively to the fundamental mode. Capacitive coupling is realised with an antenna placed in the region of maximum electric field amplitude, while inductive coupling uses a loop where the magnetic field is at maximum. The coupling factor is adjusted by modifying the penetration depth if coupling is capacitive and by rotating the loop in the field if inductive coupling is used. Inductive coupling is easier to implement, since only a rotational flange is necessary to change the coupling, while capacitive coupling needs a complex mechanism.

The HHC will use inductive coupling, so the loop must be placed near the shorting endplate. The mutual inductance M of the loop can be calculated, if the system of solid state amplifier ($Z_0 = 50\Omega$) and cavity is assumed as a transformer circuit. The coupling loop is the primary coil and the inductance of the cavity L the secondary coil.

$$\frac{M}{L} = \sqrt{\frac{Z_0}{R_s}} \tag{4}$$

with

$$L = \frac{R_s}{\omega_{\text{RF}} Q_0} \tag{5}$$

For the HHC in the actual design (table 2) the mutual inductance needed is $M = 1.1$nH

INSTABILITY THRESHOLDS

According to Sacherer [10] a bunched beam becomes unstable if the shifts of the synchrotron frequency due to space-charge $\Delta\omega_{sc}$ and HOM-impedance $\Delta\omega_{\text{HOM}}$ exceed the synchrotron frequency spread S of the beam. The given threshold for dipole mode oscillation is:

$$\frac{|\Delta\omega_{sc}|}{\omega_s} + \frac{|\Delta\omega_{\text{HOM}}|}{\omega_s} < \frac{1}{4}\frac{S}{\omega_s} \tag{6}$$

The space charge shift is given as [10, eq. 7] :

$$\frac{\Delta\omega_{sc}}{\omega_s} = \frac{0.152}{2\beta\gamma^2}\frac{M^2}{hB^3}\frac{Z_0 I_b}{V\cos\phi_s}\left(1 + 2\ln\left(\frac{R}{r}\right)\right). \tag{7}$$

Here M is the number of bunches in the beam $(M = h)$ and $Z_0 = 377\Omega$ the waveguide impedance. The beam current is represented by I_b and the accelerating voltage is $V\cos(\phi_s)$, in our case $\phi_s = 0$. Further B is the bunching factor, which is the ratio of bunch length and bucket length. Here we define bunch length as two times 3σ to contain 95% of the particles in the bunch. The ratio of beam pipe radius to beam radius is $R/r \approx 100\text{mm}/220\mu\text{m}$ for the estimated cooled coasting beam transverse RMS emittance of $5 \cdot 10^{-3}$mm mrad.

The influence of the HOM impedance on the frequency shift is [10, eq. 10]:

$$\frac{\Delta\omega_{\text{HOM}}}{\omega_s} = 0.159 \cdot \frac{M}{hB}\frac{R_s I_b}{V\cos\phi_s}DF(\Delta\phi), \tag{8}$$

where D and $F(\Delta\phi)$ are functions describing the impedance. For a worst-case scenario one assumes the HOM being in resonance with the beam, so they are unity. The HOM's shunt impedance is denoted by R_s. Using (6) and (8) the threshold impedance R_{th} is:

$$R_{\text{th}} = \left(\frac{1}{4}\frac{S}{\omega_s} - \frac{\Delta\omega_{sc}}{\omega_s}\right)\frac{hBV\cos\phi_s}{0.159 \cdot MI_b DF(\Delta\phi)}, \tag{9}$$

Table 2: This table contains the Superfish data of the NESR cavity TM-modes with frequencies below the cut-off frequency of the beam chamber and the accelerating TEM-mode.

Mode	f [MHz]	r/Q [Ω]	Q_0	T	R_s [kΩ]
acc.	44.67	85.404	21824.6	0.996787	937.972
1	266.96	1.265	43110.4	0.889902	34.432
2	405.46	0.001	44875.8	0.759497	0.039
3	481.53	0.013	42812.9	0.674028	0.613
4	523.08	0.522	56699.3	0.62474	37.916
5	662.92	0.046	47637.6	0.454312	5.308
6	731.88	3.225	22134.1	0.372696	256.952
7	805.32	0.644	47761.4	0.29155	180.928
8	832.43	0.859	44824.1	0.263709	276.837
9	882.47	1.59	32566.5	0.216054	554.643
10	891.51	0.412	45035.9	0.208021	214.394
11	971.49	0.755	44936	0.145699	799.095
12	1035.69	0.13	95630.2	0.108729	525.796
13	1113.56	1.291	57379.6	0.082066	5499.551
14	1135.3	0.004	62492.7	0.078319	20.376

with the frequency spread as given in [11, eq. 2]:

$$\frac{S}{\omega_s} \approx \left(\frac{\pi}{4}B\right)^2 . \qquad (10)$$

The beam is unstable, if that impedance value is overcome. The threshold impedances for a beam with the given parameters are shown in table 1. Effects from electron cooling are not considered.

HOM CONSIDERATIONS

For the excitation of bunched beam instabilities only modes with frequencies below the vacuum chamber cut-off frequency have to be considered, since they are trapped in the resonator and can interact with the beam. The HHC beam pipe diameter is 200mm, whose cut-off for TM-modes is 1147.5MHz. Since only TM-modes can drive instabilities only those modes are considered.

For the beam to become unstable it is necessary to overcome the threshold impedance at the eigenfrequency of the beam, further the slope of the HOM must be capacitive were the beam spectrum interacts with the resonance (below transition energy). The latter is the case, if f_{HOM}/f_0 is slightly below an integer value.

The HHC has in its actual configuration 14 HOM below cut-off (see table 2). Their shunt impedances are ranging from some 30Ω to 5.5MΩ. Together with the thresholds obtained from table 1 one can find, that the most dangerous mode seems to be at $f = 1113.56$MHz with $R_s = 5.5$MΩ, while the other modes appear to be well below threshold, except for 740MeV/u where the modes at 882.47MHz, 971.45MHz and 1035.69MHz are also above threshold. So it might only be necessary to damp those modes with dedicated coupling antennas, that are placed in end plate of the cavity [12], if that particular mode maps to a beam eigenfrequency.

SUMMARY

The voltage demands of the HHC have been derived and input coupling was discussed. Further the actual design was analysed according to multipactor and HOM induced instabilities, both topics seem to be rather relaxed.

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