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ADAPTATION OF THE DAΦNE LONGITUDINAL KICKER GEOMETRY TO THE NEEDS OF THE BESSY II SYNCHROTRON LIGHT SOURCE

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1. Introduction

The cure of longitudinal and transverse coupled bunch instabilities is a crucial issue in modern storage rings [1]. In fact the operation of both colliders and synchrotron light sources of the last generation is based on the accumulation of high beam currents distributed over a large number of bunches. Long range e.m. fields generated by the interaction between bunches and vacuum chamber narrowband resonances are likely to excite coupled bunch motion with a growth rate that may largely exceed the natural damping rate, so that active cures are required.

Modern bunch-by-bunch feedback systems, based on fast digital processing of the position error of each individual bunch, have been demonstrated to be very effective in damping these instabilities.

In the DAΦNE case a novel longitudinal kicker, based on a waveguide overloaded pill-box cavity, has been developed and installed on the main rings as a terminal element of the feedback system [2]. The motivation for this choice is that an overloaded cavity provides high shunt impedance for the accelerating mode and at the same time has a low content of high order modes. Recently, the group of BESSY II, the new Berlin synchrotron light source whose construction is near to completion [3], started a collaboration program with the DAΦNE group aimed to adapt the design of the DAΦNE longitudinal kicker to the requirements of the BESSY II longitudinal feedback system. A report of the results of such a collaboration activity is presented here.

2. BESSY II characteristics

BESSY II is a high brilliance synchrotron radiation source presently under construction at Berlin - Adlershof [3].

Calculations using the MAFIA code have shown a high contribution of resistive impedance of undamped HOM's in the DORIS type accelerating cavities. Therefore, coupled bunch instabilities are expected, with rise times much shorter then the natural damping time, and a longitudinal bunch-by-bunch feedback system will be implemented in order to keep the beam stable.

The relevant parameters of the BESSY II machine related to the feedback are given in Table I.

Table I: BESSY II machine parameters

Beam energy	1.7	GeV
Circumference	240	m
RF frequency	499.654	MHz
Number of RF cavities	4	---
Total RF voltage	2	MV
Max. beam current	200	mA
Harmonic number	400	---
Number of bunches	320	---
Bunch spacing	2	ns
rms bunch duration	16	ps
Synchrotron frequency	10	kHz
Momentum compaction	.00073	---

The adaptation of the DAΦNE longitudinal kicker to the needs of BESSY II consists mainly in the optimisation of the device center frequency, bandwidth, shunt impedance and HOM content. The design has been based on e.m. simulations carried out with the HFSS [4] and, to a smaller extent, MAFIA [5] and URMEL [6] codes. The results are reported hereafter.

3. BESSY II kicker basic geometry and frequency response

The cross section of the BESSY II straight section vacuum chamber where the kickers will be installed is shown in Fig. 1. The simplest choice is to insert the kicker cavities in this region without special tapering sections, so that the geometry shown in Fig. 1 is also the cross-section of the pill-box beam tubes. These beam tubes are substantially smaller than those of the DAΦNE kickers (44 mm radius round beam pipes); therefore, a higher R/Q value of the accelerating mode is expected in the BESSY case, but also a larger number of trapped HOMs.

The kicker beam pipe cut-off frequencies for both DAΦNE and BESSY II cases are listed in Table II.

Since the TM_{01} cut-off is higher by a factor two in the BESSY case, it is beneficial to increase the kicker center frequency. Increasing the center frequency reduces a little the R/Q of the fundamental mode, but in terms of shunt impedance this reduction is over-compensated by an increase of the Q_L-factor, while both the physical size and the trapped HOM content of the device are reduced.

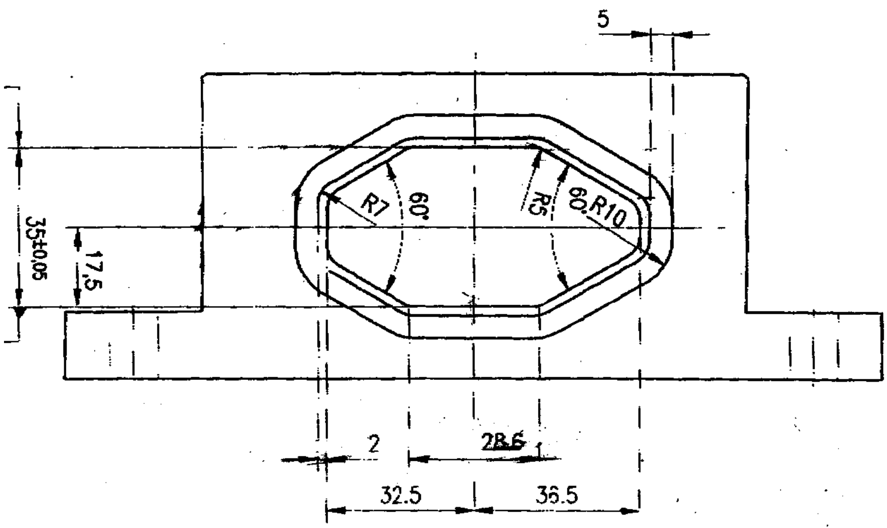


Figure 1: The BESSY II straight vacuum chamber cross section

Table II: DAΦNE and BESSY II kicker beam pipe cut-off frequencies

	TM_{01} Longitudinal modes	TE_{11} Transverse vertical modes	TE_{11} Transverse horizontal modes
DAΦNE	2.61 GHz	2.00 GHz	2.00 GHz
BESSY II	5.09 GHz	2.51 GHz	4.70 GHz

In order to optimize the efficiency, the kicker center frequency f_c and bandwidth f_{BW} have to be chosen accordingly to [7]:

$$\begin{aligned} f_c &= (n \pm 1/4) f_{RF} \\ f_{BW} &= 0.53 f_{RF} \approx 265 \quad MHz \end{aligned} \tag{1}$$

where n is a (small) integer. Accordingly to the previous arguments, we have fixed the BESSY kicker center frequency at:

$$f_c = 2.75 f_{RF} \approx 1374 \quad MHz \tag{2}$$

In principle a further increase of the center frequency up to 3.25 times the RF (≈ 1624 MHz) should enhance the benefits, but in this case the whole feedback system back-end should operate at a frequency too far from those of the already existing systems (ALS, PEP II, KEK-B, DAΦNE) loosing the advantage of relying on widely tested hardware.
Since the expected R/Q value for a pill-box resonating at 1374 MHz with the given beam tubes is ≈ 87 Ω and $Q_L = f_c/f_{BW} \approx 5.2$, the expected shunt impedance of the BESSY II kicker is:

$$R_s = 2 Q_L (R/Q) \approx 900 \quad \Omega \tag{3}$$

The HFSS model of 1/8 of a kicker cavity closely matching the required specs is shown in Fig. 2. It consists basically in a 83 mm radius pill-box with beam tubes, loaded by 8 waveguides (4 per side). The waveguides have been designed adapting the geometry of those of the DAΦNE kicker, and reducing their aperture with a cut and try procedure in order to get the desired bandwidth.

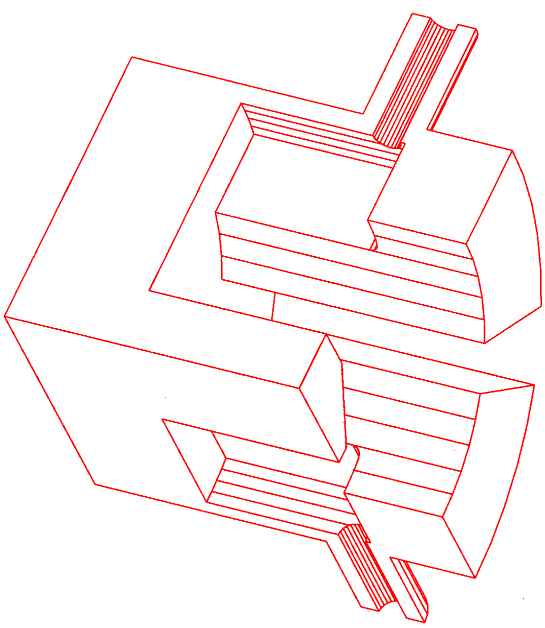


Figure 2: HFSS model the BESSY II kicker cavity

The port-to-port frequency response simulated with HFSS is shown in Fig. 3. A center frequency of about 1380 MHz with a band of about 270 MHz has been obtained.

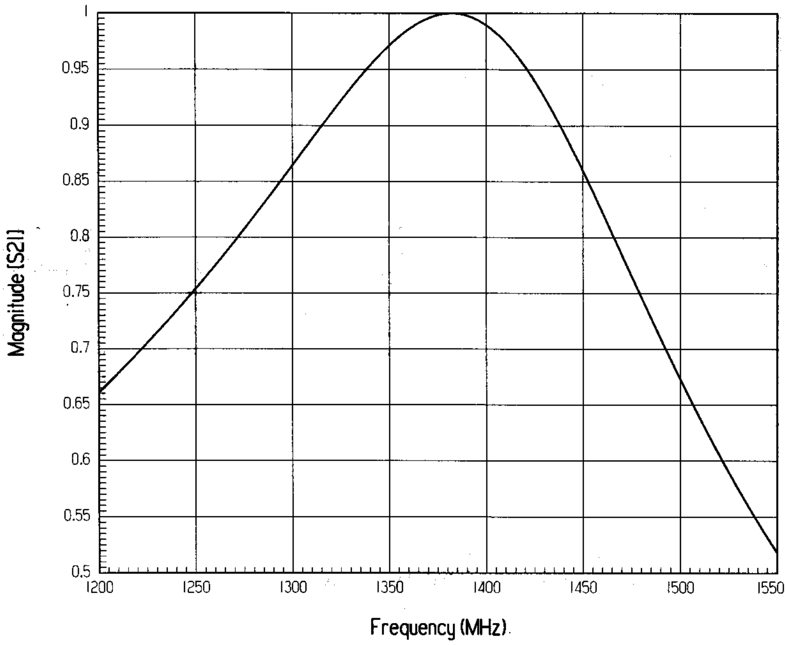


Figure 3: Frequency response of the kicker fundamental mode

The frequency response appears to be slightly distorted with respect to a pure Lorentzian function.

This is probably due to the fact that the waveguide-to-coax transitions, located near the in/out coax ports, have a frequency response which is not flat, so that they do not load uniformly the fundamental mode over its bandwidth. A broadband frequency response of the waveguide to coax transition is shown in Fig. 4.

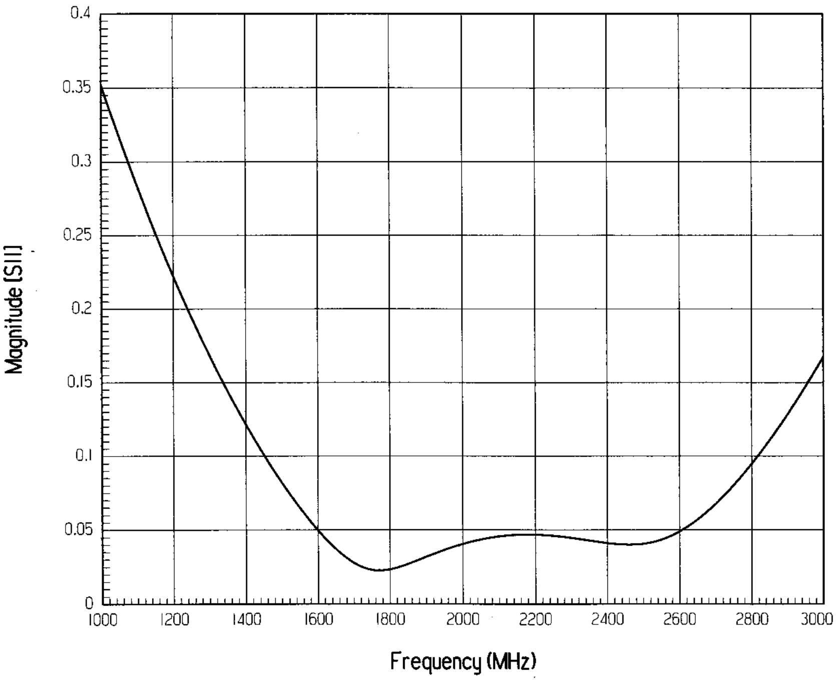


Figure 4: Frequency response of the kicker waveguide-to-coaxial transition

4. Estimate of the kicker shunt impedance

The general definition of a cavity accelerating mode shunt impedance R_s is:

$$R_s = \frac{V_{acc}^2}{2\,P_{amp}} \tag{4}$$

where V_{acc} is the accelerating voltage at the resonant frequency, and P_{amp} is the RF power expenditure of the amplifier end-stage to sustain the accelerating field.

The accelerating voltage V_{acc} is given by:

$$V_{acc} = \left| \int_{-L/2}^{L/2} E_z(z)\; e^{j[\omega z/c - \phi_z(z)]} dz \right| \tag{5}$$

where $E_z(z)$ and $\phi_z(z)$ are the amplitude and phase of the E-field component along the beam trajectory inside the cavity, that may be obtained from HFSS simulations by plotting the I and Q components (i.e. the values taken at a some given time and after 1/4 of period) of the longitudinal E-field.

The I and Q longitudinal E-field components computed by HFSS and normalized to an input power of 4 W for the BESSY kicker model of Fig. 1 are shown in Fig. 5. After a simple elaboration we got $R_s \approx 1100\ \Omega$, a figure a bit in excess with respect to our expectation.

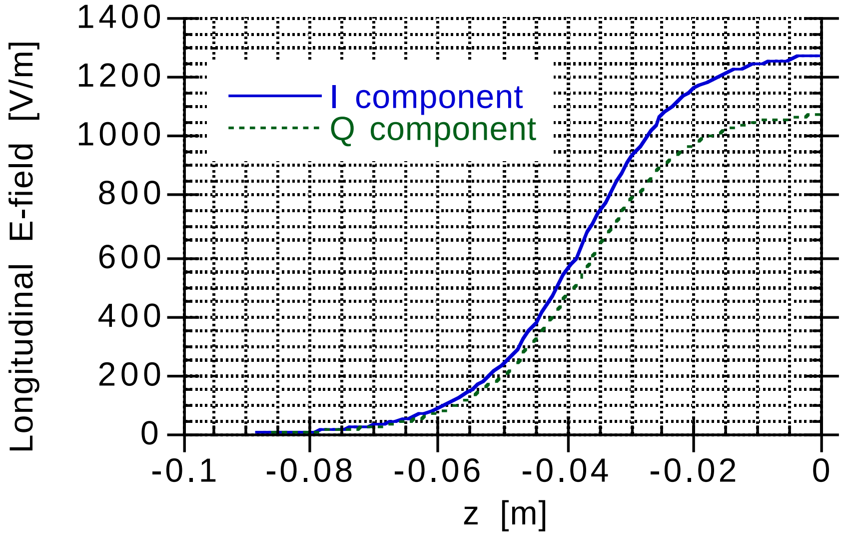


Figure 5: I and Q component of the longitudinal E-field

To check the reliability of this computation, a wire measurement of the beam coupling impedance has been simulated. A metallic wire (Ø = 3 mm) has been inserted along the beam axis in the HFSS model and the scattering matrix of the resulting structure has been computed.

From the wire method theory [8], we know that the beam coupling impedance of a mode $Z_c(\omega)$ is given by:

$$Z_c(\omega) = 2\,Z_0\left[\frac{1}{S_{21}(\omega)} - 1\right] \tag{6}$$

where $S_{21}(\omega)$ is the transmission coefficient between the two coaxial ports on the beam tubes, while Z_0 is the port characteristic impedance. The $S_{21}(\omega)$ plot is shown in Fig. 6. As expected, the resonant frequency of the fundamental mode is shifted upward by the wire insertion (f_r≈1600 MHz, $\Delta f_r / f_r \approx$ +16%). Since the characteristic impedance Z_0 is 184.5 Ω, and accordingly to the frequency response of Fig. 6, the beam coupling impedance at resonant frequency is $Z_c(\omega_r) \approx$ 480 Ω, and the shunt impedance is about twice this value [2], that means $R_s \approx$ 960 Ω.

The wire method estimate of the kicker shunt impedance seems to be in a better agreement with our expectations. The field accuracy of the HFSS simulations is probably responsible for the discrepancy between this value and that obtained by the on-axis E-field integration. It is prudent to assume the lower value ($R_s \approx$ 960 Ω) as a reliable estimate of the kicker shunt impedance.

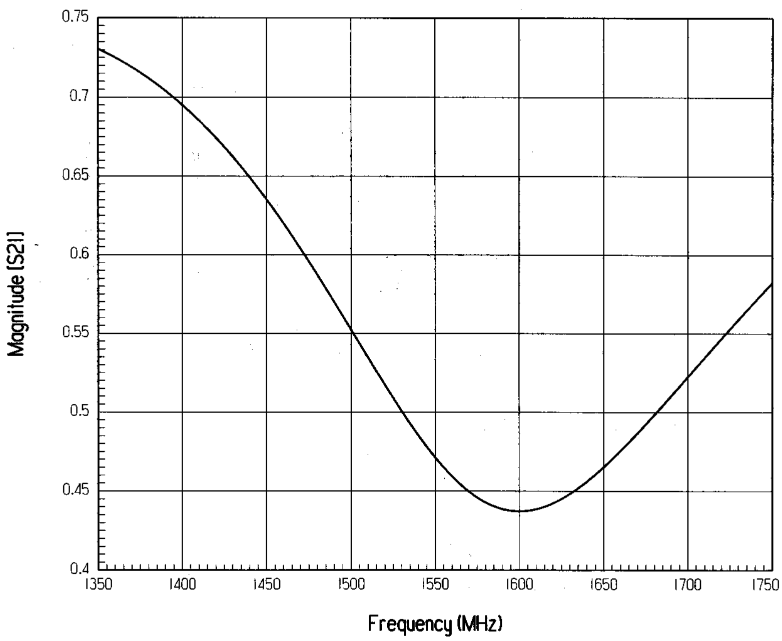


Figure 6: Fundamental mode wire measurement

5. Kicker HOM characterization

The evaluation of the HOM content of the structure is another salient issue of this job. The HFSS code, which is the only simulation tool we can use to study externally loaded cavities, can only perform a network analysis on its input geometry, computing the scattering matrix related to the defined input/output ports. Therefore, a preliminary estimate of the frequency location of the HOMs is needed in order to address the simulations. To do that we run the URMEL and MAFIA codes, that are respectively 2D and 3D eigenvalue solvers. Since these codes, in the version at our disposal, can only treat closed boundary problems, we removed the waveguides and run the basic pill-box with round beam tubes (Ø=35 mm) using URMEL, and the same pill-box with the actual beam tube cross-section (see Fig. 1) using MAFIA. The 2D URMEL simulations were helpful to distinguish the azimuthal periodicity of the modes, while the 3D MAFIA simulations gave us a more reliable indication of the mode frequency locations.

Finally, we could run the complete model (including the waveguides) with HFSS around the expected frequencies, and eventually recognised the searched modes among adjacent resonances by inspecting the internal field distributions.

The results of the HOM study for the monopole and dipole modes are reported respectively in the Tables III and IV. In Table IV the transverse $R/Q_\perp$ factor is defined as:

$$\left.\frac{R}{Q}\right|_\perp = \frac{\left.V_{acc}^2\right|_{\Delta z=1cm}}{2\,\omega_r\,U} \tag{7}$$

where ω_r is the mode resonant angular frequency, U is the energy stored in the mode field distribution and V_{acc} is the longitudinal E-field integral in eq. 5, computed 1 cm off-axis in the polarization plane of the dipole fields.

Table III: BESSY II kicker monopole modes

	URMEL		MAFIA		HFSS	
	f [MHz]	R/Q [Ω]	f [MHz]	R/Q [Ω]	f [MHz]	Q
0	1395.2	92	1405.8	86.9	1380	5.1
1	2512.2	13.9	2518.5	13.9	2608	<10
2	3219.9	4.1	3231.1	2.6	3260	65
3	3869.2	18.9	3872.4	13.6	3848	150
4	4393.0	2.5	4379.7	2.6	4195	32
5	5021.0	0.1	---	---	---	---

Table IV: BESSY II kicker dipole modes

	URMEL		MAFIA		HFSS	
	f [MHz]	R/Q⊥ [Ω]	f [MHz]	R/Q⊥ [Ω]	f [MHz]	Q
			2082.8		2062	18
1	2182.6	8.3	2190.5	4.32	2176	15
			2108.0		2085	97
2	2298.4	0.12	2279.7	0.07	2257	30
3	2977	6.72	2968.4	3.3	3019	18
4	3683	$3.4 \cdot 10^{-3}$	---	---	---	---
5	3969	1.09	3914.7	1.5	---	---

The port-to-port frequency responses of the monopole modes 1,2,3 and 4 computed by HFSS are shown in Figs. 7a, 7b, 7c and 7d. That of mode #1 appears strongly distorted, and the Q value can be hardly defined. A possible explanation for that is again the unflatness of the waveguide-to-coaxial transition response over the mode band. However, the mode seems so broad that its contribution to the machine longitudinal instability should be negligible. Mode #2 and #3 are both adequately damped, and mode #3 shows the largest beam coupling impedance ($Z_c(\omega_r) \approx 2\div3$ kΩ).

The identification of Mode #4 was not trivial. No resonances have been found near its original frequency location (≈4.4 GHz), while a field distribution similar to that of this mode has been found at a lower frequency (≈4.2 GHz), at the edge of the frequency band of some other not monopolar resonances. We tried to extrapolate the resonant frequency and Q-value of the 4th monopole mode applying a multi-resonance fit technique to resolve the frequency response computed by HFSS in that region of the spectrum.

As shown in Fig. 7e, a very good fit of such a frequency response has been obtained with 4 resonances, whose parameters have been summarized in Table V.

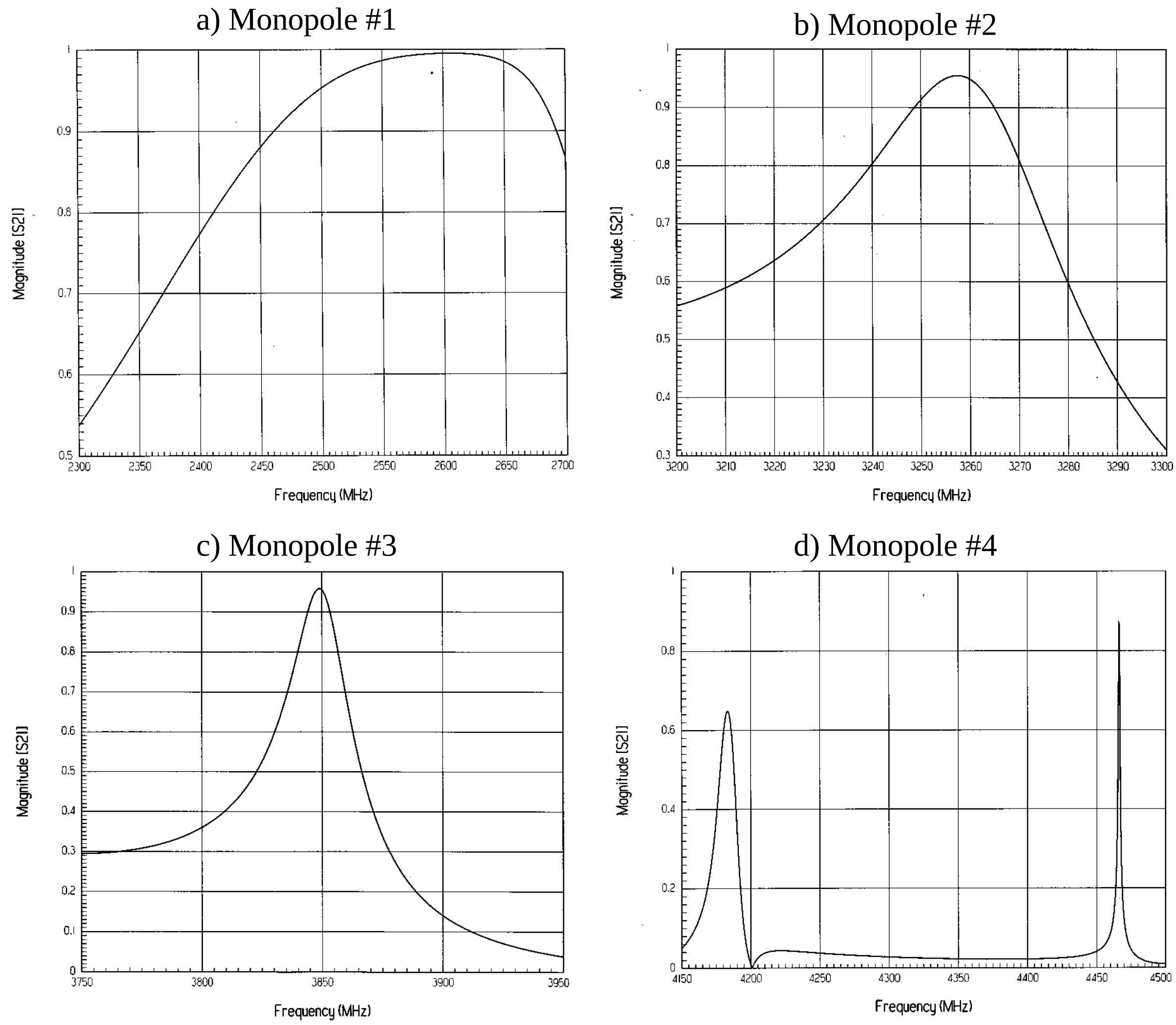


Figure 7 (a,b,c,d): Frequency response of the first 4 high order monopoles

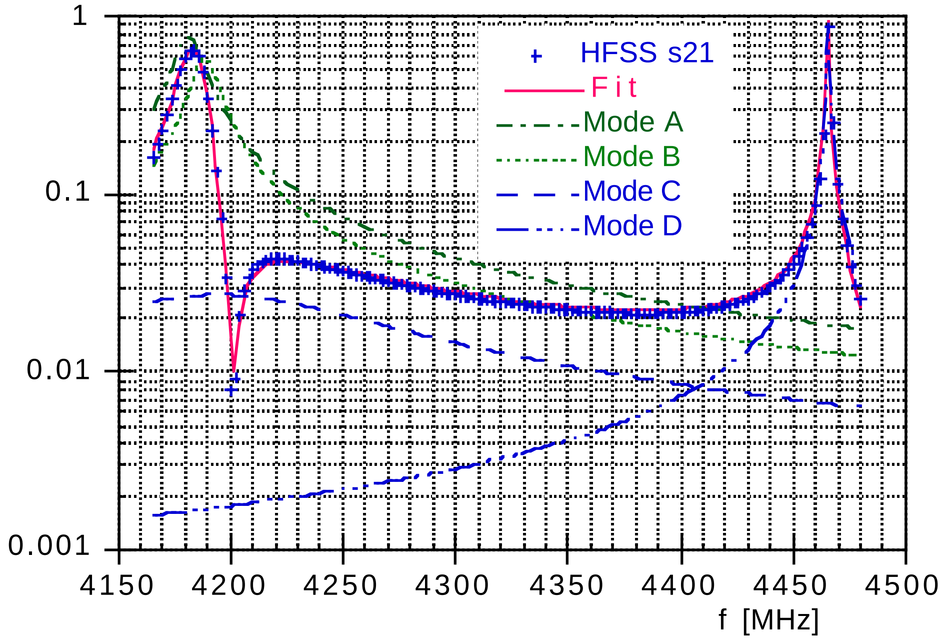
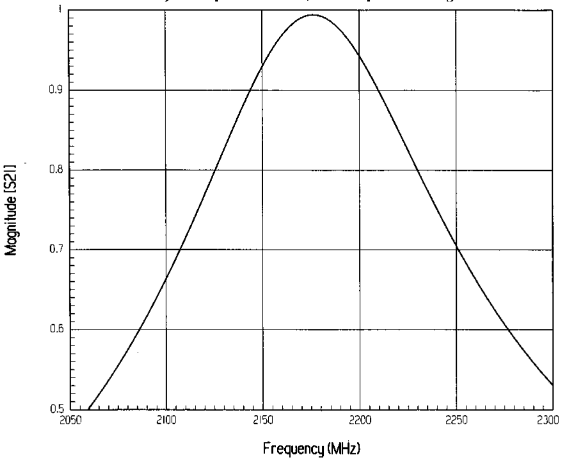


Figure 7 (e): Fit of the kicker frequency response nearby monopole #4

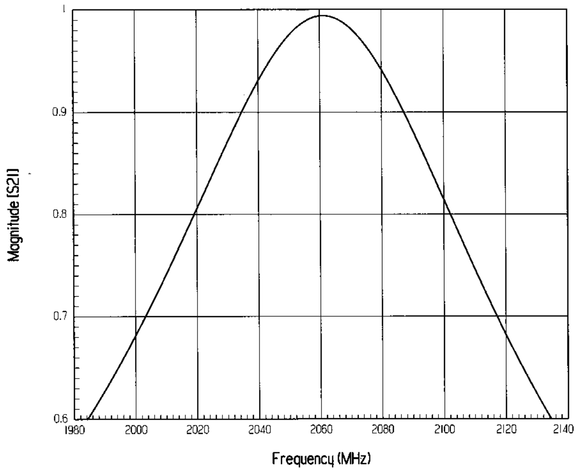
Table V: mode parameters obtained with a multi-resonance fit

	Mode A	Mode B	**Mode C**	Mode D
Frequency [MHz]	4181.6	4188.9	**4195**	4466.1
Q_L	316.7	356	**31.7**	4557.5
Amplitude	0.767	-0.587	**0.027**	-0.982

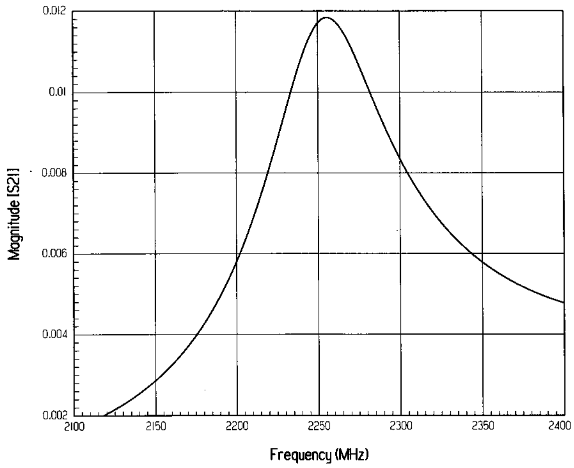
a) Dipole #1, 1st polarity



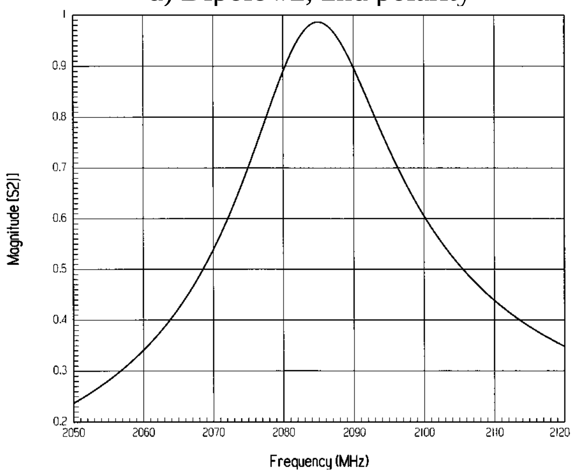
b)Dipole #1, 2nd polarity



c) Dipole #2, 1st polarity



d) Dipole #2, 2nd polarity



e) Dipole #3

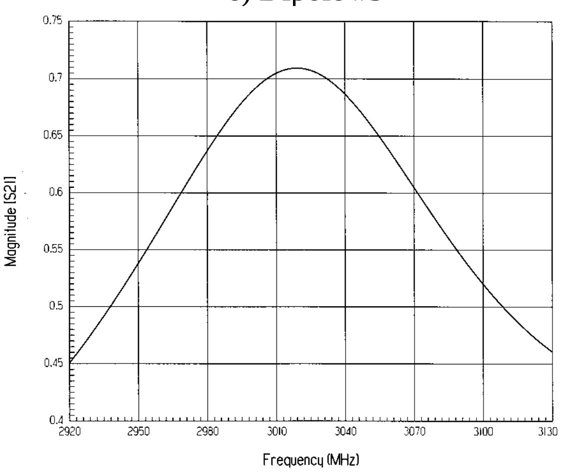


Figure 8: Frequency response of the damped HOM dipoles:

a,b) Dipole #1, two polarities

c,d) Dipole #2, two polarities

e) Dipole #3, one trapped polarity

The inspection of the e.m. fields revealed that near the frequency values where the relative weights of modes A,B and D dominate, the field configuration is different from that of the searched monopole mode, while a field distribution more similar to that of this mode has been found for frequency values around 4.25 GHz, a spectrum region where the relative weight of Mode C in the frequency response is more relevant. For these reasons we identified Mode C as the searched 4th monopole of the Bessy kicker. It shows a resonant frequency value $f_r \approx 4195$ MHz and a Q_L value of ≈32, a value that corresponds to an expected beam coupling impedance $Z_c(\omega_r) \approx 80\ \Omega$.

We could not find Mode #5, probably because it is located so close to the longitudinal cut-off frequency of the vacuum chamber that it propagates deeply along the beam tubes.

In the case of the dipole modes, due to the asymmetric shape of the vacuum chamber, we had to consider that only one polarity survives for the modes resonating between the two transverse cut-off frequencies (2.5 and 4.7 GHz). That's why in Table IV we report just one set of values from mode #3 on.

The HFSS frequency response for dipole modes #1,2 and 3 is shown in Fig. 8. We stopped the investigation at ≈3 GHz since above that frequency the transverse $R/Q_{\perp}$ value of the modes are not troublesome.

As a general comment on this section, the kicker HOMs are very well damped, since the mode Q-values are at the most of the order of 100, while the highest longitudinal beam-coupling impedance is below 3 kΩ, a negligible value compared to the expected contributions of the RF cavities.

6. Power delivered to the kicker by the beam

Lastly, we estimated the amount of power delivered by the interaction between the beam and the kicker longitudinal modes. Assuming the modes listed in Table III and a beam current at its maximum value (I_b=200 mA, see Tab. I), we considered 3 cases:

A) 320 buckets filled with a charge of 0.5 nC and followed by a gap of 80 buckets;

B) every second bucket filled up to 160, with a charge of 1 nC, followed by a gap of 80 buckets;

C) every fourth bucket filled up to 80, with a charge of 2 nC, followed by a gap of 80 buckets.

The power delivery estimates are summarized in Table VI.

Table VI: beam delivered power estimate for the BESSY II kicker

	Total Power	Accelerating mode Power	HOM Power [W]
A	49.2 W (6.2 W/port)	35.6 W (4.5 W/port)	13.6 W (1.7 W/port)
B	118.8 W (14.9 W/port)	69.1W (8.6 W/port)	49.7 W (6.2 W/port)
C	289.7 W (36.2 W/port)	149.9 W (18.7 W/port)	139.8 W (17.5 W/port)

Of course, the more intense the current per bunch, the higher the power dissipation. However, due to the low current value (200 mAmps) compared to those of DAΦNE and of the others factory projects, the power delivered is always relatively small, and no devices as RF circulators or filters have to be implemented to protect the feedback power amplifier against the backward power in the BESSY case.

Conclusions

We believe that the structure analyzed in this paper copes very well with the requirements of the BESSY II longitudinal feedback system and therefore is a good candidate for being the longitudinal kicker. The proposed kicker has a shunt impedance of about 1 kΩ and the required bandwidth of 270 MHz. At the same time all the trapped HOMs are damped to a harmless level.

The power released due to the kicker-beam interaction is modest. No additional devices are necessary to protect the amplifier from the backward power.

References

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