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memorandum

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SUBJECT: Beam effects of SNS vacuum valves and bellows

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This memo summarizes an EM analysis performed for the SNS vacuum chamber elements – the vacuum valves and bellows. As all other discontinuities of the vacuum chamber, these elements influence the beam producing the wake fields resulting in the beam energy loss and transverse deflection. Typically the beam effects of such discontinuities in proton linacs are rather small. This study was initiated by Zukun Chen's request to check the electromagnetic properties of the existing design before proceeding with a further development and procurement.

The EM code package MAFIA [1] and time-domain code ABCI [2] have been applied to the analysis of electromagnetic characteristics of the SNS vacuum valves and bellows. The bunch energy loss factors and the coupling impedances of the elements are computed. The frequencies of the most important resonances are identified and compared with the (multiples of) SNS bunch repetition frequency f_b=402.5 MHz.

SNS Vacuum Valve

The vacuum valve assembly, consisting of a box with a sliding valve, sits on a beam pipe as shown in Fig. 1. The valve dimensions [3] correspond to the bore radius of 20 mm.

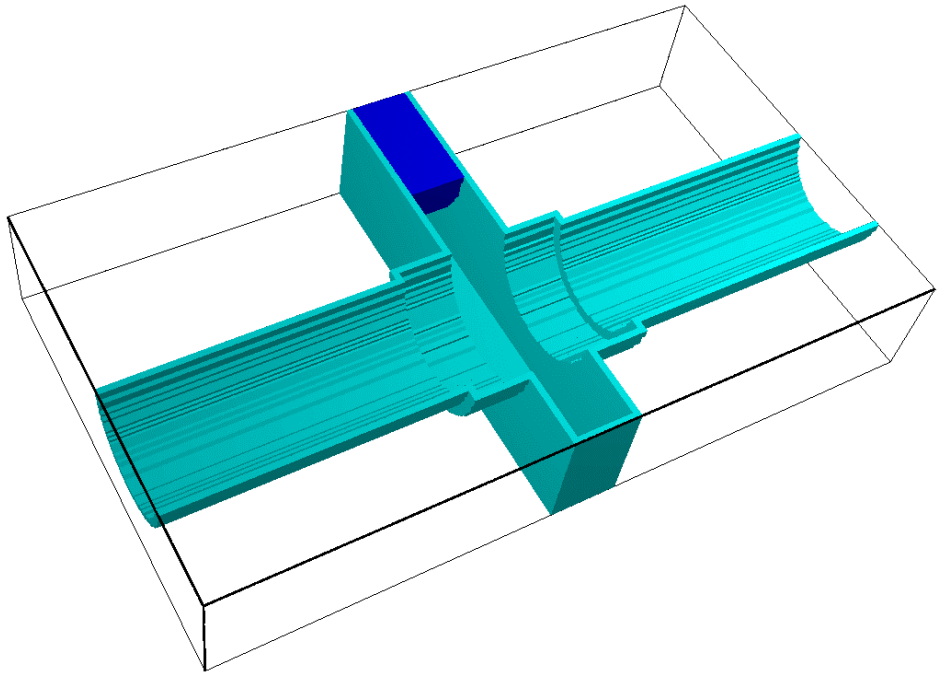

Figure 1: MAFIA model of the SNS vacuum valve (one-half cut). The valve (one quarter) is dark-blue.

Time-domain analysis

Direct 3D time-domain computations with an ultra relativistic (β=1) bunch passing the structure at the axis or parallel to the axis have been performed. MAFIA T3 code calculates the beam wakes. We use a Gaussian bunch with the charge Q=1 Coulomb and a variable rms length σ in the range 2.5 to 5 mm. Since the T3 code can simulate the open boundary conditions on the beam pipe ends only for β=1, we vary the bunch length and will scale the ultra relativistic result for the loss factor to β<1 following Ref. [4]. The Figure 2 shows the longitudinal wake field of a Gaussian bunch with σ=5 mm.

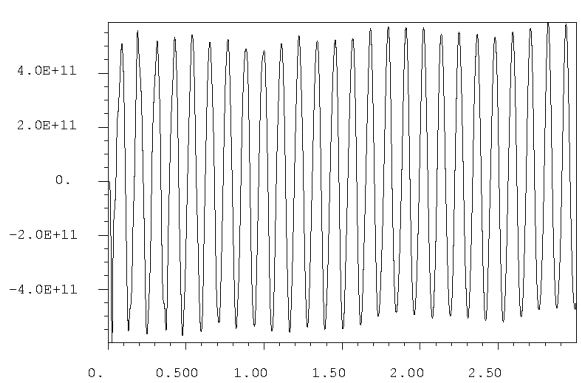

Figure 2: Longitudinal wake potential W (V/C) versus bunch trailing distance s (m).

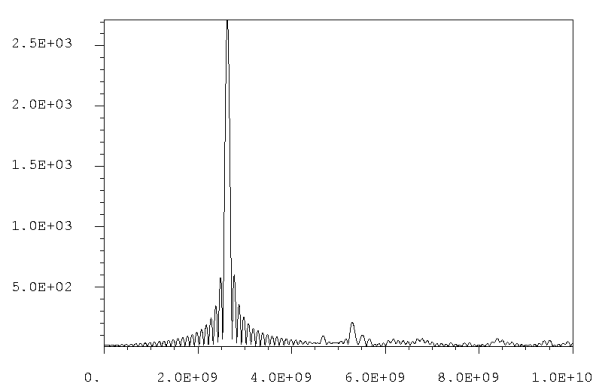

Figure 3: Absolute value of the beam coupling impedance $|Z|$ (Ω) versus frequency f (Hz).

By integrating the wake potential with the bunch power spectrum, we calculate the longitudinal loss factor k_1=0.43 V/pC. A similar procedure repeated for a σ=2.5 mm bunch leads to the loss-factor value of 0.81 V/pC. The comparison of the two results suggests an approximate inverse proportionality, $k \sim 1/\sigma$. This behavior corresponds to the loss-factor due to a single narrow resonance well within the bunch frequency spectrum because the Gaussian-bunch power spectrum is proportional to $1/\sigma$, see in [4].

In fact, it is easy to conclude from Fig. 2 that the wake has a pronounced one-resonance behavior. We perform its Fourier transform to find the coupling impedance and locate the resonance, see Fig. 3. The strong peak in Fig. 3 corresponds to the resonance slightly above 2.6 GHz, which is well below the beam-pipe cutoff frequency for TM_{010} mode, equal to 5738 MHz for the pipe radius 20 mm.

Eigenmode analysis

To study this resonance, as well as other resonances below the beam-pipe cutoff frequency, the MAFIA 3D eigenmode solver was applied to the one half of the model shown in Fig. 1, with appropriate symmetry conditions in the cut planes. Frequencies of a few lowest modes are listed below (in MHz): odd – 2628, 3197, and 4318 (the mode longitudinal electric field is symmetric with respect to the mirror plane, the right edge of the left picture in Fig. 4); and even – 3743 and 4441 (E_z is antisymmetric).

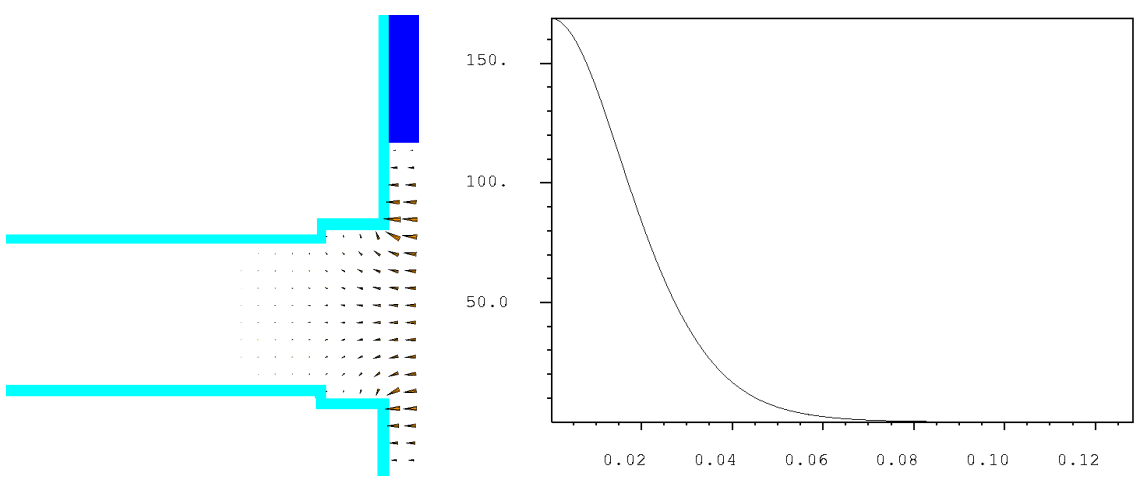

Figure 4: Electric field of the lowest longitudinal mode, 2628 MHz, in the vacuum valve: left – one-half of vertical cut along the beam path, cf. Fig. 1; right – on-axis field $|E_z|$ (arbitrary units) versus z (m).

The beam energy loss for a single bunch pass ΔU is related to the loss factor k of a chamber element as $\Delta U = kq^2$, where q is the bunch charge. For a continuous beam with the bunch repetition frequency f_b, the power dissipated in the element is $P_c = kq^2 f_b = kI^2/f_b$, where $I = qf_b$ is the beam current. For the SNS vacuum valve with I=56 mA, the value of P_c is 3.35 W. With the account of the chopping factor 0.65, the average power during the macropulse is $P_m = 0.65 P_c = 2.2$ W, and with account of the 60-Hz beam structure the average power $P_{av} = 0.06 P_m = 0.13$ W. Since the resonance frequency is well below the pipe cutoff, all this power will be dissipated in the valve; however, its value is obviously very small. One should also emphasize that this value

corresponds to an ultra relativistic (β=1) beam. Using the computed mode field profile (the right picture in Fig. 4) and applying the method of Ref. [4], we calculate how the loss factor and, correspondingly, the dissipated power depend on the beam velocity $v=\beta c$. The results are presented in Fig. 5, where k_1=0.43 V/pC is the β=1 result.

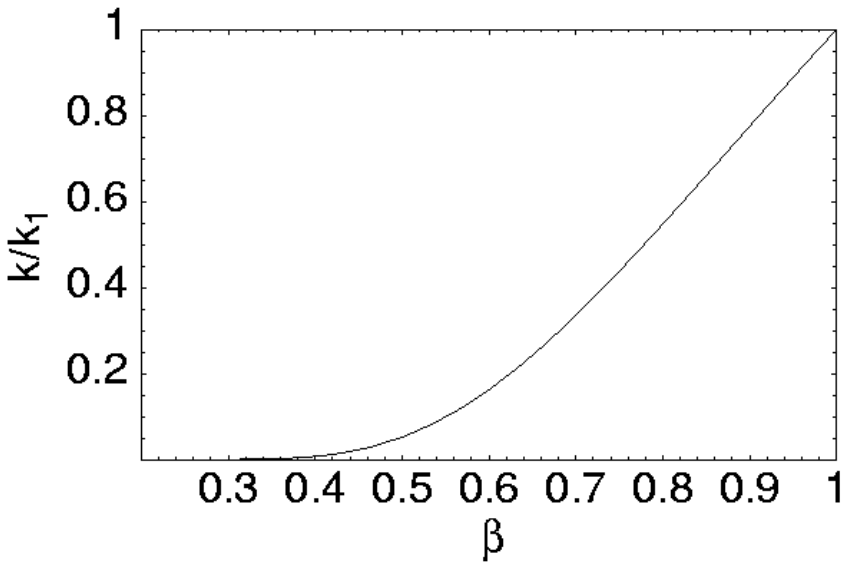

Figure 5: The beam energy loss factor in the SNS vacuum valve versus the beam velocity.

SNS Bellows

For analyzing the SNS bellows a model shown in Fig. 6 was used. We assumed an axisymmetric structure with four convolutions, the beam pipe radius 15 mm, the external bellows radius 25 mm, and the bellows longitudinal length of 16 mm [3].

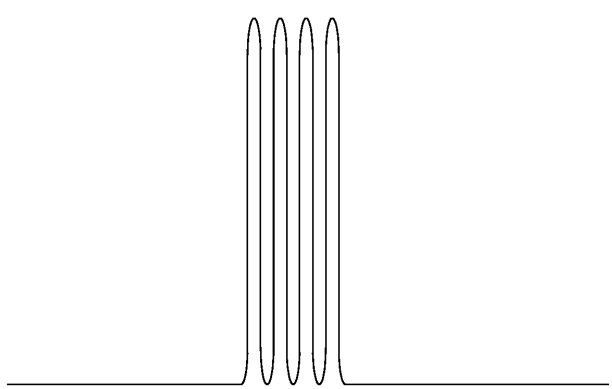

Figure 6: SNS bellows shape used in ABCI computations (partial longitudinal cut along the beam axis).

Taking into account the axial symmetry of the structure, we used the 2-D time-domain code ABCI [2] for calculating the wakes and loss factors. The code is faster than its 2-D counterpart in the MAFIA package, and has more convenient postprocessing for impedances and loss factors. The Figure 7 shows the calculated longitudinal wake potential of the bellows for a Gaussian bunch with β=1 and σ=5 mm.

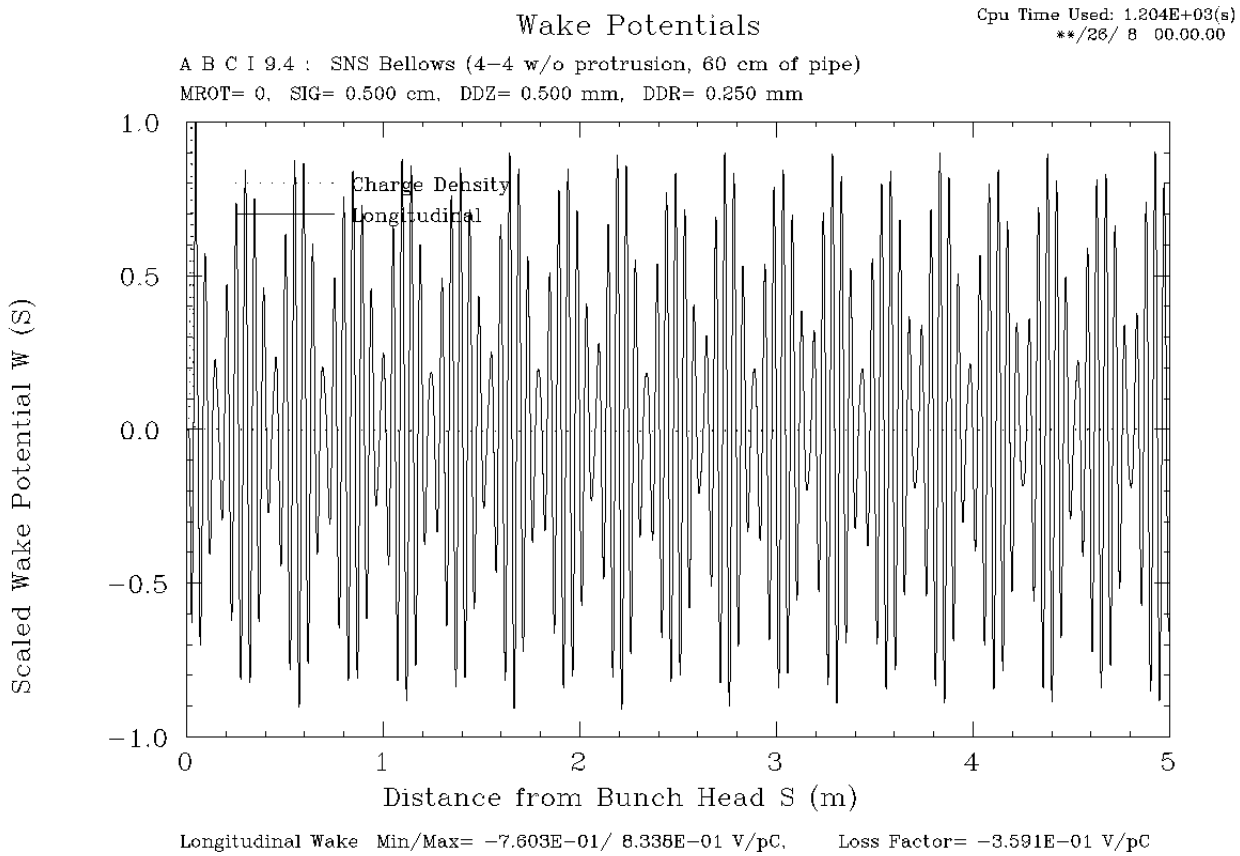

Figure 7: The longitudinal wake potential due to the SNS bellows.

The longitudinal loss factor of the bellows for σ=5 mm and β=1 is k_1=0.36 V/pC, and the average power dissipated on the bellows due to the passing beam is P_{av}=0.11 W. For a shorter bunch, σ=2.5 mm, the loss factor becomes k_1=0.69 V/pC. From this comparison, as well as from the beating pattern in the wake potential, one can conclude that a couple of close sharp resonances dominate the loss factor. It is confirmed by Fig. 8, where the real part of the longitudinal coupling impedance of the bellows is shown as a function of the frequency. The two resonances are at 6.0 GHz and 7.1 GHz, still below the beam pipe cutoff frequency 7.65 GHz. The Figure 9 shows their relative contributions to the beam loss factor. Since the resonance frequencies are close to each other, the loss factor dependence on the beam velocity is similar to one shown in Fig. 6 for the vacuum valve: the loss factor decreases as β decreases, and k_1 provides its upper estimate [4].

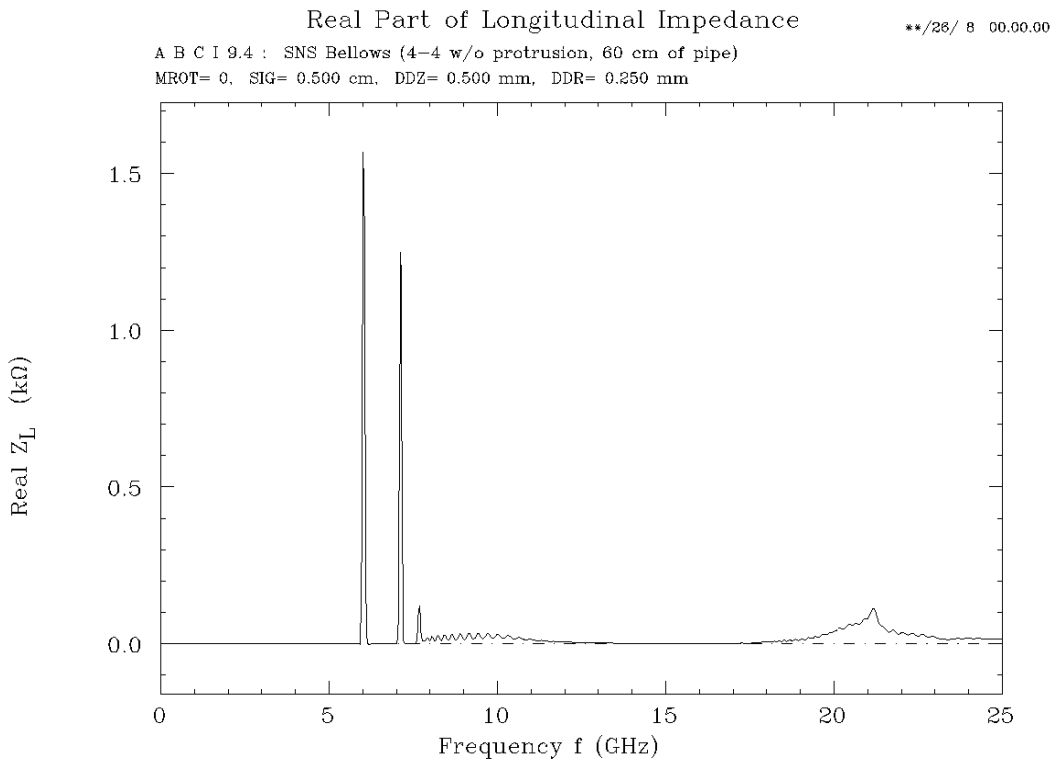

Figure 8: The longitudinal coupling impedance of the SNS bellows.

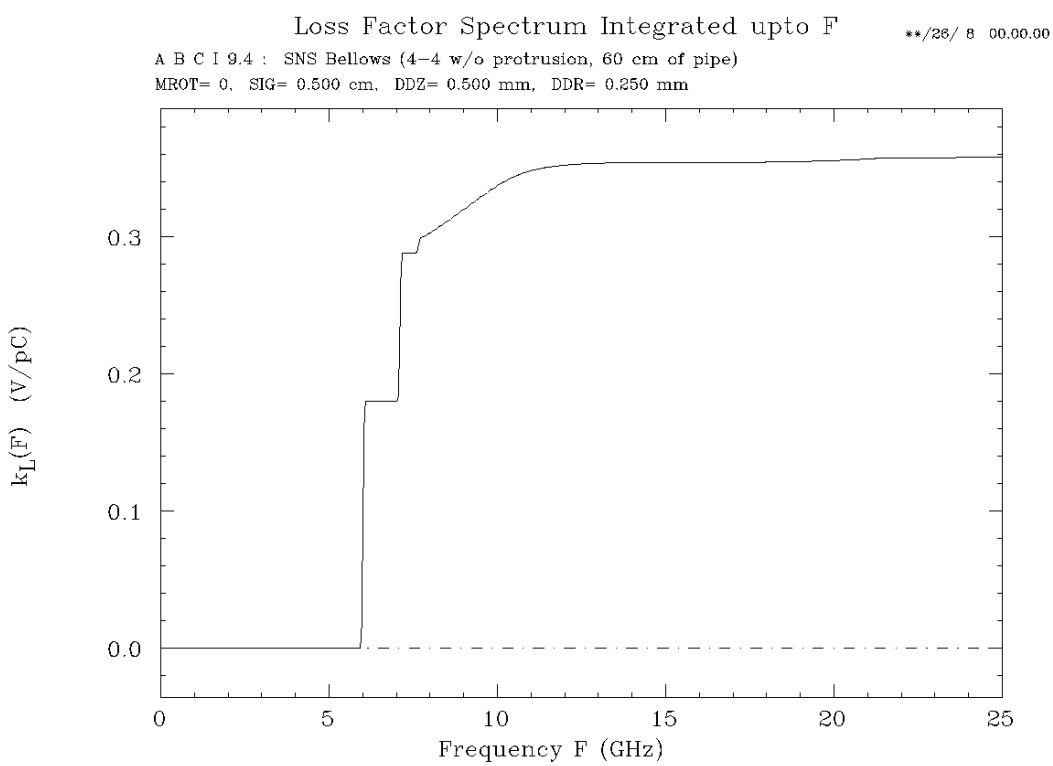

Figure 9: The longitudinal loss factor spectrum integrated up to a given frequency versus frequency.

Certainly, the resonance frequencies depend on the bellows length, and they will change as the bellows contracts or expands. In any case, the resonance frequencies are high enough; they will vary from one bellows to another, so that these resonances will not produce dangerous beam effects.

Conclusions

The longitudinal beam coupling impedances and loss factors for the SNS vacuum valves and bellows are calculated. For both discontinuities the high-frequency narrow resonances are found, but their frequencies are not close to the multiples of the bunch repetition frequency. Taking into account that both elements are made of stainless steel, one can estimate the resonance width on the order of 1 MHz. Small variations of the dimensions from one discontinuity to another will shift the resonance frequency by a larger amount producing a natural frequency spread, so that one should not expect any noticeable collective effects on the beam.

The calculated average beam power dissipation on the valves and bellows is rather small, on the order of 0.1 W. Obviously, this power dissipation will not produce any significant heating.

The transverse impedances and loss factors have not been calculated here, but from the longitudinal results one can conclude that they will also be very small. A quick comparison with the APT results for the coupling impedances and loss factors [5] shows that the SNS numbers are in the same ballpark. Since the average SNS beam current is about 50 times lower, one should not expect any significant beam effects from these elements.

References

1. MAFIA Release 4.00, CST, Darmstadt, 1997.
2. Y.H. Chin, Report LBL-35258, Berkeley, 1994.
3. Z. Chen, Private communication, August 1999.
4. S.S. Kurennoy, "Dependence of bunch energy loss in cavities on beam velocity." Phys. Rev. ST Accel. Beams, v.2, 032001 (1999); also LA-UR-98-6017, Los Alamos, 1998.
5. S.S. Kurennoy, LANSCE-1 memo, 10/17/97.