DESIGN OF A COMPACT L-BAND TRANSVERSE DEFLECTING CAVITY WITH ARBITRARY POLARIZATIONS FOR THE SACLA INJECTOR

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Abstract

For the X-ray free electron laser, SACLA, fine-tuning of the injector part of a drive linac is quite important. Since one of the most effective ways for this tuning is to monitor the temporal structure of an electron beam, we designed a compact L-band (1428 MHz) TM110-mode transverse deflecting cavity (TCAV). The TCAV will be installed at the end of the velocity bunching section, where a bunch length ranges from 10 ps to 1 ns, the kinetic energy of the beam is approximately 1 MeV. In order to measure a short bunch as long as 10 ps, the TCAV system was designed to have less than 3 ps time resolution. The TCAV has 2 input ports intersecting at a right angle in order to excite either of linear and circular polarizations, depending on the measurement condition. The linear polarization is suitable for a short bunch measurement with high temporal resolution and the circular one is useful to measure a long bunch comparable to the rf period (700 ps). Thus, the TCAV system has sufficient temporal resolution and wide measurement range required at the SACLA injector and this system is expected to be beneficial for fine-tuning of the injector.

INTRODUCTION

The X-ray free electron laser (XFEL) facility, SACLA [1], has been stably operated for experimental users for more than 3 years. However, we have encountered some problems that we could not always reproduce the best XFEL performance soon after a long shutdown period. One of the reasons for this problem could be that the temporal profile of an electron beam at the injector part of SACLA was slightly changed at each time. Since a thermionic electron gun and a velocity bunching process are used at the injector, the rf phase and amplitude of a buncher cavity should be accurately adjusted to reproduce the appropriate temporal structure. Therefore, a temporal profile measurement system is demanded at the SACLA injector for fine-tuning of the velocity bunching part.

In order to clarify the necessity of the temporal structure measurement, we introduce the bunching scheme of SACLA. Figure 1 shows a schematic layout of the SACLA accelerator. An electron beam is generated by a 500 kV thermionic electron gun and chopped into a 1 ns-long bunch by a high-voltage pulse chopper. A 238 MHz buncher cavity applies a velocity modulation to the beam, which is afterward accelerated by a 476 MHz cavity. An L-band (1428 MHz) correction cavity (L-COR) operated at a deceleration phase linearizes nonlinear energy modulation on the beam generated by the rf curvature of the acceleration field in the 476 MHz cavity. The kinetic energy after the L-COR is approximately 1 MeV. The beam is accelerated by an L-band alternating periodic structure (L-APS) at an off-crest phase in order to give an energy chirp along the beam bunch for bunch compression. A C-band correction cavity again linearizes the rf curvature given by the L-APS, and the first bunch compressor (BC1) compresses the bunch length from approximately 30 ps to 3 ps. Then, S-band (2856 MHz) accelerator units accelerate the beam at an off-crest phase so as to compress the bunch length at the BC2. The same bunch compression mechanism is utilized to the first 12 units of the C-band (5712 MHz) accelerators and the BC3. After the BC3, a C-band transverse deflecting structure (C-TDS) [2] is installed for temporal bunch structure measurement. The beam is finally accelerated to 8 GeV by remained C-band accelerators.

As mentioned above, there are 5 cavities in the injector part before the BC1. Therefore, we have to adjust all the rf phases and amplitudes of these cavities. These parameters are, at first, set to those from a simulation result or those of the previous operation condition. Then, they are fine-tuned so as to maximize the XFEL power. This tuning process is quite time-consuming. Once the injector is tuned to an appropriate condition, since a temporal beam profile after the BC2 or BC3 can be measured by the C-TDS, we can tune the S-band and C-band accelerators by using the temporal profile information. However, we cannot tune the injector part only by using the C-TDS. In the injector components, the velocity bunching instruments are quite important, because they determine the initial condition of the electron beam. Thus, we designed a transverse deflecting cavity (TCAV) for the temporal bunch structure measurement in the velocity bunching section.

Since the bunch length in the velocity bunching section is variable from 10 ps to 1 ns, the TCAV system is required to have wide measurement range. For a short bunch measurement around 10 ps, this system should have a high temporal resolution of a few ps. For the design of the TCAV system, these requirements should be taken into account.

In this article, we describe the conceptual design of a transverse deflector system according to requirements for the temporal profile measurement. The design of the TCAV is then detailed. Some basics of a transverse deflector system is briefly described in the appendix.

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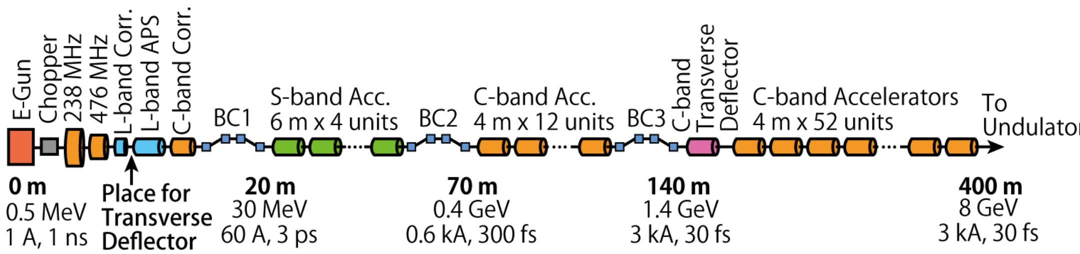

Figure 1: Schematic layout of the SACLA accelerator.

CONCEPTUAL DESIGN OF TRANSVERSE DEFLECTOR SYSTEM

Place for TCAV

In order to measure velocity bunching characteristics, the place for the TCAV should be the end of the velocity bunching section. Therefore, we decided to install the TCAV just before the L-APS, as shown in Fig. 1. In this case, the TCAV can observe the effect from each of 3 cavities, 238 MHz, 476 MHz and L-COR. At this installation point, the beam energy is around 1 MeV, which means that a kick voltage of several 10 kV is enough (several 10 mrad-kick). This kick voltage seems to be generated by a single-cell cavity, which makes the system compact. If we put the TCAV after the L-APS, the kick voltage should be 30 times larger because the beam energy is approximately 30 MeV. To obtain a large kick voltage, we need a large TCAV and a high-power rf source. Thus, the upstream of the L-APS is better for the place of the TCAV, considering the space and cost of the TCAV system. Beam parameters and requirements for this TCAV are listed in Table 1.

Since the space in the injector is limited, we have to use a screen monitor downstream of the L-APS. In addition, the energy of an electron beam is too low to pass through the L-APS without acceleration. Furthermore, there are solenoid lenses and quadrupole magnets after the TCAV. Therefore, the beam dynamics of the L-APS and other focusing devices should also be taken into account for the system design.

Measurement Range and RF Frequency

A bunch length at the entrance of the L-APS can be changed from 10 ps to 1 ns, depending on the rf phase and amplitude of each cavity of the injector. The bunch length is typically 30 ps for XFEL operation. The TCAV should cover this wide measurement range and have sufficient temporal resolution.

In order to meet the measurement range requirement, we considered using both linear and circular polarization rf fields of a TCAV, as described in the appendix. The linear polarization is effective in a short bunch measurement with high resolution by increasing a kick angle. However, it is difficult to measure an electron bunch longer than the linear part of the sinusoidal wave. Especially for a bunch length longer than the half rf period, a part of the deflected image is overlapped due to the folding back of the sinusoidal wave. On the other hand, the circular polarization is suitable for a long bunch measurement because the bunch length comparable to the full rf period of the TCAV can be observed, as mentioned in the appendix. Another reason for using a circular polarization is the existence of a longitudinal magnetic field in a solenoid lens. Although a linearly stretched beam can be distorted by the longitudinal magnetic field, the image of a circularly stretched beam is not distorted but just rotated by the longitudinal magnetic field.

Table 1: Beam parameters and requirements for the TCAV.

Beam energy	~ 1 MeV
Bunch length	10 ps – 1 ns (typically 30 ps)
Normalized emittance	1 mm mrad
Time resolution	< 5 ps for a 10 ps bunch
RF Field polarization	Linear and Circular (Selectable)
Beam size	0.5 mm rms at the screen
Kick angle	> 60 mrad
Screen size	10 mm diameter

The resonant frequency of the TCAV should be as high as possible for high-resolution measurement, although the frequency should be sufficiently low for a long bunch measurement. Since the longest bunch length is 1 ns, the resonant frequency should be around 1 GHz. We use L-band frequency (1428 MHz) for the TCAV, because there are L-band accelerators in the injector and we can utilize the same apparatus as the L-band accelerator for the TCAV, such as a 2.5 kW solid-state amplifier. In this case, a bunch length measurement range is 700 ps at a maximum. Although this is somewhat smaller than 1 ns, most of the bunch length in the injector can be measured.

Time Resolution and Required Kick Angle

Since the minimum bunch length is 10 ps, a time resolution is required to be less than 3 ps. The time resolution can be calculated from Eq. 13 in the appendix. The beam size at the screen monitor downstream of the TCAV is 0.5 mm rms and the (1,2) element of the beam transfer matrix, m_{12}, from the TCAV to the screen is approximately −0.3 m. Therefore, the required kick angle for 3 ps resolution is estimated to be

$$y'_{\max} = \frac{\sigma_y}{|m_{12}|\sigma_t \omega} \simeq 60 \text{ [mrad]}. \quad (1)$$

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For the circular polarization measurement, the kick angle is limited by a screen monitor size. Since the screen size of SACLA is 10 mm in diameter, the radius of the deflected beam image should be 3 mm at most, for a reliable measurement. In this case, a time resolution is estimated to be 19 ps, which is sufficient for more than a 100 ps bunch length.

Phase Acceptance of L-APS

Since there is the L-APS between the TCAV and the screen monitor, the phase acceptance of the L-APS should be considered especially for a long bunch measurement. The longitudinal phase space orbit of the L-APS can be expressed as [3]

$$\cos\theta - \cos\theta_\infty = \frac{kc}{eE_0}\left[\sqrt{p^2+(mc)^2} - p\right], \qquad (2)$$

where θ is the rf phase with respect to a zero-crossing phase, as shown in Fig. 2, θ_∞ is the constant determined by an initial condition, p is the electron momentum, k is the wave number of the acceleration rf field, E_0 is the average acceleration electric field, c is the speed of light, e is the elementary charge and m is the electron rest mass. The longitudinal phase space trajectory of the L-APS is shown in Fig. 2 [3]. The minimum phase to capture electrons can be calculated from Eq. 2 with $\cos\theta_\infty = -1$. If we set the L-APS acceleration gradient to the typical value, 13.9 MV/m, and the initial kinetic energy to 1 MeV, the minimum phase, $\theta_{\min}$, is calculated to be

$$\cos\theta_{\min} = \frac{kc}{eE_0}\left[\sqrt{p^2+(mc)^2} - p\right] - 1 \simeq -0.911, \qquad (3)$$
$$\therefore \quad \theta_{\min} \simeq -156\ [\text{deg.}].$$

To calculate the maximum phase, we firstly evaluate $\cos\theta_\infty$ from the initial condition, $p = \theta = 0$,

$$\cos\theta_\infty = 1 - \frac{kmc^2}{eE_0} \simeq -0.100, \qquad (4)$$

Thus, the maximum phase, $\theta_{\max}$, for a 1 MeV electron is estimated to be

$$\cos\theta_{\max} = \frac{kc}{eE_0}\left[\sqrt{p^2+(mc)^2} - p\right] + \cos\theta_\infty \simeq 0.092, \qquad (5)$$

$$\therefore \quad \theta_{\max} \simeq 85\ [\text{deg.}].$$

Thus, the phase interval to capture electrons by the L-APS is approximately 240 degrees, corresponding to 470 ps. This means that we can measure a 470 ps-long temporal structure at once. Nevertheless, we can measure a longer bunch than this value by scanning the L-APS phase.

DESIGN OF L-BAND TRANSVERSE DEFLECTING CAVITY

According to the conceptual design of the transverse deflector system, we designed an L-band TCAV, as shown in Fig. 3. Design values of the TCAV are summarized in Table 2. The TCAV has 2 input rf couplers intersecting at a right angle in order to choose the polarization freely. The cavity diameter is determined to be 256 mm so that the TM110 mode is excited at the resonant frequency of 1428 MHz. The cavity length is 60 mm, corresponding to a quarter wavelength of the rf. The TCAV has 3 tuners: two of them adjust resonant frequencies for the port 1 and 2 and the other is for the orthogonality between the 2 ports.

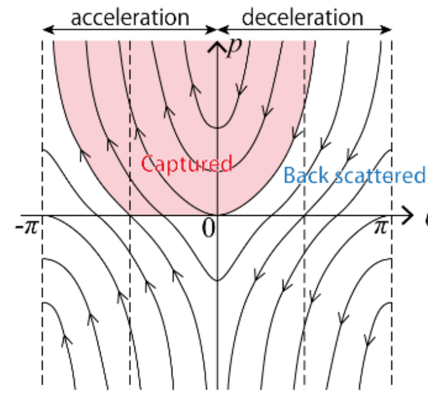

Figure 2: Longitudinal phase space trajectory of an electron beam in the L-APS. The hatched area shows electron-captured region by the L-APS.

By using a 3-dimensional rf simulation code, HFSS [4], the excited field was analyzed and the TM110 mode was confirmed to be properly excited, as plotted in Fig. 4. The unloaded Q factor was calculated to be 2.3 x 10^4. The external Q factor for each port was adjusted to 1.6 x 10^4 and the load Q factor was determined to be 9.5 x 10^3. The coupling factor, $\beta = Q_0/Q_{\text{ext}}$, is 1.44 (strong coupling), which slightly reduces the filling time. The transverse shunt impedance was evaluated to be 2.1 MΩ.When 2.5 kW solid-state amplifiers drive the TCAV, the maximum kick angle for a 1 MeV electron beam is approximately 63 mrad. As calculated in Eq. 1, this angle is sufficient for the requirement of a temporal resolution of 3 ps, which is applicable to a 10 ps long bunch.

Table 2: Design values of the L-band TCAV.

Resonant Frequency	1428 MHz
Resonant Mode	TM110 (linear and circular)
Shunt Impedance	2.1 MΩ
Input Power	2.5 kW max. for each port
Maximum Kick Angle	60 mrad for 1 MeV electrons
Cavity Inner Radius	256 mm
Cavity Inner length	60 mm
Unloaded Q (Q_0)	2.3 x 10^4
Loaded Q (Q_L)	9.5 x 10^3
External Q (Q_{ext})	1.6 x 10^4
Filling Time	6.6 µs

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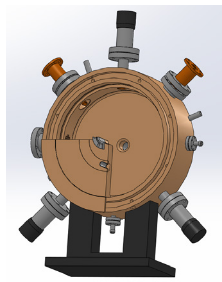

Figure 3: Schematic drawing of the L-band TCAV.

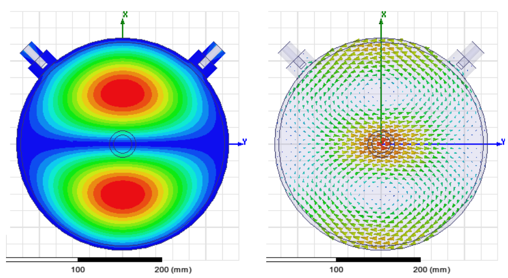

Figure 4: Electric field contour plot (left) and magnetic field vector plot (right) of the TM110-mode in the TCAV.

SUMMARY

In order to measure the temporal structure of an electron beam after the velocity bunching section of SACLA, we designed an L-band TCAV system. Since the bunch length range in the injector is so wide, 10 ps – 1 ns, we considered using both linear and circular polarizations for this system. The temporal structure is linearly stretched by the linear polarization and the time resolution can be enhanced by increasing the deflecting force. Therefore, the linear polarization is suitable for a short bunch measurement. On the other hand, the circular polarization converts the temporal structure to a circular image and enables us to use the full rf period (700 ps). Consequently, the circular polarization is useful to measure a longer bunch. We estimated the performance of the TCAV and the expected time resolution was obtained to be 3 ps for a 1 MeV electron beam. Thus, the designed TCAV system has sufficient performance for the temporal structure measurement at the SACLA injector and meets to the fine-tuning of the injector part.

APPENDIX

Basics of Transverse Deflector System

A schematic setup of a transverse deflector system is illustrated in Fig. 5. A transverse rf field in a TCAV gives a transverse kick to an electron beam. If the rf phase of the cavity is set to zero-crossing, the temporal structure of the beam is converted to a transverse profile. The temporal structure is taken by a transverse image on a screen monitor.

Here, the beam direction is supposed to be z-axis and the beam is to be kicked to y direction. The kick force, F_y, is evaluated from the Lorentz force,

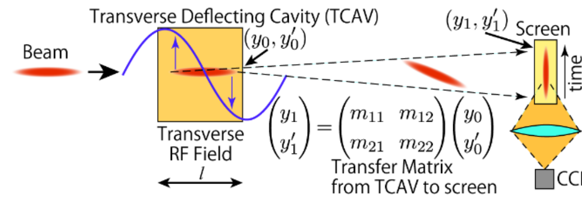

Figure 5: Schematic setup of a transverse deflector system.

$$F_y = -e(E_0 + \beta c B_0)\sin(\omega t + \phi_0), \tag{6}$$

where E_0 and B_0 are the y component of the peak electric field and the x component of the peak magnetic field, respectively, e is the elementary charge, c is the speed of light, β is the beam velocity normalized by c, ω is the resonant angular frequency of the TCAV, and ϕ_0 is the rf phase when an electron is at the cavity center. For simplicity, we assume the TM110 mode of a pillbox cavity from now, because this mode is one of the simplest transverse rf modes. In this case, E_0 can be ignored and B_0 becomes constant, since this mode only generates a magnetic field along the cavity axis and its field strength is independent of the longitudinal position.

The transverse momentum of the electron given by the TCAV is calculated to be

$$\begin{aligned} p_y &= \int_{-\frac{l}{2\beta c}}^{\frac{l}{2\beta c}} F_y dt = -e\beta c B_0 \int_{-\frac{l}{2\beta c}}^{\frac{l}{2\beta c}} \sin(\omega t + \phi_0)\, dt \\ &= -\frac{\sin\frac{\omega l}{2\beta c}}{\frac{\omega l}{2\beta c}} e B_0 l \sin\phi_0 = -e B_0 l\, T \sin\phi_0 , \end{aligned} \tag{7}$$

where l is the cavity length and T is the transit time factor defined to be

$$T \equiv \frac{\sin\frac{\omega l}{2\beta c}}{\frac{\omega l}{2\beta c}}. \tag{8}$$

The kick angle, y_0', can be written as

$$y_0' = \frac{p_y}{p_0} = -\frac{e B_0 l\, T \sin\phi_0}{p_0} \simeq -\frac{e B_0 l\, T \phi_0}{p_0}, \tag{9}$$

where p_0 is the initial beam momentum and ϕ_0 is sufficiently small. We define the maximum kick angle, y'_{max}, as

$$y'_{\mathrm{max}} \equiv \frac{e B_0 l\, T}{p_0}. \tag{10}$$

The transverse position of the electron, y_1, is calculated by using the (1,2) element of a beam transfer matrix in Fig. 5, m_{12},

$$y_1 = m_{12} y_0' = -m_{12} y'_{\mathrm{max}} \phi_0 = -\frac{m_{12} e B_0 l\, T \phi_0}{p_0}. \tag{11}$$

The position-to-time conversion factor, C, on the screen is

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$$C = \frac{\phi_0}{y_1\omega} = -\frac{1}{m_{12}y'_{\max}\omega} = -\frac{p_0}{m_{12}eB_0 l T\omega}. \quad (12)$$

The finite beam size at the screen without deflection, σ_y, limits the time resolution of the transverse deflector system. Therefore, the time resolution, σ_t, is evaluated to be

$$\sigma_t = |C\sigma_y| = \frac{\sigma_y}{|m_{12}|y'_{\max}\omega} = \frac{p_0\sigma_y}{|m_{12}|eB_0 l T\omega}. \quad (13)$$

Thus, in order to obtain a better time resolution, the initial momentum and the beam size at the screen should be small, and the integration of the rf field ($B_0 l T$), the resonant frequency and the (1,2) element of the transfer matrix (m_{12}) should be large.

A screen size or an rf period limits the measurement range. In the case of the limited screen size, the measurement range, $\Delta t_{\max}$, is calculated to be

$$\Delta t_{\max} = |C y_{\mathrm{scr}}| = \frac{p_0 y_{\mathrm{scr}}}{eB_0 l T\omega m_{12}}, \quad (14)$$

where y_{scr} is the half size of the screen. For the rf period limitation case, we suppose that the approximately linear part of the rf sinusoidal wave is a quarter of the rf period. The measurement range is estimated to be

$$\Delta t_{\max} \simeq \frac{\pi}{2\omega}. \quad (15)$$

Thus, the rf frequency should be sufficiently small for a long bunch-length measurement range. The limitation from the screen size can be relaxed by reducing the rf power instead of decreasing the temporal resolution.

Polarization Control of Transverse RF Field

The polarization of a transverse rf resonant mode, such as TM110 mode in a pillbox cavity, can be freely chosen, if the cavity has 2 input ports intersecting at a right angle, as shown in Fig. 6. The input rf signals at the port 1 and port 2 are defined to be $A_1\cos(\omega t + \phi_1)$ and $A_2\cos(\omega t + \phi_2)$, respectively.

When the rf phase difference between the 2 ports is 0 or π, a linearly polarized rf field is excited. The polarization direction is determined by the arctangent of the amplitude ratio between the 2 ports. The amplitude of the rf field in the cavity is proportional to $\sqrt{A_1^2 + A_2^2}$.

When the rf phase difference between the 2 ports is $\pm\pi/2$ and the amplitudes of the 2 ports are the same, a

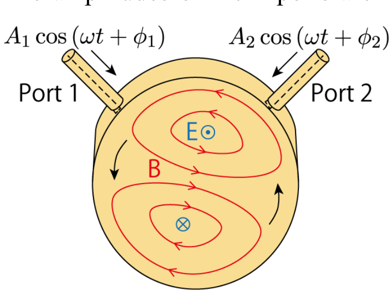

Figure 6: Schematic view of a 2-port pillbox cavity with a circularly polarized TM110 mode.

circularly polarized rf field is excited. The rotation direction depends on the sign of the phase difference. The amplitude of the rf field in the cavity is proportional to A_1 ($= A_2$).

Characteristics of Circular Polarization Deflector System

If a circularly polarized rf field is excited in a TCAV, the temporal structure of an electron beam is circularly stretched, as shown in Fig. 7. In this case, the full rf period of the TCAV can be used for a temporal profile measurement. Therefore, this mode is suitable for long bunch measurement.

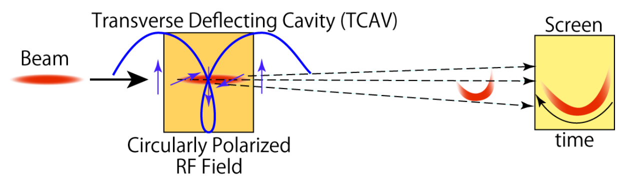

Figure 7: Schematic setup of a transverse deflector system with a circular polarization.

The radial force to an electron in the cavity, F_r can be written as

$$F_r = \beta c e B_0 \cos\omega t. \quad (16)$$

We can get the radial momentum from the kick force, p_y, as follows:

$$p_r = \int_{-\frac{l}{2\beta c}}^{\frac{l}{2\beta c}} F_r dt = eB_0 l T. \quad (17)$$

The kick angle, r'_0, and the radius of an image circle, r_1, are calculated to be

$$r'_0 = \frac{p_r}{p_0} = \frac{eB_0 l T}{p_0}, \quad (18)$$

$$r_1 = |m_{12}|r'_0 = \frac{|m_{12}|eB_0 l T}{p_0}. \quad (19)$$

The time scale of the image is apparently obtained from the azimuthal angle on the screen. For the time resolution, the expression is the same as the rightmost formula of Eq.13. Since the image circle must be within the screen size, the kick strength is limited by this condition. Thus, although the measurement range of the circular polarization case is longer than the linear polarization, the time resolution is not better than the linear polarization case.

REFERENCES

[1] T. Ishikawa, et al., Nature Photonics **6**, 540 (2012).
[2] H. ego, et al., Nucl. Instrum. Methods in Phys. Res., Sect. A **795**, 381 (2015).
[3] R. Helm, R. Miller, Particle Dynamics, in: P. M. Lapostolle, A. L. Steptier (Eds.), Linear Accelerators, North-Holland Publ. Co., Amsterdam (1970).
[4] http://www.ansys.com

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