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Analysis of beam acceleration and instability on TWRR accelerator structure in PNC by beam-cavity interaction

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Analysis of beam acceleration and instability on TWRR accelerator structure in PNC by beam-cavity interaction

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Abstract

It is important for high current accelerators to estimate the contribution of the space charge effect to keep the beam off its beak up (BBU). The CW electron linac is designed in order to study BBU experimentally. The design is primary on the consideration which type of accelerator structure is suitable to reduce the BBU threshold, and how to observe and control BBU when it appears.

The contribution of beam charge for the acceleration characteristics is surveyed by means of the comparison between traveling wave and standing wave structures in this report. At first, the characteristics of both traveling wave and standing wave structures are calculated analytically and the conversion efficiency and accelerator gain are presented. The merits and drawbacks are also mentioned concerning with unit accelerator length. Next, the choice of RF frequency on energy conversion is mentioned as independent matter of the types of accelerator structure.

After that, the characteristics of TWRR are described as the advanced accelerator structure compared with above structures. The effect of longitudinal induced field is estimated by means of the loss parameter.

The result from the analysis shows that the unit accelerator length is 1 m to get high conversion ratio from RF to beam power and that the BBU for transverse component is small. Therefore, total BBU is expected small in the accelerator, for transverse BBU is already expected small in previous reports.

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進行波還流型加速管のビーム-空洞 相互作用を考慮した加速特性と不安定性の解析

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要旨

大電流の安定加速では、ビーム発散を防止するため、荷電効果を考慮に入れることが重要である。現在動燃で開発が進められている大電流電子線形加速器は、ビーム発散閾値を小さくし、また観測された際には加速器を制御して、ビーム発散の抑制を実験的に研究することを目的としている。

今までの解析では、荷電効果によるビーム方向垂直面の発散力を数値解析し、1アンペアの電流までビーム発散が生じないことが分かっている。

今回の報告では、ビーム電流による荷電効果を考慮したビーム進行方向の加速特性を解析した。まず、進行波と定在波両者の加速特性の解析式を求め、エネルギー変換効率や加速利得が計算される。次に、進行波と定在波構造の特徴を長さ1 mの加速管を基準に比較する。 その後、加速管の運転周波数の決定のために、エネルギー変換効率の観点からRF(高周波)加速周波数の最適化について議論する。最後に、エネルギー変換効率や加速利得の観点で、進行波還流型加速管(TWRRと呼ばれる)の特性が進行波と定在波の長所を持つことを示し、ビーム発散の一つの原因であるビーム加速方向の誘導電界をビーム-空洞相互作用から計算したロスパラメータから評価する。

解析の結果、長さ1mの進行波還流型加速管は高効率が高く、ビーム進行方向のビーム発散の小さいことが分かった。今までのビーム方向垂直面の解析と併せて、全体のビーム発散も小さいことが分かった。

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I. Introduction

The development of a high power electron linac is in progress and its test linac is settled in Quantum Technology Development Facility (QTF) in PNC Oarai Engineering Center in order to study the feasibility of high efficient acceleration for transmutation and other applications as well. The Traveling Wave Resonant Ring (TWRR) for an accelerating structure and CW RF power supply are the main features of the linac. CW acceleration will be now up to date technology for industrial stage after the development of this linac and other L-band linacs. TWRR is somewhat new structure for particle acceleration even though a resonant ring is familiar with some accelerator.

In previous reports, the effect of transverse space charge effect as well as the effect of the wake field on TWRR was estimated by analytic and numerical approaches [1,2]. In these reports, the design principle for beam stabilization associated with TWRR compared with basic accelerator characteristics is evaluated by means of analytic calculation for various types of accelerator structures.

In chapter 2, requirement to PNC linac is briefly mentioned. In chapter 3, comparison of accelerator structures is discussed in order to make it clear to employ traveling wave structure to TWRR. In chapter 4, RF frequency and Q value are discussed for the choice of operating frequency. In chapter 5, TWRR accelerator structure is discussed to mention the advantage of this structure. Conclusion is given in chapter 6. In appendix, the some formula are derived and summarized for helping the quick use which is occasional for the calculation.

2. Requirement to PNC linac

The accelerator structure for high power linac in PNC was designed to be accompanied with following conditions;

. The accelerator can accelerate CW beam in order to get high current beam nominally.

. The accelerator has to achieve high energy conversion to beam power in order to get excellent energy saving.

. A short accelerator section is preferable to testing the machine with CW or long pulse operation such as in our case.

. Beam break up (BBU) can be under the control up to 100 mA by means of beam focusing system if it appears.

In addition to above conditions, total design was achieved so as to get low emittance and high beam energy resolution as much as possible.

3. Comparison of accelerator structures

In this chapter, the comparison with traveling wave and standing wave are mentioned in the points of the energy gain, energy conversion to beam power, the difference of each structures and operation.

3.1 Traveling wave accelerator structure

There are lots of accelerators for electrons which employ traveling wave accelerator structure. Each accelerator wave guide for traveling wave has a dummy load into which RF power unconsumed for particle acceleration is fed to be absorbed. The longer accelerator structure is, the less power loss is achieved, because RF power excites the electric field for particle acceleration.

The behavior of RF power, its transmission, accelerator gain and beam loading are examined by parameters of the attenuation for accelerator structure.

At first, the power into the dummy is calculated by the formula in the other report 1], changing the length of accelerator wave guide. Fig. 3.1a shows the result from the calculation for an accelerator structure length dependence of the power at the dummy load by equation (27) for constant gradient type in the appendix of the previous report[1]. The calculation is executed for the case of constant value input RF power P_0 800 kW, shunt impedance r_s 40 MΩ/m and beam current I_0 100 mA which are design parameters for PNC accelerator respectively, changing the attenuation τ in the range from 0.05 to 1.0 in neper/m. Solid lines and dashed lines correspond to the power fed into the dummy loads without and with beam loading. It is obvious from Fig. 3.1a that the loss power gets small less than 20% from initial value, when the length of the accelerator structure gets longer then 2 meters and τ is less than 0.5. Fig. 3.1b shows the energy transmission from input RF to beam power. It is clear that from Fig. 3.1b higher attenuation more than 0.5 neper makes it possible to get approximately 100 % power transmission in 2 m.

Accelerator gain is one of the important characteristics. The total gain for PNC parameters are summarized in Fig. 3.2 in which the gradients are calculation parametrized by the attenuation mentioned above paragraph. The gain in Fig. 3.2 is the case for the average beam current is 100 mA. It is seen that the optimum length for the gradient shifts to about 7 m as the attenuation gets smaller. Typical traveling wave structure for S band linac has the gain more than 10 MeV/m with a few tens MW RF which attenuation is around 1.0 nepers/m, and the optimum length is shorter than 2 m. Higher attenuation is of course favorable to achieve higher gradient. Nowadays usual value for t is 0.4 to 0.7 after the compromise against the RF energy conversion to beam power.

A beam loading is also quite important characteristics for high current linacs. Fig. 3.3 shows the result from the calculation for the current dependence of the gradient with 1 m long accelerator structure which has various attenuation parameter. The RF power and shunt impedance employed are the same as the case of Fig. 3.1. The current limit to be accelerated is higher in lower attenuations, while the gradient is totally smaller. Morever, it is seen that the vias of a beam loading gets affected mild to the gradient when structures have lower attenuation.

3.2 Standing wave accelerator structure

The high shunt impedance of a standing wave accelerator structure is favor to get high gradient. The shunt impedance for p mode is up to 100 MΩ/m, which is one of highest among various structures. The cavity structures are making a lot of progress like APS which has bi-periodic structure and side coupled cavities structure which is reverted from π /2 mode cavity. The cavity structure for standing wave is complicated in order to reduce transit time factor and get high gradient almost equal to one from π mode. The small diameter for the iris in each cavities is preferable to realize stronger electric fields and get high effective shunt impedance.

The transit time effect essentially causes the phase slip between beam and RF which results in the energy spread in accelerated beam. This is one major reason why traveling wave structure is employed in free electron laser device. The dimensions have not large difference between standing wave structures and traveling wave structures. The specific phenomenon for standing wave cavity is a detune dependent of the beam current. Tuners are equipped to each cell to cancel the induced voltage caused by beam bunches. The relationship between detuning angle and frequency shift is summarized in Appendix.

The standing wave structure is still sensitive to the beam loading, and power reflection to RF source is significant problem which is aviodable by using a circulator. A circulator is equipped between RF source and cavity in many case. This device is certainly larger because it generally consists of wave guide and high power Faraday rotation device which needs cooling circuit even though there is no power loss in an ideal case. The circulators for L-band was not applicable at the first stage of development of PNC accelerator.

4. RF frequency and Q value

The choice of frequency is of vital importance for efficiency in order to get high RF energy conversion to beam power and beam transmission along the accelerator structure. Those two for traveling wave structures are also estimated by means of Q values which usually designate resonator characteristics for standing wave accelerator structures.

$$\tau = \frac{\omega\, t_f}{2Q}, \qquad (1)$$

The relationship between the attenuation τ and frequency ω is presented bellow, where t_f and Q are a filling time of RF in accelerator structure and a Q value. The filling time is presented as bellow[3] in constant gradient type,

$$t_f \approx \frac{L}{v_f} \approx K^{-1}(\frac{a}{b})^{-4}, \qquad (2)$$

where v_g, a, b and K are a group velocity, a bore radius, a beam hole radius and the constant, respectively. The ratio a/b can be approximately independent of frequency. It is seen from above two equations that low RF frequency leads high RF energy transmission to beam power because the attenuation causes low power loss into the wall.

High Q value also contributes to high energy saving. It is general that the low frequency resonating cavities are favor to high Q values because the ratio from bulk volume to surface is proportional to ω and induction loss at wall is proportional to $\omega^{1/2}$. The Q values for $2\pi/3$ mode from SLAC (2856 MHZ) and PNC(1249 MHZ) are typically 15000 and 20000, which means approximately 1.5 times increase according with the inverse square value

1.51 calculated from the frequency ratio from PNC to SLAC.

From above discussion, it is natural for traveling wave structures that high Q value and low frequency operation suggest high current beam loading, not because the energy stored is necessarily high but because the attenuation is low.

In addition, lower frequency is preferable to high transmission because the diameter of beam holes varies by the function of ω^{-1}. Larger beam radius can reduce the space charge effect in beam bunches.

There is no transient feature for an accelerator gradient because the RF devices for PNC linac are identically designed for CW operation. However, the filling time should be estimated for TWRR in the case for pulsed operation which is actually realistic under the limited distribution from the power station here in OEC.

Beam loading causes an energy aberration and a detuning. Energy aberration means that actual electric field on beam bunches is reduced by induced field generated by the interaction between the beam bunches and accelerator structures, while detuning means that the beam bunches cause the shift of resonant frequencies of the accelerator structures. Here, the effect of these two phenomena are estimated in order to make assure to accelerate the stable electron beam.

5. TWRR accelerator structure

5.1 Advantage of TWRR accelerator structure

TWRR structure consists of a traveling wave accelerator guide and an RF feed back loop. The conceptual diagram is seen in Fig. 5.1.

The attenuation of accelerator structure is lower than the value between 0.4 and 0.7 which range is usual case for traveling wave structures. Low attenuation makes it possible to keep larger beam irises. The large aperture has the advantage that the beam has less possibility to hit accelerator structure.

TWRR structure can accumulate RF power which is accumulated inside TWRR structure. The inside power is determined by the energy conservation of RF power fed into recirculator and dissipation energy to wall of TWRR structure. Fig. 5.2 shows the power multiplication for various attenuation τ by means of dependence of coupling parameter C from the directional coupler in TWRR seen in Fig. 5.1. The dashed line in Fig. 5.1 corresponds to optimum field multiplication by the coupling C. It is seen that the inside power is more than twice than input power into TWRR when the attenuation τ is low. This power multiplication compensates the intrinsic low shunt impedance of traveling wave accelerator and identically power recirculation can achieve the same acceleration gain from standing wave structure.

Another advantage to choose this type is simple characteristics for RF feeding to accelerating structure because there is no RF reflection at the input coupler of the accelerator structure by the change of a beam loading. Moreover, there is no detuning effect in TWRR because beam is accelerated in a traveling wave which causes no RF resonance inside the structure.

5.2 Beam loading in TWRR

The charge of the beam bunch creates the induced field which causes the longitudinal BBU. The dynamics on each particles is evaluate microscopic calculation which is rather complicated in actual cases. Beside, total induced voltage can be calculated by means of the loss factor which is attainable from the result from previous reports [1,2].

The relationship between the induced voltage Vin and the loss factor k_1 is mentioned as follows,

$$V_{in} = 2\ k_l\ q \qquad (3)$$

where, q is a single bunch charge. The loss factor for TWRR structure is calculated by ABCI [4] and shown in previous report which is seen in Table 5.1 in a single bunch for cylindrical chamber. The maximum induced voltage is 1.8 kV and it is clear that the induced voltage is almost negligible small compared with acceleration whose magnitude is 1 MV.

6. Conclusion

The TWRR can accelerate electron beam with high energy conversion (70% or more) from RF to beam. The structure is simpler than the standing wave structure which has high shunt impedance. The accelerator gain is increased almost the same magnitude as much as the accelerator gain from π mode standing wave structure. TWRR has more advantages to stable beam acceleration because it can have wider beam irises and has less induced field and no beam detuning effect which causes BBU. The longitudinal BBU is quite small compared with acceleration voltage. Then total BBU is expected small as the results from previous reports.

References

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[3] P.M.lapostole and A.L.Septier ed.; "Linear Accelerators," North Holland Pub. 1970

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Appendix

A. 1 Transient characteristics of TWRR

The rise time and falling time are dominated by the filling time and the Q value of accelerating structure. RF time structure is summarized in a simpler cavity and an actual cavity with coupling holes.

The voltage V is governed by the equation from the analysis of the equivalent circuit of a cavity which is shown in Fig. 1 (b) in previous report

$$\ddot{V}+\frac{1}{CR}\dot{V}+\frac{1}{LC}V=0 \ . \tag{1}$$

The resonant frequency ω_0 and energy dispersion factor λ_0 are respectively,

$$\omega_0=\sqrt{\frac{1}{LC}}\sqrt{1+\frac{3LC}{4C^2R^2}}\approx\sqrt{\frac{1}{LC}}\ , \quad \lambda_0=-\frac{1}{2LC}=-\frac{\omega_0}{Q} \tag{2}$$

Then, the detuning of the TWRR is quite small when a shunt impedance is high enough to accelerate particles. The Q value in this case is called unloaded Q, because the there is no loading coupler.

The energy store is released exponentially with its time constant is λ_0, that is,

$$U(t)=U_0\ e^{-\omega_0 t/Q}\ . \tag{3}$$

. There is power dissipation from coupling holes beside the conduction losses in the case of cavities with coupling holes. The Q value for this structure is called loaded Q_L. Power flow via the coupling holes is resistive loss in general situation. Q value for coupling structure is called external Q_e. There is a relationship between Q_e, Q and Q_0 ,that is,

$$\frac{1}{Q_L}=\frac{1}{Q_e}+\frac{1}{Q}\ , \tag{4}$$

because the loaded Q_L can be composed of parallel combination of resistors in the point of equivalent circuit..

Q values for the same structures are different for each electromagnetic mode because induction current pattern at the wall are different for each modes at least.

A2. Detuning of standing wave cavity

The resonant frequency of a standing wave cavity shifts by a beam loading from bunched beam structure. This phenomena is called detuning. Here, the quantity called detuning angle Φ is derived and the method in order to cancel the detuning effect are analytically suggested.

The input impedance near resonance is presented as,

$$Z_{in} = \frac{R}{1+jQ\beta} \tag{5}$$

where R, Q, β are shunt impedance, loaded quality factor and detuning parameter, respectively. Q is presented by means of coupling parameter g and unloaded Q_0 as follow,

$$\frac{Q_0}{Q} = 1+g \tag{6}$$

and,

$$\beta = \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \approx 2\frac{\omega-\omega_0}{\omega_0} \tag{7}$$

where ω and ω_0 are induced field frequency and cavity resonant frequency, respectively. Hence, the input impedance is finally presented as,

$$Z_{in} \approx \frac{R}{1+Q_0\beta^2}\left(1- 2\,j\frac{Q}{1+g}\frac{\omega-\omega_0}{\omega_0}\right) \tag{8}$$

Then,

$$Tan\Phi = -2j\frac{Q}{1+g}\frac{\omega-\omega_0}{\omega_0} \tag{9}$$

The imaginary part of equation (9) corresponds to phase slip between the beam bunch and resonant RF. Φ should be zero to RF phase in order to synchronize to the beam bunch. Eventually, cavity resonant frequency is changed by the tuner which is equipped in the cavity to the induced field frequency. Lower Q is favorable to making it easier to tune the cavity resonant frequency for smaller adjustment by the tuner.

Table 1 Loss factor and induced voltage

	Beam displacement (cm)	Loss factor* (V)***	Induced voltage** (V)
σ= 1 cm			
	0.5	-17.4	112.0
	1.0	-61.0	210.0
	2.0	-243.8	420.0
	3.0	-548.4	630.0
σ= 0.3 cm			
	0.5	-56.8	89.9
	1.0	-199.9	168.8
	2.0	-798.0	338.9
	3.0	-1792.5	511.0

*   Longitudinal.
** Transverse.
*** Normalized to a single bunch current.

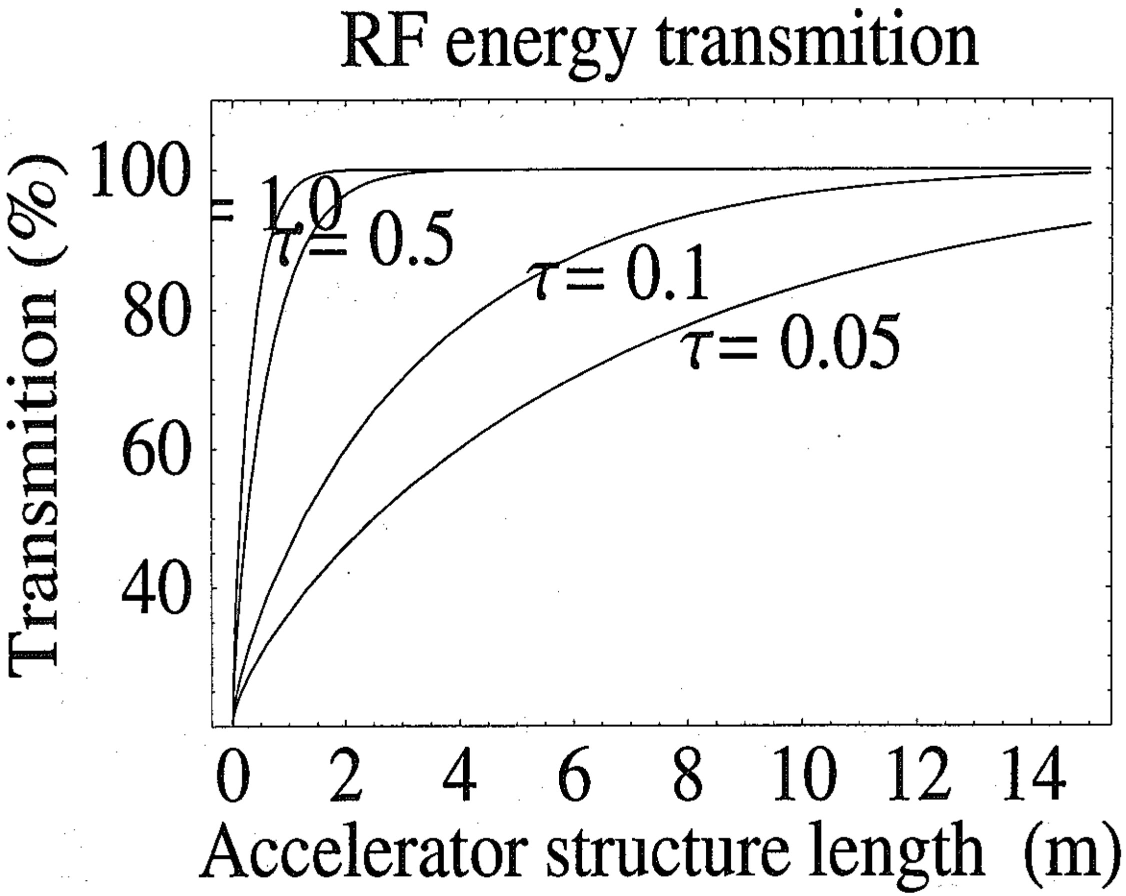

Fig3.1a Power at dummy load with various attenuation parameters.

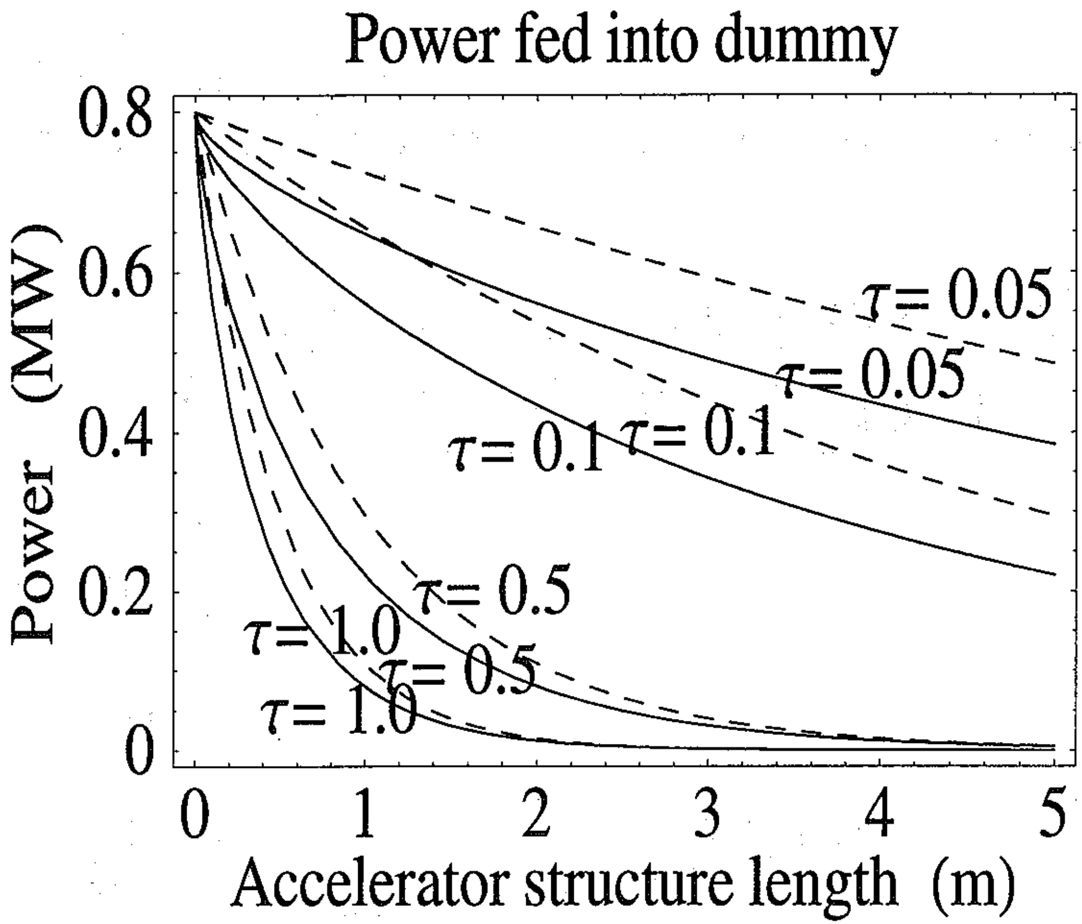

Fig. 3.1b Energy transmission from input RF to beam power.

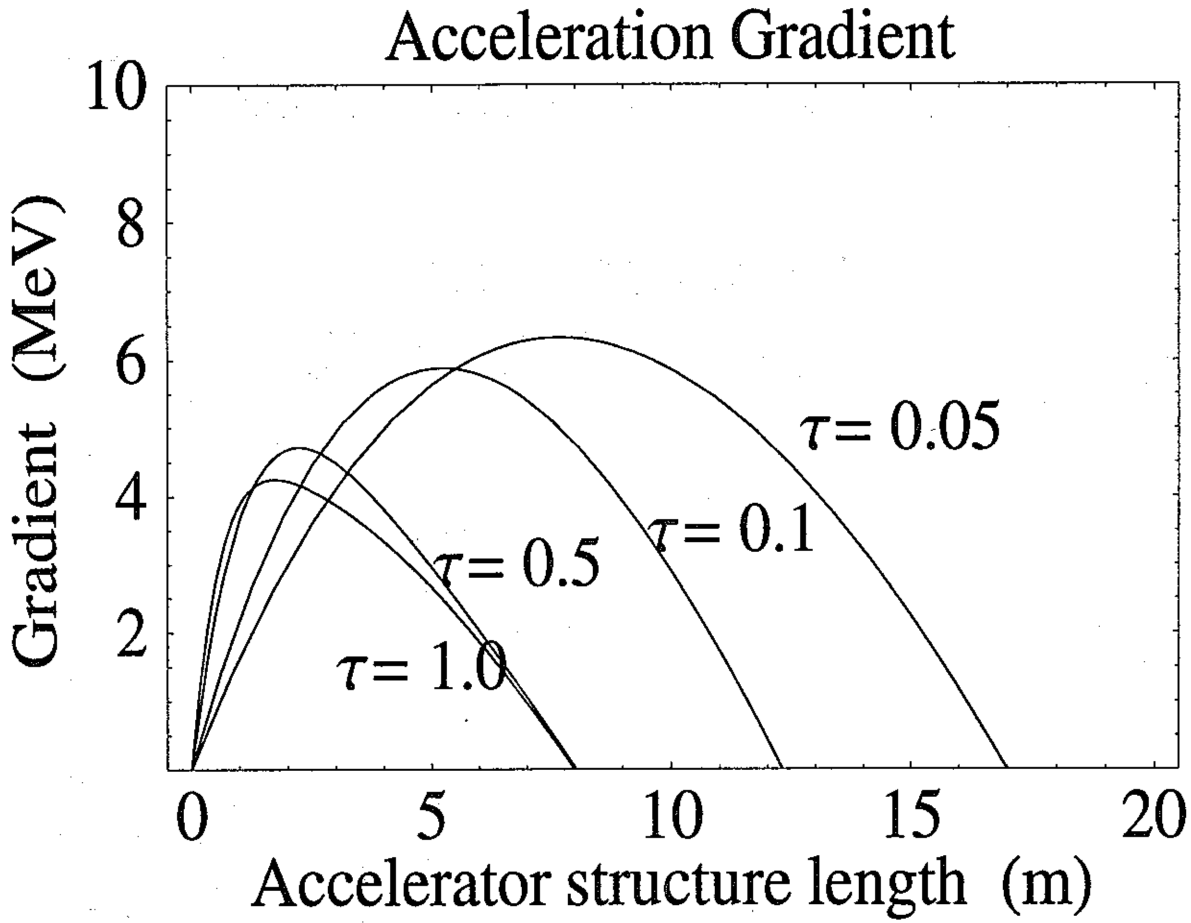

Fig3.2 Accelerator gain with various attenuation parameters.

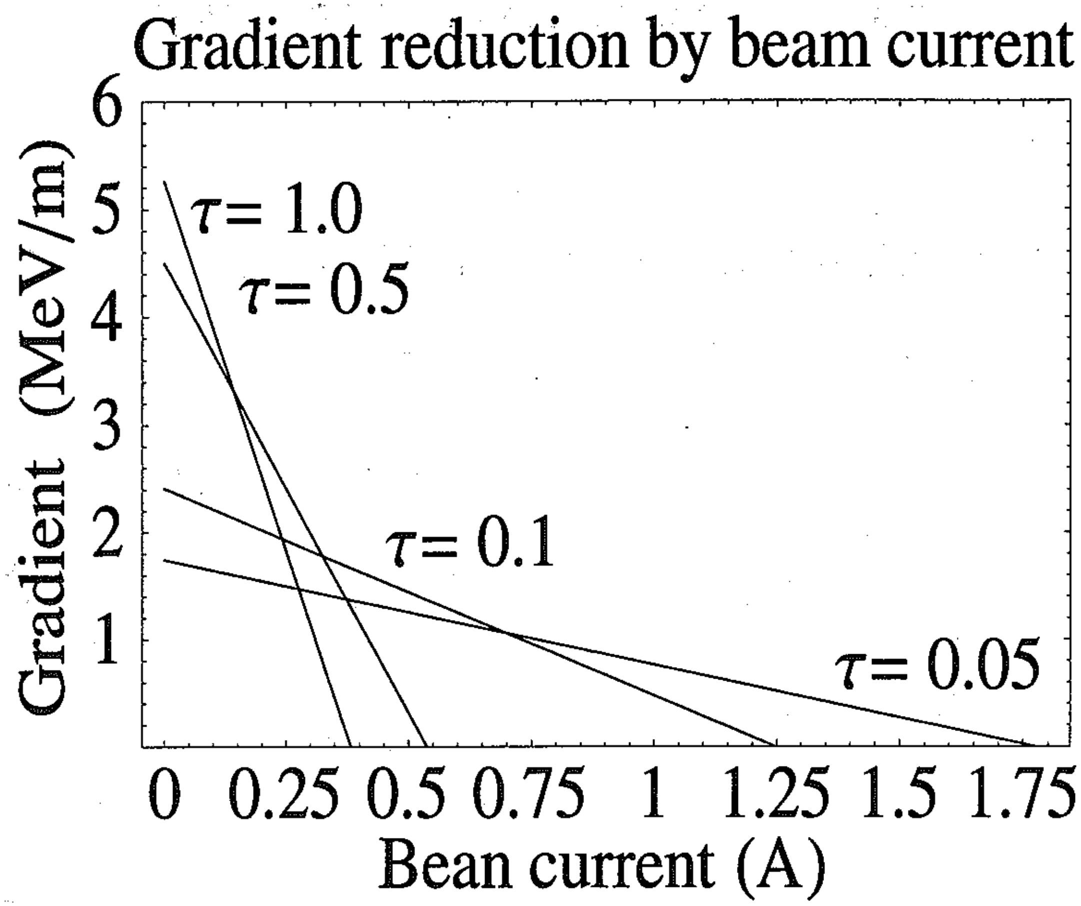

Fig. 3.3 Current dependence of the gradient with 1m long accelerator structure.

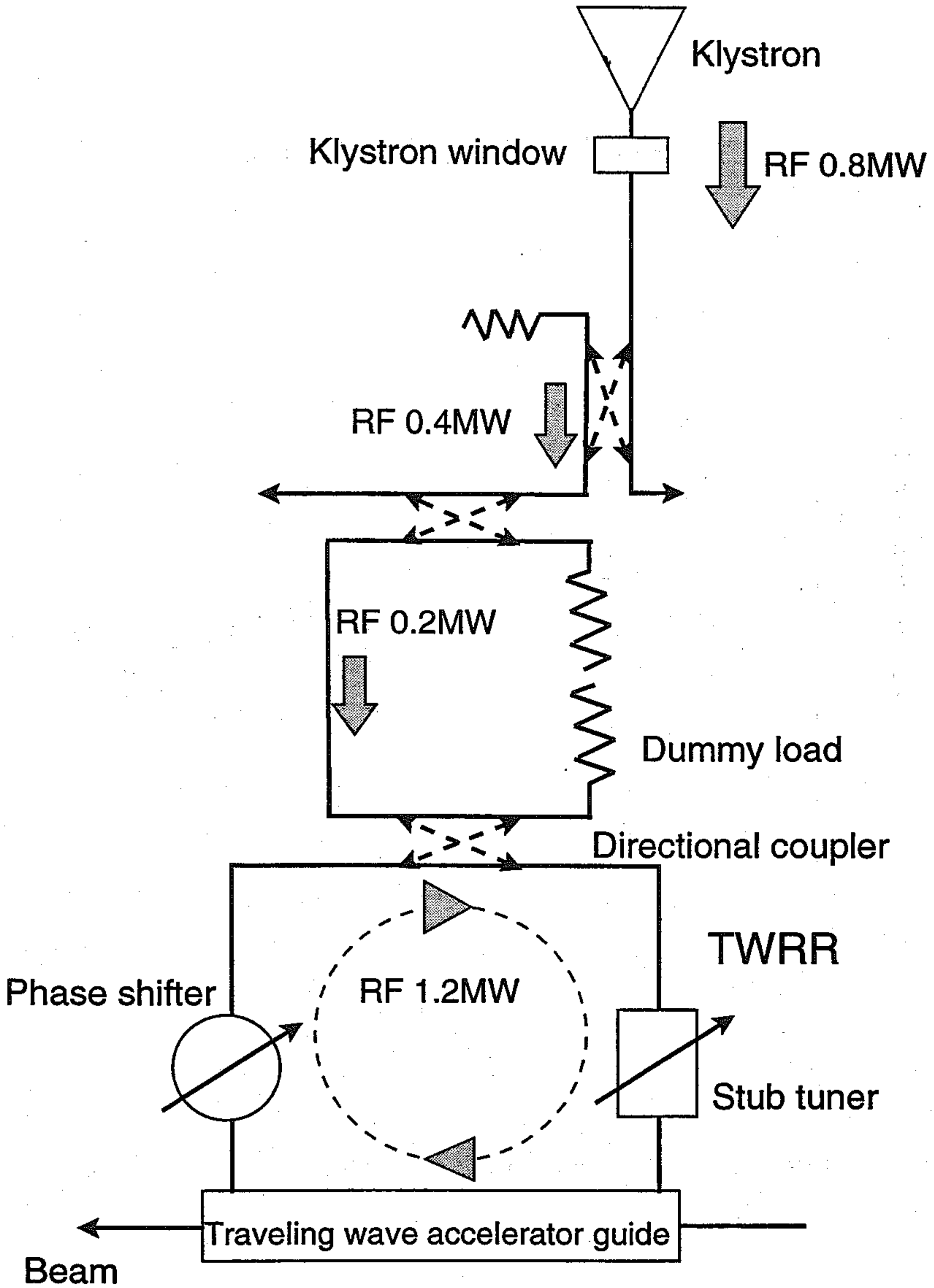

Fig. 5.1 Diagram of TWRR

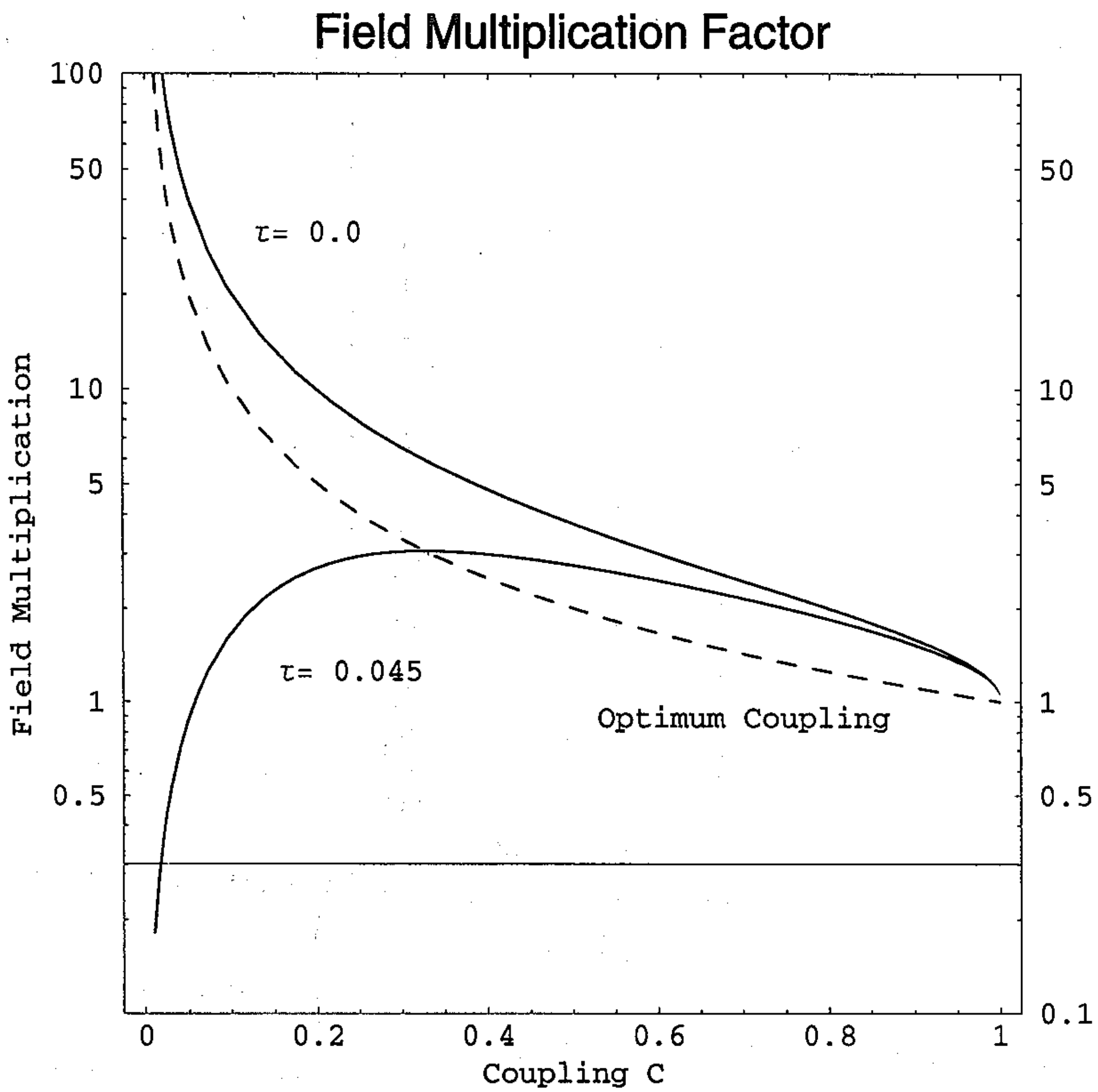

Fig. 5.2 Amplification of electric field in TWRR.