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DEVELOPMENT OF ACCELERATING UNIT FOR HIGH BEAM CURRENT

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OARAI ENGINEERING CENTER
JAPAN NUCLEAR CYCLE DEVELOPMEENT INSTITUTE

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Abstract

A short traveling wave accelerator with a traveling wave resonant ring is proposed for high beam current accelerators (including the linear accelerator, circular accelerator and storage ring). It is a normal conducting accelerator. The CW beam current can be as high as 10A. Such kind of accelerator unit has large beam holes for damping all of the cavity high order modes in order to avoid the resonant buildup of the fields that would cause multibunch instabilities at high currents. It has high efficiency, high power input capability and low K_{loss}. It is called "single mode" type. Even though beams are accelerated off the crest for phase stability in circular accelerator, the cavities do not need detuning.

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大 電 流 加 速 管 の 開 発
（研究報告）

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平野　耕一郎*、山崎　良雄*、佐藤　勇**

要　旨

線形加速器だけでなく、円形加速器や蓄積リングを含めた大電流加速器として進行波還流型加速構造を提案する。その構造は常伝導の加速構造であるが、連続波でビーム電流を10Aまで加速することが可能である。このような加速管では大電流においてビーム不安定性による共鳴電界が発生し易く、空洞内で発生した高次モードを消すためにはビーム輸送の口径を大きくする必要がある。このような加速構造は、高効率であるだけでなく大電力入力も可能であり、また励起モードの蓄積エネルギーも非常に小さい。このような加速管は、シングルモード型と呼ばれており、円形加速器の位相安定化のためビームがＲＦの最適位相からずれても、空洞のデチューニングは必要としない。

本報告書では、このような特徴を有する大電流加速管について、検討結果を報告する。

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1. INTRODUCTION

With the developing of the science and technology, the accelerator beam current will be higher and higher.

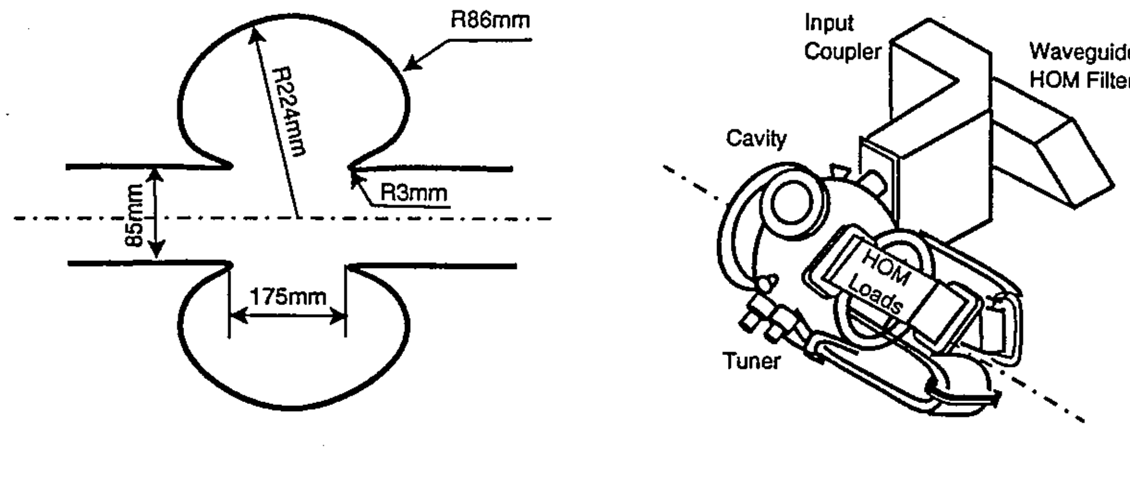
Japan Nuclear Cycle Development Institute (JNC) is developing high power CW electron linac to transmute radioactive wastes. Preliminary evaluation has shown that an accelerator whose beam energy ranges from several hundreds MeV to GeV with beam current of a few amperes is needed to transmute FPs(fission products) in an industrial scale.[1] Now JNC has developed a 10MeV 100mA CW linac for the high power accelerator test.[2,3]

And in the electron-positron rings, the hadron colliders, and the synchrotron light sources to meet the need of higher and higher luminosities, the magnitudes of the beam current continue to increase.

The first generation of accelerating cavities, such as LEP II, TRISTAN, HERA and CESR, both normal conducting and superconducting cavities, operating at current up to several hundred mA have been successful. They have operated much as predicted and the reliability has been satisfactory. Now the second generation of accelerating cavities, like PEP II, KEK-B, and CESR-B, operating at currents of 1-2 amperes are at various stages of design or construction or test.[4,5,6,7]

These high currents bring a set of new and difficult challenges. Even though the normal conducting and superconducting cavities have significant differences, the challenges addressed are rather similar.

Fig.1 (a) shows a typical normal conducting cavity. Its shunt impedance is made as high as possible in order to maximize the accelerating field, E_{acc}, for a given amount of dissipation in the cavity. The two factors which are the small beam hole size and the reentrant noses on the cell bring about the high value of R/Q. Both these factors unfortunately lead to high value of K_{loss}. It has been specifically designed to encounter the challenges of very high electron currents in PEPII.



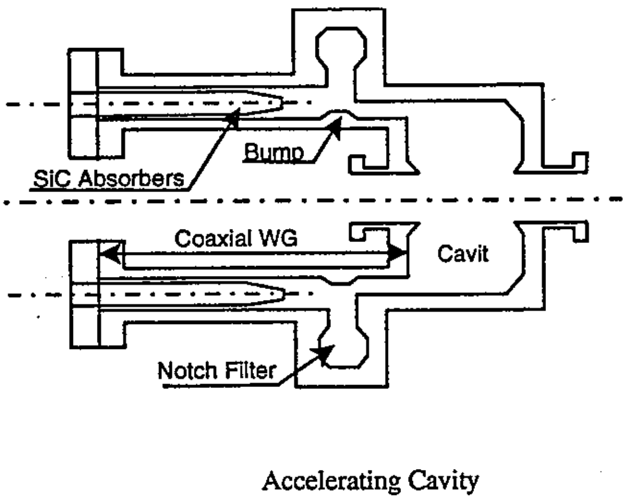
(a) (b)

Fig.1 PEP II RF Accelerating Station

The input power per cell, up to 400 kW, is coupled in through a planar waveguide window, then into the cell with either a loop or an iris. Some of the higher order mode (HOM) power(TM_{021} mode) will be coupled out through the input coupler. The damping of the rest of the HOMs with significant R/Q is accomplished with three waveguide coupling slots. The damping waveguides are folded back along the beam line to make as compact a package as possible. The insertion of these three slots, unfortunately, further increase the peak dissipation density of the fundamental mode to as high as 70 W/cm^2.

When the beams are accelerated off the crest for phase stability, the beam will generate the reactive power into the cavity. The RF cavity is operated off resonance, in order to compensate for the imaginary part of the beam loading current and to minimize the required generator power. In a high beam current machine, the detuning frequency Δf could approach or even exceed the revolution frequency of the beam. In this case, the multibunch longitudinal instability is excited by the high impedance of the fundamental (accelerating) mode. One solution is to use multiple levels of sophisticated feedback circuits around the klystron-cavity-beam system.

Another solution is to reduce the detuning frequency of the cavity to eliminate this type of instability. A new type of RF cavity system called ARES(accelerator resonantly coupled with energy storage) has been developing in KEK. The required frequency detuning is equal to the reactive energy flow per cycle to the stored energy inside the cavity. Therefore increasing the stored energy leads reduce the frequency detuning. Fig.2 shows a schematic of ARES which is made of three separate cavities coupled together. The first cell is for acceleration, the second one is for coupling and the third one is for energy storage. Moreover, in order to suppress HOMs, a choke-mode cavity is used as the accelerating cell. The choke reflects back the fundamental mode only, and hence HOMs propagate out and are absorbed by the SiC absorbers.



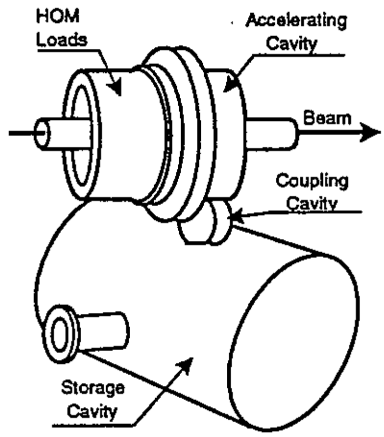
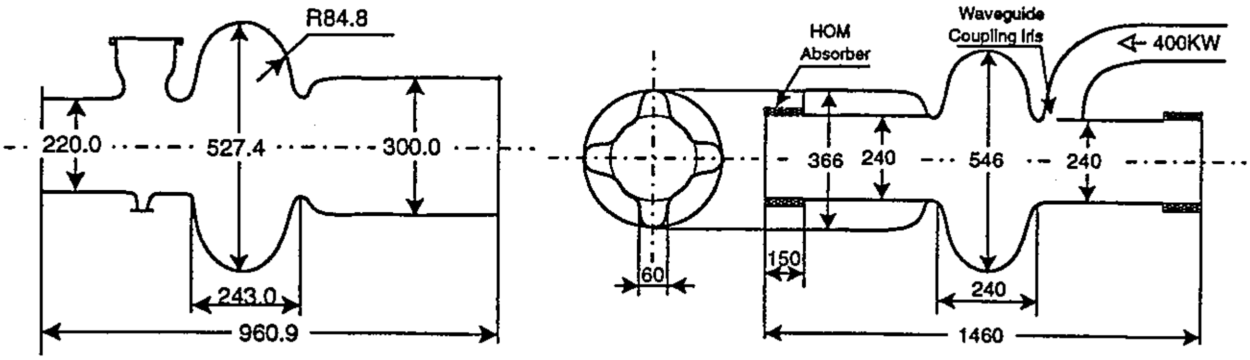


Fig.2 KEK B LER Accelerating Cavity System

Fig.3 shows two superconducting cavities. The Fig.3 (a) is a KEKB cavity which has two large-aperture beam pipes. HOMs propagate toward the beam pipes, since their frequency are above the cut-off frequency of the beam pipes. The diameter of the one pipe is made larger than that of the other in order to make a few transverse modes otherwise trapped propagate. The iris between the cell and the large beam pipe prevents the fundamental mode from propagating toward the beam pipe. The Fig.3 (b) is a Cornell CESR B cell which is to use a fluted shape. The cell has a lower cut-off frequency for the transverse modes without affecting the decay rate of the trapped TM_{010} mode. With a superconducting cavity the detuning frequency is substantially reduced by virtue of the lower R/Q from the cell shape, and it is possible to achieve the higher cell voltage by the higher gradient with superconducting cavities.



(a) (b)

Fig.3 KEK B HER and CESR B Superconducting Cavities (unit: mm)

A traveling wave resonant ring with an accelerator (abbreviation is TWRRA) is proposed for high beam current accelerators. It has a special characteristic that the cavities do not need any detuning when the beams are accelerated off the crest for phase stability. TWRRA is a normal conducting accelerator, but it has some advantages of the superconducting one. The accelerating cavities can have very large beam holes for damping all of the cavity HOMs, in order to avoid resonant buildup of the fields that would cause multibunch instabilities at high current. It has high accelerating efficiency, and has high power input capability. TWRRA can be called "single mode" type. It is possible that the CW beam current can be accelerated as high as 10 A or more.

It must be pointed out that the traveling wave accelerator is not good for counter rotating particles in the circular machine. But TWRRA can be used for the electron-positron colliders used two separate rings, like KEKB and PEPII.

2. CHARACTERISTICS OF TWRR FOR HIGH BEAM CURRENT

TWRRA is developed for JNC high power CW electron linac[3,8,9,10]. Fig.4 shows a schame of TWRRA. We had developed L-band RF window which maximum CW power tested was 1.7 MW and used on L-band CW 1.2 MW klystron [11] for JNC high power CW electron linac.

TWRRA includes a short traveling wave accelerator and a traveling wave resonant ring. It possesses two resonant systems: the accelerator has a resonant characteristic of the traveling wave accelerator, and the ring has another traveling wave resonant characteristic. Making them together can bring about some rare characteristics.

For a cavity, its resonance depends on its boundary conditions, and the fields superpose in the opposite directions, therefore it is a standing wave resonator. For a ring, its resonance depends on its phase length of the ring, and the fields superpose in the same direction, so it has the characteristics of a traveling wave resonator.

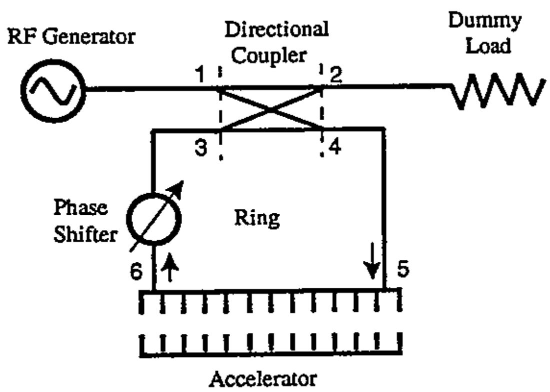


Fig.4 Scheme of TWRRA

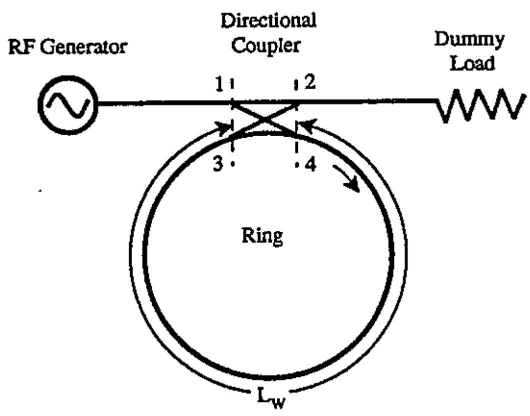


Fig.5 Scheme of TWRR

Now let's look at a simple travelling wave resonant ring (abbreviation is TWRR) shown in Fig.5, and analyze its some characteristics.

We suppose that the signals a_1, a_2, a_3 and a_4 are input waves and b_1, b_2, b_3 and b_4 are output waves, respectively on port 1, port 2, port 3 and port 4. And we introduce following RF quantities,

E_0 is signal from RF generator to the directional coupler port 1, C is coupling coefficient of the directional coupler, α_w is attenuation constant, β_w is phase constant, L_w is length of the ring, θ is phase length between the port 3 and port 4, $\tau_w = \alpha_w L_w$ is attenuation,

$\varphi_w = \beta_w L_w$ is phese length of the waveguide in the ring.
The following equations for signals can be listed:

$$\begin{cases} a_1 = E_0 \\ a_2 = 0 \\ a_3 = b_4\, e^{-\tau_w} e^{j\varphi_w} \\ a_4 = 0 \\ b_1 = 0 \\ b_2 = a_1\sqrt{1-C^2}\, e^{j\theta} + a_3\, C\, e^{j(\theta+\pi/2)} \\ b_3 = 0 \\ b_4 = a_1\, C\, e^{j(\theta+\pi/2)} + a_3\sqrt{1-C^2}\, e^{j\theta} \end{cases}$$

Solving the set of equations, the field multiplication factor M and nullification factor N can be got.

$$b_4 = \frac{E_0 C\, e^{j(\theta+\pi/2)}}{1-\sqrt{1-C^2}\, e^{-\tau_w} e^{j(\theta+\varphi_w)}} = M E_0$$

$$M = \frac{C\, e^{j(\theta+\pi/2)}}{1-\sqrt{1-C^2}\, e^{-\tau_w} e^{j(\theta+\varphi_w)}}$$

$$b_2 = E_0\sqrt{1-C^2}\, e^{j\theta} - \frac{E_0 C\, e^{j(2\theta+\pi)}}{1-\sqrt{1-C^2}\, e^{-\tau_w} e^{j(\theta+\varphi_w)}} = N E_0$$

$$N = \sqrt{1-C^2}\, e^{j\theta} - \frac{C\, e^{j(2\theta+\pi)}}{1-\sqrt{1-C^2}\, e^{-\tau_w} e^{j(\theta+\varphi_w)}}$$

When the phase length of the ring $(\varphi_w + \theta) = 2n\pi$, the waves from port 1 and port 3 are added in port 4 and are cancelled in port 2. They superpose one turn by one turn, until achieve a steady state. The field multiplication factor M becomes a maximum and the nullification factor N becomes a minimum and will be zero under optimum coupling.

For TWRRA shown in Fig.4, the electric field in the accelerator under the beam loading is as following:

$$E(z) = E_{a0}\, e^{-\tau_{ac}} e^{j\varphi_{ac}} - IR(1-e^{-\tau_{ac}})\, e^{j(\varphi_{ac}+\varphi_b)}$$

where, τ_{ac} and φ_{ac} are the attenuation and phase length of the accelerator, R is shunt impedance of the accelerator, I is the beam current, and φ_b is the phase difference between the beam bunch center and the crest of the electric field respectively, and z means beam coordinate in the accelerator.

The field multiplication factor under beam loading M_b is as following:

$$M_b = \frac{Ce^{j(\theta+\pi/2)} - \frac{IR}{Eao}\sqrt{1-C^2}\,(1-e^{-\tau_{ac}})e^{-\tau_w}e^{j(\theta+\pi/2+\varphi_r+\varphi_b+\varphi_{adj})}}{1-\sqrt{1-C^2}\,e^{-\tau_{ac}}e^{-\tau_w}e^{j(\varphi_r+\varphi_{adj})}}$$

where, $\tau_r = \tau_{ac} + \tau_w$ and $\varphi_r = \varphi_{ac} + \varphi_w + \theta$ are total attenuation and phase length of the ring, φ_{adj} is adjusting phase of the phase shifter in the ring, and E_{ao} is the accelerating field in the accelerator without beam loading.

M_b is a maximum when $\varphi_r + \varphi_{adj}$ is equal to $2n\pi$. It means that the ring is at resonance. The power at port 4 (in the ring) is as $(M_b)^2$ times higher as the power at port 1. The power at port 2 becomes a minimum, and will be zero under optimum coupling.

So the TWRRA has higher efficiency than the traveling wave accelerator, because there is no power loss on the dummy load.

For the TWRRA, both R/Q values of the fundamental and HOMs modes in the traveling wave accelerator can be reduced by using an accelerator with short length and large beam hole(including large diameters of the disk hole and beam duct). Then let the ring resonate at an accelerating mode frequency to make accelerating field times the multiplication factor M_b, but HOMs will not be resonated. It means that TWRRA has high accelerating field and low HOMs K_{loss}.

From a point of view of the traveling wave accelerator, all modes can be excited in the accelerator structure. Its frequency spectrum is shown in Fig.6 (a). But both of longitudinal and transverse modes which frequency is higher than the cut-off frequency of the beam duct, will propagate in a waveguide mode through the beam ducts and be absorbed by HOM absorbers. There are solely TM_{01} modes for pass-band in the traveling wave accelerator. This situation is shown in Fig.6 (b).

From a point of view of the resonant ring, the resonant ring can resonate at a lot of frequencies corresponding to the total phase length to be equal to $2n\pi$, (n=1,2,3...). It is shown in Fig.6(c). One can make the ring resonate at the accelerating mode (TM_{01} $2\pi/3$ mode) frequency. It means that the phase length of the total ring is adjusted to $2n_0\pi$ at this frequency, and let the ring next resonant frequency at which the phase length of the ring correspond to $2(n_0+1)\pi$ located out of the TM_{01} pass-bend. So for the TWRRA case only fundamental frequency with TM_{01} $2\pi/3$ mode is excited in the accelerator. It is shown in Fig.6 (d). It is so called "single mode".

As mentioned above, the standing wave cavities need detuning to operate off resonance when the beam are accelerated off the crest for phase stability. The function is shown in Fig.7. The reference phase (positive real axis) is taken in the direction of $-i_b$, V_{br} is the voltage excited by beam in the cavity. V_{gr} is the voltage excited by RF power in the cavity with no beam current. V_{cr} is the voltage of the cavity with the beam current which is vectorial sum of V_{gr} and V_{br}. θ_g and θ_c is the argument of vector V_{gr} and V_{cr}, respectively, and θ_g is generally equal to synchronous phase φ_s, under external control by means of a phase shifter. The larger beam current, the larger different between the θ_g and θ_c. Let ψ is equal to θ_c- θ_g. one can get $V_g=V_{gr}\cos(-\psi)\,e^{-j\psi}$, $V_b=V_{br}\cos(-\psi)\,e^{-j\psi}$, and $V_c=V_{cr}\cos(-\psi)e^{-j\psi}$, after the cavity detuning by angle $-\psi$, . One can make the cavity voltage look "real", that is , just as is the case at resonance with no beam current, the net cavity voltage V_c must have the same synchronous phase φ_s.

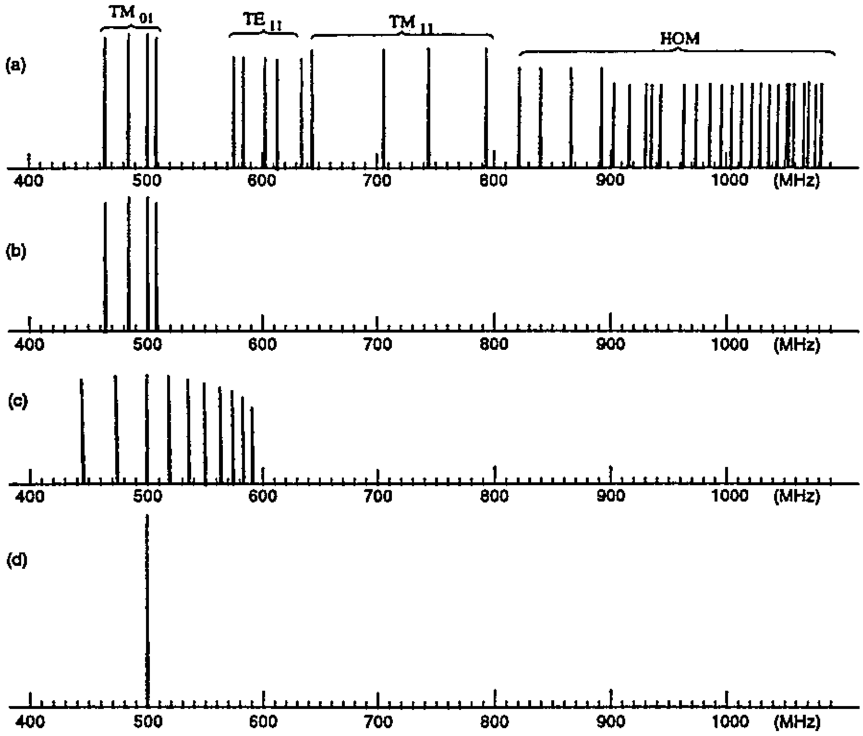


Fig.6 Single Mode of the TWRR

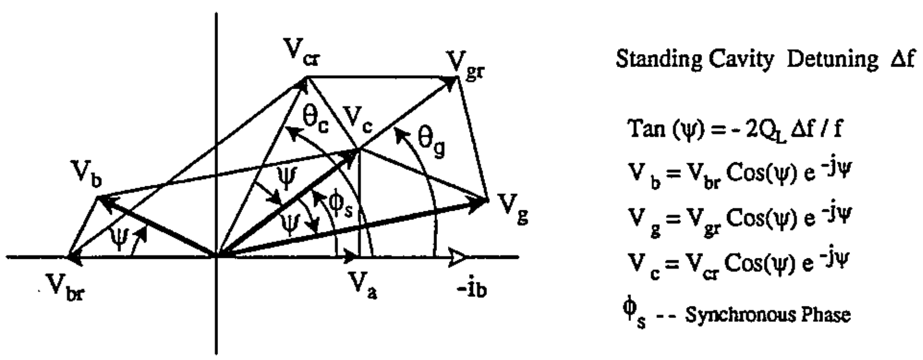


Fig.7 The Cavity Detuning to Compensate the Beam Induced Field

So the beam accelerating voltage V_a is simply the real component of the net cavity voltage, $V_a = V_c \cos(\varphi_s)$.

The cavity detuning angle ψ depends on the cavity detuning frequency Δf, by $\psi = \arctan(-2Q_L \Delta f/f)$. And one can get the detuning frequency Δf as following:

$$\frac{\Delta f}{f} = \frac{I}{2V_c}\frac{R}{Q}\sin(\varphi_s)$$

As mentioned above, there are two resonant systems for the TWRRA. Changing only one of them can meet the needs for the beams accelerated off the crest. One way is detuning the accelerating cavities, the another is adjusting the phase of the resonant ring. The latter can compensate for the imaginary part of the beam loading current, but does not change characteristics of the accelerating cavity.

Without beam loading case, there is solely RF field E_s in the accelerator. The ring is at resonance, when the phase length φ_r for total ring is adjusted in order to get the condition $\varphi_r=\varphi_{ac}+\varphi_w+\theta=2n\pi$,. The relationships of the phase are shown in Fig.8 (a), (b) and (c).

Under beam loading, the electrical field in the accelerator is as following:

$$E(z) = E_{ao}e^{-\alpha_{ac}z}e^{j\varphi_{ac}} - IR(1-e^{-\alpha_{ac}z})e^{j(\varphi_{ac}+\varphi_b)}$$

The right side of the equation has two terms, the first term is RF field E_g, the second is the beam induced field E_b. In the port 6 of Fig.4 (output of the accelerator), the total field E_{6T} is their vectorial sum, that is $E_{6T} = E_{6g}+E_{6b}$. In the port 5 of Fig.4 (input of the accelerator)which position is on z=0, there is only RF field, that is, $E_{5T}= E_{5g}$.

In the ring, φ_b and φ_s could be arbitrary, that is, $\varphi_b=\varphi_s\neq 0$. Therefore, the phase of the total field at the output of the accelerator will be change φ_a. Thereafter, total field is squeezed into off-resonance, that is, $\varphi_r=\varphi_{ac}+\varphi_a+\varphi_w+\theta\neq 2n\pi$. The phase of the field at input of the accelerator is changed too. So the beam bunches can not keep the same synchronous phase φ_s. It is still possible for beam loading case to keep resistive acceleration in TWRRA by means of the phase shifter which can have φ_a cancelled out. After adjusting the phase of the phase shifter in the ring, the phase length of the ring φ_r is equal to $2n\pi$, that is, $\varphi_r = \varphi_{ac}+\varphi_a+\varphi_w+\theta+\varphi_{adj}= 2n\pi$. On tuning condition $\varphi_{adj}=-\varphi_a$, the ring can still keep at resonance, as if with no beam loading. The beam bunches can keep the same synchronous phase φ_s. The relationships of the phase are shown in Fig.8(d), (e) and (f).

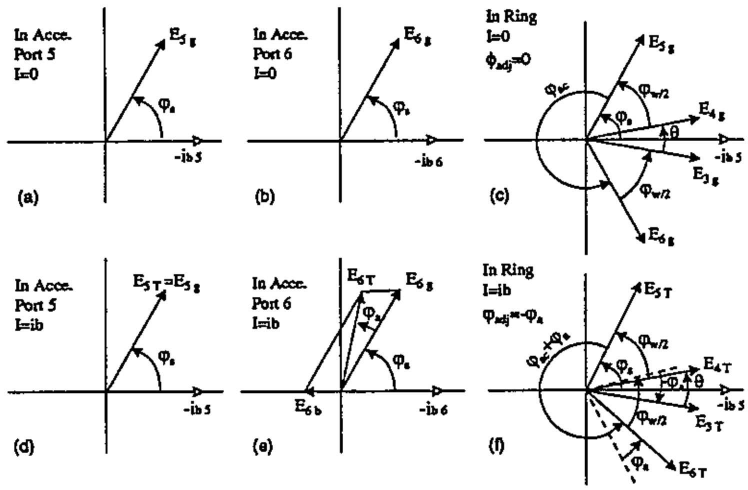


Fig.8 Adjusting the Phase to Compensate the Beam Induced Field in TWRRA

3. DESIGN EXAMPLE

One can chose large disk hole (240mm) and beam duct hole (240mm) and use the fluted beam ducts for damping all of the cavity HOMs in order to avoid resonant buildup of the fields that would cause multibunch instabilities at high currents. One accelerating unit consists of three cells(including an input coupler and output coupler) operating at $2\pi/3$ mode. A main waveguide connects with a resonant ring by a directional coupler. There is a phase shifter to make the ring resonance and a stub tuner to make the ring matching in the resonant ring. Fig. 9 shows a scheme of the TWRRA for the high beam current.

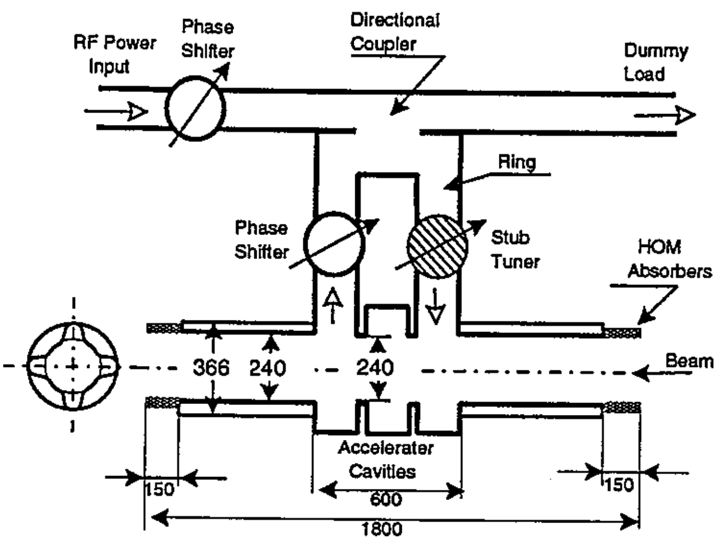


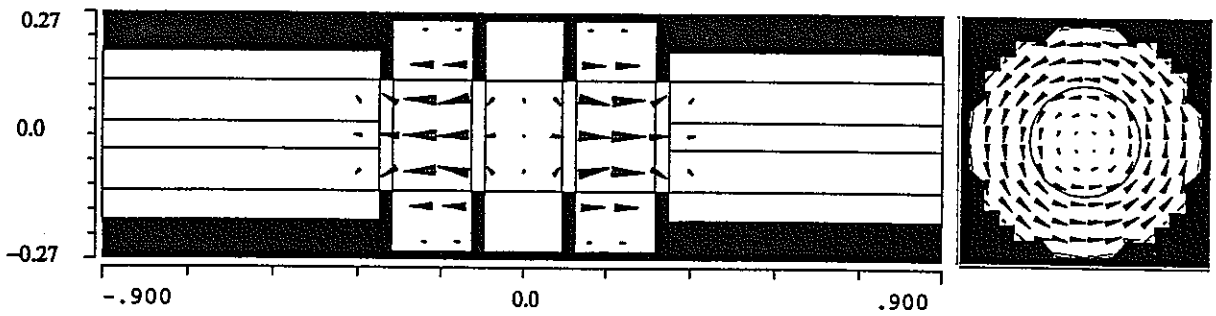
Fig.9 Scheme of TWRRA for the High Beam Current

Table 1 lists the frequency, Q value, shunt impedance and K_{loss} of the lowest TM_{01}, TE_{11} and TM_{11} modes which are calculated by MAFIA for three cells traveling wave accelerator. The subscript $\parallel$ and $\perp$ is the longitudinal and transverse component, respectively.

Fig.10 shows the field patterns of TM_{01} $2\pi/3$ mode that is accelerating mode, TE_{11} mode, and TM_{11} like mode.

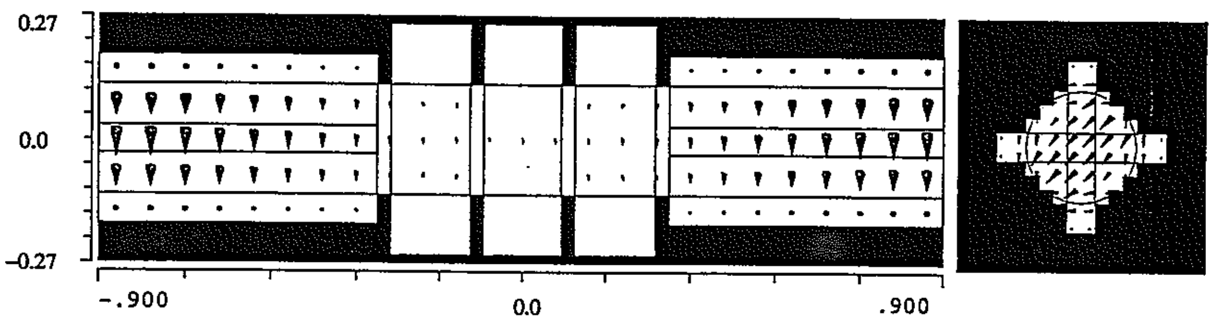
Table 1 Results of MAFIA Calculation

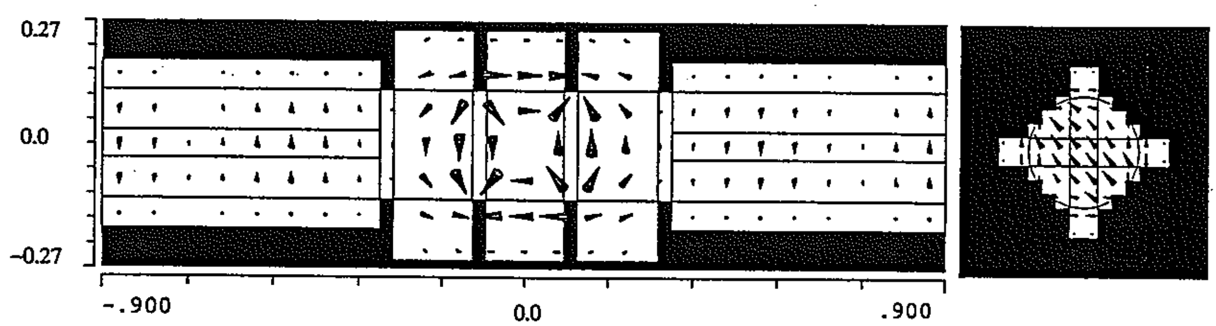
No	Mode	f MHz	Q	$R_{\parallel}$ MΩ/unit	$R_{\perp}$ MΩ/unit	$R_{\parallel}/Q$ Ω	$R_{\perp}/Q$ Ω	$K_{loss\,\parallel}$ V/pc	$K_{loss\,\perp}$ V/pc
1.	TM01 π/3	488.00	40252	.3786E+00	.1742E-02	.9405E+01	.4327E-01	.7210E-02	.3317E-04
2.	2π/3	500.46	39826	.1218E+02	.4796E+00	.3059E+03	.1204E+02	.2405E+00	.9467E-02
3.	π	514.36	39321	.1264E+02	.4405E-02	.3214E+03	.1120E+00	.2597E+00	.9050E-04
4.	TE11	535.50	19572	.2747E-08	.9506E+00	.1404E-06	.4857E+02	.1181E-09	.4086E-01
5.		535.50	19572	.1454E-09	.9518E+00	.7426E-08	.4863E+02	.6247E-11	.4091E-01
6.		535.55	19555	.9843E-09	.1895E+01	.5033E-07	.9692E+02	.4234E-10	.8154E-01
7.		535.55	19554	.8234E-09	.1894E+01	.4211E-07	.9685E+02	.3542E-10	.8147E-01
8.		599.60	47124	.3198E-09	.3182E+01	.6786E-08	.6753E+02	.6391E-11	.6361E-01
9.		599.60	47124	.3008E-10	.3182E+01	.6384E-09	.6753E+02	.6012E-12	.6361E-01
10.		613.68	30201	.2520E-11	.6475E+01	.8346E-10	.2144E+03	.8045E-13	.2067E+00
11.		613.68	30201	.8980E-11	.6475E+01	.2973E-09	.2144E+03	.2866E-12	.2067E+00
12.		621.85	31410	.2886E-10	.5756E+00	.9187E-09	.1833E+02	.8974E-12	.1790E-01
13.		621.84	31410	.2929E-10	.5757E+00	.9325E-09	.1833E+02	.9108E-12	.1790E-01
14.	TM11	640.56	43484	.4491E-09	.1062E+01	.1033E-07	.2442E+02	.1039E-10	.2457E-01
15.		640.56	43484	.2065E-09	.1062E+01	.4748E-08	.2442E+02	.4778E-11	.2457E-01
16.		644.62	17774	.1336E-09	.2560E-07	.7515E-08	.1440E-05	.7610E-11	.1458E-08
17.		644.62	17774	.9191E-10	.1751E-07	.5171E-08	.9854E-06	.5236E-11	.9978E-09
18.		689.80	42598	.1068E-09	.8563E+01	.2508E-08	.2010E+03	.2717E-11	.2178E+00
19.		689.80	42598	.3120E-10	.8555E+01	.7325E-09	.2008E+03	.7937E-12	.2176E+00
20.		689.83	42623	.5145E-11	.9115E+00	.1207E-09	.2138E+02	.1308E-12	.2317E-01
21.		689.84	42623	.2113E-10	.8940E+00	.4957E-09	.2097E+02	.5371E-12	.2273E-01
22.		729.48	22559	.6286E-11	.1013E-09	.2786E-09	.4489E-08	.3193E-12	.5144E-11
23.		729.49	22560	.1064E-10	.8297E-10	.4717E-09	.3678E-08	.5405E-12	.4214E-11
24.		754.56	57407	.2330E-10	.1681E+01	.4059E-09	.2927E+02	.4811E-12	.3470E-01
25.		754.57	57407	.2454E-10	.1681E+01	.4274E-09	.2928E+02	.5066E-12	.3470E-01
26.		779.29	47058	.5891E-10	.2235E+01	.1252E-08	.4749E+02	.1532E-11	.5813E-01
27.		779.30	47059	.1998E-11	.2233E+01	.4245E-10	.4746E+02	.5197E-13	.5810E-01
28.		795.61	49584	.2305E-11	.5788E+02	.4648E-10	.1167E+04	.5809E-13	.1459E+01
29.		795.62	49585	.2146E-10	.5788E+02	.4328E-09	.1167E+04	.5409E-12	.1459E+01
30.		837.12	71766	.4773E-10	.3255E+01	.6651E-09	.4535E+02	.8746E-12	.5964E-01
31.		837.12	71767	.2289E-10	.3254E+01	.3189E-09	.4535E+02	.4194E-12	.5963E-01
32.		856.63	30578	.3507E-11	.7147E-09	.1147E-09	.2337E-07	.1543E-12	.3145E-10
33.		856.64	30576	.4317E-11	.5734E-09	.1412E-09	.1875E-07	.1900E-12	.2524E-10
34.		897.63	59370	.4495E-11	.1061E-08	.7571E-10	.1787E-07	.1067E-12	.2519E-10
35.		900.38	56615	.7962E-11	.5863E-09	.1406E-09	.1036E-07	.1989E-12	.1465E-10
36.		901.24	22596	.3814E-11	.4975E-09	.1688E-09	.2202E-07	.2389E-12	.3117E-10
37.		901.25	22595	.1641E-10	.1879E-08	.7262E-09	.8318E-07	.1028E-11	.1177E-09
38.		916.33	58655	.3439E-07	.1572E+02	.5863E-06	.2681E+03	.8438E-09	.3859E+00



a), TM_{01} and $2\pi/3$ mode

b), TE_{11} mode





c), TM_{11} like mode

Fig.10 Field Patterns of Modes in the Accelerator

Table 2 shows the parameters of TWRRA for linear accelerators. In the linac, the beams are almost accelerated at the crest of the field except the buncher section. TWRRA can get the efficiency for energy conversion from RF to beam higher than 90% for the high beam current.

Table 3 shows the parameters of TWRRA for storage rings and the comparison with KEKB and PEPII normal conductive cavities.

Table 2 Parameters for the Linear Accelerators

	JNC	TWRRA	TWRRA	TWRRA
Frequency(MHz)	1250	500	500	500
Beam Current (A)	0.1	1.0	5.0	10.0
Energy Gain / unit (MeV)	1.63	0.777	0.197	0.099
Number of Cells / unit	15	3	3	3
Pinput/unit(kw)	240	1000	1000	1000
Pring (kw)	927	32530	2590	1144
Pbeam (kw)	162	777.2	985.4	995
Pac-loss (kw)	63	67.5	5.4	2.4
Pwg-loss (kw)	13	155.2	9.3	2.2
Pload (kw)	2	0.01	0.01	0.06
Coupling Coefficient	0.493	0.176	0.62	0.93
Multiplication Factor M_b	1.97	5.70	1.61	1.07
Efficiency(Pbeam/Pinput) %	67.5	77.7	98.5	99.5

Table 3 Comparison of Parameters in the Circular Accelerators

	KEKB	TWRRA	PEPII	TWRRA	TWRRA
Frequency(MHz)	508	500	476	500	500
Beam Current Io (A)	2.6	2.6	2.1	2.1	10
Pinput/unit(kw)	217	217	393	393	1000
Vcavity/unit(MV)	0.6	0.76	0.59	0.94	1.16
Vbeam/unit(kV)	26	17.5	110	111	82.6
φ_s (deg.)	87.5	87.5	79.2	79.2	79.2
Pbeam (kw)	67	45.5	231	236	825.9
Pac-loss (kw)	57	51.4	50	47.1	52.9
Psto-loss (kw)	93	120.1		109.4	121.0
Pload at I=Io(kw)		0.01		0.05	0.03
Pload at I=0(kw)		3.2		69.5	499
Coupling Coefficient		0.094	3.6	0.13	0.20
Multiplication Factor M_b		10.68		7.60	5.05
Detuning Δf(kHz)			211		
Phase Adjust φ_a (deg.)		2.06		1.72	7.82
Efficiency(Pbeam/Pinput) %	30.8	21.0	58.7	60.1	82.6

From the Table 3, one can see that the cavity voltage of TWRRA are higher than the KEKB and PEPII under the same beam current, input power and synchronous phase. When the beam current is zero, the most input RF power will not be reflected, but go to the dummy load.

The results show that the smaller synchronous phase, the higher efficiency. When the synchronous phase near the 90°, the efficiency becomes very low. There is another characteristic, the higher beam current, the higher efficiency for both linear and circular accelerator. So TWRRA is very nice for the high beam current accelerators.

REFERENCES

[1] T.Tomimasu, et al. J.At Energy Soc.Jpn.,33(11), pp.1030, 1991

[2] Y.L.Wang et.al., "Design of High Power Electron Linac at PNC". Journal of Nuclear Science and Technology, 30 (12), pp.1261 December 1993

[3] Y.L.Wang et.al., "Status of PNC High Power CW Electron Linac" . Proc. 1998 Asian Particle Accelerator Conference, 1998

[4] J.Kirchgessner, Proc. 1995 Particle Accelerator Conf., ,pp.1469, 1995

[5] J.Kirchgessner, Particle Accelerators, 46, .pp.151, 1994

[6] H.Padamsee et.al., Particle Accelerators,40, ,pp.17, 1992

[7] J.Kirchgessner et.al., Proc. of the 1992 Linear accelerator Conf., ACEL Rpt, 10728, pp.453, 1992

[8] Y.L.Wang," Research on Electron Linear Accelerator with Traveling Wave Resonant Ring(1)." IEEE Trans.Nucl. Sci. NS-28(3), pp. 3526 (1981)

[9] Y.L.Wang, " Research on Electron Linear Accelerator with Traveling Wave Resonant Ring(2)."IEEE Trans.Nucl. Sci. NS-30(4), pp. 3024, 1983

[10] Y.L.Wang, "Study of Traveling Wave Resonant Ring Characteristics", PNC TN 941093-203, 1993

[11] K.Hirano. Y.L.Wang et.al., Proc. of 1995 Particle Accelerator Conf. pp.1539, 1995