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DESIGN OF A NOVEL CHOPPER SYSTEM FOR PNC CW HIGH POWER LINAC

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大強度CW電子線形加速器用チョッパーシステムの設計

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要旨

動燃では大強度CW電子線形加速器用に新しいチョッパーシステムの開発を行っている。この新しいチョッパーシステムではエミッタンスの増加を低く押さえることができる。このチョッパーシステムでは１つのRFキャビティー中に３種類の磁場モードを立たせる事により、チョッパースリットを通過する電子はチョッパーキャビティー中の磁場の影響を受けないようにしている。３種類の磁場モードとは、基本周波数f_0のTM210モード、基本周波数の倍の周波数$2f_0$のTM410モードとDCタイプのバイアス磁場である。

本報告書ではこの新しいチョッパーシステムの原理及び現実化の方法について述べる。更にビームエミッタンスに影響を与える幾つかの要因についても述べる。

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DESIGN OF A NOVEL CHOPPER SYSTEM FOR PNC CW HIGH POWER LINAC

Wang Yuan lin*

Abstract

A novel chopper system is developed for PNC high power CW (Continuous Wave) linac. It has very low emittance growing up. There is only one RF cavity in the chopper system. In the cavity there are three magnetic fields added by TM_{210} mode at f_0 frequency, TM_{410} mode at $2f_0$ frequency and DC magnetic bias. When the beam passes through the cavity there is no field for the part of beam which will pass through the chopper slit and a deflecting magnetic field for the remainder part of the beam which will stop at the chopper slit.

The new idea and how to realize this idea are mentioned. Some factors having influence on the emittance are discussed

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1. Introduction

In the low energy electron linac, even though using prebuncher and buncher most particles can be bunched into narrow phase, there are some particles like a tail that will bring about some troubles to increase beam loading, increase energy spread and decrease BBU (Beam Break-Up) start current. The chopper system can cut the tail to improve the beam characteristics. But it will add transverse momentum to make emittance grow up.

The important thing is how to make the chopping system very little emittance growth. For basic chopping system it consists of a RF (Radio Frequency) chopping cavity and a slit showed on Fig 1. The rectangular cavity with TM_{210} mode is usually used for the chopping cavity. The beam bunch-length depends on the RF power into the cavity and width of the slit. On the fig.1 it shows that 90° beam bunch-length passes though the chopper. This system has two disadvantages: one is very large transverse momentums added to the beam; other is one RF period having two beam bunches.

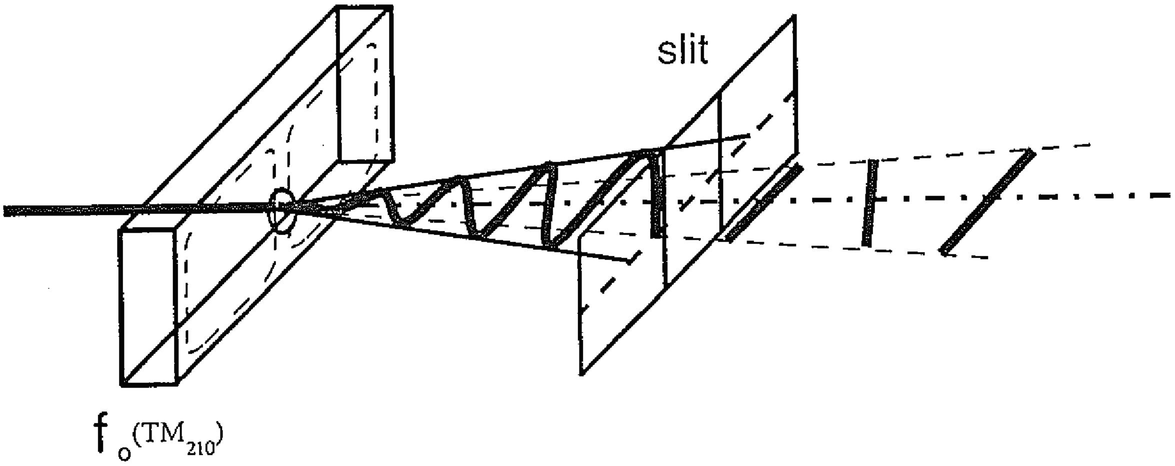


Fig.1, Basic chopping system

If a DC magnetic bias [1,2] is added on the cavity range , there is only one beam bunch in one RF period, and beam transverse momentums added become small. It shows on Fig.2. But it is not enough for low emittance accelerator yet.

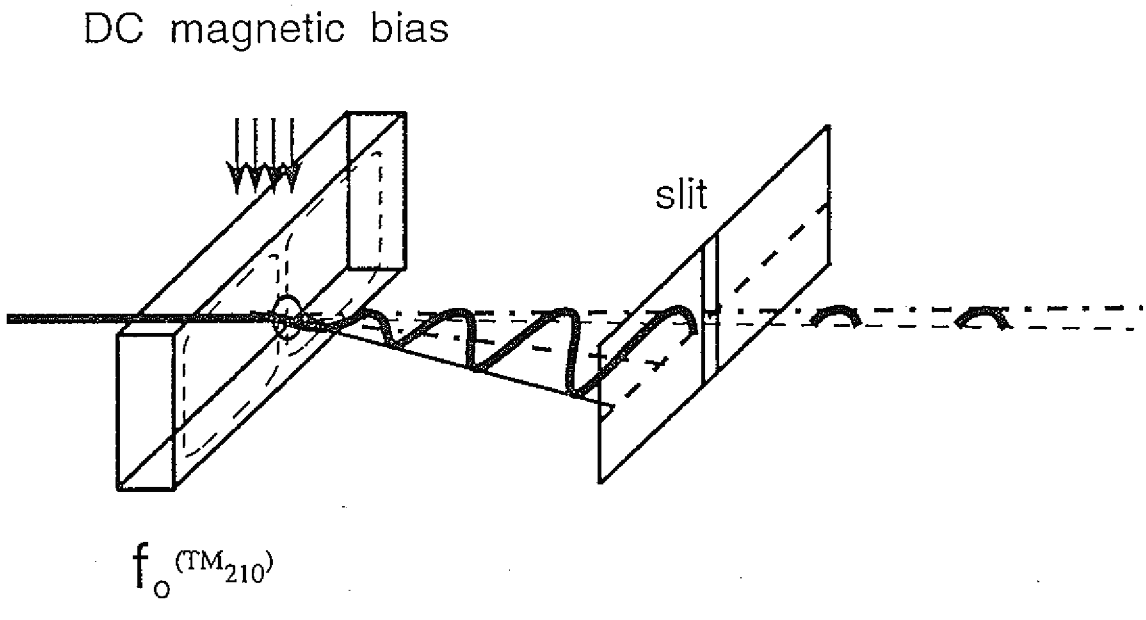


Fig.2, Chopper with DC magnetic bias system

Some laboratories [3,4]use two RF cavities with a slit and a solenoid system shown on Fig.3. The bunch-length can be tuned both by variation RF-amplitude and the slit-width. The focal length of the solenoid is half the distance between the cavities. When the part of beam, which will pass through the slit, passes through the first cavity, the particles with different longitudinal phase will be added different transverse momentum. After traveling a distance, being different phase particles have different transverse position and momentum to get the slit. Passing through slit they will be focused to the axis at the second cavity . If the second cavity has the same amplitude as the first one and opposite phase , their transverse momentum can be cancels perfectly in ideal case.

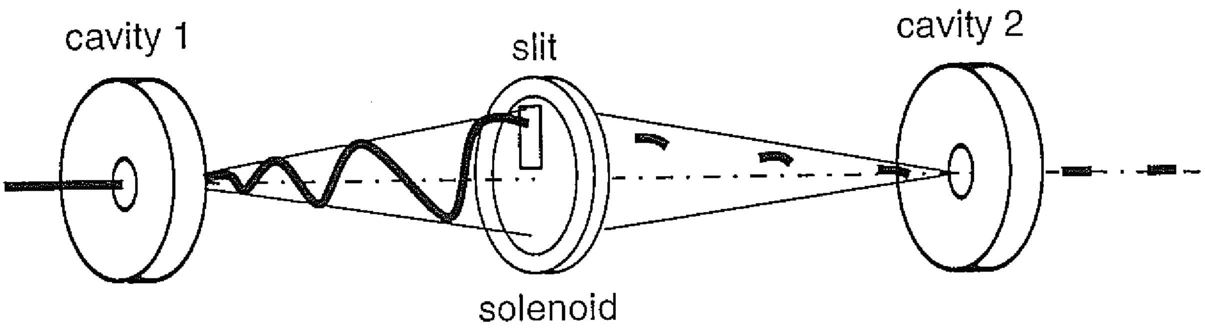


Fig. 3, Double cavity chopper system

If the beam current is not so high, beam diameter is small and bunch-length is not so long (for example MAINZ [4] injector: I=100μA, r=0.5mm and bunch-length Δϕ=40°), the double cavity chopper system can get very low emittance beam. But when the beam current becomes high , or beam diameter is large or beam bunch-length is large, this double cavity chopper system can not cancel the transverse momentum perfectly. Each factor will cause emittance to grow up.

2. New idea

For PNC linac injector , beam current I=100mA, r=2.5mm and bunch-length Δϕ=90°, it is very difficult to cancel its transverse momentum using this kind of two cavities system. A novel idea is that when the beam passes through a chopper cavity, the cavity does not add or adds very little transverse momentum to the part of the beam passing through the chopper slit; the transverse momenta are only added to other part of beam, which will be stopped on the chopper collimator. It is showed on Fig.4. In the chopper cavity there are three field added together. First one is a fundamental (f_0) magnetic field, second one is a second harmonic ($2f_0$) magnetic field and third one is a DC magnetic bias. Tuning each field amplitude and phase, one can get a compositive field that has a flat part that the magnetic field is equal to zero on the beam center line in 90° phase length. Fig.5 shows their magnetic fields and the compositive field.

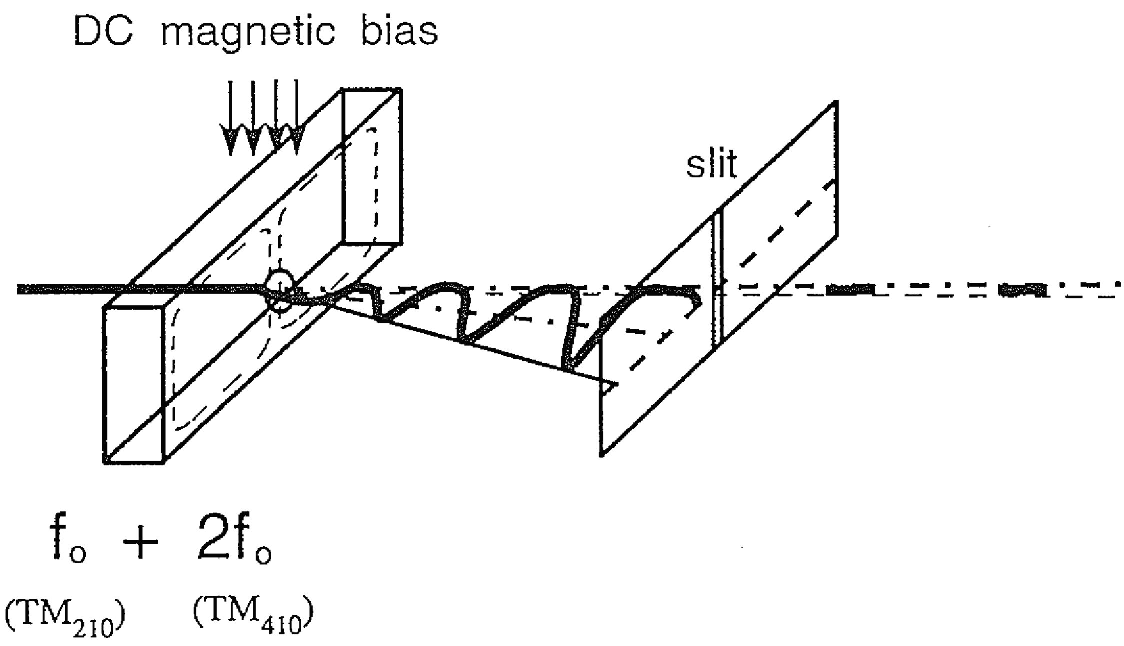


Fig.4 Chopper with DC magnetic bias and harmonic cavity

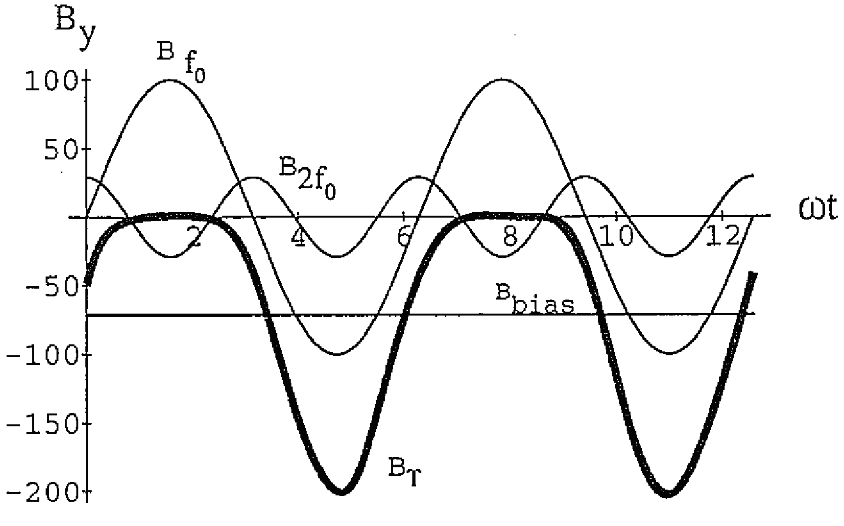
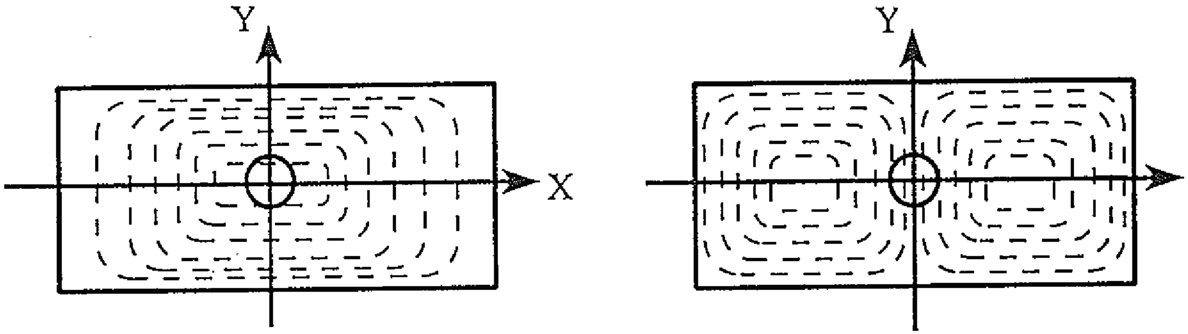


Fig. 5, Magnetic fields in the chopper cavity

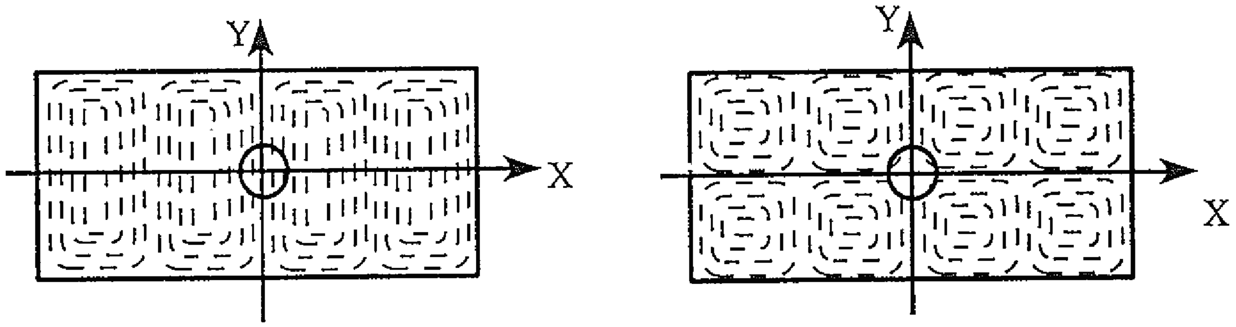
3. Cavity design

The key point of the chopper system is how to generate the magnetic field shown on fig.5 in one cavity. According to the MAFIA calculation, for a general rectangular cavity, if the frequency of the TM_{210} mode is f_0, the frequency of the TM_{410} mode is not equal to $2f_0$. Only the frequency of the TM_{420} mode is equal to $2f_0$ but this mode can not be used for this purpose. Fig.6 shows the magnetic fields of the TM_{110} mode, TM_{210} mode, TM_{410} mode and TM_{420} mode.



TM_{110} mode magnetic

TM_{210} mode magnetic field

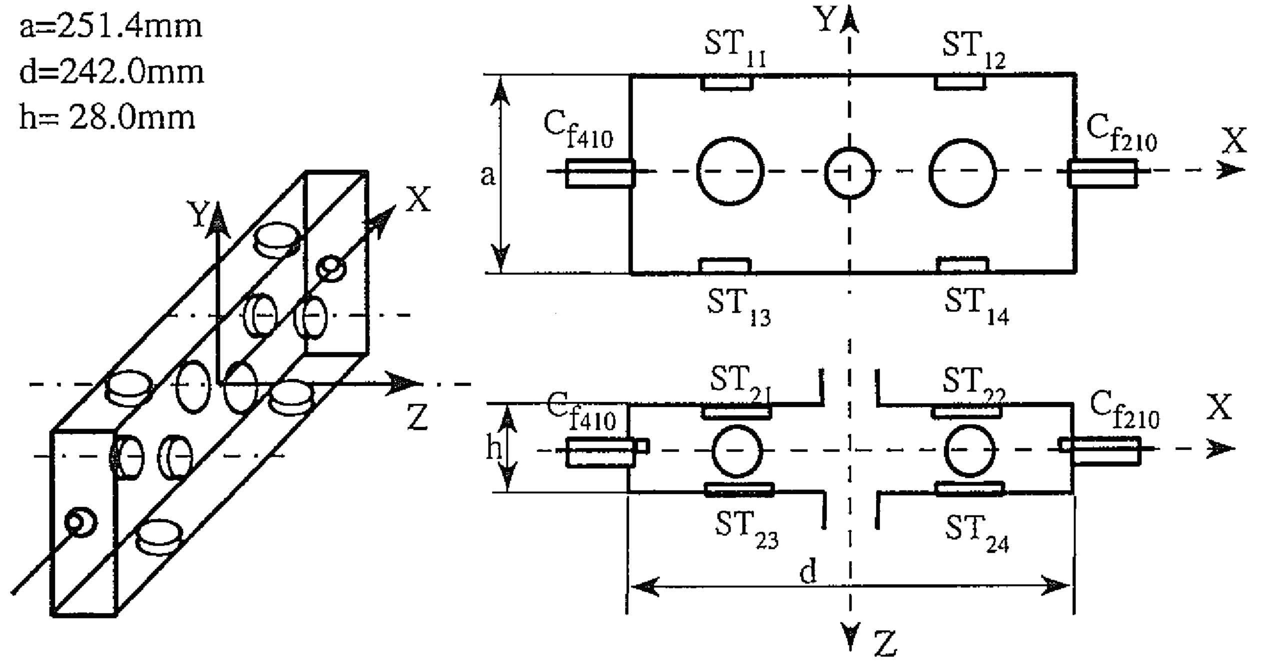


TM_{410} mode magnetic field

TM_{420} mode magnetic

Fig,6 , Magnetic fields of the TM_{110} mode ,TM_{210} mode ,TM_{410} mode and TM_{420} mode in the chopper cavity

One idea is that if a variable stub tuner is located at the maximum electric field of TM_{210} mode and the maximum magnetic field of TM_{410} mode, according to the perturbation theorem the frequencies of the TM_{210} mode and the TM_{410} mode will be tuned in the opposite direction. So it is possible to make the ratio of the frequencies of the TM_{410} mode and the TM_{210} mode exactly two. The actual test cavity is shown on the Fig.7. There are four variable stub tuners (ST_{11}, ST_{12}, ST_{13} and ST_{14}) on the XZ planes to tune the fundamental frequency, other four variable stub tuners (ST_{21}, ST_{22}, ST_{23} and ST_{24}) on the XY planes to tune the frequency ratio of the TM_{410} mode and the TM_{210} mode and two magnetic coupler loops (C_{f210} and C_{f410}) on the YZ planes to excite the TM_{210} mode of f_0 frequency and TM_{410} mode of $2f_0$ frequency fields, respectively.

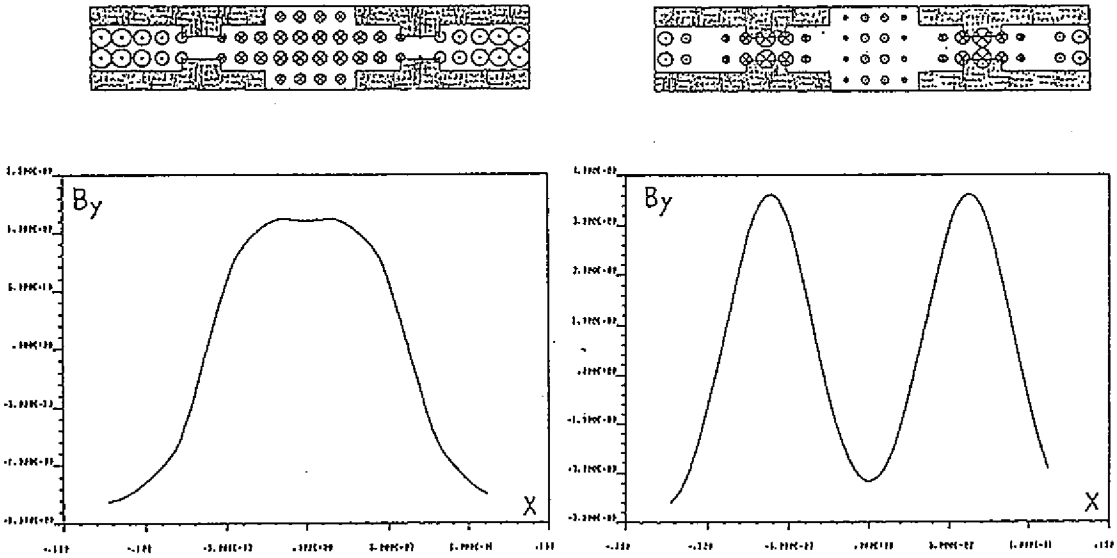


Fig,7, Chopper Cavity

The cavity sizes are following: a = 251.4mm, d = 242.0mm, h = 28.0mm. Table 1 lists the results of calculation by MAFIA. There are frequency , Q value, store energy, power loss and magnetic field of each mode. Fig.8 shows the magnetic fields of the TM_{210} mode and the TM_{410} mode in the chopper cavity. Fig.9 shows the electric fields of the TM_{210} mode and the TM_{410} mode in the chopper cavity.

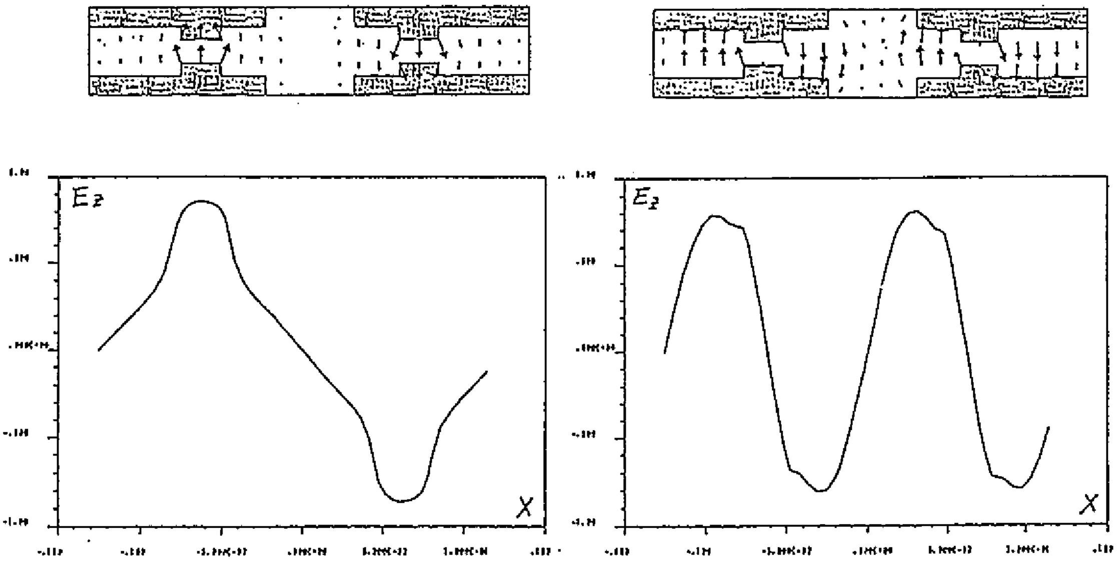
Table 1. Results of calculation by MAFIA

```
          ******************************************************
          *  calculating quality factors for a range of modes    *
          ******************************************************
          * mode range from          1     to        10          *
*****************************************************************************
    mode      f(GHz)        Q      energy(J)           loss(W)          By(Tesla)
*****************************************************************************
 1            0.837531626    9691  3.001450925E-16  1.629805457E-10
 2   TM210    1.249342084   12250  1.833187615E-16  1.174623593E-10     1.1073E-09
 3            1.806570530   14369  1.599401228E-16  1.263443933E-10
 4            1.949722171   14757  3.832113108E-16  3.181160058E-10
 5            2.087855577   15126  2.778835314E-16  2.409919486E-10
 6   TM410    2.497986794   16405  6.970827575E-16  6.669050312E-10    -2.1576E-09
 7            2.521357536   16890  2.925695740E-16  2.744039440E-10
 8            2.975537777   16498  1.821397975E-16  2.064006049E-10
 9            3.036289454   18434  5.561585509E-16  5.755747545E-10
10            3.116830826   19074  5.756154271E-16  5.909896461E-10
*****************************************************************************
```



TM_{210} mode . TM_{410} mode

Fig. 8, The magnetic fields in the chopper cavity



TM$_{210}$ mode TM$_{410}$ mode

Fig. 9, The electric fields in the chopper cavity

4. Some influential factors

4–1. Beam transit angle effect

In general speaking, for sinusoidal signal, the transit angle only affects its amplitude, its sinusoidal signal can be still kept. But for our case the effect of the transit angle is shown on Fig.10. The larger transit angle the smaller flat part.

B$_T$ is total magnetic field in the chopper cavity, B$_I$ is the beam passed through the chopper cavity suffers magnetic field for different input phase. As following:

$$B_T = B_{210} Sin\left(\tfrac{2\pi}{\beta\lambda_o} z\right) + B_{410} Sin\left(\tfrac{4\pi}{\beta\lambda_o} z + \tfrac{\pi}{2}\right)$$

$$B_I = \int_0^L \left[B_{210} Sin\left(\tfrac{2\pi}{\beta\lambda_o} z + \phi_o\right) + B_{410} Sin\left(\tfrac{4\pi}{\beta\lambda_o} z + \tfrac{\pi}{2} + 2\phi_o\right)\right] Sin\left(\tfrac{\pi}{L} z\right) dz.$$

where β is the beam relative velocity, λ_0 wave length ϕ_0 input phase and α is transit angle.

According to MAFIA calculation the magnetic field By(z) in the chopper cavity is shown on Fig.11. The efficient length depends on the cavity length the diameter of the beam hole and the beam velocity. For our case the transit angle is about 108 degree, so the flat part is very narrow.

How to solve this problem, two ways have been found. One way, using very short cavity length and very small diameter of the beam hole, the transit angle is very small, so 90 degree flat part can be kept. But large power will be needed. Another way, it is good and easy way that changing the ratio of the amplitude between TM_{210} and TM_{410} modes can get good results. Fig.12 shows that on a), $B_{410}/B_{210}=0.29$, during 90 degree the spread dBT/BT=1.9%, considering transit angle the spread dBI/BI = 9.6%; on c), $B_{410}/B_{210}=0.38$, dBT/BT =13.1%, dBI/BI =1.9%. So one can use this way to adjust the length of chopping beam.

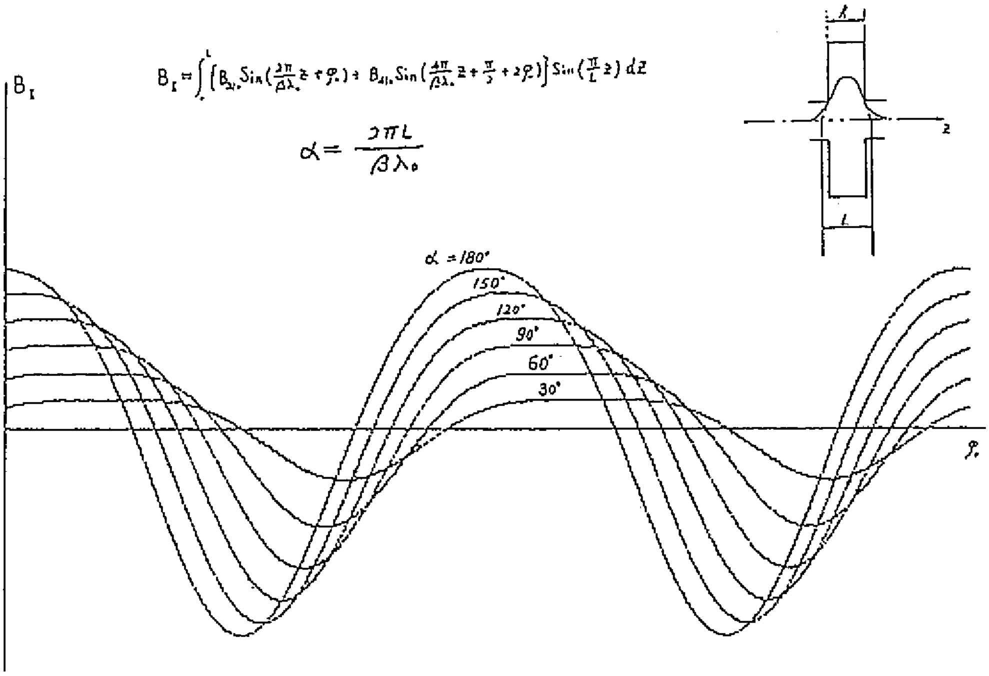


Fig. 10, Beam transit angle effect

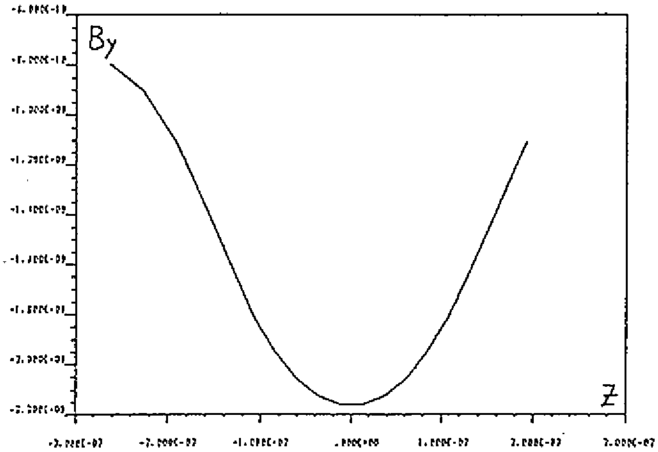
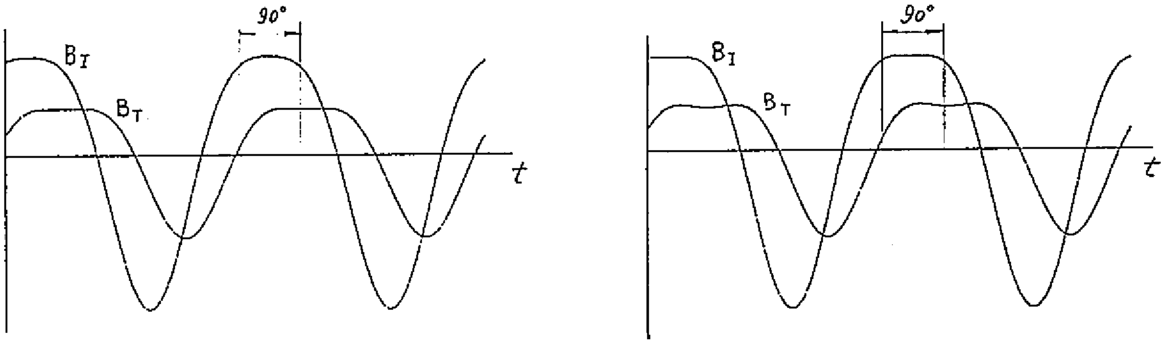
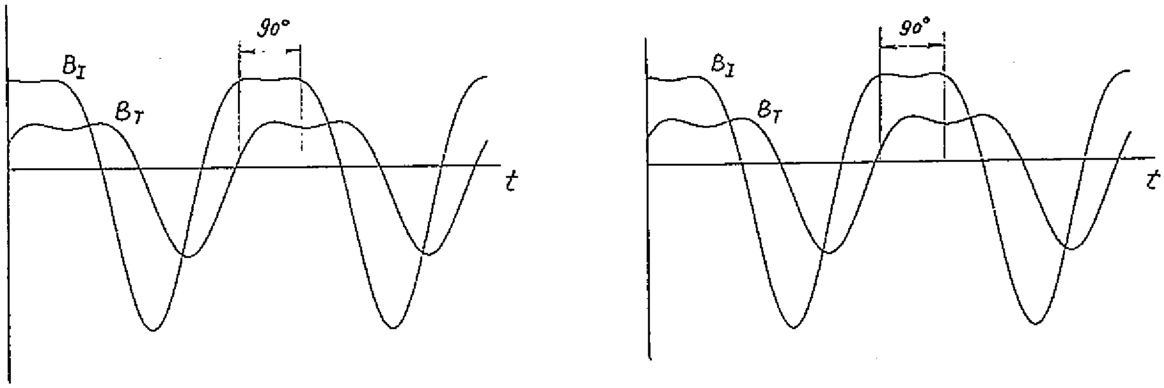


Fig. 11, Distribution of the field in the chopper cavity



a), B410/B210 = 0.29.
$dB_I/B_I = 9.59\%$
$dB_T/B_T = 1.95\%$

b), B410/B210 = 0.33
$dB_I/B_I = 5.58\%$
$dB_T/B_T = 5.62\%$



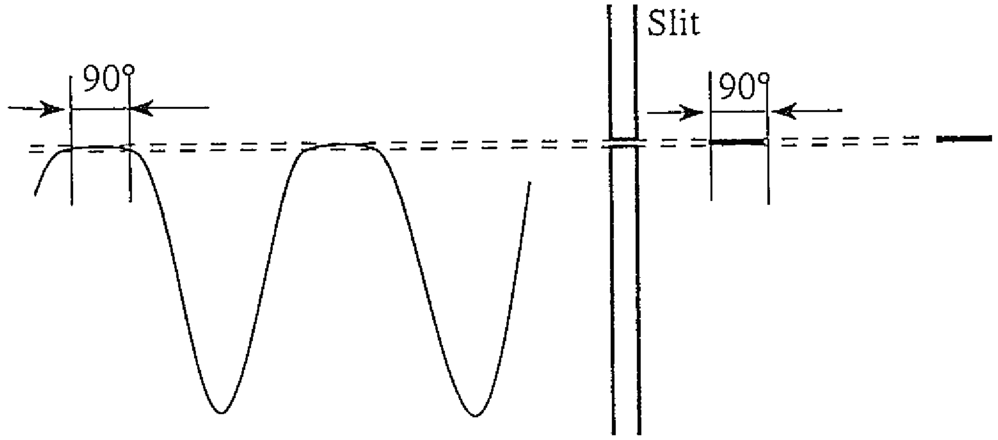
c), B410/B210 = 0.38
$dB_I/B_I = 1.95\%$
$dB_T/B_T = 13.13\%$

d), B410/B210 = 0.41
$dB_I/B_I = 3.96\%$
$dB_T/B_T = 18.06\%$

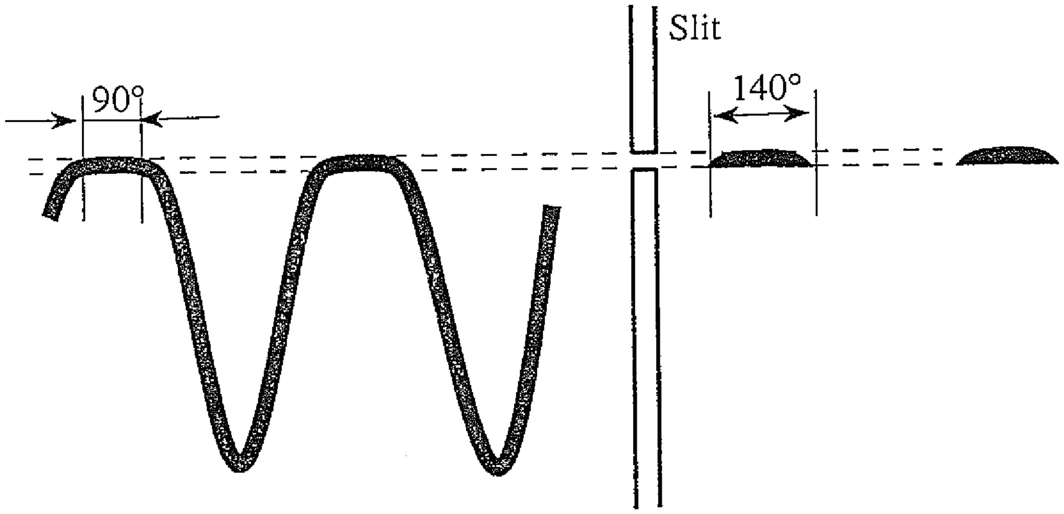
Fig. 12, The radio of B410 / B210 affects the beam transit effects

4–2.Beam size and chopper slit size effect

At above discussion it is assumed that the beam size and slit size are very small. Actually, for example, beam diameter is 5mm, then choosing slit width is the same size of beam diameter. In this case, the edge effect will become important. Fig.13 shows the edge effect. The edge parts will add some transverse momenta. Using two slits for collimator can cut the edge parts.



a) Ideal case



b) Actual case

Fig.13, Beam size effact

5. Chopper system design and simulation

According to the calculated data chopper system can be designed, suppose that the length between the chopper cavity and slit s = 0.5m, the width of slit is equal to the beam diameter, the maximum deflecting distance $\chi = 40$mm, one can get input power for f_0, P_{f_0}= 1234 W and for $2f_0$, P_{2f_0} = 280W. The maximum magnetic field of the TM_{210} mode, B_{TM210} = 25 gauss, one of the TM_{210} mode, B_{TM410} = 9.755 gauss and DC bias magnetic field B_{bias} = 15.25gauss on the beam center line. The maximum electric field near the stub tuners E_{max} = 2.0MV/m. So there is no discharge problem. The chopper system is shown on Fig.4. The chopper slit needs special design because of very high power dissipation.

Using MAFIA TS3 code (the particle-in-cell-code) the results of simulation are shown on Fig.14.

Now the test chopper cavity is under construction.

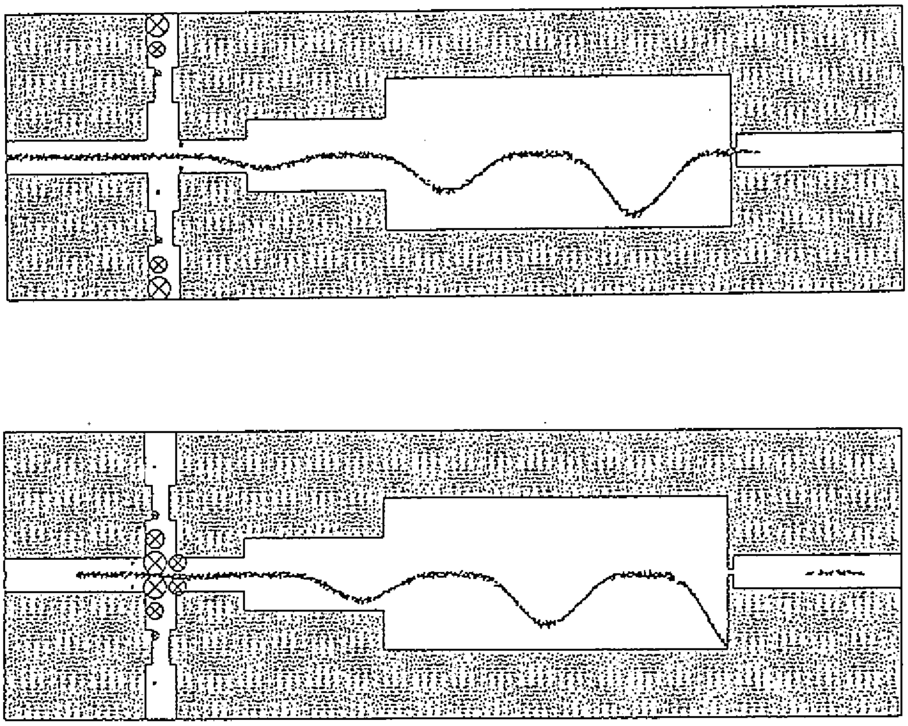


Fig.14 , The chopper system simulation by MAFIA TS3 code

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