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THE NEW CHOPPER CAVITY DESIGN AND TEST SUMMARY

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新型チョッパー空洞の設計とその試験概要

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要旨

RF(高周波)チョッパー装置において、RF周期の一部を切り出すために、エミッタンス増加という犠牲を払っていることは、良く知られている。新しい概念として、チョッパースリットを通過するビームに対して、チョッパー空洞がほんの僅かな垂直方向の運動量しか与えない方式を提案した。この方式は、一つの空洞 に対して特異なモードを基本周波数と二倍高調波について共鳴させる点にある。

本発表において、設計、MAFIAコードによる数値解析および試験概要を述べる。試作チョッパー空洞の試験結果によれば、単空洞に対して二つの周波数を共鳴させることは、難しく無いことが示された。測定された結果は、設計値と良い一致を示している。

この低エミッタンス新型チョッパー空洞は動燃大電力CWリニアックに設置される予定である。

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THE NEW CHOPPER CAVITY DESIGN AND TEST SUMMARY

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Abstract

It is known that a RF chopper system can remove a part of unusable beam in a RF period with penalty of emittance growth. A new idea is proposed that the chopper cavity does not add or adds very small transverse momentum to the part of the beam passing through the chopper slit. The key point of this idea is to make the fundamental and second harmonics resonate at the special mode respectively in one cavity.

The design, the results of simulation by MAFIA code and prototype test are mentioned in this presentation. The test results of prototype chopper cavity show that it is not so difficult to tune two frequencies to resonate in one cavity. The measurement data of the test chopper cavity are good agreement with the calculated results.

This new chopper cavity with very low emittance growth will be installed in PNC high power CW linac.

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1. Introduction

In the low energy electron linac, even though using a 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 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 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, width of the slit and distance between the cavity and slit. This system has two disadvantages: one is very large transverse momentums added to the beam; other is one RF period having two beam bunches.

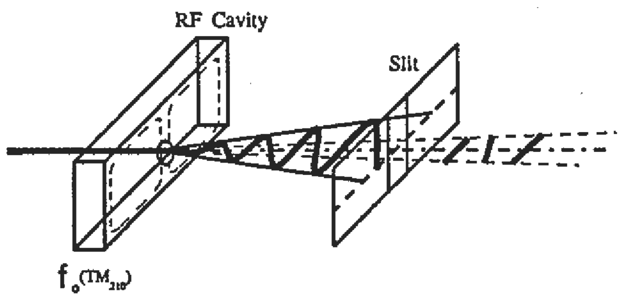


Fig. 1, Basic chopper system

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 to beam become small. It shows on Fig.2. But it is not enough small for low emittance accelerator yet.

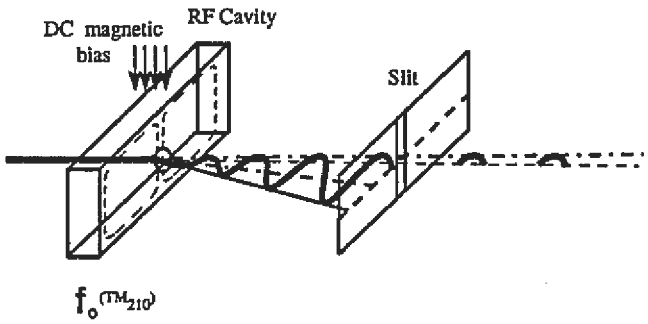


Fig. 2, Chopper with DC magnetic bias system

Some laboratories [3,4] use two RF cavities with a slit and a solenoid system shown on Fig.3. 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. The slit is like a mirror. Passing through the slit the particles 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 cancelled in ideal case.

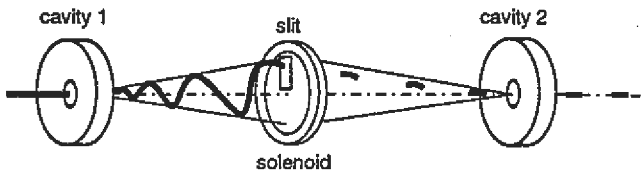


Fig. 3, Double cavity chopper system

This concept is that some transverse momenta are added to the beam for deflecting by the first cavity, then are cancelled by the second cavity after the beam transporting a distance.

2. Novel idea

A novel idea is that when the beam passes through a chopper cavity, the cavity does not add (in ideal case) or adds a very small 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 slit. It means that the fields in the chopper cavity are zero when a part of beam passes through the chopper cavity, so this part of beam will pass through the chopper slit without any additional transverse momentum from the cavity; but there is a deflecting field in the cavity when the remainder part of beam during one RF period passes through the cavity, and the remainder part of beam will stop at the chopper slit. It is showed on Fig.4.

The key point of this new idea is how to generate above-mentioned field in one chopper cavity.

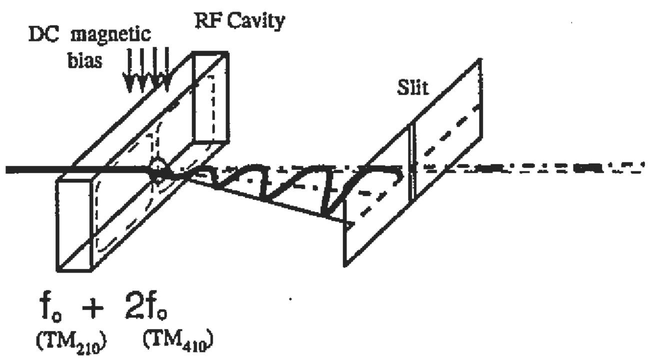


Fig. 4, A novel chopper system

3. Special cavity design

Fig.5 shows a total magnetic field (B_T) added by three magnetic fields that are a RF magnetic field with the fundamental frequency (B_{f_0}), a RF magnetic field with the second harmonic frequency (B_{2f_0}) and a DC magnetic bias field (B_{bias}). The total magnetic field has a flat part which field is equal to zero. Tuning amplitude and phase of each field, the length of flat part can be changed.

In the rectangular cavity if one chooses TM_{210} mode for the chopper fundamental mode. According to the MAFIA calculation, 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.

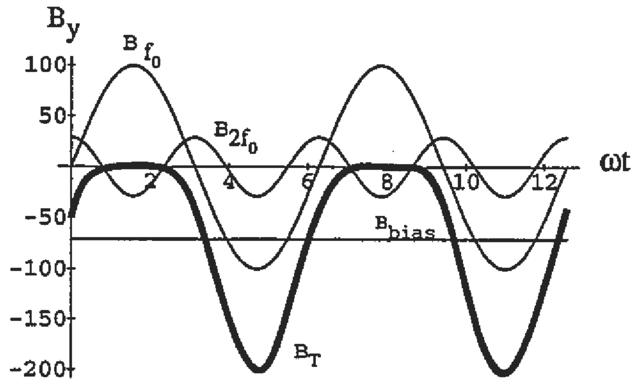


Fig. 5, Magnetic fields in the chopper cavity

Fig.6 shows the magnetic fields of the TM_{110} mode, TM_{210} mode, TM_{410} mode and TM_{420} mode in the cavity. The beam hole is located at the cavity center.

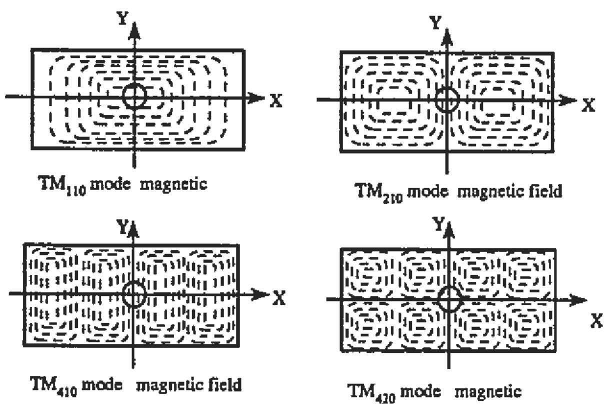


Fig. 6, Magnetic fields of the TM_{110} mode, TM_{210} mode, TM_{410} mode, and TM_{420} mode

According to the perturbation theorem 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, 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.

A test chopper cavity is shown on the Fig.7. Chopper cavity size are: d = 252.4mm, a = 243.3mm, h = 28.0mm, r_{beam} = 10.0mm, rs_{fixed}= 15.0mm, hs_{fixed} = 6.7mm, rs_{fine}= 4.0mm and rs_{side}= 10.0m. There are four fixed stub tuners (S_{fixed1}, S_{fixed2}, S_{fixed3} and S_{fixed4}) on the B-B section to tune the frequencies roughly. Four fine stub tuners (S_{fine1}, S_{fine2}, S_{fine3} and S_{fine4}) on the C-C section to tune the frequencies finely. Four side stub tuners (S_{side1}, S_{side2}, S_{side3} and S_{side4}) on the cavity side to tune the frequencies with different ratio. Two couplers on the A-A section, one is electric coupler for TM_{210} mode and another magnetic coupler for TM_{410} mode.

Using these stub tuners one can make the TM_{210} mode frequency f_0 and the TM_{410} mode frequency $2f_0$. 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	TM110	0.837531626	9689	6.002060112E-16	3.259610915E-10	
2	TM210	1.249342084	12247	3.665386054E-16	2.349247186E-10	1.1073E-09
3		1.806570530	14367	3.198437437E-16	2.526887866E-10	
4		1.949722171	14753	7.662335215E-16	6.362320115E-10	
5		2.087855577	15125	5.557318051E-16	4.819838972E-10	
6	TM410	2.497986794	16392	1.393084383E-15	1.333810062E-09	-2.1576E-09
7		2.521357536	16889	5.850735558E-16	5.488078880E-10	
8		2.975537777	16491	3.641353877E-16	4.128012099E-10	
9		3.036289454	18421	1.111540690E-15	1.151149509E-09	
10		3.116830826	19071	1.151082412E-15	1.181979292E-09	

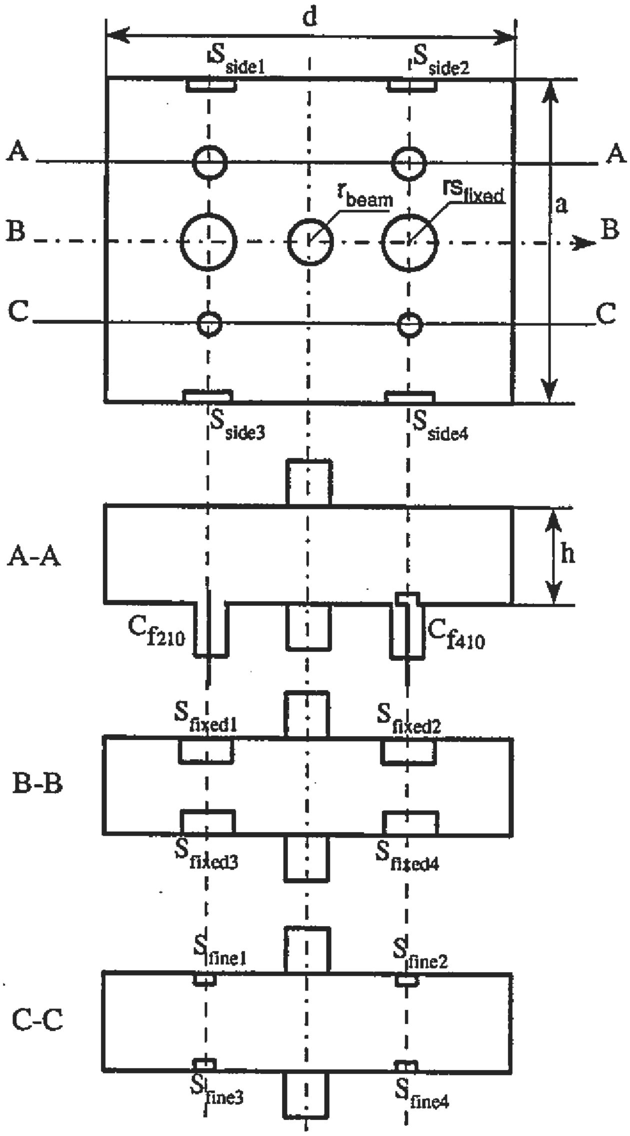


Fig.7 A test chopper cavity

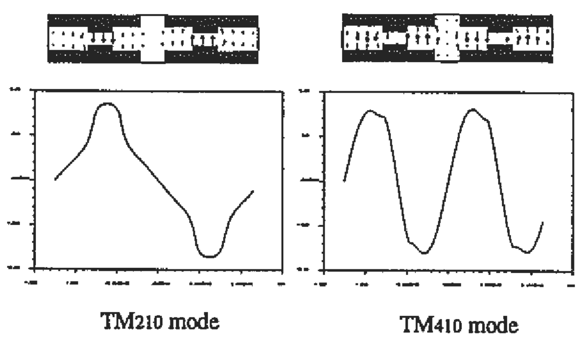


Fig. 8 Electric fields in the chopper cavity

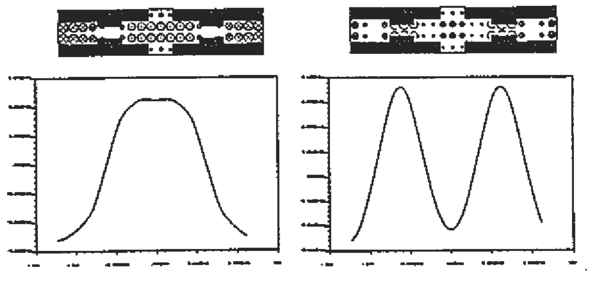


Fig. 9 Magnetic fields in the chopper cavity.

4. Some influential factors

4.1. Beam transit time effect

In general speaking, when the field in the cavity is changing sinusoidally with time the transit time factor is equal to $\mathrm{Sin}(\pi L/\lambda o)/(\pi L\lambda o)$. But for the field $B_T(t)$ shown on the Fig.5, the length of the flat part will depend on the transit angle (transit angle $\alpha=2\pi L/\beta\lambda o$) 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 magnetic field that the beam passing through the chopper cavity suffers with different input phase.

As following:

$B_T = B_{f0}\,\mathrm{Sin}(2\pi z/\beta\lambda o)+B_{2f0}\,\mathrm{Sin}(4\pi z/\beta\lambda o+\pi/2)$

$B_I = \int [\, B_{f0}\,\mathrm{Sin}(2\pi z/\beta\lambda o+\phi o) + B_{2f0}\,\mathrm{Sin}(4\pi z/\beta\lambda o+\pi/2+2\phi o)\,]\mathrm{Sin}(\pi z/L)\, dz$

where β is the beam relative velocity, λo wave length, ϕo input phase, α transit angle, L the length of the cavity and integration from 0 to L.

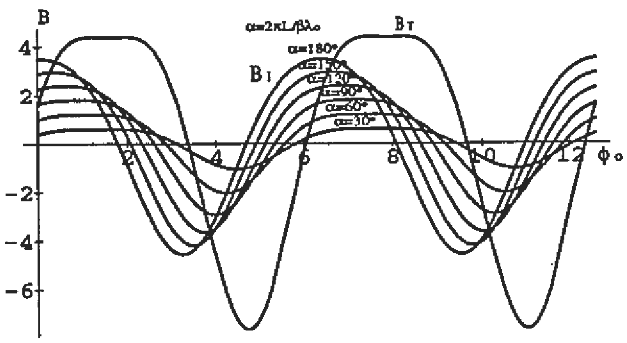


Fig. 10 Beam transit angle effect

It is found that for a fixed transit angle (α=108°) changing the amplitude ratio of the magnetic fields between B_{f0} and B_{2f0} can change the length of the flat part. Fig.11 shows that for the different ratio of B_{2f0}/B_{f0} during the buncher length 120°, their magnetic field spread:

a), B_{2f0}/B_{f0} = 0.28, dB_T/B_T = 3.99%, dB_I/B_I = 8.92%;
b), B_{2f0}/B_{f0} = 0.33, dB_T/B_T = 1.94%, dB_I/B_I = 6.05%;
c), B_{2f0}/B_{f0} = 0.43, dB_T/B_T = 7.53%, dB_I/B_I = 2.17%;
d), B_{2f0}/B_{f0} = 0.48, dB_T/B_T = 11.0%, dB_I/B_I = 3.34%.

It is shown that case "c)" is the optimum.

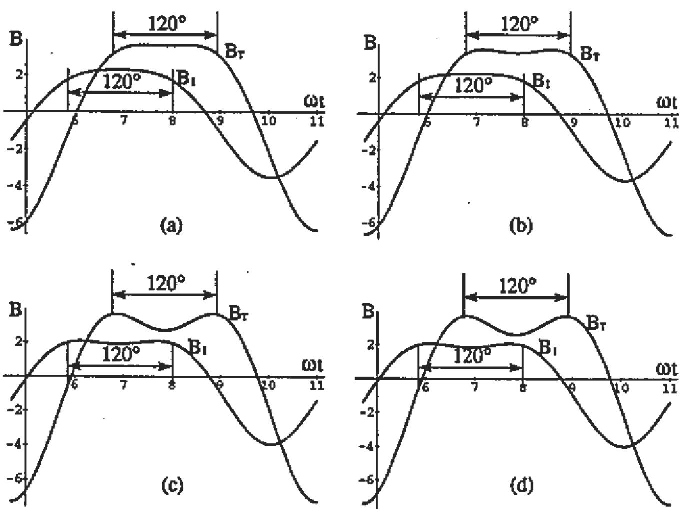


Fig.11 Ratio of B_{2f0} / B_{f0} effects

4.2. Beam size effect (edge effect)

At above discussion it is assumed that the beam size and slit size are very small. If the beam diameter is not so small, for example, 5mm, then choosing slit width is the same size of beam diameter. In this case, the edge effect will become important. Fig.12 shows the edge effect. The edge parts will add some transverse momenta. In principle, using two slits can cut the edge parts.

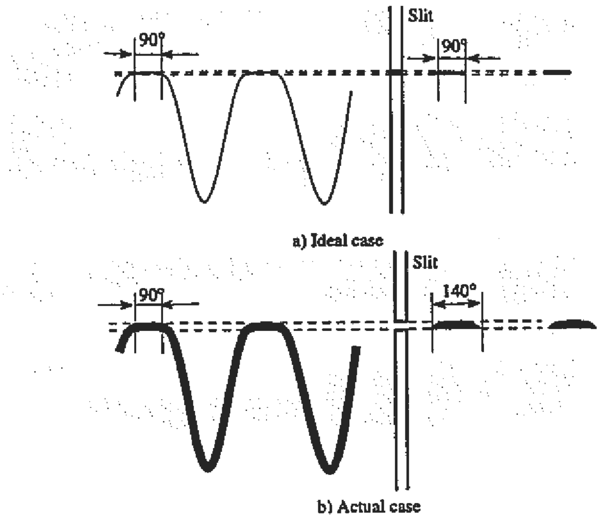
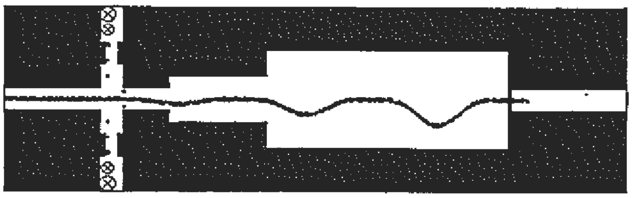


Fig. 12 Beam size effect

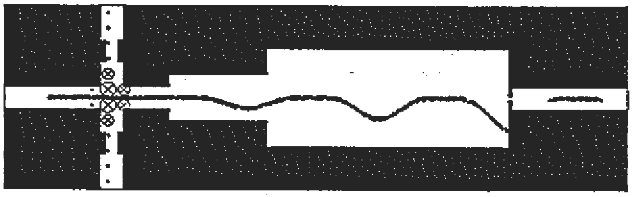
5. Chopper system design and simulation

According to the data calculated by MAFIA chopper system can be designed. Suppose that the length between the chopper cavity and slit S is 0.5m, the width of slit is equal to the beam diameter(5mm), after chopping the bunch length 120°, the maximum deflecting distance dd = 40mm. One can get that the maximum magnetic field of the TM_{210} mode, $B_{TM_{210}} = 25$ gauss, one of the TM_{410} mode, $B_{TM_{410}} = 9.755$ gauss and DC bias magnetic field $B_{bias} = 15.25$ gauss on the beam center line, the input power $P_{f0} = 1250W$ for f_0, and $P_{2f0} = 300W$ for $2f_0$ is necessary. 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.13.



(a)



(b)

Fig. 13 Chopper system simulation by MAFIA.

6. Chopper cavity test

After the test cavity manufacture, one measured resonant frequencies of all modes and using bead perturbation method checked each mode. Then measured the changing ratio of frequency by each parameter changing.

Cavity resonant frequency:

mode	calculation (MAFIA)	measurement	Δf/f (%)
TM_{110}	833.326 MHz		
TM_{210}	1249.068 MHz	1255.000 MHz	0.475
TM_{120}	1382.277 MHz	1377.900 MHz	-0.317
TM_{220}	1735.212 MHz	1728.900 MHz	-0.364
TM_{310}	1810.258 MHz	1933.900 MHz	6.83
TM_{130}	1938.030 MHz	2080.200 MHz	7.33
TM_{230}	2085.437 MHz	2134.900 MHz	2.37
TM_{320}	2173.216 MHz	2171.200 MHz	-0.0927
TM_{410}	2498.416 MHz	2488.800 MHz	-0.385
TM_{330}	2508.504 MHz	2505.200 MHz	-0.132
TM_{140}	2553.587 MHz	2550.000 MHz	-0.140
TM_{420}	2679.020 MHz	2671.200 MHz	-0.292

Frequency changing ratio:

	TM_{210} mode		TM_{410} mode		
	cal.	meas.	cal.	meas	(unit)
$\partial f/\partial d$	- 3.57	-1.611	-9.30	-9.636	(MHz/mm)
$\partial f/\partial hs_{fixed}$	-25.43	-27.50	9.45	9.91	(MHz/mm)
$\partial f/\partial hs_{fine}$	-0.108	-0.118	0.136	0.1026	(MHz/mm)
$\partial f/\partial hs_{side}$	0.111	0.0512	0.016	0.00756	(MHz/mm)
	(rs_{side}=10)	(rs_{side}=7.5)	(rs_{side}=10)	(rs_{side}=7.5)	

One can use the fine stub tuners and side stub tunes to adjust the frequency using following formulae to estimate Δhs_{fine} and Δhs_{side}.

$$\Delta hs_{fine}=(\partial f_{210} / \partial hs_{side} * \Delta f_{410} - \partial f_{410} / \partial hs_{side} * \Delta f_{210}) / (\partial f_{210} / \partial hs_{side} * \partial f_{410} / \partial hs_{fine} - \partial f_{410} / \partial hs_{side} * \partial f_{210} / \partial hs_{fine})$$

$$\Delta hs_{side} = (\Delta f_{210} - \partial f_{210} / \partial hs_{fine} * \Delta hs_{fine}) / (\partial f_{210} / \partial hs_{side})$$

If the range is over its adjusting possibility, the cavity size (d) and fixed stub tuner must be changed. Using following formulae to estimate Δd and Δhs_{fixed}

$$\Delta d=(\partial f_{210} / \partial hs_{fixed} * \Delta f_{410} - \partial f_{410} / \partial hs_{fixed} * \Delta f_{210}) / (\partial f_{210} / \partial hs_{fixed} * \partial f_{410} / \partial d - \partial f_{410} / \partial hs_{fixed} * \partial f_{210} / \partial d)$$

$$\Delta hs_{fixed}=(\Delta f_{210} - \partial f_{210} / \partial d * \Delta d) / (\partial f_{210} / \partial hs_{fixed})$$

For this test chopper cavity, the range was over fine stub tuners, so at first one decided Δd=-0.6mm and Δhs_{fixed}=0.3mm for each fixed stub tuner. Then the TM_{210} mode frequency became 1248.997MHz and TM_{410} mode frequency 2497.200MHz.

After a few steps adjusting the fine stub tuners and side stub tunes one can get TM_{210} mode frequency is 1249.135MHz and TM_{410} mode frequency 2498.270MHz.

Then one can use communications signal analyzer CSA 803 to get the waveform in L-band. The chopper cavity test scheme is shown on Fig.14. 1249.135MHz signal from electric coupler feeds to the chopper cavity showed on Fig.15 and 2498.270MHz signal from magnetic coupler feeds to the chopper cavity showed on Fig.16 simultaneously. Adjusting their amplitude and phase of each signal ,the total magnetic field in the chopper cavity can be displayed by communications signal analyzer and showed on Fig.17. There is about 120° flat part.

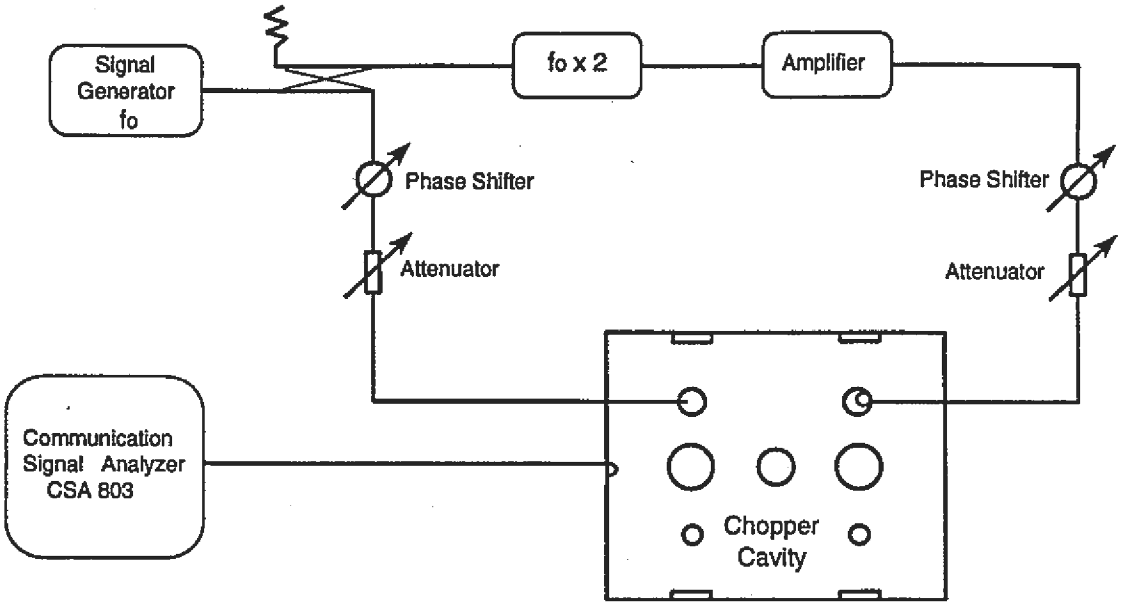


Fig.14 Chopper cavity test scheme

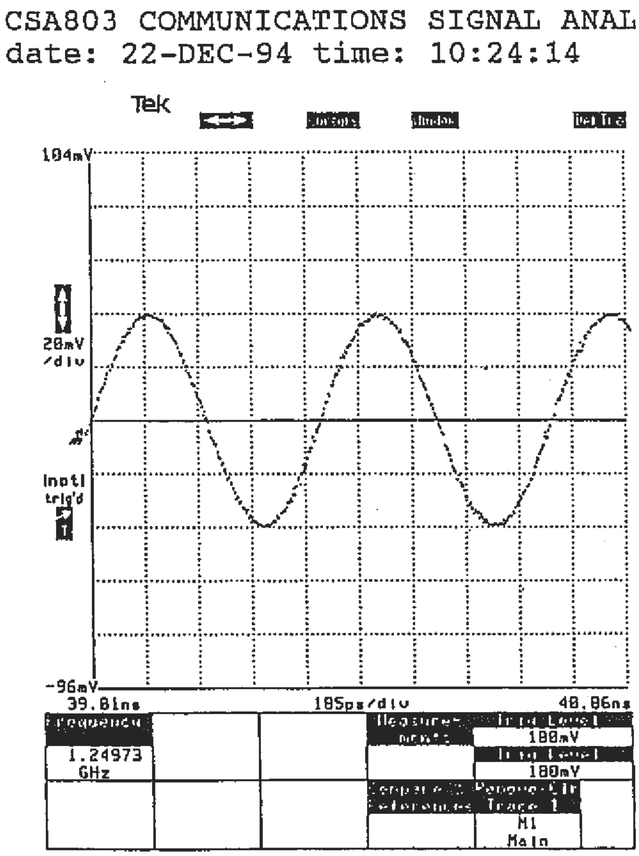


Fig.15 1249.135MHz signal shown on CSA 803.

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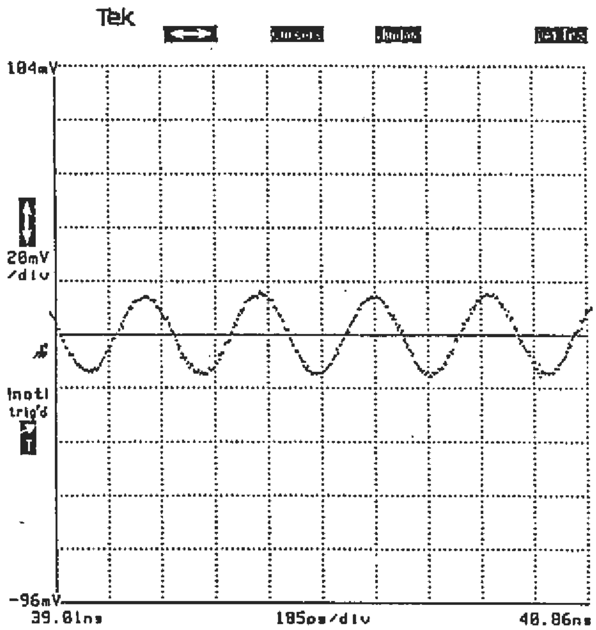

Fig.16 2498.270MHz signal shown on CSA 803

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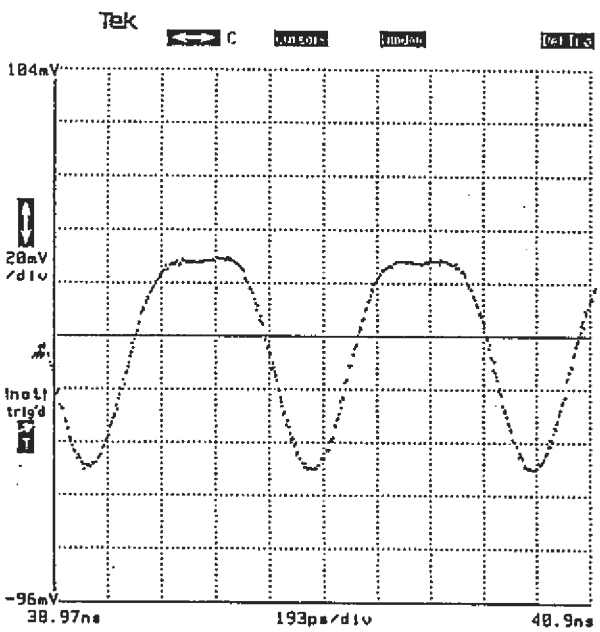

Fig.17 The total field in the chopper cavity shown on CSA 803

7. Summary

The results show that the measurement data are good agreement with the design values. Their parameters and stability required are listed on the table 2.

Table 2, Chopper cavity parameters

mode	TM_{210}	TM_{410}
frequency f	1249.135MHz	2498.270MHz
Q_0	12296	16411
Coupling β_{210}	1	<<1
Coupling β_{410}	<<1	1
Q_L	6200	8200
By	25G	10G
Power P	1250W	300W
$\Delta P/P$	<±1%	<±1%

$\Delta\Phi$	<±0.5°
ΔT	<±0.2°C
B_{bias}	15G
$\Delta B_{bias}/B_{bias}$	<±0.5%

After the test of this new chopper cavity it can be pointed that it is not so difficult to adjust the chopper cavity to the operation point which TM_{210} mode frequency is 1249.135MHz and TM_{410} mode frequency is 2498.270MHz simultaneously to get 120° flat part of the magnetic field in one RF period. So using this kind of cavity can chop the beam with very small transverse momentum. This new chopper system can be realized in PNC high power CW linac.

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