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TOLERANCE REQUIREMENTS ON 720 Hz RIPPLES IN THE MAIN QUADRUPOLE CURRENT DURING RESONANCE EXTRACTIONS

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SUMMARY

Two arrangements, one based on half-integer resonance and the other on one-third integer resonance, are presented as a possible slow extraction system. With the momentum spread of the beam $\Delta p/p = 2 \times 10^{-4}$ ($\Delta\nu_x = \pm 0.0046$) and the spill time ~150 ms, tolerance requirements on 720 Hz ripples in the main quadrupole current during the extraction are:

$$\Delta I/I \lesssim \pm 10^{-3} \text{ for half-integer resonance}$$
$$\lesssim \pm 10^{-4} \text{ for one-third integer resonance.}$$

The radial emittance of the beam is assumed to be 0.25 π mm-mrad at 200 GeV.

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REQUIRED ELEMENTS AND THEIR LOCATIONS

In the main ring quadrupoles, the deviation of the field from a pure quadrupole field is not of a simple octupole type. Nevertheless, it would be desirable to cancel the average (zeroth harmonic) octupole component by means of correction octupole magnets. Data on quadrupole field gradients are by no means complete, especially for 4' quadrupoles. As far as one can tell, the maximum possible value of the relevant quantity

$$\sum \beta_x^2 B_o''' \ell \qquad (\ell = \text{length})$$

is $+4.9 \times 10^8$ kG. In order to compensate for this, one needs correction octupole magnets with

total length = 6'

aperture diameter = 5"

pole tip field = 1.4 kG if placed at β_x = 90m,

= 4.6 kG if placed at β_x = 50m.

The field of each magnet is

$$B_y(y=0) = (B_o'''/6)x^3 \text{ with } \underline{B_o'''<0}.$$

If the maximum radial excursion of the beam is everywhere less than ~3 cm during the extraction, these correction octupoles may turn out to be unnecessary.

A. Half-integer resonance at $\nu_x = 41/2$

quadrupoles: $\sum B'\ell = 31.4$ kG at 200 GeV

or total length = 2'

aperture diameter = 5"

pole tip field = 1.3 kG

octupoles: $\sum B'''\ell = 31.7$ kG/(inch)^2 at 200 GeV

or total length = 2'

aperture diameter = 5"

pole tip field = 3.4 kG

locations for both quadrupoles and octupoles:

B'>0 or B'''>0	B'<0 or B'''<0
A26	D26
A38	D38
A15	D15
F19	C19

This arrangement produces odd harmonic components only. These locations are not unique. With suitable modifications in quadrupole and octupole strengths, one can place these extraction elements at

$$41\phi = 2\pi(\delta + n/2); \qquad n = 0,1,2,.....$$

with $0.20 \lesssim \delta \lesssim 0.25$. The phase advance ϕ (normalized to 2π) is measured from the septum position. If n is even (odd), magnets should have B'>0 (B'<0) or B'''>0 (B'''<0). Suitable locations are listed in Appendix. Existing trim quadrupoles

(each 0.3 m long, B' = 4 kG/m, total number = 36) may be used for this purpose if a suitable rearrangement is possible. With the radial beam emittance 0.25 π mm-mrad, the extraction starts at $\nu_x = 20.4646$. The width of the stopband is 0.067 extending from 20.4665 to 20.5355. It should be noted that the field gradient error in main ring quadrupoles has also 41st harmonic component that gives rise to a stopband (width ~0.03). Since the phase of this component may or may not be favorable for the extraction, the quadrupole set should have the capability of compensating for this contribution.

B. One-third integer resonance at $\nu_x = 61/3$

This is essentially the same as the one discussed elsewhere.[1]

sextupoles: $\sum B''\ell = 40.3$ kG/inch at 200 GeV

It is possible to use the existing iron-core sextupoles for this purpose:

total number = 36 plus a few spares

length $\ell = 6"$

B" = up to 0.19 kG/(inch)^2

$\sum B''\ell = 41$ kG/inch

locations	B">0	B"<0
	A17	D17
	D44	A44
	B13	E13
	E38	B38
	F22	C22
	F34	C34

With the emittance 0.25 π mm-mrad, the onset of the extraction is at $\nu_x = 20.3303$. Beyond $\nu_x = 61/3$, the stable area reappears (an inverted triangle) and the entire beam is stable for $\nu_x \geq 20.3364$. The sextupole components of the main ring dipoles are too small to give any sizable effect at 200 GeV.

TOLERANCE REQUIREMENTS ON 720 Hz RIPPLES

The acceptance in x=x' phase space of the extraction channel at the entrance of the wire septum is shown in Fig. 1. The origin (x=0, x'=0) of this acceptance relative to the main ring beam axis can be adjusted by a suitable set of bump magnets. However, the standard setup is to place the septum 3 cm away from the main ring axis. Ideal extraction scheme should therefore give $\lesssim$1 cm turn separation* at 3 cm. Aside from the wire septum, the element that is responsible for limiting the acceptance is the vertical H magnet (MX80). In calculating tolerance requirements, the beam is assumed to have a tune spread of ± 0.0046 corresponding to $\Delta p/p = \pm 2 \times 10^{-4}$. The radial emittance of the beam is 0.25 π mm-mrad.

A. Half-integer resonance extraction

The trim quadrupole current is adjusted such that the radial tune increases linearly in time from 20.46 to 20.475 in ~150 ms. A sinusoidal ripple in the main quadrupole current is then introduced with the frequency 720 Hz. For a given value of

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* One turn = two revolutions for half-integer resonance and three revolutions for one-third integer resonance.

ν_x, approximately 50 particles are chosen just outside of the separatrix and they are traced until extracted ($x \geq 3$ cm). Particles are considered as successfully extracted when the turn separation is between 0.5 cm and 1 cm and the final values of x, x' are within the acceptance in Fig. 1. The maximum tolerable amount of the fluctuation in ν_x is

ν_x	$\Delta\nu_x$(maximum)
20.4646	±0.035~±0.040
20.4653	±0.030~±0.035
20.4660	±0.025~±0.030
20.4665	±0.020~±0.025

Since $\Delta\nu_x \simeq 23(\Delta B'/B')$, the entire beam will be extracted in ~150 ms if the fluctuation of the field gradient is $\sim\pm 10^{-3}$.

B. One-third integer resonance extraction

The radial tune is increased linearly in time from 20.3257 to 20.341 in ~150 ms. The maximum tolerable amount of the fluctuation in ν_x is

ν_x	$\Delta\nu_x$(maximum)	
20.3303	±0.0105	~35%
20.3315	±0.0063	~80%
20.3327	±0.0020	~95%

The last column is the expected fraction of the beam that will be extracted for each $\Delta\nu$ in the middle column. In order to extract more than 95% of the beam, the fluctuation of the field gradient must be less than $\pm 10^{-4}$.

DISCUSSION

If two extraction schemes are compared purely from the standpoint of tolerance requirements on 720 Hz ripples, there is no question about the superiority of half-integer resonance. On the other hand, there are some features in this scheme that should be carefully evaluated.

1. In addition to the extraction quadrupole set, one needs two sets of octupoles, one for eliminating the average octupole component of the main ring quadrupoles and the other for providing the necessary driving term (41st harmonics). It seems difficult to satisfy both requirements by one control knob.

2. The quadrupole set must compensate for the existing 41st harmonic component due to imperfections in main ring quadrupoles. This component is not known too well so that one should be able to produce 41st harmonic component with a wide range of amplitude and phase. The difficulty may be avoided by increasing the width of the stopband (stronger quadrupoles for the extraction).

3. When the closed orbit is distorted at octupole locations, quadrupole and sextupole fields are also introduced at these locations. The quadrupole field is porportional to Δ^2 (Δ = closed orbit displacement at each octupole) so that the contribution from octupoles does not cancel each other. Any 41st harmonic

component of this field could influence the extraction. The sextupole field may contain an undesirable 61st harmonic component which is dangerous if ν_x must cross 61/3 before the onset of the extraction. One might be forced to use bump magnets to center the beam at octupole locations.

One of the important problems in any kind of radial extraction is the possible vertical beam growth during the extraction.[1,2] However, this has not been covered in the present study.

Discussions with L. C. Teng have been helpful in clarifying various aspects of the problem treated in this note.

REFERENCES

1. S. Ohnuma, IEEE Transactions on Nuclear Science, NS-18 (1971), 1015.
2. A. W. Maschke and K. R. Symon, Extraction System for the 200 GeV Accelerator, August 5, 1968 (unpublished note).
3. L. C. Teng, TM-375, June 6, 1972.

APPENDIX

When the phase advance ϕ (normalized to 2π) measured from the septum satisfies the condition

$$4l\phi = 2\pi(\delta+n/2); \qquad n = 0,1,2,.....$$

with

$$0.20 \lesssim \delta \lesssim 0.25$$

the location is suitable for quadrupoles or octupoles of the half-integer resonance extraction system. B' or B''' should be positive (negative) when n is even (odd). Locations with n > 0 are:

Station	δ
A15	0.261
A26	0.252
A38	0.243
B10*	0.212
B11	0.230
E13	0.196
F19	0.224
F32	0.215
F44	0.206

* End of 50 m drift space.

The example given in this report is for $\delta = 0.25$. Another choice by L. C. Teng[3] is

$$\sum B'\ell = 47.2 \text{ kG}$$

$$\sum B'''\ell = 27.1 \text{ kG/(inch)}^2$$

$$\delta = 0.206$$

For this system, suitable locations are

B'>0 or B"'>0	B'<0 or B"'<0
F44	C44
B10	E10
F32	C32
E13	B13

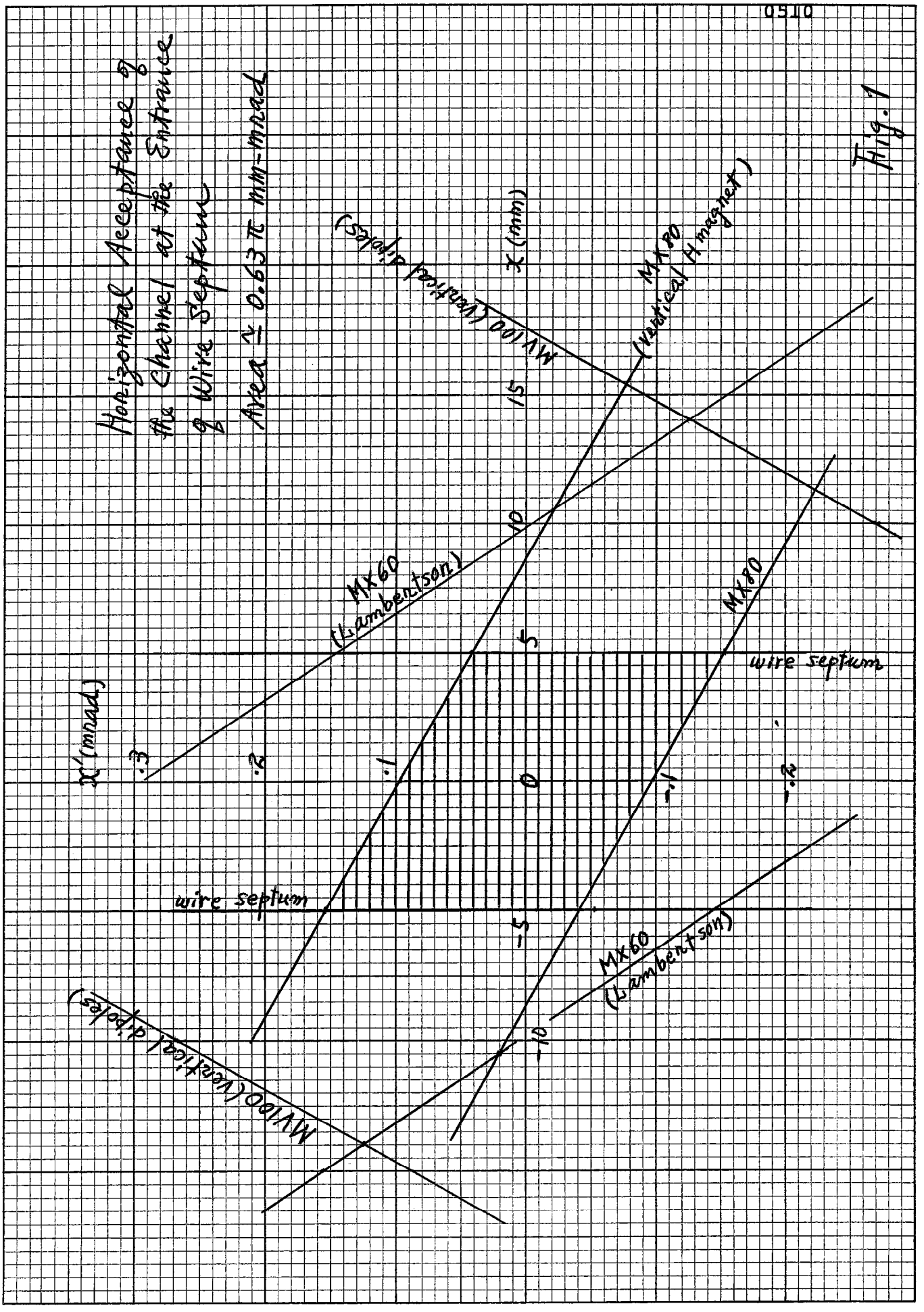
Horizontal Acceptance @ the Channel at the Entrance @ Wire Septum
Area ≈ 0.63 π mm-mrad
x (mm)
x' (mrad)
MX60 (Lambertson)
MX80 (Vertical H magnet)
MX80
MX60 (Lambertson)
wire septum
wire septum
MV100 (Vertical dipoles)
MV100 (Vertical dipoles)
15
10
5
0
-5
-10
.3
.2
.1
0
-.1
-.2

Fig. 1