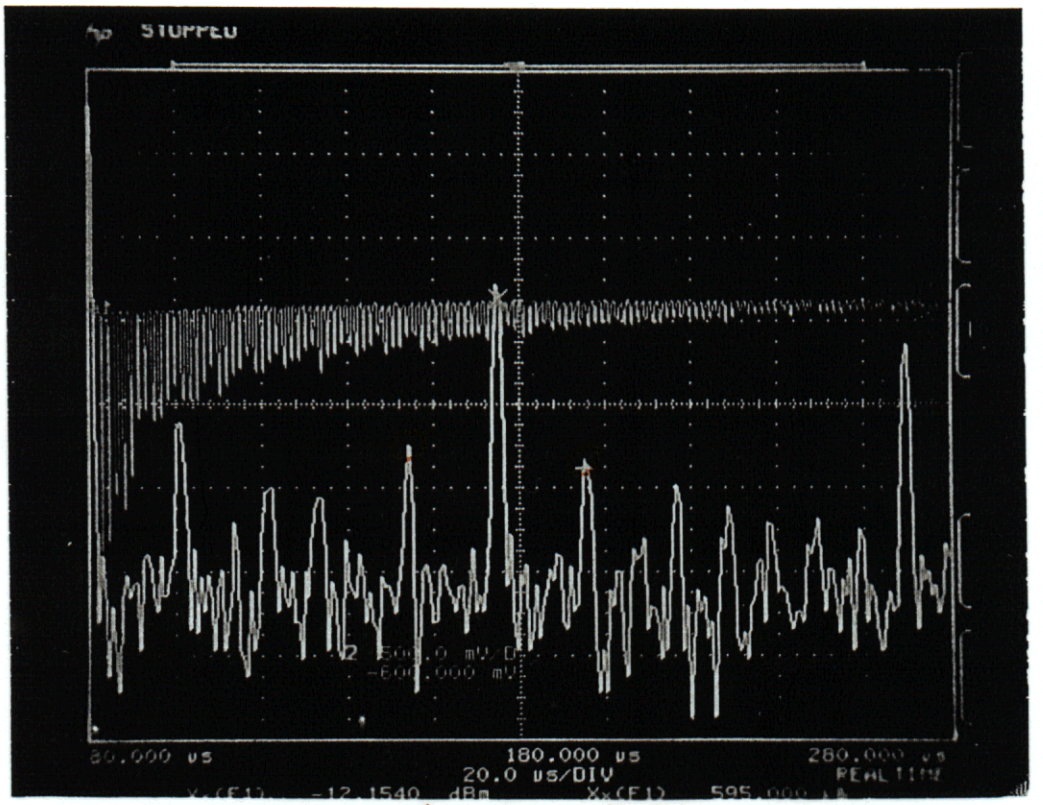
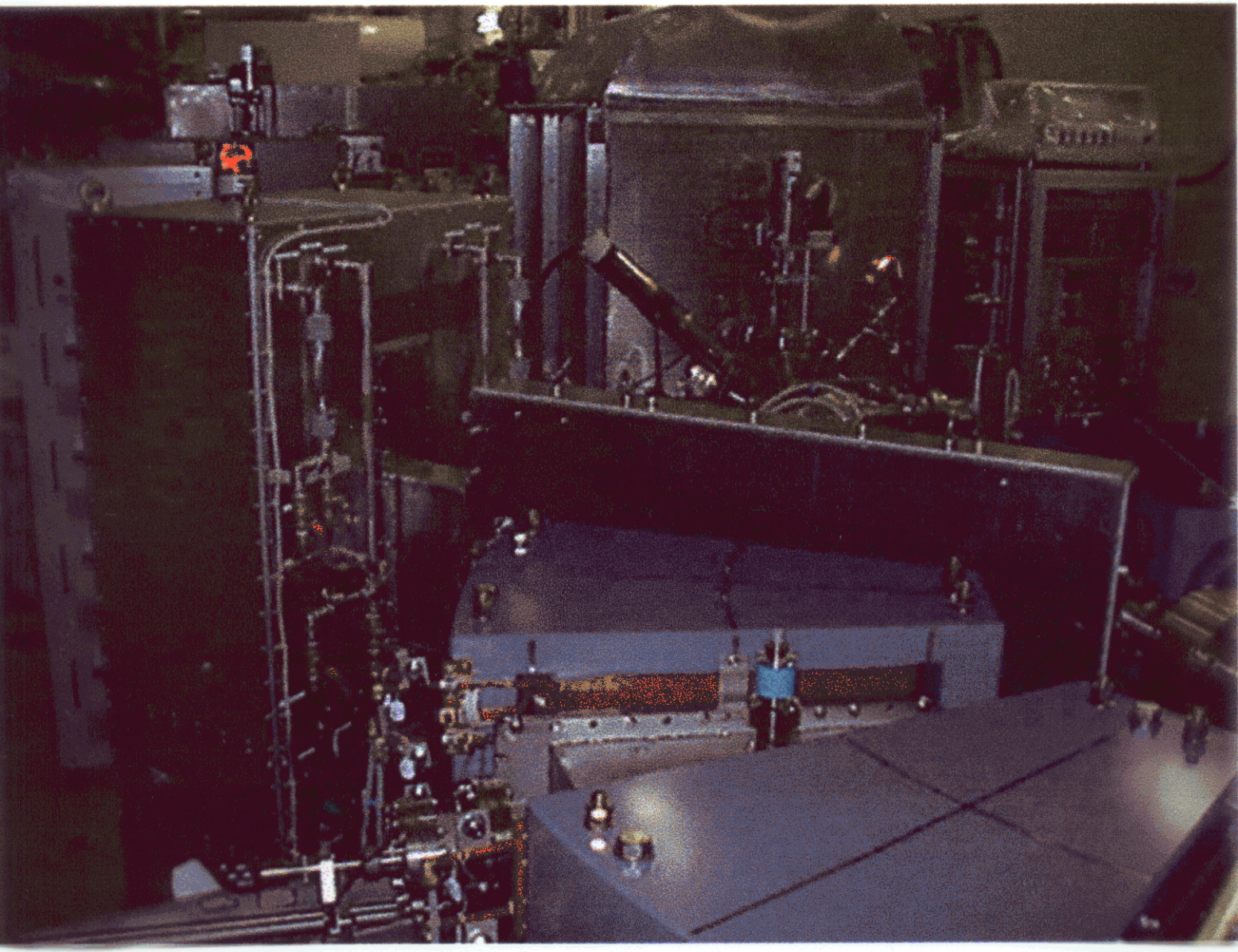


POP machine

tune hor. $\Delta Q_H = 0.22$



POP (Proof-of-Principle) machine

Proton model — under development

demonstration ⇒ 1 kHz operation

E_k = 0.1 ~ 1 MeV (9 MeV max.)

$\hat{r}$ = 0.8 ~ 1.1 m

< first "proton" model of FFAG >

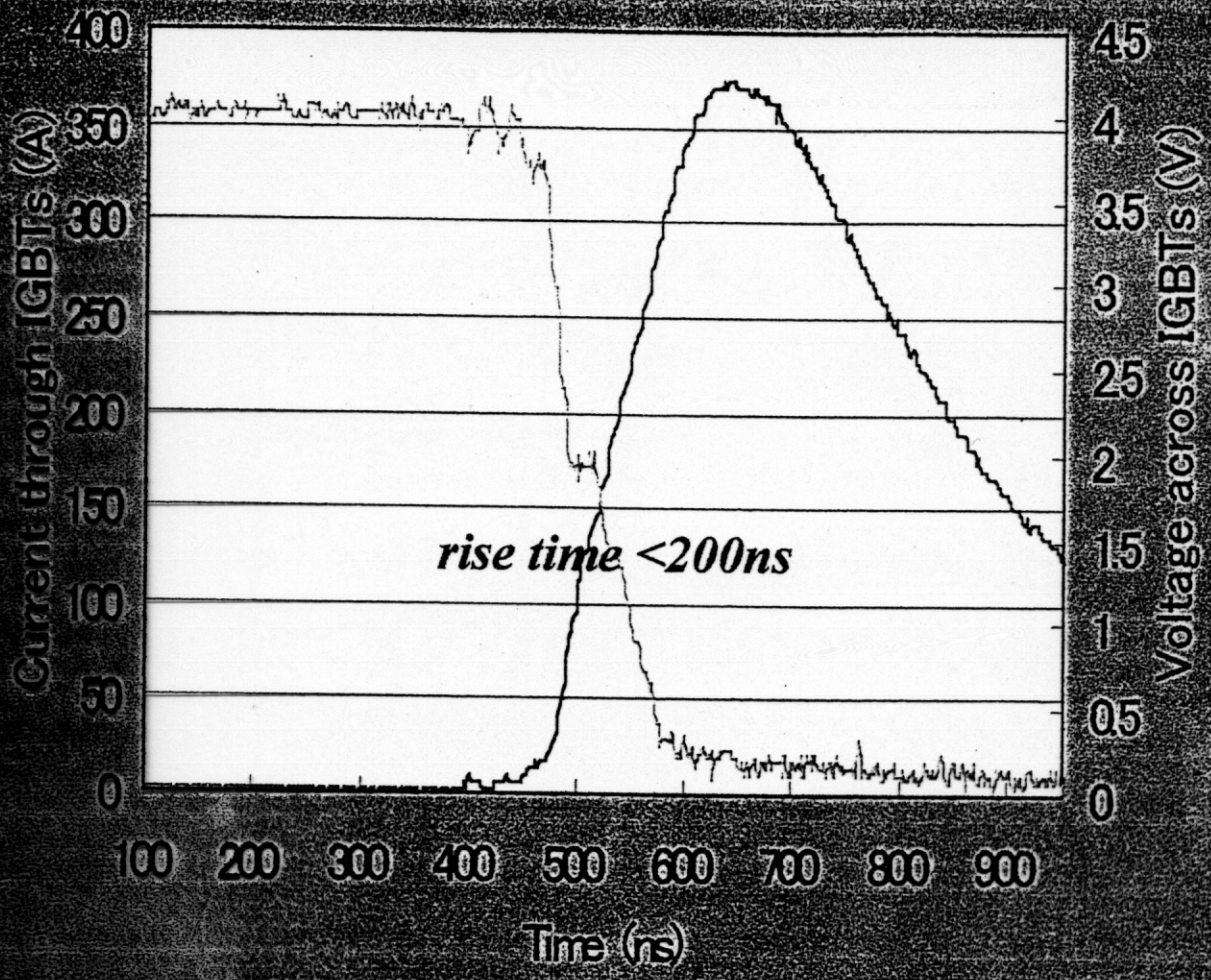
(studies)

(1) rf (longitudinal) gymnastics

- stacking
- multi-bunch in different orbit
- ...

(2) Space charge

2. High Reliability Switch

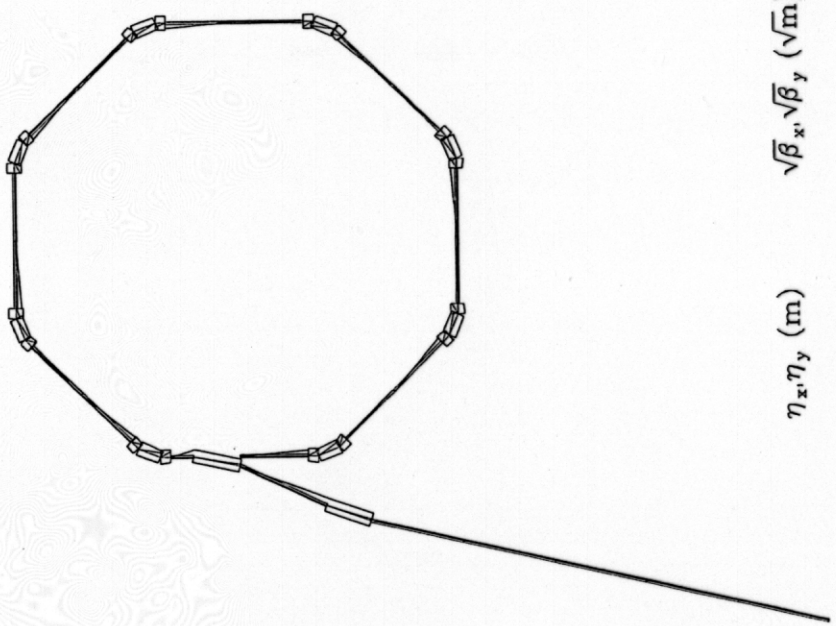


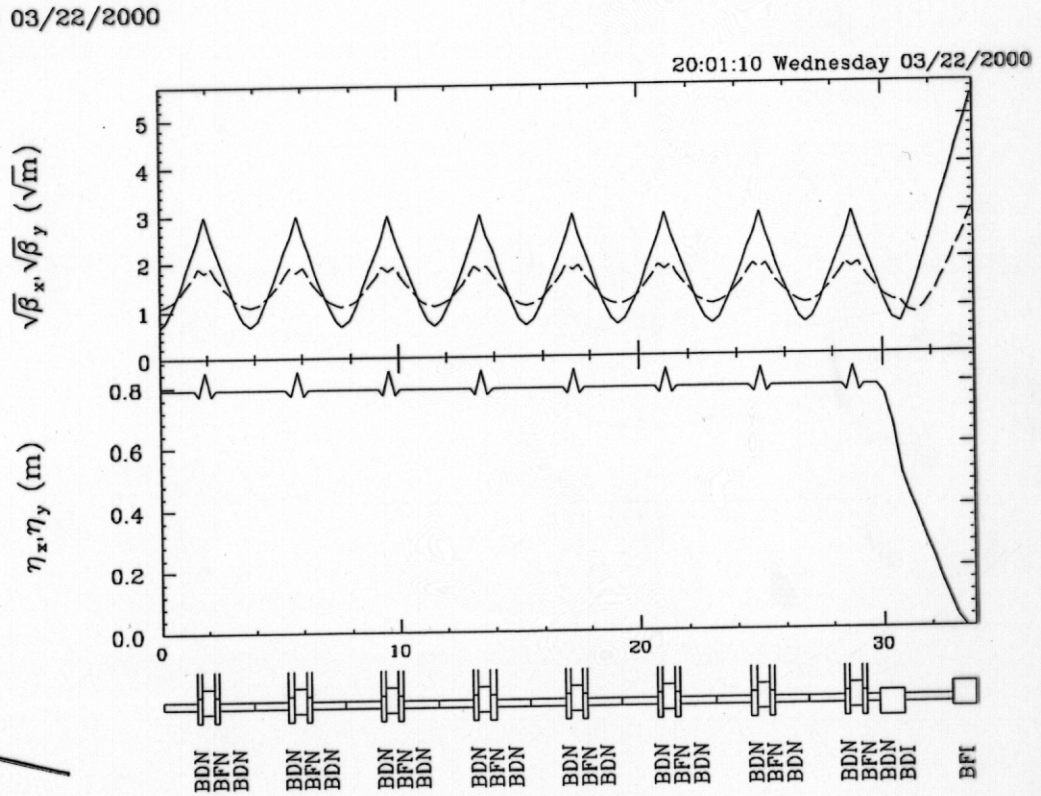
Turn-on characteristics of 4 series IGBTs

PRISM (phase rotator) with Injection Matching Section (1)

deflection angle 11.8 deg & -25 deg

use of edge focus of kicker magnet

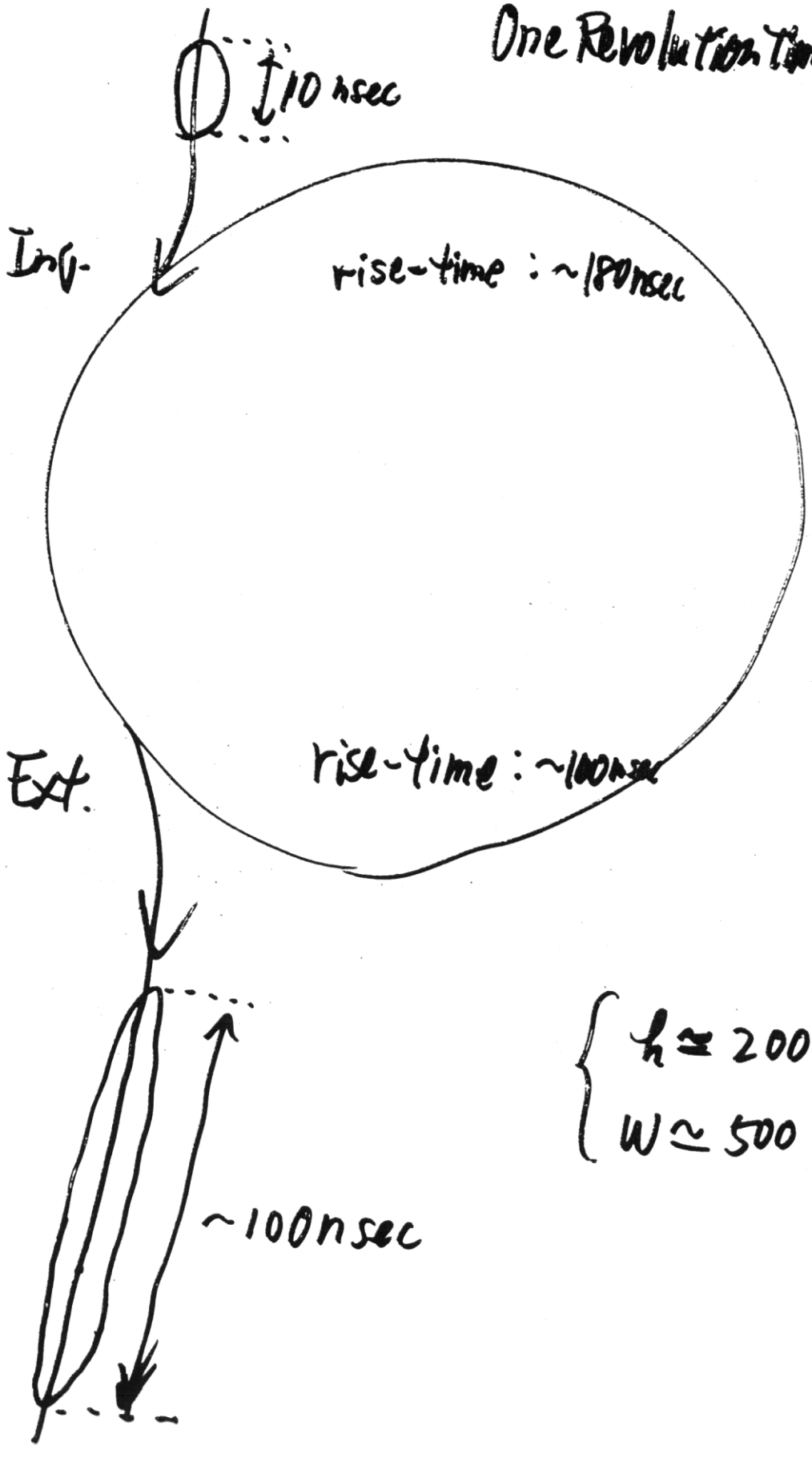




PRISM - FFAG

Circumference : ~30 m

One Revolution Time : ~200 nsec



$$\begin{cases} h \simeq 200\ \mathrm{mm} \\ W \simeq 500\ \mathrm{mm} \end{cases}$$

Helical Quadrupole Focssing Channel

Helical quadrupole focusing channel

*axial symmetry rotation coordinate : x-y coupling

*strong focusing

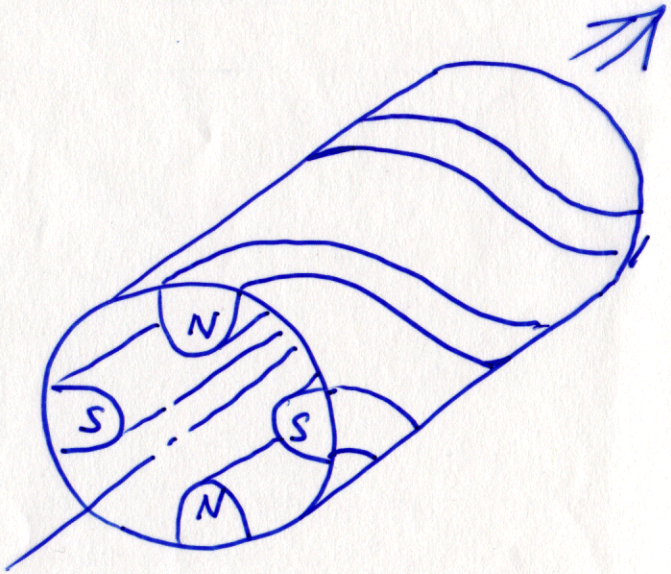
$$B' \sim \frac{B\rho}{L_p^2}$$

betafunction

$$\bar{\beta} \approx \frac{L_p}{\phi}$$

L_p : one pitch length

ϕ: phase advance



Assume : $p \sim 0.1 GeV/c, \phi = \frac{\pi}{2}, L_p = 0.1m, \varepsilon = 10000\pi mm \cdot mrad$

$\Rightarrow r \cong 3cm, \ B' \cong 30T/m$

Permanent Quadrupole Magnet

$B' > 100T/m$, $r \sim 2cm$

Helical Quadrupole Focusing Channel

Muon capture channel

large transverse momentum

Conventional scheme => solenoid channel (superconducting)

*axial symmetry x-y coupling

*adiabatic reduction of transverse momentum

(problem)

"weak focusing" => Large Magnetic Field : Superconducting Solenoid

no-

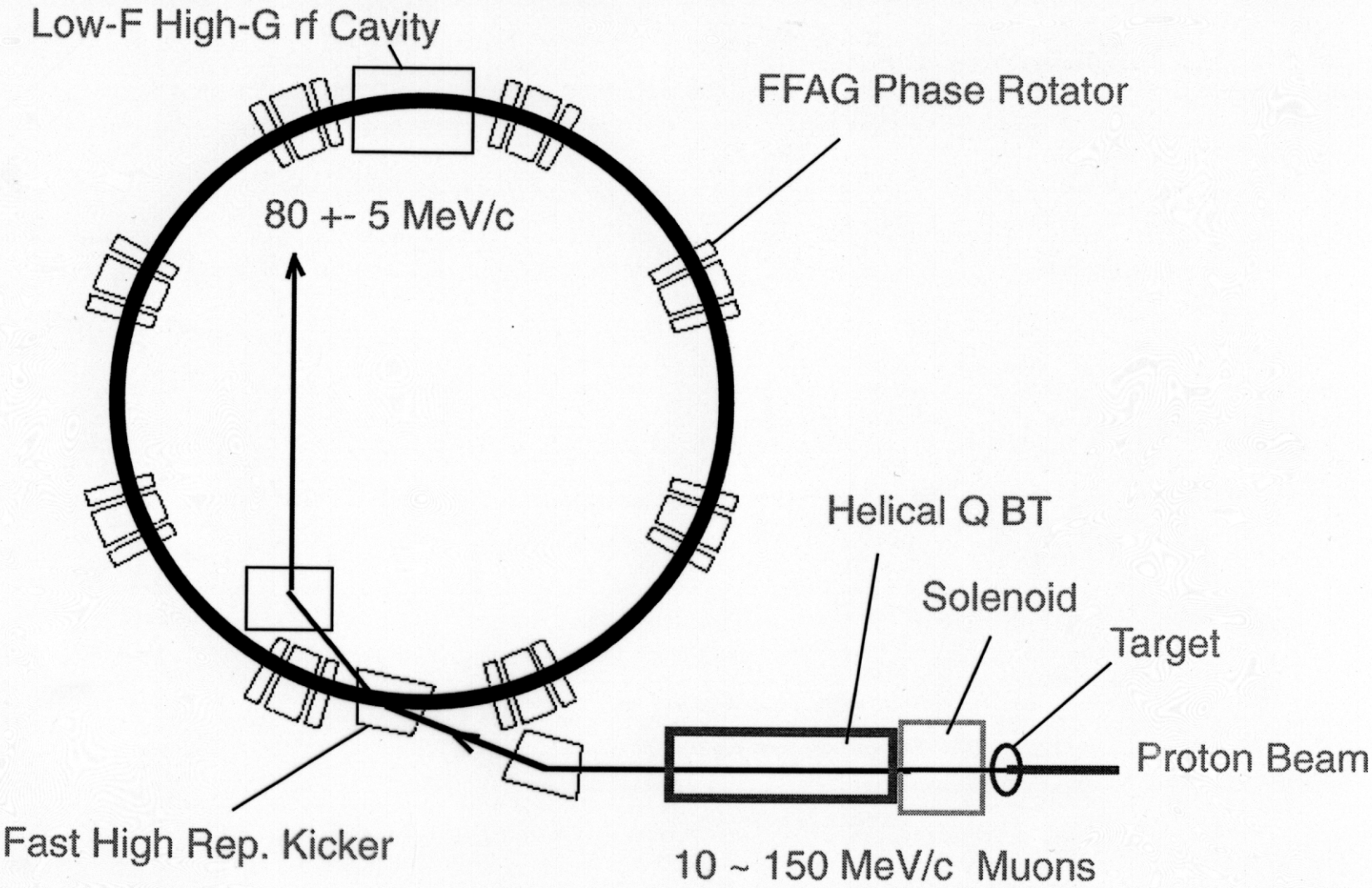
$$R(m) = \frac{2 \times P_T(GeV/c)}{0.3 \times B(T)}$$

cf.

$$P_T = 0.1(GeV/c), B = 10(T)$$

$$\rightarrow R = 0.067(m) = 6.7(cm)$$

PRISM - "A Miniature of Neutrino Factory"



Power Test of High Gradient Test Cavity

TEST CAVITY

*Single core (O.D=580mm,I.D=250mm, t=25mm)

*Direct water cooling

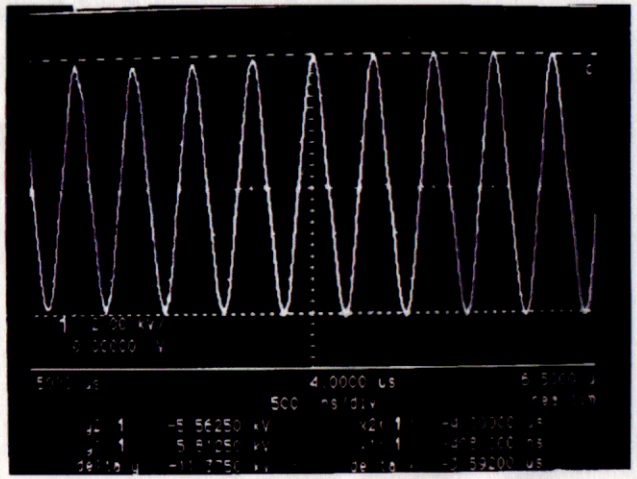
*RF power :30kW max.(B-class)

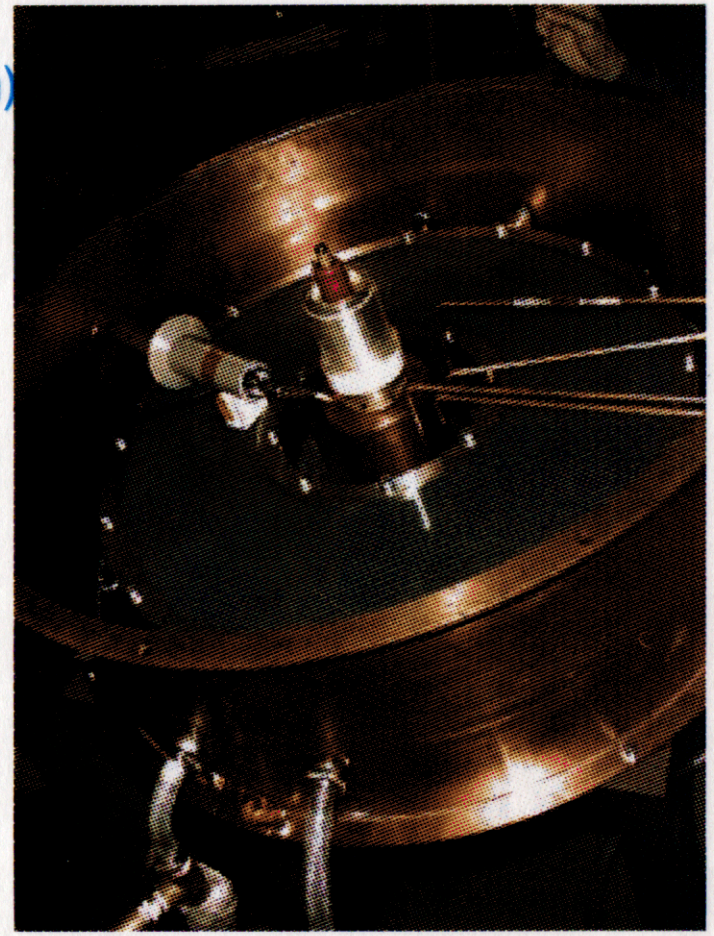
Achieved:

EFG = 100kV/m (cw)

EFG = 220kV/m (burst)

(limited by RF amplifier)





The gap voltage of the test cavity. The maximum RF voltage of 5.5kV(=220kV/m)was obtained.

Types of rf Cavity Candidates

1 MA (magnetic alloy) loaded

Successfully developed at KEK

1) high field gradient E~ 0.25 MV/m
2) wide band ----> saw-tooth waveform
3) high duty operation

2 Ferrite loaded

Ni-Zn with CoO doped.

1) very high field gradient : E ~ 1MV/m
2) less tunability Q ~ 100
3) only low duty operation : burst mode

3 Air-core

CERN anti-proton ring 9.5 MHz : ~ 2 m in diameter and 2 m long for single gap.

1) very high field gradient : E > 1MV/m
2) narrow band : Q ~10000
3) modest duty operation

RF for PRISM Phase Rotation

Phase rotation of low energy muons

(1) low frequency (~MHz)

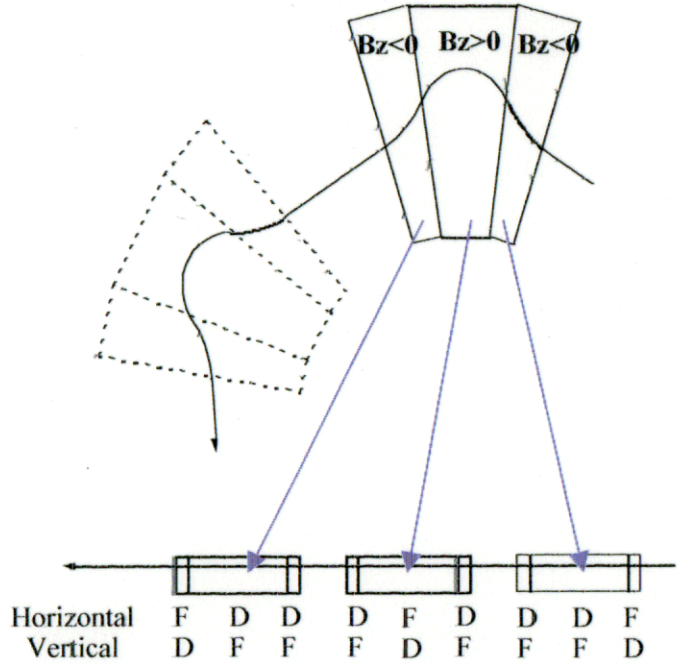
(2) high field gradient > 0.25 - 1MV/m

(3) minimizing non-linear effects

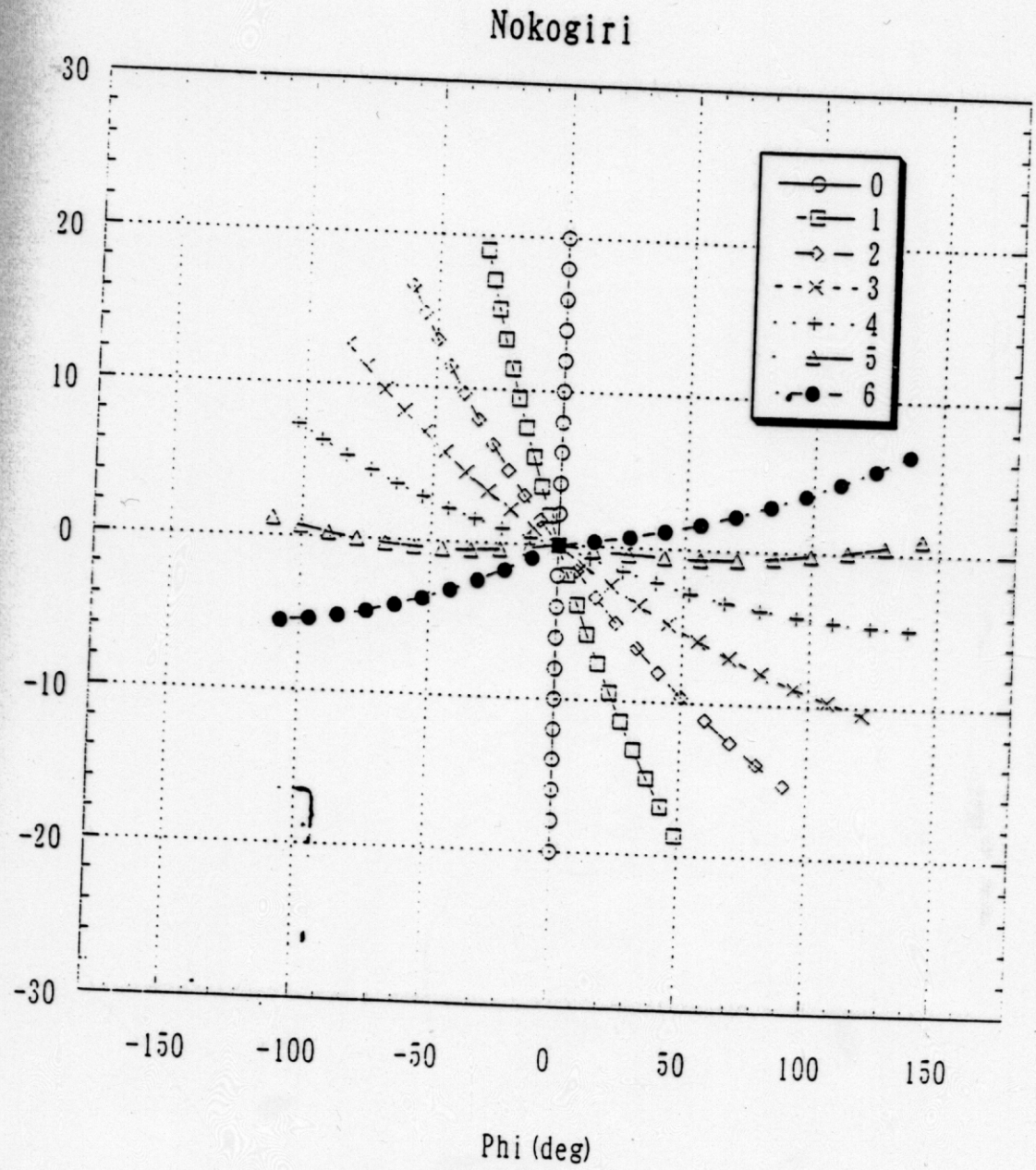
(4) high repetition rate > 1 kHz

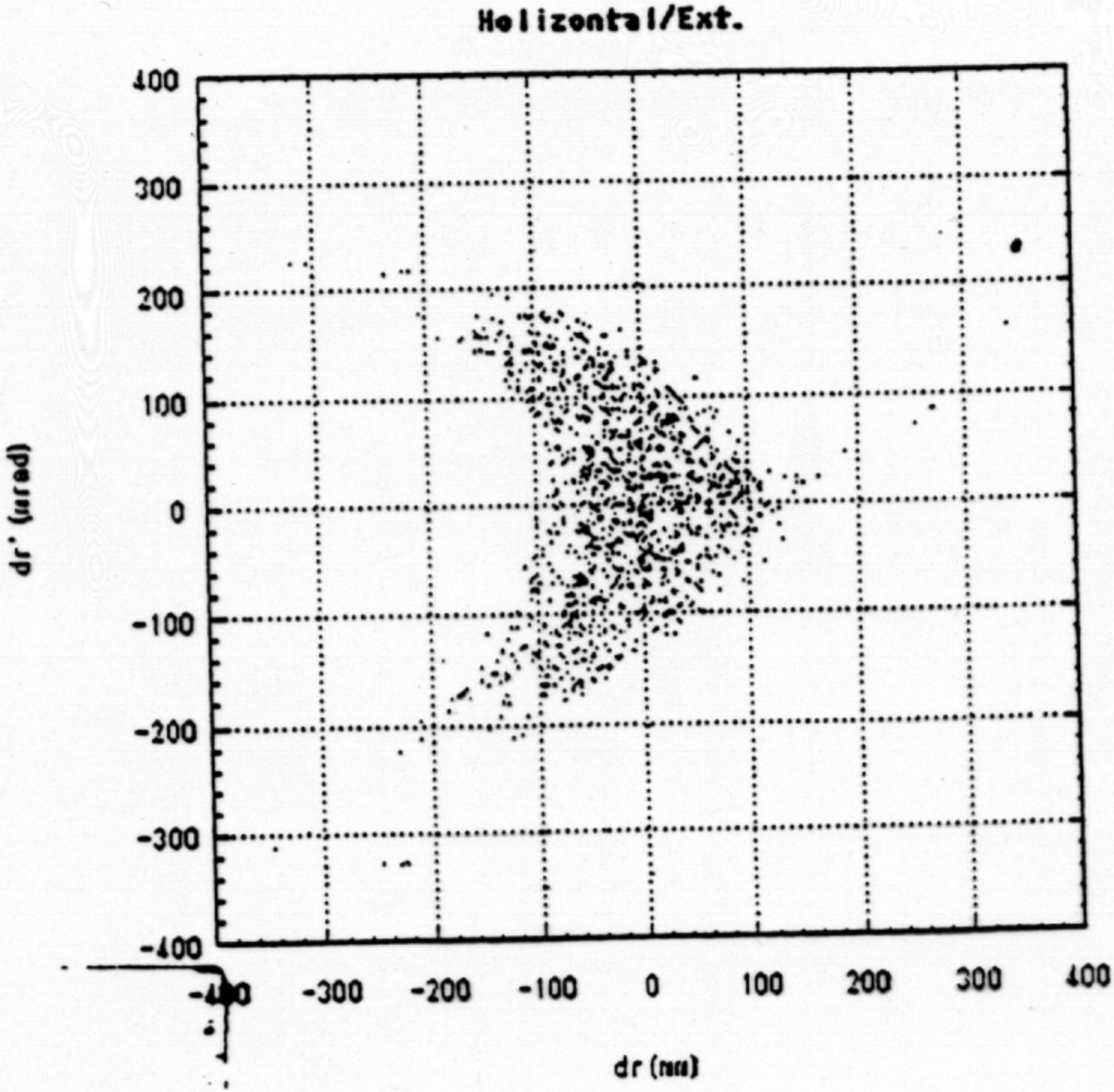
* (1) & (2) are also essential to get narrow banch width at proton driver.

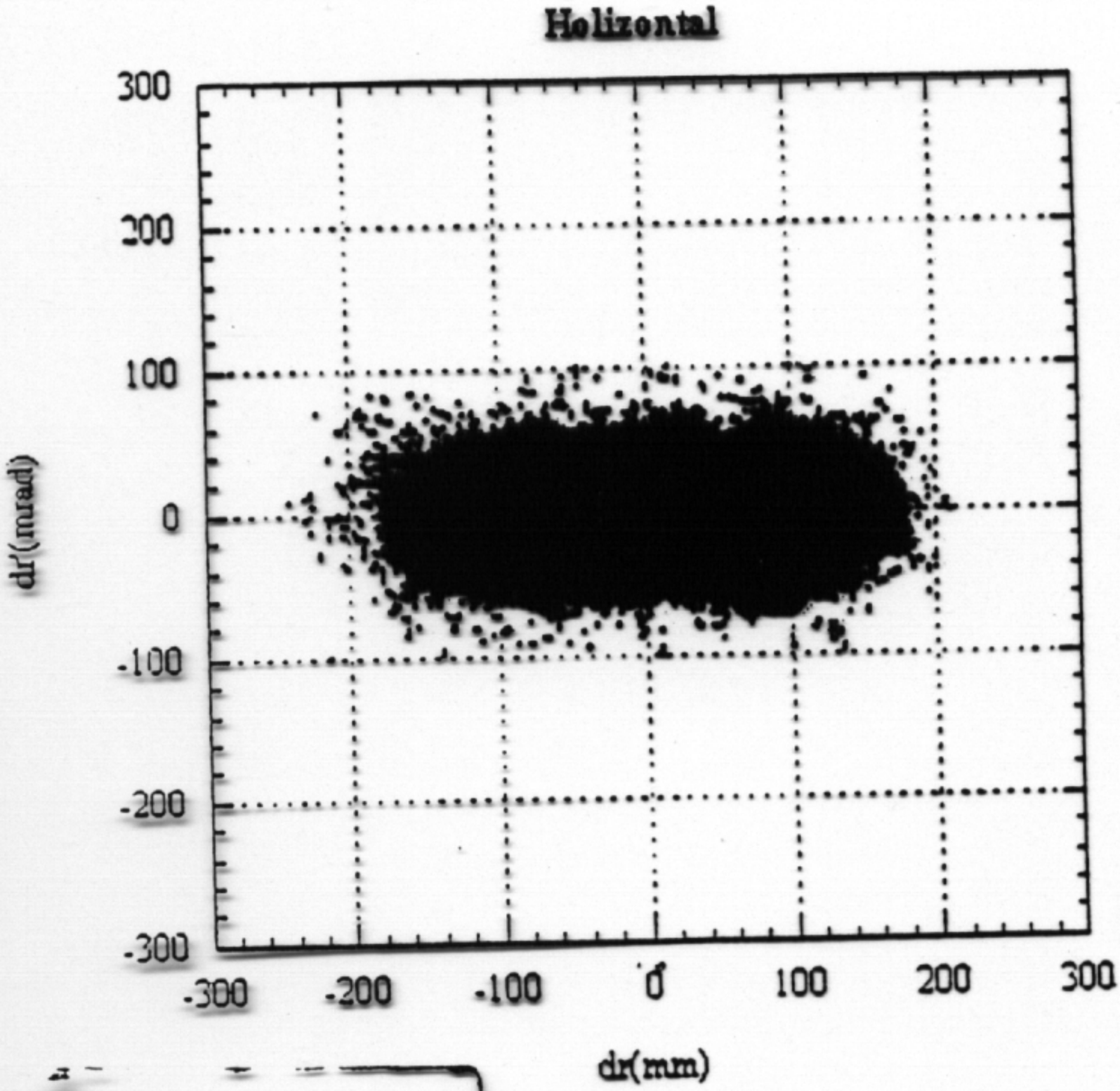
FFAG synchrotron Triplet

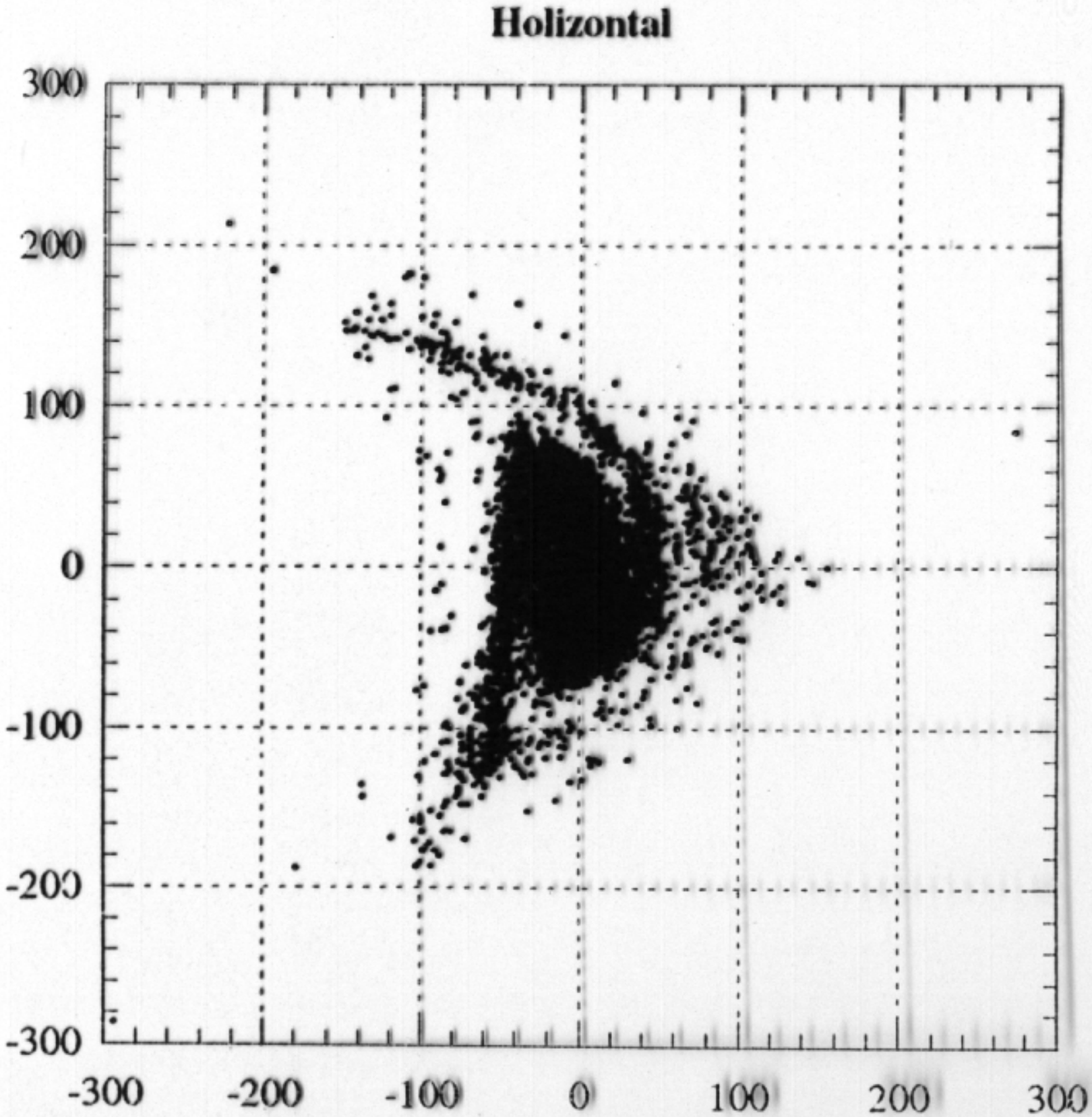


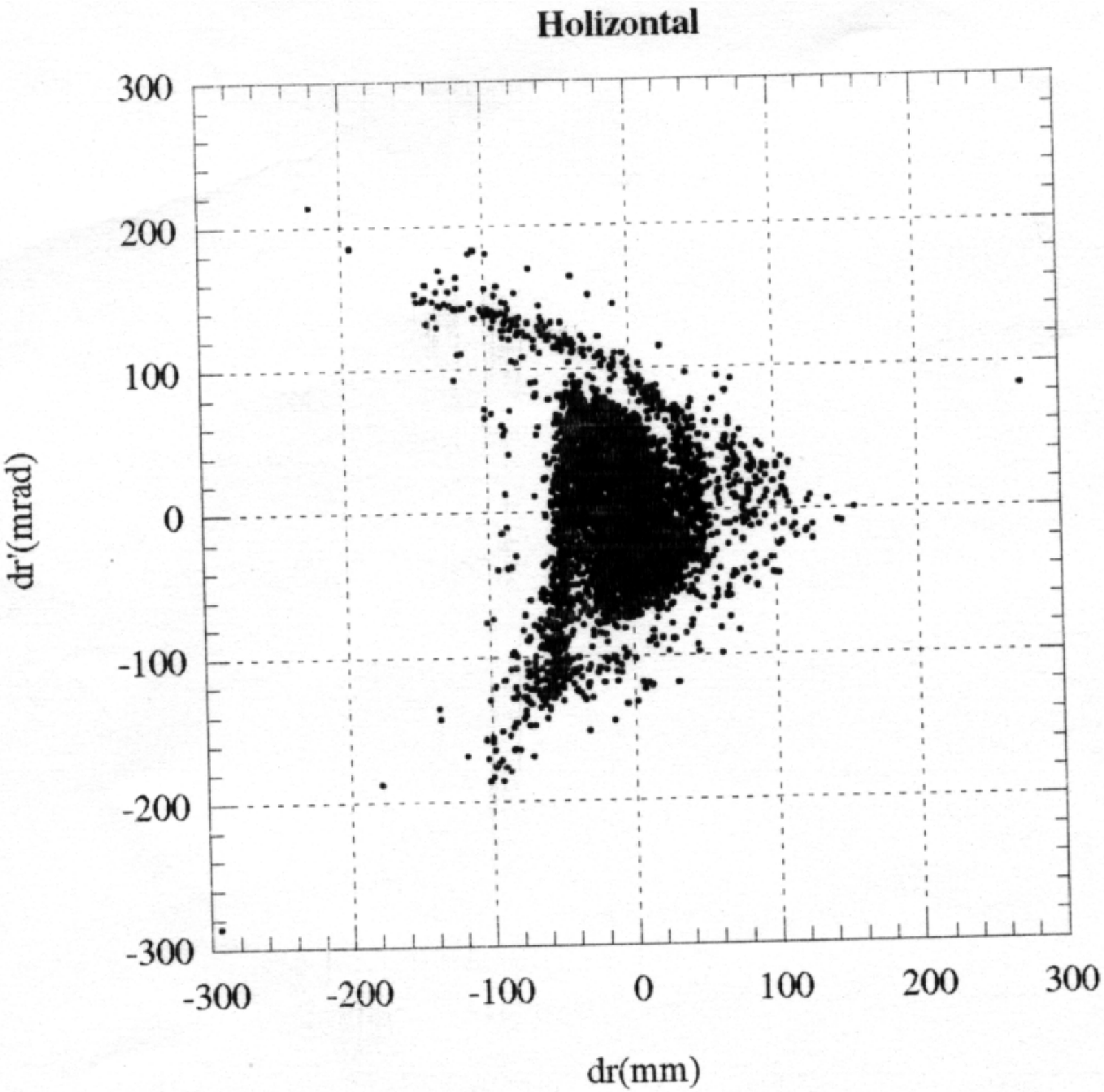
-Longer straight section than usual radial sector type.
-Perpendicular orbit to radius at the center of straight section.
-Weak effect of the fringing field between Fmag. and Dmag.

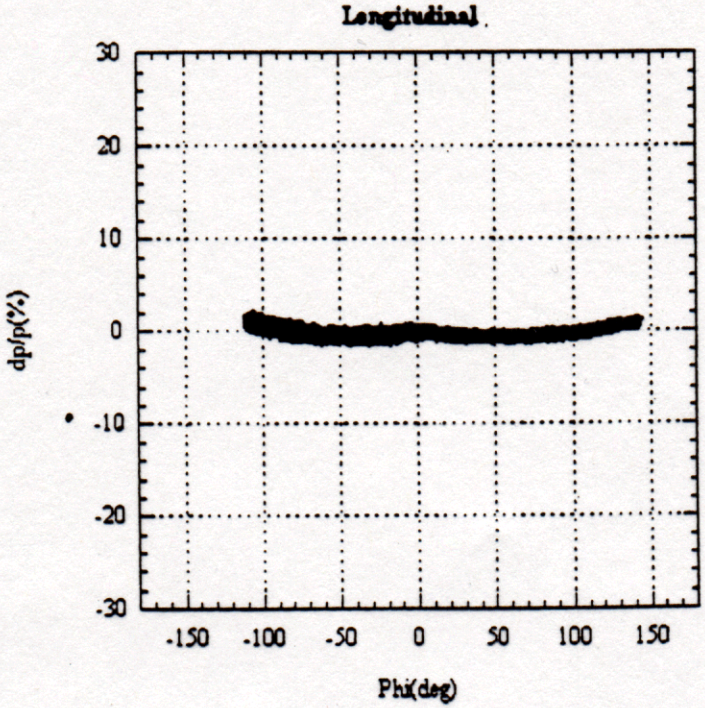

Nokogiri
30
20
10
0
-10
-20
-30
-150
-100
-50
0
50
100
150
Phi (deg)
0
1
2
3
4
5
6

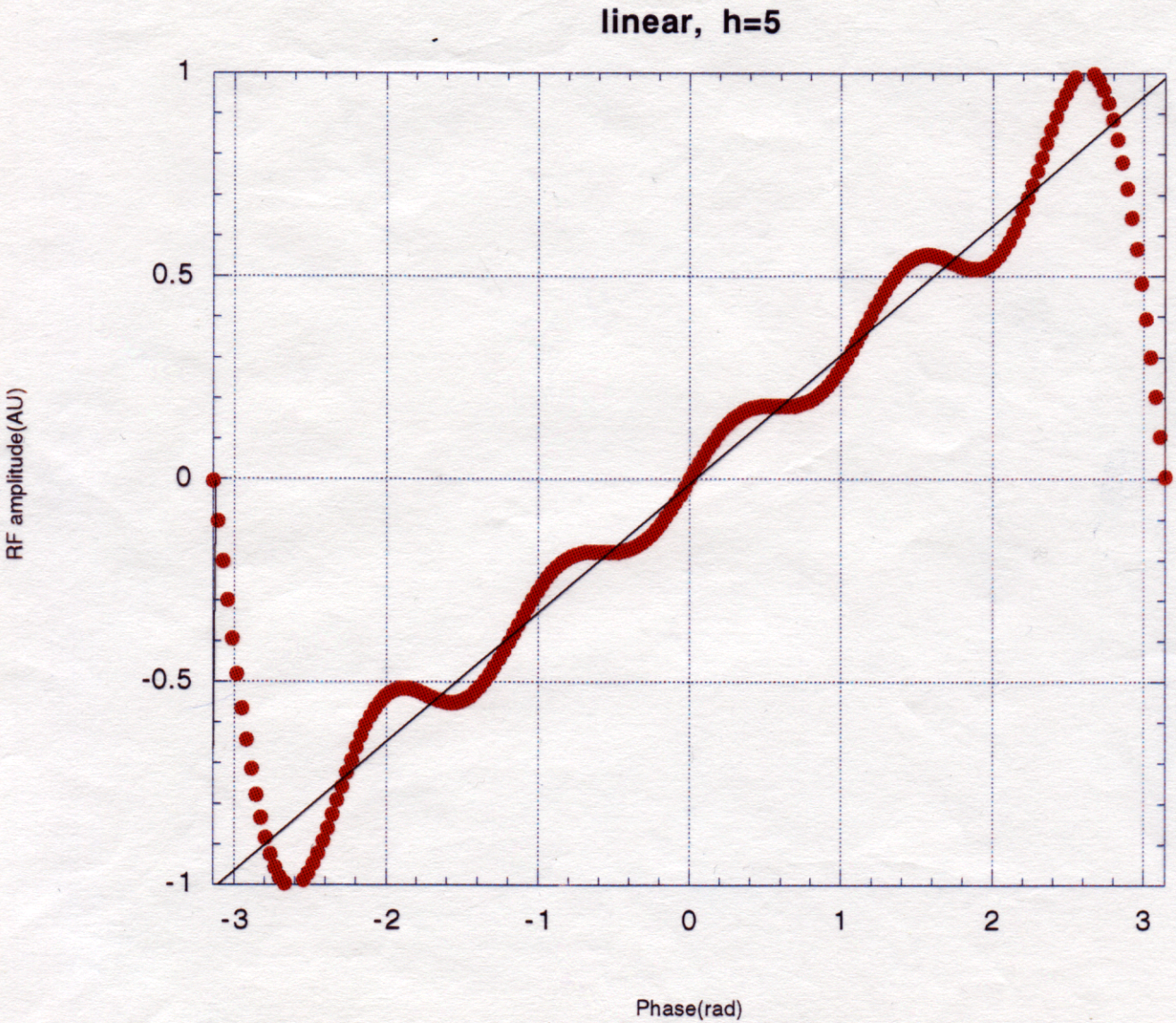

Helizontal/Ext.
400
300
200
100
0
-100
-200
-300
-400
dr' (μrad)
-300
-200
-100
0
100
200
300
400
dr (mm)

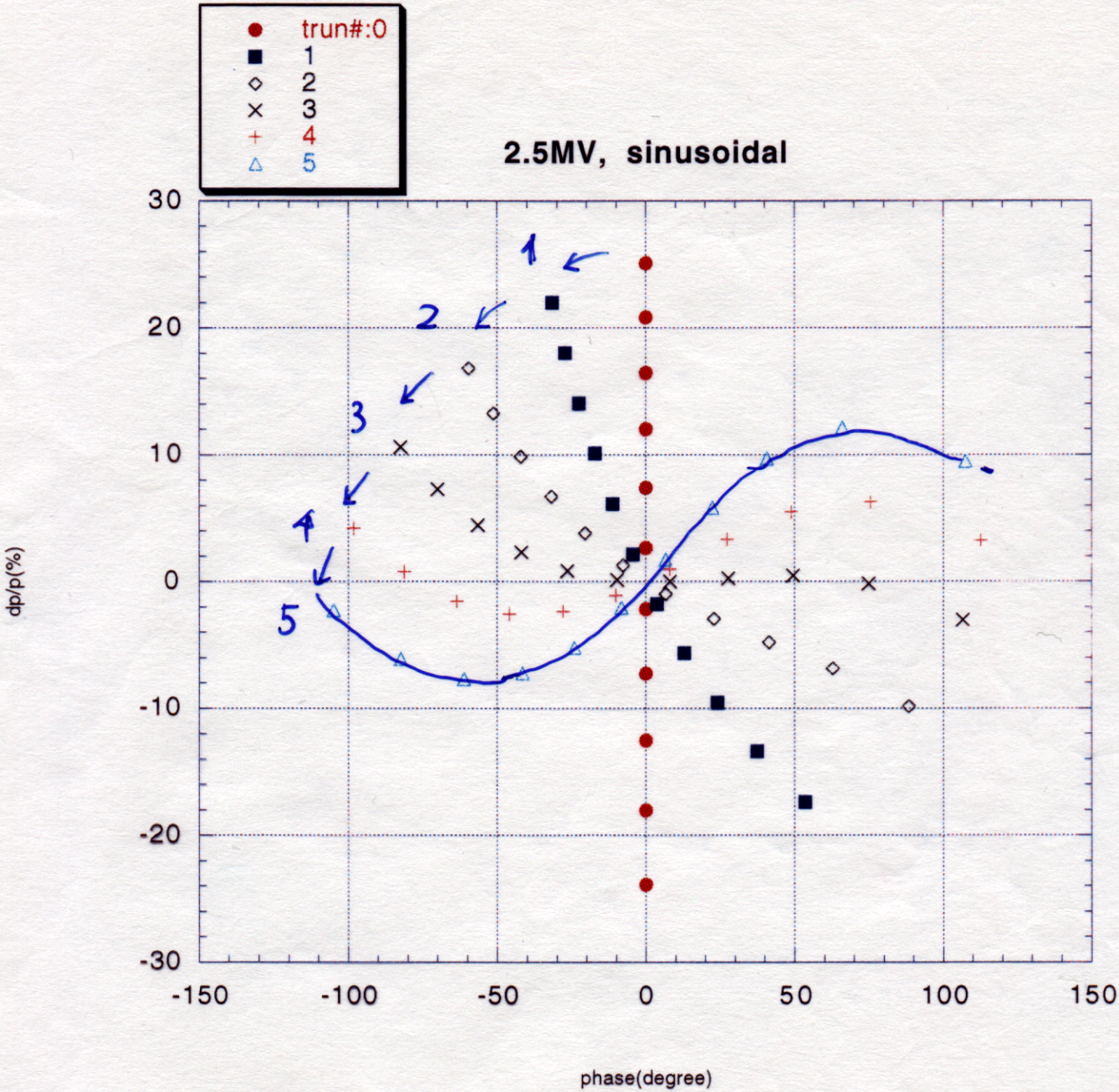

Holizontal
300
200
100
0
-100
-200
-300
dr'(mrad)
-300
-200
-100
0
100
200
300
dr(mm)


Holizontal
300
200
100
0
-100
-200
-300
-300
-200
-100
0
100
200
300

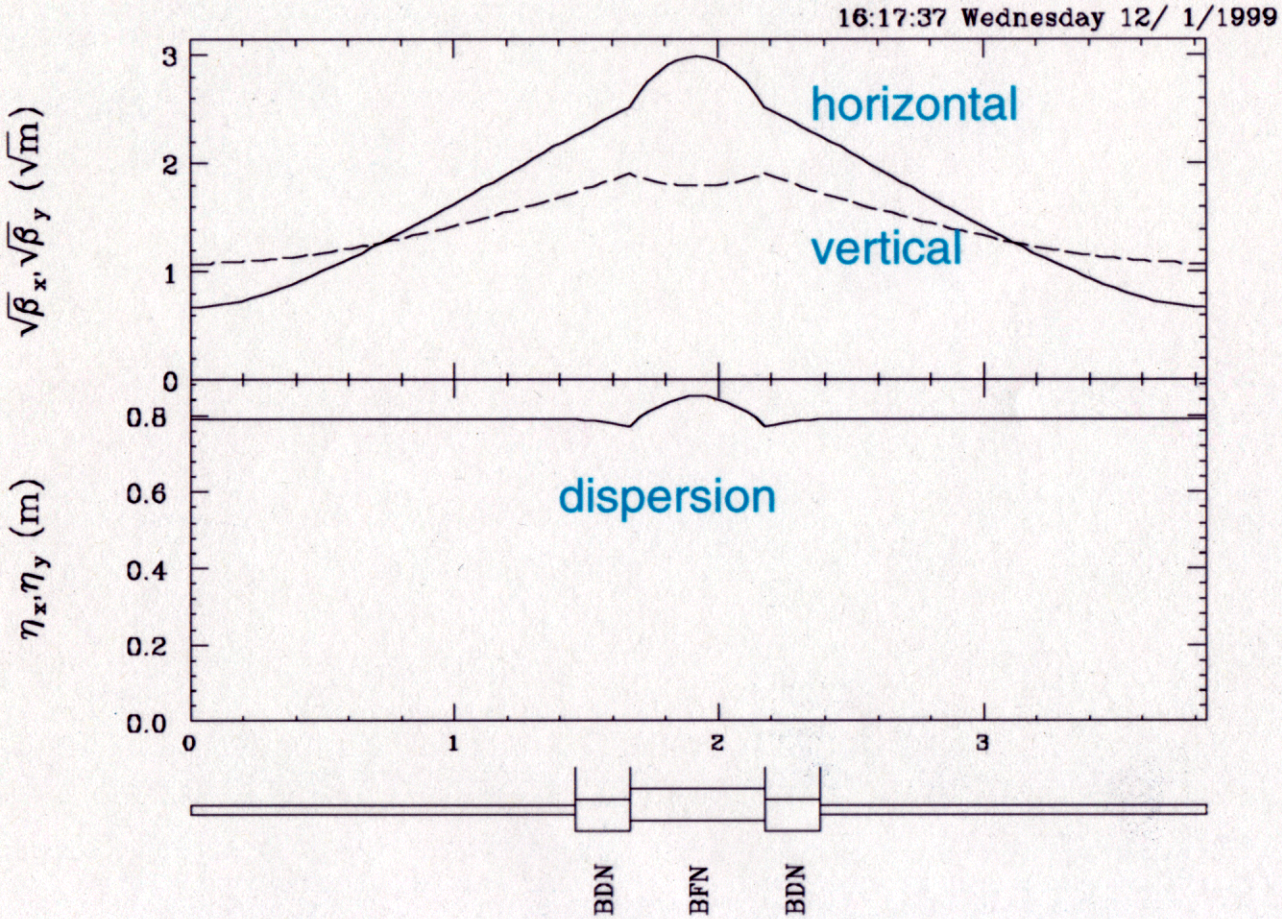

Holizontal
300
200
100
0
-100
-200
-300
dr'(mrad)
-300
-200
-100
0
100
200
300
dr(mm)


Longitudinal
30
20
10
0
-10
-20
-30
dp/p(%)
-150
-100
-50
0
50
100
150
Phi(deg)


linear, h=5
1
0.5
0
-0.5
-1
-3
-2
-1
0
1
2
3
RF amplitude(AU)
Phase(rad)


trun#:0
1
2
3
4
5
2.5MV, sinusoidal
30
20
10
0
-10
-20
-30
dp/p(%)
-150
-100
-50
0
50
100
150
phase(degree)
1
2
3
4
5

Beam Parameters



FFAG Phase Rotation Ring

Phase Rotation : Circular system

synchrotron oscillation

bucket height

$$E = 2\sqrt{\frac{eVE_s\beta_s{}^2}{2\pi h\eta}\left[-\cos\phi_s + \left(\frac{\pi}{2} - \phi_s\right)\sin\phi_s\right]}$$

synchrotron freq.

$$\Omega_s = \omega_0\sqrt{-\frac{heV\eta\cos\phi_s}{2\pi E_s}}$$

FFAG : Fixed Field Alternating Gradient

Large momentum acceptance >+-100%

Zero Chromaticity

Large transverse acceptance > 3000 πmm.mrad

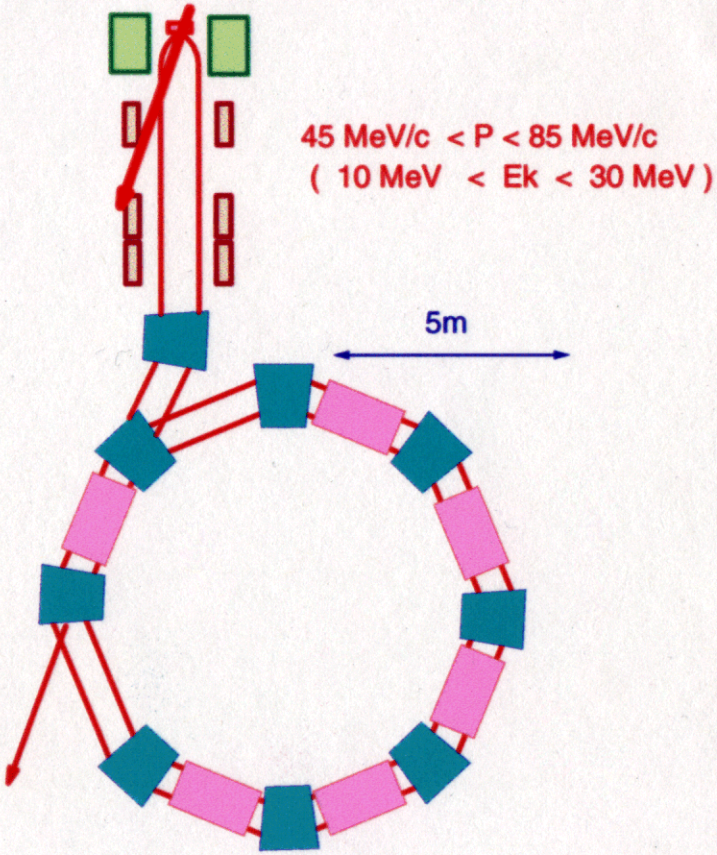
key issue : RF E> 0.2 MV/m@ ~5 MHz

FFAG Phase Rotation Ring (PRISM)

Parameters

Circumference	30.7 m
Straight section	25 m
Focusing	radial sector(triplet)
Field index	5
Average radius	4.3 m@10 MeV
	4.6 m@20 MeV
	4.8 m@30 MeV
Magnetic field	0.3 T @20 MeV
rf voltage	3.2 MV(~200 kV/m x 16 m)
rf frequency	5.6 MHz @20 MeV

FFAG Phase Rotation Ring



1MV/m @5MHz

$$Brf = \frac{V}{\omega S} = \frac{Vrf}{2\pi f_{rf} d(b-a)}$$

$$V = 25kV$$

$$f_{rf} = 5.0 \times 10^6\ Hz$$

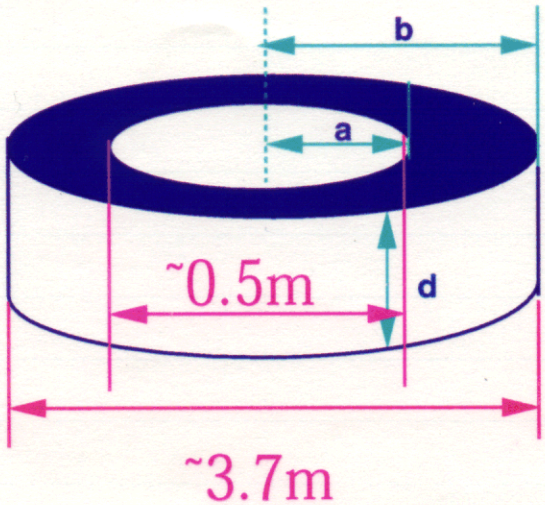
$$d = 25mm \longrightarrow b - a = 1.59m$$

$$R_{sh} = \mu Qf \times \mu_0 \times d \times \ln\frac{b}{a}$$

$$= 1756\Omega$$

$$P_{peak} = 177kW$$

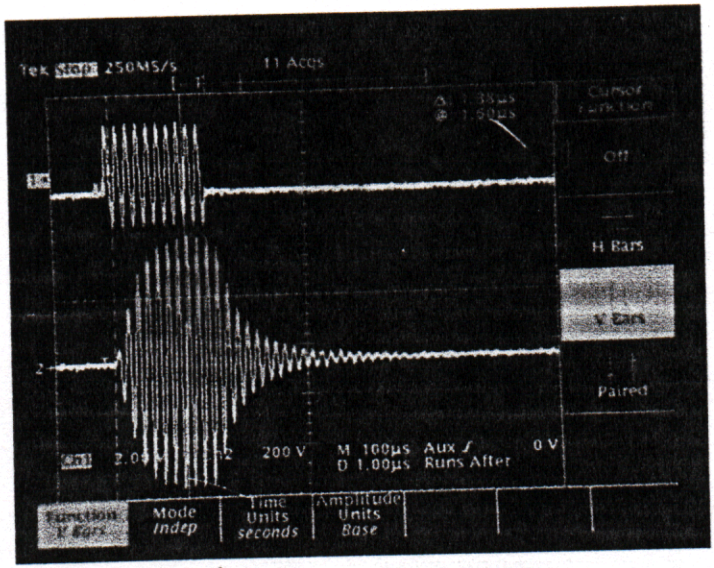
10MV @5MHz



$$d = 10m$$

$$P_{peak} = 7.0MW/m$$

Q value

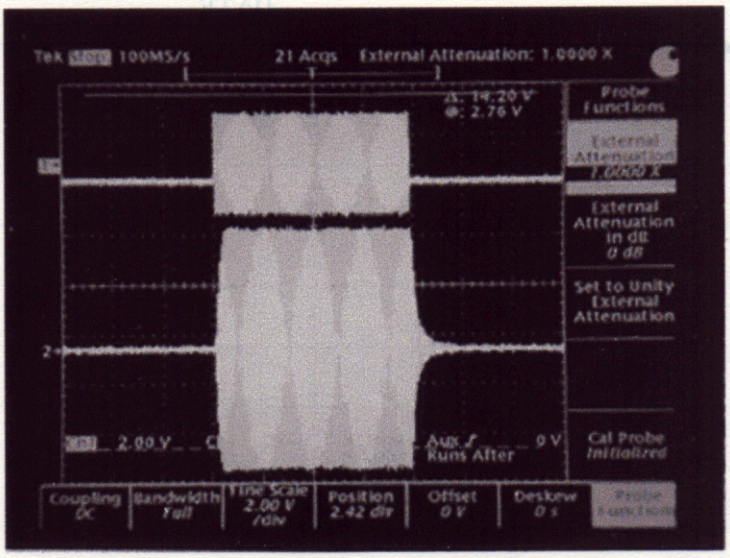


1µsec/div

filling time = 0.5µsec

SY20: Q~10

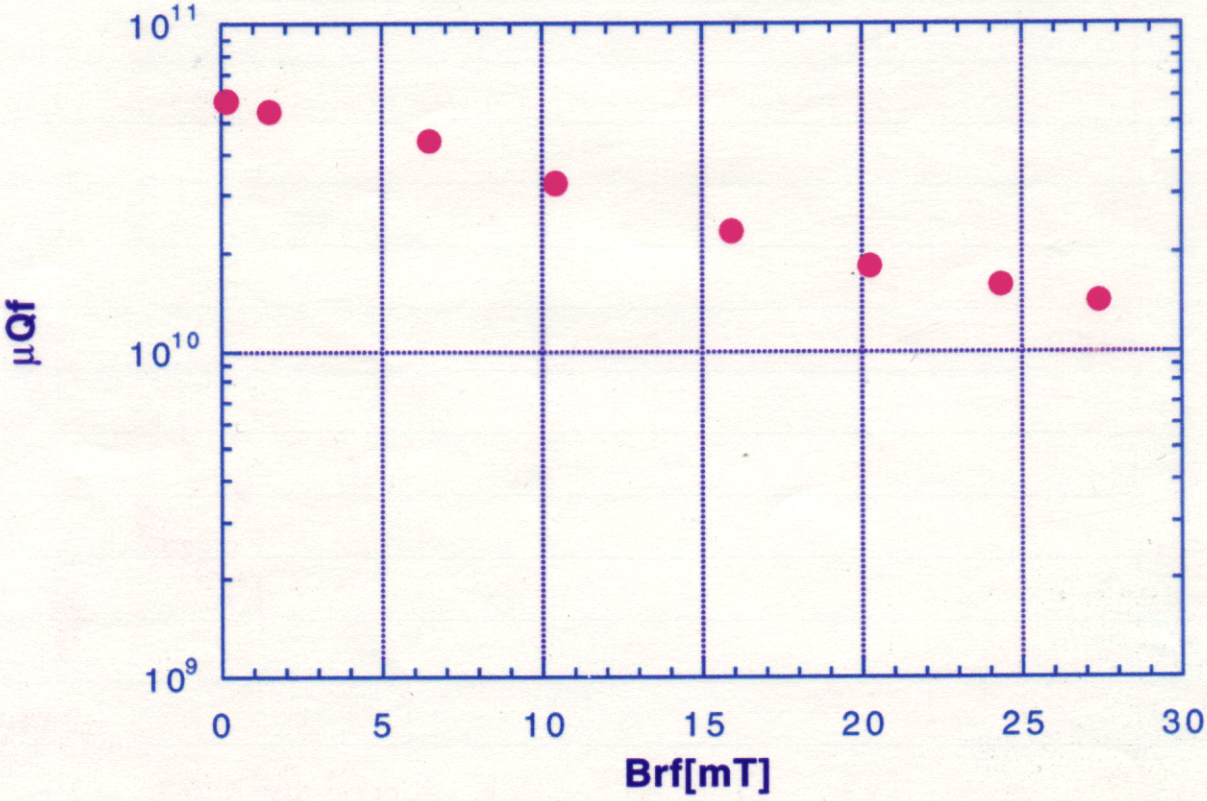
BURST MODE



F.G.

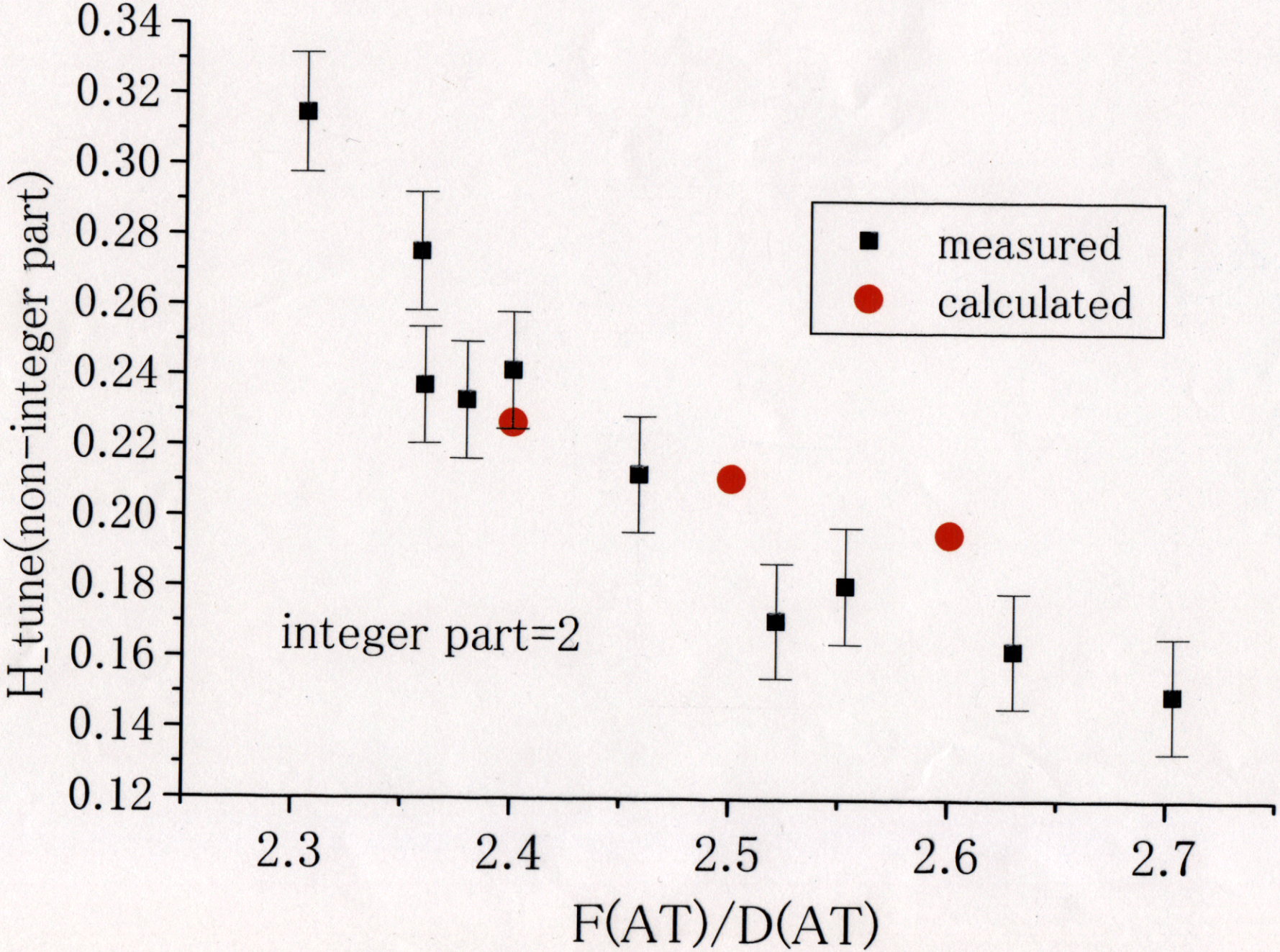
probe

5μsec/div



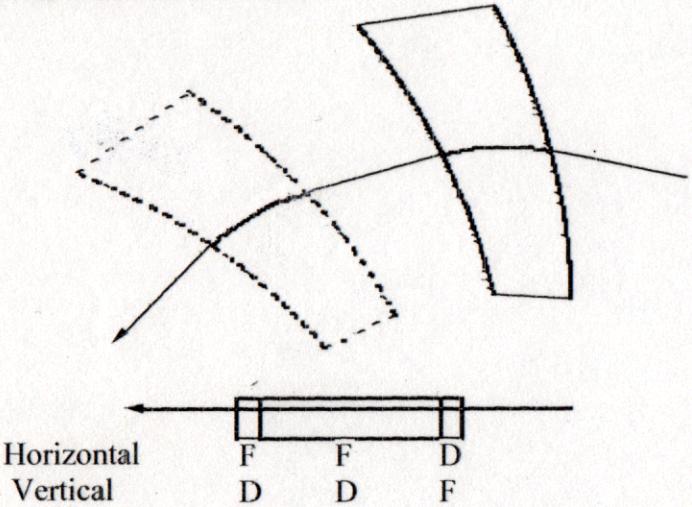
@ Brf = 30mT

Rsh(SY20)= 10 *Rsh(FINEMET)

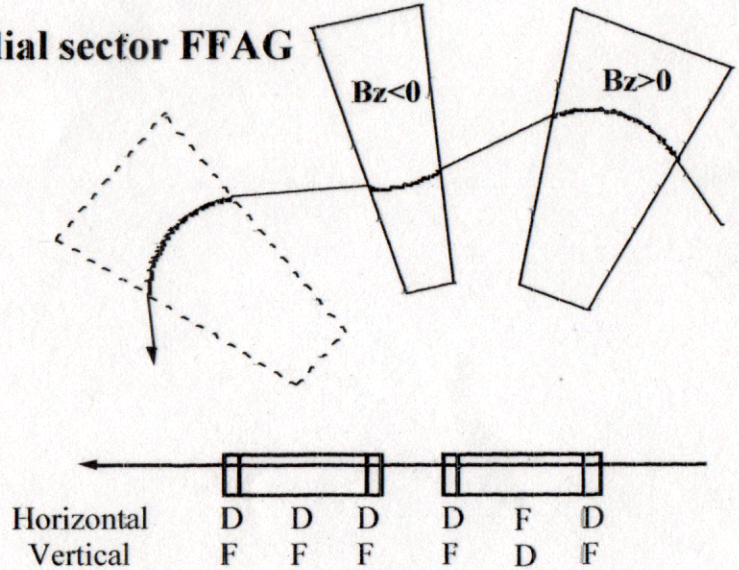

0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
H_tune(non-integer part)
measured
calculated
integer part=2
2.3
2.4
2.5
2.6
2.7
F(AT)/D(AT)

FFAG synchrotron

Spiral sector FFAG

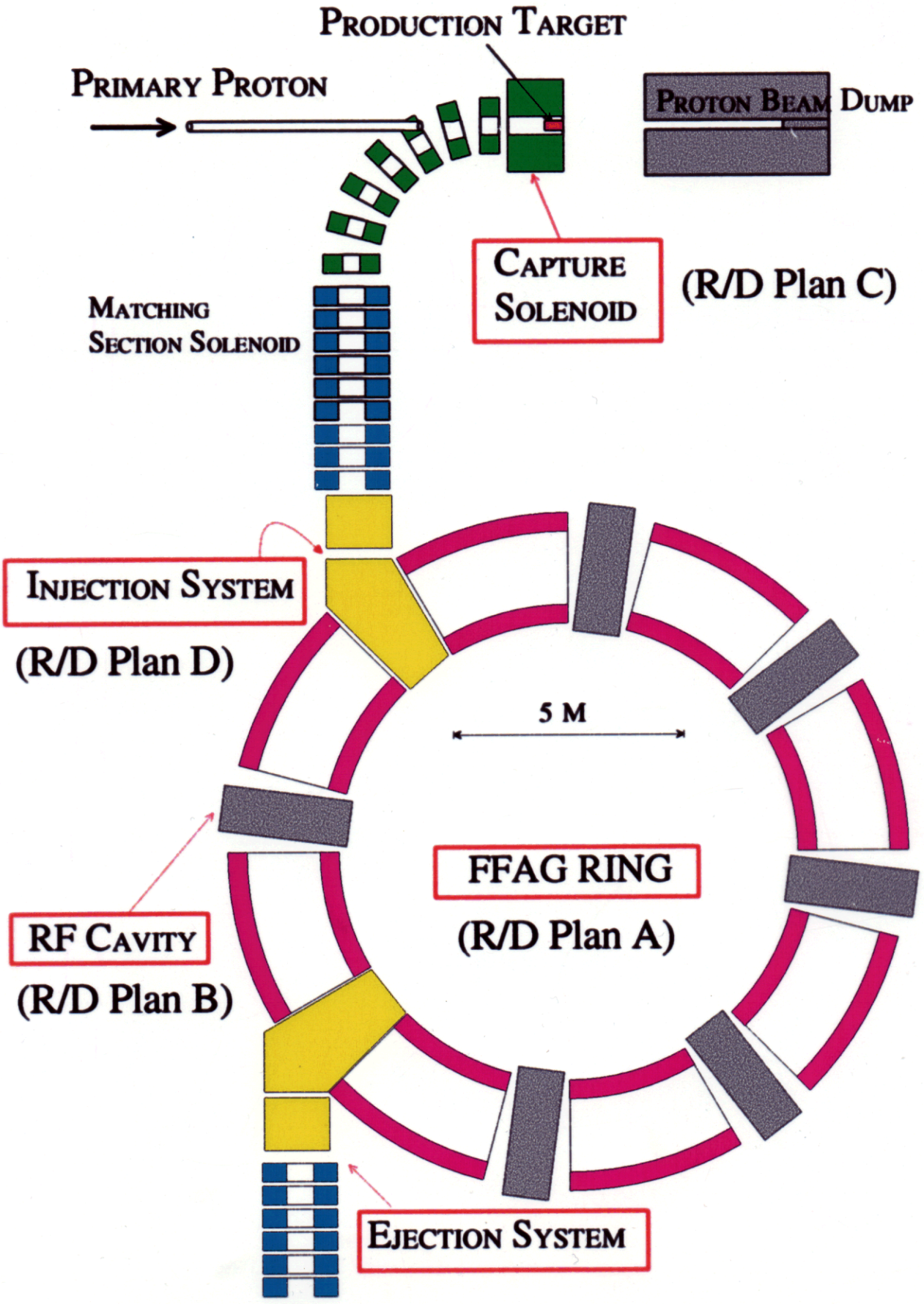


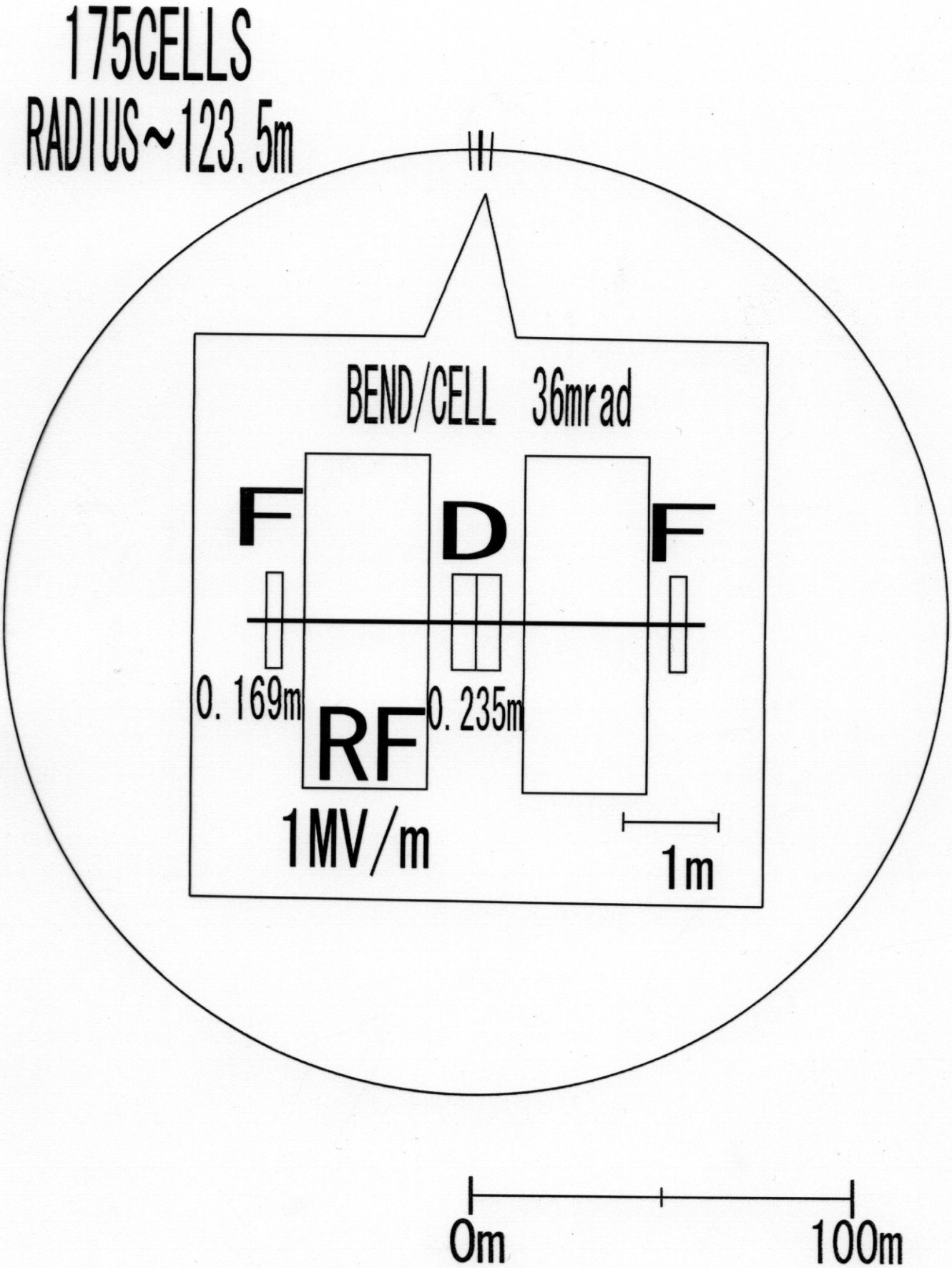
Radial sector FFAG



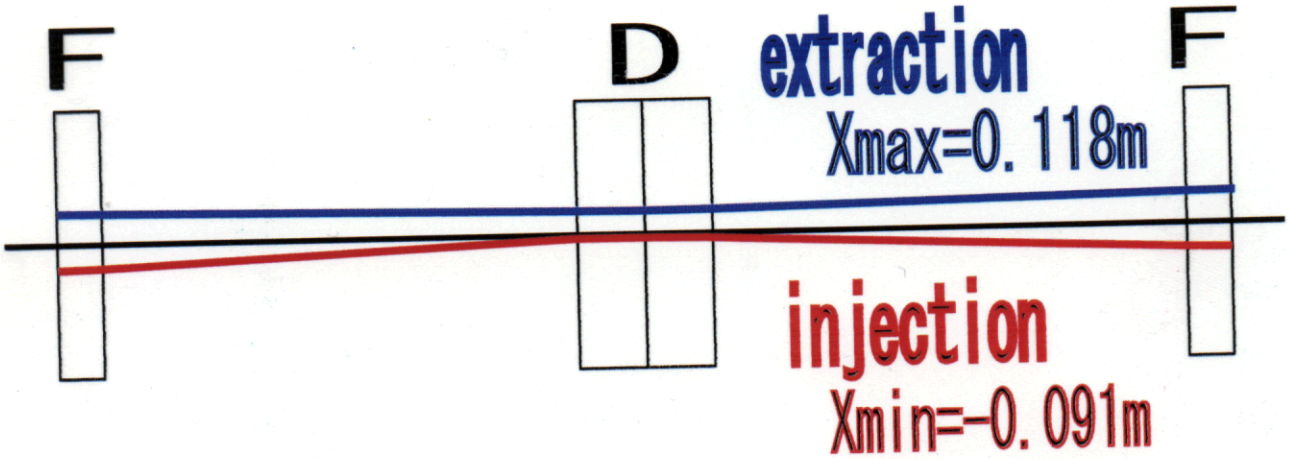
-Smaller magnet.
-Complexity of the magnetic field.
-Defocusing force only by the edge focus.

-Larger magnet and machine size.
-Simplicity of the magnetic field.
-Enable to control the betatron tune by changing the ratio of Fmag. and Dmag. magnetic field.


Production Target
Primary Proton
Proton Beam Dump
Capture Solenoid
(R/D Plan C)
Matching Section Solenoid
Injection System
(R/D Plan D)
5 M
FFAG RING
(R/D Plan A)
RF Cavity
(R/D Plan B)
Ejection System


175CELLS
RADIUS~123.5m
BEND/CELL 36mrad
F
D
F
0.169m
0.235m
RF
1MV/m
1m
0m
100m

ORBIT EXCURSION



rf frequency change

1m

$$\frac{\Delta f_{rf}}{f_{rf}} \sim 0.2\% \rightarrow Q_0 = 100$$

untuned rf cavity

→ high μ ferrite
SY20

Medium Energy FFAG - Non-scaling

by Johnstone

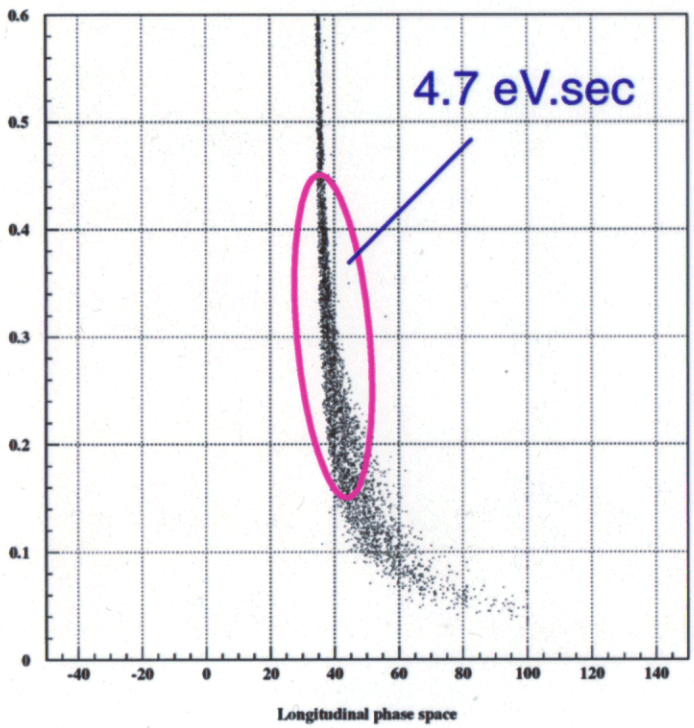
parameters

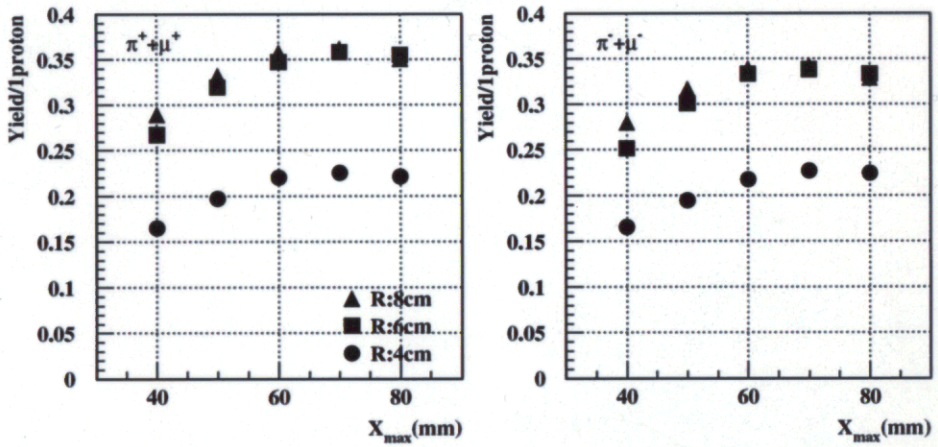
energy	3 GeV ~ 11GeV
acceptance (100%normalized)	10,000 πmm.mrad(~1/5 small)
$\Delta p/p$	+- 6% @3 GeV (does not matter to FFAG)
beam aperture	+- 15cm;Horiz., +-4.5cm;vert. "F"
	+- 10cm;Horiz., +-6cm; vert. "D"
Bmax	< 4T
rf voltage(peak)	1 MV/m

Accelerator Scenario - FFAG Option

Direct Acceleration by Low Frequency RF

No Phase Rotation, No Cooling





$\Delta p/p$=+-50%@300MeV/c, A=0.01-0.02πm.rad

~ 0.3muons / proton @ 50-GeV PS

Accelerator Scenario - FFAG Option

FFAG(Fixed-Field Alternating Gradient) Accelerator

(1) Large Momentum Acceptance

$\Delta p/p$ ~ +- 50% or more

(2) Large Aperture

A ~ 0.01-0.02 πm.rad

(3) Scaling

$p/p_0 \sim (r/r_0)^{k+1}$: tunes=const., $\xi=0$, $\alpha=1/(k+1)$:no higher orders

(4) Non-scaling

linear system

FFAG R & D activities at KEK

Y. Mori (KEK)

1 Introduction

2 Why FFAG ? FFAG for proton driver

3 FFAG for PRISM (Phase Rotation Intense Slow Muons)

4 PoP (proof-of-principle) Machine

Introduction

大河 (1953)

FFAG ---> “Fixed-Field Alternating Gradient” Synchrotron
固定磁場強収束シンクロトロン

特徴

1 磁場が時間的に一定 (Time-invariant Magnetic Field)

2 強収束 (Strong Focusing)

軌道がエネルギーとともに変化
Orbit Excursion
ビームパラメターがエネルギーに依らない
Zero Choromaticity
-----> Very Rapid Acceleration (Cycling)

FFAGの特徴

1 3次元（Trans. & long.）方向の収束

＊強収束

＊シンクロトロン加速

2 一定磁場

＊超伝導化による消費電力の解消

＊高安定性

3 速い繰り返し運転が可能

＊大強度ビーム

4 連続（DC）ビーム取り出しが可能

＊ターゲットの熱負荷が軽減

5 コンパクト

FFAG Phase Rotation Ring

Phase Rotation : Circular system

synchrotron oscillation

bucket height

$$E = 2\sqrt{\frac{eVE_s\beta_s{}^2}{2\pi h\eta}\left[-\cos\phi_s + \left(\frac{\pi}{2} - \phi_s\right)\sin\phi_s\right]}$$

synchrotron freq.

$$\Omega_s = \omega_0\sqrt{-\frac{heV\eta\cos\phi_s}{2\pi E_s}}$$

FFAG : Fixed Field Alternating Gradient

Large momentum acceptance >+-100%

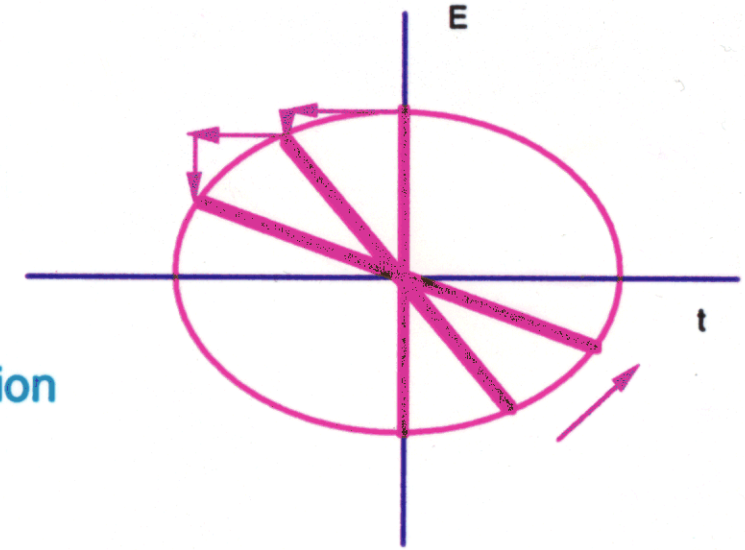
Zero Chromaticity

Large transverse acceptance > 3000 πmm.mrad

key issue : RF E> 0.2 MV/m@ ~5 MHz

Phase Rotation - Monochrometer

Energy - time space (longitudinal phase space)

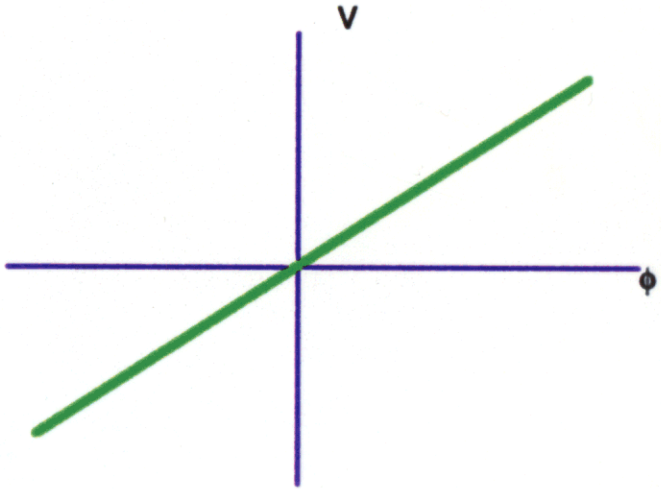


Drift & Linear Kick ----> Synchrotron Oscillation

Non-linear

Kick : RF(sinusoidal)

Drift : relativistic, path length



Power Test of High Gradient Test Cavity

TEST CAVITY

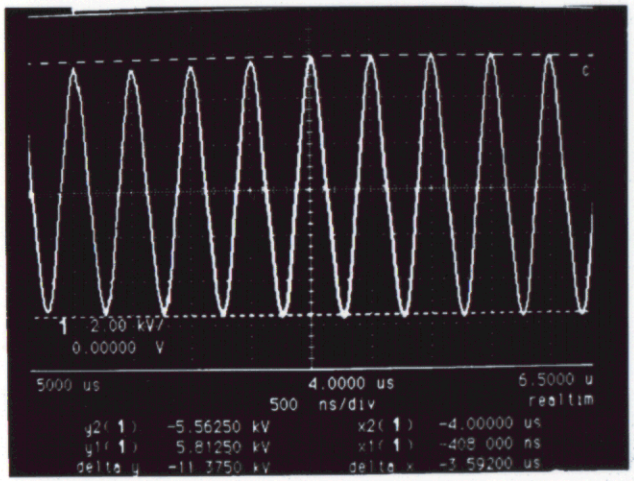
- *Single core (O.D=580mm,I.D=250mm, t=25mm)
- *Direct water cooling
- *RF power :30kW max.(B-class)

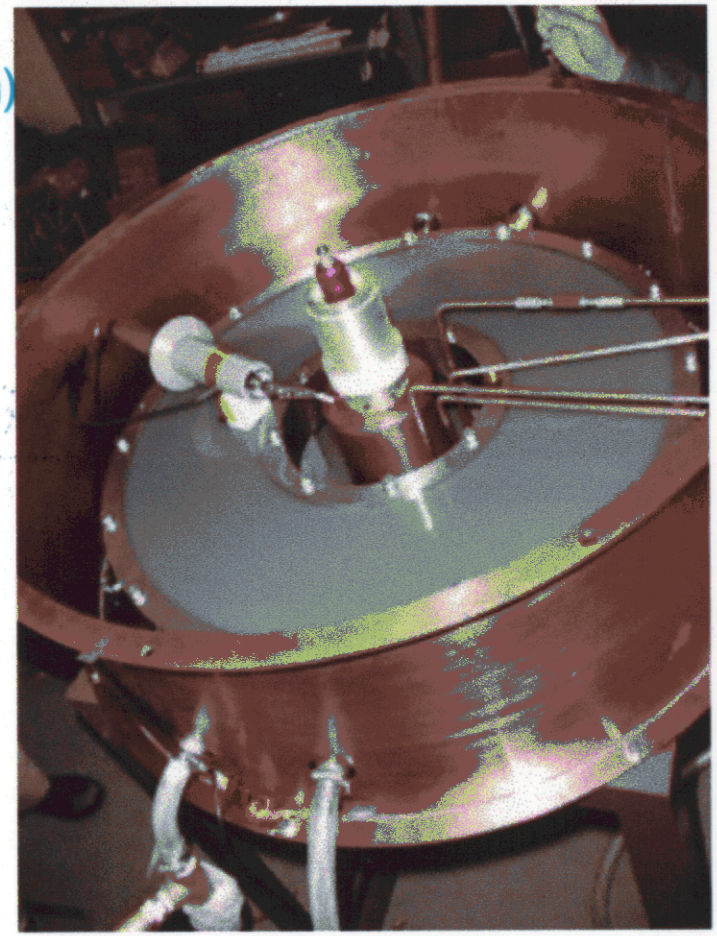
Achieved:

EFG = 100kV/m (cw)

EFG = 220kV/m (burst)

(limited by RF amplifier)





The gap voltage of the test cavity. The maximum RF voltage of 5.5kV(=220kV/m)was obtained.

Phase Rotation

phase rotation : synchrotron motion in rf bucket

synchrotron tune : $$\nu_s = \sqrt{\frac{eV|\eta|}{2\pi\beta^2 E_s}}$$

bucket height : $$E = 2\sqrt{\frac{eVE_s\beta^2}{2\pi|\eta|}}$$

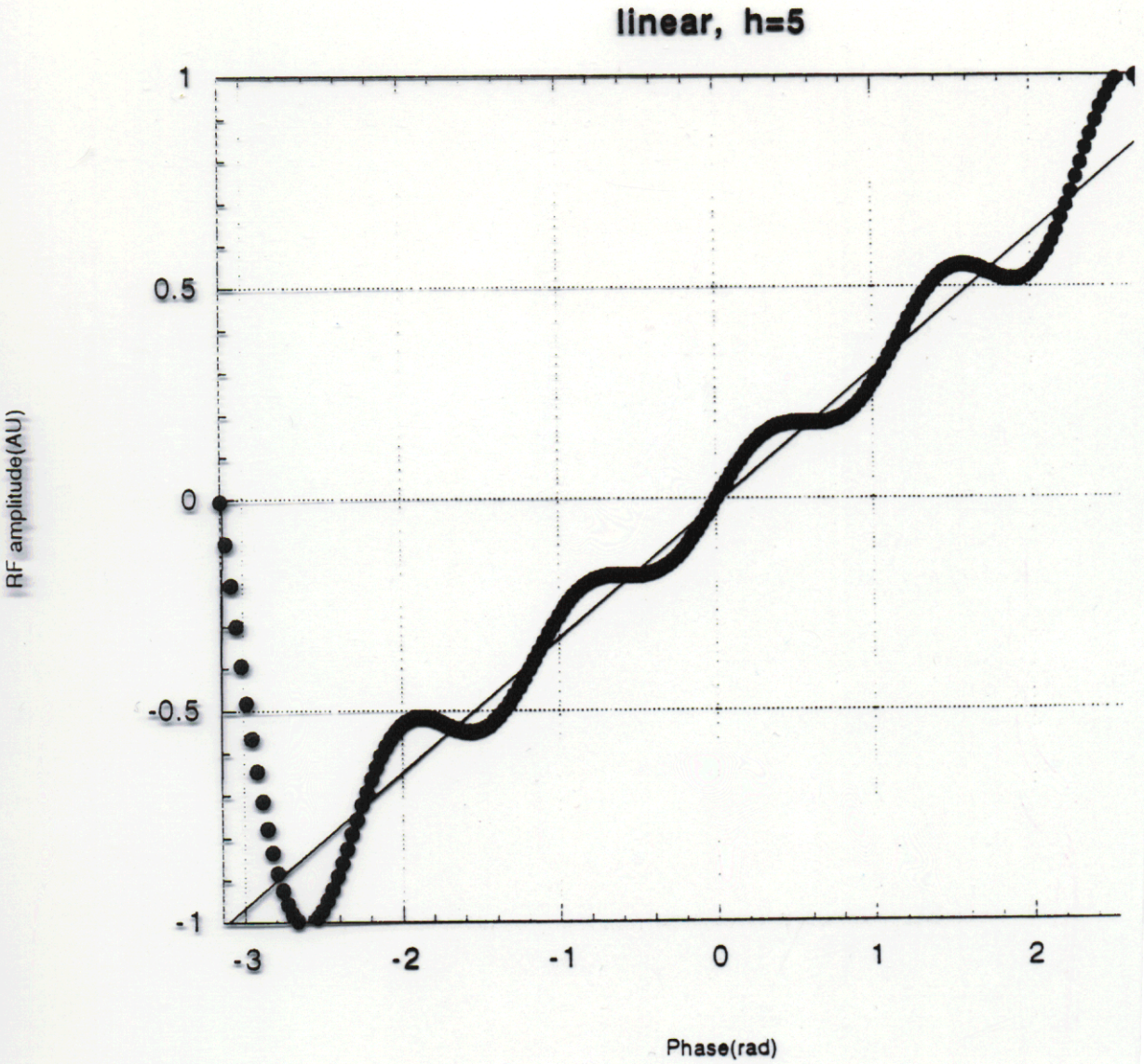
η: slippage factor $\Delta T/T=\eta(\Delta p/p)$

$T=C/v$

$\Delta T/T=\Delta C/C - \Delta v/v$

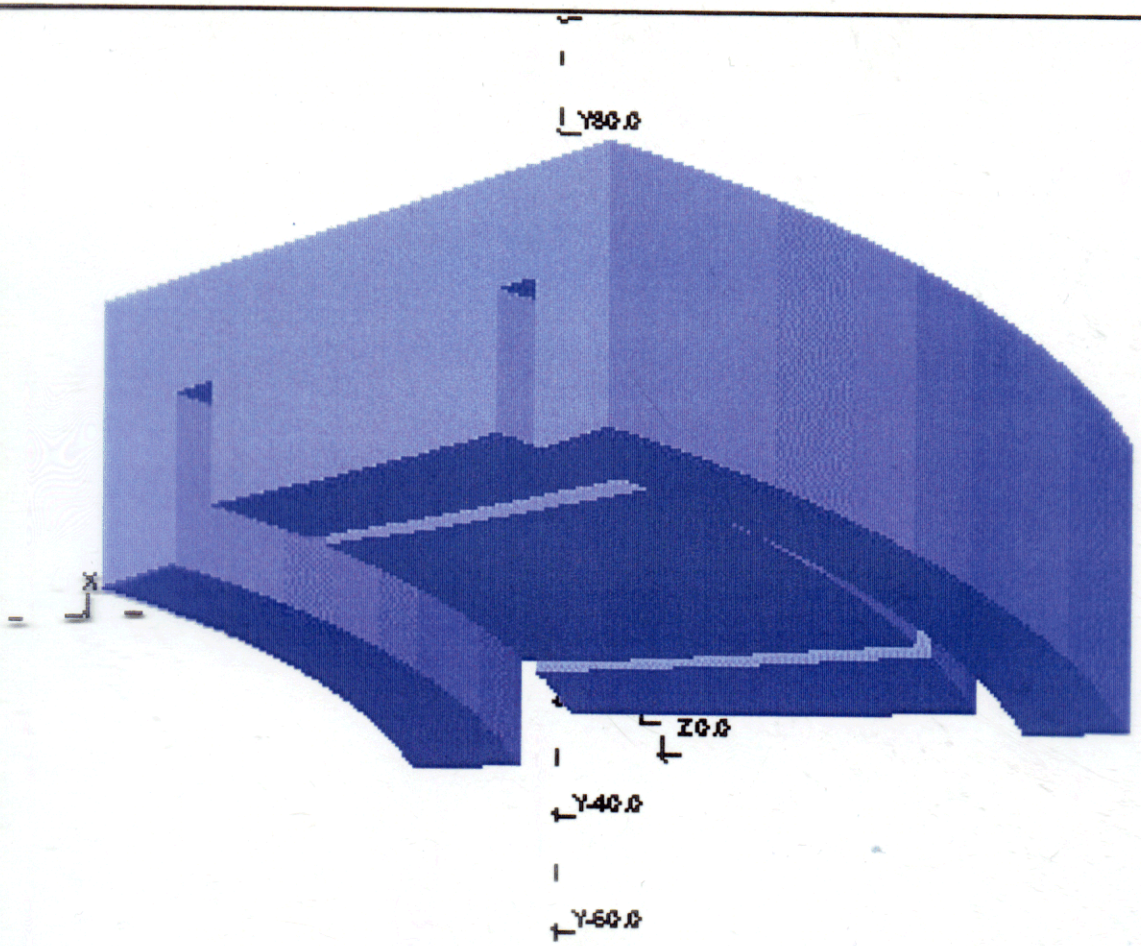
Linac : $\Delta C/C=0$ ===> $\Delta T/T=-\Delta v/v=-1/\gamma^2(\Delta p/p)$

Ring : $\Delta C/C=\alpha(\Delta p/p)$ ===> $\Delta T/T=(\alpha-1/\gamma^2)(\Delta p/p)$

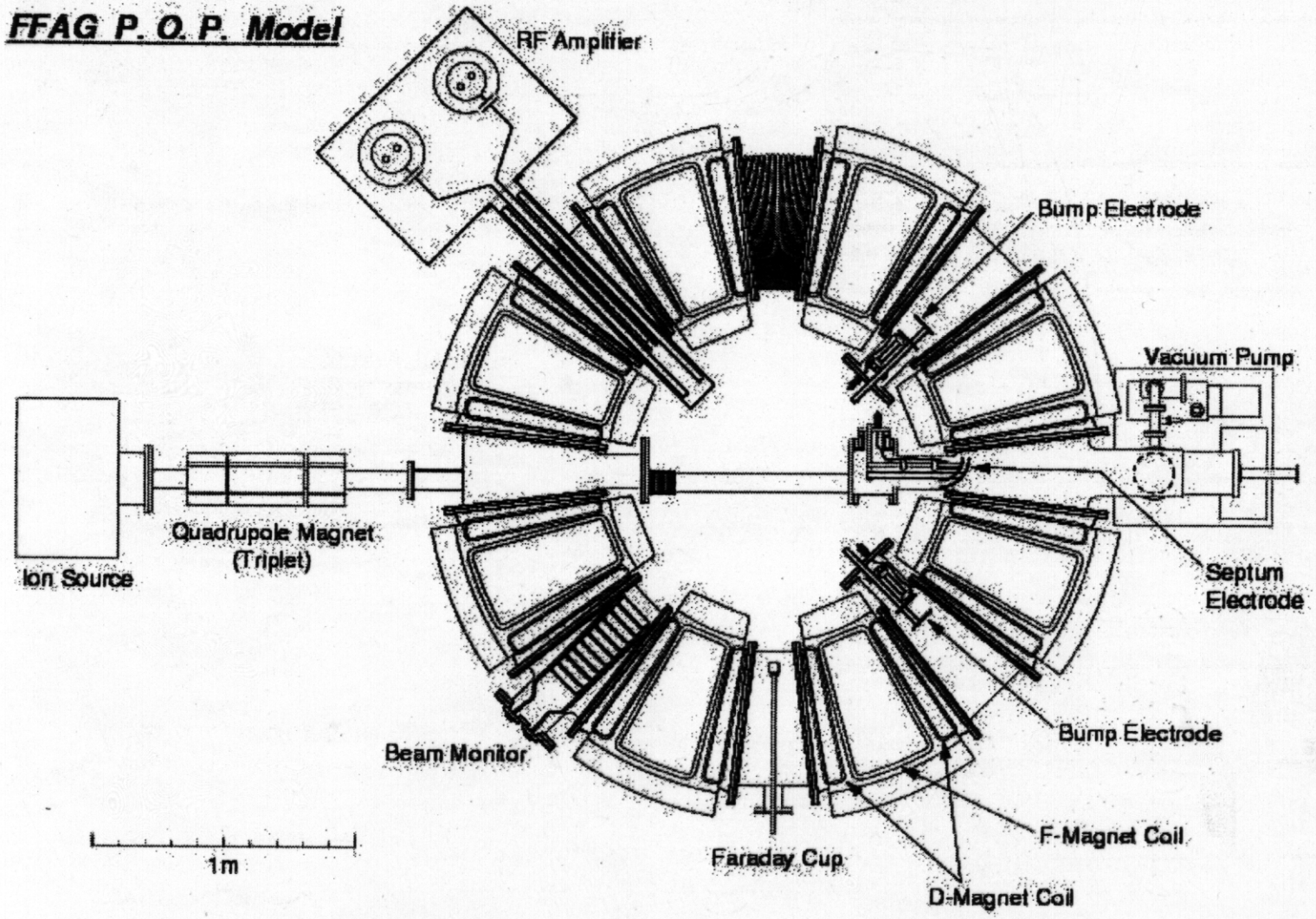

linear, h=5
1
0.5
0
-0.5
-1
-3
-2
-1
0
1
2
RF amplitude(AU)
Phase(rad)

FFAG 1MeV POP Model parameters

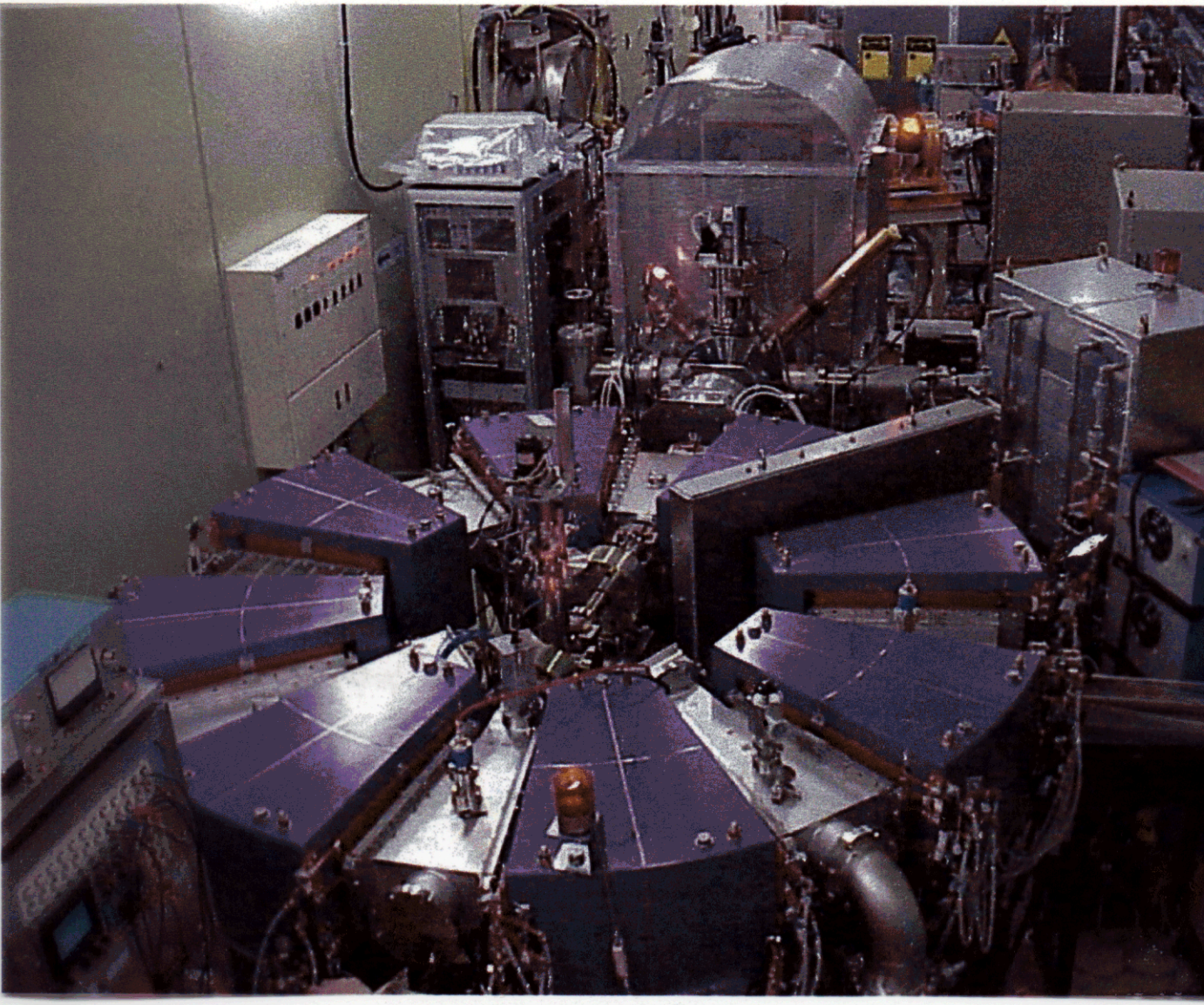
Type of magnet	Radial sector type (Triplet)
No. of sector	8
Field index (k-value)	2.5
Energy	100keV～1MeV
Repetition	1kHz
Magnetic field	Focus mag. : 0.2T～0.5T
	Defocus mag. : 0.1T～0.2T
Radii of closed orbits	0.89m～1.14m
Betatron tune	2.24～ 2.19 (Horizontal)
	1.38～ 1.33 (Vertical)
RF frequency	1.10MHz ～1.97MHz
RF Voltage	～3kVp (aiming 6kVp)



200MeV FFAG MAGNET



2000年2月のPOP機コミッショニングに大きな期待

未来開拓学術研究推進事業準備研究
平成12年1月22日

FFAG POP model