Ultra-Precise Beams of RCNP Cyclotron
- Practice and New Non-Linear Orbit Theory -
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ＲＣＮＰサイクロトロンの超高品質ビーム
－　その実践と新しい非線形軌道理論　－
平成１３年１０月１６日　ＳＰｒｉｎｇ－８

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Successful Achievement of Ultra-Precise Beams
But
Happenings of Deteriolation of Ultra-Precise Beams
Reveals Necessity of
New Non-Linear Orbit Theory

A thing left in cyclotrons
without being noticed by anyone so far

超高品質ビームの実現に成功
しかし
超高品質ビームが悪化する現象が発生し、その説明には
新しい非線形軌道理論
が必要

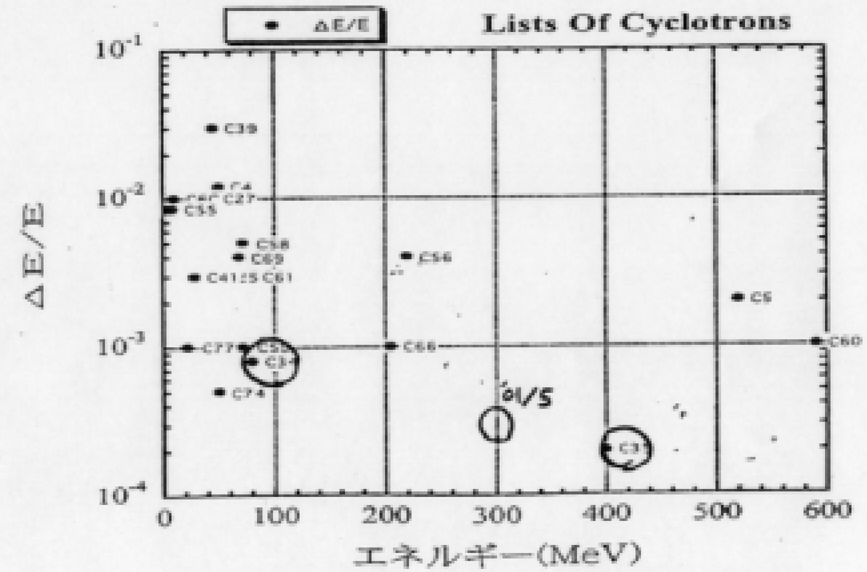
誰も気付かなかった、サイクロトロンの忘れ物

Further Achivement of Hyper-Precise Beams
Beyond Ultra-Precise Beams
due to Development and Invention of a New Device
for Curing a Non-Linear Behavior

超高品質ビームを越える
極超高品質ビームの実現を目指して
非線形ビーム挙動を矯正する新装置の開発と発明

Lists of Cyclotrons

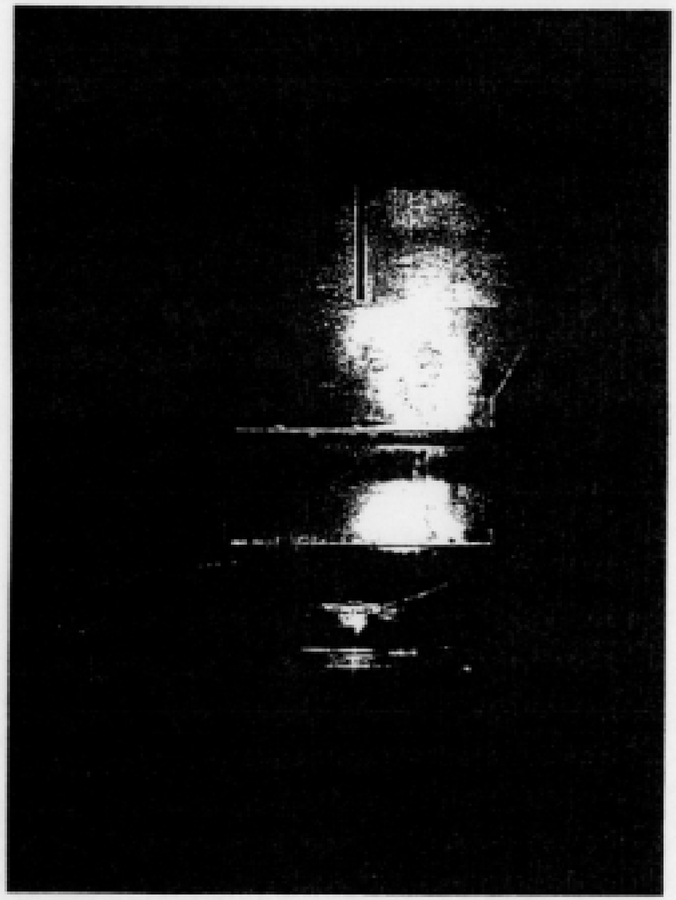
識別番号	研究所の名称		k値	ΔE/E
C1	Louvain-la-Neuve(BELGIUM)	85MeV, p,,,,h.I.	K=110	0.003
C4	Winnipeg(U.of Man)(CANADA)	50MeV, p,....		0.012
C5	Vancouver(TRIUMF)(CANADA)	520MeV, H-		0.002
C6	Santiago(U.de Chile)(CHILE)	10MeV, p,...		0.01
C10	Shanghai(INR)(CHINA)	30MeV, p,...		0.01
C23	Berlin(HMI)(GERMANY)	72MeV, p,,,h.I.	k=130	0.001
C25	Julich(KFK)(GERMANY)	45MeV, H-,..,	k=180	0.003
C27	Karlsruhe(KFK)(GERMANY)	42MeV, H-		0.01
C28	Munich(Tech. U.)(GERMANY)	22MeV, p,...		0.001
C34	Osaka(RCNP)	80MeV, p,..	k=140	0.0009
C35	Osaka(RCNP)	400MeV, p,..	k=400	0.0002
C39	Tokyo(INS)	45MeV, p,..,h.I.	k=68	0.03
C40	Alma Ata(INP)(KAZAKHSTAN)	30MeV, p,...		
C41	Amsterdam(Vrije U.)(NETHERLANDS)	28MeV, p,...		0.003
C43	Eindhoven(U. of Tech)(NETHERLANDS)	29.5MeV, p,...		
C54	Faure(NAC)(SOUTH AFRICA)	8MeV, p,..		0.0085
C55	Faure(NAC)(SOUTH AFRICA)	8MeV, p,..,h.I.	k=11	0.0085
C56	Faure(NAC)(SOUTH AFRICA)	220MeV, p,,h.I.	k=220	0.004
C58	Villigen(PSI)(SWITZERLAND)	72MeV, p,...		0.005
C59	Villigen(PSI)(SWITZERLAND)	72MeV, p		0.001
C60	Villigen(PSI)(SWITZERLAND)	590MeV, p		0.001
C61	Kiev(INR-UAS)(UKRAINE)	78MeV, p,..		0.003
C66	Bloomington(IUCF)(UNITED STATES)	205MeV, p,..		0.001
C66	Bloomington(IUCF)(UNITED STATES)	205MeV, p,..		0.001
C69	Davis(U. of Cal.)(UNITED STATES)	68MeV, p,..		0.004
C74	Princeton(U.)(UNITED STATES)	50MeV, p,...		0.0005
C77	Tashkent(NP)(UZBEKISTAN)	22MeV, p,...		0.001



Proposal of Upgrading Project: Part 1
Flat–topping of rf accelerating voltage

The 5th higher harmonics for flat topping:
  contaminated by a parasitic half–wave resonance
Control of a resonant frequency of a parasite:
  by installing a center slit for Dee electrode

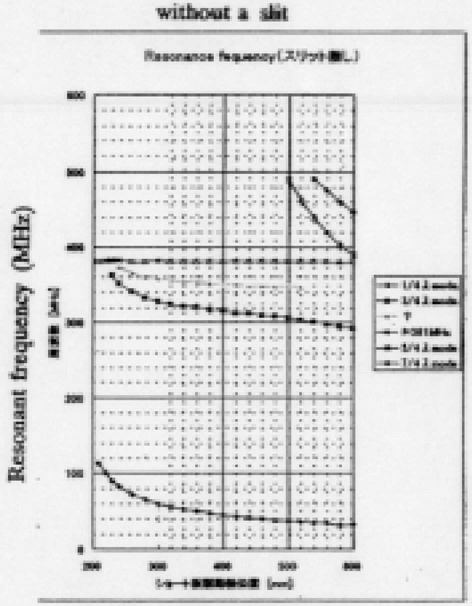
Investigations by Model Dee Electrode with a Slit

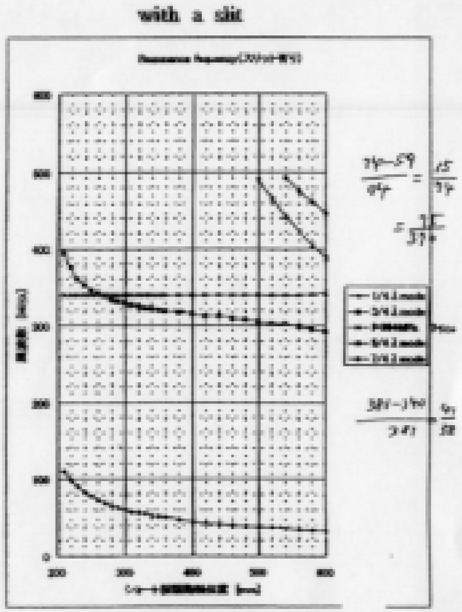


Measurement of Resonant Frequencies in a Model

Dependence on a shorting plate position

Without a center slit **With a center slit**





Frequency shift of a half–wave resonance with a center slit:
  10 % down as expected and
  enough for avoidance of overlapping of resonances

VII. 当面,何をすれば良いのか（阪大RCNPの場合）

① 電磁石の鉄芯温度の制御による磁場の安定化

② AVF：取り出し半径での２種類のビームスクレーパ

③ AVF：加速電圧のフラット・トップ化

④ 加速電圧の振幅,周波数,位相の変調

⑤ これらに加えて,プラス・アルファの何かが必要！

イオン源

↓ トランスポートでの整形：縦方向マッチング

AVF入射

↓

AVF取り出し

↓ トランスポートでの整形：縦方向マッチング

リング入射

↓

リング取り出し

軌道理論として今後解きたいこと

横方向運動と縦方向運動の結合運動

‖ ‖

調和振動 ＝二重の非線形振動の

$\cos\phi$, r^2

Isochronous cyclotrons

$\nu_r = \nu_z$

General equations of motion

$$\ddot{x} + \nu_n^2 \dot{\theta}_n^2 x = \frac{c^2 \dot{\theta}_n}{\nu_n r_n} r - 2\left(\frac{3}{4} - \frac{1}{\nu_n^2}\right)\frac{c^4}{\nu_n^4 r_n^3} r^2 + \frac{g r_n \dot{\theta}_n}{m_0 \nu_n} b$$

$$\dot{\phi} - 2\left(\frac{3}{4} - \frac{5}{4}\frac{1}{\nu_n^2} + \frac{1}{\nu_n^4}\right)\frac{h c^4}{\nu_n^4 r_n^4 \dot{\theta}_n} r^2$$

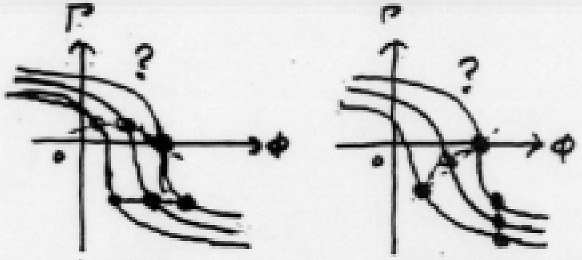
$$= -\frac{h}{\nu_n^2 r_n \dot{\theta}_n}\ddot{x} + \frac{h g}{m_0 \nu_n^3} b + \omega_{rf} - \omega_{rf,n} + \dot{\phi}_{rf}$$

$$\dot{r} = \frac{g V_n}{2\pi m_0 c^2}(\cos\phi - \cos\phi_n) + \frac{g v}{2\pi m_0 c^2}\cos\phi_n$$

Problems

Problem 1. What is an initial beam condition to realize a desired final beam performance ?

Narrow energy spread	Narrow phase spread	Narrow position spread
		See the following relation between x and Γ and $\dot{\phi}$.



$$\dot{\phi}+\frac{k c^2}{\kappa_n^2 r_n^2}\Gamma-\left(\frac{3}{2}-\frac{1}{\kappa_n^2}\right)\frac{k c^4}{\kappa_n^4 r_n^4 \dot{\theta}_n}\Gamma^2-\frac{k\dot{\theta}_n}{r_n}x=\omega_f-\omega_{f,n}+\dot{\phi}_f$$

Note : It can be considered that the tuning of the deviation of the magnetic field controls a shape of the final beam for the given initial beam condition.

Problem 2. How an initial beam condition can be realized at injection to cyclotrons ?

Invent a non-linear device for an injection beam transport line in order to control a relation among Γ, ϕ and x.

Problem Make clear beam dynamics at flat-top of rf accelerating voltage.

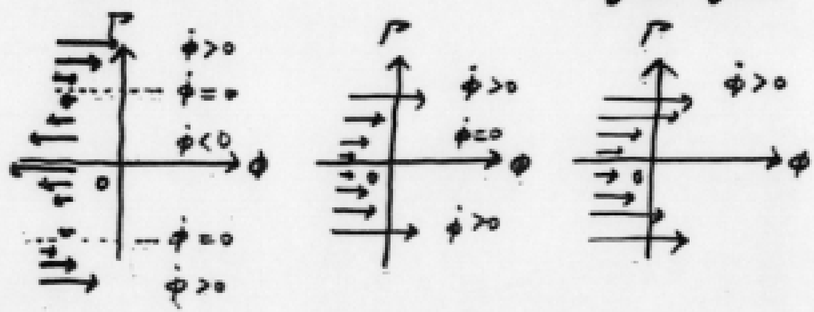
Ideal flat-top

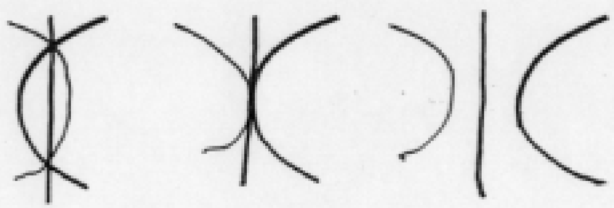
$$\begin{cases}\dot{\phi}=2\left(\frac{3}{4}-\frac{5}{4}\cdot\frac{1}{\kappa_n^2}+\frac{1}{\kappa_n^4}\right)\frac{k c^4}{\kappa_n^4 r_n^4 \dot{\theta}_n}\Gamma^2+\frac{k\delta}{m_n \kappa_n^3}b\\ \dot{\Gamma}=0\end{cases}$$

$\Gamma=$ const.

$$\dot{\phi}=2\left(\frac{3}{4}-\frac{5}{4}\cdot\frac{1}{\kappa_n^2}+\frac{1}{\kappa_n^4}\right)\frac{k c^4}{\kappa_n^4 r_n^4 \dot{\theta}_n}\left\{\Gamma^2+\frac{\frac{k\delta}{m_n \kappa_n^3}}{2\left(\frac{3}{4}-\frac{5}{4}\cdot\frac{1}{\kappa_n^2}+\frac{1}{\kappa_n^4}\right)\frac{k c^4}{\kappa_n^4 r_n^4 \dot{\theta}_n}}b\right\}$$

$b<0$	$b=0$	$b>0$
Increase of magnetic field		Decrease of magnetic field





Increase of magnetic field : $b<0$

$$\Gamma_u-\Gamma_\ell=2\Gamma_u=2\frac{\gamma_n}{\dot\theta_n}\left(\frac{r_n\dot\theta}{c}\right)^2\sqrt{-\frac{1}{2}\cdot\frac{1}{\frac{3}{4}-\frac{5}{4}\frac{1}{\gamma_n^2}+\frac{1}{\gamma_n^4}}\cdot\frac{b}{|B_{0n}|}}$$

where $\left(\frac{r_n\dot\theta_n}{c}\right)^2\simeq\frac{\gamma_n^2-1}{\gamma_n^2}=\frac{(\gamma_n+1)(\gamma_n-1)}{\gamma_n^2}$

$$(\phi_u-\phi_\ell)\cos\phi_n-(\sin\phi_u-\sin\phi_\ell)$$

$$=-\frac{2h\frac{\gamma_n+1}{\gamma_n^3}}{\frac{3}{2}\cdot\frac{1}{2\pi}\cdot\frac{eV_n}{m_0c^2(\gamma_n-1)}}\cdot\frac{b}{|B_{0n}|}\sqrt{-\frac{1}{2}\cdot\frac{1}{\frac{3}{4}-\frac{5}{4}\frac{1}{\gamma_n^2}+\frac{1}{\gamma_n^4}}\cdot\frac{b}{|B_{0n}|}}$$

Relative energy difference to kinetic energy

$$\frac{\Delta E}{E}=\frac{\gamma_u-\gamma_\ell}{\gamma_n-1}=\frac{\dot\theta_n(\Gamma_u-\Gamma_\ell)}{\gamma_n-1}=2\frac{\gamma_n+1}{\gamma_n}\sqrt{-\frac{1}{2}\frac{1}{\frac{3}{4}-\frac{5}{4}\frac{1}{\gamma_n^2}+\frac{1}{\gamma_n^4}}\cdot\frac{b}{|B_{0n}|}}$$

Polynominal approximation of phase difference

$$(\phi_u-\phi_\ell)(\cos\phi_n-\cos\phi_\ell)+\frac{1}{2}(\phi_u-\phi_\ell)^2\sin\phi_\ell+\frac{1}{6}(\phi_u-\phi_\ell)^3\cos\phi_\ell$$

$$=-\frac{2h\frac{\gamma_n+1}{\gamma_n^3}}{\frac{3}{2}\cdot\frac{1}{2\pi}\cdot\frac{eV_n}{m_0c^2(\gamma_n-1)}}\cdot\frac{b}{|B_{0n}|}\sqrt{-\frac{1}{2}\cdot\frac{1}{\frac{3}{4}-\frac{5}{4}\cdot\frac{1}{\gamma_n^2}+\frac{1}{\gamma_n^4}}\cdot\frac{b}{|B_{0n}|}}$$

In case of $\phi_\ell=\phi_n=0$,

$$\frac{1}{6}(\phi_u-\phi_\ell)^3=-\frac{2h\frac{\gamma_n+1}{\gamma_n^3}}{\frac{3}{2}\cdot\frac{1}{2\pi}\frac{eV_n}{m_0c^2(\gamma_n-1)}}\cdot\frac{b}{|B_{0n}|}\sqrt{-\frac{1}{2}\cdot\frac{1}{\frac{3}{4}-\frac{5}{4}\cdot\frac{1}{\gamma_n^2}+\frac{1}{\gamma_n^4}}\cdot\frac{b}{|B_{0n}|}}$$

$$\phi_u-\phi_\ell=\left(+\frac{6\times2\cdot h\frac{\gamma_n+1}{\gamma_n^3}}{\frac{3}{2}\cdot\frac{1}{2\pi}\frac{eV_n}{m_0c^2(\gamma_n-1)}}\sqrt{-\frac{1}{2}\frac{1}{\frac{3}{4}-\frac{5}{4}\frac{1}{\gamma_n^2}+\frac{1}{\gamma_n^4}}}\right)^{\frac{1}{3}}\sqrt{-\frac{b}{|B_{0n}|}}$$

Numerical example : $b<0$

50MeV proton ; $m_0c^2(\gamma_n-1)=50\,\text{MeV}$, $\gamma_n\simeq1.053$

100kV rf accelerating voltage ; $eV_n=100\,\text{keV}$

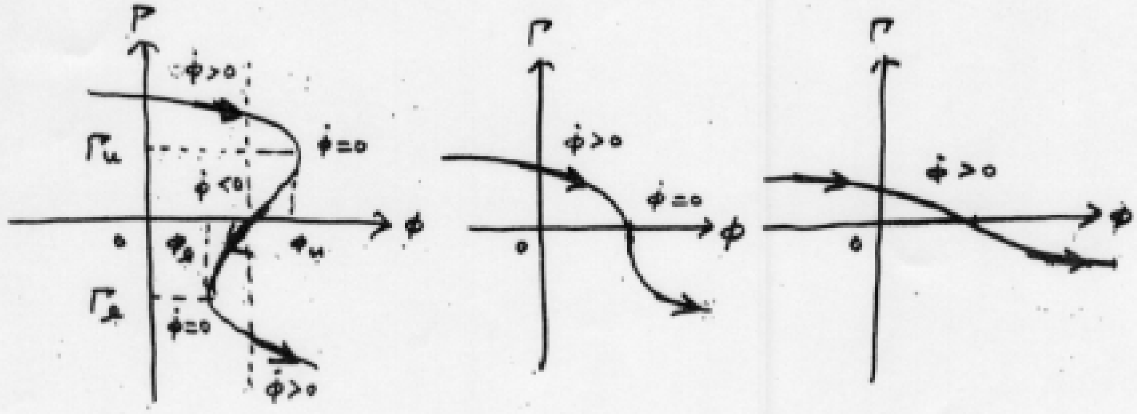
harmonic number ; $h=1$

$$\frac{\Delta E}{E}\simeq4.18\sqrt{-\frac{b}{|B_{0n}|}}$$

$$\phi_u-\phi_\ell\simeq36.2\sqrt{-\frac{b}{|B_{0n}|}}$$

$-\frac{b}{\lvert B_{0n}\rvert}$	$\frac{\Delta E}{E}$	ΔE	$\phi_u-\phi_\ell$ (rad)	$\phi_u-\phi_\ell$ (deg)
1 ppm $=10^{-6}$	4.18×10^{-3}	209 keV	3.62×10^{-2}	2.07°
10 ppm $=10^{-5}$	1.32×10^{-2}	661 keV	1.14×10^{-1}	6.56°

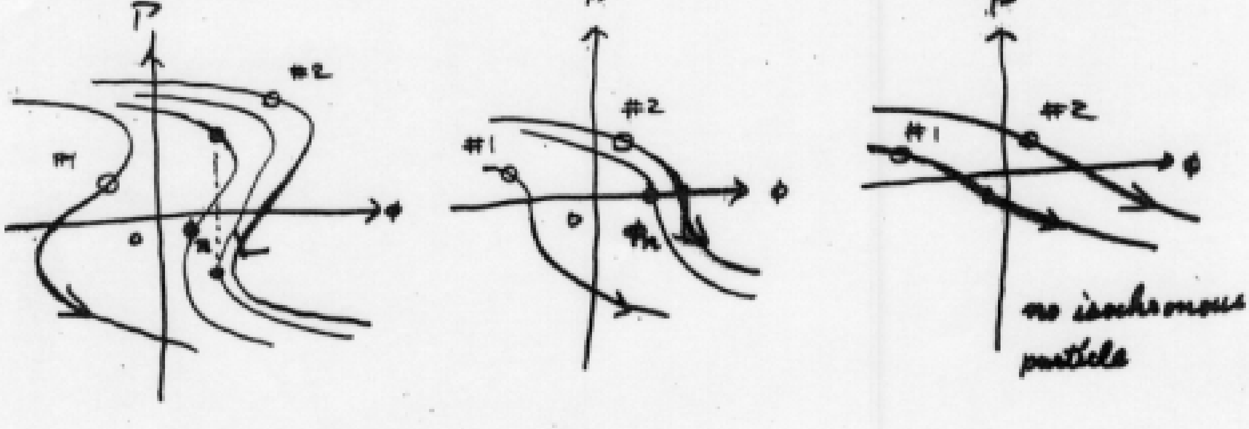
$b<0$	$b=0$	$b>0$
Increase of magnetic field		Decrease of magnetic field



$\Gamma_\ell = -\Gamma_u$ *no isochronism!*

Trajectory of different particles

$b<0$	$b=0$	$b>0$
Increase of magnetic field		Decrease of magnetic field



○ : initial condition of each particle at $t=0$

● : unstable fixed points = isochronous particle

Ordinary theory of longitudinal motion

$$\begin{cases} \dot{\phi} = \dfrac{e\xi}{m_0 \gamma_n^{3}}\, b & ① \\[2ex] \dot{\Gamma} = \dfrac{eV_n}{2\pi m_0 c^2}(\cos\phi - \cos\phi_n) & ② \end{cases}$$

Useful relation

$$\dot{\phi}\dot{\Gamma} = \frac{eV_n}{2\pi m_0 c^2}(\dot{\phi}\cos\phi - \dot{\phi}\cos\phi_n) = \frac{d}{dt}\left\{\frac{eV_n}{2\pi m_0 c^2}(\sin\phi - \phi\cos\phi_n)\right\}$$

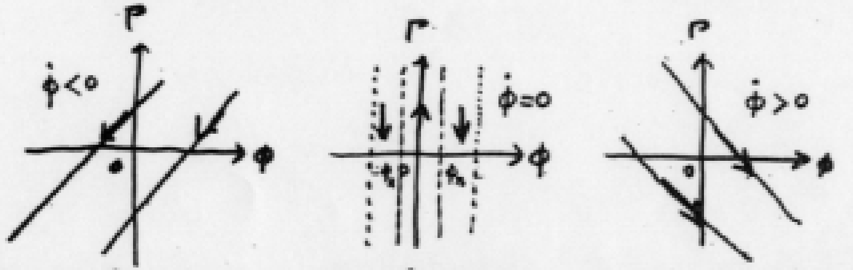
$① \times \dot{\Gamma}$

$$\dot{\phi}\dot{\Gamma} = \frac{e\xi}{m_0 \gamma_n^{3}}\, b\,\dot{\Gamma}$$

Integration by time

$$-\frac{e\xi}{m_0 \gamma_n^{3}}\, b\,\Gamma = \frac{eV_n}{2\pi m_0 c^2}(\phi\cos\phi_n - \sin\phi - K)$$

$b < 0$	$b = 0$	$b > 0$
Increase of magnetic field		Decrease of magnetic field



no isochronism — Isochronism — no isochronism

Longitudinal motion only

with second-order term of energy deviation but without coupling to betatron oscillation

Other conditions : $b = \text{const.} \neq 0$, $E_r = 0$

$v = 0$, $\omega_f = \omega_{f\,n}$, $\dot{\phi}_{rf} = 0$

$$\begin{cases} \dot{\phi} - 2\left(\dfrac{3}{4} - \dfrac{5}{4}\cdot\dfrac{1}{\gamma_n^{2}} + \dfrac{1}{\gamma_n^{4}}\right)\dfrac{e c^4}{\gamma_n^{4} r_n^{4} \dot{\theta}_n}\,\Gamma^2 = \dfrac{e\xi}{m_0 \gamma_n^{3}}\, b & ① \\[2ex] \dot{\Gamma} = \dfrac{eV_n}{2\pi m_0 c^2}(\cos\phi - \cos\phi_n) & ② \end{cases}$$

Useful relation

$$\dot{\phi}\dot{\Gamma} = \frac{eV_n}{2\pi m_0 c^2}(\dot{\phi}\cos\phi - \dot{\phi}\cos\phi_n)$$

$$= \frac{d}{dt}\left\{\frac{eV_n}{2\pi m_0 c^2}(\sin\phi - \phi\cos\phi_n)\right\} \qquad ③$$

$① \times \dot{\Gamma}$

$$\dot{\phi}\dot{\Gamma} - 2\left(\frac{3}{4} - \frac{5}{4}\cdot\frac{1}{\gamma_n^{2}} + \frac{1}{\gamma_n^{4}}\right)\frac{e c^4}{\gamma_n^{4} r_n^{4} \dot{\theta}_n}\,\Gamma^2\dot{\Gamma} = \frac{e\xi}{m_0 \gamma_n^{3}}\, b\,\dot{\Gamma}$$

Integration by time

$$-\Gamma\left(\Gamma^2 + \frac{3}{2}\cdot\frac{1}{\frac{3}{4} - \frac{5}{4}\cdot\frac{1}{\gamma_n^{2}} + \frac{1}{\gamma_n^{4}}}\cdot\frac{\gamma_n^{4} r_n^{4} \dot{\theta}_n}{e c^4}\cdot\frac{e\xi}{m_0 \gamma_n^{3}}\, b\right)$$

$$= \frac{3}{2}\cdot\frac{1}{\frac{3}{4} - \frac{5}{4}\cdot\frac{1}{\gamma_n^{2}} + \frac{1}{\gamma_n^{4}}}\cdot\frac{\gamma_n^{4} r_n^{4} \dot{\theta}_n}{e c^4}\cdot\frac{eV_n}{2\pi m_0 c^2}(\phi\cos\phi_n - \sin\phi - K)$$

where $K = \text{const.}$

Elimination of $B_{zn}(r_n)$ by synchronous (isochronous) condition : $eB_{zn}(r_n) = \frac{m_0\gamma_n\ddot{r}_n}{r_n\dot{\theta}_n} + \frac{m_0\dot{\gamma}_n\dot{r}_n}{r_n\dot{\theta}_n} - m_0\gamma_n\dot{\theta}_n$

First-step approximation : $\dot{r}_n \simeq 0$, $\ddot{r}_n \simeq 0$

so that $\gamma_n \simeq \frac{1}{\sqrt{1-\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}}$

Further approximation : $\dot{\gamma}_n \simeq 0$

Definition of transition-γ : $\gamma_t^2 = 1 - n$

$\gamma_n \leq \gamma_t$

Three basic equations of motion

$$\dot{\phi} + \frac{hc^2}{\gamma_n^3 r_n^2}\Gamma - \left(\frac{3}{2}-\frac{1}{\gamma_n^2}\right)\frac{hc^4}{\gamma_n^4 r_n^4\dot{\theta}_n}\Gamma^2 - \frac{h\dot{\theta}_n}{r_n}x = \omega_{rf} - \omega_{rf,n} + \dot{\phi}_{rf}$$

$$\ddot{x} + \gamma_t^2\dot{\theta}_n^2 x = \frac{c^2\dot{\theta}_n}{\gamma_n r_n}\Gamma - 2\left(\frac{3}{4}-\frac{1}{\gamma_n^2}\right)\frac{c^4}{\gamma_n^4 r_n^3}\Gamma^2 + \frac{e r_n\dot{\theta}_n}{m_0\gamma_n}b + \frac{e}{m_0\gamma_n}E_r$$

$$\dot{\Gamma} = \frac{eV_n}{2\pi m_0 c^2}\underset{\sin\phi - \sin\phi_n}{(\cos\phi - \cos\phi_n)} + \frac{eV}{2\pi m_0 c^2}\underset{\sin\phi_n}{\cos\phi_n}$$

Deduced equation of motion from upper two equations by elimination of x

$$\dot{\phi} + \left(\frac{1}{\gamma_n^2}-\frac{1}{\gamma_t^2}\right)\frac{1}{\gamma_n r_n^2}\Gamma - 2\left\{\frac{3}{4} - \frac{1}{2\gamma_n^2} - \frac{1}{\gamma_t^2}\left(\frac{3}{4}-\frac{1}{\gamma_n^2}\right)\right\}\frac{hc^4}{\gamma_n^4 r_n^4\dot{\theta}_n}\Gamma^2$$

$$= -\frac{h}{\gamma_t^2 r_n\dot{\theta}_n}\ddot{x} + \frac{he}{m_0\gamma_t^2\gamma_n}b + \frac{he}{m_0\gamma_t^2\gamma_n r_n\dot{\theta}_n}E_r + \omega_{rf} - \omega_{rf,n} + \dot{\phi}_{rf}$$

Isochronous cyclotrons

$\gamma_n = \gamma_t$

General equations of motion

$$\ddot{x} + \gamma_n^2\dot{\theta}_n^2 x = \frac{c^2\dot{\theta}_n}{\gamma_n r_n}\Gamma - 2\left(\frac{3}{4}-\frac{1}{\gamma_n^2}\right)\frac{c^4}{\gamma_n^4 r_n^3}\Gamma^2 + \frac{e r_n\dot{\theta}_n}{m_0\gamma_n}b + \frac{e}{m_0\gamma_n}E_r$$

$$\dot{\phi} - 2\left(\frac{3}{4} - \frac{5}{4}\frac{1}{\gamma_n^2} + \frac{1}{\gamma_n^4}\right)\frac{hc^4}{\gamma_n^4 r_n^4\dot{\theta}_n}\Gamma^2$$

$$= -\frac{h}{\gamma_n^2 r_n\dot{\theta}_n}\ddot{x} + \frac{he}{m_0\gamma_n^3}b + \frac{he}{m_0\gamma_n^3 r_n\dot{\theta}_n}E_r + \omega_{rf} - \omega_{rf,n} + \dot{\phi}_{rf}$$

$$\dot{\Gamma} = \frac{eV_n}{2\pi m_0 c^2}(\cos\phi - \cos\phi_n) + \frac{eV}{2\pi m_0 c^2}\cos\phi_n$$

$$\dot{\phi} + \frac{hc^2}{\gamma_n^3 r_n^2}\Gamma - \left(\frac{3}{2}-\frac{1}{\gamma_n^2}\right)\frac{hc^4}{\gamma_n^4 r_n^4\dot{\theta}_n}\Gamma^2 - \frac{h\dot{\theta}_n}{r_n}x = \omega_{rf} - \omega_{rf,n} + \dot{\phi}_{rf}$$

Equations of motion of a special particle

See general equations of motion

Longitudinal-Transverse Coupling Motion with Second-Order Term of Energy Deviation in Circular Accelerators

Kenji Sato, RCNP, Osaka Univ., 13 June 2001

Cylindrical coordinates : (r, θ, z)

Equation of motion in a median plane

$z = 0,\ \dot{z} = 0$

$$\begin{cases} \gamma = \dfrac{1}{\sqrt{1-\left(\frac{\dot{r}}{c}\right)^2-\left(\frac{r\dot{\theta}}{c}\right)^2}} \\ m_0\gamma\ddot{r} + m_0\dot{\gamma}\dot{r} - m_0\gamma r\dot{\theta}^2 = q r\dot{\theta}B_z(r) + qE_r \\ m_0c^2\dot{\gamma} = \dfrac{qV}{2\pi}\dot{\theta}\cos\phi \\ \qquad\qquad\qquad \sin\phi \end{cases}$$

where $\phi = \omega_{rf}t + \phi_{rf} - h\theta$

$q>0,\ B_z(r)<0$ so that $\dot{\theta}>0$

Synchronous (Isochronous) conditions

$\phi_n = \omega_{rf,n}t - h\theta_n = \text{const.}$

$\dot{\phi}_n = 0,\ \ \omega_{rf,n} = h\dot{\theta}_n$

$$\begin{cases} \gamma_n = \dfrac{1}{\sqrt{1-\left(\frac{\dot{r}_n}{c}\right)^2-\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}} \\ m_0\gamma_n\ddot{r}_n + m_0\dot{\gamma}_n\dot{r}_n - m_0\gamma_n r_n\dot{\theta}_n^2 = q r_n\dot{\theta}_n B_{zn}(r_n) \\ m_0c^2\dot{\gamma}_n = \dfrac{qV_n}{2\pi}\dot{\theta}_n\cos\phi_n \\ \qquad\qquad\qquad \sin\phi_n \end{cases}$$

Definitions of deviation

$\phi - \phi_n = -h(\theta-\theta_n) + (\omega_{rf}-\omega_{rf,n})t + \phi_{rf}$

$\dot{\phi} - \dot{\phi}_n = -h(\dot{\theta}-\dot{\theta}_n) + \omega_{rf}-\omega_{rf,n} + \dot{\phi}_{rf}$

$x = r - r_n$

$\Gamma = \dfrac{\gamma-\gamma_n}{\dot{\theta}_n}$

Definitions of deviation

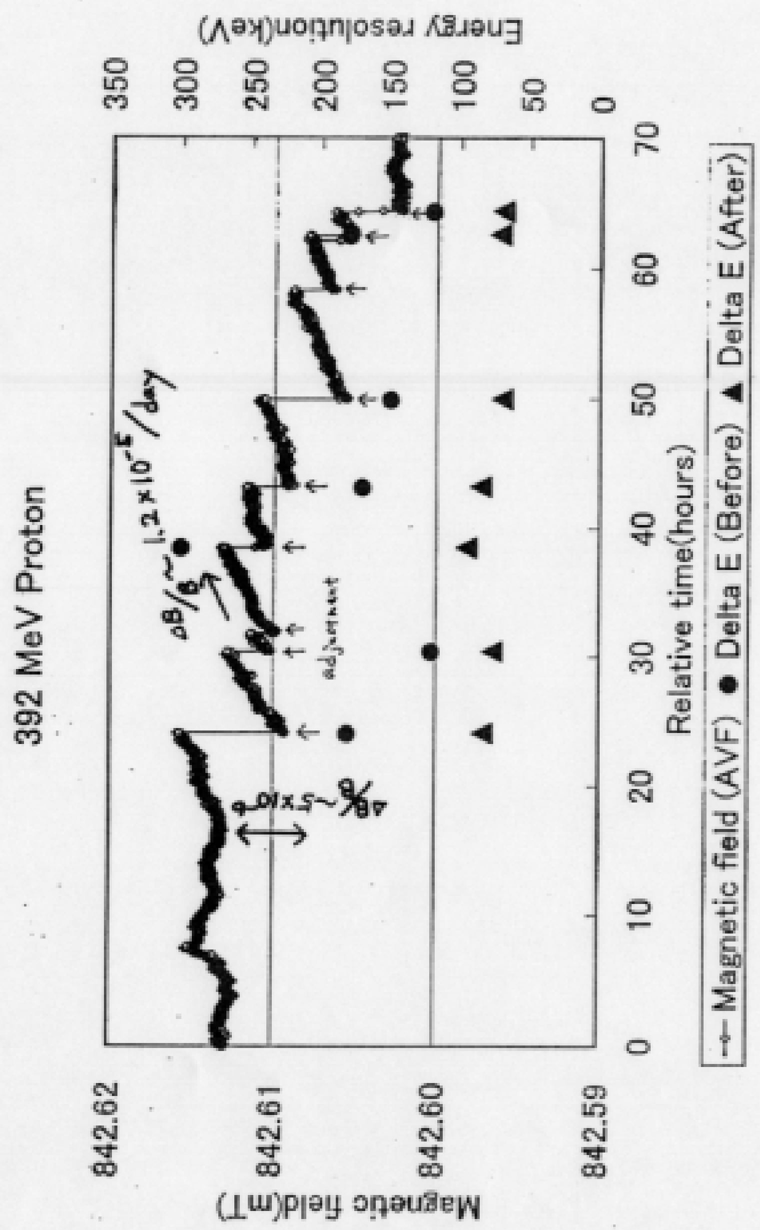
$B_z(r) = B_{zn}(r_n)\left(1-n\dfrac{r-r_n}{r_n}\right) + b$

$V = V_n + v$

Equation of motion with second-order term of energy deviation

$$\frac{\dot{\theta}-\dot{\theta}_n}{\dot{\theta}_n} = -\frac{r-r_n}{r_n} - \frac{\left(\frac{\dot{r}_n}{c}\right)^2}{\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}\frac{\dot{r}-\dot{r}_n}{\dot{r}_n} + \frac{\frac{1}{\gamma_n^2}}{\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}\frac{\gamma-\gamma_n}{\gamma_n} - \frac{\frac{1}{\gamma_n^2}\left\{\frac{3}{2}-\frac{1}{\gamma_n^2}-\frac{3}{2}\left(\frac{\dot{r}_n}{c}\right)^2\right\}}{\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}\left(\frac{\gamma-\gamma_n}{\gamma_n}\right)^2$$

$$\frac{\dot{\theta}^2-\dot{\theta}_n^2}{\dot{\theta}_n^2} = -2\frac{r-r_n}{r_n} - 2\frac{\left(\frac{\dot{r}_n}{c}\right)^2}{\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}\frac{\dot{r}-\dot{r}_n}{\dot{r}_n} + 2\frac{\frac{1}{\gamma_n^2}}{\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}\frac{\gamma-\gamma_n}{\gamma_n} - 3\frac{\frac{1}{\gamma_n^2}}{\left(\frac{r_n\dot{\theta}_n}{c}\right)^2}\left(\frac{\gamma-\gamma_n}{\gamma_n}\right)^2$$



サイクロトロンが分かった！

－ 誰も気付かなかった、サイクロトロンの忘れ物 －

円形加速器の軌道理論において、エネルギーのずれの二乗の項を含むときの非線形運動が、磁場のずれに影響された運動

シンクロトロン、サイクロトロン、ＦＦＡＧの中では、サイクロトロンが特殊な加速器
エネルギーのずれの一次の項を消すように装置を製作
エネルギーのずれの二乗が磁場のずれに比例
エネルギーのずれが磁場の正のずれの平方根に比例

ＡＶＦのフラット・トップ化に加えて、非線形運動を制御して、縦方向運動を整合させる装置の開発ができれば、これまでにＲＣＮＰが実現してきた世界記録をさらに更新できる
佐藤の経験では、エネルギー分解能が数倍良くなることが期待できる

サイクロで、やれば良いこと

新装置のアイデアと開発、ＡＶＦフラット・トップ化
予算、マン・パワー
物理の成果が出るのであれば、前段サイクロを更新

ＲＣＮＰイノベーション

－ビームが良くなってもイノベーションとは呼ばない－

モチベーションは物理
ム・ム・ム？！

超々高品質ビーム核物理実験
緊急アッピール！

知恵を出せ、頭を捻れ、総力をあげよ、結集せよ、
そして、ＲＣＮＰとしての物理を研究せよ

Ｕｌｔｒａ－Ｐｒｅｃｉｓｅ Ｂｅａｍｓ 実現の小史

平成１３年７月１２日
大阪大学核物理研究センター　佐　藤　健　次

核物理研究センターのサイクロトロン・カスケードでは、リング及びAVF の電磁石鉄芯温度の安定化を通して、磁場を長時間、高度に安定化することで、 Ultra-Precise Beams を実現できた。

過渡的渦電流による磁場の空間分布測定の必要性を主張
①コイル電流を調整すると過渡的渦電流が発生するはず
②それも、長い時定数で、六極状の磁場分布のはず

リング・サイクロトロンでの磁場分布の時間変化の測定
①大中小及びビームの外の異なる半径でのNMR 測定
②トリムコイル冷却水の温度を変化させたときの測定で短い時定数の高速応答の磁場変化に遭遇
③コイル電流の変化に対する磁場分布の変化の測定データについては全く思い出せないのは、上のデータに驚いたためか？
④リング・サイクロトロン鉄芯温度測定開始

リング・サイクロトロンでの新しい磁場調整方法
①磁場が変化すると、コイルの電流ではなく、冷却水温度を調整

GRAND-RAIDENでの画期的測定結果
①０度方向での低バック・グラウンド測定が実現

AVF も行け行けで、NMR を開発して、磁場測定を実現
①絶対値の測定でなくとも、磁場の変化が読めれば良い
②磁場勾配を作れる補正コイル付きNMR の開発に成功

スローガン「磁場の安定化が全てである」を提唱
スローガン「磁場よりも温度」の実現に向けた改造
①機能付加：リング及びAVF の電磁石鉄芯やコイルの温度制御のため、コイル冷却水の入口温度を制御する方式を導入
②鉄芯温度を一定に保つには、入口と出口の平均温度を一定に保つよりは、出口温度を一定に保つ状態に近いことを経験的に学び、それを評価できるモデルを提案

冷却水系改造の成果
①磁場が長時間、高度に安定化した
②運転停止時も冷却系を連続運転することにした結果、磁場の強さの変更に要する時間を短縮できた
③空調の影響や空気の流れの影響の制御の必要性を認識できるようになり、その温度管理と風向変更板を設置
④コイル電流を調整することが激減したので、過渡的渦電流の発生を無視できると考えて良さそうである
⑤加速電圧用高周波共振器の冷却水の温度制御の不具合を、周波数調整用トリマーの動きから発見し、修正

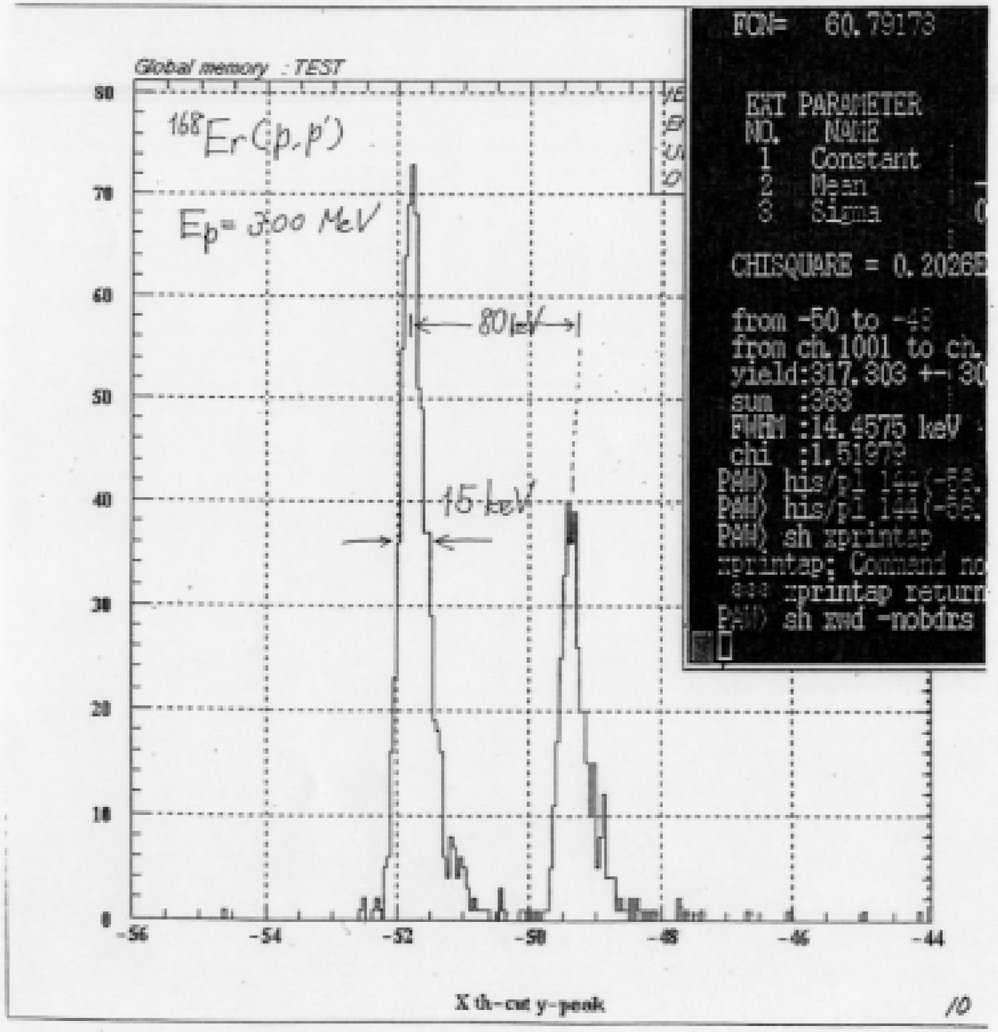
Ultra-Precise Beams の実現
①サイクロトロン・ビーム単独で$\Delta E/E \sim 2 \times 10^{-4}$
②WS新ビーム・ラインと GRAND-RAIDEN での分散整合と角度分散整合で$\Delta E/E \sim 4 \times 10^{-5}$

サイクロトロンでのビーム軌道理論の新展開の根拠
①磁場が猛烈に安定になると高品質ビームの実現が可能
②他方、磁場がわずかにずれると、品質が極端に悪化
③線形軌道理論では、こうした現象の説明が困難であると思われ、非線形効果を導入することを提案したい

非線形効果を矯正できる新種の装置の必要性を指摘
①エネルギーのずれと加速位相の間の関係において収差を矯正する装置が必要
②例えば、ビーム輸送系ならば六極電磁石のような装置

WS-course project

- E-resolution 15 keV at E_p=300 MeV
- $\frac{\Delta E}{E} \sim 5 \times 10^{-5}$: World Record



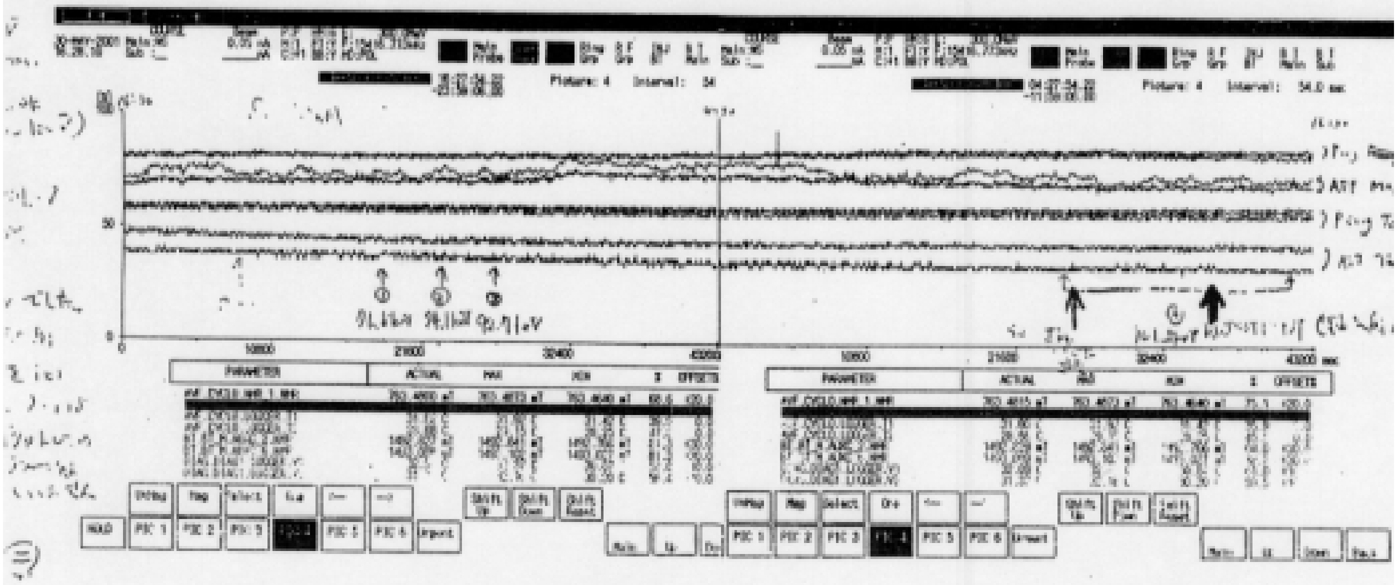
10

Ions	E(MeV)	ΔE(keV)	ΔE/E	Current	Year/Month
H	300	55	1.8×10^{-4}	1nA	00/12
	392	62	1.6×10^{-4}	2nA	00/6
^{3}He	450	170	3.8×10^{-4}	15nA	99/5
^{4}He	400	193	4.8×10^{-4}	—	99/11
		245	6.1×10^{-4}	1nA	
		259	6.5×10^{-4}	10nA	
Dispersive mode					
H	300	12.8	4.3×10^{-5}	1nA	00/4
	392	16.7	4.3×10^{-5}	1nA	00/6

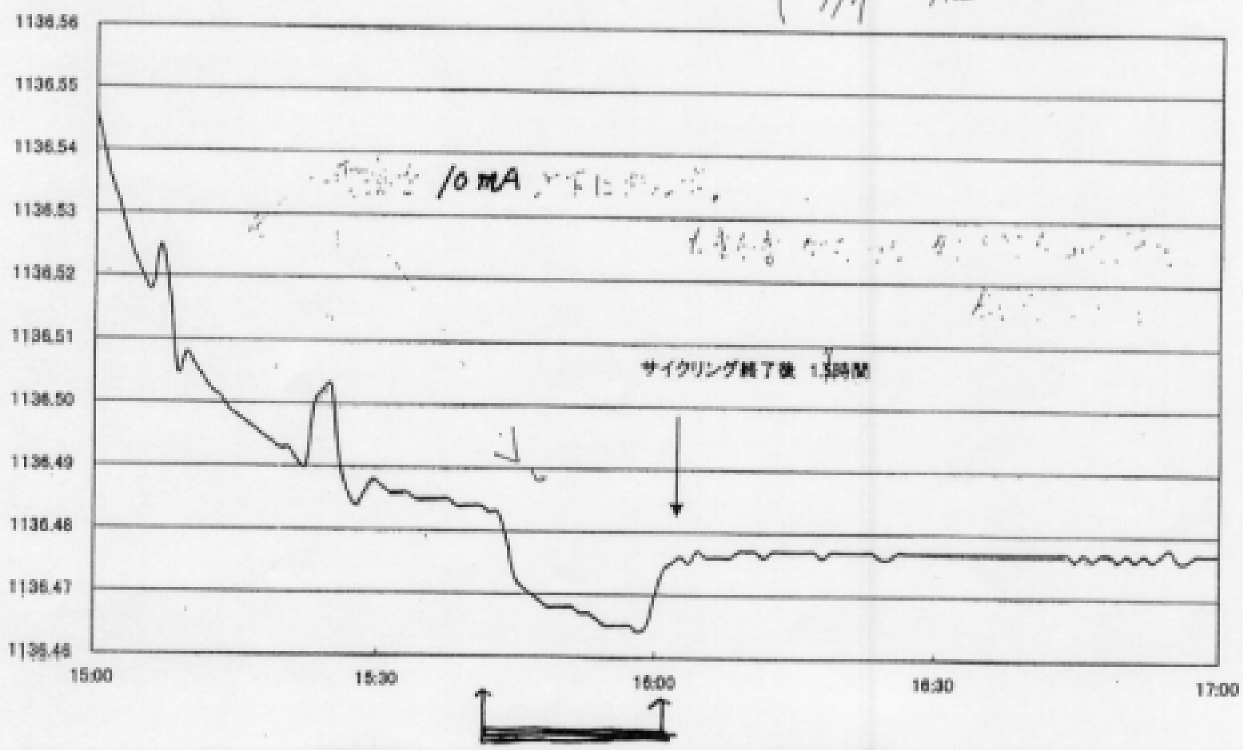
300 MeV protons

24時間で，サイクロのパラメータ調整は1回のみ

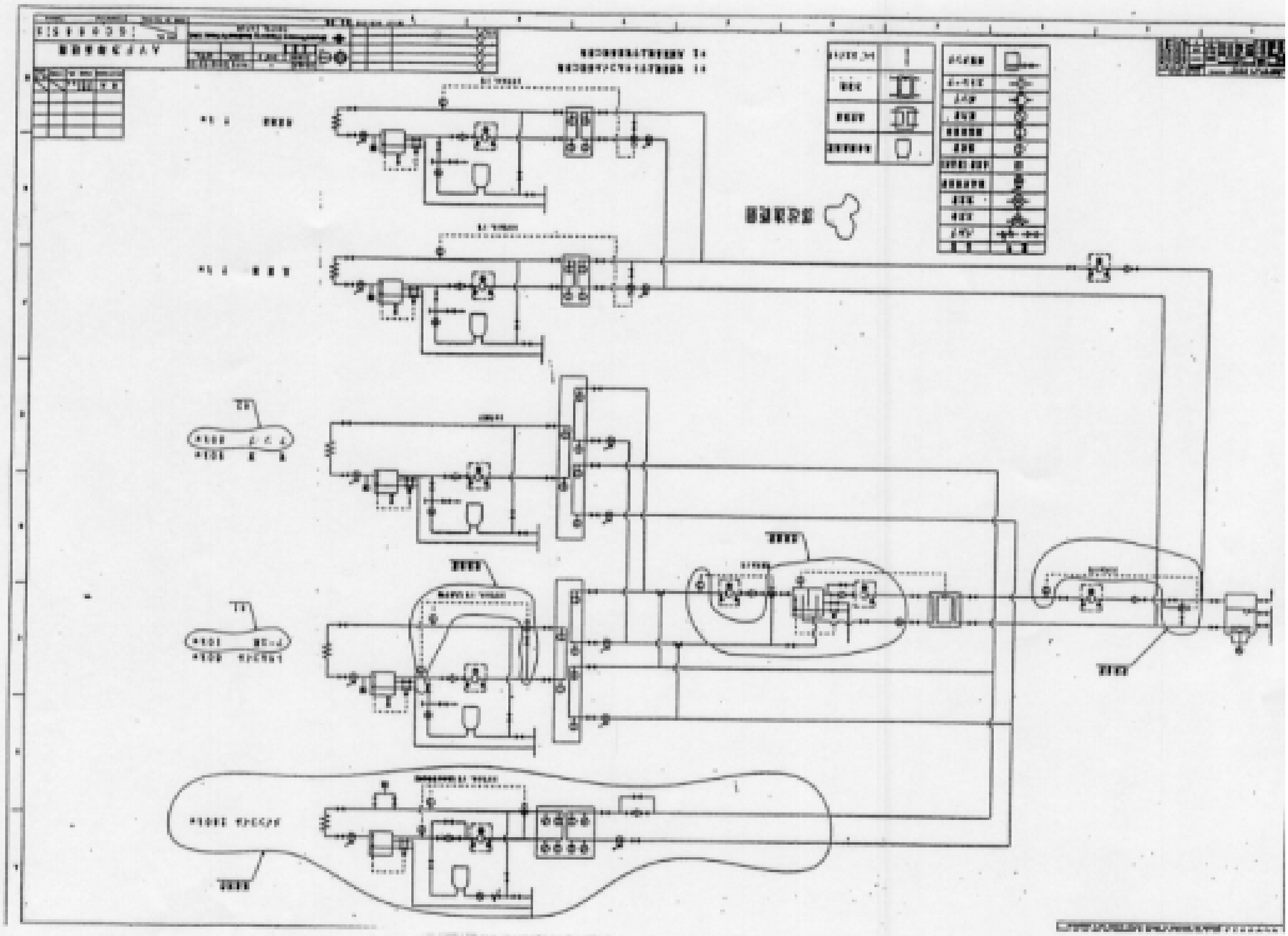
（ただし，ΔEのこれまでの最高は55keV）



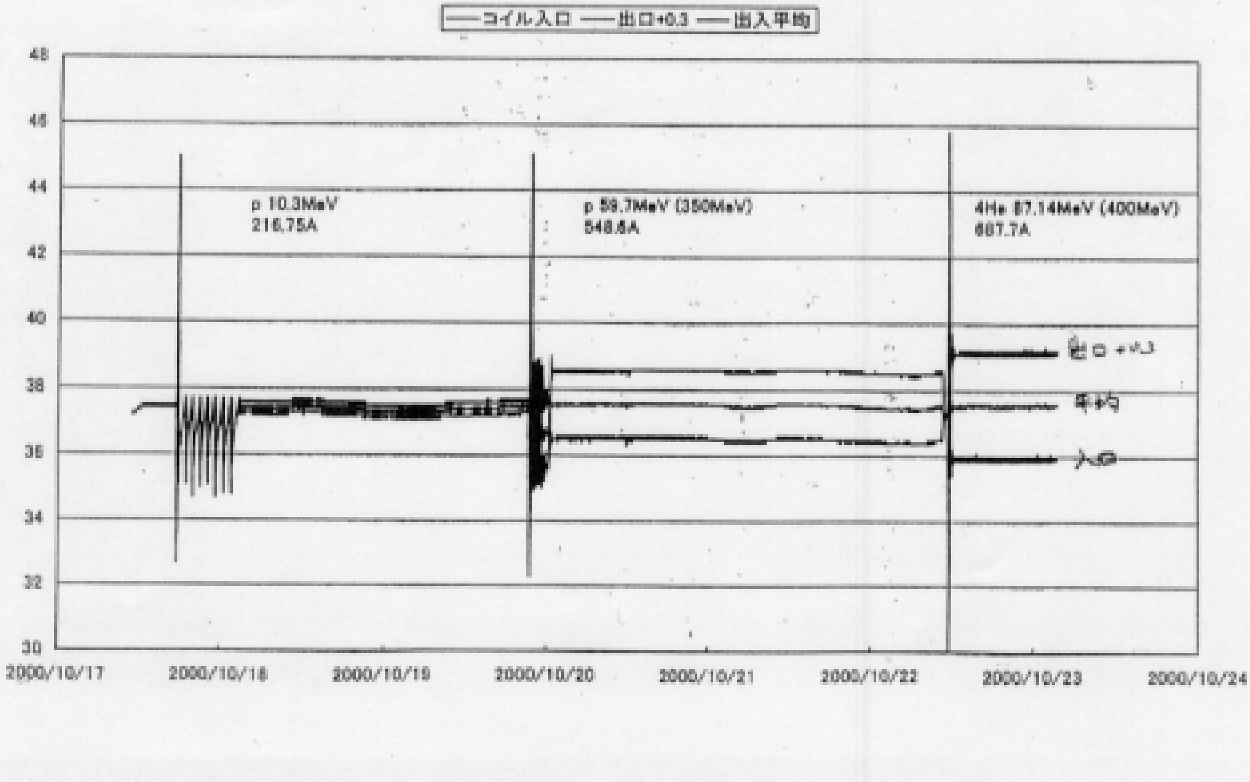
リングNo.2磁場　（7/7 ⁴He 210 MeV 立上げ時）



漏電流のクリティカルダンピングのつもりが，たまたま，きれいに成功！

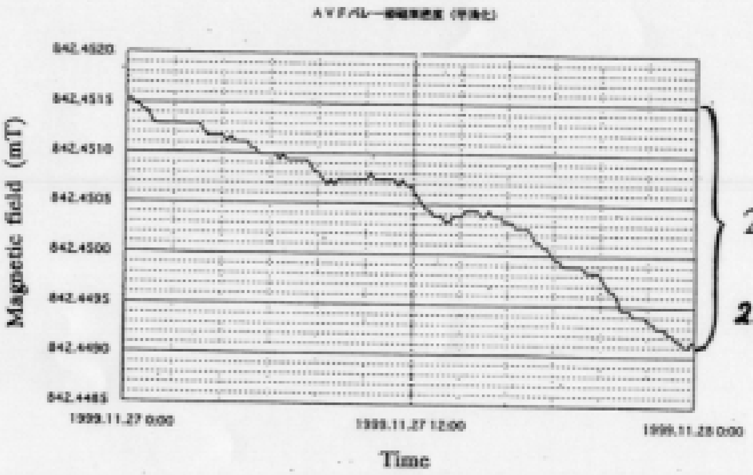


AVF主コイル出入口温度



Remarkable Achievement

High−Resolution Measurement of Magnetic Field of AVF Cyclotron by NMR Probes



25mG/day
ll
2.8 ppm/day

Resolution of 1 mG:
very helpful for tuning of AVF cyclotron

磁場よりも温度！

測定で気付かれた鉄芯の温度の問題

参った！鉄芯の温度が変われば磁場の強さが変わり、磁場測定にならない。

鉄芯の温度が一定に出来る電磁石の開発が必要。

補　足

リングサイクロトロンと
ＡＶＦサイクロトロン

リングサイクロトロン

トリムコイルの冷却水の温度を制御すると、ＮＭＲで測定している磁場を一定にできる。

高品質ビーム、世界記録！

４００ＭｅＶ陽子でエネルギー半値幅６５ｋｅＶ。
１．7×10^{-4}

これをターゲットなしで、ＧＡＲＮＤ　ＲＡＩＤＥＮにて、分散整合と角度分散整合を同時に実現させると、１６ｋｅＶに見えた。
4×10^{-5}

1ppm 程度の
安定度が必要！

ＡＶＦサイクロトロン

この夏期運転休止期間中に、主コイルとトリムコイルの冷却水温度を独立して制御出来るように改造した。

しかし、そこで見えてきたことは、ＮＭＲを固定しているトリムコイル枠が温度で変形する効果であり、このため、ＮＭＲの読みを頼りに出来ないということである。

これを称して、対症療法と呼びたい。

ＡＧＯＲ

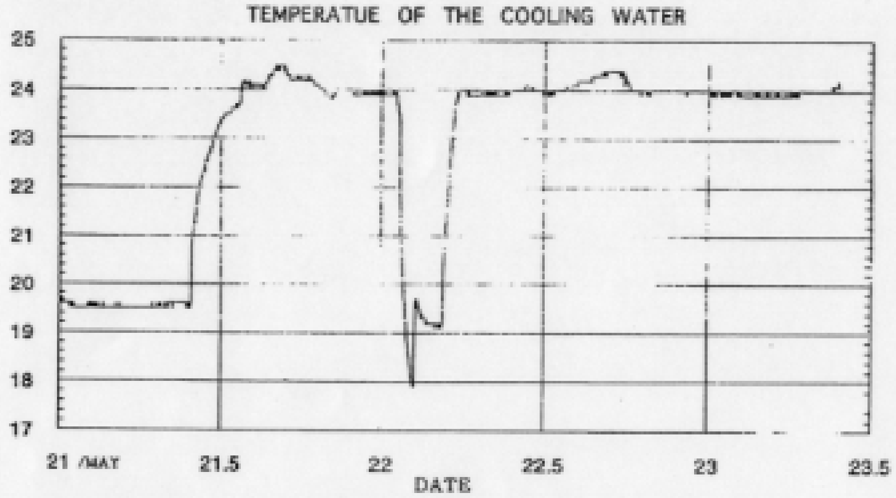
ＡＧＯＲが発信して世界を駆け巡っていそうな話：

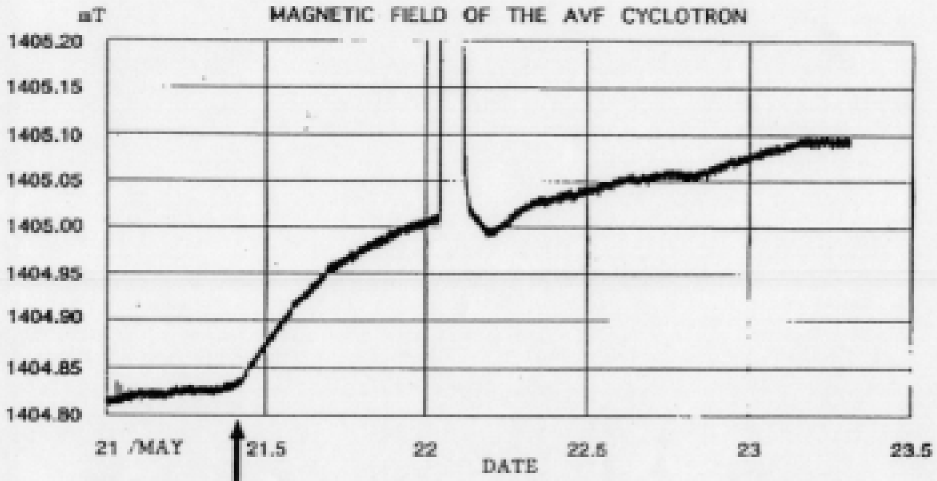
サイクロトロンの運転において最後に残された問題は磁場の再現性で、その解決には、鉄芯温度の安定化と鉄芯温度の再現性を高める必要がある。

透磁率の温度依存性

AVF cyclotron

Field change with temperature of cooling water of magnet coils





temperature change of cooling water

Slow response

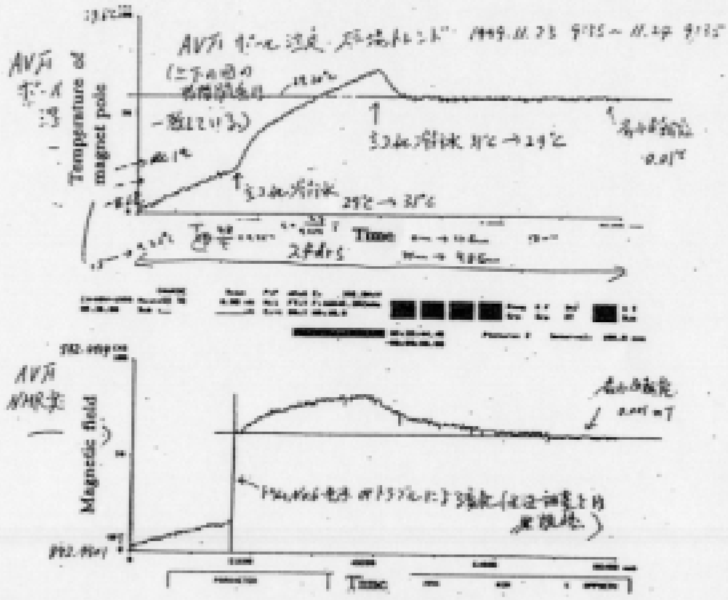
Proposal of Upgrading Project: Part 2

Stabilization of the Magnetic Field

Measurement on Critical Damping

Temperature of cooling water for main coils:

29°C → 31°C → 29°C



Critical Damping of temperature change of pole: provides a critical damping of magnetic field

Efficient method under investigation:

Average temperature of inlet and outlet cooling water is kept constant but is damped critically

磁場勾配のある

AVFサイクロトロンの磁場の時間変動を

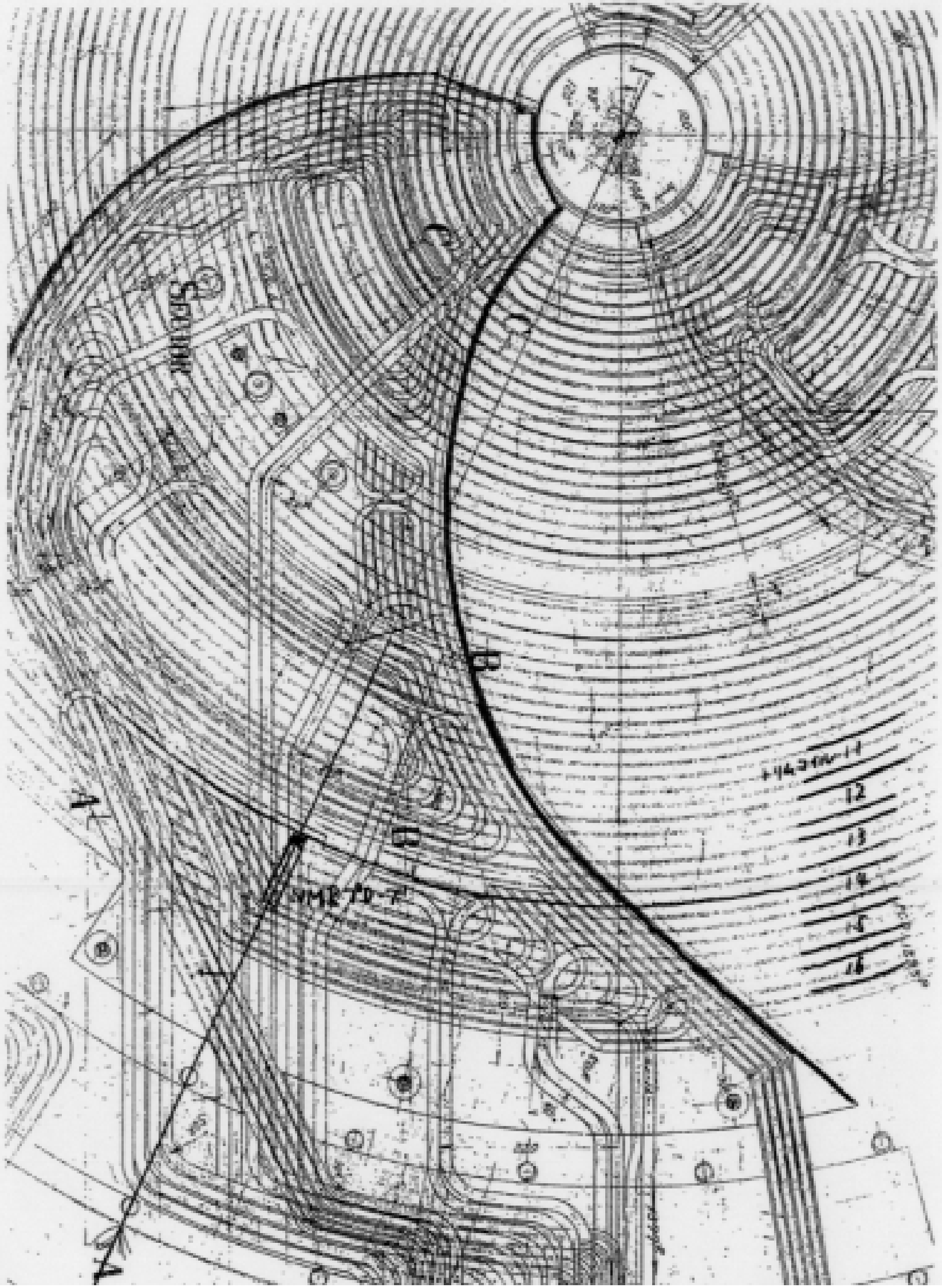
NMRプローブで測定したい。

磁場の絶対値を測定しなくても良い。

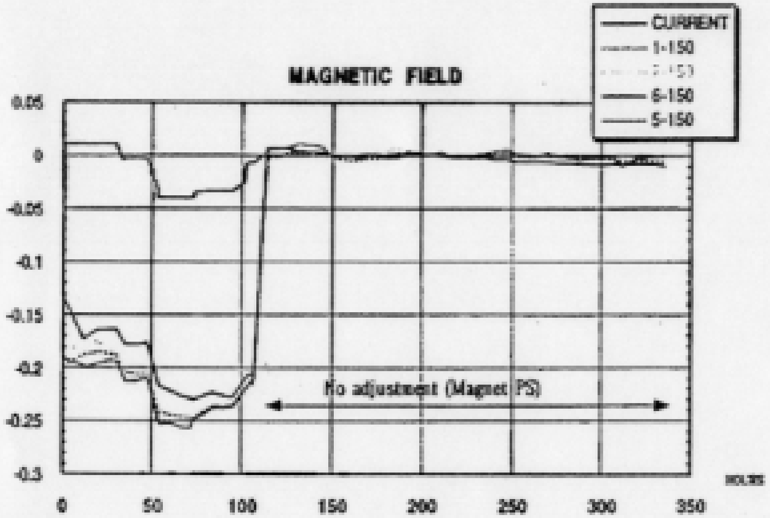
磁場勾配相殺用補正コイルを設けた

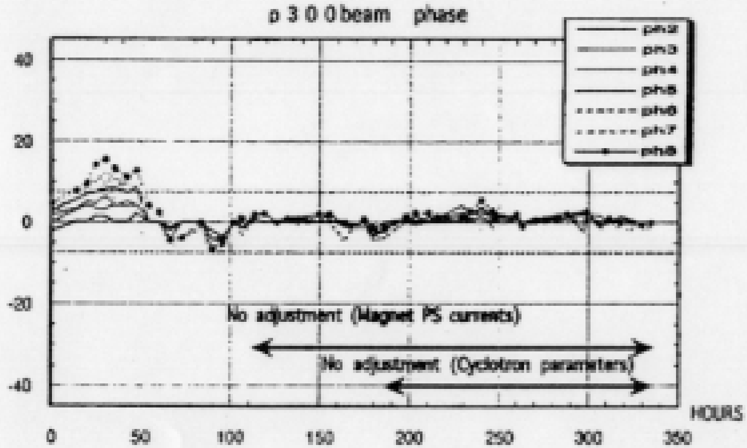
NMRプローブを開発。

その写真が見当らない!!!



Ring cyclotron
Remarkable achievements in July,1997

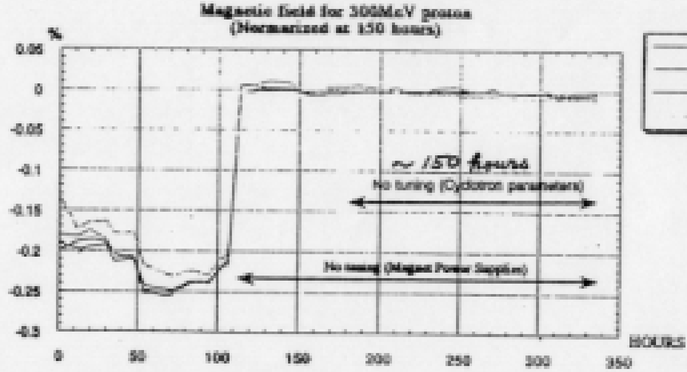




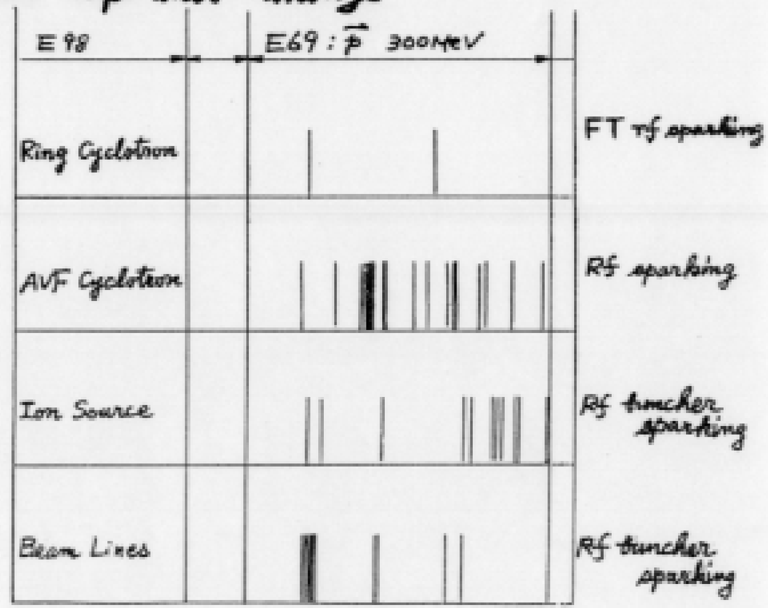
No adjustment of Ring cyclotron parameters:
in a long term of about 10 days

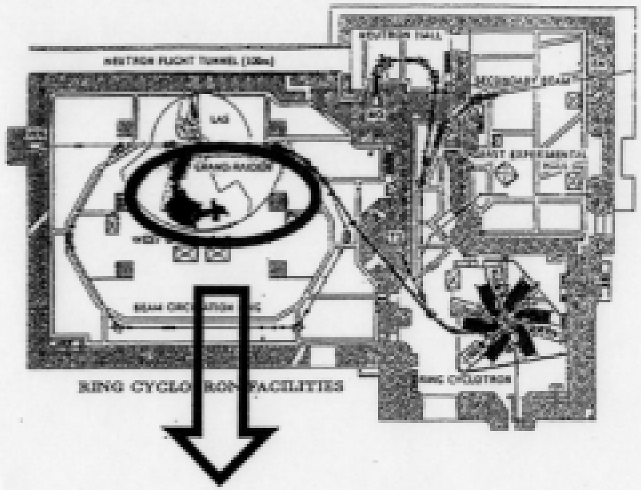
Upgrading of AVF–Ring Cyclotron Cascade

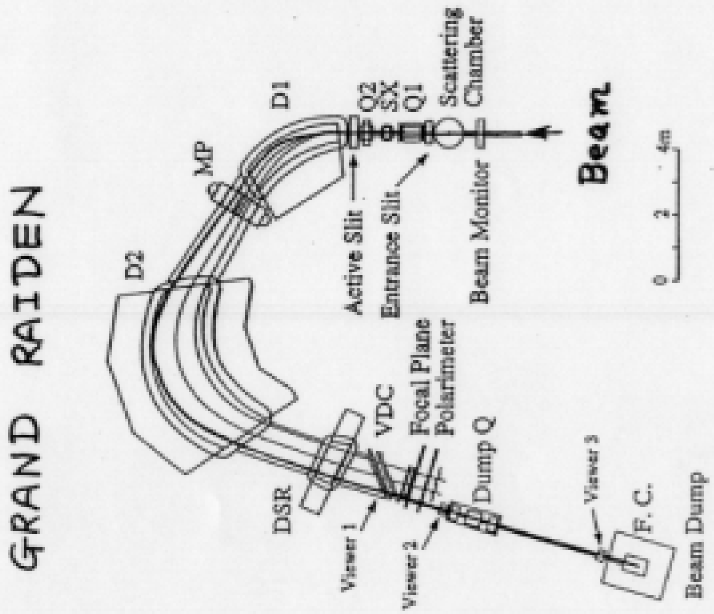
Reproducible remarkable achievement in July, 1997, of highly–stable long–term operation of Ring Cyclotron without any tuning of all Ring Cyclotron parameters



Beam Trips and Tunings

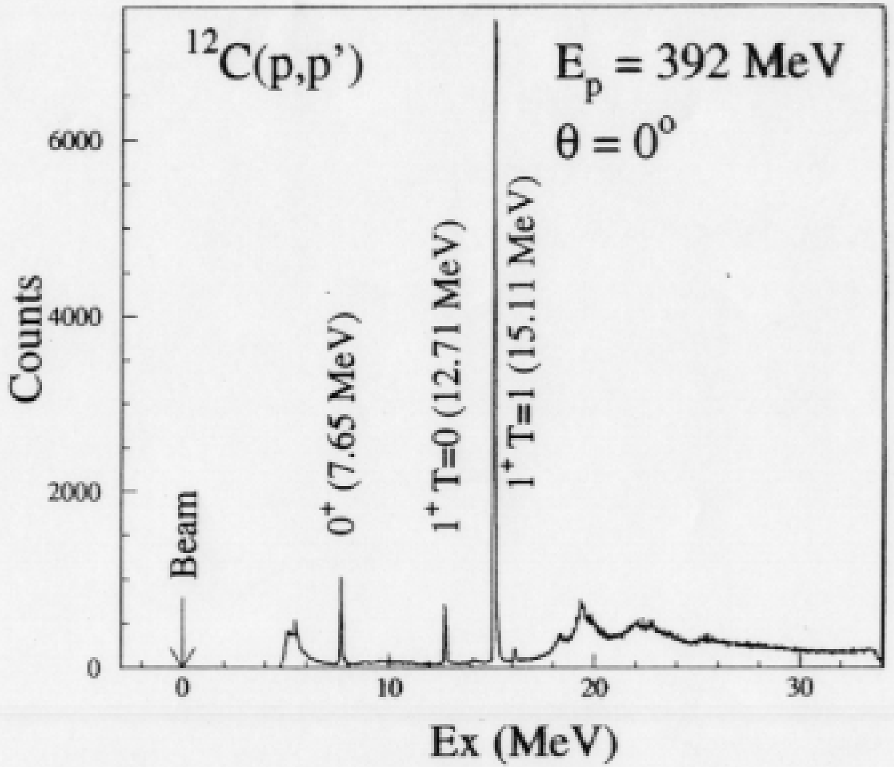






Remarkable achievements in 1997

The world's nicest low background 0^0-measurement at $E_p = 392MeV$ at GRAND RAIDEN

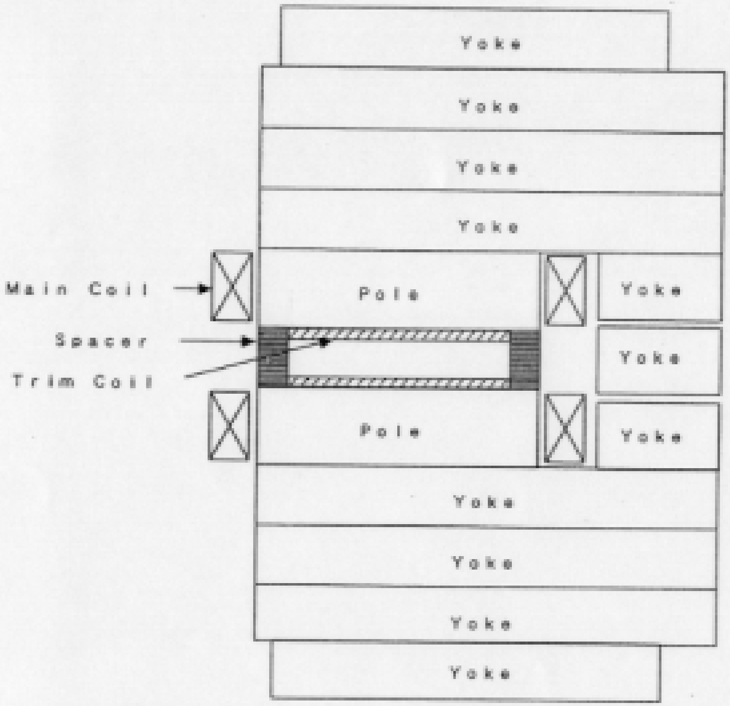


$$\Delta E_{beam} \cong 140\text{keV}$$

$$\left(\frac{\Delta E}{E}\right)_{beam} \cong 3.6\times10^{-4}$$

$$|\theta| \leq 0.5^0$$

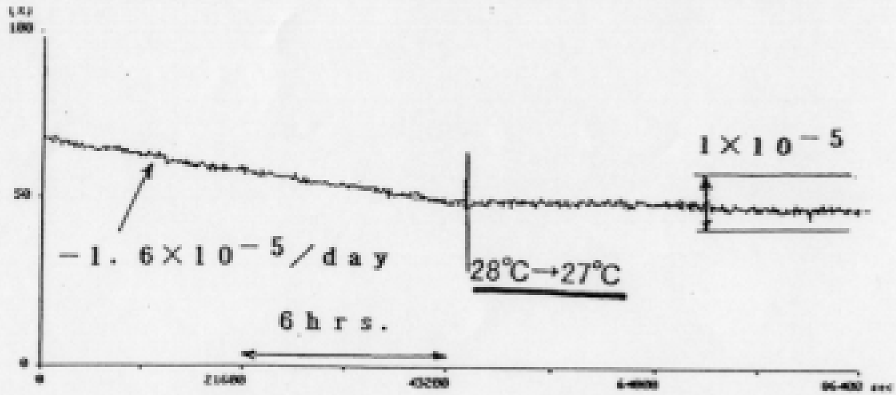
The best performance;
attainable for a long term



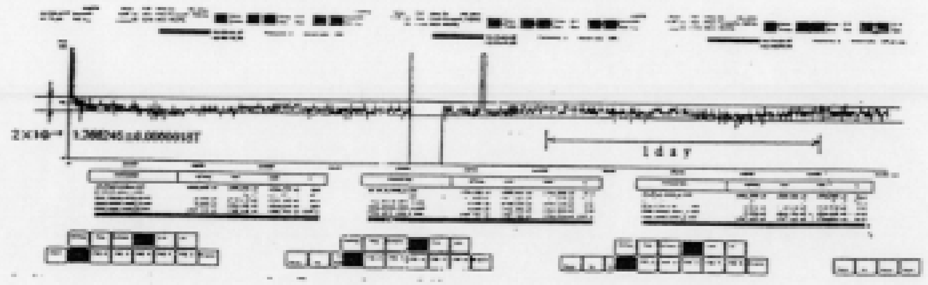
Structure of the Sector Magnet for the Ring Cyclotron

Ring cyclotron

Adjustment of temperature of cooling water of magnet coils

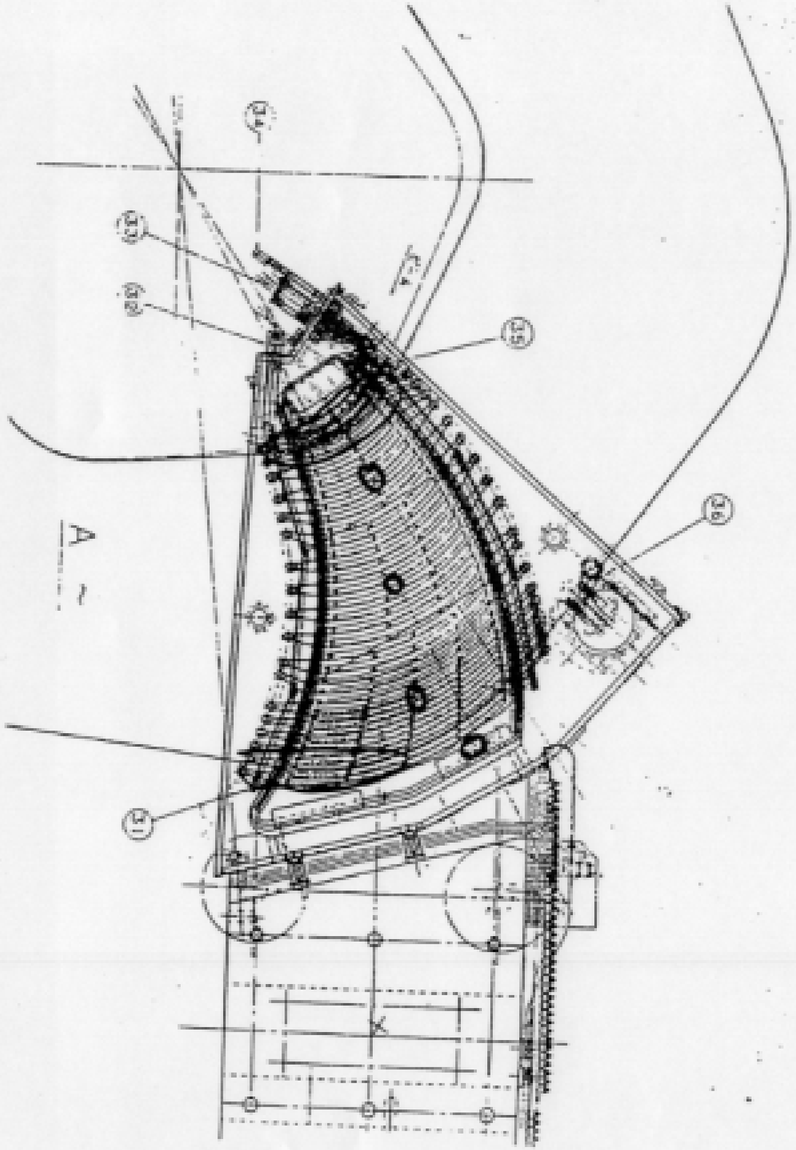


Remarkable achievement in February,1997



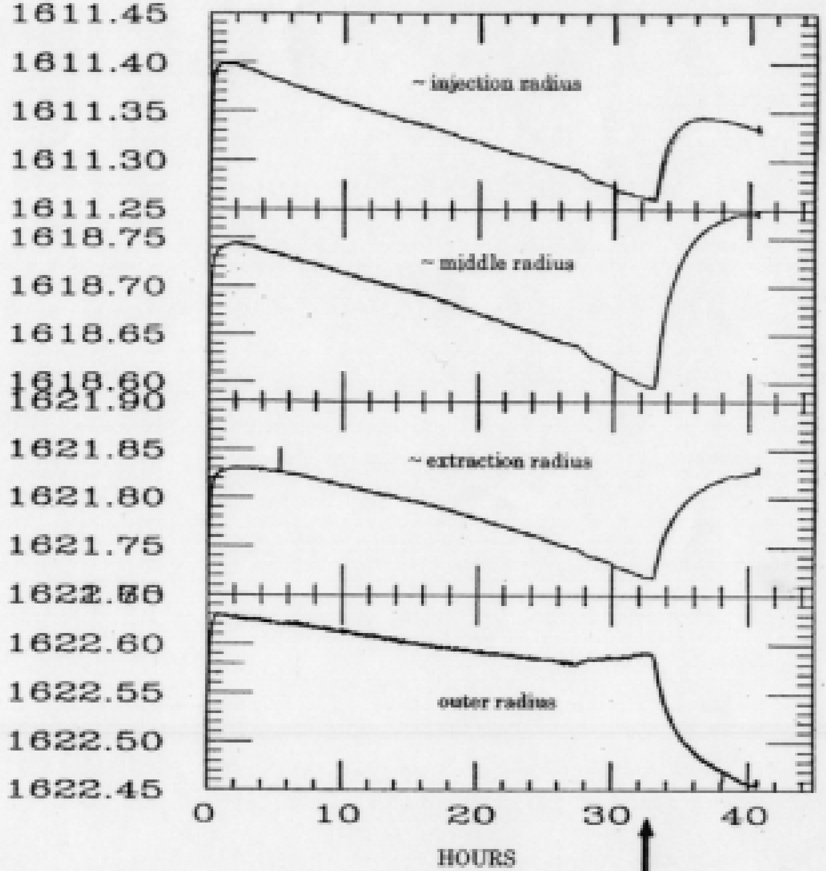
Relative field change:

less than 2×10^{-6} in a long term of 3 days



Ring cyclotron

Field change with temperature of cooling water of magnet coils



temperature change of cooling water

Fast response

due to

a special structural feature of magnets

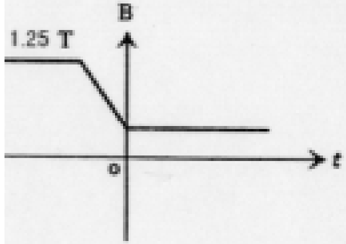
1.1 Unique experimental fact of a long time-constant

H.N. Jungwirth of NAC, South Africa

"Field Setting for a Cyclotron Sector Magnet"

Proc. of MT9, 1985, Zurich, pp.138-141.

Transition measured from 1.25 T to different filed level



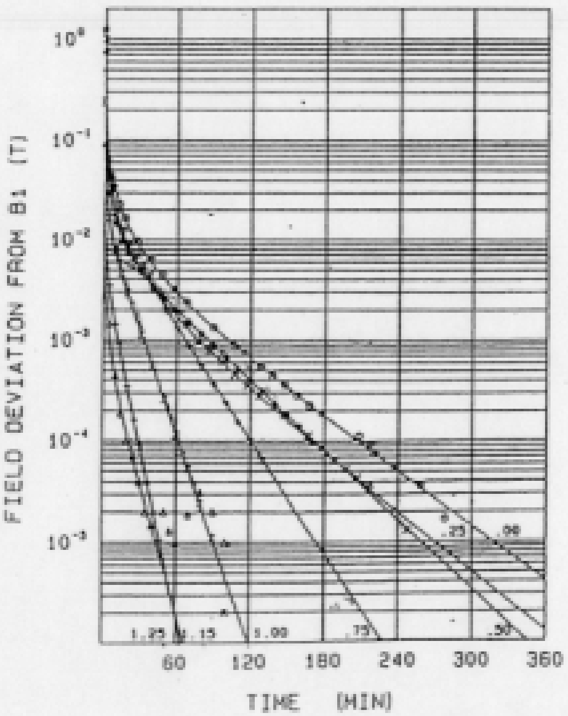


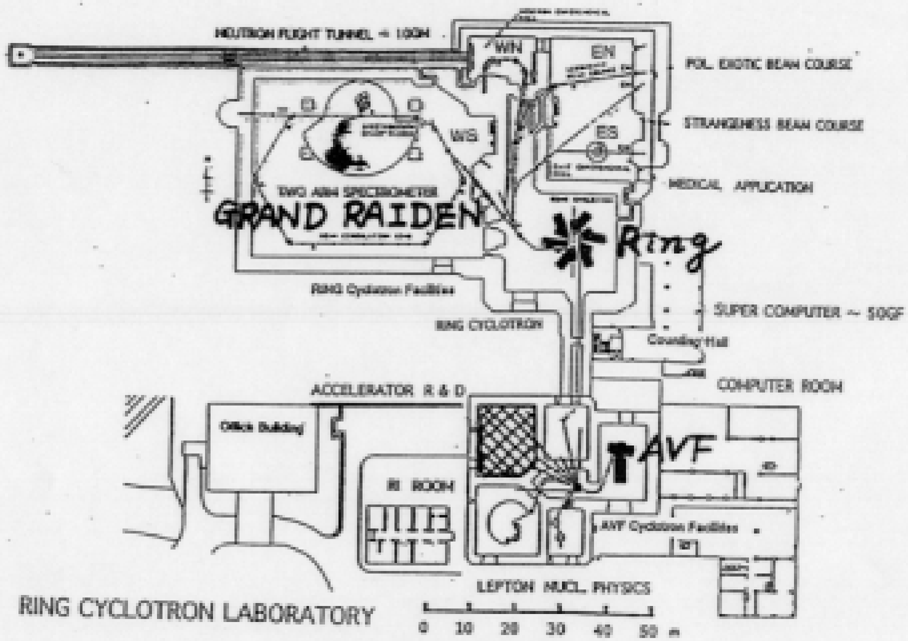
Fig. 3 - Field transition characteristics measured at different field levels B1 in the pole gap of a sector magnet.

Reproducibility

Six standard excitations ranging from 0.25 T to 1.25 T have been set many times, both by hand and under computer control, using these procedures during the field measurements for the sector magnets. The mapping equipment made use of two Hall-probes as field sensors with a resolution of 20 µT. The field was also monitored with NMR-probes to within 2 µT at one or two positions in the pole gap, sometimes up to 12 hours after the field has become stable according to the setting procedure. No field drift was observed except for variations within the stability limit of the power supplies and at maximum excitation, where a remanent magnetization deficiency cannot be completely avoided.

When making use of computer controlled field setting a field reproducibility of 0.2 mT was measured at maximum excitation, improving gradually to about 50 µT at lower field levels. Deviations by up to a factor of two larger were encountered when different operators were setting the power supplies manually, because of increased variations in the time structure of the procedure, including somewhat differently ramped currents. Most of the deviations for computer controlled setting have been observed after fields with high trim-coil excitation, but these should now be erased during the modified first stage of the procedure. When the magnets were fully excited for the first time after they had not been in operation for a few days or longer, the maximum field was up to 0.3 mT lower than during continuous operation, probably due to temperature effects.

I. Overview of AVF–Ring Cyclotron Cascade



RING CYCLOTRON LABORATORY

1971 RCNP established.
Construction of the AVF cyclotron started.

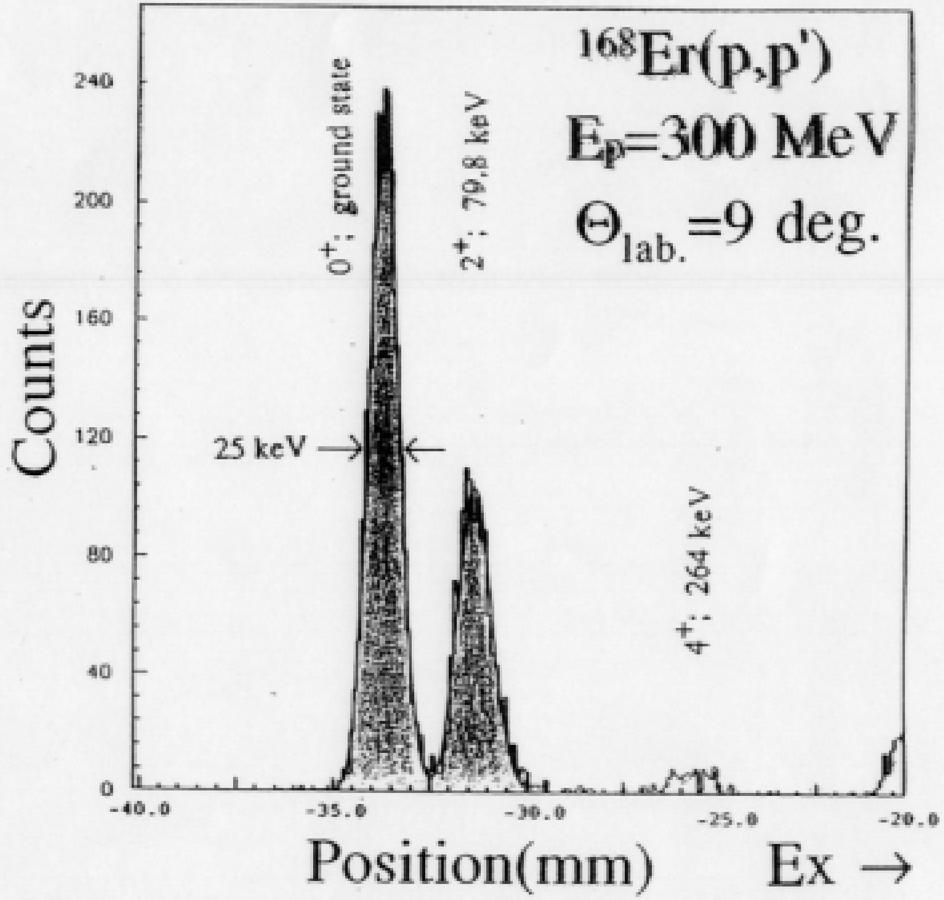
1975 The 1st beam extracted from the AVF cyclotron.

1987 Construction of the Ring Cyclotron started.

1991 The 1st beam extracted from the Ring Cyclotron.

1997 Remarkable achievement of highly–stable long–term operation of the Ring Cyclotron without any tuning of all cyclotron parameters.

The measurement of a high resolution (p,p') spectrum
at GRAND RAIDEN



$$\Delta E_{beam} \cong 100keV$$

$$\left(\frac{\Delta E}{E}\right)_{beam} \cong 3.3\times10^{-4}$$

The best performance;
attainable for a short term only