SAD2006 : Sep. 05

Tracking and Analysis Code for Beam Dynamics in SPring-8:CETRA

J. SCHIMIZU : JASRI/SPring-8

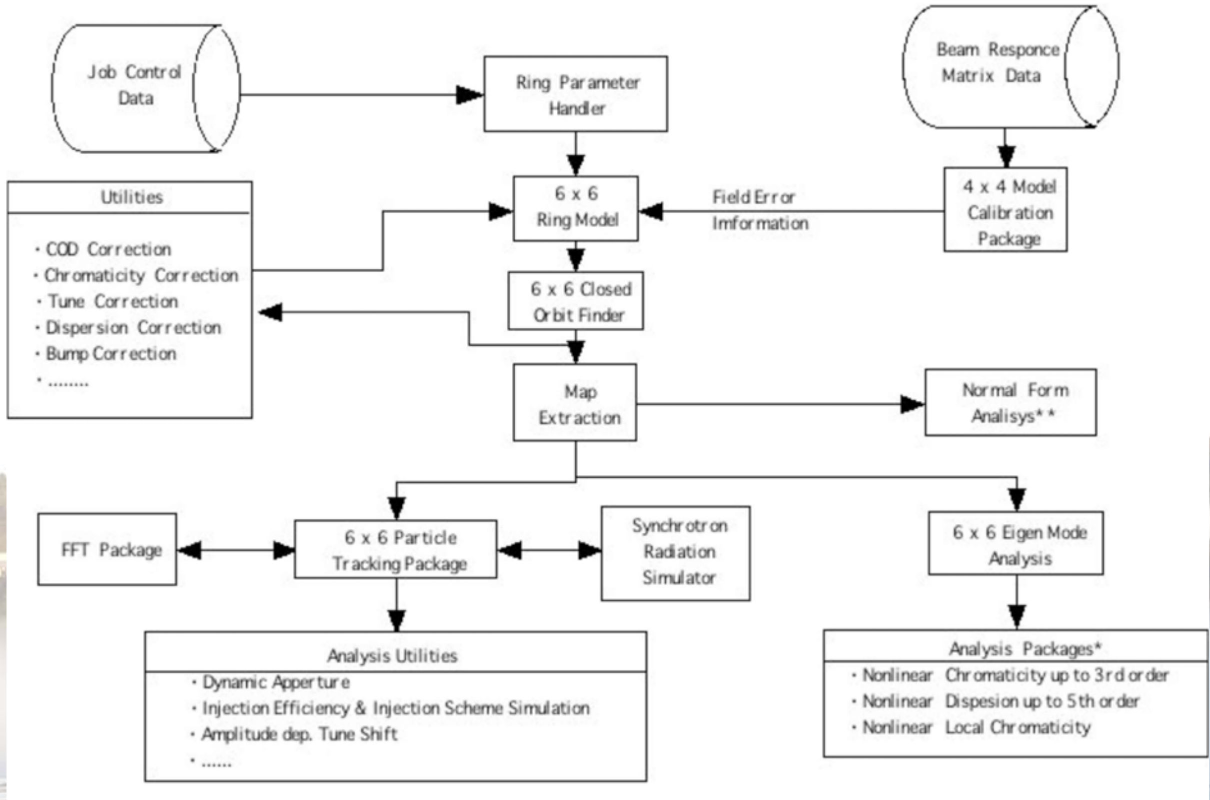
Co-workers: M. Takao and H. Tanaka

Objectives

- Understanding of Beam Dynamics in SPring-8
- Upgraid of Beam Quality in SPring-8
- Treatment as exact as possible

J. Schimizu, K. Soutome, M. Takao, H. Tanaka, Proc, 13th Symp. on Accelerator Science and Technology, Suita, Osaka, Japan, October 29-31, 2001, p.80.

Code Construction



(Fortran77 : Xeon 3.6GHz x 2, Memory 4 GB, Redhat Enterprise Linux 3)   * : 4 × 4、** : unfinished

Base : RACETRACK, A. Wrulich, DESY 84-026 (1984).

Differential Algebra is used for map extraction [M. Berz, Particle Accelerators, 1989, Vol.24, pp.109-124.]

Outline of the Code

Model Calibration and Analysis Packages

- **Model Calibration package**

  H. Tanaka, et. al., Proc, 13th Symp. on Acclerator Science and Technology, Suita, Osaka, October 2001, p.83.

- **Analysis packages**

  ・Nonlinear dispersion

  H. Tanaka, M. Takao, K. Soutome, H. Hama, M. Hosaka, NIM **A431** (1999), pp.396-404.

  ・Nonlinear chromaticity

  M. Takao, H. Tanaka, K. Soutome, J. Schimizu, Phys. Rev. **E70** (2004) 0616501.

Hamiltonian and Devices

Normalized Hamiltonian

$$\hat{H} = P_\sigma - h\left[\left\{(1+\delta)^2 - \left(\hat{p}_x - \frac{q}{p_0}A_x\right)^2 - \left(\hat{p}_y - \frac{q}{p_0}A_y\right)^2\right\}^{1/2} - \frac{q}{p_0}A_s\right]$$

$$\delta = \frac{p - p_0}{p_0}, \quad \hat{p}_{x,y} = \frac{p_{x,y}}{p_0}, \quad \sigma = s - v_0 \cdot t, \quad P_\sigma = \frac{E - E_0}{p_0 v_0}$$

$$h = 1 + K_x x + K_y y$$

Devices

- Kicks
  BH, Q, Sx, ... , 20-pole ; BV, skew Q, skew Sx, ... , skew 20-pole
- Symplectic Integrators
  BH†, Q †, Sx †, BV †, skew Q † *, ID ... *Include radiation energy losses*+
  Drift Space, Solenoid † *
- Others
  Cavity, Wakefield , BPM, Aperture Limit, Marker

† possible to include fringe effect、 *impossible to use for map extracion
+ after each symplectic integration steps, calls radation loss routine if nessesary

Radiation loss

$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}, \quad u_c = \hbar\omega_c, \quad P_\gamma = \frac{cC_\gamma}{2\pi}\frac{E_G{}^4}{\rho^2}$$

$$N = \frac{15\sqrt{3}}{8}\frac{P_\gamma}{u_c} \quad \text{(photons/sec)}$$

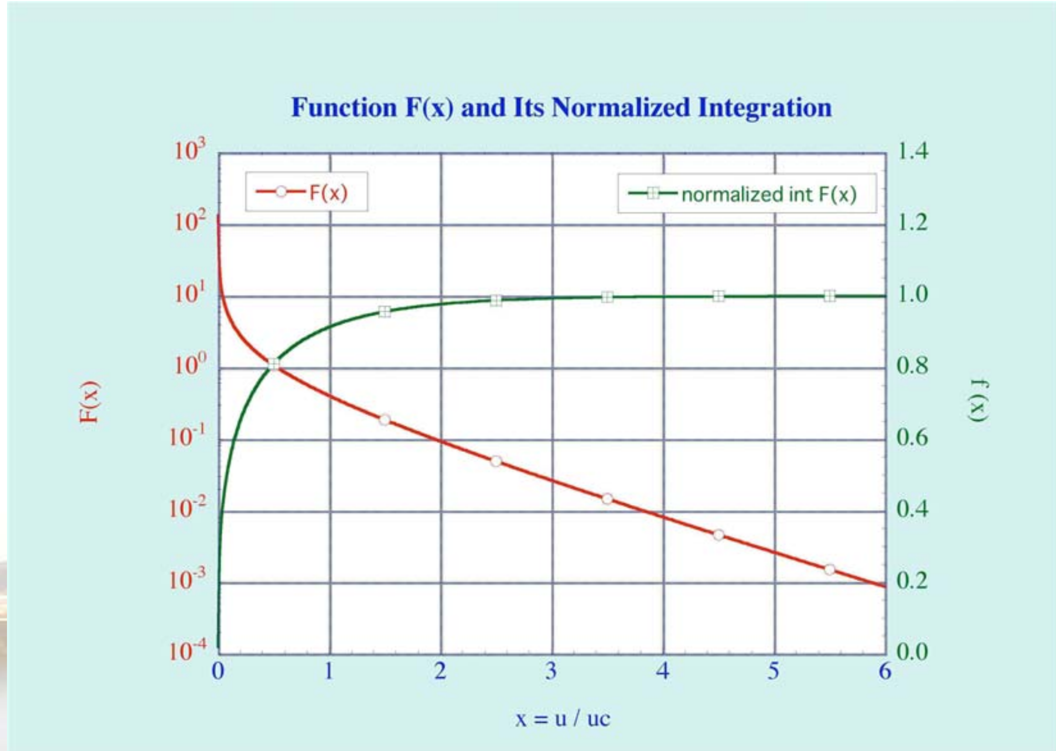
$$S(\xi) = \frac{9\sqrt{3}}{8\pi}\xi\int_\xi^\infty K_{5/3}(\eta)d\eta$$

spectum function, u_c = critical energy

$$n(u) = \frac{P_\gamma}{u_c{}^2}F\left(\frac{u}{u_c}\right) \quad \text{photon distribution}$$

$$F(\xi) = \frac{1}{\xi}S(\xi), \quad f(X) = \int_0^x F(\xi)d\xi \Big/ \int_0^6 F(\xi)d\xi$$

F(ξ) = photon number spectrum
max of X(=u/uc) is assumed as 6.0



After closed orbit search, function f(x) is calculated and srored as f(x) table、 ΔX = 0.001、maximum of x is 6.
Photon energy $u=u_c*x$ is determined by linear interpolation of function f(x), where f(x) is determined by random number *r* .

M. Sands, Proc. Int. School of Physics <<Enrico FERMI>> Course XLVI, edited by B. Touschek, June 1969, pp.257-411.

Symplecti Integrators

- Bending magnet（BM） and Fringe field
  Sector and Rectangular Bends: Analytic solutions
  E. Forest, M. F. Reusch, D. L. Bruhwiler, A. Amiry, Particle Accelerators, 1994, **Vol. 45**, pp.65-94.

  Fringes of BH, BV, Q, skew Q and Sx: All the same treatment

- Q, skew Q and Sx
  4th order leap-frog method: $H = T(p) + V(q)$
  H. Yoshida, Celestial Mechanics and Dynamical Astronomy **56**, 27-43, 1993.

- Insertion devise（ID） and Solenoid
  Linearized Hamiltonian in x' and y'
  Explicit solution by generating function
  E. Forest and K. Ohmi, KEK Report 92-14 September 1992 A.

  2 models for solenoid: <u>Sharp-edge model</u> and <u>Soft-edge Bump function model</u>
  A. J. Dragt, Nuclear Instruments and Methods in Physics Research **A298** (1990) 441-459.

・Drift space

$$\hat{H} = p_\sigma - \left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}, \quad A_x = A_y = A_s = 0$$

$$x' = \frac{\hat{p}_x}{\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}}; \quad \hat{p}_x{}' = 0, \quad y' = \frac{\hat{p}_y}{\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}}; \quad \hat{p}_y{}' = 0$$

$$\sigma' = 1 - \frac{(1+\delta)\beta_0/\beta}{\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}}; \quad p_\sigma{}' = 0$$

$$x^f = x^i + x' \cdot L; \quad \hat{p}_x{}^f = \hat{p}_x{}^i, \quad y^f = y^i + y' \cdot L; \quad \hat{p}_y{}^f = \hat{p}_y{}^i$$

$$\sigma^f = \sigma^i + \sigma' \cdot L; \quad p_\sigma{}^f = p_\sigma{}^i$$

・ Bendig magnet and fringe

Sector Bend

$$\hat{H} = p_\sigma - (1 + K_x \cdot x + K_y \cdot y)\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2} + \frac{1}{2}(1 + K_x \cdot x + K_y \cdot y)^2, \quad A_x = A_y = 0$$

$$\hat{p}_x{}^f = \hat{p}_x{}^i \cos(K_x \cdot s) + \left\{\sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}} - K_x\left(\frac{1}{K_x} + x^i\right)\right\} sin(K_x \cdot s)$$

$$x^f = \frac{1}{K_x{}^2}\left\{K_x\sqrt{(1+\delta)^2 - \hat{p}_x{}^{f2} - \hat{p}_y{}^{i2}} - \frac{\partial \hat{p}_x{}^f}{\partial s} - K_x\right\}$$

$$\hat{p}_y{}^f = \hat{p}_y{}^i, \quad \delta^f = \delta^i (= \delta)$$

$$y^f = y + \hat{p}_y{}^i \cdot s + \frac{\hat{p}_y{}^i}{K_x}\left\{\arcsin\left(\frac{\hat{p}_x{}^i}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right) - \arcsin\left(\frac{\hat{p}_x{}^f}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right)\right\}$$

$$\sigma^f = \sigma^i + (1+\delta)s + \frac{(1+\delta)}{K_x}\left\{\arcsin\left(\frac{\hat{p}_x{}^i}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right) - \arcsin\left(\frac{\hat{p}_x{}^f}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right)\right\} - s$$

Rectangular Bend: Cartesian coordinate

$$H = p_\sigma - \left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2} + K_x \cdot x \qquad M = Y_{rot}\left(\frac{\theta}{2}\right) Fringe(1) M_{\|} Fringe(2) Y_{rot}\left(\frac{\theta}{2}\right)$$

Body $M_{\|}$

$$\hat{p}_x{}^f = \hat{p}_x{}^i - K_x \cdot z, \quad \hat{p}_y{}^f = \hat{p}_y{}^i$$

$z = 2sin(\theta/2)/K_x$: trajectory length

$$x^f = x^i + \frac{1}{K_x}\left\{\sqrt{(1+\delta)^2 - \hat{p}_x{}^{f2} - \hat{p}_y{}^{i2}} - \sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}}\right\}$$

$$y^f = y^i + \frac{\hat{p}_y{}^i}{K_x}\left\{\arcsin\left(\frac{\hat{p}_x{}^i}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right) - \arcsin\left(\frac{\hat{p}_x{}^f}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right)\right\}$$

$$\sigma^f = \sigma^i + \frac{(1+\delta)}{K_x}\left\{\arcsin\left(\frac{\hat{p}_x{}^i}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right) - \arcsin\left(\frac{\hat{p}_x{}^f}{\sqrt{(1+\delta)^2 - \hat{p}_y{}^{i2}}}\right)\right\} - s$$

Coordinate rotation

$$x^f = \frac{x^i}{\cos(\theta)\left\{1 - \dfrac{\hat{p}_x{}^i tan(\theta)}{\sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}}}\right\}}, \quad \hat{p}_x{}^f = \hat{p}_x{}^i \cos(\theta) + sin(\theta)\sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}}$$

$$y^f = y^i + \frac{\hat{p}_y{}^i x^i \cdot tan(\theta)}{\sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}}\left\{1 - \dfrac{\hat{p}_x{}^i tan(\theta)}{\sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}}}\right\}}, \quad \hat{p}_y{}^f = \hat{p}_y{}^i$$

$$\sigma^f = \sigma^i + \frac{(1+\delta) x^i \cdot tan(\theta)}{\sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}}\left\{1 - \dfrac{\hat{p}_x{}^i tan(\theta)}{\sqrt{(1+\delta)^2 - \hat{p}_x{}^{i2} - \hat{p}_y{}^{i2}}}\right\}}$$

Fringes(B, Q, skew Q and Sx)

BH case

$$H = -\sqrt{(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2}\,\frac{\hat{p}_x a_x}{\sqrt{(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2}} + B_0(z)x$$

$$b_0(z) = \frac{q}{p_0} B(z), \quad a_x = \frac{q}{p_0} A_x$$

$$g_\pm(q,p) = \lim_{\Delta \to 0} \int_{-\Delta}^{\Delta} H_\pm(q,p)\,ds = \pm K_x \frac{y^2 \hat{p}_x / 2}{\sqrt{(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2}} \longrightarrow \pm \frac{1}{2} K_x \frac{y^2 \hat{p}_x}{1+\delta}$$

$$\left(\frac{\hat{p}_x}{1+\delta}\right)^2 << 1, \quad \left(\frac{\hat{p}_y}{1+\delta}\right)^2 << 1$$: assumption

・Q, skew Q and Sx

$$\hat{H} = p_\sigma - \left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2} + \frac{1}{2} g_0 \left(x^2 - y^2\right) - n_0 x \cdot y + \frac{1}{6}\lambda_0\left(x^3 - 3xy^2\right), \quad A_x = A_y = 0$$

$$x' = \frac{\partial \hat{H}}{\partial \hat{p}_x} = \frac{\hat{p}_x}{\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}}, \quad \hat{p}_x' = -\frac{\partial \hat{H}}{\partial x} = -g_0 x + n_0 y - \frac{1}{2}\lambda_0\left(x^2 - y^2\right)$$

$$y' = \frac{\partial \hat{H}}{\partial \hat{p}_y} = \frac{\hat{p}_y}{\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}}, \quad \hat{p}_y' = -\frac{\partial \hat{H}}{\partial y} = +g_0 y + n_0 x + \frac{1}{2}\lambda_0 xy$$

$$\sigma' = \frac{\partial \hat{H}}{\partial p_\sigma} = 1 - \frac{(1+\delta)\beta_0/\beta}{\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}}, \quad p_\sigma' = -\frac{\partial \hat{H}}{\partial \sigma} = 0$$

4th order leap-frog method

$$q_i = q_{i-1} + \Delta s \cdot c_i \left(\frac{\partial T}{\partial \hat{p}}\right)_{\hat{p}=\hat{p}_{i-1}} , \quad \hat{p}_i = \hat{p}_{i-1} - \Delta s \cdot d_i \left(\frac{\partial V}{\partial q}\right)_{q=q_{i-1}}$$

$$\sigma_i = \sigma_{i-1} + \Delta s \cdot c_i \left(1 - \frac{(1+\delta)\beta_0/\beta}{\left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2}}\right)_{\hat{p}=\hat{p}_{i-1}}$$

$$c_1 = c_4 = \frac{1}{2\left(2 - 2^{1/3}\right)}, \quad c_2 = c_3 = \frac{1 - 2^{1/3}}{2\left(2 - 2^{1/3}\right)}, \quad d_1 = d_3 = \frac{1}{2 - 2^{1/3}}, \quad d_2 = \frac{-2^{1/3}}{2 - 2^{1/3}}, \quad d_4 = 0$$

・Insertion Device (ID) and Solenoid

$$\hat{H} = P_\sigma - \left\{ (1+\delta)^2 - \left(\hat{p}_x - \frac{q}{p_0} A_x \right)^2 - \left(\hat{p}_y - \frac{q}{p_0} A_y \right)^2 \right\}^{1/2}, \quad A_s = 0$$

Firsrt order in x' and y'

$$\hat{H} \Rightarrow P_\sigma - \delta + \frac{(\hat{p}_x - f)^2}{2(1+\delta)} + \frac{(\hat{p}_y - g)^2}{2(1+\delta)}, \quad f = \frac{q}{p_0} A_x, \quad g = \frac{q}{p_0} A_y$$

$$\hat{p}_x^{\,f} = \frac{\left\{ \hat{p}_x^{\,i} - (f \cdot f_x + g \cdot g_x)\Delta z \right\}(1 - g_y \Delta z) + \left\{ \hat{p}_y^{\,i} - (f \cdot f_y + g \cdot g_y)\Delta z \right\} g_x \Delta z}{(1 - f_x \Delta z)(1 - g_y \Delta z) - f_x \cdot g_y \Delta z^2}$$

$$\hat{p}_y^{\,f} = \frac{\left\{ \hat{p}_y^{\,i} - (f \cdot f_y + g \cdot g_y)\Delta z \right\}(1 - f_x \Delta z) + \left\{ \hat{p}_x^{\,i} - (f \cdot f_x + g \cdot g_x)\Delta z \right\} f_y \Delta z}{(1 - f_x \Delta z)(1 - g_y \Delta z) - f_x \cdot g_y \Delta z^2}$$

$$x^f = x^i + \Delta s \frac{\hat{p}_x^{\,f} - f}{1+\delta}, \quad y^f = y^i + \Delta s \frac{\hat{p}_y^{\,f} - g}{1+\delta}, \quad \Delta z = \frac{\Delta s}{1+\delta}$$

$$\sigma^f = \sigma^i + \Delta s \left(1 - \frac{\beta_0}{\beta} \right) - \frac{\Delta s}{2} \left\{ \left(\frac{\hat{p}_x^{\,f} - f}{1+\delta} \right)^2 + \left(\frac{\hat{p}_y^{\,f} - g}{1+\delta} \right)^2 \right\} \frac{\beta_0}{\beta}$$

Insertion Device (ID)

$$A_x = \frac{1}{\rho_0 k_s}\cos(k_x x)\cosh(k_y y)\sin(k_s s) - \frac{1}{\rho_1 k_s k_{x1}}\sin(k_{x1} x)\sinh(k_{y1} y)\sin(k_s s - \phi)$$

$$A_y = \frac{1}{\rho_0 k_s k_y}\sin(k_x x)\sinh(k_y y)\sin(k_s s) - \frac{1}{\rho_1 k_s}\cos(k_{x1} x)\cosh(k_{y1} y)\sin(k_s s - \phi)$$

or

$$A_x = \frac{1}{\rho_0 k_s}\cos(k_x x)\cosh(k_y y)\sin(k_s s) - \frac{1}{\rho_1 k_s k_{x1}}\sinh(k_{x1} x)\sin(k_{y1} y)\sin(k_s s + \phi)$$

$$A_y = \frac{1}{\rho_0 k_s k_y}\sin(k_x x)\sinh(k_y y)\sin(k_s s) - \frac{1}{\rho_1 k_s}\cosh(k_{x1} x)\cos(k_{y1} y)\sin(k_s s + \phi)$$

Solenoid

- Sharp-edge

$$A_x = -\frac{1}{2}b_0(s)y, \quad A_y = +\frac{1}{2}b_0(s)x$$

$b_0(s)=0$ for outside, $b_0(s)=B_0$ for inside of solenoid

- Soft-edge Bump function

$$B_s(0,0,s) = B_0 \cdot bump(s,\lambda,L), \quad bump(s,\lambda,L) = \frac{1}{2}\left[tanh\left(\frac{s}{\lambda}\right) - tanh\left(\frac{s-L}{\lambda}\right)\right]$$

L = length of solenoid body, λ = depth of fringe region

$$A_x = -yU(s,\rho^2), \quad A_y = +xU(s,\rho^2), \quad A_z = 0$$

$$U(s,\rho^2) = \sum_{n=0}^{\infty}\frac{(-1)^n(\rho^2)^n b_{2n}}{\{2^{2n+1} n!(n+1)!\}}, \quad b_{2n} = \frac{\partial^{2n} B_s(0,0,s)}{\partial s^{2n}}, \quad \rho^2 = x^2 + y^2$$

Cavity

・Normal Operation

$$\hat{H} = P_\sigma - \left[(1+\delta)^2 - \hat{p}_x{}^2 - \hat{p}_y{}^2\right]^{1/2} - \frac{L}{2\pi h}\frac{q}{p_0 c}V(s)\cos\left(\frac{2\pi h}{L}\sigma + \varphi_0\right), \quad A_x = A_y = 0$$

$$V(s) = V_0\delta(s)$$

L = circumference, h = harmonic number

・Power-off (under construction : temporary treatment)

・Intact cavity (power is constant during m sec period)

$$P_T = \frac{V_0^2}{R} + \frac{U_0 \cdot I}{eN_c} = const$$

P_T = total power / cavity, U_0 = radiation loss / revolution,
N_c = number of cavity, I = stored current, R = shunt impedance

$$P_L = \sum_{n=1}^{Np}\frac{I}{N_p}V_0 \cdot sin\left(\frac{2\pi h}{L}\sigma_n + \varphi_0\right)$$

: Load, after power-off, V_0 => V_{RF}

$$V_{RF} = \sqrt{(P_T - P_L)\cdot R}$$

A-, B-, C-, D-RF Stations
8 cavities/RF Station
Total 32 cavities

・Power-off cavity

$$V_b = \frac{1}{2}\frac{I \cdot R \cdot \cos^2(\phi(n))}{1+\beta}$$

$$tan(\phi) = \frac{sin(\alpha) - I \cdot R \cdot sin(\theta)/(1+\beta)/V_0}{\cos(\alpha)} = -2 \cdot Q_L\frac{\omega_{RF} - \omega_0}{\omega_0}$$

$$\theta = \varphi_0 - \alpha, \quad \omega_0(n) = \omega_0(n=0) + \Delta\omega\left[1 - \exp\left(-\frac{n}{n_\tau}\right)\right]$$

n = revolution after power-off, V_b = reverse voltage, β= coupl. const, α= tuner offset,
ω_0 = resonance angular frequency(determined at steady state), n_τ = time const.

Co-workers :
T. Ohshima, T. Fujita, T. Takashima, M. Hara, H. Yonehara

Step and sawtooth corrections are under consideration for φ_0 : rise τ_1、 down τ_2

Wakefield

・Longitudinal (Energy loss)

$$\Delta U_j = \frac{I \cdot C_l}{M\sqrt{\sigma_s}} N_j$$

I = current/bunch, M = number of macro particles,
N_j = number of particles going before j-th particle,
σ_s = bunch length, C = coefficient

・Transverse (kick)

$$\theta_j = \frac{I \cdot C_{t0} \cdot \sqrt{\sigma_s}}{M} \sum_i x_i \quad or \quad \theta_j = \frac{I \cdot C_t \cdot \sigma_s}{M} \sum_i x_i$$

x_i = transverse amplitude of i-th macro particle
Summation of amplitude is performed for macro-particles going before j-th particle.

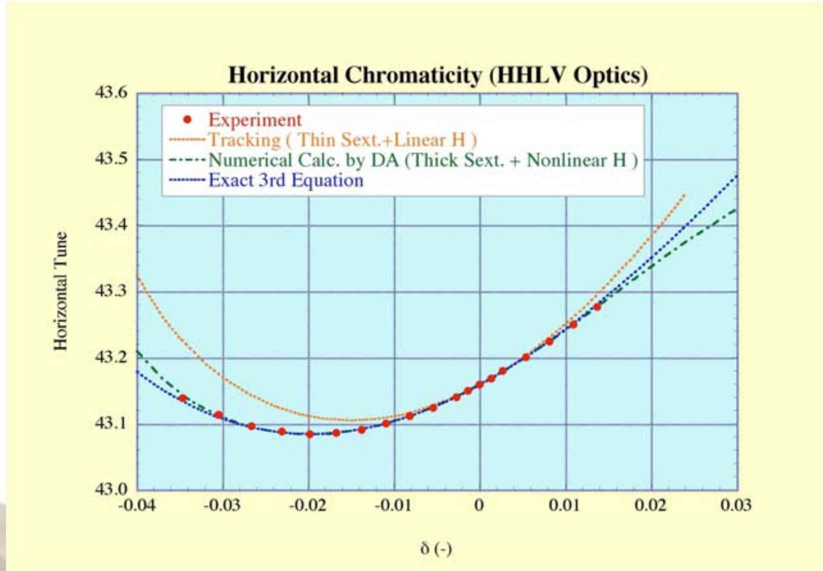
Wakefield is usually neglected (option off)

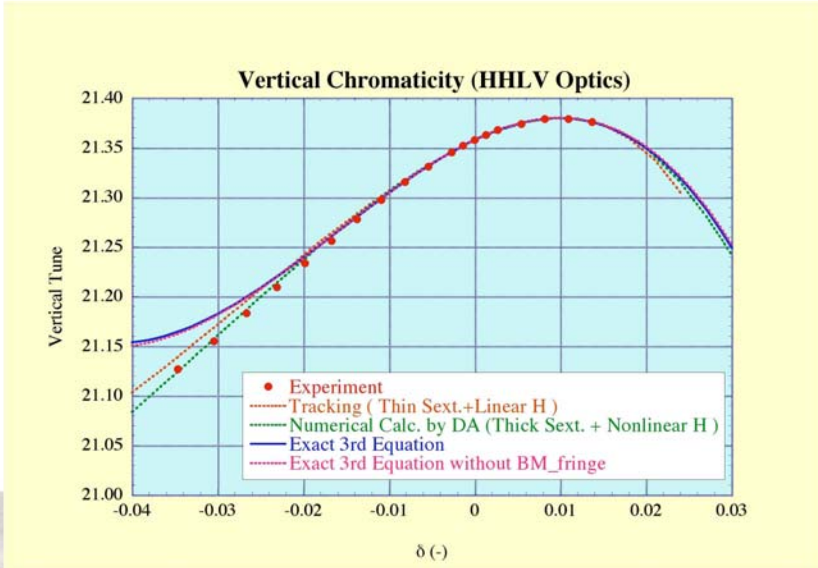
K. Bane and M. Sands, SLAC-PUB-4441, November 1987 (A).
K. Ohmi and Y. Kobayashi, Phys. Rev. **E59** (1999),p.1167.

Comparisons with experiments

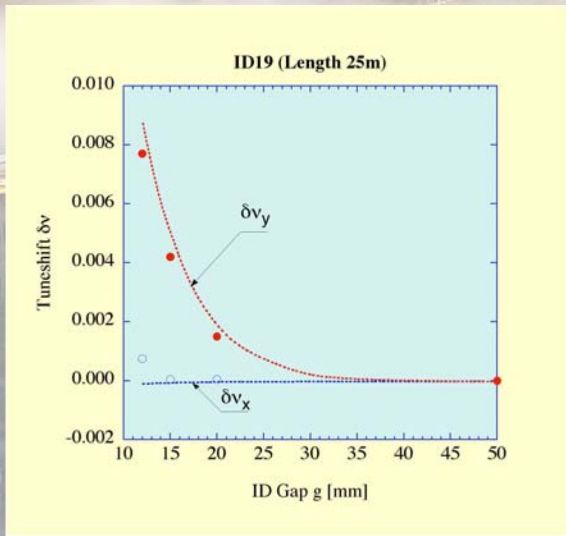
- Chromaticity: Effect of thick Sx

Green dotted line is the results of CETRA

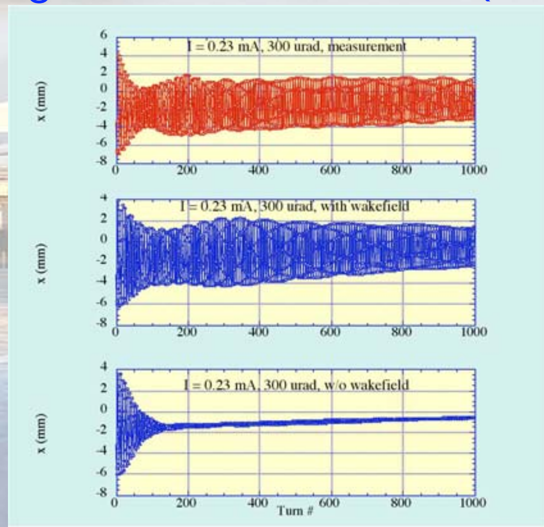




- Tune shift: Effect of ID



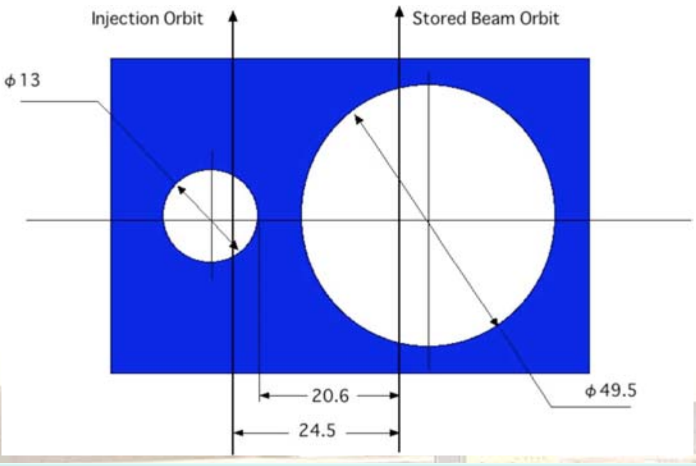
- Ping: Effect of wakefield (transverse only)

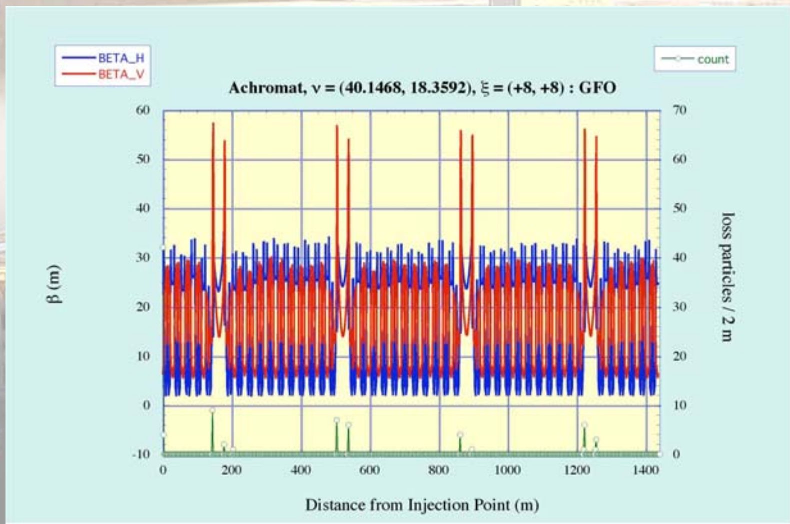


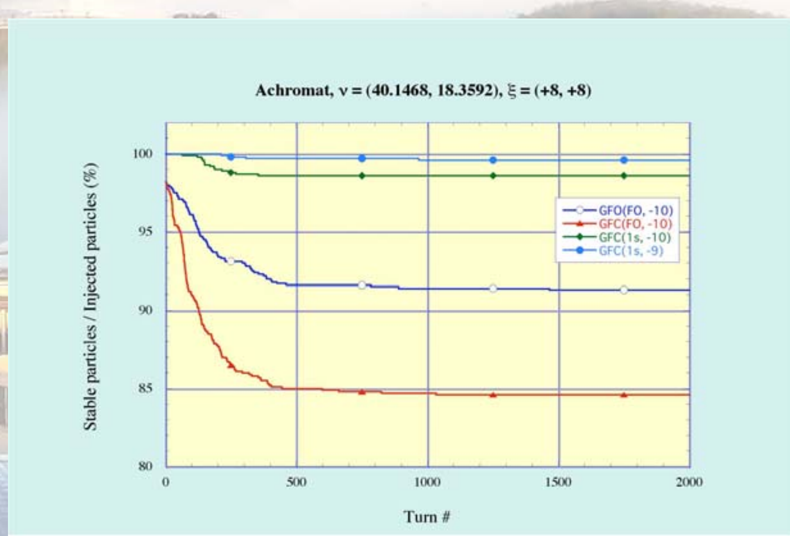
red : experiment
blue : CETRA
middle : with wakefield
bottom : w/o wakefield

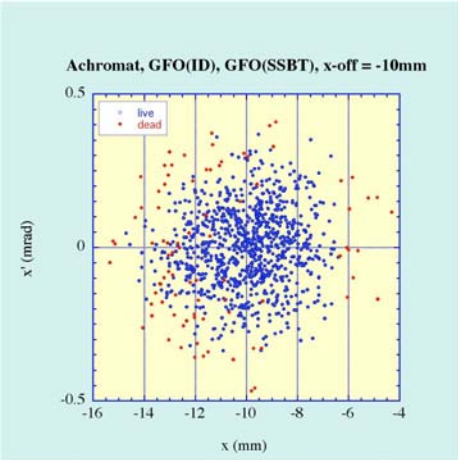
Examples of Tracking simulation

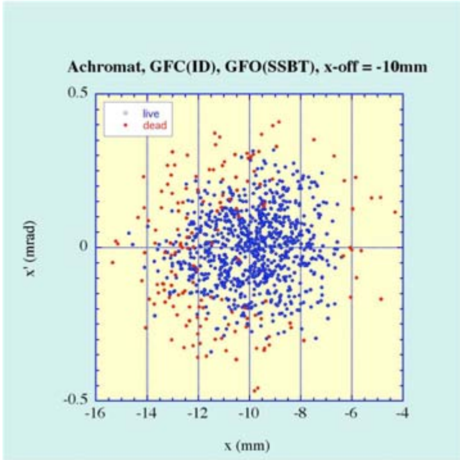
- Injection efficiency

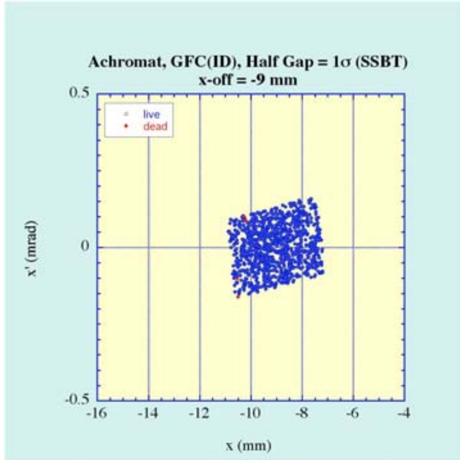




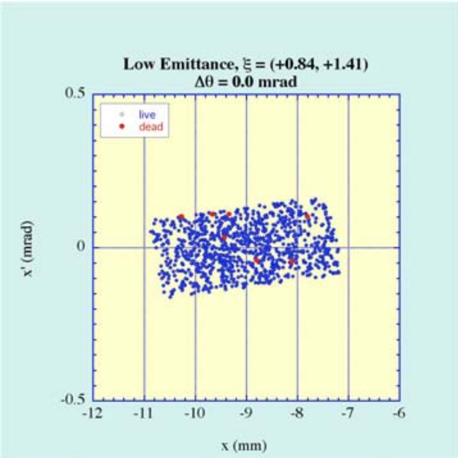


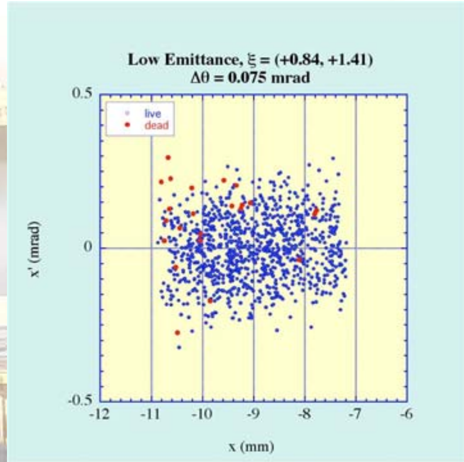


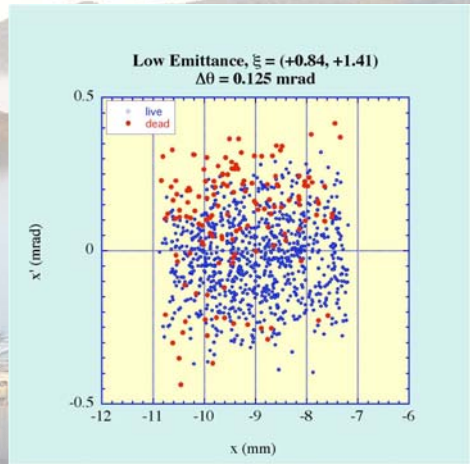




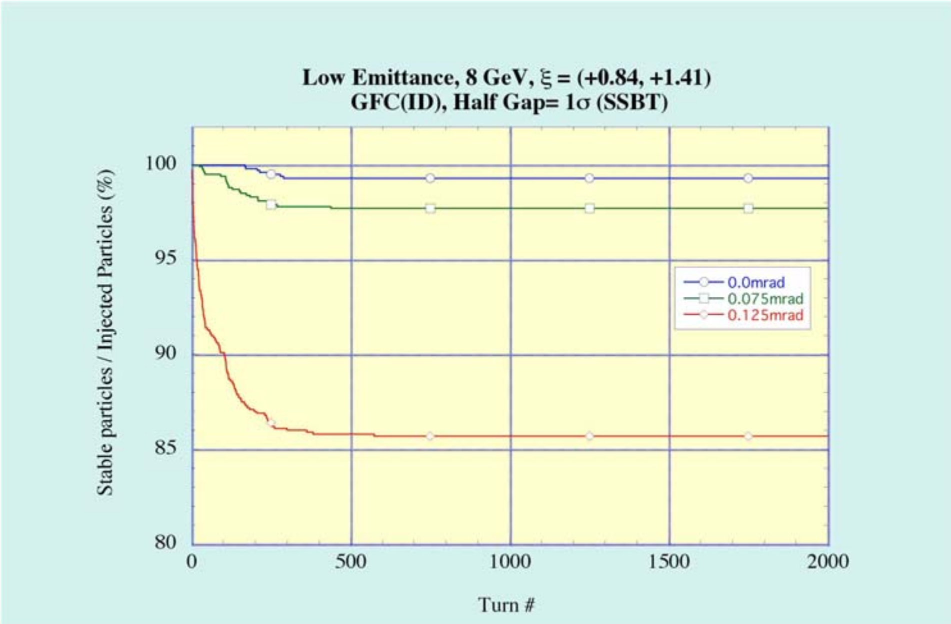
Initial distribution at injection point : w/o window effect (achromat)

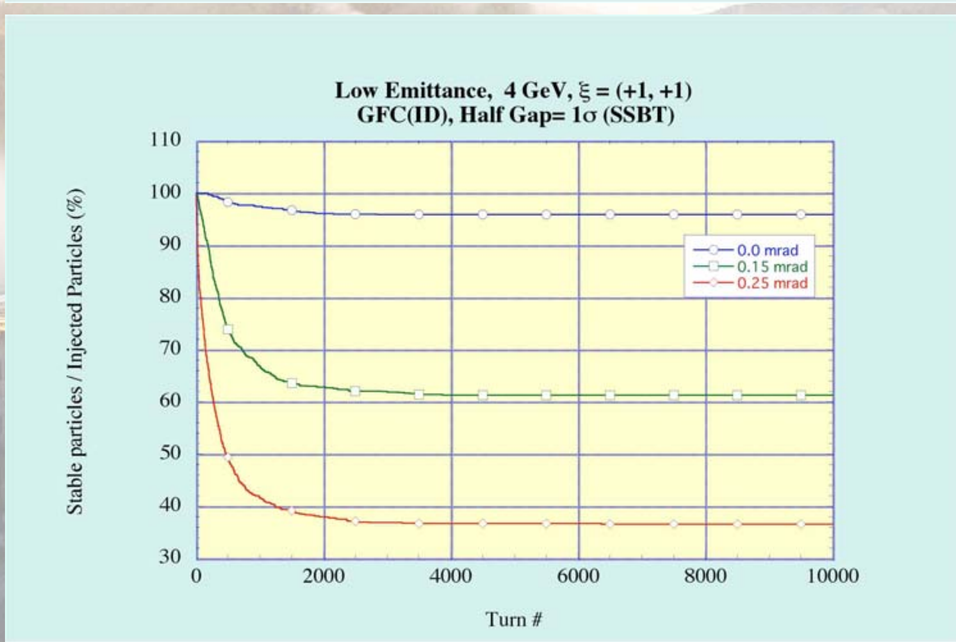






Initial distribution at injection point : with window effect (Low Emittance)





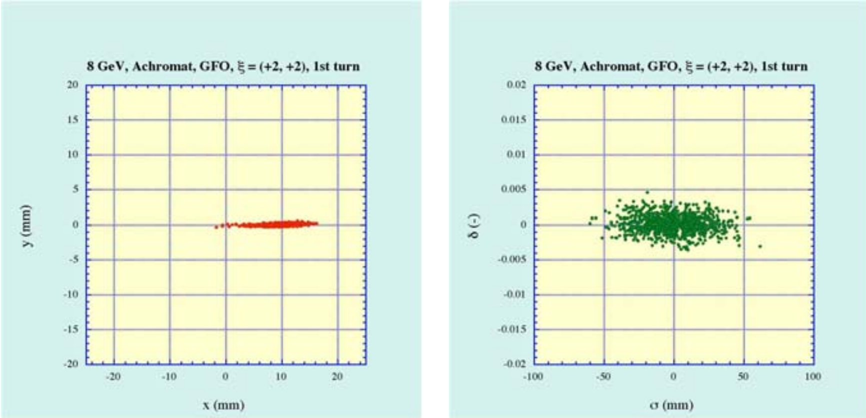
Multiple scattering effect in septum chamber

E(GeV)	condition	Δθ (mrad)
8	w/o window	0.000
	window, He	0.075
	window, Air	0.125
4	w/o window	0.00
	window, He	0.15
	window, Air	0.25

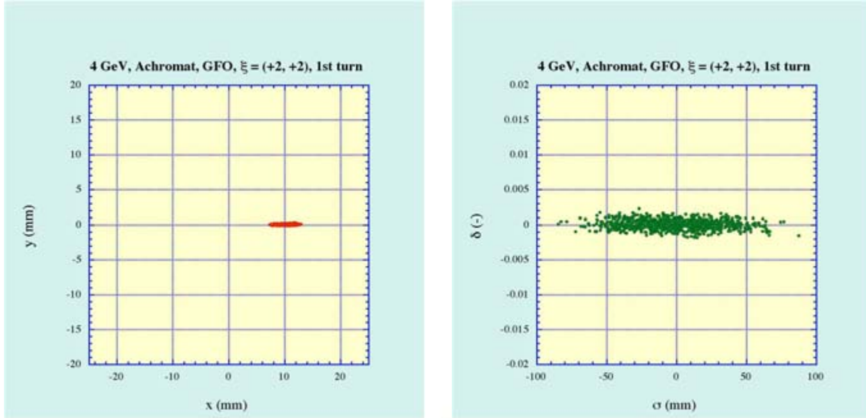
window :

Be 0.5mm
Al 0.1mm
Kapton 0.1mm

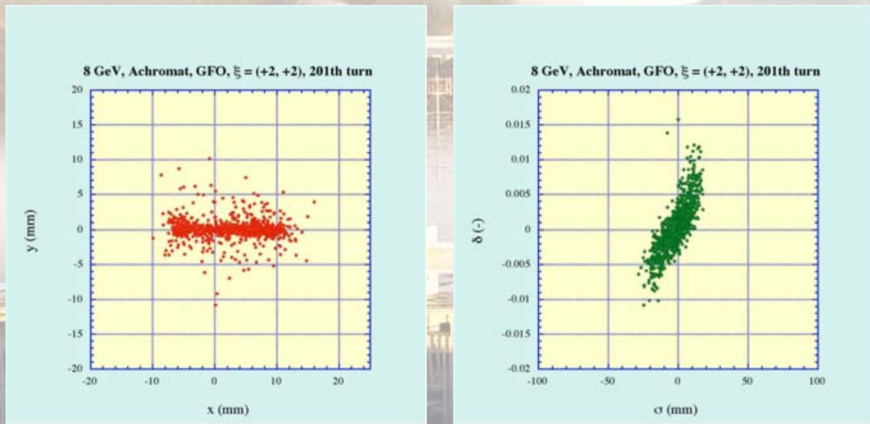
xy profiles and σ-δ phase plots of injected beam (1,000 particles injection). Gaps of ID are full open.



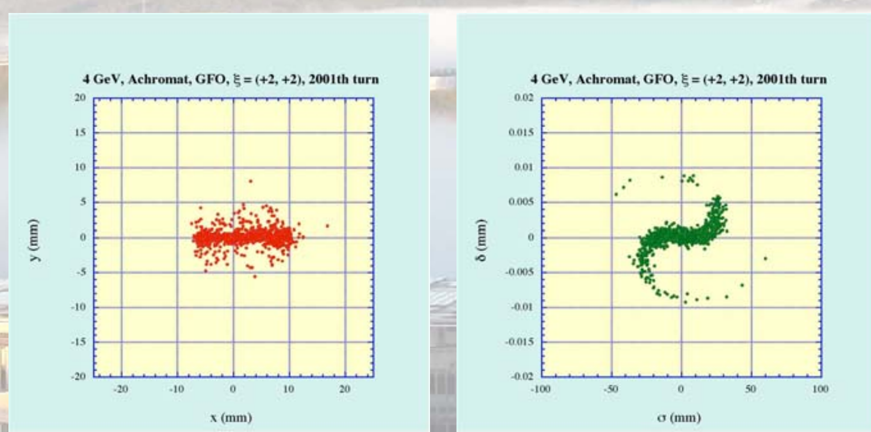
8 GeV 1st trun



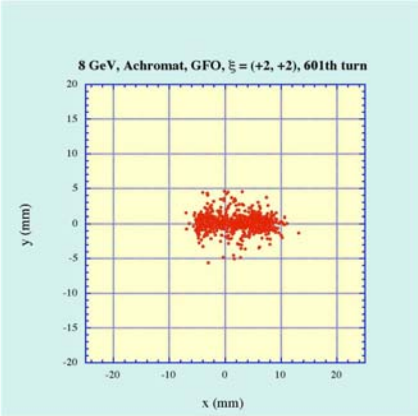
4 GeV 1st turn

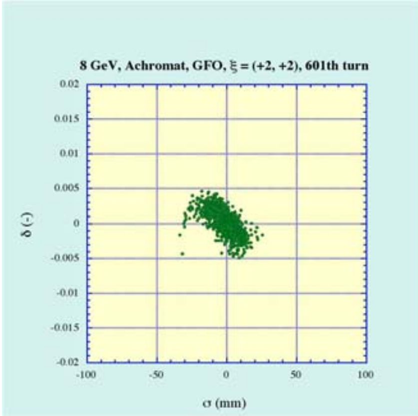


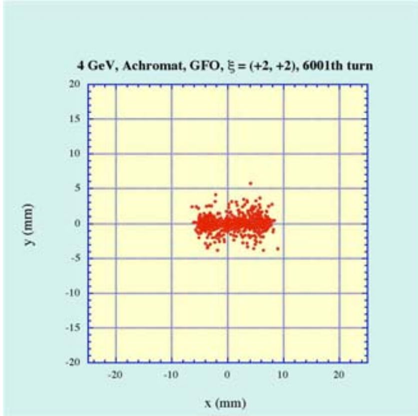
8 GeV 201th trun

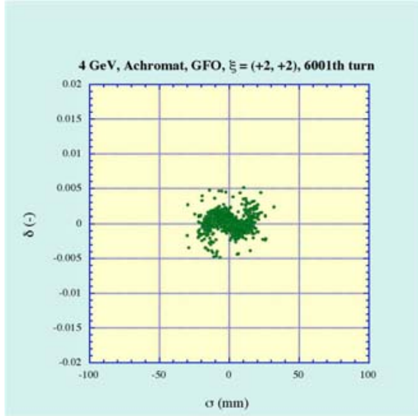


4 GeV 2,001th turn



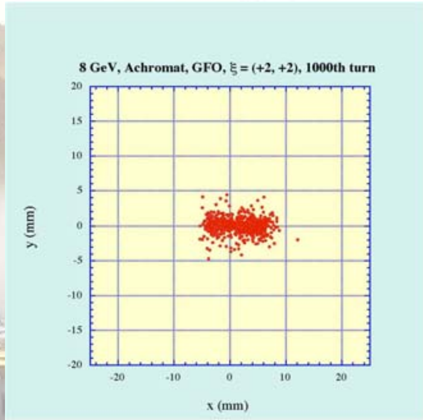


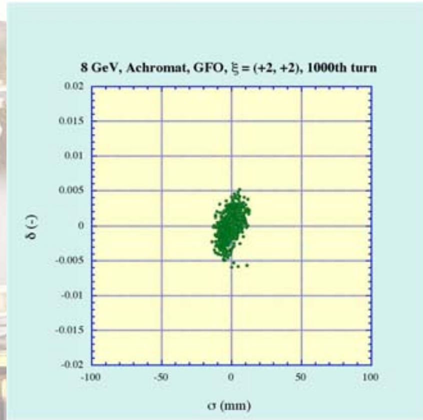


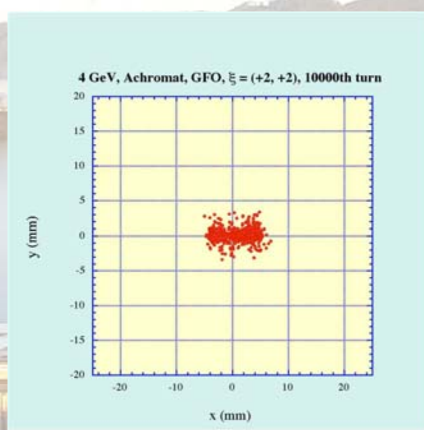


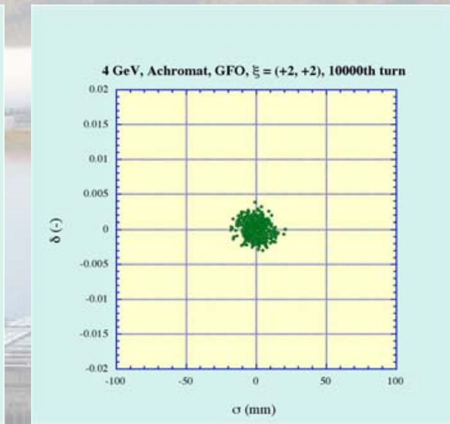
8 GeV 601th trun

4 GeV 6,001th turn





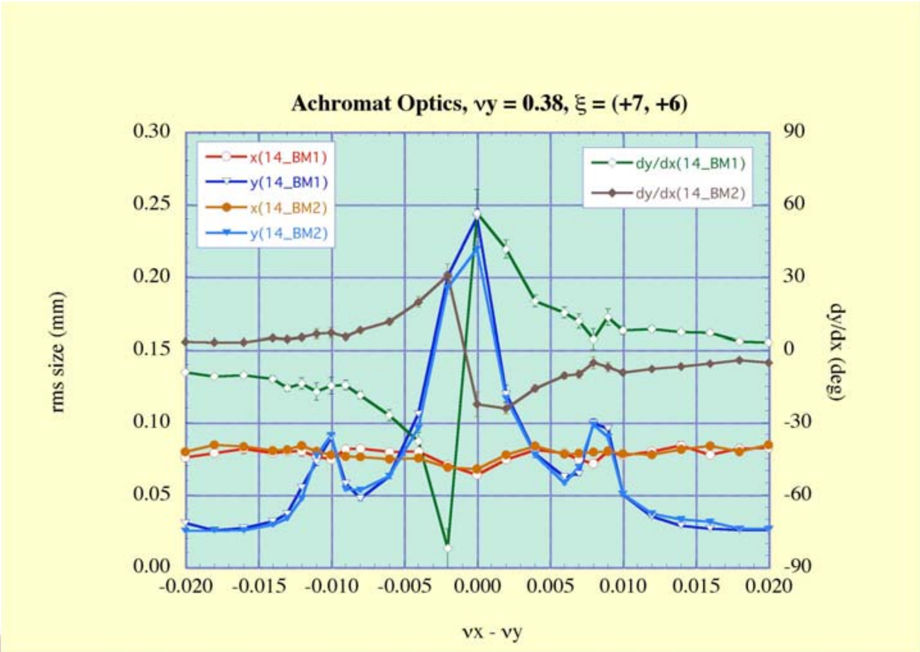




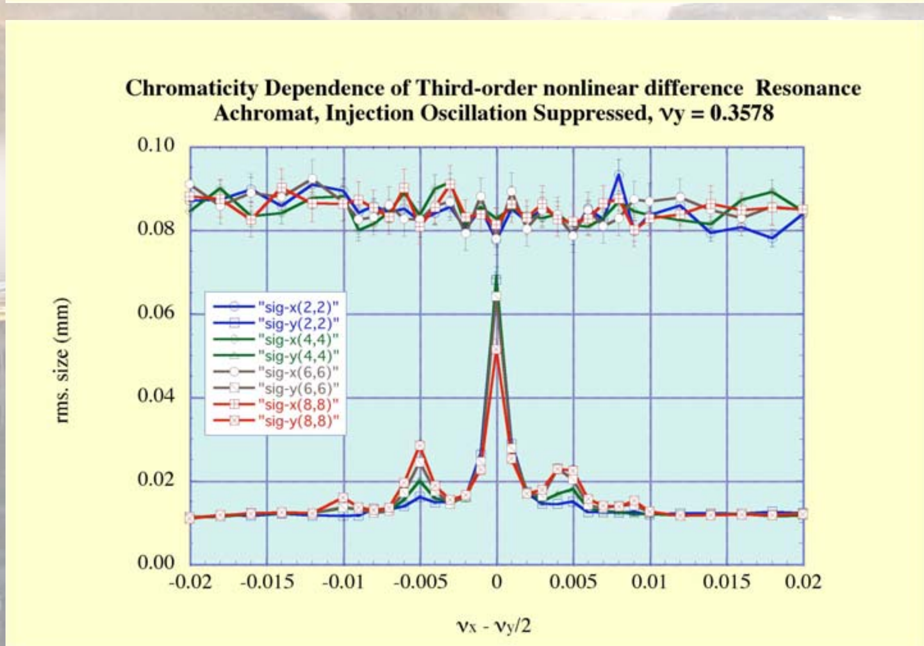
8 GeV 1,000th trun

4 GeV 10,000th turn

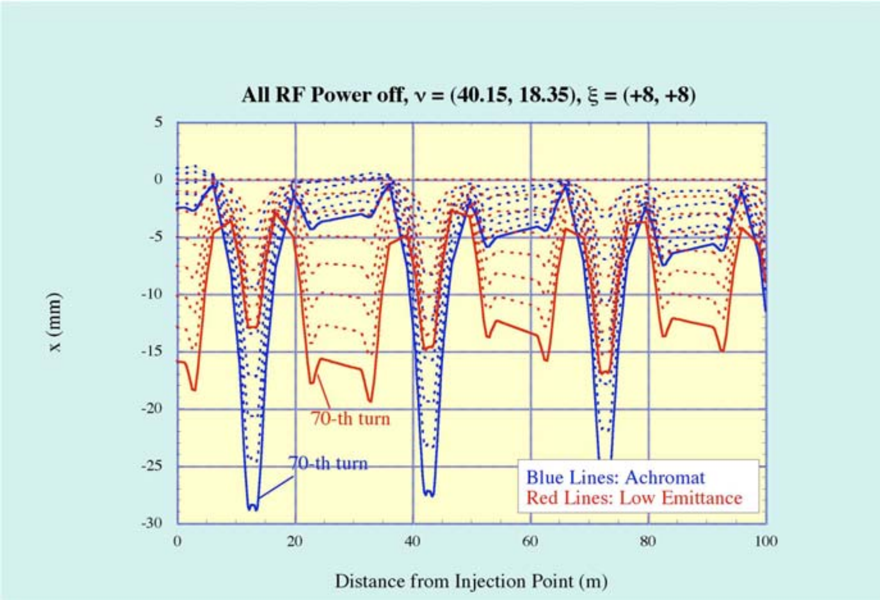
・Resonances

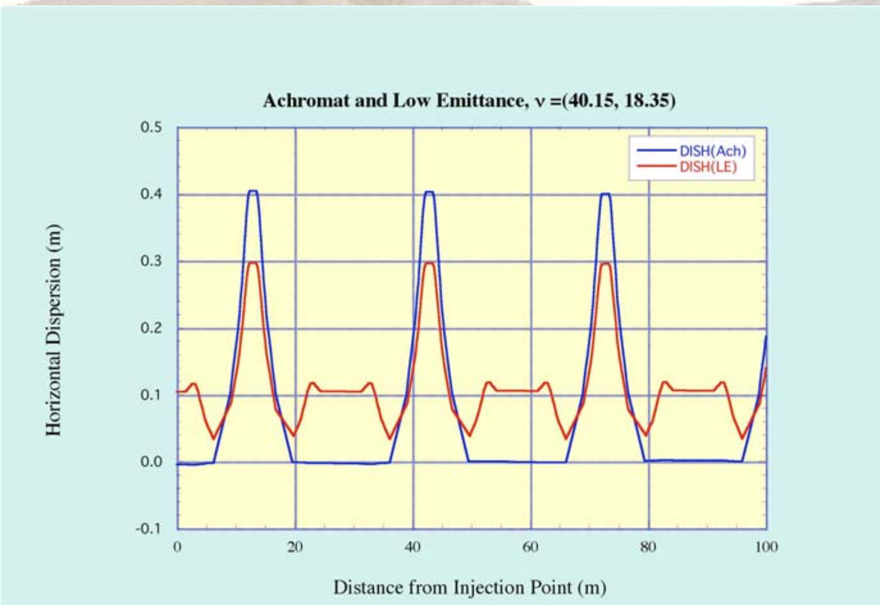


Beam size and dy/dx of beam profiles in the center of cell-14 BM near the differential resonance ($\nu_x=\nu_y$)



The chromaticity dependence of beam size in the center of cell-14 upstream BM near the third-order resonance ($2\nu_x=\nu_y$)





・RF power off

All the RF station power off; trajectories of 1st, 10th, ・・・, 70th revolution

（Cavity model off、classical radiation loss assumed）

In the Low Emittance operation, most particles bombards the injection chamber for all rf power off condition. （red lines）.

Inner radius of injection chamber = 18.6 mm.

upstream : Al alloy (r = 20.0 mm)

downstream: SUS (r = 18.6 mm)

Horizontal radius of other chambers = 35.0 mm.

Energy loss by BM : about 9.23MeV/rev

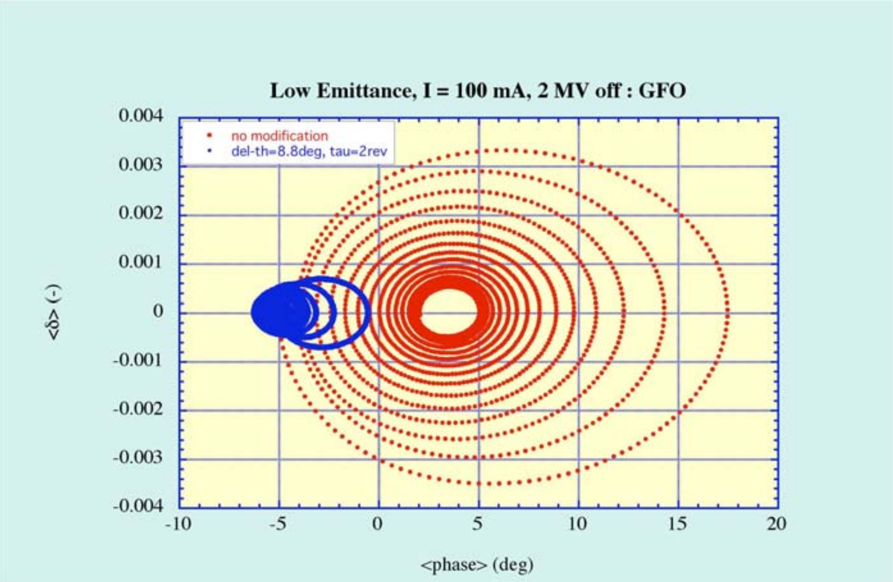
Energy loss by IDs : usually about 1MeV/rev (max is over 2MeV/rev)

A-, B-, C-, D-RF Stations

8 cavities/RF Station

Total 32 cavities

0.5MV× 32=16MV

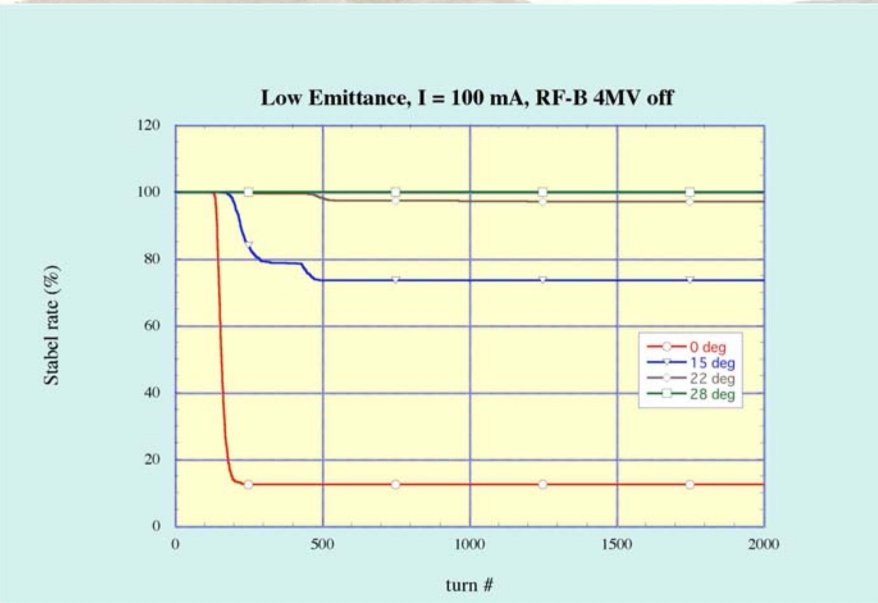


4 cavities in downstream of RF-A station powered off（16 MV→14 MV)

blue dots : synchronous phase is mannually +8.8° corrected, with assumption of time const. = 2 revs. (~10 μsec)　[test simulation by temporary model]

red dots : without correction、 large σ(phase) and δ oscillation

Topup operation can be maintained for 2MV off case.



All (eight) cavities of RF-B station powered off（16 MV→12 MV)

Sawtooth phase correction : stored current is 100mA

τ_1=3rev, τ_2=10,000rev　(4.79 μs/rev)

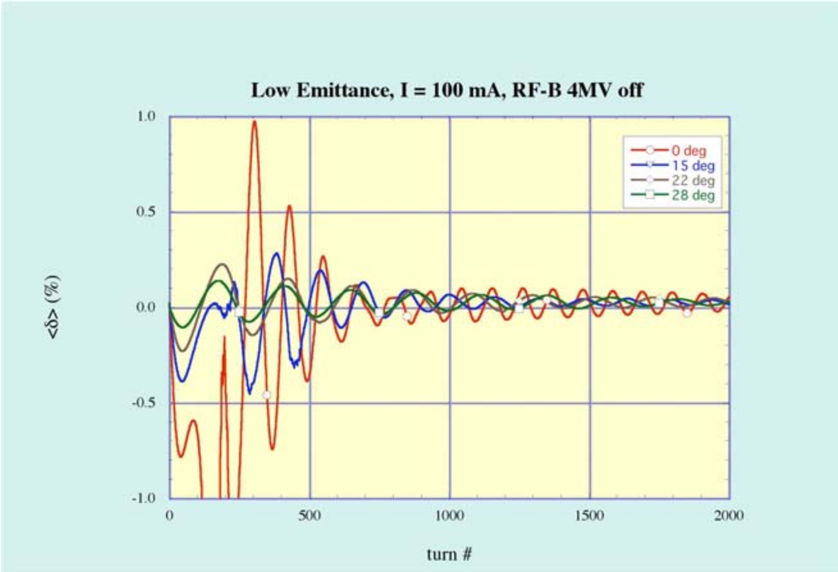
Phase in figure shows $\Delta\varphi_0$.

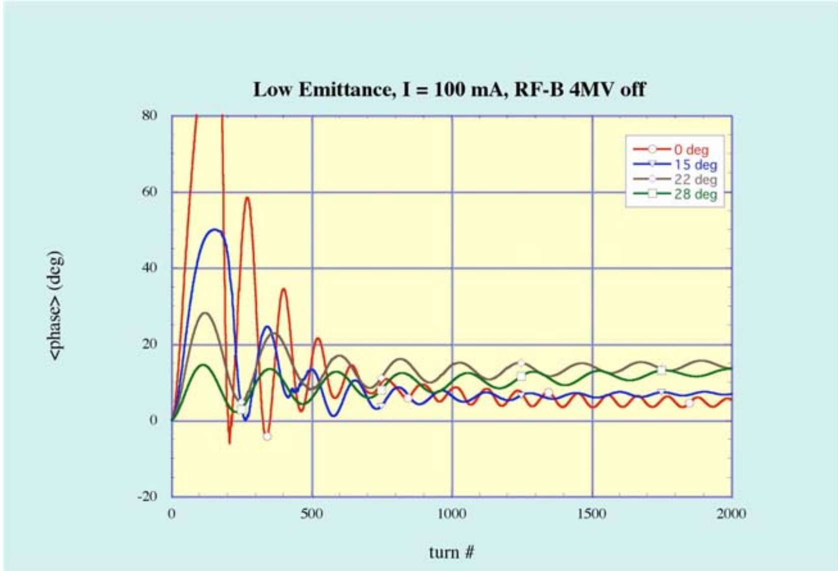
[Results of test simulation with temporary model]

The case of 4MV off needs +15° correction, when I is small.

+22° correction, beam current decreases

+28° correction, beam is not lost





- without phase correction（red）：
  Momentum and phase oscillations are large, most particles are lost
  → topup operation stopped, beam should be re-injected

- with phase correction：
  Phase correction corresponds to 4MV off（+15°） is not sufficient for 100 mA.
  About twice phase correction is required for 100mA.
  with +28°(green) correction, small phase oscillation
  → possibility to maintain topup operation
  When IDs under operation increase, what happens?

Summary

- Use exact equations of motion derived from exact Hamiltonian
- Use symplectic integrators for real devices in SPring-8, if possible
- Equations of motion for ID and solenoid are derived from expanded Hamiltonian in first order of x' and y'
- Nonlinear chromaticity can be reproduced with thick Sx
- Useful tool for investigation and improvement of injection efficiency for topup operation
  - Upgraid injection efficiency with slits in SSBT
  - Multiple scattering at injection chamber contributes degradation of injection efficiency, especially in 4 GeV operation
- Possible tool for investigation of beam dynamics in RF power off
  - 2MV off; simulation can reproduce the beam behavior, fairly well
  - 4MV off; possibility to avoid beam abort
- Home made code to respond to the demands of the times

Appendix

Symplecticity

When $M^T J M = J$, matrix M is symplectic, where M and J are 6 by 6 matrices for us.

$$\mathbf{M} = \begin{vmatrix} m_{x,x} & m_{x,px} & m_{x,y} & m_{x,py} & m_{x,\sigma} & m_{x,\delta} \\ m_{px,x} & m_{px,px} & m_{px,y} & m_{px,py} & m_{px,\sigma} & m_{px,\delta} \\ m_{y,x} & m_{y,px} & m_{y,y} & m_{y,py} & m_{y,\sigma} & m_{y,\delta} \\ m_{py,x} & m_{py,x} & m_{py,y} & m_{py,py} & m_{py,\sigma} & m_{py,\delta} \\ m_{\sigma,x} & m_{\sigma,px} & m_{\sigma,y} & m_{\sigma,py} & m_{\sigma,\sigma} & m_{\sigma,\delta} \\ m_{\delta,x} & m_{\delta,px} & m_{\delta,y} & m_{\delta,py} & m_{\delta,\sigma} & m_{\delta,\delta} \end{vmatrix} \qquad \mathbf{J} = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{vmatrix}$$

M is one turn matrix. A sample of check write is as follows:

```
 1 turn matrix am
        1   5.232489E-01   1.822018E+01   0.000000E+00   0.000000E+00   0.000000E+00   5.012416E-02
        2  -3.585530E-02   6.626100E-01   0.000000E+00   0.000000E+00   0.000000E+00   3.742622E-03
        3   0.000000E+00   0.000000E+00  -9.237297E-01   4.860075E+00   0.000000E+00   0.000000E+00
        4   0.000000E+00   0.000000E+00  -1.366636E-01  -3.635311E-01   0.000000E+00   0.000000E+00
        5  -3.755540E-03  -3.497847E-02   0.000000E+00   0.000000E+00   1.000000E+00  -1.324282E-01
        6   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   1.000000E+00
det =  0.999999999999944
amt x J x am
        1   0.000000E+00   1.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00  -1.456734E-15
        2  -1.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00  -7.476658E-14
        3   0.000000E+00   0.000000E+00   0.000000E+00   1.000000E+00   0.000000E+00   0.000000E+00
        4   0.000000E+00   0.000000E+00  -1.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
        5   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   1.000000E+00
        6   1.456734E-15   7.476658E-14   0.000000E+00   0.000000E+00  -1.000000E+00   0.000000E+00
```