Simulation Code Development for High-Power Cyclotron

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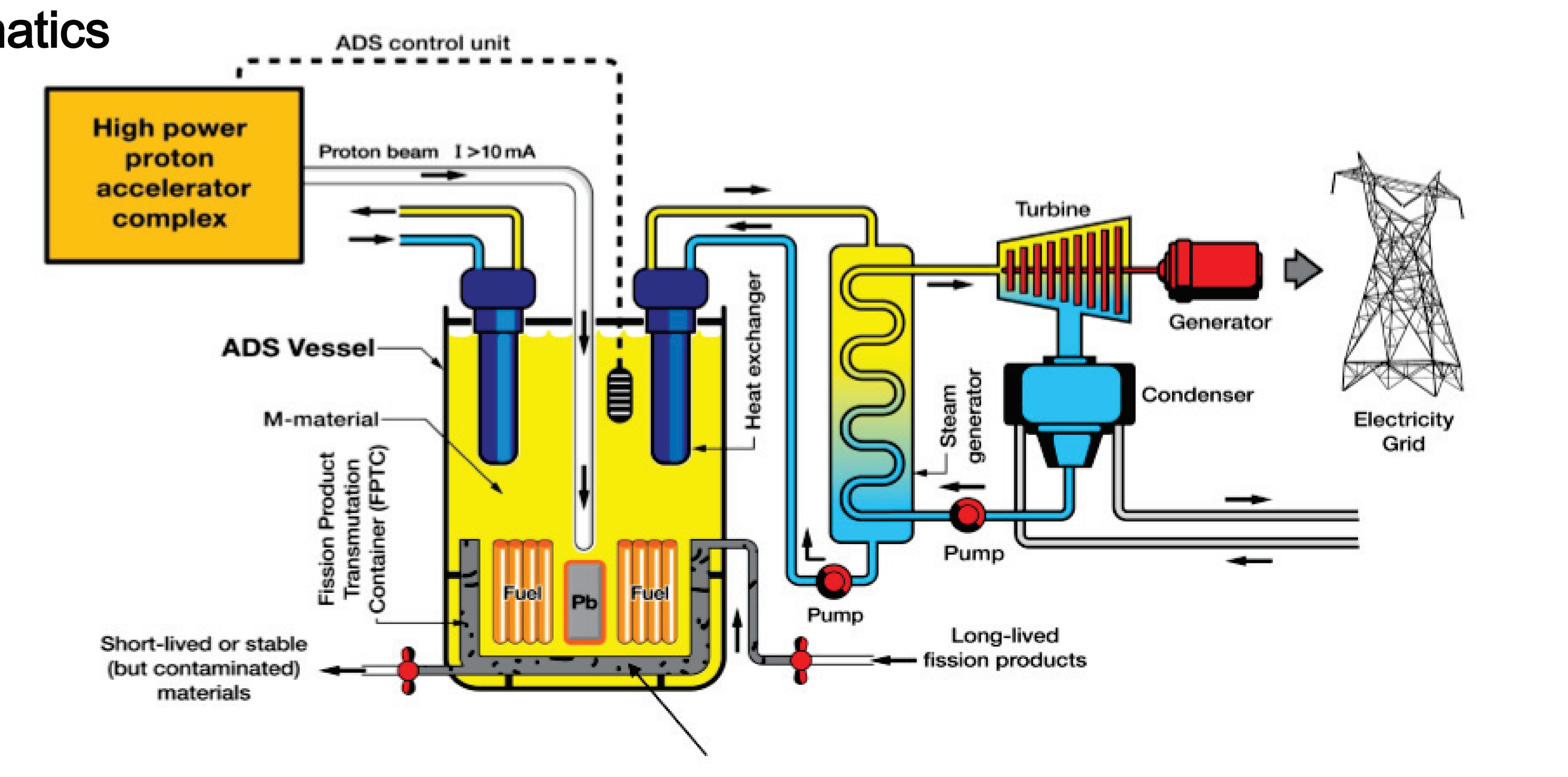
MOP09

Abstract

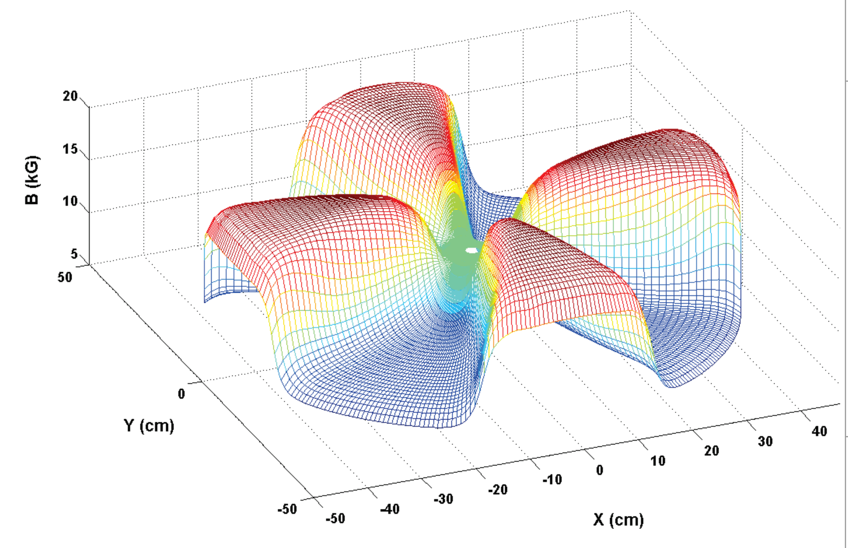
A high power cyclotron is a good candidate as a driver of the accelerator driven system for the transmutation of long lived nuclear wastes. In this work, a simulation code has been developed for describing the beam dynamics in the high power cyclotron. By including higher order terms in transverse transfer matrix and space charge effects, we expect to describe the beam motion more accurately. The present code can describe equivalent orbit at each energy, calculate the tunes, and also perform multi-particle tracking. We report the initial results of the code for the simulation of a 13 MeV cyclotron. Lastly, an upgrade plan is discussed to add more features and to increase calculating efficiency.

Schematics for Accelerator Driven System (ADS)

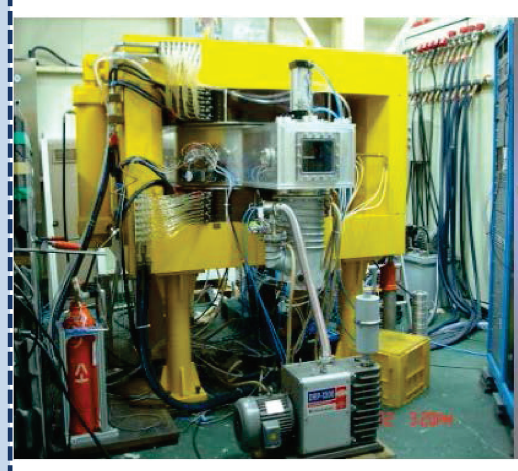
Schematics

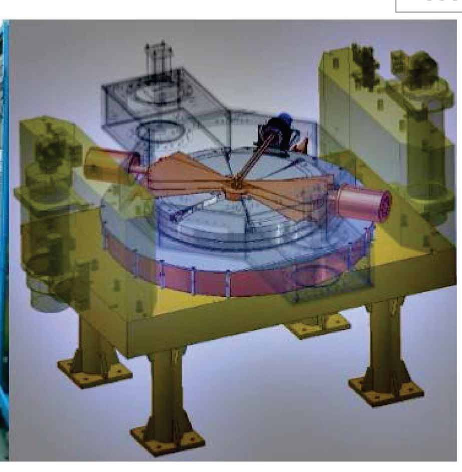


Magnetic field data of KIRAM-13 (13 MeV cyclotron)



Beams	Ions	Protons
	energy/ current	13MeV / 80uA
Magnet	type	H-type
	# of sectors	4
	pole diameter	0.96 m
	hill/valley gap	4 cm / 12 cm
	ν_r / ν_z	1.025 / 0.25~0.3
	B_{max} (hill) / B_{max} (valley)	1.99 T / 0.99 T
	coil current	135 A
	power	12 kW
RF	frequency	77.3 MHz
	harmonic #	4
	# of dees	2
	dee angular width	39 °
	dee voltage	45 kV
Extraction	Carbon foil	
Ion Source	Internal cold cathode PIG	

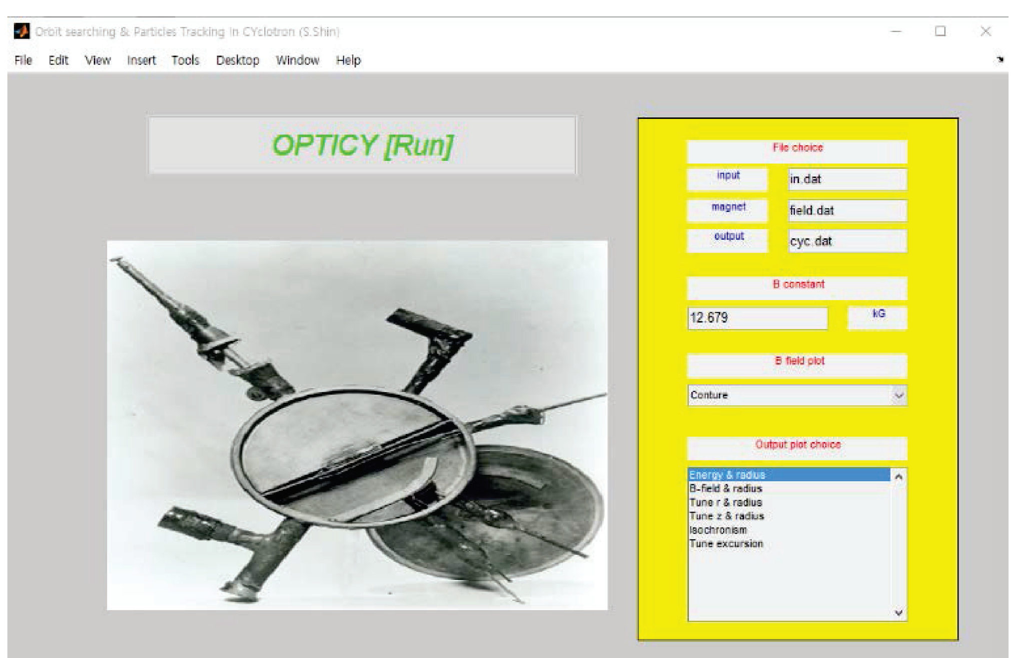




Simulation code for High Power Cyclotron

E.O. code

- Runge-Kutta tracking
- Find Equilibrium Orbits
- Tune
- Twiss parameter
- Multi-particle tracking using transfer matrix
- Acceleration effect
- Second order transfer matrix
- Space charge effect



Algorithm of E.O. Code

Equation of motion for x and p_x

$$\frac{dx}{d\theta}=\frac{p_r}{p_\theta}x+\frac{rp^2}{{p_\theta}^3}p_x \qquad \frac{dp_x}{d\theta}=-\frac{p_r}{p_\theta}p_{x1}-x_1\left(r\frac{\partial B}{\partial r}+B\right)$$

Equation of beam motion

$$\frac{dr}{d\theta}=\frac{rp_r}{p_\theta} \qquad \frac{dp_r}{d\theta}=p_\theta-q'rB(r,\theta)$$

Transfer matrix from θ_i to θ

$$X(\theta,\theta_i)=\begin{pmatrix}x_1 & x_2\\ p_{x1} & p_{x2}\end{pmatrix} \qquad \begin{pmatrix}x\\ p_x\end{pmatrix}_\theta=\boldsymbol{X}(\theta,\theta_i)\begin{pmatrix}x\\ p_x\end{pmatrix}_i$$

Find the errors in the trial values $\theta_{i=}$ θ_f

$$\begin{pmatrix}r_f\\ p_{rf}\end{pmatrix}_\theta=\begin{pmatrix}r\\ p_r\end{pmatrix}_\theta+\boldsymbol{X}(\theta,\theta_i)\begin{pmatrix}\delta r\\ \delta p_r\end{pmatrix}_i \qquad r_f=r_i+\delta r_i \quad p_{rf}=p_{ri}+\delta p_{ri}$$

$$0=\begin{pmatrix}\epsilon_1\\ \epsilon_2\end{pmatrix}+[\boldsymbol{X}(\theta,\theta_i)-I]\begin{pmatrix}\delta r\\ \delta p_r\end{pmatrix}_i \qquad \epsilon_1=r_f-r_i \quad \epsilon_2=p_{rf}-p_{ri}$$

Add corrections

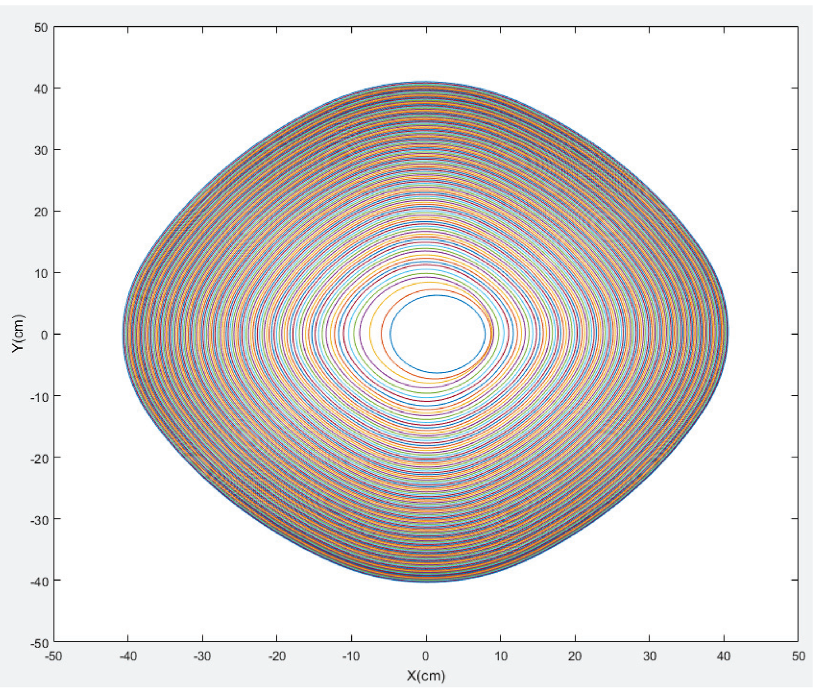
$$\delta r_i=\frac{(p_{x2}-1)\epsilon_1-x_2\epsilon_2}{x_1+p_{x2}-2} \qquad \delta p_{ri}=\frac{(x_1-1)\epsilon_2-p_{x1}\epsilon_1}{x_1+p_{x2}-2}$$

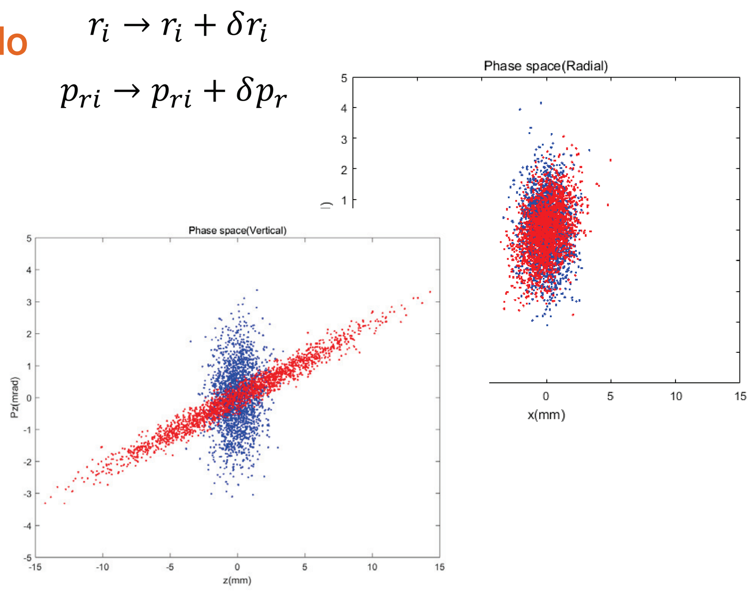
Error factor $\epsilon=\frac{1}{r_i}\left[(\delta r_i)^2+\left(\frac{a\delta p_{ri}}{a'\gamma^2}\right)^2\right]^{1/2}$

Is Closed Orbit made?

No: $r_i\rightarrow r_i+\delta r_i$, $p_{ri}\rightarrow p_{ri}+\delta p_r$

Yes: $\epsilon<\epsilon_0$





Equation of vertical motion

$$\frac{dz}{d\theta}=\frac{rp_z}{p_\theta} \qquad \frac{dp_z}{d\theta}=q'\left(\frac{\partial B_r}{\partial r}-\frac{p_r}{p_\theta}\frac{\partial B_\theta}{\partial\theta}\right)z$$

Add small energy and iteration above algorithm

Calculation of tune and Twiss parameters

$$Y(\theta_f,\theta_i)=I\cos\sigma+J(\theta_i)\sin\sigma \qquad \mathrm{J}(\theta_i)=\begin{pmatrix}\alpha_i & \beta_i\\ -\gamma_i & -\alpha_i\end{pmatrix}$$

$$\cos\sigma=\frac{1}{2}(Y_{11}+Y_{22})$$

$$\alpha\sin\sigma=\frac{1}{2}(Y_{11}-Y_{22})$$

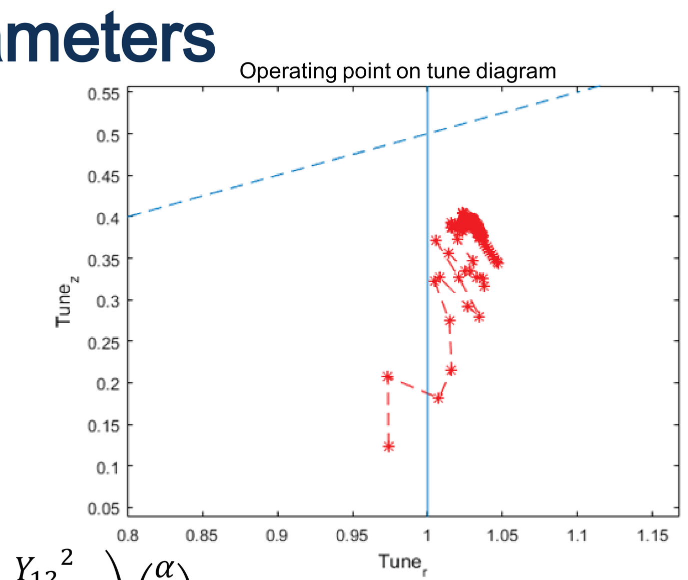
$$\beta\sin\sigma=Y_{12}$$

$$\gamma\sin\sigma=Y_{21}$$

Tune $v=\frac{N\sigma}{2\pi}$

Transfer matrix for Twiss parameters

$$\begin{pmatrix}\alpha\\ \beta\\ \gamma\end{pmatrix}_\theta=\begin{pmatrix}{Y_{11}}^2 & -2Y_{11}Y_{12} & {Y_{12}}^2\\ -Y_{11}Y_{21} & Y_{11}Y_{21}+Y_{12}Y_{21} & -Y_{12}Y_{22}\\ {Y_{21}}^2 & -2Y_{21}Y_{22} & {Y_{22}}^2\end{pmatrix}\begin{pmatrix}\alpha\\ \beta\\ \gamma\end{pmatrix}_{\theta_i}$$



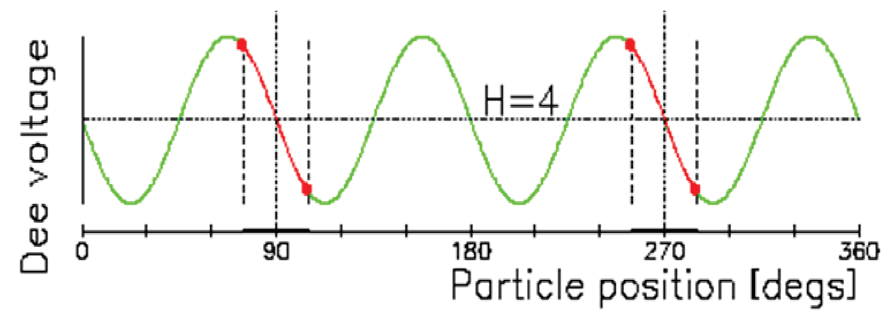
Future plan

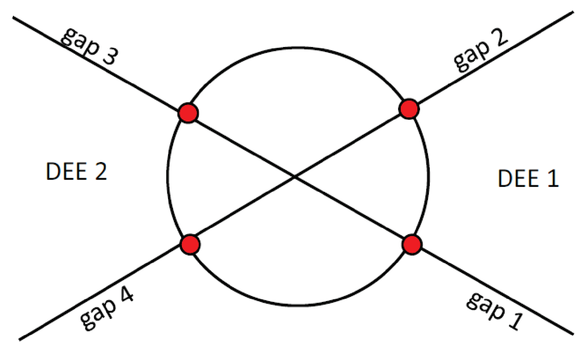
2016

- Include acceleration effect

$$\Delta E_k=V_0\cos\varphi\cdot N\cdot q\cdot\sin\left(\frac{h\cdot\alpha}{2}\right)$$

- Second order transfer matrix





2017

- Implementation of space charge effect algorithm

2018

- High power cyclotron design using developed code

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