Differential Algebraic Methods for Space Charge Modeling and Applications to the University of Maryland Electron Ring

Edward Nissen

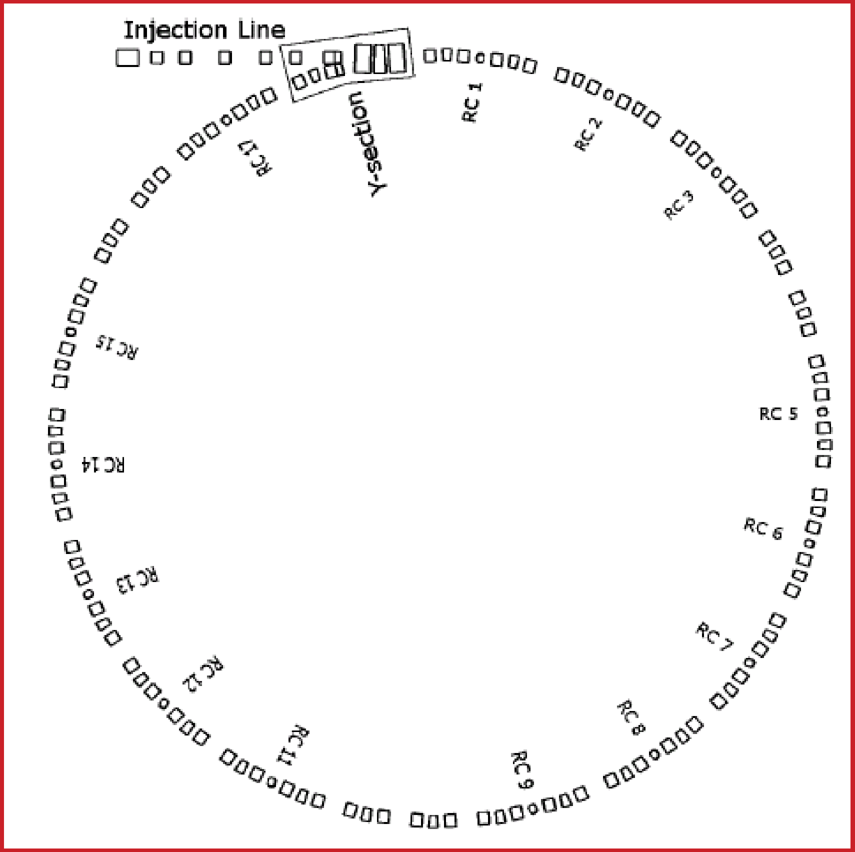
Motivation

- Extract relevant information from the transfer map of a given system using normal form methods.
- Include effects not normally included in a transfer map.
- Provide new insights into the effects of space charge on particle beams.

Outline

- Overview of the Research
- The University of Maryland Electron Ring (UMER)
- Mathematical Tools
- UMER’s modeling, and early experiments
- Adding space charge to the simulation
- Parallelization of the space charge code
- Alternatives for space charge calculation
- Summary

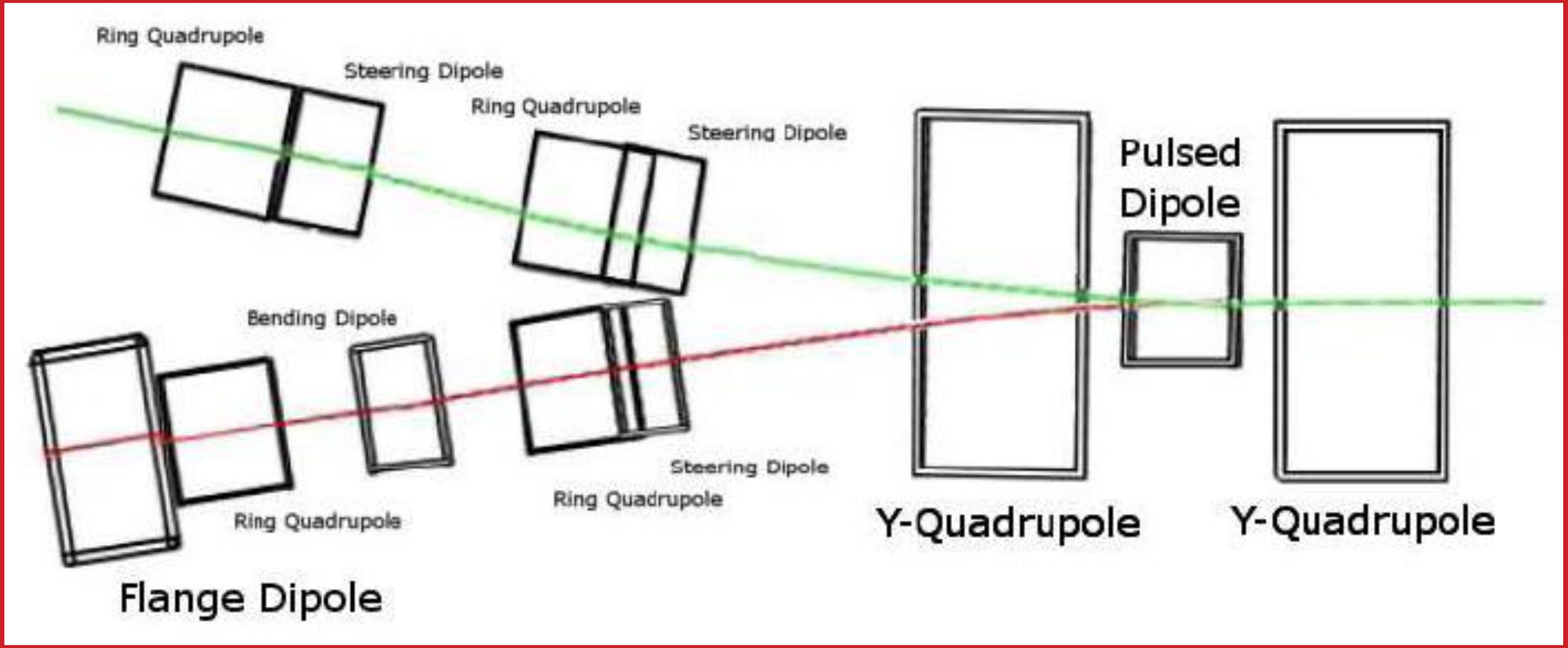
UMER



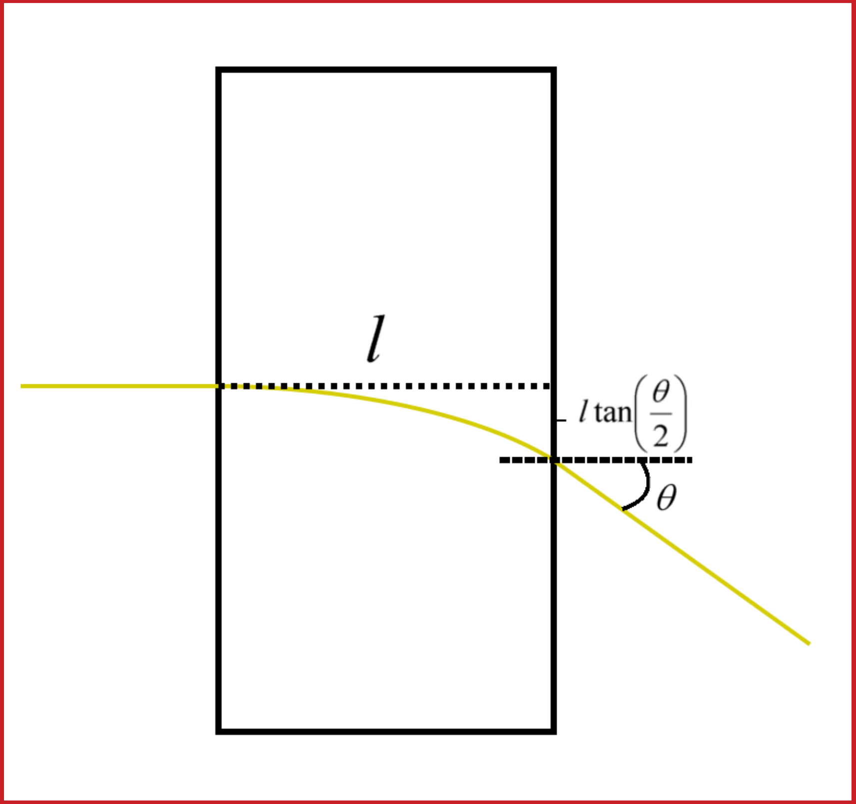
- 10 Kev electron ring
- 15 Beam position monitors.
- 16 Intercepting Phosphor screens
- 1 fast phosphor screen
- 3 Current monitors

Geometry (Injection)

- The off-axis nature of the injection line made modeling the Y-section also difficult.



Geometry (dipoles)



- COSY dipoles assume that the steering is perfect, so a beam that enters straight will exit straight. If we want to use them for steering we need to adjust for how a dipole will change the path of the beam.

Differential Algebras and Numerical Derivatives

First we introduce the ${}_1D_1$ Differential Algebra, which is a first order one variable vector.

$$
\begin{aligned}
(q_0, q_1) + (r_0, r_1) &= (q_0 + r_0, q_1 + r_1) \\
n(q_0, q_1) &= (nq_0, nq_1) \\
(q_0, q_1)(r_0, r_1) &= (q_0 r_0, q_0 r_1 + r_0 q_1)
\end{aligned}
$$

It follows that,

$$
\begin{aligned}
(f(x), f'(x)) &= f(x + d) \\
d &= (0, 1)
\end{aligned}
$$

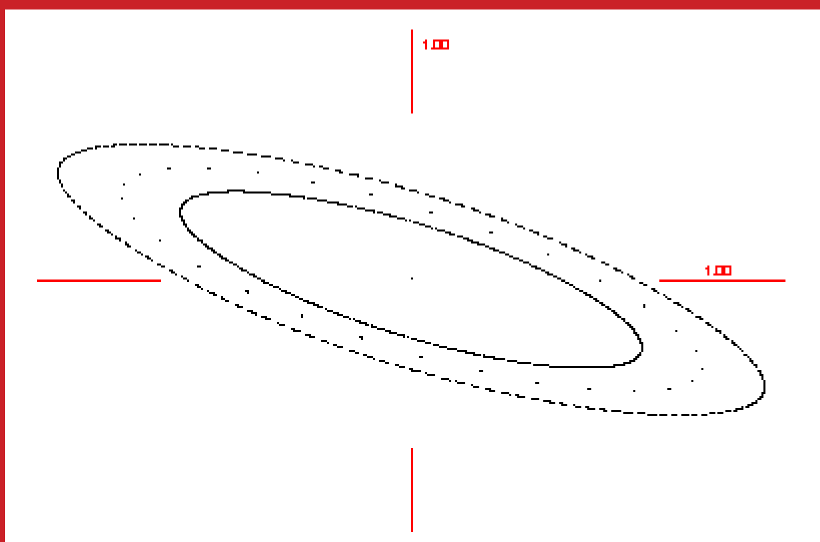
As an example,

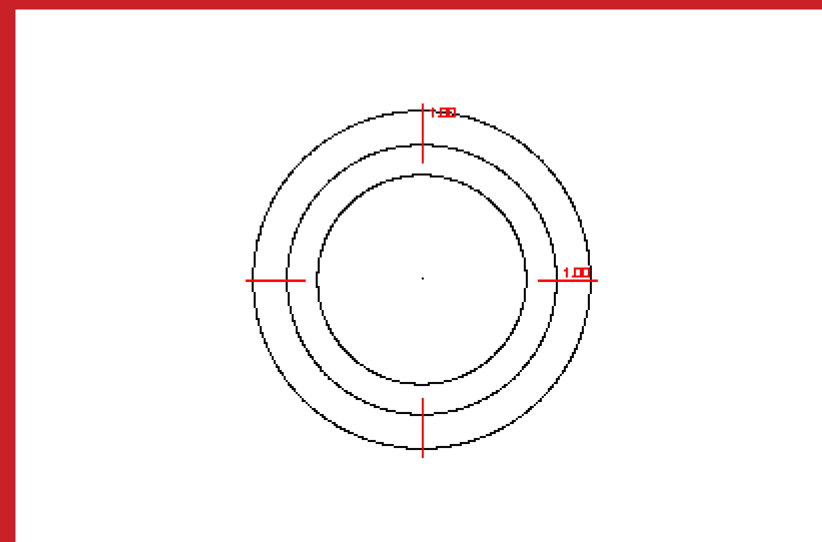
$$
\begin{aligned}
f(x) &= 2x^2 - x + 3 \\
f'(x) &= 4x - 1
\end{aligned}
$$

$$
\begin{aligned}
f(2) &= 9 \\
f'(2) &= 7
\end{aligned}
$$

$$
\begin{aligned}
f(2 + d) &= f(2, 1) \\
&= 2(2,1)(2,1) - (2,1) + (3,0) \\
&= 2(4,4) - (2,1) + (3,0) \\
&= (8,8) - (2,1) + (3,0) \\
&= (9,7)
\end{aligned}
$$

Normal Form Methods





$$\mathcal{N} = \mathcal{A} \circ \mathcal{M} \circ \mathcal{A}^{-1}$$

External Fields

- These are modeled using Strang Splitting.

Diffeq1(L) $\longrightarrow$ Solution1(L)

Diffeq2(L) $\longrightarrow$ Solution2(L)

Diffeq1(L)+Diffeq2(L) $\longrightarrow$?

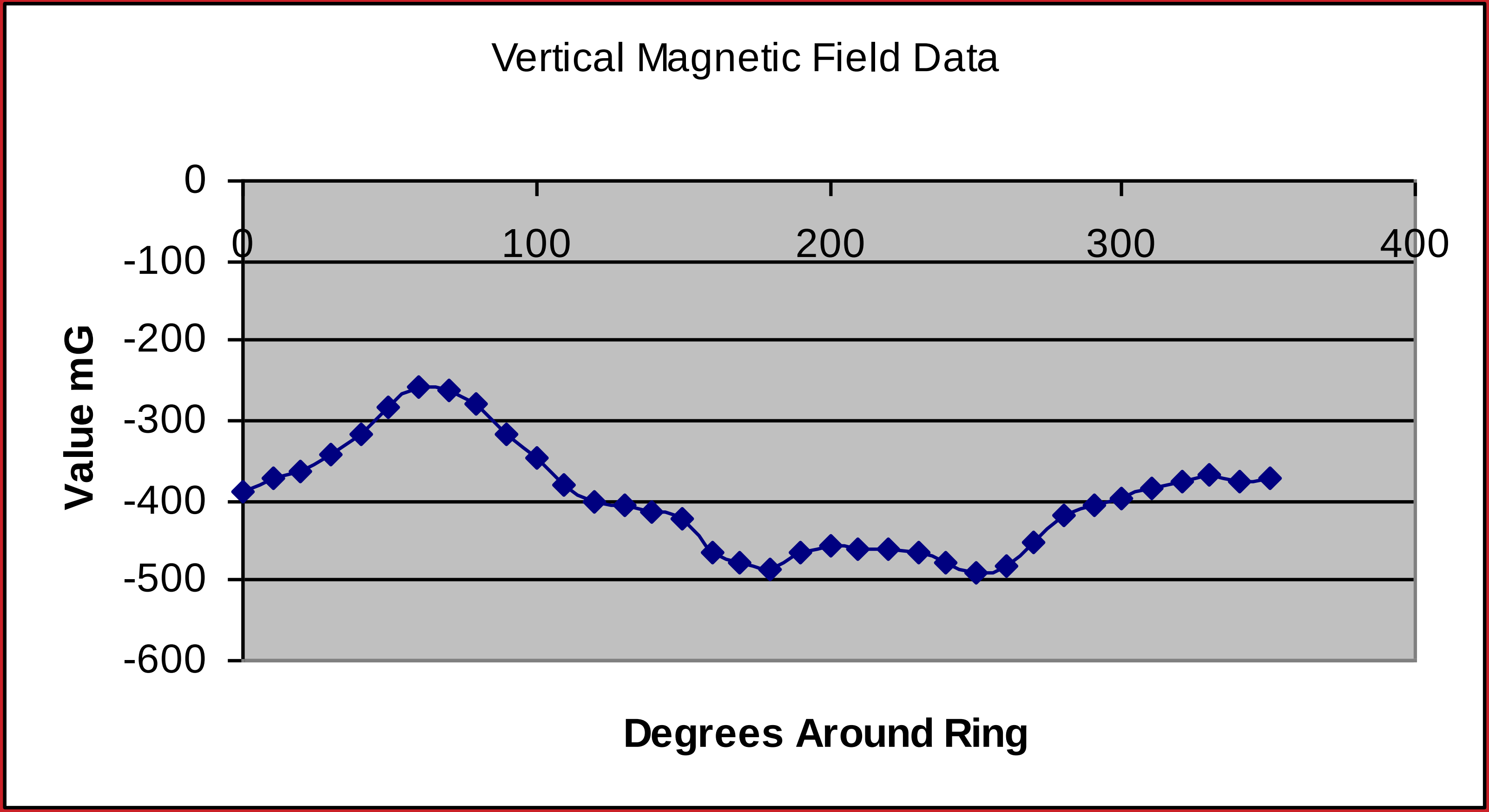
External Fields (cont'd)

Solution1(L) $\longrightarrow$ $\mathcal{M}$(L)

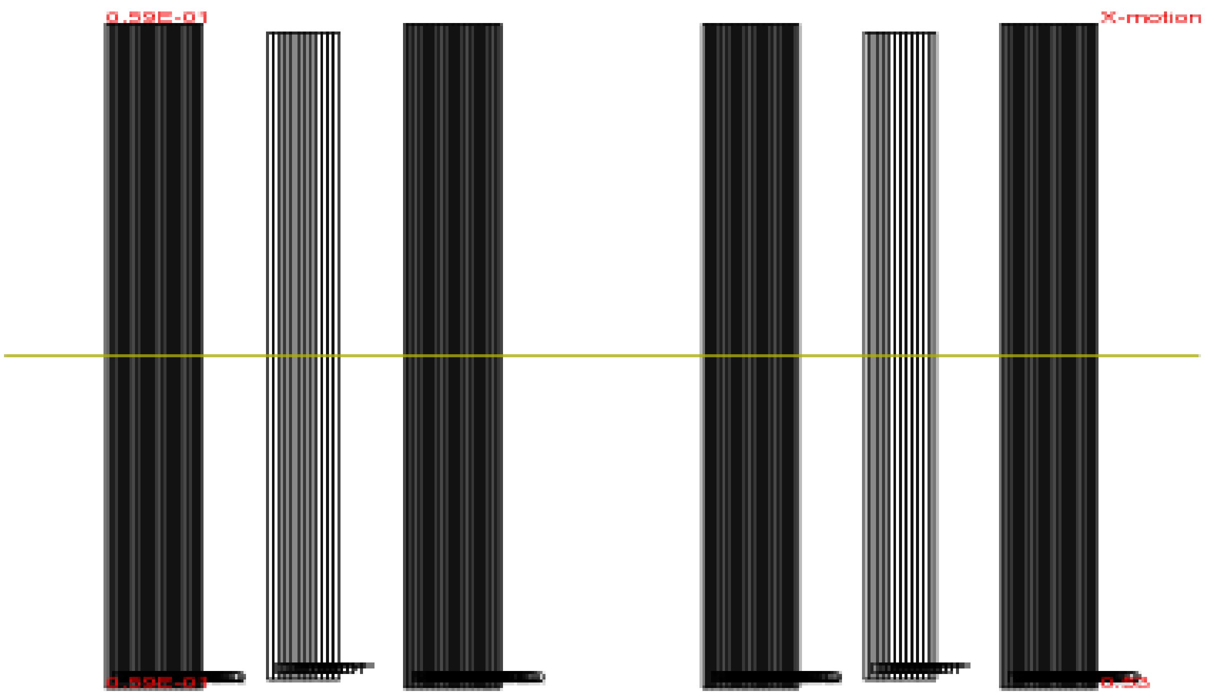
Solution2(L) $\longrightarrow$ Kick(L)

$\mathcal{M}$(L/2) Kick(L) $\mathcal{M}$(L/2) +O(L^3)

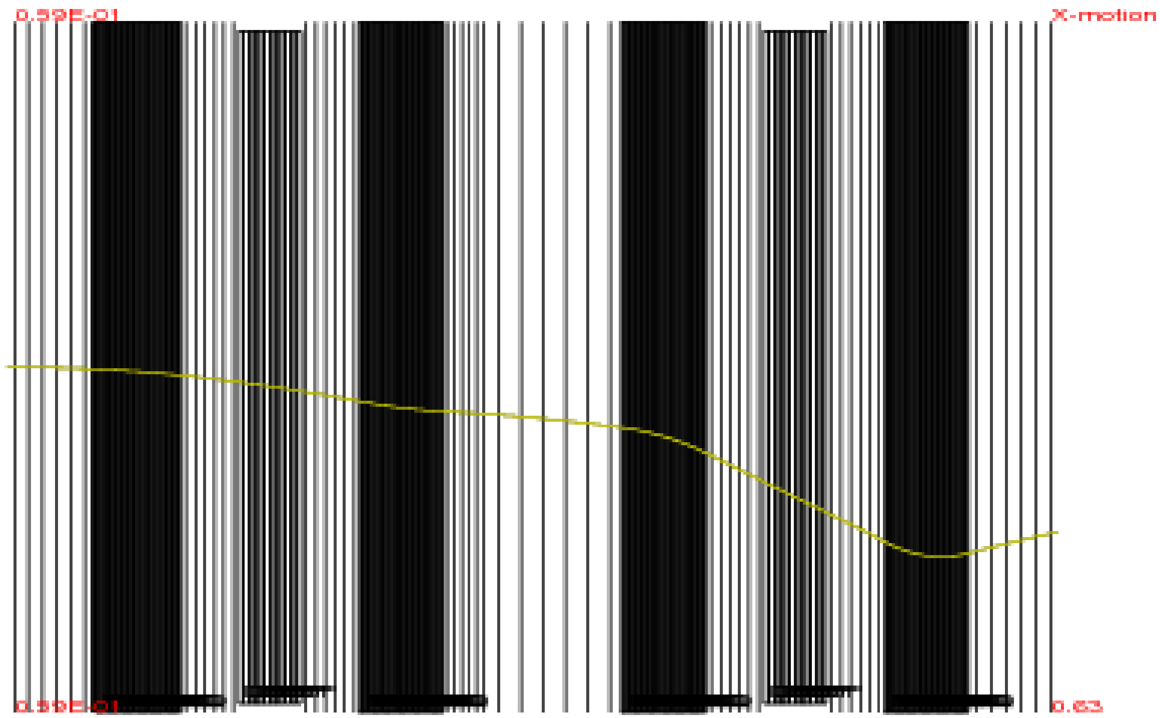
Earth's Magnetic Field



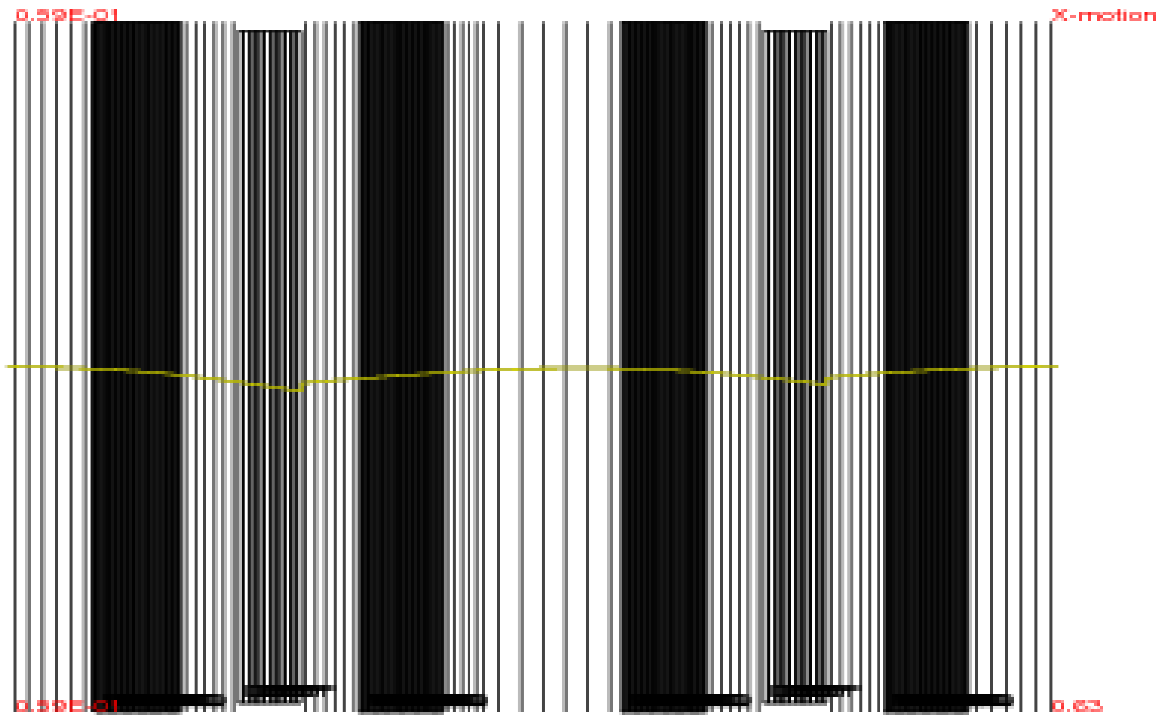
Steering (no fields)



Steering (Earth's Field)

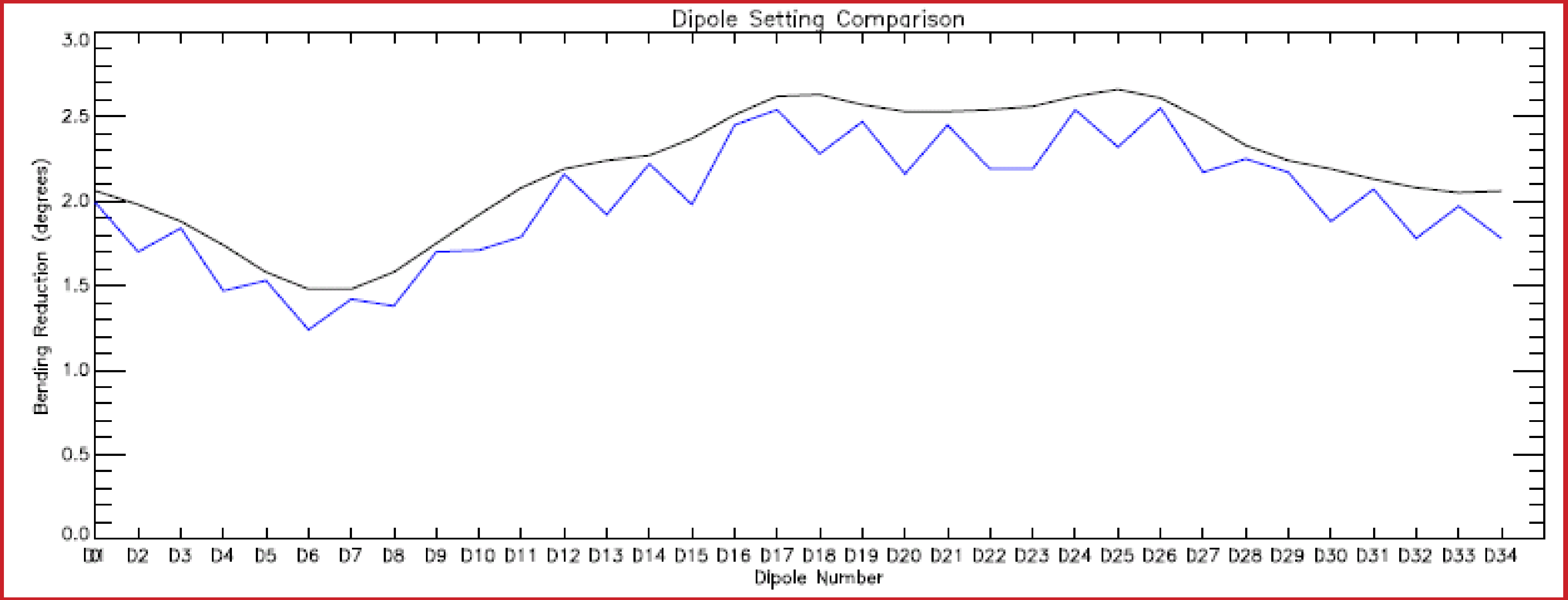


Steering (Earth’s field with Dipole Corrections)



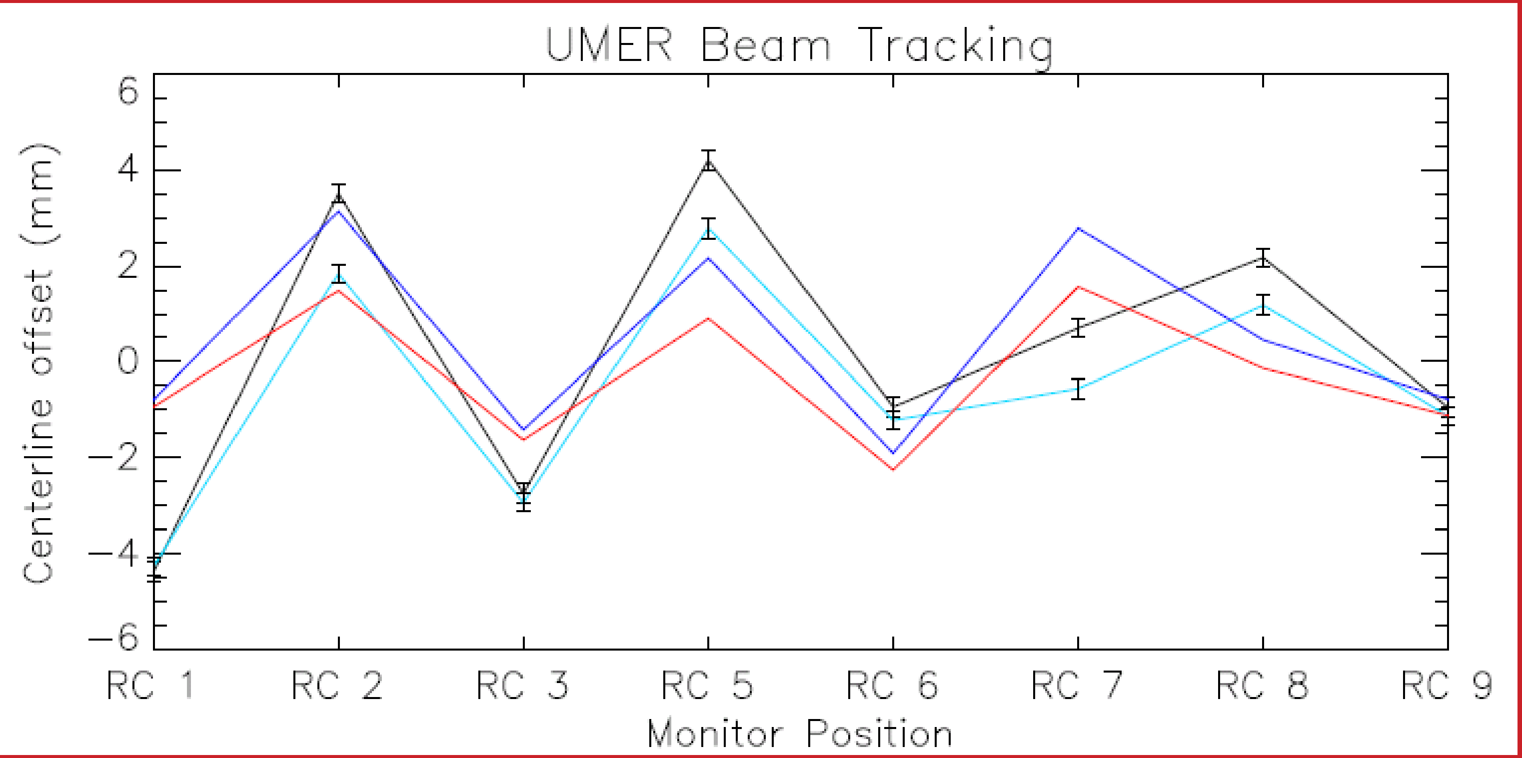
Steering Comparison

- COSY fitted steering v. field integration offsets.

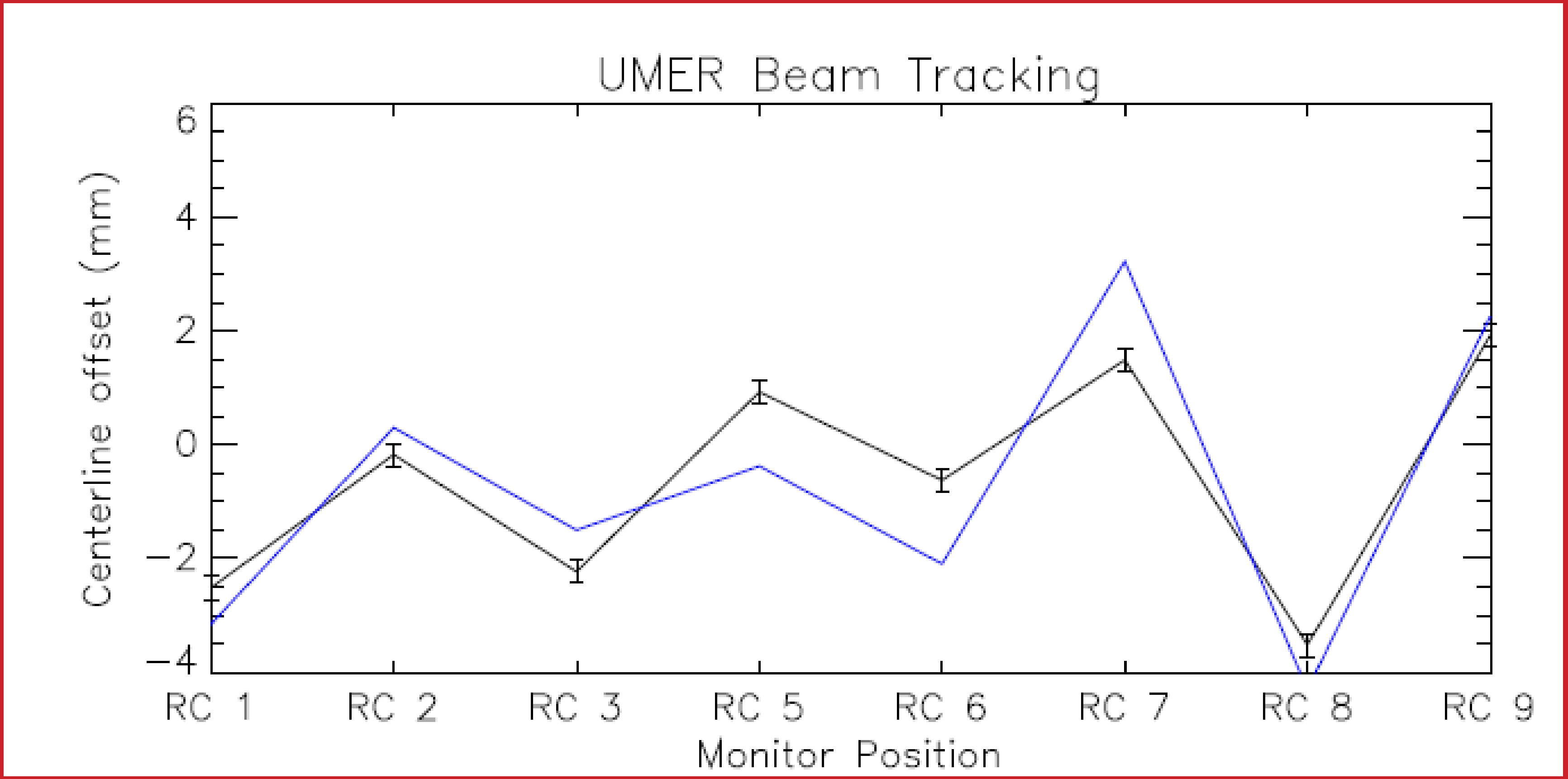


Steering Comparison

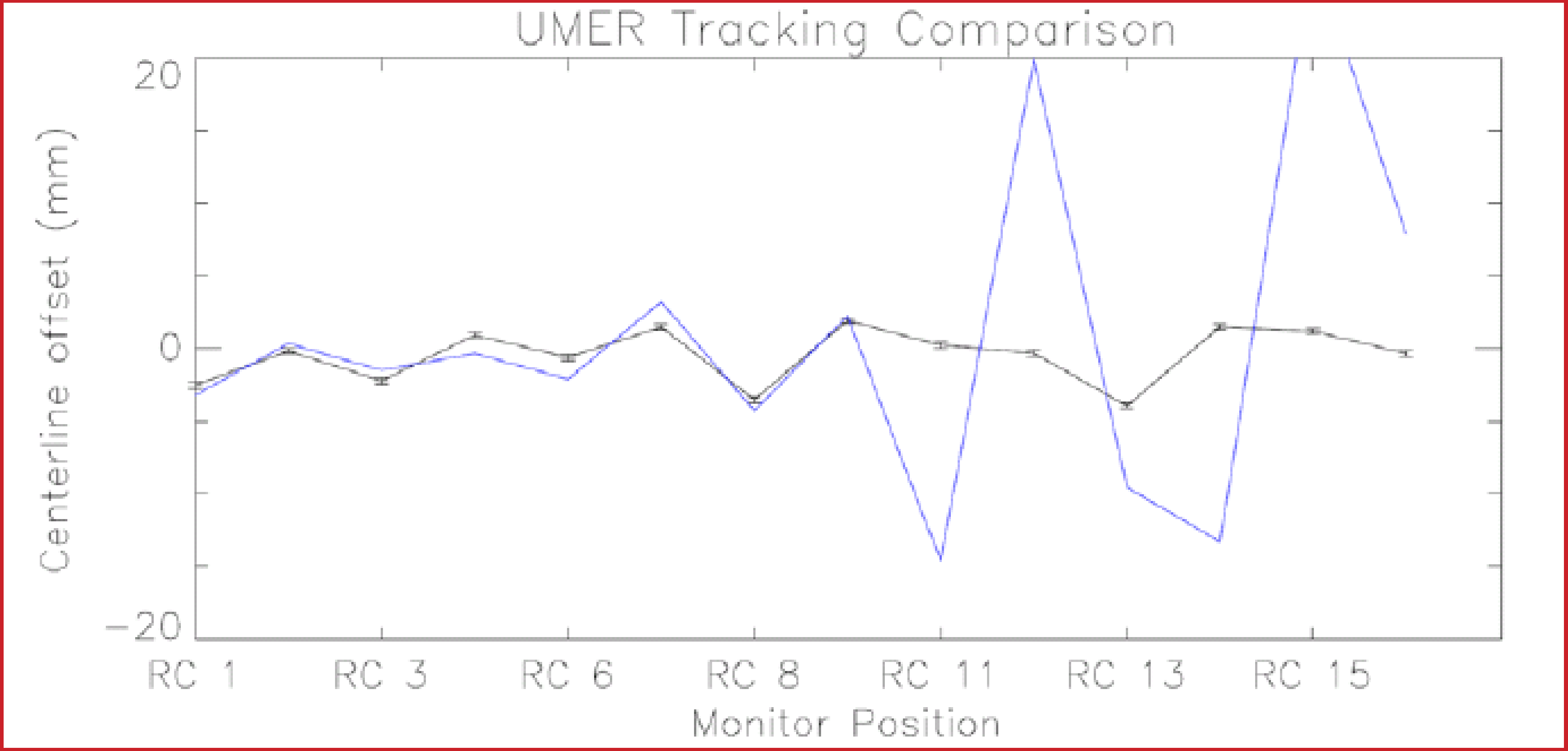
- COSY fitted steering v. field integration offsets.



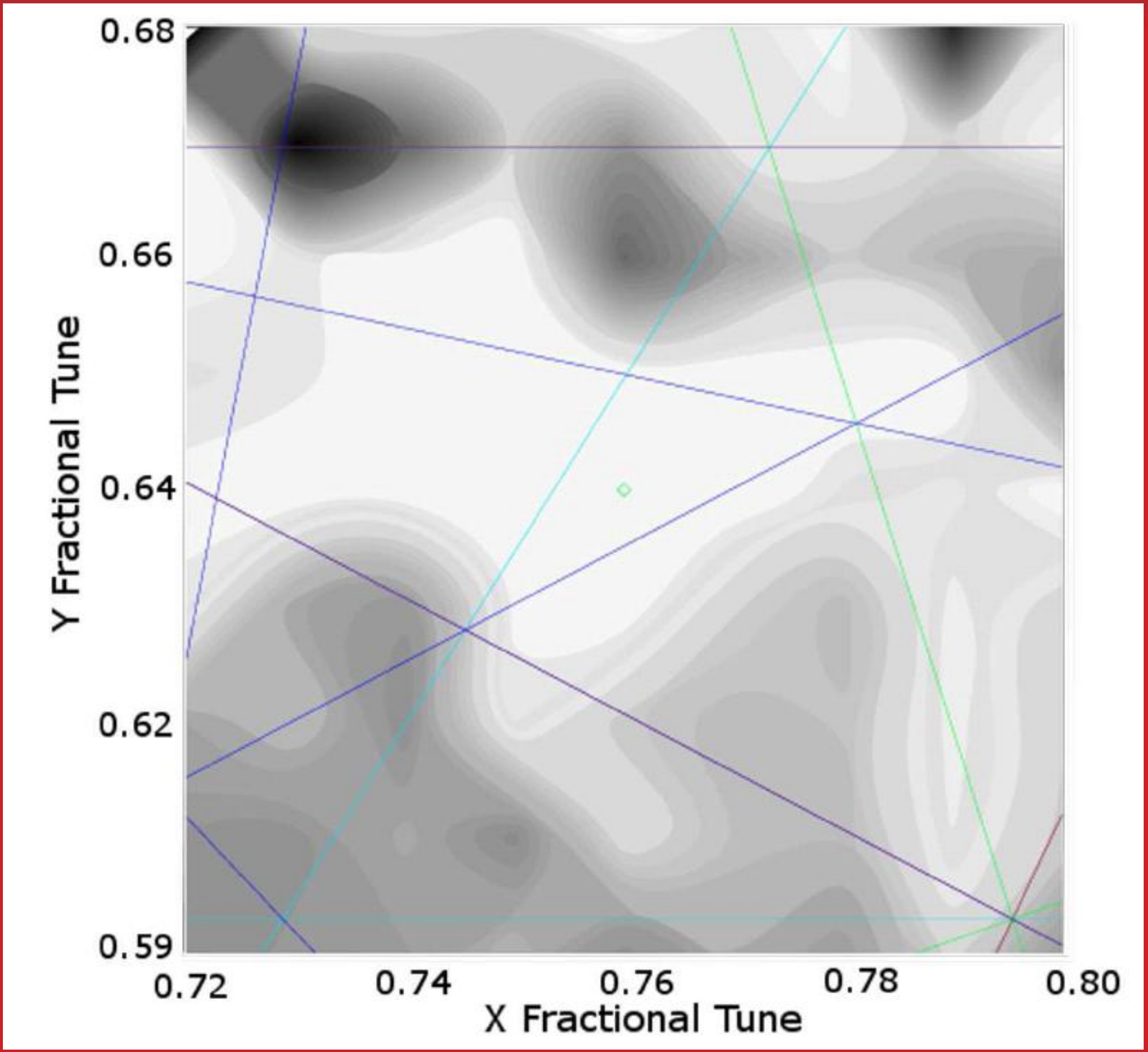
Comparison of Predicted to Measured Trajectories



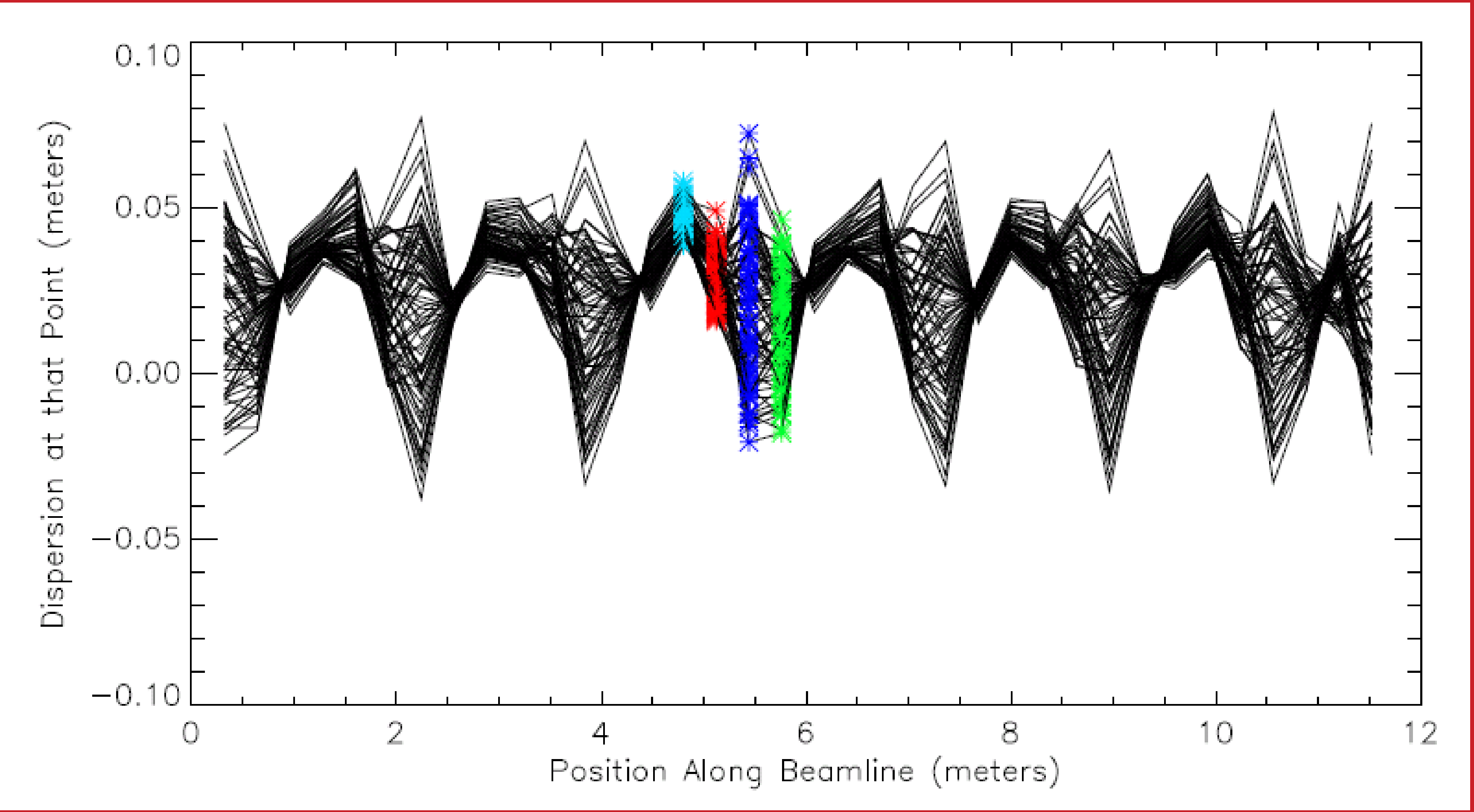
Extended Comparison



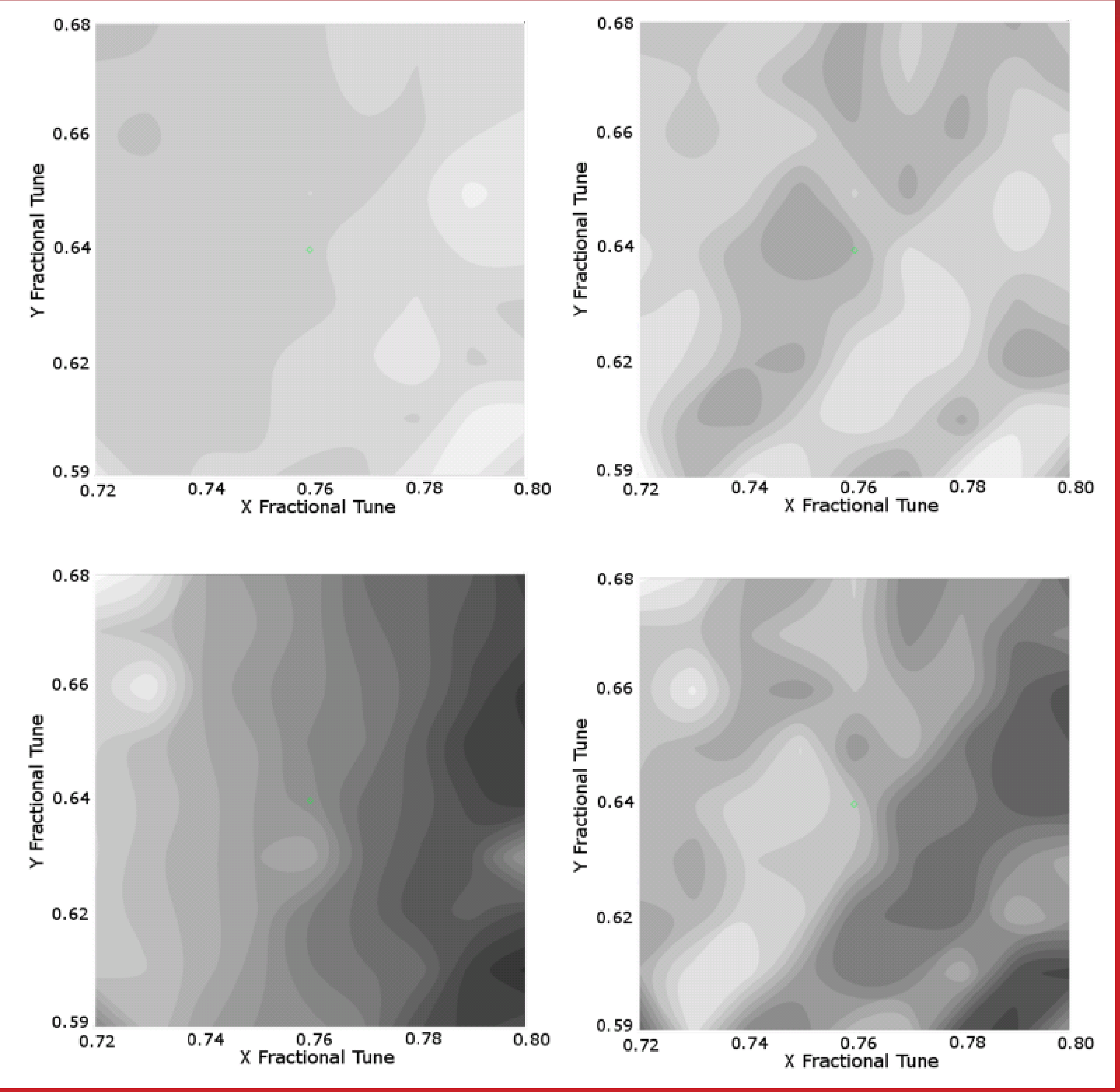
Tunes/Matching Dynamic Aperture



Dispersion Evolution



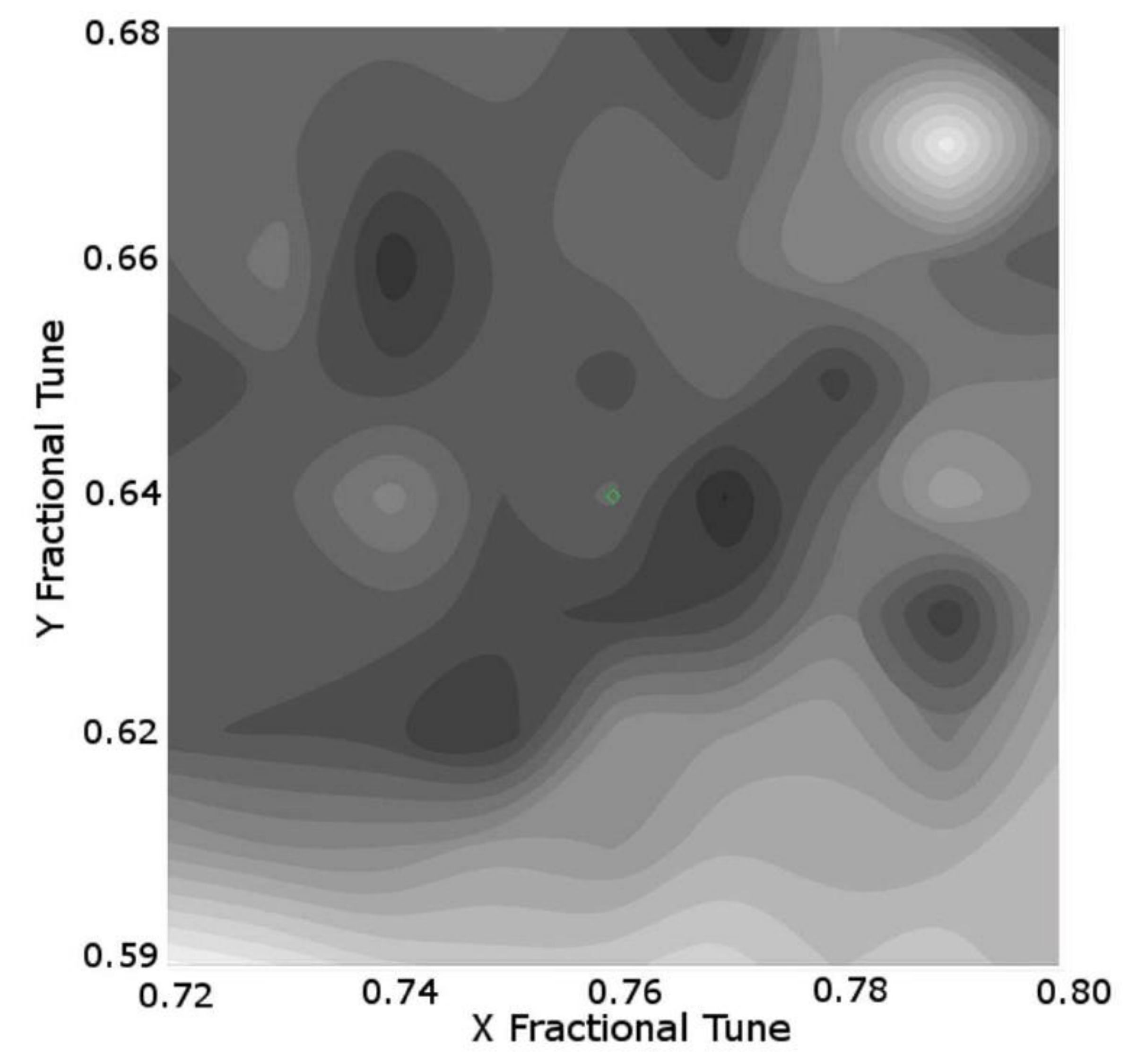
Dispersion Evolution (cont'd)



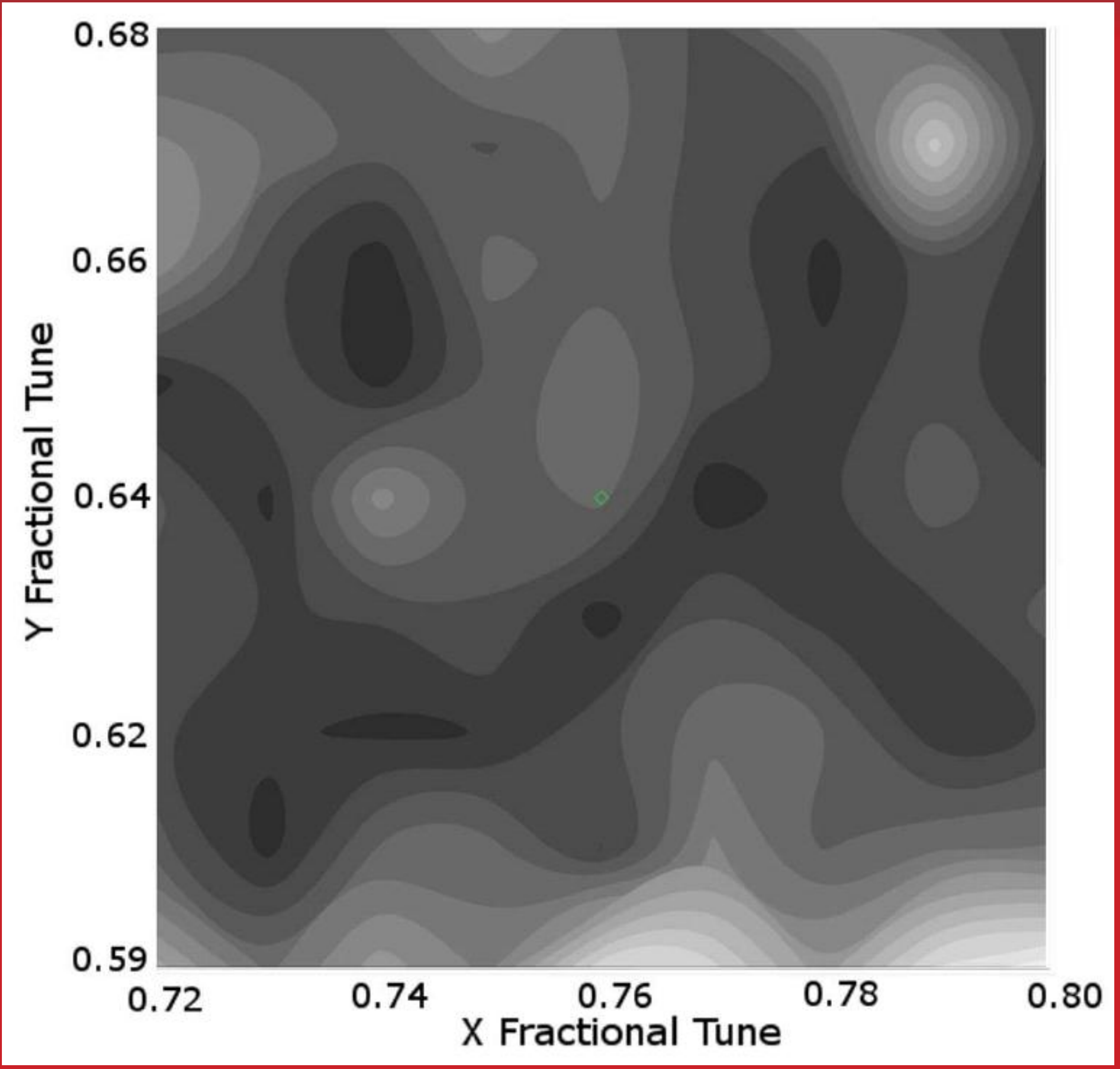
Tunes at Higher Order

Pencil Beam		7 mA Beam	
Order	$\mu(\delta)$	Order	$\mu(\delta)$
0	.747	0	.63722
1	-7.1058	1	-4.4947
2	111.479	2	-25.83
3	-4787.3359	3	-969.6789
23 mA Beam		**80 mA Beam**	
Order	$\mu(\delta)$	Order	$\mu(\delta)$
0	.6796	0	.6900
1	-6.172	1	-5.0174
2	-11.2667	2	-31.2928
3	2034.3401	3	-1221.4241

Resistance to Errors (Magnet Placement)



Resistance to Errors (Magnet Current)



Space Charge

- Space charge has eluded normal form analysis for some time
- A Differential Algebraic approach could allow us to determine how it affects other quantities
- Allows us to understand UMER better
- Allows for investigations into the intensity frontier

The Distribution Function

$$\rho(x,y)=\sum_i \delta(x-x_i)\delta(y-y_i) \rightarrow \rho(x,y)=\sum_j \sum_k C_{jk} x^j y^k$$

- If two distributions have the same moments then they are mathematically indistinguishable.

Distribution: (Cont'd)

$$M_{ij} = \int\int x^i y^j \sum_l \sum_m C_{lm} x^l y^m dxdy$$

$$M = TC$$

$$C = T^{-1} M$$

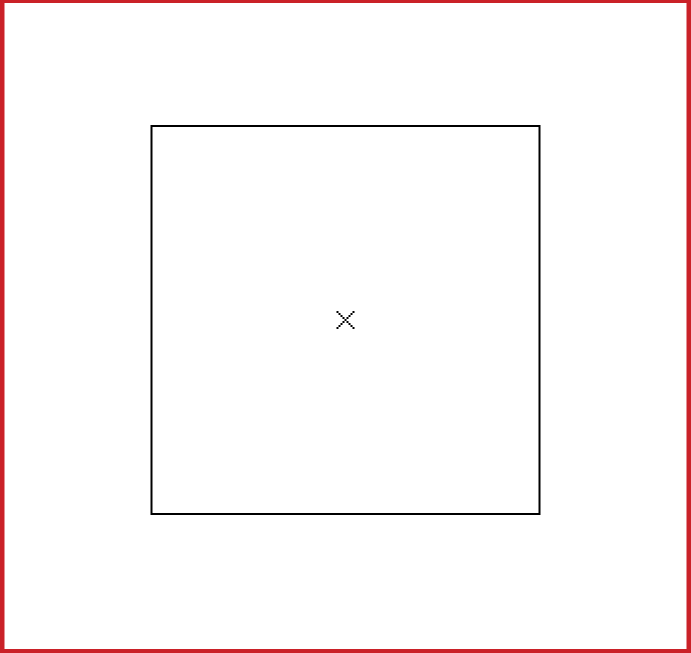
Potential Calculation

- Since we now have a Taylor series for the distribution can't we just integrate and find the potential.

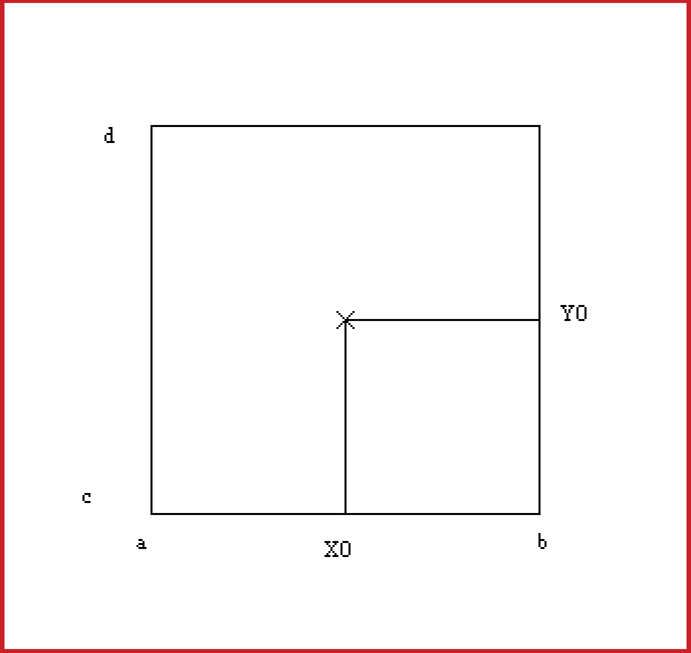
- No, Since the expansion is occurring inside the distribution Singularities become an issue.

$$G(r,r') = \ln(|r - r'|); \lim_{r \to r'} (G(r,r')) = -\infty$$

Duffy Transformation

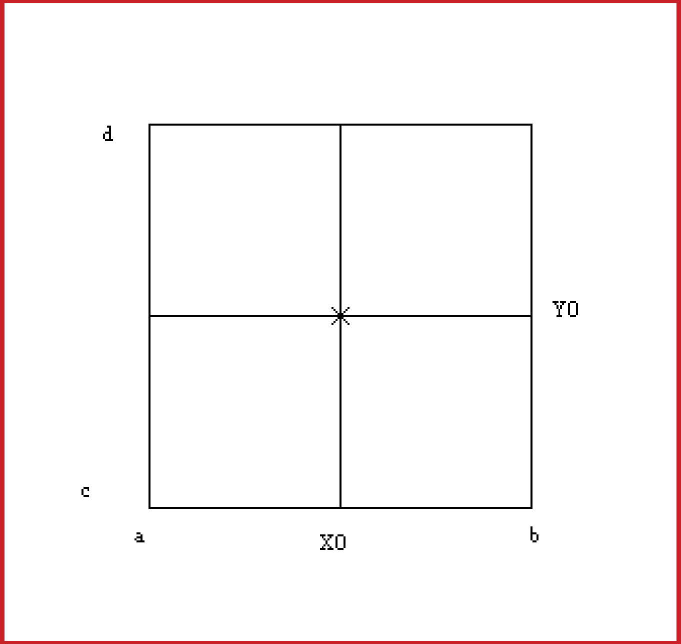


Duffy Transformation



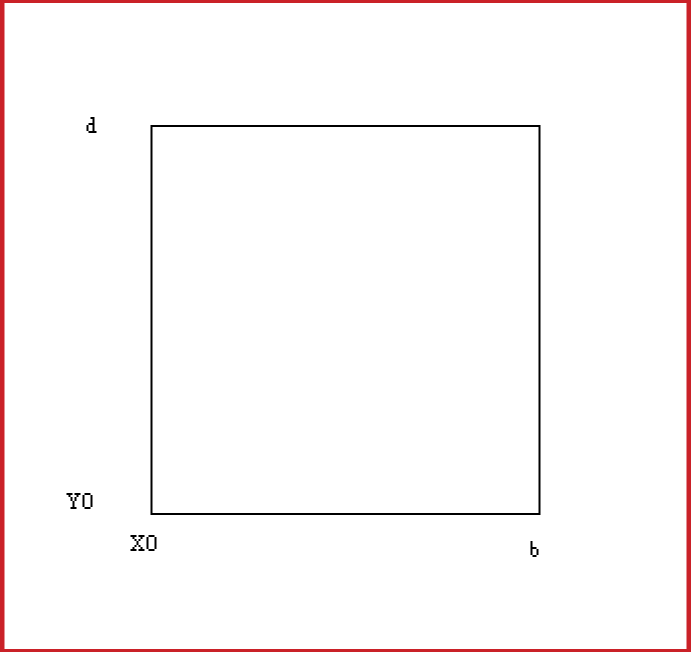
$$\int_{c}^{d}\int_{a}^{b}\ln\left(\sqrt{(x-x_0)^2+(y-y_0)^2}\right)dxdy$$

Duffy Transformation



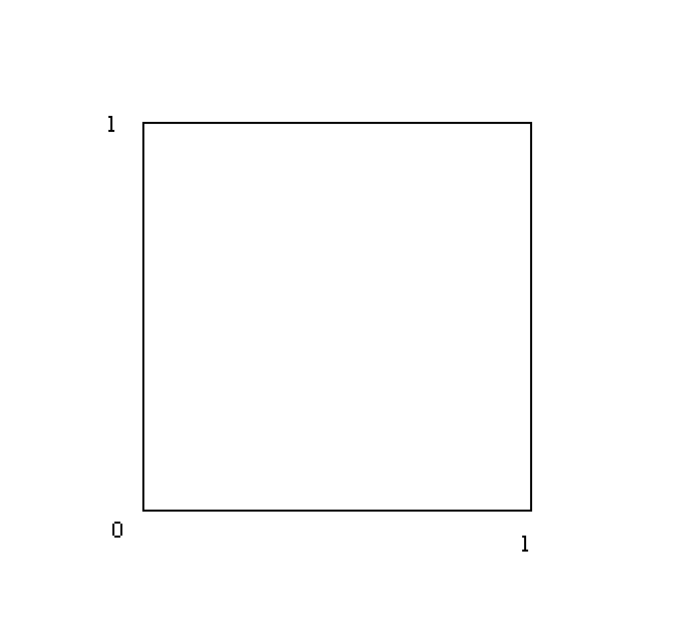
$$\int_c^{y_0}\int_a^{x_0}\ln(\sqrt{(x-x_0)^2+(y-y_0)^2})dxdy+\int_c^{y_0}\int_{x_0}^{b}\ln(\sqrt{(x-x_0)^2+(y-y_0)^2})dxdy+\int_{y_0}^{d}\int_a^{x_0}\ln(\sqrt{(x-x_0)^2+(y-y_0)^2})dxdy+\int_{y_0}^{d}\int_{x_0}^{b}\ln(\sqrt{(x-x_0)^2+(y-y_0)^2})dxdy$$

Duffy Transformation



$$\int_{y_0}^{d}\int_{x_0}^{b}\ln\left(\sqrt{(x-x_0)^2+(y-y_0)^2}\right)dx\,dy$$

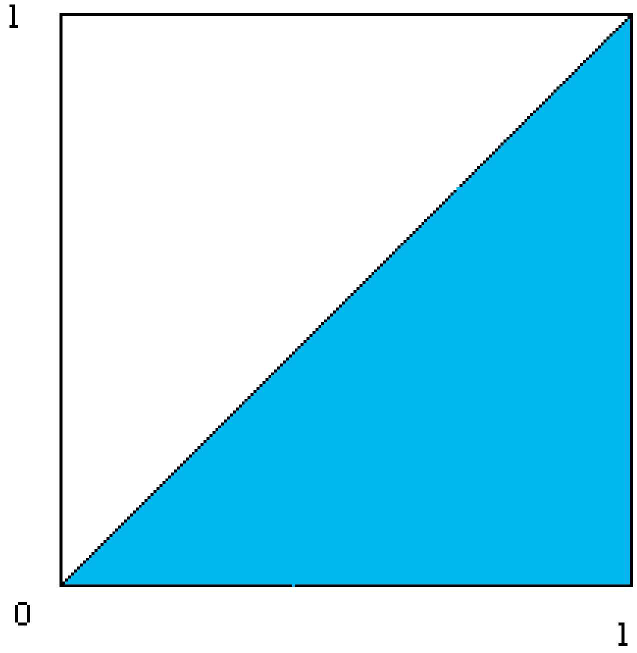
Duffy Transformation



$$u_1 = \frac{x - x_0}{b - x_0}; u_2 = \frac{y - y_0}{d - y_0}; \lambda_1 = (b - x_0); \lambda_2 = (d - y_0);$$

$$\lambda_1 \lambda_2 \int_0^1 \int_0^1 \ln\left(\sqrt{(\lambda_1 u_1)^2 + (\lambda_2 u_2)^2}\right) dx dy$$

Duffy Transformation



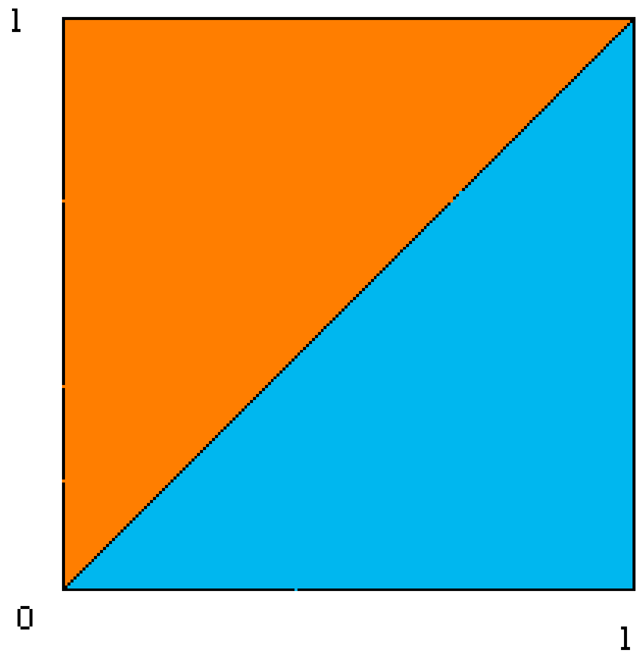
Duffy Transformation

- This is done using the following set of coordinate transformations:

$$w_1 = u_1; w_2 = \frac{u_2}{u_1}$$

$$\lambda_1 \lambda_2 \int_0^1 \int_0^1 w_1 \ln(\sqrt{\lambda_1^2 w_1^2 + \lambda_2^2 w_1^2 w_2^2})\, dw_1 dw_2$$

Duffy Transformation



Duffy Transformation

- This is done using the similar set of coordinate transformations:

$$w_2 = u_2; w_1 = \frac{u_1}{u_2}$$

$$\lambda_1 \lambda_2 \int_0^1 \int_0^1 w_2 \ln\left(\sqrt{\lambda_2^2 w_2^2 + \lambda_1^2 w_2^2 w_1^2}\right) dw_1 dw_2$$

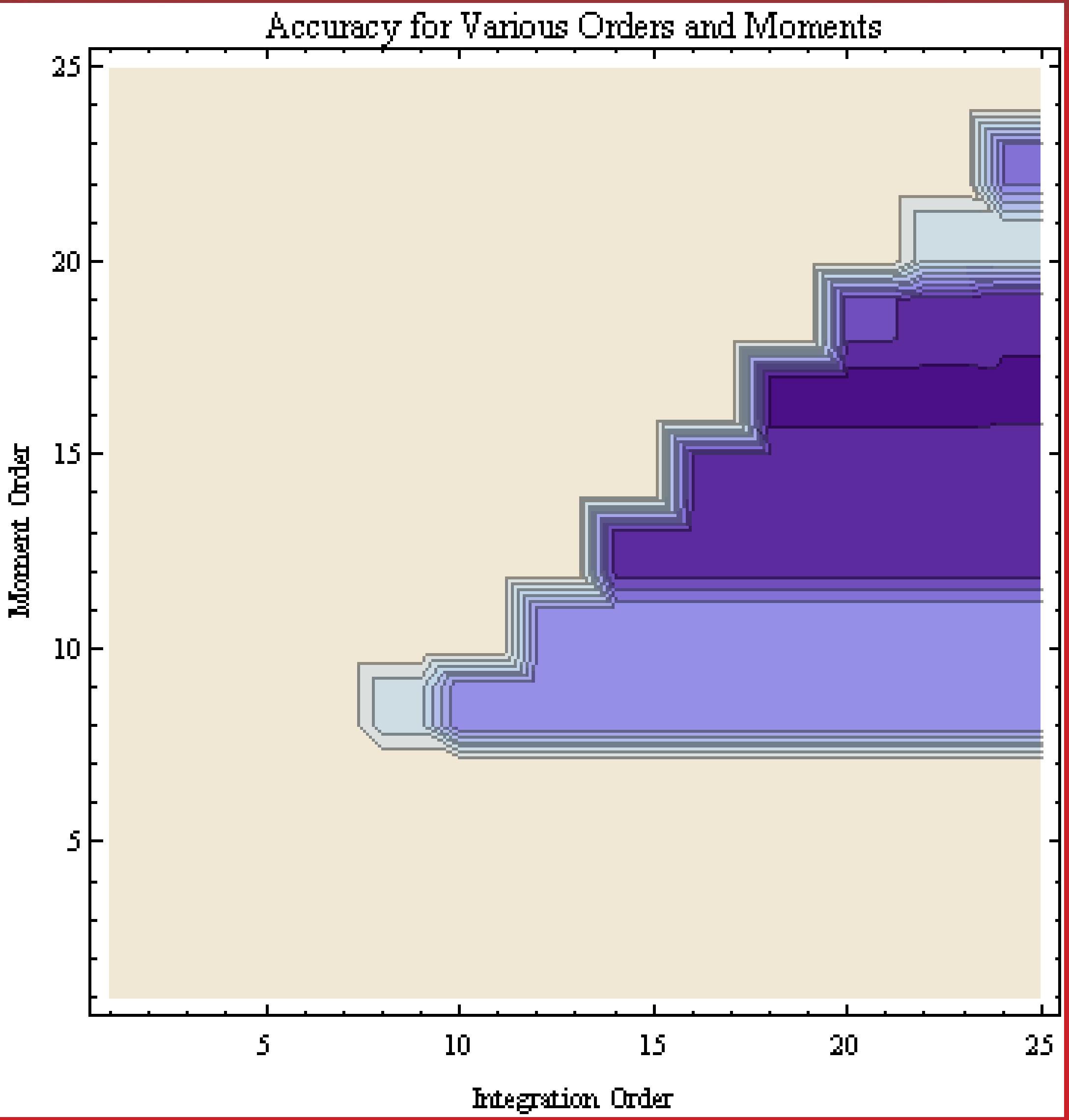
Duffy Transformation

$$\lambda_1 \lambda_2 \int_0^1 \int_0^1 w_1 \ln(w_1) + \ln(\sqrt{\lambda_1^2 + \lambda_2^2 w_2^2}) dw_1 dw_2$$

$$+ \lambda_1 \lambda_2 \int_0^1 \int_0^1 w_2 \ln(w_2) + \ln(\sqrt{\lambda_1^2 w_1^2 + \lambda_2^2}) dw_1 dw_2$$

$$\underset{x \to 0}{Lim}(x \ln(x)) = 0$$

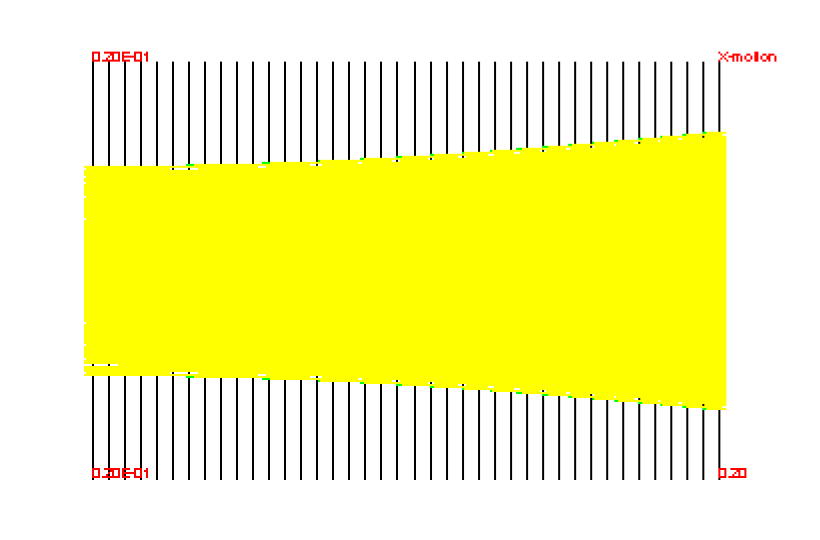
Accuracy

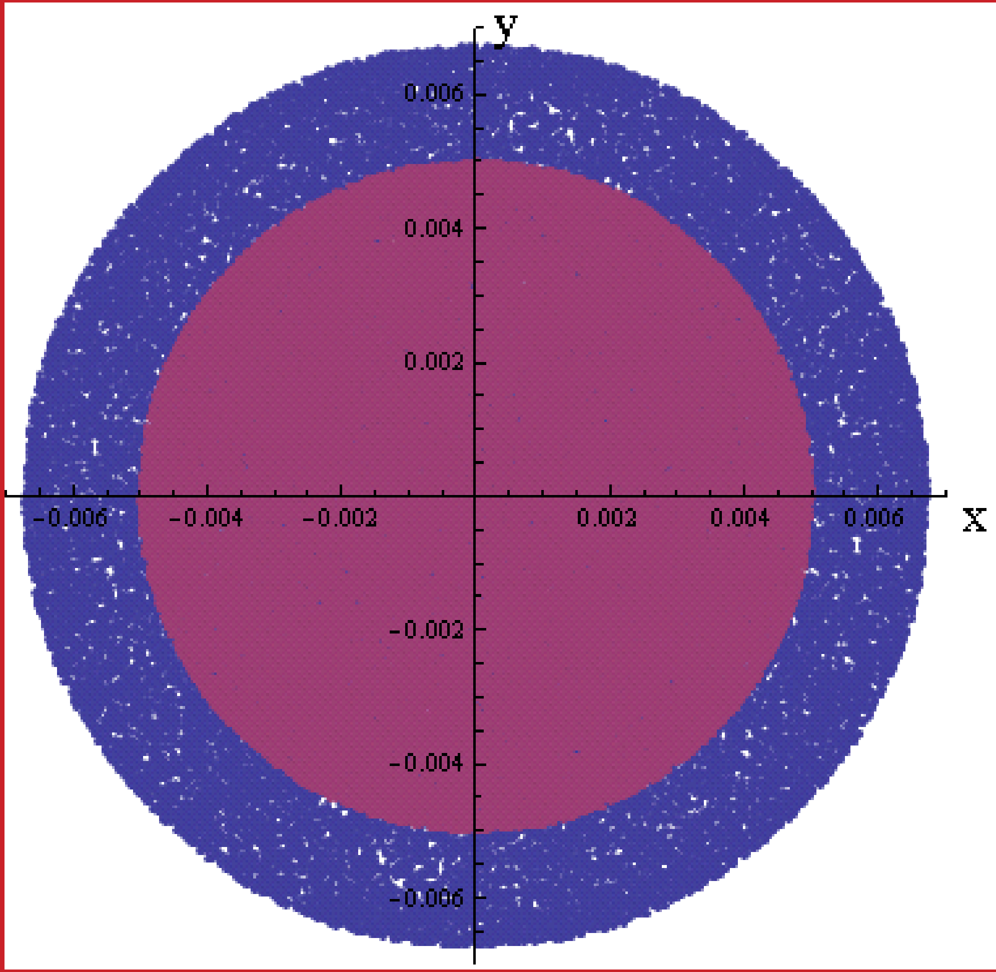

Accuracy for Various Orders and Moments
Moment Order
Integration Order
5
10
15
20
25
5
10
15
20
25

Example

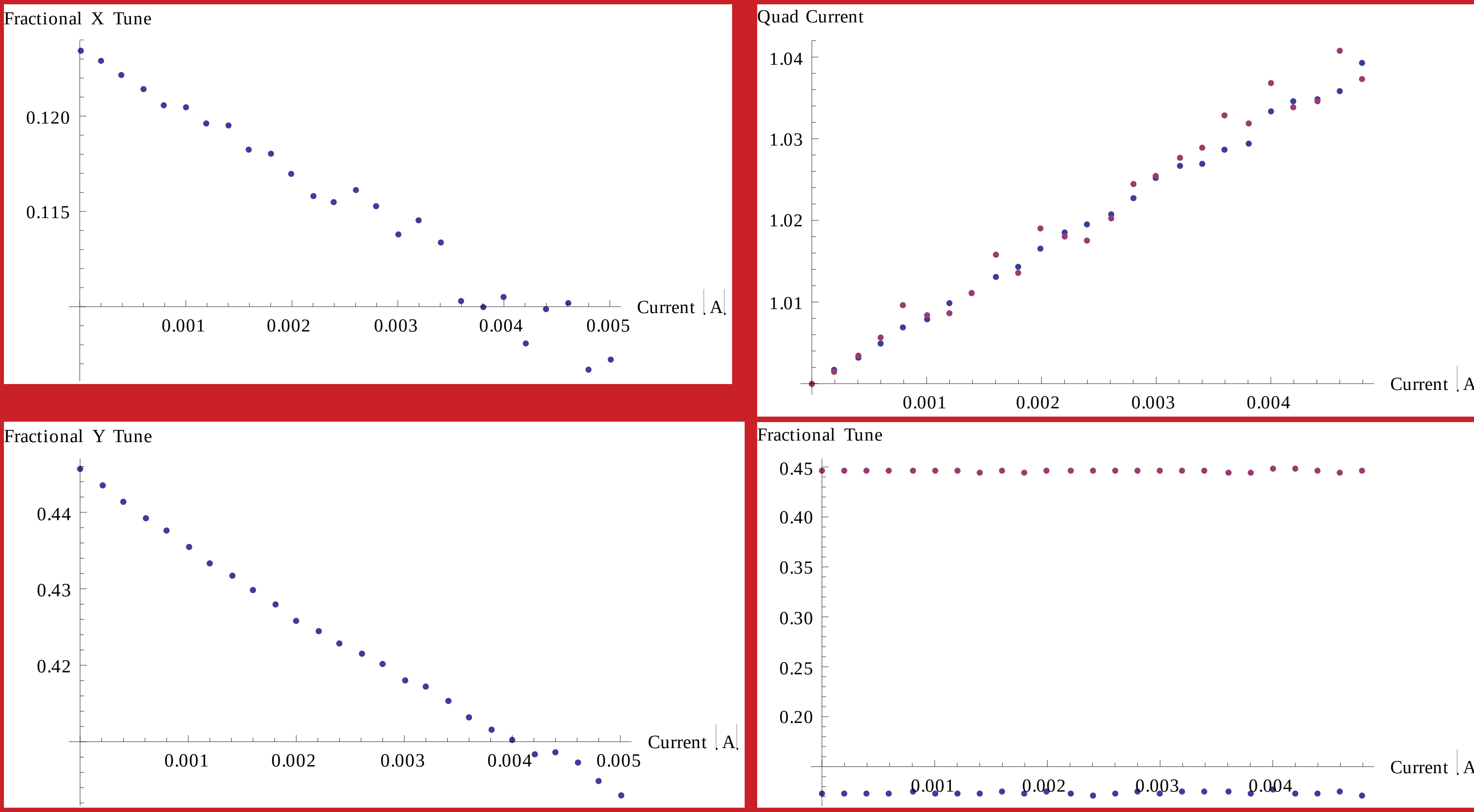
$$\frac{r_m}{r_0} = 1 + 5.87 \times 10^{-5} \frac{I}{(\gamma^2 - 1)^{\frac{3}{2}}} \left(\frac{z}{r_0}\right)^2$$

Method	Growth
Edge Point x	35.27 %
Edge Point y	35.30 %
Map Element x	31.21 %
Map Element y	31.34 %

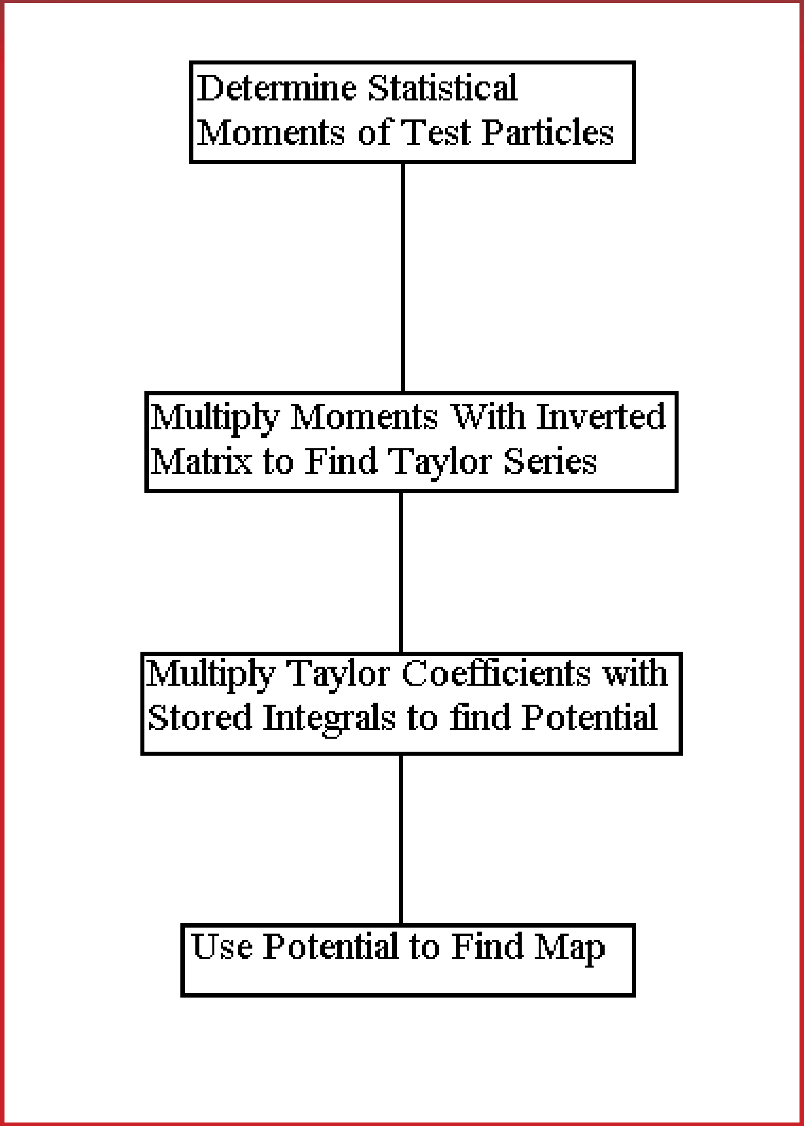




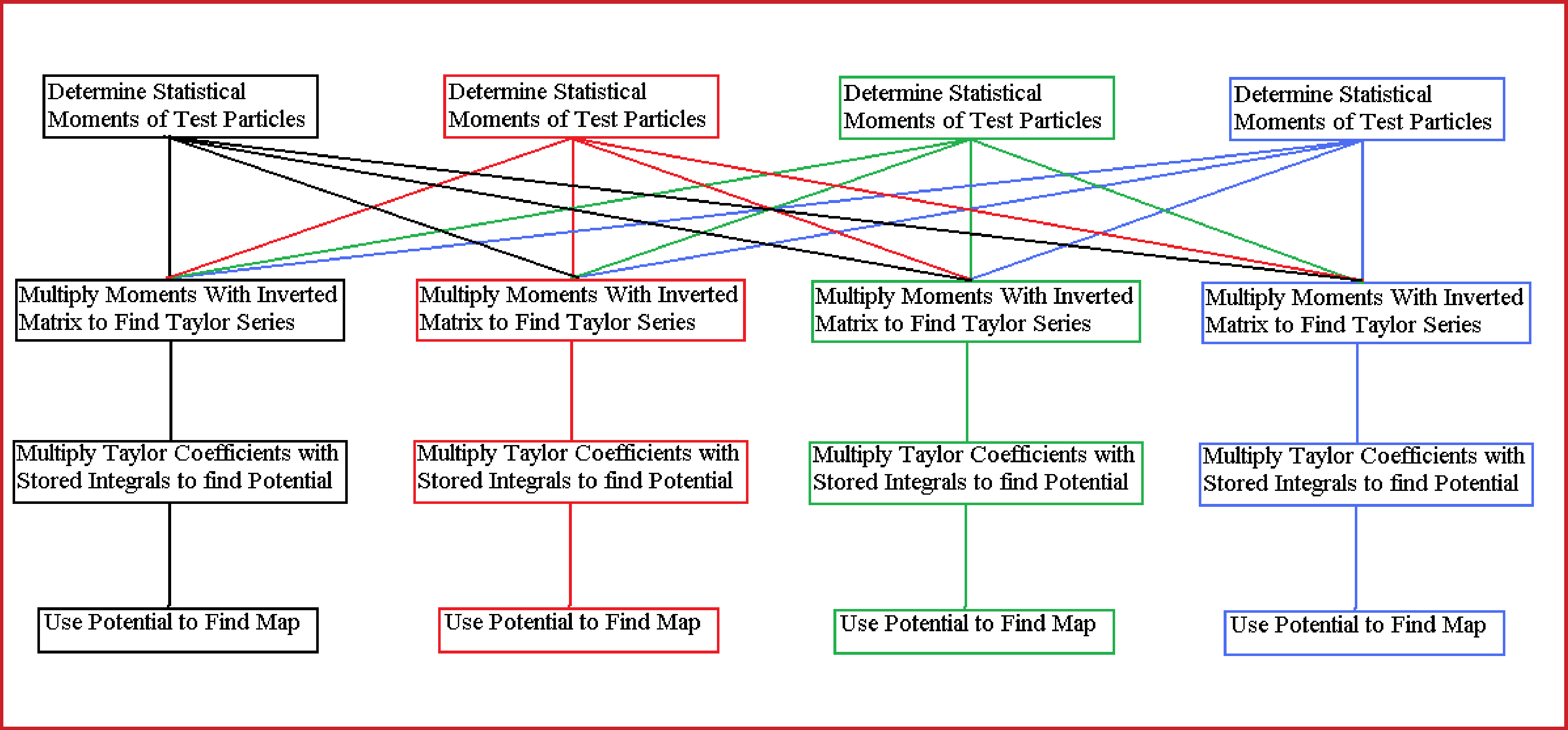
Tune Measurement



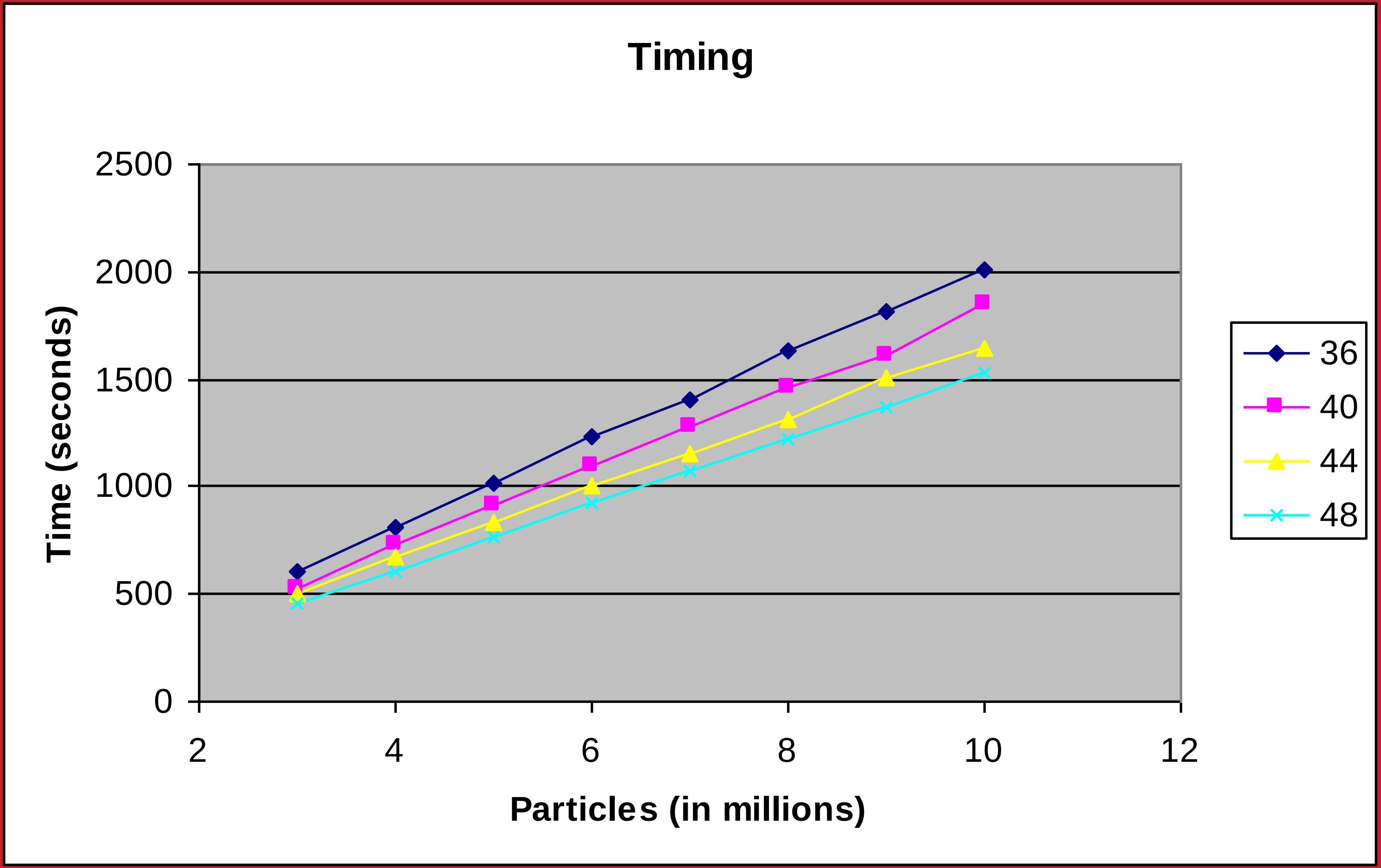
Space Charge Serial



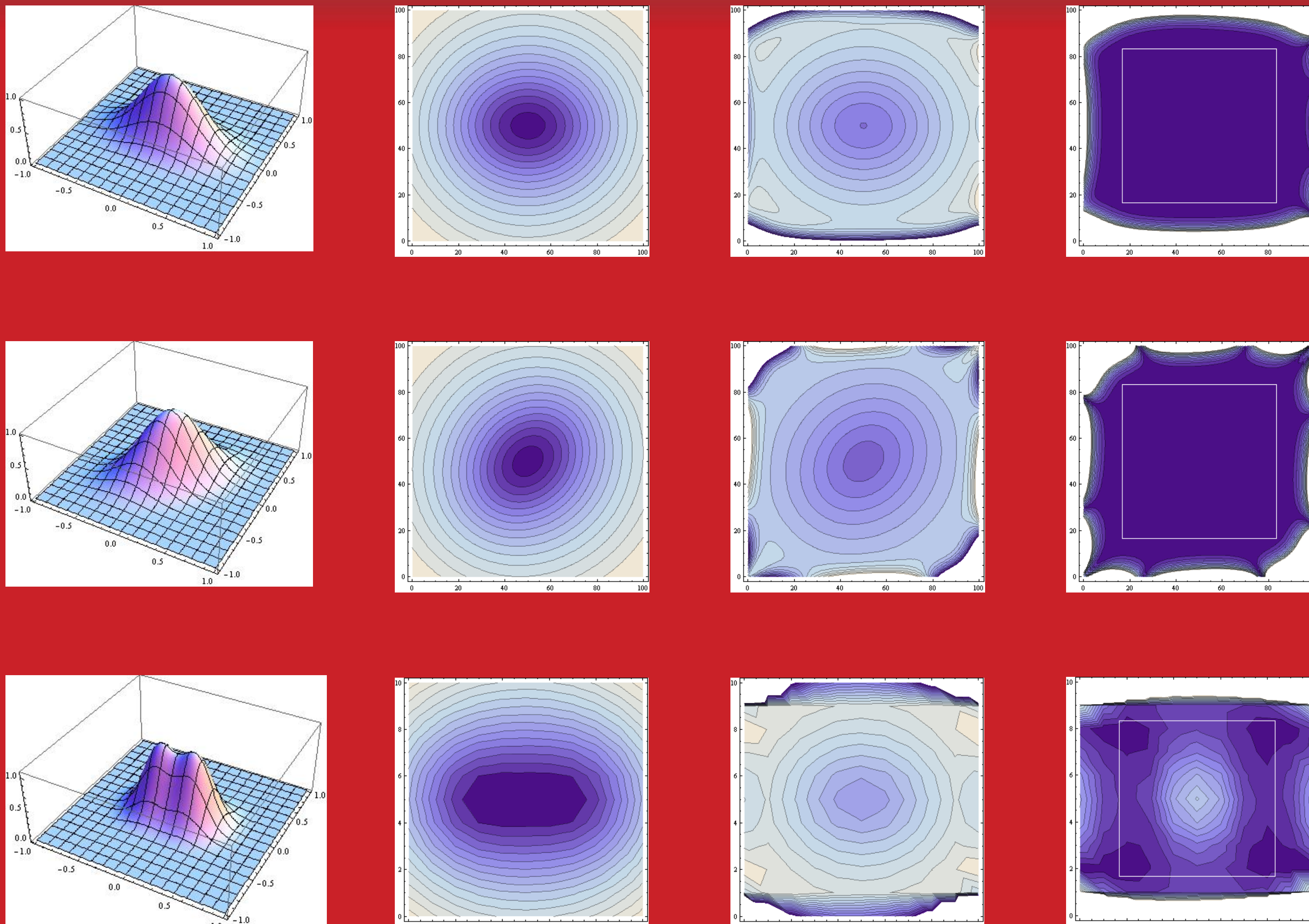
Space Charge Parallel



Parallel Scaling (cont'd)



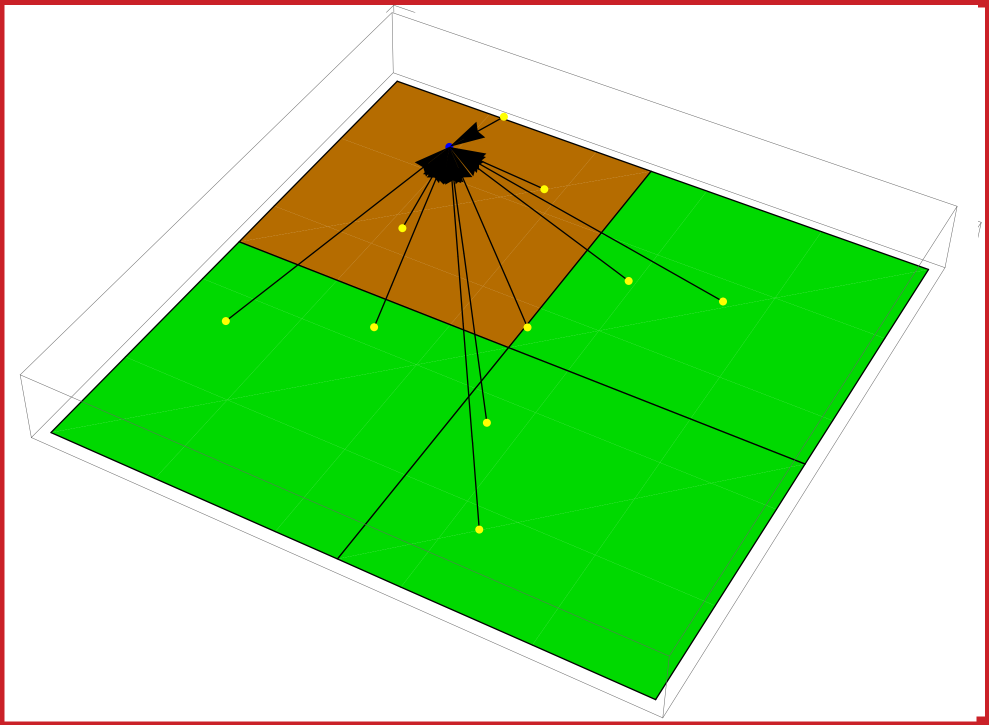
Limitations



Fast Multipole Method

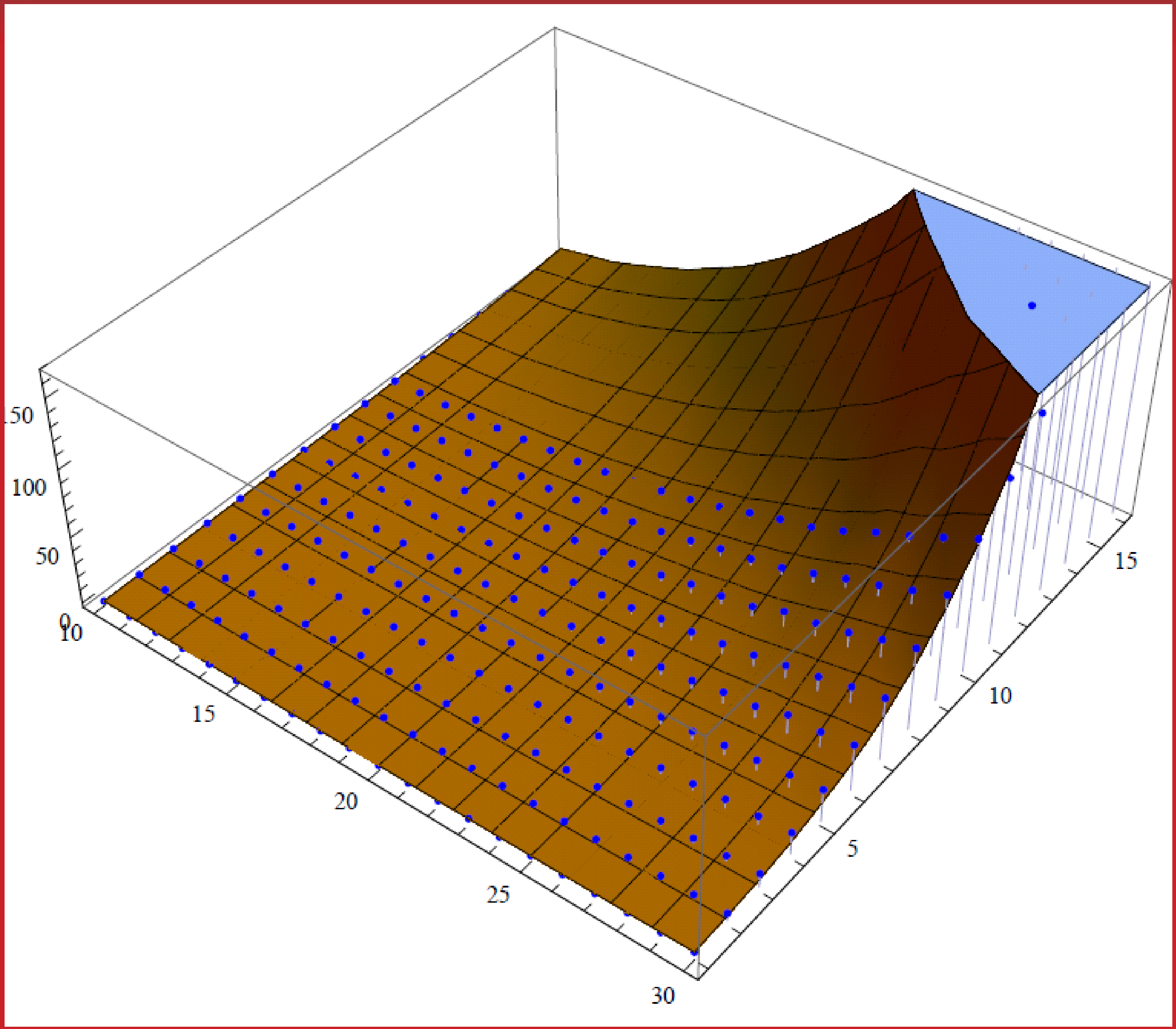
- Uses multipole expansions for distant particles
- Uses direct coulomb interactions for close particles
- Currently used in solid state physics, fluids, and chemistry

FMM: Examples



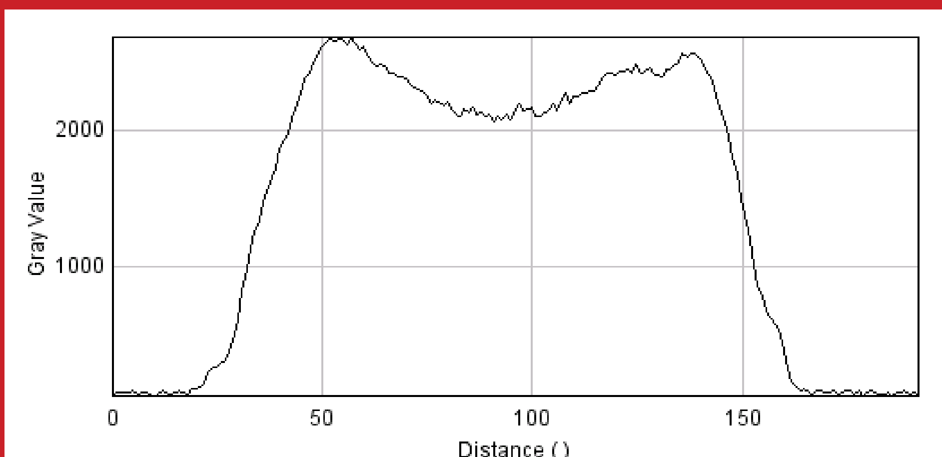
$$\phi(z) = \sum_i \left(Q \log(z_i) + \sum_k \frac{a_k}{z_i^k} \right) + \sum_j q_j \log(z_j)$$

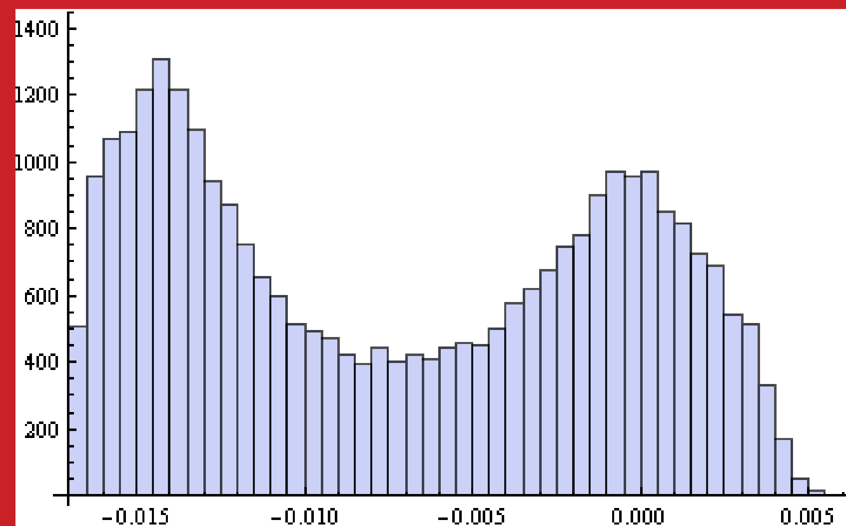
Timing Comparison



Distribution Tracking Experiments

Experimental Comparison





Summary

- Differential Algebraic methods can be used to model the single and multiple particle effects of a system.
- The University of Maryland Electron Ring is a useful tool for verifying machine codes.
- Adding the effects of space charge to the transfer map of a system is both possible and feasible
- New insights can be found using this method in conjunction with normal form analysis
- Can even analyze complex distributions using the fast multipole method

Questions?

Map Overview

- A map is a method of advancing particles which takes the form

$$z_f = Mz_i$$

$$x_f = (x_f \mid x_i)x_i + (x_f \mid p_{xi})p_{xi} + (x_f \mid x_i^2)x_i^2 + (x_f \mid x_i p_{xi})x_i p_{xi} + (x_f \mid p_{xi}^2)p_{xi}^2$$

$$p_{xf} = (p_{xf} \mid x_i)x_i + (p_{xf} \mid p_{xi})p_{xi} + (p_{xf} \mid x_i^2)x_i^2 + (p_{xf} \mid x_i p_{xi})x_i p_{xi} + (p_{xf} \mid p_{xi}^2)p_{xi}^2$$

Legendre Polynomials

- Legendre Polynomials have the following orthogonality property.

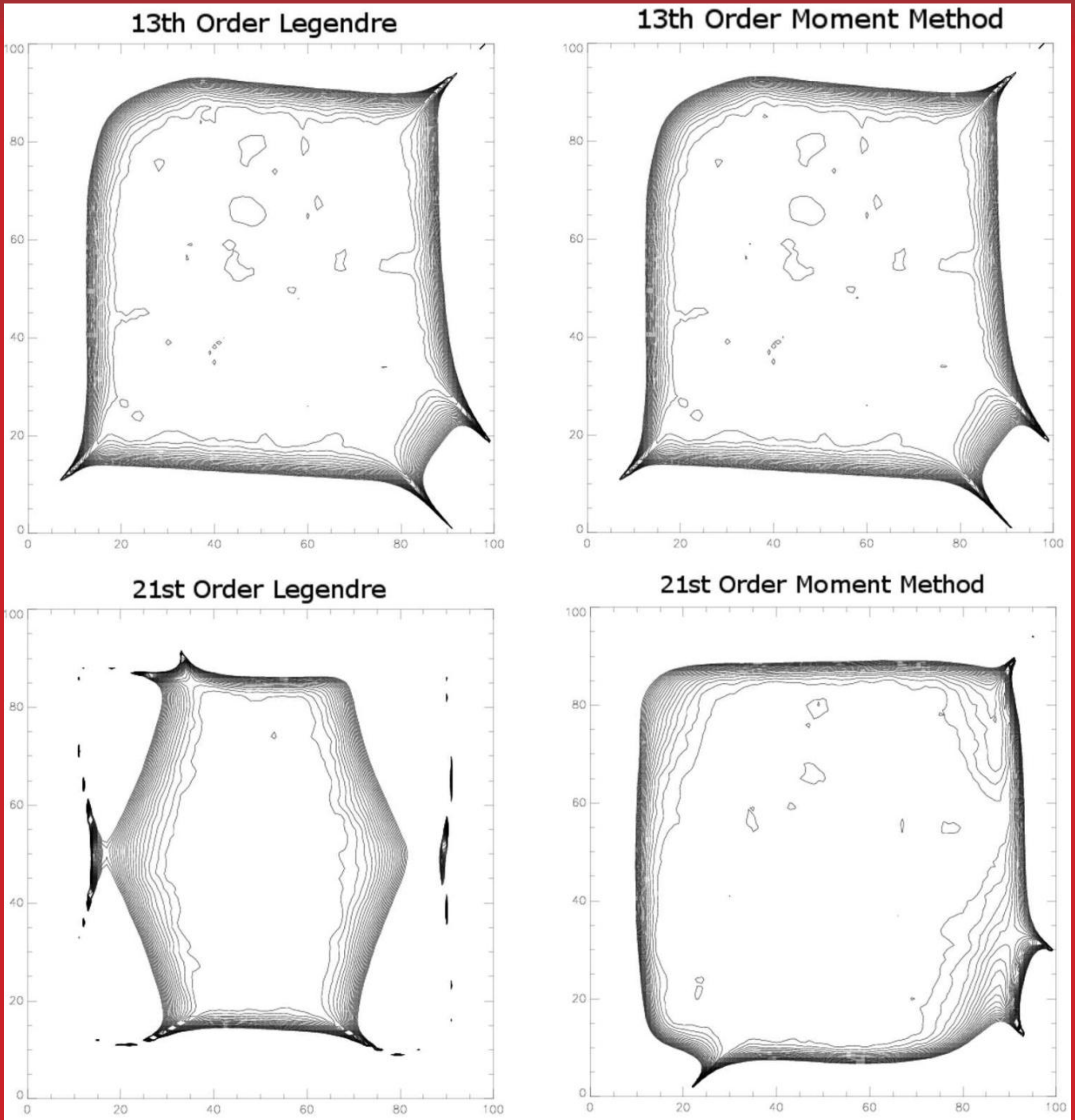
$$\int_{-1}^{1} P_m(x) P_n(x) dx = \frac{2}{2n+1} \delta_{mn}$$

- If we assume that the distribution can be modeled as a sum of legendre polynomials, we can easily find the coefficients.

$$\rho(x) = \sum_n C_n P_n(x)$$

$$\int_{-1}^{1} P_m(x) \rho(x) dx = C_m \frac{2}{2m+1}$$

Method Comparison



Three Dimensions