MICHIGAN STATE UNIVERSITY

Beam Dynamics: From Theory to Simulation The MSU Program

Martin Berz
Kyoko Makino

Michigan State University

Current Ph.D. Students

Supported by DOE, and Other Sources

• Shashikant Manikonda	DOE and GSI
• Youn-Kyung Kim	DOE
• Johannes Grote	DOE and StuSti
• Pavel Snopok	FNAL/ILC
• Alexey Poklonskiy	FNAL/Muon
• Gabi Weizman	GSI
• Stephen Weathersby	SLAC

Support leveraging: 2-3 DOE students → 7 total

Former Ph.D. Students

• Georg Hoffstätter	Assoc. Prof. Cornell
• Weishi Wan	Staff Scientist LBNL
• Kyoko Makino	Assoc. Prof. UIUC / MSU
• Khodr Shamseddine	Assist. Prof. WIU
• Jens Hoefkens	GeneData
• Bela Erdelyi	Assist. Prof. NIU/ANL

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Map Methods

- **Understanding dynamics**
  - Numerically integrate
  - Look at the flow: initial coordinates -> final coordinates
- **Perturbation theories for flows**
  - Transfer matrix methods: Transport (2^{nd} order), GIOS (3^{rd} order), Trio (3^{rd} order), COSY 5.0 (5^{th} order)
  - Lie algebraic methods: MaryLie (3^{rd} order)
- **In principle, arbitrary order – but mostly in principle:**
  - Arbitrary order here implies arbitrarily painful
  - Even Chinese graduate students don't have the patience and stamina to do it (German graduate students have no chance…)
  - Even formula manipulators don't. Those used for COSY 5.0 produce >40,000 lines of code for ONE element.

The Difference between Theory and Practice
Is greater in Practice than in Theory

Differential Algebras

- **Allow to solve the flow computation problem**
  - Arbitrary order
  - Very straightforward, even lazy German grad students can do it
  - Converting existing integrators with TPSA (our first idea): easy to understand
  - Much more efficient: use differential algebraic structure of Picard Operator of ODEs, PDEs, …
- **Allows arbitrary order for Normal Form problems**
  - Resonances, tune shifts
  - Long-term stability
- **Allows arbitrary order for Generating Functions**
  - General theory of extended generators, infinite dimensional family containing common F1 – F4
  - Symplectic tracking, “Optimal” generators, very stable

COSY INFINITY

- **First Arbitrary Order Beam Dynamics Code**
  - Based on Differential Algebraic and TPSA methods, both introduced by us. Can handle LHC to order 13.
  - Normal forms, generating functions, symplectic tracking
  - Rigorous treatment of remainder errors
  - Large library of standard elements, DIY elements (give fields)
- **Features of the Code**
  - About 50,000 lines of code
  - Versions for Unix, Windows, Cray
  - Parallel Version for MPI, installed at NERSC, uses up to 2000 processors
- **User Base**
  - As of December 2004, more than 1000 registered users
  - Two-volume user manual (downloadable – 150 pages)
  - User questions are a major effort for our group

Courses Offered at MSU

- **PHY861 – Introduction to Beam Physics**
  - Linear Theory, ODEs and Maps, Intro to Nonlinearities
  - Basic Types of Accelerators and their Components
- **PHY961 – Nonlinear Beam Dynamics**
  - Nonlinearities, DA methods, Lie methods, Symplectic Tracking
  - Normal Forms, Resonances, Tunes, Stability
- **PHY962 - The World of Accelerators**
  - Guest lectures from all major accelerator labs
  - Videoconference format
- **PHY963 - Participation in USPAS**
  - Students sent to participate in semi-annual courses
- **PHY964 - Special Topics in Beam Physics**
  - Advanced research topics
  - Structured online programs exist

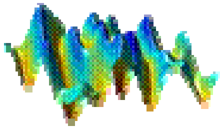
The VUBeam Program

- **Participation in individual courses**
  - About 80 student-courses per year
  - Largest MSU Physics graduate specialization field
- **Remote M.Sc. Degree**
  - Accumulate 30 credits through online courses, USPAS, …
  - Pass departmental Qualifying Exam
  - Can earn up to 12 credits with thesis via local mentor
- **Remote Ph.D. Degree**
  - All of remote M.Sc., plus:
  - Departmental Subject Exams in four core areas
  - Dissertation
    - Done in collaboration with remote mentors in National Labs
    - Committee Meetings at MSU or teleconference

The VUBeam Logistics

- **Live Lectures – Local and Remote Lecturers**
  - IP-based videoconferencing
  - RealVideo streaming
  - (Classroom – how old fashioned)
- **Downloadable Lectures and Material**
  - RealVideo and RealAudio
  - Lecture notes as pdf, entire books, weblinks …
- **Online Homework System**
  - Computational and Multiple Choice (interactive)
  - Extended narrative problems (FAX or scan)
- **Send Students to USPAS**
  - Rich assortment of classes, taught by world leaders
  - A concept that cannot be duplicated by any university

Former VUBeam Students



• **Mohamed Nasr**	**MSc 2002, now Riyad U.**
• **Mandi Meidlinger**	**MSc 2002, now NSCL**
• **David Meidlinger**	**MSc 2002, now NSCL**
• **Jason Ong**	**MSc 2002**
• **Reiko Taki**	**MSc 2003, now KEK**
• **Pavel Snopok**	**MSc 2003, now FNAL**
• **Alexey Poklonskiy**	**MSc 2003, now FNAL**
• **Stephen Weathersby**	**MSc 2004, now SLAC**
• **Andrew Steere**	**MSc 2005, now Sidney**
• **Mahuya Sengupta**	**MSc 2006, now ANL**

DOE-Supported Output

- **Publications**
  - >100 refereed papers
  - >100 invited talks
  - Many non-refereed conference proceedings contributions
- **Books**
  - M. Berz, Modern Map Methods in Particle Beam Physics, Academic Press, 1999
  - M. Berz, W. Wan and K. Makino, An Introduction to Beam Physics, Taylor&Francis, 2006
  - High-Order Numerical Methods, Springer (in preparation, expected 2006)
- **Three Volumes of Conference Proceedings**
  - Computational Differentiation 1996 (MSU / SIAM)
  - Computational Accelerator Physics 2002 (MSU)
  - Computational Accelerator Physics 2004 (St. Petersburg)

External Collaborations

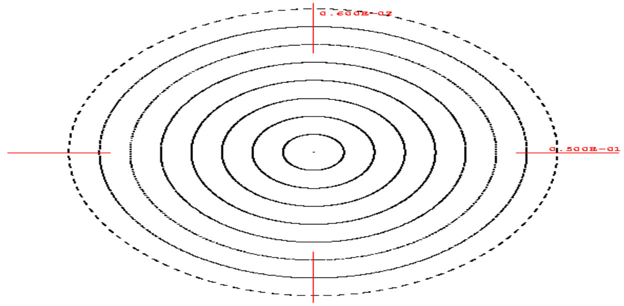
- **Fermilab**
  - Tevatron Dynamics
  - Muon Collider Simulations
  - ILC
- **Argonne**
  - Aberrations in Spectrographs
  - Dynamics in LINACs, RIA
  - High-Performance Computing
- **Verified Computing**
  - DA with Remainder Bounds
  - Significantly reduces the main curse of verified methods, the so-called dependency problem
  - Verified Integration and Global Optimization

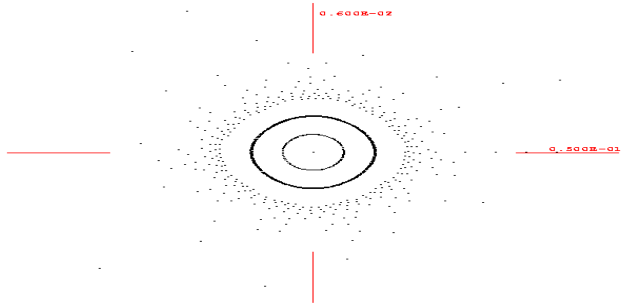
Fringe Field Effects in a Muon Storage Ring

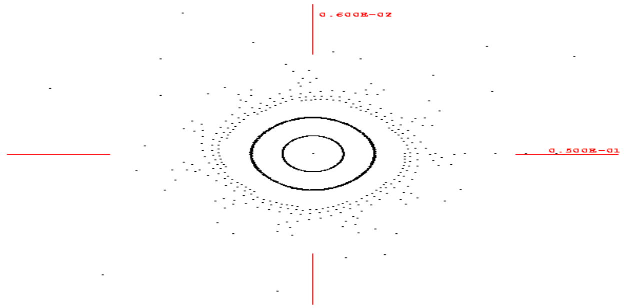
No Fringe Field Effects, With Fringe Field Effects.

With Fringe Field Effects but Kinematic Correction.

30GeV. Frames: 50mm x 6mrad.

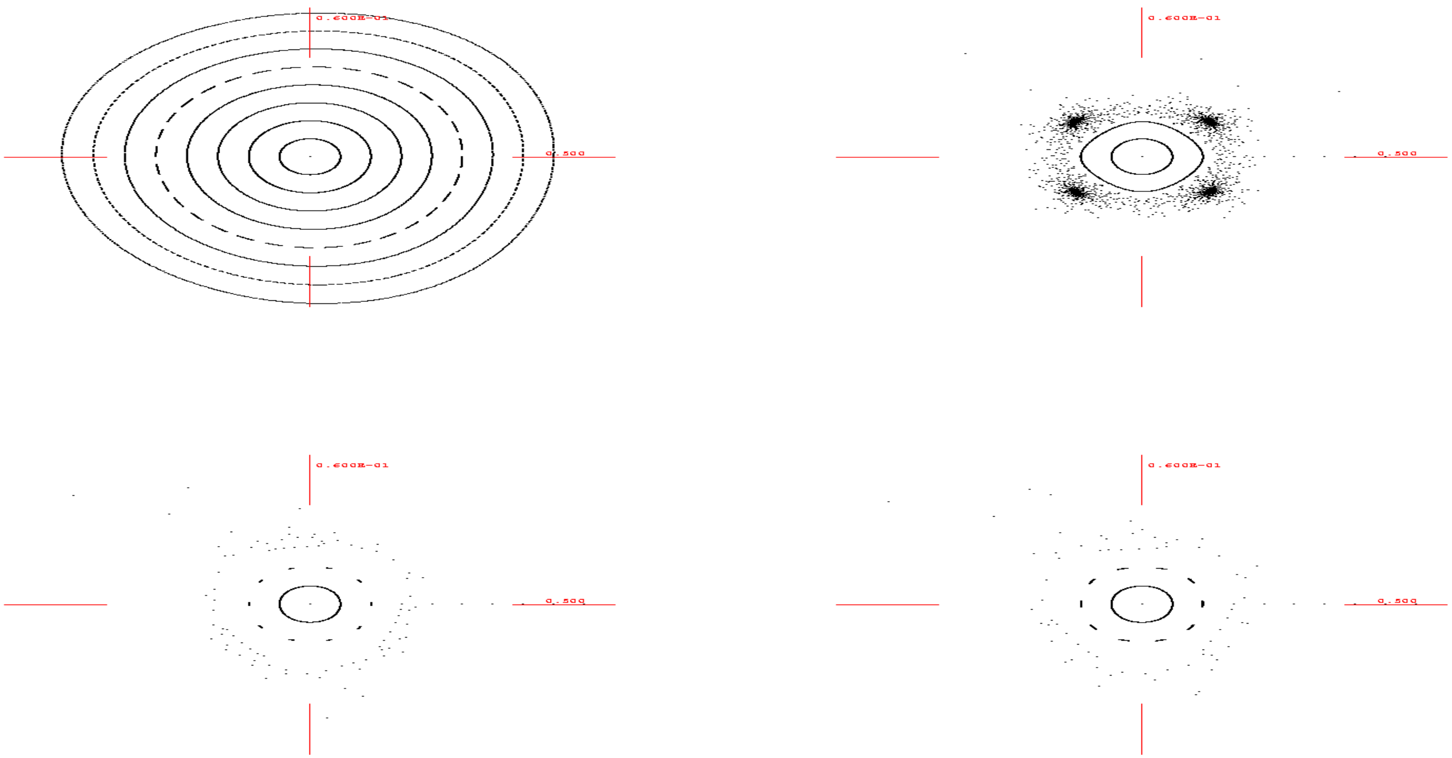






Kinematic Correction in a Muon Storage Ring

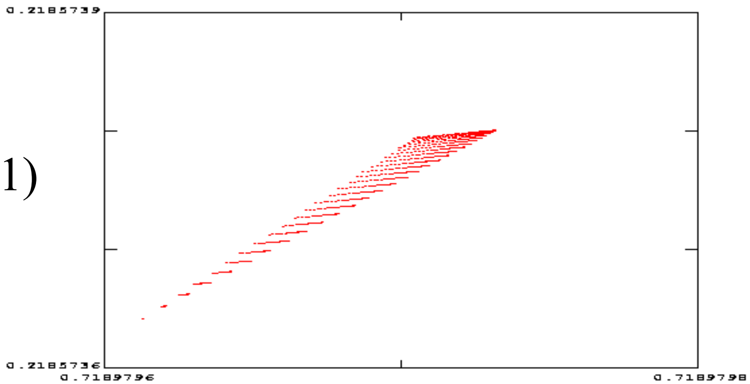
No Correction, Full Correction, 30GeV. Frames: 500mm x 60mrad.
Lowest Order Correction, -- Symplectified.



Kinematic Correction and Fringe Field Effects on Tune Footprint in a Muon Storage Ring

1) No Kinematic Correction. No Fringe Field Effects.
(0.7189796 - 0.7189797) x (0.2185736 - 0.2185738)

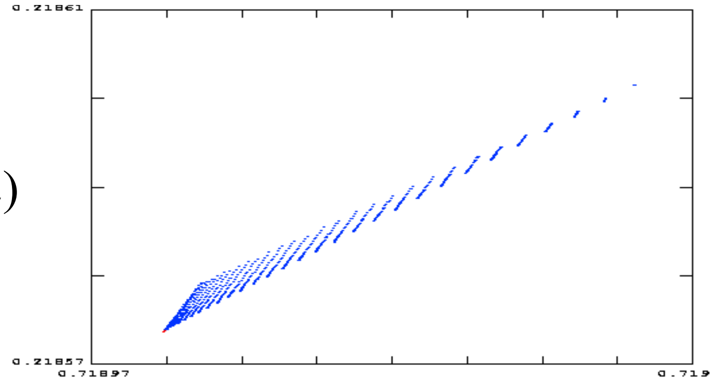
1)



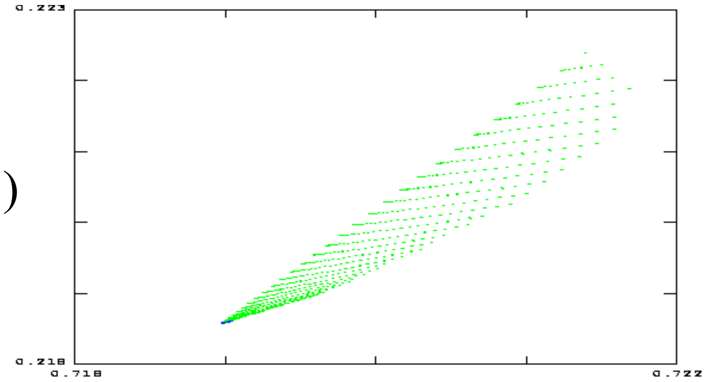
2) With Kinematic Correction. No FF.
(0.71898 - 0.71904) x (0.21857 - 0.21860)

3) With Kinematic Correction.
With Fringe Field Effects.
(0.719 - 0.722) x (0.218 - 0.223)

2)



3)



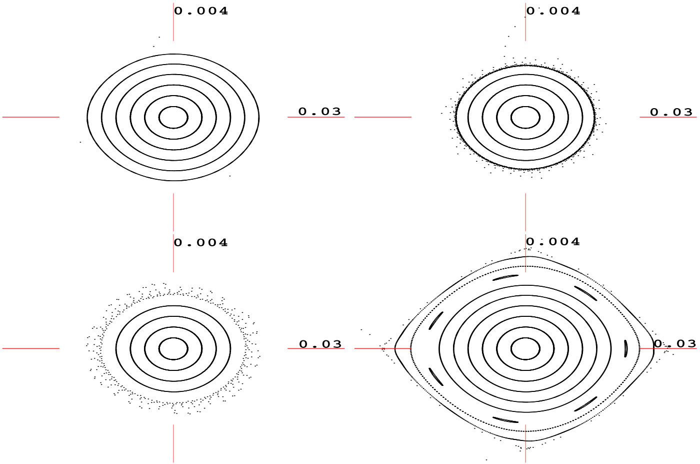


Figure 8: 1000 turn symplectic tracking of a lattice of the proposed Neutrino Factory with the conventional generating functions (F_1 through F_4)

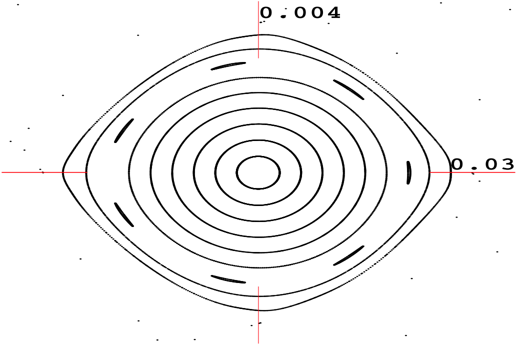
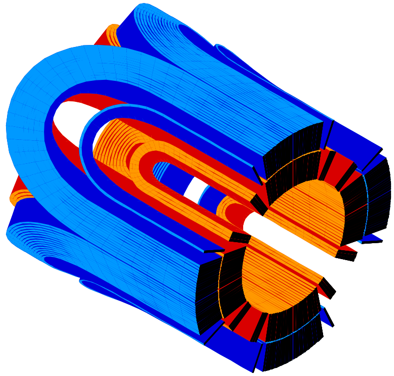
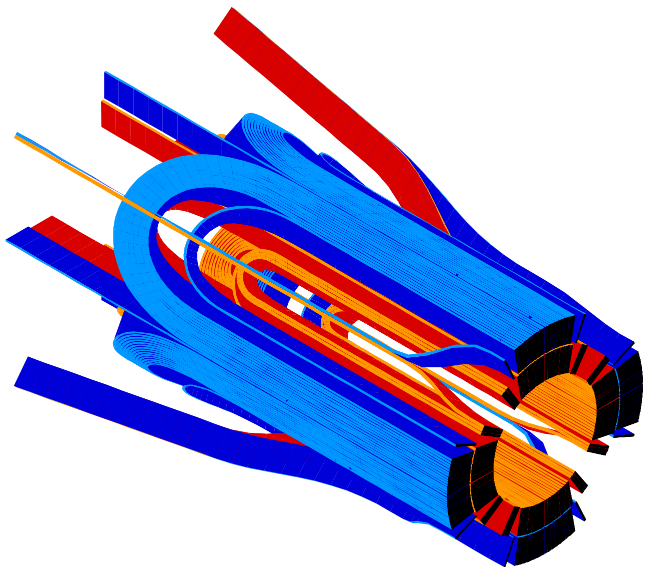


Figure 9: 1000 turn symplectic tracking of a lattice of the proposed Neutrino Factory with the generator type associated to $S = 0$



The HGQ return end

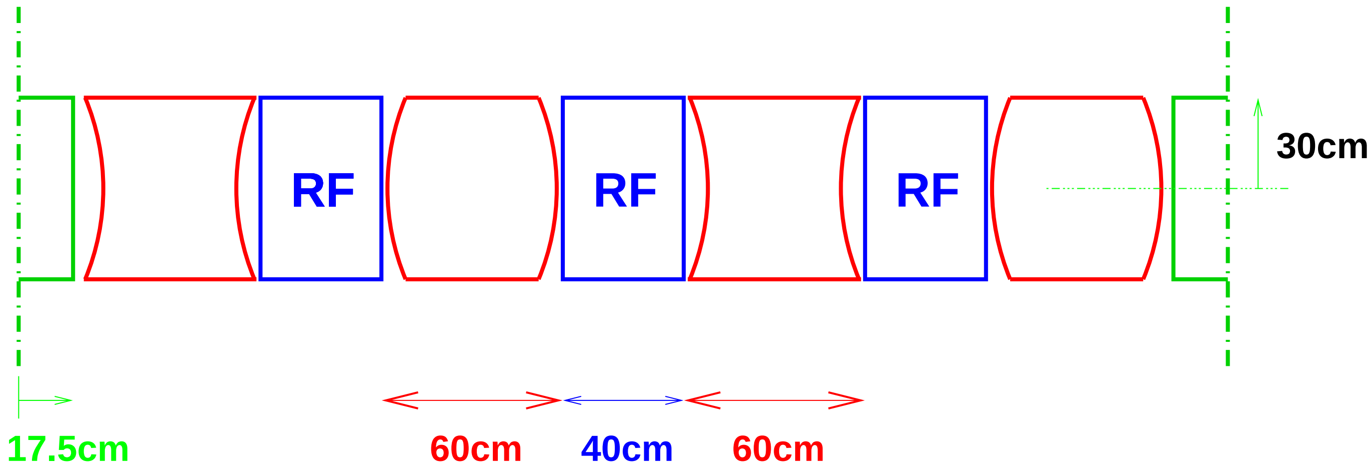


The HGQ lead end

Pictures :

G. Sabbi, "Magnetic Field Analysis of HGQ Coil Ends"

Quad Cooling Cell (4m Cell)



- Incoming Muons: 180 MeV/c to 245 MeV/c
- Magnetic Quadrupoles: k=2.88
- 35cm Liquid H Absorber: Energy loss $\approx$ 12 MeV.
  The same design as Study II 2.75m sFOFO cell.
- RF Cavity: Energy gain to compensate the loss.
  About 200 MHz, $\phi = 30°$.

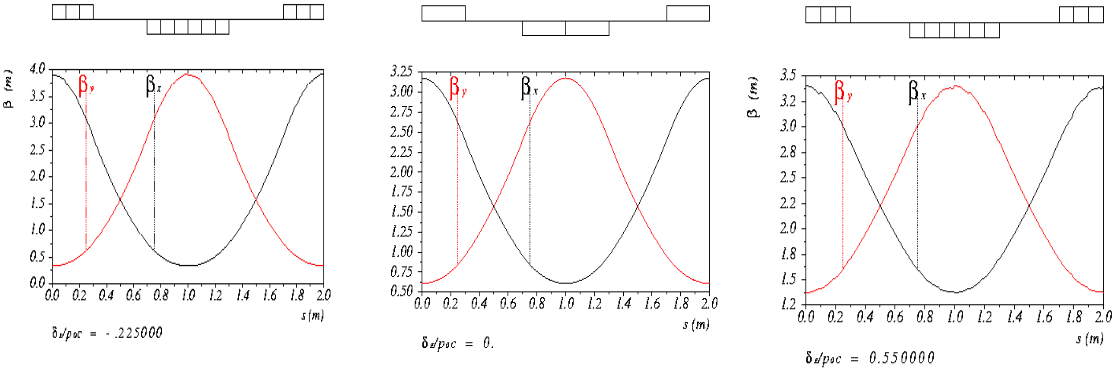
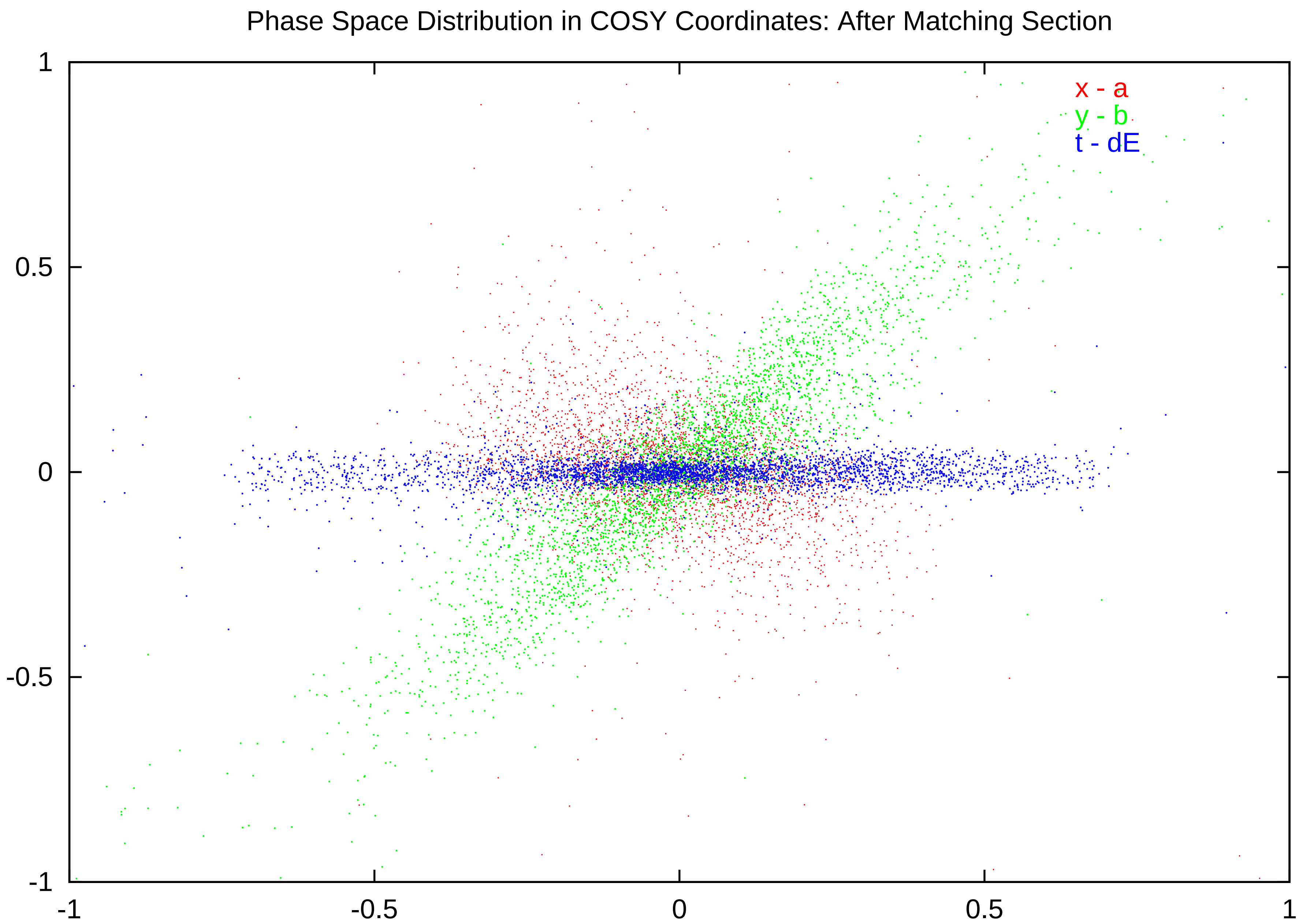
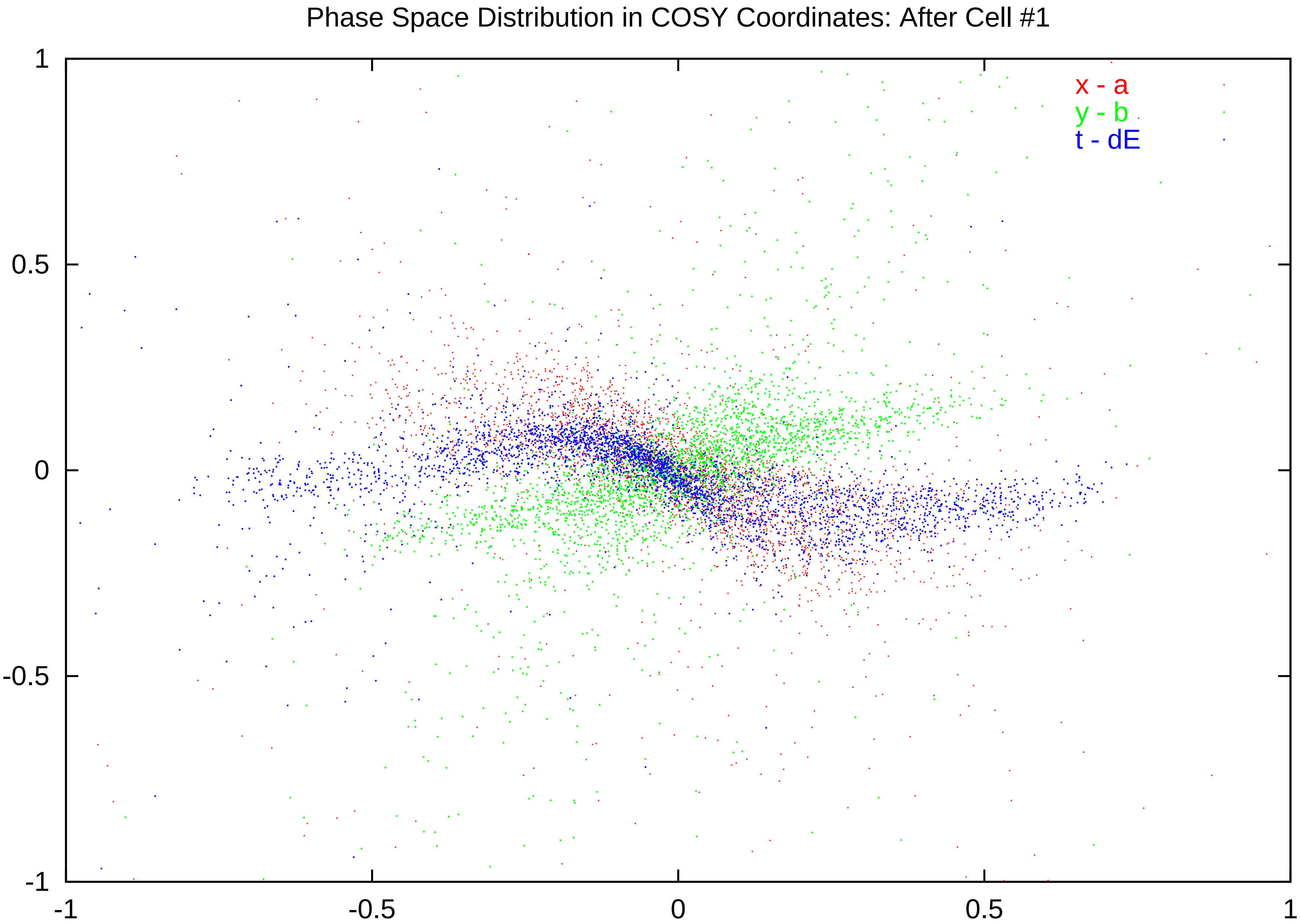
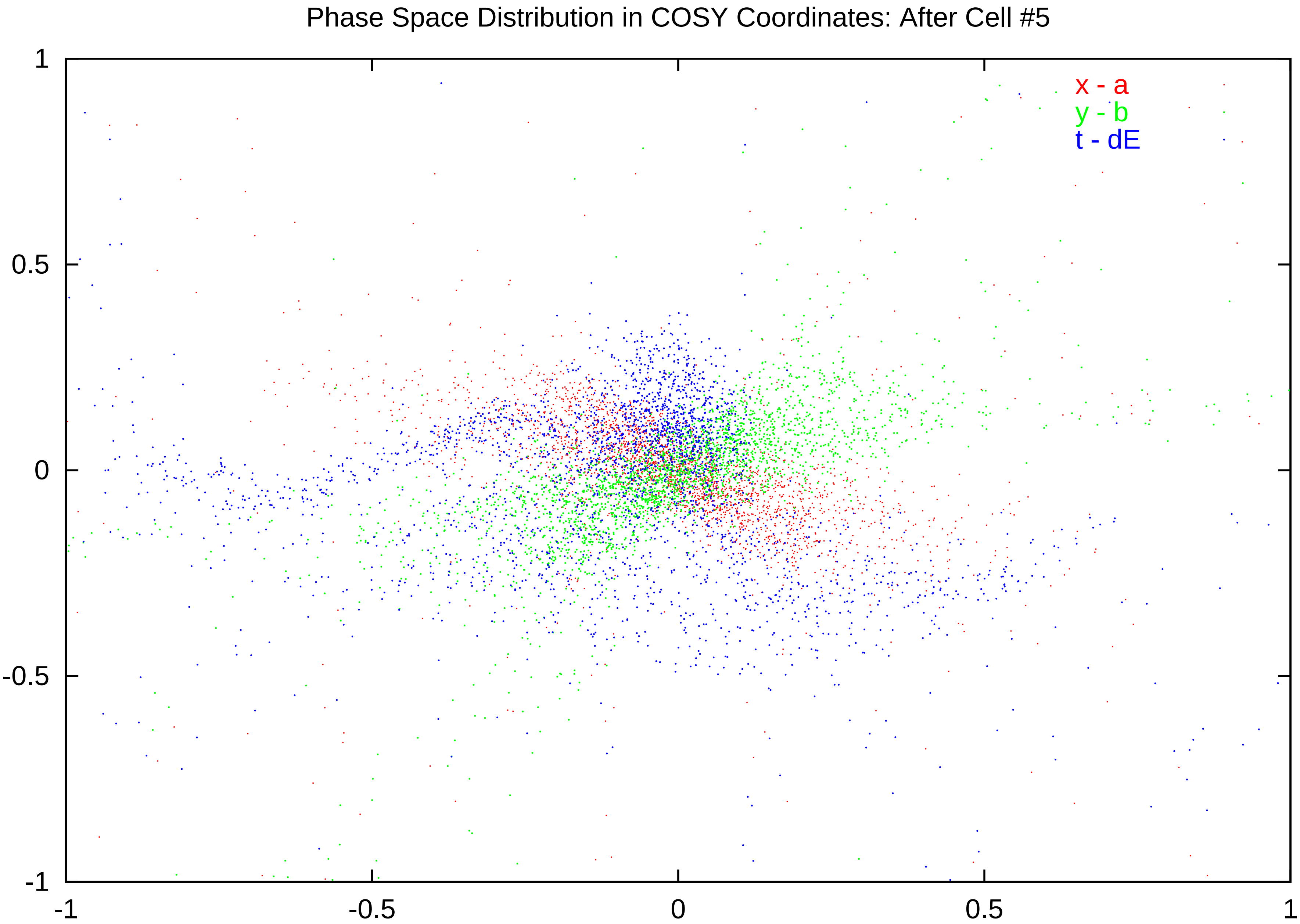


Figure 4. Plots of the beta functions for the quadrupole cooling cell at p = 155 MeV/c, 200 MeV/c and 300 MeV/c.

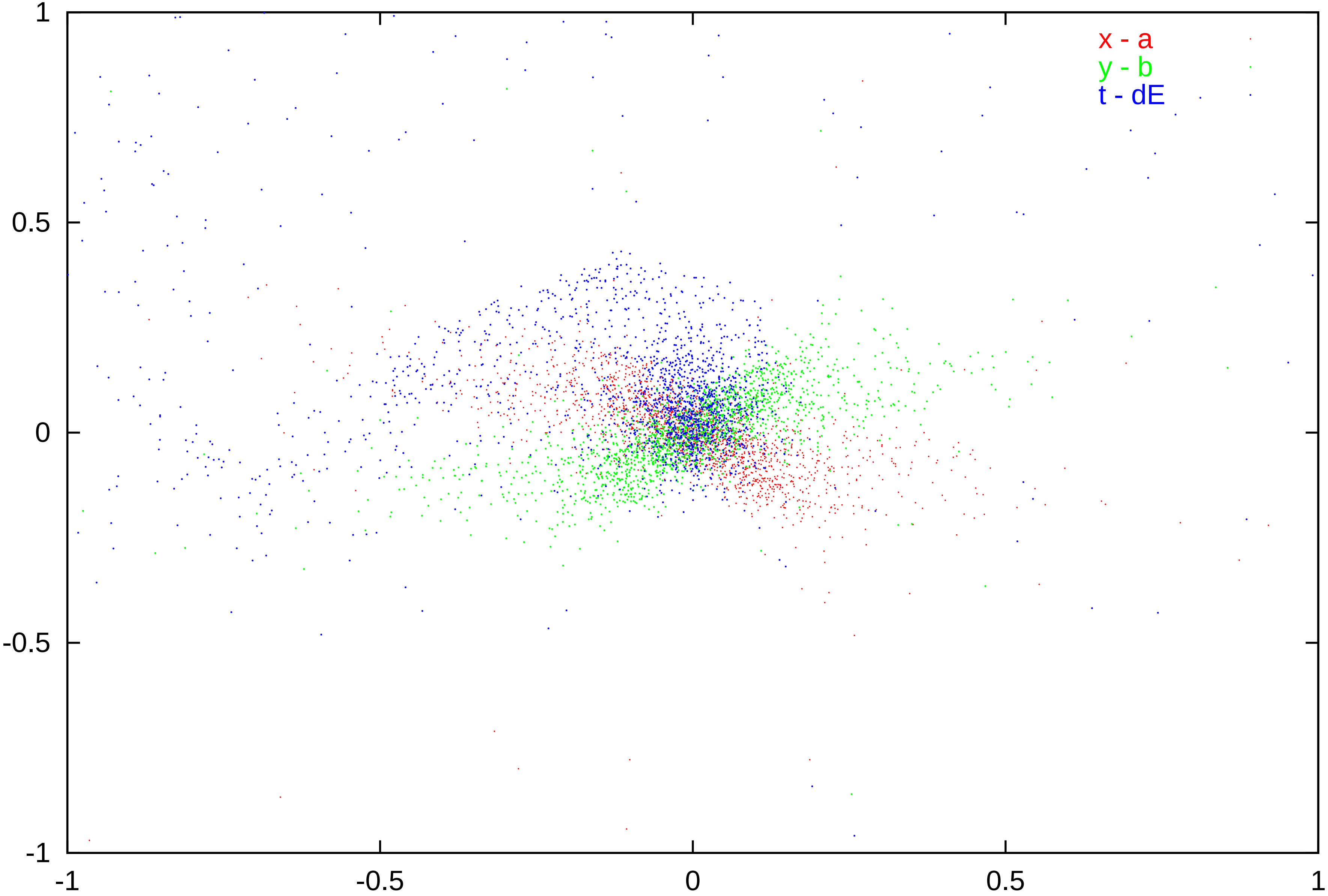


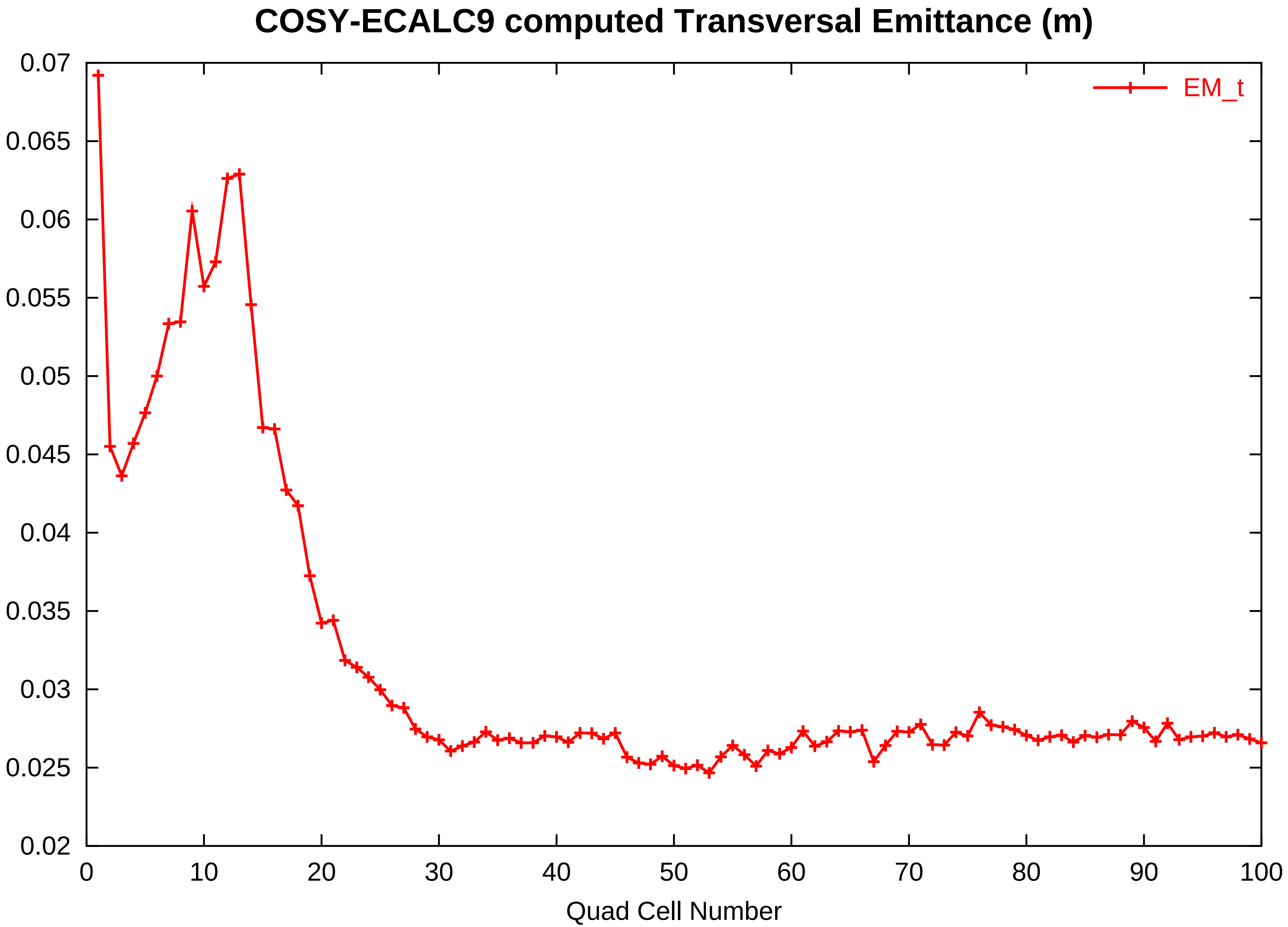
Phase Space Distribution in COSY Coordinates: After Matching Section
x - a
y - b
t - dE
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1


Phase Space Distribution in COSY Coordinates: After Cell #1
x - a
y - b
t - dE
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1


Phase Space Distribution in COSY Coordinates: After Cell #5
x - a
y - b
t - dE
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1

Phase Space Distribution in COSY Coordinates: After Cell #20





COSY-ECALC9 computed Transversal Emittance (m)
EM_t
0.07
0.065
0.06
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0
10
20
30
40
50
60
70
80
90
100
Quad Cell Number

From: Ramon Edgar Moore [moore.47@osu.edu]
Sent: Saturday, June 27, 1998 6:17 PM
To: Martin Berz
Cc: 'Makino, Kyoko'
Subject: RE: YES !

Martin,

YES !

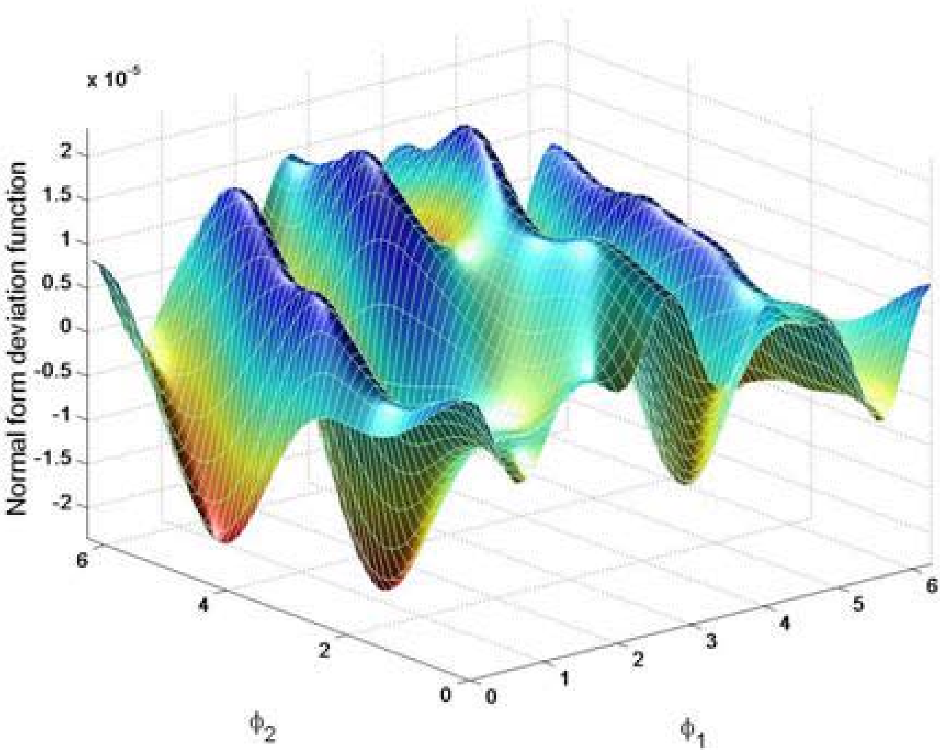
I now understand your method completely. It SOLVES the "wrapping effect" problem, something I and many others (Krueckeberg, Lohner, et al) have tried off and on for three decades and failed to do.

I do not have words for the exhilaration I feel at your solution, for which I have waited so long. I'm chagrined I did not find out about it sooner, but never mind. Now is just fine. It will be the centerpiece of my talk in Toronto.

There is one more thing I need to know, now or in Toronto if you can't get back to me before then. Have you applied it yet to asteroid orbit calculations? I mean to determine the distance of closest approach, taking into account observational errors, and following their effect on orbital elements, and subsequent calculations? I have been in contact with Paul Chodas and Donald Yeomans at JPL concerning possibilities for using interval methods for such purposes. Your method would be ideal, and by far the best approach. Have you already done it? If not, it HAS TO be put on the "must do" list.

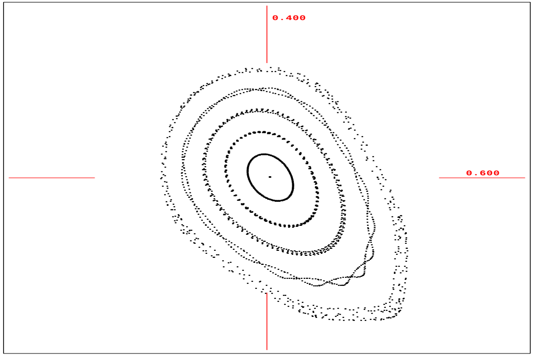
With astonishment and gratitude,

Ramon

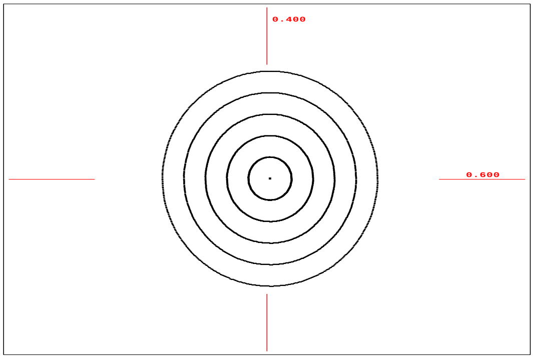


x 10^-5
Normal form deviation function
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
6
4
2
0
0
1
2
3
4
5
6
ϕ2
ϕ1

Example of Phase Space Motion

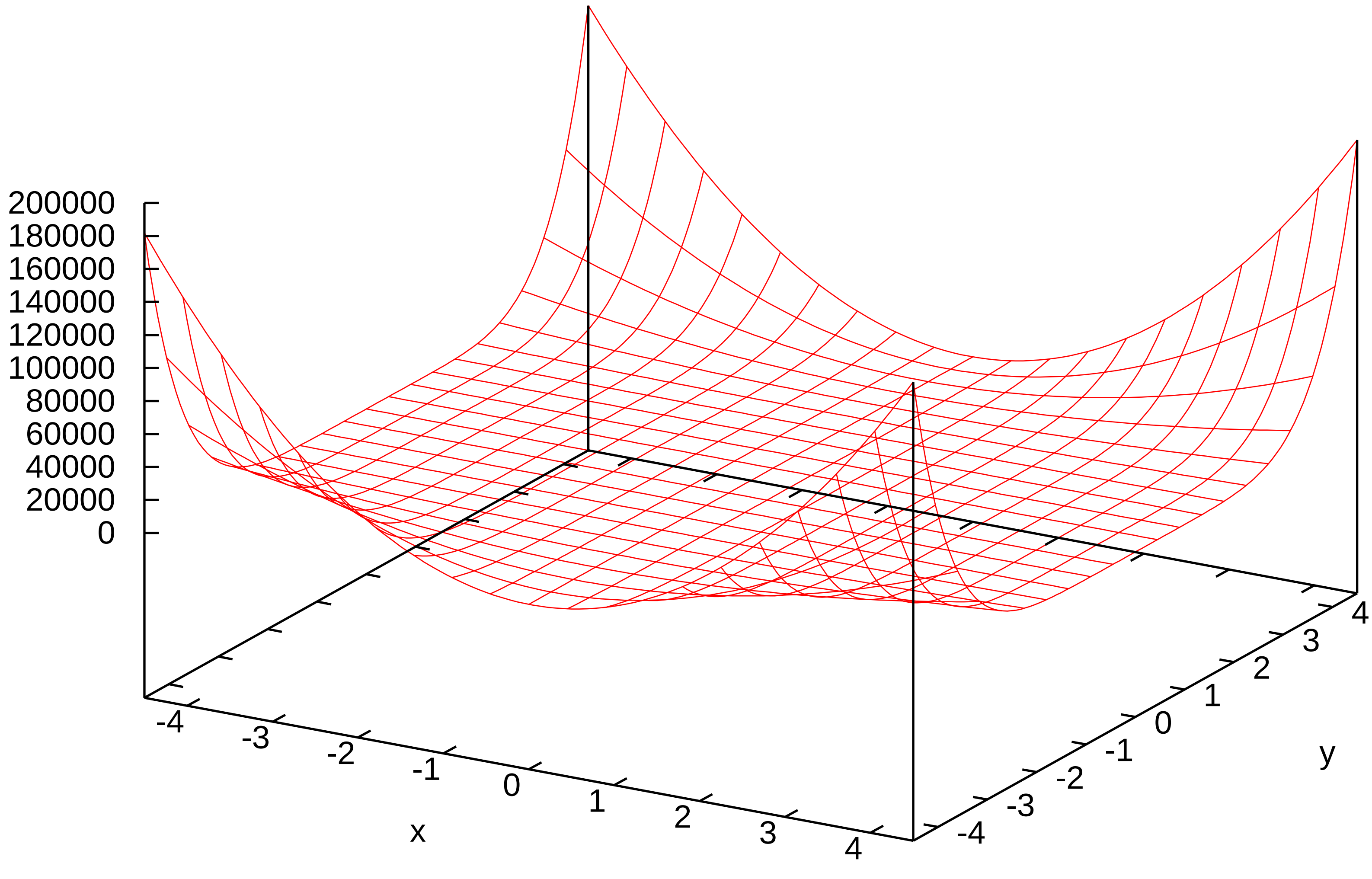


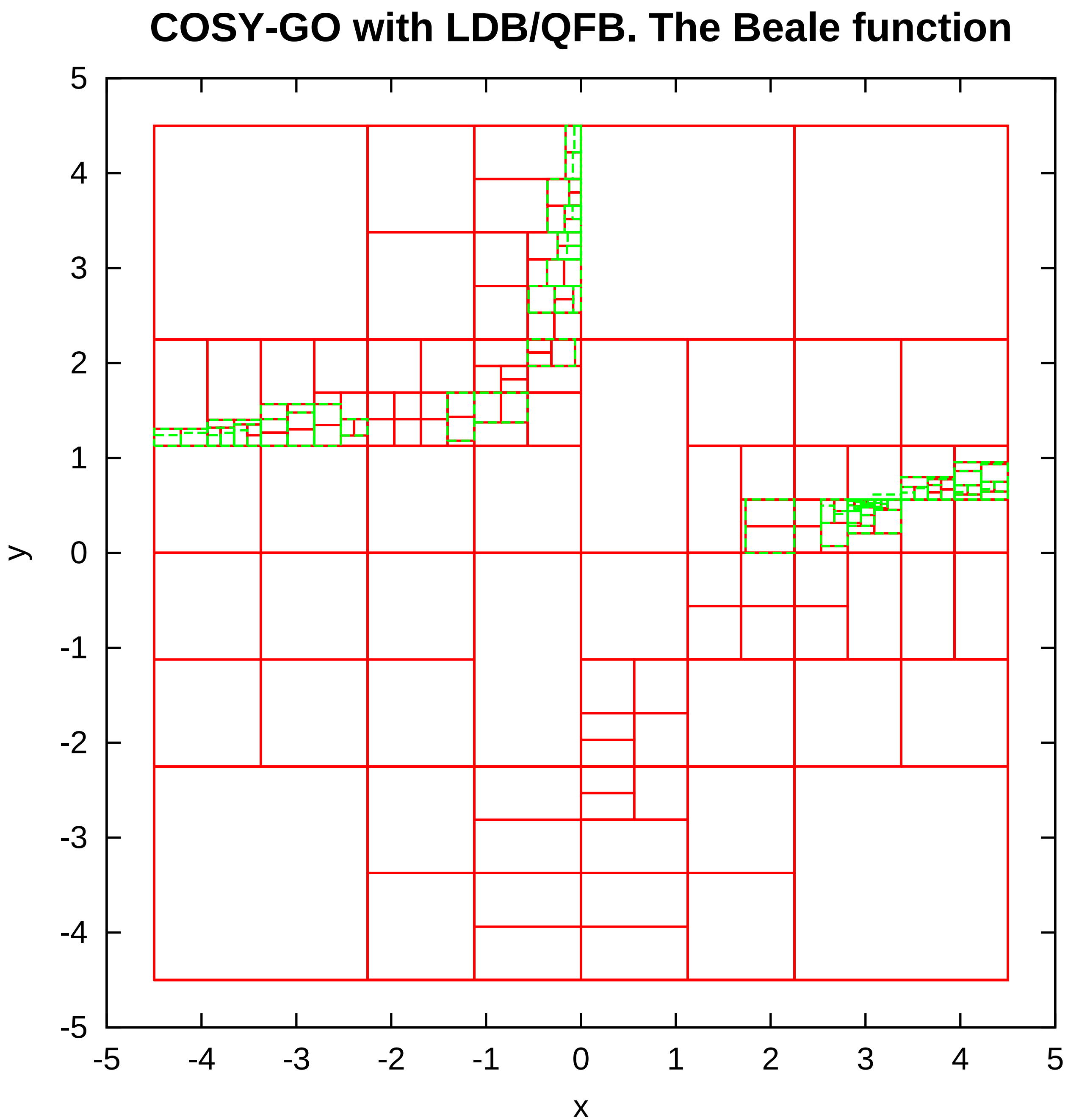
Tracking Phase Space Motion of 5 Particles in Regular Coordinates

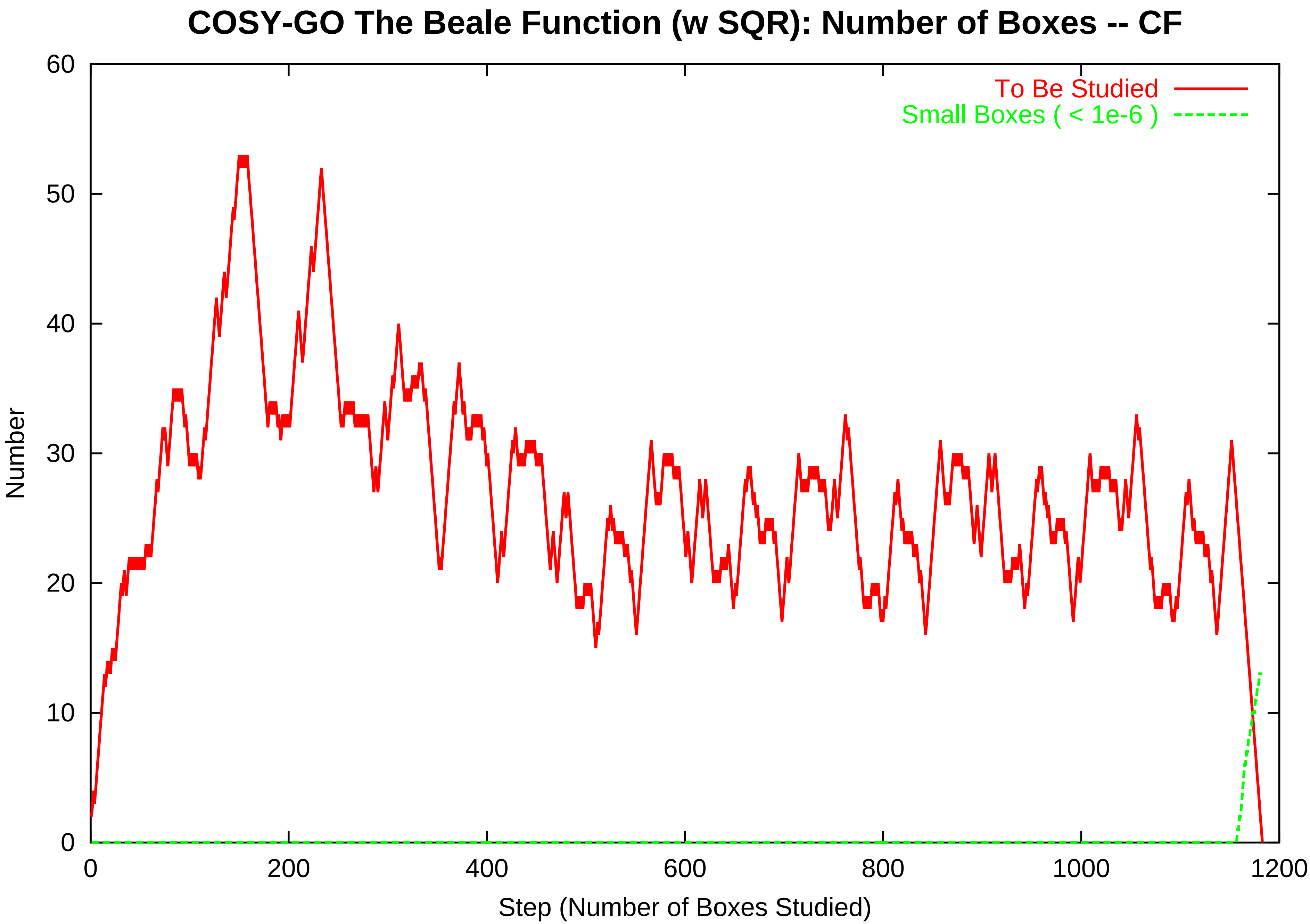


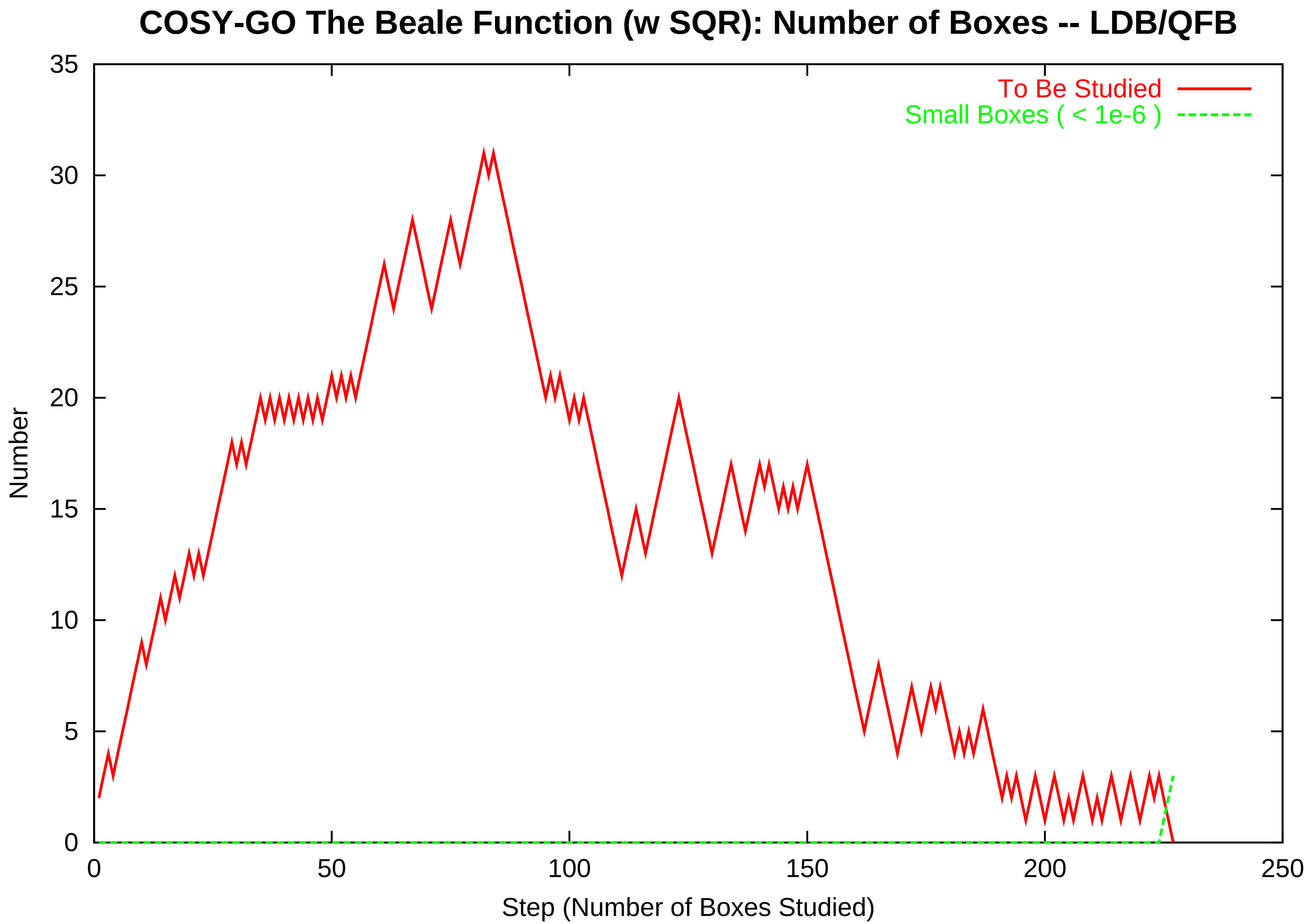
Tracking Phase Space Motion of 5 Particles in Normal Form Coordinates

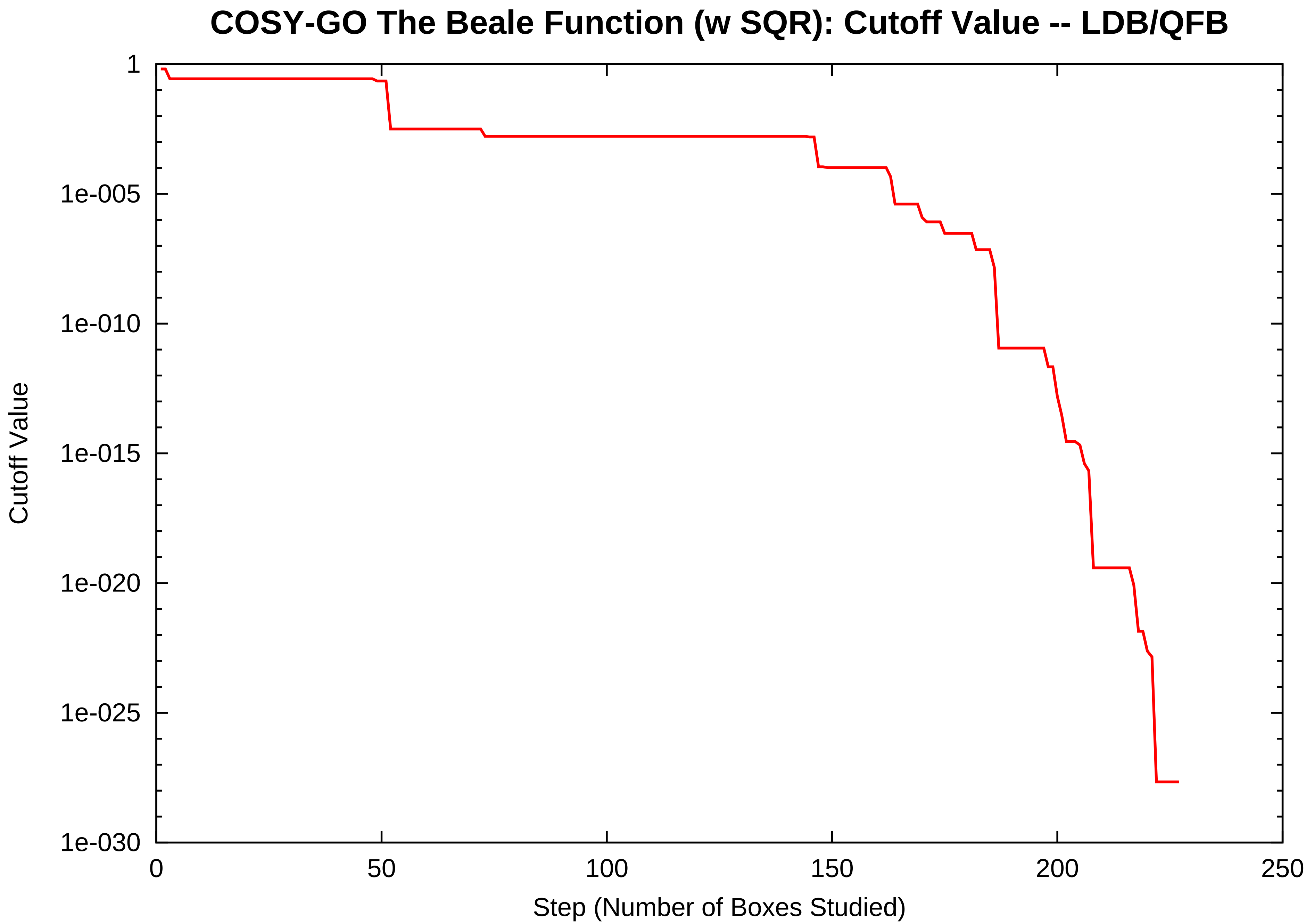
The Beale function. f = [1.5-x(1-y)]^2 + [2.25-x(1-y^2)]^2 + [2.625-x(1-y^3)]^2

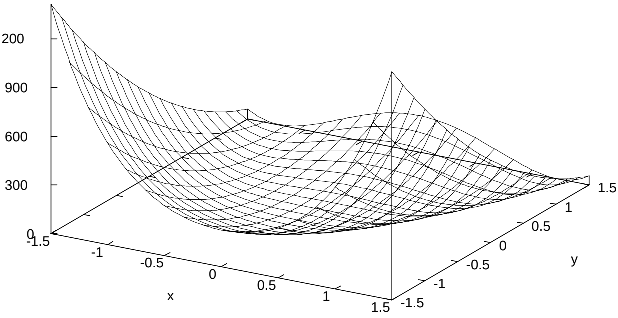


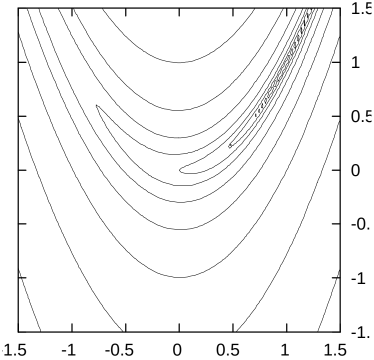

COSY-GO with LDB/QFB. The Beale function
5
4
3
2
1
0
-1
-2
-3
-4
-5
y
-5
-4
-3
-2
-1
0
1
2
3
4
5
x


COSY-GO The Beale Function (w SQR): Number of Boxes -- CF
To Be Studied
Small Boxes (< 1e-6)
Number
Step (Number of Boxes Studied)
0
10
20
30
40
50
60
0
200
400
600
800
1000
1200


COSY-GO The Beale Function (w SQR): Number of Boxes -- LDB/QFB
To Be Studied
Small Boxes (< 1e-6)
Number
Step (Number of Boxes Studied)
0
5
10
15
20
25
30
35
0
50
100
150
200
250


COSY-GO The Beale Function (w SQR): Cutoff Value -- LDB/QFB
1
1e-005
1e-010
1e-015
1e-020
1e-025
1e-030
Cutoff Value
0
50
100
150
200
250
Step (Number of Boxes Studied)


200
900
600
300
0
-1.5
-1
-0.5
0
0.5
1
1.5
x
-1.5
-1
-0.5
0
0.5
1
1.5
y


1
0
-1
-1
-0.5
0
0.5
1
1.5

	LMDIF	Simplex	Anneal
Number of Steps	$100,000$	225	$100,000$
Error in $f(x,y)$	$1 \cdot 10^{-10}$	$2 \cdot 10^{-13}$	$3 \cdot 10^{-4}$
Error in (x,y)	$2 \cdot 10^{-5}$	$4 \cdot 10^{-7}$	$6 \cdot 10^{-3}$

Table 1
Performance of various local optimizers for finding the minimum of the Rosenbrock function in $[-1.5, 1.5]^2$ from the starting point $(-1.2, 1.0)$.

	IN	CF	COSY-GO
Total box processing steps	1325	1325	143
Max number of active boxes	47	47	9
Retained small boxes ($< 10^{-6}$)	15	15	1
LDB domain reduction steps	–	–	43

Table 2
Performance of various validated global optimizers for finding the minimum of the Rosenbrock function in $[-1.5, 1.5]^2$.

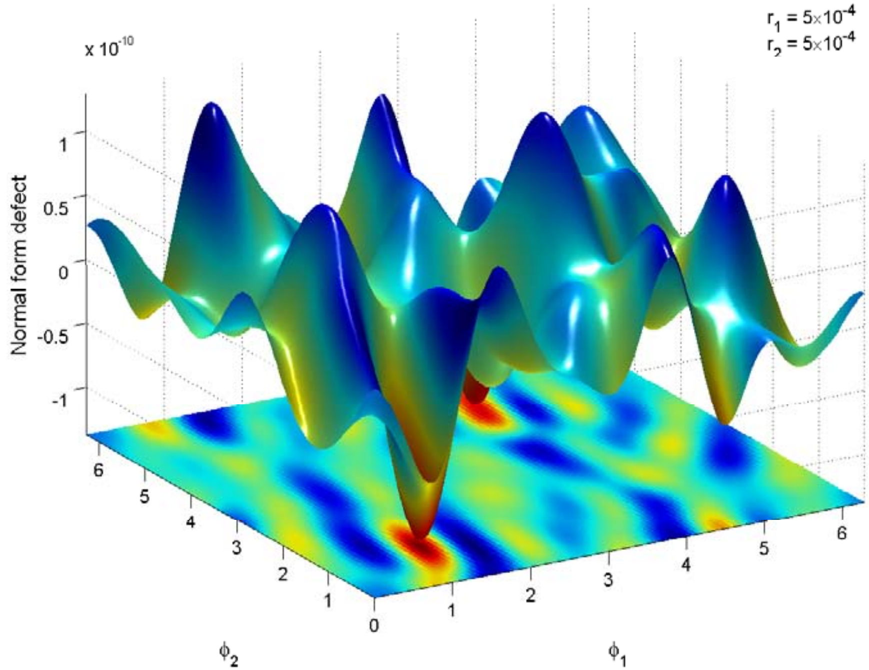


Fig. 9. Projection of the normal form defect function. Dependence on two angle variables for the fixed radii $r_1 = r_2 = 5 \cdot 10^{-4}$

Region	Boxes studied	CPU-time	Bound	Transversal Iterations
$[0.2, 0.4] \cdot 10^{-4}$	82,930	30,603 sec	$0.859 \cdot 10^{-13}$	$2.3283 \cdot 10^8$
$[0.4, 0.6] \cdot 10^{-4}$	82,626	30,603 sec	$0.587 \cdot 10^{-12}$	$3.4072 \cdot 10^7$
$[0.6, 0.9] \cdot 10^{-4}$	64,131	14,441 sec	$0.616 \cdot 10^{-11}$	$4.8701 \cdot 10^6$
$[0.9, 1.2] \cdot 10^{-4}$	73,701	13,501 sec	$0.372 \cdot 10^{-10}$	$8.0645 \cdot 10^5$
$[1.2, 1.5] \cdot 10^{-4}$	106,929	24,304 sec	$0.144 \cdot 10^{-9}$	$2.0833 \cdot 10^5$
$[1.5, 1.8] \cdot 10^{-4}$	111,391	26,103 sec	$0.314 \cdot 10^{-9}$	$0.95541 \cdot 10^5$

Table 8

Global bounds obtained for six radial regions in normal form space for the Tevatron. Also computed are the guaranteed minimum transversal iterations.