NERSC's 6,656-processor IBM RS/6000 SP
has 416 16-CPU POWER3+ SMP nodes
with a peak performance of 10 teraflop/s.

Modeling of Particle and Power Control for Compact Stellarators

ARIES-CS Project Meeting

8-9 March 2004

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UCSD

Power and Particle Handling

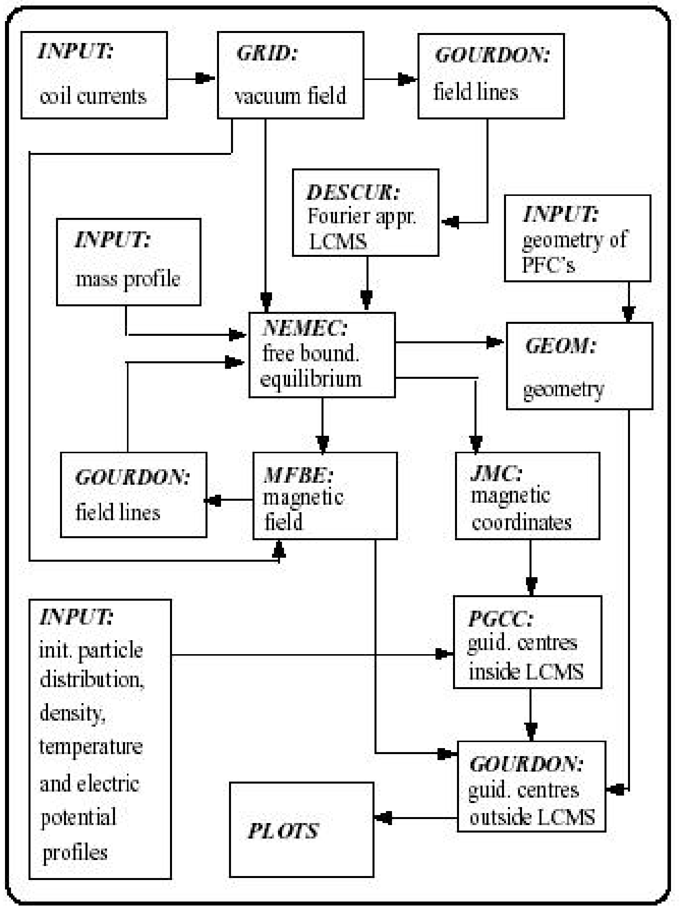
- Many issues are generic to both tokamaks and stellarators.
- Divertors are the preferred solution for both tokamak and stellarator. But the fully 3D Magnetic structure outside LCMS in a stellarator does not always permit a divertor.
  - Continuous coil systems have natural diversion of field lines between helical coils. But separatrix not as clear as in tokamak because of ergodization near boundary.
  - Modular stellarators more complex, but techniques exist for helical divertor formation and flux bundle diversion [eg Strumberger 1992].
  - First efforts to determine if divertor is possible for compact stellarator (this work). Field line tracing is first and most basic task to answer this question.

Collisionless Particle Confinement- Stellarators and Tokamaks are Very Different

- Tokamaks completely confine collisionless orbits (ideal 2D axisymmetry) but fully 3D stellarators suffer severe particle loss to walls, with the following exceptions:

1) QAS-Quasi-axisymmetric stellarator- magnetic field strength independent of generalized toroidal magnetic coordinate (NCSX, Aries-CS).
2) QHS-Quasi-helically symmetry (HSX)
3) Quasi-isodynamic stellarator- poloidal closure of 2^{nd} adiabatic invariant (W7-X).

Adaptation of W7-X Codes For Scrape-off Layer and Divertor Study



- MFBE (Magnetic Field Solver for Finite Beta Equilibria-[assumes stellarator symmetry]) parallelized for T3E replaced by MFBE_2001[no symmetry assumed] parallelized for IBM. Both were adapted for net toroidal current via Shafranov "virtual casing".
- NEMEC replaced by VMEC2000 version 6.8

Geometric and Magnetic Quantities

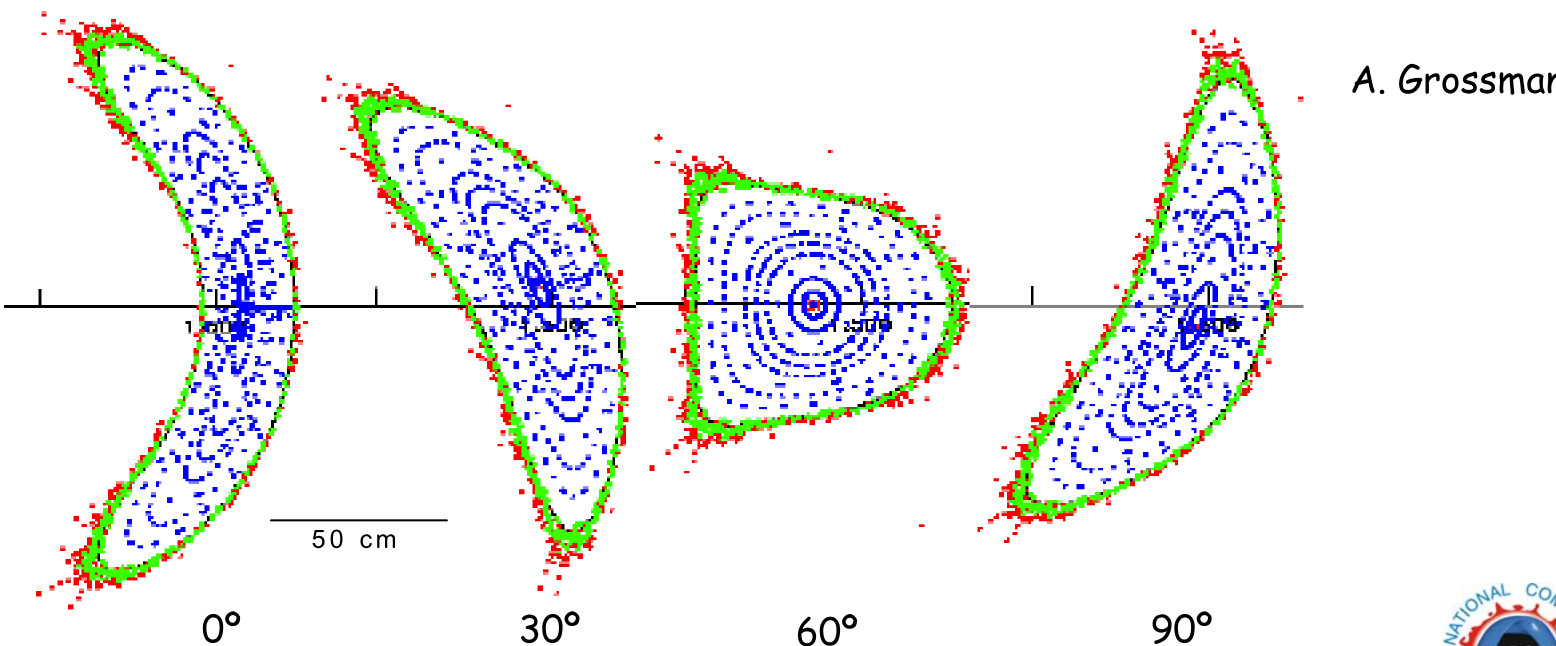
	W7-X	NCSX	Aries-CS
Aspect Ratio	10.0	4.466	4.478
Minor Radius [m]	0.55	0.3225	1.846
Major Radius [m]	5.5	1.440	8.270
Surface Area [m^2]	120.0	23.93	782.1
Plasma Volume [m^3]	30.0	2.959	556.8
Volume Average B [T]	2.5	1.574	6.692

The NCSX Boundary Has Long Connection Lengths !

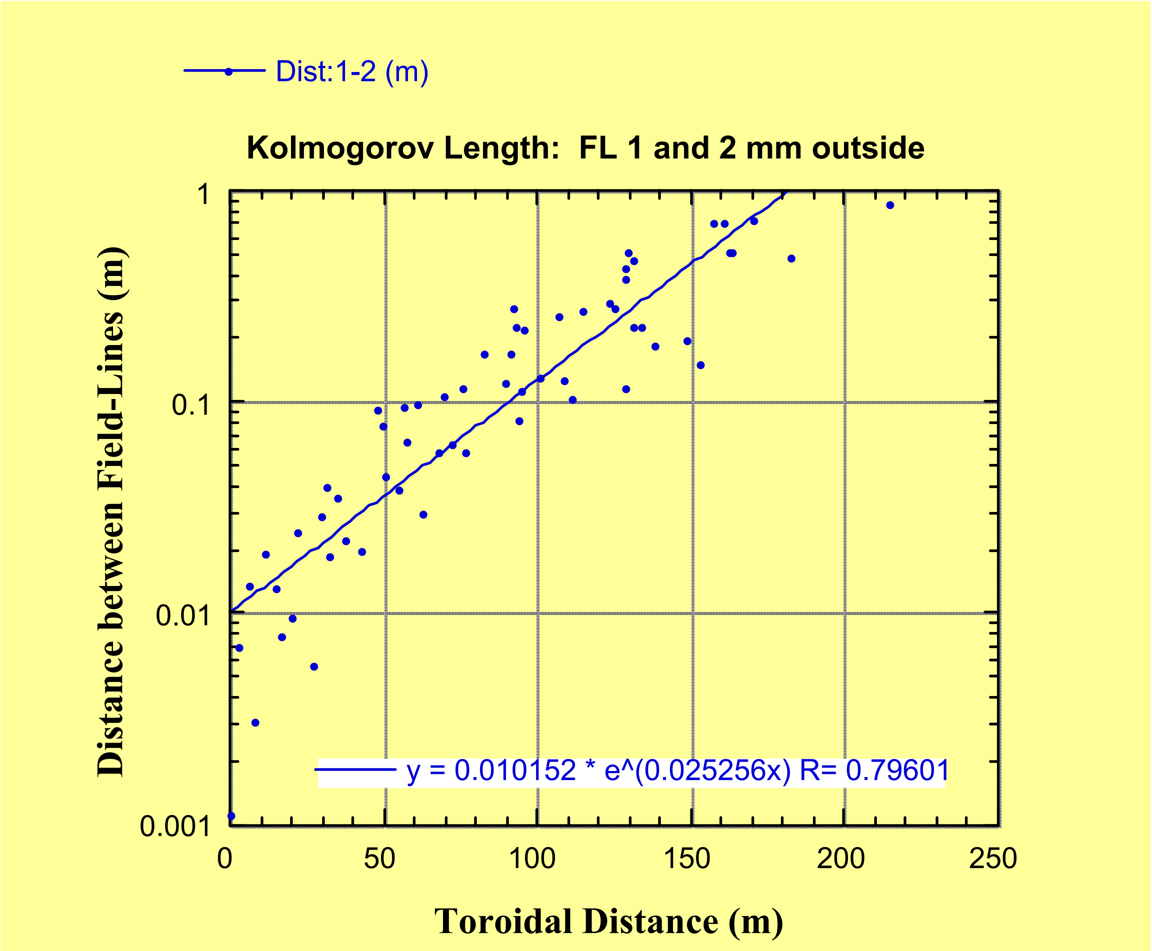
- Poincaré plots, generated with the MFBE* and Gourdon codes: 20 field-lines were started at the outer/inner midplane (0-1 cm) and followed for 20 toroidal revolutions (Lc~180 m)

*E. Strumberger

  - Significant flux expansion
  - Long connection lengths: here up to 180 m
  - Kolmogorov lengths are ~30-50 m
  - Suitable for divertor operation



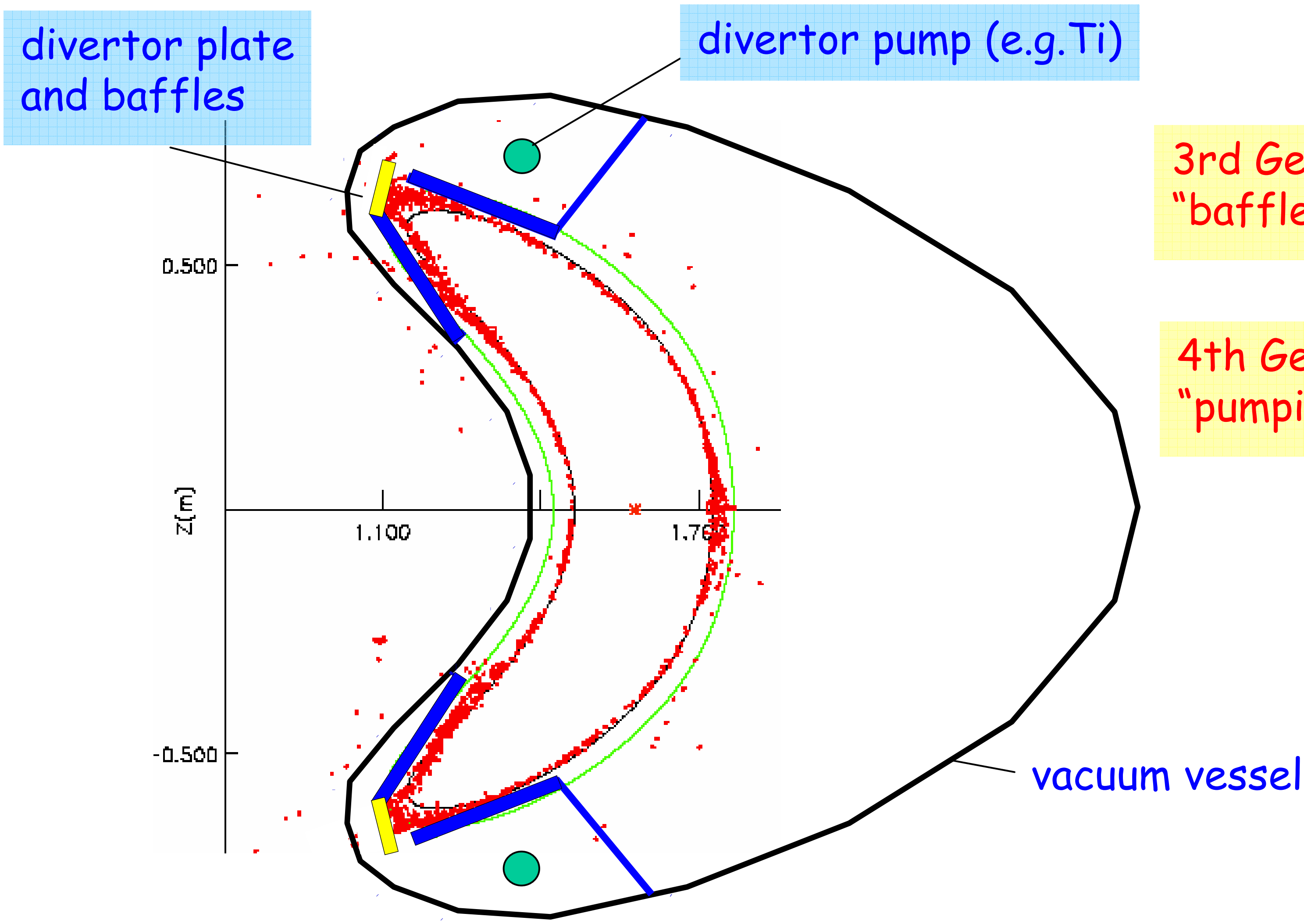
Kolmogorov Length for Field-Lines Launched At Outside Midplane



$L_k \sim$ 40 m

$L_c \sim$ 180 m

3rd and 4th Generation PFCs : Divertor



3rd Generation
"baffle mode"

4th Generation
"pumping mode"

MFBE_2001 has now been applied to these NCSX Equilibria:

m50_256.multi: multi-filament coils derived directly from the PIES healing algorithm with plasma at full beta/full current.

m50_e04: single-filament coil set obtained after smoothing out some kinks in the m50_256 coils with above LCMS and (almost) same plasma properties.

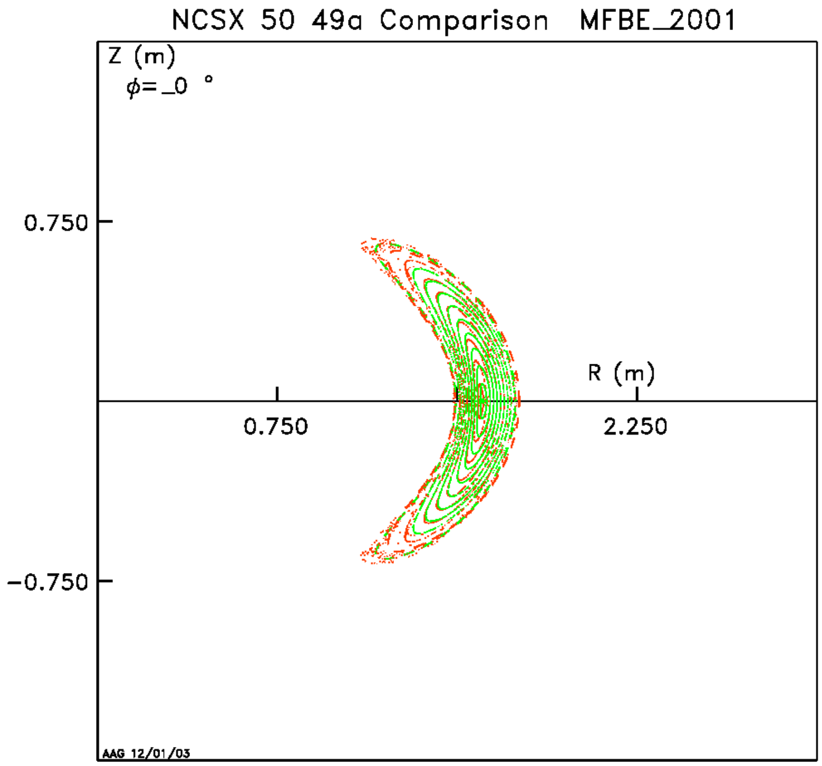
c08r00_s3.b.min : s3 state (beta = 4%, Ip = -179 kA, R*Bt = 2.38)

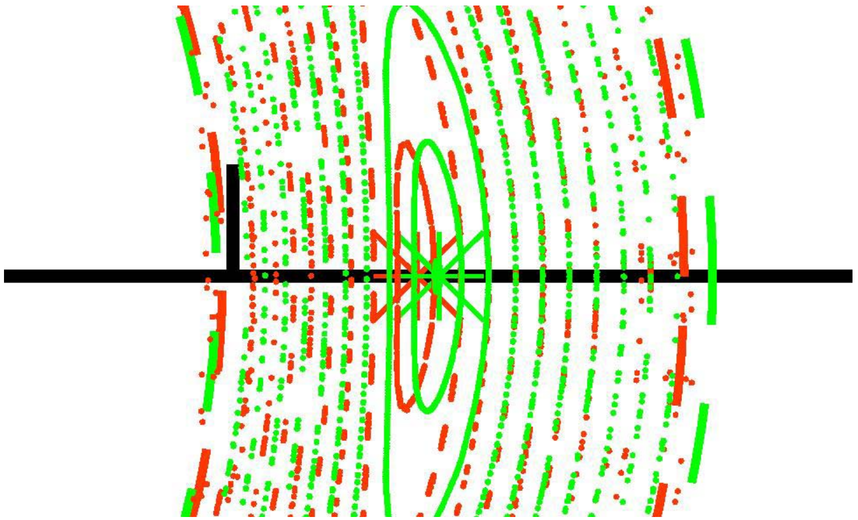
c08r00_b2.0.min: 2% beta at same current and field

c08r00_b0.0.min: 0% beta at Ip = -120 kA, full field

NZETA has been increased to 30, because of constraints on the number of processors allowed on IBM

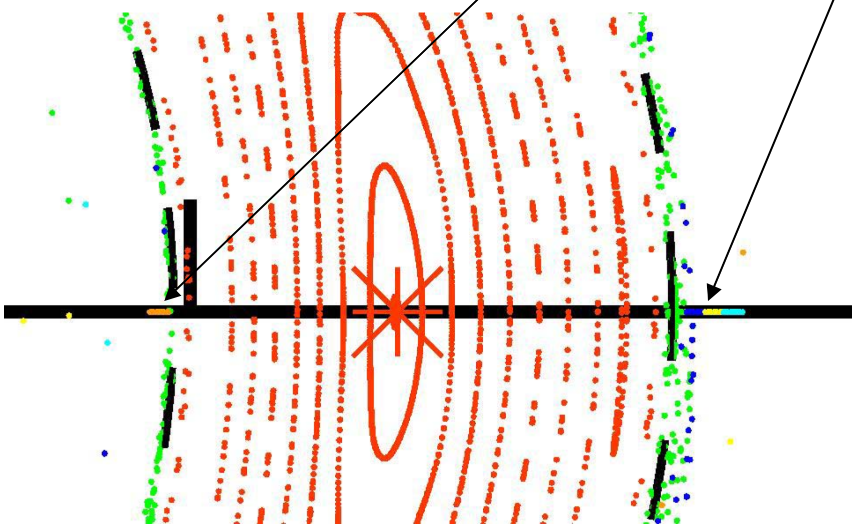
2% vs 4% Beta Core
2%- c08r00_b2.0.min - red
4%- c08r00_S3.b.min - green



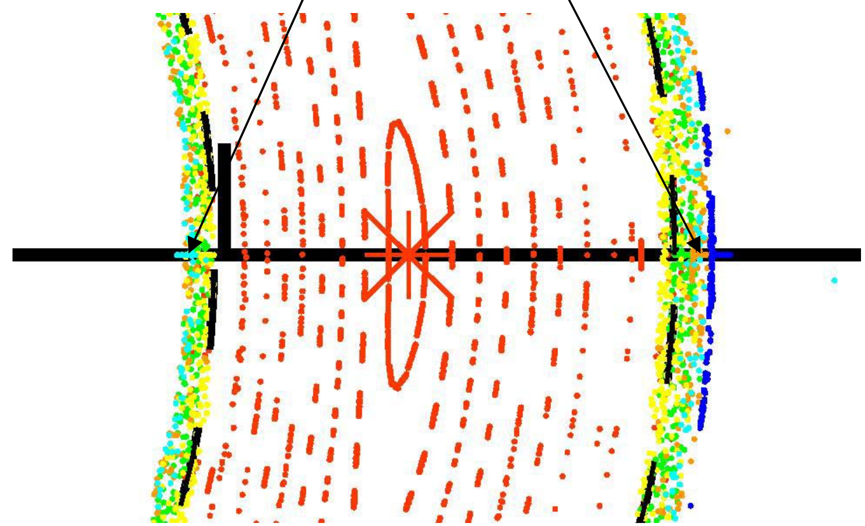


2% vs 4% Beta- SOL Starting Pts

Equidistant starting points 10 each to 1 cm with same color, all have z=0

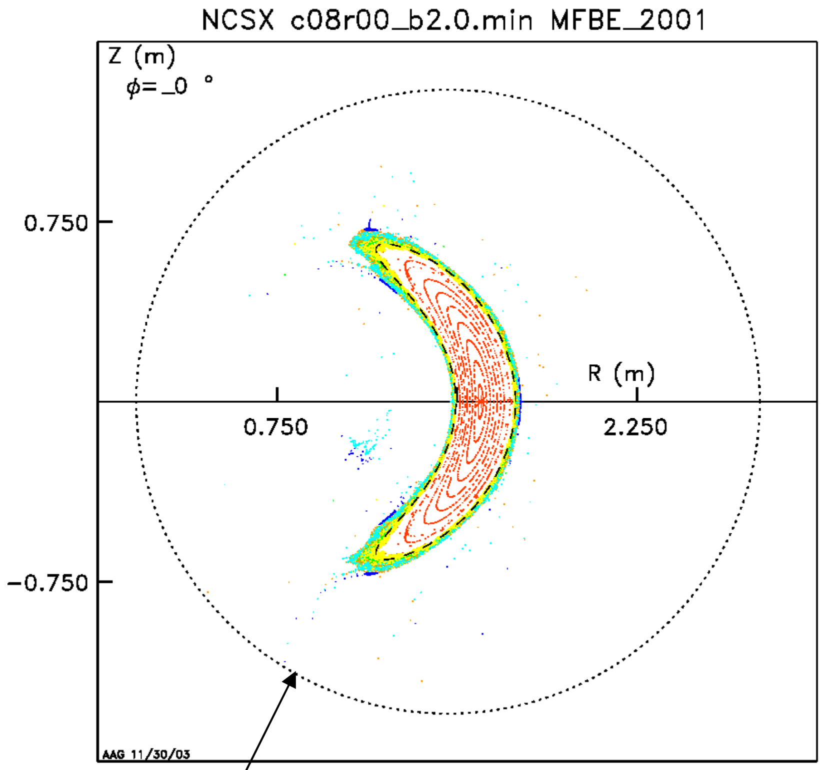


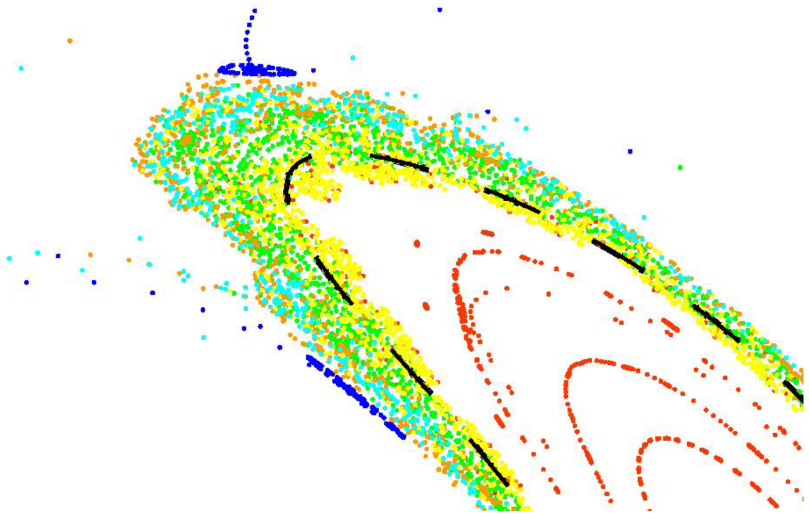
4%



2%

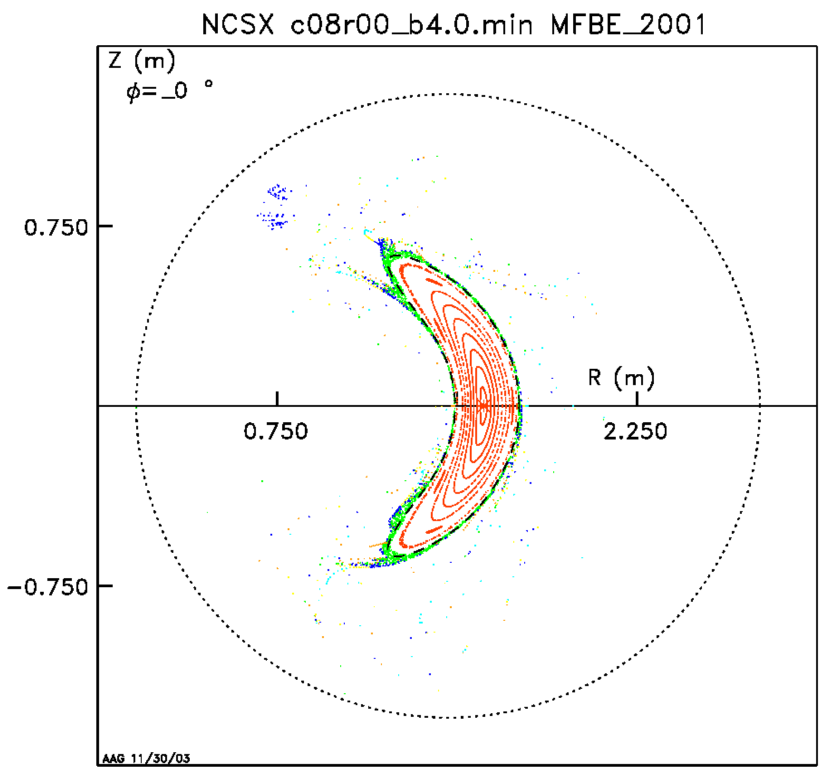
2% Beta –SOL Stochasticity plus an Island Structure c08r00_b2.0.min

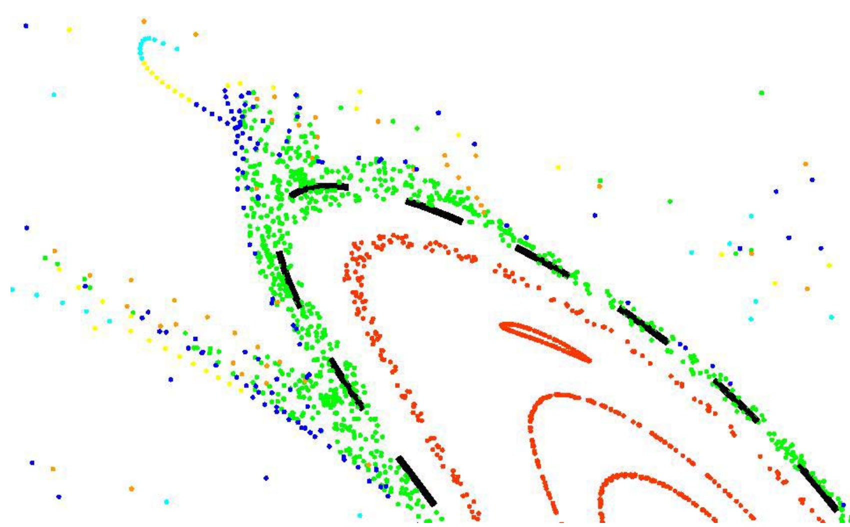




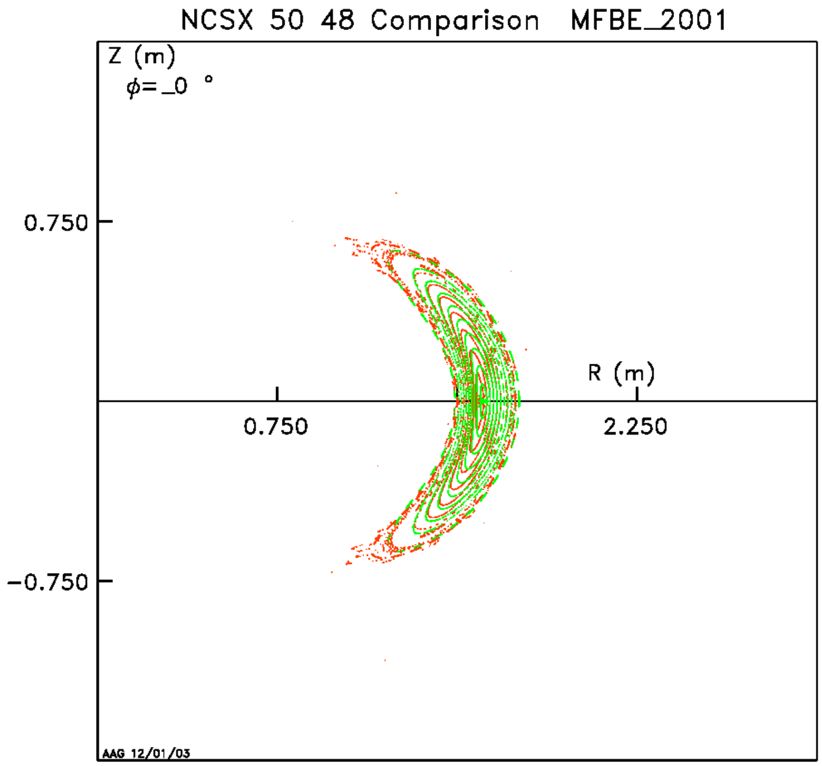
Initially an easily defined circular vacuum vessel within the rectangular grid is used, will be replaced by the NCSX vessel.

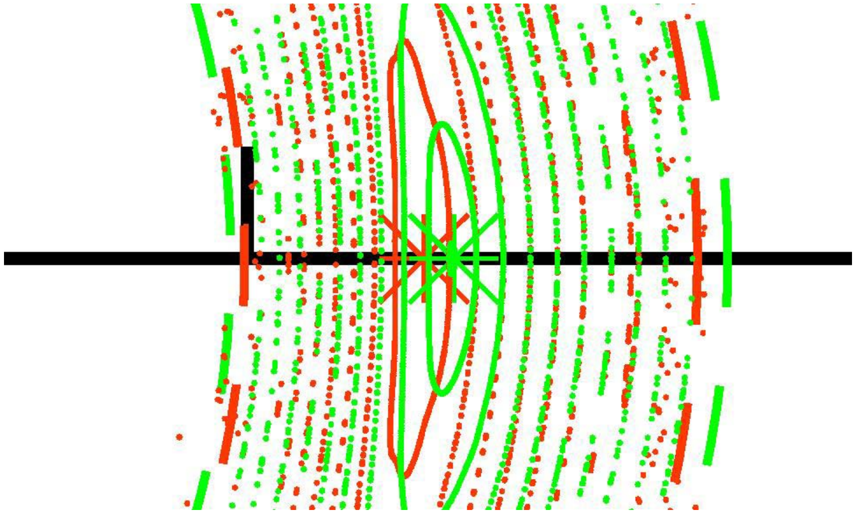
4% Beta-SOL Islands Not Seen c08r00_s3.b4.0min



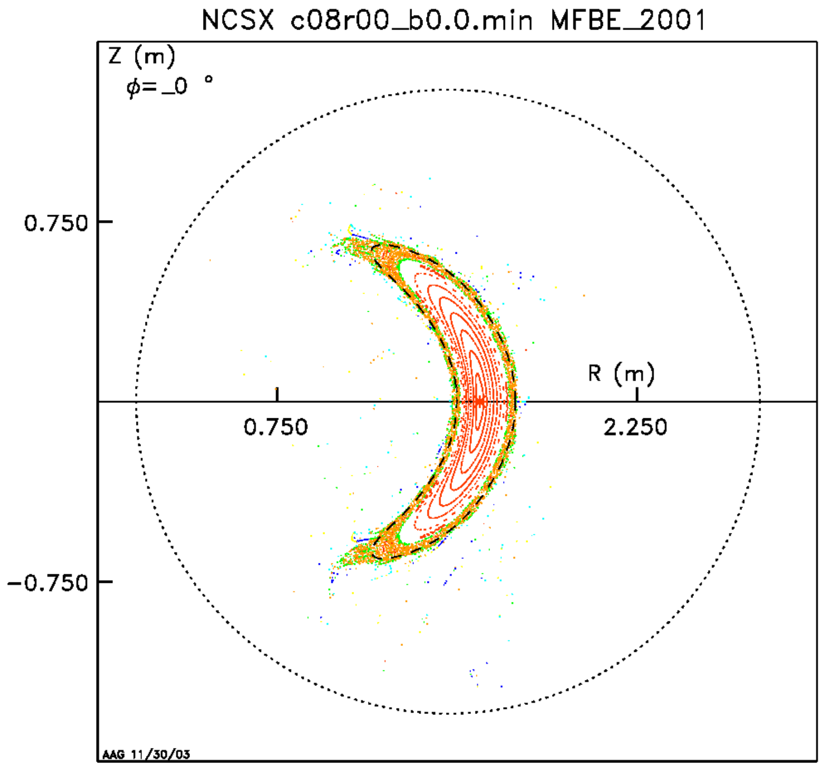


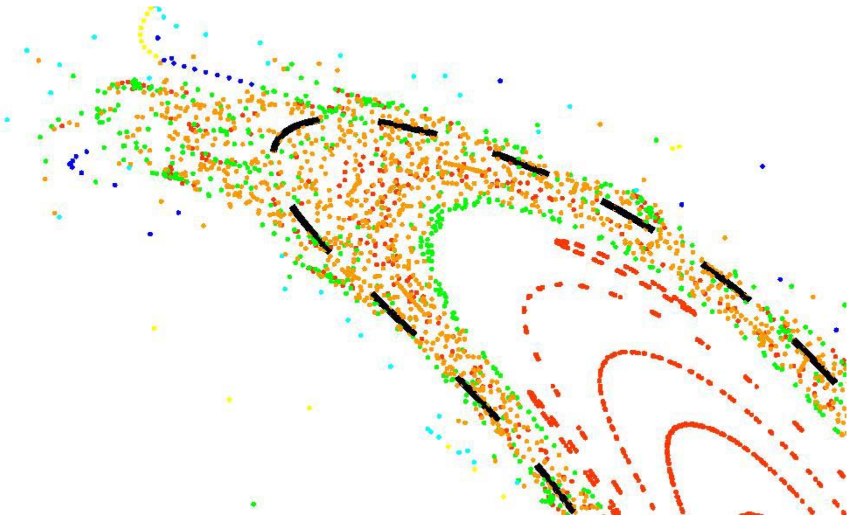
0% vs 4% Beta Core
0%- c08r00_b0.0.min - red
4%- c08r00_S3.b.min - green





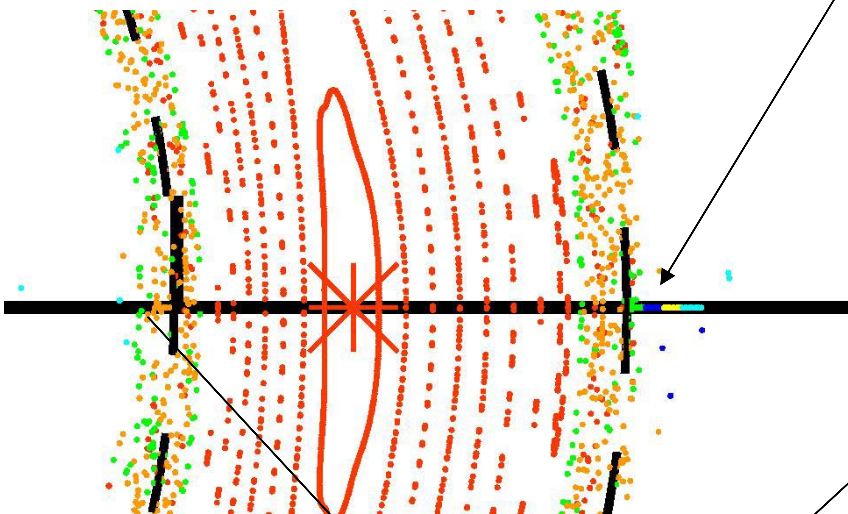
0% Beta –SOL Stochasticity c08r00_b0.0.min



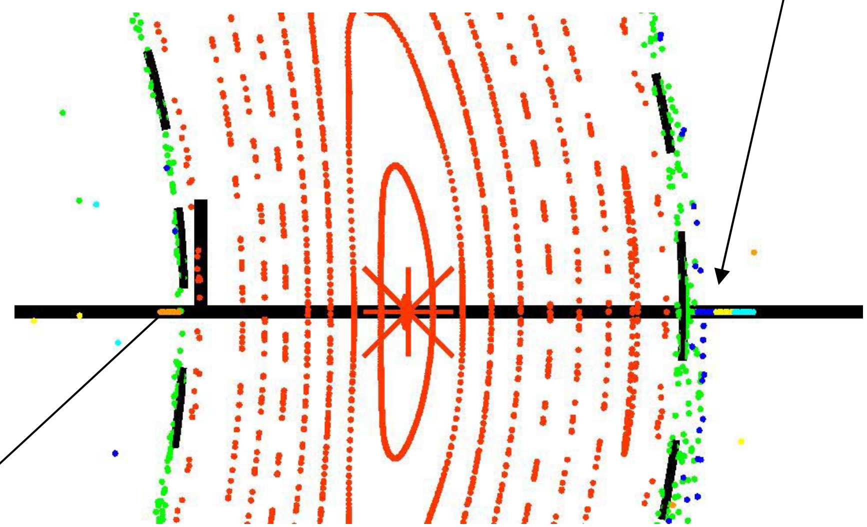


0% vs 4% Beta- SOL Starting Pts

Equidistant starting points 10 each to 1 cm with same color, all have z=0
In these two cases, the location and color coding of starting pts are the same



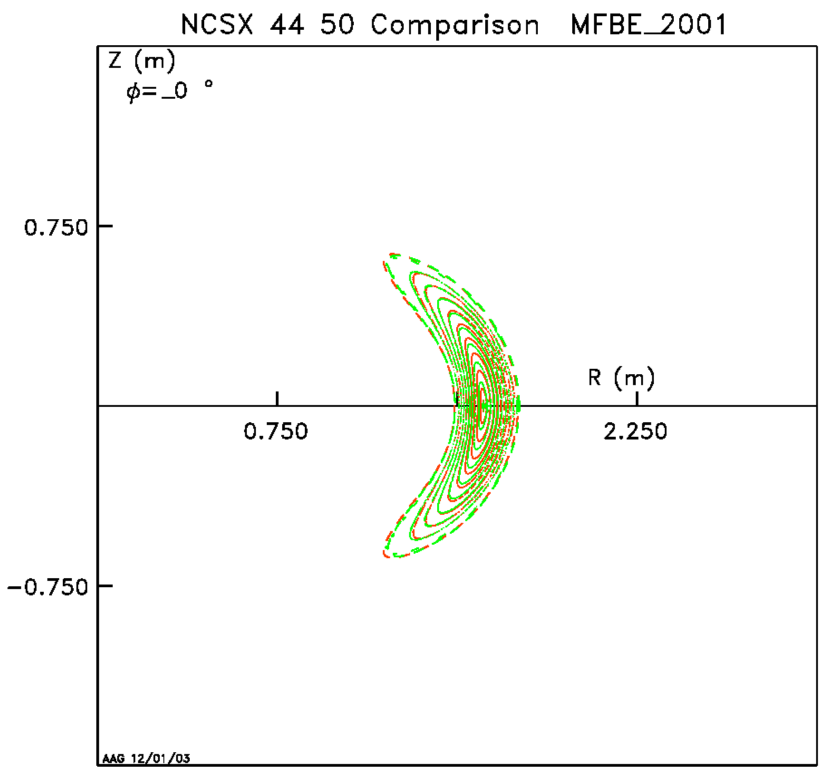
0%

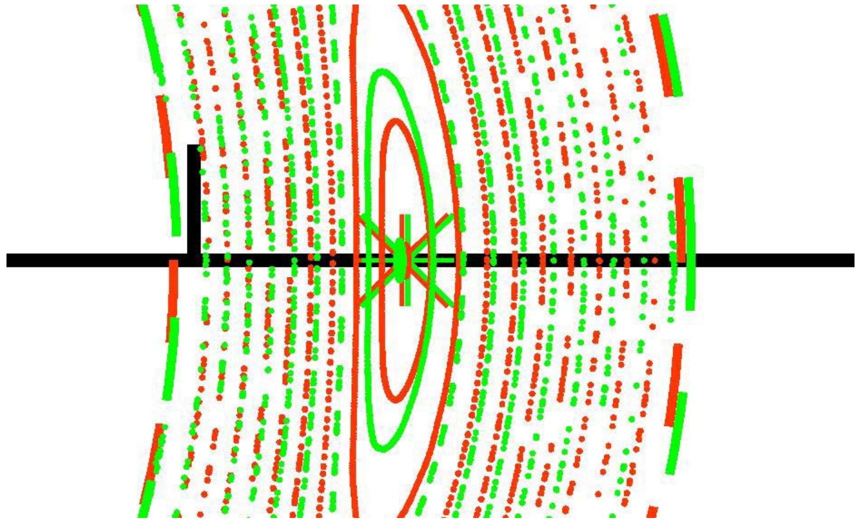


4%

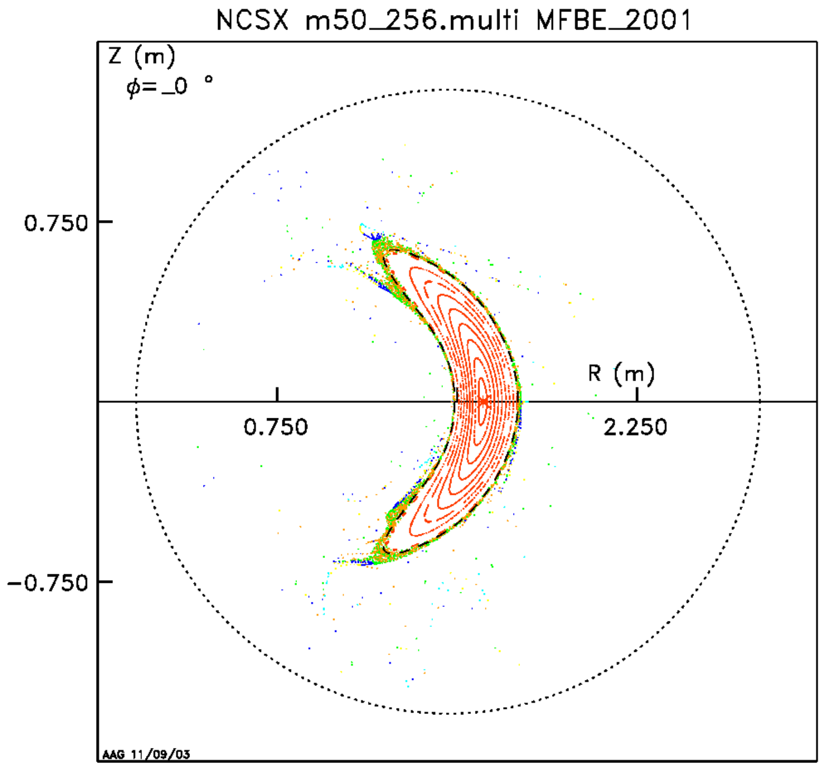
10 Inside starting points 1cm- gold

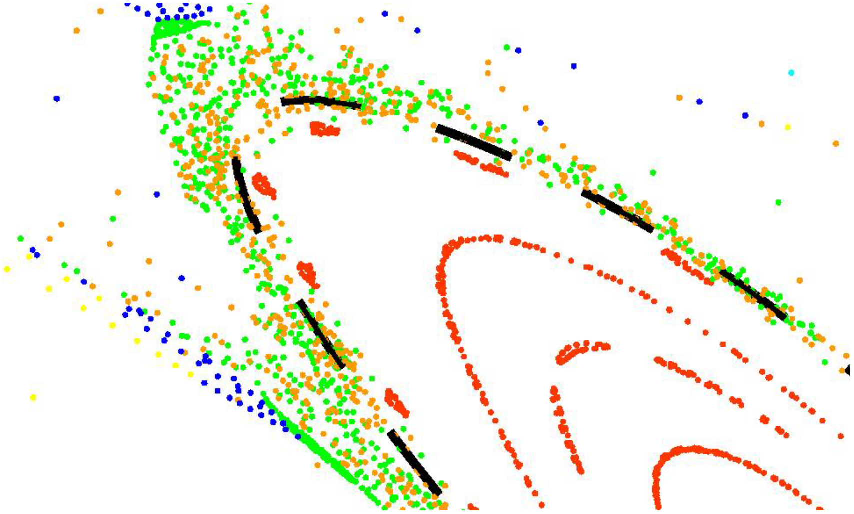
MultiFilament Base vs 4% Core
m50_256.multi - red
4%- c08r00_S3.b.min - green





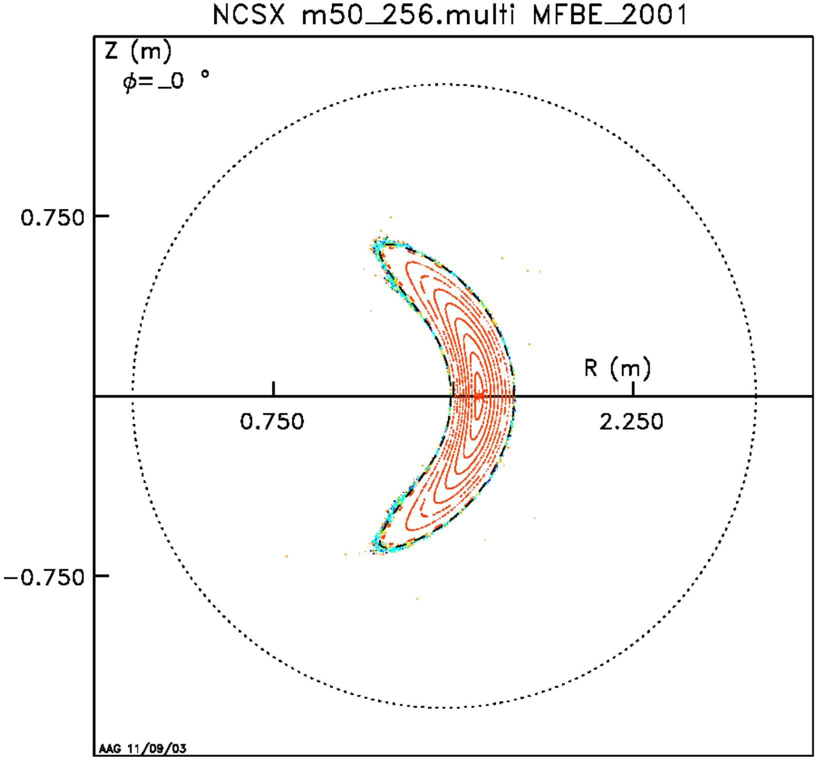
Multifilament Base –SOL Stochasticity with Island Remnants m50_256.multi

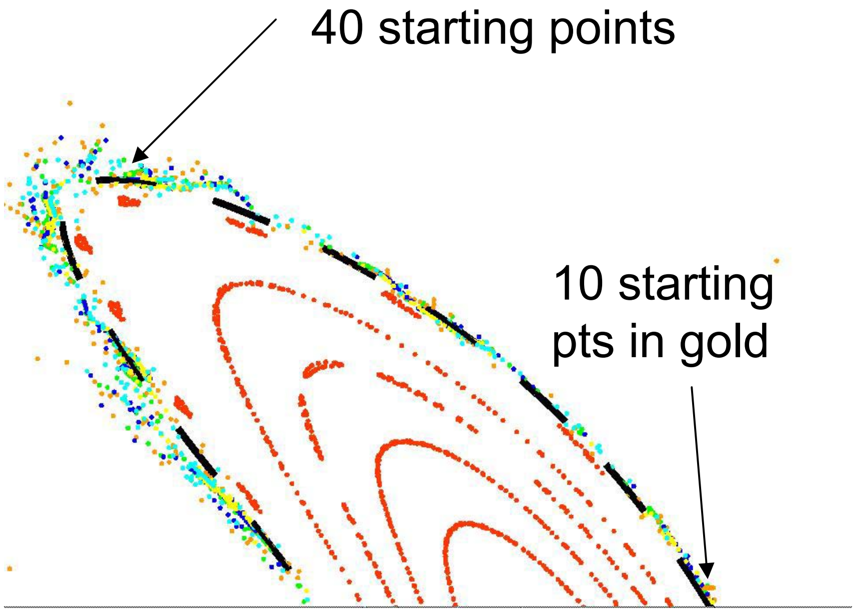




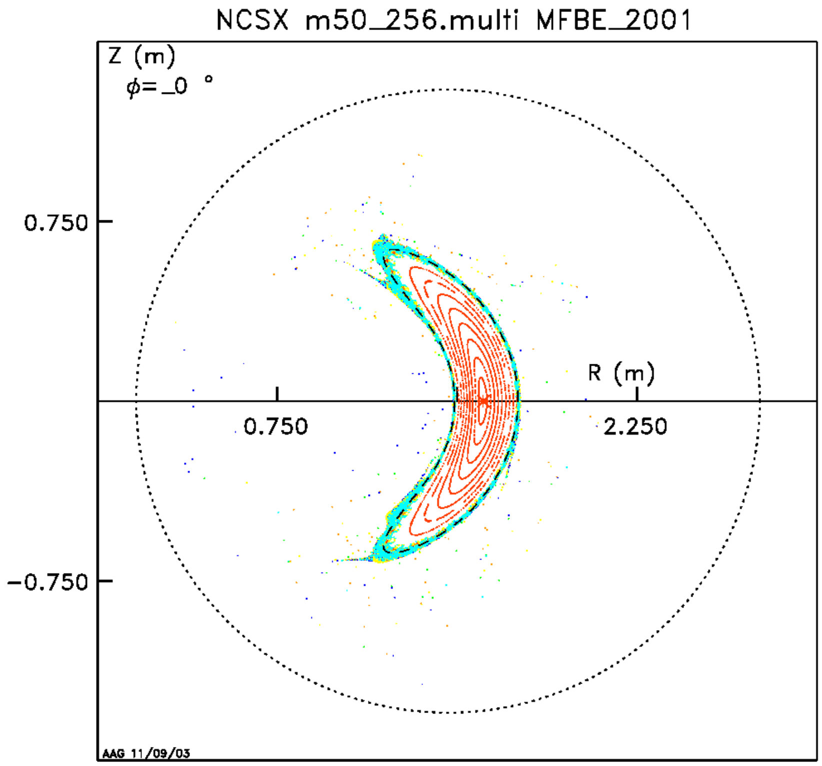
Starting points are on the midplane axis z=0

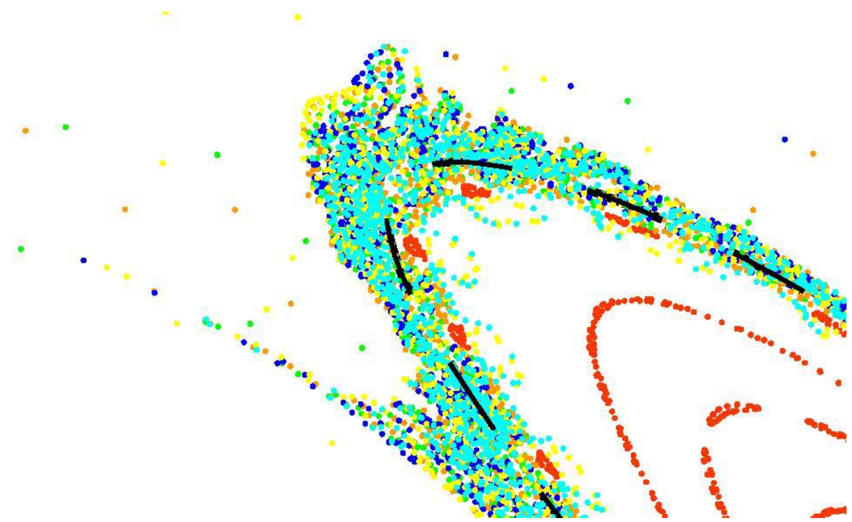
Off-Axis Starting Points- 20 turns





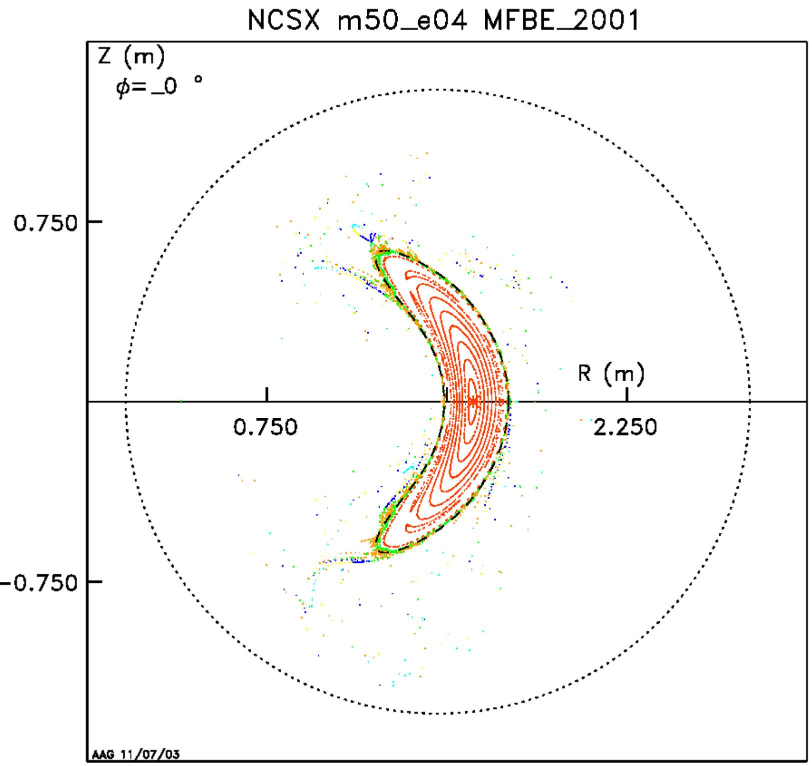
Off-Axis Starting Points- 200 Turns

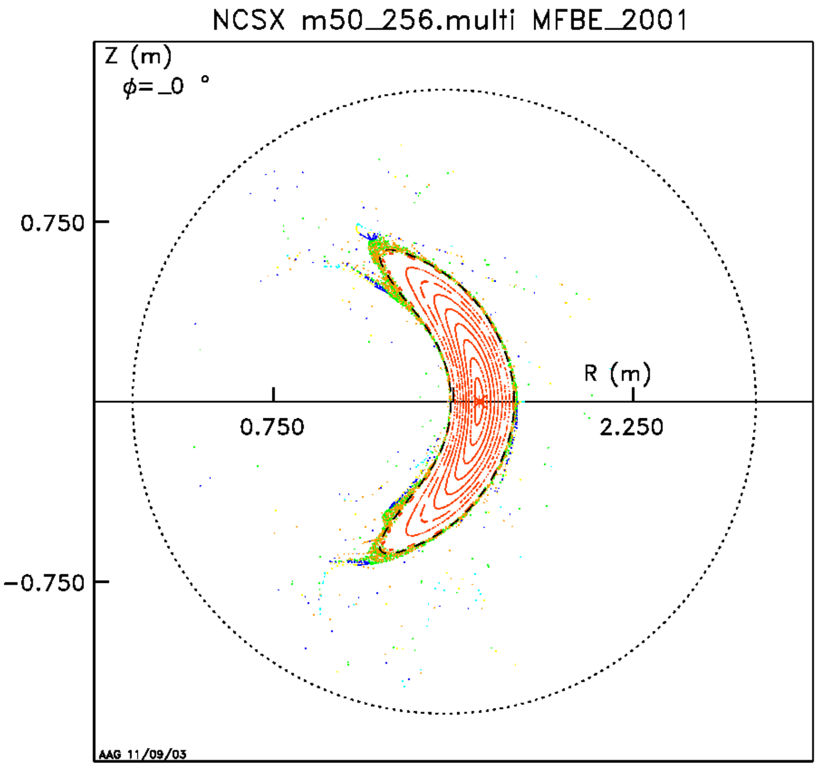




Result appears similar to on-axis starting pts shown 2 frames earlier.

Similar Results for m50_e04 and m50_256.multi



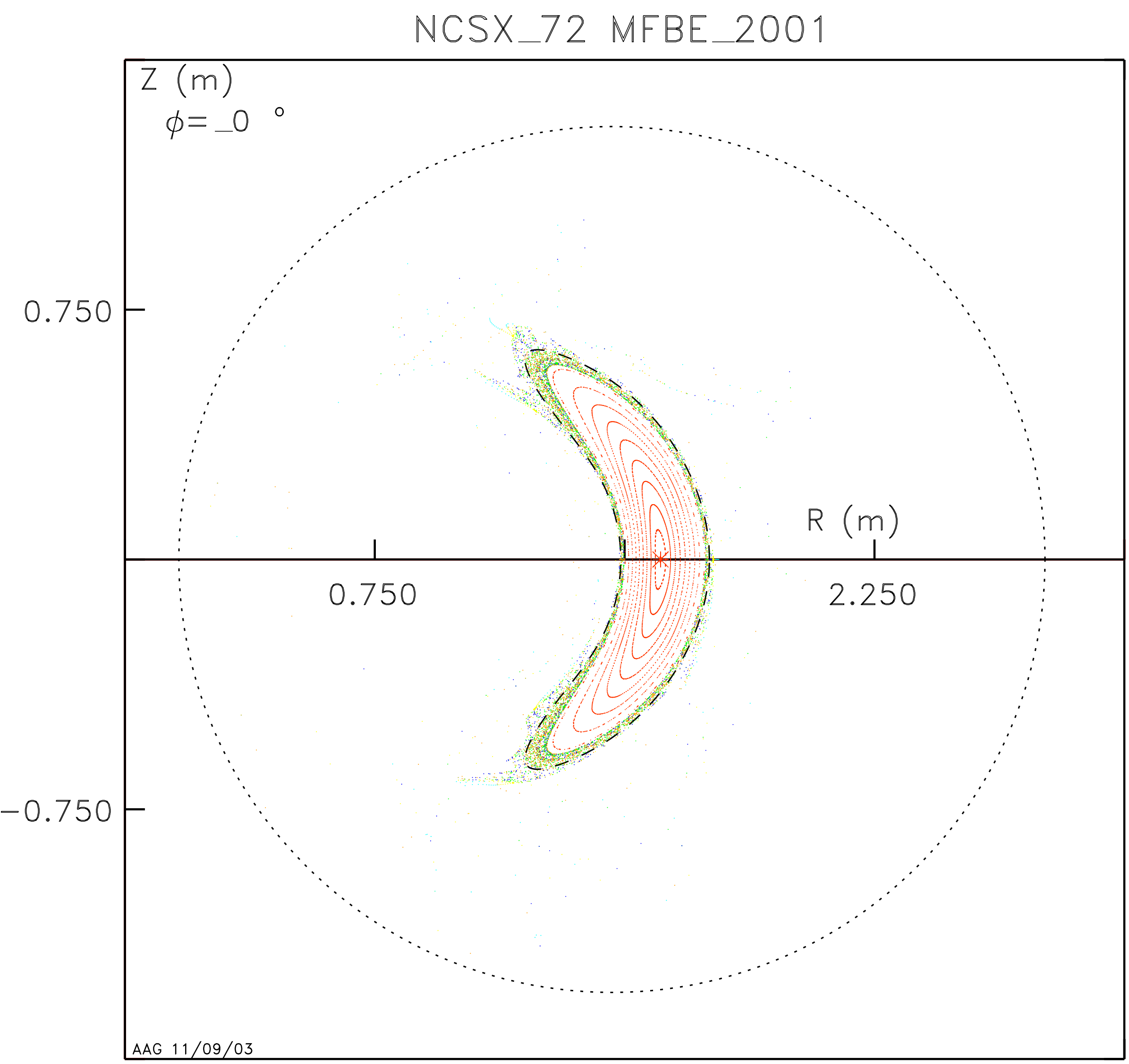


Toroidal Planes (# of processors) and accuracy of field line tracing

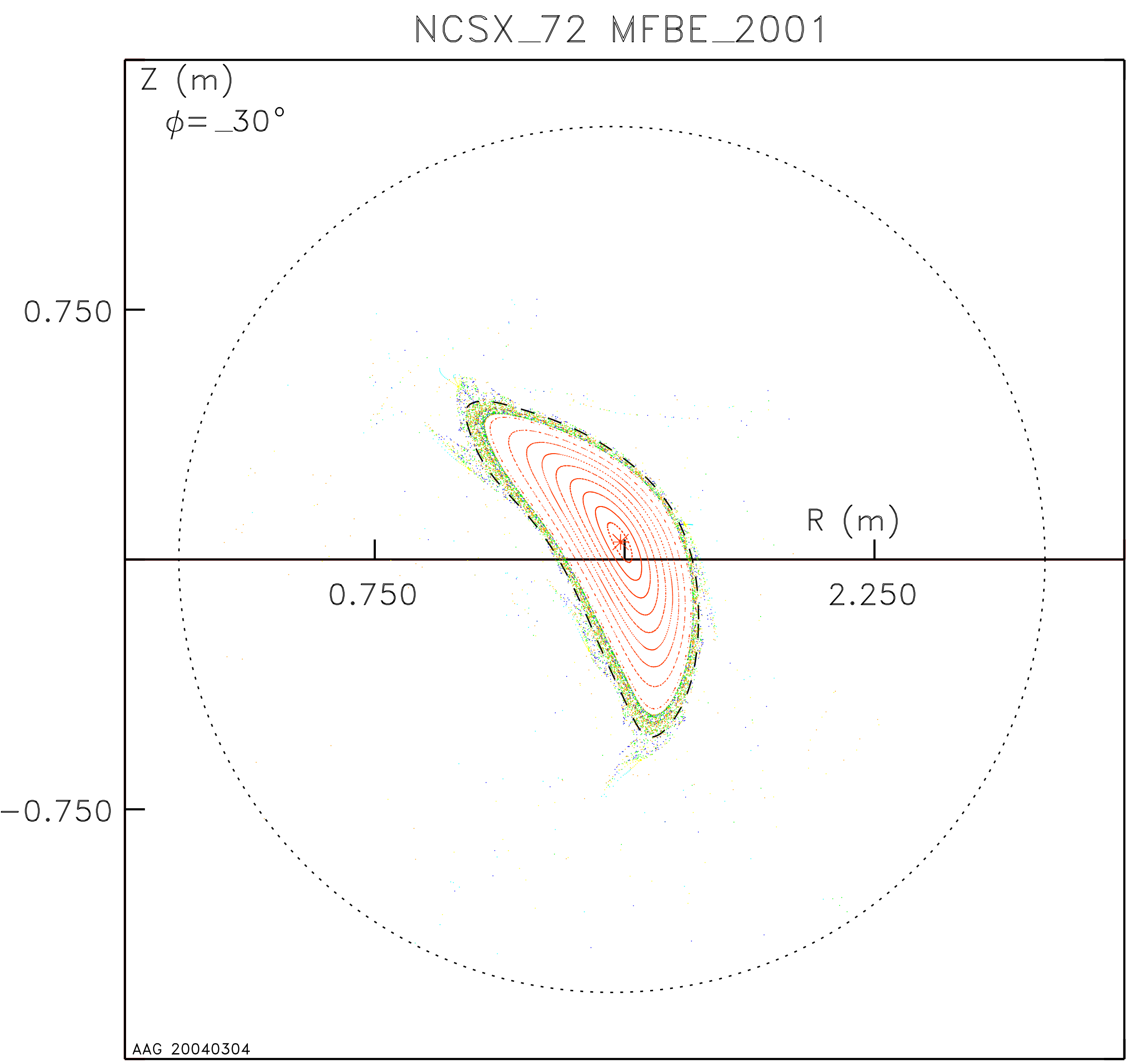
Device	R(m)	Toroidal Surfaces per half period (NZETA) (# of processors)	# of periods	Vacuum toroidal grid spacing (m)= 2piR/(2*nfp*ngrid)	comments
W7-X	5.5	100	5	0.03454	Less toroidal shaping than NCSX
NCSX	1.44	30	3	0.05024	More toroidal shaping than W7-X so this is marginal
NCSX	1.44	126	3	0.01136	Required modification to VMEC to reduce memory usage
Aries	8.27	30	3	0.28853	Using prior NCSX processor numbers
Aries	8.27	126	3	0.0686	Requires modified VMEC for reduced memory usage.
Aries	8.27	6656	3	0.0013	Best possible assuming all 6656 processors used.
NCSX	1.44	6656	3	0.000226	Best possible assuming all 6656 processors used.

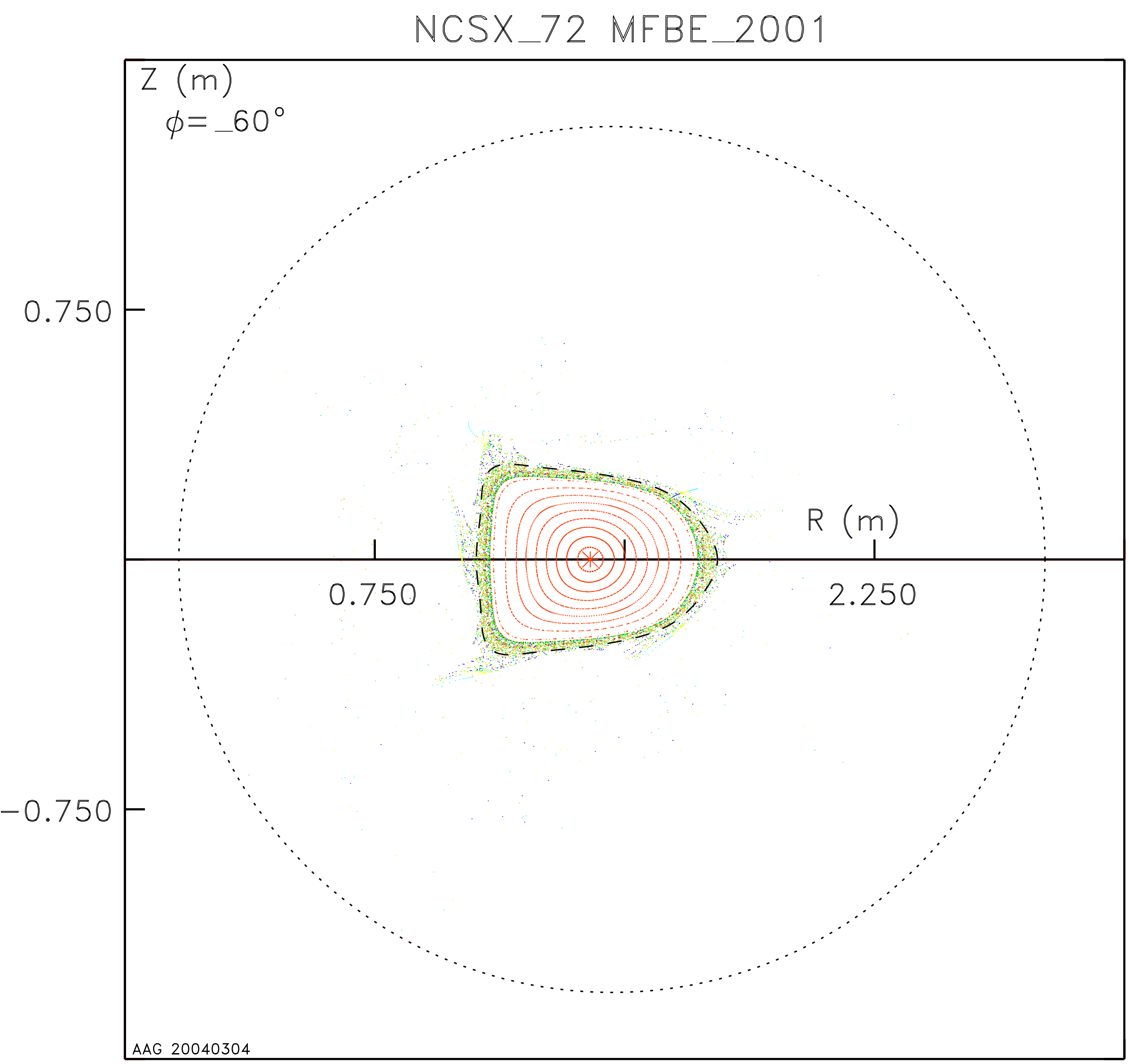
New MFBE_2001 runs with NZETA=126 VMEC2000 modified to run on IBM without exceeding its memory limits

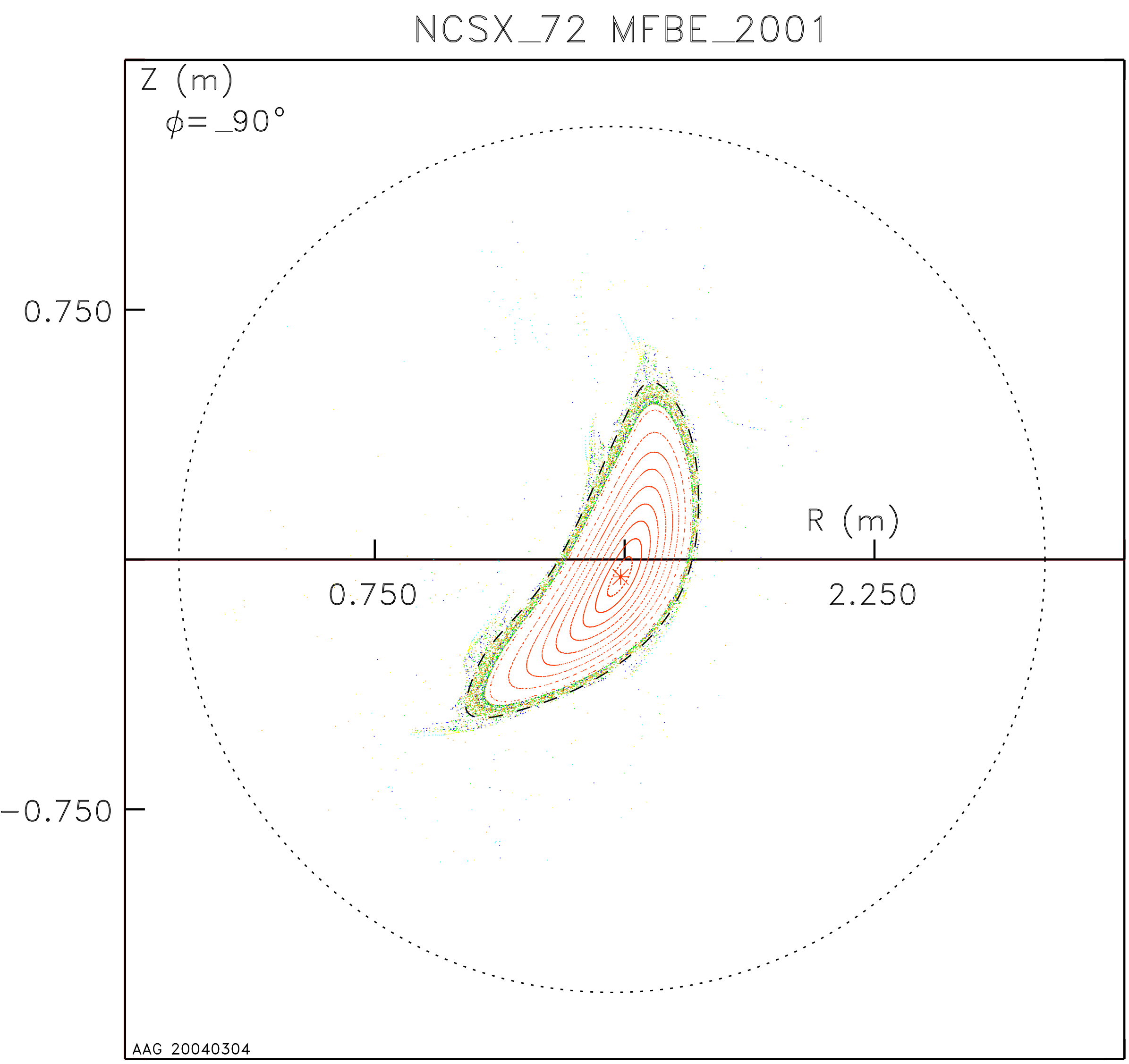
- NCSX:
  - m50_256.z01 (_72)
  - m50_e04 (_68)
  - c08r00_s3.b.min (_71)
  - c08r00_b2.0.min (_70)
  - c08r00_b0.0.min (_69)
- Aries-CS:
  - m50kzd_r8.25b6.5 (_73) and (_66-PHIEDGE sequence)



NCSX_72 MFBE_2001
Z (m)
φ=_0 °
0.750
−0.750
R (m)
0.750
2.250
AAG 11/09/03


NCSX_72 MFBE_2001
Z (m)
φ=_30°
0.750
−0.750
R (m)
0.750
2.250
AAG 20040304

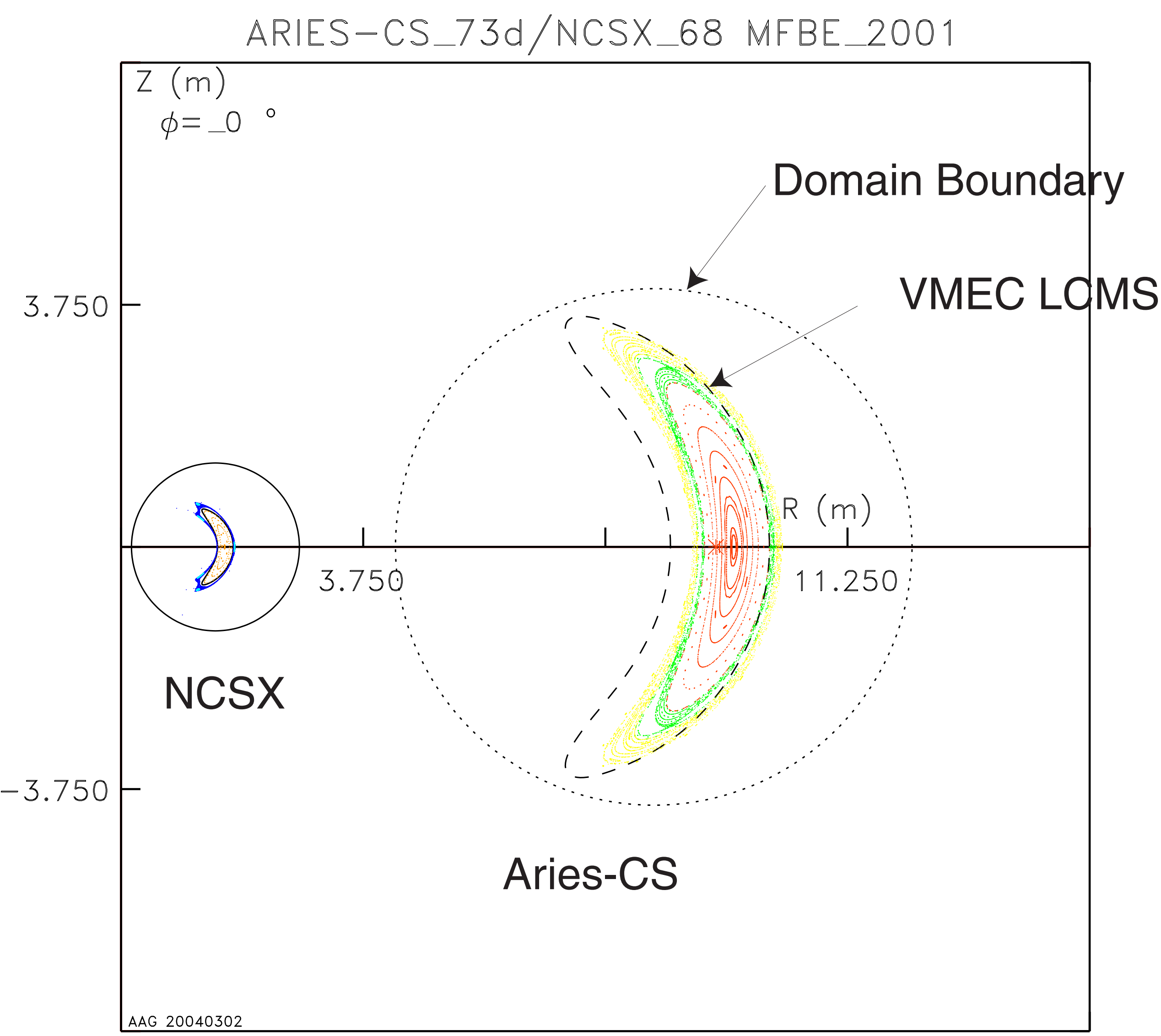

NCSX_72 MFBE_2001
Z (m)
ϕ=_60°
0.750
−0.750
R (m)
0.750
2.250
AAG 20040304


NCSX_72 MFBE_2001
Z (m)
ϕ=_90°
0.750
−0.750
R (m)
0.750
2.250
AAG 20040304

Initial line tracing for Aries Compact Stellarator

Starting Points Located on x-axis (1/cm Aries, 1/mm NCSX)

Line Tracing did not coincide with VMEC LCMS



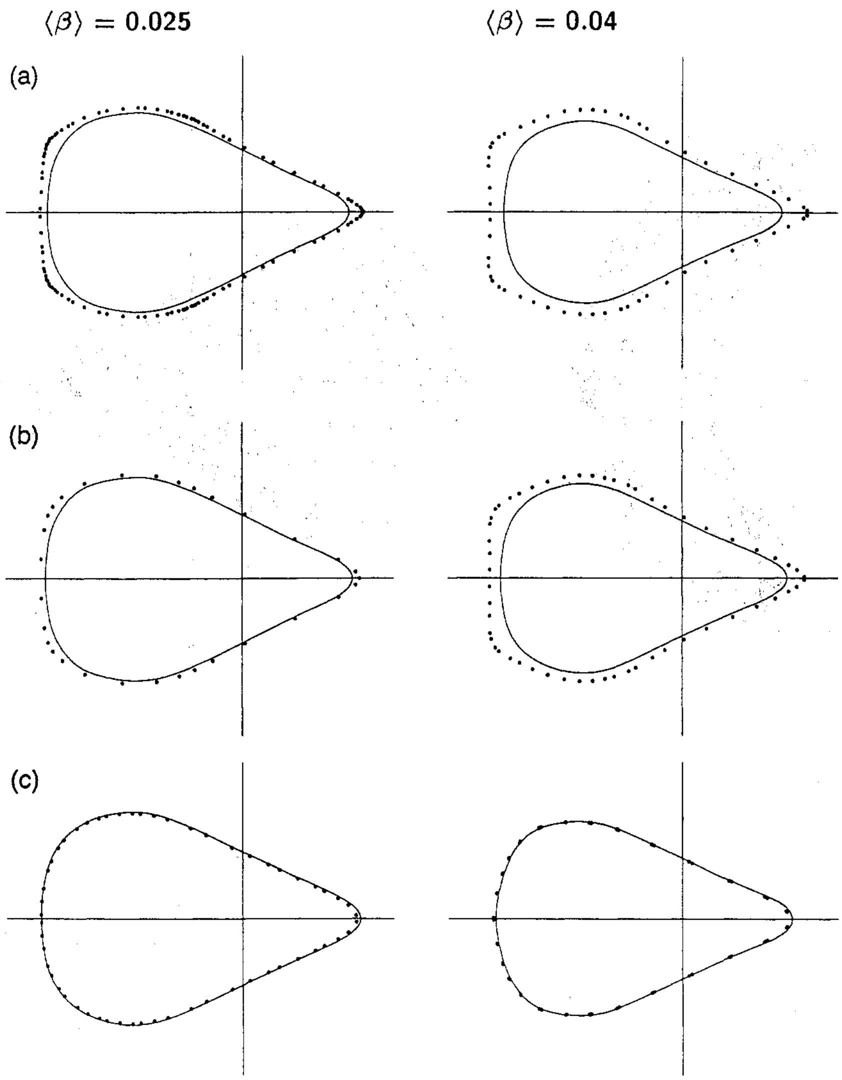
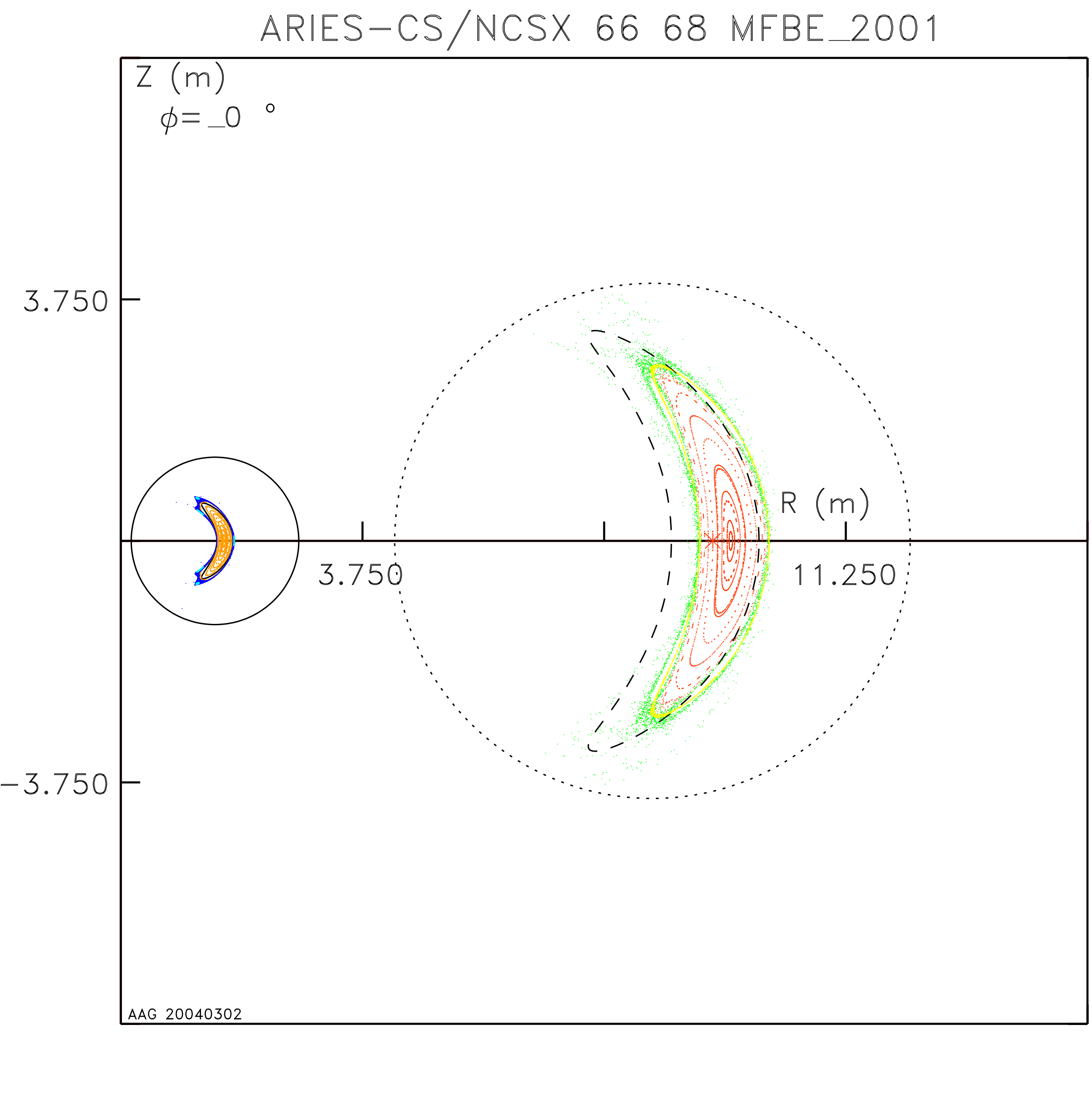


FIG. 6. Iterative determination of the toroidal flux for $\langle\beta\rangle = 0.025$ (left column) and $\langle\beta\rangle = 0.04$ (right column). The solid lines show the plasma boundaries, while the dots mark the corresponding LCMSs. The toroidal flux is increased from (a) to (c).

manner that the plasma boundary of the free boundary equilibrium agrees with the LCMS of the vacuum magnetic field. For finite-β equilibria, where such a comparison is not possible, the following method has been developed to determine the aspect ratio.

At first a sufficiently small toroidal flux is chosen that the plasma boundary of the finite-β equilibrium lies clearly inside the LCMS of the vacuum magnetic field. The corresponding magnetic field is computed inside and outside the plasma boundary with the MFBE code and its last closed magnetic surface is determined by field line tracing. In this case, the plasma boundary of the free boundary equilibrium is surrounded by further magnetic surfaces and thus lies completely inside this LCMS. Then the toroidal flux is increased until the plasma boundary of the free boundary equilibrium agrees with the LCMS of its magnetic field. Figure 6 shows this iterative determination of the toroidal flux for $\langle\beta\rangle = 0.025$ and $\langle\beta\rangle = 0.04$. In Fig. 6(a) the plasma boundaries (solid lines) and their corresponding last closed magnetic surfaces of the magnetic fields (dots) are plotted for too small toroidal fluxes. Then the toroidal flux is increased step by step (see Fig. 6(b)) until the LCMSs agree approximately with the plasma boundaries, the case shown in Fig. 6(c).


ARIES-CS/NCSX 66 68 MFBE_2001
Z (m)
ϕ=_0 °
3.750
R (m)
3.750
11.250
−3.750
AAG 20040302

Conclusions

- First efforts to determine if compact stellarators allow divertors have now been made.
- The fully 3D magnetic field structure outside the LCMS of QAS has been mapped and appears to support field line diversion.
- Advances in parallel computing are facilitating the study of 3D field structure via Poincare plot method.