Edge Magnetic Field Structure Study

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We Need the Stellarator Magnetic Field Topology Outside the LCMS

- Why?
  - Stellarators lack the ordered magnetic field line structure found in the SOL of axisymmetric devices.
  - Individual features of this boundary layer need to be considered for vacuum vessel and pfc design.
  - Want small angles of incidence and large wetted areas to distribute power loads uniformly.
  - Also want configurational flexibility, so these loads don't redistribute with changes in rotational transform, shear, beta, etc.

MFBE = Magnetic Field Solver for Finite Beta Equilibria

- Developed by E.Strumberger, (Nucl. Fus. 1997.)
- Calculates magnetic fields of finite-beta equilibria on a grid whose nodes may be arbitrarily close to the plasma boundary.
  - High Accuracy (special empirical techniques)
  - Computationally intensive
    - T3E 128 processor takes 1 hour for W7-X
    - NEMEC free boundary grids have 200 toroidal grid points per period (also 101 R and 101 Z points) takes about 20 hours on Cray J90.

Adapt MFBE For NCSX

- W7-X (No toroidal current)
  - MFBE trace of field lines based on NEMEC finite beta free boundary equilibria.
- NCSX (Bootstrap current)
  - MFBE trace of field lines using VMEC free boundary equilibria instead of NEMEC and includes magnetic fields from toroidal currents.

Modification of MFBE

- Replace:
  - NEMEC = VMEC(old version) + NESTOR by
  - VMEC (Free Boundary v6.2 used for NCSX)
- VMEC Data Transferred:
  - Fourier Coefficients of Flux Surfaces
  - Fourier Coefficients of Magnetic Field on Flux Surfaces
  - Complete vacuum magnetic fields (mgrid)

Determination of the Magnetic Field Outside of Plasma in W7X

- Nonequidistant integration mesh was required to obtain good accuracy- interval of integration has to be smaller than the distance of the grid point from the plasma boundary.

$$
\begin{aligned}
\vec{B}_{\mathrm{v}} &= \vec{B}_0 + \nabla\Phi \\
&= \vec{B}_0(\vec{r}) \\
&+ \frac{1}{4\pi}\int_{\partial R} \nabla G(\vec{r},\vec{r}')(\vec{B}_0' \cdot d\vec{f}') \\
&- \frac{1}{4\pi}\int_{\partial R} \Phi(\vec{r}')\nabla(\nabla' G(\vec{r},\vec{r}') \cdot d\vec{f}')
\end{aligned}
$$

with

$G(\vec{r},\vec{r}') = \frac{1}{|\vec{r}-\vec{r}'|}$ Green's function

$$
\Phi(\vec{r}') = \sum_{\mathrm{m}=0,\mathrm{n}=0}^{\mathrm{m_b},\mathrm{n_b}} \hat{\Phi}_{\mathrm{m,n}} \sin 2\pi(\mathrm{m}u + \mathrm{n}v)
$$

Two Methods To Add Toroidal Current to MFBE [M.Drevlak, E.Strumberger]

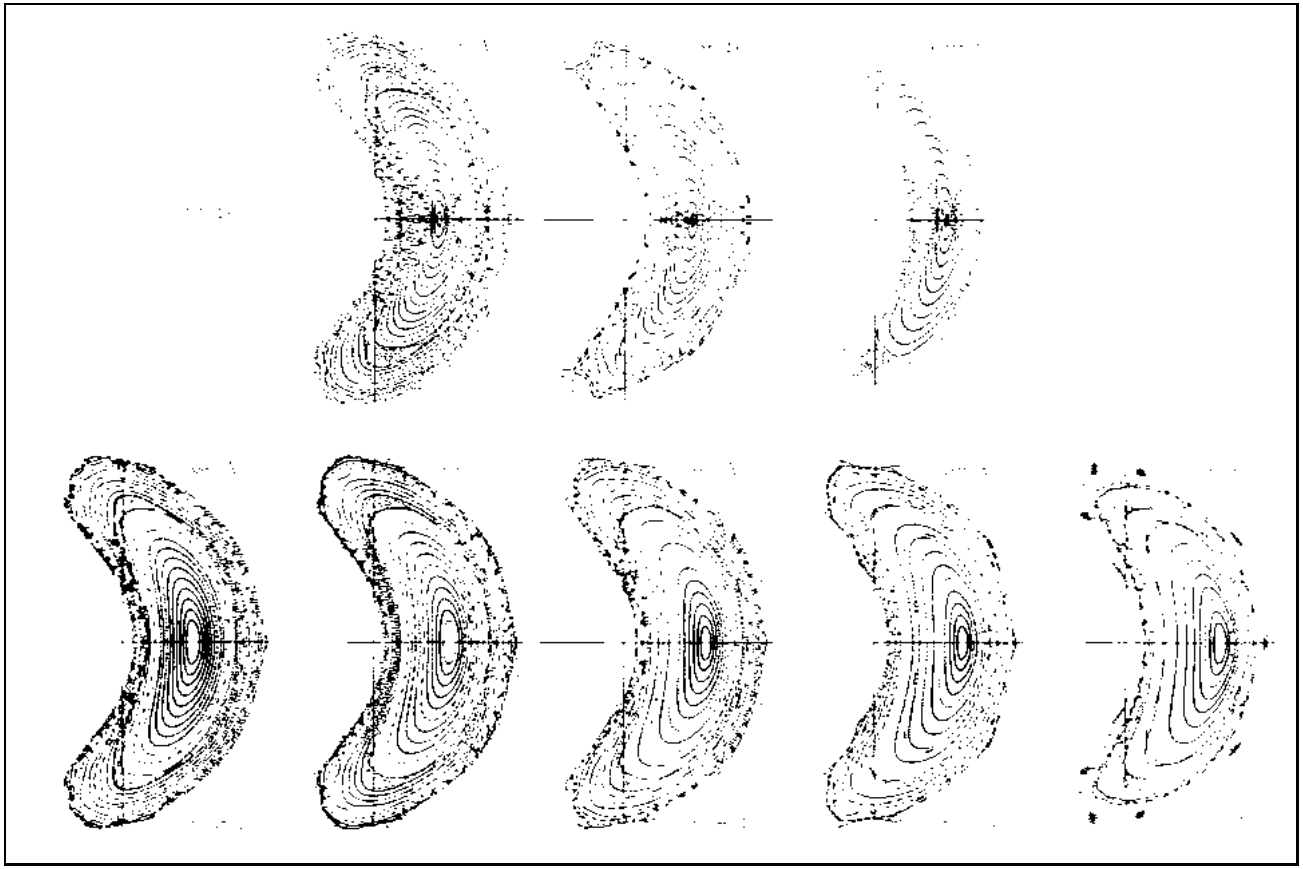
- Method 1: $B = B_0 + \text{grad}\ \Phi$ + additional term which includes toroidal current.
- Method 2: $B = B_0 - B_{JS}$ Virtual Casing Method.
- Both methods give good agreement for accurately computed W7-X equilibria.

Use Method 2: Virtual Casing Principle

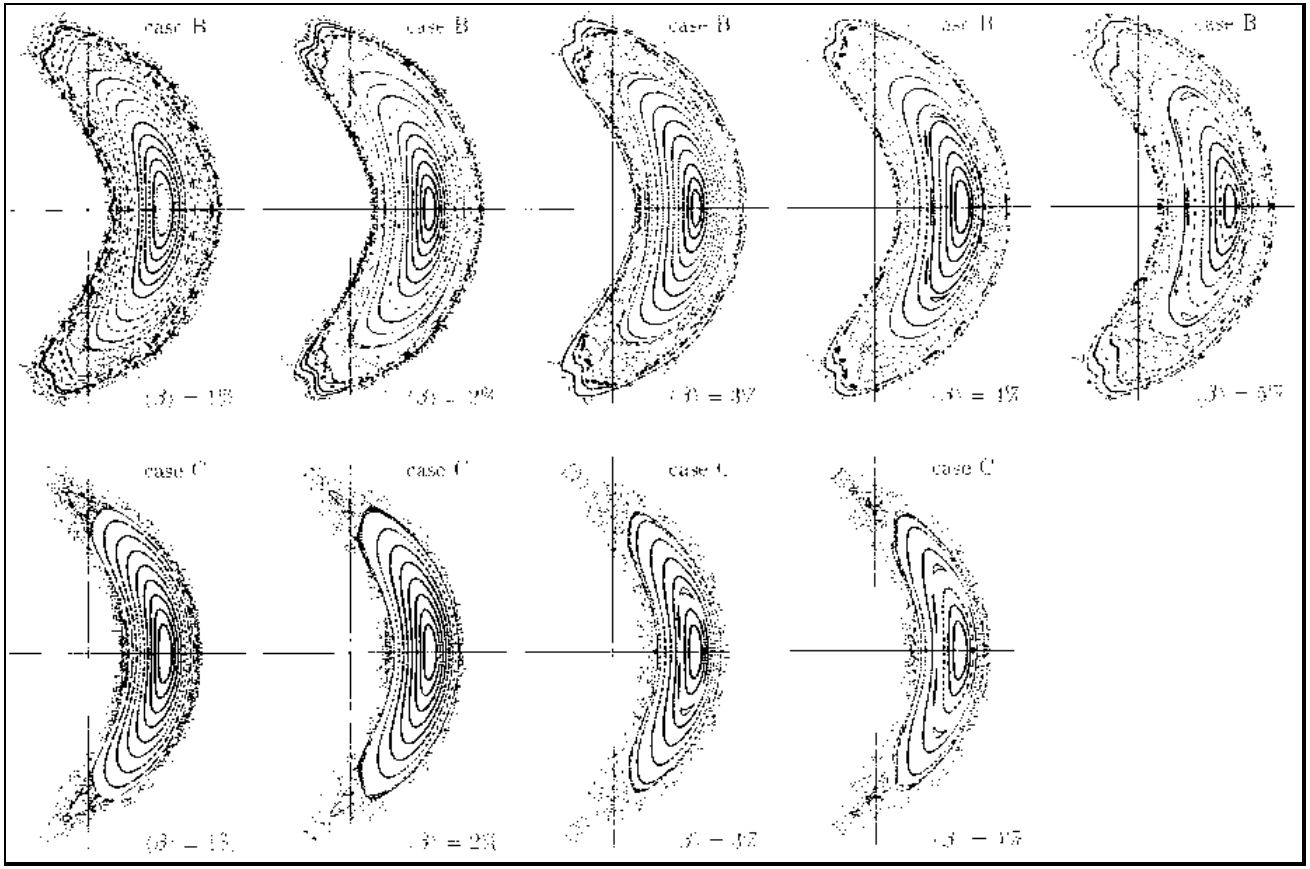
- Surface current on the plasma boundary $j_S = 1/\mu_0$ Bs x n with Bs magnetic field on the boundary(from VMEC) and n normal vector.
- $B = B_0 - B_{js}$
  - B_0 is the vacuum field.
  - Bjs computed from the surface current and is produced by all plasma currents including the toroidal current. $B_{JS} = \mu_0/(4\pi) \int$ (df' (js x (R-R'))/|R-R'|**3) (Biot Savart). R' vector on the plasma boundary and R vector of the point where you want to know the magnetic field. If R is very close to R' then R-R' becomes very small and you need a very small surface element df'.

MFBE Survey of W7X

A)Low iota B)Standard C) High iota

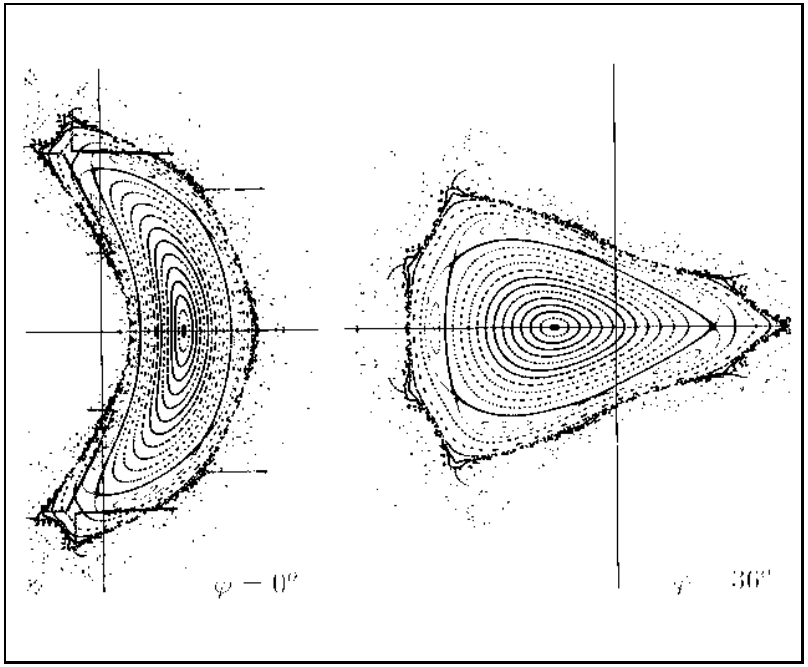


MFBE Survey of W7X



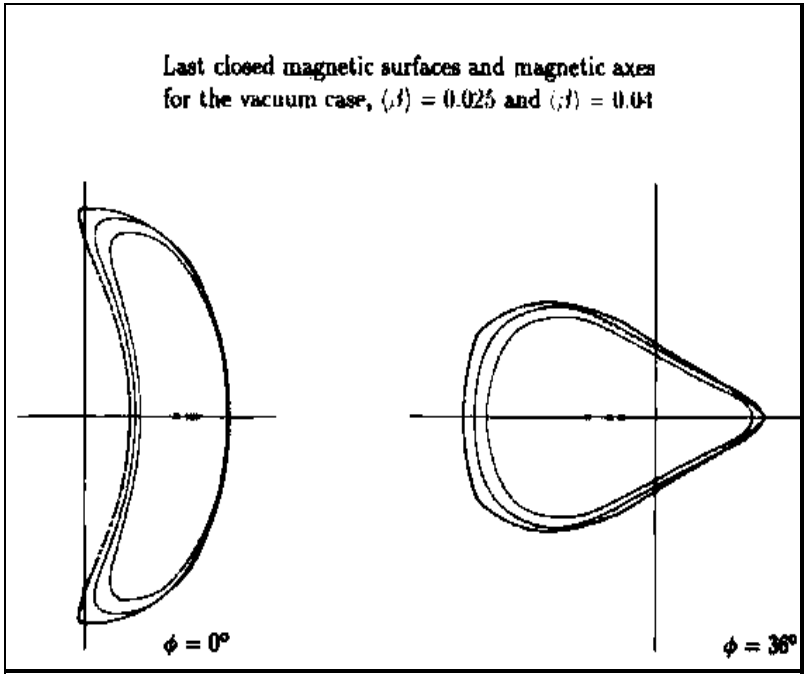
MFBE Installed at NERSC Accurately Recalculates These W7X Line Tracing Results

- NEMEC Free boundary run of W7X used as input to MFBE installed on NERSC T3E (1 hour, 128 pe).
- Gourdon line tracing routine and IDL plot reproduced previously published W7X field line plot.



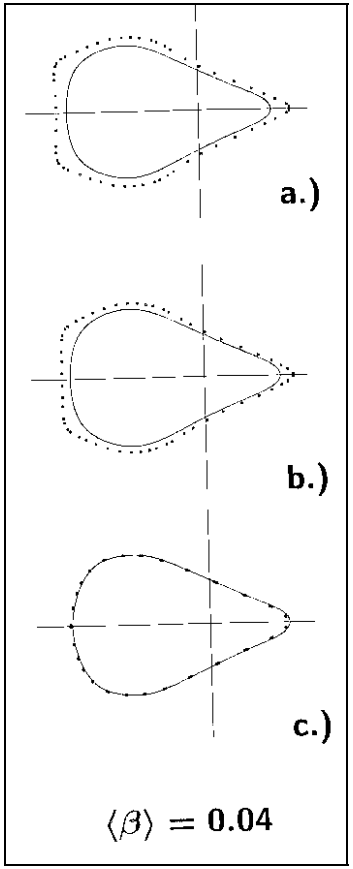
Finite Beta vs Vacuum: W7-X

- LCMS of finite beta inside LCMS of vacuum
- Small shift out with beta
- Reduction of plasma volume with beta.
- Width of islands increase with beta , but keep positions fixed.
- Increasing ergodization of edge with beta.



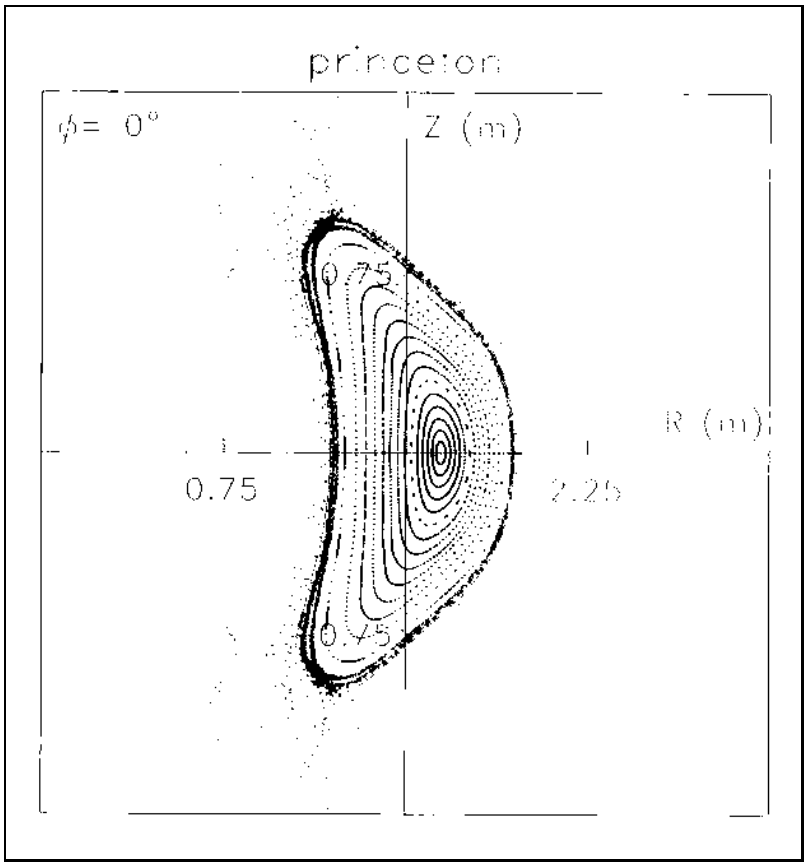
Multiple VMEC Free Boundary Calculations Required for Field Line-Surface Matching

- Toroidal flux is a free parameter of the free boundary equilibrium.
- Repeat free boundary magnetic field tracing calculations with increasing toroidal flux until lcms from line tracing and equilibrium coincide.

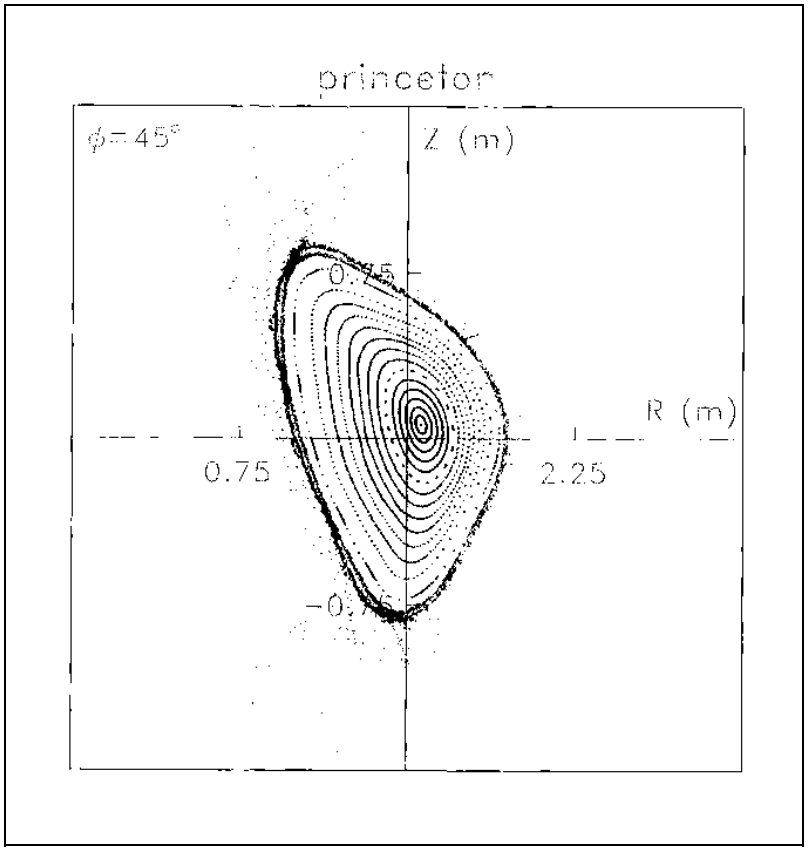


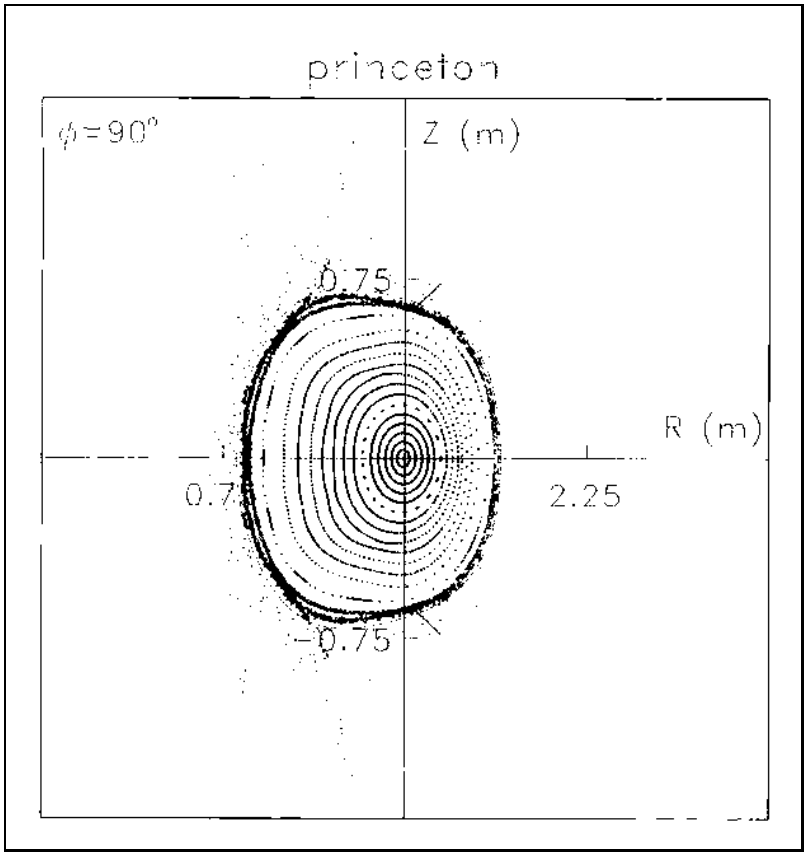
Early NCSX MFBE + NEMEC

- M. Drevlak C2 calculation using method 2.
- Shows presence of tiny islands.
- Islands are inside the LCMS (red curve)



Early NCSX Calculations





Accomplishments

- MFBE code installed on NERSC T3E computer.
- Recalculated W7X line tracing benchmark using MFBE at NERSC.
- MFBE+VMEC replaces MFBE+NEMEC.
- Debug modified MFBE+VMEC.
- Testing MFBE+VMEC with NCSX C82 (4064rev6) free boundary equilibria with 16 toroidal cross-sections (use 16 processor queue).