Implications of Field Line Tracing for Power and Particle Handling in NCSX

A. Grossman[3] P.Mioduszewski[2], and the NCSX Boundary Group- M. Fenstermacher[3], A. Koniges[3], L. Owen[2], T. Rognlien[3], M. Umansky[3]

[1]University of California at San Diego

[2] Oak Ridge National Laboratory

[3] Livermore National Laboratory

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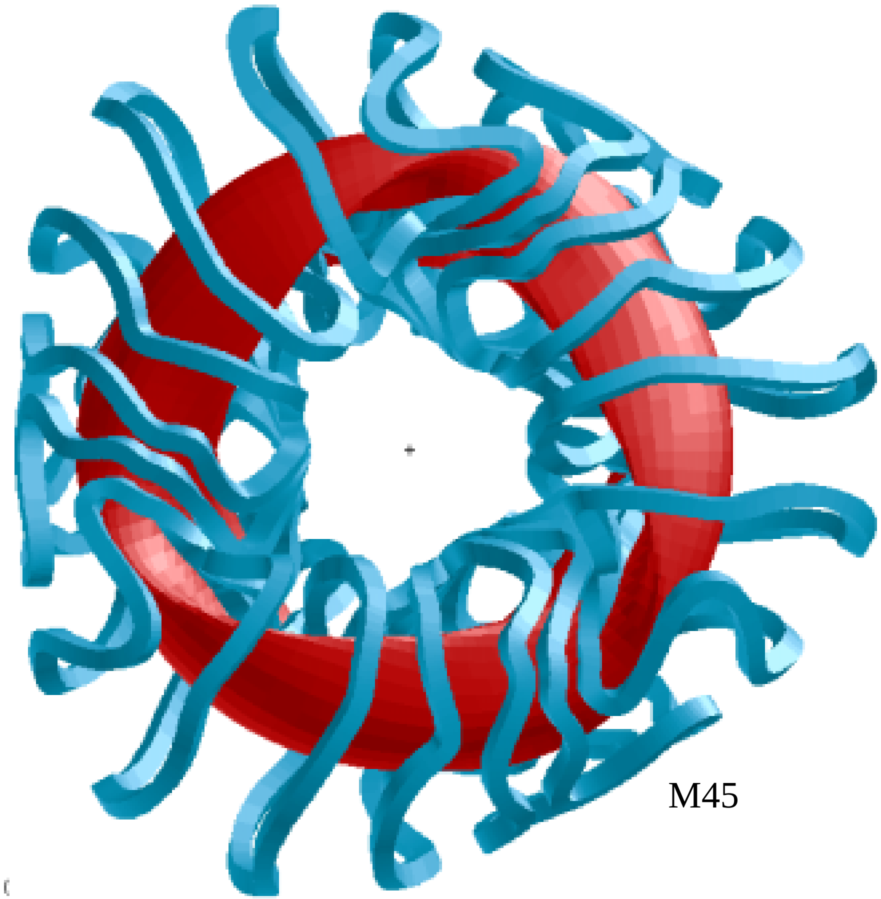
NCSX Plasma Configuration

- 3 periods, R/⟨a⟩=4.4, ⟨κ⟩~1.8
- Quasi-axisymmetric: low helical ripple transport, low flow damping
- Passively stable at β=4.1% to kink, ballooning, vertical, Mercier, neoclassical-tearing modes; without conducting walls or feedback systems.
- Steady state without current-drive
- 18 modular-coils (3 shapes)
  Full coil set includes PF coils & weak TF coil for flexibility
- Bootstrap current provides 20%-40% of rotational transform



The key to good plasma performance in NCSX is most likely boundary control with divertor-like configurations.

- **Experience in W7-AS indicates that substantial plasma performance improvement can be expected through systematic control of plasma-wall interactions with a divertor:**
  - **τ_E increases steeply with density,**
  - **τ_p and τ_{imp} decrease with increasing density**
  - **Record value of <ß> ~ 3.4% achieved (at B = 1.25 T)**
  - **Full density control**
  - **Plasma heating at extremely high density with EBW**
- **Although the NCSX configuration is somewhat different, the W7-AS results provide a compass for the direction of our boundary program.**

In both stellarators and tokamaks, plasma performance is improved by controlling the plasma boundary

- **Heat removal control**: avoid excess temperatures and hot spots, configuration of plasma-facing components (PFCs)
- **Impurity control**: specific PFC design and location, control of plasma edge parameters (Te, screening, etc.)
- **Recycling control**: positioning of the recycling sources away from critical locations, baffled and/or pumped divertors.

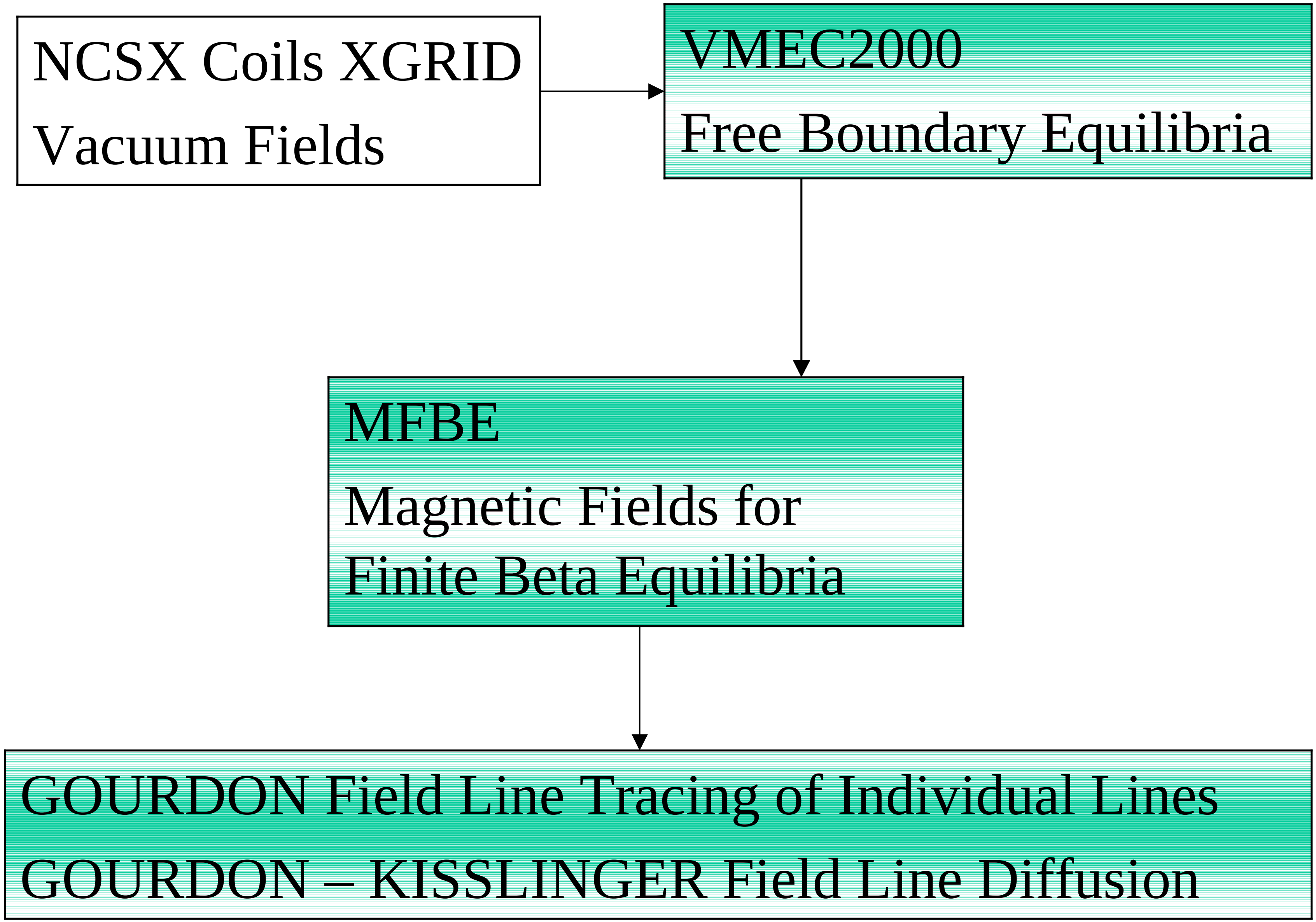
Field Line Mapping in the Boundary is the First and Most Basic Task for Stellarator Boundary Control

- 3D Topology of Stellarators:
  - May Lack Tokamak Ordered Field Sturcture Outside Separatrix
  - PFCs matched to stellarator plasma surfaces must also be 3D
- PFCs intersecting a) closed lines are limiters b) open lines are divertors:
  - Fixed set of PFCs can change between limiter and divertor with a change in magnetic topology.

- Limiters:
  - Advantage: Simplifies boundary structure by cutting off islands and ergodic regions.
  - Disadvantage: Direct contact with confined plasma thus a strong source of recycled neutrals.

- Divertors:
  - Advantage: Interface distance between plasma and solid surface
  - Disadvantage: Complex boundary structure including islands and ergodic regions can have locally short connection lengths.

Overview of Code System for Field Line Mapping In Boundary



Special Requirements for Field Line Mapping of the Boundary of NCSX

- <u>High Accuracy at the Boundary:</u>
  - SOL 1-2 cm from LCMS most important for power and particle studies
    - MFBE uses nonequidistant integration and high resolution mesh near LCMS
  - Consistency of Free Boundary solution with external coils
    - Fully converged VMEC free boundary
    - Consistency of PIES and VMEC at the boundary
    - Use PIES to set the toroidal flux parameter PHIEDGE or do iterative determination of PHIEDGE via VMEC/MFBE loop.

- <u>Finite Beta contributions to Magnetics:</u>
  - Bootstrap current must be included
    - MFBE uses Virtual Casing Principle to include plasma current
  - Shape and topology changes at high beta
    - Vacuum fields alone are not sufficient for mapping the edge.

MFBE Applications

- Iterative procedure for determining LCMS.
  - VMEC assumes nested closed surfaces.
  - MFBE used to determine location of LCMS- total toroidal flux in VMEC adjusted until agreement with MFBE on location of LCMS. (Alternative to PIES full iterative MHD determination of true LCMS).
- Magnetic topology outside LCMS- size and location of islands and extent of ergodization.
- Divertor studies- determination of deposition patterns on PFC and estimates of power loads.

MFBE Numerics

- Field line trace requires the magnetic field be calculated many times.
  - Calculation is fully parallelized. Number of Processors required scales with number of toroidal cross-sections.
  - Number of magnetic field calculations greatly reduced by calculating it on a grid and then interpolating.
  - Grid is a cylindrical box covering relevant region and sufficiently fine that results are independent of discreteness.
- MFBE uses (s=radial coordinate between two flux surfaces, u=poloidal coordinate,v=toroidal coordinate) curvilinear coordinates related to cylindrical system by:

$$R = \sum_{m=0,n=-n_b}^{m_b,n_b} [(1-s)\hat{r}^{j}_{m,n} + s\hat{r}^{i+1}_{m,n}]\cos 2\pi(mu+nv)$$

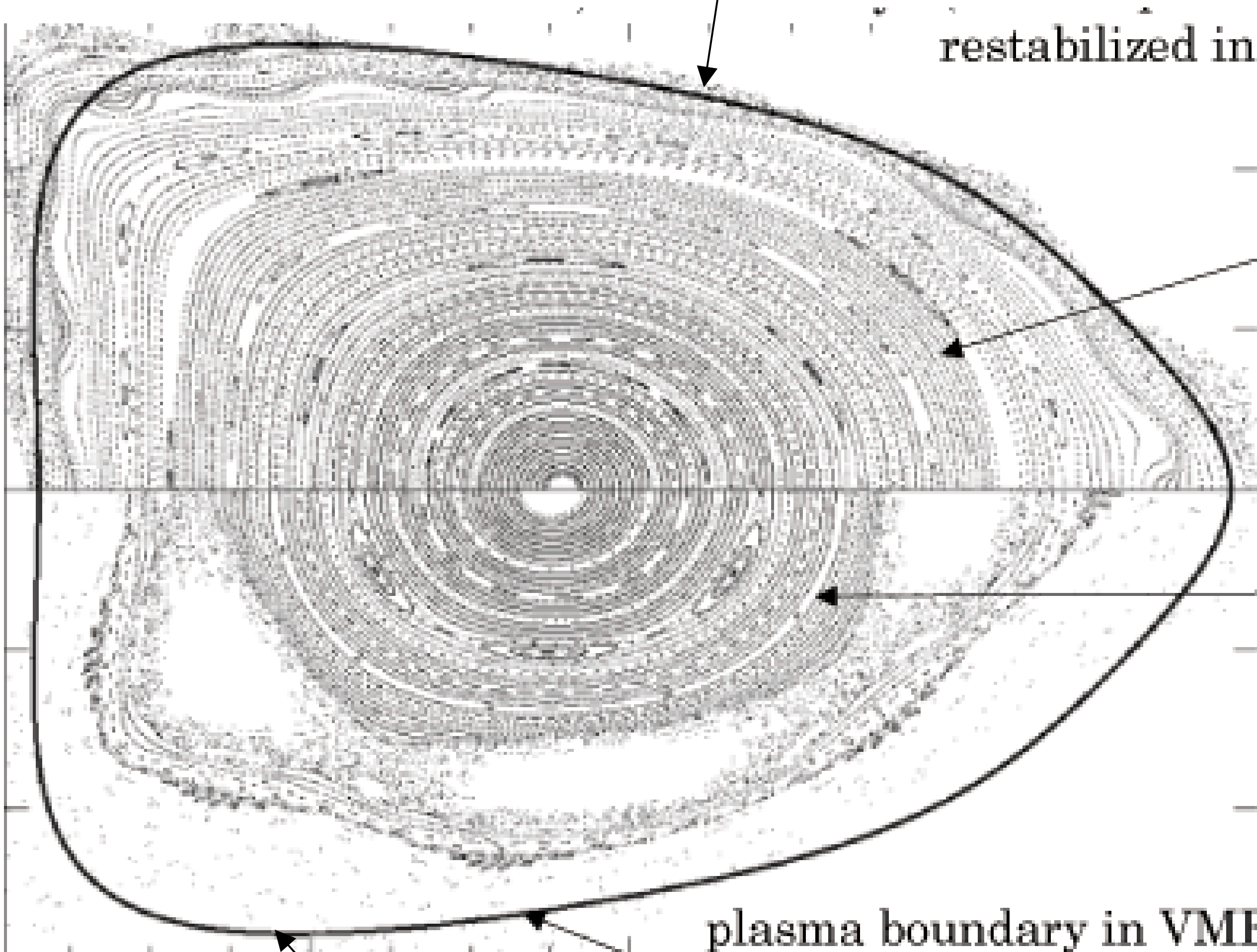
$$Z = \sum_{m=0,n=-n_b}^{m_b,n_b} [(1-s)\hat{z}^{i}_{m,n} + s\hat{z}^{i+1}_{m,n}]\sin 2\pi(mu+nv)$$

$$\phi = \frac{2\pi}{N} v$$

- Computation of magnetic field outside the plasma via Green’s function, virtual casing principle for including the contribution from the plasma current and non-equidistant integration mesh (see IPP report by E.Strumberger, 2001).

Best MFBE Result with long connection length

Island Healing Inside LCMS Improves MFBE Results

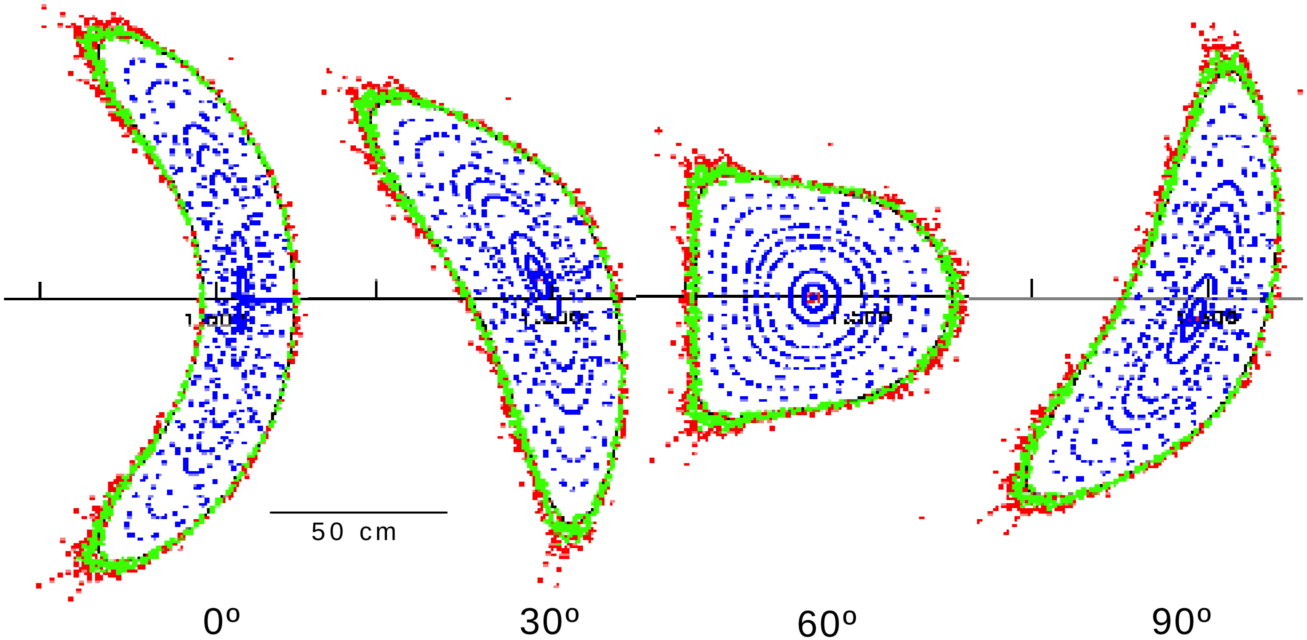


MFBE Field Line Leaves Computation Box Immediately

NCSX Boundary Has Long Connection Lengths !

- ➔ **Poincaré plots, generated with the <u>MFBE</u>* and <u>Gourdon</u> codes: 20 field-lines were started at the outer/inner midplane (0-1 cm) and followed for 20 toroidal revolutions (Lc~180 m)**
  - Significant flux expansion
  - Long connection lengths: here up to 180 m
  - Kolmogorov lengths are ~30-50 m
  - Suitable for divertor operation

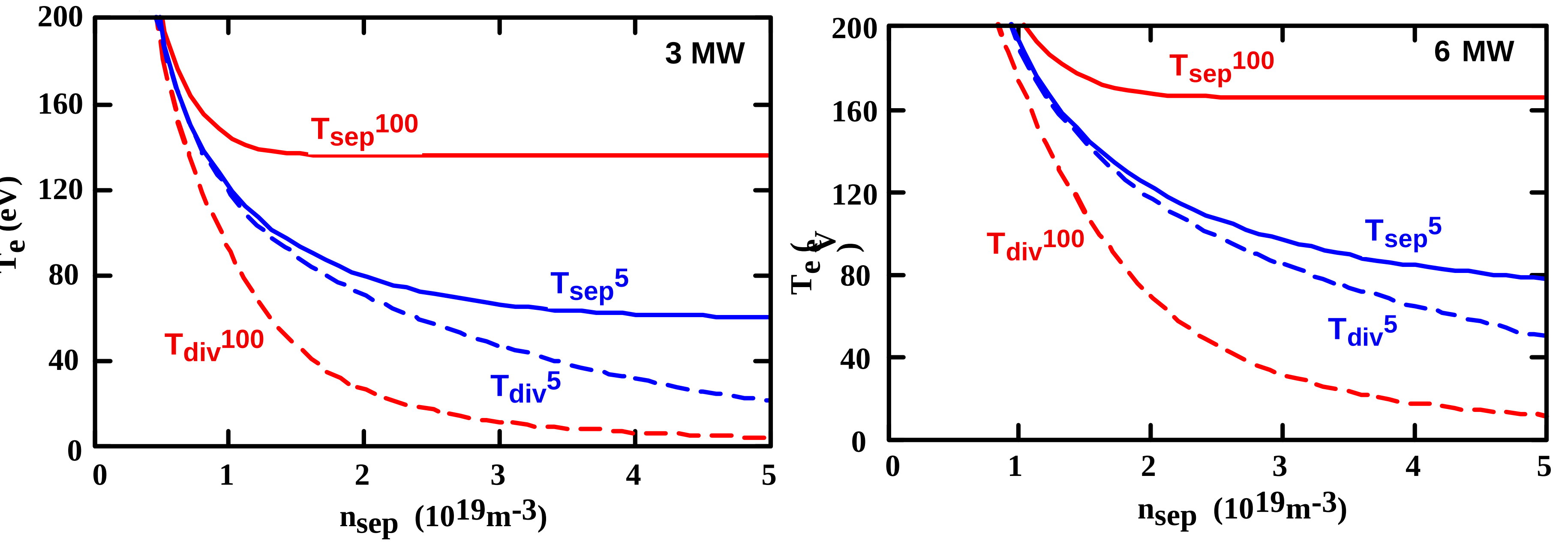
*E. Strumberger



A. Grossman

Long Connection Lengths Are Needed Between LCMS and Divertor For Sufficient Temperature Separation

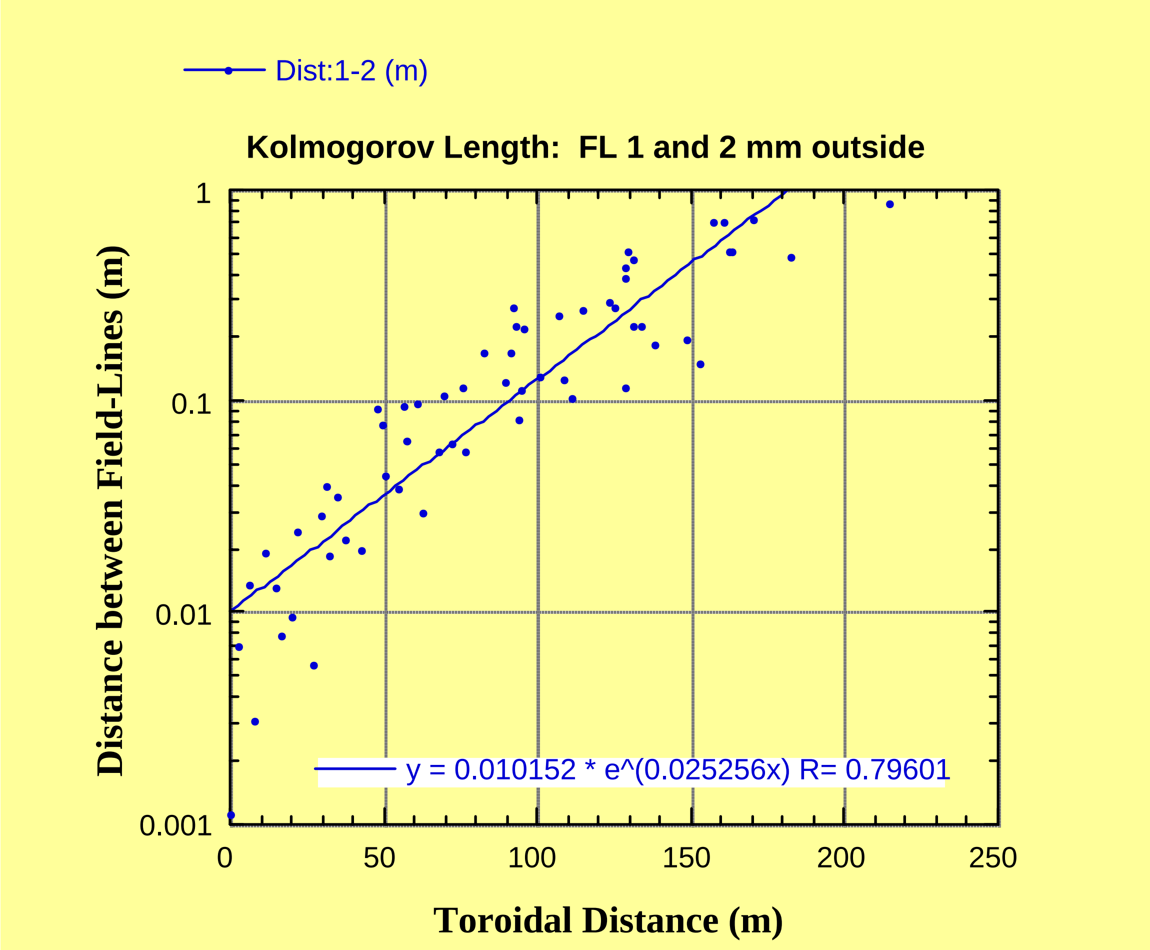
The divertor-LCMS temperature difference for NCSX can be calculated with the "2-point-model"



The figure shows: Lc = 100 m -> sufficient divertor-separatrix temperature separation

Lc = 5 m -> temperature separation insufficient, even at high ne

Kolmogorov Length for Field-Lines Launched At Outside Midplane



$L_k \sim 40$ m

$L_c \sim 180$ m

Assumptions of 2-Point 1D Parallel Conduction Model For SOL n,T Parameters

- Conduction dominates over convection
- Stagnant flow upstream and M=1 at target
- No radiative loses along SOL
- Power enters SOL uniformly along flux tube
- Te = Ti at target
- Pure hydrogen plasma

- Good assumptions under attached plasma conditons, breaks down for detached.

2-Point Open Field Line Model

- Parallel Momentum Balance: $n_{sep}T_{sep}\ (1+M_{sep}^2) = n_{div}T_{div}(1+M_{div}^2)$

- Power Balance Along Field Lines: $\frac{d}{ds}(k\frac{dT}{ds}) = \frac{P_{SOL}}{A_{SOL}L_c}$

- Parallel Thermal Conductivity: $k = k_0 T^{5/2}$ $\quad k_0 = 31000 / Z_{eff} \ln\Lambda$

- Sheath Condition: $q_{//} = P_{SOL} / A_{SOL} = \gamma n_{div}T_{div}c_s$

- Integrating Power Balance Twice: $T_{sep} = (\frac{7}{2}\frac{q_{//}L_c}{k_0} + T_{div}^{7/2})^{2/7}$

- Input power and upstream density are the usual control parameters. Solve for the target and upstream temperature using the parameters $Z_{eff} = 1.5$

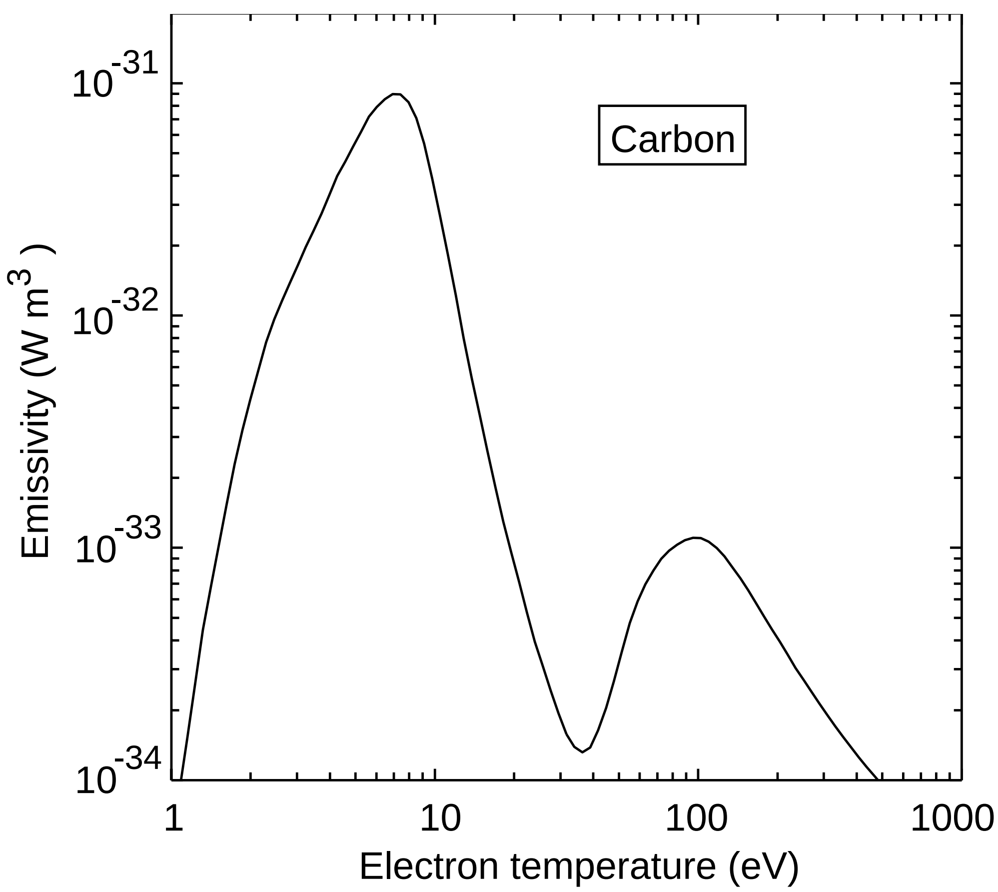
  P= 3 MW, 6 MW, core radiation fraction f = 0.2,

  Power into the SOL = P (1-f)=2.4 MW, 4.8 MW Major and Minor radii 1.4 m and 0.33 m sheath transmission factor of 7, area of SOL perpendicular to power flux $A_{SOL} = 4\pi R\lambda_{q\mathrm{T}}(B_\theta / B)$

  evaluated with an iota at edge =0.65.

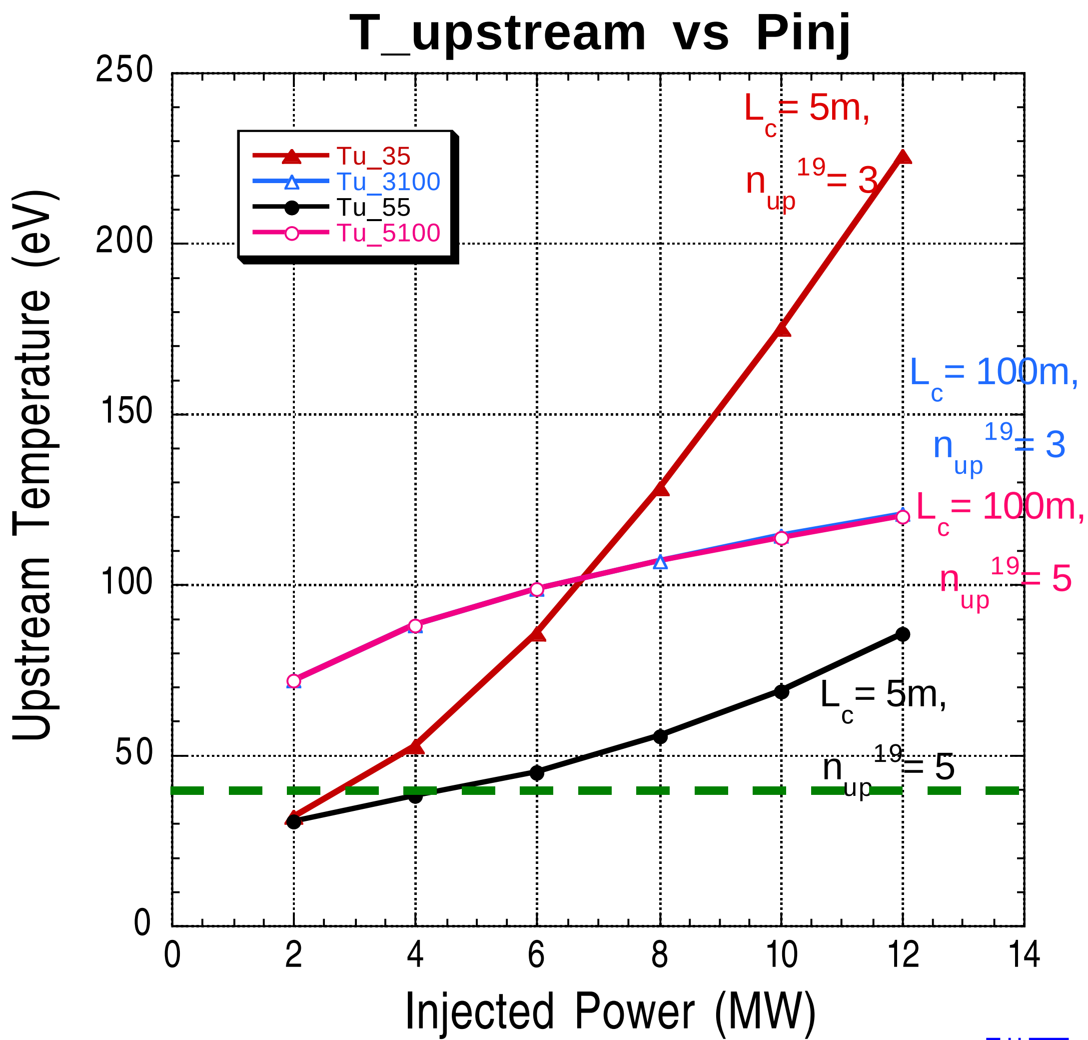
SOL near LCMS must be hot enough to burnout highly radiating charge states of carbon.

- For carbon impurity, upstream temperature must be > 40 eV to avoid negative slope of cooling curve
  - For T<40 thermal instability produces T~7 eV.
- DIII-D experience in high density operation shows core MARFE and sharp reduction of confinement when Tsep falls below 40 eV
  - Petrie PSI96 showed H-factor reduction by 2x concurrent with Tsep < 40 eV
  - SOL MARFE moved inside separatrix



The Two Point Model indicates low power or short connection length may lead to core radiative collapse.

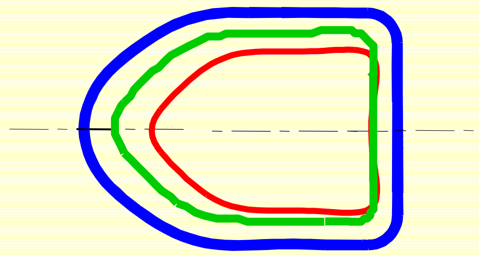
- Initial field line tracing results from Art Grossman showed that for a 4cm conformal wall Lc might be as low as 5 m (field line strikes 4cn wall within one field period).
- Wall at 10 cm allows many toroidal transits (Lc > 100m)
- Calculation assumptions:
  - R_{eff}=1.7, a_{eff}=0.35 m
  - $\lambda_{||}$ = 2 cm, γ=7
  - $Iota_{edge}$ = 0.5
  - $T_e = T_i$, f_{rad} = 0.2

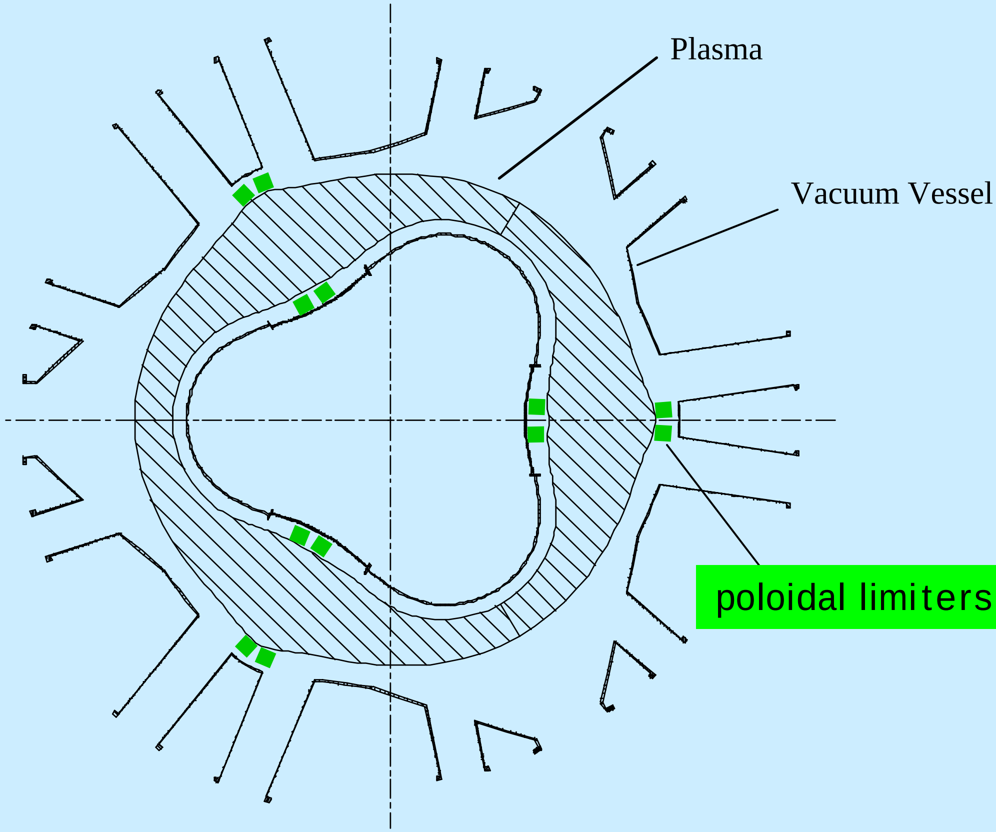


1st Generation PFCs: Poloidal Limiters at ϕ= 60°

The initial set of limiters will protect the walls and allow for initial Ohmic operation.

Poloidal cross-section at ϕ = 60°

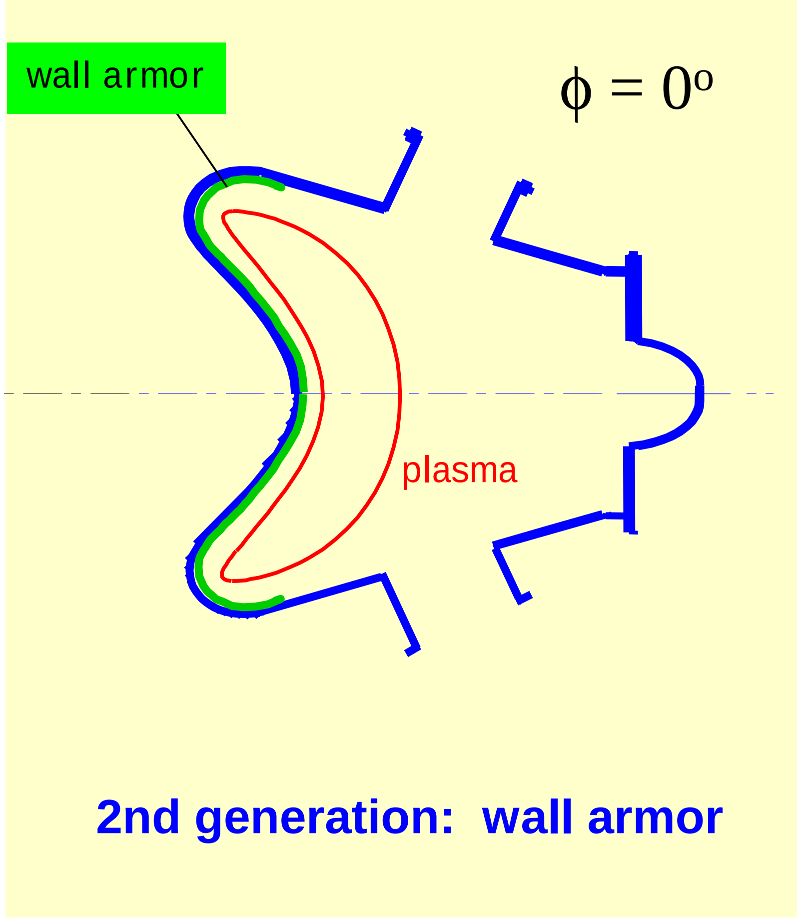




Plan view of vacuum vessel and plasma

2nd Generation PFCs: Graphite Wall Armor (Liner)

- The 2nd generation of PFCs will consist on graphite panels attached to the vacuum vessel and bakeable to 350ºC.
- This configuration will provide the first opportunity to diagnose the plasma boundary with finite beta plasmas.
- Experiments and modeling in this configuration will provide the basis for the divertor design.



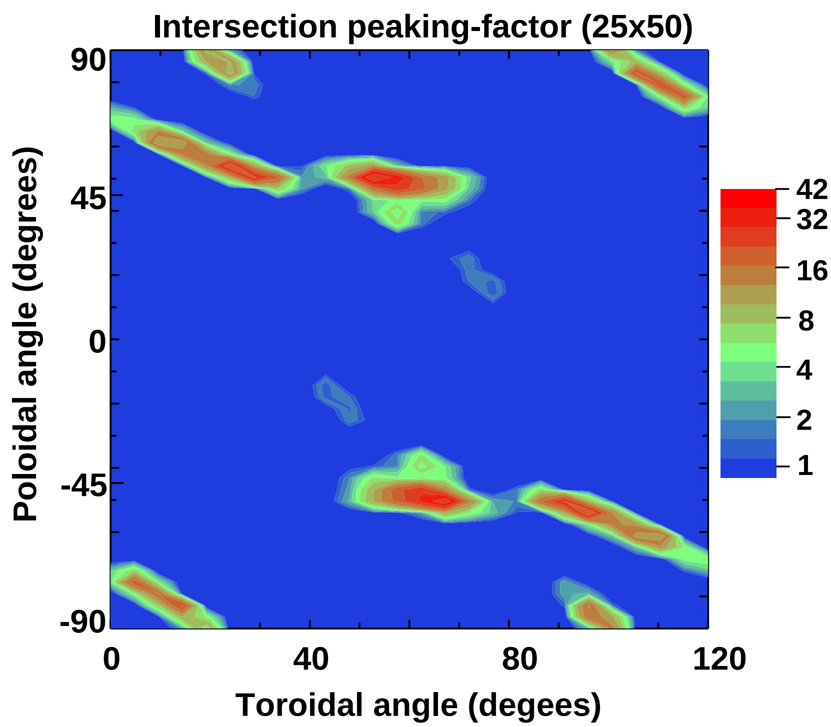


Figure 10-11. Density of field-line intersections on the wall normalized to a uniform distribution for a (ϕ,θ) mesh of (25,50) showing a maximum peaking factor of 42, assuming $D_\wedge = 1\ m^2/s$.

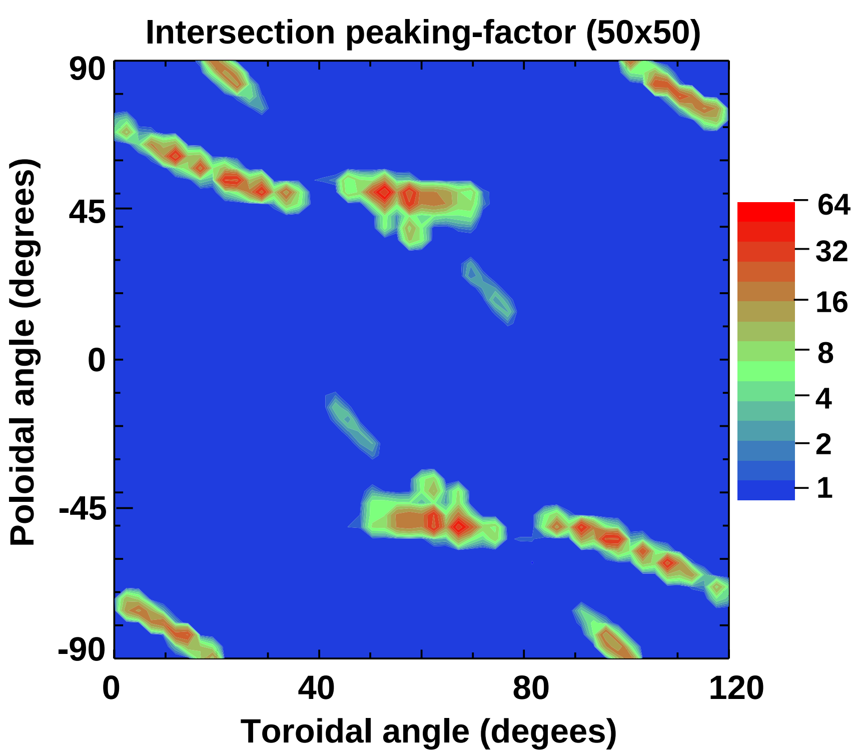
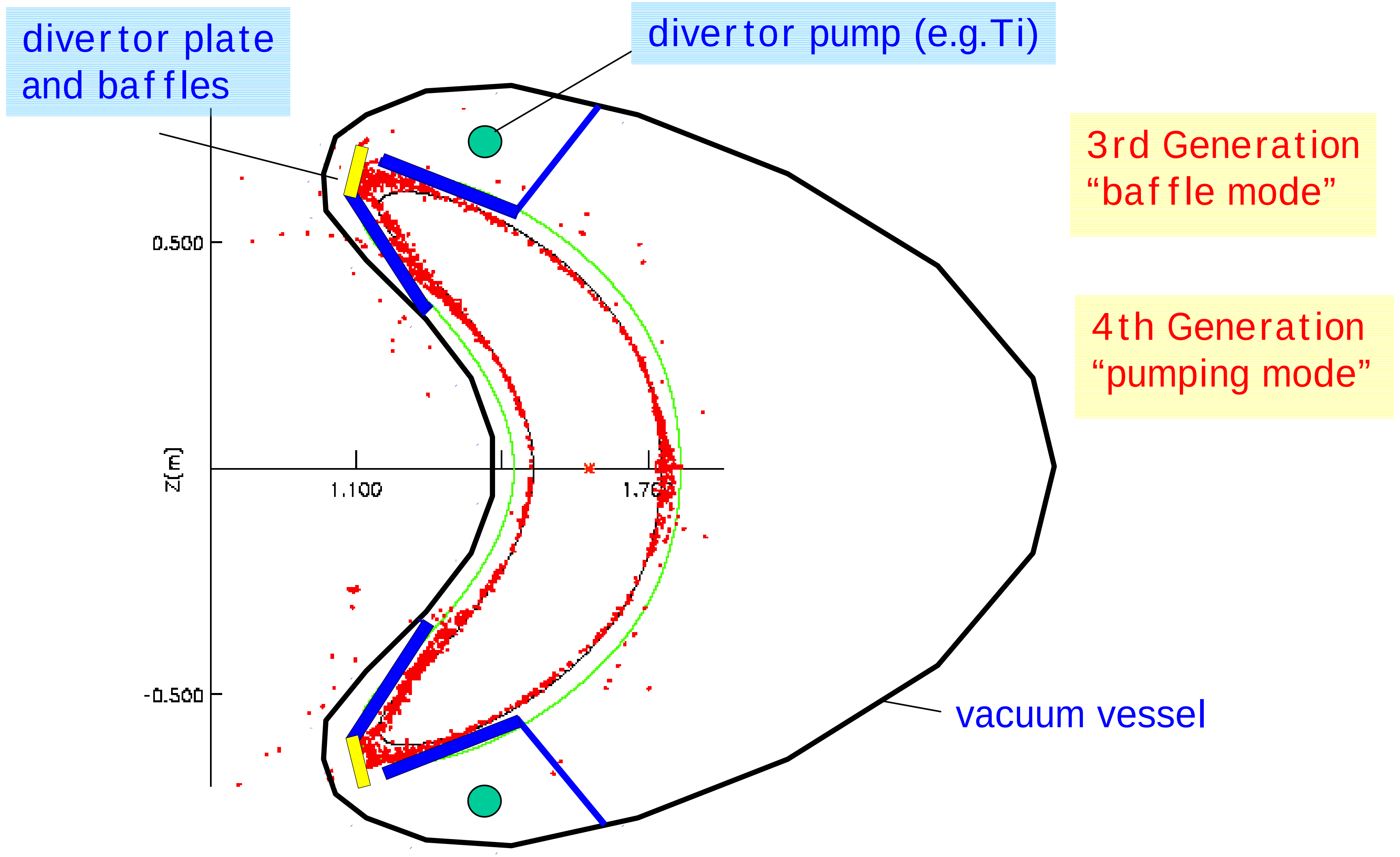


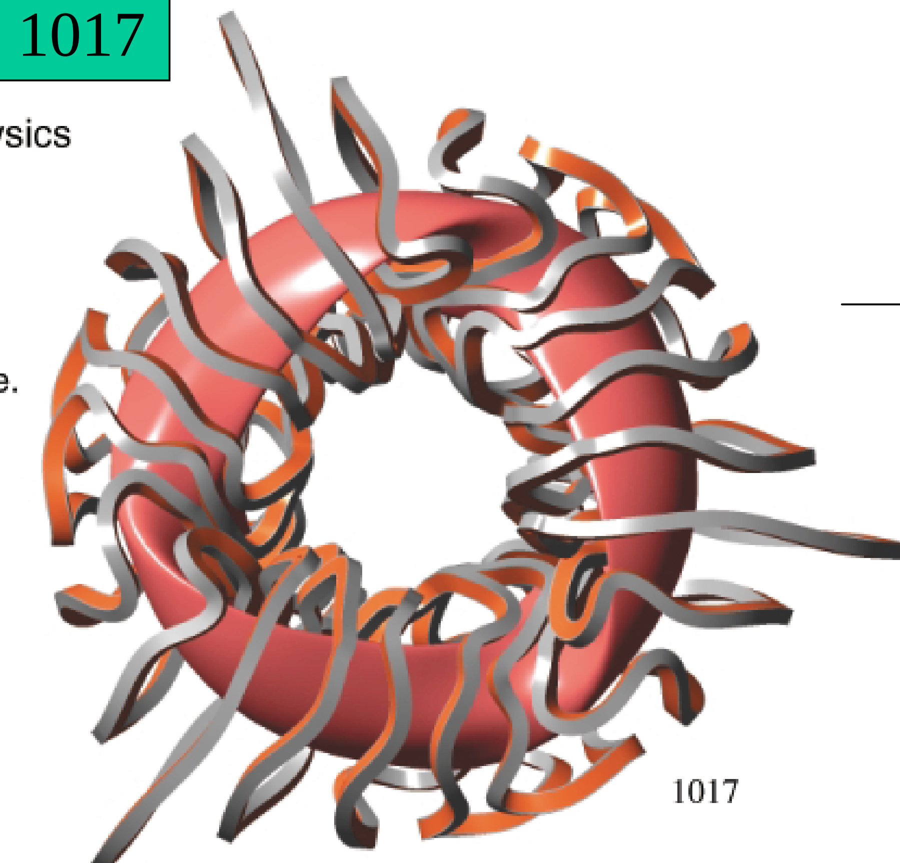
Figure 10-12. Distribution of field-line intersections for a (ϕ,θ) mesh of (50x50) giving a maximum peaking factor of 62, assuming $D_\wedge = 1\ m^2/s$.

3rd and 4th Generation PFCs : Divertor



NCSX Design Evolution from 1017 to M45

1017



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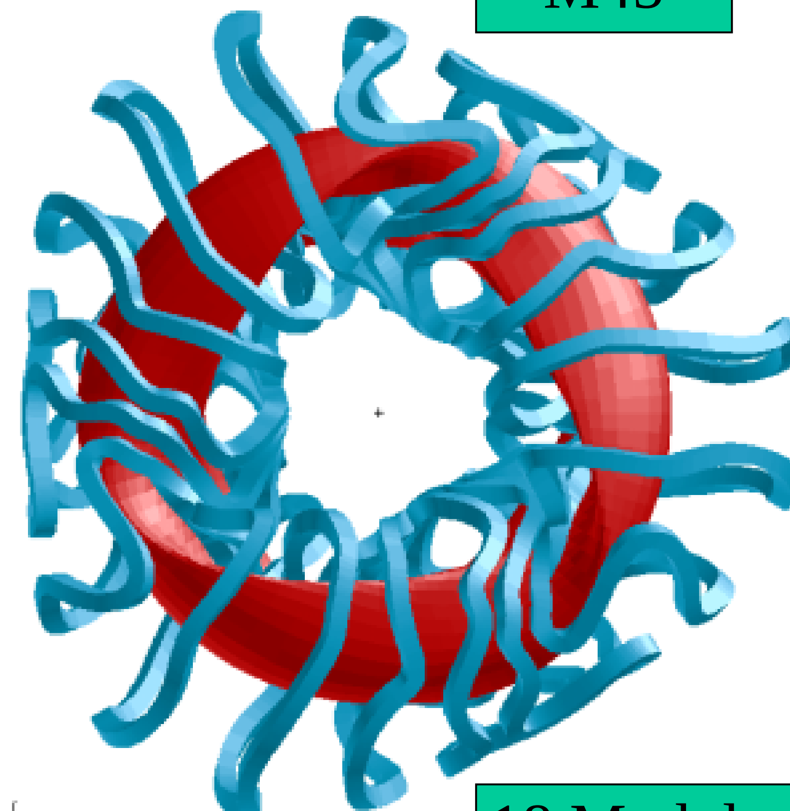
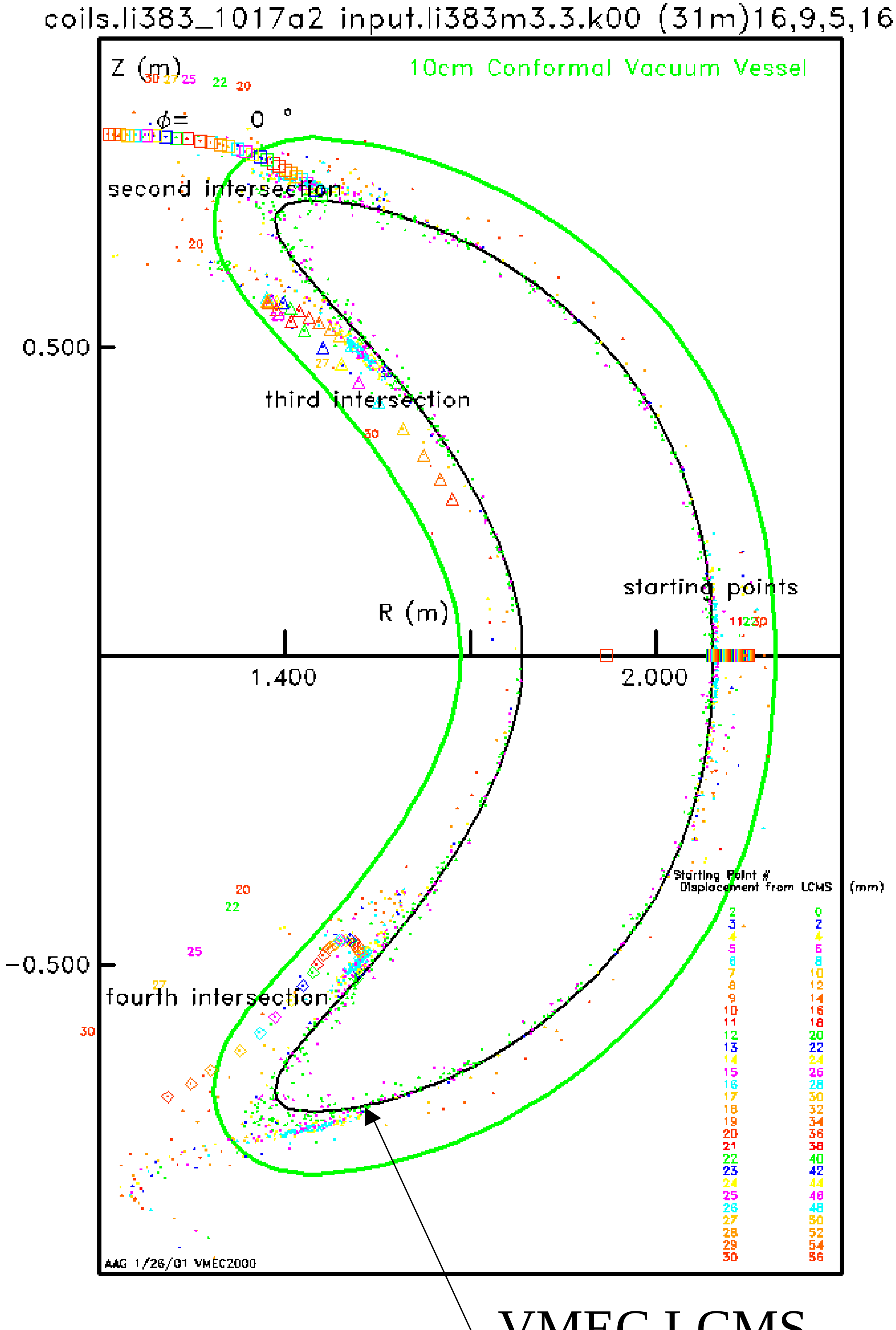
M45



21 Modulars

18 Modulars

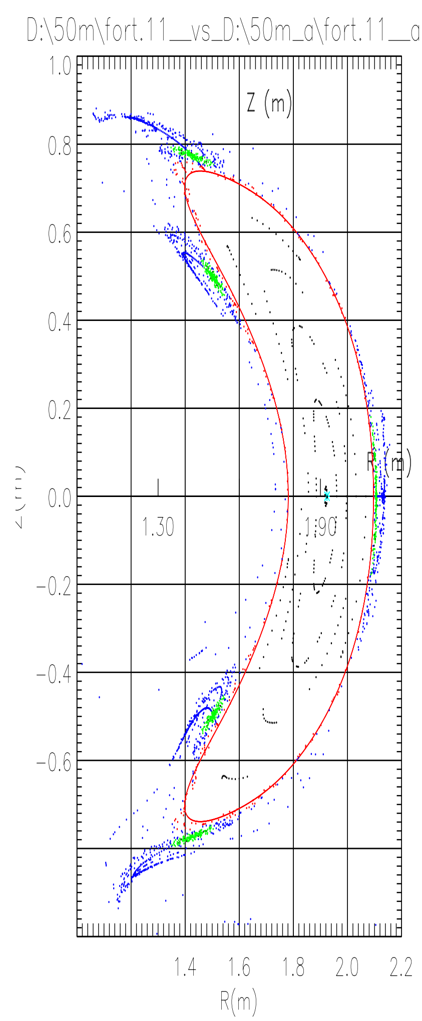
Toroidal Angle = 0°



VMEC LCMS

Poincaré Plots With Island-Healing Inside the LCMS Yield Distinct Island Structure Outside the LCMS

- 60 Field Lines were Launched on the Outside Midplane, 0 to 4cm from LCMS.
- Island Forming Lines are #9 to #25, plotted in green.
- Non-island lines are plotted in blue. LCMS is red, lines started inside LCMS are plotted in black.



Summary

- **Improved performance in W7-AS has recently demonstrated that power and particle control are essential tools for improving plasma performance in stellarators.**
- **For initial operation, our understanding of the NCSX boundary will be limited and we will start with a simple limiter configuration.**
- **The boundary in NCSX is somewhat stochastic, with Kolmogorov lengths measuring several toroidal revolutions !**
- **This guarantees sufficiently long connection lengths which - in conjunction with the observed flux expansion - are suitable for divertor operation.**
- **Earlier configurations without island healing had short connection lengths. Partial island healing inside LCMS enhanced island structure outside LCMS.**
- **As our understanding of the boundary grows, we will improve impurity and neutrals control by developing divertor configurations.**