Confinement and Equilibrium with Internal Islands in a Configuration Scan with respect to Iota in W7-X

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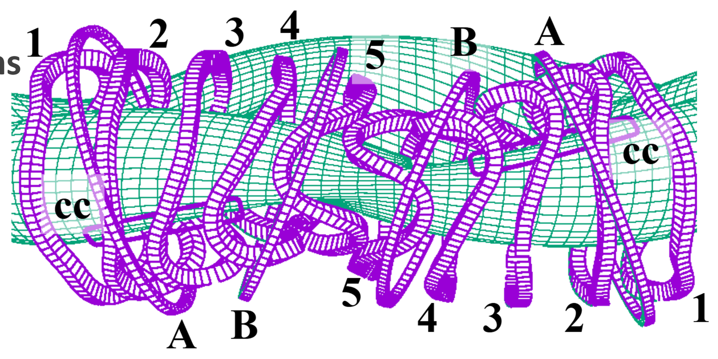
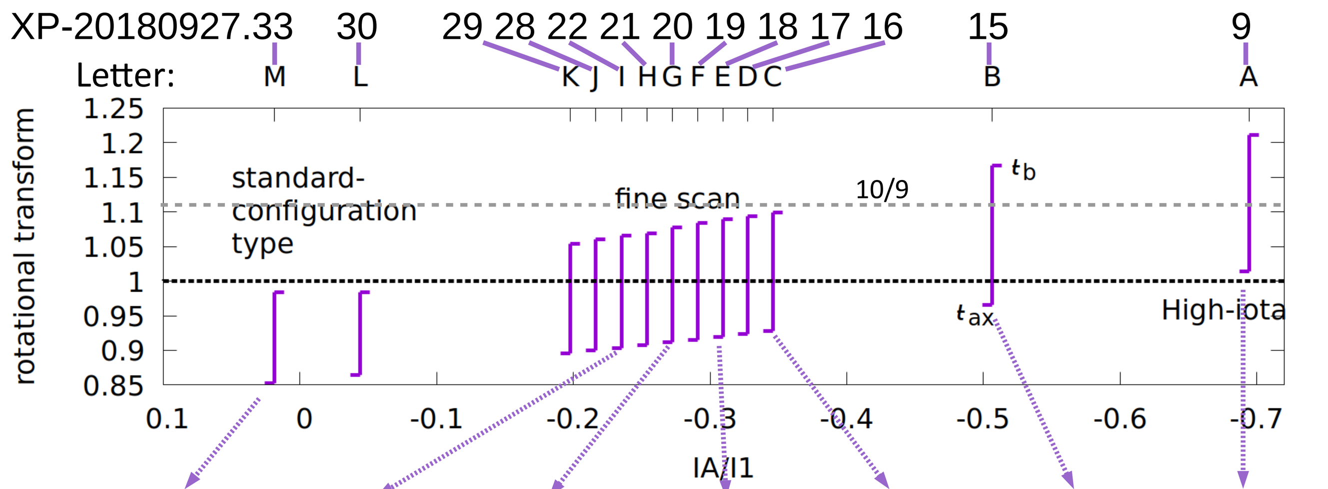
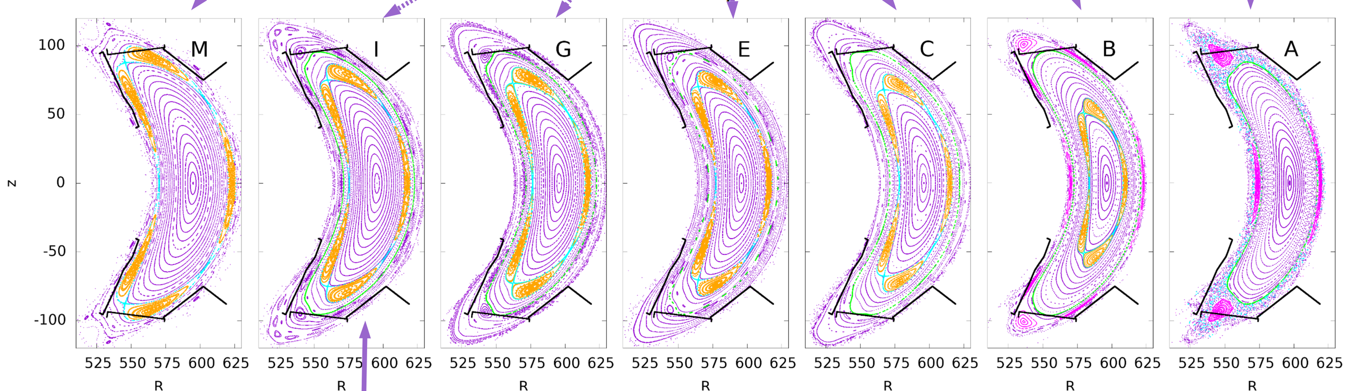
MOTIVATION

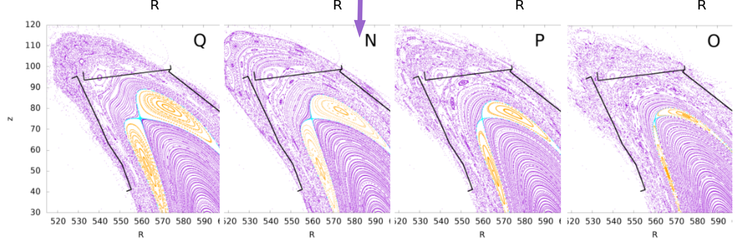
- Confinement changes in stellarators connected to rotational transform ι via low-order rationals or islands at the boundary or close to it => W7-AS, Heliotron-J, TJ-II
  - investigate confinement by systematic scan of configurations
- W7-X has flexible coil system
  - non-planar coils (1 to 5) for main field
  - planar coils (A, B) for ι- & magn. axis variation
  - control coils (cc) for island size and phase
- MHD-equilibrium calculations
  - VMEC (assumes nested flux surfaces) approximate consideration of internal islands by combination with EXTENDER
  - HINT-code (no assumption of flux surfaces) => consistent treatment of internal islands



SCAN OF MAGNETIC CONFIGURATIONS







Island size variation XP-201810917.nn

nn	21	22	23	24
letter	N (I)	O	P	Q
isl. size	-	↘↘	↘	↗

Configuration Scan
- **upper bound**
  - high-iota config. (A) ι_b=5/4
- **lower bound**
  - stand. config. (M,L) ι_b=5/5
- **intermediate config.s**
  - limiter-type config.
  - internal 5/5-islands
  - fine scan with
    - $\iota_b \leq 10/9$
    - 5/5-islands moving towards divertor plates
- **Island width variation** for config. I (=>N)
  - decreased isl. width => P &O
  - increased isl. width => Q
  - ergodization outside 10/9-islands when changing 5/5-island width

MHD-EQUILIBRIUM WITH INTERNAL ISLANDS

HINT

- No assumption of flux surfaces
- Iterative relaxation of resistive MHD-equations on Eulerian grid in two steps, repetitively:
  - 1: pressure relaxation with ***B***=const.

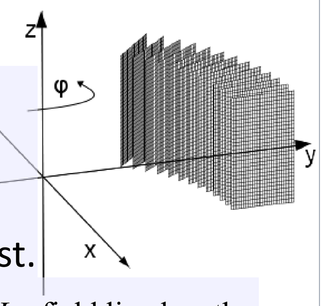
$$\vec{B}\cdot\nabla p=0 \;\Rightarrow\; p_{i+1}\sim\bar{p}=\int_L p_i\frac{dl}{B}\Big/\int_L\frac{dl}{B}\;,\quad L=\text{field line length}$$

  - 2: with p=const. advancing force balance, Faraday's Law + Ampere's Law

$$\frac{\partial\vec{v}}{\partial t}=-f_c\left(\nabla p-(\vec{j}-\vec{j}_0)\times\vec{B}\right)$$

$$\frac{\partial\vec{B}}{\partial t}=\nabla\times\left[\vec{v}\times\vec{B}-\eta\left(\vec{j}-\vec{j}_0-\vec{B}\frac{\langle\vec{j}\cdot\vec{B}\rangle_{net}}{\langle B^2\rangle}\right)\right]\;,\quad \nabla\times\vec{B}=\mu_0\vec{j}$$

- MHD-equilibrium with press. distribution and equilibrium currents consistent with magn. field

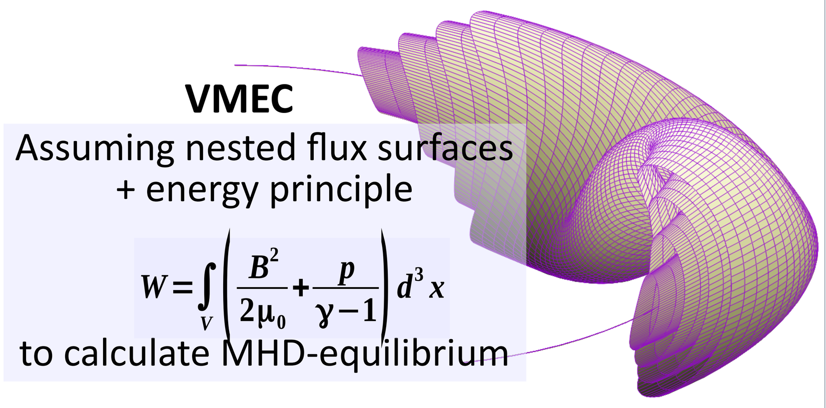


VMEC

Assuming nested flux surfaces + energy principle

$$W=\int_V\left(\frac{B^2}{2\mu_0}+\frac{p}{\gamma-1}\right)d^3x$$

to calculate MHD-equilibrium



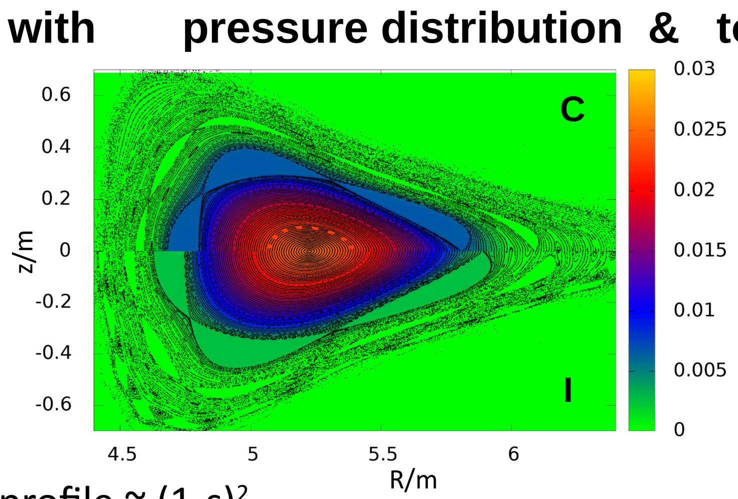
EXTENDER

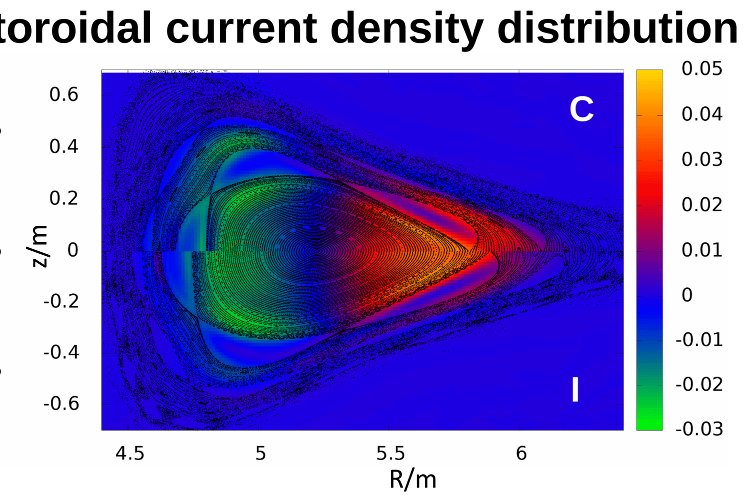
VMEC-result + Virtual casing principle
- *plasma-generated fields + vacuum-field*
- ***approximation*** *of equilibrium field with islands*

HINT-CALCULATIONS FOR IOTA-SCAN-CONFIGURATIONS

Poincaré-plots with pressure distribution & toroidal current density distribution

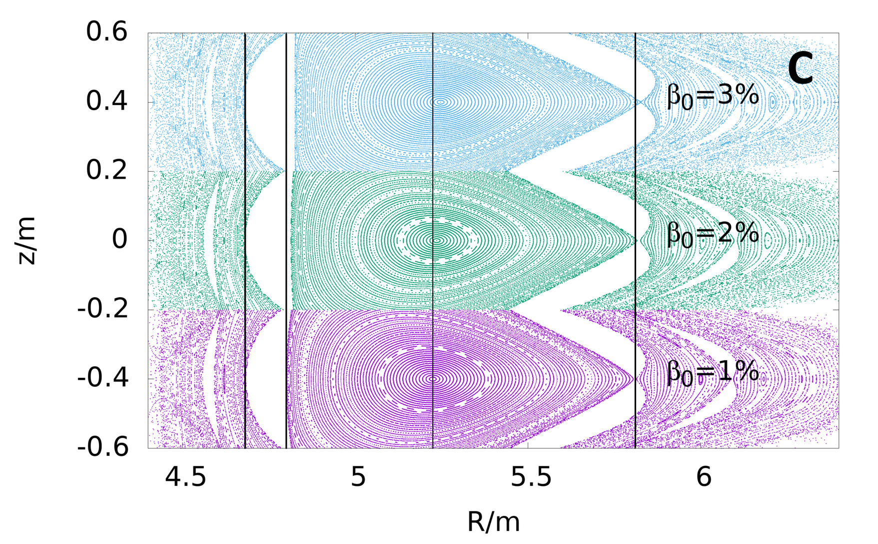
- Configuration
  - **C**=begin of fine-scan
  - **I** = around best confinement





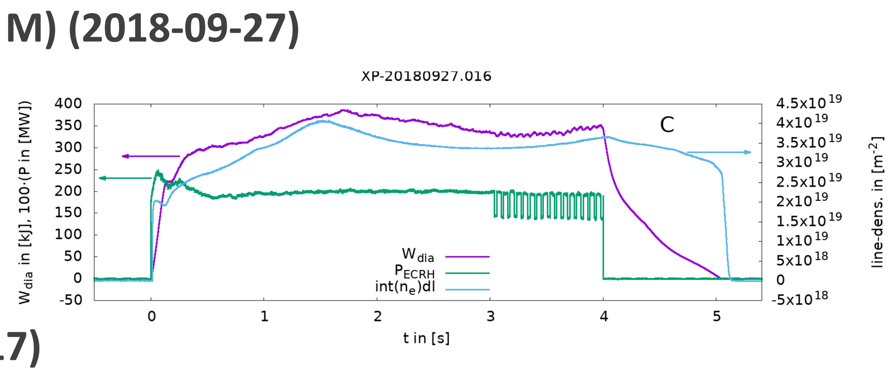
- Initial pressure profile ~ $(1-s)^2$
- final pressure distribution with flattening inside 5/5-islands
- toroidal current density with PS-dipole structure + depletion of current in island region
- β increases island width
- Note: no matching of experimental profiles yet

HINT-calculation parameters:)
L=100m (pressure equilibration length)
n=80 (main iteration steps)
256x256x128 = space-grid-resolution
3.0x3.0 = R-z-box size (centre at (5.5m,0m))

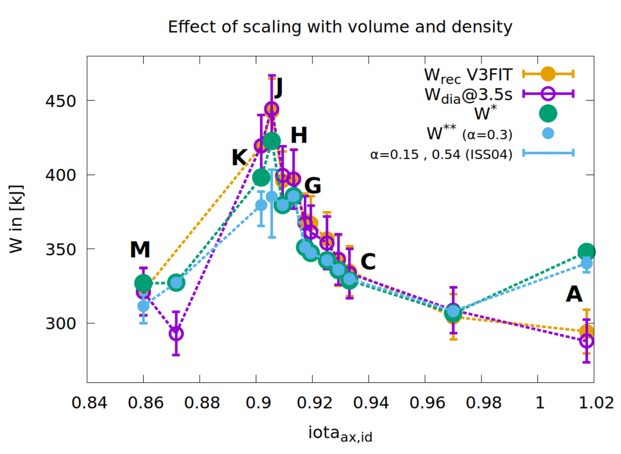


EXPERIMENTS & RESULTS

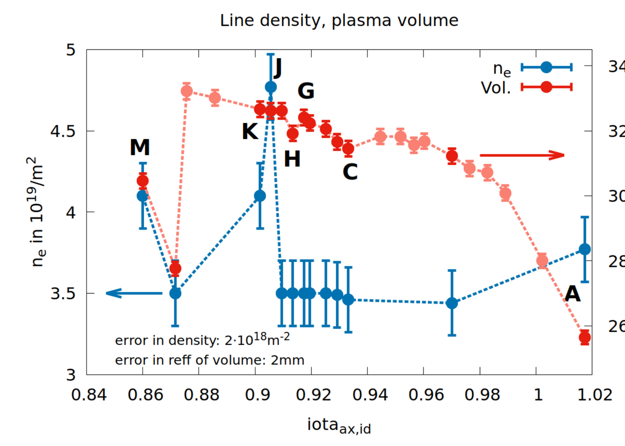
- **Experimental setup iota-variation (A to M) (2018-09-27)**
  - P_{ECRH}= 2MW (140GHz, X2)
  - duration 4s
  - from t=3s to 4s power mod.
  - target density: $\int n_e dl=3.5\cdot10^{19}m^{-2}$

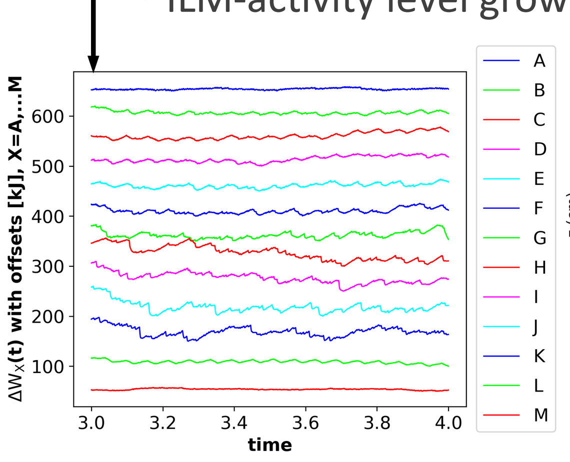


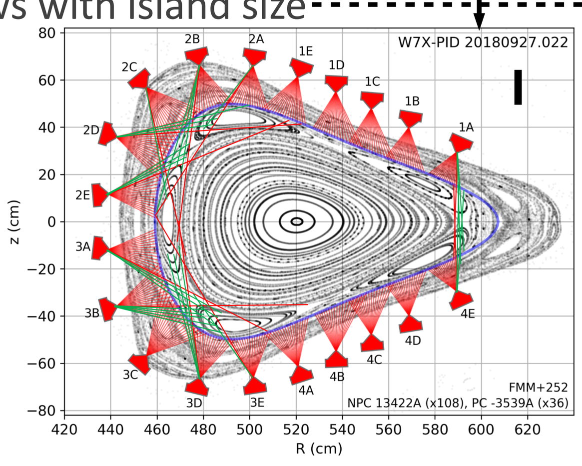
- **Island size variation (N to Q) (2018-10-17)**
  - P_{ECRH}, duration, power mod. like A to M
  - density: $\int n_e dl=6\cdot10^{19}m^{-2}$
  - NBI-blips (ca 1MW), 20ms every 200ms (O&Q)

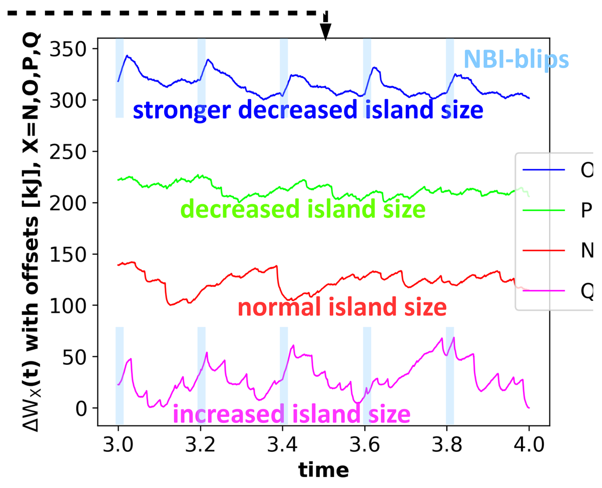


- **Results**
  - energy increase with lowering iota
  - diamagn. energy & V3FIT-reconstr. agree well
  - highest energies with 5/5-islands close to boundary: H to K
  - persists when accounting for volume and density variation
    - $W^*=W_{dia}(31.5m^3/V)$
    - $W^{**}=W^*(3.5\cdot10^{19}m^{-2}/\int n_e dl)^\alpha$ with α=0.15, 0.3, 0.54(ISS04)
  - crashing MHD-activity located at 5/5-islands
    - MHD-activity increases with better confinement
    - Island localized modes ("ILM"s)
      - SX-camera system identifies location (red/green sight-lines show signal-inversion)
    - ILM-activity level grows with island size



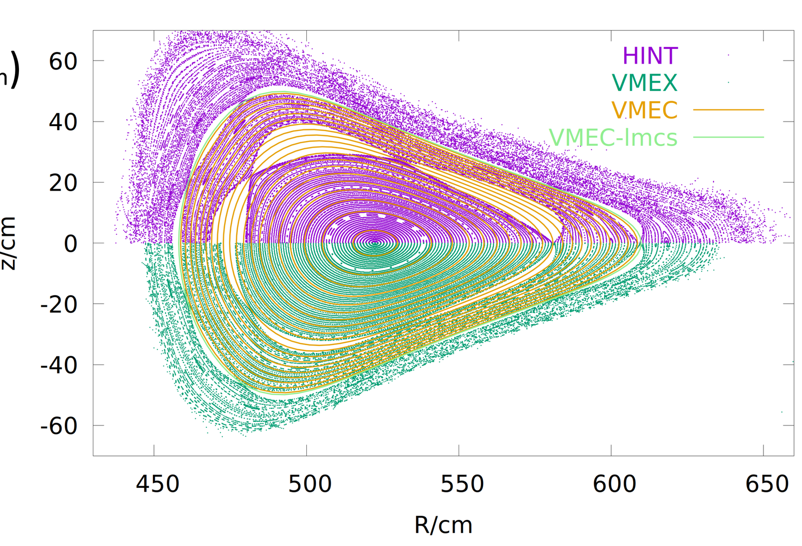


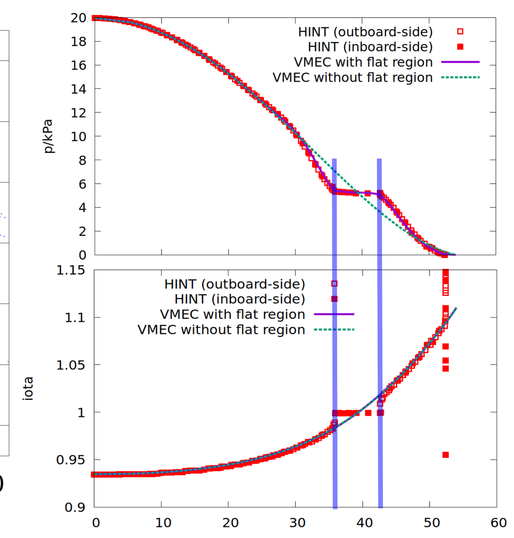




COMPARISON HINT / VMEC-EXTENDER (VMEX) - INTERNAL ISLANDS

Configuration C
- final HINT press. profile used for VMEC (same W_{kin})
  - press. prof. w/ and w/o flat region
- EXTENDER for full-field generation
- General agreement between VMEC & HINT
  - Flux surfaces, Shaf.-shift
  - expected disagreement at islands and boundary

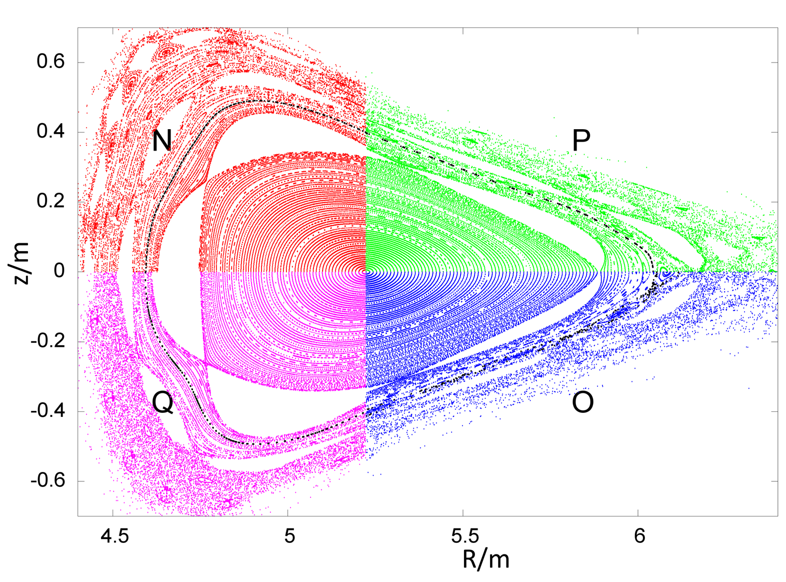


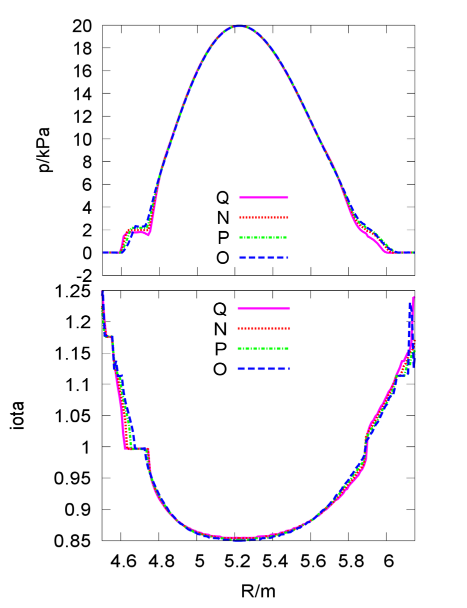


HINT- & VMEX-fields
- good agreement up to 5/5-island size (underestimated!) => shortfall of approx. (also in VMEX-vac.)
- VMEX-fields vary only marginally with pressure profile form (w/ or w/o flat region at same W_{kin}!)

ISLAND WIDTH VARIATION WITH CONTROL COILS (CCs)

Configuration N(=I) + CCs
- significant island width variation reproduced
- island size reflected in HINT-press. profiles
- last closed flux surface (lcms) defined by divertor
- stochastization around and beyond 10/9 islands by use of CCs
- increased island size closes distance to lcms





SUMMARY

- Investigation of confinement in configuration scan (iota) between two divertor configurations: high-iota (ι_b=5/4) and standard-iota (ι_b=5/5).
- Best confinement with 5/5-islands close to plasma boundary; better confinement accompanied with increasing MHD-activity at 5/5-islands (ILMs); activity level also dependent on island size.
- Calculations of consistent MHD-equilibria with internal islands using HINT for configuration-scan with flat-pressure regions of islands reflected in equilibrium current densities, e.g. PS-currents.
- Comparison with VMEC and VMEX-approach gives good general agreement, but disagreement at and around internal islands: underestimated island size shows shortcoming of VMEX-approach.

Acknowledgements
- This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission
- US researchers are supported by the US Dept. of Energy, Office of Fusion Energy Sciences.