On High Beta MHD in Stellarators

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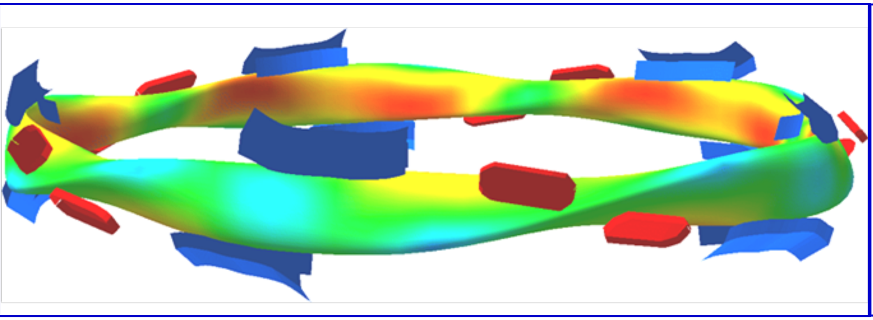

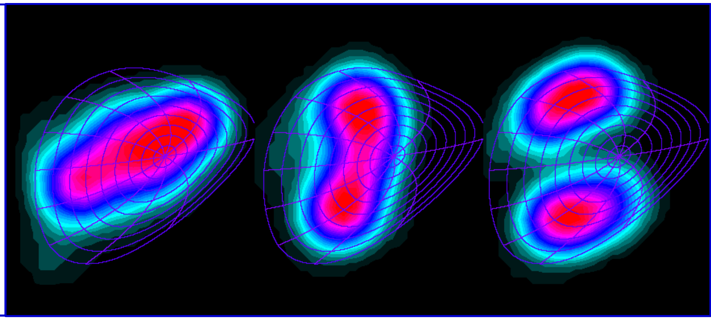

Contributors:

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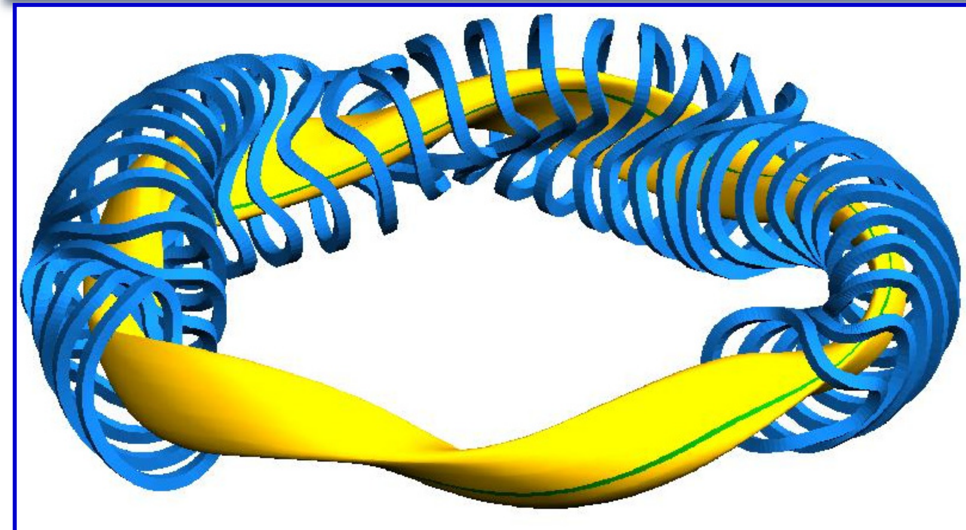
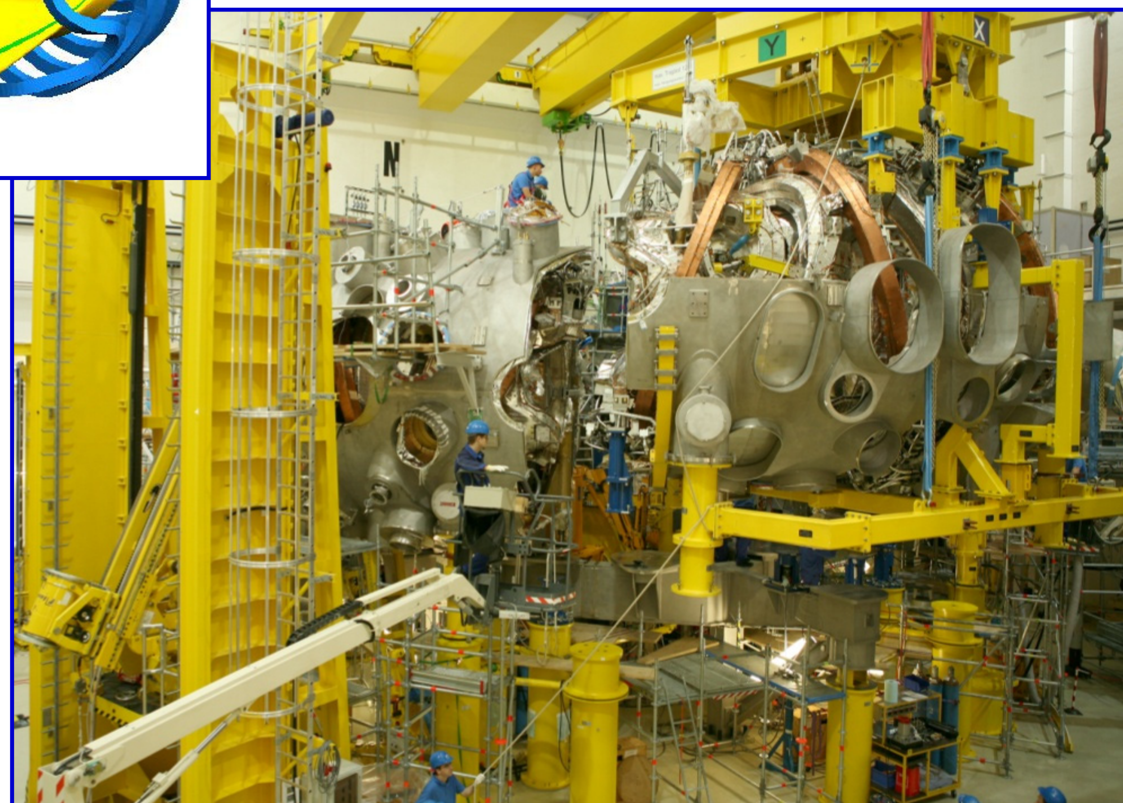
Optimized Stellarators , Wendelstein 7-X

- whole coil system provides passive control of MHD stability -



... presently under construction
(IPP Greifswald)
start operation: 2014 / 2015

Insertion of last module (16th Nov 2011)



- feasible modular coils
- good, nested magnetic surfaces
- good finite-β equilibria*)
- **good MHD stability**
- small neoclassical transport*)
- minimized bootstrap current
- good fast-particle confinement*)

*) crit. issues in stellarators

Outline

Introduction

- Magnetic configuration, high-β equilibria, control issues
- Characterization of high-β discharges in W7-AS

Observed MHD Mode Activity & Computational Studies

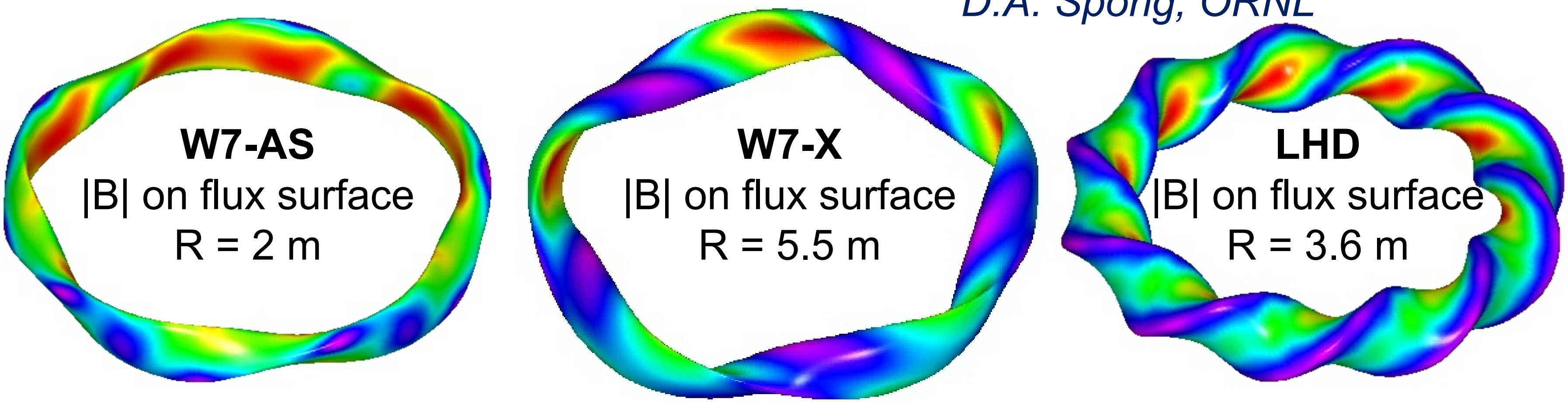
- Pressure driven low-n, low-frequency modes
- Bursting MHD activity (ballooning m. ?)
- MHD effects in high-β configurations with net current
- Energetic particle driven modes
- Stability & equilibrium limits, operational boundaries

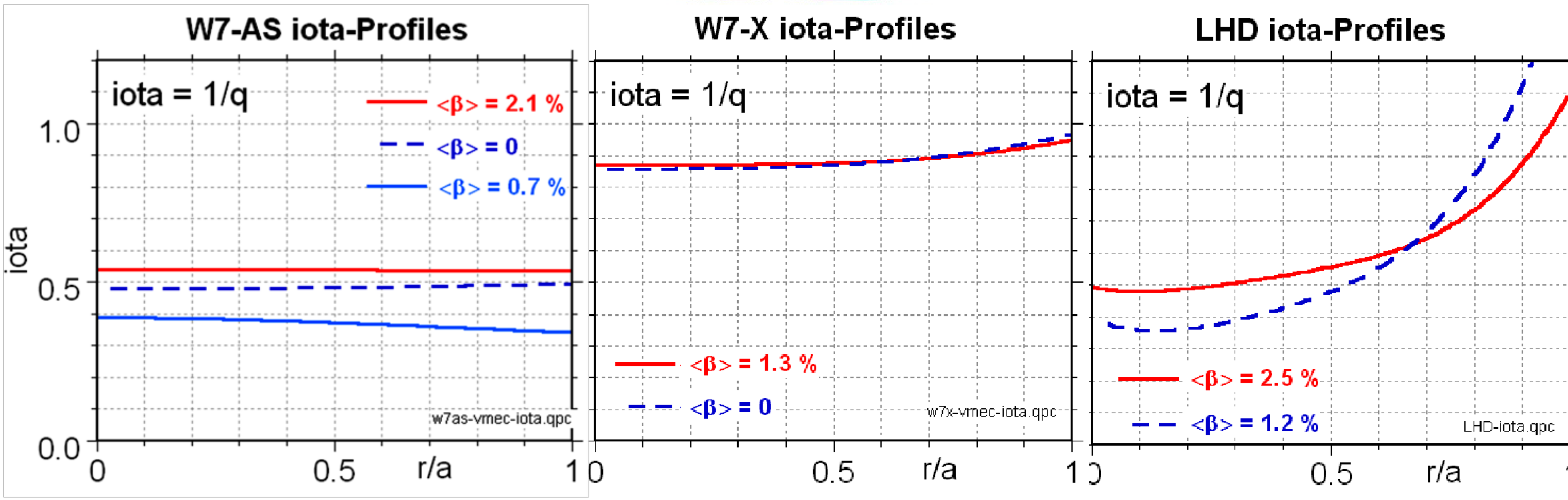
Summary, Conclusions

Stellarator Configurations

- fields, flux surfaces, rotational transform (iota-profiles) -

D.A. Spong, ORNL

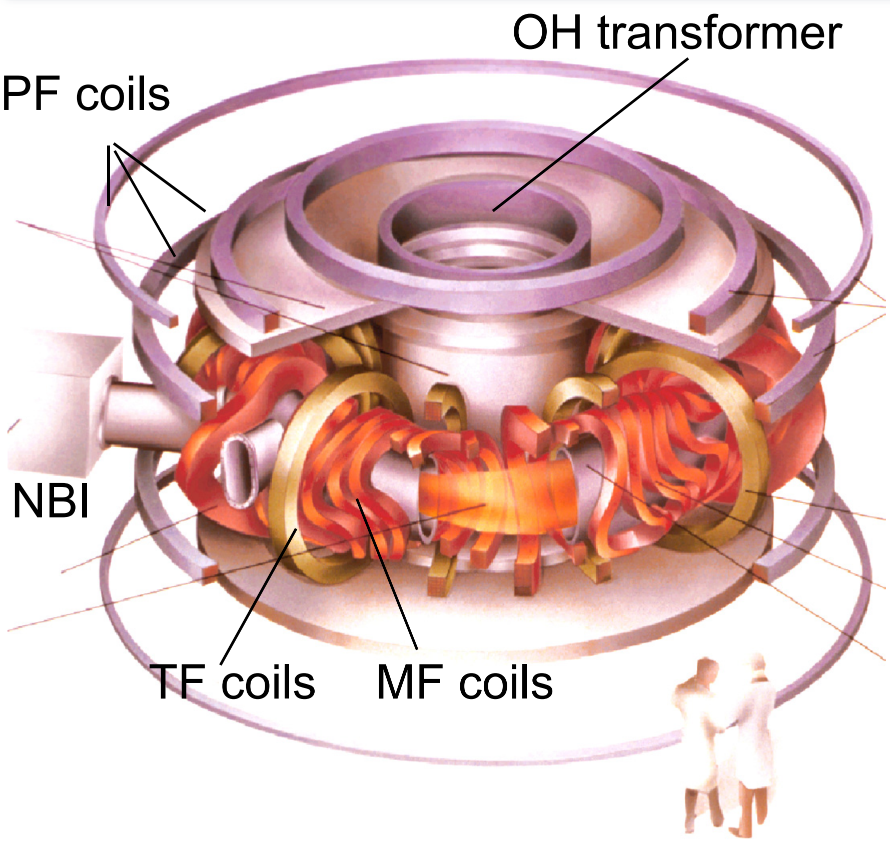




W7- strategy: avoid islands by low shear

LHD: high shear, small islands

W7-AS Coil System, Configuration Control



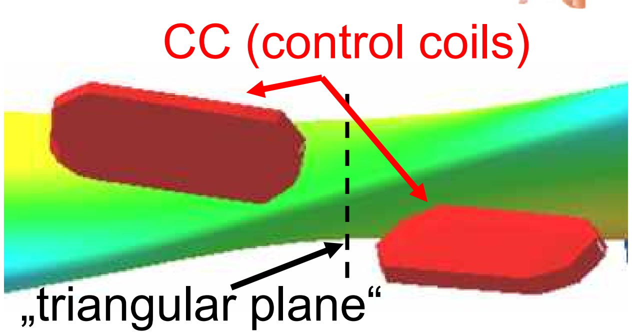
W7-AS (1988-2002):

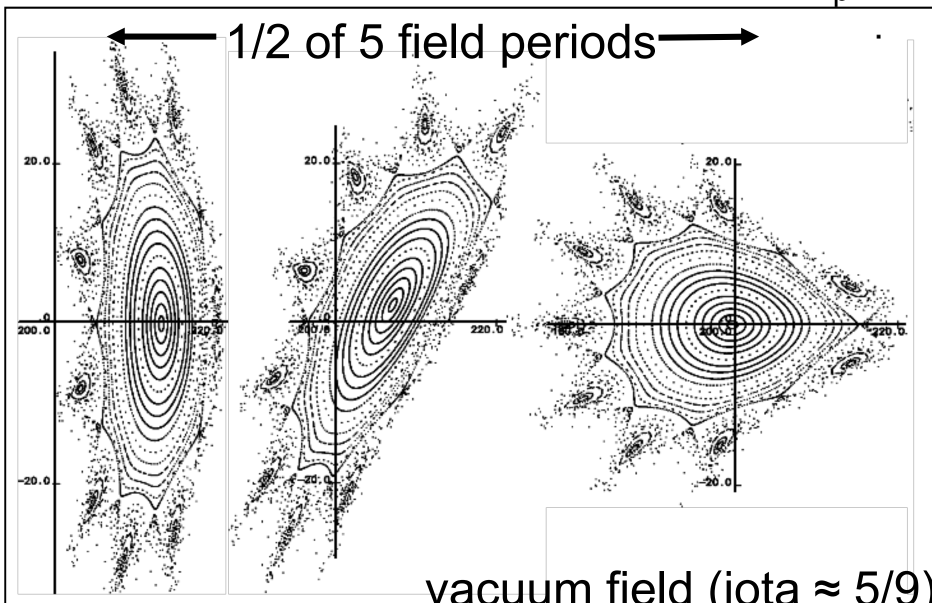
R = 2 m, a ≤ 0.18 m, 5 field periods

B ≤ 2.5 T, 0.25 ≤ ι_{ext} ≤ 0.6, low shear

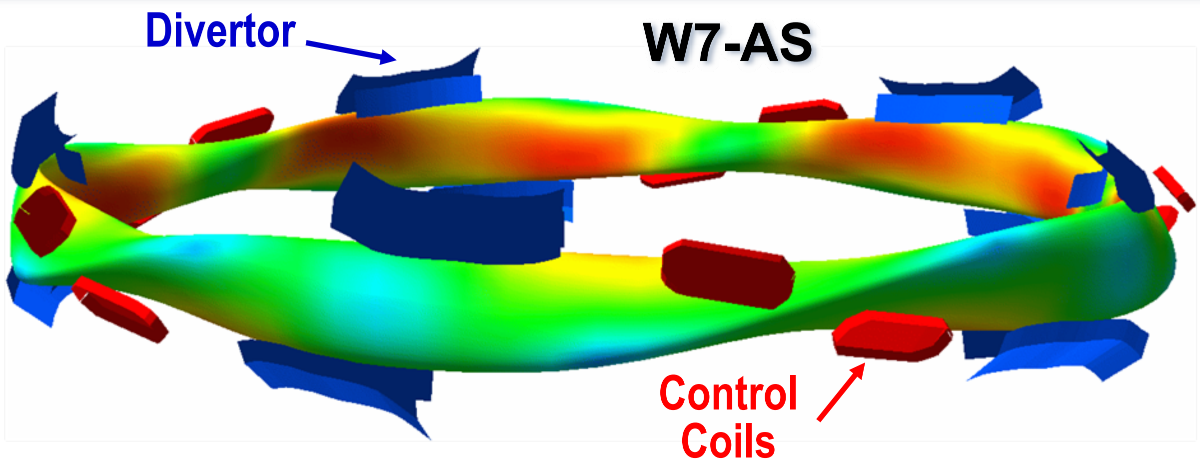
Configuration space:

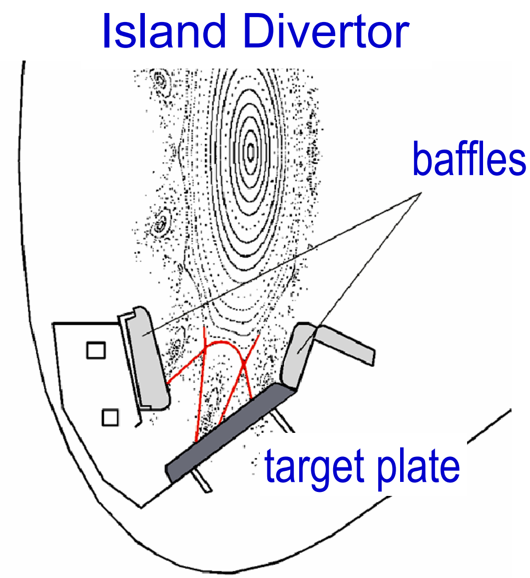
- MF coils: I_5 / I_M → modular field ripple
- TF coils: I_T / I_M → iota
- PF coils: I_{PF} / I_M → R_{ax}
- CC coils: I_{cc} / I_M → edge island size
- OH transformer: → iota-control, I_p

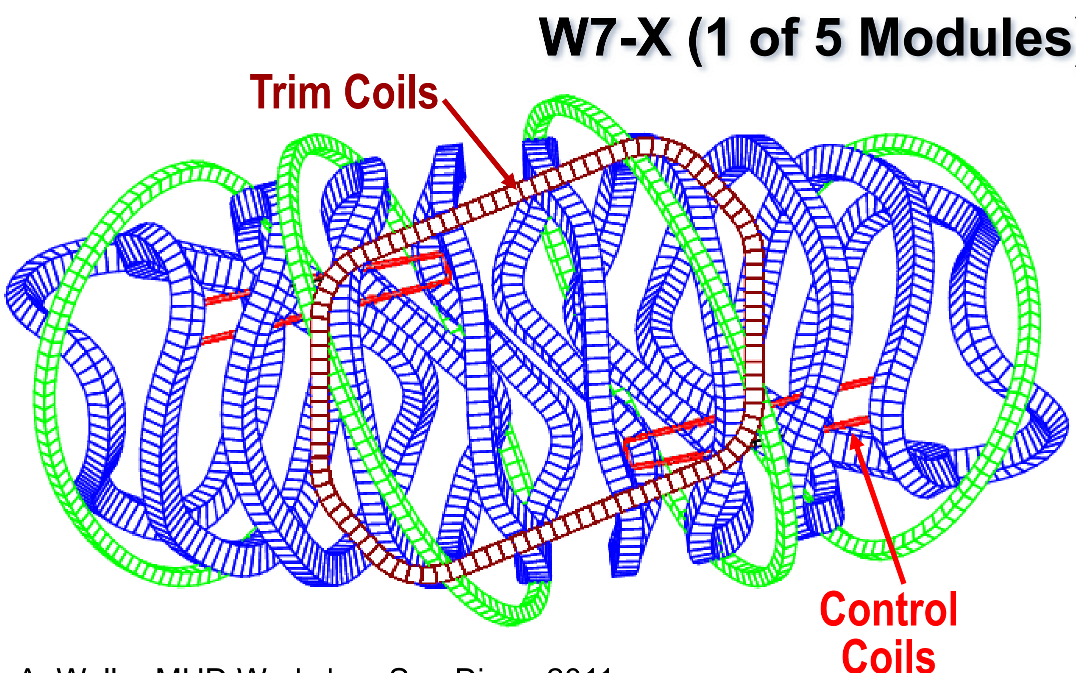




Control Issues of Wendelstein Stellarators



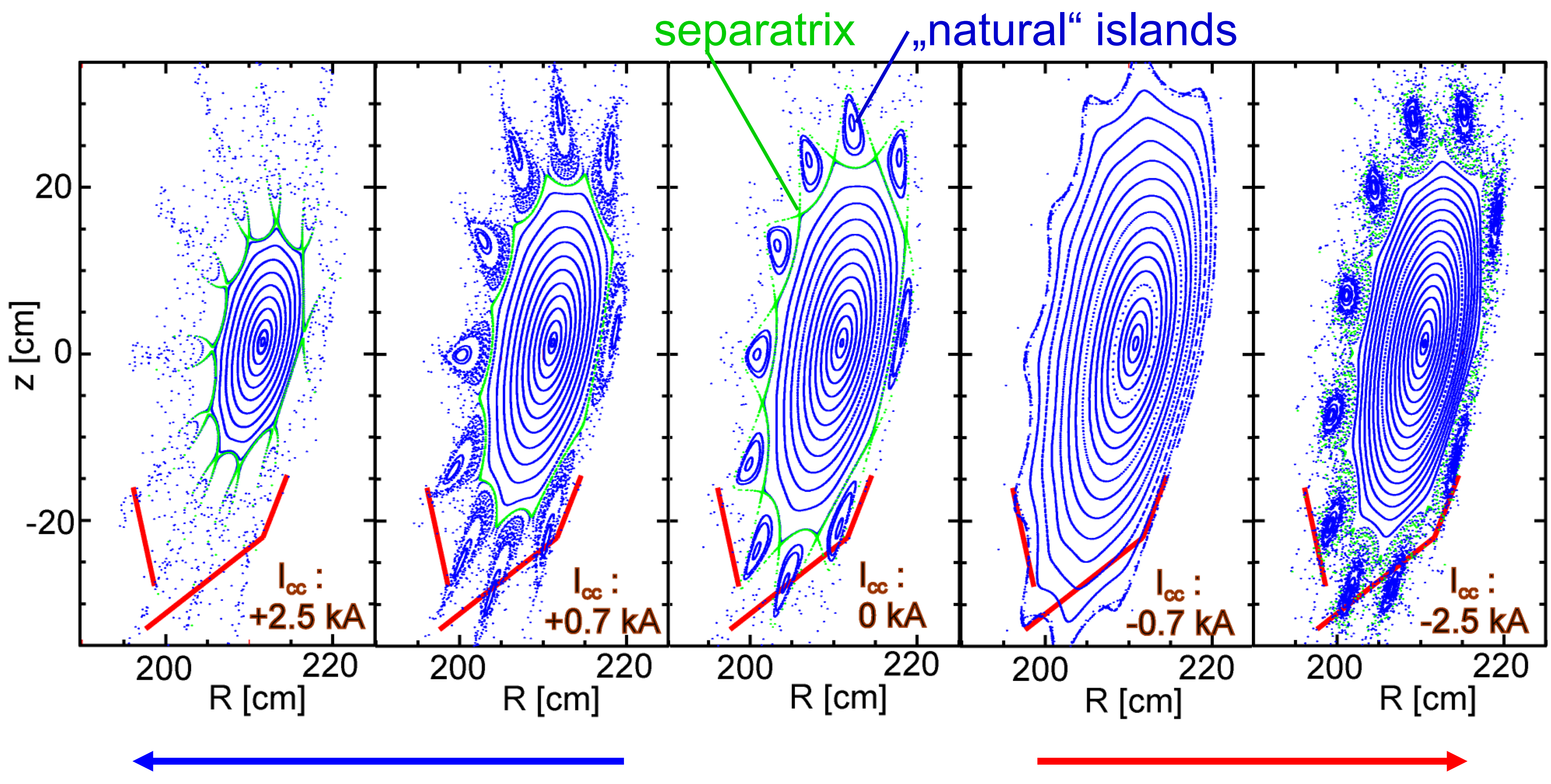




- optimize edge **edge island size** and location of **X-points** (divertor)
- **edge iota** needs to be controlled (compensation of I_{boot} by **ECCD**)
- **sweeping** of strike point (heat load)
- correction of **field errors**
  - issue of magnetic **surface quality**
  - **heat load symmetry** issue

Effect of Control Coils at iota ≈ 0.5 (q ≈ 2)

W7-AS Vacuum Fields with positive and negative CC currents

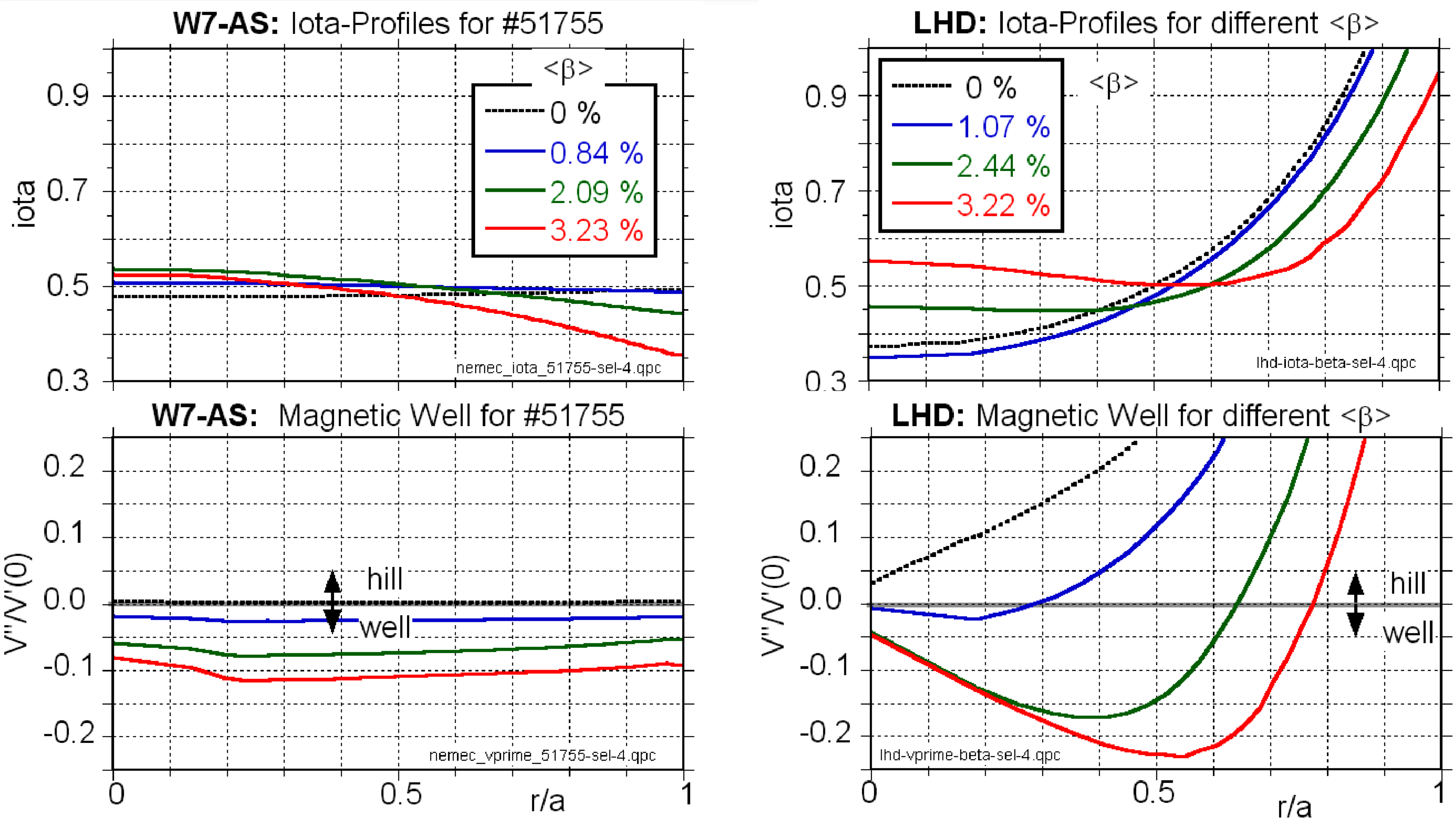


„Divertor-Configurations“

„High-β-Configurations“ (Divertor used as Limiters)

- **perturbations by control coils attenuated by plasma response !**

W7-AS and LHD Equilibria
- iota (1/q) and magnetic well, finite-β effects -



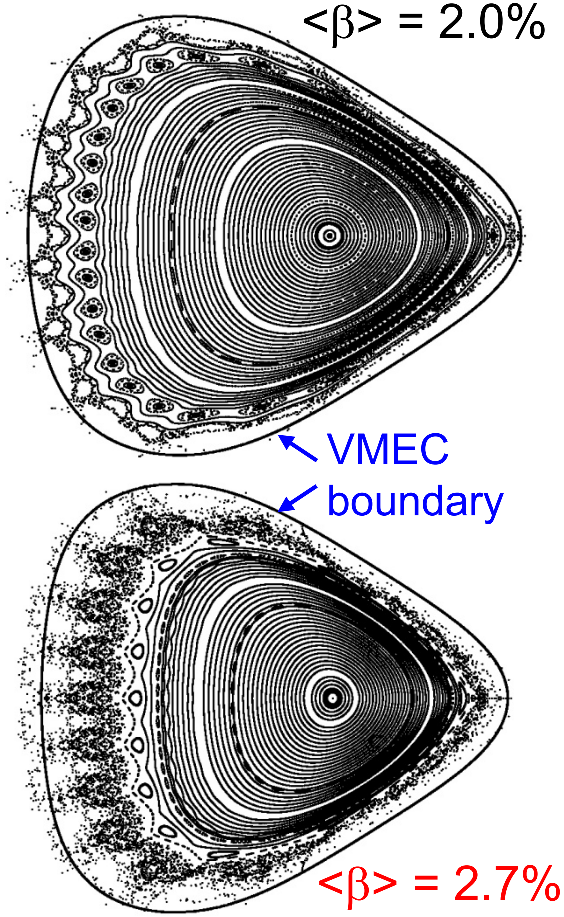
W7-AS: inward shifted configuration
at very low β: magn. well lost, **low shear**,
but rational surfaces can be avoided

LHD: inward shifted configuration
magnetic well in center by β-effect,
edge: magn. hill region, **strong shear**
(opposite to tokamak)

Equilibria with Edge Islands & Stochastic Regions

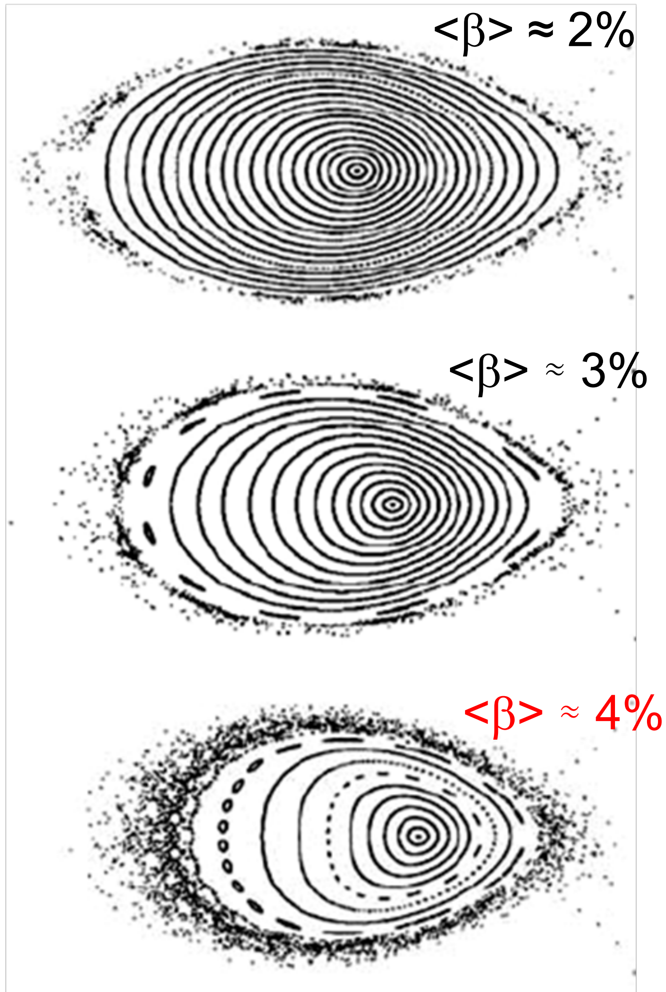
- effects increase with beta (sym. breaking parts of PS current) -

PIES-Analysis for W7-AS



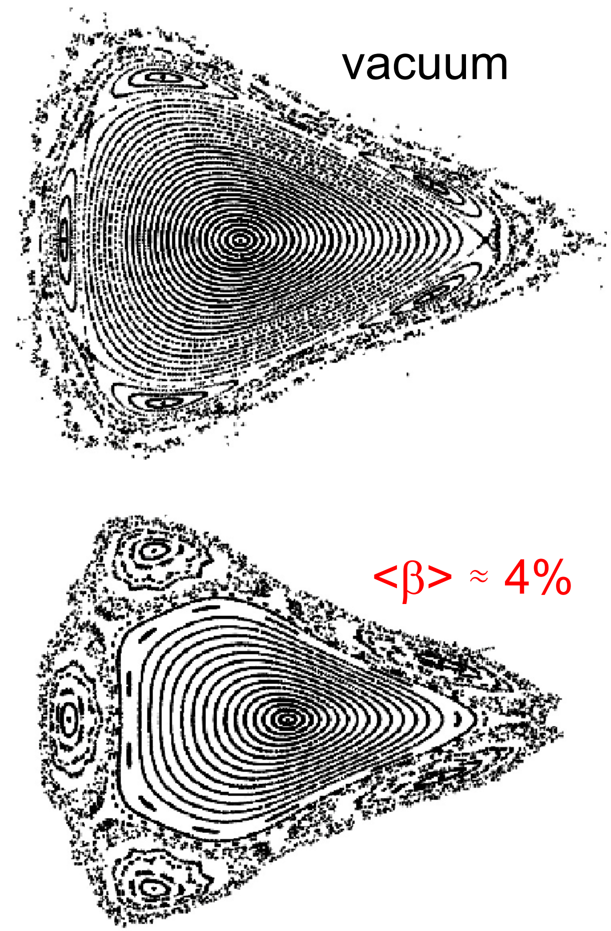
M.C. Zarnstorff, A. Reiman
PPPL

HINT-Analysis for LHD



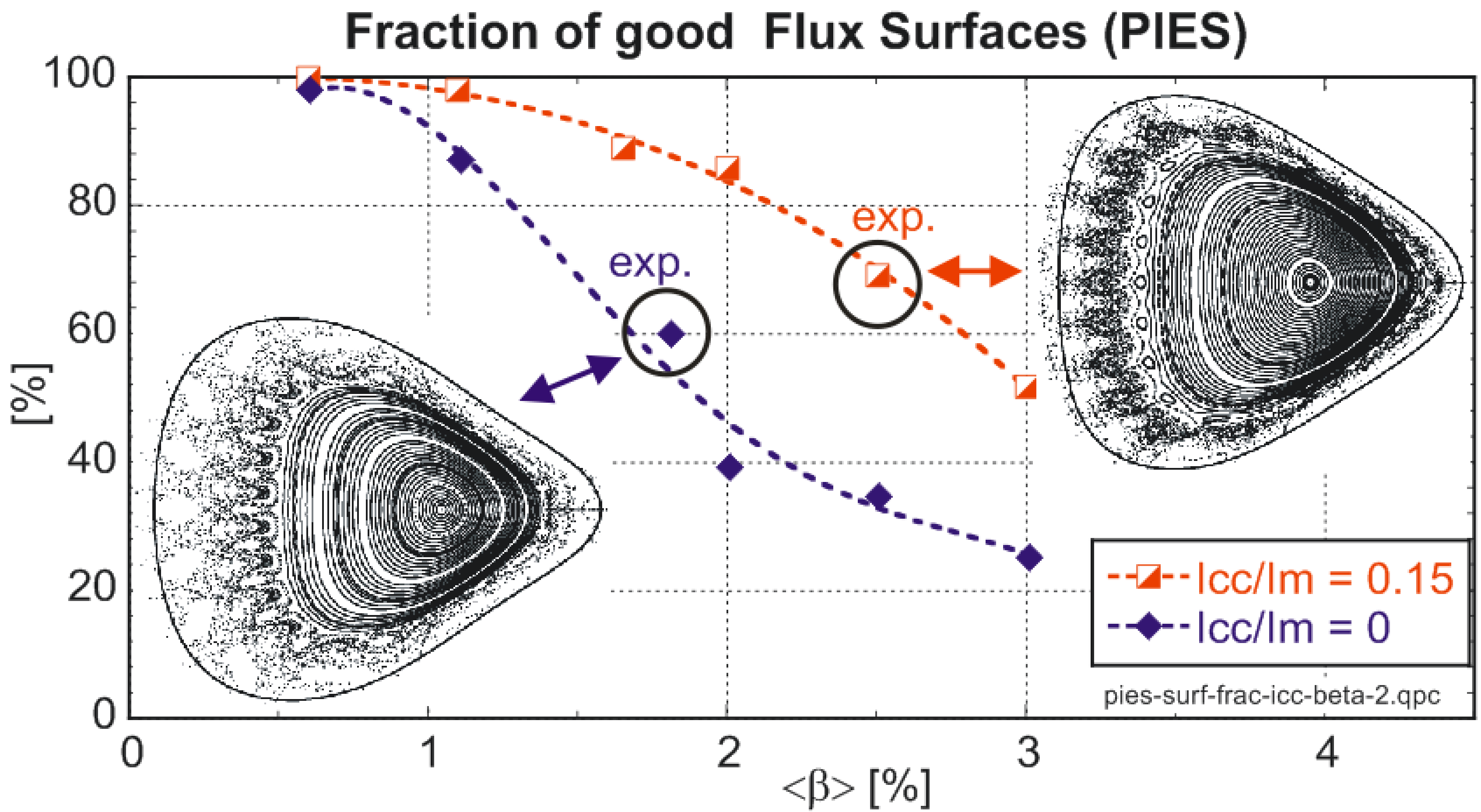
S. Sakaibara, Y. Suzuki
NIFS

PIES-Analysis for W7-X



M. Drevlak
IPP Greifswald

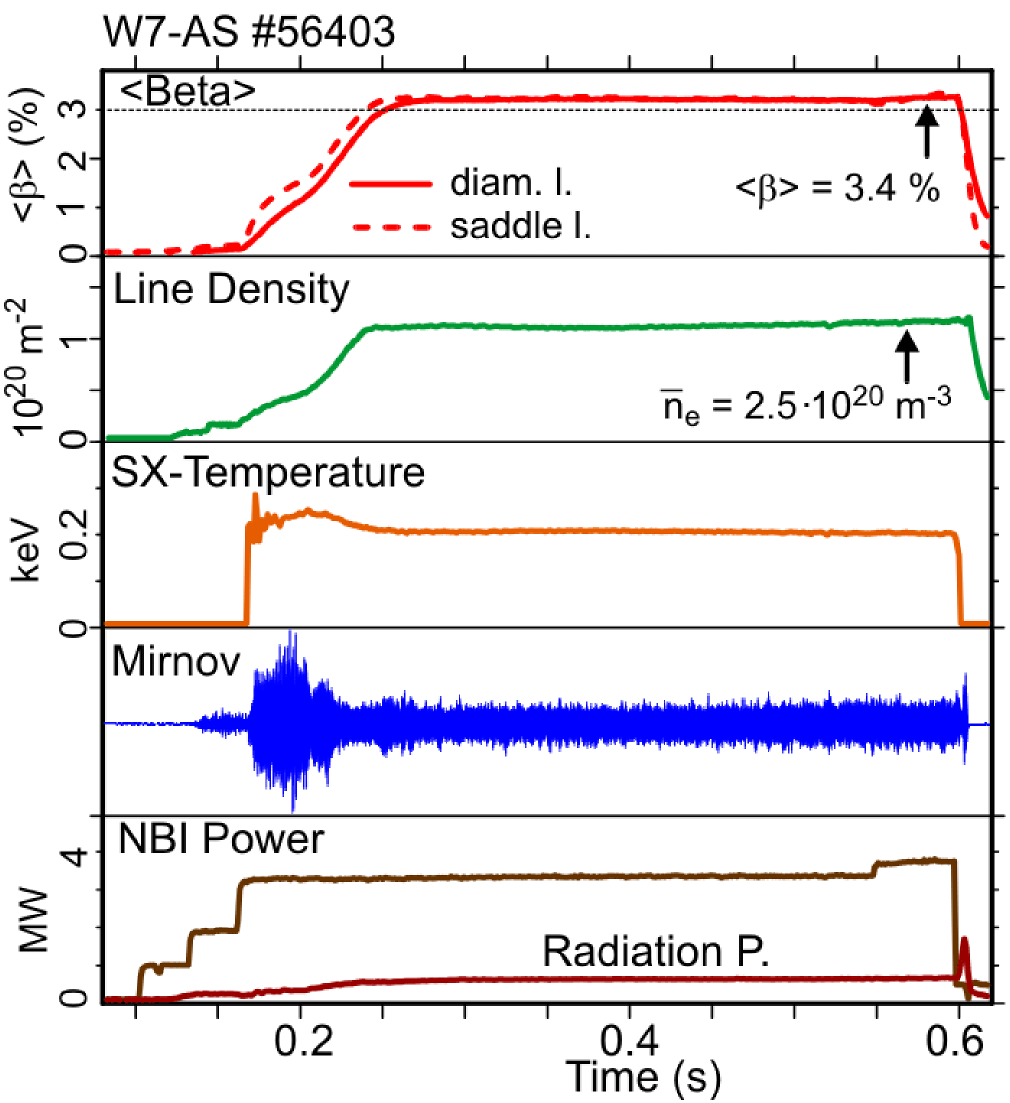
Effect of Control Coils on W7-AS High-β Equilibria



- Fraction of good flux surfaces decreases with β
- Control coils diminish β-induced destruction of magnetic surfaces

 A. Reiman, D. Monticello, M. Zarnstorff (PPPL)

Net-Current-Free High Beta Discharges in W7-AS
- $\langle\beta\rangle_{max} \approx 3.4$ %: Quiescent, Quasi-stationary -



- highest β at B = 0.9 T, $iota_{ext} \approx 0.5$
- quasi-stationary, $\tau_{flat\text{-}top} / \tau_E \approx 70$
- high density, density control, low radiation (edge localized)
- $\tau_{Imp} / \tau_E \leq 2$ from impurity injection
- Almost quiescent high-β phase, MHD-activity in medium-β Phase
- No ELMS, but low Z_{eff} (QC Mode ?)
  ELM mitigation by intrinsic RMP (stochastic edge) and high density ?
- Global behaviour similar to High Density H-Mode (HDH)

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- Bursting MHD activity (ballooning m. ?)
- MHD effects in high-β configurations with net current
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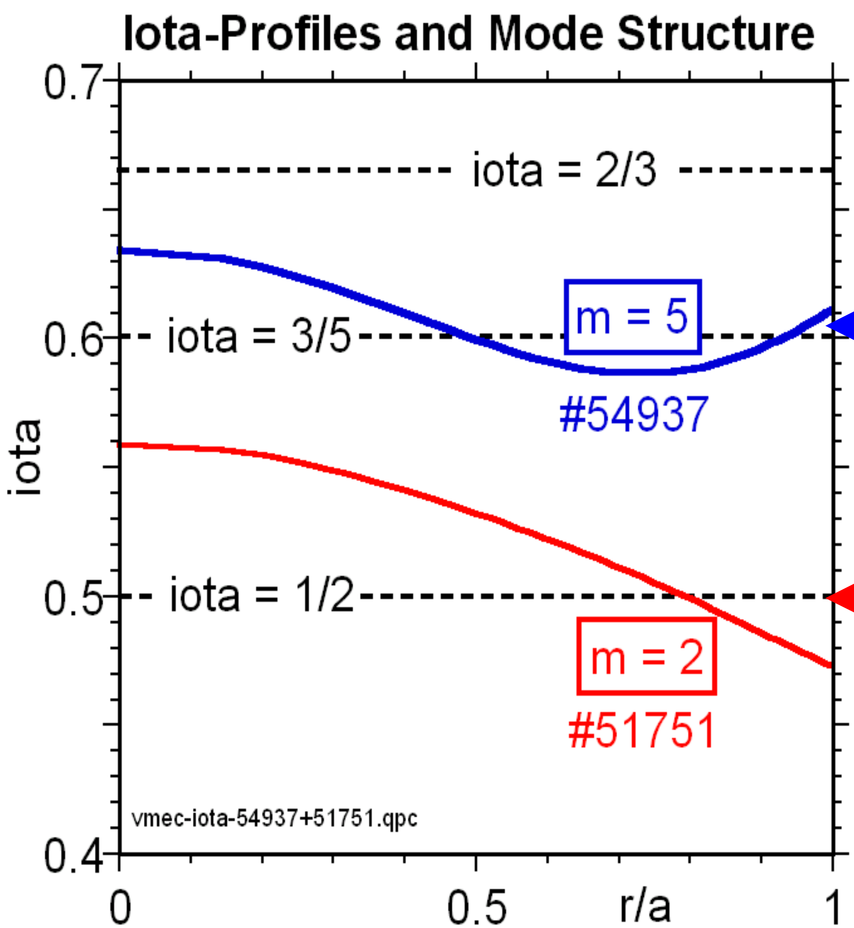
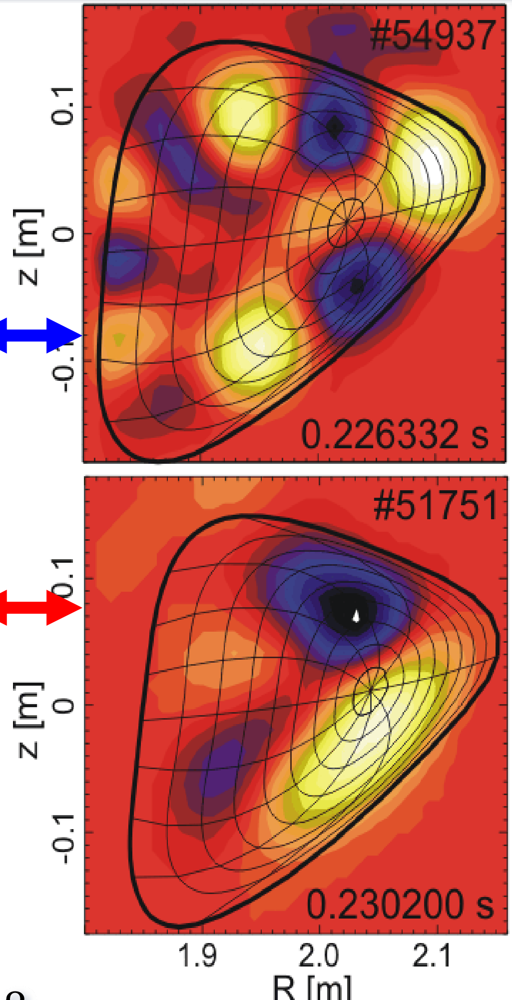
Summary, Conclusions

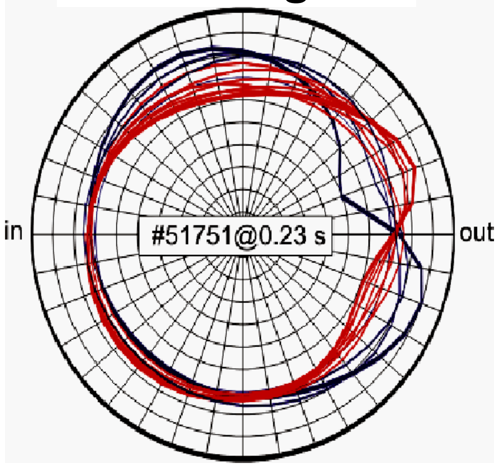
Global Low-n, Low-Frequency Modes in W7-AS High-β Configurations





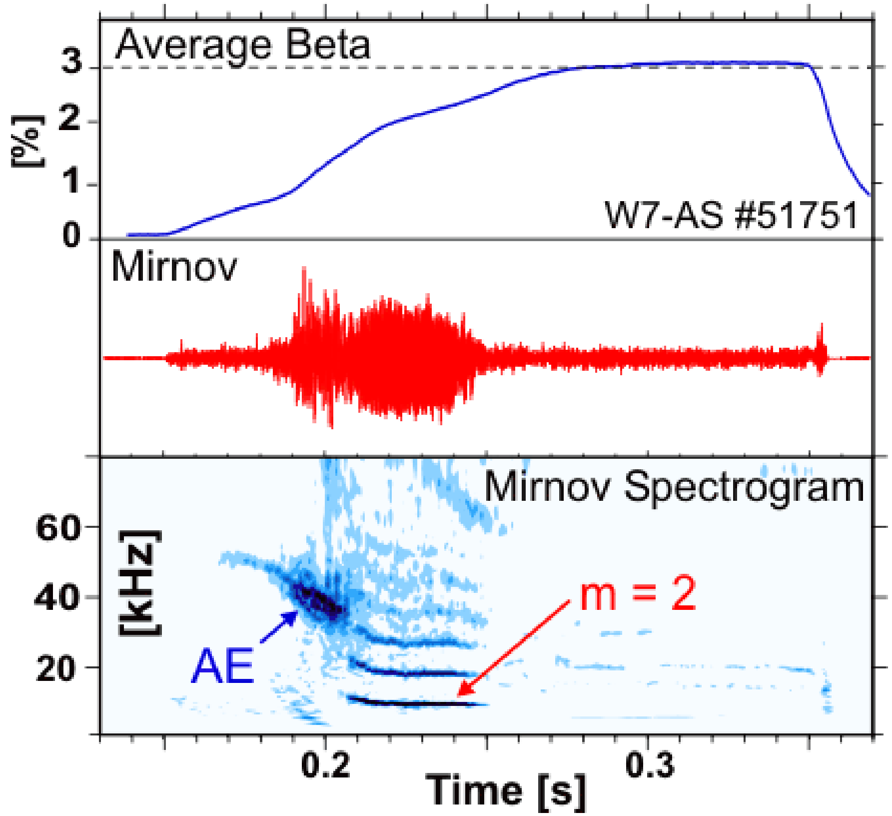
Perturbed X-Ray Emissivity (Tomog.)

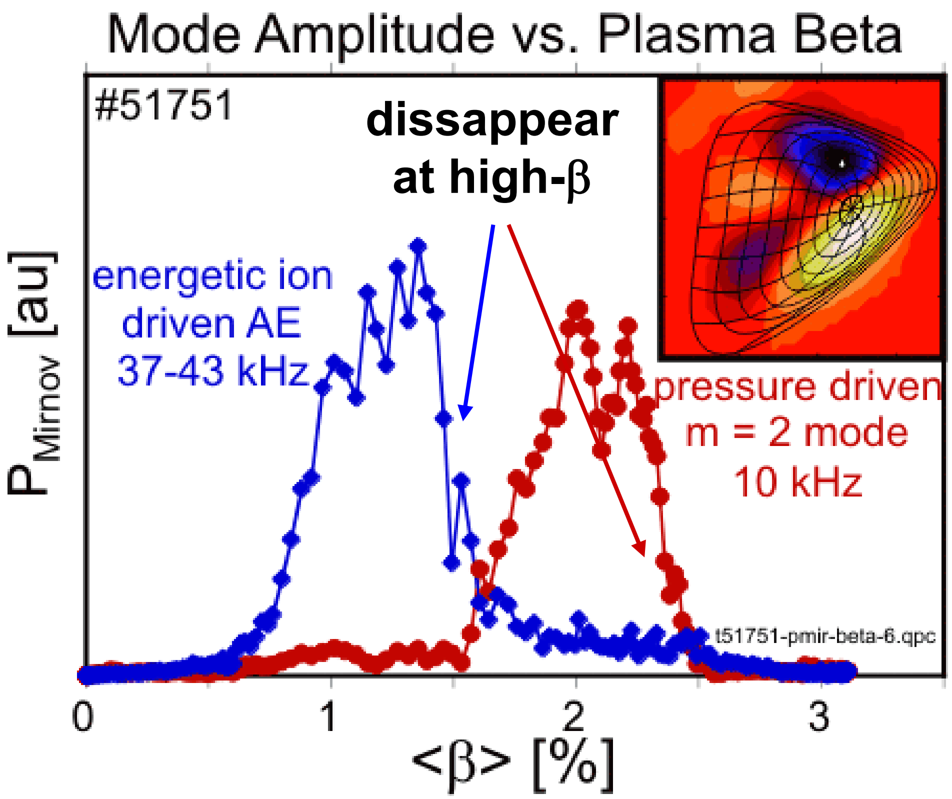
Mirnov-Ampl. Polar Diagram



- Mostly **transient** during intermediate β
- Mode numbers fit to **low order rational surfaces**
- Strong **ballooning effect** at outboard side in X-ray tomograms and magnetic data

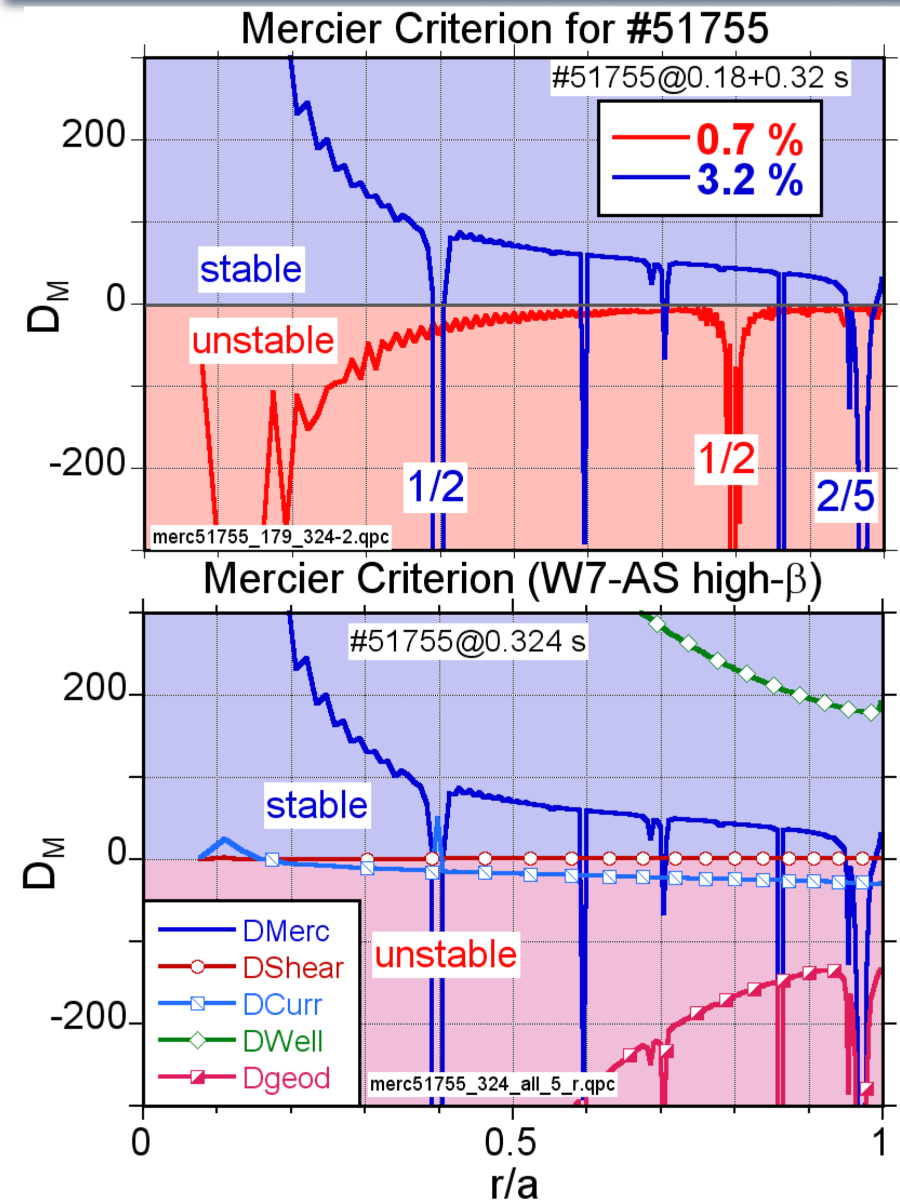
High-β MHD Activity in W7-AS
- Self-Stabilization of Low-n Modes -





- Predominantly benign pressure driven low-n mode activity below <β> =2.5 %
- Alfvén Instabilities restricted to lower density (higher fraction of fast ions)

High-β Stability Analysis in W7-AS
with 3D Equilibrium & Stability Codes



Mercier stability (local interchange modes)

- Mercier criterion necessary condition for stability of any ideal mode (m,n)
- violated at low-β in W7-AS high-β config.!
- index for stability of low-n modes localized around single rational surfaces

Global low-n mode stability

- global modes can be more stable or more unstable than Mercier modes

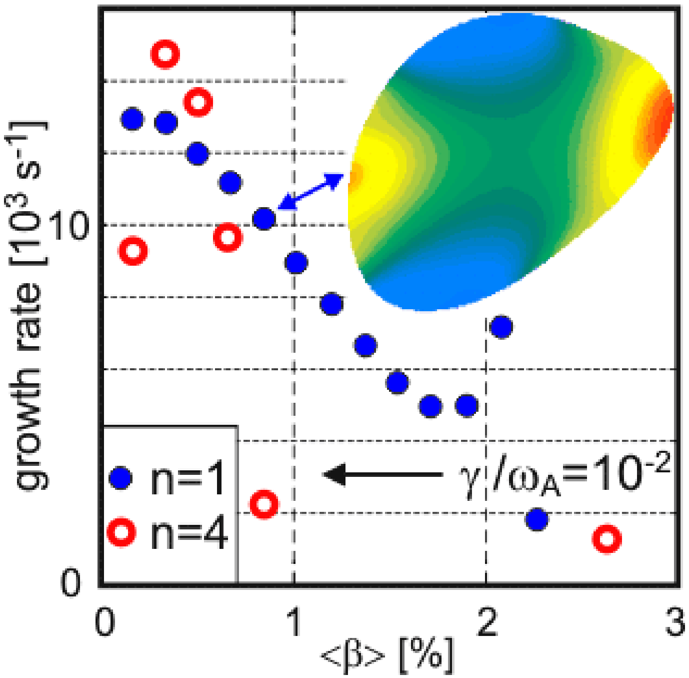
High-n ballooning stability

- necessary & sufficient condition
- typically, **Mercier criterion** imposes a **stricter stability limit** than ballooning m.

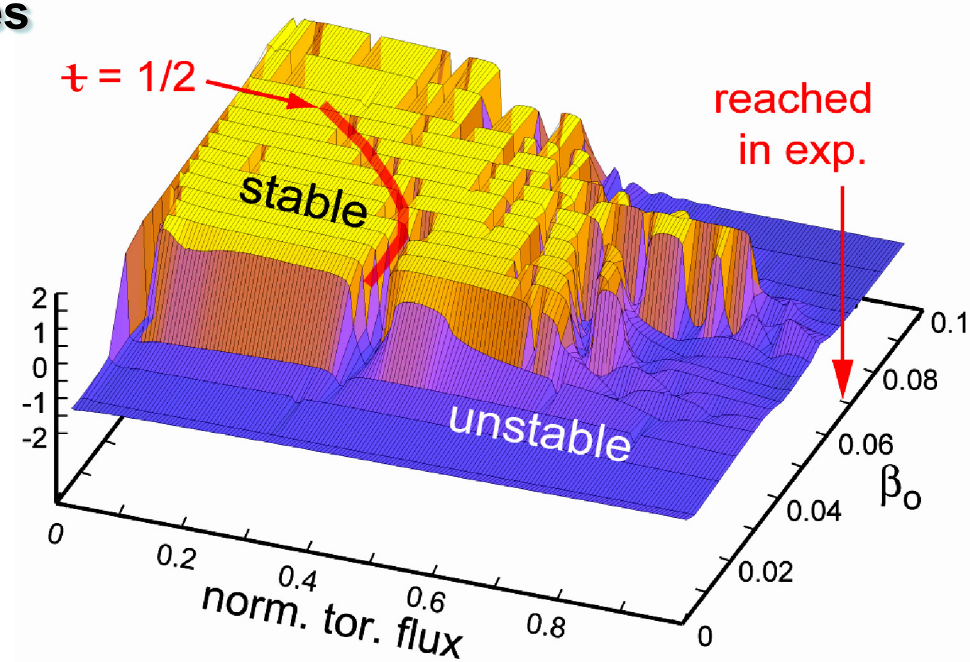
Linear MHD Stability Analysis (W7-AS)

- numerical beta scan confirms self stabilization -

CAS3D*): growth rates & perturbed pressure of unstable global ideal modes



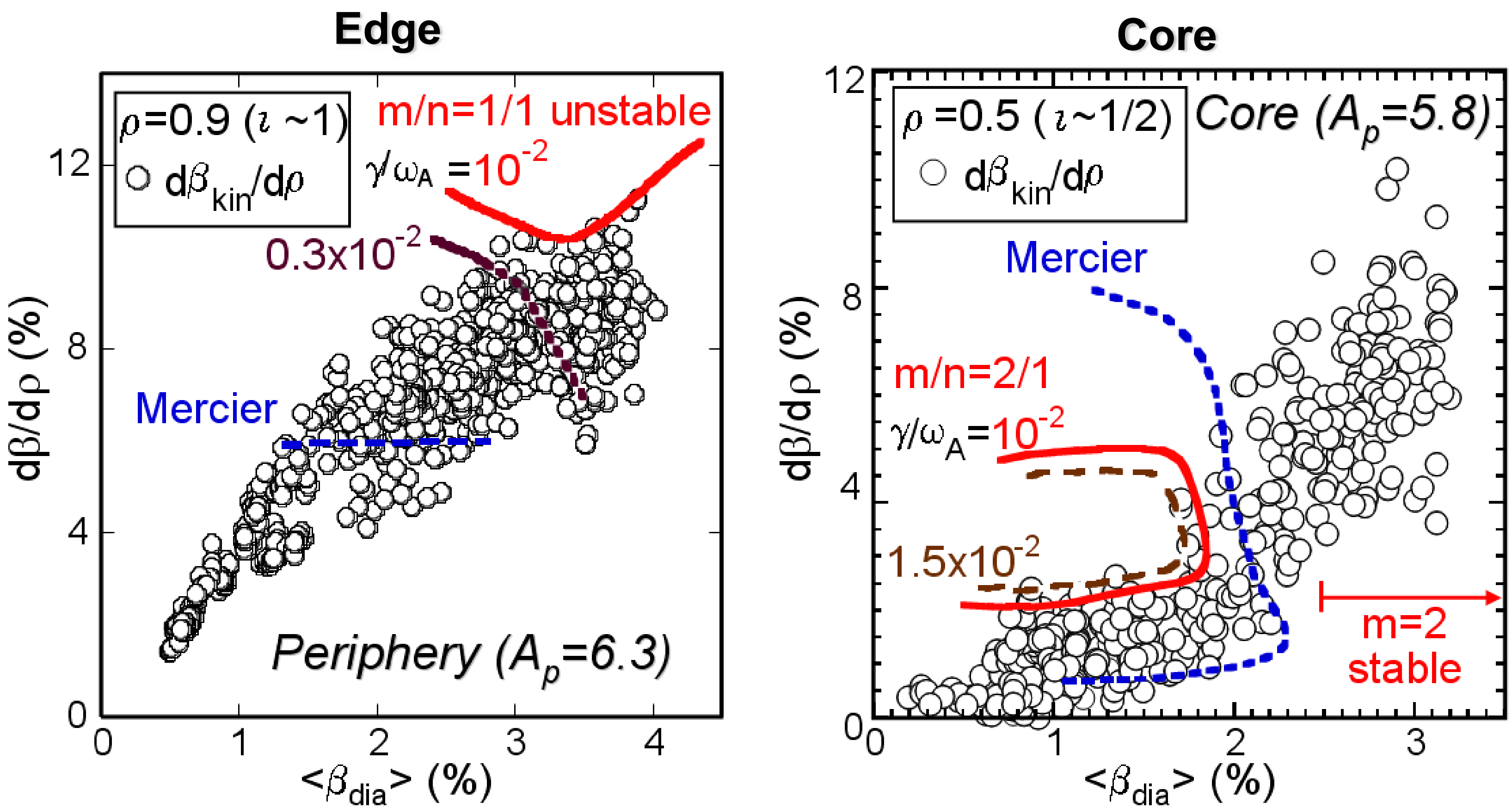
Mercier Stability Diagram



- **Unstable low-β region** (ideal global modes & local instability) predicted, but: observed **MHD mode activity stays on harmless level**
- **Self-stabilization at high β** (associated with Shafranov shift):
  - magnetic well depth & shear increased, equilibrium Mercier stable
  - shift of relevant rational surface

*) *C. Nührenberg (IPP Greifswald)*

Stability Boundaries in LHD
- pressure gradients maintained beyond Mercier limit -



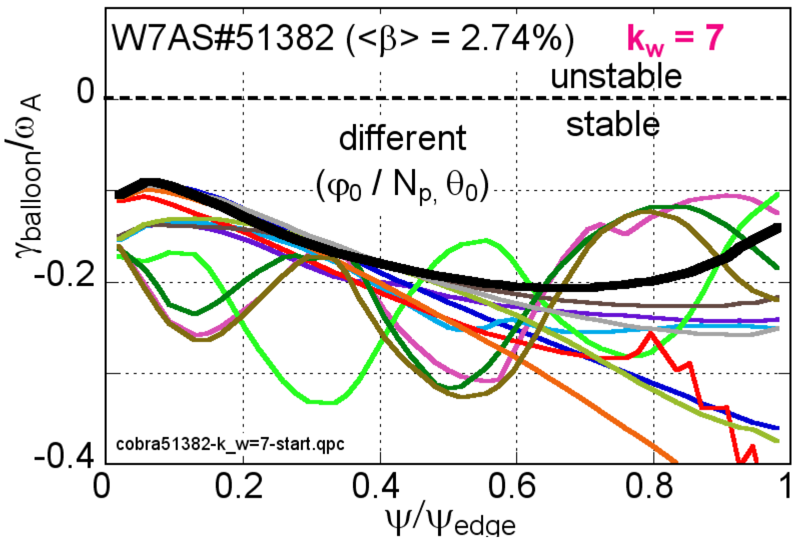
- **Mercier stability boundary** does not inhibit access to higher β, but (low level) mode amplitudes correlate with Mercier unstable region
- regions of unstable **low-n modes** with $\gamma/\omega_A \sim 10^{-2}$ (mode width $\delta/a \sim 5\%$) determines β-limit in LHD! (“relevant modes”) , but no disruptive phenomena !

K.Y. Watanabe, NF45 (2005) 1247

Analysis of Field Line Ballooning Stability

- with COBRA*) for high-β discharge 51382 in W7-AS -

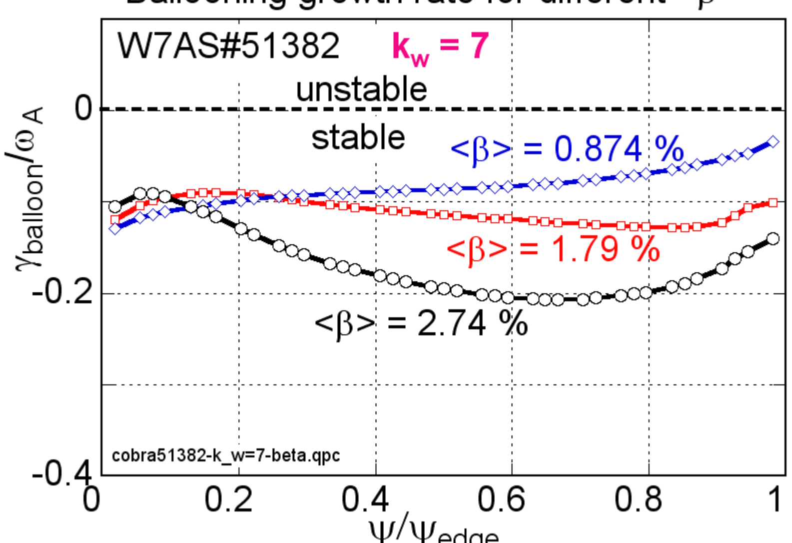
Ballooning growth rates for different start points



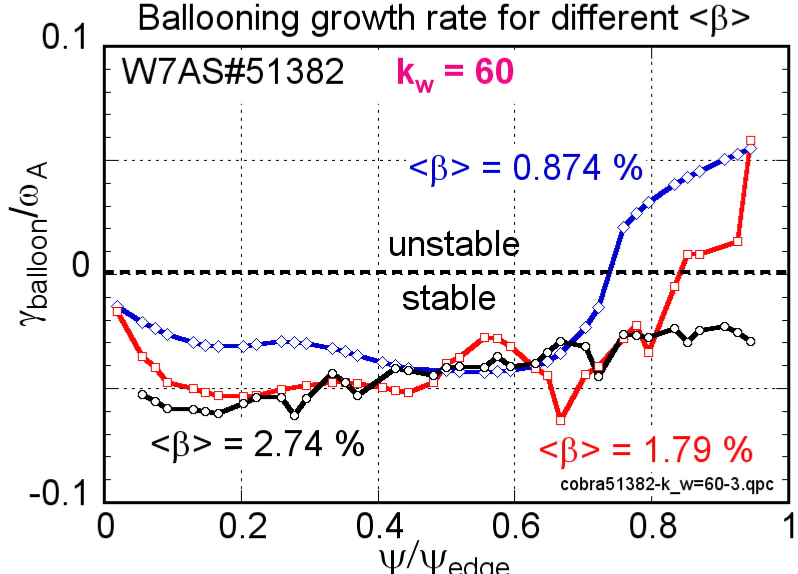
- Stellarator: ballooning stability depends on starting point of field line
- Strongly localized B.M. (k_w = 7) stable !
- Stability increases with beta ! (well depth)
- Extended B.M. (k_w = 60) unstable at edge and lower beta (approaching Mercier stab.)

k_w: periods of good and bad curvature

Ballooning growth rate for different <β>

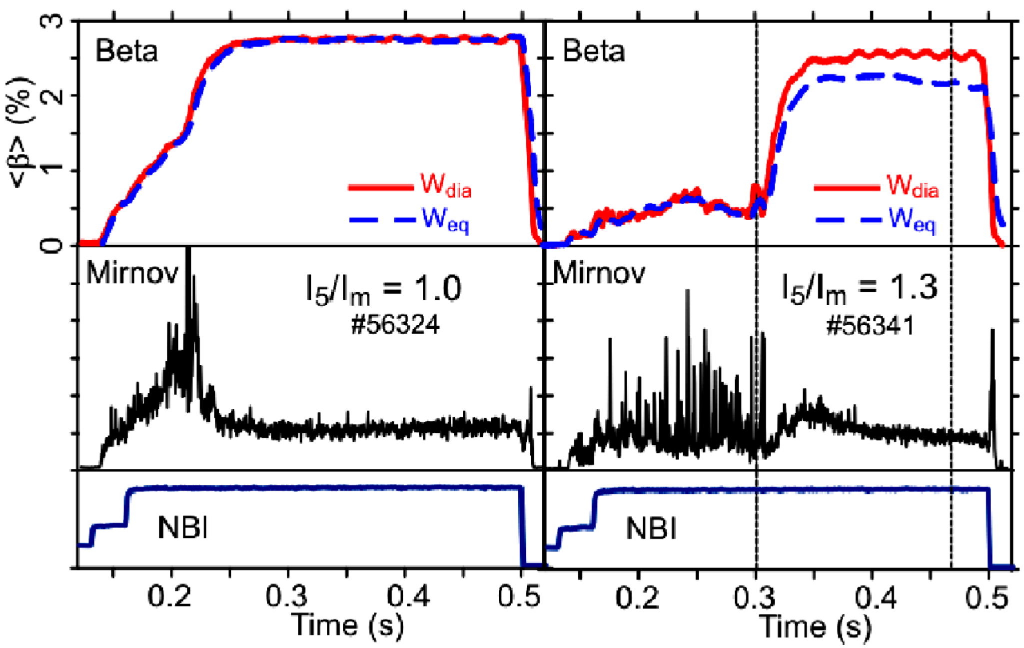


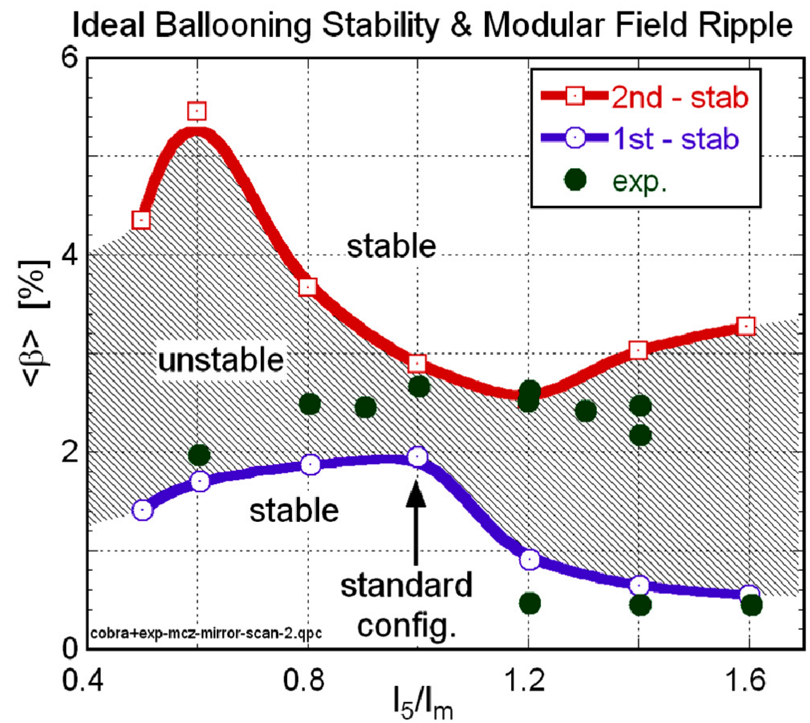
Ballooning growth rate for different <β>



*) R. Sanchez, D.A. Spong (ORNL)

Confinement Degradation by Ballooning Modes in W7-AS Configurations with Modular Ripple

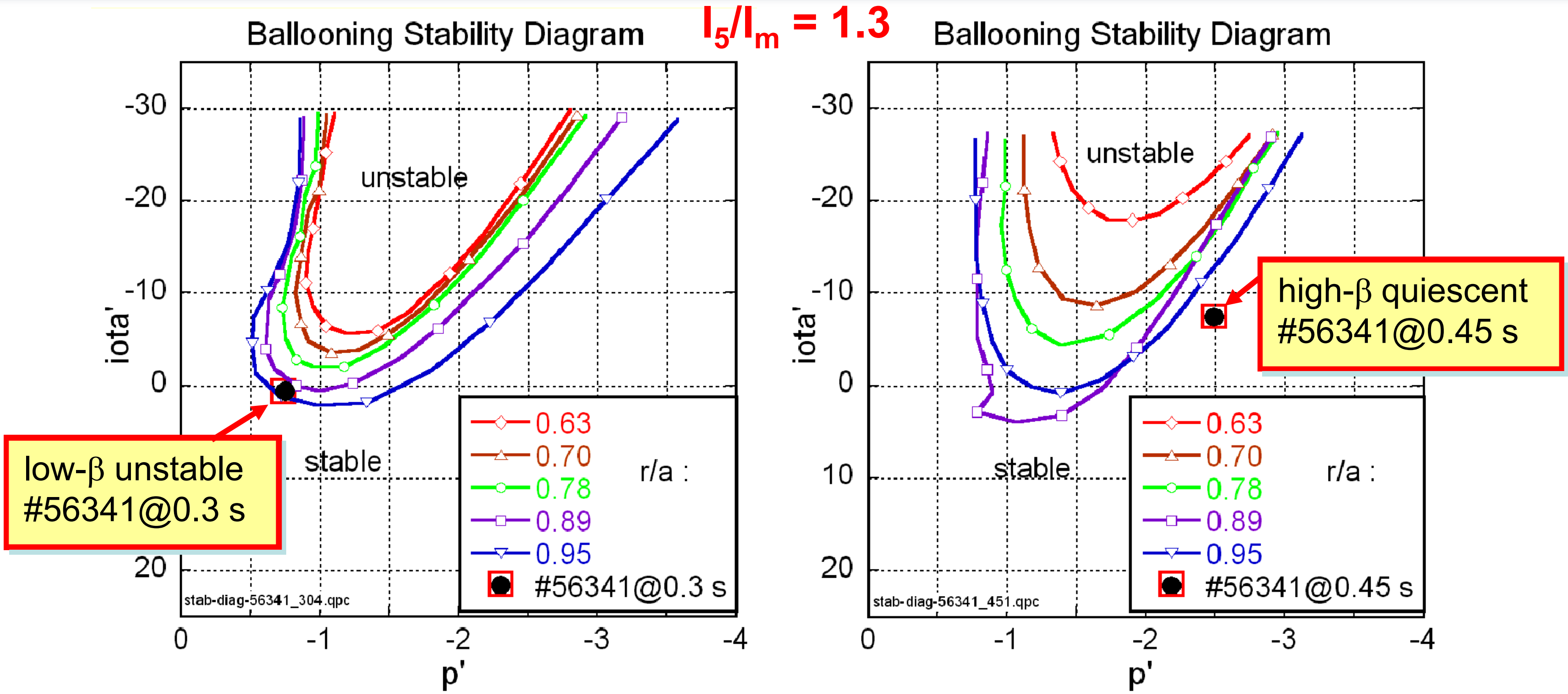




- **Bifurcation of <β>** observed in discharges with **non-standard I_5/I_m** (modular field ripple)
- Strong **ELM-like MHD bursts** during low-β phase of **degraded confinement**, transition from 1st to 2nd stability regime ?
- width of unstable band predicted by **3D ballooning code COBRA***)
  has a minimum for the standard configuration

**) R. Sanchez, NF 42 (2000) 641*

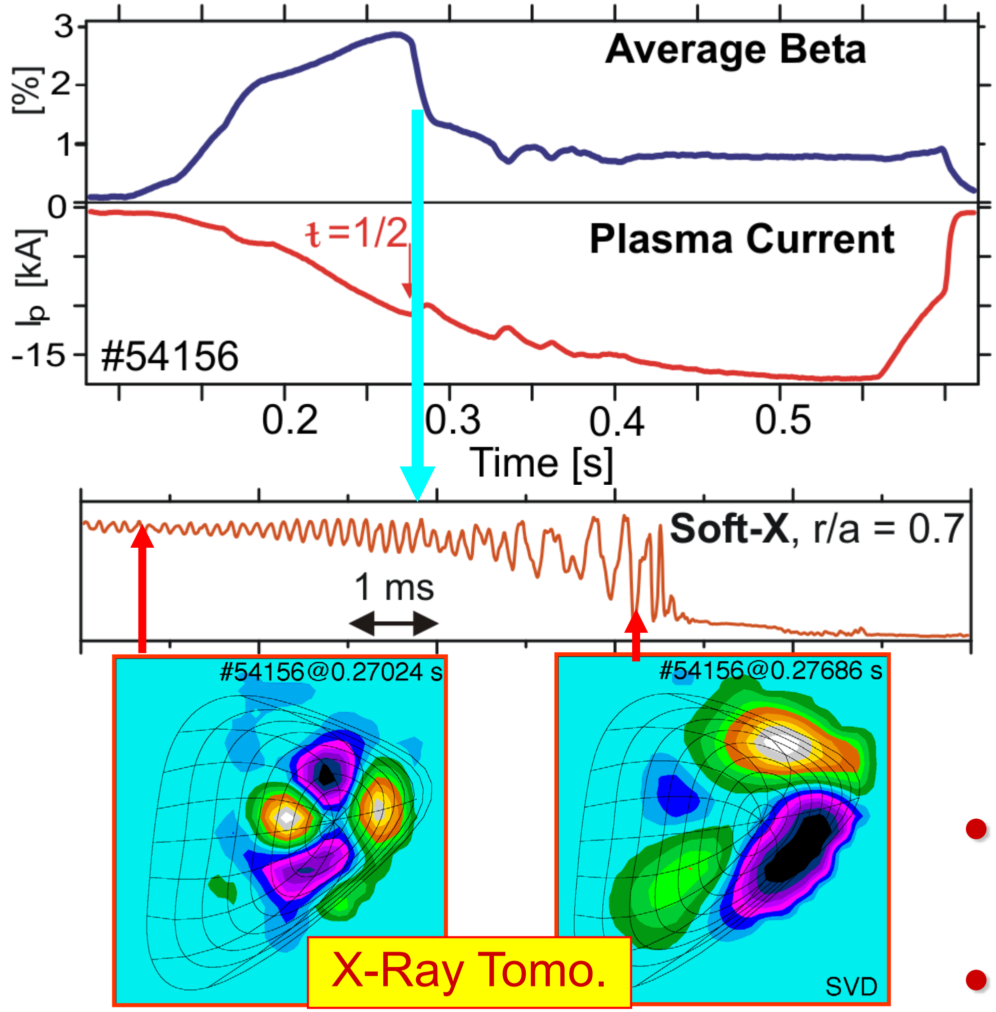
Ballooning Mode Stability in W7-AS Configurations with Modular Ripple

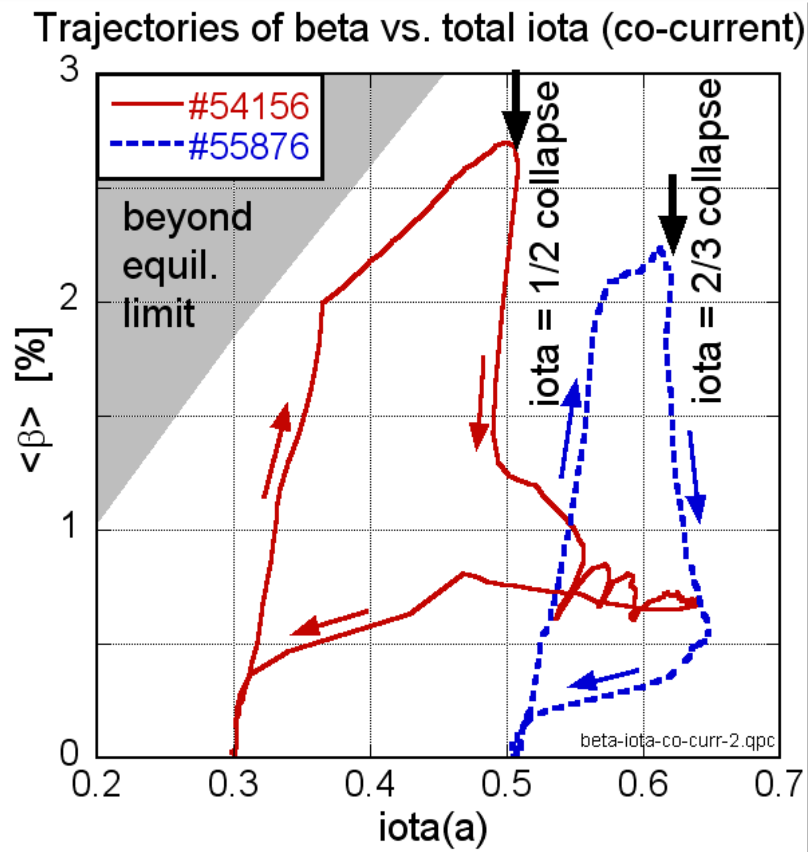


- **Marginal stability diagrams** for **infinite-n ballooning modes** obtained by a 3-D equilibrium perturbation method*) for different flux surfaces
- Two cases shown refer to **low- and high-β phases of I_5/I_m = 1.3 case** ("de-optim.")
- **Low-β phase** (with strong MHD) close to **1st stability boundary**
- Transition into high-β phase along **stable trajectory from 1st to 2nd stability** regime

 *) *S.R. Hudson and C.C. Hegna, Phys. Plasmas 10 (2003) 4716*

High-β Configurations with Co- toroidal Currents
- rotational transform increased by OH-current -

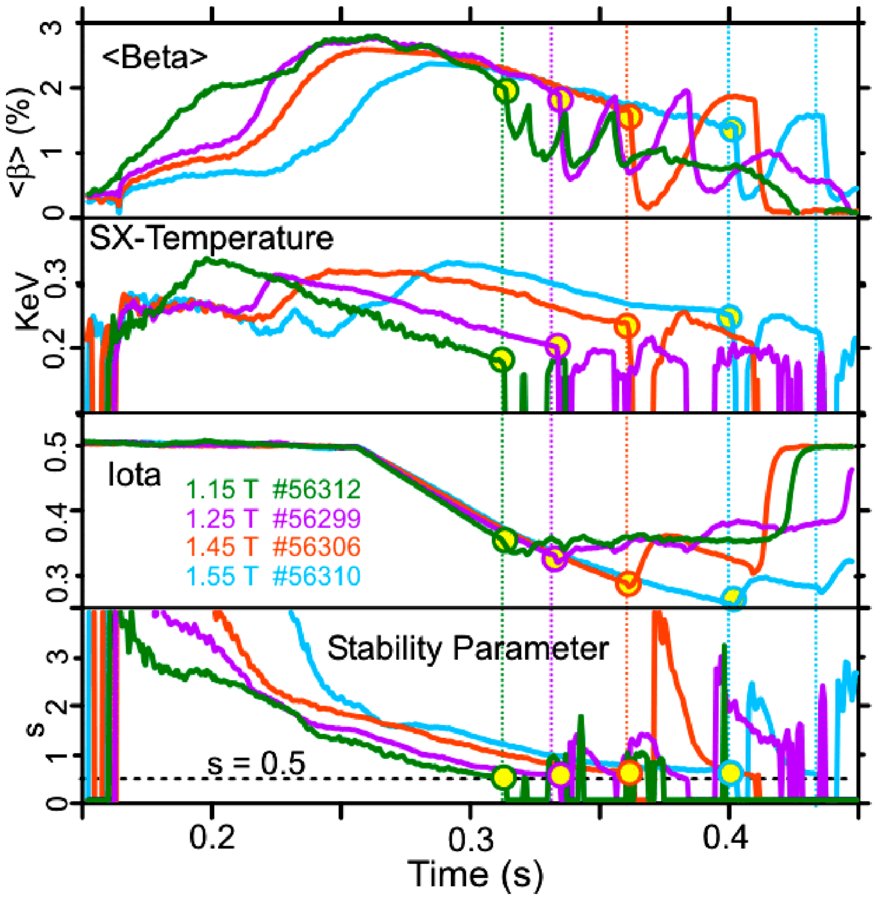


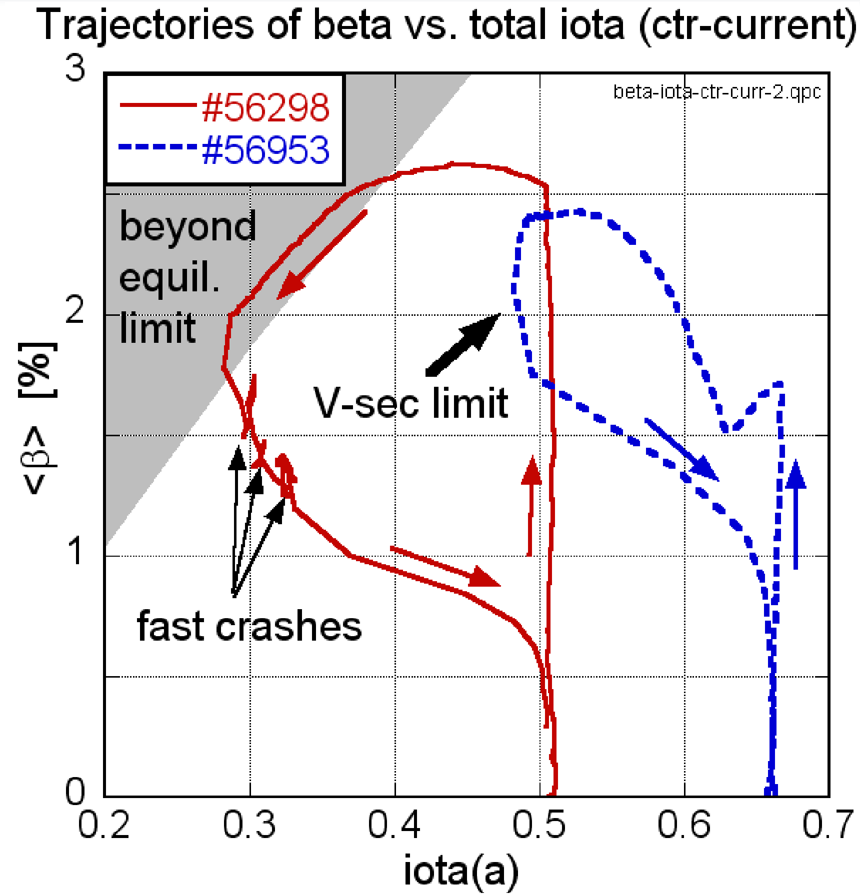


- β increases (equilibrium limit effect) transport adapts to the **equilibrium limit**
- **Tearing mode** activity & disruptive-like collapses when edge iota ≈ 1/2 or 2/3

High-β Configurations with Ctr- toroidal Currents

- rotational transform decreased by OH-current -

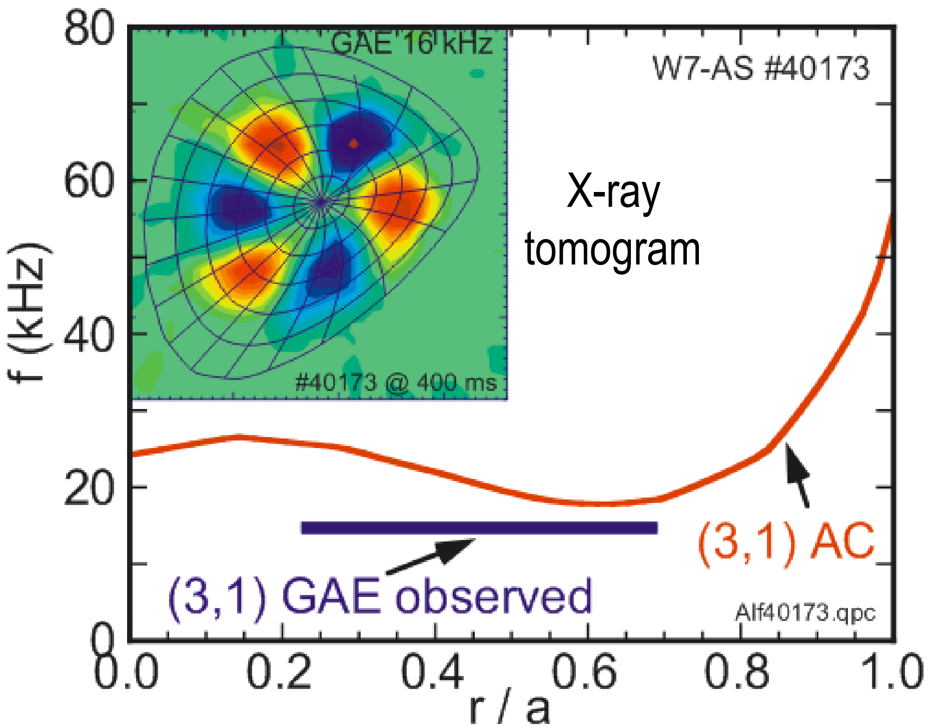




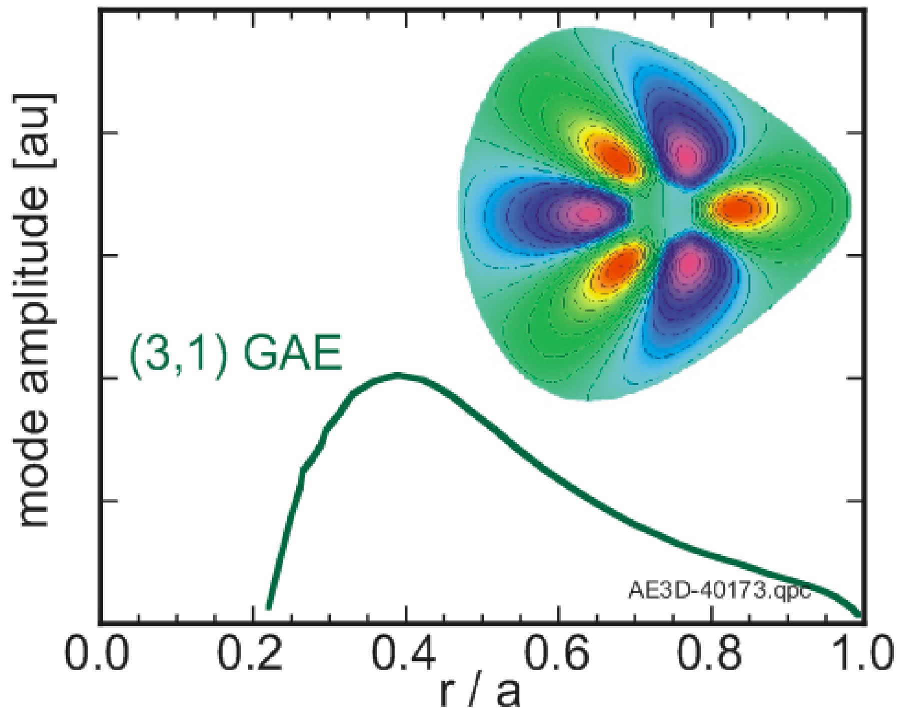
- β decreases (equilibrium limit effect), transport adapts to the **equilibrium limit**
- reproducible **fast MHD collapses** (~ 100 μs), preferentially at low iota and low T_e
- Growth of **resistive ballooning mode**: $\gamma \approx \left(\langle\beta\rangle / \langle\beta\rangle_c\right) \eta k^2 / \mu_0 \propto \left(\langle\beta\rangle / \iota^2\right) T_e^{-3/2}$
- Critical „**stability parameter**" s = 0.5 observed, $s \equiv 100\left(\iota^2 / \langle\beta\rangle\right) \cdot T_e^{3/2}$

NBI Driven Global Alfvén Eigenmodes in W7-AS
- AEs usually absent at high β (low β_{fast} / β_{th}) -

Low shear leads to formation of GAE gaps and low frequency single harmonic GAE



Modeling with 3D-gyrofluid code AE3D

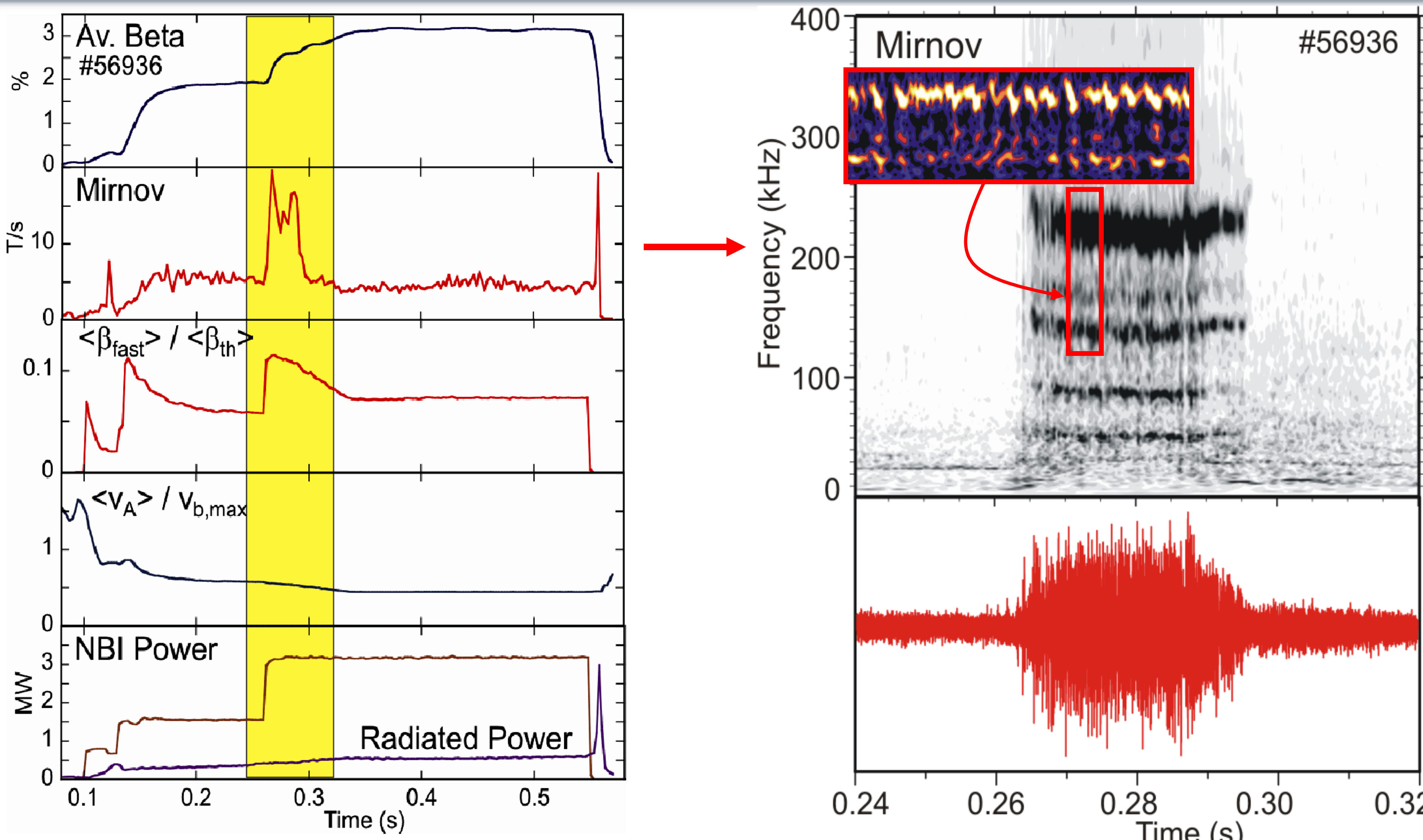


D.A. Spong, ORNL

WENDELSTEIN 7-X

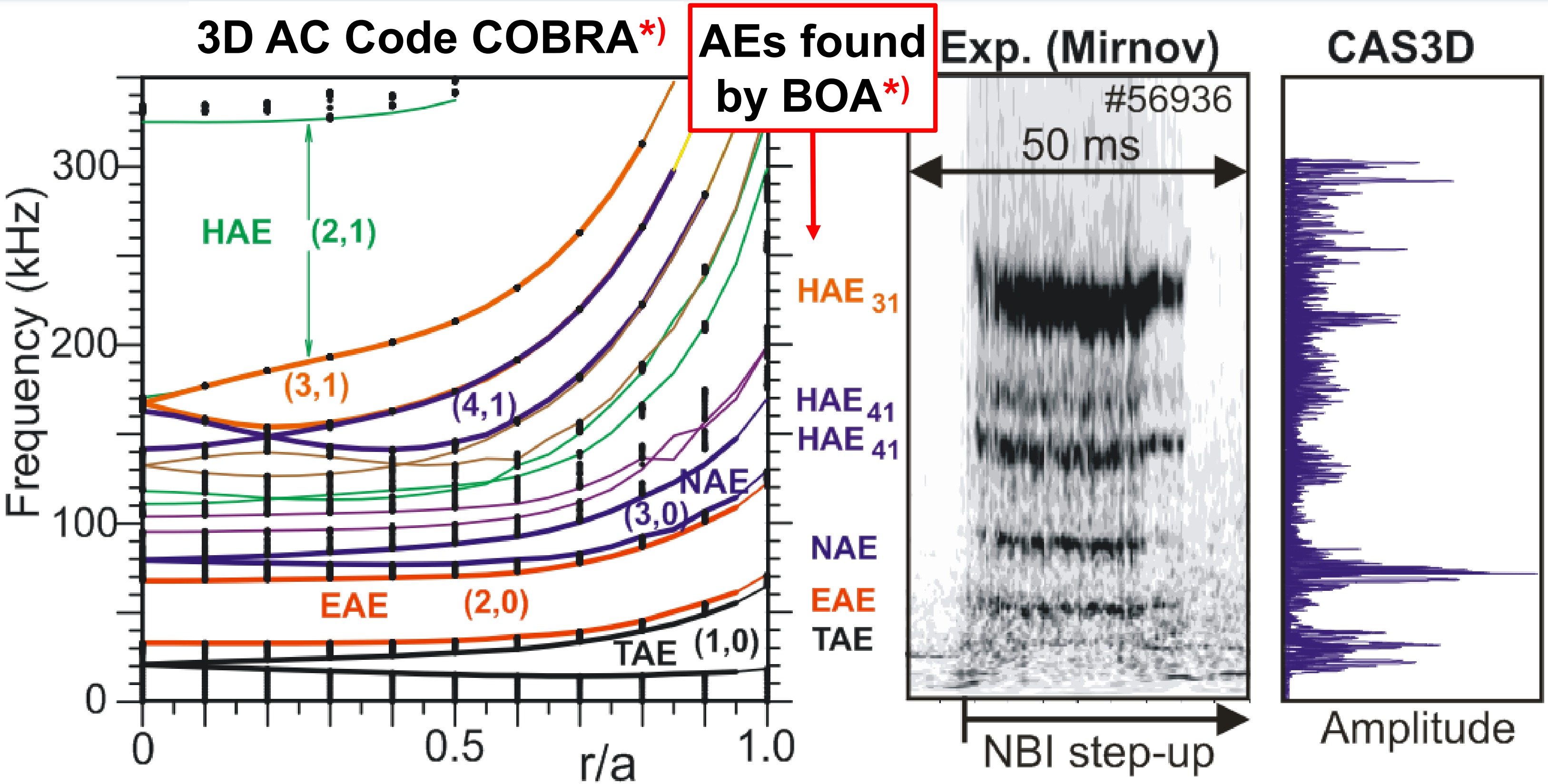
Transient Alfvén Instabilities in High-β Discharges

IPP



- AE Activity during **transiently increased** ⟨β_{fast}⟩/ ⟨β_{th}⟩ (~ fast particle drive)
- **HAE** (f > 50 kHz, |m| ≤ 20) stronger damped than low-m **TAE/EAE**

Transient Alfvén Instabilities in High-β Discharges
- Evidence of Helicity induced Alfvén Eigenmodes (HAE) -



$$|\mathbf{B}| = B_0\left[1+0.5\sum_{\mu\nu}\varepsilon_B^{\mu\nu}(\psi)\cos\left(\mu\theta-\nu N_p\phi\right)\right]$$

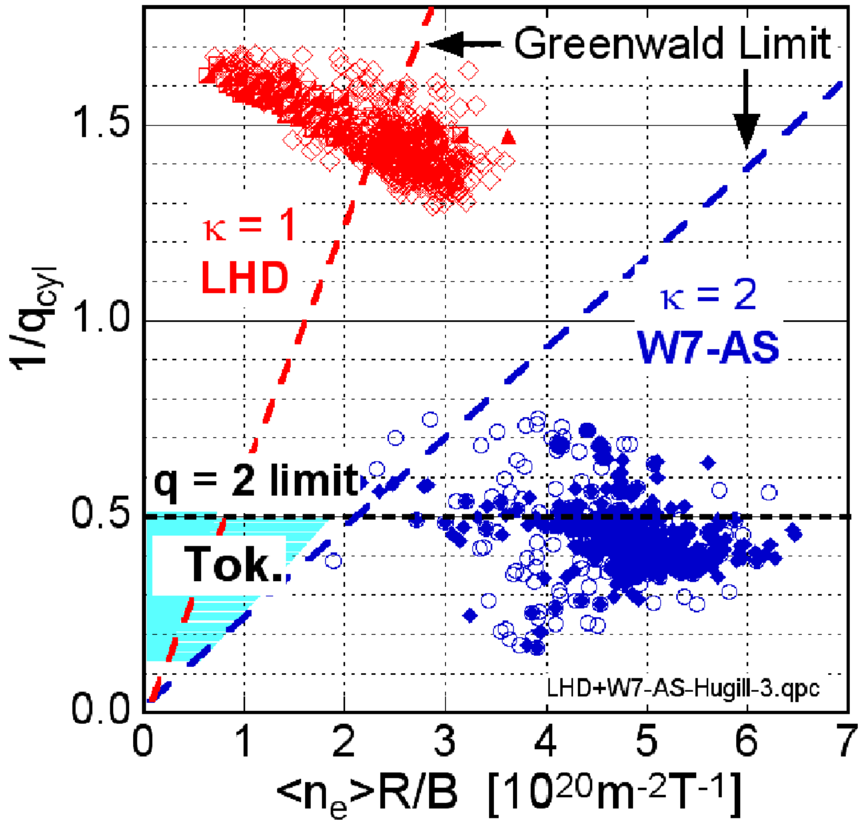
- **Characteristic frequencies** determined by intersections of cylindrical AC branches $k_{||}(m,n)v_A = -k_{||}\left(m+\mu, n+\nu N_p\phi\right)v_A$ (at $r = r_*$)

*) *Y.I. Kolesnichenko Fusion Sci. Technol. 46 (2004)54*

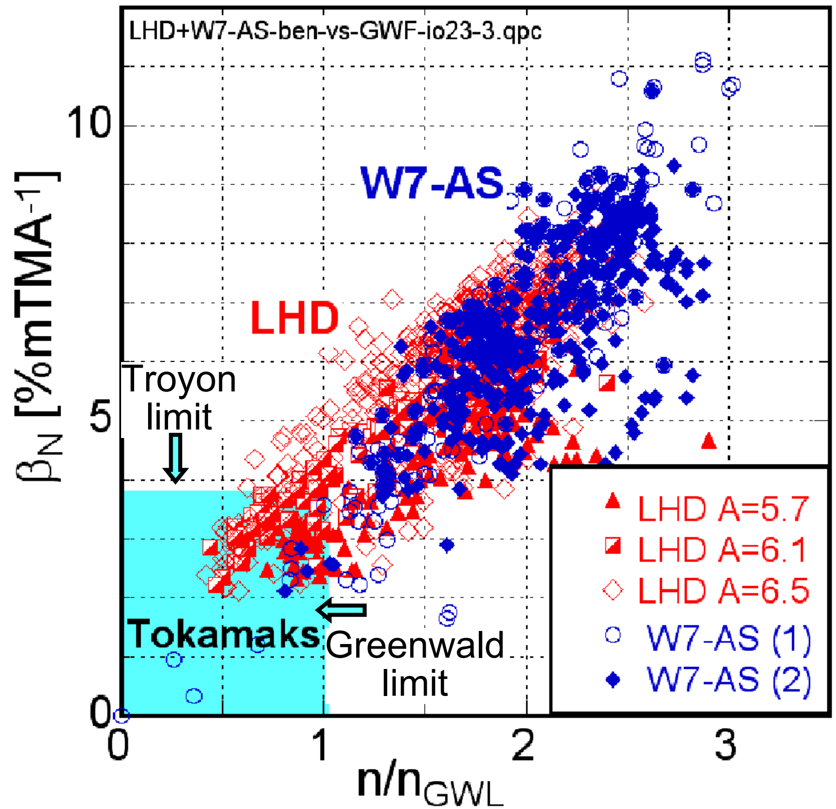
High-Beta Operational Boundaries
- comparison with tokamaks via „equivalent current“ -

$$I_{eq} = f(\varepsilon)\iota\left(\tfrac{2}{3}a\right)\left(5a_c^2B/R\right)\left[1+\kappa^2\left(1+2\delta^2-1.2\delta^3\right)\right]/2\kappa \qquad \iota(I_{eq}) \cong \iota\left(\tfrac{2}{3}a\right)$$

Hugill-Diagram for **LHD** & **W7-AS** (high-β)



Normalized Beta vs. Greenwald Factor



- **No disruptive** or Greenwald–like **density limit** in current-free helical systems
- **Beta** in stellarators **not limited by violent MHD** up to reactor relevant values

Summary, Conclusions

- Quasi-stationary, disruption-free **high-β** plasmas realized **w/o active control** in **W7-AS** ($\langle\beta\rangle > 3\ \%$) and **LHD** (up to $\langle\beta\rangle \approx 5\ \%$)
- High-β configurations have **inherent stochastic edge, no ELMs** but efficient impurity flushing and good density control (**HDH in W7-AS**)
- **Correction coils** in W7-AS essential for optimizing **island divertor** and **high-β** operation (in opposite directions)
- High-β **MHD stability** governed by **self-stabilization** effects induced by beta induced changes of equilibrium configuration)
- **MHD modes** mostly **benign or absent**, even in Mercier unstable regions
- Fast MHD crashes (W7-AS) attributed to **ballooning modes**, only present in **de-optimized configurations** including ctr-current drive)
- **Alfvén Instabilities** suppressed at high β due to high density (W7-AS)
- Operational boundary set by **equilibrium β-limit**, not by stability limit
- Good MHD stability up to $\langle\beta\rangle \approx 5\ \%$ expected for **W7-X**

Summary, Conclusions

- Quasi-stationary, disruption-free **high-β** plasmas realized **w/o active control** in **W7-AS** (<β> > 3 %) and **LHD** (up to <β> ≈ 5 %)
- High-β configurations have **inherent stochastic edge, no ELMs** but efficient impurity flushing and good density control (**HDH in W7-AS**)
- **Correction coils** in W7-AS essential for optimizing **island divertor** and **high-β** operation (in opposite directions)
- High-β **MHD stability** governed by **self-stabilization** effects induced by beta induced changes of equilibrium configuration)
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