Particle balance at HSX and W7-X, stellarators with different edges

L. Stephey, D. T. Anderson, F. S. B. Anderson, A. R. Akerson, A. Bader, C. Biedermann, S. Bozhenkov, C. Deng, P. Drews, F. Effenberg, J. Harris, R. Koenig, P. Kornejew, M. Krychowiak, Y. Liang, S, Liu, O. Neubauer, G. Satheeswaran, O. Schmitz, E.A. Unterberg, H. Viebke, G. A. Wurden, and the W7-X Team

Coordinated Working Group Meeting, Greifswald Germany

21 March 2016

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EUROfusion

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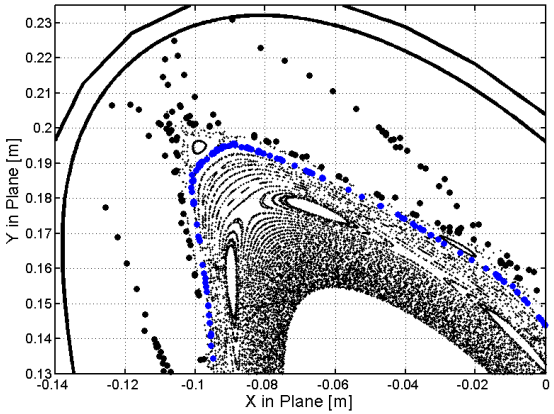
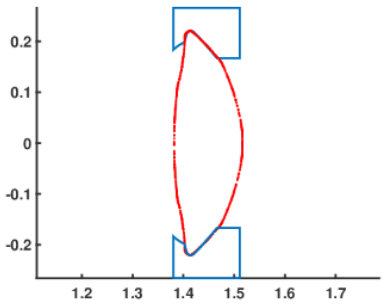
Motivation and goals

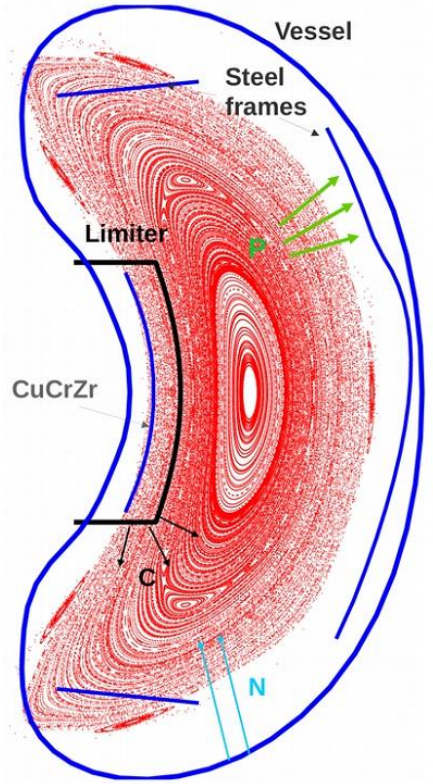
- Explore confinement, recycling, and particle balance in HSX and W7-X
- HSX
  - SOL with 8/7 islands outside LCFS
  - 2 movable limiters to intercept all or part of islands
  - Can transition from island to ‘pure’ SOL
- W7-X
  - 5 fixed limiters
  - No edge islands
  - Movable 5/6 island in confinement region
- Examine impact of islands on global particle confinement and recycling behavior

HSX





W7-X

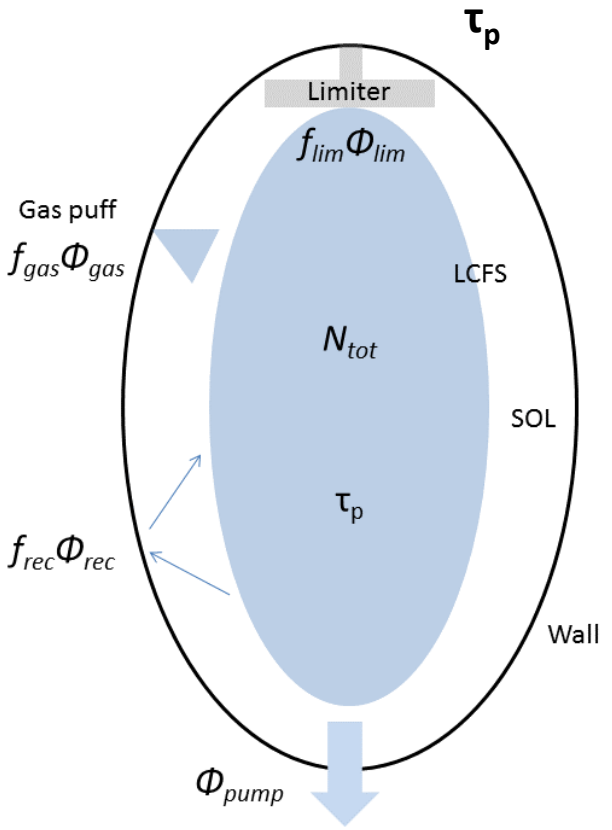


Compare particle balance in HSX and W7-X

Single reservoir model

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim}$$

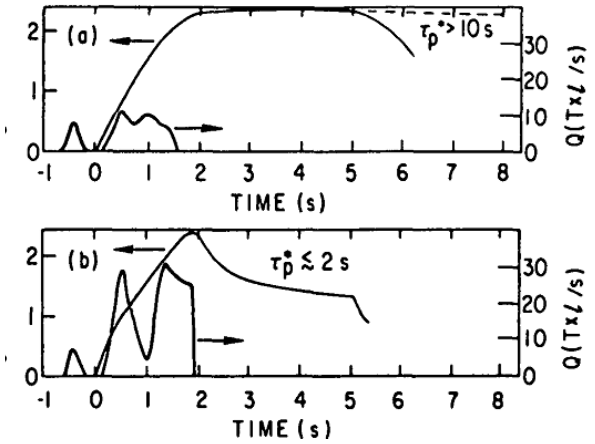
- An indication of global particle confinement (τ_p)
- Together with τ_p * experiments, can provide measurement of global recycling coefficient *R*



Global recycling coefficient

$$R = 1 - \frac{\tau_p}{\tau_p^*}$$

τ_p *



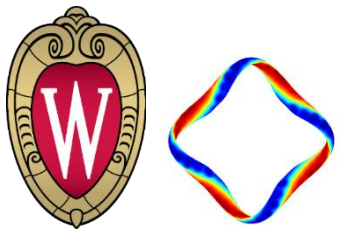
H. F. Dylla et al., "Conditioning of the graphite bumper limiter for enhanced confinement discharges in TFTR." Nucl. Fusion Vol 27, No. 8, 1987.

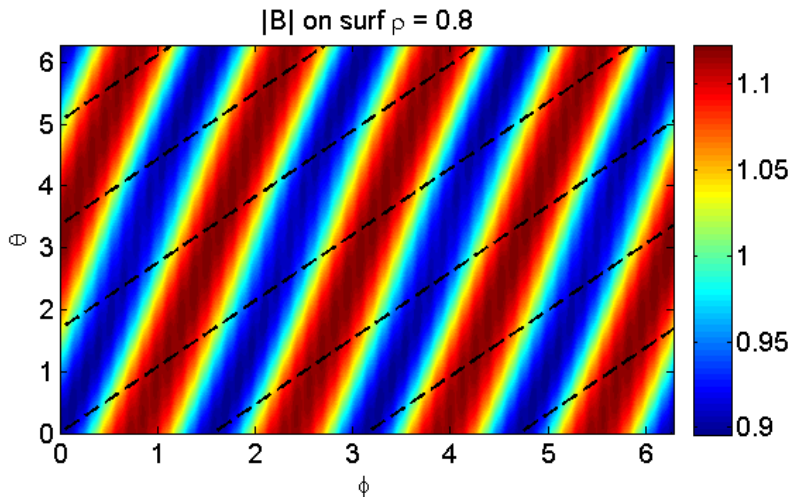
HSX is an optimized stellarator with a direction of symmetry in |B|

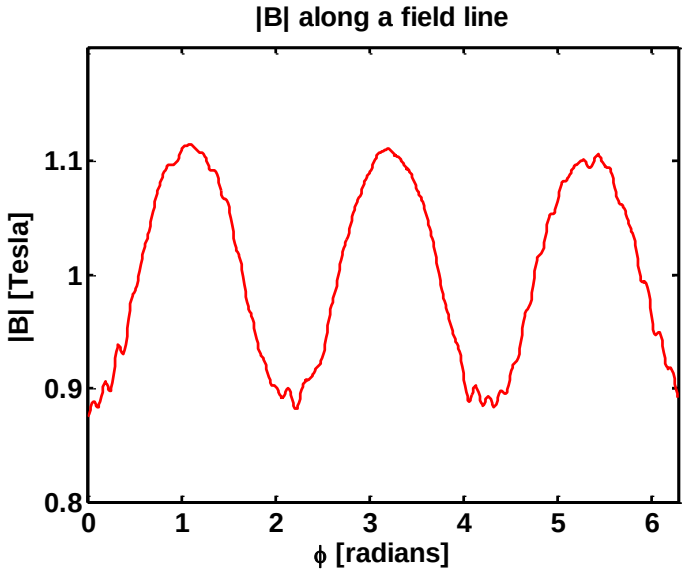
- HSX has been optimized for quasi-helical symmetry: |B| symmetric in the helical direction (n=4, m=1)
- This is designed to give tokamak-like neoclassical transport properties
- High effective transform leads to smaller excursions from a flux surface, reduced BS and PS currents, reduced neoclassical transport

$$B/B_0 = 1 - \varepsilon_h \cos\left(n - m\iota\right)\phi$$

$\iota_{eff} \sim 3$

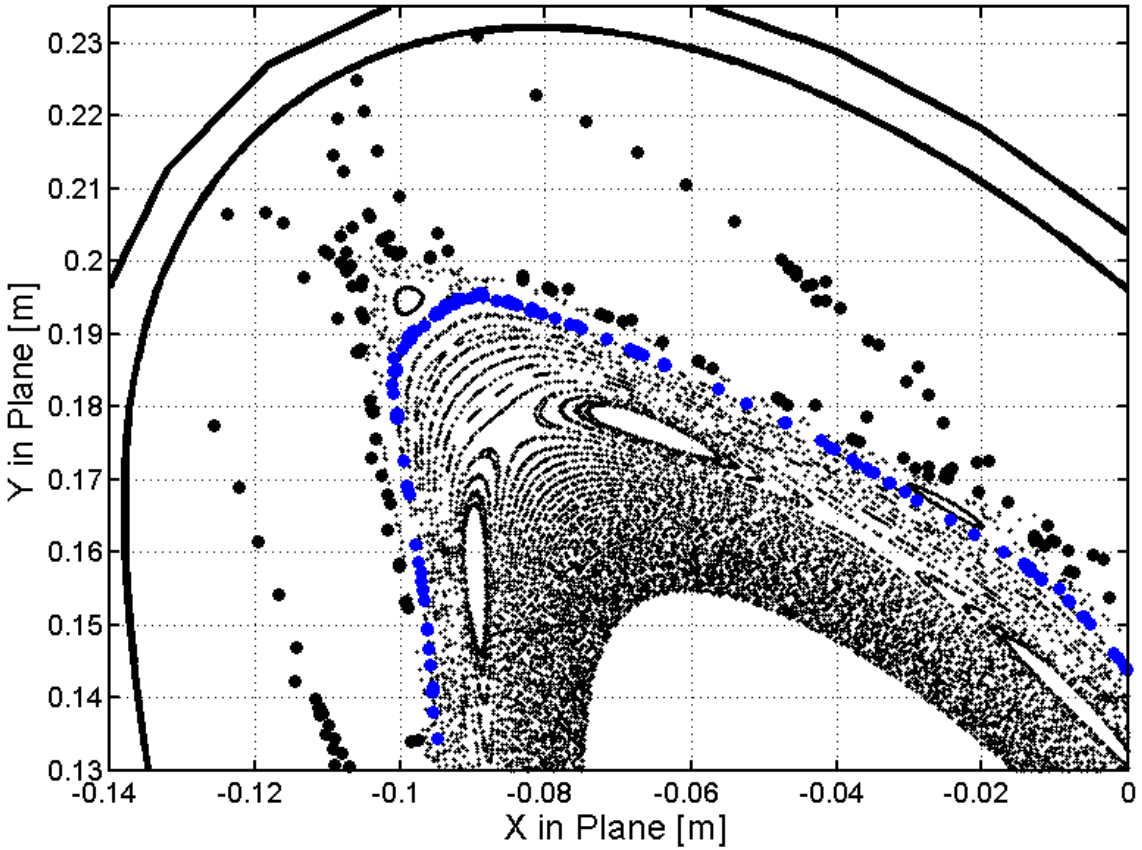






HSX experimental parameters

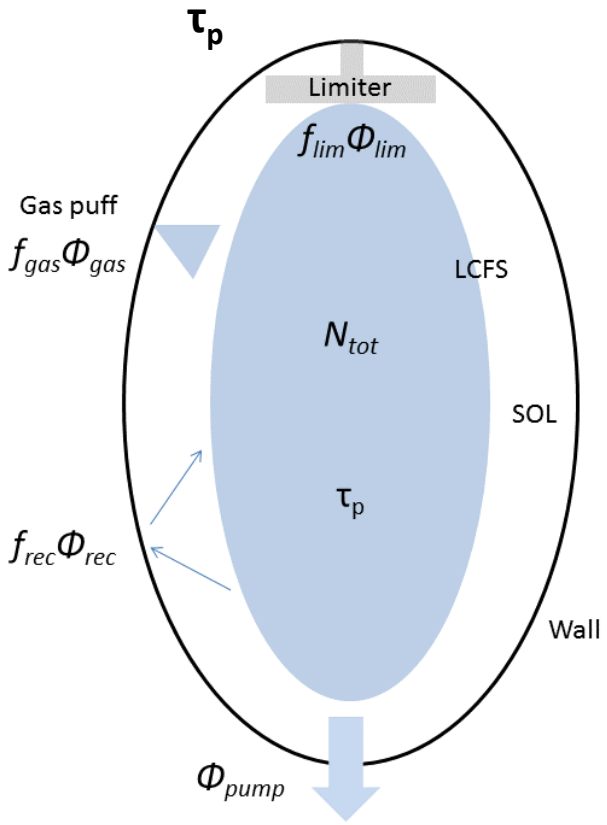
R	1.2 m
r	0.15 m
$n_{e,\,core}$	5E18 m^{-3}
$T_{e,\,core}$	2.5 keV
$T_{i,\,core}$	60 eV
$n_{e,\,edge}$	5E17 m^{-3}
$T_{e,\,edge}$	70 eV
$T_{i,\,edge}$	25 eV

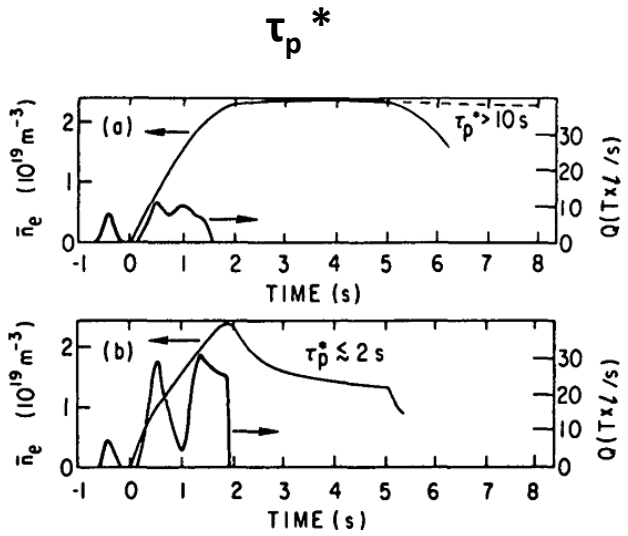


In the QHS configuration, HSX has an 8/7 island chain outside the LCFS

Particle balance and recycling in HSX

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim} \qquad R = 1 - \frac{\tau_p}{\tau_p^*}$$





Particle balance and recycling in HSX

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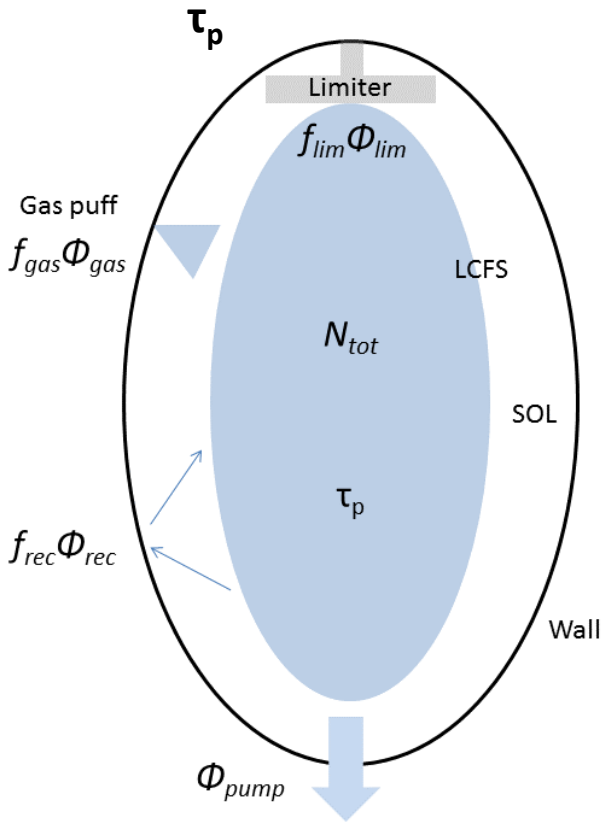
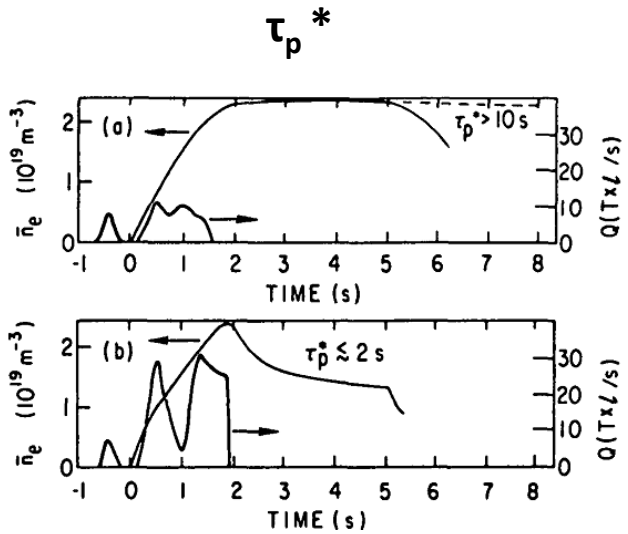
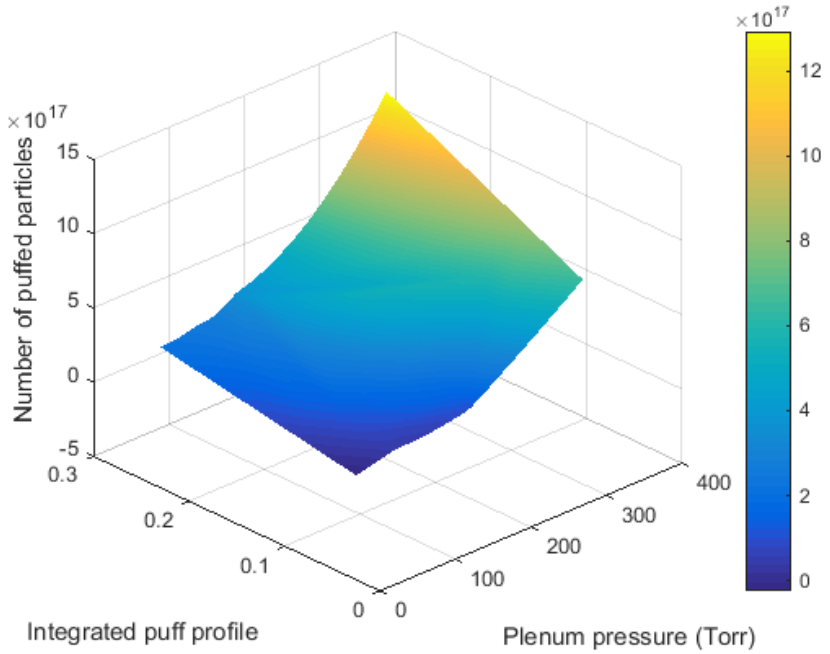
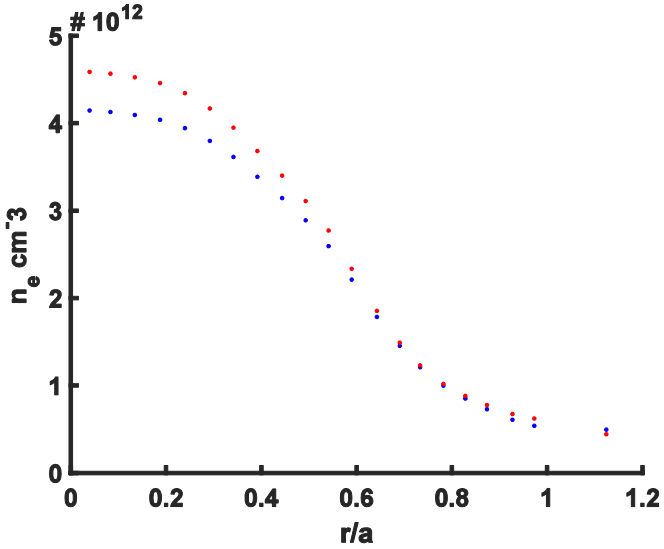


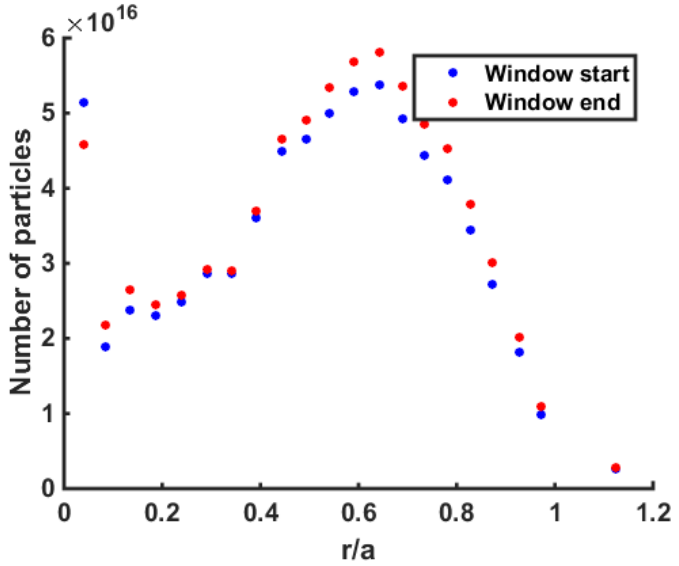


Φ_{gas} and N_{tot} have been determined



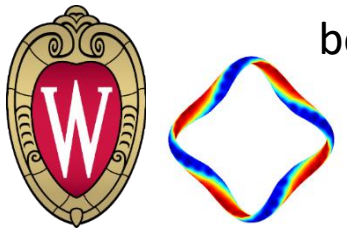
HSX interferometer inversion (C. Deng)





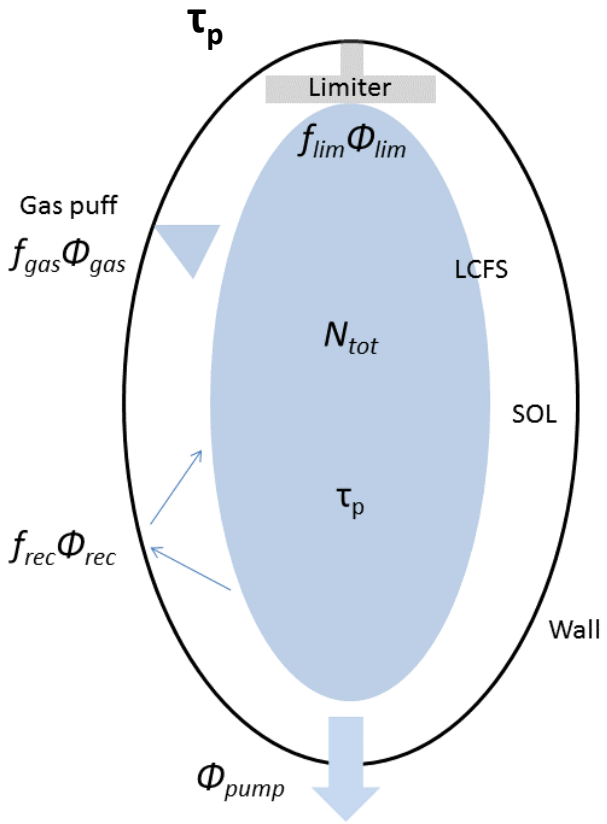
Total gas puff throughput calibrated for both H and He in HSX

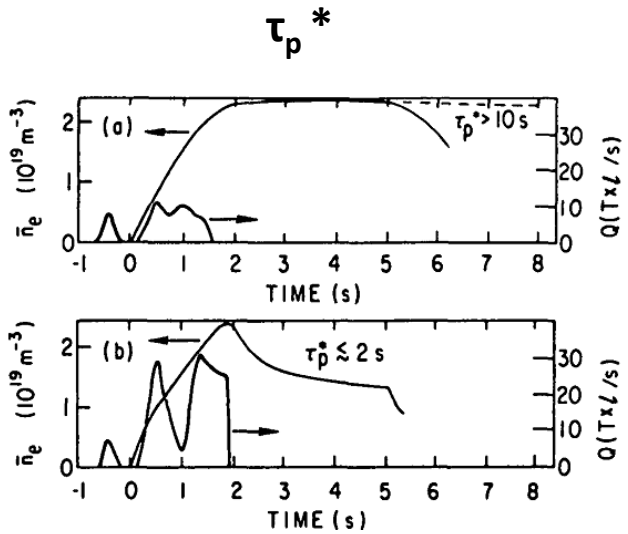
Using volume of each annulus, density inversion converted to number of particles at each minor radius → total number of particles, N_{tot}



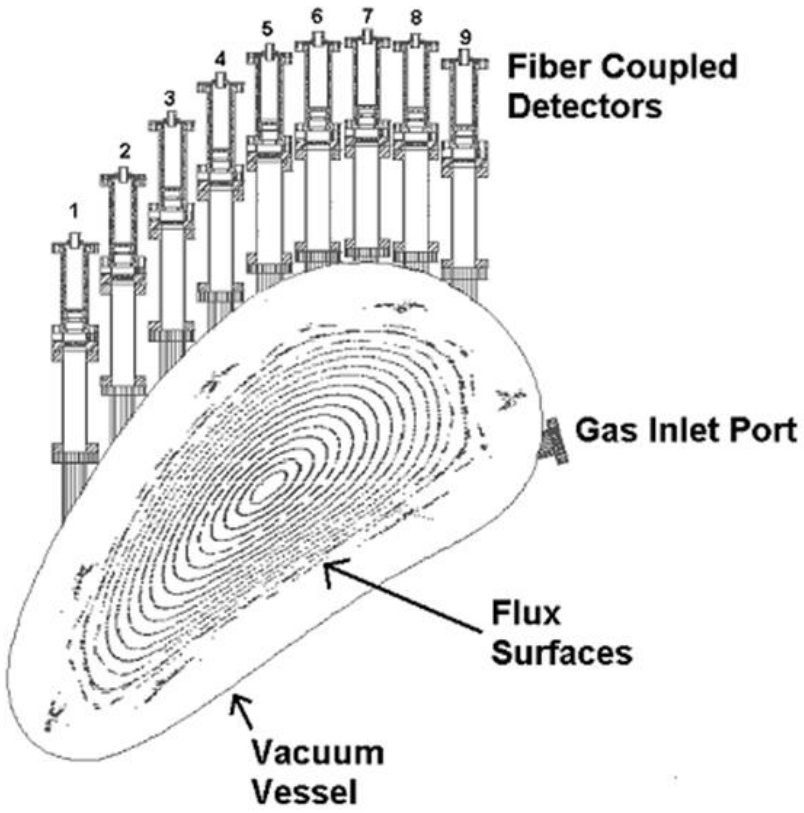
Particle balance and recycling in HSX

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim} \qquad R = 1 - \frac{\tau_p}{\tau_p^*}$$

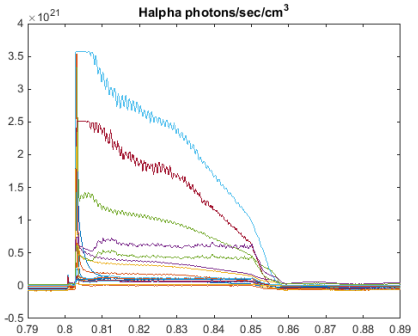


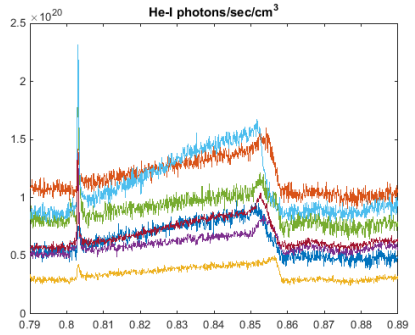


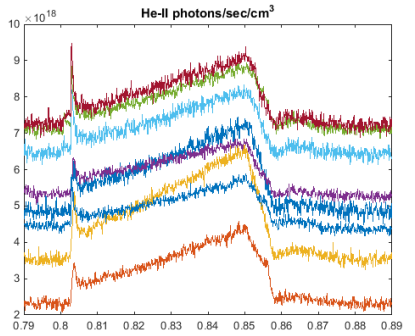
Upgraded filtered photodiode system to provide Φ_{rec}



- Have H-alpha, He-I, and He-II filters in a total of 36 detectors
- Poloidally and toroidally distributed measurements
- Absolutely calibrated
- Photon flux will be used with edge temperature and density data (A. Akerson) to calculate recycling flux
- Use in conjunction with EMC-EIRENE (A. Bader) to provide flux for areas we can't measure



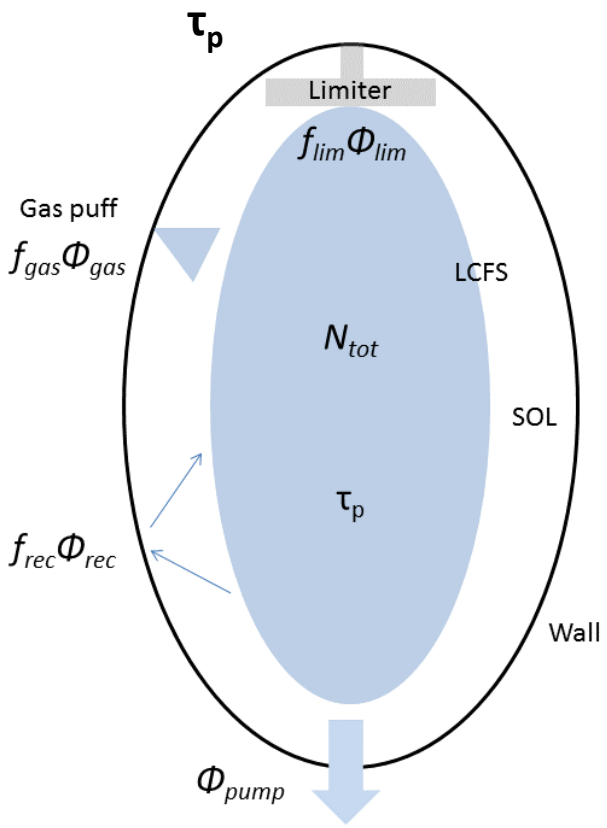




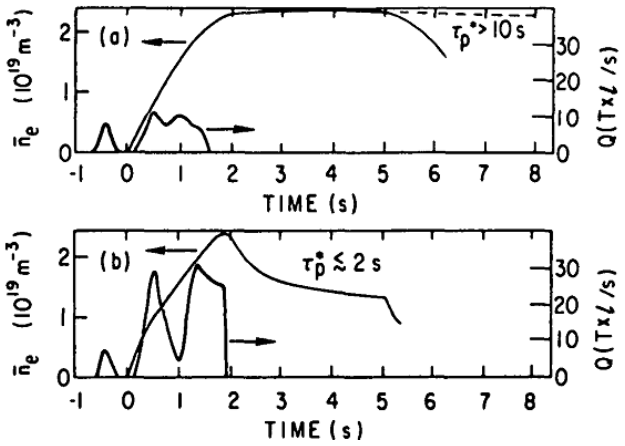
Particle balance and recycling in HSX

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim}$$

$$R = 1 - \frac{\tau_p}{\tau_p^*}$$



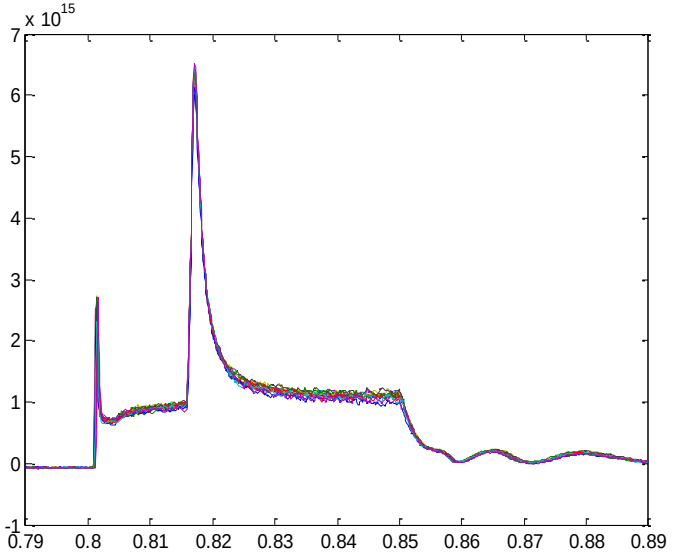
τp *



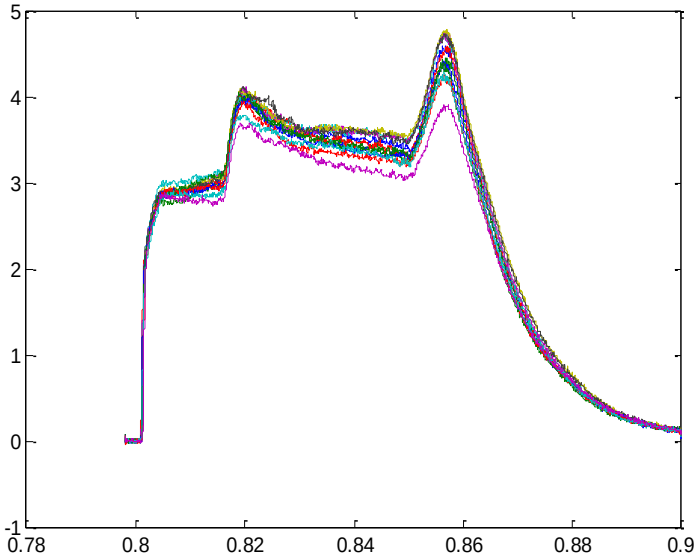
Preliminary τ_p^* experiments performed in HSX

- Perturbative H puff into H plasma
- Good diagnostic capability to observe decay
  - Measured decay on interferometer density
  - Measured decay on H-alpha detector near gas puff

H-alpha near gas puff



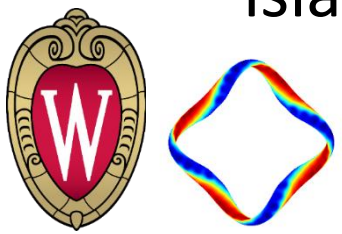
Central n_e from interferometer



HSX completed and future work

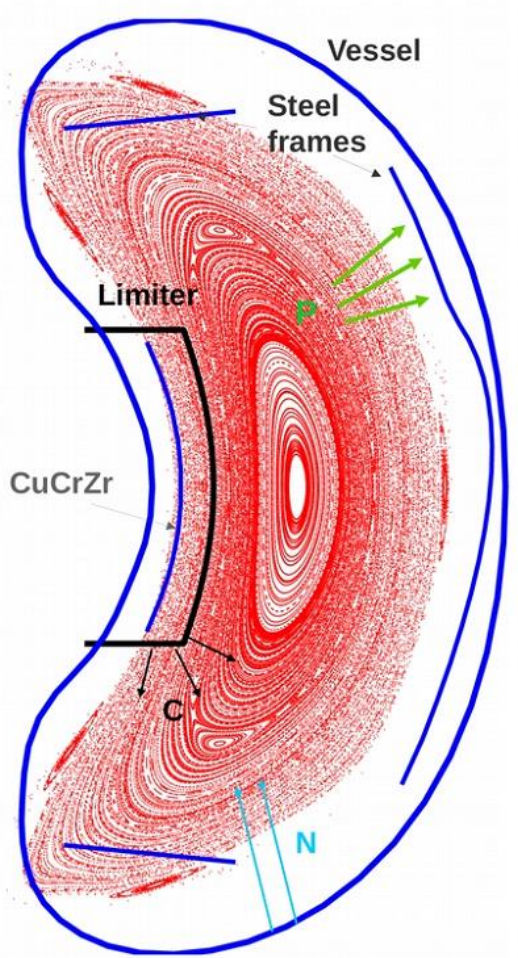
$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim} \qquad R = 1 - \frac{\tau_p}{\tau_p^*}$$

- Measured: N_{tot}, Φ_{rec}, Φ_{gas}, τ_p^*
- In progress: Φ_{lim} measurements
- In progress: determining f fueling efficiency coefficients with EMC3-EIRENE
- Calculate τ_p, R for 8/7 island and 'pure' SOL, determine effect of islands



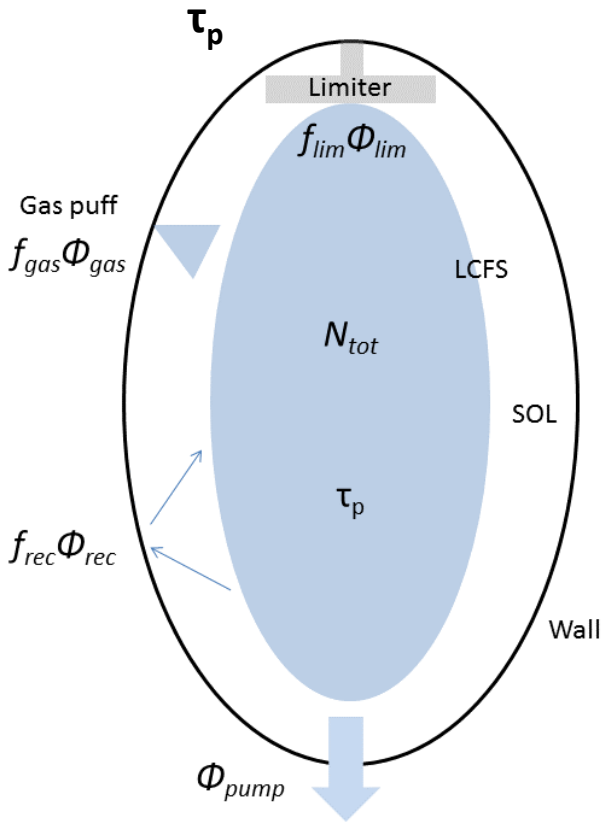
W7-X experimental parameters (OP 1.1)

R	5.5 m
r	0.53 m
$n_{e,\,core}$	5E19 m^{-3}
$T_{e,\,core}$	8 keV
$T_{i,\,core}$	1 keV
$n_{e,\,edge}$	0.5E19 m^{-3}
$T_{e,\,edge}$	10-15 eV
$T_{i,\,edge}$	?

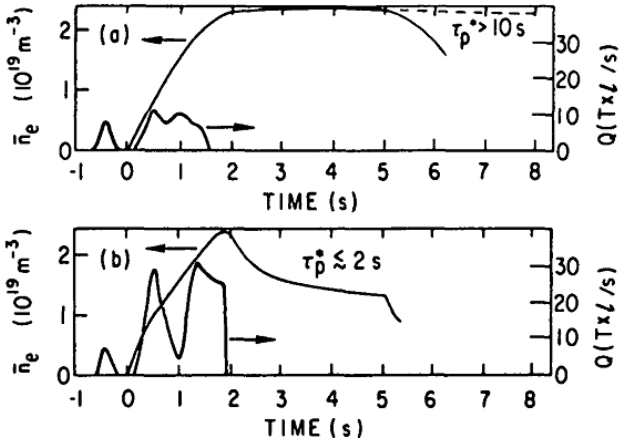


Particle balance and recycling in W7-X

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim} \qquad R = 1 - \frac{\tau_p}{\tau_p^*}$$

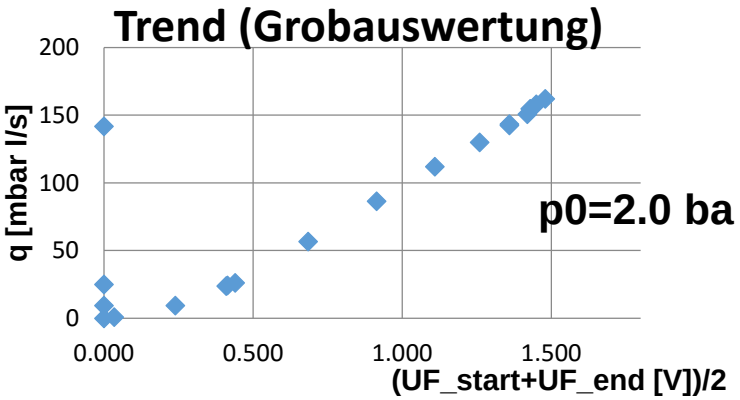


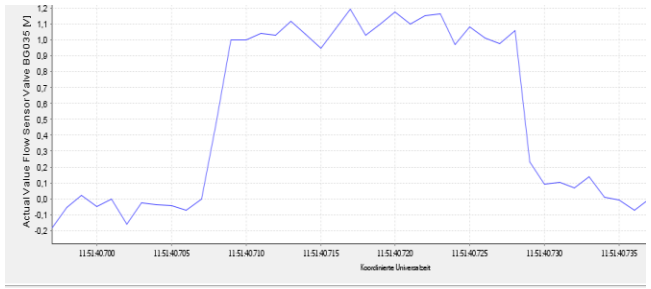
τp *



W7-X Gas puff flux, Φ_{gas}, known

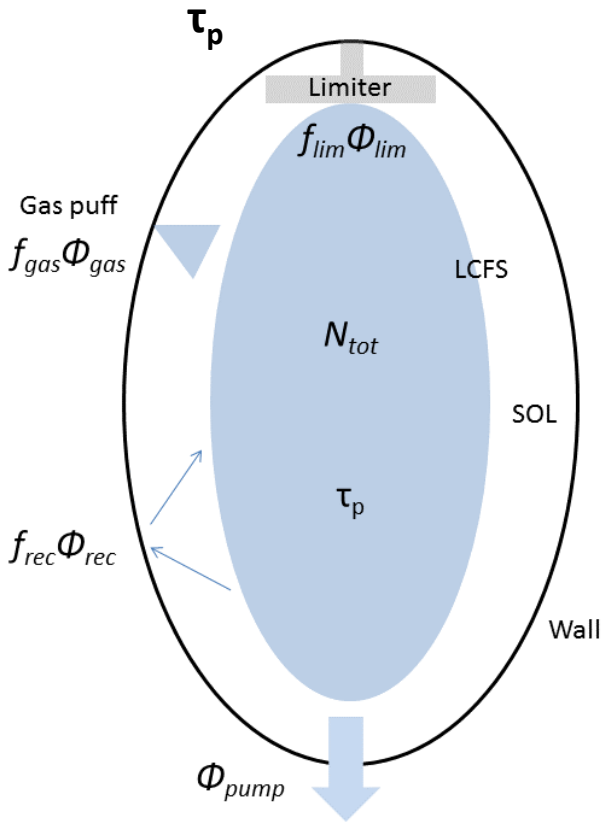
- Main W7-X gas valve throughput data courtesy of H. Viebke
  - Data for both He and H plasmas
  - Data for density and heating power scans
- Data for He beam diagnostic valves (fast response) courtesy of M. Krychowiak

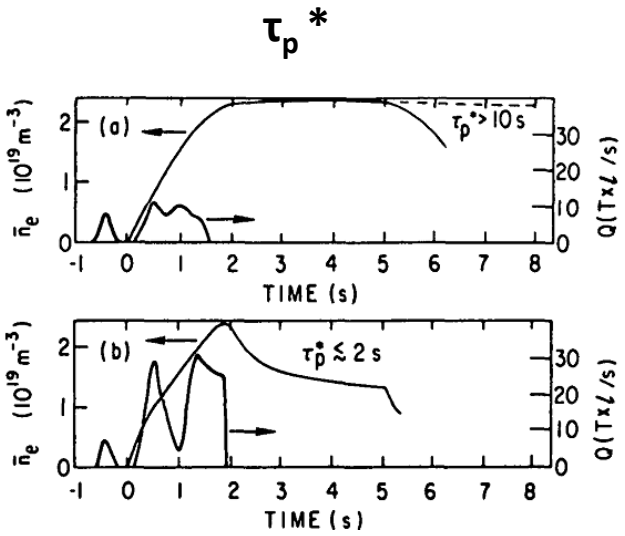




Particle balance and recycling in W7-X

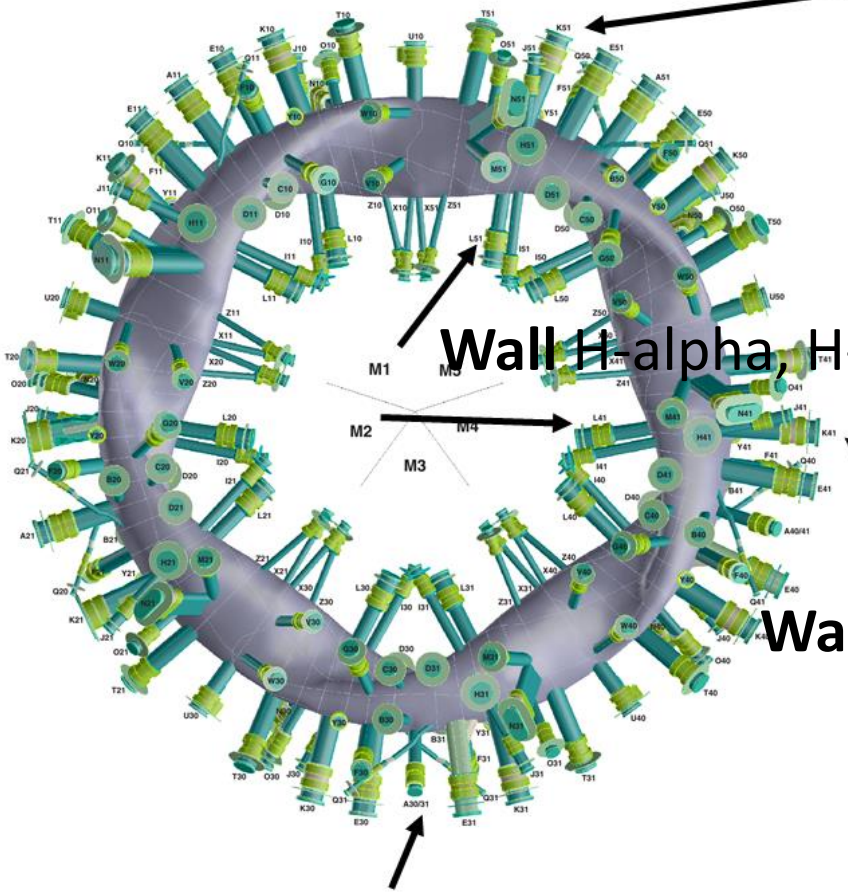
$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim} \qquad R = 1 - \frac{\tau_p}{\tau_p^*}$$





ORNL Filterscope used to measure Φ_{rec}

- Use filterscope system to provide spectroscopic data from 5 W7-X fibers
  - Two outboard views
  - Two inboard views
  - One limiter view
- Each fiber split into several channels via a beamsplitter



Wall visible bremsstrahlung, He-II

Wall H-alpha, H-beta, He-I, C-II

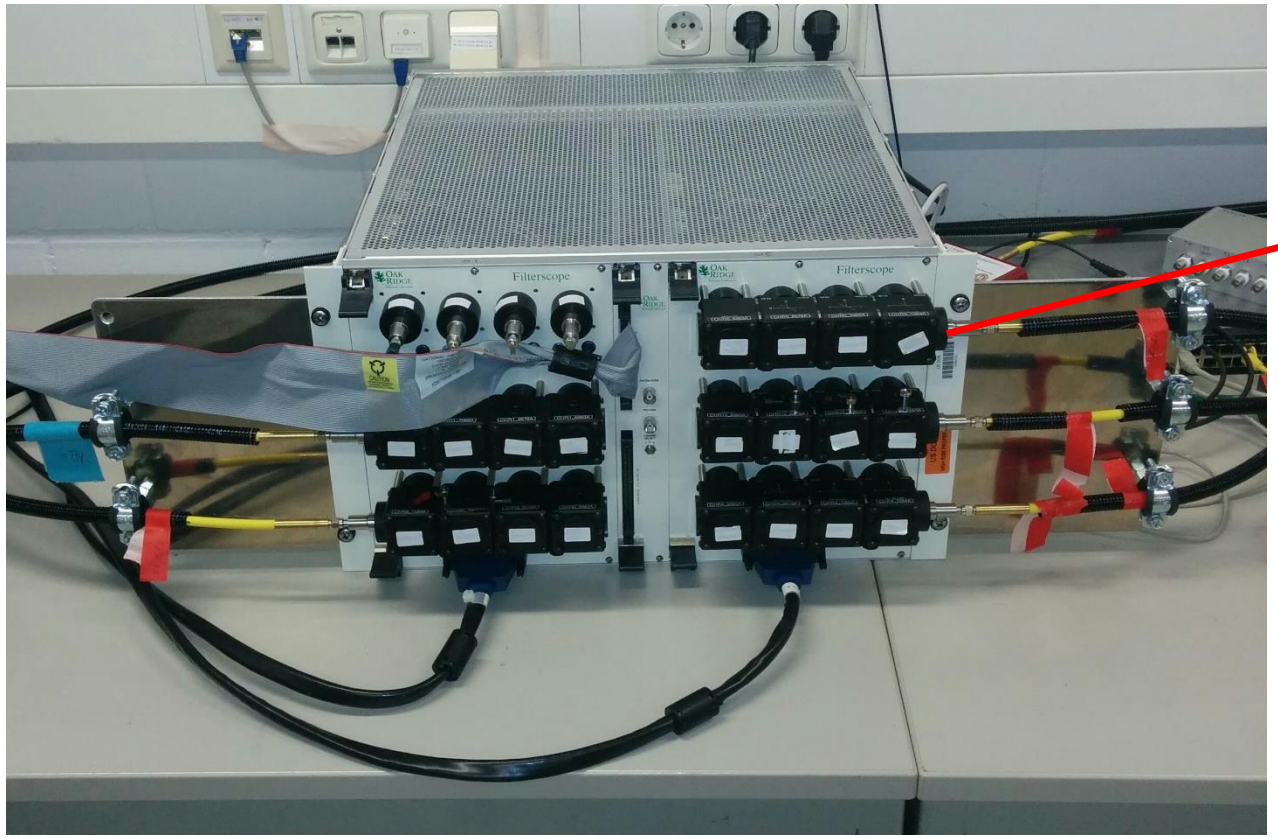
Wall H-alpha, H-beta, He-I, C-II

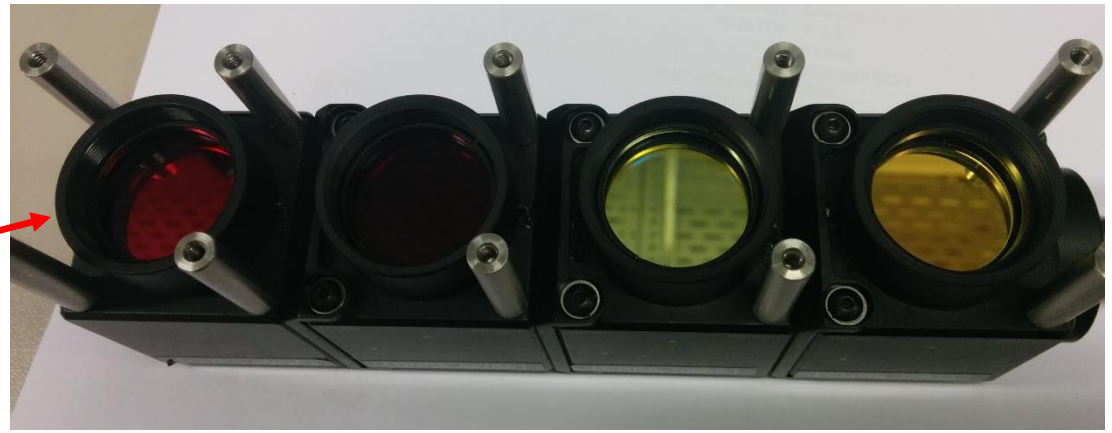
Limiter 3 H-alpha, H-beta, He-I, C-II

IPP

OAK RIDGE National Laboratory

ORNL Filterscope used to measure Φ_{rec}

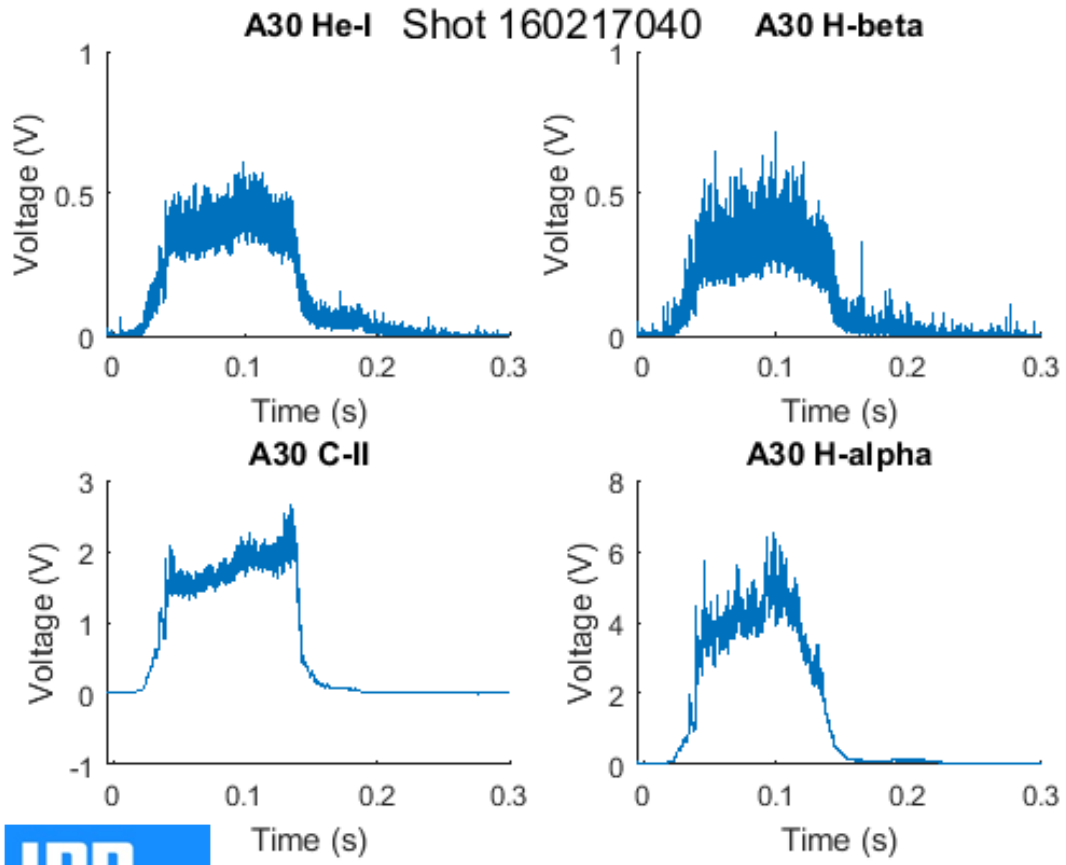




- Designed and built by Oak Ridge National Laboratory [1]
- 24 channels, 100 KHz acquisition
- PMTs with automatic overvoltage protection
- 4-way beamsplitter provides 4 spectral channels for each spatial channel:
  - H-alpha (656 nm)
  - H-beta (486 nm)
  - He-I (668 nm)
  - C-II (515 nm)
- "Extra" visible Bremsstrahlung, He-II, C-III, CD channels

1. R. J. Colchin et al., Rev Sci Instrum Vol 74, Num 3, 2003.

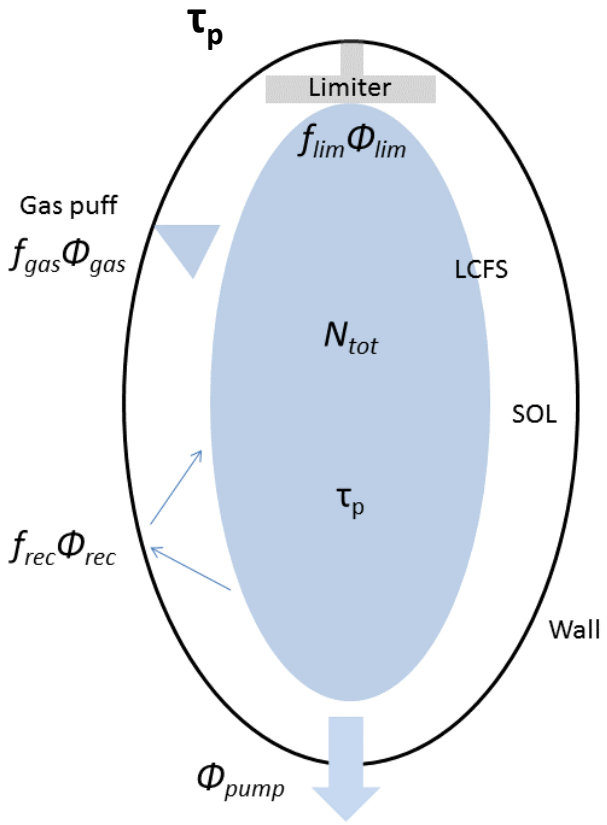
Filterscope data provides photon flux at limiter



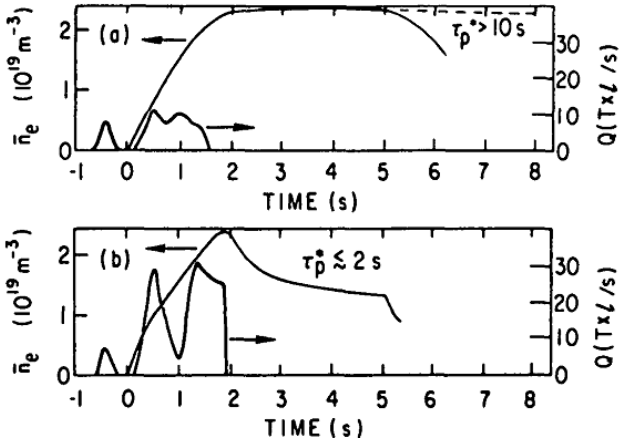
- Absolute calibration just completed
- Edge temperature and density can be used with atomic data to convert measured photon flux to particle flux (FZJ MPM)
- Will yield Φ_{lim} and local Φ_{rec}
- Comparison to EMC3-EIRENE synthetic emission to provide flux for areas we can't measure

Particle balance and recycling in W7-X

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim} \qquad R = 1 - \frac{\tau_p}{\tau_p^*}$$

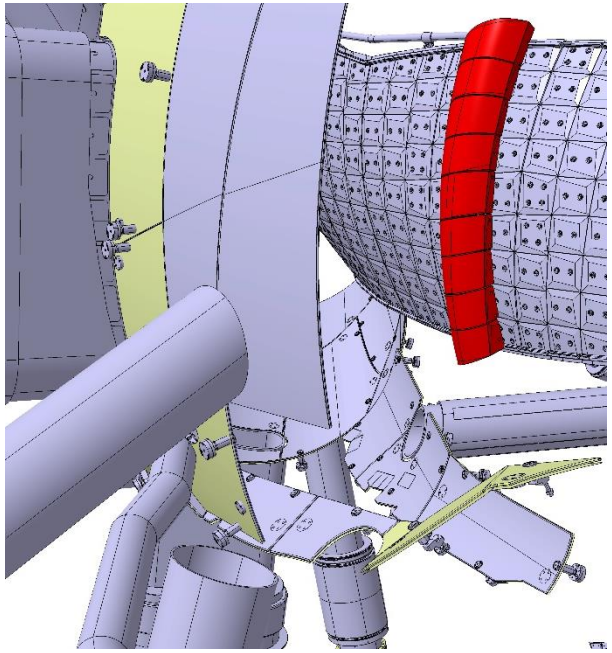


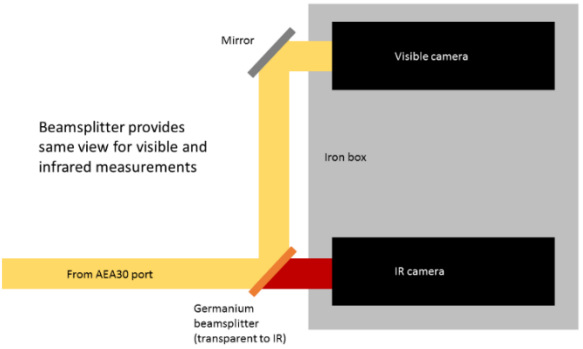
τp *

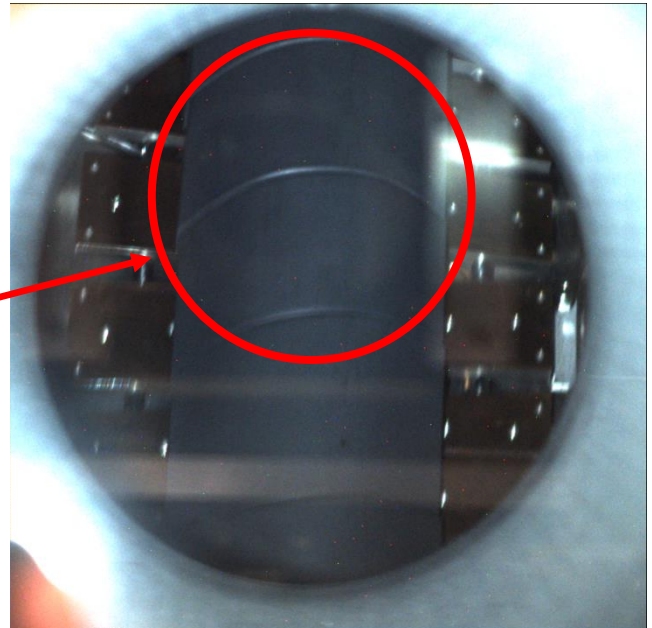


LANL camera measurements to determine Φ_{lim}

- Beamsplitter provides same view of limiter 3 for both IR (G. Wurden) and visible cameras
- Will be used to determine particle flux, Φ_{lim}
- Filterscope view covers approx. half of camera view
- Together provide excellent spatial and temporal resolution of limiter particle flux



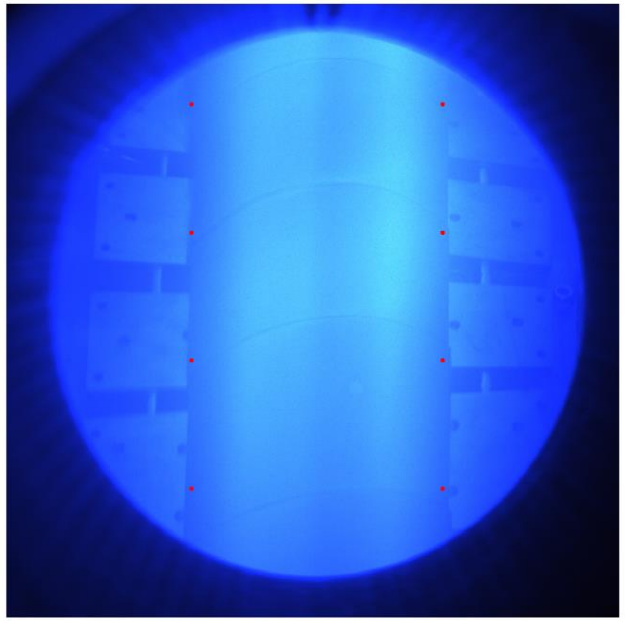


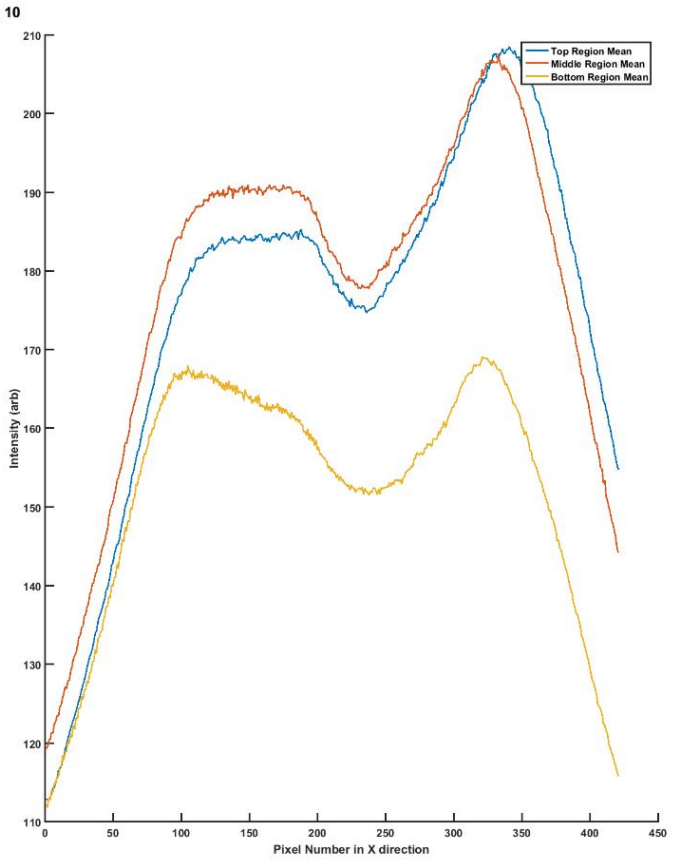


Filterscope spot size is about 50% of camera view

LANL camera measurements to determine Φ_{lim}

- RGB visible camera data at 100 Hz
- C-II and H-alpha filters used
- Will be absolutely calibrated and compared to filterscope channel in same location
- Data show profiles of photon emission at the limiter
- Will be compared to synthetic atomic emission generated by EMC3-EIRENE (F. Effenberg)
- Edge values of T_e and n_e necessary to convert to particle flux (FZJ MPM)

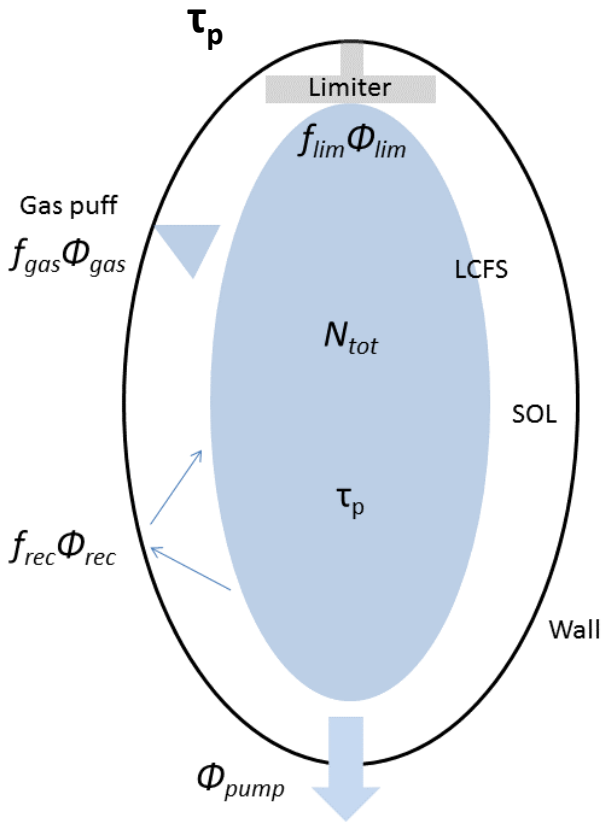




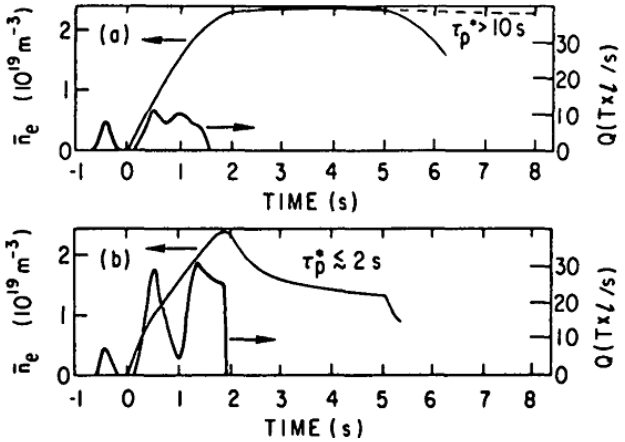
Particle balance and recycling in W7-X

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_p} + f_{rec}\Phi_{rec} + f_{gas}\Phi_{gas} + f_{lim}\Phi_{lim}$$

$$R = 1 - \frac{\tau_p}{\tau_p^*}$$



τp *



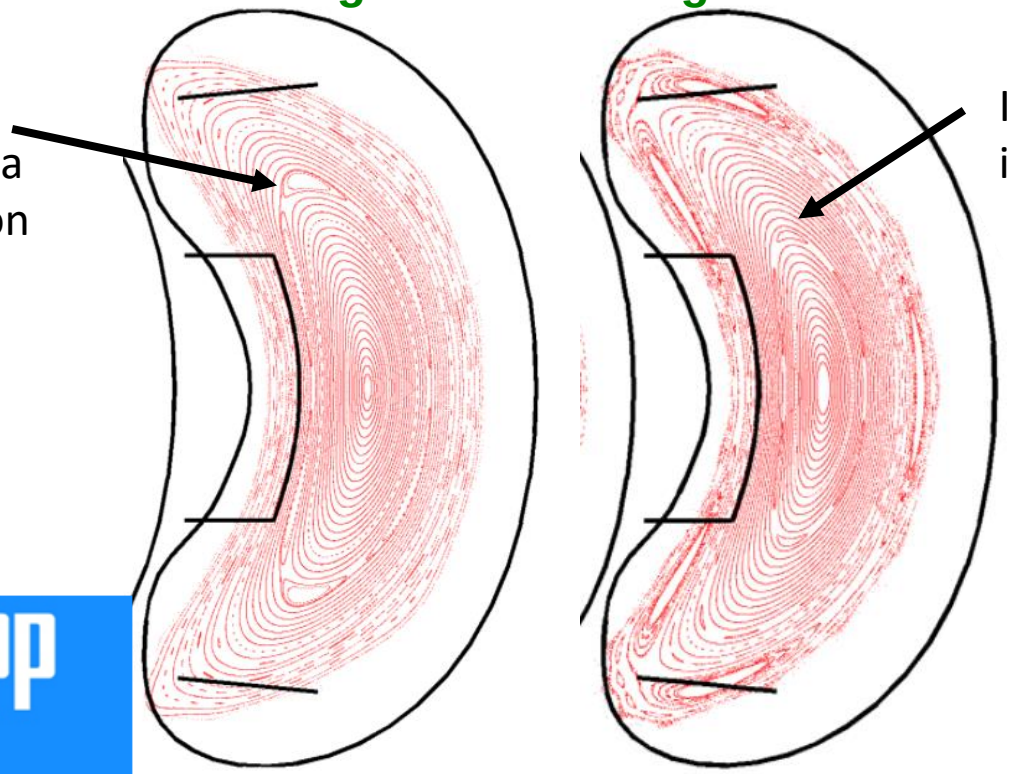
Used τ_p^* He measurements as a marker for changes in confinement for High-Iota configuration

Explanation might be connected to convective cell activity of island, strong collisionality gradient across island if located in plasma edge and connection length.

Hypothesis: If this holds for W7-X, the density might be higher with island deeper inside of plasma!

Standard Configuration **High-Iota**

Islands in edge, plasma source region



Islands moved inwards

Reference [0.0, 0.13]

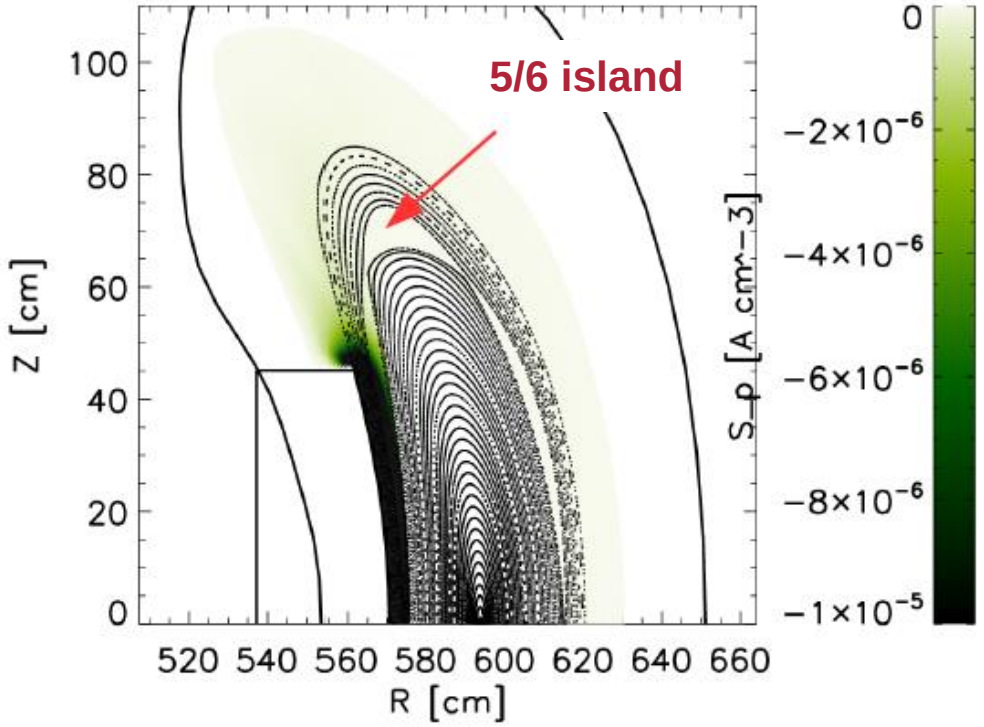
Critical aspects for feasible experiment:

- **Island location vs. plasma source**
- **Small effect on plasma edge (recycling comparable)**
- **EMC3-EIRENE predicts that this will have a measurable effect**

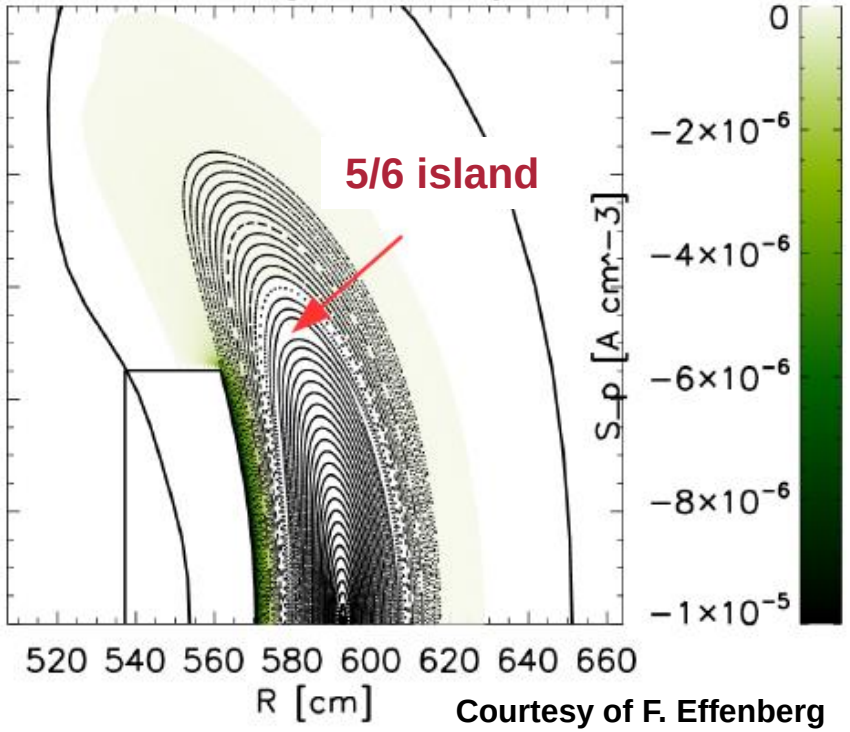
Courtesy of F. Effenberg

EMC3-EIRENE suggests that 5/6 island can be moved out of particle source region with inward shifted, high iota configuration

Standard limiter case



High iota I_{AB}=[0.13, 0.0]



Courtesy of F. Effenberg

Island is located right inside of main particle source region

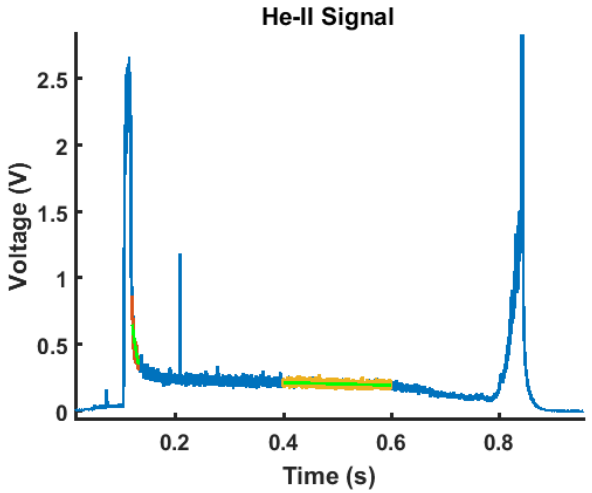
Island is located deeper inside than main particle source location

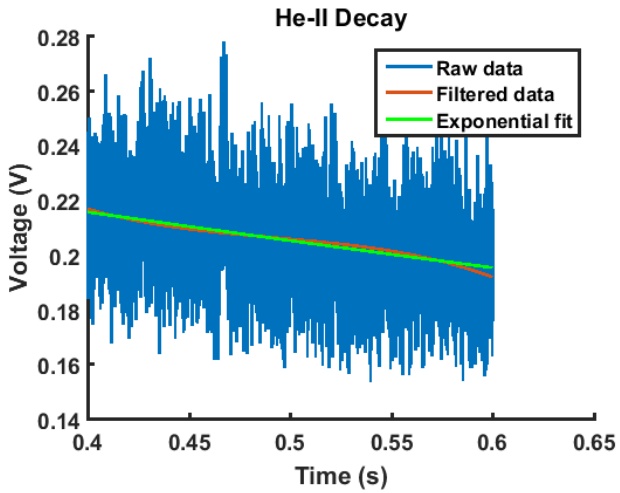
Recycling flux to reach same plasma density is reduced!

This suggests substantial improvement of global particle balance.

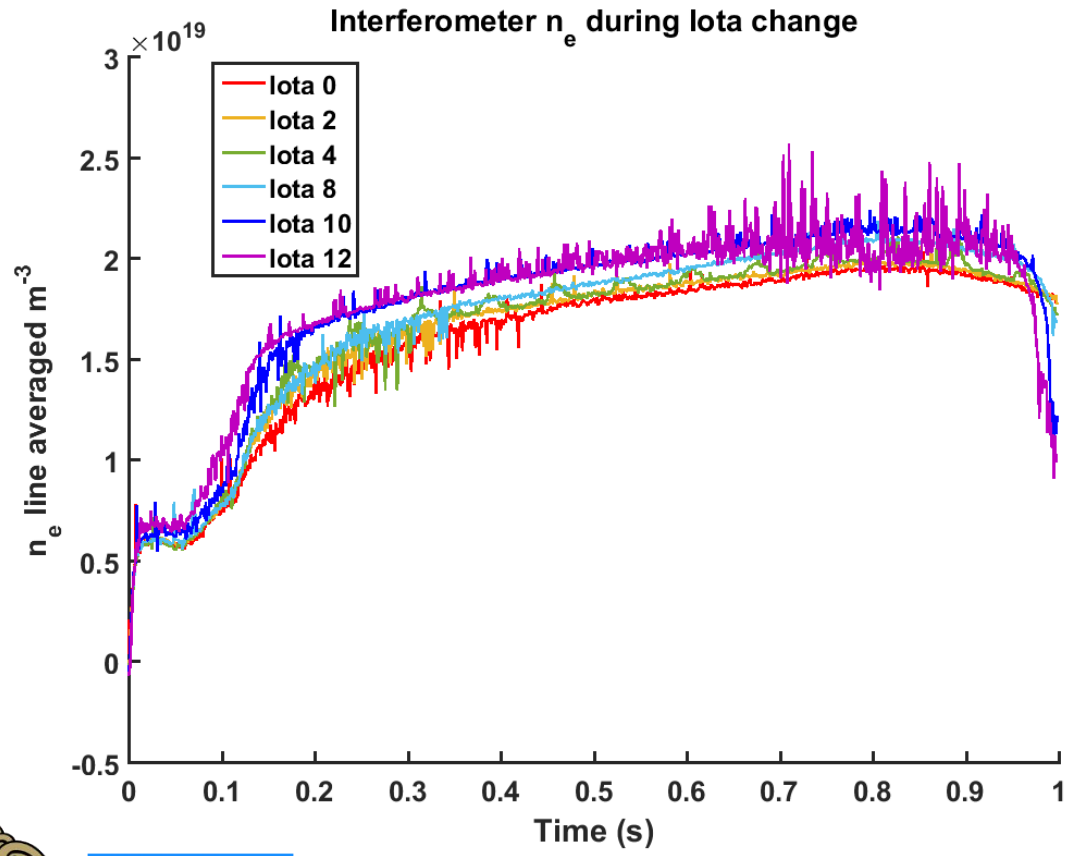
Used τ_p^* He measurements as a marker for changes in confinement for High-Iota configuration

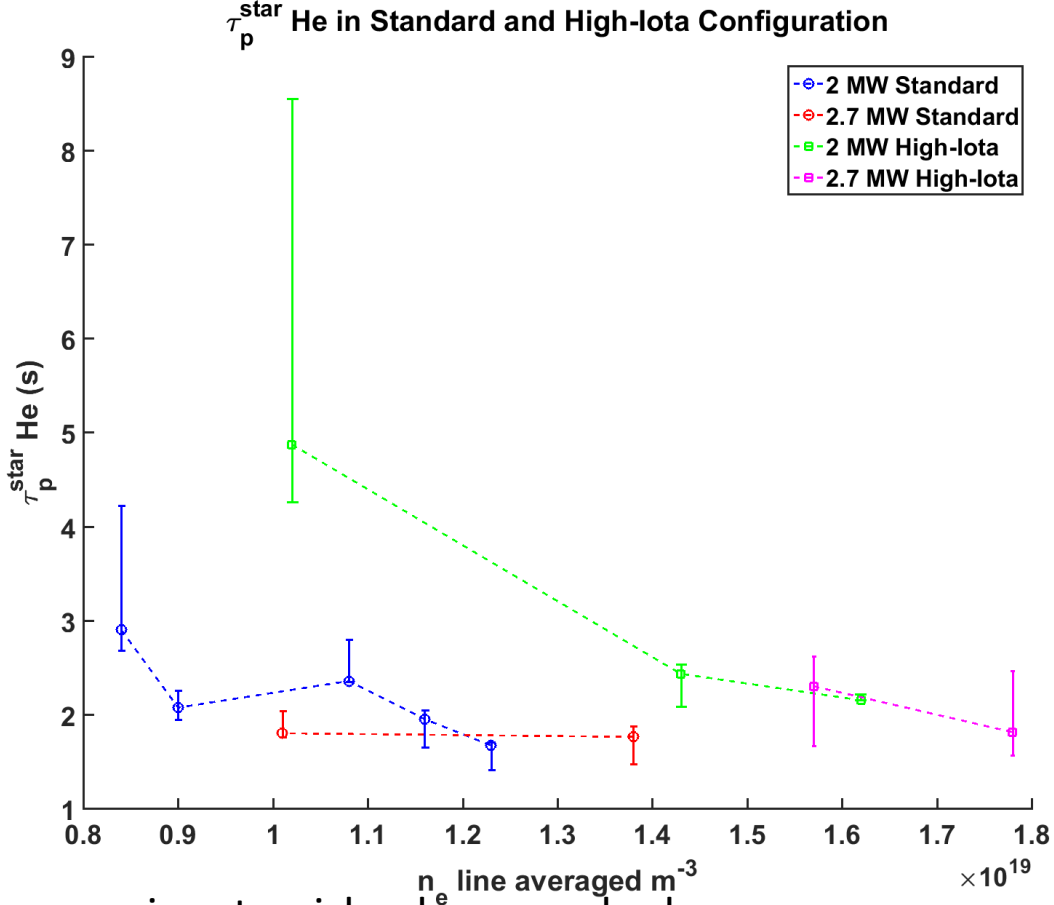
- Performed series of τ_p^* He experiments to asses changes in confinement
  - In Standard configuration (islands in source region)
  - In transition between Standard and High-Iota
  - In High-Iota (islands pushed inward, out of source region)





Larger values of τ_p^*, higher densities reached in High-Iota configuration



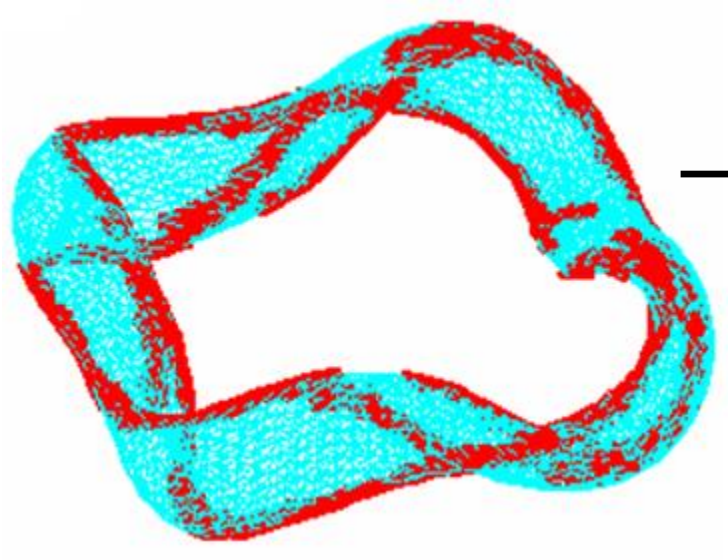


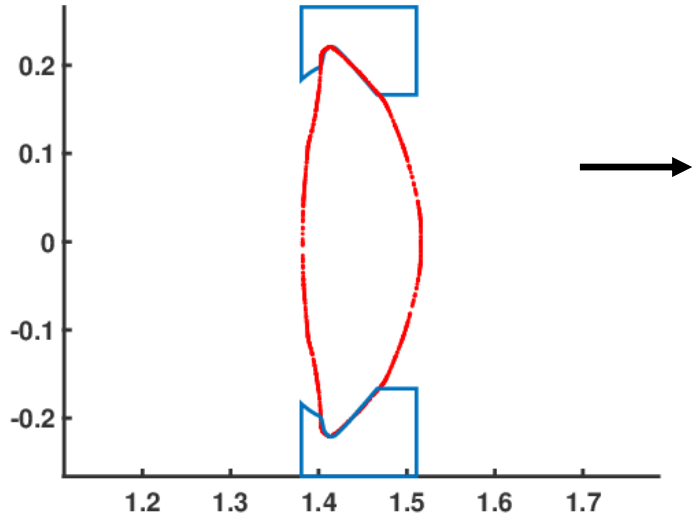
- Line averaged density increasing for same gas input as islands are pushed inward (out of plasma source region)
- Factor of two increase in τ_p^* He in High-Iota configuration

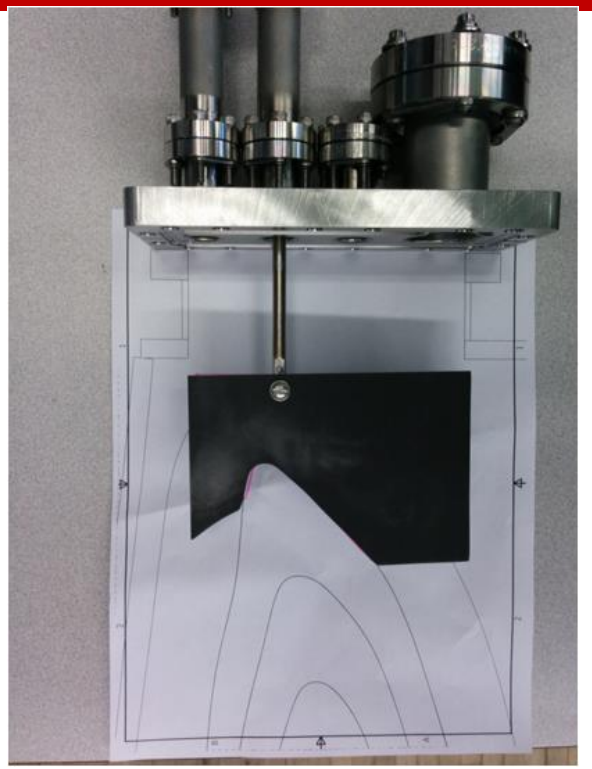
Summary and outlook

- Particle balance experiments in progress at HSX, completed at W7-X
  - HSX 8/7 island in SOL, ‘pure’ SOL created by limiter insertion
  - W7-X Standard and High-Iota
- Compare confinement time, global recycling coefficient
- Compare effects of islands present in source region
- Comparison of Standard and High-Iota configuration shows improvement in fueling efficiency and confinement– confirms hypothesis, analysis still in progress

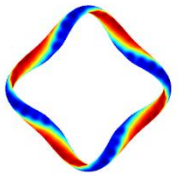
Measuring Φ_{lim} in HSX using limiters







Without limiters, HSX is
d to have strike
er a large area



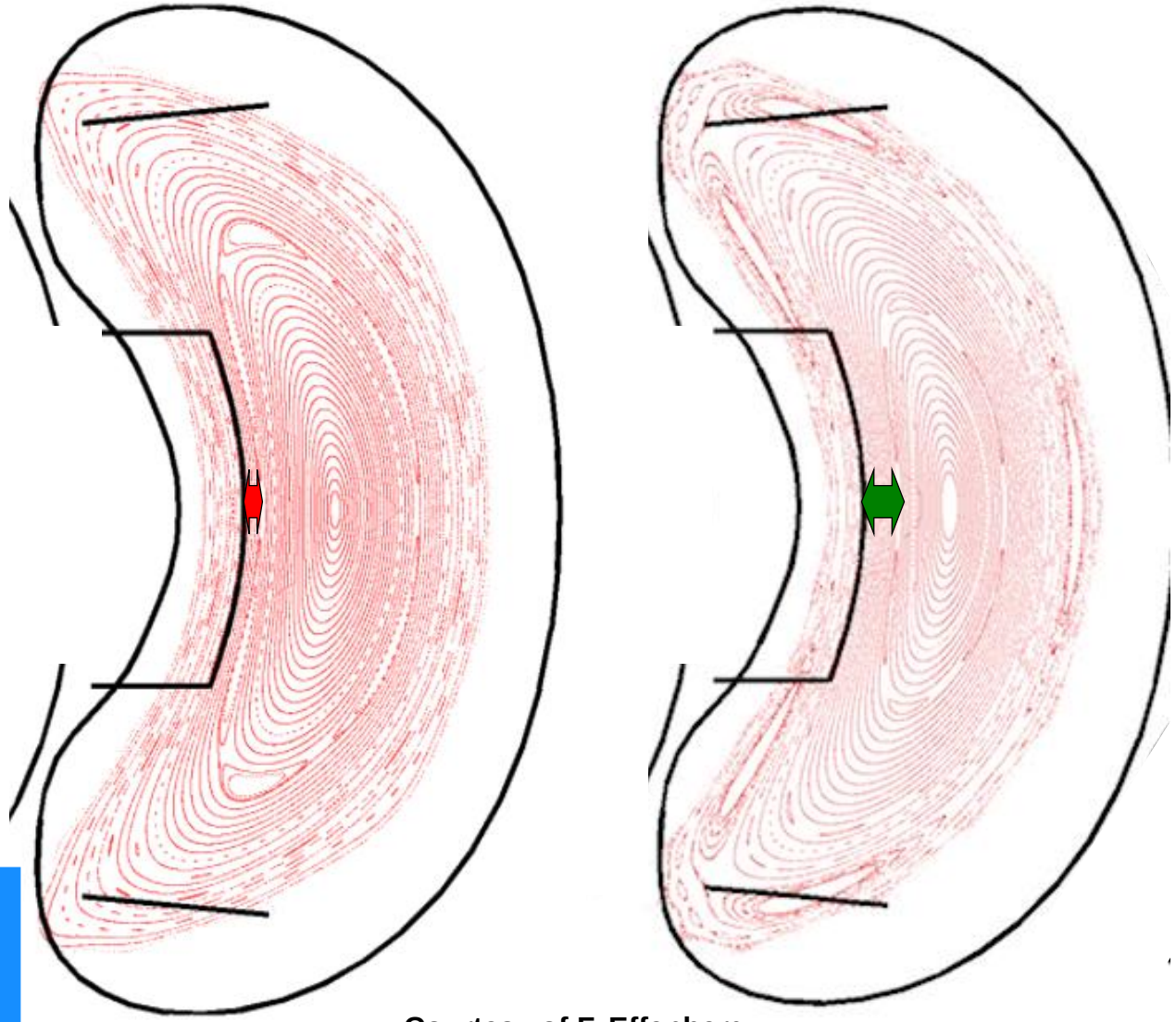
Two limiters predicted to intercept 99% of field lines outside the LCFS

One limiter installed, second limiter ready to be installed

High iota configuration with save SOL features was identified

Standard limiter case

High iota I_{AB}=[0.13, 0.0]



Courtesy of F. Effenberg