LLNL Tokamak Boundary Research On DIII-D

by
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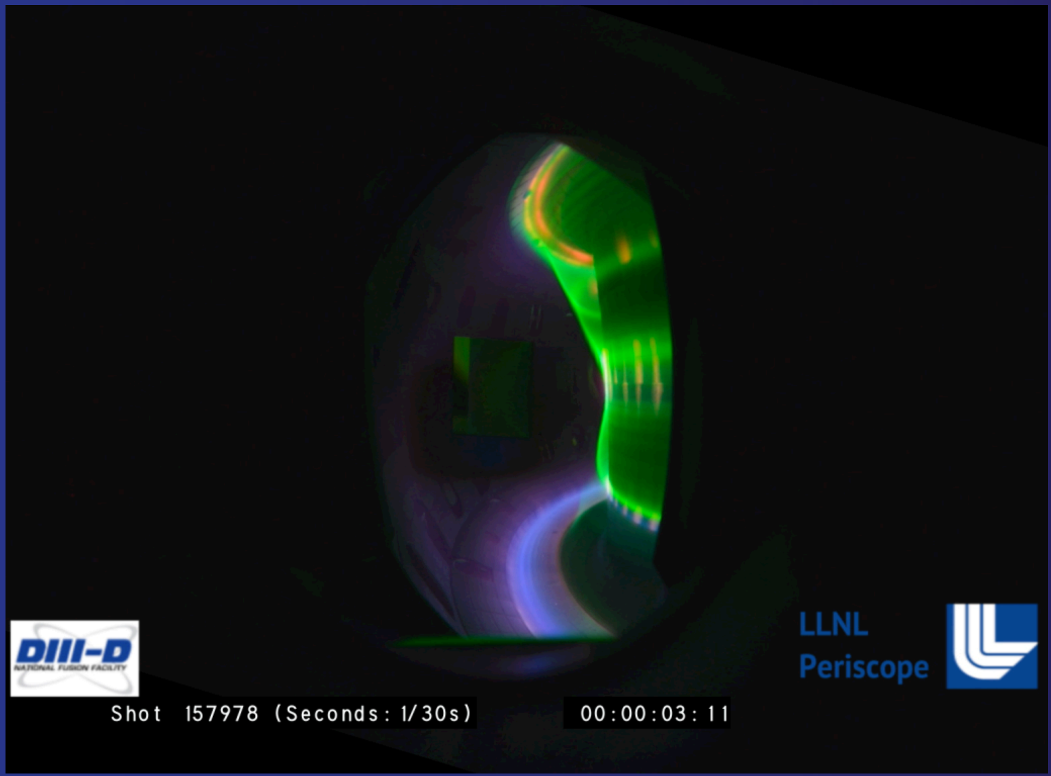
Presented at the
Fusion Power Associates 35th Annual Meeting and Symposium
Fusion Energy: Recent Progress and The Road Ahead



December 16-17, 2014

This work was supported by the US Department of Energy under DE-AC52-07NA27344, DE-FC02-04ER54698, DE-AC02-09CH11466, SC-G903402, DE-AC05-00OR22725, DE-FG02-08ER85195, and DE-FG02-04ER54761. LLNL-PRES-665382

Developing Advanced Divertor Solutions Requires an Innovative Approach in Physics Combined w/Engineering

Divertor Heat Flux

$$q_{target} = \frac{(1-f_{rad})P_{loss}\sin(\theta_{div})}{4\pi\,\lambda_q\, f_{exp}\, R_{target}}$$

$$P_{loss} = P_{CD} + 0.2 \times P_{\alpha}$$

($\lambda_q \sim 1/I_p$)

Divertor Geometry (R, θ_{div}, L_{pol})

- Control neutrals, impurities.
- Enhance divertor radiation (f_{rad}).

Magnetic Configuration (R, f_{exp})

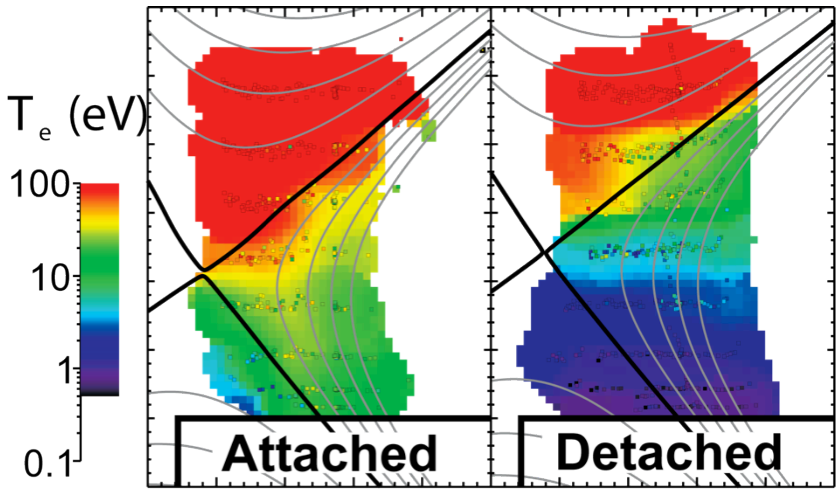
- Maximize flux expansion, Divertor Index (?)
- Maximize radius
- Increase field line length.

Edge Radiative Dissipation (f_{rad})

- Enhance divertor radiation
- Enhance edge radiation

2D Divertor Thomson Scattering Measurement Opens Unique Window Into Physics of Divertor Detachment

2D Temperature Map



A. McLean, PSI 2014

- **Detached divertor solution provides**
  - Low heat flux, low erosion
- **Gap – Validated predictive capability for optimizing divertor**
  - Expand operating window
  - Enable high performance core
- **Recent divertor Thomson upgrade improves low-Te performance**
  - Sub-eV temperature range captures recombination physics
- **Systematic studies quantify key dependencies to compare with divertor simulation codes**

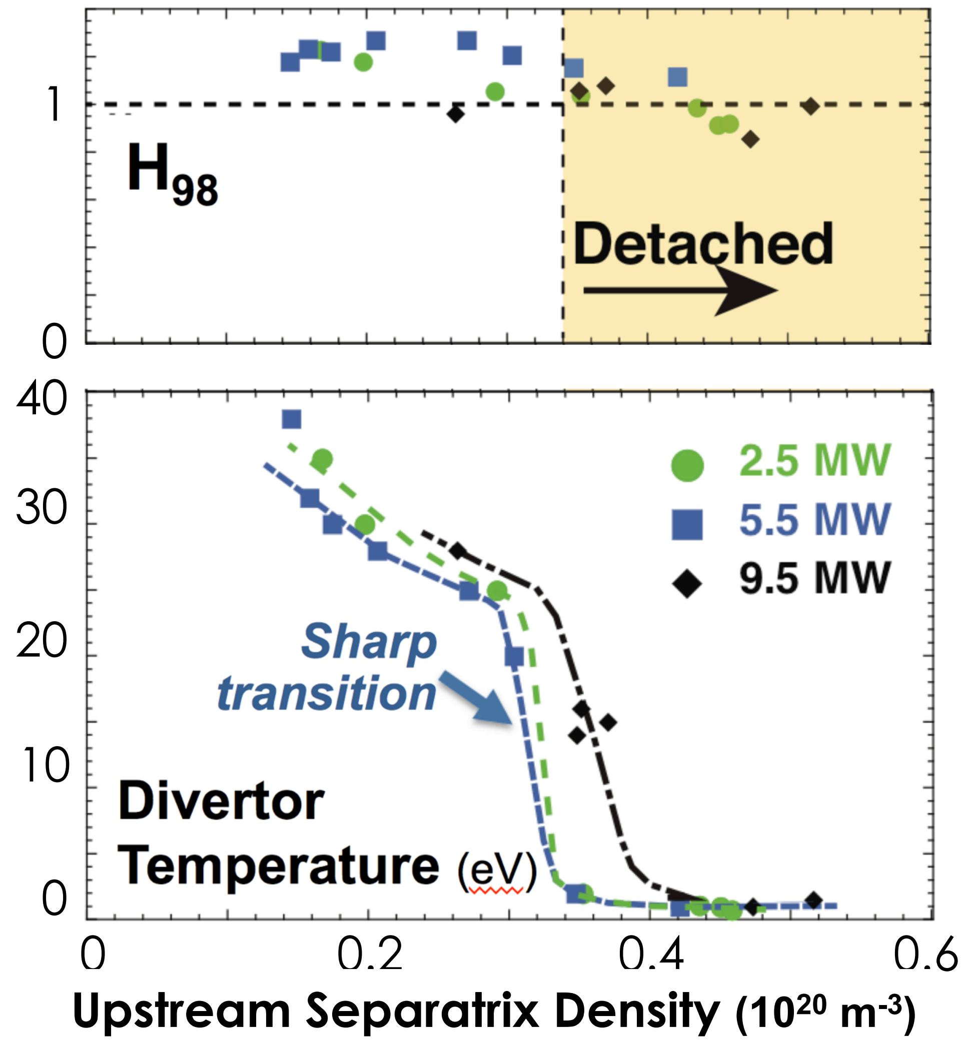
A. McLean, PSI 2014

H-mode NBI Power Scan (Fixed I_p and B_{tor}) Shows Constant Detachment Transition Threshold Separatrix Density

- **Detachment onset has a weak effect on H_{98}, even though radiation localized near X-point**

- **Sharp detachment transition at nearly fixed separatrix density**

This is highly desirable for decoupling divertor from core

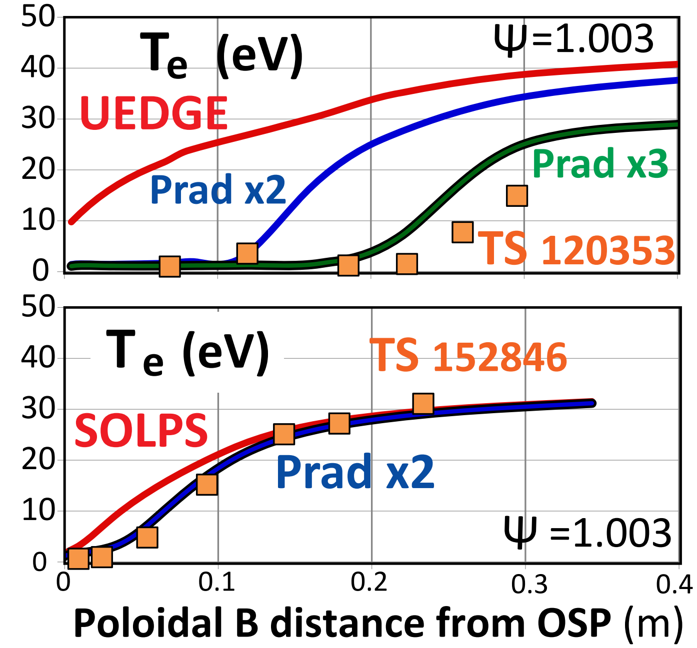


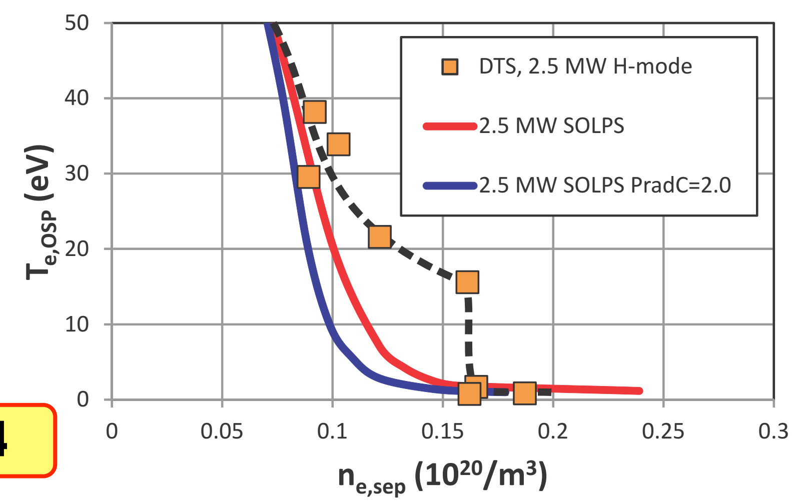
A. McLean, APS 2014

Comprehensive Detachment Studies Challenge Divertor Simulations to Drive Improvements to Edge Models

- **Both SOLPS and UEDGE over-predict divertor T_e with measured C levels**
  - Raising total radiation (P_{rad}) to observed levels matches divertor T_e
  - But over-predicts line radiation
- **Nonlinear detachment physics also challenges models**
  - Codes predict more gradual transition to detachment than experiment
  - Atomic/molecular rates exponentially sensitive to T_e < 2eV

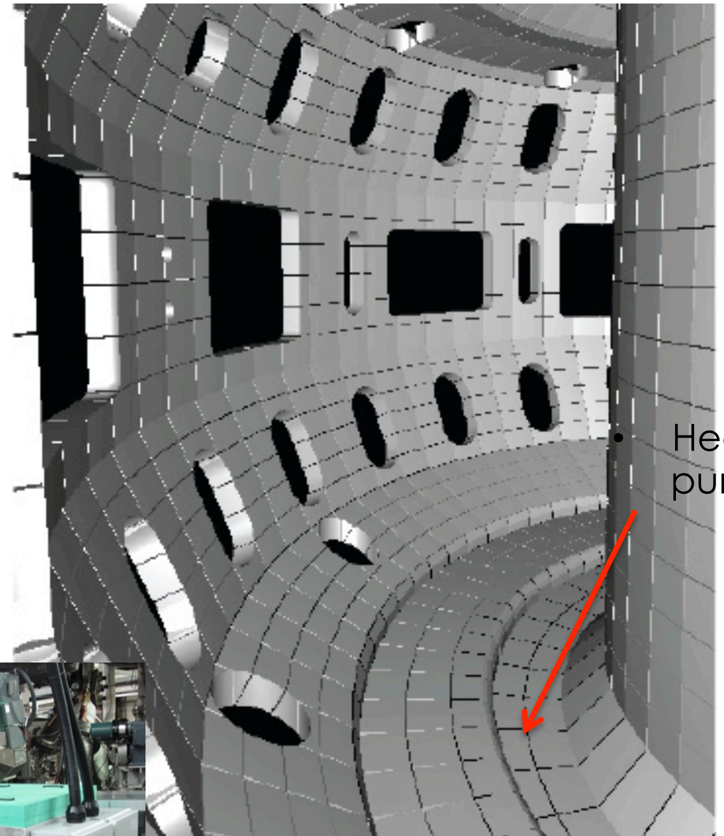
Expect dramatic improvement over next five years!

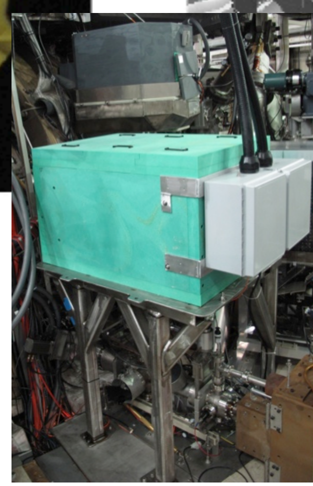




M. Groth, APS 2014

LLNL Developed a Prototype Wide View Visible-IR Periscope for ITER and Installed It on DIII-D

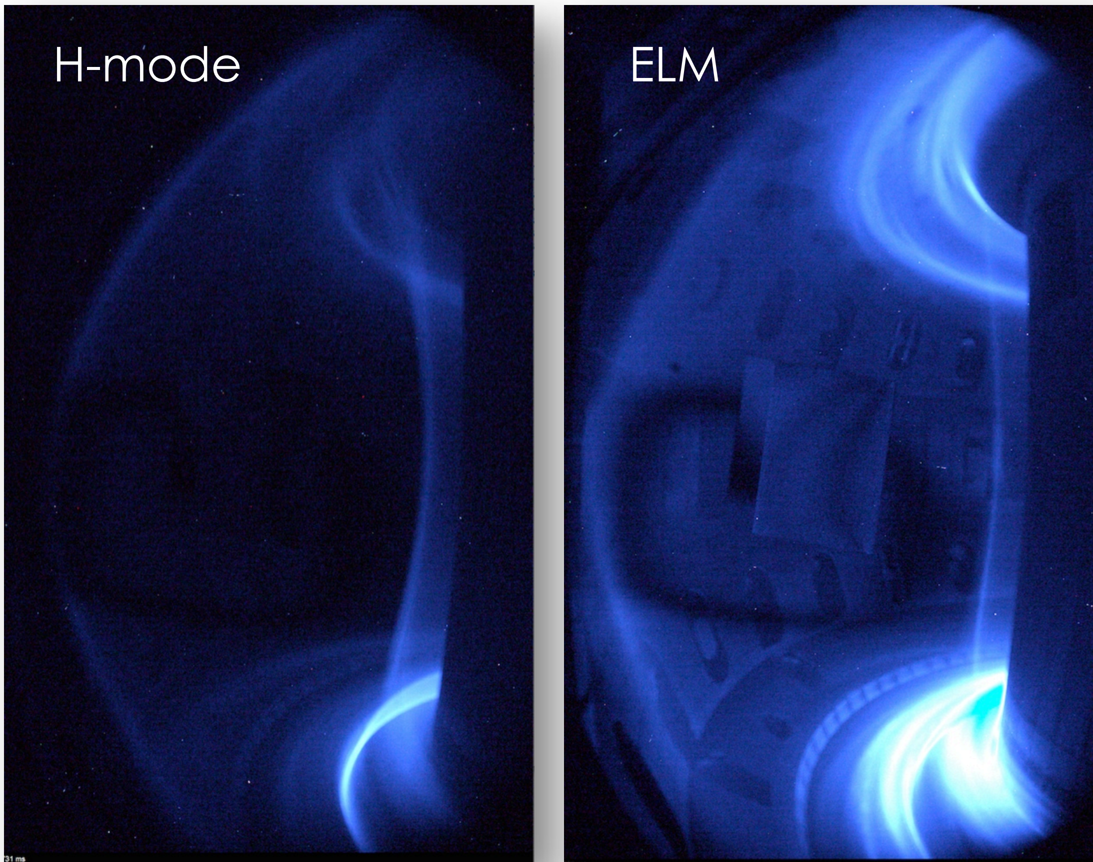




**C. Lasnier, S.L. Allen
RSI 2014**

Wide-Angle Periscope View Shows ELM Interaction With Plasma Facing Components in DIII-D

ΔTime = 1.25 ms

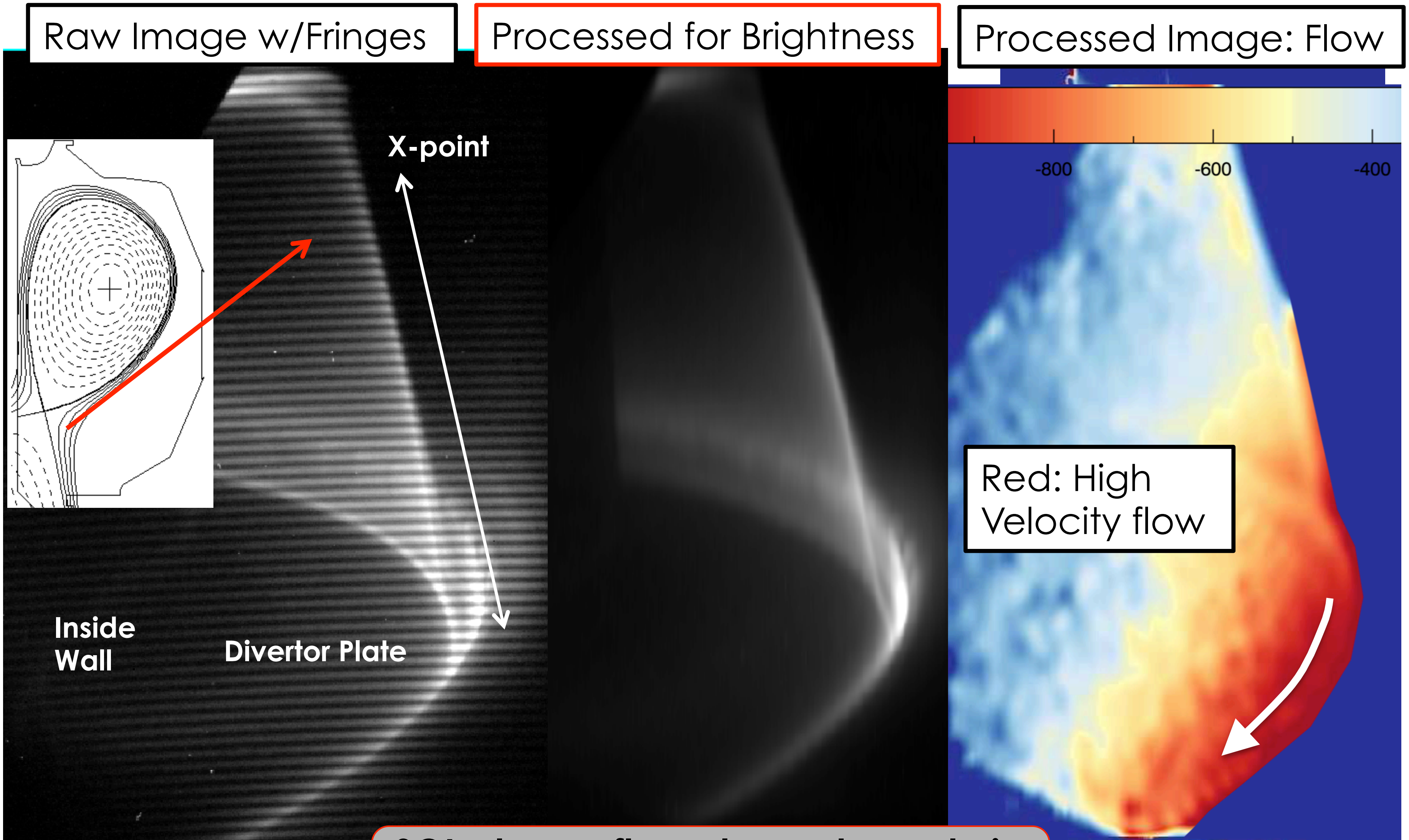


1679.731 ms   1680.981 ms

- High speed (~1ms), high resolution color camera
  - 2560 by 1600 pixels
  - 800 frames per second
- Used with filters for positive identification
- Doubly-ionized carbon (C^{+2}) emission before and during an ELM
- Coherence imaging for plasma flow measurements will be added in 2015

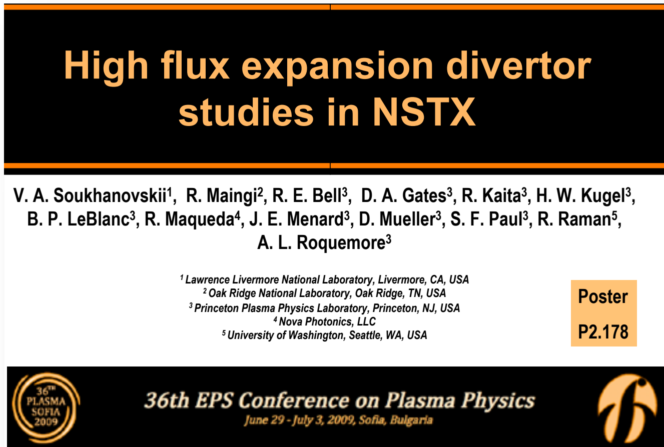
S.L. Allen, APS 2014

Visible-light Coherence Imaging Reveals 2D Ion Flow Distribution in the Divertor



SOL plasma flow plays a key role in detachment and impurity retention

Large Poloidal Flux Expansion Reduces Peak Divertor Heat Flux Leading to Naturally Detached Divertor


High flux expansion divertor studies in NSTX

V. A. Soukhanovskii[1], R. Maingi[2], R. E. Bell[3], D. A. Gates[3], R. Kaita[3], H. W. Kugel[3], B. P. LeBlanc[3], R. Maqueda[4], J. E. Menard[3], D. Mueller[3], S. F. Paul[3], R. Raman[5], A. L. Roquemore[3]

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[2] Oak Ridge National Laboratory, Oak Ridge, TN, USA
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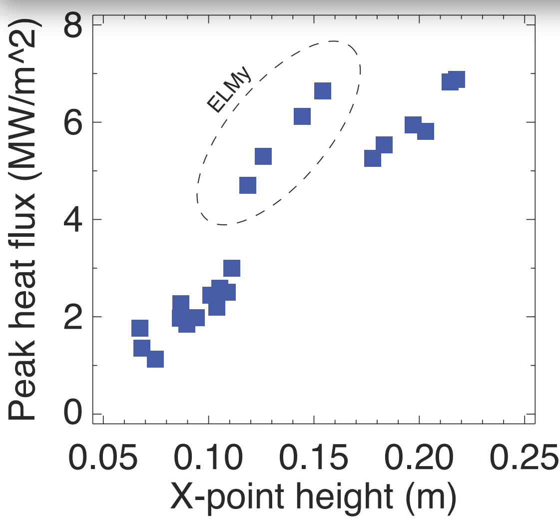
[4] Nova Photonics, LLC
[5] University of Washington, Seattle, WA, USA

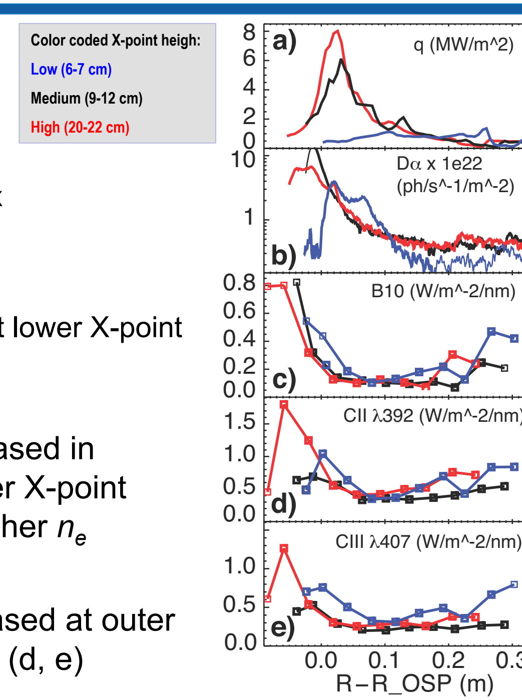
Poster P2.178

36th EPS Conference on Plasma Physics
June 29 - July 3, 2009, Sofia, Bulgaria



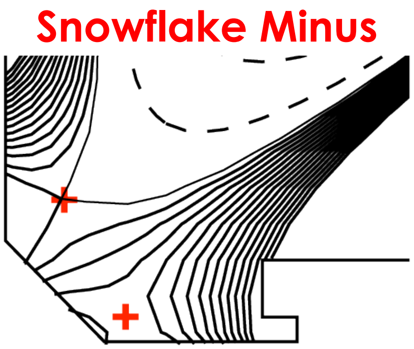
Divertor approached detachment at lower X-point heights

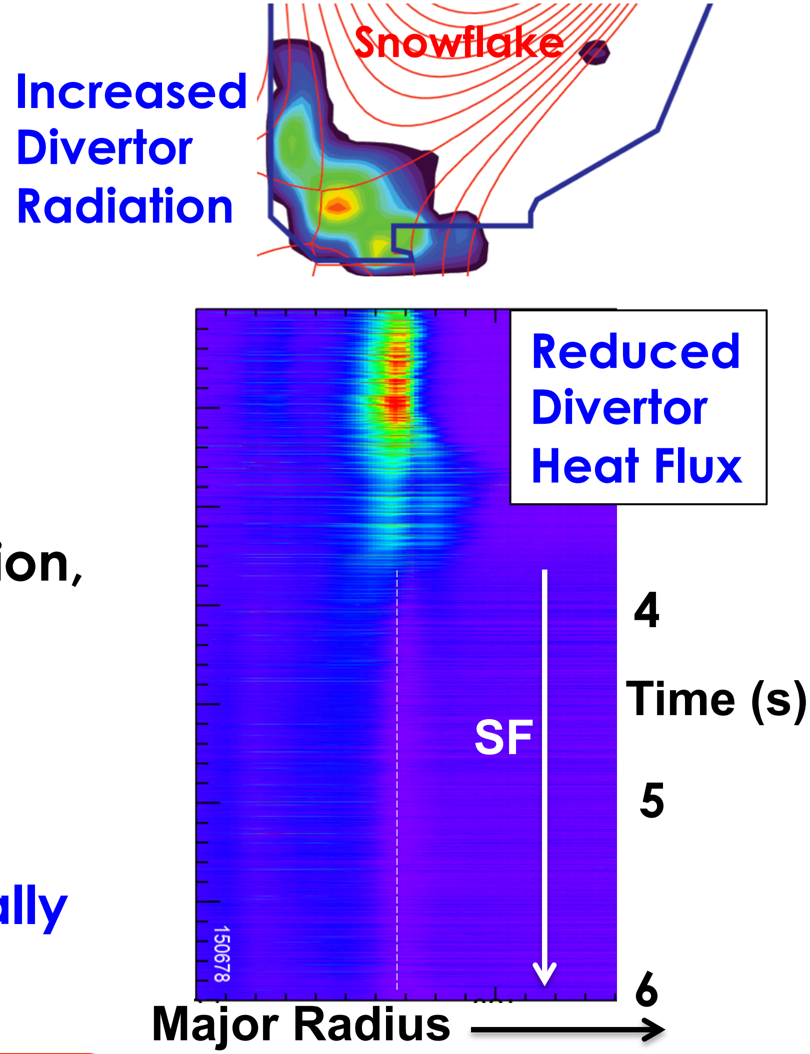
- Heat flux profiles (a)
  - Peak q reduced by x 8
  - Width changed substantially
  - Peak moved away from separatrix
- D-α profiles (b)
  - Higher peak and broader profile at lower X-point due to recombination
- Balmer $n=10\text{-}2$ line intensity increased in vicinity of outer strike point at lower X-point height (c) – recombination and higher n_e
- Emission from C II and C III increased at outer strike point at lower X-point height (d, e)



Soukhanovskii, EPS 2014: Large poloidal flux expansion leads naturally to detachment.

Snowflake-Minus Configuration Features Large Poloidal Flux Expansion in Full Divertor, Large Reduction In Heat Flux





- **<u>Snowflake Divertor</u> configuration (D. Ryutov, V. Soukhanovskii) reduces heat flux by flux expansion,** *all along X-point to target plate.*

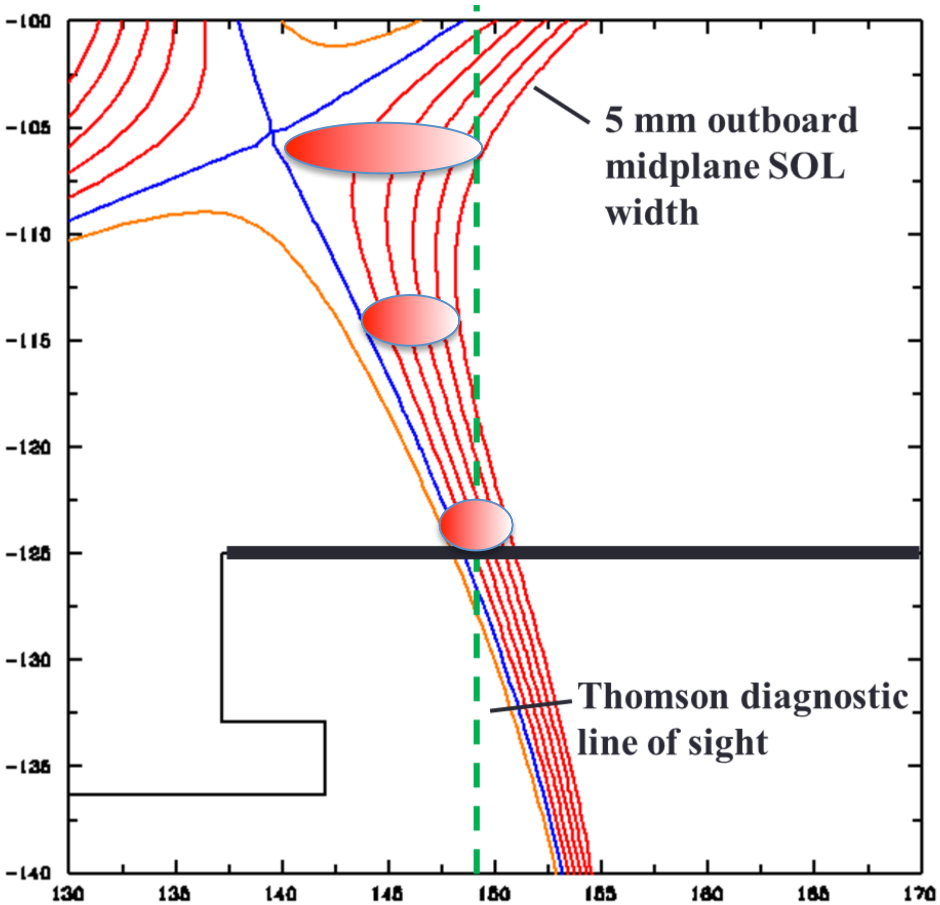
- **Core confinement remains high**

- **ELM heat flux reduced dramatically with gas puffing**

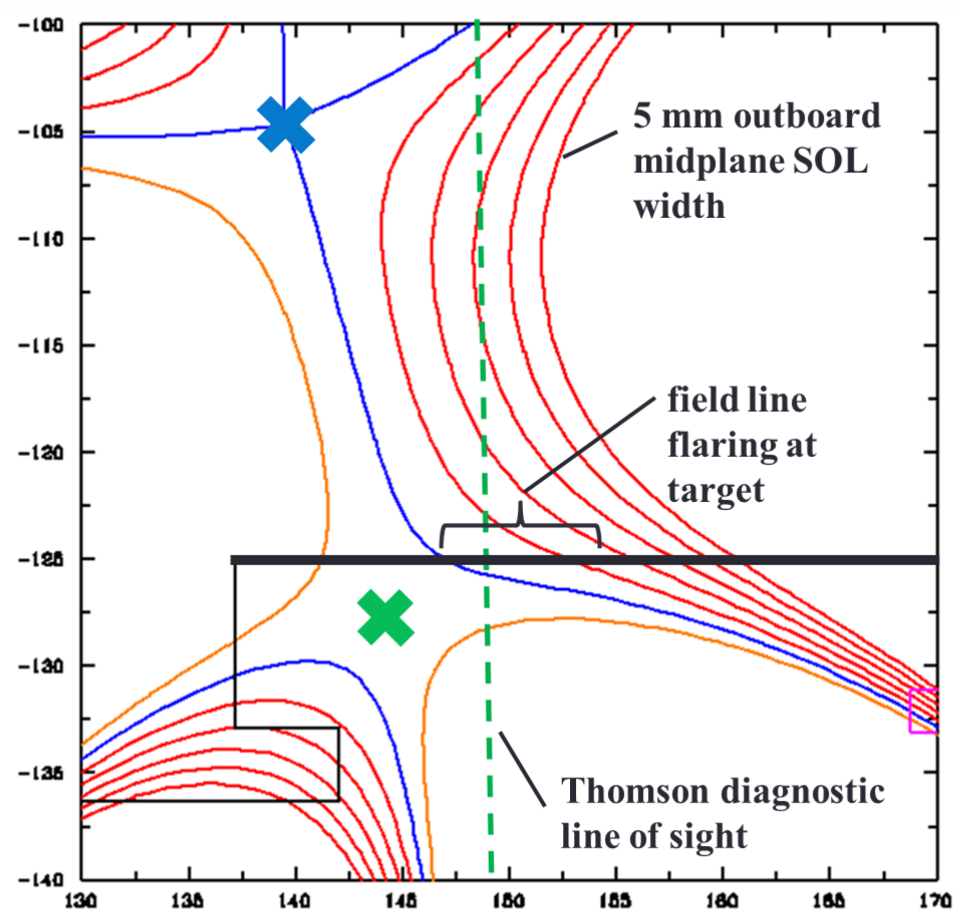
S.L. Allen, IAEA 2012
V. Soukhanovskii, IAEA 2014

Configurations to Increase Divertor-Target Poloidal Flux Expansion in DIII-D (U Texas X-Divertor)

Standard Divertor



X-Divertor



Recent UT experiments at DIII-D
B. Covelle, M. Kotschenreuther

DIII-D NATIONAL FUSION FACILITY

IFS

LLNL Team Provides World-Class Science to DIII-D and NSTX to Help Develop the Divertor Solution for Tokamaks

DIII-D Responsibilities

- Divertor Thomson scattering
- Divertor IR heat flux imaging
- Divertor impurity imaging
- Full cross section VIS/IR ITER prototype periscope
- Coherence Imaging Flow measurements
- NIR spectrometer
- EUV SPRED spectrometer soon

NSTX-U Responsibilities

- Supersonic gas injectors
- EUV Spectrometers (3)
- Laser blow-off system
- High resolution divertor spectroscopy (VUV, NIR, UV-VIS)
- Divertor impurity imaging (9 line cameras, 2D fast cameras, bolometers, and filterscopes)
- Optical Penning Gauge

LLNL Edge and Divertor Simulation Codes: UEDGE, BOUT++, COGENT