Measurements and Diagnostics
Past, Present and Future

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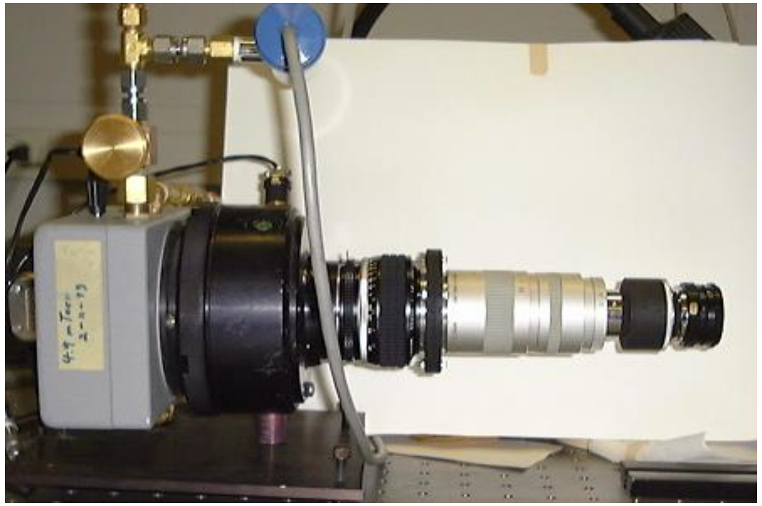
June 19th, 2020

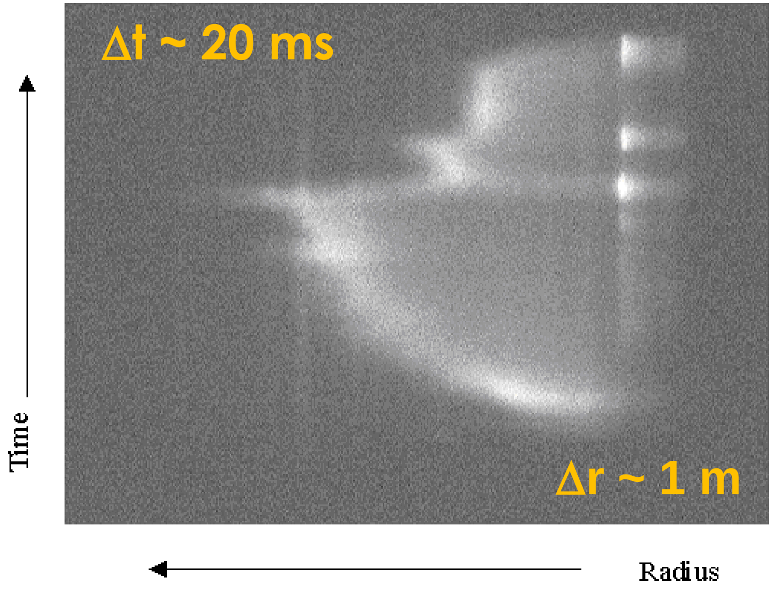
Thanks to L. Delgado-Aparicio (PPPL) for contributions on ME-SXR

Who Am I

- senior R&D Scientist at ORNL in the Fusion Energy Division in the Fusion Measurements and Integration Group
  - undergraduate work on Pegasus at W
  - PhD work on Alcator C-Mod at MIT
  - before joining ORNL I was a Lecturer at THE UNIVERSITY of York in the United Kingdom
- building and operating diagnostics on tokamaks has been a focus of my career
  - VUV and SXR spectroscopy to characterize core impurity concentrations and transport
  - UV/visible spectroscopy for studying impurity induced divertor detachment
  - bolometers for measuring radiated power

My first diagnostic: 1D visible bremsstrahlung imaging diagnostic on Pegasus (2002)





This Presentation May Not be Very Useful….

- the goal of this talk is not to fully educate you on how to infer plasma properties from observations & make great diagnostics
  - textbooks: I.H. Hutchinson "Principles of Plasma Diagnostics"
  - bi-annual conferences (HTPD, ECPD) produce hundreds of manuscripts that detail how innovations in technology are applied to diagnostics
- instead, the focus is how the role of diagnostics for magnetically confined fusion has evolved and is evolving
  - why are diagnostics necessary and what are some best practices?
  - how diagnostics play a role in making progress in fusion and how has technology impacted that role (ex: on x-ray spectroscopy)?
  - how are measurements and diagnostics going to evolve as we push toward the first generation of fusion pilot plants?
- …and play a game

"Your Eyes Can Deceive You, Don't Trust Them…"

- human senses are ill-evolved to understand plasmas
  - sight: eye [390-700 nm], plasma [below 1 nm to 10's of MHz (10's of m)]
  - touch: hot coffee [~75 degC], cold detaching divertor [~30000 degK]
  - sound: ear [20 Hz – 20 kHz], electron/ion plasma frequency [90/2 GHz]
  - taste: please don't eat plasma
  - smell: …ozone?

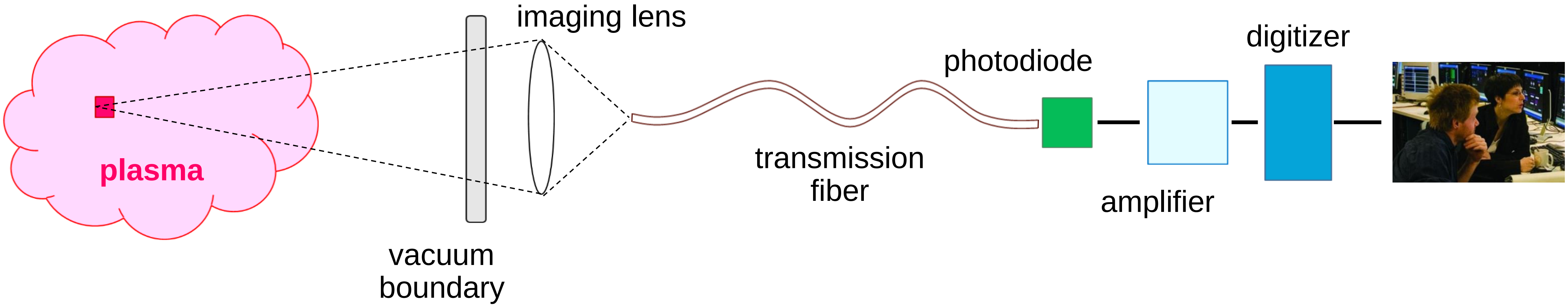
Considerations When Designing and Using Diagnostics

- (A) understand the fundamental mechanism and approximations you're using to generate information from the plasma
  - example: contrast magnetic sensors vs. Langmuir probes
- (B) understand that information is altered as its transmitted through the plasma (absorption, scattering) and to sensors
- (C) understand the relevant device physics that occurs when converting information to 'volts' and then do digital format

SPECIAL ISSUE ON PLASMA DIAGNOSTICS FOR MAGNETIC FUSION RESEARCH (12 chapters about fusion diagnotsics)

https://www.tandfonline.com/toc/ufst20/53/2

Example: Photodiode Measurement (Your Plasma Eye)



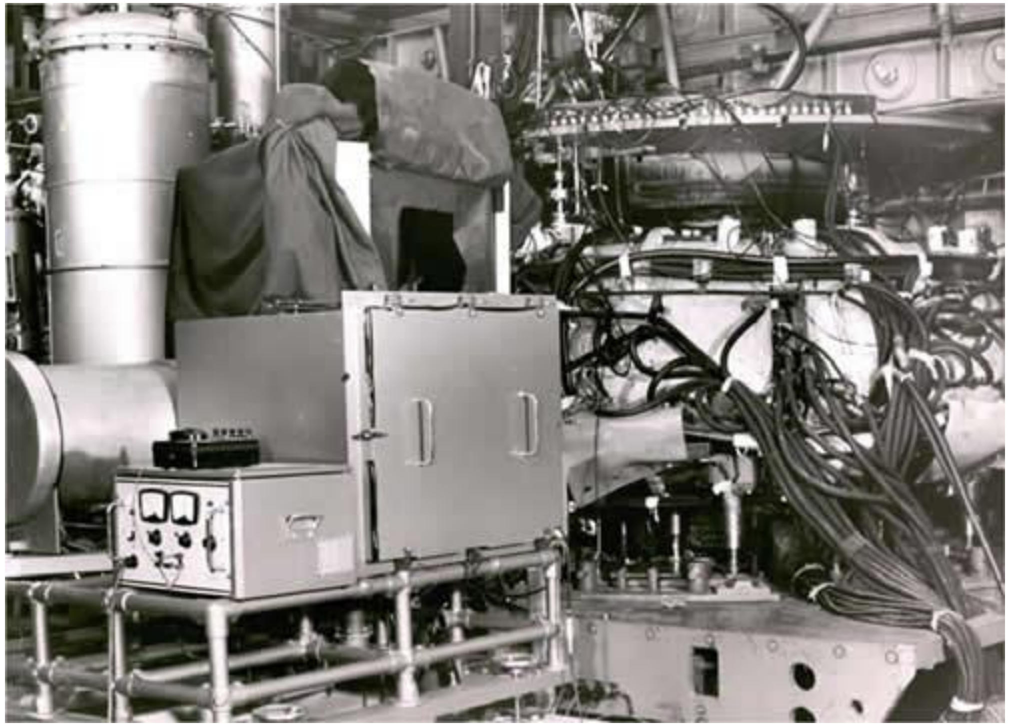
- (A) generation of information from the plasma
  - local emission combines many plasma properties, line-integration
- (B) transmission of information
  - λ-dependent signal attenuation that evolves (damage, coatings)
- (C) conversion of information
  - λ-dependent sensitivity in semi-conductor, gain-bandwidth curves

Measurements Can Trigger Paradigm Shifts

"Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3" Peacock, *et al.* Nature **224** 488 (1969)

- claims of high τ_E > 10 ms, T_e > 1 keV in T-3 'tokamak' at IAEA 1968
- UKAEA team demonstrated Thomson scattering on Zeta (pinch) and were invited to Novosibirsk to independently confirm the results
- confirmation of the results in 1969 (Nature, APS-DPP) led to the worldwide focus on the tokamak concept

https://www.euro-fusion.org/news/detail/detail/News/success-of-t-3-breakthrough-for-tokamaks/
https://www.iter.org/newsline/102/1401
https://royalsocietypublishing.org/doi/pdf/10.1098/rsbm.2011.0012



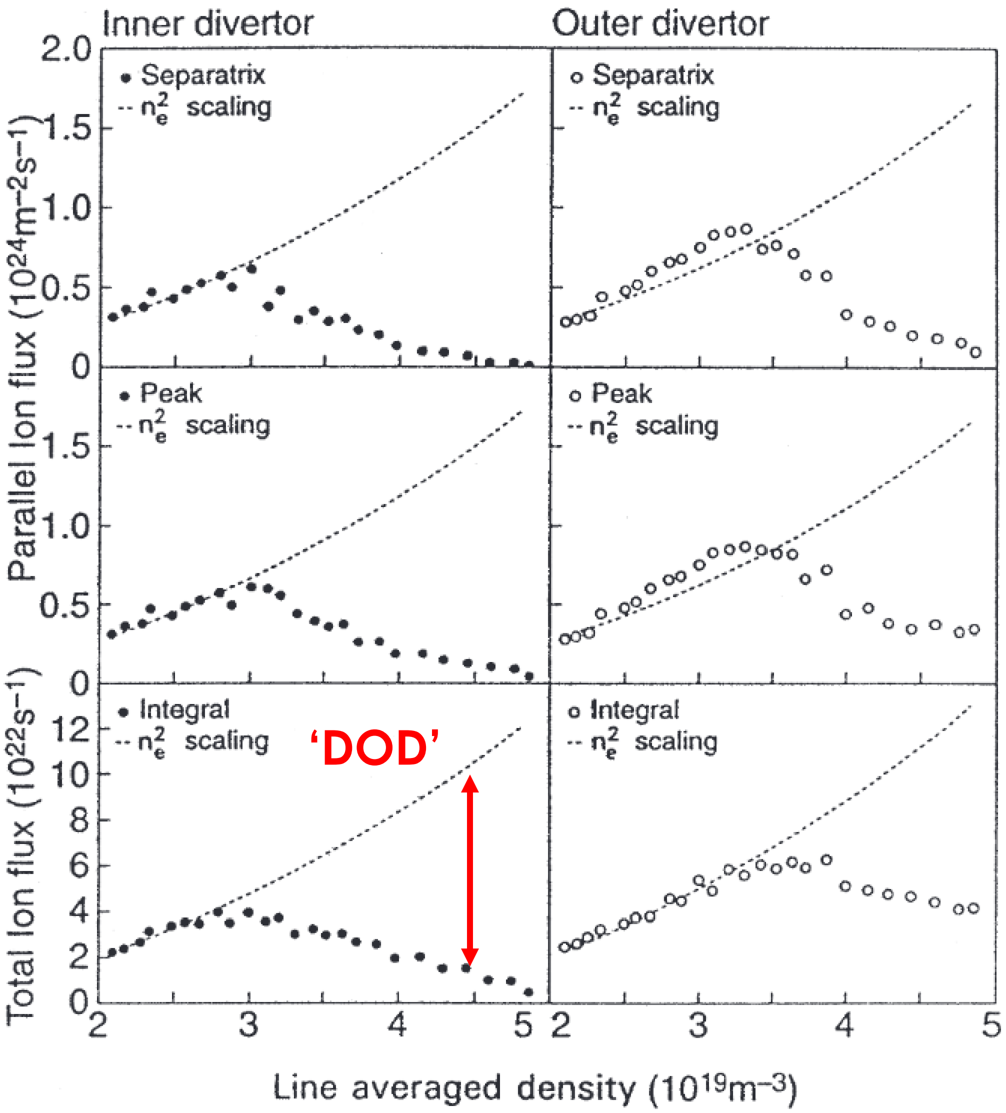
This concept is being applied in the U.S. through ARPA-E 'capability teams' partnering with private fusion companies

https://www.ornl.gov/news/ornl-team-builds-portable-diagnostic-fusion-experiments-shelf-items

The Language We Use is Based on Measurements

- research on divertor ‘detachment’ is ongoing at tokamaks worldwide in order to find solutions excessive heat and particle flux for ITER, pilot plants
- the basic physics of detachment is still the subject of debate, and discussions are still very phenomenological
- Langmuir probes measurements of j_{sat}, interpreted into Γ_i, define the onset of detachment as a ‘roll-over’ from expectation as a function of density

see: G. Matthews “Plasma detachment from divertor targets and limiters” J. Nucl. Mat. ***220*** *104 (1995)*



https://doi.org/10.1088/0029-5515/38/3/303

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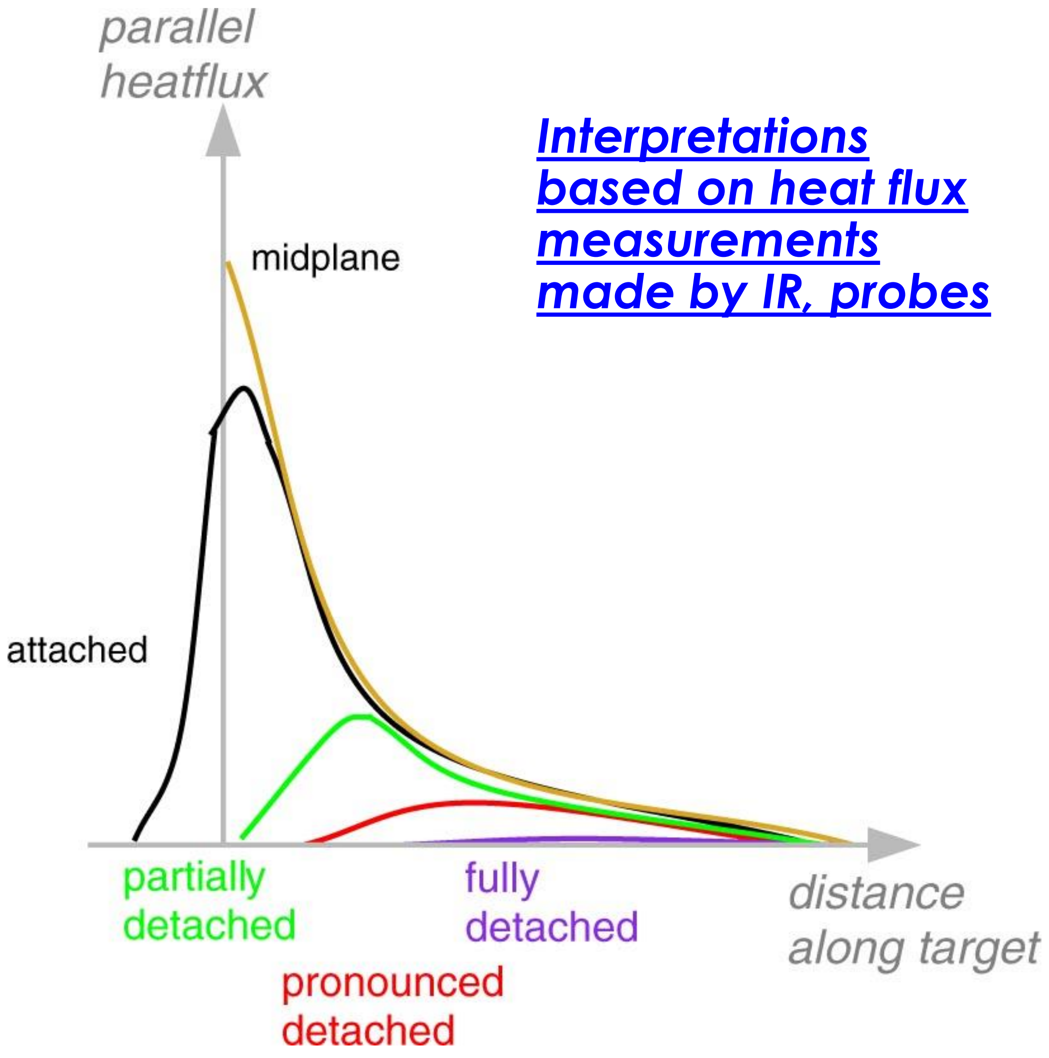
- this language starts becomes more complicated and confusing as we make more observations



Interpretations based on heat flux measurements made by IR, probes

https://doi.org/10.1088/0029-5515/55/5/053026

Technology Has Reduced the Barrier to Make Measurements

- decades of advancement in sensor technology, lasers, etc. have pointed to other resource limitations that limit our ability to validate models and improve understanding

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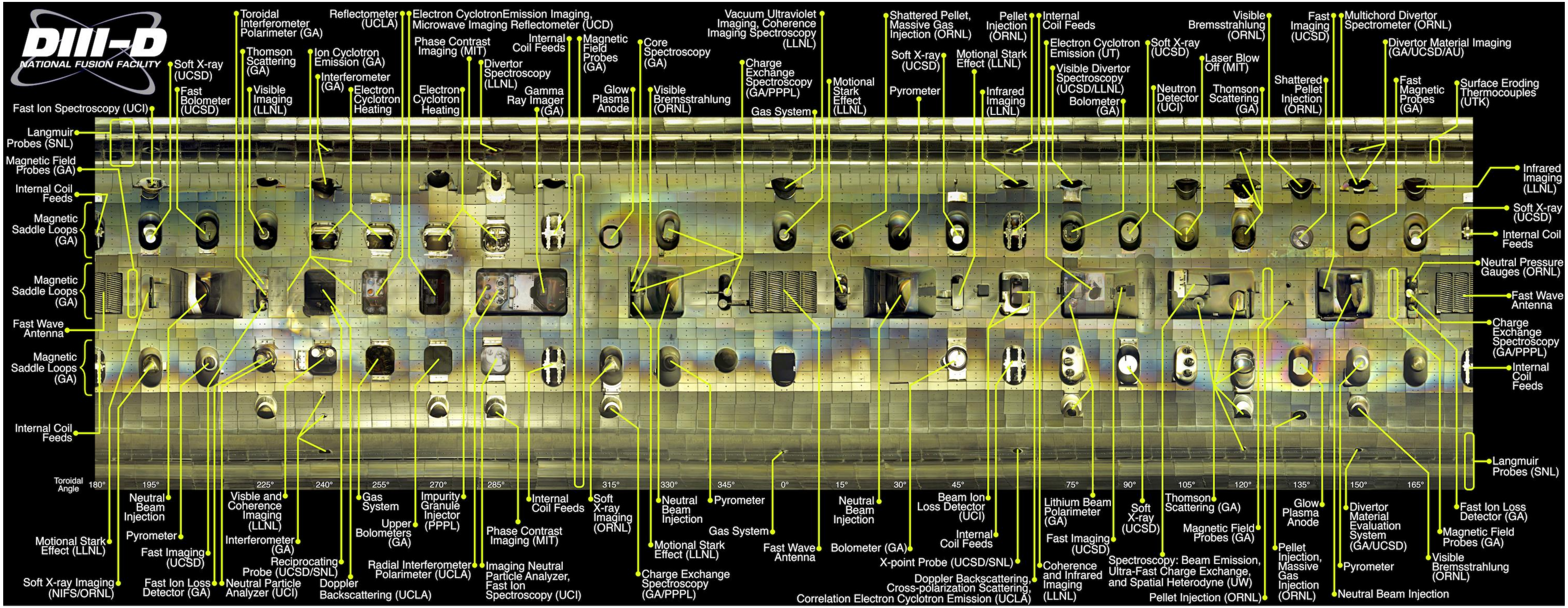
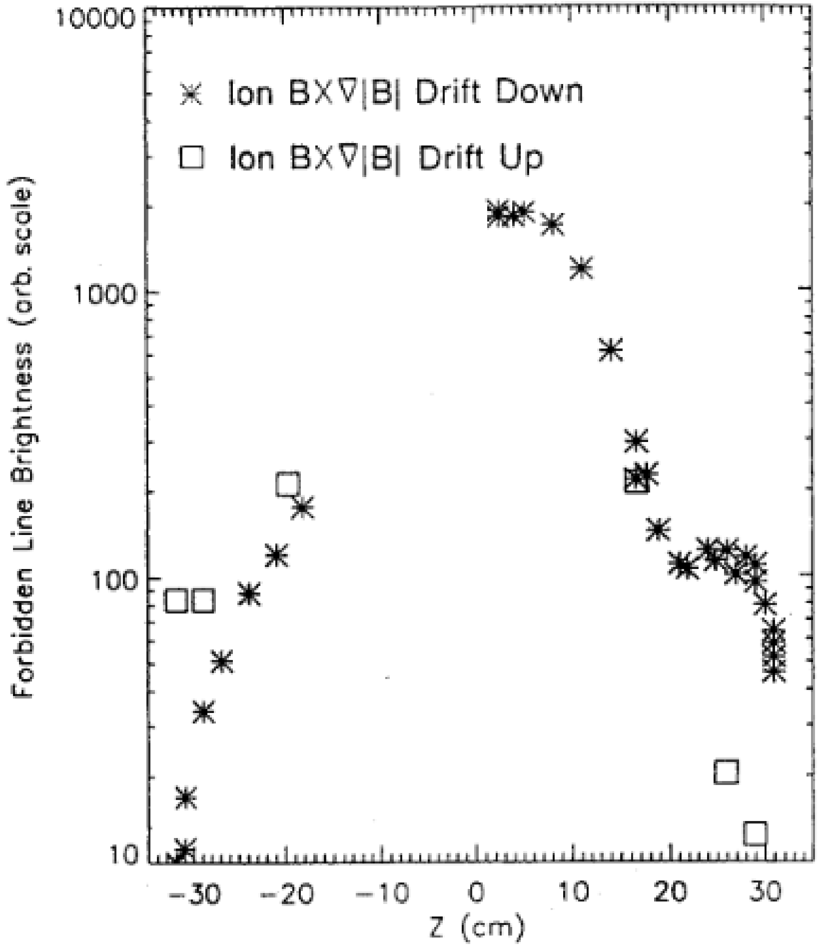


Ex: Impact of Hybrid Pixel Detectors on X-Ray Spectroscopy

principles of bent crystal x-ray spectroscopy have been known for > 100 years and used in plasma physics for > 50 years

- single line-of-sight x-ray spectrometers could resolve Br, v_Z, and T_Z, but needed to be scanned over the plasma shot-to-shot
  - ex: C-Mod (Rice 1997) up/down asymmetry



https://doi.org/10.1088/0029-5515/37/2/I09

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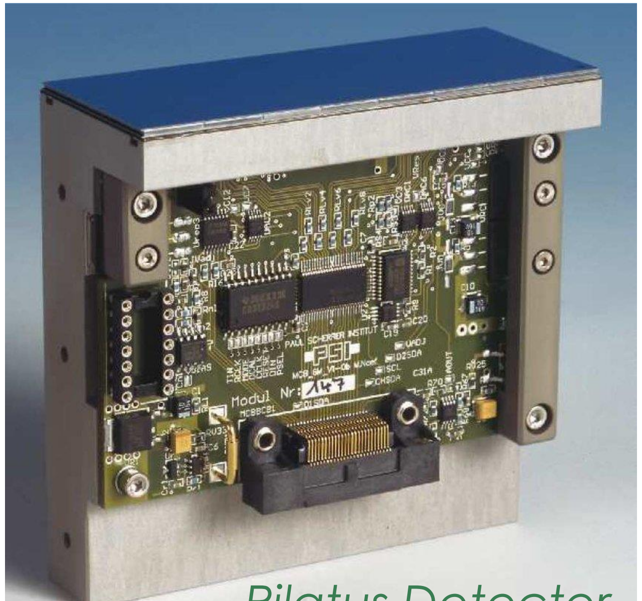
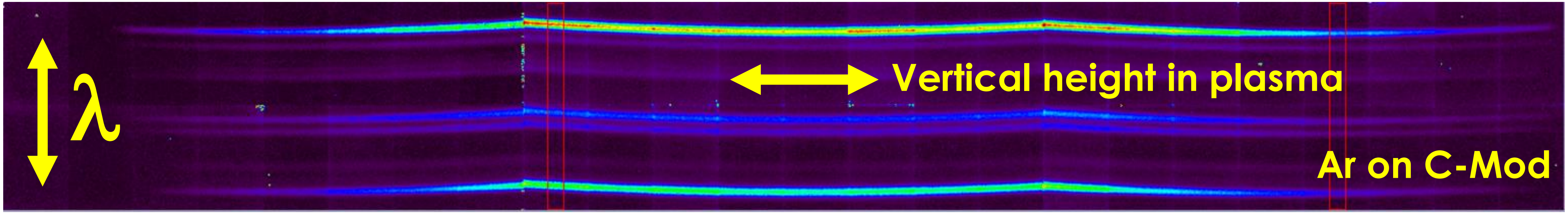
- an innovative hybrid pixel detector invented at the Paul Scherrer Institut (and spun-off into Dectris Ltd) enabled low-noise, x-ray imaging crystal spectroscopy



Pilatus Detector



Technology Has Made What Took ‘Days’ take ‘Shots’

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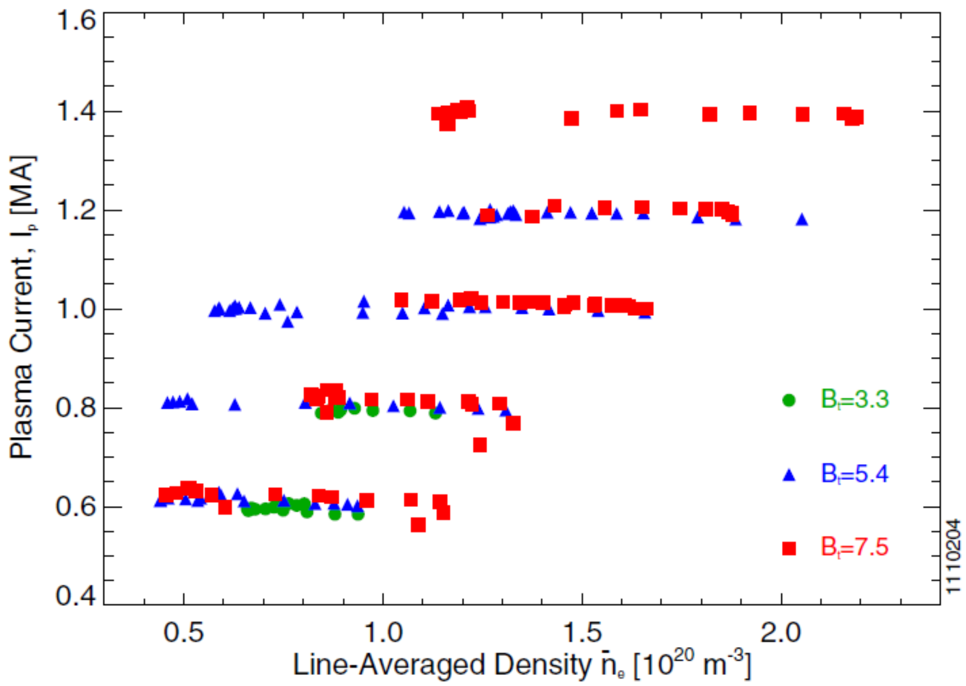
- XICS allowed intra-shot scans in n_e and shot-to-shot scans in I_p, B_t, full op. space

https://doi.org/10.1088/0029-5515/53/4/043006



XICS was used to measure a/L_{Ti} for multi-scale gyrokinetics sim. and $nT_i\tau$ in W7-X

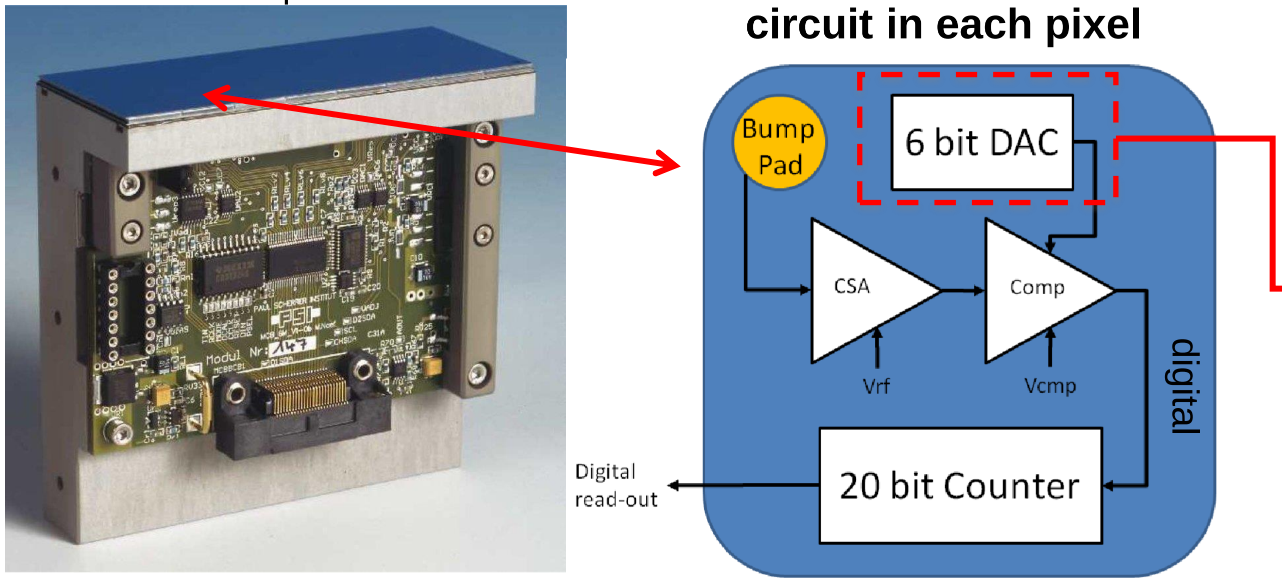
https://doi.org/10.1088/0029-5515/56/1/014004
https://doi.org/10.1038/s41567-018-0141-9

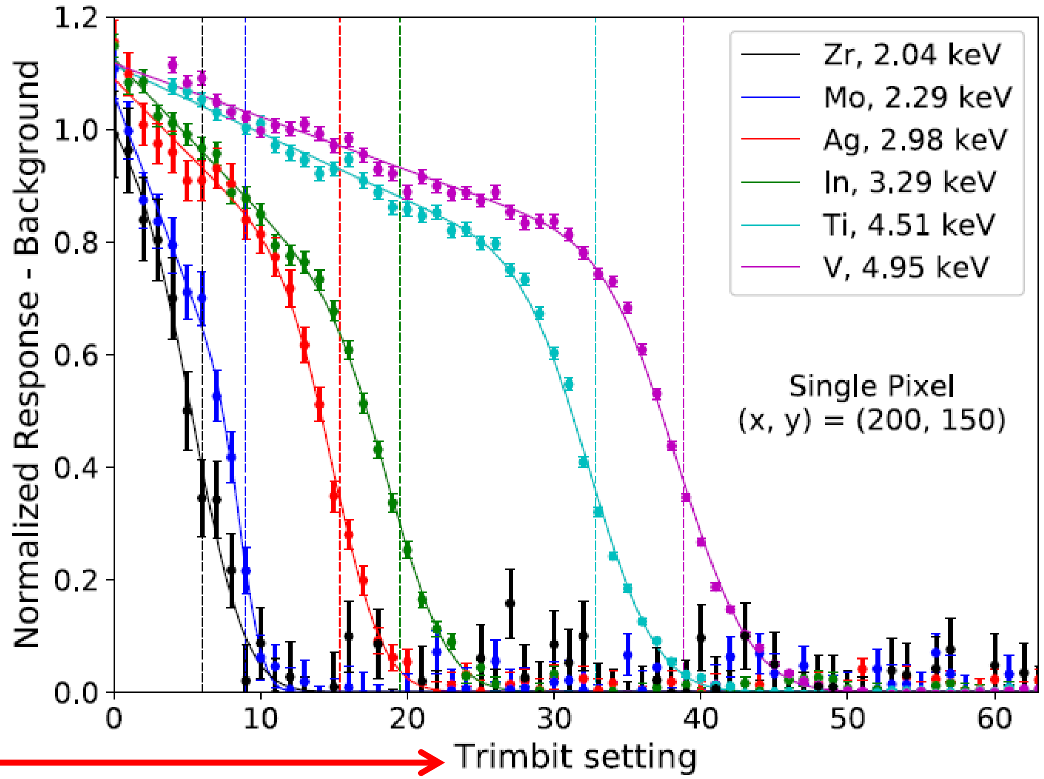
One Success Can Lead to Further Innovative Ideas

- a feature of the Pilatus detector used to calibrate the sensor before shipping was repurposed by PPPL scientists to create an x-ray imaging camera that can multiple colors

~100,000 pixels

Photon counting circuit in each pixel





https://doi.org/10.1063/1.5037347
https://doi.org/10.1063/1.4732177

from L. Delgado-Aparicio (PPPL)

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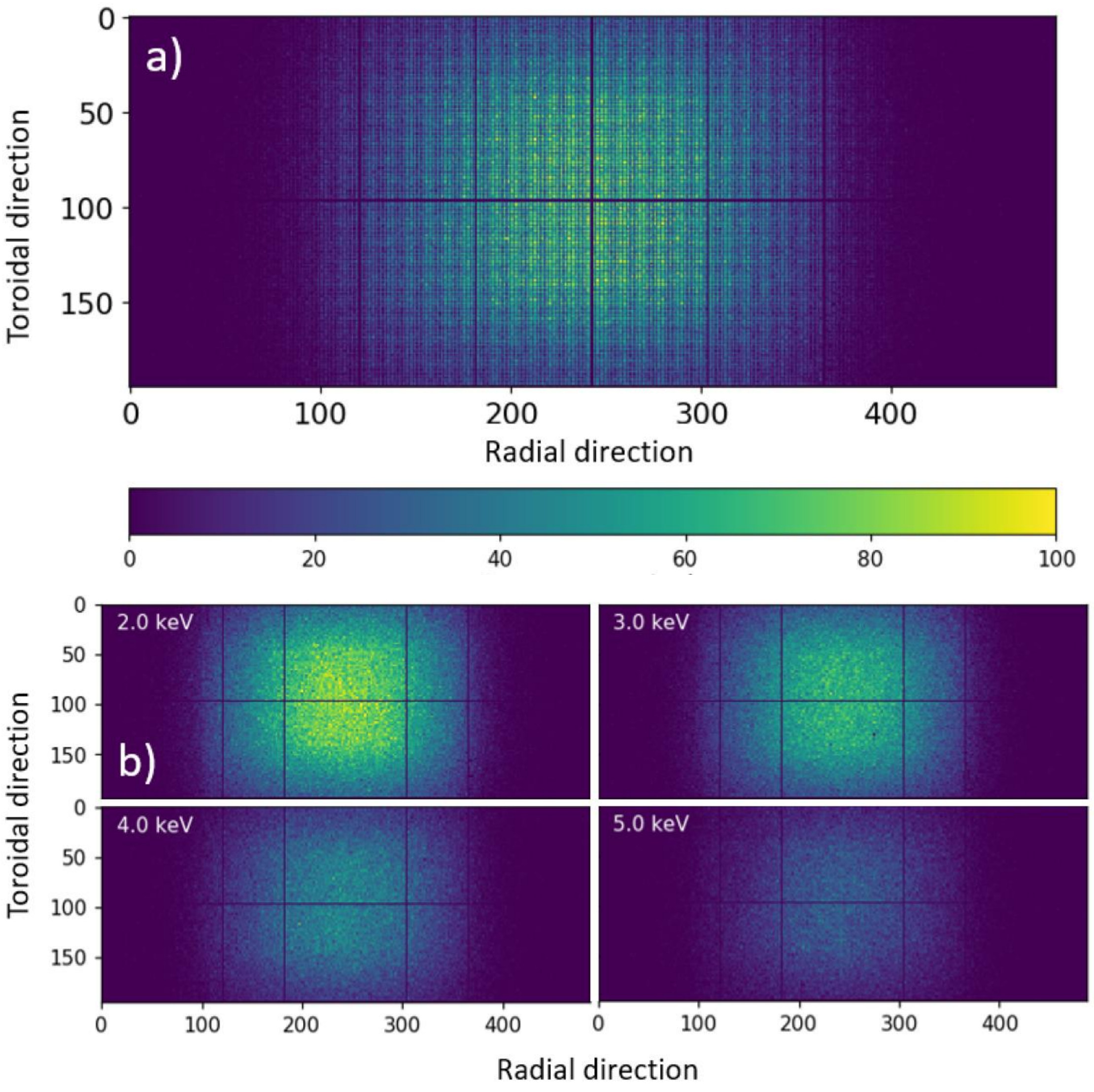
- PPPL+UW (MST) worked further to demonstrate the calibration and quantitative interpretation of the multi-energy soft x-ray (ME-SXR) pinhole imaging technique
  - T_e profiles on MST
- U.S. team is now exporting this measurement approach to EU devices and extending it to HXR



https://doi.org/10.1063/1.4964807
https://doi.org/10.1088/1748-0221/14/09/C09009

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- limited budgets ($$$)
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- improvements in our ability to model and simulate plasmas have driven need to measure smaller spatial and time scales to observe characterizes of plasma turbulence
  - tokamak programs + dedicated"Measurement Innovation" funding continue support new ideas

Motivation for Measurements Must Evolve

Science Experiments → **Reactor Prototypes**

measurements will get progressively difficult to make

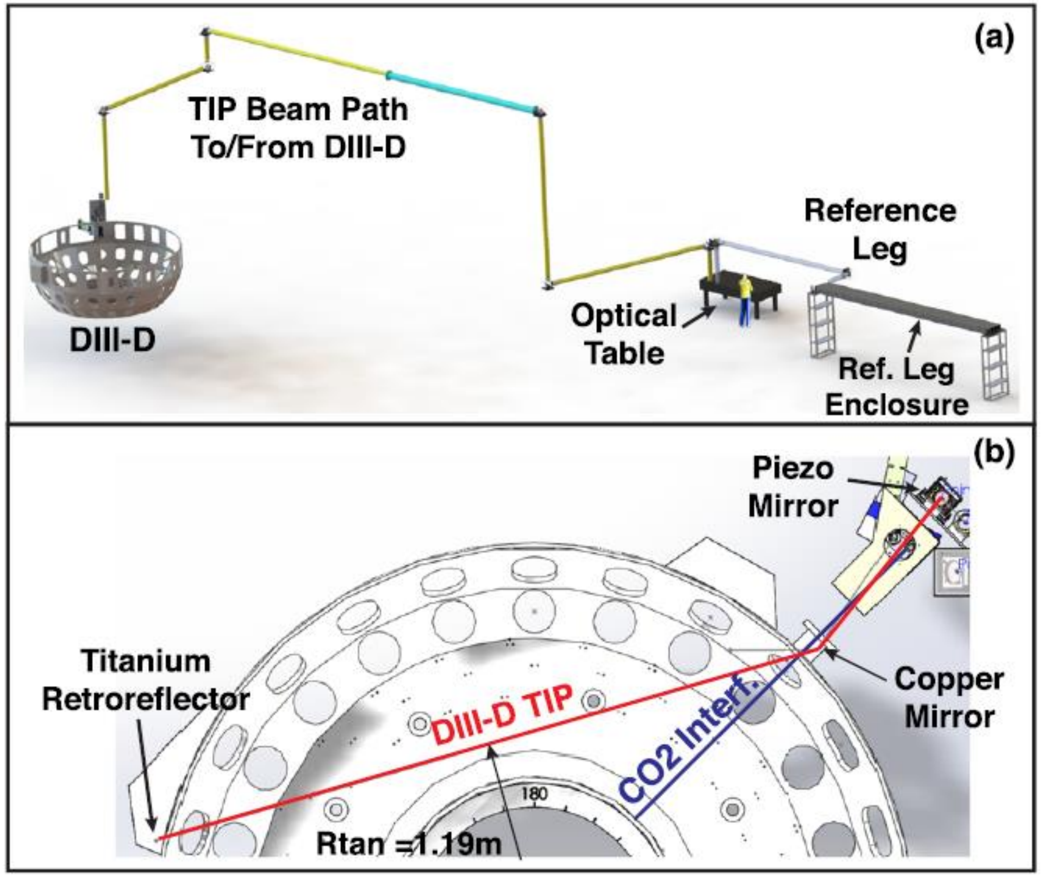
- measurements in today's experiments provide data needed for risk-basked decision making in designing tomorrow's devices

that risk will never be zero, no matter what!

- will making a measurement result in a change of behavior?
  - change an in-progress design? be used in feedback control?
- do we need to observe something directly when we can make inferences with model predictions from other data?

The Future: Present Devices versus ITER

- minimize risk for the diagnostics that <u>have</u> to work for ITER
- systems engineering driven design with substantial prototyping effort to ensure that requirements can be met



Two Great Examples from HTPD 2018

- full-scale toroidal interferometer and polarimeter built & tested on DIII-D

  https://aip.scitation.org/doi/10.1063/1.5037461

- R&D on steady-state magnetic Hall sensors, to be tested on WEST

  https://doi.org/10.1063/1.5038871

The Future: ITER versus a Demonstration Reactor

- ITER is still fundamentally a science experiment and so it needs a comprehensive & versatile set of diagnostics
  - SRD55 IDM UID VJR8F5 is 113 pages of requirements for the 85 diagnostics
  - *probably the worst situation; need for the most information in the harshest environment with the least background*
- a reactor's need for "diagnostics" for science will be subsumed by it's needs for control
  - evolve into a facet of 'plant I&C'

https://doi.org/10.1016/j.fusengdes.2017.05.038

ITER plans to have 550 channels

List of channels for spectroscopic and radiation measurements (without limiter observations).

Diagnostic method and target	Number of channels	Integration approach
Radiation power (core)	2 × 2 × 10	20 in Eq. Port 20 in. Vert. Port
X Ray spectroscopy (core)	2 × 3	6 in E.P.
VUV spectroscopy (core)	2 × 4	8 in E.P.
VUV spectroscopy (edge)	2 × 3 x 4	16 in E.P. 8 in. V.P.
VIS spectroscopy (outboard divertor and x-point)	2 × 2 x 2	8 in E.P.
Thermography (divertor)	2 × 2	4 in E.P.
X-ray intensity	2 × 2 × 10	20 in E.P. 20 in. V.P.
Total		82 in E.P. 48 in. V.P.

For more info: W. Biel, *et al*. "Diagnostics for plasma control – from ITER to DEMO"
https://doi.org/10.1016/j.fusengdes.2018.12.092 & R. Boivin TEC Paper

A Community Driven Plan for Measurements and Diagnostics for Fusion Science and Technology

FST Program Recommendation - E in the Recent CPP Report

"Establish a program for developing diagnostics, measurement, and control techniques that can be used in a reactor environment"

1. Develop critical *in situ* and combined effect diagnostics for fusion materials research and plasma science needed to validate models, which includes new capabilities on existing confinement devices as well as on smaller "lab-scale" experiments

2. Initiate the R&D needed to solve diagnostic survivability challenges (materials & electronics) imposed by the nuclear conditions expected throughout a fusion pilot plant facility

A Community Driven Plan for Measurements and Diagnostics for Fusion Science and Technology [continued]

3. Develop nuclear environment compatible plasma diagnostics and engineering instrumentation needed for control and safe operation of an FPP and benchmark these new instruments on available facilities
4. Develop advanced control techniques to maintain high-performance burning plasmas without disruptions or other major excursions

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Measurements and Diagnostics also identified as a 'Cross-Cut' with actions that benefit both fusion energy and plasma science

Diagnostic collaborations are a prime opportunity for private-public partnerships (INFUSE), allowing decades of experience to help industry make fast progress in testing fusion concepts

Summary: Where Have We Been?

- specialized diagnostics have co-evolved alongside magnetic confinement fusion concepts to overcome the limitations of our feeble primate senses
  - diagnostic measurements have and continue to play an important role in demonstrating the potential of different concepts
- improvements in technology from outside of the fusion community can quickly revolutionize the status-quo
- while the ‘cutting-edge’ continues to move, there remain plasma features that we cannot resolve and information that is needed in order to validate our best plasma models

Summary: Where Do We Need to Go (Now → Reactor)

- prove a scientific hypothesis for a peer-reviewed publication → inform risk-based decision for next-step devices
- make high resolution, wide coverage measurements → observe only critical pieces of data that cannot be otherwise inferred
- bespoke diagnostics that can be flexibly configured → robust sensors that are not accessible for routine maintenance
  - non-nuclear → OMG neutrons!
- perform inter-shot analysis → rely on real-time control
- require advanced degrees to operate and maintain → can be staffed by a trained technical workforce

Your generation will have the challenge and the excitement of leading this transition!