Development of Radiated Power Diagnostics for NSTX-U

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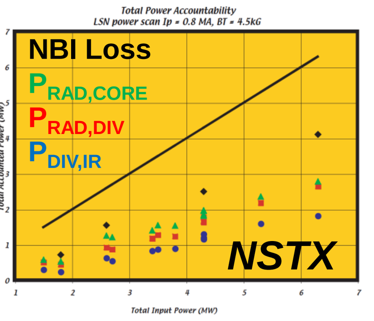
NSTX-U & Radiation Diagnostics

accurate radiation measurements contribute to high level NSTX-U research objectives

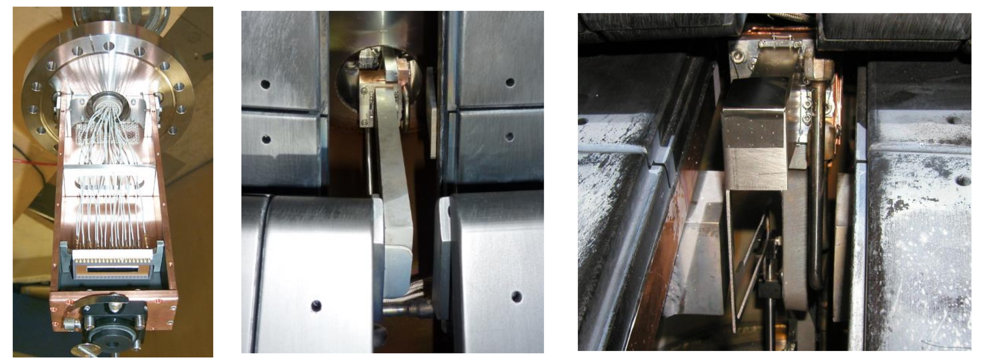
- demonstrate stationary operation at performance that extrapolates to ≥ 1MW/m² neutron wall loading in FNSF
  - utilize core radiation for power balance, metallic impurity estimates
- develop and utilize the high-flux-expansion "snowflake" divertor combined w/ radiative detachment to mitigate heat fluxes
  - physics progress benefits from knowing divertor/edge radiation
- begin to assess high-Z PFCs plus liquid lithium to develop high-duty-factor integrated PMI solutions for FSNF & beyond
  - core P_{RAD} to asses high-Z and divertor P_{RAD} for vapor shielding

long term Oak Ridge National Laboratory collaboration goal is to demonstrate ST power balance (see T. Gray NP10.00049 for heat flux diagnostics)



- prior attempts [S. Paul – JNM 2005] could only account for ~60% of the input power
- reliable power balance important when extrapolating designs
  - avoid intensifying localized losses (NBI losses)
- will likely need to account for 3D too!

- upgraded radiation tools compliment new NSTX-U diagnostics and modeling activities
  - UV/visible spec. Soukhanovskii, RSI **77**, 10F127 (2006), RSI **81**, 10D723 (2010)
  - VUV transmission grating imaging spec. Tritz, PPCF **56** 125014 (2014)
  - boundary modeling of snowflakes O. Izacard (NP10.0030)
  - VUV/SXR spectroscopy M.E. Weller (NP10.00152) and ME-SXR imaging Delgado-Aparicio (NP10.00046) for core impurities
- previous NSTX radiation diagnostics insufficient to support NSTX-U mission
  - 16 CH midplane AXUV diode array (sensitivity issues)
  - 16 CH of divertor resistive bolometers (did not survive bake)

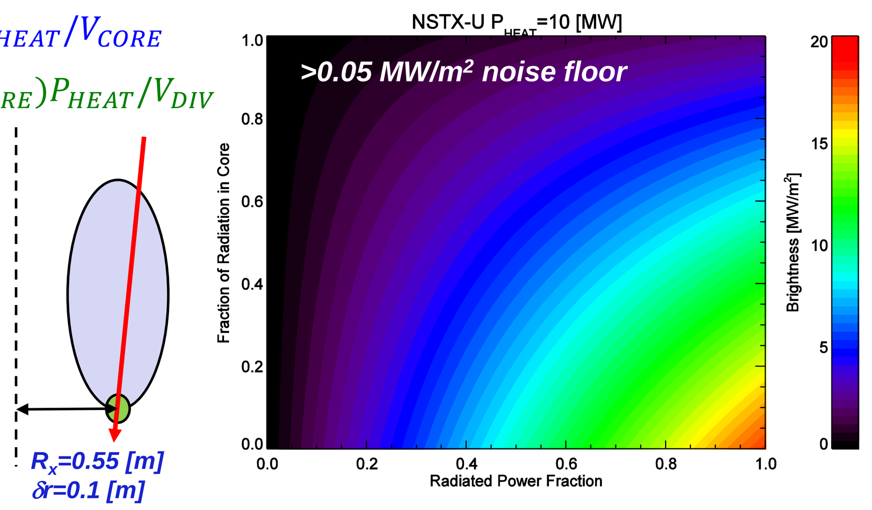


- simple estimates using radiated power fractions show NSTX-U signals should be measurable

$\varepsilon_{CORE} = f_{RAD} f_{CORE} P_{HEAT}/V_{CORE}$

$\varepsilon_{DIV} = f_{RAD}(1-f_{CORE}) P_{HEAT}/V_{DIV}$

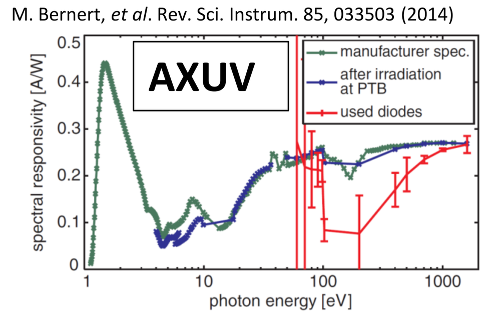
- line-integrate through both volumes
- vary core and divertor radiated power fractions

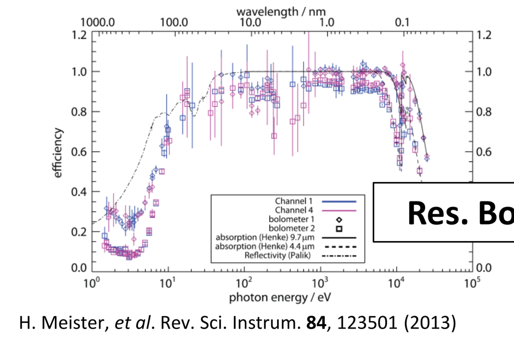


What Makes a Good Bolometer?

- approximately flat, known responsive over photon energy range of plasma emission
  - bolometers use temperature rise of an absorber
  - AXUV diodes responsivity changes after plasma exposure

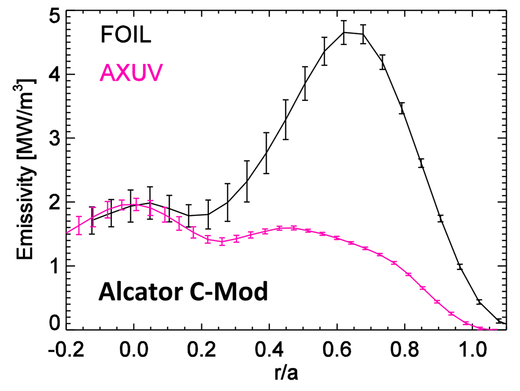
M. Bernert, *et al.* Rev. Sci. Instrum. 85, 033503 (2014)





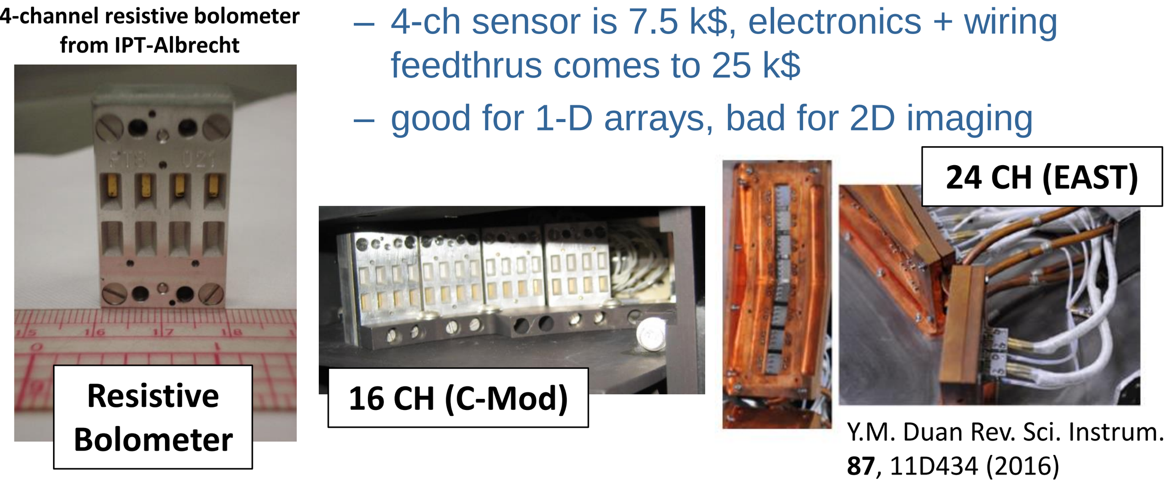
H. Meister, *et al.* Rev. Sci. Instrum. **84**, 123501 (2013)

- ex: viewing Mo radiation in C-Mod plasma, P_{RAD} off by ~x3, Z-dependent
- 'correcting' not been demonstrated due change in manufacturer's specs
  - neural networks ? (Tritz NP10.00043)



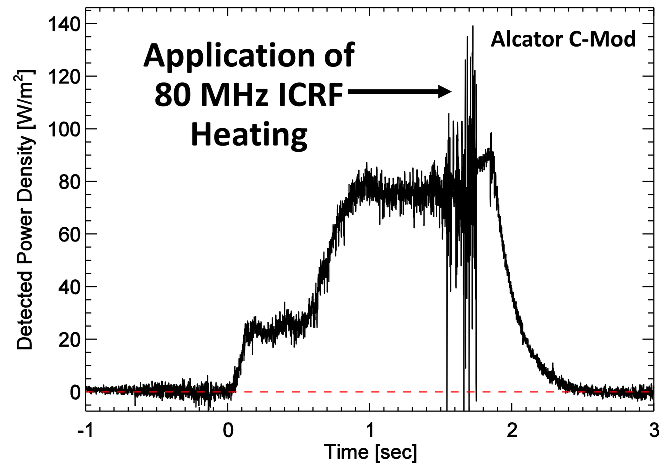
- can be deployed in large compact arrays at reasonable cost, to enable tomography
  - 4-ch sensor is 7.5 k\$, electronics + wiring feedthrus comes to 25 k\$
  - good for 1-D arrays, bad for 2D imaging

4-channel resistive bolometer from IPT-Albrecht



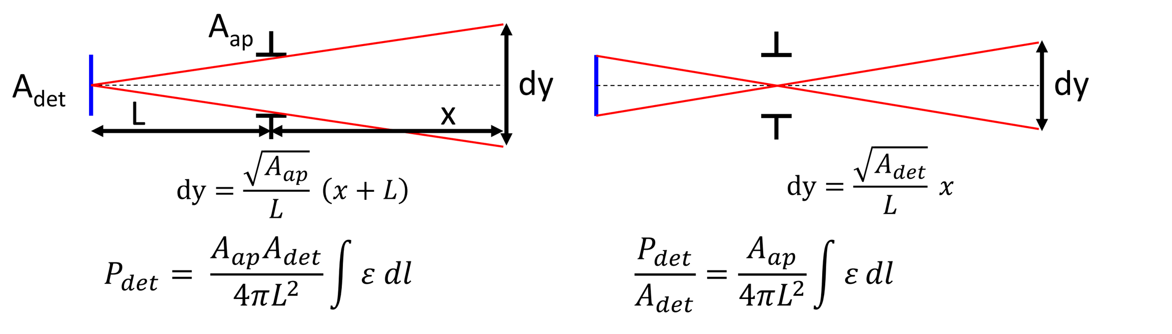
Y.M. Duan Rev. Sci. Instrum. **87**, 11D434 (2016)

- is resistant to electromagnetic interference
  - resistive bolometers can 'pick-up' ICRF heating in cases of weak(er) single pass absorption
  - magnet systems used in feedback control can provide a low-level of increased noise



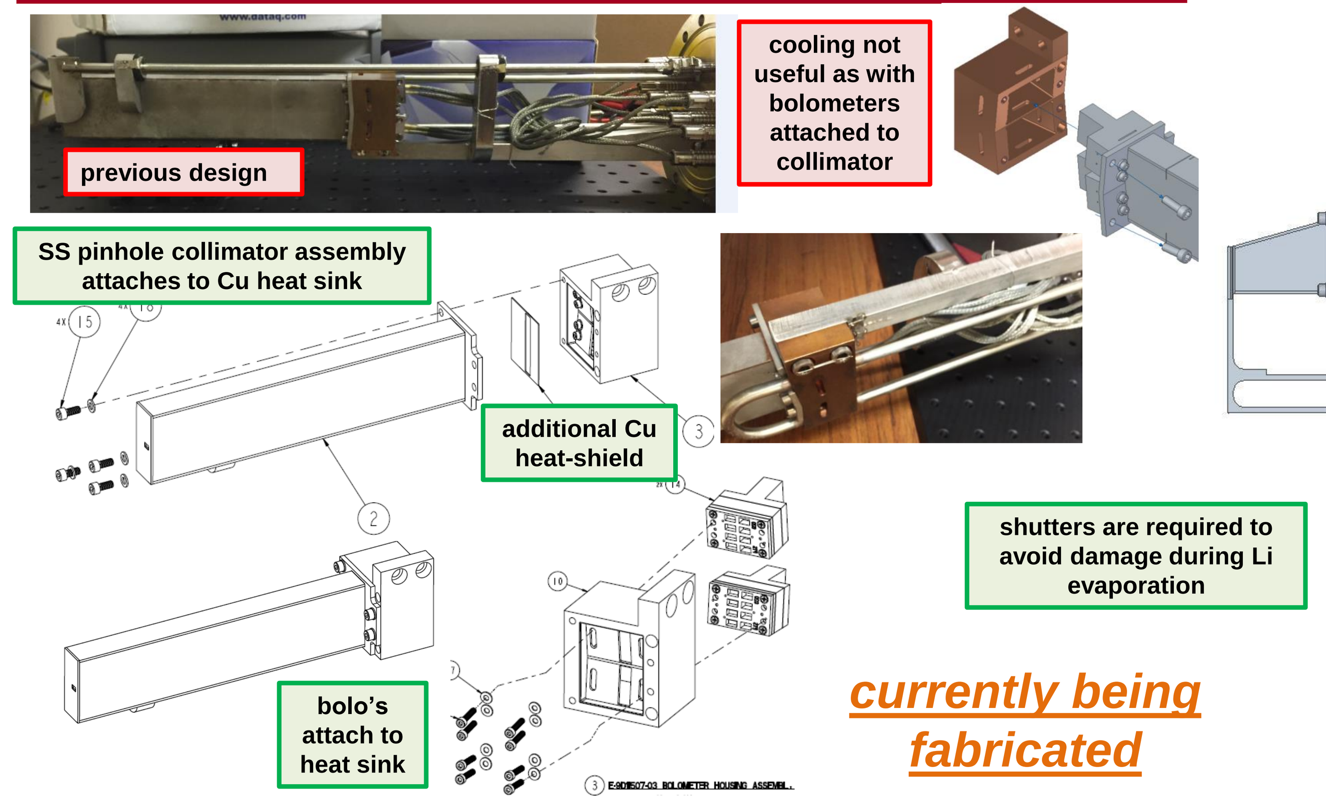
infrared video bolometers (IRVB) which are noise resistant and great for 2D imaging, but are more difficult to field in arbitrary locations

- has low Noise Equivalent Power Density (NEPD)



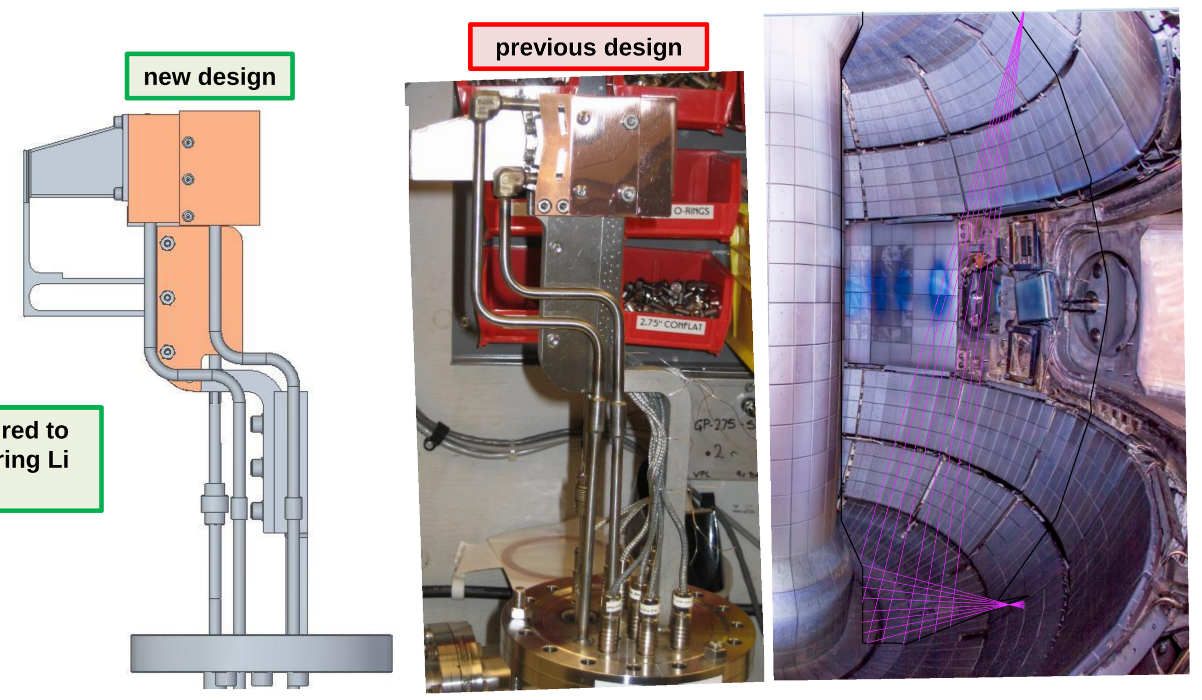
- for fixed spatial resolution, dy, the power density at the sensor is independent of the size and location of the sensor if $A_{ap} \sim A_{det}$
- P_{det}/A_{det} must exceed the Noise Equivalent Power Density (NEPD)

Upgraded Divertor Bolometers

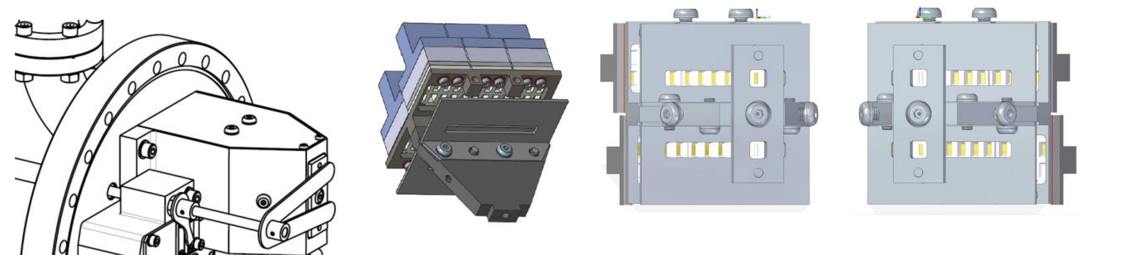


- primary concern to improve ability to survive the bake and also reorient views for NSTX-U
  - re-entrant pinhole cameras view between passive plates
  - cooling active only during bake (300+ degC)

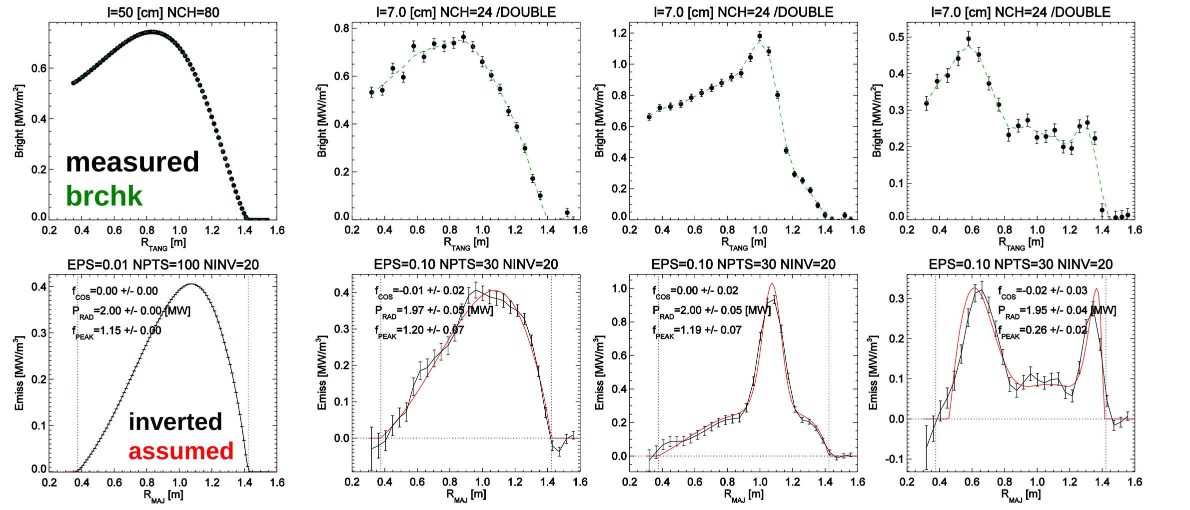
currently being fabricated



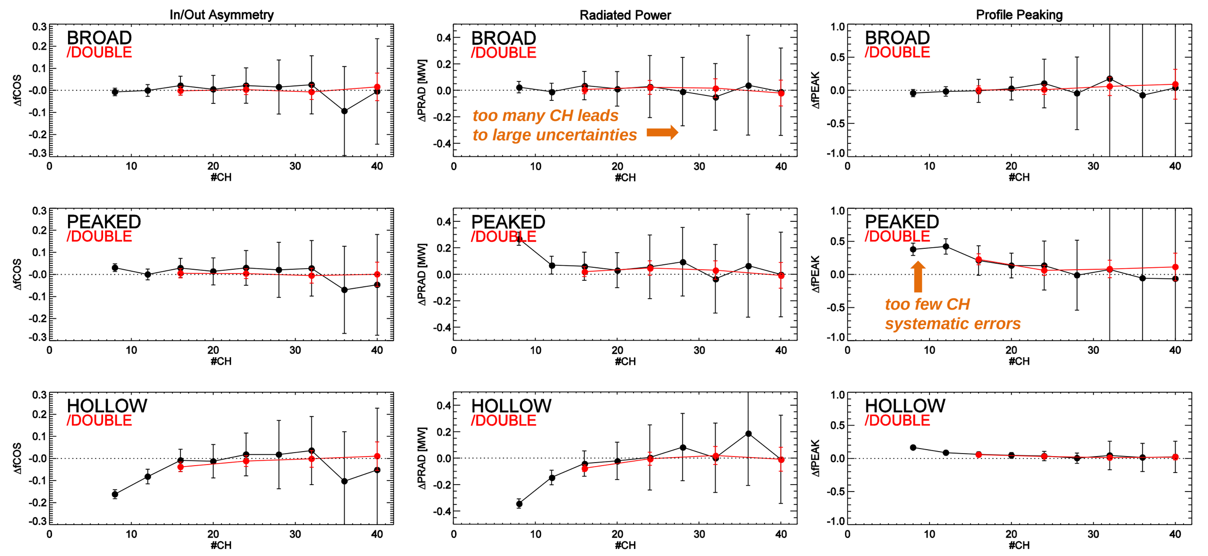
Midplane Tangential Bolometers



- novel double layer array allows compact diagnostic with high spatial resolution and high throughput
- shares space with midplane AXUV, ME-SXR diodes



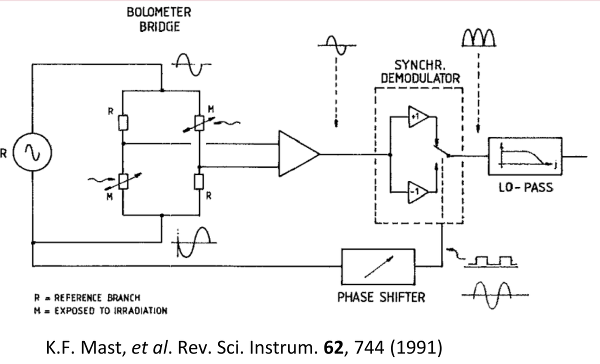
- new diagnostic capability for NSTX-U, goal to measure full midplane emissivity profile (24 CH)
  - scoping study to specify the number of channels needed
  - assume 2 MW P_{RAD}, 2% + 10 μW noise, NSTX-U equilibrium
  - use same ΔR_{TANG}, #CH increases, pinhole/det. distance increase
- fCOS = ratio of outer and inner emissivity (LFS-HFS)/(LFS+HFS) = 0.0
- PRAD= total radiated power from profiles, resolving 'cosine' term = 2.0
- fPEAK= ratio of radiation ψ_n < 0.4 and ψ_n > 0.4 = 1.15, 1.10, 0.23



Using New FPGA-Based Analyzers

- traditional resistive bolo. use analog analyzers
  - AC waveform (5-50 kHz) drives the Wheatstone bridge
  - phase-shifted drive signal mixed with bolometer response, filtered
  - high cost per channel (~3 k\$/ch), large rack space needed

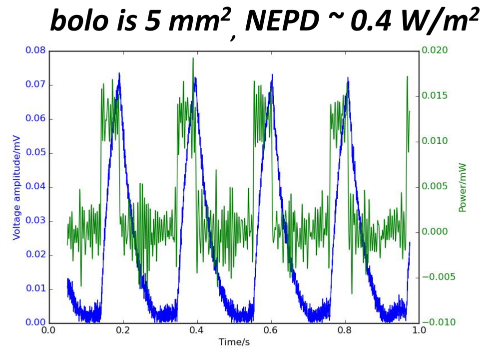
4-channel analyzer from IPT-Albrecht



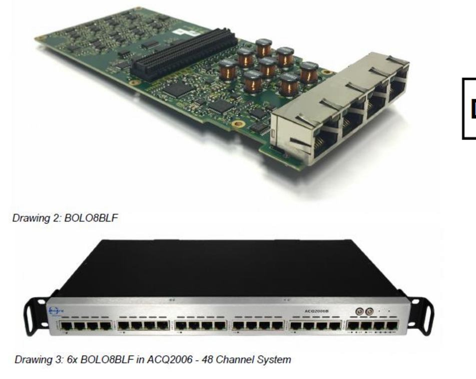
K.F. Mast, *et al.* Rev. Sci. Instrum. **62**, 744 (1991)

- advantages of FPGA approach
  - compact, low cost (< 0.5 k\$/ch)
  - DAC drives bridge, precision ADC measures imbalance
  - signal processing done in FPGA
  - DAC can apply voltage waveform of arbitrary frequency, allowing drive voltage to be 'tuned' to the room environment

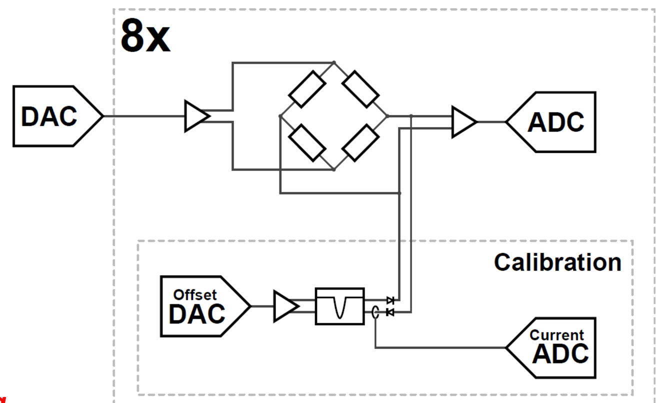
bolo is 5 mm², NEPD ~ 0.4 W/m²



see: J. Lovell, et al Proceeding of the 1st EPS Conference on Plasma Diagnostics **1** 137 (2015)



48-channel analyzer from D-tAcq

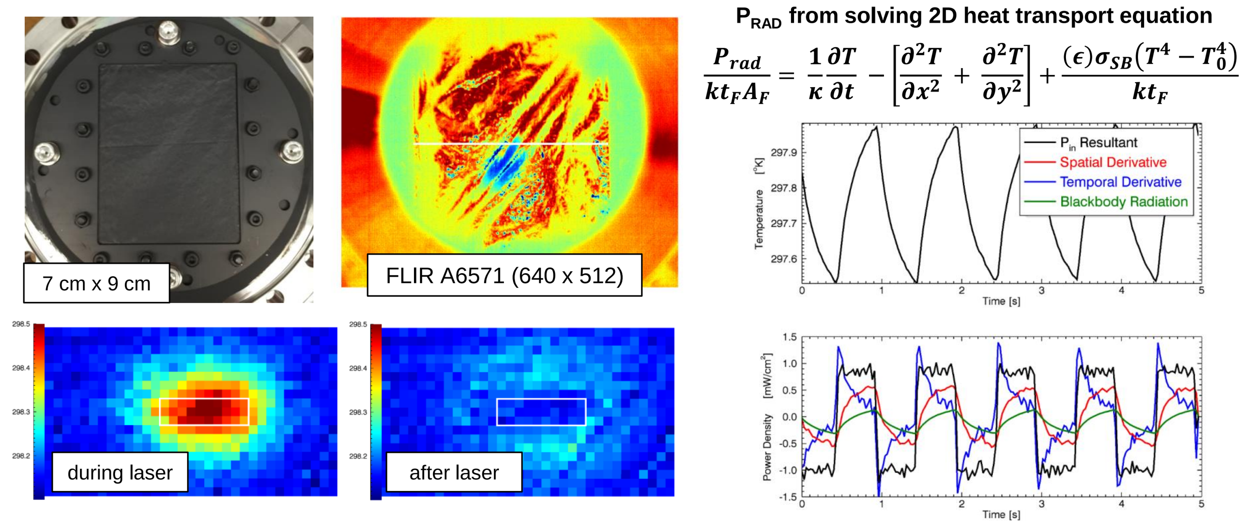


Testing New Bolometer Concepts

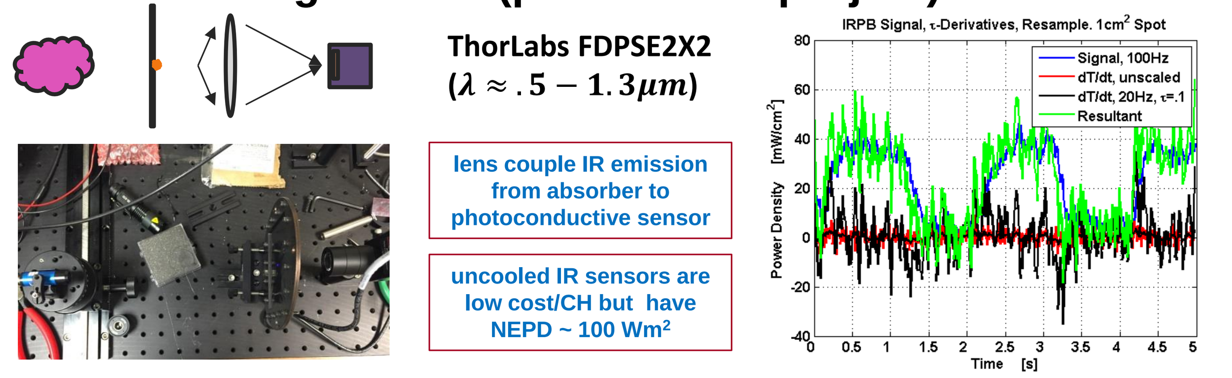
- use IR emission to measure the temperature change of the absorber, utilize 2D absorbers (IRVB)
  - technique developed by LANL (Wurden RSI 1997) and utilized in LHD to measure 3D radiation distributions (Peterson RSI 2003)

P_{RAD} from solving 2D heat transport equation

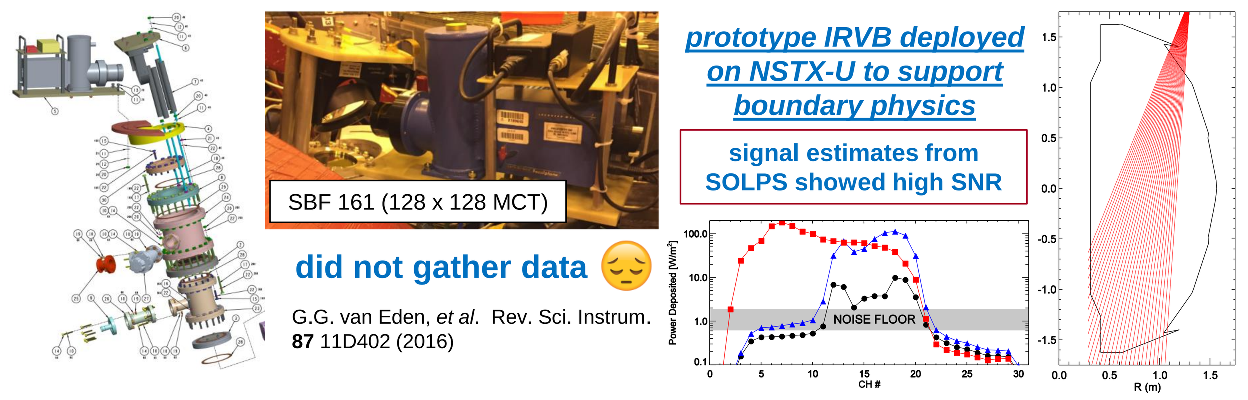
$$\frac{P_{rad}}{k t_f A_F} = \frac{1}{\kappa}\frac{\partial T}{\partial t} - \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] + \frac{(\epsilon)\sigma_{SB}(T^4 - T_0^4)}{k t_F}$$



- demonstrated photoconductive sensors are usable but have high NEPD (part of SULI project)

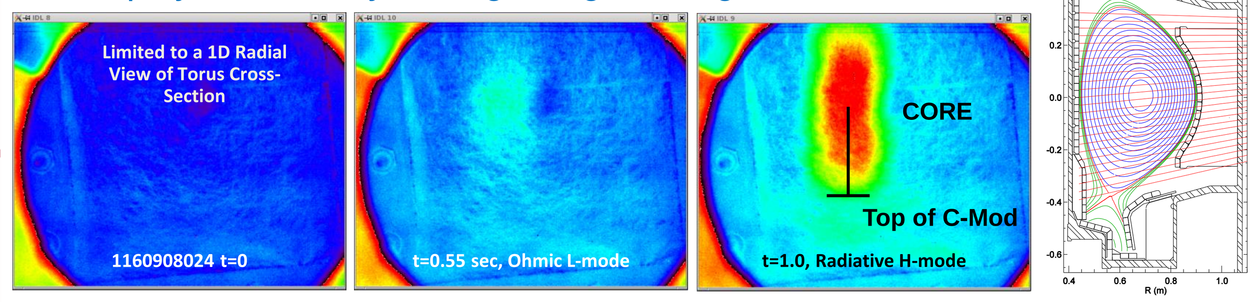


- IRVB system built and deployed on NSTX-U (5/16)

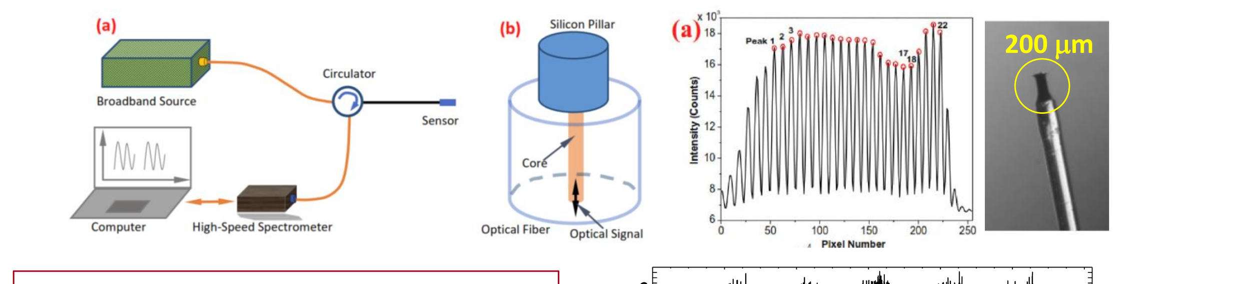


G.A. van Eden, *et al.* Rev. Sci. Instrum. **87** 11D402 (2016)

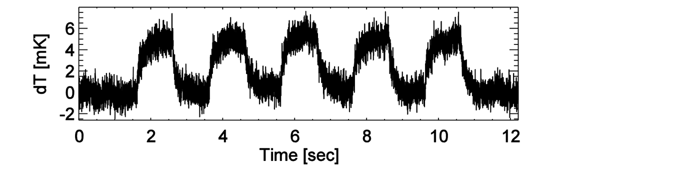
- initial plasma testing on Alcator C-Mod (9/16)
  - deployed for 2 day testing using existing FLIR SC7000



- developing fiber-optic temperature sensors using existing Fabry-Pérot sensor: tested w/ NEPD < 10 W/m²
  - 200 μm long, 80 μm diameter Si pillar is Fabry-Pérot cavity (Univ. Nebraska)
  - white light in NIR (λ_o ~ 1550 nm) input into fiber returns multiple peaks, and wavelength shift of ~24 peaks tracked, 84.6 pm/°C



40 W/m² input into fiber-optic sensor



see: M.L. Reinke, *et al* Rev. Sci. Instrum. **87**, 11E708 (2016) for more details