

CORONAL HEATING ORIGINS OF SOLAR SPECTRAL IRRADIANCE

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Research Program

- Goal: construct physics-based models of active regions and eventually the global Sun
- Prerequisite: must understand coronal loops and coronal heating
- Strategy:
 - Model loops and active regions using generic coronal heating
 - Investigate specific heating mechanisms (secondary instability)

State of Knowledge

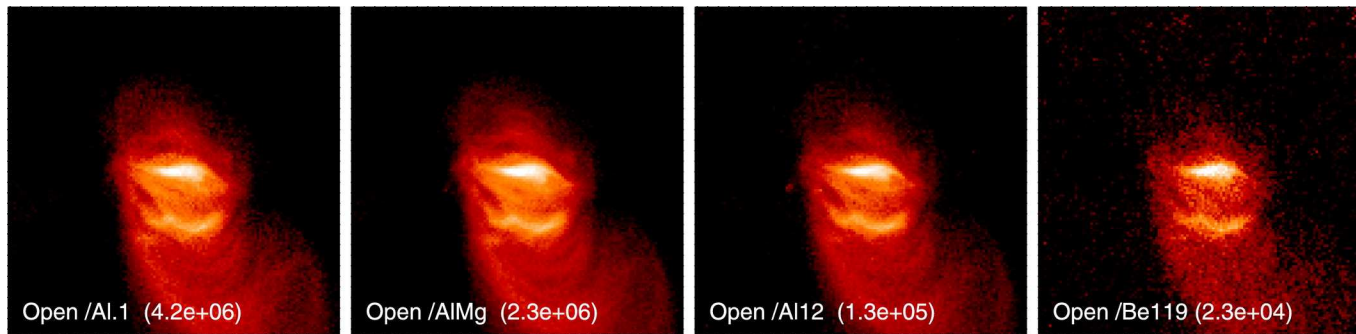
- Static equilibrium can reproduce SXR (hot) emission
 - (Schrijver et al. 2004; Lundquist et al. 2004; Mok et al. 2005; Warren & Winebarger 2006)
- SE **cannot** reproduce EUV (warm) emission
 - Warm loops too faint
 - Moss at footpoints of hot loops too bright
- Does impulsive heating (nanoflares) work?
 - Warren & Winebarger
 - Klimchuk & company
- Does thermal nonequilibrium work?
 - Lionello & company (Mok et al. 2008)
 - Klimchuk & company (loops only)

Static Equilibrium

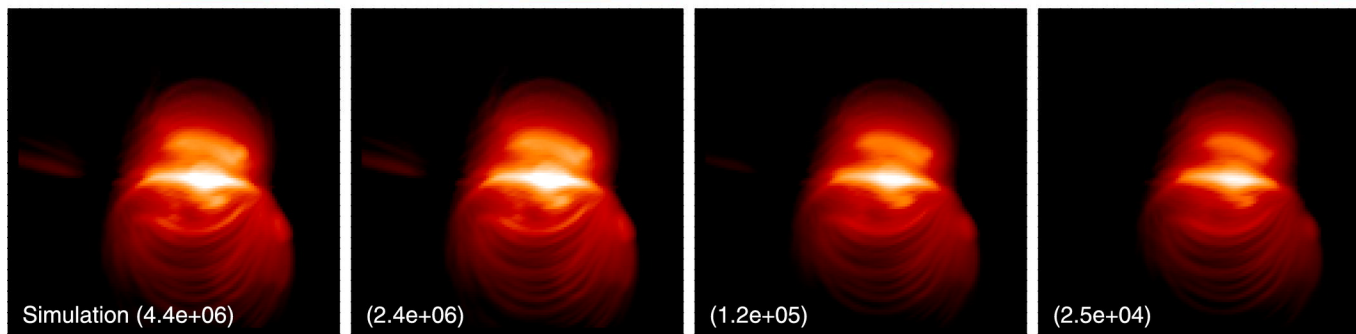
(Warren & Winebarger 2006)

Yohkoh/SXT

Obs.



Sim.

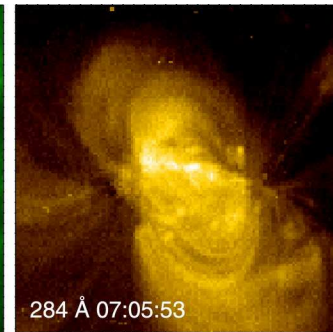
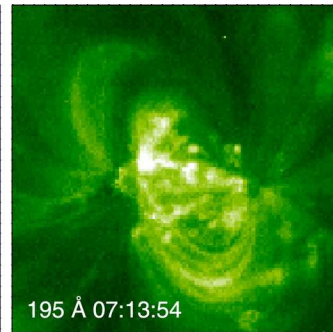
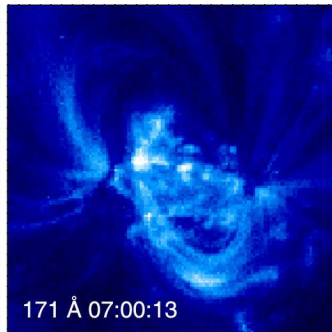
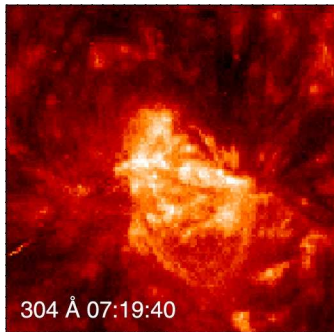


Static Equilibrium

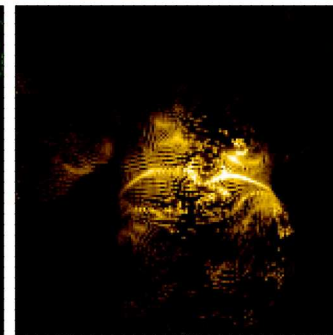
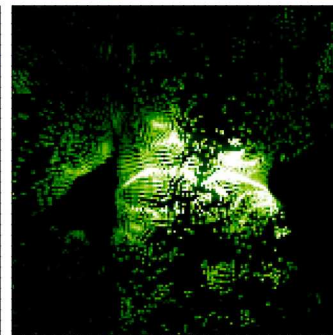
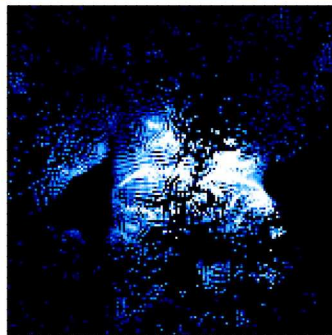
(Warren & Winebarger 2006)

SOHO/EIT

Obs.



Sim.



Idealized Active Region Arcade

(Patsourakos & Klimchuk 2008)

- Nested semi-circular loops
 - EBTEL “0D” hydro simulations
- Heating: $Q \sim L^{-2.8}$ (secondary instability)
- Steady vs. Impulsive
- Impulsive model uses time average
 - Loop as bundle of unresolved strands
- SXT AlMg and TRACE 171 intensities

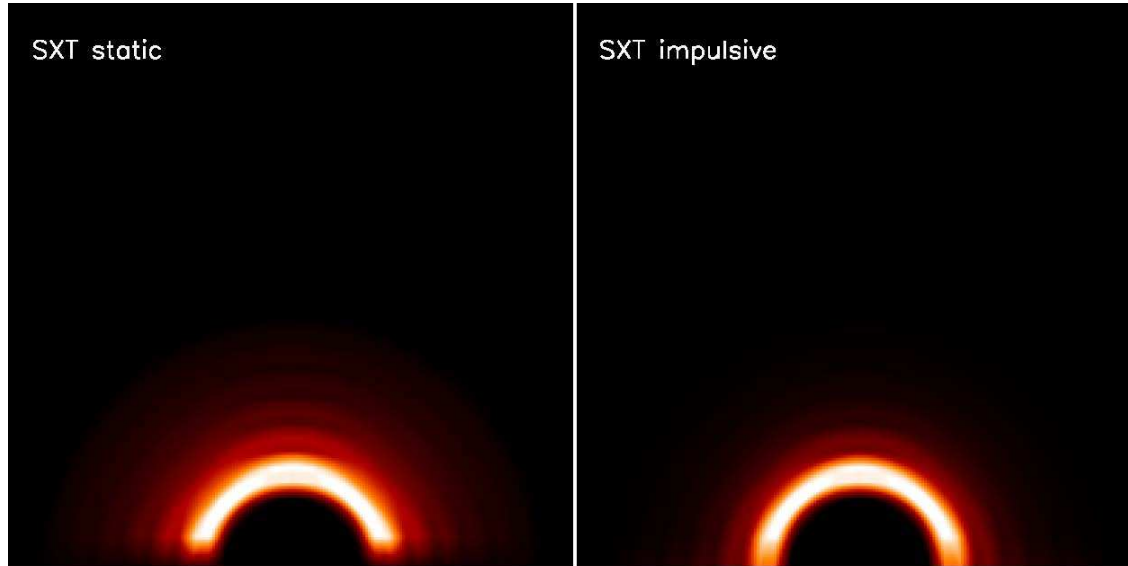
Static

Impulsive

SXT

SXT static

SXT impulsive



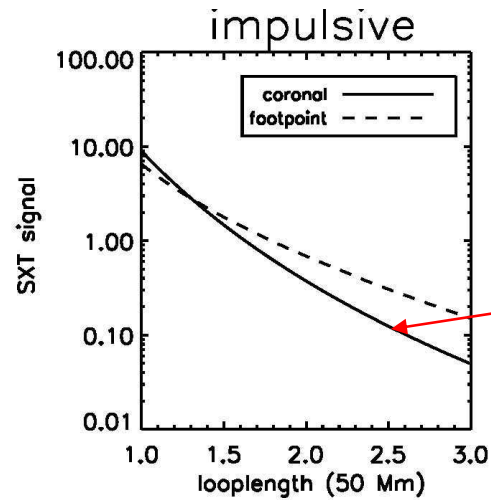
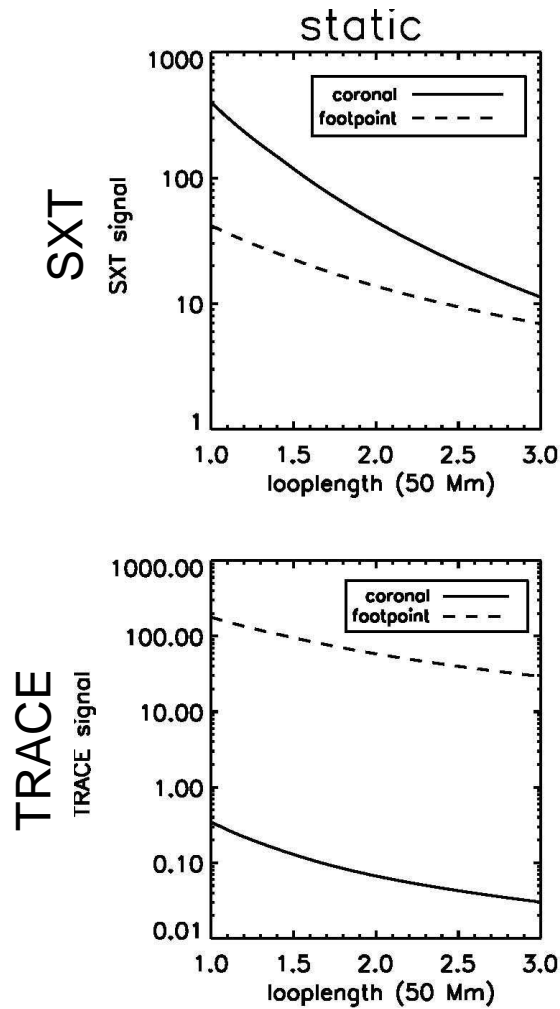
TRACE

TRACE static

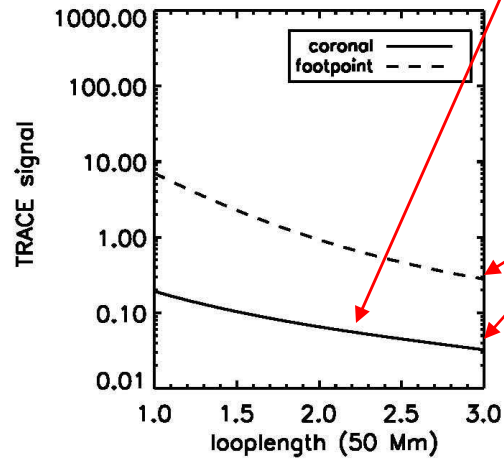
TRACE impulsive



Intensity Profiles



Reduced SXT-to-TRACE
contrast in corona
(1000 \rightarrow 10)



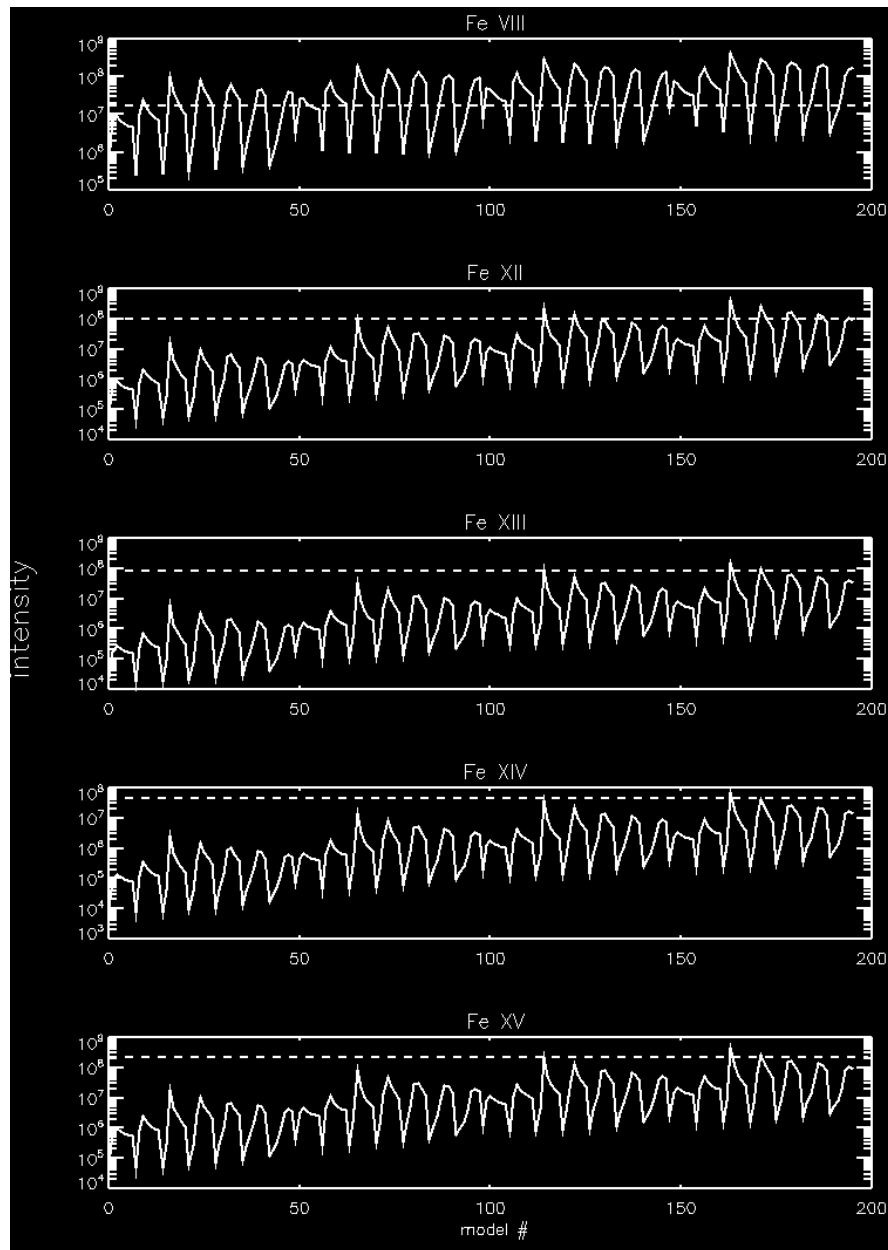
Reduced footpoint-to-corona
contrast in TRACE
(1000 \rightarrow 10)

Impulsive Model Better Matches Observations

- Reduced SXT-to-TRACE contrast in corona
 - Reduced footpoint-to-corona contrast in TRACE
 - Steeper SXT gradient across arcade (emission concentrated in active region core)
 - Explanation:
 - Static model has shallow temperature gradient across arcade
- $$T_c \sim Q^{2/7} L^{4/7} \sim L^{-0.22}$$
- Only “SXT plasma” in corona; only “TRACE plasma” at footpoints
 - Impulsive model has “TRACE plasma” both in corona and at footpoints

Active Region Modeling Plans

- Real active region
- Magnetic skeleton from extrapolated magnetogram
- Populate field lines with plasma using EBTEL hydro code and impulsive heating
- Generate synthetic images and spectra
- Vary heating parameters to get best fit (W&W looked at one parameter set only)



Intensity vs Model #
(from Spiros this morning!)

$$Q \sim B^a L^b$$

```

for a = 1, n_a
  for b = 1, n_b
    run simulation
  end
end

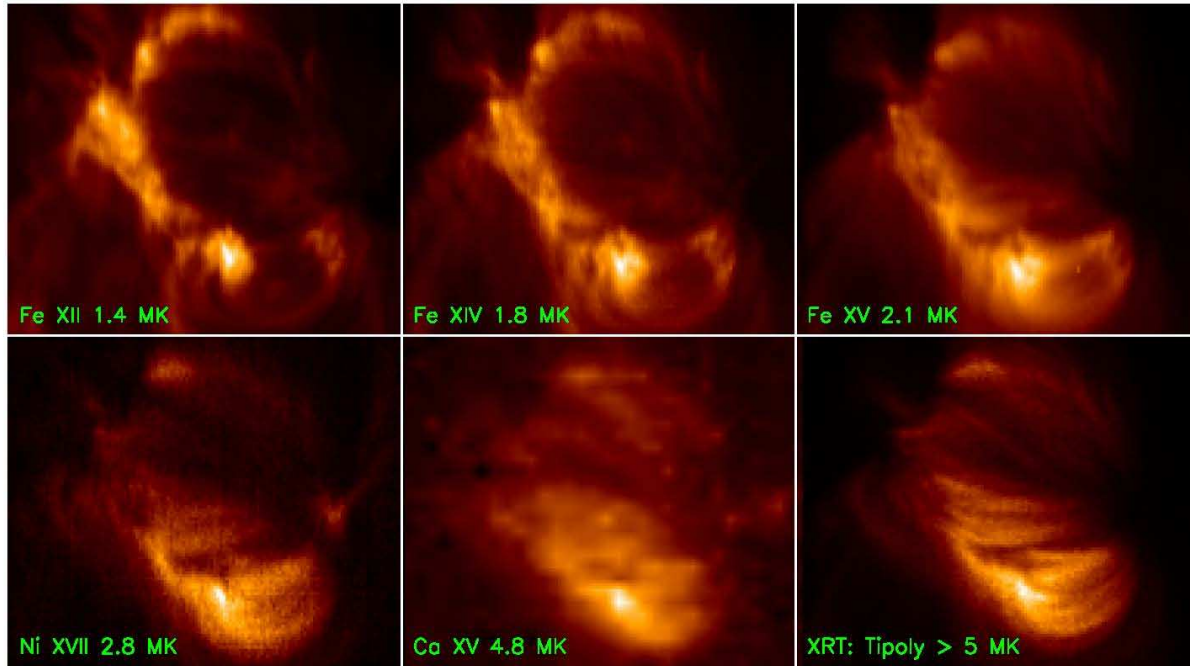
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$$a = [-1, 2]$$

$$b = [-3, 3]$$

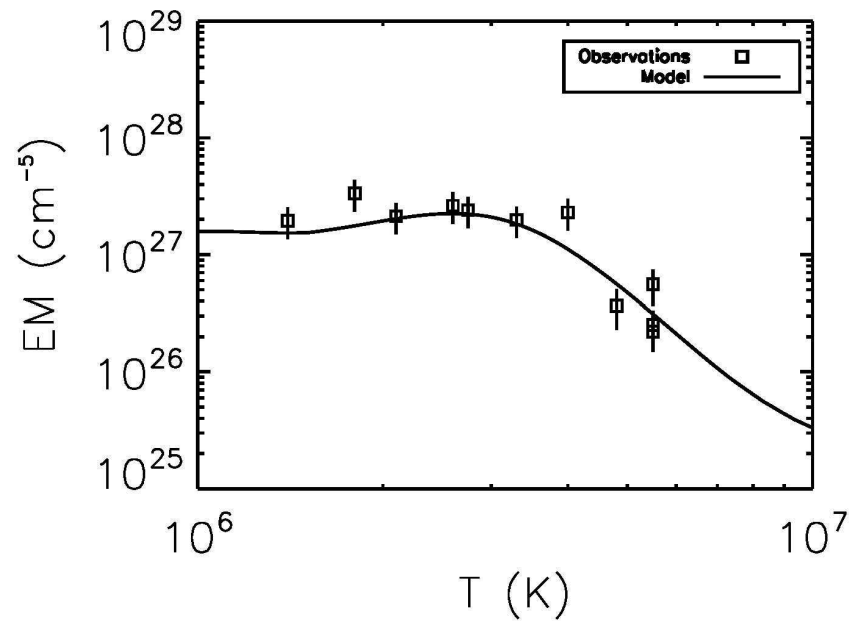
Criticisms of Impulsive Heating

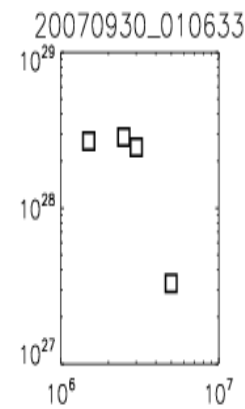
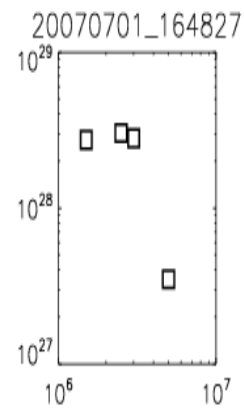
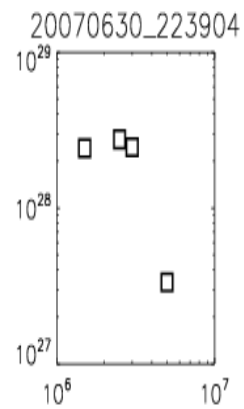
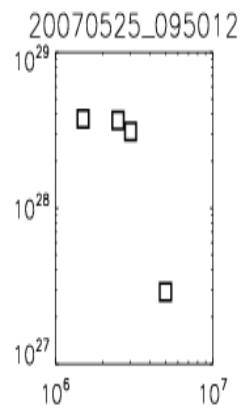
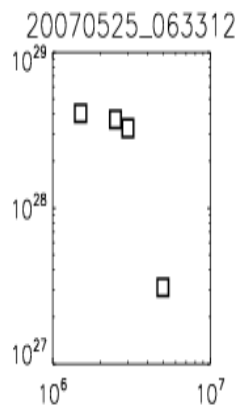
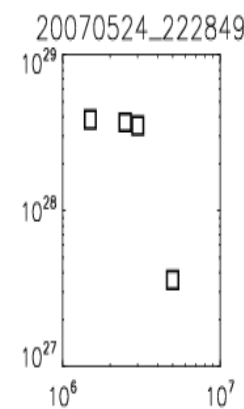
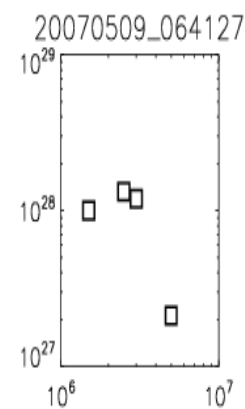
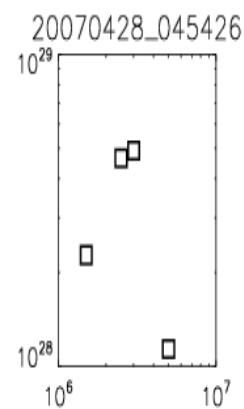
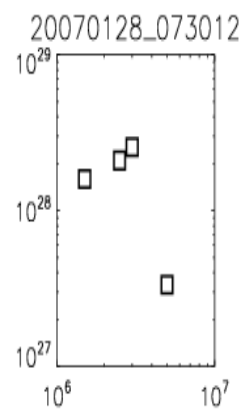
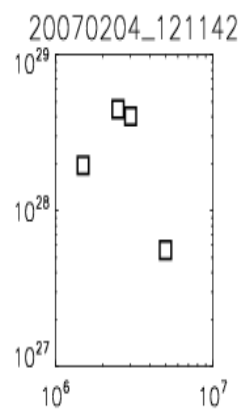
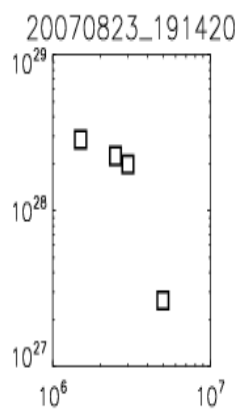
- Hot ($> 4\text{MK}$) emission is predicted but not observed
 - Response: Predicted to be faint and is observed (EIS and XRT)
- “Standard” nanoflare model predicts cospatial hot and warm loops, which are only sometimes observed
 - Response: No hot emission is predicted if enough (\sim half) of the nanoflare energy goes into nonthermal electrons



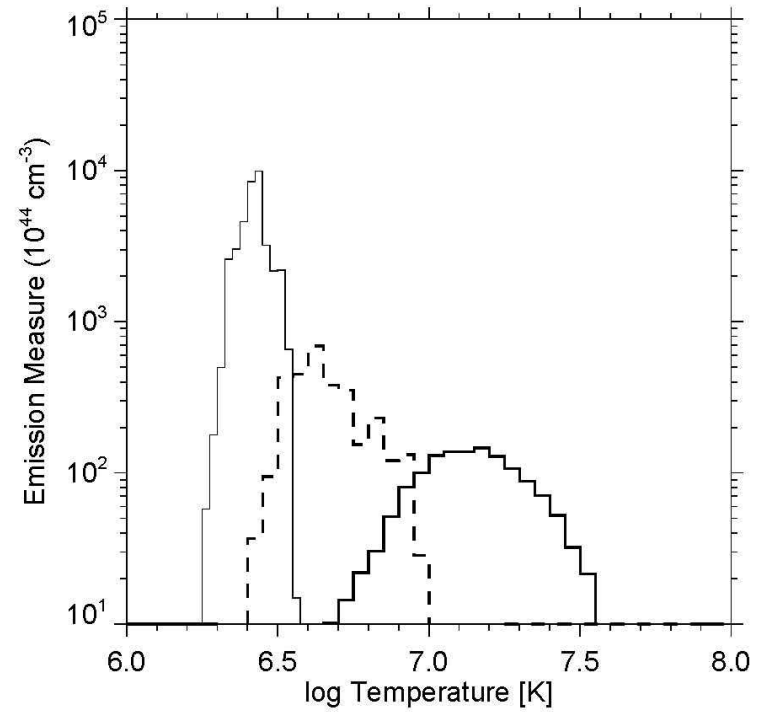
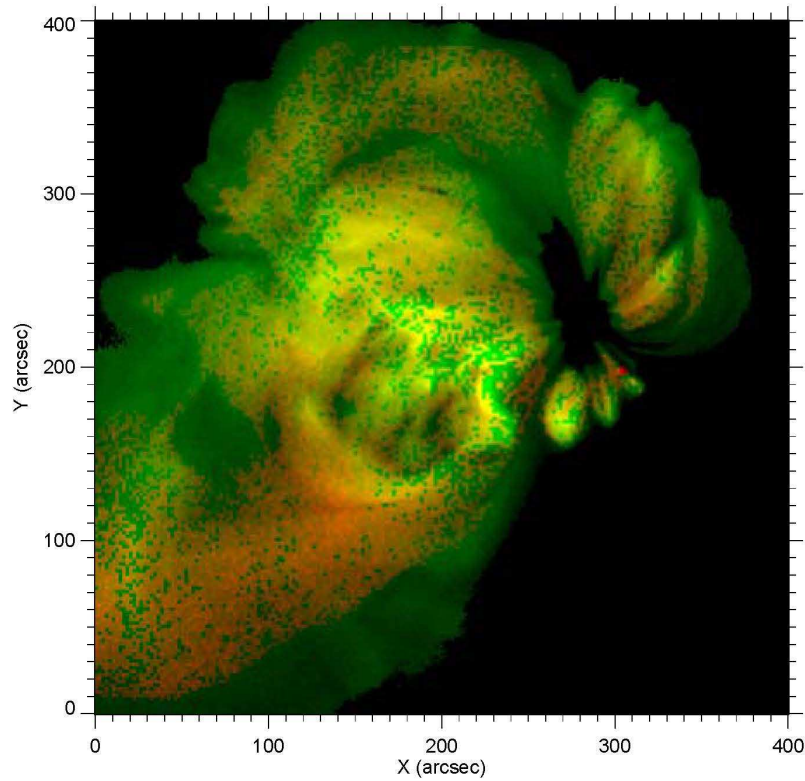
Hinode/EIS Observations

Patsourakos & Klimchuk (2008)



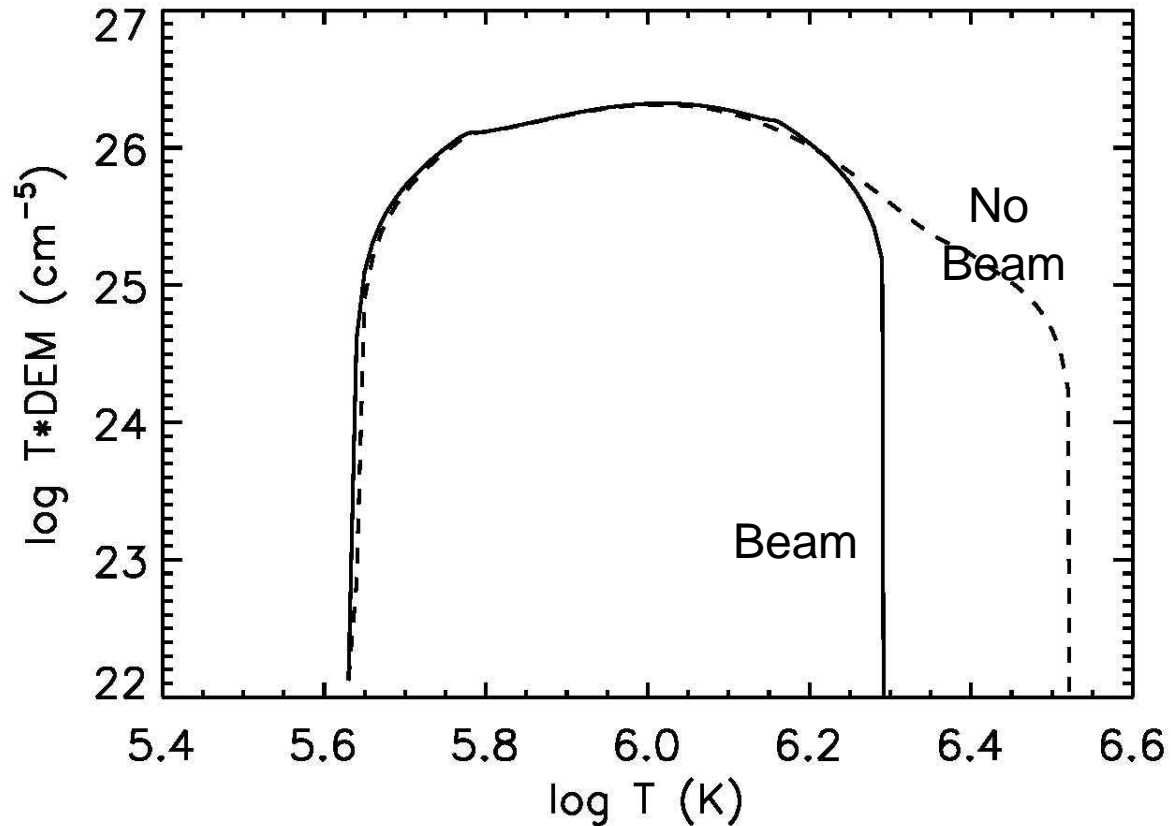


Hinode / XRT
Reale, Parenti, Testa, & Klimchuk (2008)



Green: $\log T < 6.7$
Red: $\log T > 7$

Differential Emission Measure



Time average of single nanoflare heated strand
(approximates snapshot of multi-strand bundle)

Klimchuk, Patsourakos, & Cargill (2008)

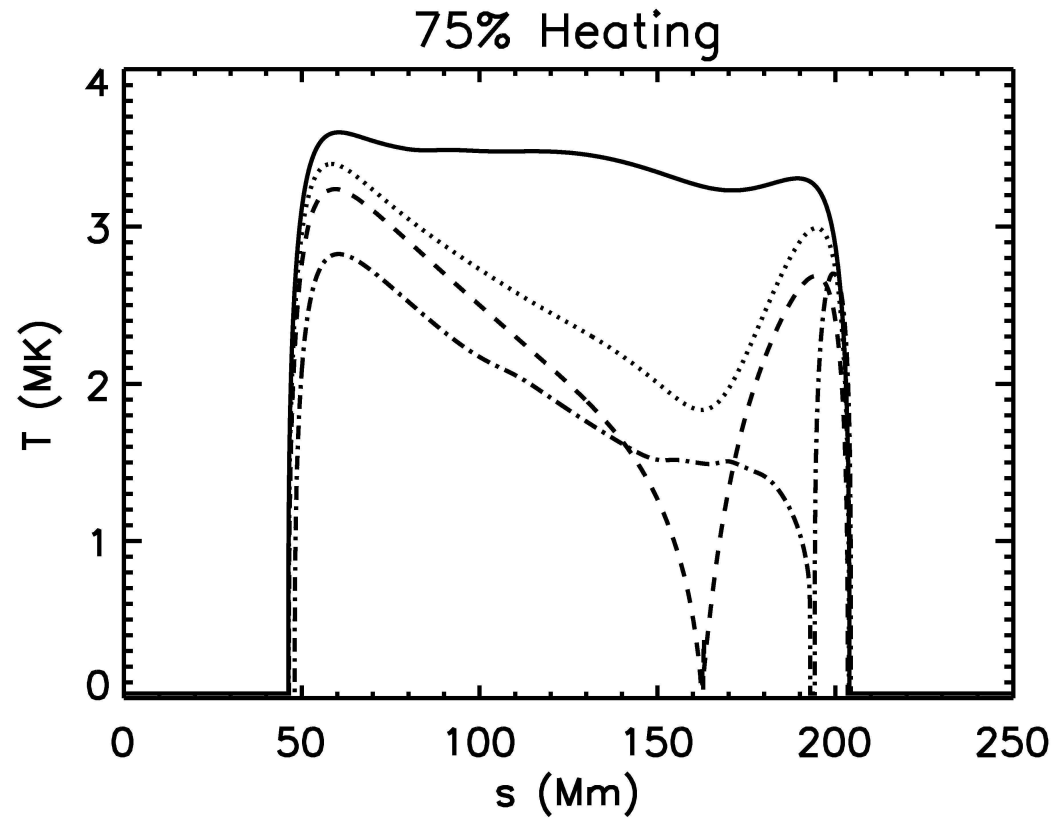
Warm (~1 MK) Coronal Loops

- Over-dense relative to static equilibrium (too bright)
- Larger than hydrostatic scale heights (too uniform)
- Flat temperature profiles, as inferred from TRACE filter ratios (too isothermal)
- Live longer than a cooling time

THERMAL NONEQUILIBRIUM

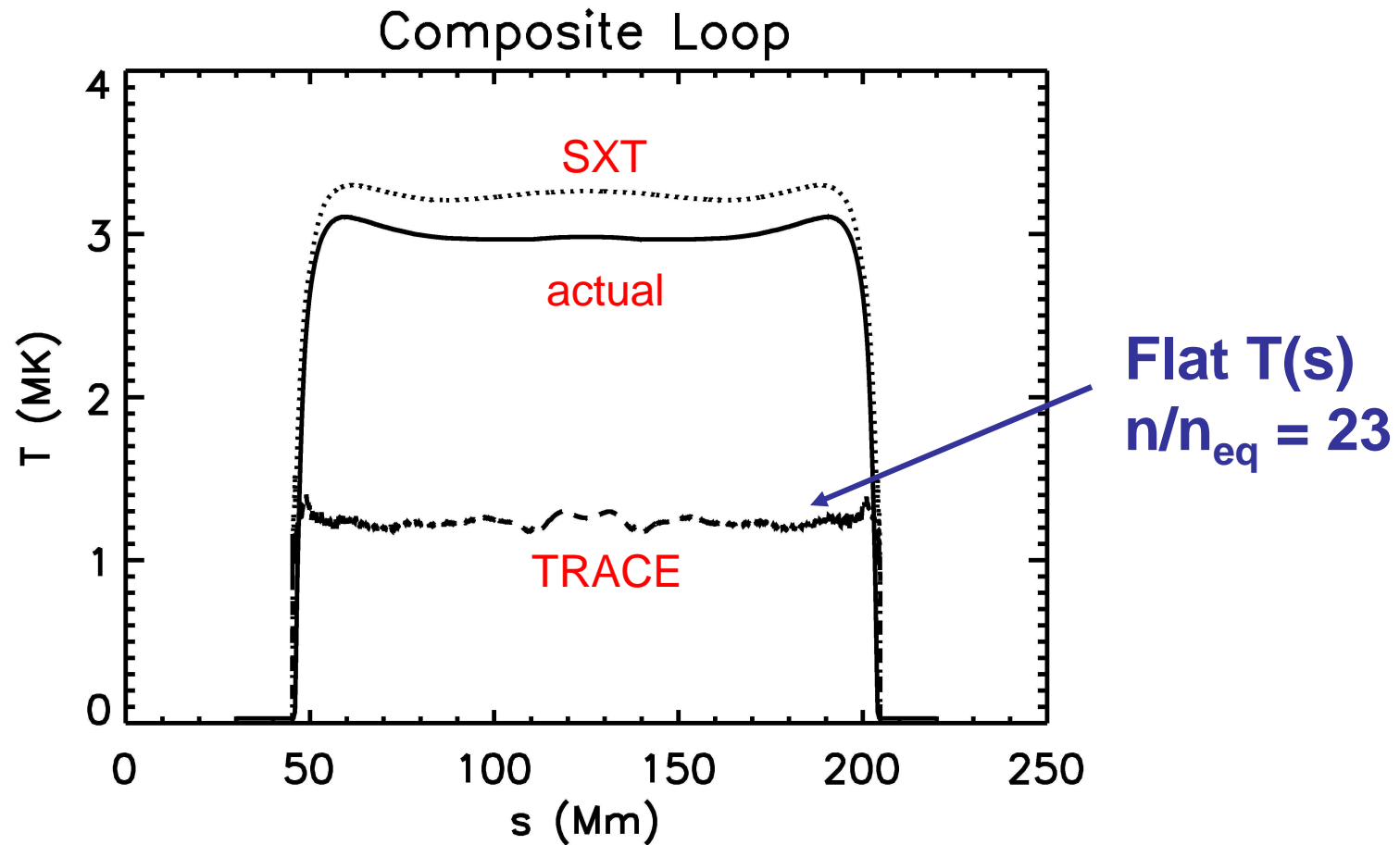
- Dynamic behavior with steady heating!
- No equilibrium exists if the heating is concentrated close to the loop footpoints
- Cool condensations form and fall to the chromosphere in cyclical pattern

Serio et al. (1981), Antiochos & Klimchuk (1991), Karpen et al. (2001-2008), Mueller et al. (2003-2005), Mok et al. (2008)



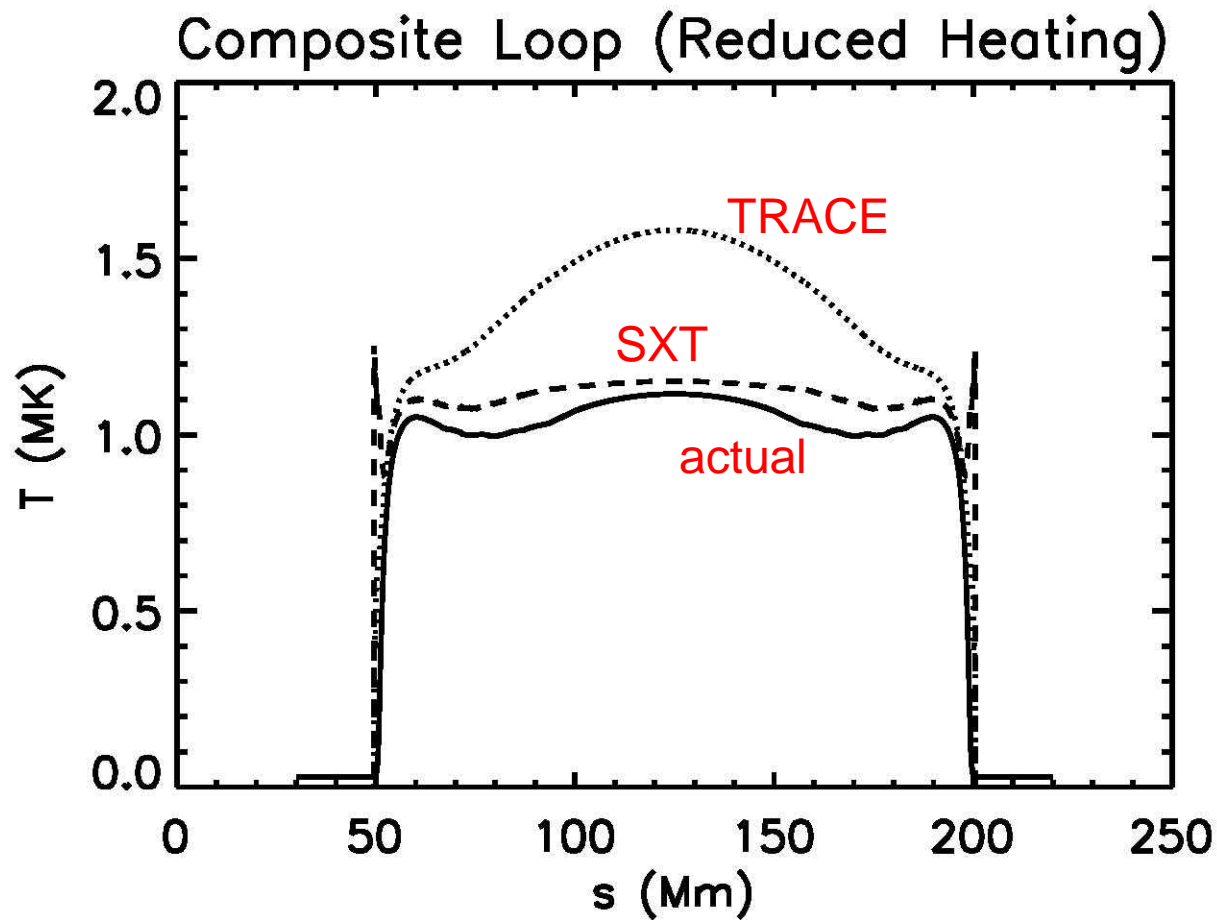
$t = 2950, 4500, 4850, 5750 \text{ s}$

Heating scale height = 5 Mm = $L/15$
Imbalanced heating (right leg = 75% left leg)



6 strands: 50%, 75%, 90% heating imbalance
(left/right and right/left)

Temporal average

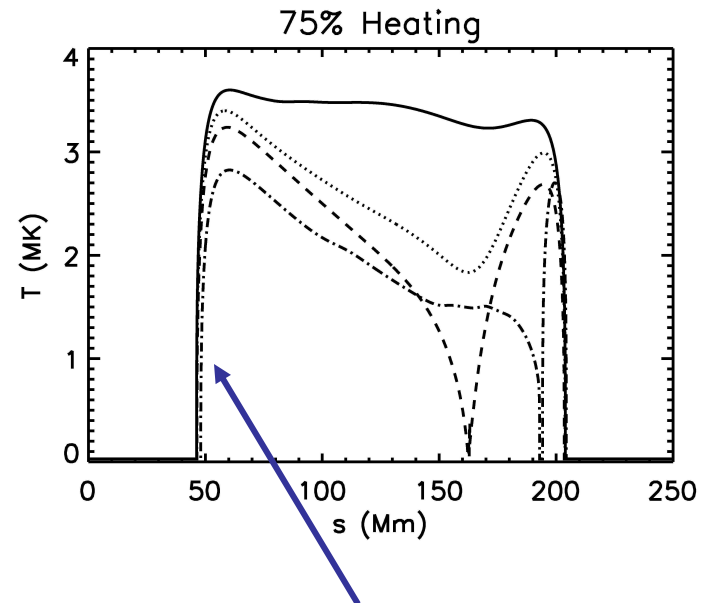


$$n/n_{eq} = 10$$

6 strands: 50%, 75%, 90% heating imbalance
(left/right and right/left)

Temporal average

EXPLANATION



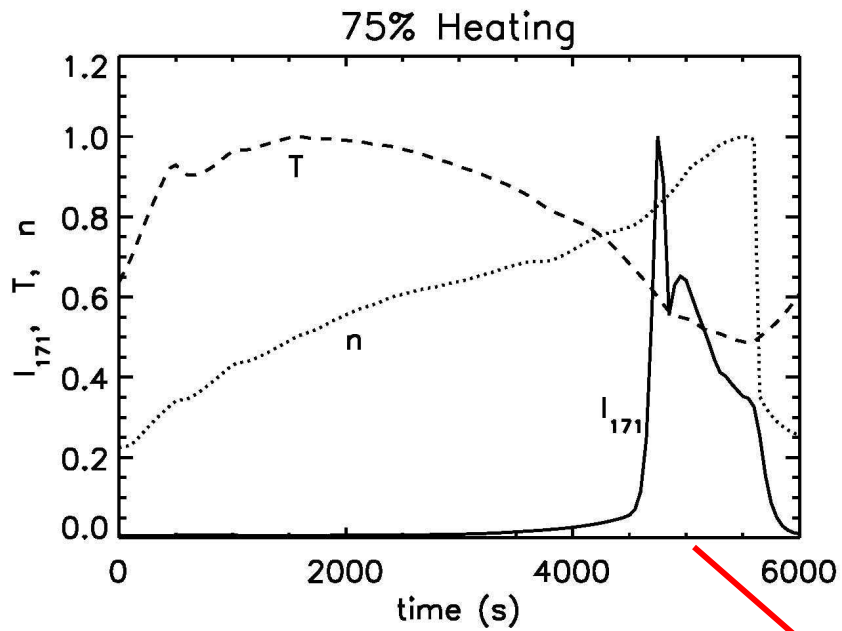
Quasi-static equilibrium is established in lower leg section between chromosphere and T_{\max} :

$$n \sim 1/H, \quad H = \text{section length} = 14 \text{ Mm}$$

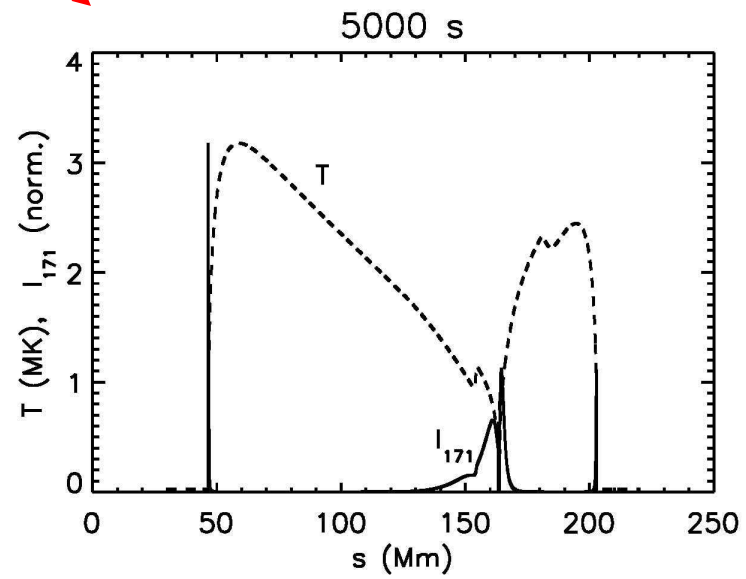
Static equilibrium density for entire loop: $n_{\text{eq}} \sim 1/L$

Density enhancement factor: $n/n_{\text{eq}} = L/H = 11$

For $H = \text{constant}$, expect $n/n_{\text{eq}} \sim L$, as observed



Monolithic loop
 $T_{\max} = 4.44 \text{ MK}$



Monolithic loop
Reduced heating
 $T_{\max} = 1.80 \text{ MK}$

