Hybrid Simulations of Chromospheric Flare HXR Sources

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Motivation

Recent RHESSI measurements of vertical extent of HXR sources are inconsistent with predictions given by CTTM (Brown, 1971).

RHESSI observations:

- energy dependent size typically 2 - 6 arcsec
  i.e. 1.5 - 4.5 Mm (Kontar et al. 2008, 2010, Battaglia et al. 2011)

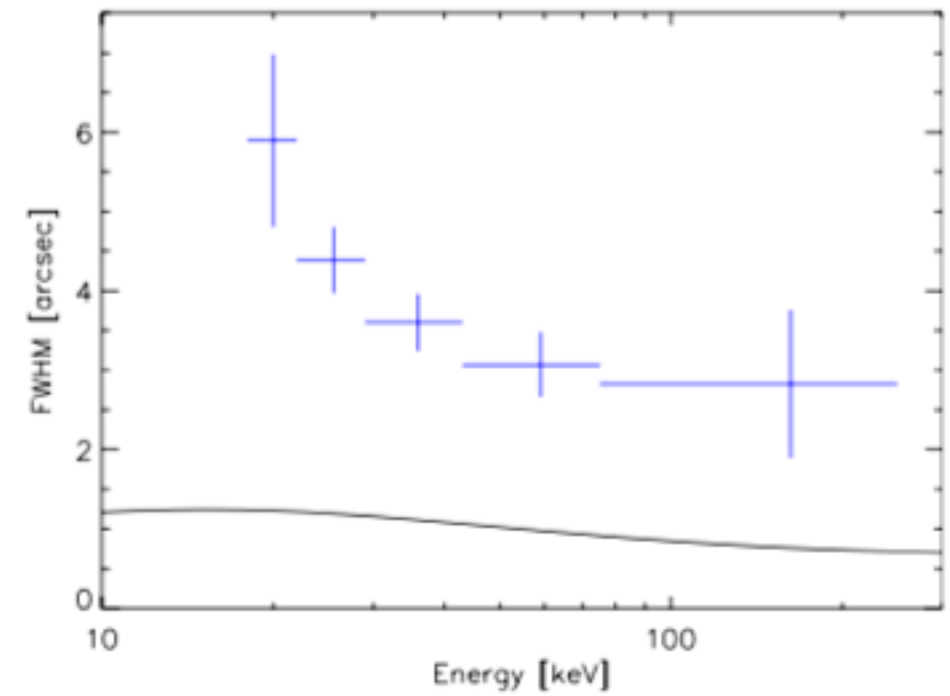
Theory (CTTM):

- ~ 1 arcsec and smaller (under ~1 Mm)

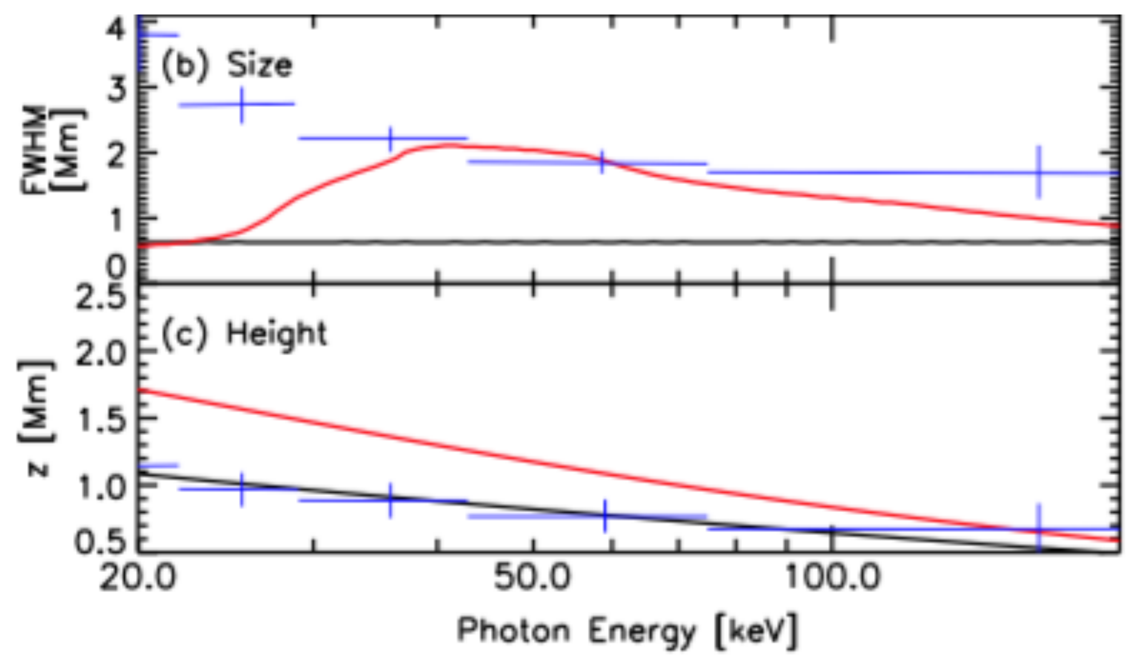
Attempts to model HXR sizes:

- source sizes modelled for prescribed density structures of the atmosphere with magnetic mirroring and various μ_0 distributions (Battaglia et al. 2012) - sources under ~1.5 arcsec

- accounting for NUI effects of target plasma - prescribed artificially (O'Flannagain et al. 2015)
  - sources up to ~ 2.3 arcsec at 40 keV



Observed FWHM of HXR source event 6th January, 2004 (Battaglia et al. 2012)



(Flannagain et al. 2015)

HXR source vertical sizes

The key factors influencing HXR source sizes (also talk of M. Kuhar HXR and WL):

- electron beam: F(t), delta, E_0, initial pitch angle distribution
- target atmosphere - temperature, density and ionisation structure
- magnetic structure of the loop (mirroring)

Observations done by RHESSI:

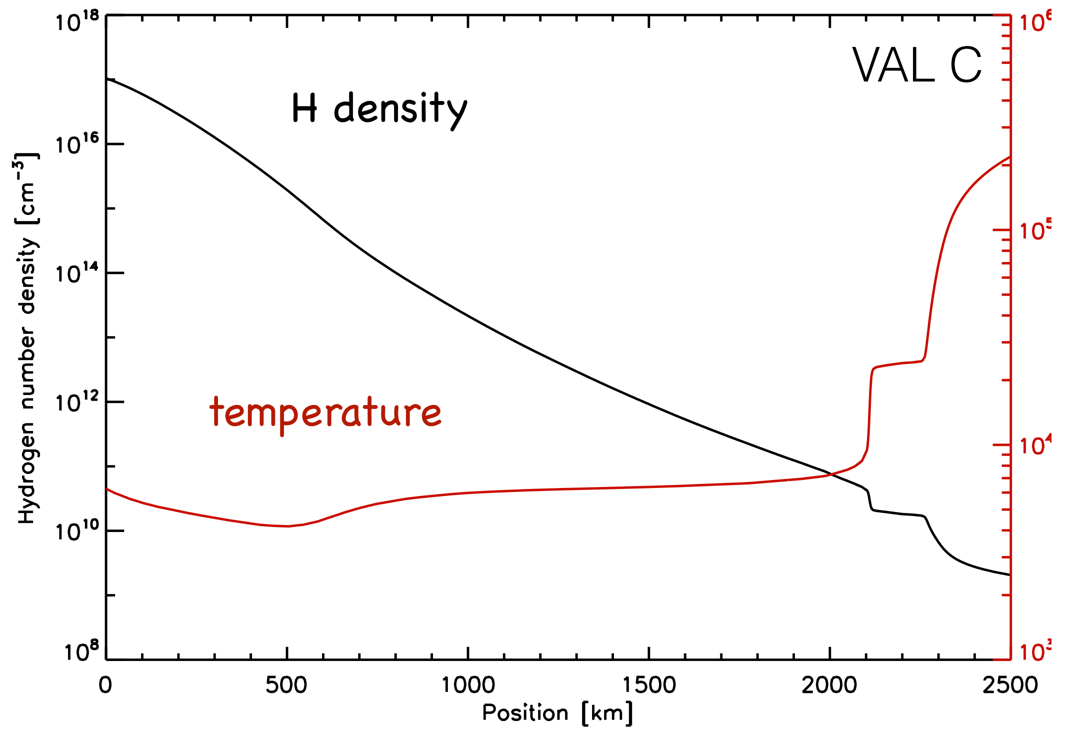
- S/N ratio to produce a RHESSI image - ~ 5 - 10 rotations: 20 - 60 s of time evolution in a single flare loop

Substantial changes in the flaring atmosphere within first several tens of seconds -> vertical evolution of HXR source expected.

Modelling of HXR source sizes

Parameters:

- non-convergent semicircular single flare loop L=15 Mm
- HS VAL C initial atmosphere (Vernazza et al., 1981)
- power-law beam generated at the apex



$$F(E, \mu_0, z_0 = 0) = M(\mu_0)(\delta_p - 2)\frac{F_0}{E_0^2}\left(\frac{E}{E_0}\right)^{-\delta_p}$$

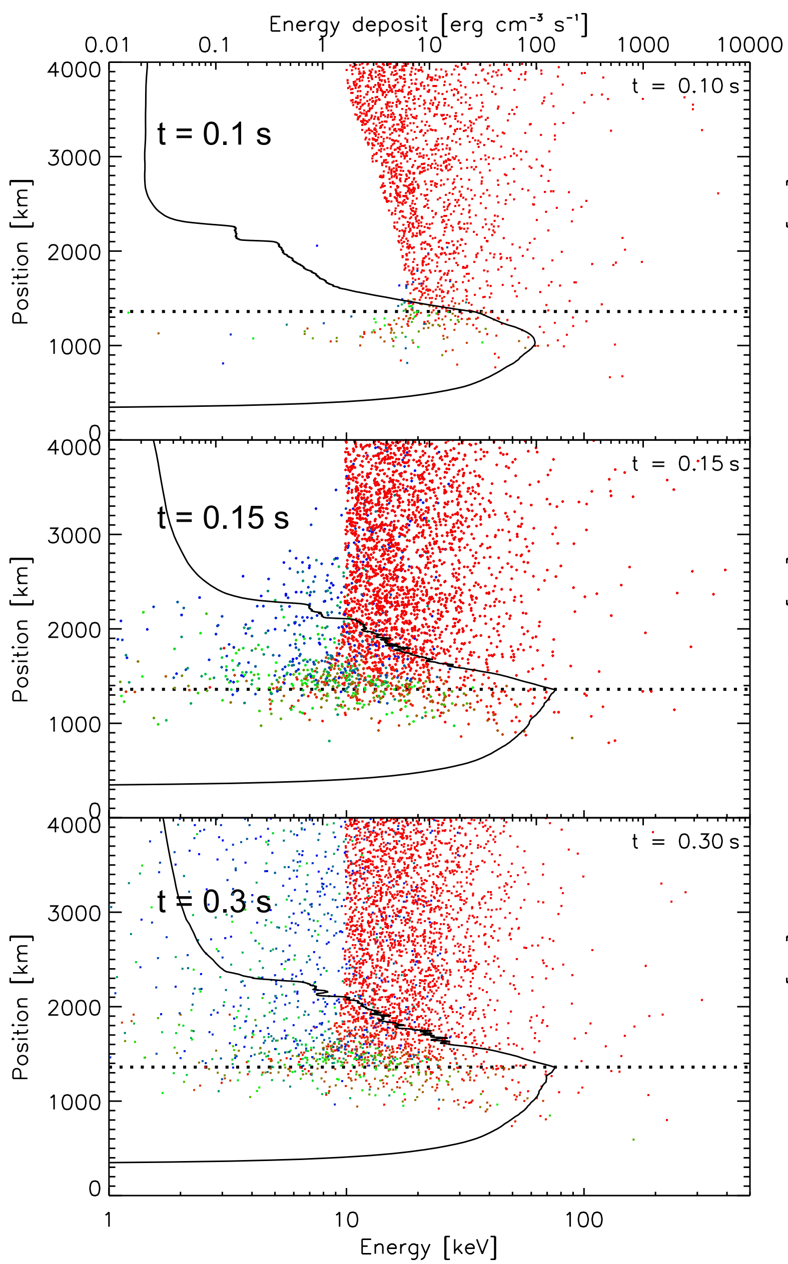
- E_0 = 20 keV, E_1 = 150 keV, δ = 3, 5, 7, F_0 = 1 and 2x10^{10} erg cm^{-2} s^{-1}, M(μ_0) - uniformly distributed pitch-angle cosines in $\mu_0 \in (0.5, 1)$, $F_0(t) = F_0$ for t > 2.5 s

Hybrid code Flarix (generally hybrid non-LTE code):

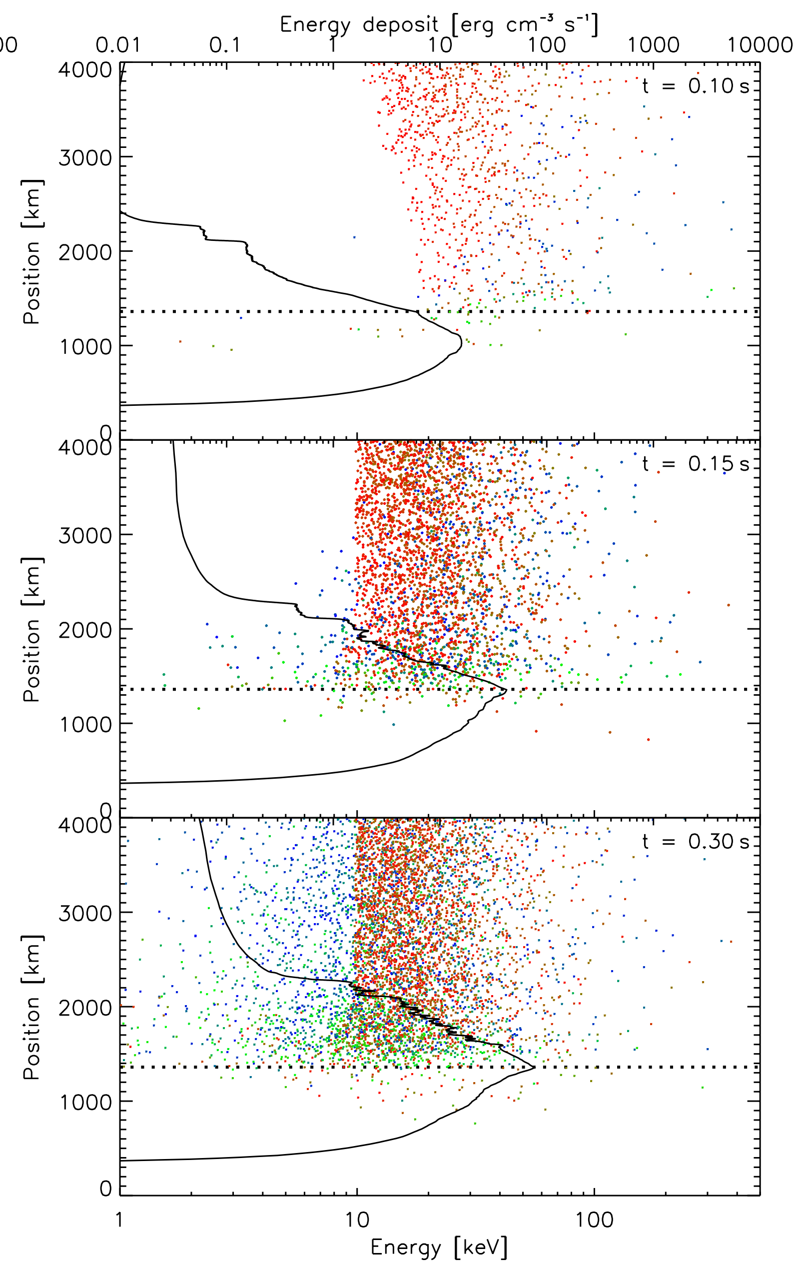
- test particle code + 1D HD code (Kašparová et al. 2009, Varady et al. 2010, Varady et al. 2014)
- TP code - based on Bai (1982) - alternative to direct solution of Fokker-Planck eq. (MacKinnon & Craig 1991)
- self-consistent modelling of time evolution of chromospheric HXR sources -> source sizes (metodology according to Battaglia et al., 2012)

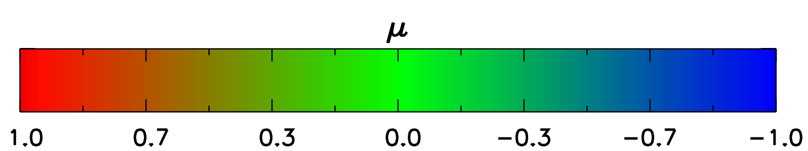
Test particle code

Fully focused beam:



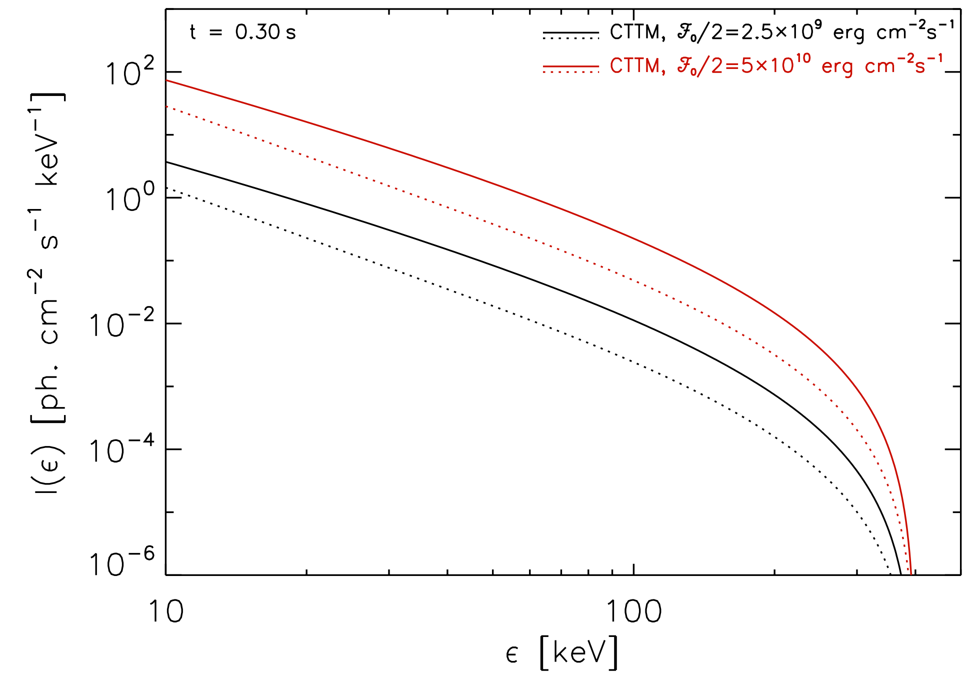
Semi-uniform distribution:



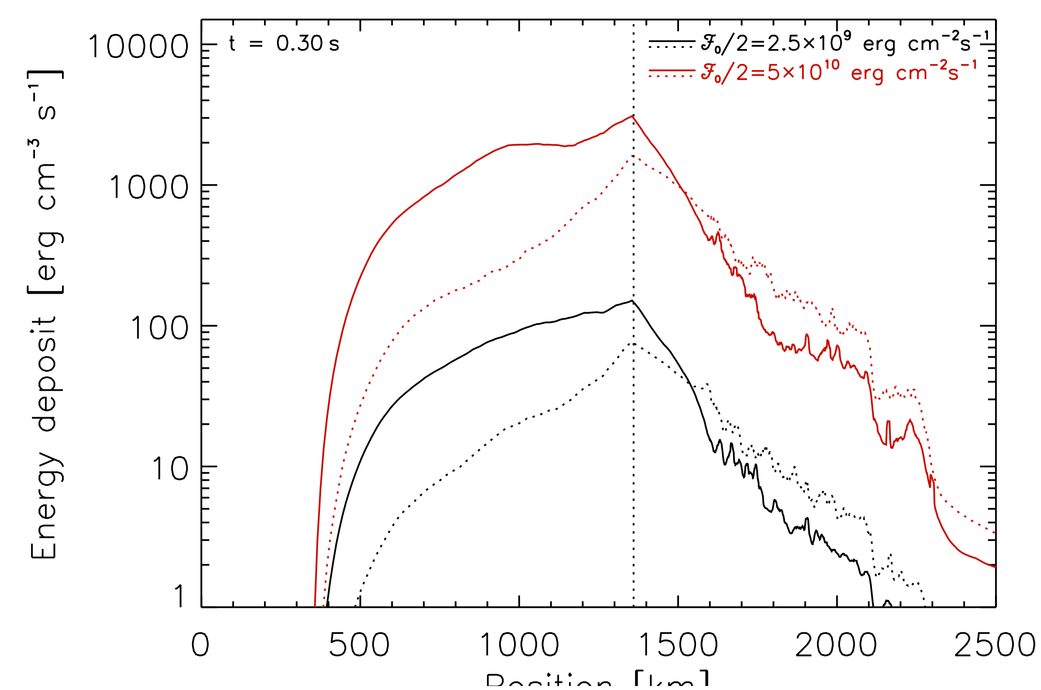


(Varady et al. 2014)

Corresponding HXR spectra:



Corresponding energy deposits:

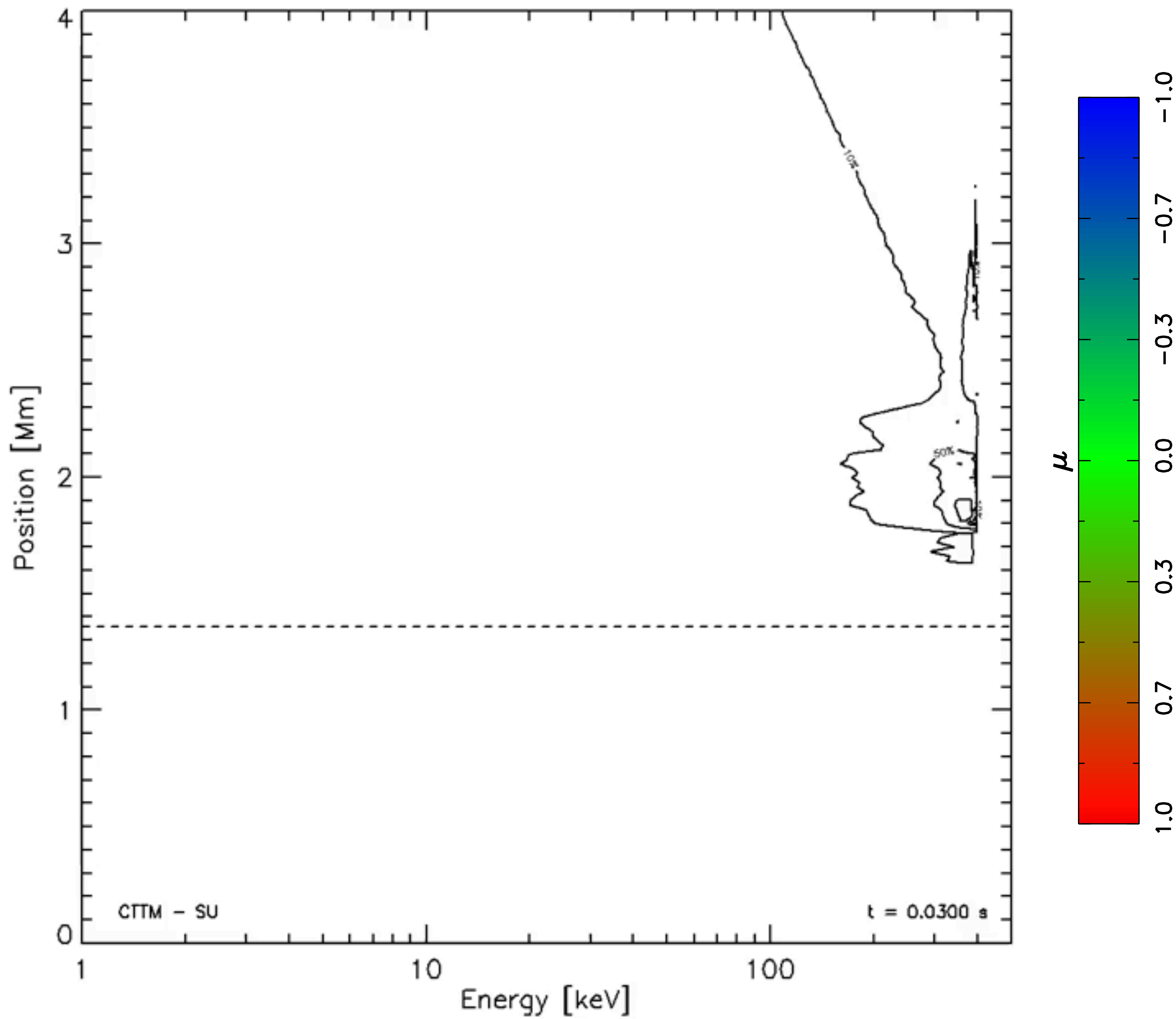


- kinematics of non-thermal e^- $\delta = 3$ for VAL C atmosphere with magnetic mirror $R_m = 5$ (bottom of the mirror - dotted line)
- energy deposits for $F = 2.5\times10^9$ erg cm^{-2} s^{-1} (solid line).

Non-thermal e- propagation and HXR distribution

For:

- static VAL C atmosphere
- convergent magnetic field $R_m = 5$
- $\delta = 3$
- initial μ_0 distribution uniform for $\mu_0 = (0.5,1)$
- no HD response of the atmosphere



1-D hydrodynamics

Evolution of low beta plasma along magnetic field lines in one fluid approximation (Kašparová et al. 2009, Varady et al. 2010).

Physics:

- flare heating - calculated by the test particle code
- thermal conduction - classical Spitzer formula (along field lines)
- H ionisation - H ionisation modified Saha eq. (Brown 1973)
- RL optically thin - corona and TR
- RL optically thick – analytic approximation of RL from VAL (Peres, 1982) - no radiative transfer

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v_s) = 0$$

$$\frac{\partial \rho v_s}{\partial t} + \frac{\partial}{\partial s}(\rho v_s^2) = -\frac{\partial P}{\partial s} + F_g + F_\nu$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial s}(E v_s) = -\frac{\partial}{\partial s}(v_s P) + \frac{\partial}{\partial s}\mathcal{F}_c + \Delta\mathcal{E}_p - \mathcal{R} + \mathcal{I} + \mathcal{S}$$

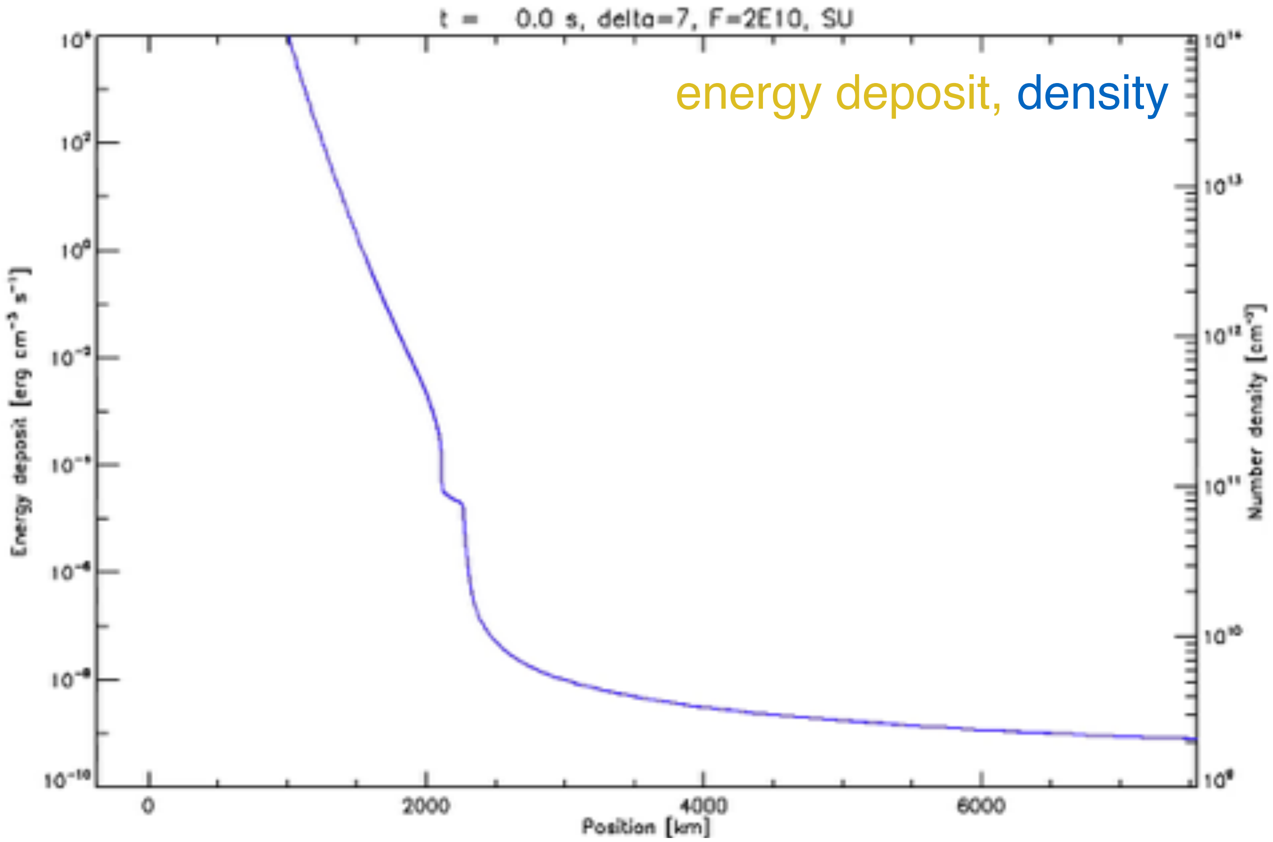
$$P = n_H k_B(\vartheta + x + \varepsilon)T \qquad E = U + \frac{1}{2}\rho v_s^2$$

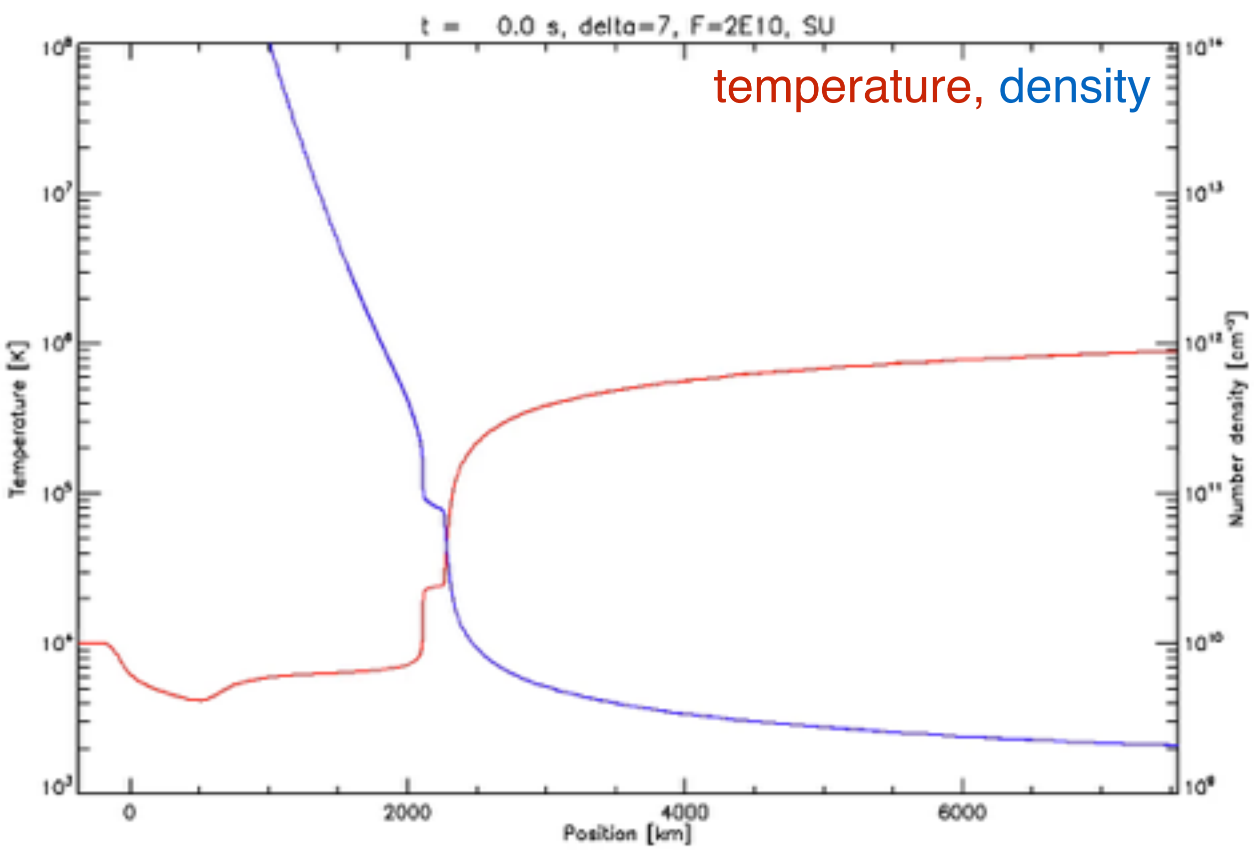
Numerical methods:

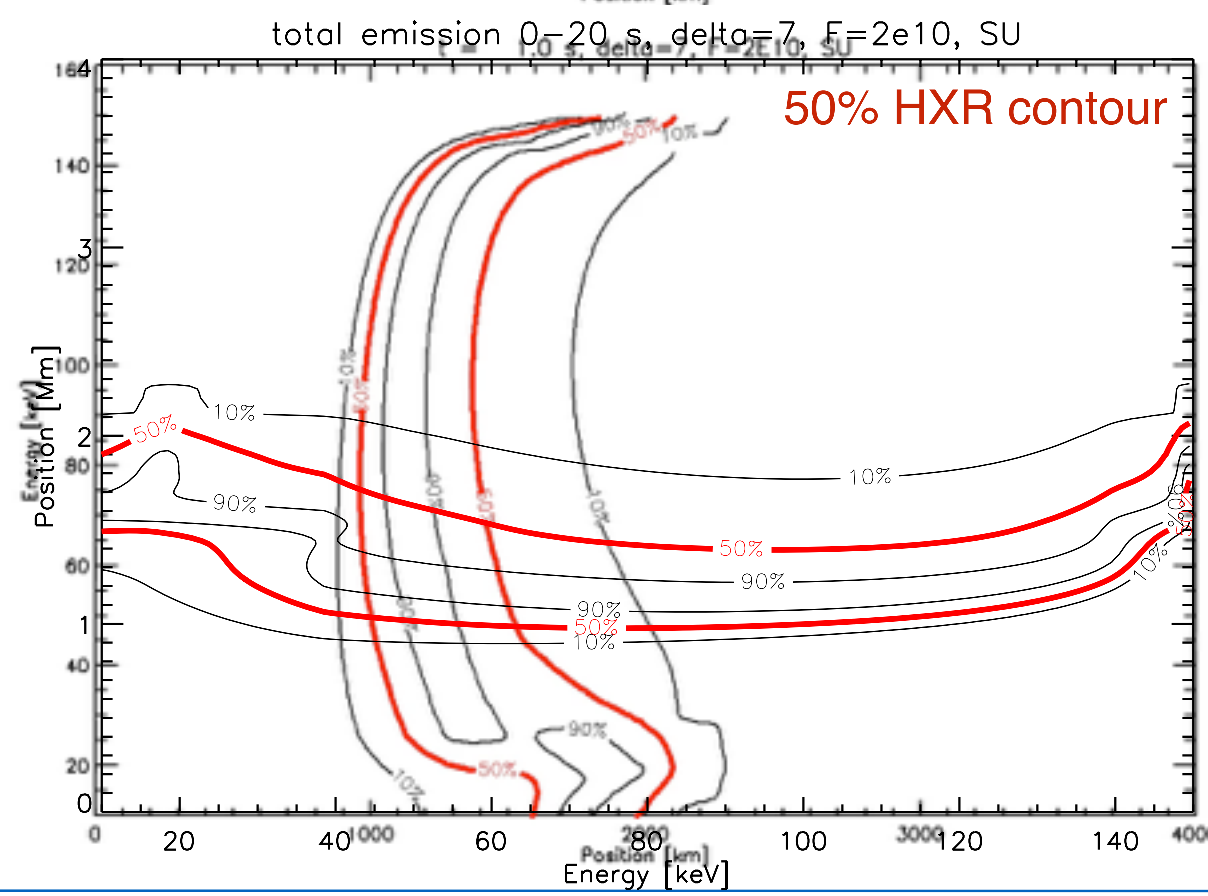
- convection - LCPFCT algorithm for solving generalised continuity equations (NRL)
- explicit algorithm time-step splitting method
- thermal conduction in flare loop - centred algorithm (Crank-Nicholson)

Typical results ($F_0 = 2x10^{10}$, delta = 7)

- $F_0 = 2x10^{10}$ erg cm^{-2} s^{-1}
- $E_0 = 20$ keV
- $E_1 = 150$ keV
- $\delta = 7$
- evolution 20 s
- most extreme case (6 cases in total)



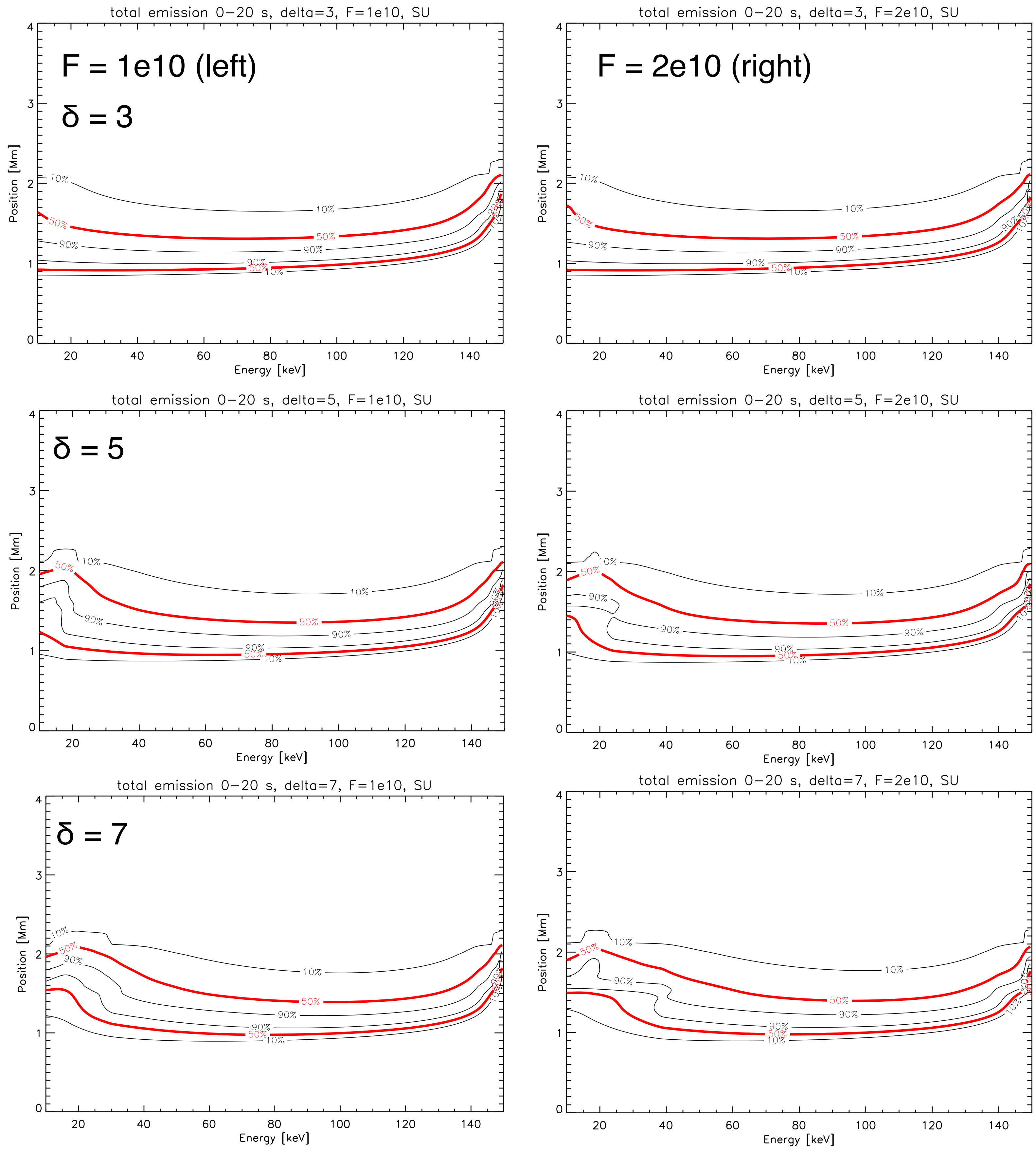




Results - HXR source sizes

For first 20 s of heating and a single loop:

- maximum source sizes on small or medium energies 20-40 keV < 1.5 arcsec
- at high energies sources smaller
- week and obscured dependence of source size on energy flux and delta



Conclusions

- chromospheric HXR source sizes modelled assuming a single flare loop and 20 s time evolution resulting in significant changes of density, temperature and ionisation structure along the loop are < 1.5 arcsec - inconsistent with observations, confirmation of results obtained by Battaglia et al. (2012)
- for energies above ~50 keV the size of chromospheric HXR sources tends to decrease with energy
- no obvious relations between energy flux, delta and source size

Plans for future:

- longer simulations ~10^2 s will be performed for more initial pitch angle distributions (incl. uniform in angles) and a single flare loop with converging B
- extension of the single loop model to multi-thread flare loop

F-CHROMA

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