Laboratory nano-flares generated from multiple braided current loops

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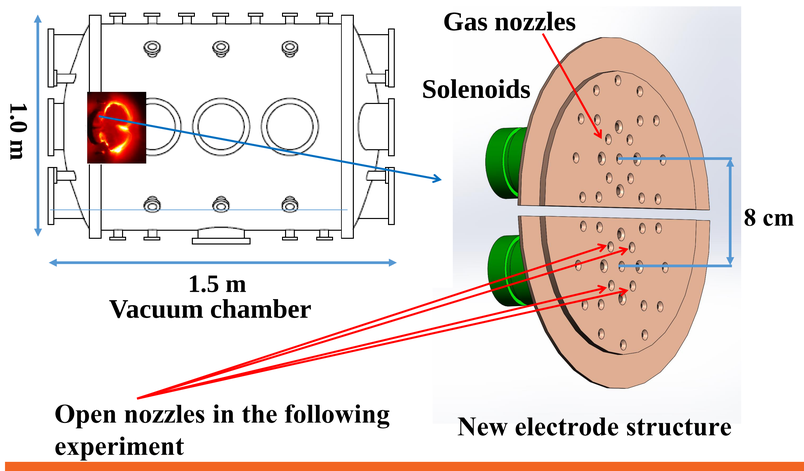
ABSTRACT

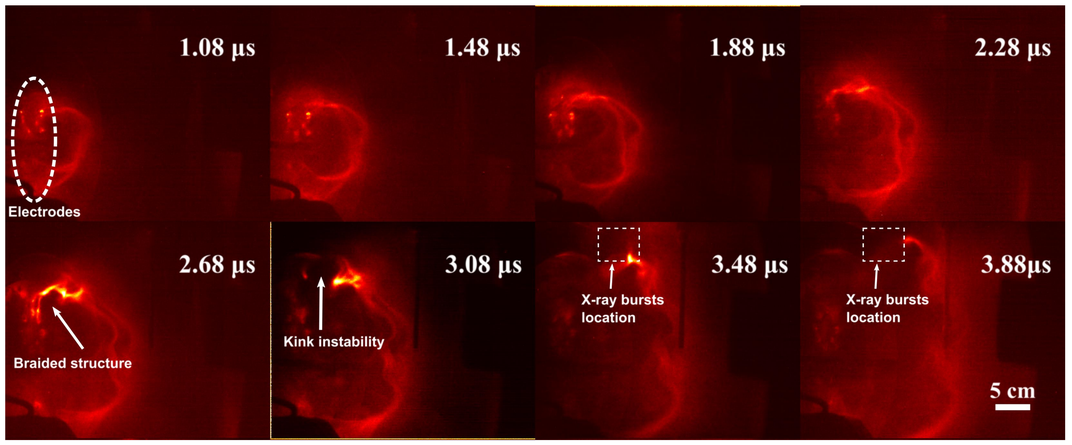
Braided loop structures are observed in a new Caltech lab experiment replicating the braiding of solar coronal loops. Individual strands of the braided magnetic structure are observed to undergo MHD magnetic Rayleigh-Taylor Instabilities driven by the effective gravity of hoop force acceleration and also kink instabilities. The MHD instabilities choke the strand so its radius becomes smaller. A burst of 7.6 keV X-rays and a high inductive voltage spike ~ a few kV are detected simultaneous with this process. These observations reveal a clear path from MHD dynamics to non-MHD physics generating solar energetic particles and X-ray bursts: a solar flux rope consists of current-carrying, fractally-scaled braided flux ropes. The finest-scale strand in the fractal set has a radius marginally larger than the greater of the ion skin depth or the ion Larmor radius (this criterion gives the finest scale at which MHD remains valid). Fast-growing MHD instabilities (e.g., Rayleigh Taylor or kink) develop that choke the radius of the marginal strand to be less than the greater of the ion skin depth or the ion Larmor radius; when this happens, MHD fails and kinetic instabilities develop that increase the local effective resistivity. The increased resistivity acts like an opening switch that abruptly reduces the current flowing in the strand and causes the large-scale exterior circuit inductive energy to be dumped into the localized increased-resistivity region. This dumping is manifested by a localized large inductive voltage spike LdI/dt that accelerates charged particles to extreme energies, and electron bremsstrahlung produces X-ray bursts.

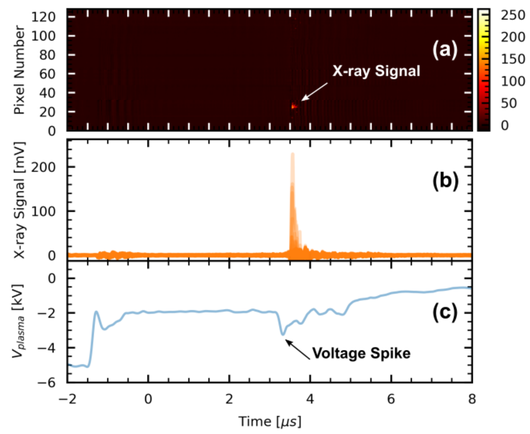
EXPERIMENTAL SETUP



EXPERIMENTAL RESULTS

- **Braided loop structure is observed in a laboratory experiment and the kink instability develops on the structure.**





- **Kinetic instability**

Kinetic instability occurs when the electron drift velocity $v_d = J_z/ne$ associated with electric current becomes comparable to some characteristic wave velocity such as the acoustic or Alfvén velocity. It stops the drift motion of electrons and increases the local effective electrical resistivity.

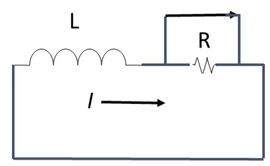
Fastest growing MHD instabilities are incompressible. They reduce the cross section and so increase $v_d = J_z/ne$ at choke points and causes kinetic instability that increases resistance.

$$\frac{v_d}{v_A} = \frac{J_z}{ne}\frac{\sqrt{\mu_0 n m_i}}{B_z} = \sqrt{\frac{m_i}{\mu_0 n e^2}}\frac{1}{B_z r}\frac{\partial}{\partial r}\left(rB_\varphi\right) = \frac{d_i}{B_z r}\frac{\partial}{\partial r}\left(rB_\varphi\right)$$

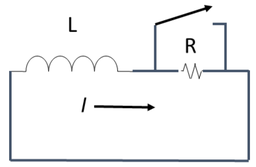
If B_φ is of order B_z , v_d will become of order v_A if the scale length of r becomes of the order of d_i.

For a hydrogen plasma loop, $n = 1\times10^{21}\mathrm{m}^{-3}$, $d_i = 0.7$ cm.

- **Opening switch circuit**



Before kinetic instability
Ideal MHD, perfect conductor

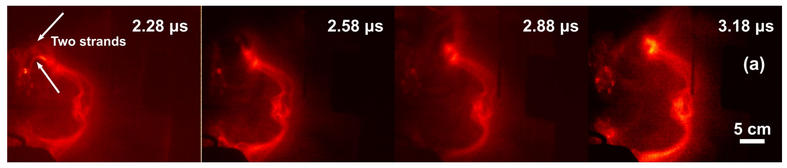


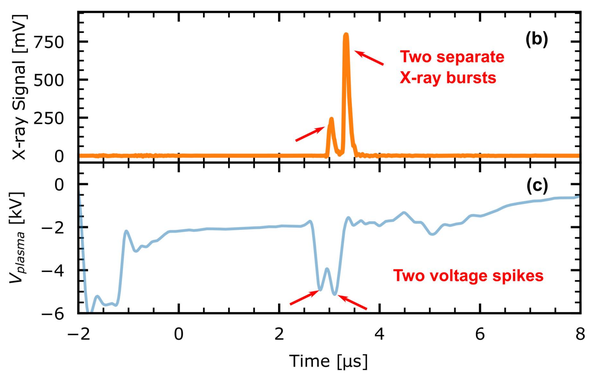
After kinetic instability,
resistor spliced into circuit

All magnetic energy is dumped in opening switch resistor [2]

$$-L\frac{dI}{dt} + IR = 0 \rightarrow -\frac{d}{dt}\left(\frac{1}{2}LI^2\right) + I^2R = 0 \rightarrow \frac{1}{2}LI^2 = \int I^2R\,dt$$

- **Two nanoflares generated from two broken strands**





SIMILAR PROCESS HAPPEN ON THE SUN

The ion skin depth is of order of 10 m in solar corona, while the radius of a solar coronal loop is of 10^6 m.

It is hard to choke a 10^6 m flux rope to 10 m.

It is proposed that a megameter solar flux tube is composed of a braid of successively smaller filamentary current-carrying flux tubes.

The radius of the finest strand would be a few d_i .

This finer-scale braided loop structure conclusion is consistent with observations which show that flux ropes have significant internal structure such that when resolution is increased, additional finer-scale structure is always observed.[3]

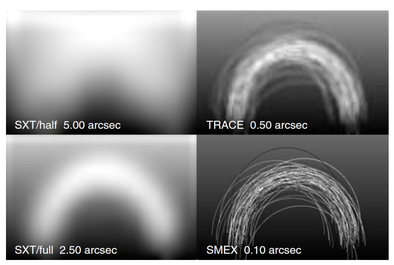
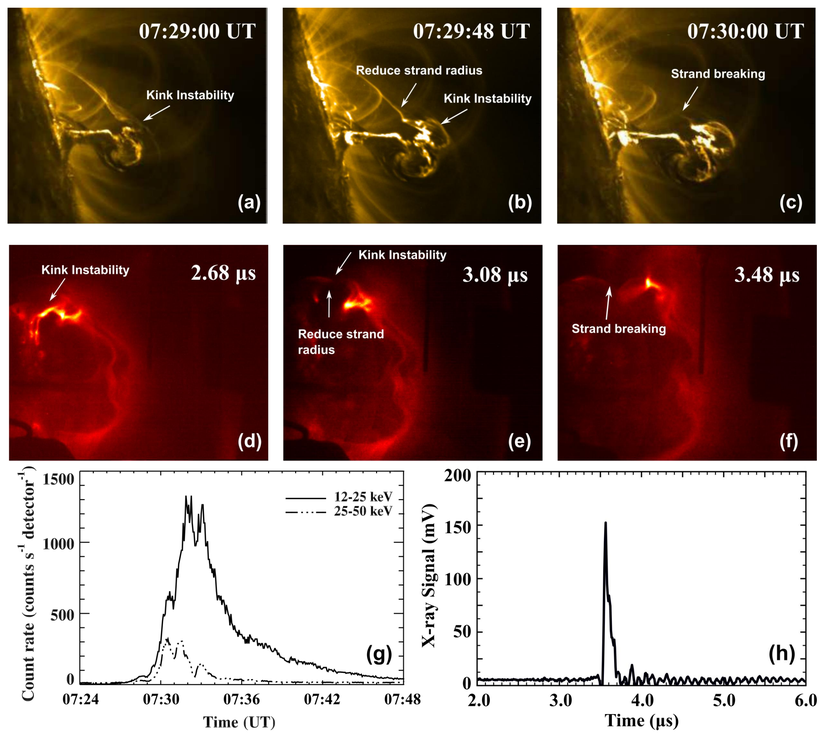


Fig. 1.18 from Ref. [3]



(a-c) SDO/AIA 171 (T~0.6 MK)˚A EUV images showing the development of kink instability, associated flare which occurred in active region NOAA 1163 on 2011 February 24. They present the same process as observed from our experiment as shown in (d-f). (g) RHESSI hard X-ray flux profiles. (h) X-ray signal from the experiment. (a, b, c, g) are reproduced from Ref. [4]

From these observations and our experimental results, it is reasonable to propose a path how the nanoflare is generated on the sun.

(i) A solar flux rope is composed of a braid of a very large number of fine-scale flux ropes with the finest scale being somewhat larger than d_i or $\beta^{-1/2}d_i$;

(ii) Electric current flows along the flux rope and a corresponding hoop force accelerates the expansion of the flux rope;

(iii) Each strand then develops a fast-growing MHD instabilily such as kink instability and magnetic RTI which then chokes the strand down to a critical scale at which kinetic instabilities develop and increase the effective resistivity of the choked segment;

(iv) This increase corresponds to an opening switch so the inductive energy of the entire circuit would be dumped into this region of increased resistivity;

(v) A very high voltage drop resulting from LdI/dt would accelerate electrons and ions to extreme energies and the bremsstrahlung radiation of the electrons would produce X rays.

[1] Y. Zhang, et al. (2020). [2] H. Alfvén and P. Carlqvist (1967). [3] M. Aschwanden, (2006). [4] P. Kumar, et al, (2012).

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