FASR Science Case # WG1-1

Where is the Primary Electron Acceleration Site in Solar Flares?

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1 Science Goal(s)

Briefly summarize the key science goal(s) for this science case. A few sentences will be sufficient.

Solar flares are the most powerful explosions in the solar system and, at the same time, very efficient particle accelerators. Hence, they serve as an excellent "laboratory" to understand how charged particles are accelerated to nonthermal energies. This science case aims to use ultra-wideband radio imaging spectroscopy observations offered by FASR to address the question of where and how energetic electrons are accelerated in solar flares.

2 Scientific Rationale

2.1 Scientific Importance

Provide a brief discussion on the scientific importance of this science case.

Where and how energetic electrons are accelerated in solar flares remains one of the most debated topics in solar flare physics. Candidates of the electron acceleration site include the reconnection X line(s), the reconnection outflows, the above-the-looptop cusp region, the top of the flare arcade, and the flare arcade itself. Mechanisms involved in accelerating the electrons include stochastic acceleration by turbulence or cascading waves, merging magnetic islands, shocks, collapsing traps, large-scale Alfvén waves, and DC electric field. Despite significant progress over the past few decades, thanks to the advent of spaceborne and ground-based hard X-ray and radio instrumentation such as RHESSI and EOVSA, we have been unable to pinpoint the primary acceleration site for flares with various sizes in a routine manner.

2.2 Uniqueness to FASR Capabilities

Is this science case uniquely addressed by FASR? Why can't other facilities address this science and achieve the same goal?

One of the primary challenges in the past was that previous and currently operating hard X-ray and radio instruments lacked the necessary dynamic range to perform spectral imaging for both strong sources and extremely weak sources in the flaring region. This capability is required to reconstruct the spatial, spectral, and temporal distribution of energetic electrons throughout the flaring region, enabling us to pinpoint the primary site of electron acceleration and the responsible acceleration mechanism(s).

There has been ample observational evidence suggesting that energetic electrons should be present throughout the flaring region. However, the regions outside of the flare arcade have relatively weaker magnetic fields, rendering emissions from energetic electrons there difficult to observe, particularly in the presence of a strong source near the flare looptops. Modeling results (e.g., Chen et al. 2023) suggest that in order to faithfully measure the energy content of energetic electrons in the extended flaring region, a dynamic range of $\sim 1000:1$ is required. FASR is the only instrument that provides the perfect combination of high dynamic range imaging, ultrawide frequency coverage, and adequate angular resolution to perform detailed spatially resolved radio spectral analysis throughout the flaring region.

2.3 Synergies

Describe potential synergies/complementarities between this FASR science case and those from current/future/planned facilities at all wavelengths (e.g., DKIST, MUSE, FIERCE, COSMO, ngGONG, etc.).

FASR diagnostics of the flare-accelerated energetic electrons will critically complement those made by the current and potential hard X-ray instruments, including SolO/STIX and FIERCE, which primarily probe energetic electrons of < 100 keV in regions with a relatively high ambient density, while radio diagnostics also include > 100 keV electrons, weighted more strongly by the background magnetic field. In addition, the ability of FASR to outline magnetic loops/field lines "illuminated" by energetic electrons in a broad flaring region also allows detailed tracing of the electrons from the coronal region to the lower atmosphere, enabling detailed comparison with EUV and optical/IR observations made by, e.g., IRIS, MUSE (future), BBSO/GST, and DKIST.

2.4 Measurements Required by FASR

Provide a description of the necessary measurements to be carried out by the FASR to adequately address this science case. Please coordinate these measurements with the Science Requirements table in Section III.

High-dynamic-range imaging ($\sim 100:1$ at low frequencies to $\sim 1000:1$ at high frequencies) over a frequency range of 1–20 GHz with adequate spectral resolution (400 channels sampled over this range, preferably logarithmically spaced).

III. Science Requirements Tables

(A) Observational Target Description

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

<table>
<tr><th colspan="3">(A) OBSERVATIONAL TARGET</th></tr>
<tr><td>Type of observation
(what defines a ‘target’)</td><td colspan="2">Provide a brief description of the target.
Gyrosynchrotron radiation from the flaring region in the low corona.</td></tr>
<tr><td>Number of targets</td><td colspan="2">1 to few (number of flare sources across the disk)</td></tr>
<tr><td>Size of a single target (arcsec x arcsec)</td><td colspan="2">Up to $300'' \times 300''$</td></tr>
<tr><td>Distribution of all targets (arcmin x arcmin)</td><td colspan="2">Up to $30' \times 30'$</td></tr>
<tr><td>Peak brightness (sfu/beam or Kelvin)</td><td colspan="2">100–1000 MK</td></tr>
<tr><td>RMS brightness (sfu/beam or Kelvin)</td><td colspan="2">$\sim$ 0.1–1 MK</td></tr>
<tr><td rowspan="2">Expected circularly polarized flux density</td><td>Stokes V (sfu/beam or Kelvin)</td><td>–</td></tr>
<tr><td>V/I</td><td>Low at low frequencies and $< 40\%$ above several GHz</td></tr>
<tr><td rowspan="2">Expected linearly polarized flux density</td><td>Stokes Q or U (sfu/beam or Kelvin)</td><td>–</td></tr>
<tr><td>Q/I or U/I</td><td>?</td></tr>
</table>

(B) Spectro-Temporal Requirements Discussion

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

(B) SPECTRAL-TEMPORAL REQUIREMENTS	
Central Frequency (GHz)	10
Instantaneous Bandwidth (GHz/pol)	20
Spectral resolution [MHz]	50
Temporal resolution (in seconds)	1

(C) Polarization Product Discussion

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

(C) POLARIZATION DATA PRODUCTS REQUIRED	
y	Stokes I
n	Stokes Q
n	Stokes U
y	Stokes V

(D) Imaging Requirements Discussion

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

See discussions in Appendix.

(D) IMAGING REQUIREMENTS		
Required angular resolution (arcsec) (single value or range)	$20''$/GHz	
Largest angular scale required (arcsec)	$300''$	
Mapped image size (arcmin x arcmin)	$30' \times 30'$	
Required pixel resolution (arcsec)	$10''$/GHz	
Number of output/image channels	400	
Output bandwidth (minimum and maximum frequency - GHz)	1–20 GHz	
Channel width (MHz)	50	
Required rms (sfu/beam or Kelvin) [per channel] (if polarization products required define for each)	0.1 MK for I, 0.01 MK for V	
Dynamic range within image (if polarization products required define for each)	50:1 at 1 GHz, and increasing linearly with frequency (e.g., 1000:1 at 20 GHz)	
Polarization accuracy (%)	$\sim 2\%$	
Zero spacing/total power required?	n	
Required maximum latency (in seconds, or N/A)	N/A	
Required flux density scale calibration accuracy		1-3%
	x	5%
		10%
		20-50%

2.5 Other Performance or Functional Requirements

If there are any additional performance or functional requirements not captured above, describe them here. For example, beamforming array mode, phased array, etc.

3 Appendix

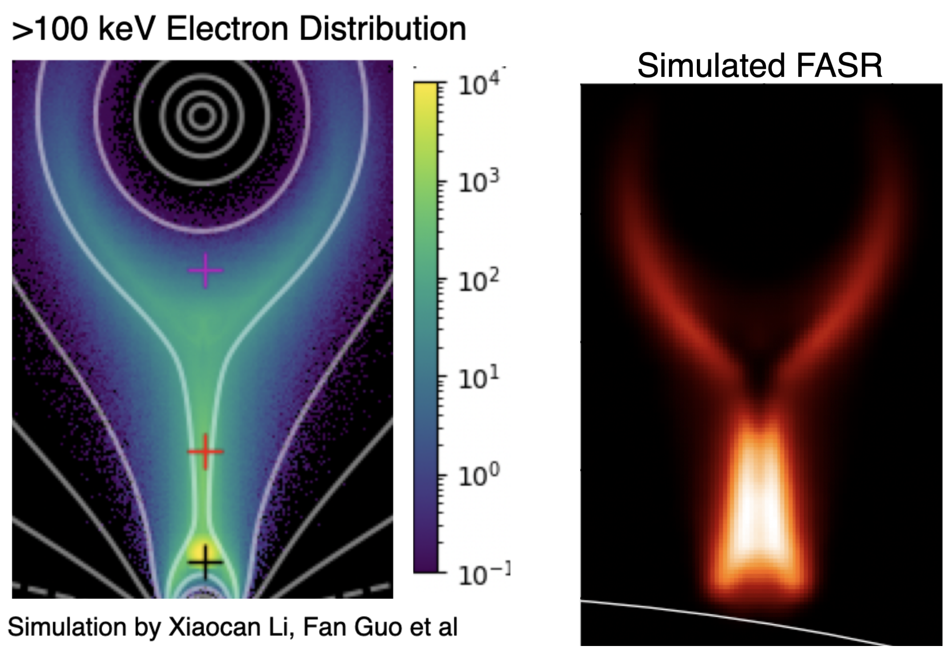
Please provide any other relevant material necessary to understand and substantiate this Science Case.

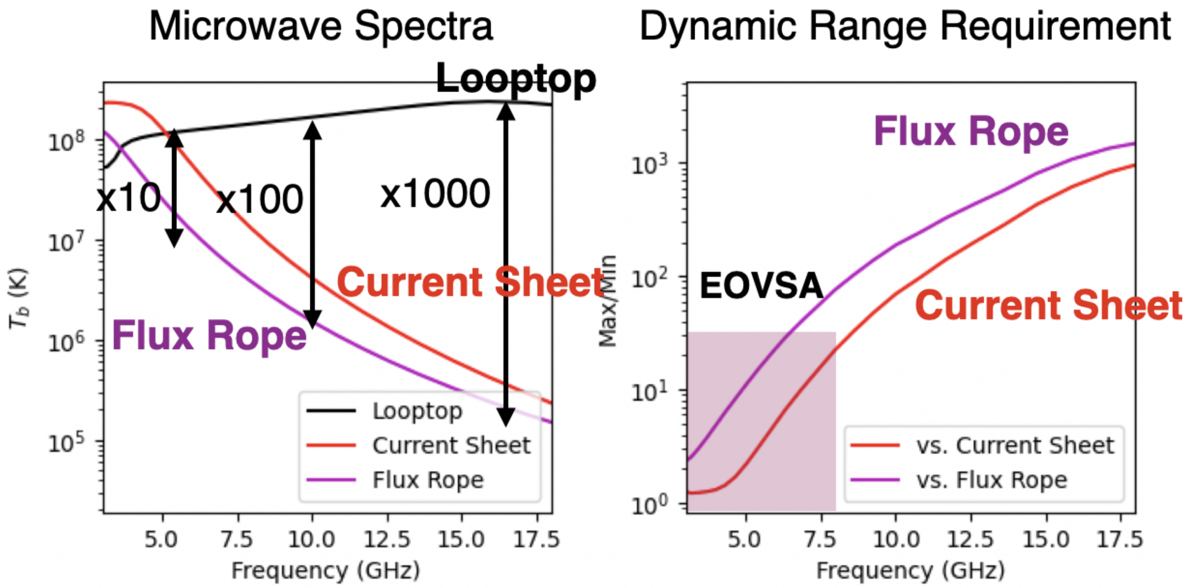
Estimates of the dynamic range requirements come from the flare model, which gives us synthetic microwave spectra at multiple locations, including the (brightest) looptop region, the current sheet, and the flux rope region.

The spectral resolution requirement of ~ 50 MHz corresponds to resolving $\Delta B \sim 4$–6 G through $\nu = s\nu_B$, with $\nu_B = 2.8B$ MHz, for $s = 3$–5 of electron gyrofrequency (typical harmonic number at the spectral peak). Given a typical flaring magnetic field of $B > 200$ G, this spectral resolution will give us a maximum accuracy of magnetic field diagnostics of $\gtrsim 2\%$, needed to further constrain the energetic electron distribution.

The requirement for the accuracy of V/I polarization degree measurements of $\sim 2\%$ comes from the typical polarization degree of optically thin gyrosynchrotron radiation of $\lesssim 40\%$.

The requirement of time resolution of ~ 1 s is chosen to capture "snapshots" of the distribution of energetic electrons. Recent modeling (e.g., Xiaocan Li et al. 2022) results suggest that the overall, macroscopic distribution of flare-accelerated electron distribution evolves at MHD scales. With an angular resolution of $2''$ at 10 GHz (mid-frequency) and a characteristic Alfvén speed of 1000 km/s, this gives us a typical timescale of 1.5 s. Therefore, a time cadence of 1 s is sufficient to study the collective evolution in most cases, although a much higher time resolution is desired to decouple the transport effects from acceleration, which is described in another science case.





Reference

Chen, B., Gary, D., Yu, S., Mondal, S., Fleishman, G., Li, X., Shen, C., Guo, F., et al. 2023. "Quantifying Energy Release in Solar Flares and Solar Eruptive Events: New Frontiers with a Next-Generation Solar Radio Facility." Bulletin of the American Astronomical Society, 55, 060. https://doi.org/10.3847/25c2cfeb.aa2ad1d0.

Li, X., Guo, F., Chen, B., Shen, C., and Glesener, L. 2022. "Modeling Electron Acceleration and Transport in the Early Impulsive Phase of the 2017 September 10th Solar Flare." The Astrophysical Journal, 932, 92. https://doi.org/10.3847/1538-4357/ac6efe.