Using topology to locate the position where fully three-dimensional reconnection occurs

Walter Gekelman¹ · Tim DeHaas² · Christopher Prior³ · Anthony Yeates³

Received: 18 May 2020 / Accepted: 16 November 2020 / Published online: 13 December 2020
© Springer Nature Switzerland AG 2020

Abstract

In two-dimensional magnetic reconnection, involving neutral sheets and magnetic islands it is generally a straightforward task to recognize reconnection sites when detailed data sets or simulations are available. In fully three-dimensional reconnection, their analogues can be challenging to identify. In this study, we demonstrate how locations of high reconnection activity can be detected in highly complex turbulent plasmas. We use a recently developed topological measure of reconnection based on the magnetic winding number, which measures the entanglement of pairs of field lines, to identify sub-regions of magnetic field lines which are reconnecting. This diagnostic is combined with established measures of magnetic field complexity, such as quasi-separatrix layers and regions of high magnetic twisting, to characterize the spatial and temporal distributions of reconnection activity of the field. It is demonstrated that the regions with the highest reconnection activity do not always coincide with the largest QSL signatures are, thus indicating this is a more complete methodology for quantifying reconnection activity than standard methods. This framework can serve as a model for reconnection analysis in future studies, in combination with established methods for identifying the specific form of reconnection once its location is established.

Keywords Plasma physics · Magnetic field line reconnection · Laboratory experiment · Magnetic flux ropes · Plasma flows and magnetic fields

1 Introduction

A great deal of computer simulations and laboratory studies on reconnection have focused on 2D reconnection. These studies feature antiparallel magnetic field lines driven together by plasma flow which generate the “classic” picture of ion jets in a perpendicular direction. When the oppositely directed fields collide, some magnetic energy is transferred to other forms (flow, waves, heat, etc.); this process is magnetic reconnection [1]. The first experimental results were published 40 years ago [2]

which led to a series of papers in JGR [3–8]. Data from the paper shown in Fig. 1 clearly illustrate the 2D geometry [9].

The merging fields induce an out of plane electric field which drives a current. There is little or no out-of-plane magnetic field. Reconnection is identified by the presence of a magnetic null. This simplified geometry has generated hundreds of simulations and several experiments which explore current sheets as narrow to an electron skin depth ($\delta_e = \frac{c}{\omega_{pe}}$) or wider than an ion skin depth ($\delta_i = \frac{c}{\omega_{pi}}$) along with variations of the flow and field topology. They are too numerous to list here; early reviews by Coppi [10]

Supplementary Information The online version contains supplementary material available at (<https://doi.org/10.1007/s42452-020-03896-4>).

✉ Walter Gekelman, gekelman@physics.ucla.edu | ¹Department of Physics and Astronomy, University of California, Los Angeles, CA, United States of America. ²Tri Alpha Energy, Irvine, CA, United States of America. ³Department of Mathematical Sciences, Durham University, Durham, UK.

SN Applied Sciences (2020) 2:2187 | <https://doi.org/10.1007/s42452-020-03896-4>

Fig. 1 **a** Measured magnetic field in a two-dimensional reconnection experiment. Two oppositely directed magnetic fields are forced together and reconnection occurs in a current sheet in the center. **b** Measured plasma ion flows show horizontal jetting of ions. In this experiment the device axis and weak guide field are in the y direction

and Kadomtsev [11] and more recent ones by Zweibel et al. [12] and Pontin [13] discuss some of these. This type of geometry can occur under the right conditions in the earth's magnetotail. Drawing on the models discussed above a crossing of such a region was identified using data from 4 satellites in the cluster mission [14].

The overwhelming number of reconnection events in space are not like those shown in Fig. 1. They are fully three dimensional; the axial magnetic field can be much larger than the transverse and may be curved as in the corona of the sun. There are no X points or neutral sheets, and reconnection occurs when components of the highly twisted magnetic fields collide.

3D magnetic reconnection has been studied in conjunction with a number of processes which occur in very different environments. It was first proposed over 80 years ago as a mechanism for the release of tremendous energy in solar flares [15, 16]. The range from astrophysical observation and theory [17–19] seen indirectly in the solar corona using UV and X ray emission [20, 21], solar flares [22, 23], the Earth's magnetotail [14], as well as magnetospheres of other planets [24, 25] thermonuclear fusion experiments [26, 27], and basic plasma physics laboratory experiments [28–32]. We present several examples but point out that excellent review papers [12, 33–35] books [36–38] and compendiums of articles [39] are out there. A review of all the observations and

theoretical analysis over the broad range of venues in which magnetic field-line reconnection occur is well beyond the scope of this paper.

Reconnection is a process that must be avoided in fusion devices such as Tokamaks. Sawtooth oscillations were first reported [40] in 1971 and have been observed many times in a large number of machines since. The sawtooth shape of periodic slow rise in the temperature followed by a fast crash was documented using electron cyclotron and X ray diagnostics [41] and has been studied using a variety of methods in the past several decades. The crash occurs when internal reconnection generates “magnetic islands” and stochastic field lines. When this occurs heat and particles can leave the device. Theoretical analysis by Kadomtsev [42] and others predicted this would occur when $q(r) \equiv \frac{B_\phi}{B_p} \frac{r}{R}$ (R is the radius of the device and ϕ , ρ are the toroidal and poloidal directions) is slightly less than one. This agreed with a great deal of observations, but not all. Observations in a number of Tokamaks including TFTR [43] found sawtooth disruptions at $q \sim 0.7$ not explained by well accepted theories. Recently, Smiet et al. [44] used field line mapping coupled with a group theoretical approach and predicted that crashes can occur at $q = 2/3$. Our work uses an alternative approach to analyze the magnetic topology in a more global way, rather than focusing on the structure near to closed field lines. Finally, current sheets in fusion devices or in space can experience tearing modes [45]. The magnetic islands and attendant temperature gradients which occur as a result drastically change particle transport in the reconnection region [46].

The theory of 3D reconnection however is in its nascent stage. This is especially the case when there are no locations where the magnetic field goes to zero, null points. Early pioneering work was done by Priest and his colleagues [47, 48]. 3D reconnection involves intense currents with strong spatial gradients. The reconnection rate can be defined as

$$\Sigma = \int E_{\parallel} ds \quad (1)$$

The integral is performed along magnetic field lines in the volume that reconnection occurs. It has been measured in the laboratory [31]. 3D reconnection occurs in current layers not associated with magnetic nulls and their structure as well as their origin and where they terminate. Most 3D work use the Magnetohydrodynamic (MHD) formalism, with the addition of terms for the plasma resistivity. The resistivity is a term in Ohms law, but it is not at all clear if that can be used at all [62]. To the author's knowledge none of the theories can be used to pinpoint the location of reconnection when null points or lines do not exist.

Priest et al. [49] discussed fully three-dimensional reconnection using as an example two flux tubes embedded in a plasma where there are no magnetic nulls. Even when a simple version of Ohm's law is used they found that the field lines continually change in direction and in the diffusion region where the conductivity is not infinite, the tubes split into four. The identity of the original tubes is lost.

To tackle the identification problem, solar physicists developed the concept of the Quasi-Separatrix Layer [50] (QSL). QSLs are domains of field line footpoints which, when initially in a local neighborhood, diverge as the field-lines are followed. The rationale for seeking such structures is twofold. First QSLs tend to be a good indicator of the location of current sheets in the magnetic field, hence likely sites for likely reconnective activity. Second, if reconnection occurs, two closely spaced field lines, which initially remain closely spaced as they twist through a complicated geometry, will then spatially diverge after reconnection. Thus, the temporal appearance/disappearance of QSL structure is a sign of reconnective activity. The QSL is a quantitative measure of this. The QSL is a collection of field lines defined by the quantity Q , a.k.a. the squashing factor in Eq. (2). Briefly, consider two points on separate field-lines separated by distances (dx, dy) in a plane z_0 and wind up being separated by distances (dX, dY) on plane z_1 . If they do not separate, $dx=dX=dY=dy$, then the numerator of Q is 2. The denominator accounts for a difference in the axial (B_z) field strength on the two planes. A large Q value indicates the fieldlines diverge and hence can be classified as QSL structures. In short the QSL measure is an **indirect** diagnostic of reconnective activity. The existence of a QSL cannot pinpoint the reconnection location(s). The existence of large electric fields, parallel to the background magnetic field, the formation of twisted flux tubes which thin out as reconnection proceeds and the appearance of anomalous resistivity are all indicators [51] but can occur due to other processes.

$$Q = \frac{\left(\frac{\partial X}{\partial x}\right)^2 + \left(\frac{\partial X}{\partial y}\right)^2 + \left(\frac{\partial Y}{\partial x}\right)^2 + \left(\frac{\partial Y}{\partial y}\right)^2}{\left|\frac{B_z(z_0)}{B_z(z_1)}\right|} \quad (2)$$

QSLs are routinely calculated for solar flux ropes using simulations [52, 53]. The first experimental verification [54] occurred in 2009. This was made possible when 3D magnetic data at thousands of locations were obtained to accurately follow field lines. Since then, QSLs have been evaluated in flux rope experiments with two or more ropes [55]. The magnetic field discussed in this manuscript involved the acquisition of $\vec{B}(\vec{r}, t)$ at over 42,000 spatial locations. There were several previous experiments in

which the QSL was calculated for different flux ropes but this data set is far more complete. The plasma density, electron temperature, flow, plasma potential and magnetic field were measured at these locations.¹ Acquisition of this data made the calculations outlined below possible. There are no assumptions of symmetry or invariance along a particular direction in space sometimes used to justify incomplete datasets.

When a significant scale QSL is identified, one knows that reconnection occurs somewhere inside it. However, often fields or regions of field can have significantly complex field geometry but no large scale QSL; instead exhibiting rather more diffuse entanglement. Prior and Yeates [56] developed topological tools to **directly** quantify reconnection of magnetic fieldlines. These were applied to magnetic data from a previous experiment similar (the ropes were smaller and closer together and the spatial resolution lower) to that analyzed here. These tools are based on the winding number [56], a measure of mutual field-line entanglement which **only** changes when the field lines reconnect. We will utilize these tools in this manuscript to highlight how they impart information missed by the QSL technique for locating sites of reconnective activity.

This paper does not present a theory of three-dimensional reconnection. Instead it addresses the issue of identifying the location of reconnection sites when fully three-dimensional magnetic data and flows are available from experiments or simulations. To do this we introduce several topological quantities which can be calculated from the experimental data.

This work fits well in the topical collection on "Interfaces, Mixing and Non-equilibrium dynamics". The ropes interact with each other and mix with the cooler, less dense, background plasma as evidenced by diffusion of the plasma current electron temperature and rope density as a function of distance from their origin [62, 63]. The interface between the ropes and background magnetic fields is blurred as the currents diffuse. The same can be said for ion flows.

2 Experimental setup

The flux rope experiments were done in the Large Plasma Device (LAPD) at UCLA [57]. The ambient plasma is produced by a DC discharge between a barium oxide-coated cathode [58] and mesh anode. The bulk of the

¹ Subsets of this data relevant to particular investigations can be made available upon approval of the first author. See data management plan (<http://plasma.physics.ucla.edu/data-management>).

Fig. 2 Photograph of the LAPD device and schematic showing flux rope generation. **a** The 18 m long plasma column is surrounded by 100 solenoidal magnets. There are 450 access ports on the device. Many ports have vacuum interlocks for the introduction and removal of probes while the machine is running. The BaO plasma source is inside an end chamber on the far end of the photo. **b** Schematic view of the components, including the electrical connections. Also shown is the internal LaB₆ cathode, carbon mask and anode used in the generation of flux ropes

plasma carries no net current and is therefore quiescent. The background plasma parameters are:

$$\frac{\delta n}{n} \approx 3\%, T_e = 5\text{ eV}, n \approx 2 \times 10^{12} \text{ cm}^{-3}, T_i \approx 1\text{ eV}$$

The background plasma is pulsed at 1 Hz with typical plasma duration of 15 ms. The LAPD can run continuously for approximately four months before the cathode has to be cleaned and recoated. A schematic of the machine indicating how the background plasma and flux ropes are generated is shown in Fig. 2.

The background plasma is generated by an oxide-coated cathode schematically shown on the right of Fig. 2b. A transistor switch capable of switching 25 kA currents [59] in series with a 4 F capacitor bank is used to pulse a voltage between the negatively biased cathode and a molybdenum anode located 50 cm away. The background plasma is 18 m in length and 60 cm in diameter. A second, high emissivity lanthanum hexaboride cathode [60] is inserted in the machine. The LaB₆ cathode is masked with a carbon plate with two holes 3.5 in radius and 1 cm apart edge-to-edge. The current is forced through the unmasked areas to form the flux ropes.

When the ropes are pulsed on, there is additional ionization; the plasma density in the ropes doubles, and the electron temperature rises to over 12 eV in the helium discharge. At this point the plasma in the ropes is highly ionized. The electrical systems, which generate the ropes, and background plasma are independent of one another. A second transistor switch, electrically independent from the first with its own capacitor bank and charging supply is used to generate the ropes. The experimental sequence is as follows. First, the background plasma is switched on for 11 ms ($V_D = 80\text{ V}$, $I_D = 4\text{ kA}$). The internal LaB₆ cathode is energized ($V_D = 125\text{ V}$, $I_D = 750\text{ A}$, each flux rope carries half of this current) 5 ms after the background plasma and remained on for 6 ms. Both flux ropes are kink unstable [61] ($I_{\text{kink}} = 133\text{ A}$, $I_{\text{rope}} = 375\text{ A}$). Three axis magnetic pickup coils measured $\frac{\partial B}{\partial t}$ from which the plasma currents are derived. Other quantities measured were the plasma flow, electron temperature, density, and plasma potential, which were used to show that Ohm's law is nonlocal [62]. All quantities were measured at 42,200 spatial locations and 7000 timesteps ($\delta t = 3.3 \times 10^{-7}\text{ s}$). These volumetric data were used to generate the topological quantities in this paper.

3 Evaluation of the winding number L

A quantity underpinning the ones below is the winding number L. Consider the two magnetic field lines illustrated in Fig. 3. Let γ be one of thousands of field lines and $\tilde{\gamma}$ represent one of all the other field lines that originate on a plane D_0 and pass through D_1 . Choosing an arbitrary starting coordinate in D_0 , as illustrated by the orthogonal axis, an angle θ_0 between the field lines is defined. As one moves from plane to plane, the vector between the field lines rotates, and the winding angle Θ is defined as:

$$\Theta(\vec{r}_0, \vec{r}, z, t) = a \tan \left(\frac{\gamma_y(\vec{r}, z, t) - \tilde{\gamma}_y(\vec{r}_0, z, t)}{\gamma_x(\vec{r}, z, t) - \tilde{\gamma}_x(\vec{r}_0, z, t)} \right) \quad (3)$$

Here, γ is the vector of x, y coordinates for the curve anchored at $\vec{r}_0, \vec{r}$ the start locations in D_0 for all the other field lines $\tilde{\gamma}$, and z the height of the plane in which Θ is evaluated. Each field line is parameterized by height z , and time t . The ropes are switched on at $t = 0$. To measure the average entanglement of γ with the rest of the field we integrate Θ over all field lines anchored at positions $\vec{r}$. The winding of γ with the field is given by.

$$L(\vec{r}_0, z, t) = \frac{1}{2\pi} \int_{D_0(t)} [\Theta(\vec{r}_0, \vec{r}, z, t) - \Theta(\vec{r}_0, \vec{r}, 0, t)] dA \quad (4)$$

Fig. 3 Model showing two field lines used to evaluate Θ . γ is a test field line and one of the thousands of other field lines used in the calculation. D_0 and D_1 are two of the 15 planes on which data was collected (2810 positions on each plane). To follow the field lines, data were interpolated throughout the volume using divergence cleaning and bi-cubic spline functions [63]

The total winding of the field given by Eq. 4 is the mean entanglement over all field lines γ :

$$L(z, t) = \int_{D_0(t)} L(\vec{r}_0, z, t) dA_0 \quad (5)$$

By evaluating changes in Eq. 3, magnetic reconnection may be identified as L only changes when field lines reconnect [56]. However, several precautions must be made in order to interpret the results correctly. First, one must be careful as branch cuts which may occur in calculating the arctangent lead to Θ greater than 2π , in which case Eq. 3 must be modified. We have established that this is not the case for this experiment since the largest angle Θ was 68 degrees. Second, since the experimental volume is larger than the domain on which the field is sampled some magnetic field lines leave the volume during the fields' evolution. The formula for quantifying this effect, which measures the change in the area of magnetic field footpoints over a small time step dt , was derived in [56], the calculated quantity depends also on the winding associated with the fieldlines lost. It was found in this experiment that the effect on the quantities calculated was negligible, so we do not discuss the issue further here.

Figure 4 gives a sense of the structure of the field lines, $\tilde{\gamma}$ used in the evaluation of L . The tracing begins for points on a rectangular grid at $z=64$ cm (the ropes originate at $z=0$). As one moves away from the initial plane the rectangle becomes deformed and at $z=9.3$ m, several field lines have left the measurement plane. As indicated in Fig. 5, the change in the set of fieldlines remaining in the domain is small; when coupled with the fact that the winding rate is at its weakest near the boundary this change was found to have little effect on the changing winding distribution, as mentioned above.

The product of the winding and the magnetic flux $B_z dA$ ($dA = dx dy$) is the magnetic helicity, whose fieldline density may be defined in terms of the winding angle [56, 64] as

$$H(\vec{r}_0, z, t) = \frac{1}{2\pi} \int_{D_0(t)} B_z(\vec{r}, t) \frac{\partial}{\partial t} [\Theta(\vec{r}_0, \vec{r}, z, t) - \Theta(\vec{r}_0, \vec{r}, 0, t)] dA \quad (6)$$

The branch cut discontinuity in the function H also manifests itself in the helicity and can be linked to the Aharonov–Bohm effect [65, 66]. By removing the magnetic flux it was shown by Prior and Yeates [56] that the field line distribution of L will change only if the field changes connectivity. Thus, its time evolution can be used to locate

Fig. 4 Puncture plot of magnetic field lines passing 4 planes at $t = 1.27$ ms after the ropes are switched on

Fig. 5 Puncture plot of field lines at the edge of a domain D located $z = 5.76$ m from the flux rope origin. Using the plasma flow the advance of the boundary was calculated after one time step and the new boundary displayed

changes in connectivity in a complex magnetic field with diffuse QSL structure. This is not generally true of the field line distribution of the helicity.

Figure 6 shows the winding number density L_D (i.e., the integrand of Eq. 3), on two planes and a line through the plane at a fixed time on three different planes. Note that the winding number changes sign across the machine indicating that the direction of Θ changes sense on either side. This is, in all likelihood a result of the kink mode. The value of L_D changes in time, but L_D does not oscillate as a function of time at any given position. On the left side of Fig. 6b, c it is always positive at every z location as a function of time and always negative on the right of the centerline.

To demonstrate the fully three-dimensional nature of the problem, the 3D winding number density, L_D , the QSL, and some magnetic field lines are displayed in Fig. 7. From Fig. 7 it is apparent that the winding becomes significant midway down the length of the device. The QSL exhibits a sharp twist at that location along with draping of the field lines over the QSL. This points to significant reconnection occurring 3 to 5 m from the origin of the ropes.

4 Evaluation of the reconnective activity

We define R' as the change in the winding number that is not due to the ideal motion of the field lines.

Fig. 6 The winding number density L_D (in radians/ cm^3). **a** Lineout of L_D ($y = 1.6 \text{ cm}$) at a fixed time on three planes. **b**, **c** $L_D(x, y)$ at a fixed time on two transverse planes $z = 1.28, 7.68 \text{ m}$. The magenta line indicates the y position of the data in 6a. The winding number

shows that most of the flux linkage is associated with the ropes which tilt and become deformed at a further distance from the origin

$$R'(\vec{r}_0, z, t) = L(\vec{r}_0, z, t) - L(\vec{r}_0, z, t - dt) - \Delta L_{\text{ideal}}(\vec{r}_0, z, t, dt) \quad (7)$$

R' is the unnormalized reconnection activity and has units of area. If we do not integrate over the transverse

planes, L_D is the winding number density and R_D' is the reconnective activity density. With ΔL_{ideal} given by:

Fig. 7 Two isosurfaces of the winding number density L_D (radians/ m^3) shown as red and blue surfaces. The $Q=100$ surface is shown in magenta and field lines on it are black lines. Magnetic field

lines stored within the flux ropes are displayed in green and blue. Arrows of current density in the first plane that data was acquired in ($z=0.64$ m) show the transverse extent of the ropes

$$\Delta L_{\text{ideal}}(\vec{r}_0, z, t, dt) = \int_{D_0(t)} [\Delta \theta_{\text{vel}}(\vec{r}_0, \vec{r}, z, t, dt) - \Delta \theta_{\text{vel}}(\vec{r}_0, \vec{r}, 0, t, dt)] dA \quad (8)$$

The term L_{ideal} , represents the fact that the velocity at the end planes of the sampling domain are nonzero. If the plasma conductivity is high, the field lines are frozen into the plasma and they would move with the plasma. Thus, the plasma flow can lead to the winding or unwinding of the field lines due to disentangling fluid motions at the boundary. The change $\Delta \theta_{\text{vel}}$ represents the change in angle, over a period $[t-dt, dt]$, of the pair curve curves anchored at $\vec{r}_0$ and $\vec{r}$, if the field is frozen in the plasma. By calculating and removing this change, any other changes in L over time must be due to reconnection [56]. To calculate ΔL_{ideal} , the local position of each line was advected by changing its position from $t-dt$ by $\vec{v}_{\text{ion}} dt$.

Similarly the change in magnetic helicity may be corrected for ideal motion using Θ_{ideal} in Eq. 4, i.e., magnetic flux density in the limit dt approaches 0 is:

$$\Phi(\vec{r}_0, z, t) = \frac{1}{dt} [H(\vec{r}_0, z, t) - H(\vec{r}_0, z, t-dt) - \Delta H_{\text{ideal}}(\vec{r}_0, z, t, dt)] \quad (9)$$

The helicity density on a plane 6.13 m from the origin of the ropes is shown in Fig. 8.

Using the quantities calculated above we define the reconnection activity density as:

$$R(z, \vec{r}, t) = R'(z, \vec{r}, t) \Phi(z, \vec{r}, t) \quad (10)$$

where R' and Φ are given by Eqs. 5 and 9, respectively. When integrated over planes transverse to the background field as in Eq. (3), R' has the units of area and the product of flux density and R' gives R in Volts after integration over D_0 . The reconnection activity density is shown at a fixed time in Fig. 9. As the case with L_D and helicity, the value of R_D is very small for $z < 4$ m. This indicates that substantial reconnection does not spatially occur over the first half of the spatial extent of the ropes.²

Another important quantity that sheds light on the reconnection location is the magnetic twist defined as [56]

$$T(\vec{r}, t) = \int_{\gamma(\vec{r})} \frac{\vec{J} \cdot \vec{B}}{B^2} ds \quad (11)$$

The twist is the local rotation of the field about a field line γ where ds is an element of arclength along γ . It has units of A/Tesla- m^3 . The plasma is said to be in a force free state [67] when $\vec{J} = \alpha(\vec{r}) \vec{B}(\vec{r})$ (α is a scalar field) the

² RT4486_leftd.jpg, RT4486_rightd.jpg, RT4486_lrbd.jpg

Fig. 8 Helicity density (integrand of Eq. 6) at two times at $z=6.13$ m. Unlike the winding number the helicity changes sign as a function of time at a given spatial position. Note that the QSL is centered close to the “S” shape in the center

Fig. 9 Two isosurfaces of reconnection activity, R_D , at a fixed time, $t=5.496$ ms. Also shown is the $Q=100$ surface at that time and magnetic field lines. The cut planes on the back and side are colored by R , green corresponding to $R_D=0$. This is illustrated in 3D stereo pairs shown in a second supplementary document

magnetic field is parallel to the plasma current, where the Lorentz force vanishes.

Taylor [68] conjectured that plasmas will transition to a force free state under the constraint that helicity is conserved. This is not the case for this experiment. The magnetic twist is calculated and shown in Fig. 10 along with the QSL and the reconnection activity as shown in Fig. 9. The twist density is proportional to $\vec{J} \cdot \vec{B}$. At increasing distance, the angle between $\vec{J}$ and $\vec{B}$ grows, the twist becomes small, and R_D , which is greatest when both the helicity and the winding number are large, grows from noise. This indicates that past the location for reconnection, i.e., the field lines diverge and unravel on either side of Q.

The twist oscillates at the kink frequency ($f=5.2$ kHz, $\tau=192$ μ s). Its temporal behavior is shown in Fig. 11.

Figure 11b shows $\int T(t, x, y, z) dx dy$ as a function of axial distance and time. The twist becomes small at $z > 4$ m, which is where the winding number and the reconnection activity starts to rise (see Figs. 9, 10). The spatially averaged reconnection activity is shown in Fig. 12. Both the positive and negative components of $\langle R \rangle$ grow in time and do not show the single frequency kink oscillation as seen in Fig. 11. The spatial distribution is opposite from the twist. R begins to grow at $z > 4$ m and continually increases as a function of z . Also shown in Fig. 12 is the maximum value of the squashing factor Q throughout the volume as a function of time. The peaks line up perfectly with those of the reconnection activity. Note they were calculated by entirely different methods. As seen in Figs. 9, 10 and the movie in a supplementary

Fig. 10 Reconnective activity density, R_D , and $Q=100$ surface at the same time shown in Fig. 9. Two isosurfaces of twist density (in orange and green) are displayed. The Twist is largest close to the origin of the ropes and becomes small where R becomes large. The cut planes on the end and bottom of the figure show R at the boundaries. We also provide a stereo slide pair (left and right views)

Fig. 11 **a** The volume integrated twist (in amps/Tesla) as a function of time. The integrals over space positive and negative twists are shown separately. **b** The temporal and spatial evolution of the positive twist density in $A/T\text{-m}^2$. The positive and negative twists are largest for $z < 4 \text{ m}$

Fig. 12 Top Maximum value of the QSL throughout the volume as a function of time. Bottom: Volume averaged reconnection activity. The positive and negative components were averaged separately as the total is very small. The data were averaged over 5 (out of 5000) timesteps to eliminate high frequency noise

document³ they are **not**, however, spatially coincident, so in order to identify all regions of reconnective activity **we must** calculate R . This topological method, in fact, has shown that there are regions where reconnection occurs that are missed by the QSL.

The QSL, twist and R can be used in conjunction to determine the most likely position of the reconnection region. This is where the median twist becomes small and R starts to rise. In this experiment, this location is at approximately at $z = 4$ m. Inspection of the magnetic field lines at $z = 4$ m do not show oppositely directed magnetic

fields even when the background field is subtracted. This is to be expected.

The plasma resistivity has been calculated using the fluctuation dissipation theorem [62]. One would expect that it would be large four meters from the flux rope origin. Figure 13 verifies this. It shows the plasma resistivity as a function of distance, z as well as a contour map of η_z on the $z = 4$ m plane. The resistivity as a function of axial position taken at a single point ($x = -1.2$, $y = 1.8$ cm) strongly peaks at $z = 4$ m. If it is averaged over the magenta region the peak is broader but still largest at this position. There are two other regions of enhanced resistivity in Fig. 13. These correspond to the current channels of the flux ropes and we associate them

³ Reactivity.mp4

Fig. 13 **a** The field aligned plasma resistivity in Ohm-m as a function of axial distance as a location where the resistivity is largest in the x - y plane at that axial position. Contours of constant resistiv-

ity divided by the local classical (Spitzer) resistivity are displayed in Fig. 13b. The largest η_z in the magenta colored region is 41 times the classical value

with current driven instabilities. The region in the center is coincident with the QSL.

5 Comments on theory and experiment

The theory underpinning the reconnection measure R is detailed in Ref. [56]. It makes no physical assumptions regarding the nature of the field's evolution. It only requires the existence of a vector field $\mathbf{B}$ whose field lines can be traced and a flow $\mathbf{V}$ which acts to distort the field continuously (under isotopy). Application of the measure to this experiment relies on the assumption that the electric field component parallel to $\mathbf{B}$ can be written as the gradient of a scalar potential. This holds because there are no closed-loop magnetic field lines in the experiment, and means that there is an effective field line flow, into which $\mathbf{B}$ is frozen [69].

This measure (R) contrasts with existing methods for measuring which make some additional assumptions. Some studies assume a constitutive law regarding the field's evolution (e.g., some form of magnetohydrodynamics [70, 71]). Some utilize indirect measures of reconnection, e.g., methods evolving QSL structures [72] or Poincare sections [73]. The most commonly utilized assumption is to require some clear localized and isolated region of reconnection, as in the methods developed from the classical Sweet-Parker models [74–78].

Our method makes none of these assumptions and directly quantifies the changing field line connectivity of $\mathbf{B}$. As such it can be applied to a wide variety of physical regimes and fields of significant complexity (i.e., those which have no easily identifiable localized region of reconnection).

The key experimental measurements were those of magnetic field and plasma flow. The magnetic $\mathbf{B}$ -dot probes were calibrated with the use of a three-axis Helmholtz coil system and network analyzer. The magnitude and phase as a function of frequency were measured. For frequencies of order 10 kHz the probes could measure fields as low as 20–50 μG , or one thousand times smaller than the typical field of the ropes. The plasma flow was measured using Mach probes, which measure the difference in ion signals between opposite faces. In another experiment using an Argon plasma the Mach probes agreed with Laser Induced Fluorescence measurements to within 10 percent. The flows in the flux rope experiment are not large as evidenced by the small correction to Eq. 7 (see Fig. 5).

6 Conclusions

Locating regions of high reconnective activity in a plasma with a strong guide field is non-trivial as the three-dimensional analogues of “classical” X points or

neutral sheets can be hard to characterize. An established method for identifying the likely location reconnection activity is to calculate the squashing-factor. This can identify Quasi-Separatrix Layers (QSL's), regions of highly divergent fields lines, which are locations of likely reconnection. However, squashing factor calculations are not direct measures of reconnection and our results indicate that in highly turbulent fields the squashing factor alone does not always provide a clear guide to the regions where reconnection most significant. To solve this location problem and unearth further insights, we used supplemental topological quantities, namely the winding number, magnetic twist, and reconnective activity. The reconnective activity, here denoted R , is a direct measurement of reconnection, which need not take place only at the most obvious QSL's.

Using these additional topological measures we were able to locate the axial (magnetic field aligned) location of an area within the QSL that reconnection occurs. In addition we observed, for the first time, that the highest rate of magnetic field line reconnection occurs away from the dominant quasi-separatrix layer. The most significant reconnective activity, R , was observed along the edges of the flux ropes. Axially, this increase in R was accompanied with a marked decrease in the field-line twist and also a transition from a relatively flat to a highly deformed QSL. The magnetic field, initially aligned with the plasma current becomes frayed in the vicinity of this reconnection region, leading to an increase in both the winding number and R . Both these quantities are large either side of the QSL, not in it. The topological study therefore has unveiled additional reconnection in regions away from where researchers would traditionally look.

To evaluate these quantities an experiment must have a fully three-dimensional data set of magnetic and plasma flow fields. The experimental approach here was to acquire fully three-dimensional data of key plasma parameters all on the same spatial locations and time-steps. To accomplish this data was acquired at a one Hertz rep rate, day and night, for about one month. This was possible because the LAPD generated highly reproducible plasmas. The measure R does not rely on any particular modeling assumptions, only the ability to trace fields lines and the existence of a magnetic field $\mathbf{B}$ and some isotopic distorting flow $\mathbf{V}$ (here the ion velocity). Thus, it can be adapted to a variety of scenarios. In particular, this methodology can also be used in computer simulations or empirical reconstructions in which these quantities can be calculated on a large number of grid points.

Acknowledgements We also would like to thank Zoltan Lucky, Marvin Drandell, and Tai Ly for their expert technical support. The work was performed at the Basic Plasma Science Facility, which is funded by DOE (DE-FC02-07ER54918) and the National Science Foundation (NSF-PHY 1036140). Thanks to Shawn W. Tang for careful proofreading.

Compliance with ethical standards

Conflict of interest The author's declare they have no conflict of interest.

References

1. Vasyliunas VM (1975) Theoretical models of magnetic field line merging I. *Rev Geophys Space Phys* 13:303
2. Stenzel RL, Gekelman W (1979) Experiments on magnetic field line reconnection. *Phys Rev Lett* 42:1055–1057
3. Stenzel RL, Gekelman W (1981) Magnetic field line reconnection experiments I. field topologies. *J Geophys Res* 86:649–658
4. Gekelman W, Stenzel RL (1981) Magnetic field line reconnection experiments. 2. plasma parameters. *J Geophys Res* 86:659–666
5. Gekelman W, Stenzel RL, Wild N (1982) Magnetic field line reconnection experiment. 3. Ion acceleration, flows and anomalous scattering. *J Geophys Res* 87:101–110
6. Stenzel RL, Gekelman W, Wild N (1982) Magnetic field line reconnection experiments. 4. Resistivity, heating and energy flow. *Jour Geophys Res* 87:111–117
7. Stenzel RL, Gekelman W, Wild N (1981) Magnetic field line reconnection experiments. 5. Current disruptions and double layers. *J Geophys Res* 88:4793
8. Gekelman W, Stenzel RL (1984) Magnetic field line reconnection experiments, part 6 magnetic turbulence. *J Geophys Res* 89:2715–2733
9. Gekelman W, Urrutia JM, Stenzel RL (1987) Measurement of magnetic helicity during the disruption of a neutral current sheet. In: Lui AT (ed) *Magnetotail physics*. Johns Hopkins Press, Baltimore, pp 261–274
10. Coppi B, Mark JW-K, Sugiyama L (1979) Magnetic reconnection in collisionless plasmas. *Ann Phys* 119:370
11. Kadomtsev BB (1987) Magnetic field line reconnection. *Rep Prog Phys* 50:115
12. Zweibel E, Yamada M (2009) Magnetic reconnection in space and astrophysical plasmas. *Annu Rev Astro Astrophys* 47:291
13. Pontin DI (2011) Three dimensional magnetic reconnection regimes: a review. *Adv Space Sci Res* 47(9):1508
14. Chen L-J et al (2009) Multispacecraft observations of the electron current sheet, neighboring magnetic islands, and electron acceleration during magnetotail reconnection. *Phys Plasmas* 16:056601
15. Giovanelli RG (1939) The relation between eruptions and sunspots. *Astrophys J* 89:555
16. Giovanelli RG (1946) A theory of chromospheric flares. *Nature* 158:81
17. Contopoulos I (2007) The role of reconnection in the pulsar magnetosphere. *Astron Astrophys* 466:301–307
18. Arons J (1984) Astrophysical implications of reconnection. In: Hones EW (ed) *Magnetic reconnection in space and laboratory plasmas*. American Geophysical Union, Washington, D. C., pp 366–368
19. Lazarian A, Eyink GL, Vishniac ET, Kowal G (2015) Magnetic reconnection in astrophysical environments. In: Lazarian A, de

- Gouveia Dal Pino EM, Melioli C (eds) Magnetic fields in diffuse media. Springer-Verlag, Berlin, Germany
20. Aschwanden JP, Wulser NN, Lemen J Jr (2008) First three-dimensional reconstructions of coronal loops with the stereo A and B spacecraft I Geometry. *Astrophys Jour* 679:827
 21. Golub L, Bookbinder J, DeLuca E, Karovska M (1999) A new view of the solar corona from the transition region and coronal explorer (TRACE). *Phys Plasmas* 6:2205
 22. Tajima T, Shibata K (1997) Plasma astrophysics chapter 3 in frontiers in physics series. Addison Wesley, Boston
 23. Parker EN (1963) The solar-flare phenomenon and the theory of reconnection and annihilation of magnetic fields. *Astrophys J* 8:177
 24. Zao ZH et al (2017) Corotating magnetic reconnection site in saturn's magnetosphere. *Astrophys J Letts* 846:L25
 25. Kivelson MG, Southwood D (2005) Dynamical consequences of two modes of centrifugal instability in Jupiter's outer magnetosphere. *J Geophys Res* 110:A12209
 26. Tanabe H et al (2017) "Recent progress of magnetic reconnection research in the MAST spherical tokamak. *Phys Plasmas* 24:056108
 27. Yamada M, Levinton FM, Pomphrey N, Budny R, Manickam J, Nagayama Y (1994) Investigation of magnetic reconnection during a sawtooth crash in a high-temperature tokamak plasma. *Phys Plasmas* 1:3269
 28. Brown MR (1999) Experimental studies of magnetic reconnection. *Phys Plasmas* 6:1717
 29. Gekelman W, Stenzel RL, Wild N (1982) Magnetic field line reconnection experiments. *Phys Scr T2*–2:277–287
 30. Intrator TP, Sun X, Lapenta G, Dorf L, Furno I (2009) Experimental onset threshold and magnetic pressure pile-up for 3D reconnection. *Nat Phys* 5:521
 31. Gekelman W, DeHaas T, Daughton W, Van Compernelle B, Intrator T, Vincena S (2016) Pulsating magnetic reconnection driven by three dimensional flux rope interactions. *Phys Rev Lett* 116:235101
 32. Yamada M, Ji H, Hsu SC, Carter T, Kulsrud RM, Bretz N, Jobes F, Ono Y, Perkins F (1997) Experimental investigation of the neutral sheet profile during magnetic reconnection. *Phys Plasmas* 4:1936
 33. Hesse M, Cassak PA (2018) Magnetic reconnection in the space sciences: past, present and future. *JGR Space Phys* 10:2029
 34. Treumann R, Baumjohann W (2013) Collisionless magnetic reconnection in space plasmas. *Front Phys* 1:31
 35. Coppi B, Mark J, Sugiyama L, Bertin G (1979) Magnetic reconnection in collisionless plasmas. *Annals of Phys* 119:370
 36. Priest E, Forbes T (2000) Magnetic reconnection. Cambridge University Press, Cambridge
 37. Pontin D (2011) Three-dimensional magnetic reconnection regimes: a review. *Adv Space Res* 47:1508
 38. Hones EW Jr (ed) (1984) Magnetic reconnection in space and laboratory plasmas, geophysical monograph series, vol 30. American Geophysical Union, Washington
 39. Birn J, Priest E (eds) (2007) Reconnection of magnetic fields: magnetohydrodynamics and collisionless theory and observations. Cambridge University Press, Cambridge
 40. Goeler S, Stodiek W, Sauthoff N (1971) Studies of internal disruptions and $m=1$ oscillations in Tokamak discharges with soft-X-ray techniques. *Phys Rev Letts* 33:1201
 41. Nagayama Y, McGuire KM, Bitter M, Cavallo A, Fredrickson ED, Hill KW, Hsuan H, Janos A, Park W, Taylor G, Yamada M (1991) Analysis of sawtooth oscillations using simultaneous measurement of electron cyclotron emission imaging and X-Ray tomography on TFTR. *Phys Rev Letts* 67:3527
 42. Kadomstev BB (1975) Disruptive instability in Tokomaks. *Soviet J Plasma Phys* 1:710
 43. Levinton FM, Batha SH, Yamada M, Zarnstorff M (1993) q-profile measurements in the Tokamak Fusion nTest Reactor. *Phys Fluids B: Plasma Phys* 5:2554
 44. Smiet CB, Karner GJ, Hudson SR (2020) Bifurcations of the magnetic axis and the alternating-hyperbolic sawtooth. *Nucl Fusion* 60:084005
 45. Furth HP, Killeen J, Rosenbluth MN (1963) Finite-resistivity instabilities of a sheet pinch. *Phys Fluids* 6:459
 46. Coppi B, Basu B (2019) Asymmetric and endogenous magnetic reconnection processes in quasi-collisionless plasmas. *Phys Plasmas* 26:042115
 47. Priest E, Démoulin P (1995) Three dimensional magnetic reconnection without null points 1. basic theory of magnetic flipping. *J Geophys Res* 23(433):100-A12
 48. Schindler K, Hesse M, Birn J (1988) General magnetic reconnection, parallel electric fields, and helicity. *J Geophys Res* 93(A6):5547
 49. Priest ER, Hornig G, Pontin DI (2003) On the nature of three-dimensional magnetic reconnection. *J Geophys Res* 108(A7):1285
 50. Titov VS, Forbes ETG, Priest ER, Mikiz Z, Linker JA (2009) Slip squashing factors as a measure of three-dimensional magnetic reconnection. *Astrophys J* 693:1029
 51. Démoulin P (2007) Where will efficient energy release occur in 3D magnetic configurations. *Adv Space Sci Res* 39:1367
 52. Titov VS, Hornig G (2002) Theory of magnetic connectivity in the solar corona. *J Geophys Res* 107(A8):1164
 53. Mandrini CH, Démoulin P, Driel-Gesztelyi L, Schmieder B, Cauzzi G, Hofmann A (1996) 3D magnetic reconnection at an X ray bright point. *Solar Phys* 168:115
 54. Lawrence E, Gekelman W (2009) Identification of a quasi-separatrix layer in a reconnecting laboratory magnetoplasma. *Phys Rev Lett* 103:105002
 55. Van Compernelle B, Gekelman W (2012) Morphology and dynamics of three interacting Kink-Unstable Flux Ropes in a Laboratory Magnetoplasma. *Phys Plasmas* 19:102102
 56. Prior C, Yeates A (2018) Quantifying reconnective activity in braided vector fields. *Phys Rev E* 98:013204
 57. Gekelman W, Pribyl P, Lucky Z, Drandell M, Leneman D, Maggs J, Vincena S, Van Compernelle B, Tripathi SK, Morales G, Carter T, Wang Y (2016) The upgraded LAPD Device, a machine for studying frontier basic Plasma physics. *Rev Sci Instrum* 87:025195
 58. Leneman D, Gekelman W, Maggs J (2006) The plasma source of the large plasma device at UCLA. *J Rev of Sci Instrum* 77:015108
 59. Pribyl P, Gekelman W (2004) 24 kA solid state switch for a plasma discharge experiments. *Rev Sci Instrum* 75:669–673
 60. Cooper C, Gekelman W, Pribyl P, Lucky Z (2010) A new large area Lanthanum Hexaboride Plasma Source. *Rev Sci Instrum* 81:083503
 61. Ruytov D, Furno I, Intrator T, Abbate S, Madziwa-Nussinov T (2006) Phenomenological Theory of the Kink Instability in a Slender Plasma Column. *Phys Plasmas* 13:032105
 62. Gekelman W, DeHaas T, Pribyl P, Vincena S, Van Compernelle B, Sydora R, Tripathi S (2018) Nonlocal ohms law, plasma resistivity, and reconnection during collisions of magnetic flux ropes. *Astrophys J* 853:33
 63. Gekelman W, Lawrence E, Van Compernelle B (2012) Three dimensional reconnection involving magnetic flux ropes. *Astrophys J* 753:131
 64. Yeates AR, Hornig G (2014) Unique topological characterization of braided magnetic fields. *Phys Plasmas* 20:012102
 65. Webb GM, Anco SC (2017) On Magnetohydrodynamic gauge field theory. *J Phys A Math Theor* 50(25):255501
 66. Yahalom A (2013) Aharonov–Bohm effects in magnetohydrodynamics. *Phys Lett A* 377:1898–1904

67. Woltjer L (1958) A theorem on force-free magnetic fields, 14roc. Natl Acad Sci 44:489
68. Taylor JB (1986) Relaxation and magnetic reconnection in plasmas. *Rev Mod Phys* 58:741
69. Newcomb WA (1958) Motion of magnetic lines of force. *Annals of Phys* 3(4):347
70. Wilmot-Smith AL, Hornig G (2011) A time-dependent model for magnetic reconnection in the presence of a separator. *Astrophys J* 740:89
71. Eyink GL (2015) Turbulent general magnetic reconnection. *Astrophys J* 807:137
72. Richardson AS, Finn JM (2012) Quasi-separatrix layers and three-dimensional reconnection diagnostics for line-tied tearing modes. *Commun Nonlinear Sci Numer Simul* 17:2132
73. Smiet CB, Kramer GJ, Hudson SR (2019) Mapping the sawtooth. *Plasma Phys Control Fusion* 62:025007
74. Hesse M, Schindler K (1988) A theoretical foundation of general magnetic reconnection. *J Geophys Res Space Phys* 93:5559
75. Cassak PA, Shay MA (2007) Scaling of asymmetric magnetic reconnection: general theory and collisional simulations. *Phys Plasmas* 14:102114
76. Zenitani S, Hesse M, Klimas A, Kuznetsova M (2011) New measure of the dissipation region in collisionless magnetic reconnection. *Phys Rev Letts* 106:195003
77. Burch JL, Torbert RB, Phan TD, Chen LJ, Moore TE, Ergun RE, Wang S (2016) Electron-scale measurements of magnetic reconnection in space. *Science* 352(6290):aaf2939
78. Fu HS, Xu Y, Vaivads A, Khotyaintsev YV (2019) Super-efficient electron acceleration by an isolated magnetic reconnection. *Astrophys J* 870:L22

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.