Magnetogram-matching Energization and Eruption of Magnetic Flux Ropes

Viacheslav Titov[1], Cooper Downs[1], Tibor Torok[1], and Jon Linker[1]

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November 24, 2022

Abstract

We propose a new technique for energizing coronal magnetic equilibria toward eruptions. We achieve this via a sequence of MHD relaxations of small line-tied pulses of magnetic helicity, each of which is simulated by a suitable rescaling of the current-carrying part of the field. The whole procedure is 'magnetogram-matching' because it involves no changes to the normal component of the field at the lower boundary. The technique is illustrated by application to bipolar force-free configurations whose magnetic flux ropes (MFRs) are modeled with our regularized Biot-Savart law method. We have found that, in spite of the bipolar character of the ambient potential field in these examples, the resulting MFR eruption is generally sustained by two reconnection processes. The first, which we refer to as breakthrough reconnection, is analogous to breakout reconnection in quadrupolar configurations. It occurs at a quasi-separator field line located inside the current layer that wraps around the erupting MFR, and results from taking into account the line-tying effect at the photosphere. The second process is the classical tether-cutting reconnection that develops at the second quasi-separator inside a vertical current layer formed below the erupting MFR. Both reconnection processes work in tandem to propel the MFR through the overlying ambient field. The considered examples suggest that our technique will be beneficial for both the modeling of particular eruptive events and theoretical studies of eruptions in idealized magnetic configurations. This research was supported by NASA programs HTMS (award no. 80NSSC20K1274) and HSR (80NSSC19K0858 and 80NSSC20K1317); NASA/ NSF program DRIVE (80NSSC20K0604); and NSF grants AGS-1923377 and ICER-1854790.

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Energization via line-tied pumping of magnetic helicity

Total equilibrium field $\equiv \mathbf{B} = \mathbf{B}_{\mathrm{MFR}} + \mathbf{B}_{\mathrm{p}}$, where $\mathbf{B}_{\mathrm{MFR}}$ is a flux rope field such that $\left(\mathbf{e}_r \cdot \mathbf{B}_{\mathrm{MFR}}\right)\Big|_{r=R_\odot} = 0$
and $\mathbf{B}_{\mathrm{p}}$ is the potential field derived from a given $B_r\Big|_{r=R_\odot}$.

Magnetogram-matching rescaling of the non-potential part of the field with a factor $C_I = 1 + \varepsilon$:

New total field $\equiv \tilde{\mathbf{B}} = C_I \mathbf{B}_{\mathrm{MFR}} + \mathbf{B}_{\mathrm{p}}$

$= C_I (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) + \mathbf{B}_{\mathrm{p}}$

$= C_I \mathbf{B} - \dfrac{\varepsilon}{C_I} C_I \mathbf{B}_{\mathrm{p}} =$

(asterisk stands for rescaling) $= \mathbf{B}^* - \dfrac{\varepsilon}{C_I} \mathbf{B}^*_{\mathrm{p}}$

$\varepsilon > 0 \rightarrow$ increasing helicity

⇕

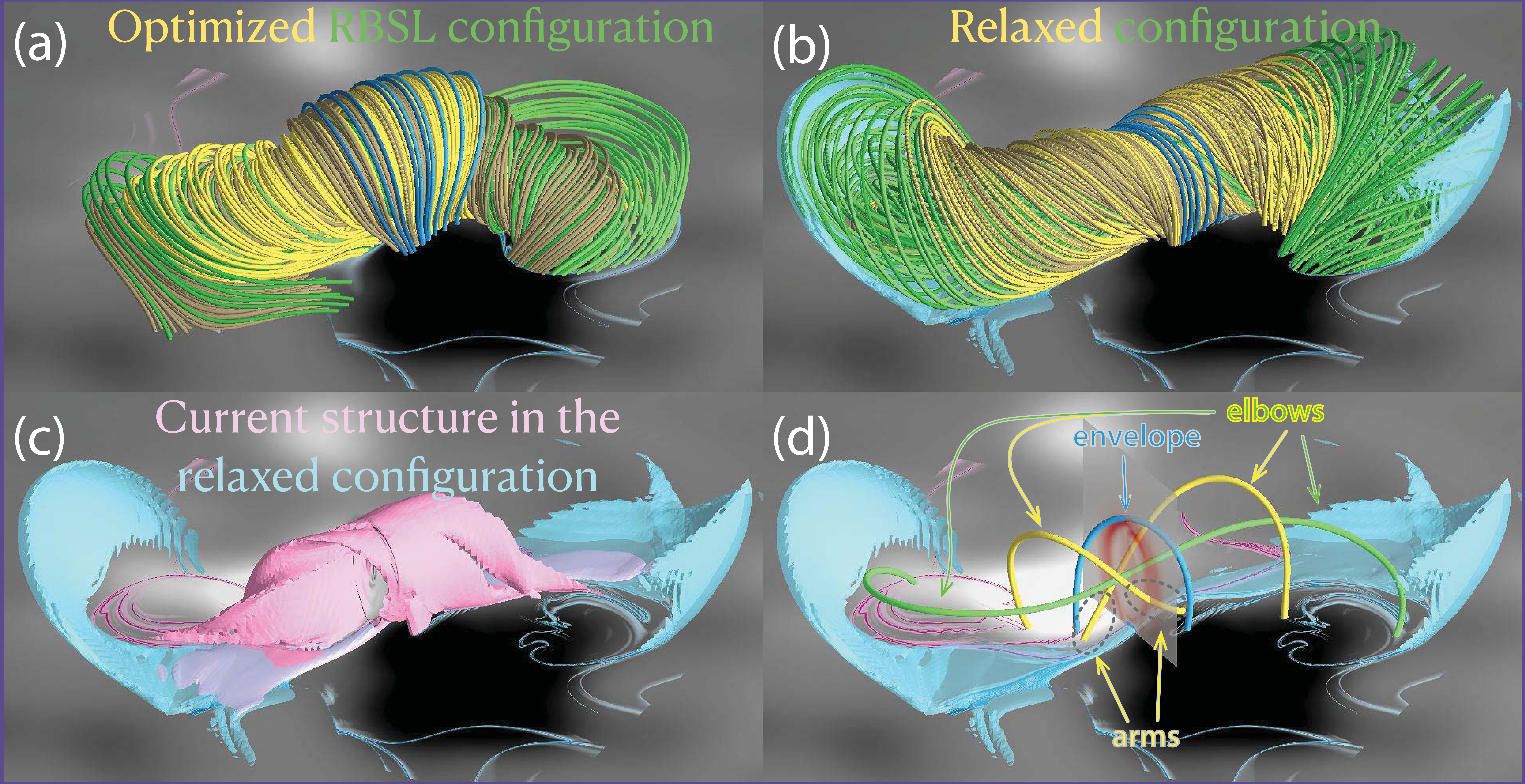
In general, $(\mathbf{B} - \mathbf{B}_{\mathrm{p}})$ is simply a non-potential field with a vanishing radial component at the boundary.

a line-tied pulse of magnetic helicity

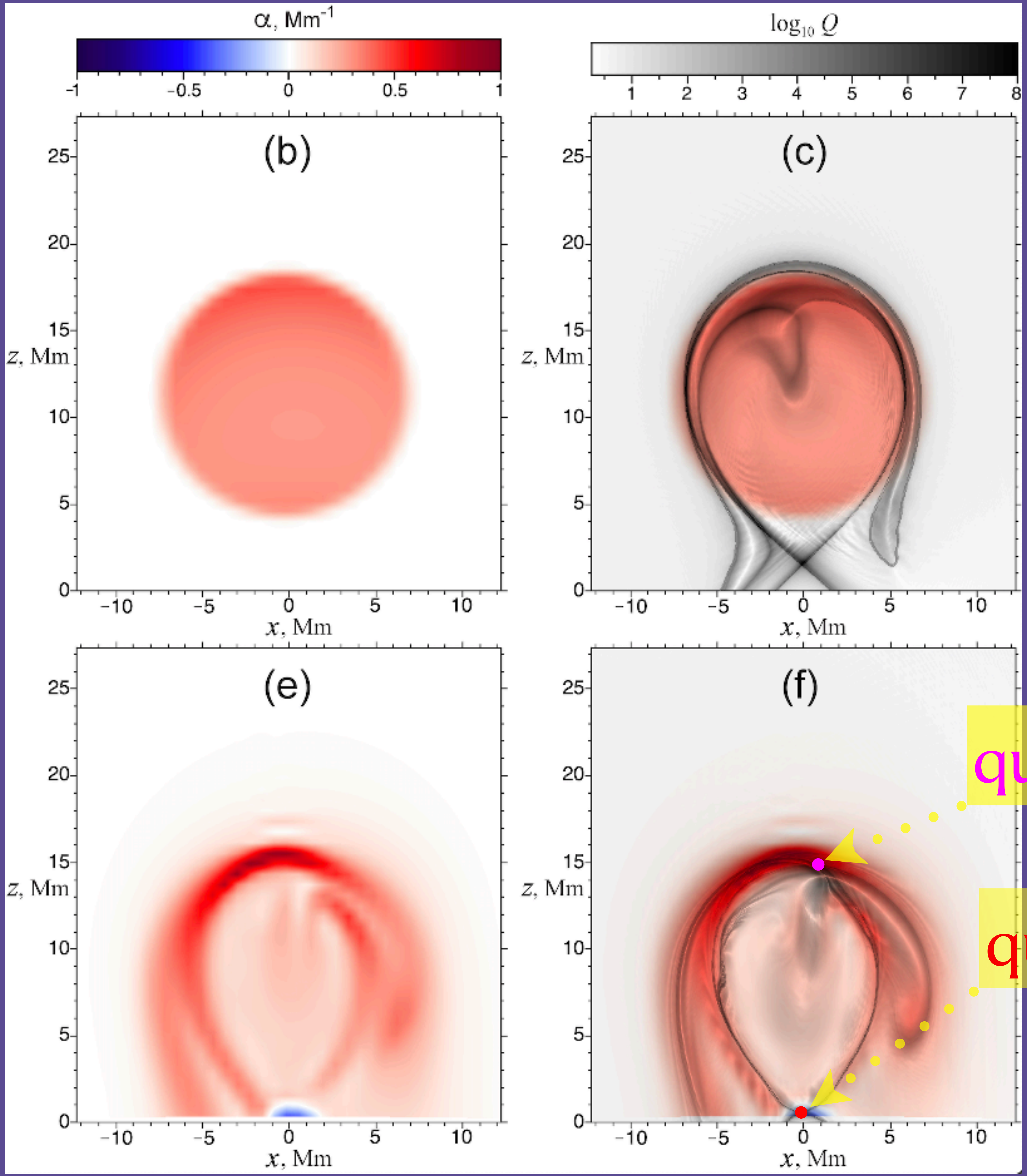
$\varepsilon > 0 \rightarrow$ decreasing strapping field (w.r.t. the rescaled field $\mathbf{B}^*$) $\rightarrow$ loosening tethers

One cycle of pumping =
- **a small line-tied pulse of helicity**
- ⇩
- **a short line-tied relaxation of magnetic stress**

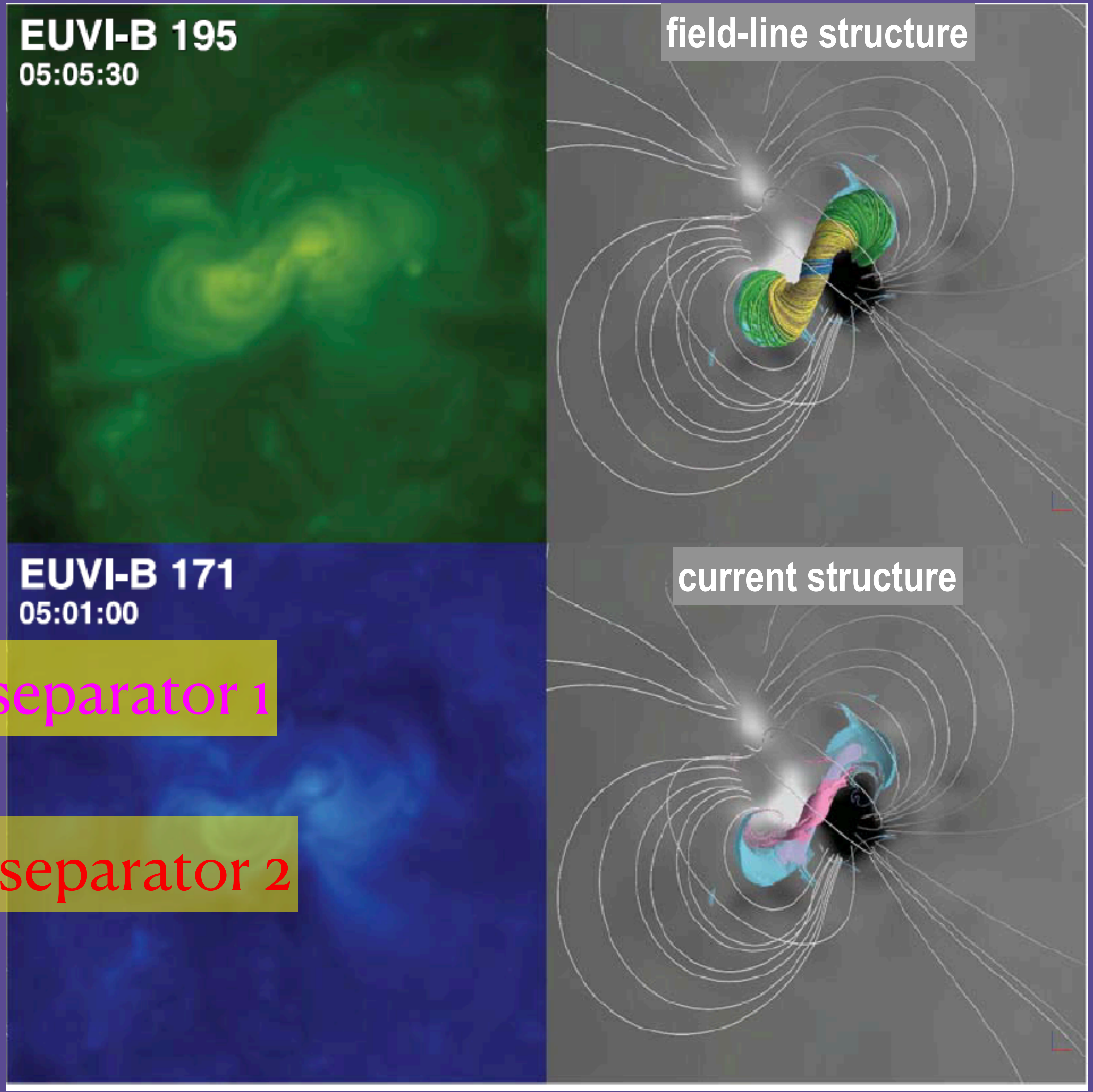
An equilibrium for the 2009 Feb 13 CME event modeled with RBSLs and line-tied zero-β MHD relaxation (Titov et al. 2021)



α- and Q-maps in the central cross-section of the MFR before (b, c) and after (e, f) MHD relaxation



Top view: EUVI images of the sigmoid prior to the eruption versus field-line and current structures

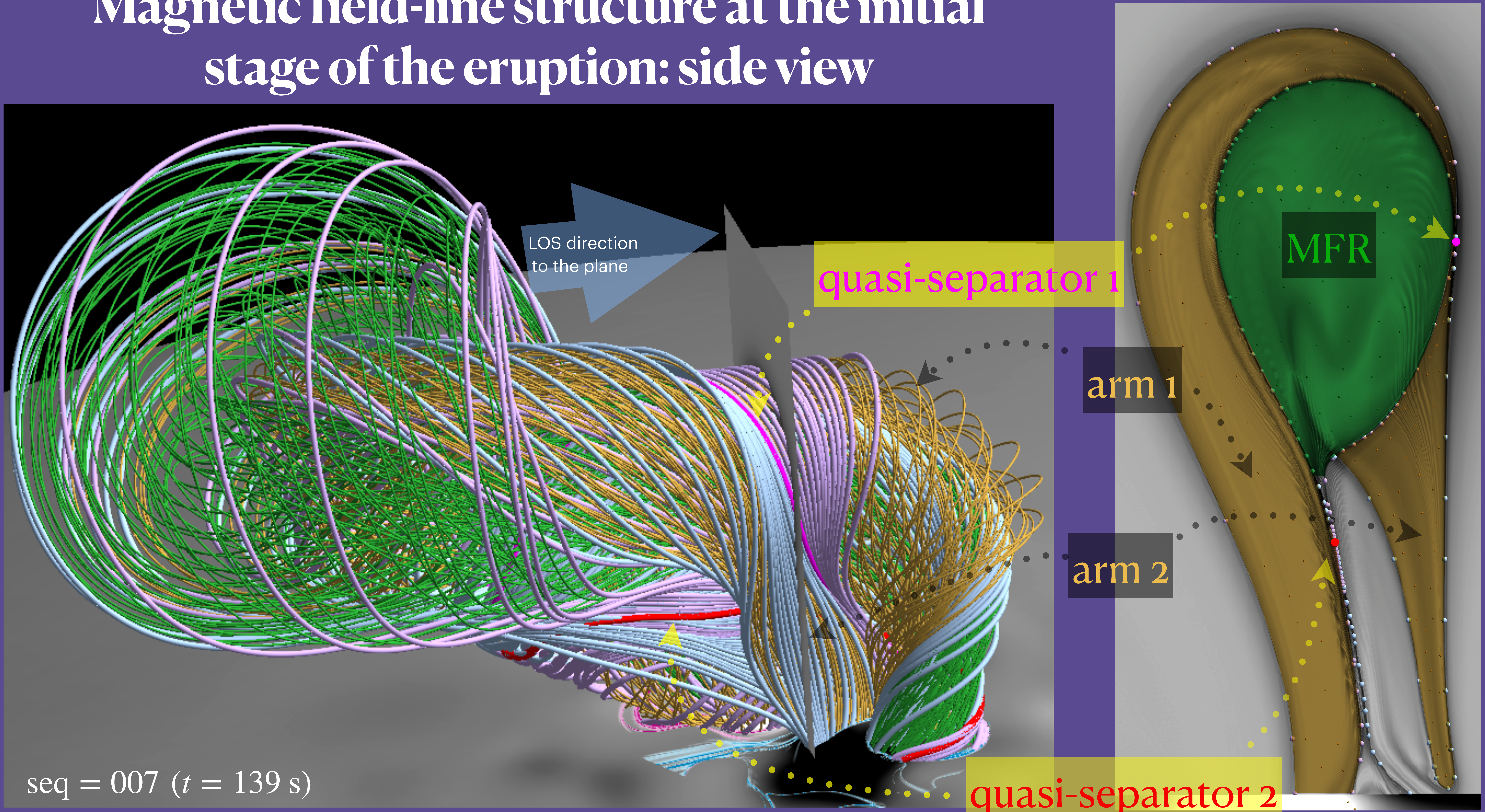


Evolution of α and free magnetic energy W_{free}

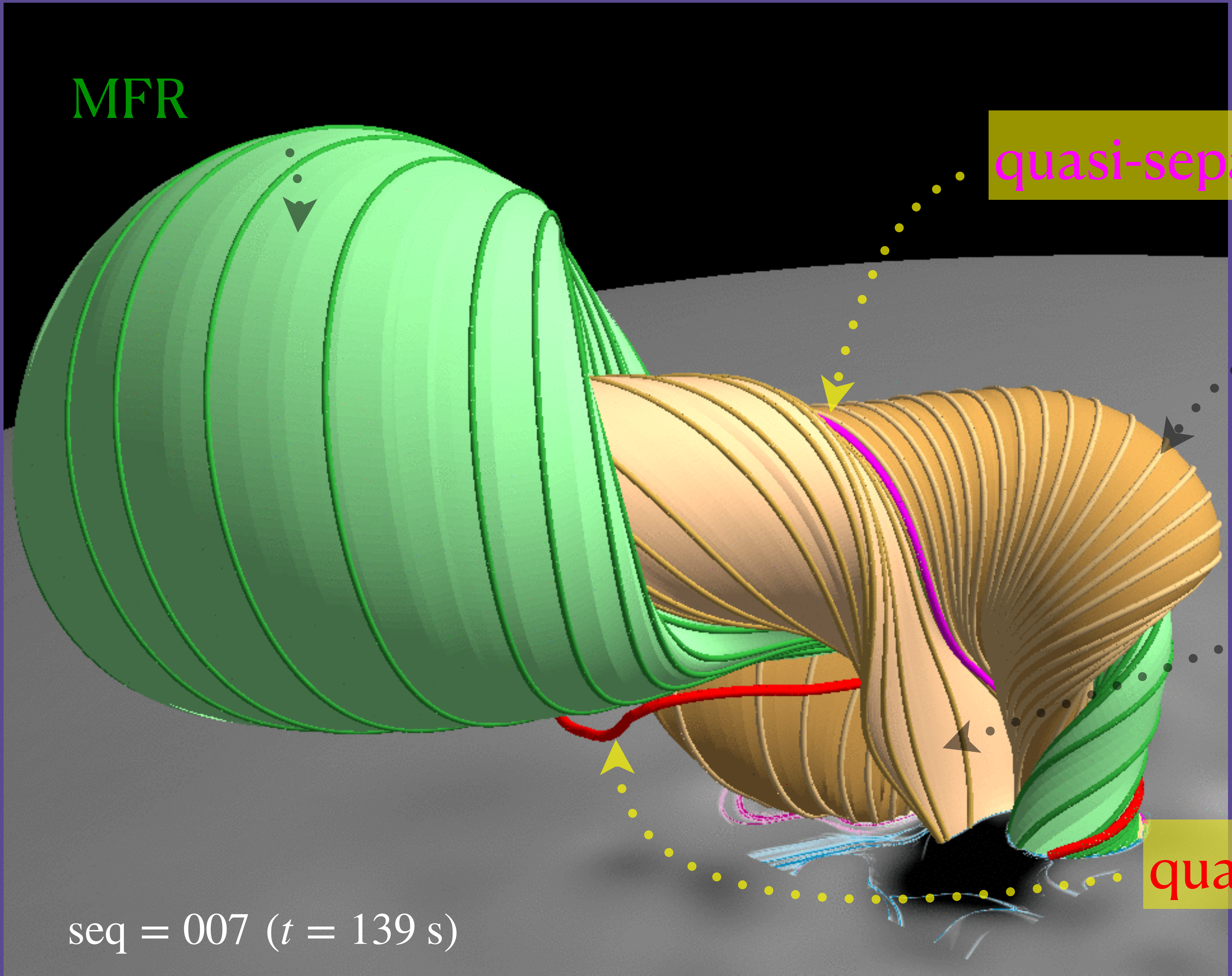
From cycle to cycle,

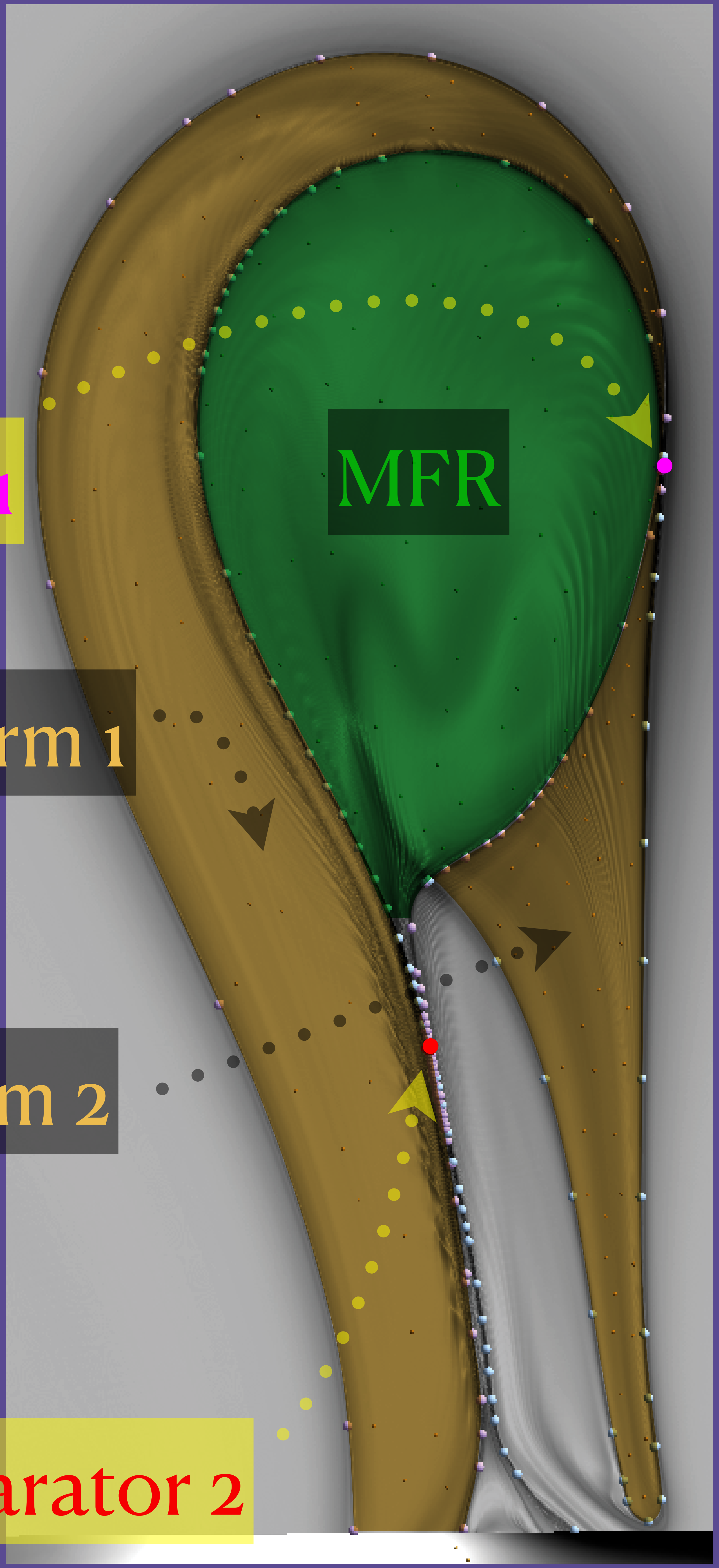
- the structure remains similar;
- it slightly expands;
- it stretches in the vertical direction;
- the boundary layer fades out;
- $\alpha_{\max}$ first decays and then grows.

Magnetic field-line structure at the initial stage of the eruption: side view

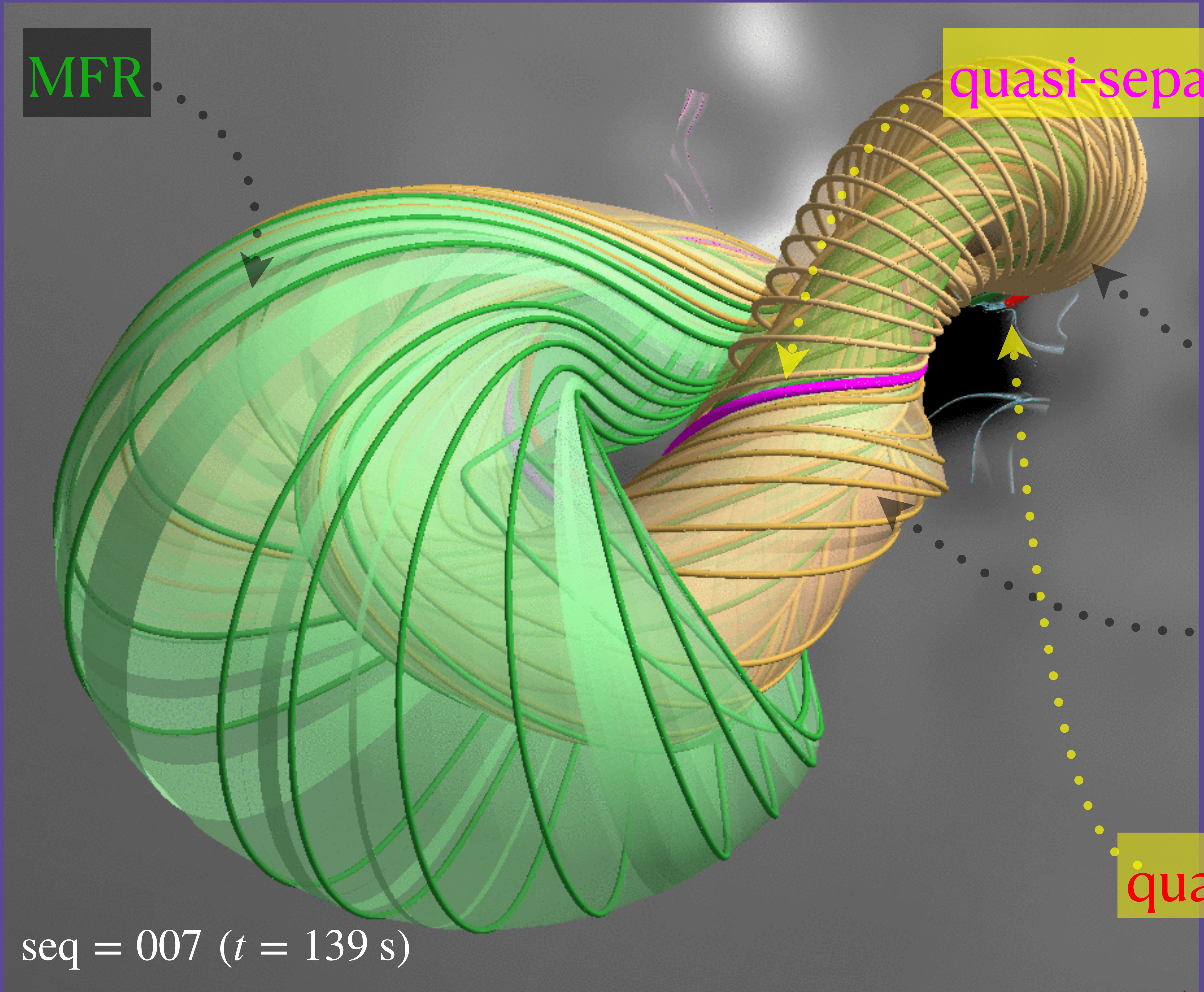


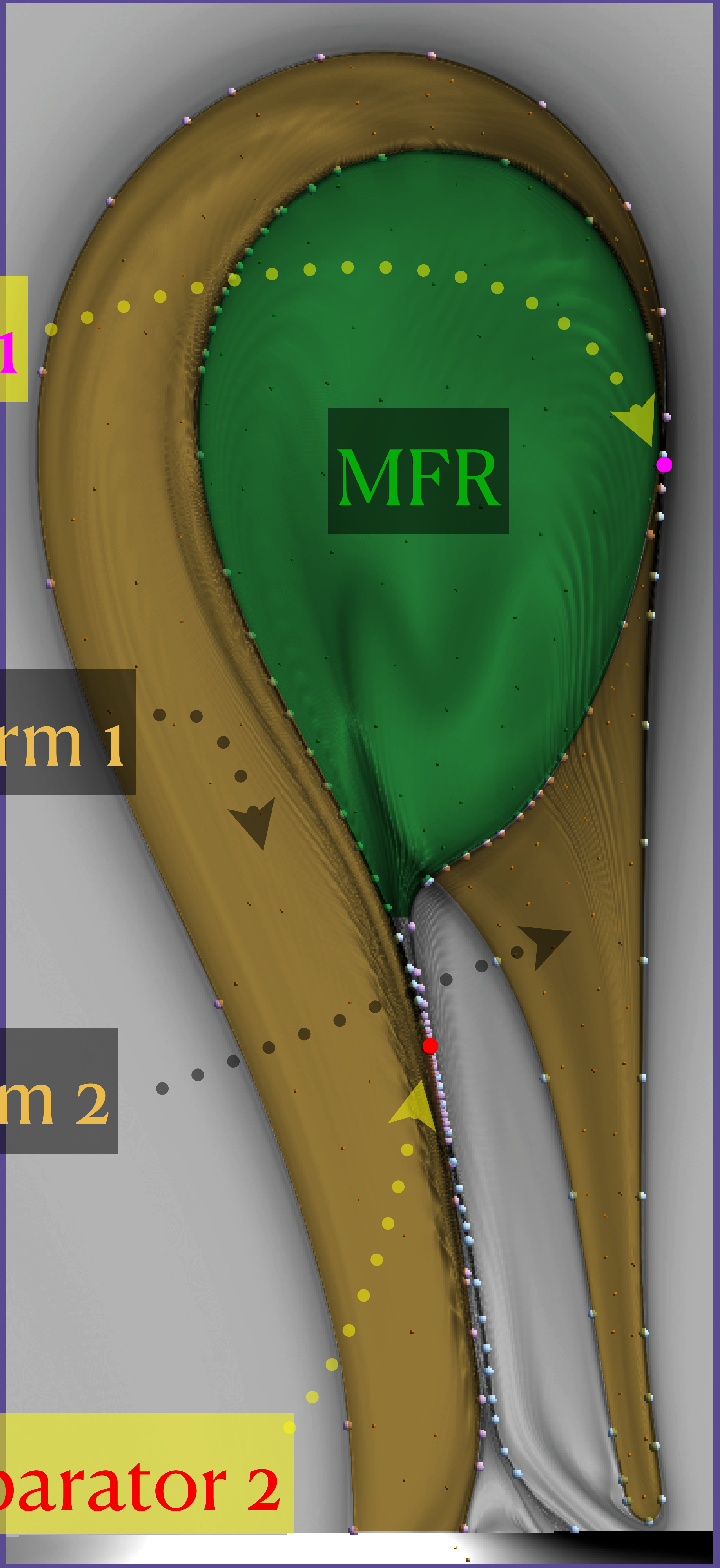
Magnetic surfaces of the building blocks: side view





Magnetic surfaces of the building blocks: top view





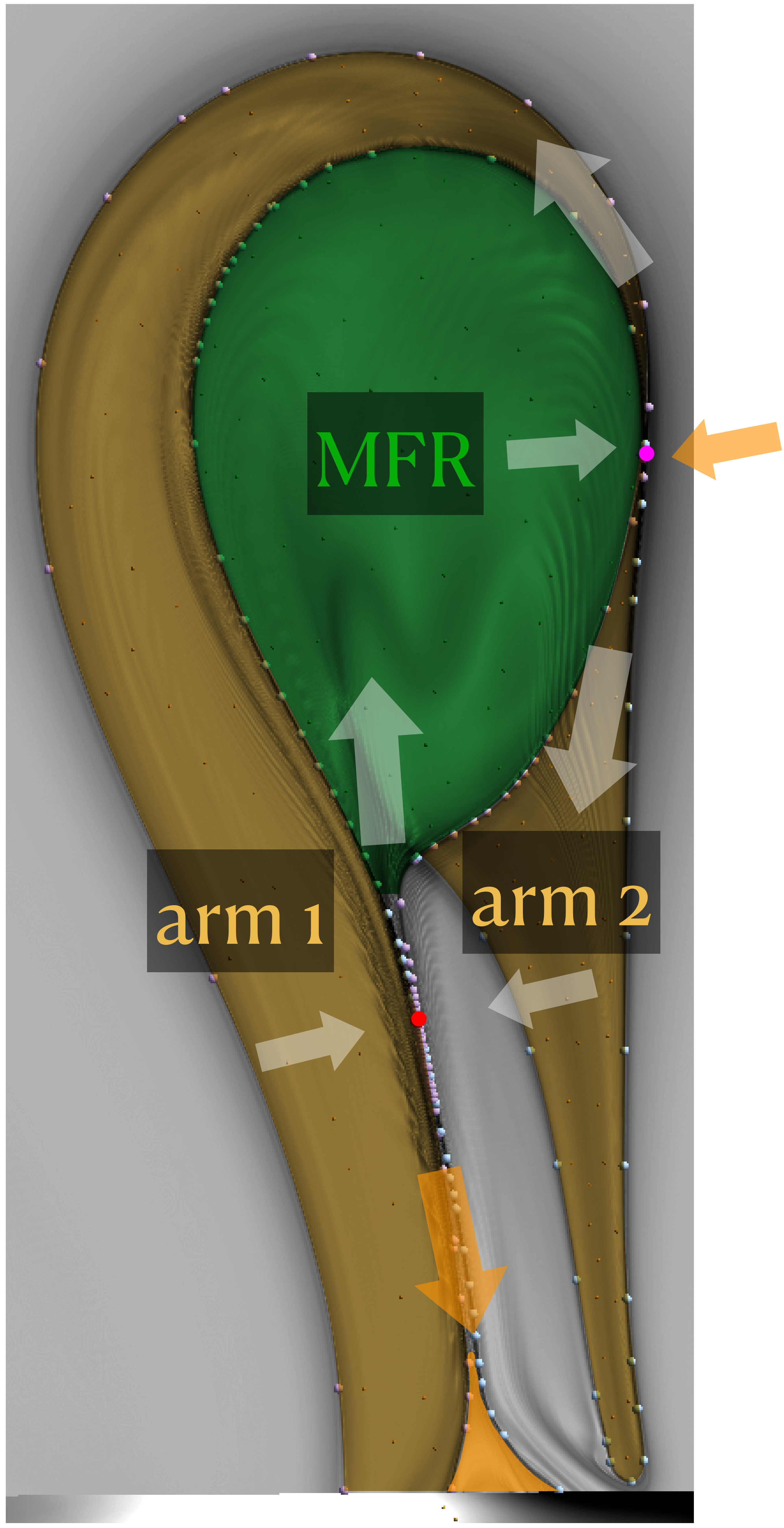
Recirculation of magnetic flux in the erupting structure

The magnetic flux recirculates between the erupting MFR and its "arms" due to the following two reconnection processes:

1. Breakthrough (~ breakout) reconnection 1) acts at the quasi-separator inside the CL that wraps around the MFR, 2) reconnects the MFR and overlying envelope fields and reduces their fluxes, and 3) raises the flux in the "arms".

2. Tether-cutting reconnection 1) acts at the other quasi-separator in the vertical CL below the MFR, 2) merges the "arms" grasping the CL and reduces their fluxes, and 3) raises the flux in the MFR and flaring arcade.

Such a recirculation of the fluxes 1) prevents a destruction of the erupting MFR body at the start of the eruption and 2) makes these reconnection processes work in tandem with each other to propel the erupting MFR through the overlying envelope field.



Summary

- We propose a new method for energizing magnetic equilibria toward an eruption without changing the initial normal magnetic field at the boundary.
- The configuration is energized via a series of cycles, each of which consists of a small pulse of magnetic helicity and a subsequent short MHD relaxation, both made under line-tying boundary conditions.
- The helicity pulse is formed by a suitable rescaling of the non-potential part of the previous cycle's configuration with a strictly tangential field at the boundary.
- Application of our method to a sigmoidal pre-eruptive equilibrium demonstrates its uniqueness, efficiency and importance.
- The magnetic flux of the MFR is sustained at the initial stage of the eruption by breakthrough and tether-cutting reconnections, which provide a recirculation of the flux between the MFR and "arms" embracing it.
- The proposed method will be useful for both modeling realistic CME events and theoretical studies of eruptions in idealized configurations.

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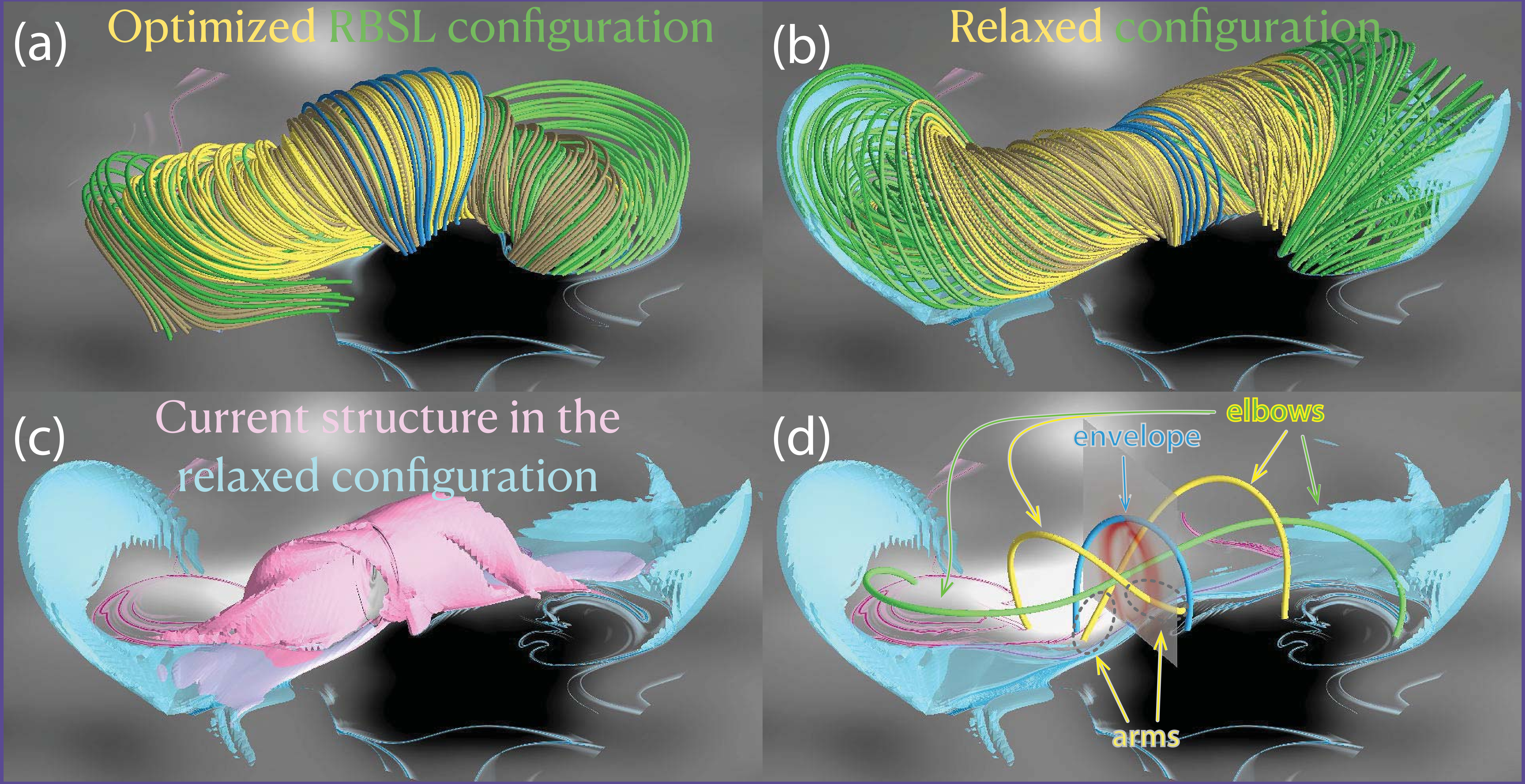

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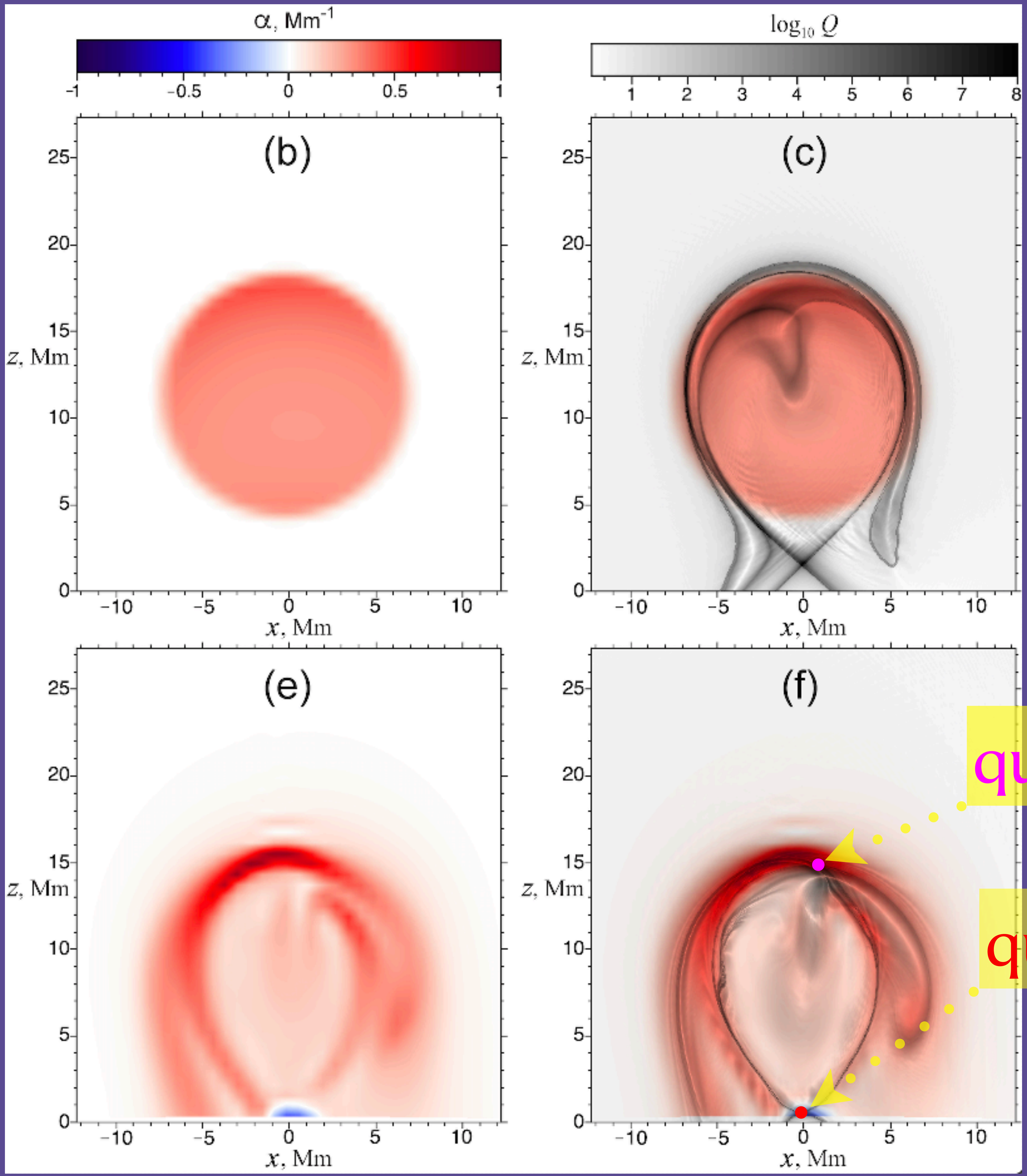

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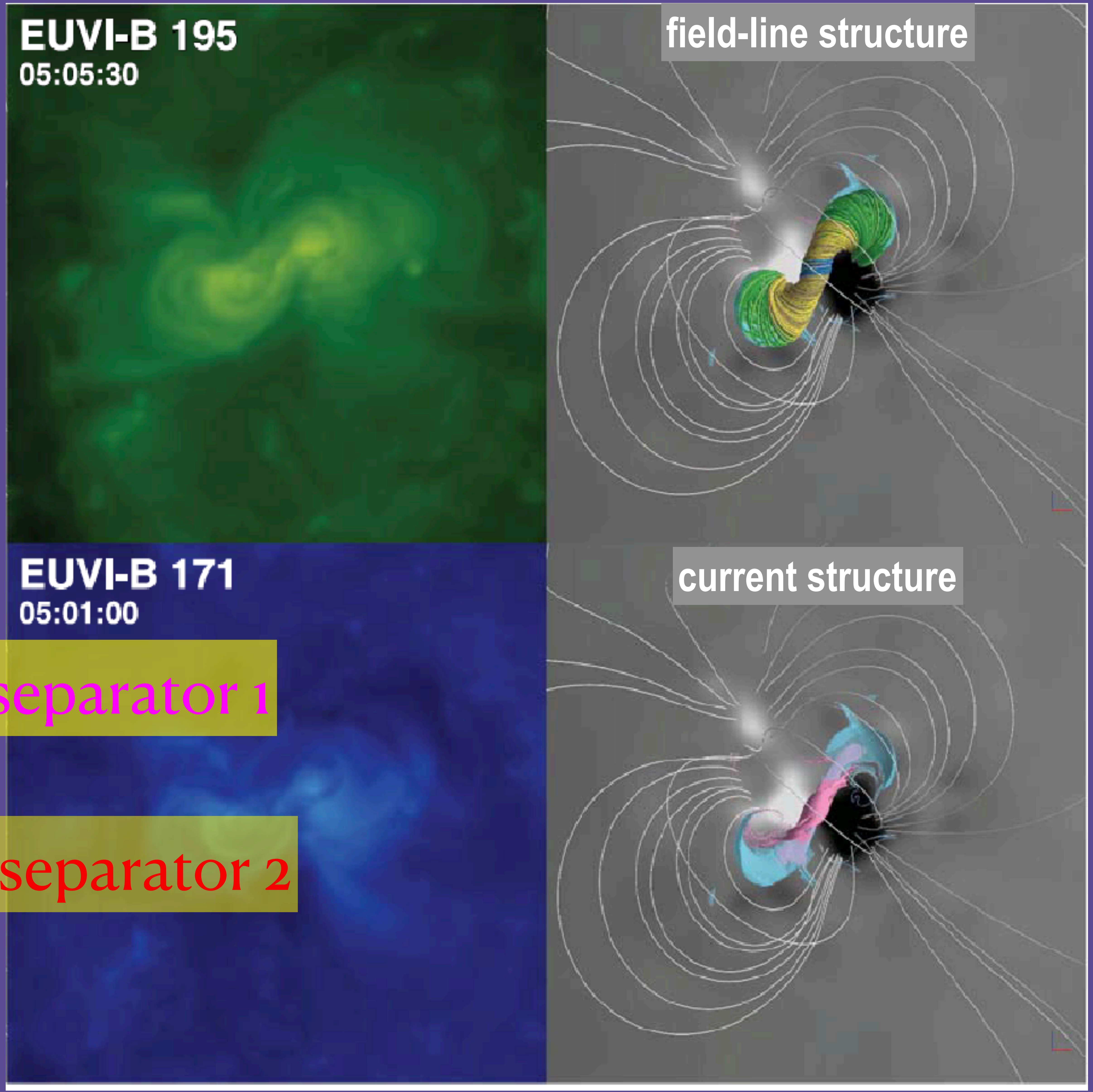

Evolution of α and free magnetic energy W_{free}

$= (\mathbf{B} \cdot \nabla \times \mathbf{B})/B^2$

$C_I = 1.05$

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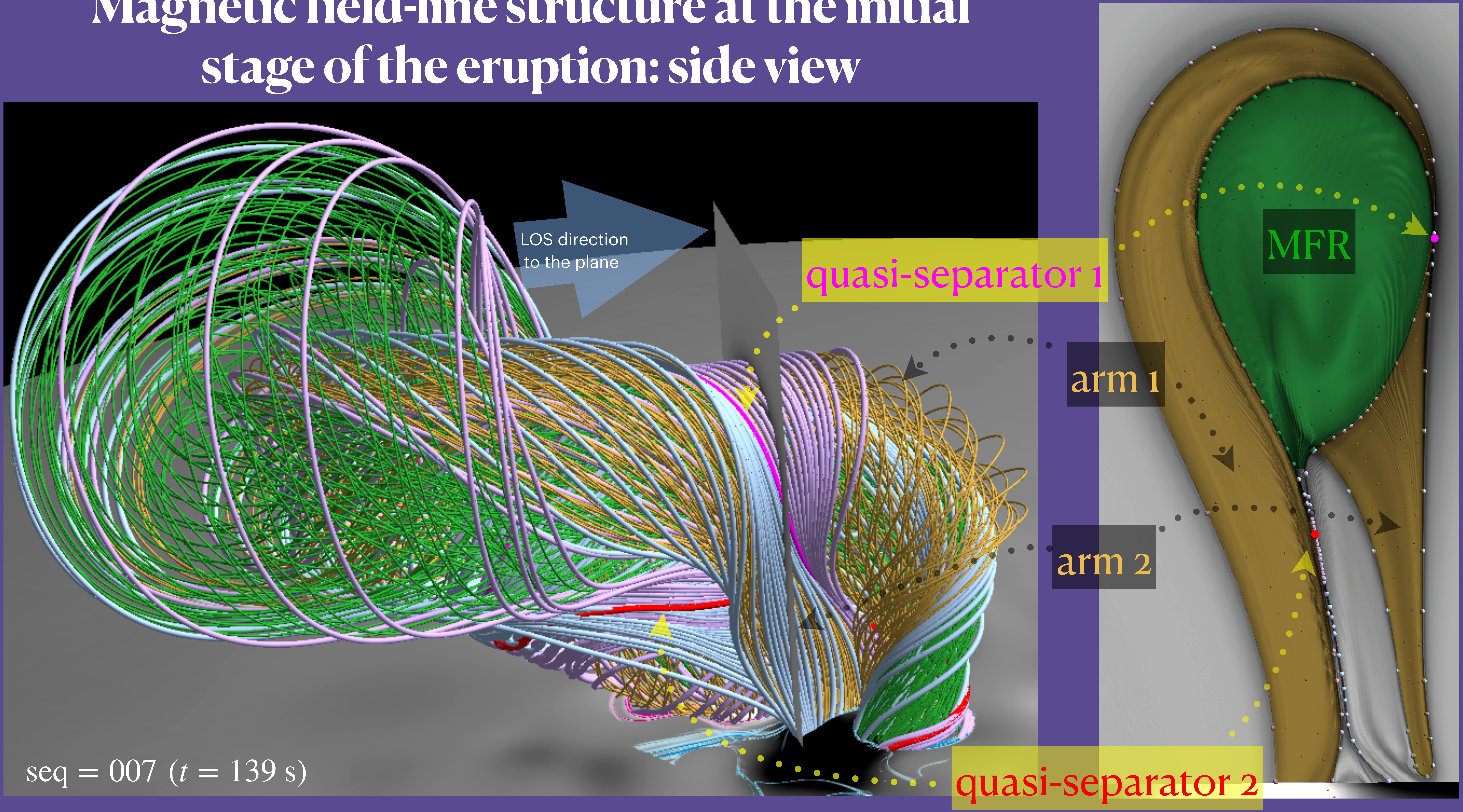

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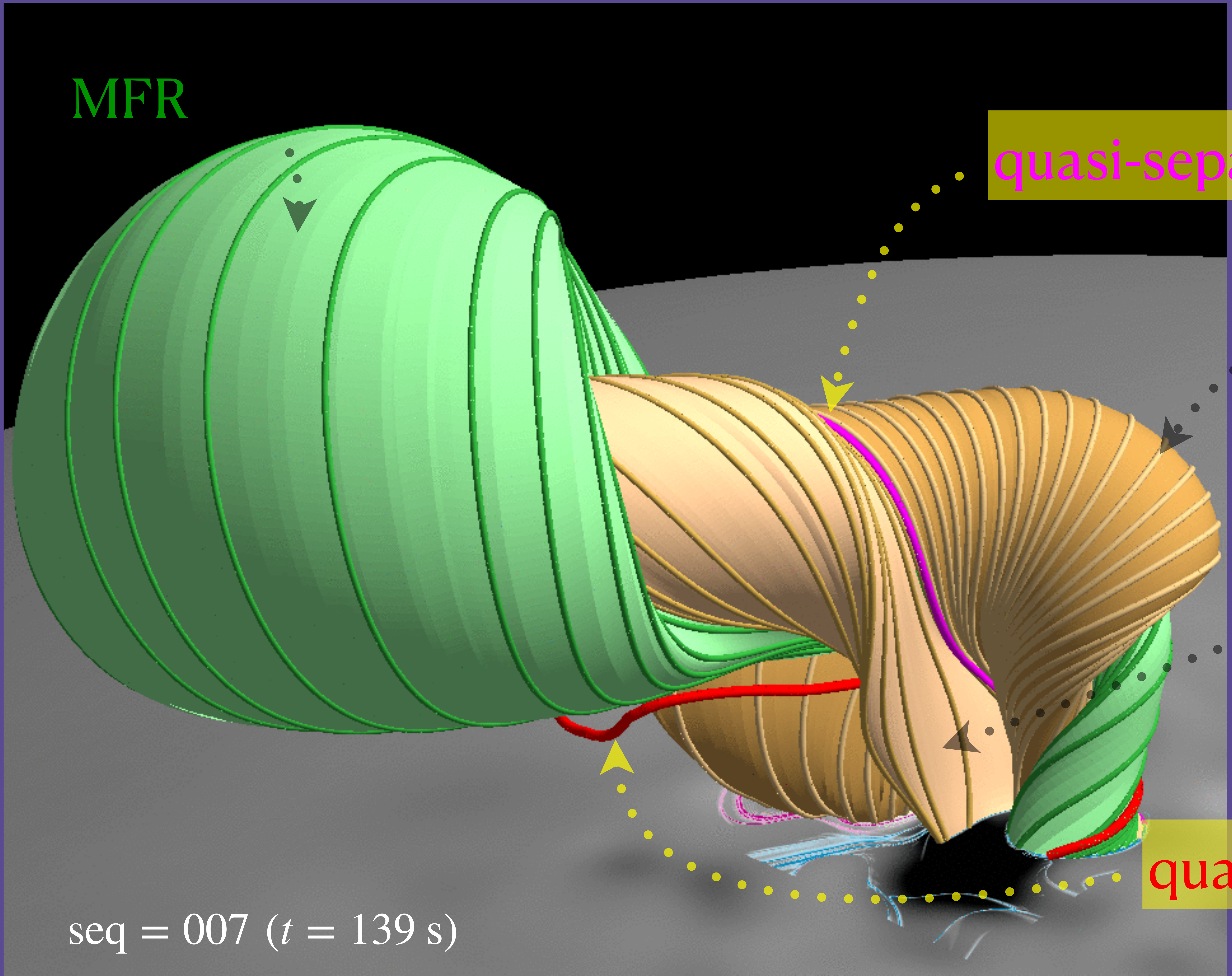

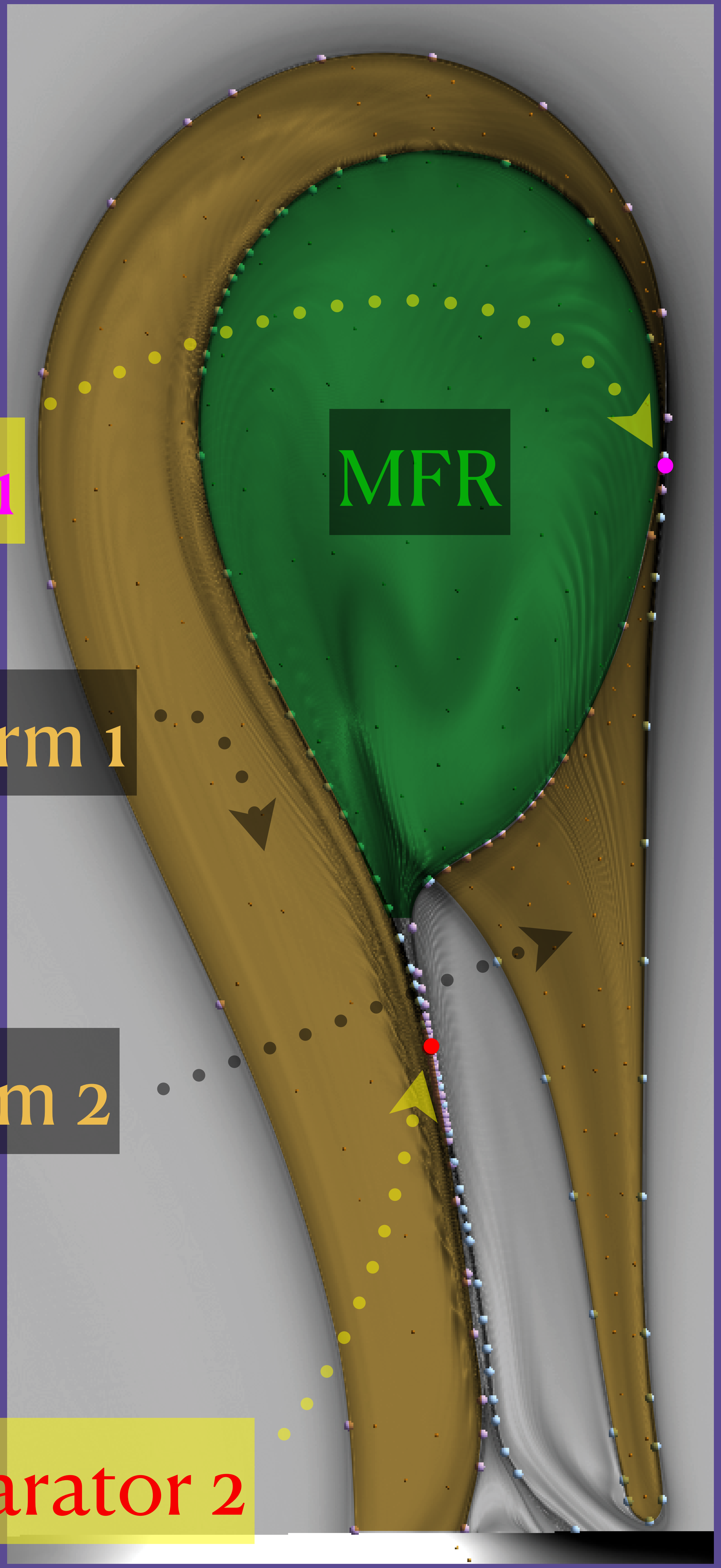

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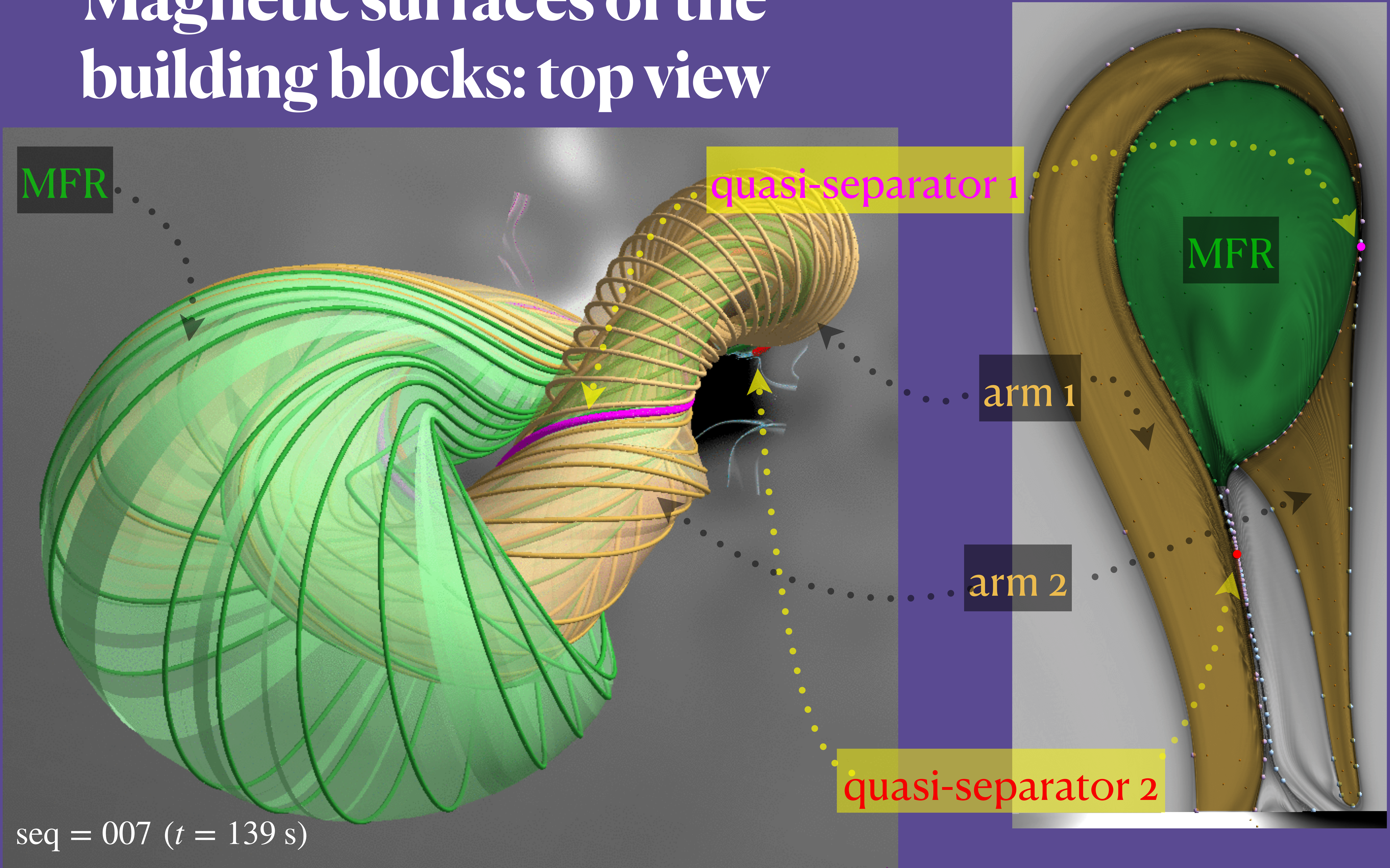

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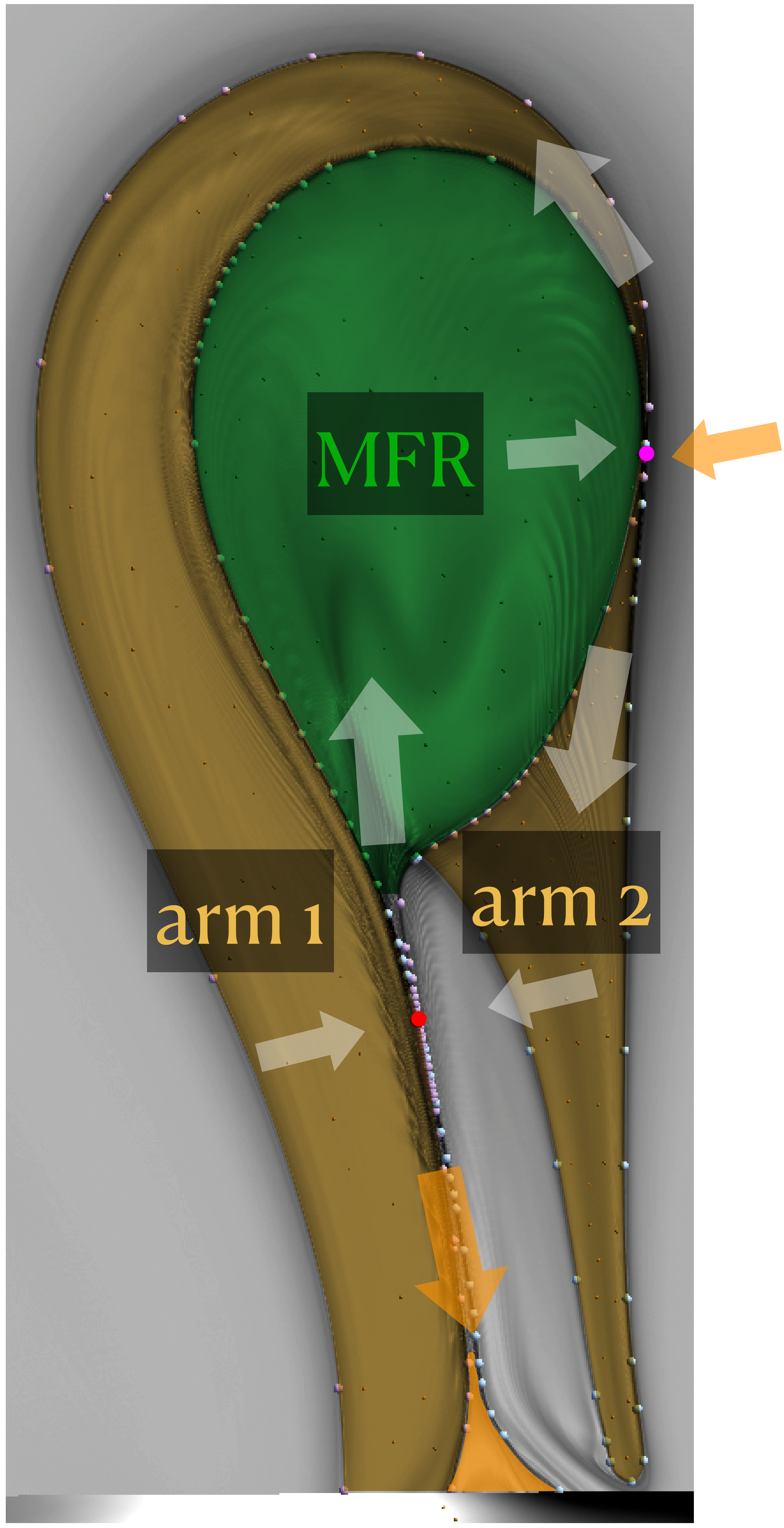

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