



# Skyrmion-skyrmion and skyrmion-edge repulsions in skyrmion-based racetrack memory

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## Skyrmion-based racetrack memory

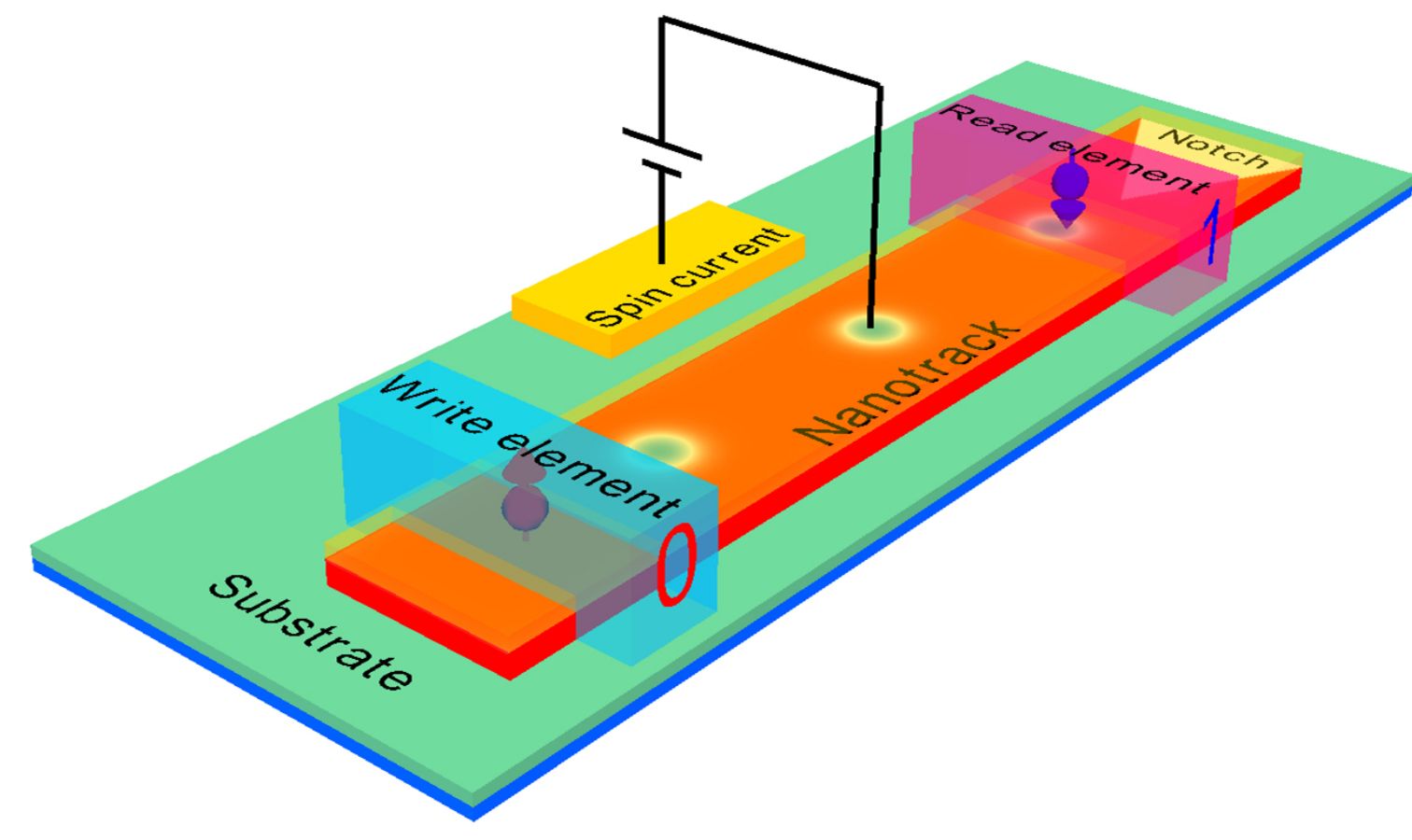


Figure 1. Schematic of typical vertical-current-driven horizontal skyrmion-based racetrack memory.

Skyrmion-based racetrack memory storage device moves the skyrmions along the racetrack in one direction only. The reading element can be positioned at one end of the racetrack. The skyrmions are annihilated upon moving them across the reading element but their corresponding information is read into one or more memory devices (e.g., built-in CMOS circuits).

We study the reliable and practicable spacing between consecutive skyrmionic bits on the racetrack that are driven by vertically injected spin-polarized currents, and demonstrate the ability to adjust that spacing. Skyrmionic bits are found to squeeze together at the end of the racetrack. We therefore propose a technological solution to address this problem and demonstrate that the end of the racetrack can be designed with notch-tip to ensure that the skyrmionic bits moving beyond the reading element can easily exit from the racetrack at low current density ( $\sim 10^{10}$  A/m<sup>2</sup>).

The micromagnetic simulations are performed using the software package OOMMF including the extension module of the Dzyaloshinskii-Moriya interaction (DMI). The motion of skyrmionic bits is simulated in 0.4-nm-thick cobalt racetracks with width of 30 ~ 100 nm and length of 200 ~ 800 nm. The parameters are adopted from Ref. [*Nature Nanotechnology* **8**, 839–844 (2013)].

## Spacing between consecutive skyrmionic bits

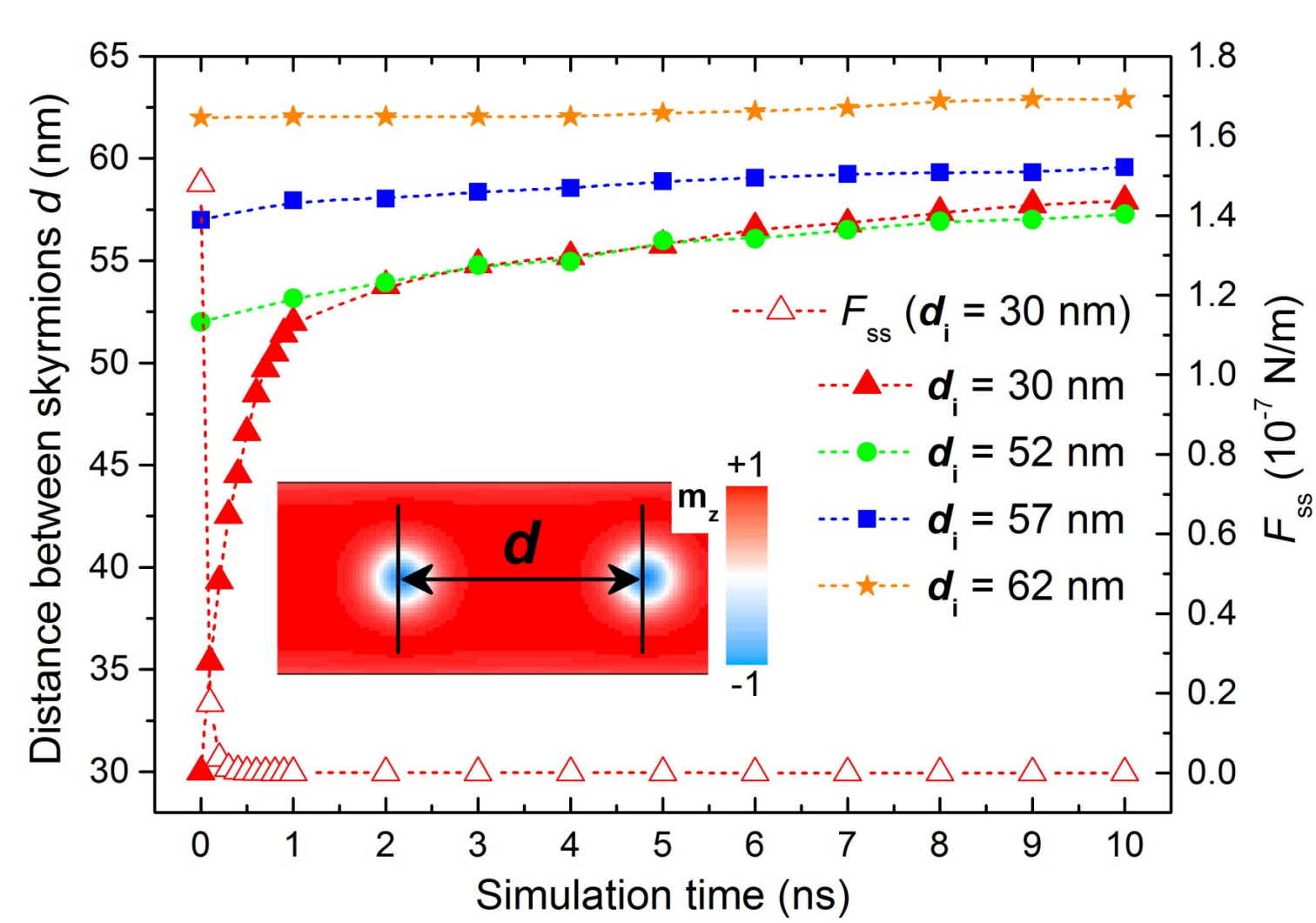


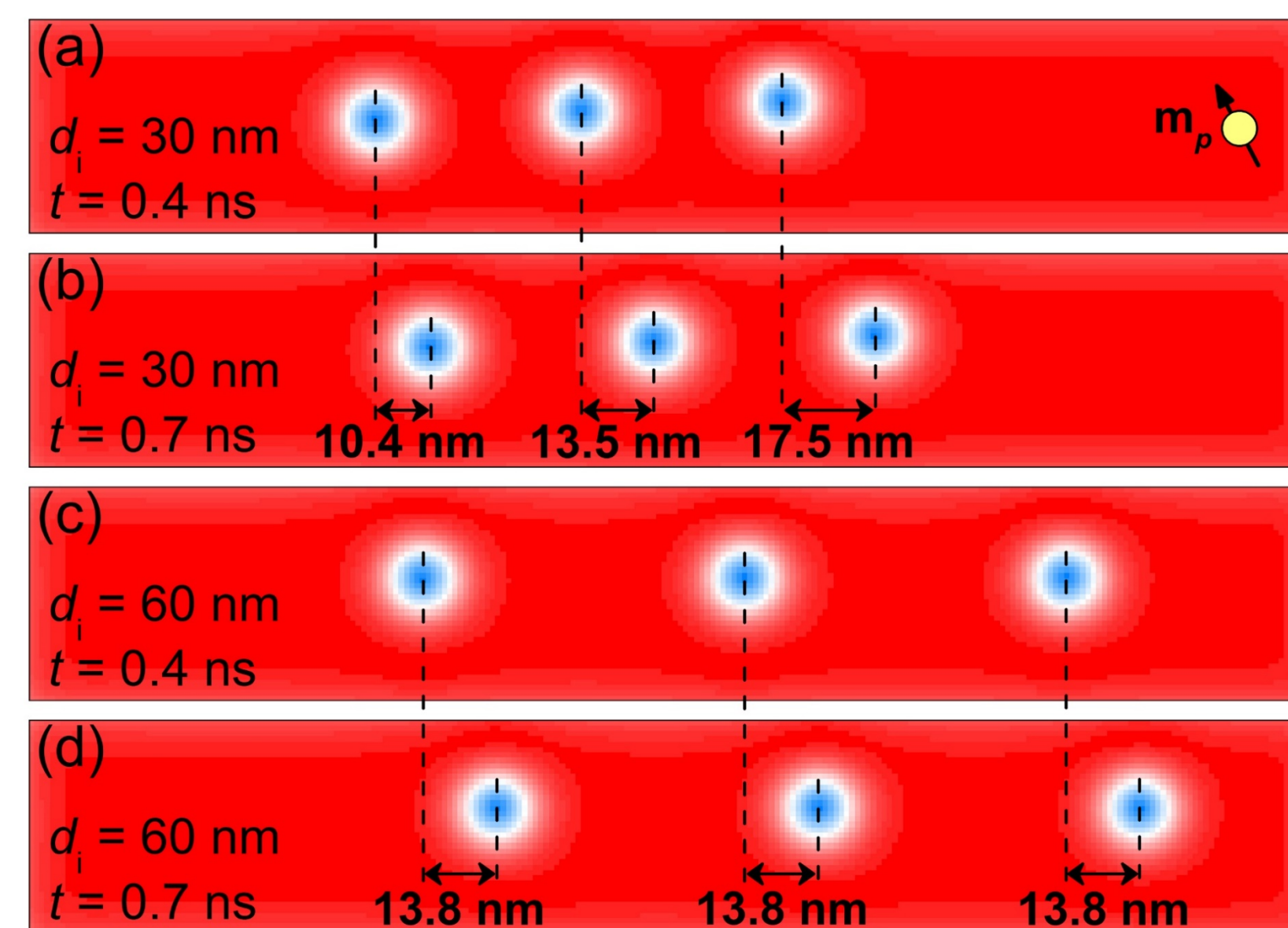
Figure 2. Distance  $d$  and repulsive force  $F_{ss}$  between two skyrmions on the racetrack as functions of the simulation time.

As the initial spacing  $d_i$  is small, the skyrmions separation distance  $d$  increases rapidly due to the repulsion between the skyrmions. At the same time, the size of skyrmion  $r_s$  increases.

For  $d_i > L_D$  ( $4\pi A/|D|$ ),  $d$  keeps a nearly constant due to the exponentially decaying interaction between skyrmions, which means that  $L_D$  would be an ideal initial spacing for writing consecutive skyrmion bits.

$d_i$ : the initial spacing between the two skyrmions  
 $F_{ss}$ : the repulsive force between two skyrmions

## Motion of skyrmionic bit chain



For  $d_i = 30$  nm, the spacing increases to  $d_e$  due to the skyrmion-skyrmion repulsion, leading to the different velocities. From  $t = 0.4$  ns to  $t = 0.7$  ns, the right skyrmionic bit moves 17.5 nm ( $v = 58$  m/s) while the left skyrmionic bit only moves 10.4 nm ( $v = 35$  m/s).

For  $d_i = 60$  nm, as shown in Fig. 5 c-d, within the same time frame, both skyrmionic bits move 13.8 nm with a steady velocity of 46 m/s.

Figure 5. Vertical-current-driven motion of a skyrmionic bit chain with initial spacing of 30 nm on the 40-nm-wide racetrack at (a)  $t = 0.4$  ns, (b)  $t = 0.7$  ns, and motion of a chain with initial spacing of 60 nm at (c)  $t = 0.4$  ns, (d)  $t = 0.7$  ns.

## Spacing versus applied field, anisotropy and racetrack width

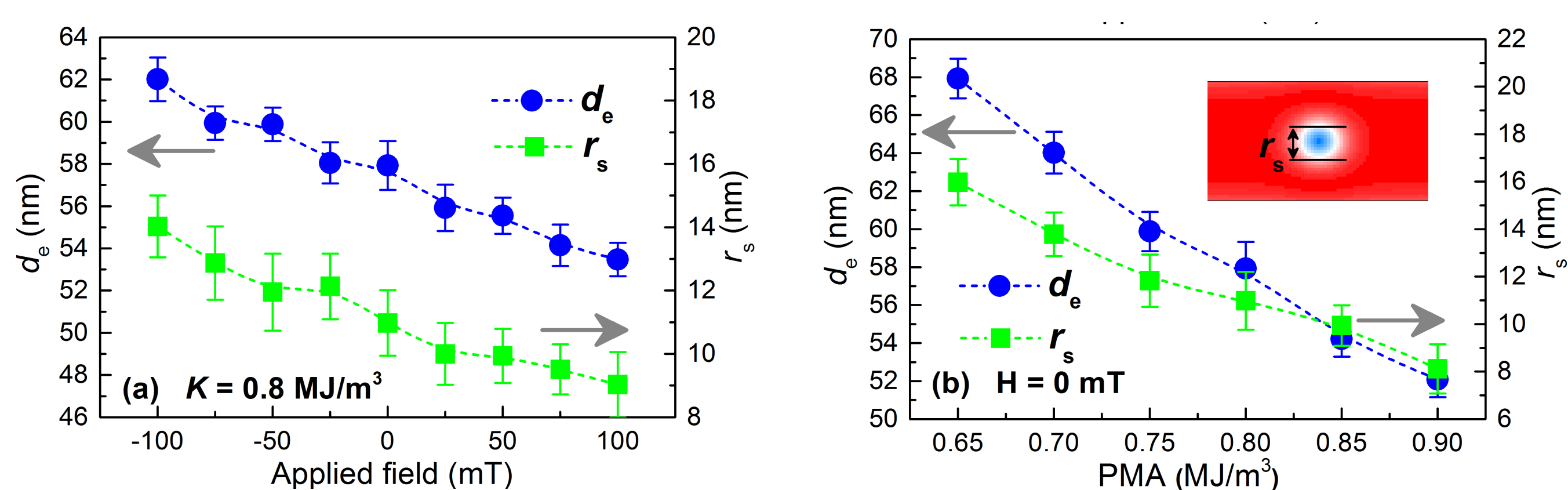


Figure 3. Effect of different (a) applied fields and (b) perpendicular magnetic anisotropies (PMA) on the equilibrium spacing  $d_e$  between consecutive skyrmions and equilibrium skyrmion size  $r_s$  on 40-nm-wide racetrack.

Applied field perpendicular to the plane and opposite to the direction of the magnetization in the core of skyrmions (i.e. positive values) can marginally reduce the relaxed skyrmion size  $r_s$  as well as the equilibrium skyrmion distance  $d_e$ .

$d_e$  and relaxed  $r_s$  decrease approximately linearly with increasing PMA.

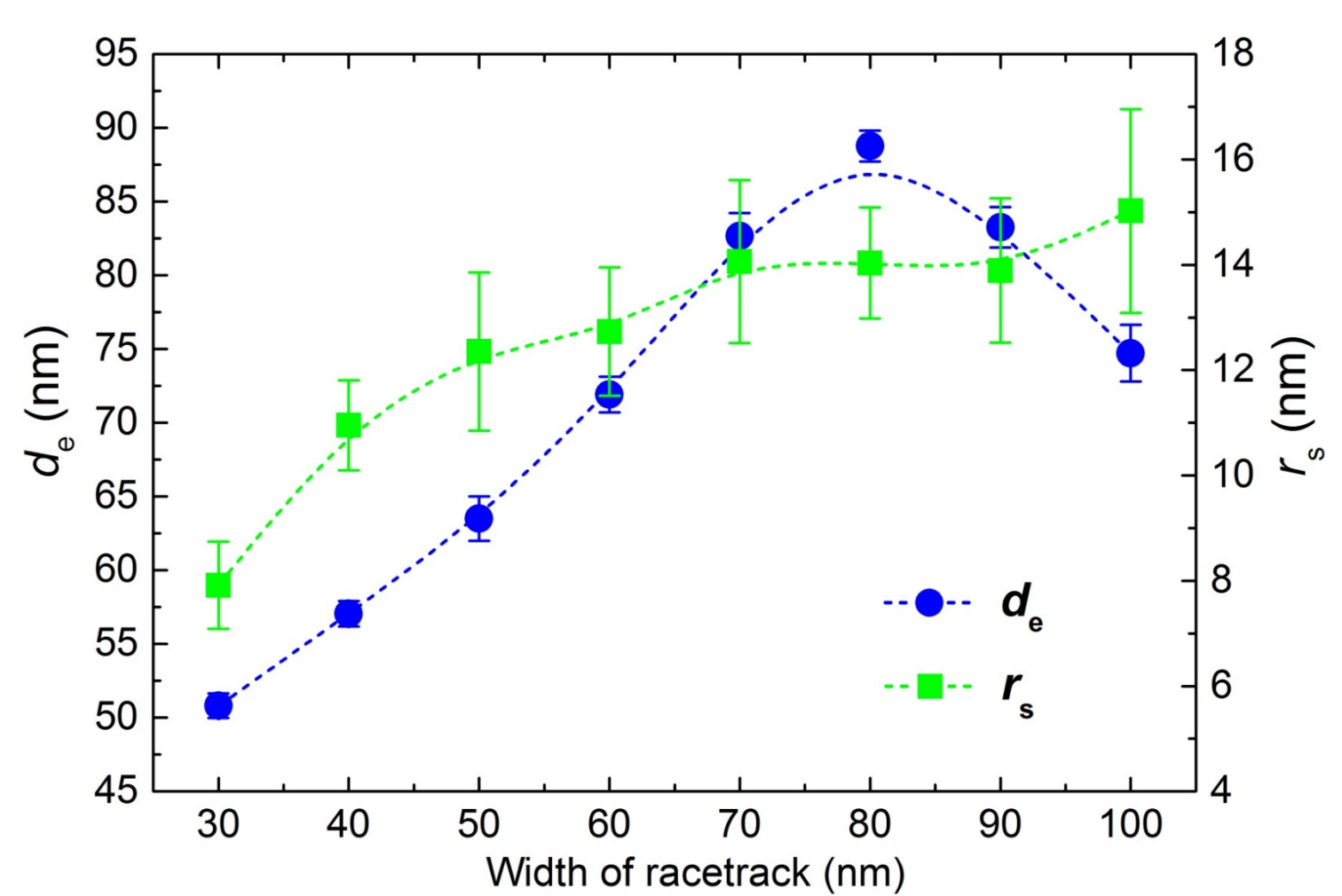


Figure 4. Skyrmion size  $r_s$  and equilibrium spacing between consecutive bits  $d_e$  as a function of racetrack width.

$d_e$  rapidly goes up from  $\sim 50$  nm to  $\sim 90$  nm with the width increasing from 30 nm to 80 nm, then decreases to 75 nm when the width continually increases to 100 nm.

When the width of the racetrack is smaller than a certain threshold ( $\sim 20$  nm in our simulation), the skyrmionic bits are not stable on the racetrack, which may quickly evolve to domain walls.

## Elimination of skyrmionic bits

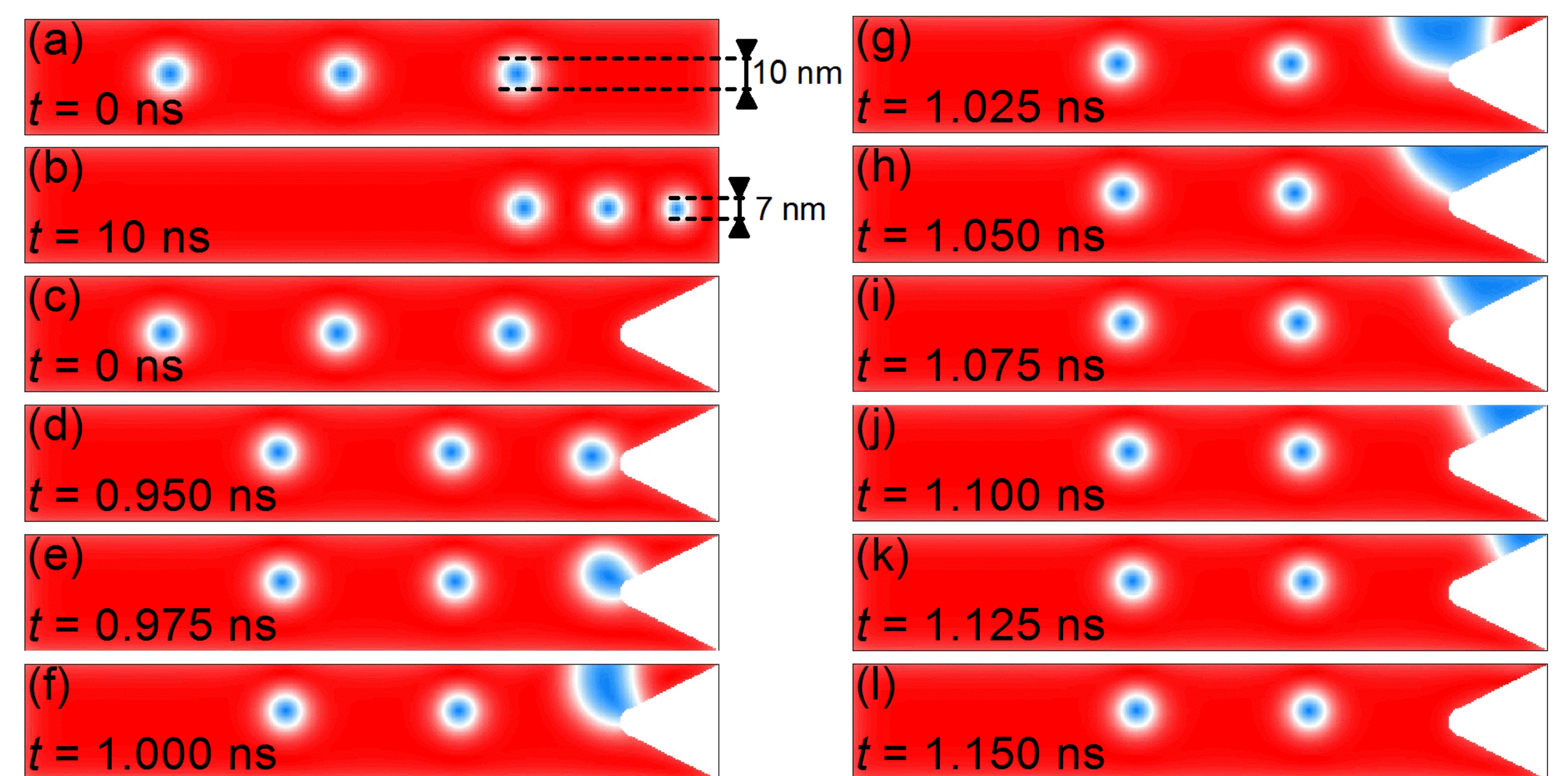


Figure 6. Vertical-current-driven motion of a skyrmionic bit chain at the end of the racetrack

For the racetrack without any notch (Fig. 6 a-b), the skyrmionic bit chain gets clogged at the end of the racetrack and the size of skyrmions will reduce, which is caused by the repulsions between skyrmions and edges as well as the repulsions between skyrmions and skyrmions. Figure 6 d-l show the process of the annihilation of a skyrmion within 0.2 ns, where the skyrmionic bit is firstly attracted by the tilts of magnetization around the notch-tip, then evolves to a domain wall pair when touching the notch edge and is eventually cleared away by the currents. In this process ( $j = \sim 10^{10}$  A/m<sup>2</sup>), the skyrmionic bit chain is not compressed at the end of the racetrack, in which all skyrmions move together coherently.

## Conclusion

The reliable and practicable spacing between consecutive skyrmionic bits on skyrmion-based racetrack memory has been studied, which is important for the writing process, reading process and storage density. We have tested that the reliable and practicable spacing can be adjusted in a limited range by tuning the perpendicular anisotropy and/or applying an external magnetic field perpendicular to the racetrack plane. We conclude that the notch-tip is a practical way to assist skyrmionic bits moving beyond the reading element to exit from the racetrack easily. Our results are relevant to the fundamental understanding of magnetic skyrmions, and more practically, to the application of magnetic skyrmions in memory technology.

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## How to cite this work

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