Quadratic to linear magnetoresistance crossover and magneto-plasmons in graphene

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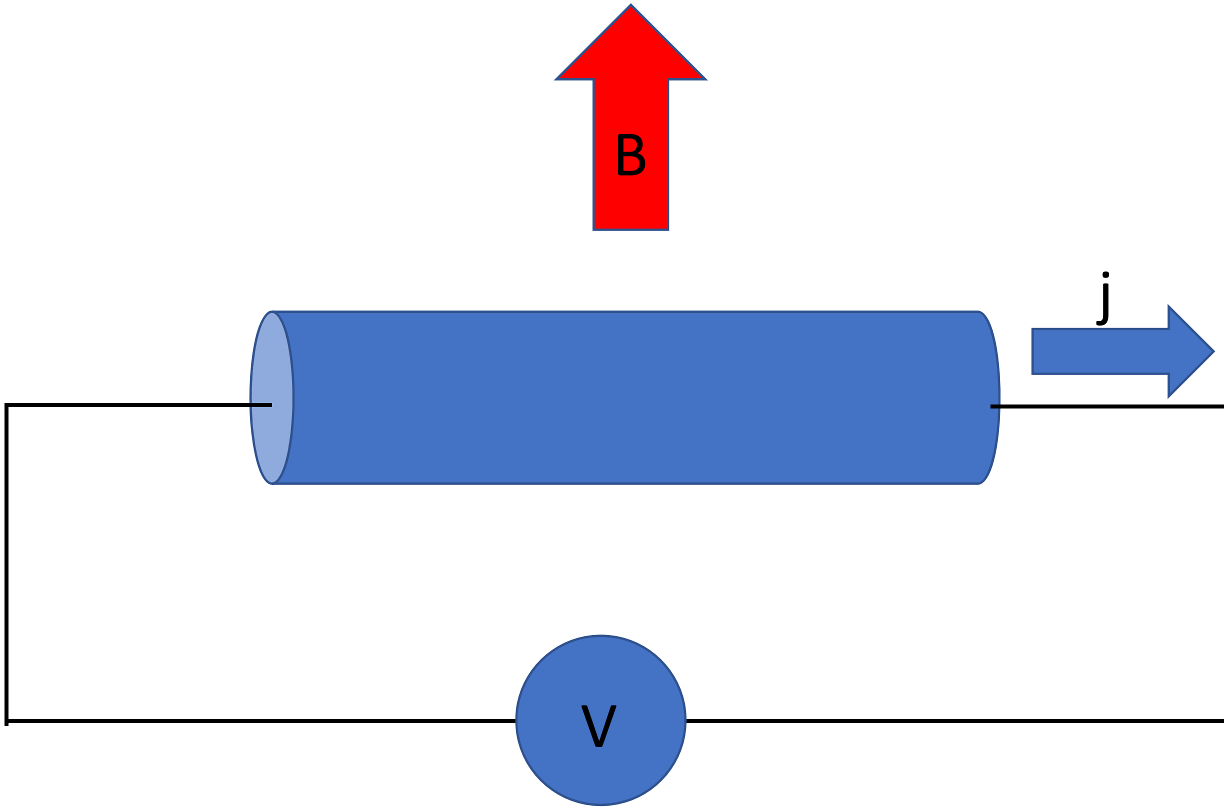
Problem statement



R=V/I

R(B)=?

Experimental evidence

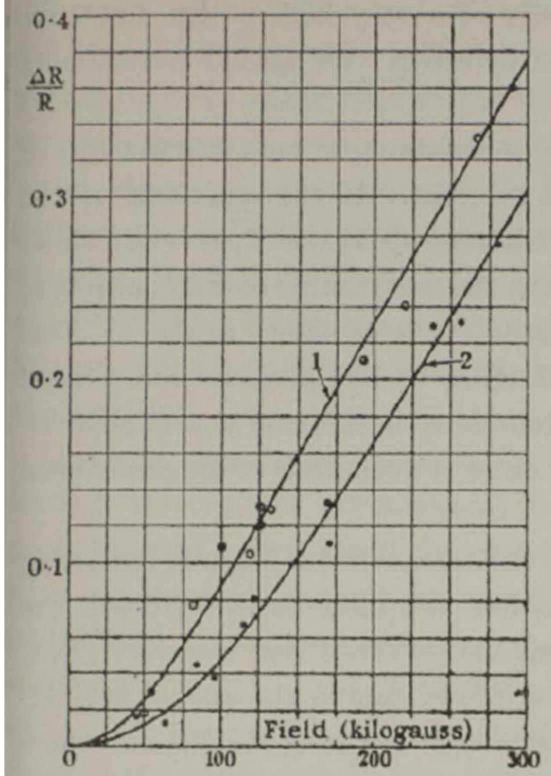


Fig. 6.—Silver H ⊥ I.

Curve I—Ag annealed. Temperature of Liquid Nitrogen.

Curve 2—Ag hard. Temperature of Liquid Air.

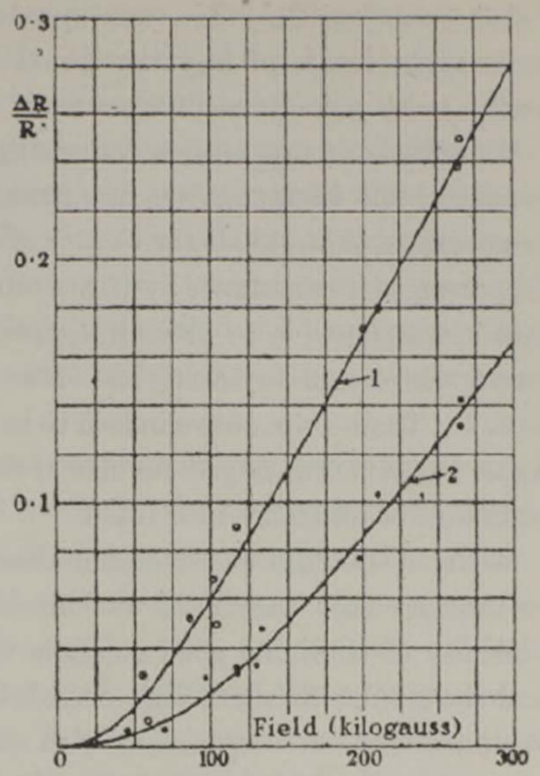


Fig. 7.—Gold H ⊥ I.

Curve 1—Au_I soft. Temperature of Liquid Nitrogen.

Curve 2—Au_{II} hard. Temperature of Liquid Air.

$$\frac{\Delta R}{R} = \beta \frac{H^2}{3H_k} \qquad H \leqslant H_k,$$

$$\frac{\Delta R}{R} = \beta \left(H - H_k + \frac{H_k^2}{3H}\right) \qquad H \geqslant H_k.$$

(2) The change of resistance in a transverse field at room temperature, at temperature of solid CO_2 and ether and at the temperature of liquid nitrogen has been studied in the following metals: Li, Na, Cu, Ag, Au, Be, Mg, Zn, Cd, Hg, Al, Ga, In, Tl, C, Ti, Ge, Zr, Sn, Pb, Th, V, As, Sb, Bi, Ta, Cr, Mo, Te, W, Mn, Fe, Ni, Pd, Pt; in a gold-silver alloy and in Cu_3As.

(4) It was found that in all the metals the change of resistance follows the same law which can be expressed by a formula which fits the experimental results quite well. This formula gives a square law in weak fields and a linear law in stronger fields.

(5) It has been shown that the physical change produced in a conductor by hardening and annealing has a strong influence on the phenomenon of change of resistance.

(6) The influence of the impurities is also very marked and was studied.

Kapitza P. and Rutherford Ernest. The change of electrical conductivity in strong magnetic fields. Part I. - Experimental results. 123. Proc. R. Soc. Lond. A (**1929**)

Patterson, Phil. Mag., vol. 3, p. 642 (**1902**)

Disagreement with Boltzman kinetic theory

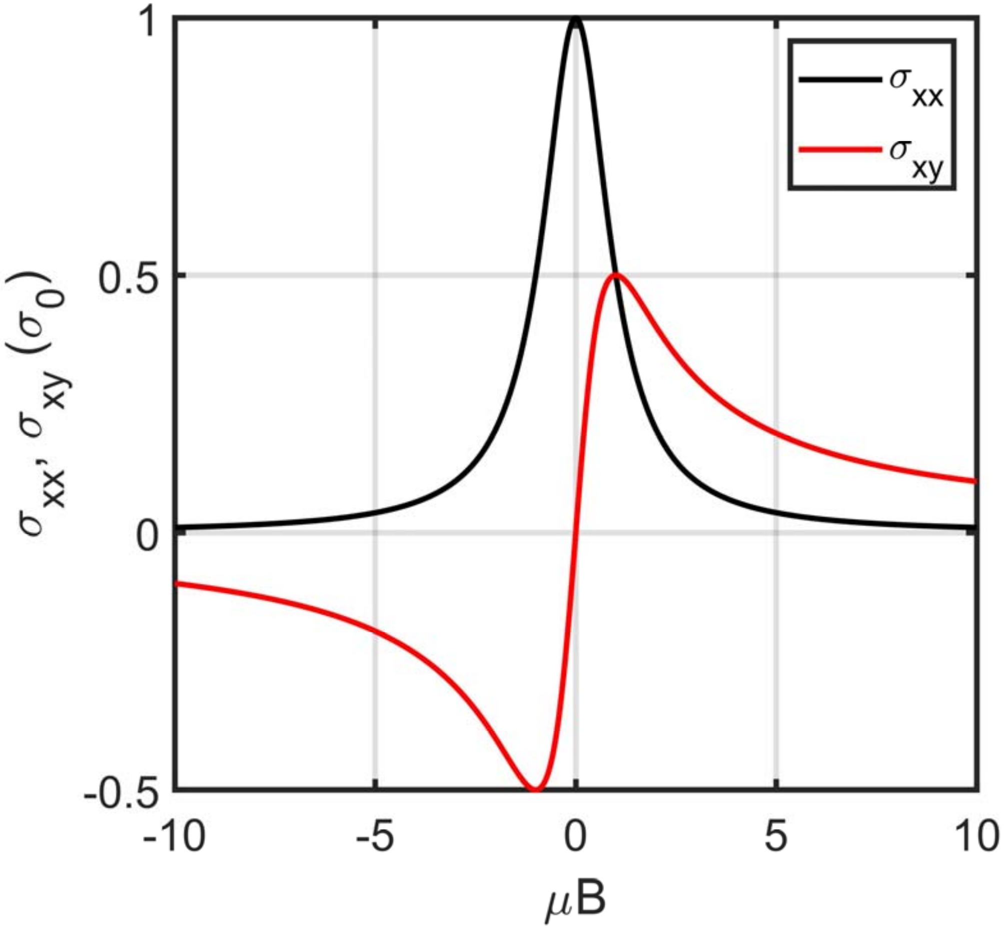
$$\mathbf{j} = \frac{en\mu}{1+(\mu B)^2}\begin{pmatrix} 1 & -\mu B \\ \mu B & 1 \end{pmatrix} \cdot \mathbf{E}$$

$$\mathbf{j} = \frac{e^2 n\tau}{m}\frac{1}{1+(\mu B)^2}\begin{pmatrix} 1 & -\mu B \\ \mu B & 1 \end{pmatrix} \cdot \mathbf{E}$$

$$\sigma_{xx} = \sigma_0 \frac{1}{1+(\mu B)^2}$$

$$\sigma_{xy} = \sigma_0 \frac{\mu B}{1+(\mu B)^2}$$

$$\mathbf{j} = \begin{pmatrix} \sigma_{xx} & -\sigma_{xy} \\ \sigma_{xy} & \sigma_{xx} \end{pmatrix} \cdot \mathbf{E} = \sigma \cdot \mathbf{E}$$



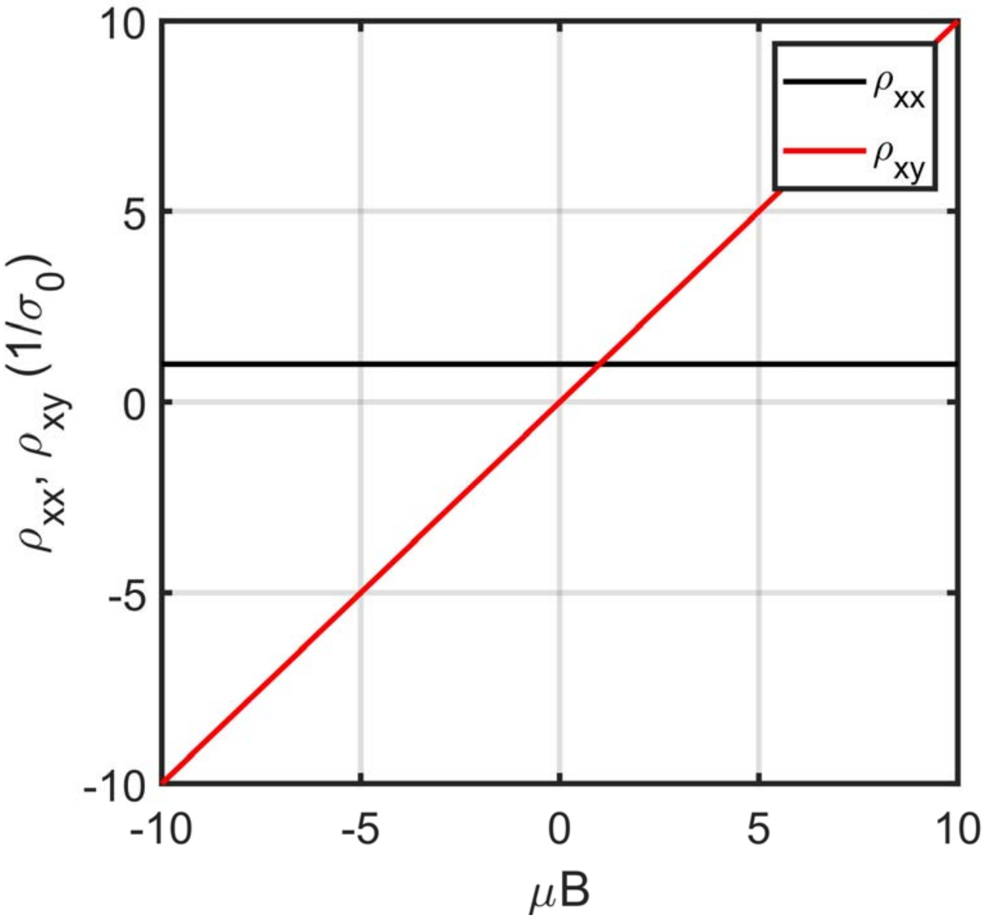
Disagreement with Boltzman kinetic theory

$$\mathbf{E} = \rho \cdot \mathbf{j} = \sigma^{-1} \cdot \mathbf{j}$$

$$\rho = \frac{1}{\sigma_0} \begin{pmatrix} 1 & \mu B \\ -\mu B & 1 \end{pmatrix}$$

$$\rho_{xx} = \frac{1}{\sigma_0}$$

$$\rho_{xy} = \frac{\mu B}{\sigma_0} = \frac{B}{en}$$



Historical perspectives

- Abrikosov, impurities, scattering centers

$$\sigma_{zz} = \frac{1}{(2\pi)^3}\left(\frac{e^2H}{c}\right)^2\frac{1}{N_i},$$

$$\sigma_{xx} = \sigma_{yy} = \frac{ecN_i}{\pi H}.$$

A. A. Abrikosov Soviet Physics JETP 29 (1969) 746.

$$\rho_{xx} = \frac{HN_i}{\pi e c n_0^2}\frac{\sinh(1/\theta)}{\cosh(m/\theta)+\cosh(m/\theta)}.$$

A. A. Abrikosov Phys. Rev. B. 60 (1999) 4231.

  - Linear, positive MR in silver chalcogenides due to the gapless and linear dispersion

A. A. Abrikosov Phys. Rev. B. 58 (1998) 2788.

$$\rho_{xx} = \frac{1}{2\pi}\left(\frac{e^2}{\varepsilon_\infty v}\right)^2 \ln \varepsilon_\infty \frac{N_i}{ecn_0^2}H.$$

- Alekseev, Phys. Rev. B 95 (2017) 165410, compensated semimetals
  - Electron-hole fluid in a confined geometry, Phys. Rev. B 97 (2018) 085109.
- Gopinadhan et al., Nat. Comm. 6 (2015) 8337 – conductivity inhomogenities
- Jervis and Johnson, Solid-State Electronics 13 (1970) 181, geometrical magnetoresistance,
- Kapitza, random disturibances (quadratic to linear crossover)

$$\frac{\Delta R}{R_0} = (\xi \mu_H B_0)^2,$$

Historical perspectives

- Khouri et al., Phys. Rev. Lett. 117 (2016) 256601, linear MR in ultra-high mobility GaAs QW

PRL **117,** 256601 (2016) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2016

Linear Magnetoresistance in a Quasifree Two-Dimensional Electron Gas in an Ultrahigh Mobility GaAs Quantum Well

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[2]*Radboud University, Institute of Molecules and Materials, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands*

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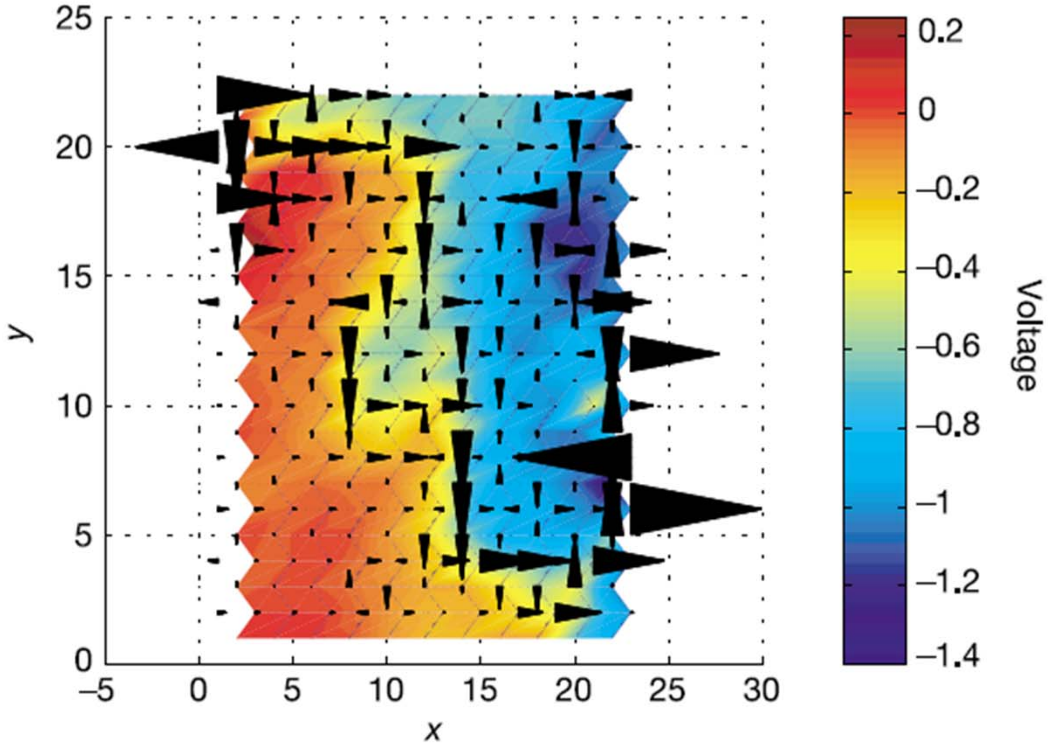
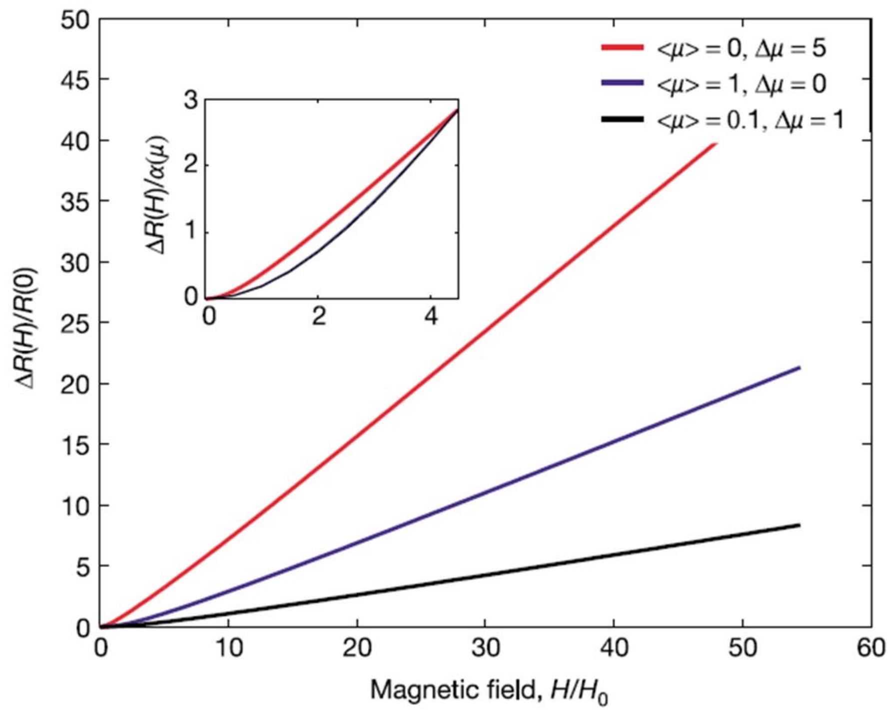
(Received 21 October 2016; published 14 December 2016)

We report a high-field magnetotransport study of an ultrahigh mobility ($\bar{\mu} \approx 25 \times 10^6$ cm^2 V^{-1} s^{-1}) n-type GaAs quantum well. We observe a strikingly large linear magnetoresistance (LMR) up to 33 T with a magnitude of order 10^5% onto which quantum oscillations become superimposed in the quantum Hall regime at low temperature. LMR is very often invoked as evidence for exotic quasiparticles in new materials such as the topological semimetals, though its origin remains controversial. The observation of such a LMR in the "simplest system"—with a free electronlike band structure and a nearly defect-free environment—excludes most of the possible exotic explanations for the appearance of a LMR and rather points to density fluctuations as the primary origin of the phenomenon. Both, the featureless LMR at high T and the quantum oscillations at low T follow the empirical resistance rule which states that the longitudinal conductance is directly related to the derivative of the transversal (Hall) conductance multiplied by the magnetic field and a constant factor α that remains unchanged over the entire temperature range. Only at low temperatures, small deviations from this resistance rule are observed beyond $\nu = 1$ that likely originate from a different transport mechanism for the composite fermions.

Historical perspectives

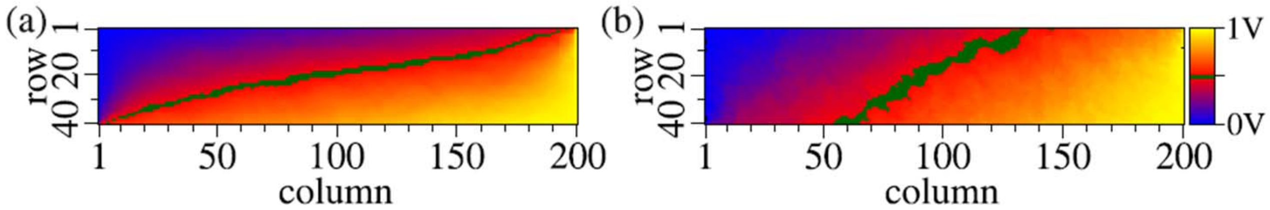
- M.M.Parish, P.B.Littlewood, Nature 426 (2003) 162, Non-saturating magnetoresistance in heavily disordered semiconductors

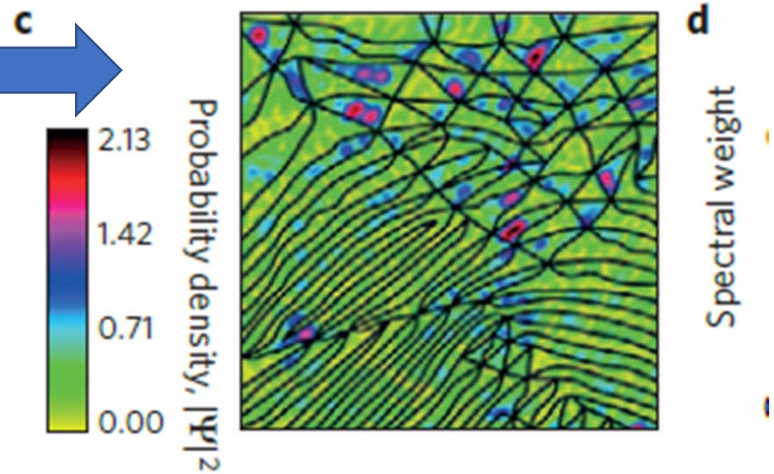


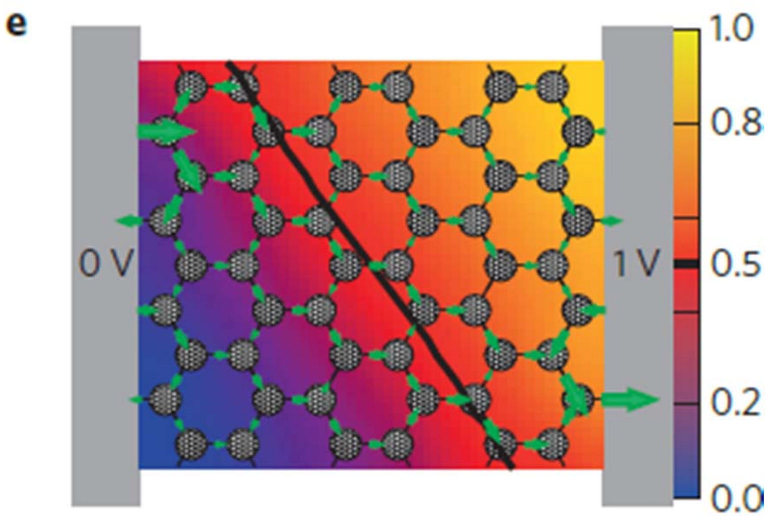


Historical perspectives

- Kisslinger et al., Nat. Phys. 11 (2015) 650...conductivity fluctuations
- Kisslinger et al., Phys. Rev. B 95 (2017) 024204







Our theoretical model

$$\mathbf{j} = \frac{en\mu}{1+(\mu B)^2}\begin{pmatrix} 1 & -\mu B \\ \mu B & 1 \end{pmatrix} \cdot \mathbf{E}$$

$$\mathbf{E} = -\nabla\varphi$$

$$\nabla \cdot \mathbf{j} = 0$$

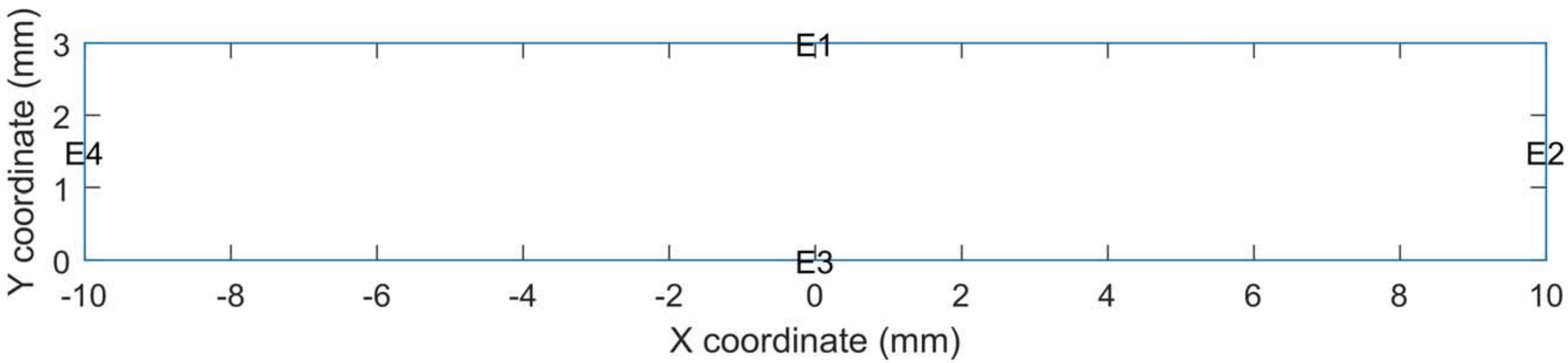
$$\nabla \cdot \left[\frac{en(\mathbf{r})\mu(\mathbf{r})}{1+(\mu(\mathbf{r})B)^2}\begin{pmatrix} 1 & -\mu(\mathbf{r})B \\ \mu(\mathbf{r})B & 1 \end{pmatrix}\right] \cdot \nabla\varphi = 0$$

$$\varphi(L) = 0, \varphi(R) = 1V$$

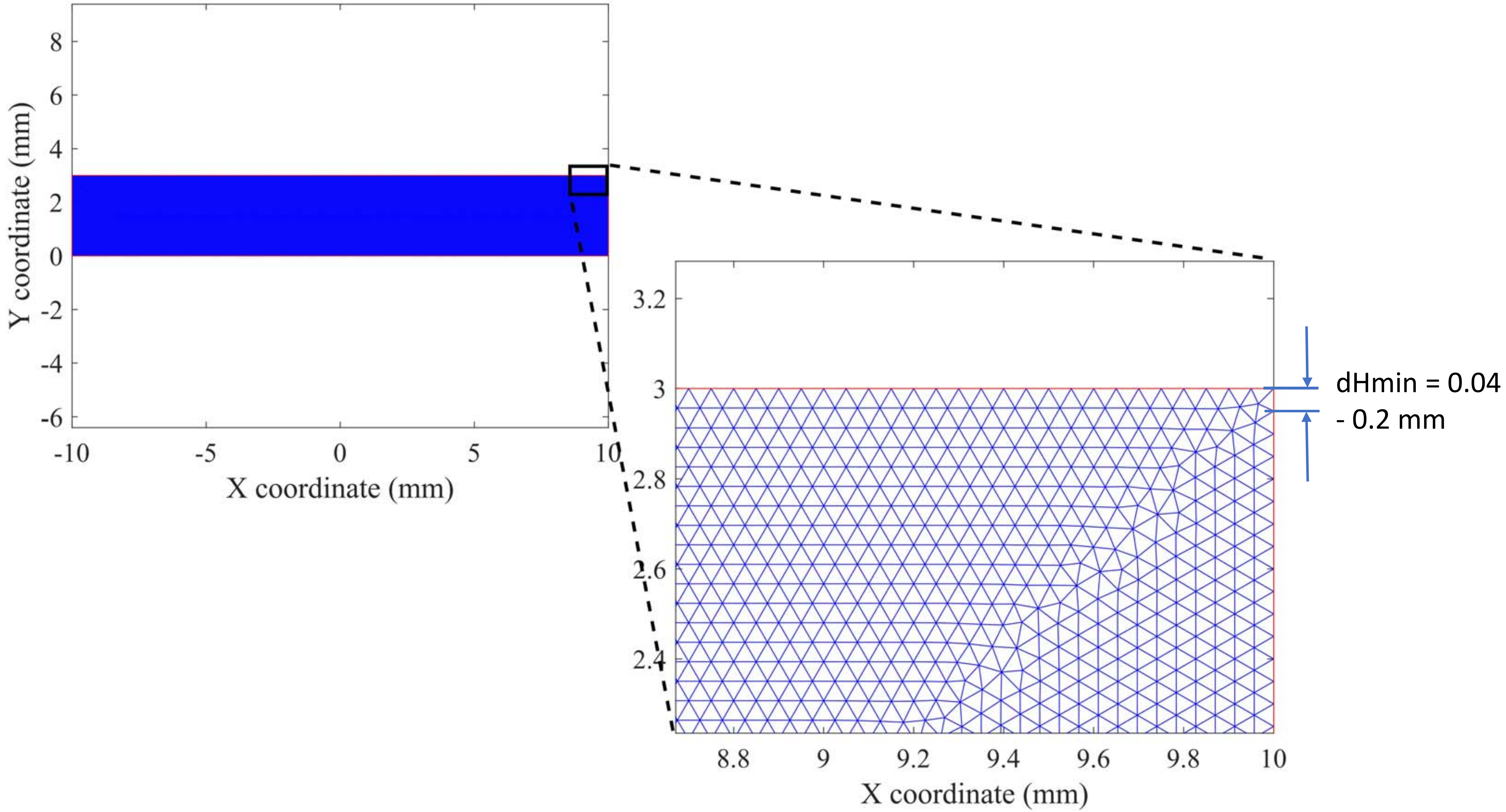
$$\mathbf{j} \cdot \mathbf{n} = 0 \qquad \text{at } \partial\Omega \setminus \{L, R\}$$

Numerical implementation

- Finite element method
- Simple rectangular geometry
- Edges of the sample are labeled E1, E2, E3 and E4
- Boundary conditions applied to the edges E1..E4

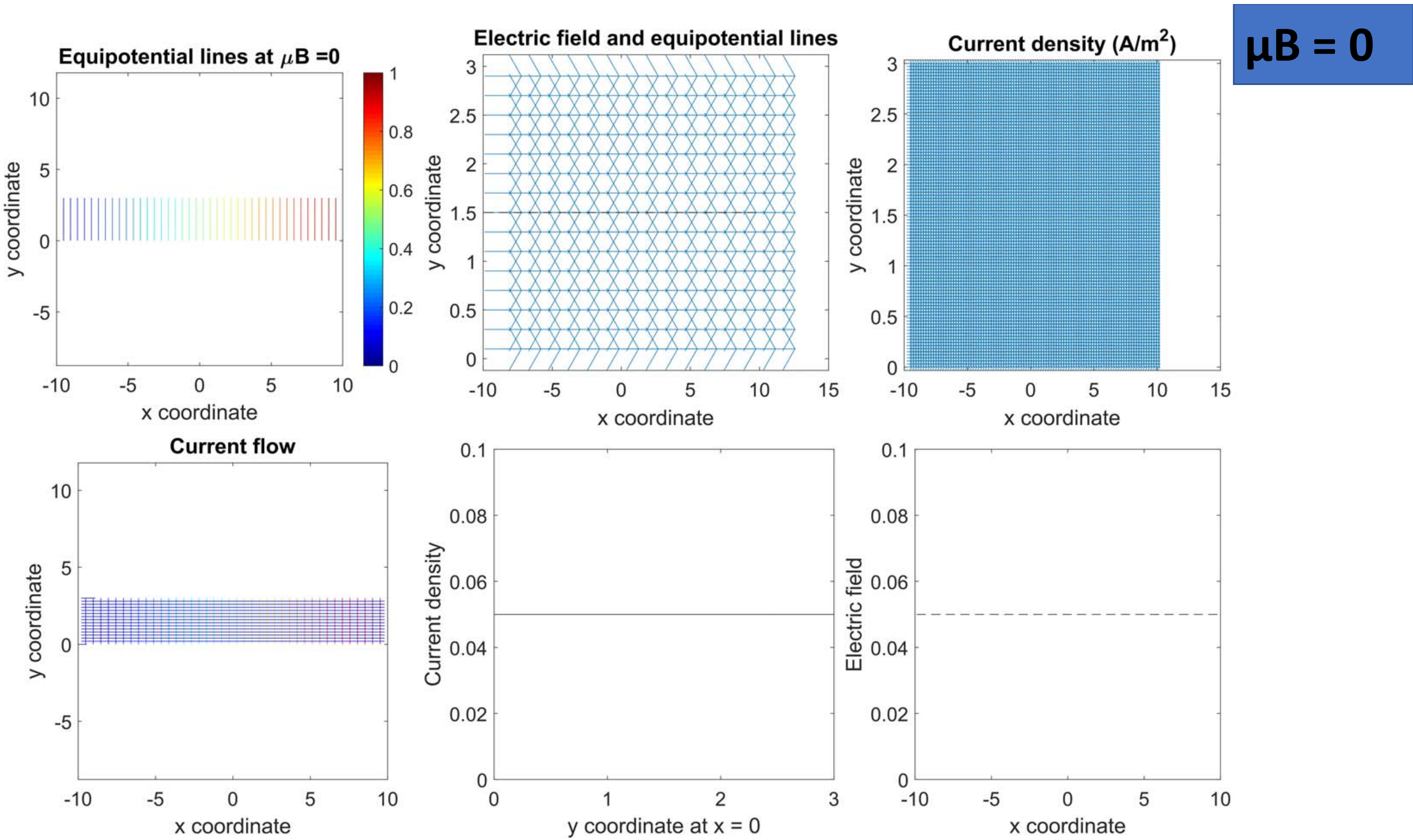


Triangulation

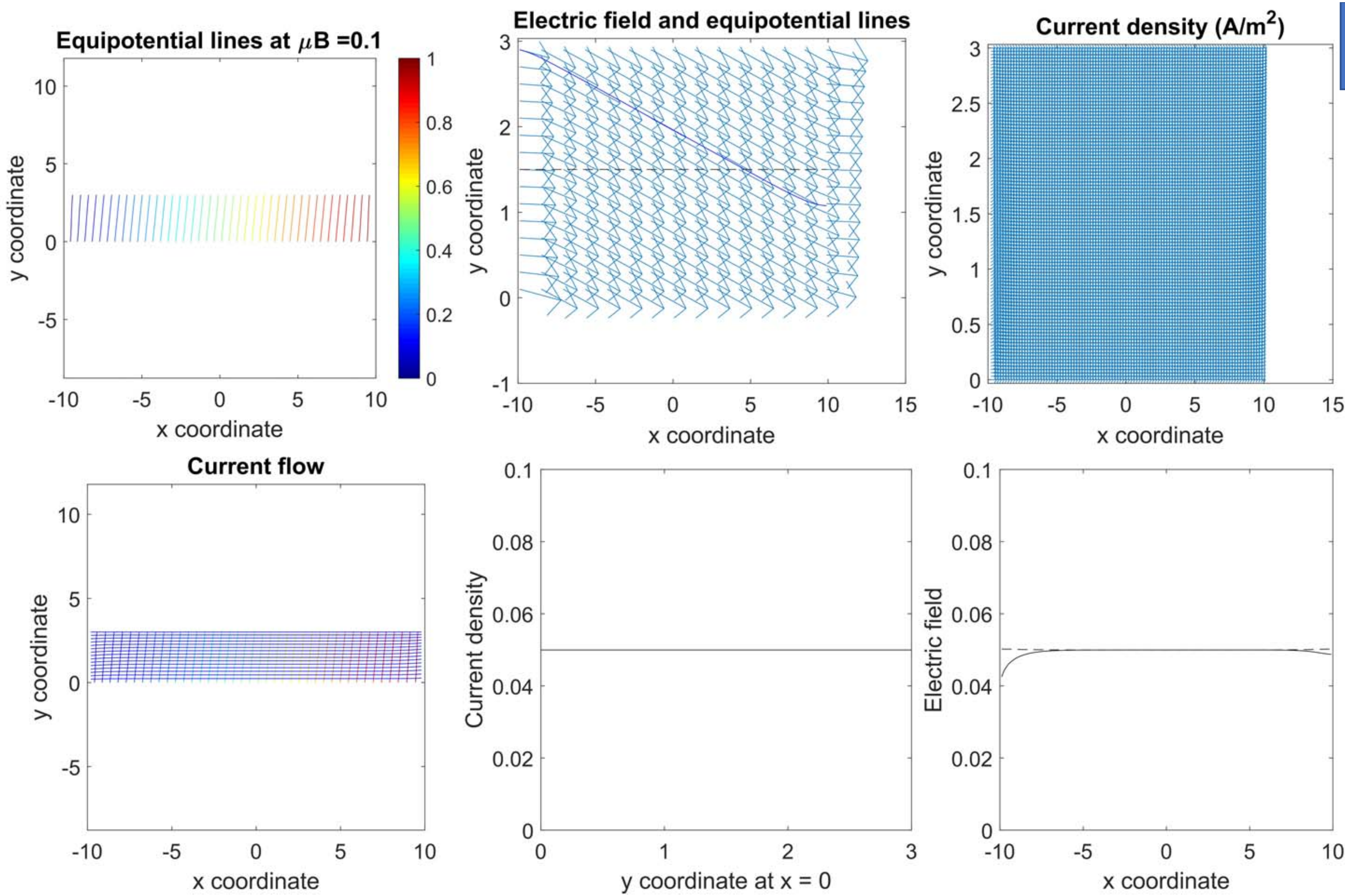


Results in an ideal conductor

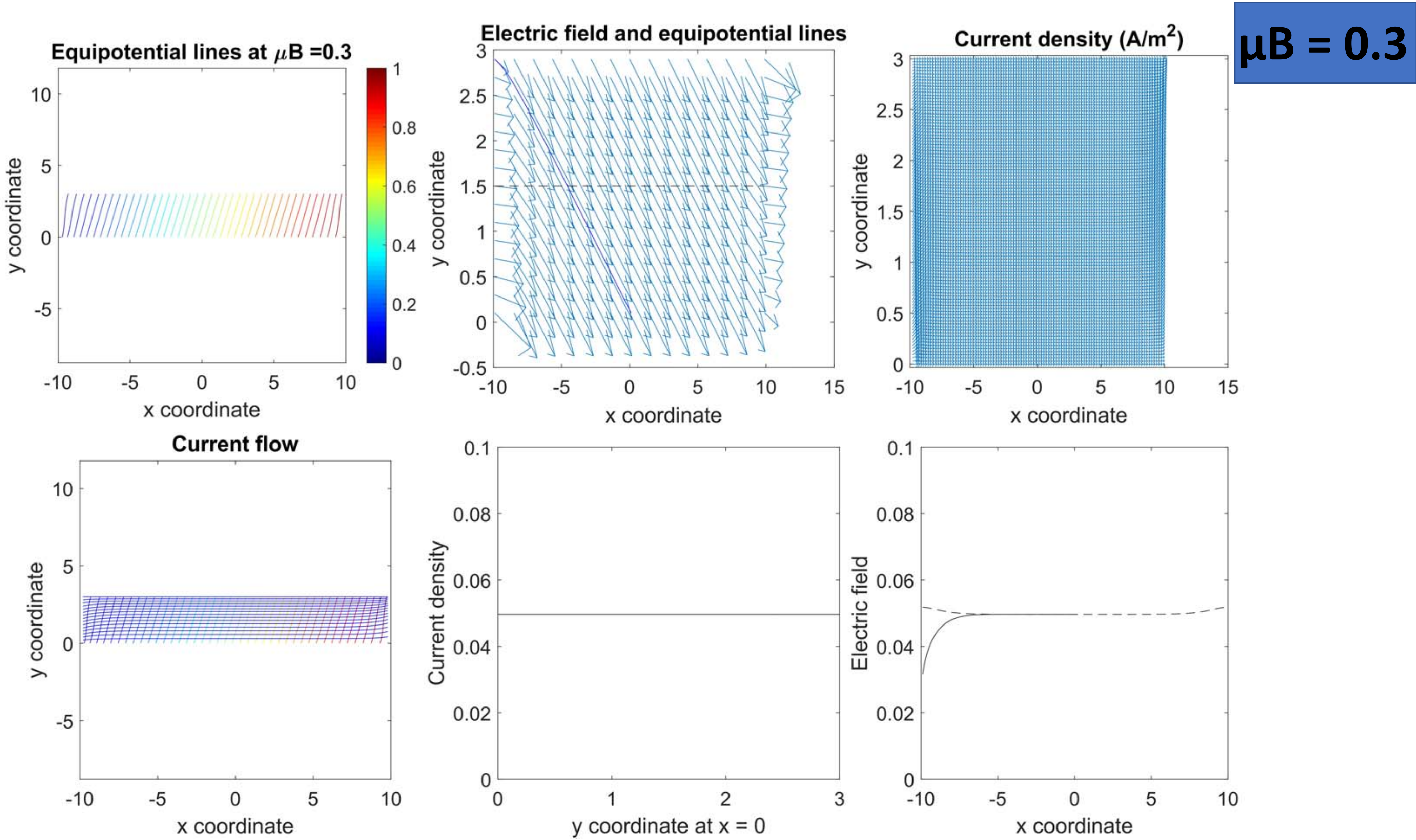
(no disorder)


μB = 0
Equipotential lines at μB =0
Electric field and equipotential lines
Current density (A/m2)
Current flow
x coordinate
y coordinate
Current density
y coordinate at x = 0
Electric field

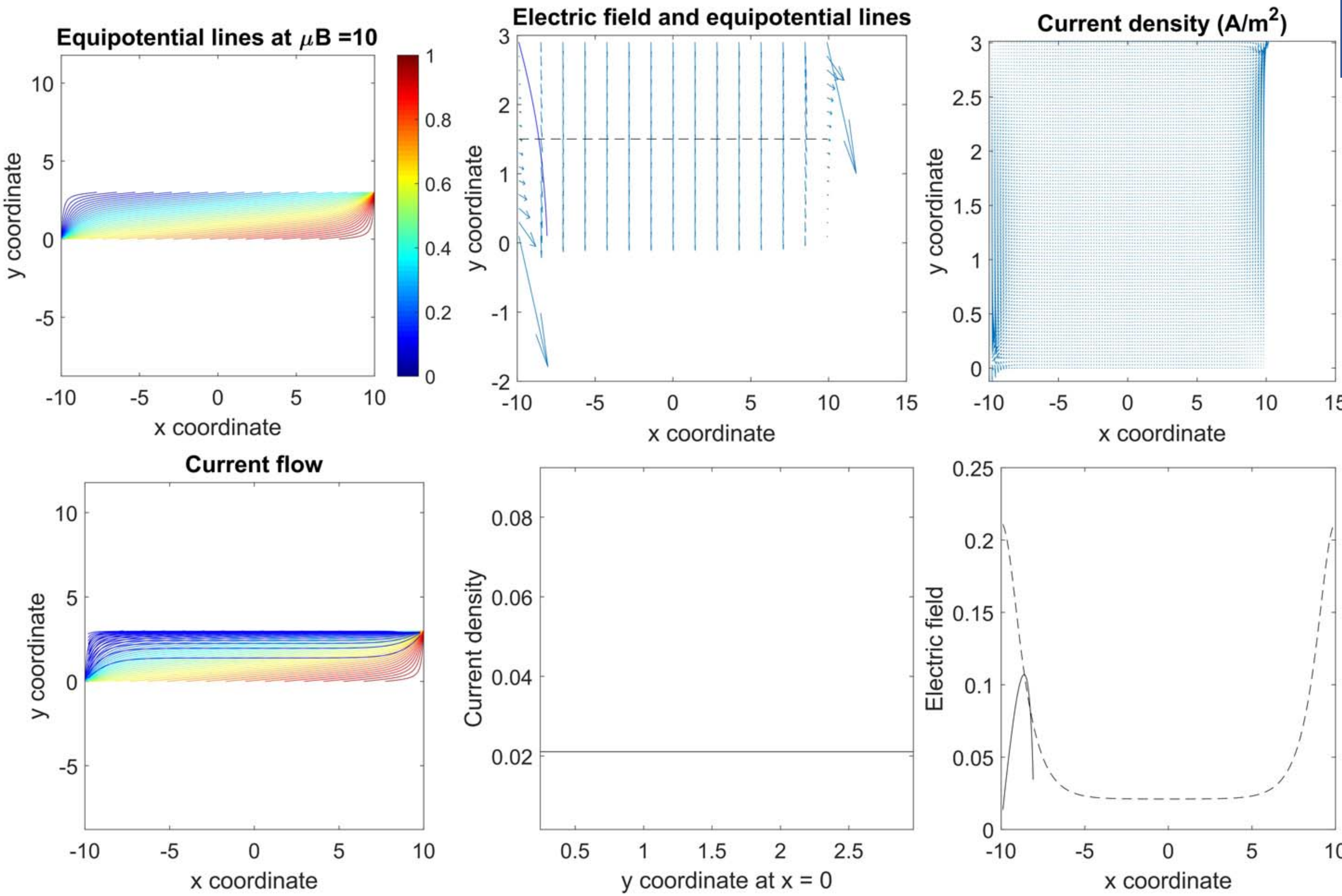
μB = 0.1



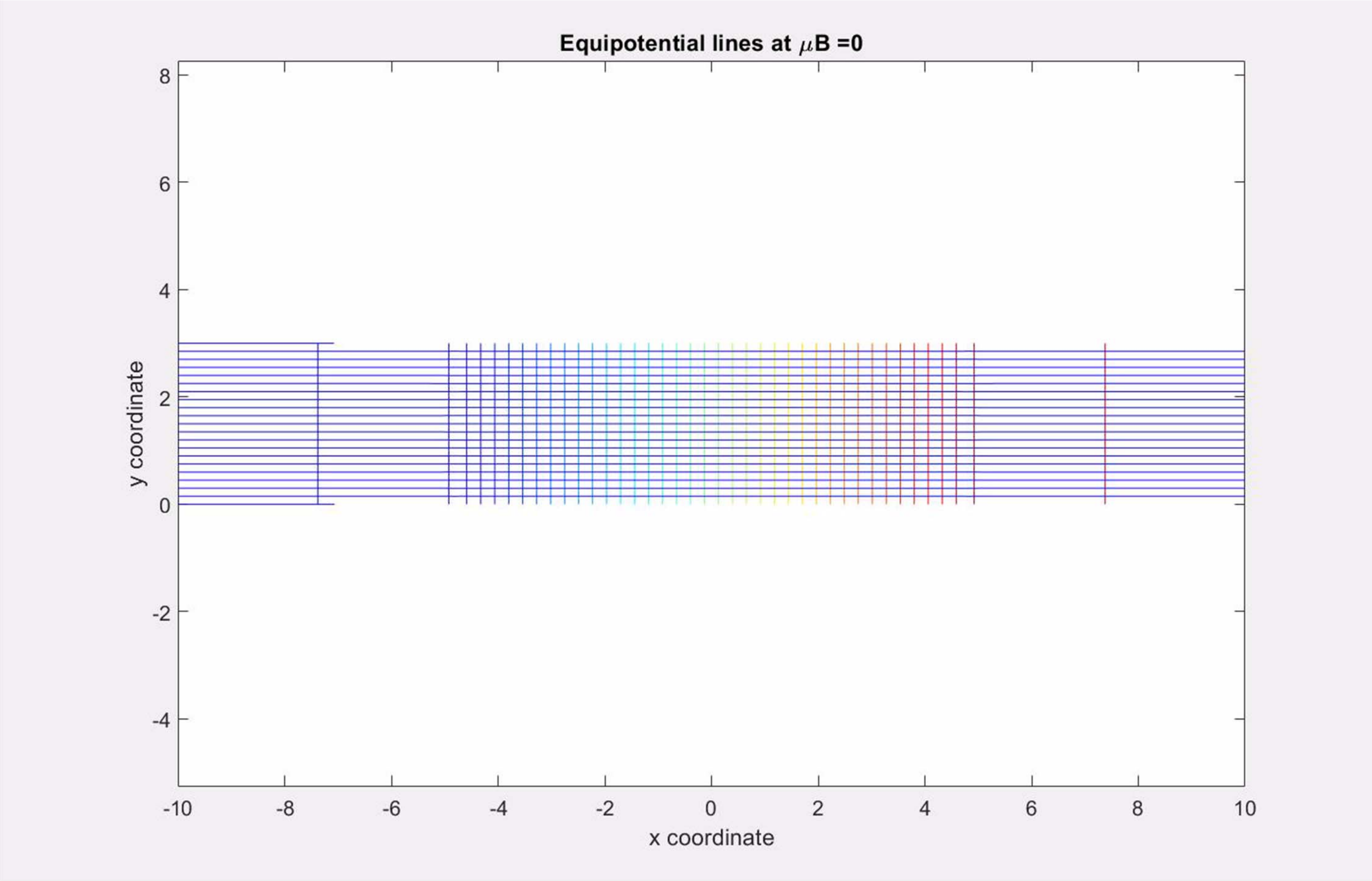
Equipotential lines at μB =0.1
y coordinate
x coordinate
Electric field and equipotential lines
y coordinate
x coordinate
Current density (A/m2)
y coordinate
x coordinate
Current flow
y coordinate
x coordinate
Current density
y coordinate at x = 0
Electric field
x coordinate

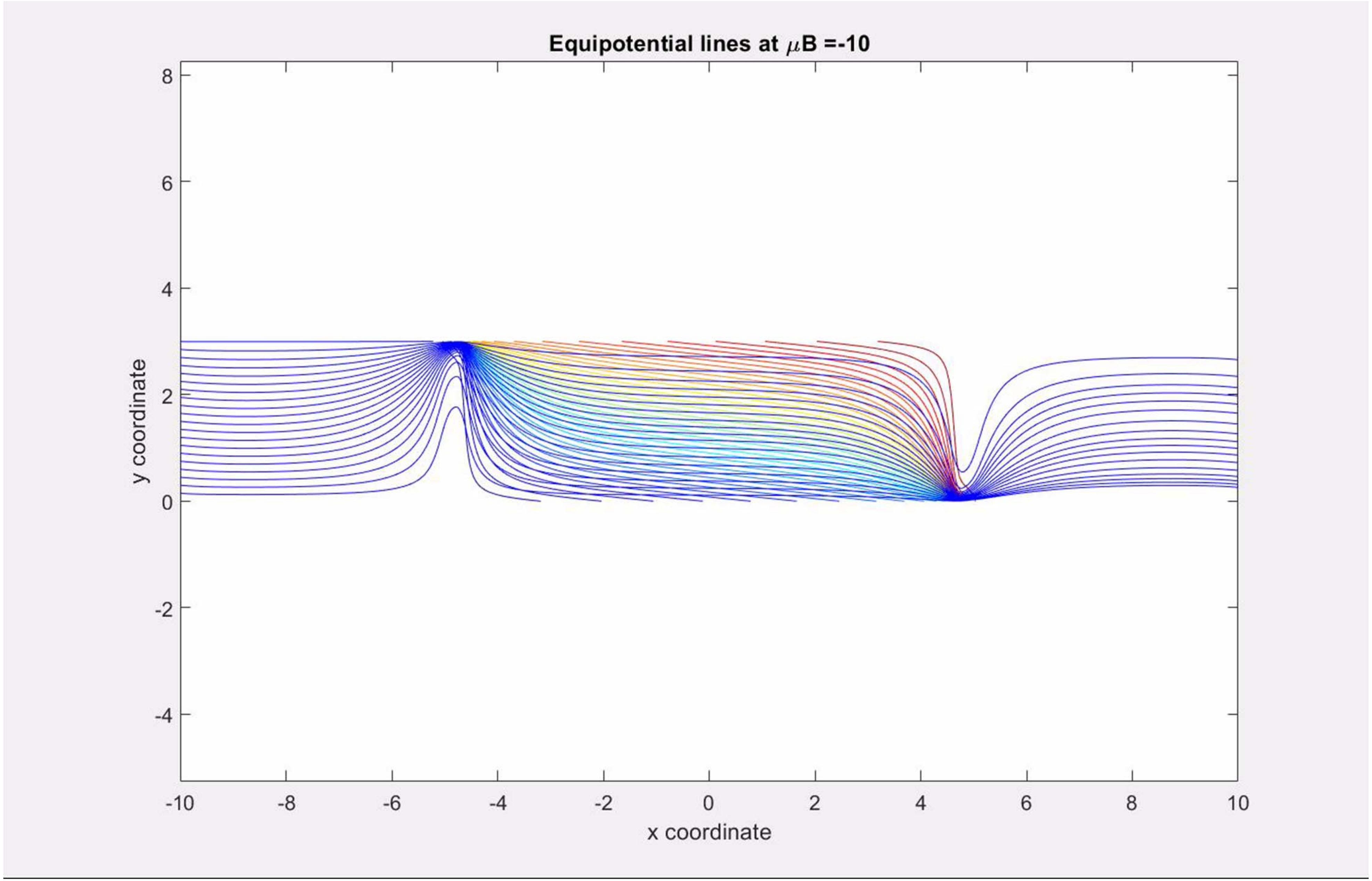

μB = 0.3
Equipotential lines at μB =0.3
Electric field and equipotential lines
Current density (A/m2)
Current flow
y coordinate
x coordinate
Current density
y coordinate at x = 0
Electric field

μB = 10



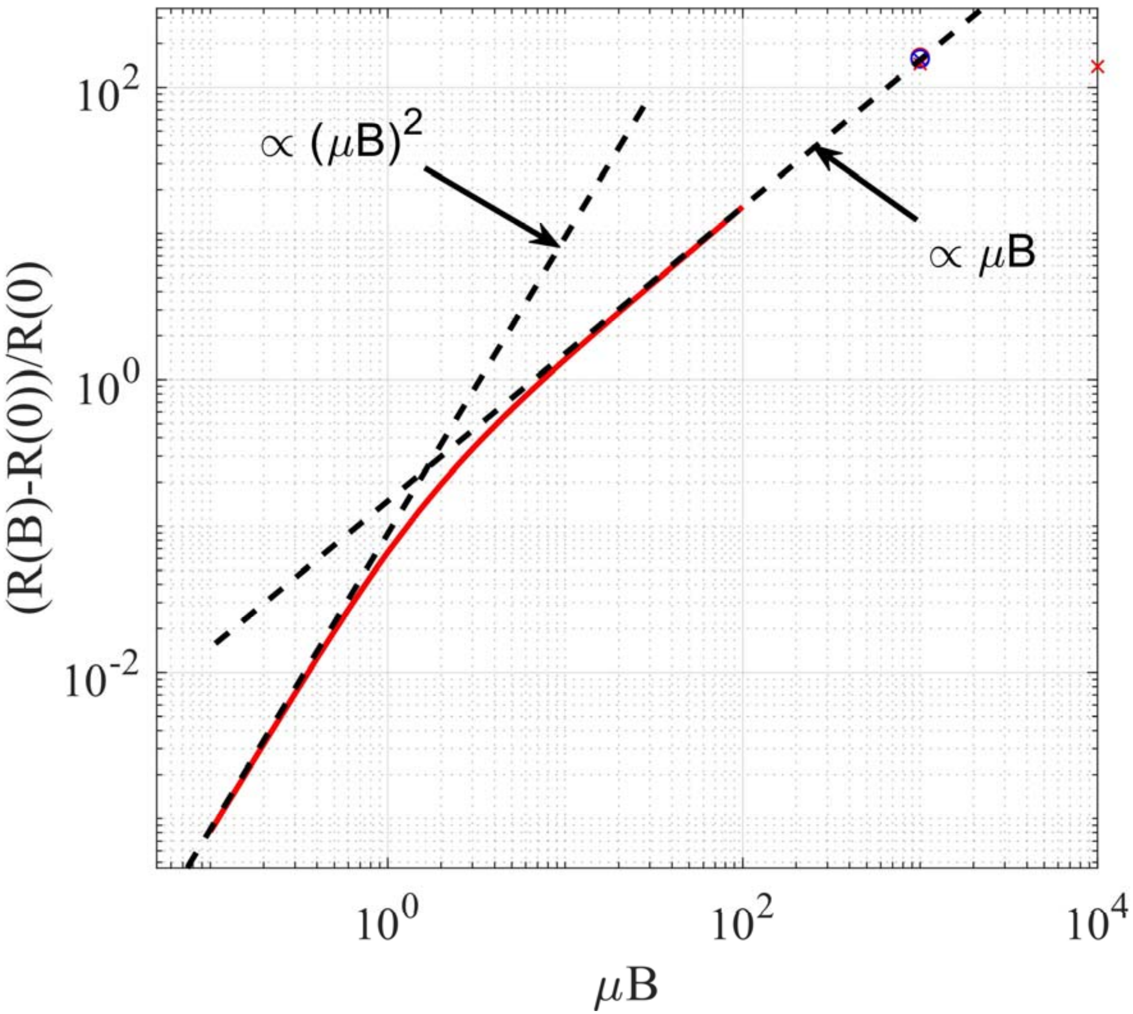
Equipotential lines at μB =10
Electric field and equipotential lines
Current density (A/m2)
Current flow
x coordinate
y coordinate
Current density
y coordinate at x = 0
Electric field

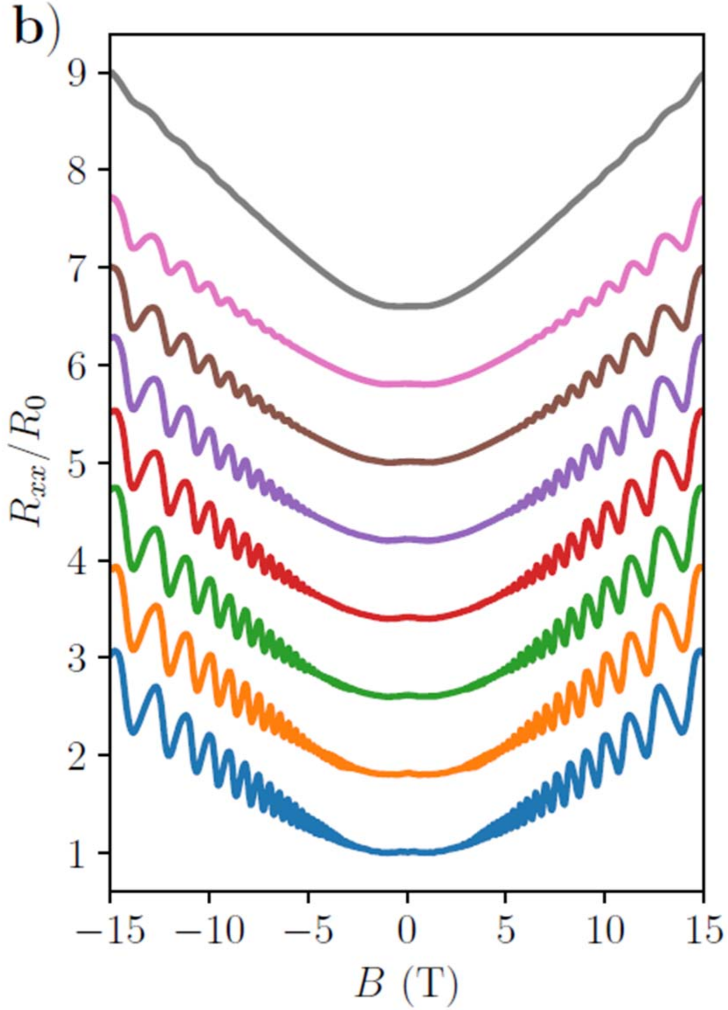

Equipotential lines at μB =0
y coordinate
x coordinate
8
6
4
2
0
-2
-4
-10
-8
-6
-4
-2
0
2
4
6
8
10



Equipotential lines at μB =-10
y coordinate
x coordinate
8
6
4
2
0
-2
-4
-10
-8
-6
-4
-2
0
2
4
6
8
10

Quadratic-to-linear magnetoresistance crossover

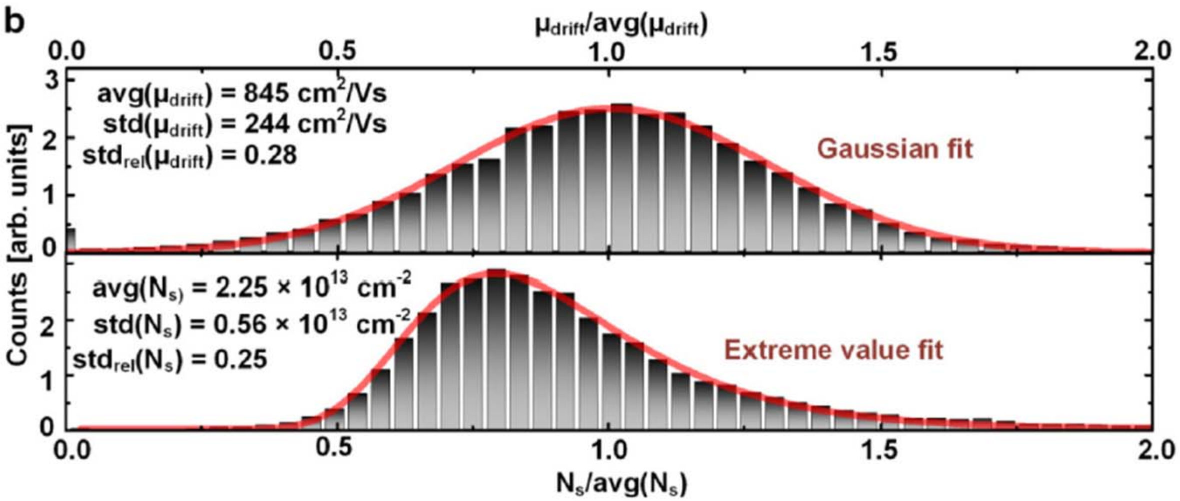




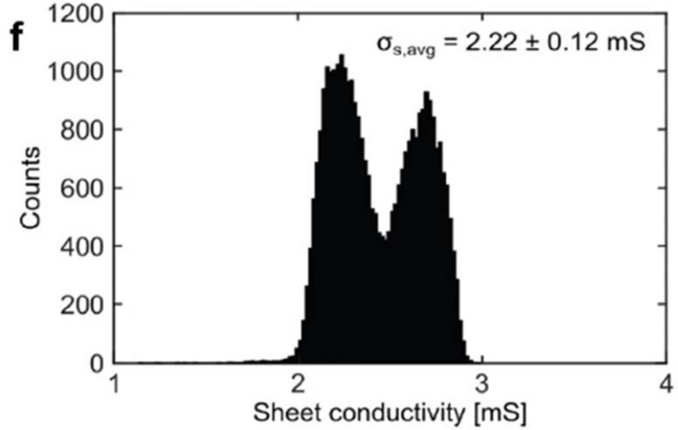
D. Bloos et al., 2D Mater. 6 (2019) 035028

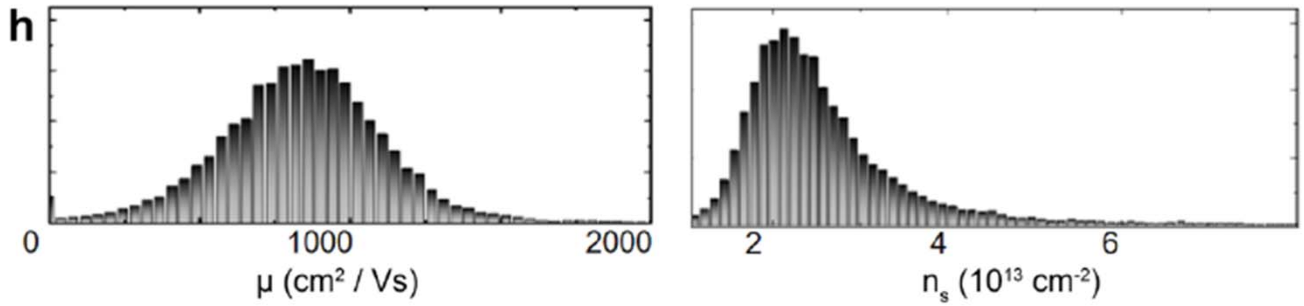
Results in a disordered conductor

How to describe disorder?



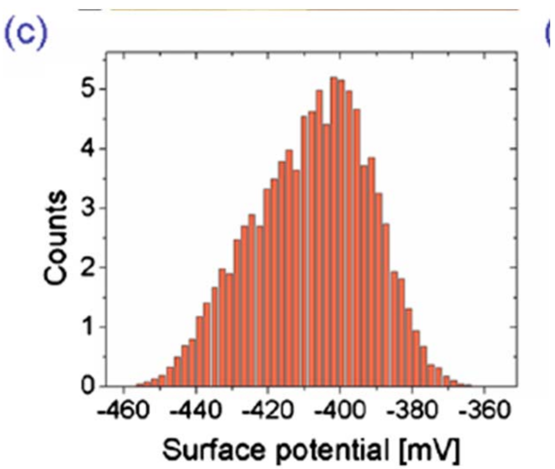
J. D. Buron et al., Optics Express 23 (2015) 30721.





P. Boggild et al., 2D Mater. 4 (2017) 042003.

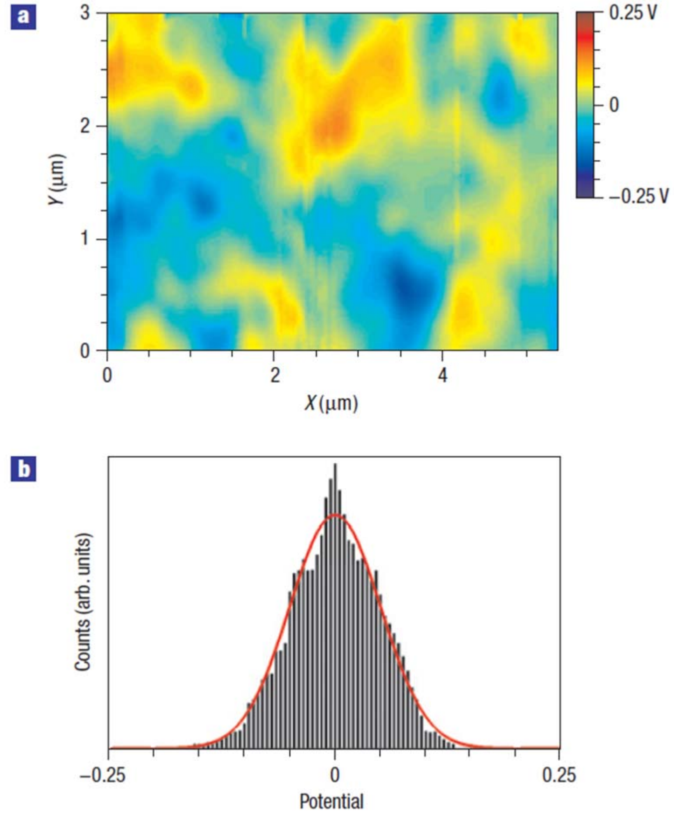
How to describe disorder? - Energy fluctuations



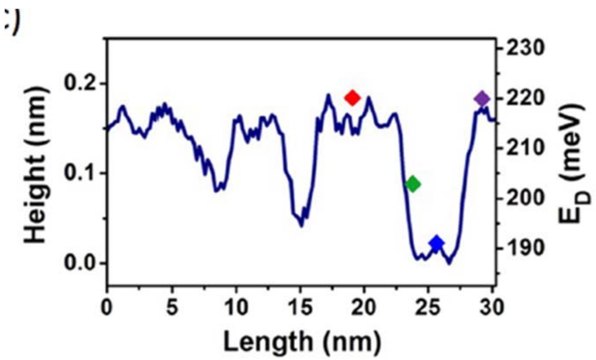
A. E. Curtin et al., Appl. Phys. Lett. 98 (2011) 243111.

Synthesis (treatment)	Disorder strength (meV)	Probing method
Epitaxial on SiC (**CD1**)	**12.7 ± 0.6**	**Magnetotransport**
Epitaxial on SiC (**CD2**)	**10.2 ± 0.4**	**Magnetotransport**
Epitaxial on SiC (**UV1**)	**31.3 ± 2.0**	**Magnetotransport**
Epitaxial on SiC (**AO**)	**15 ± 1**	**Magnetotransport**
Epitaxial on SiC	12	KPM [5]
Exfoliated on SiO_2/Si	50	SET [6]
Exfoliated on SiO_2/Si	~20	STM [7]
Exfoliated on h-BN	5.4	STM [8]
CVD on Ir(111)	~30	STM/STS [9]

J. Huang et al., Phys. Rev. B 92 (2015) 075407.



J. Martin et al. Nat. Phys. 4 (2008) 144.

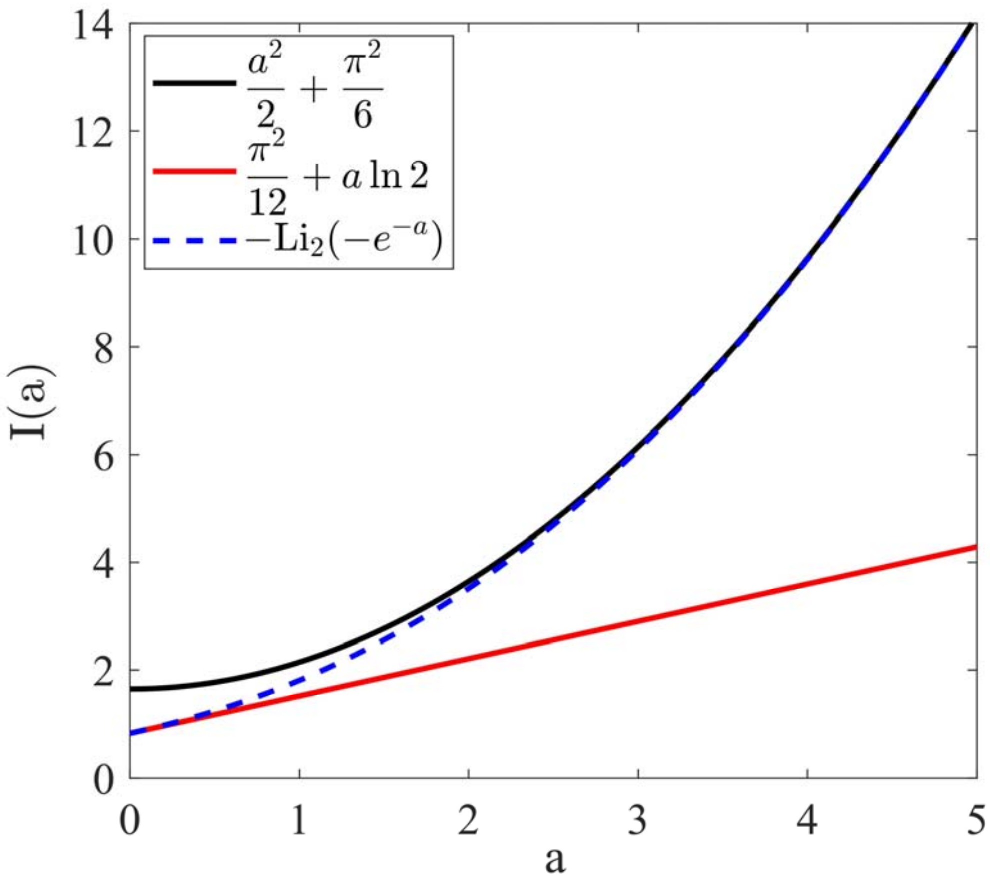


Rajput, Appl. Phys. Lett. 104 (2014) 041908.

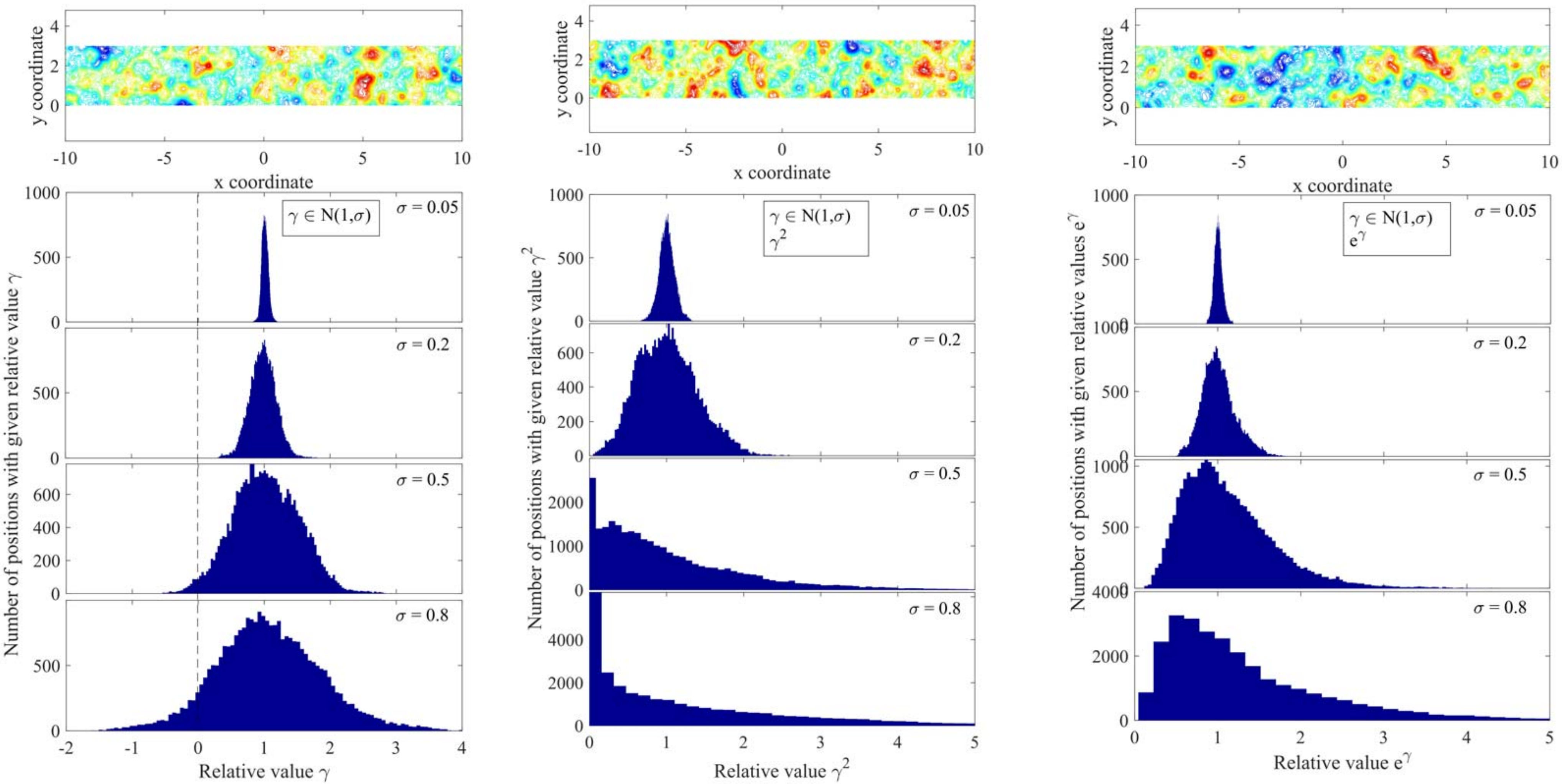
Carrier density fluctuations in graphene

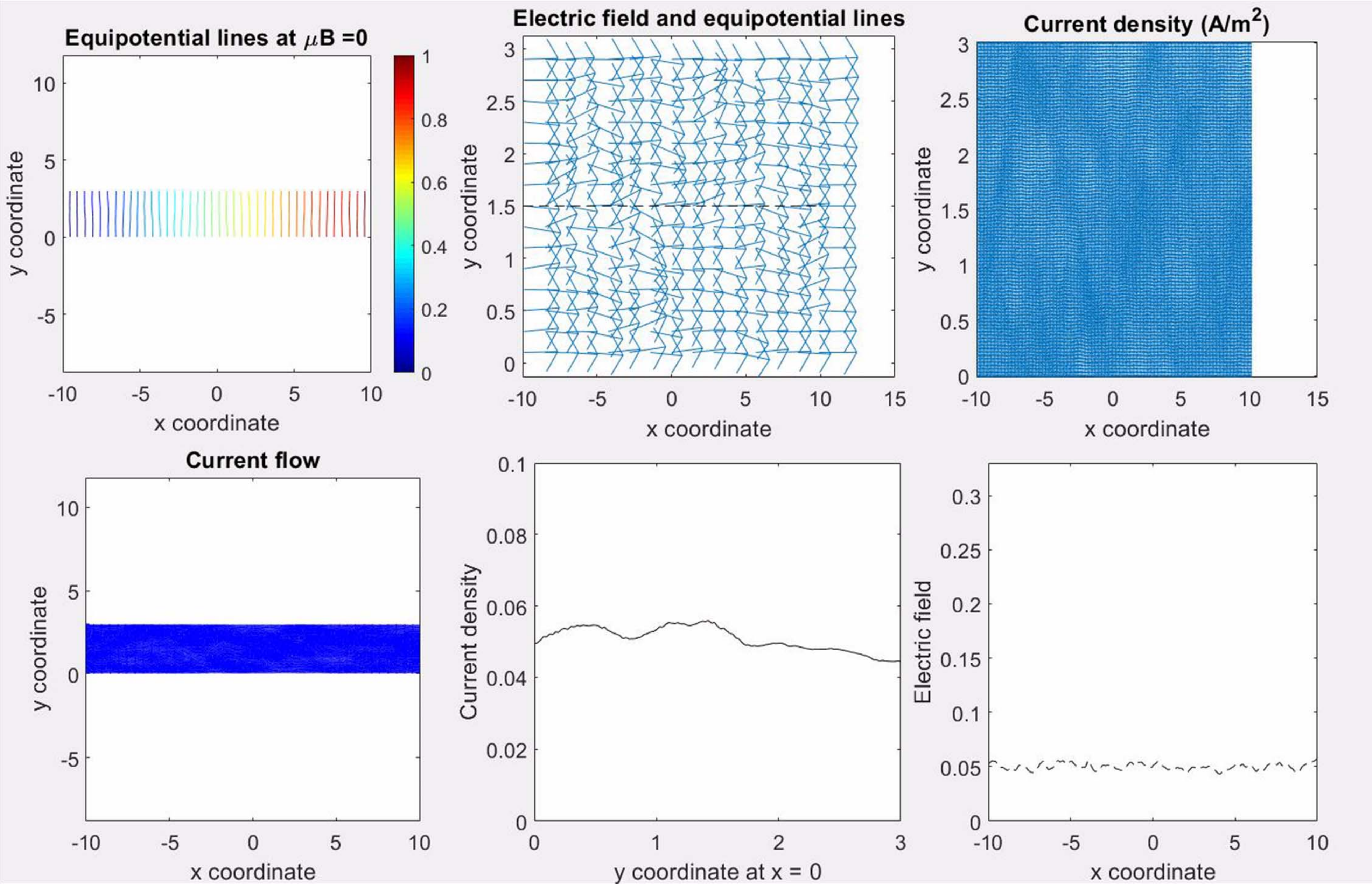
$$n_{2D} = \frac{2(k_B T)^2}{\pi(\hbar v_F)^2} I(a)$$

$$a = E_F / k_B T$$

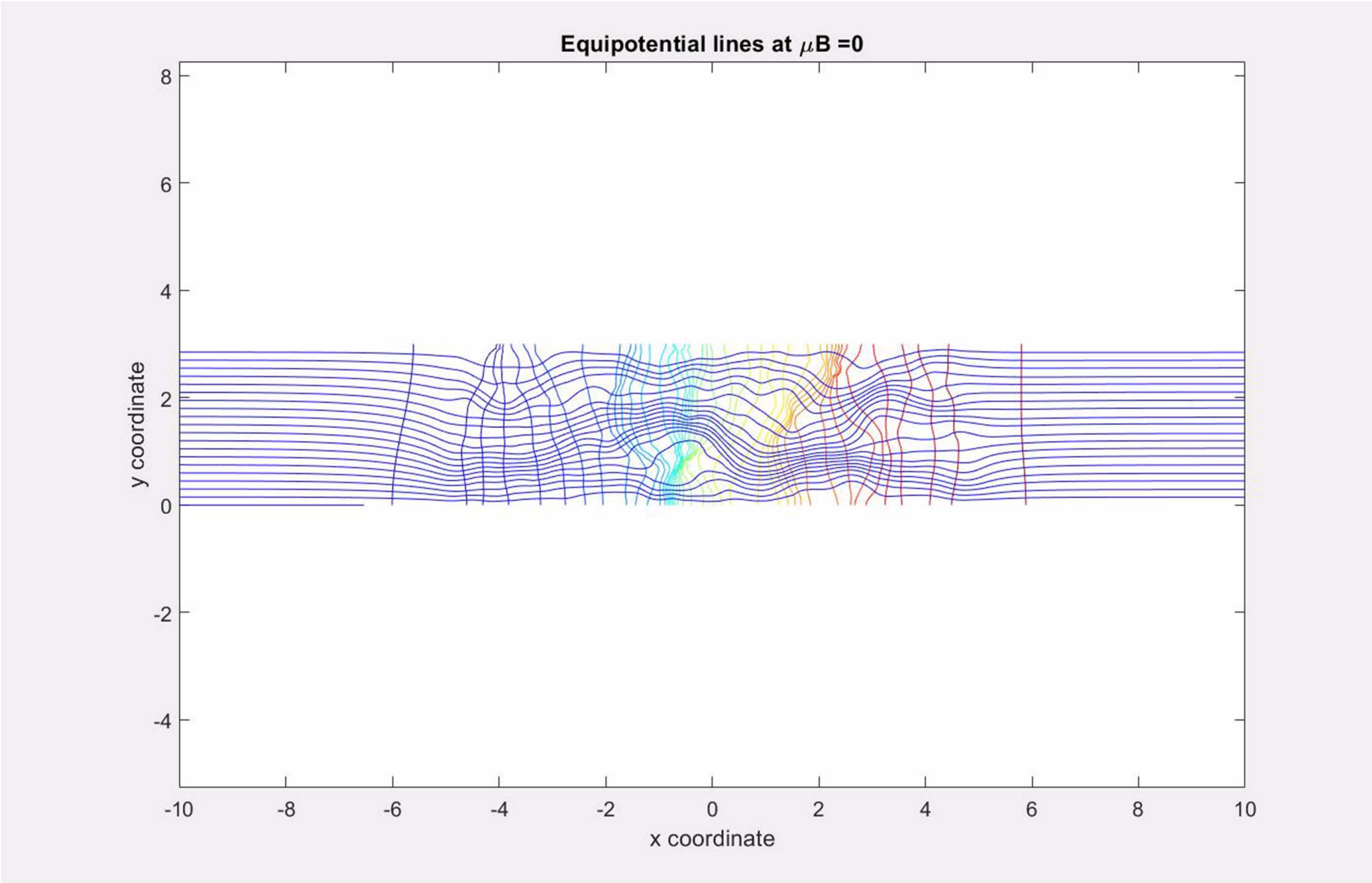


Distribution functions describing disorder





Equipotential lines at μB =0
Electric field and equipotential lines
Current density (A/m^2)
Current flow
y coordinate
x coordinate
Current density
y coordinate at x = 0
Electric field



Equipotential lines at μB =0
y coordinate
x coordinate
8
6
4
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-6
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-2
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8
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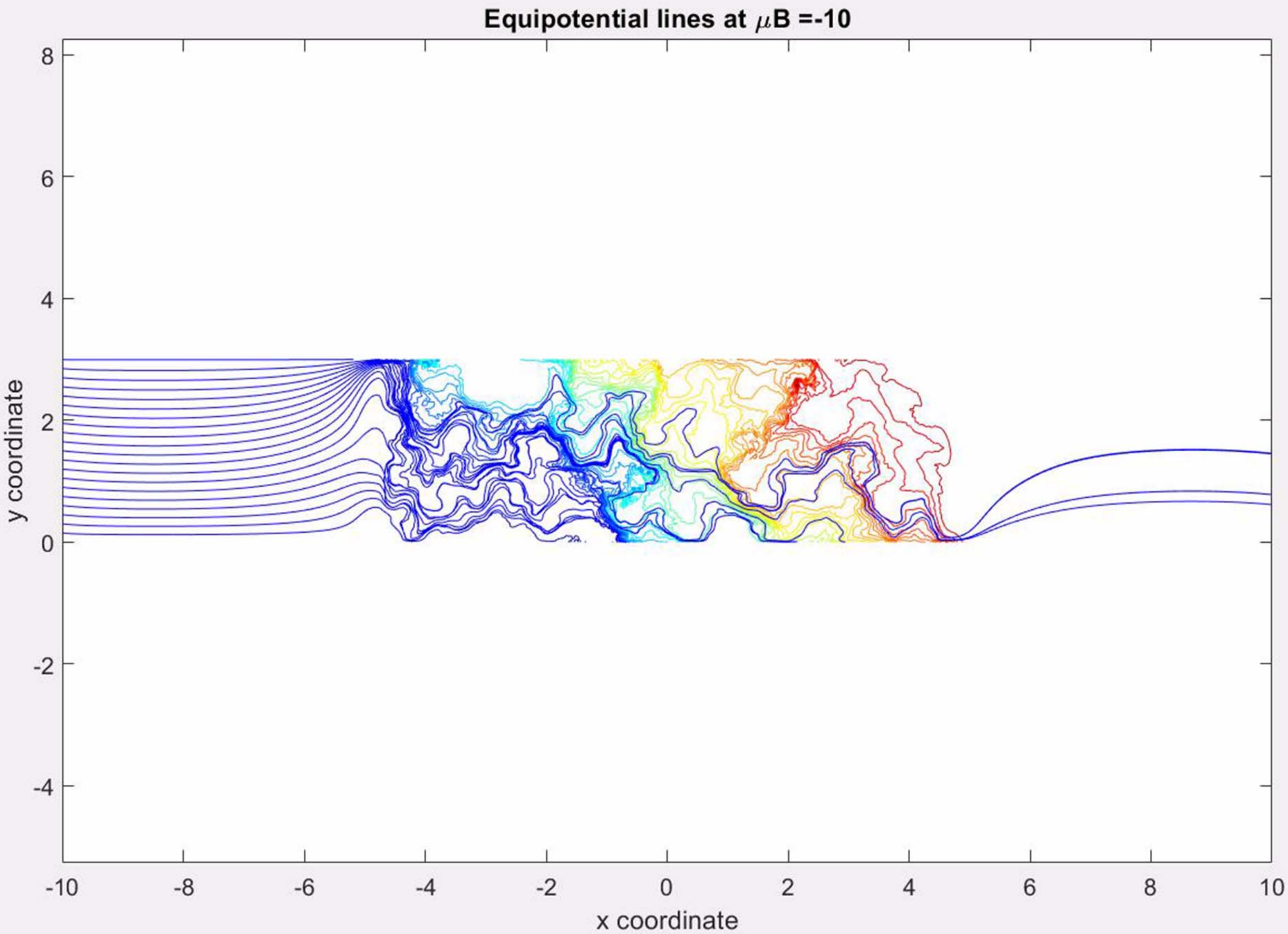
Equipotential lines at μB =-10
y coordinate
x coordinate
8
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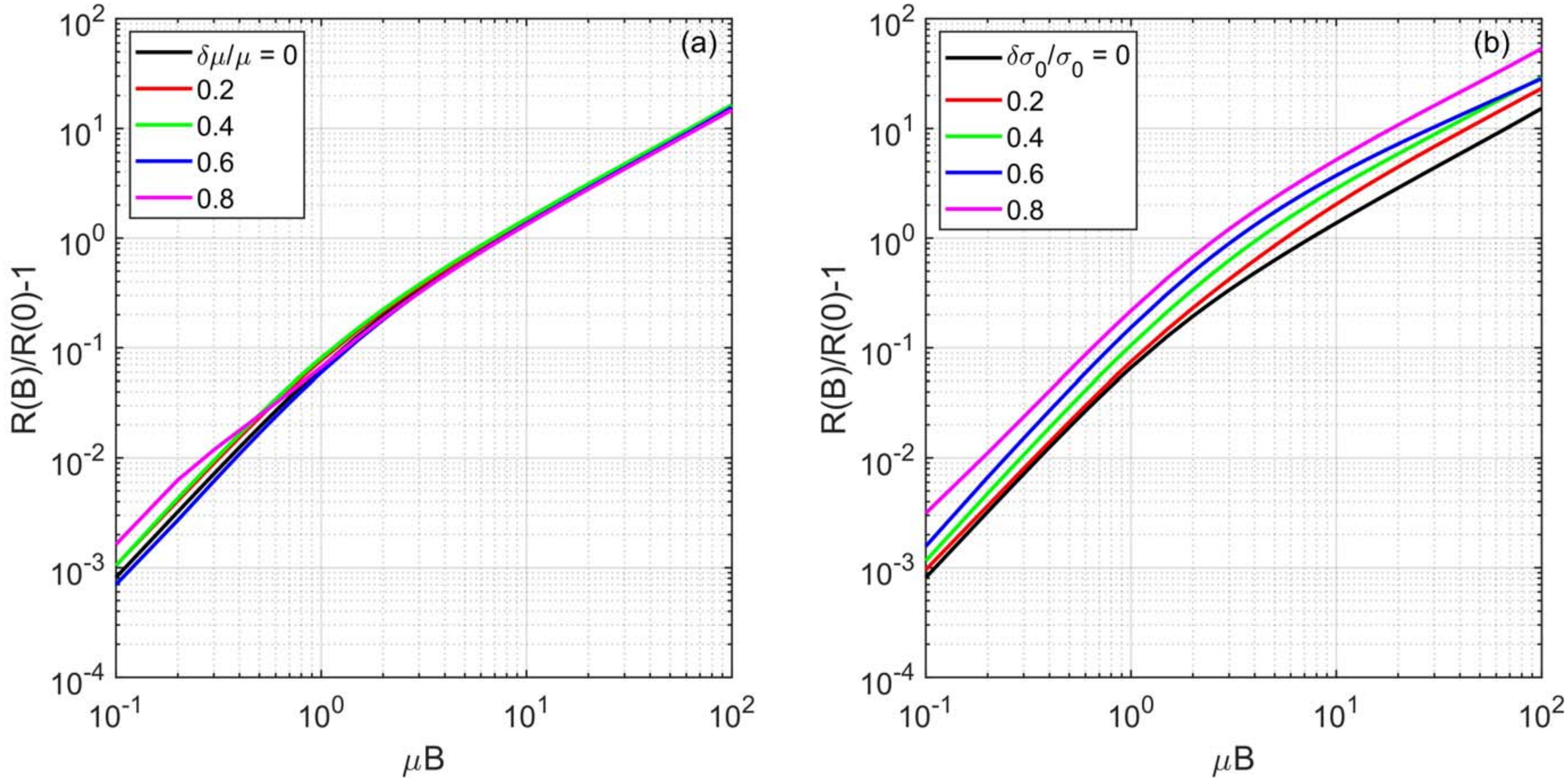
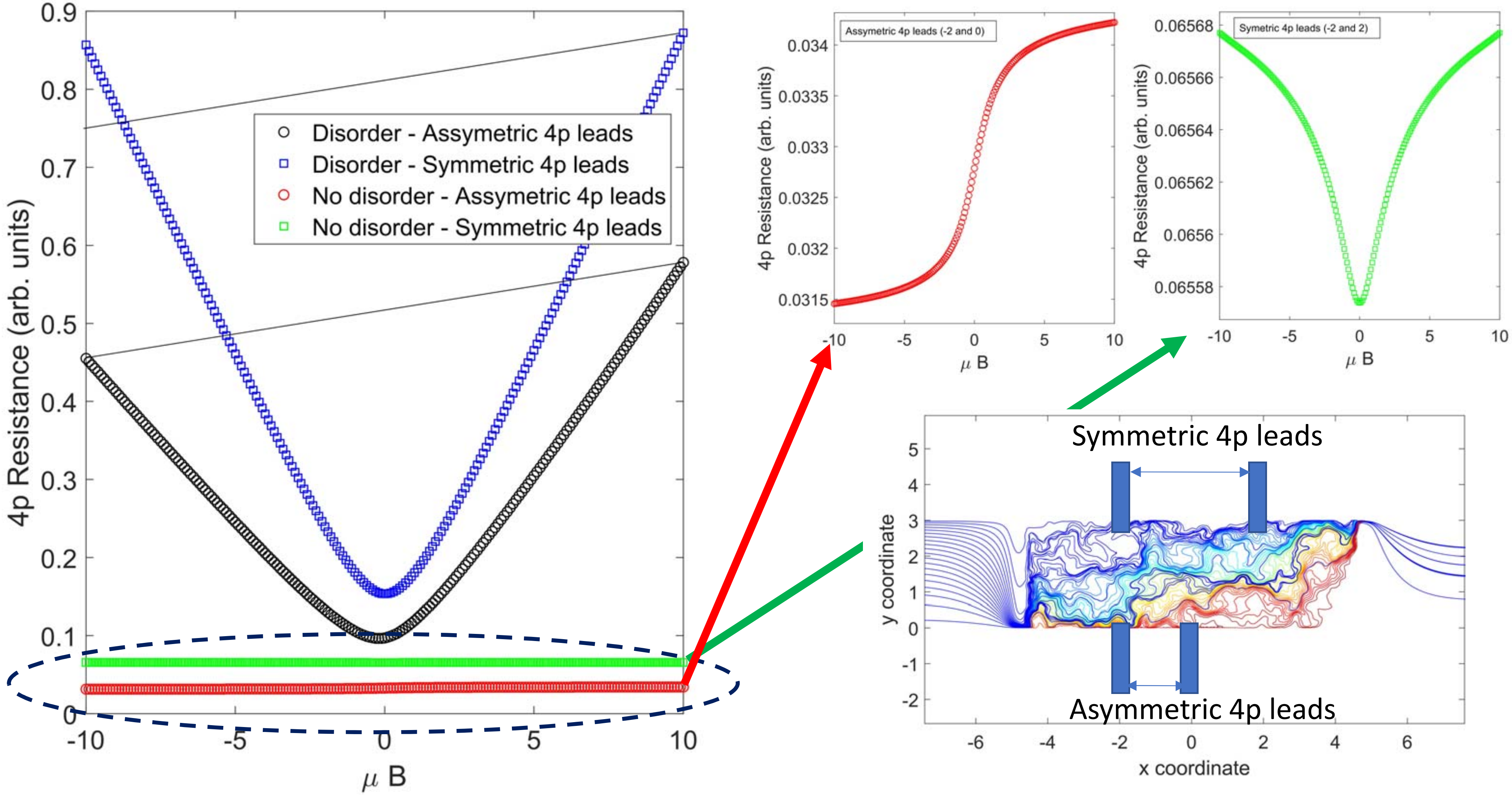
Mobility and conductivity fluctuations

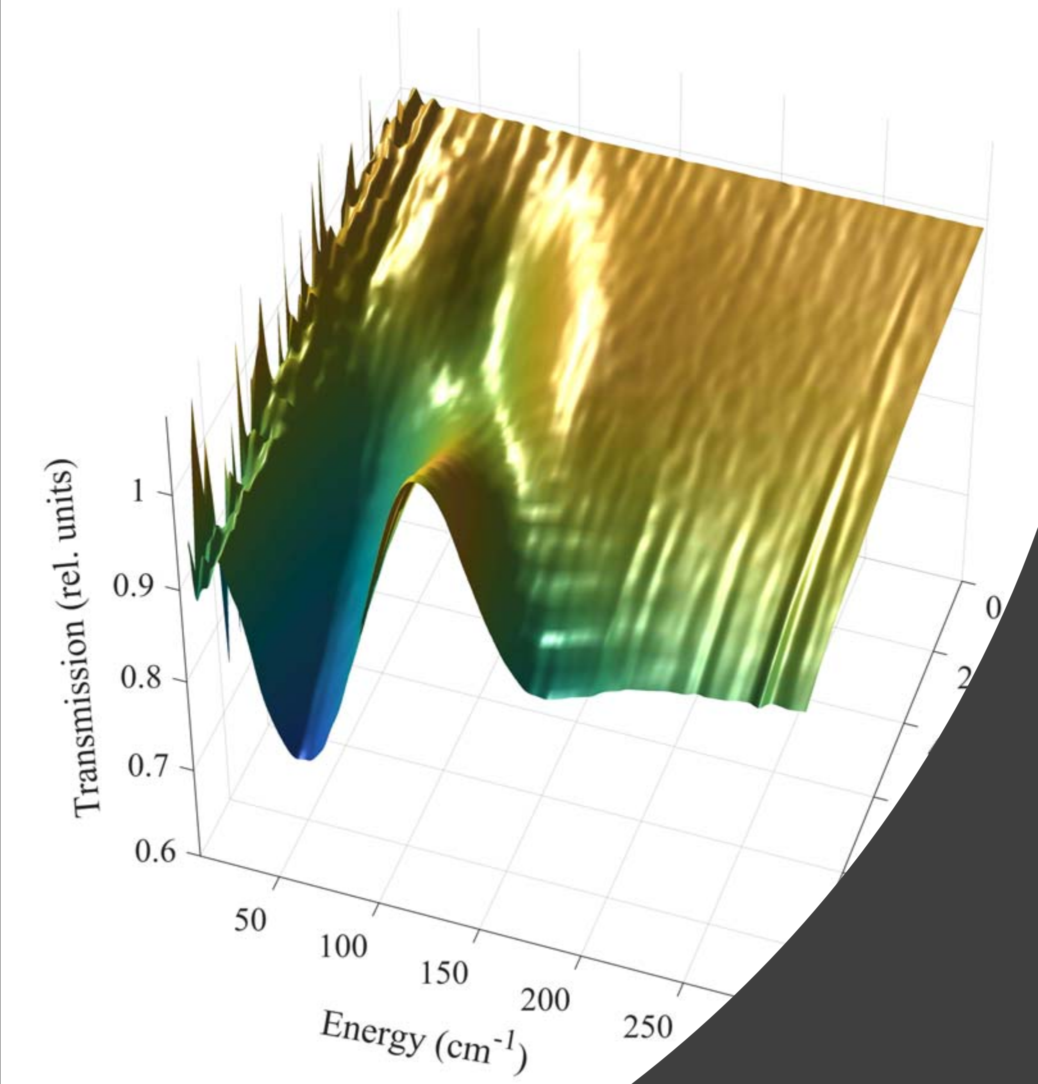


4 point measurements



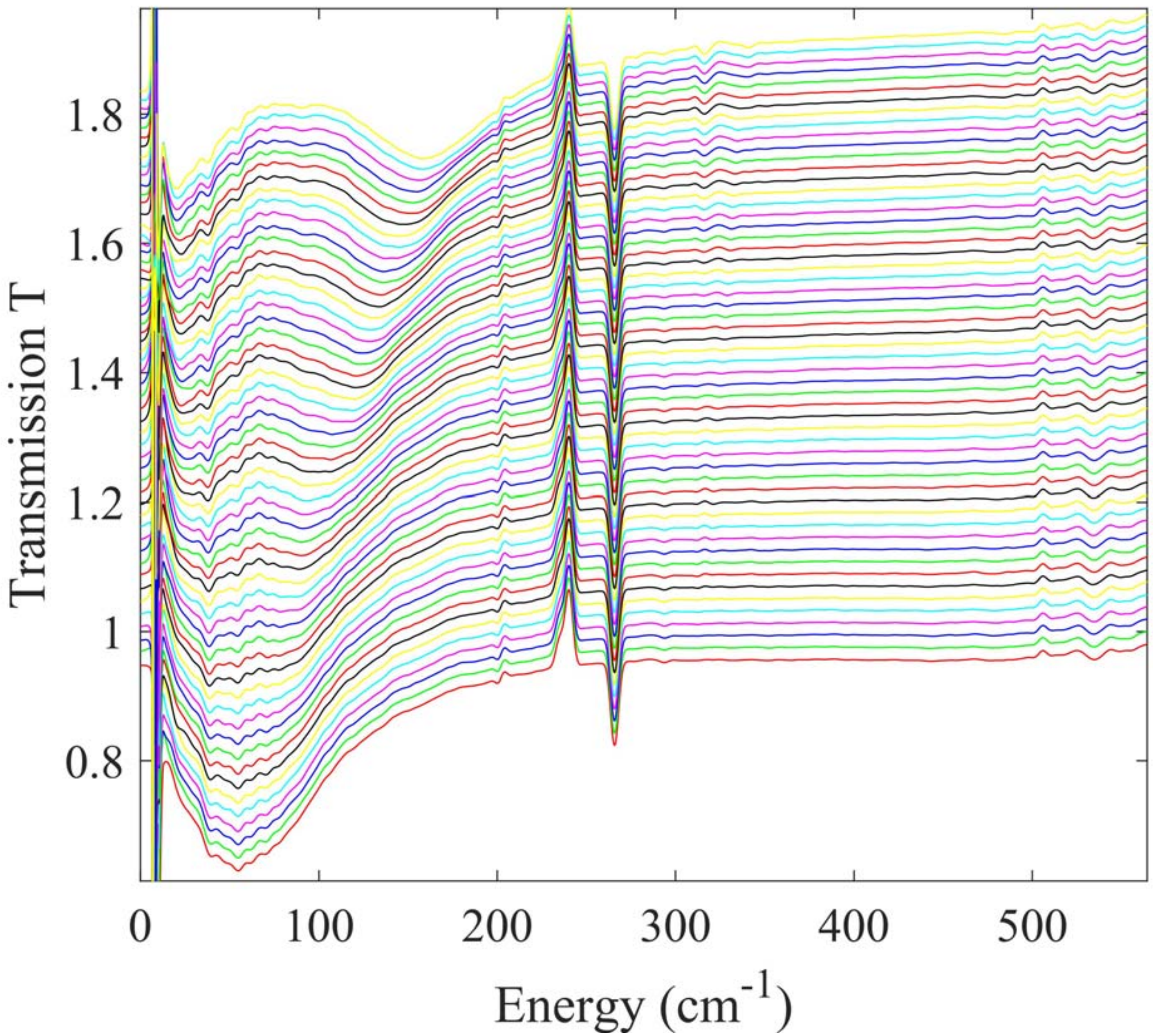
Conclusions:

- Quadratic to linear magnetoresistance crossover is caused solely by finite size geometry in a 2-point measurements
- The crossover occurs at about $\mu B = 1$
- Fluctuations of conductivity and mobility play a role in the magnetoresistance (both quadratic and linear), however; the role is minor in a two-point measurements.
- The role of disorder is crucial in a four-point measurements
- Asymmetry of the MR in 4-point measurements is also due to the non-axial location of voltage-sensing leads.
- Temperature dependence of MR is given by the temperature dependence of zero-field conductivity and mobility



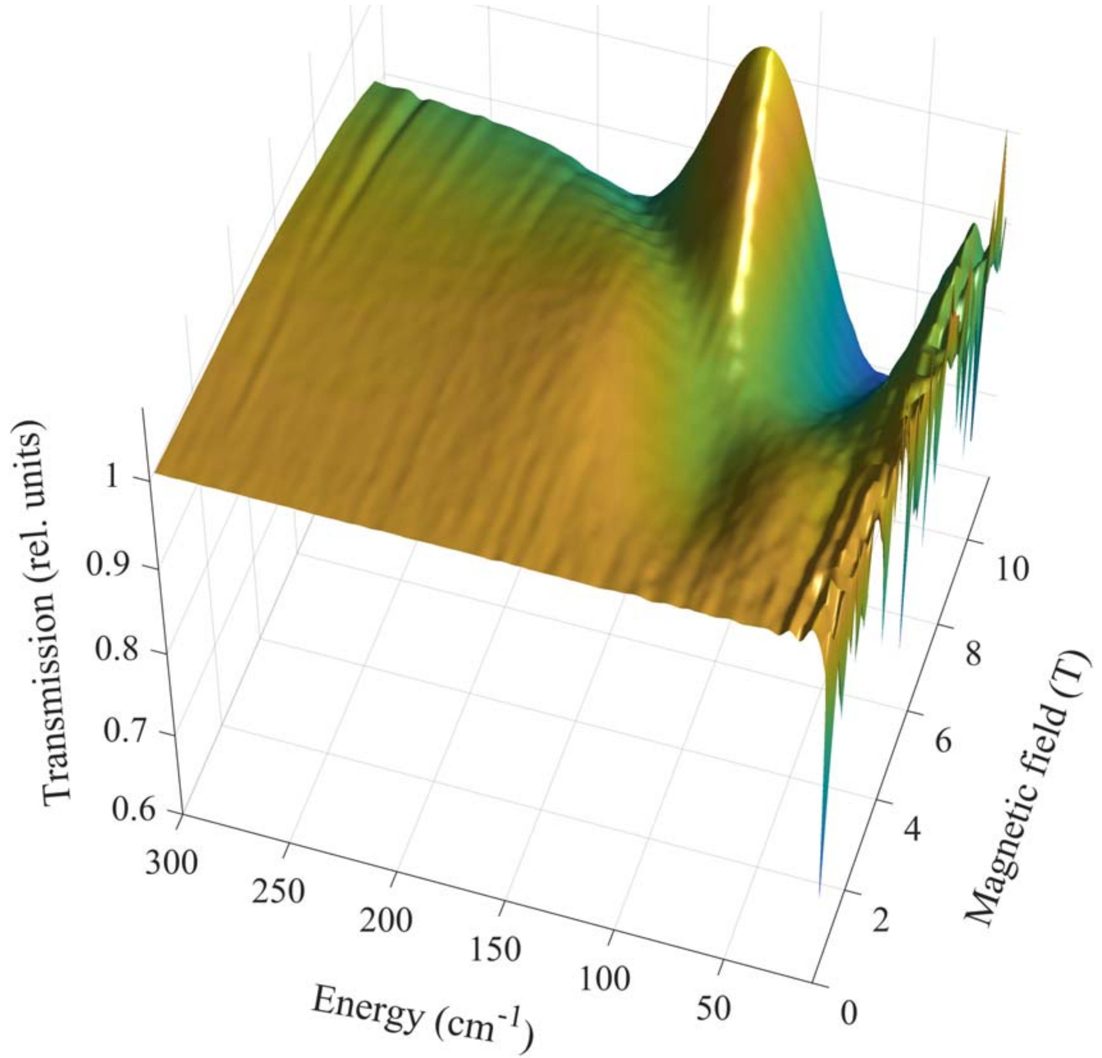
Magneto-plasmons in graphene

Transmittance

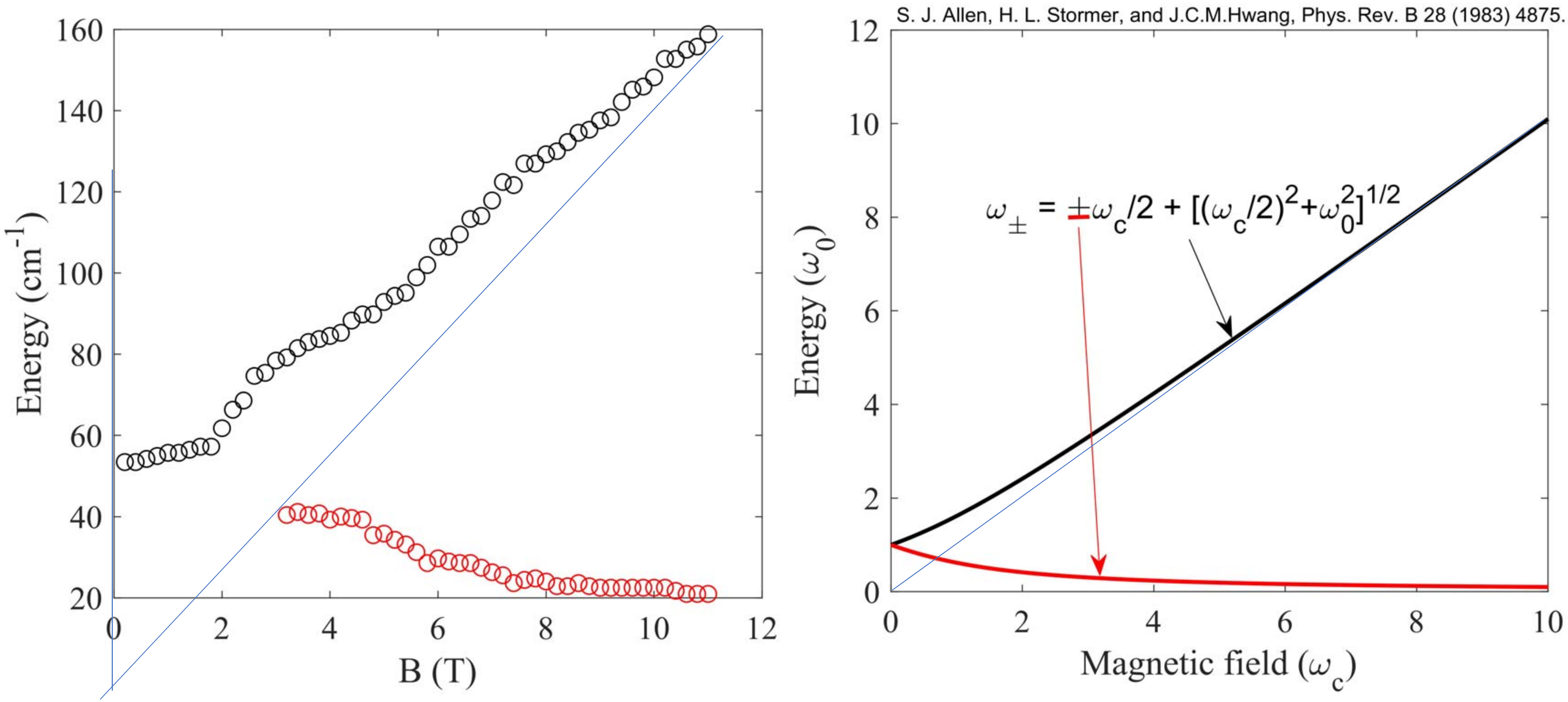


- Hydrogen intercalated buffer on SiC(0001) = quasi free-standing monolayer graphene
- The translational invariance broken by SiC step edges
- Single absorption peak at 50/cm at 0 T
- The absorption peak splits in two components (upper and lower branches)
  => magneto-plasmon

Relative-to-0T transmittance



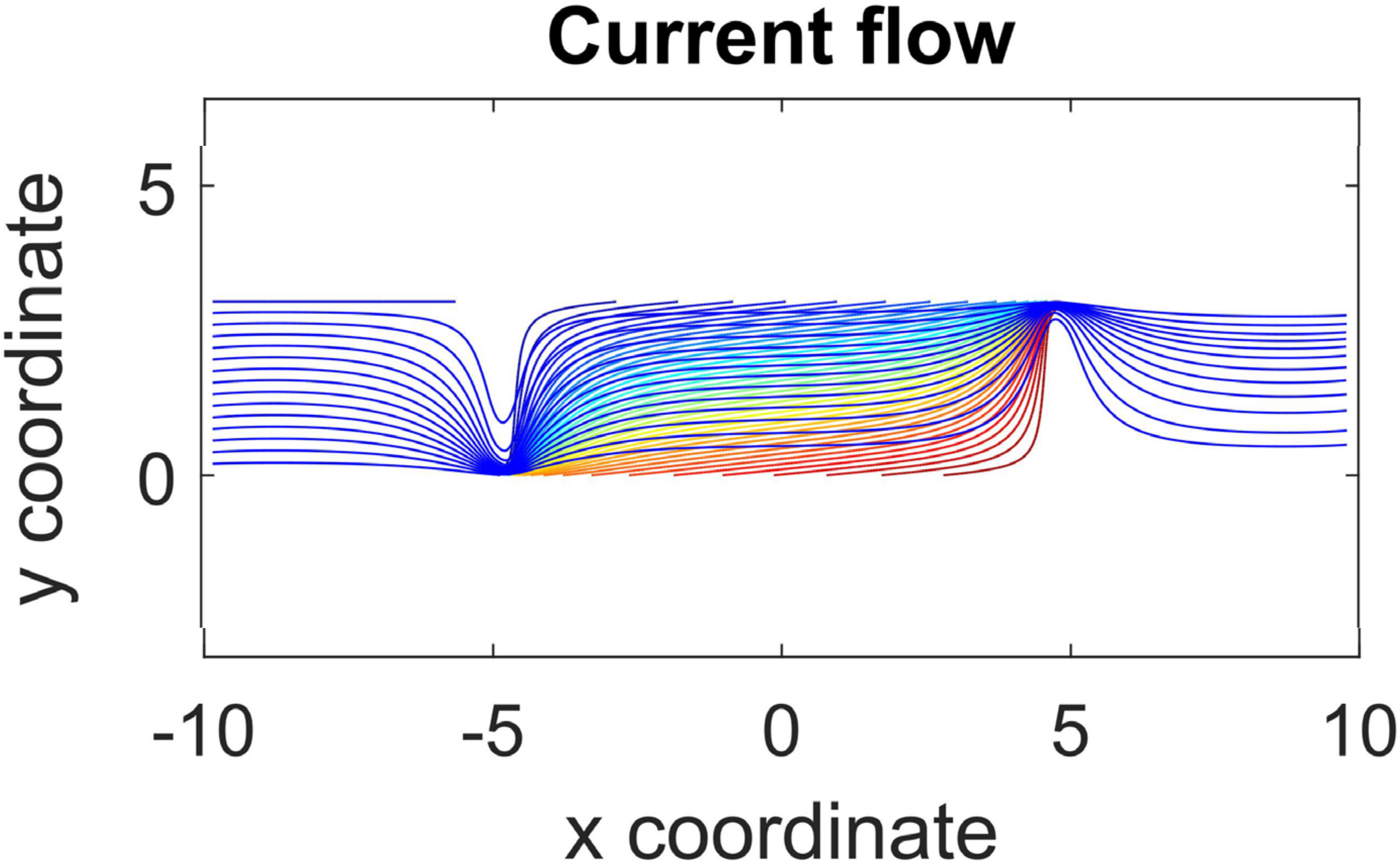
Comparison with theory



Conclusions:

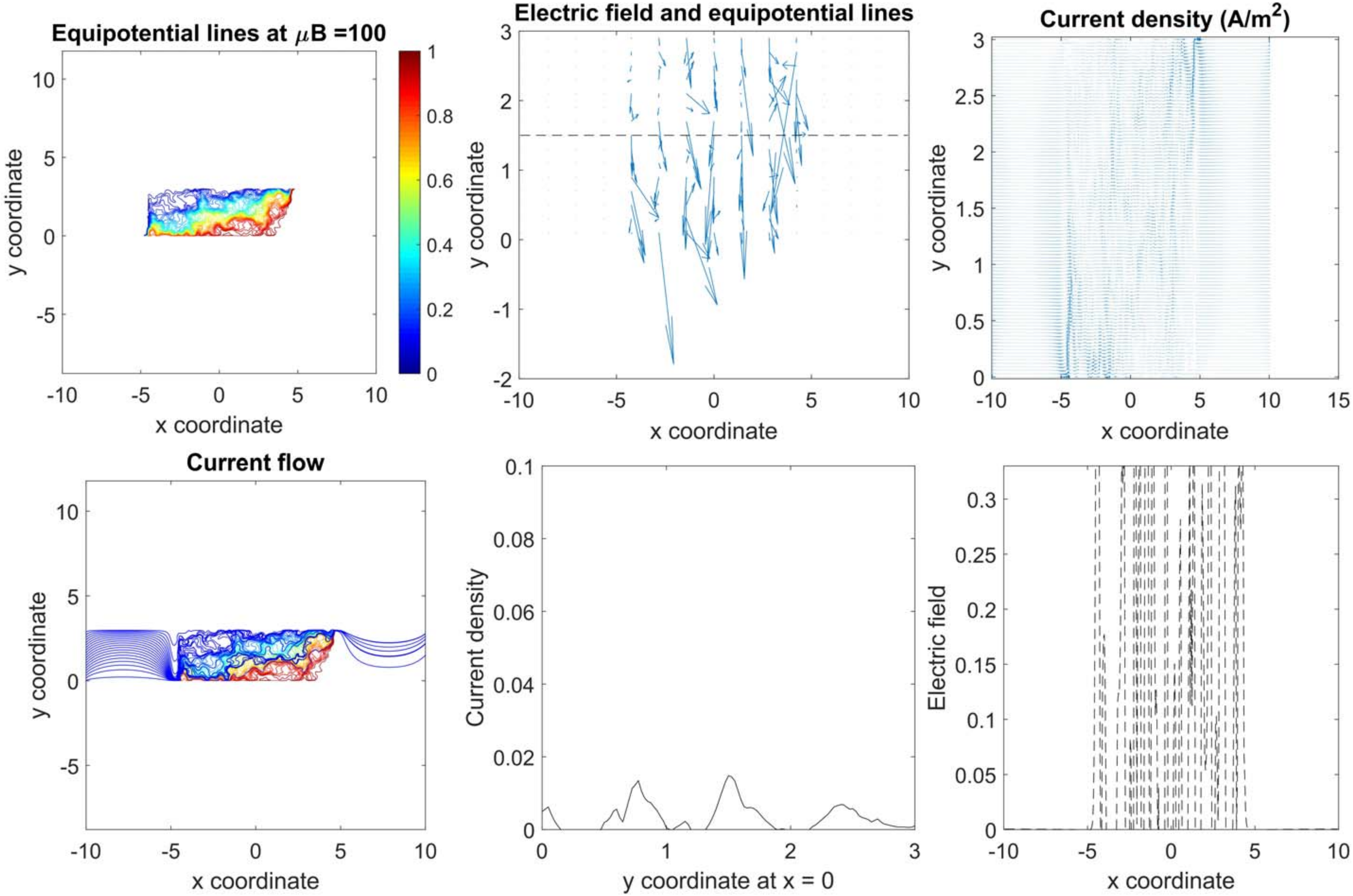
- We have observed plasmon resonance at zero magnetic field in quasi free-standing monolayer graphene on SiC
- The splitting of the plasmon resonance at high magnetic field corresponds to the lower and upper branch of magneto-plasmon
- Magneto-plason branches are qualitatively well-described by analytical theory.

Effect of external leads



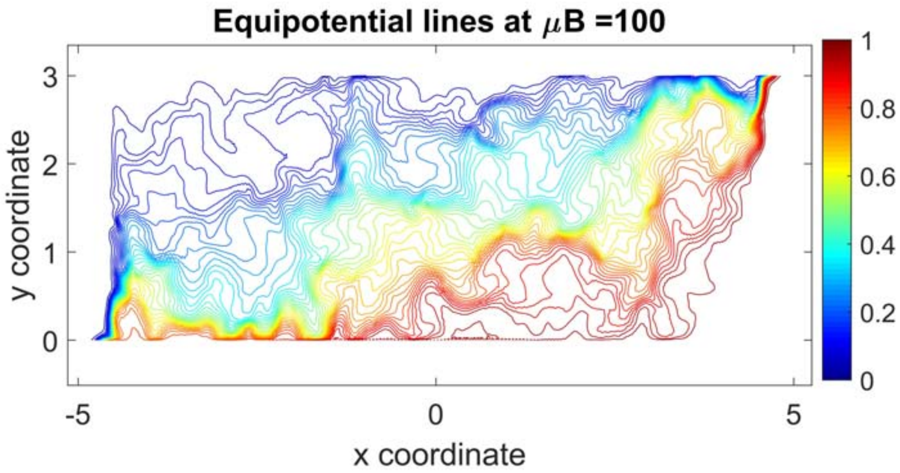
Historical perspectives

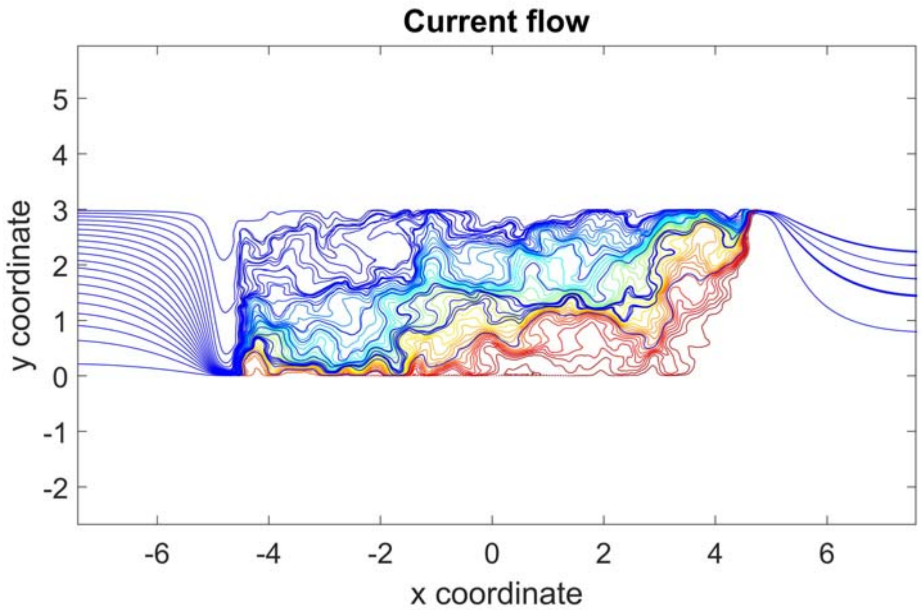
- Li et al. RSC Adv. 7 (2017) 26434, Linear magnetoresistance in gold foams
- Narayanan et al. Phys. Rev. Lett. 114 (2015) 117201, Linear Magnetoresistance caused by mobility fluctuations in n-doped Cd3As2
- Raichev, Phys. Rev. B 97 (2018) 245310, Effect of Landau quantization on linear magnetoresistance of a periodically modulated two-dimensional electron gas
- Simon, Halperin, Phys. Rev. Lett 73 (1994) 3278, relation between diagonal and off-diagonal conducitivity
- Tieke et al. Phys. Rev. Lett. 78 (1997) 4621, relation between electrical and thermoelectric properties
- Song et al. Phys. Rev. B 92 (2015) 180204(R), Linear magnetoresistance in metals: Guiding center diffusion in a smooth random potential.



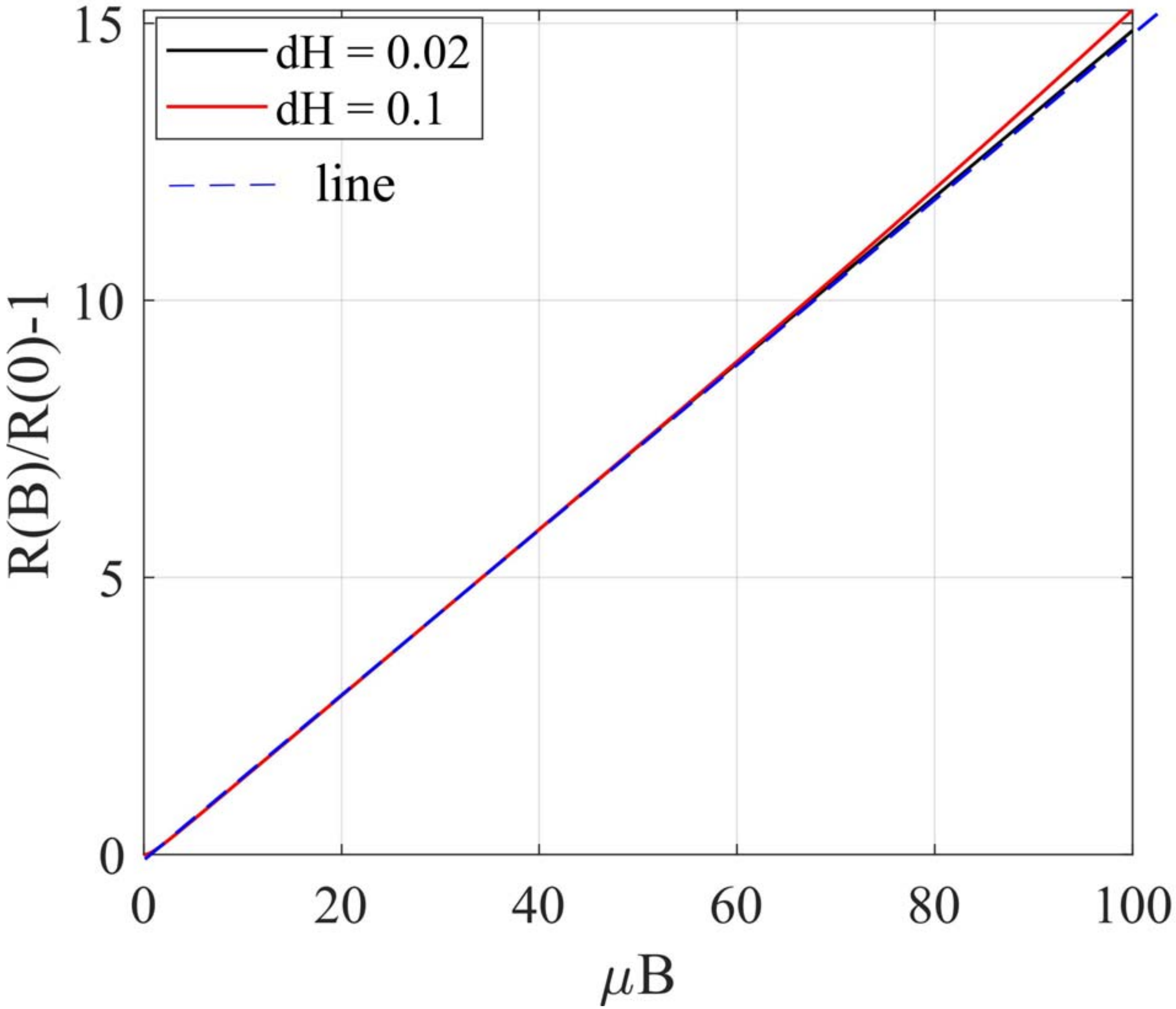
Equipotential lines at μB =100
Electric field and equipotential lines
Current density (A/m^2)
Current flow
x coordinate
y coordinate
Current density
y coordinate at x = 0
Electric field

Highly disordered conductor

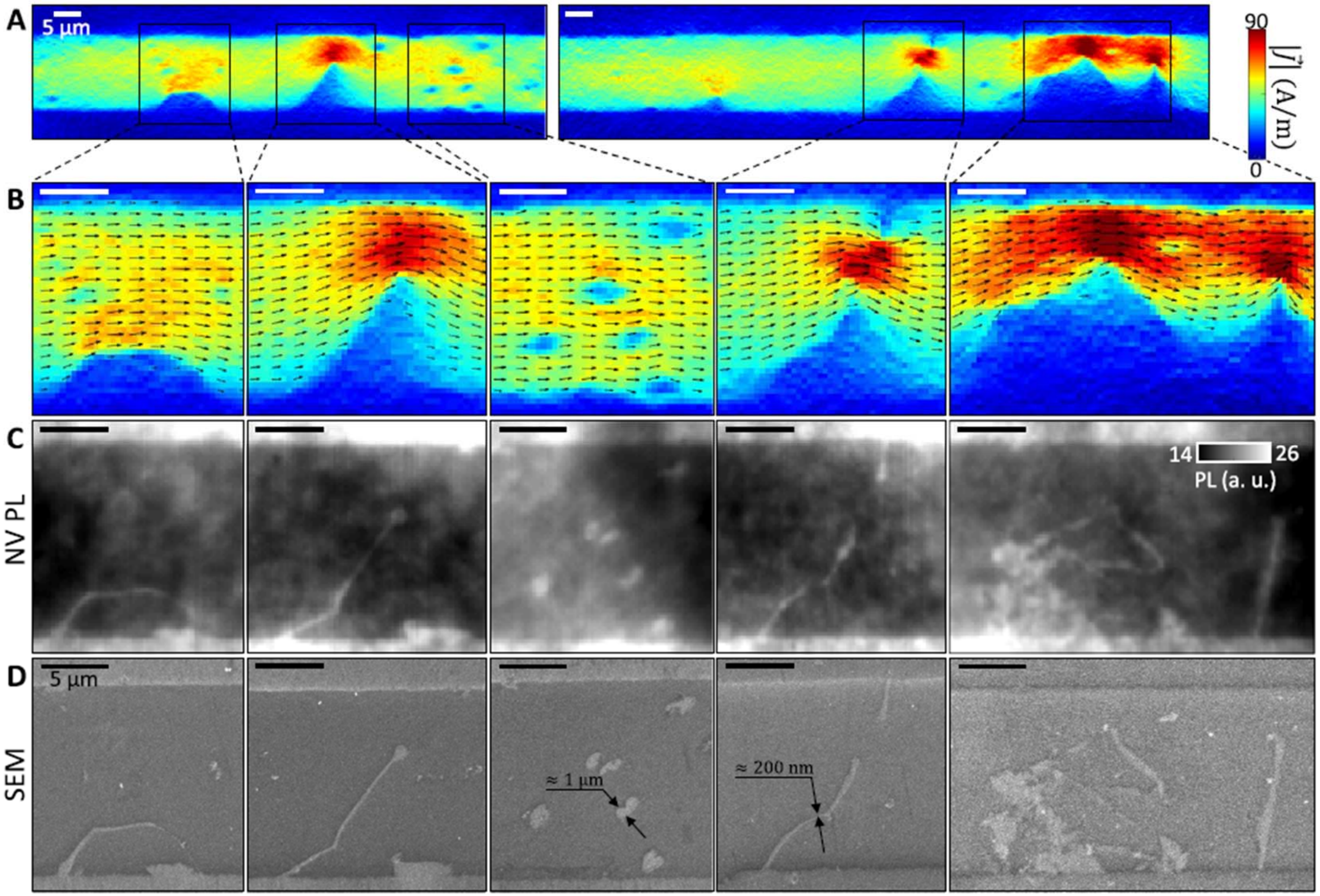




Numerical precision



Measured current distribution in graphene



J.-P. Tetienne et al., Sci. Adv. 3 (2017) e1602429.