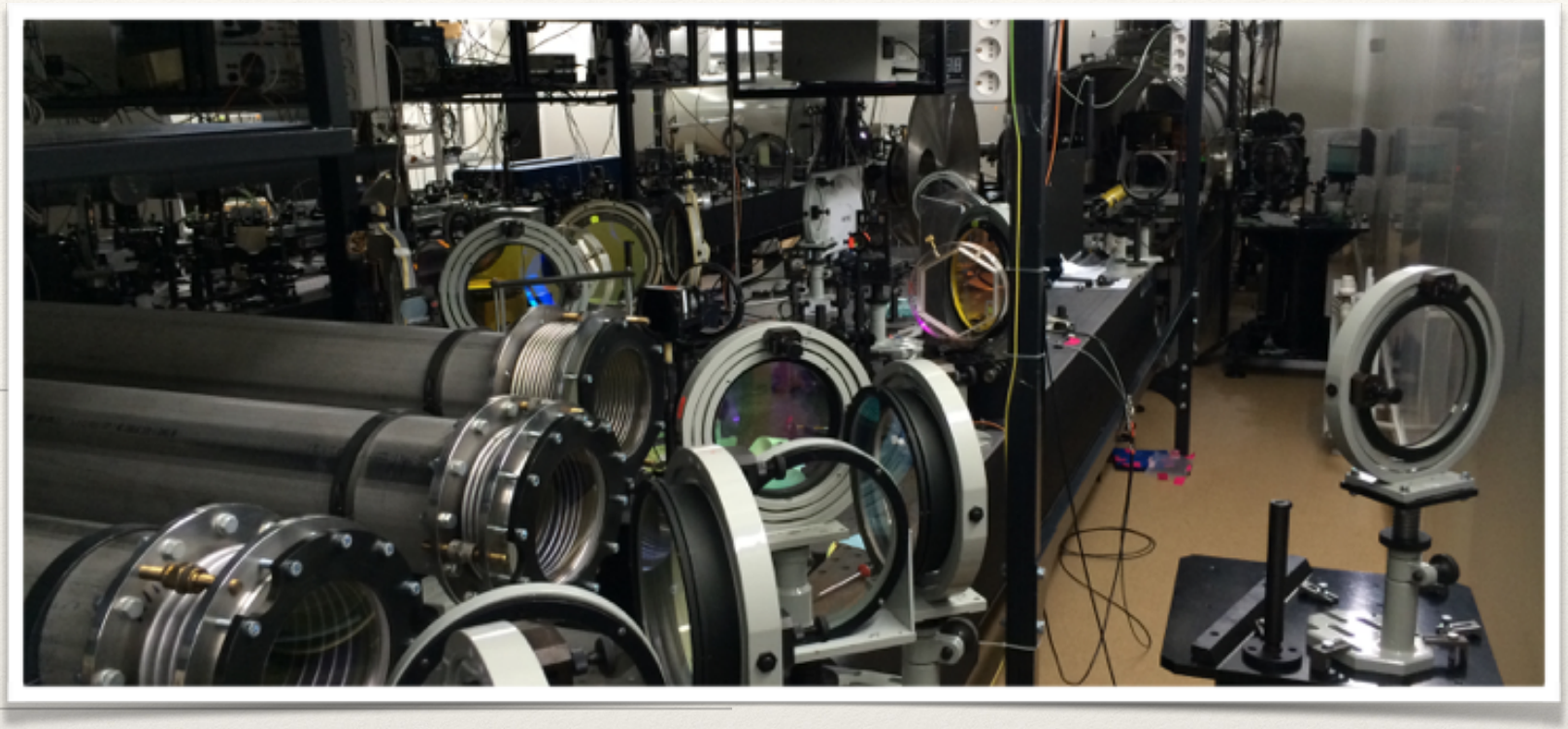

A. Soloviev[1], **K. Burdonov**[1], **S. N. Chen**[1,2], **A. Eremeev**[1], **G. Revet**[2], **S. Pikuz**[3], **E. Filippov**[3], **M. Cerchez**[4], **T. Gangly**[2], **A. Sladkov**[1], **A. Korzhimanov**[1], **V. Ginzburg**[1], **E. Khazanov**[1], **A. Kochetkov**[1], **A. Kuzmin**[1], **I. Shaykin**[1], **A. Shaykin**[1], **I. Yakovlev**[1], **M. Starodubtsev**[1], and **J. Fuchs**[1,2]

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[2] LULI, CNRS UMLR7605, Ecole Polytechnique, Palaiseau, France

[3] Joint Institute for High Temperatures, Russian Academy of Science, Moscow, Russia

[4] HHU, Dusseldorf, Germany

Laboratory investigation of laser plasma expansion across the ambient magnetic field

Collaborators

Соловьев А.А.[1]
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Хазанов Е.А.[1]
Кочетков А.А.[1]
Кузьмин А.А.[1],
Шайкин И.А.[1]
Шайкин А.А.[1]
Яковлев И.В.[1]

S. N. Chen[1,2]
G. Revet[2]
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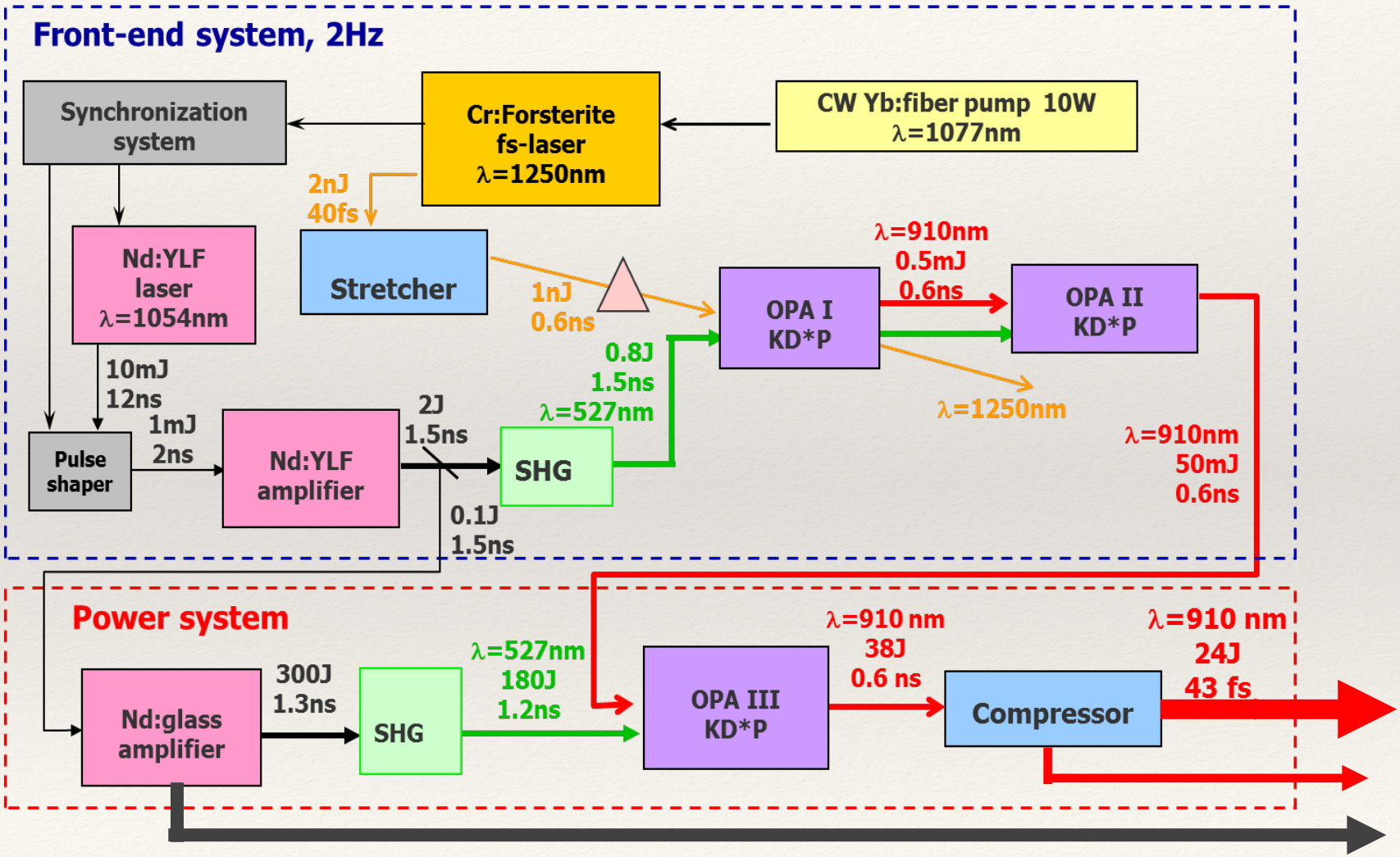
Пикуз С.А.[3]
Скобелев И.Ю.[3]
Рязянцев С.Н.[3]
Алхимова М.А.[3]
Филиппов Е.Д.[3]
Пикуз Т.А.[3]

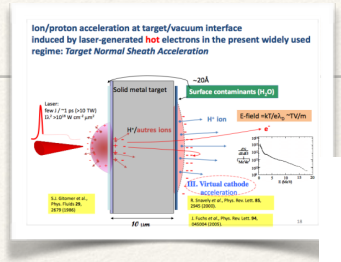
A. Chiardi[4]
B. Khiar[4]

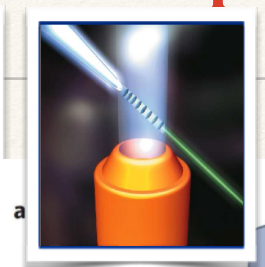
Sub-PW OPCPA PEARL laser facility

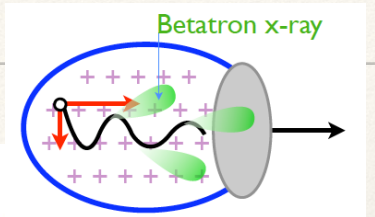


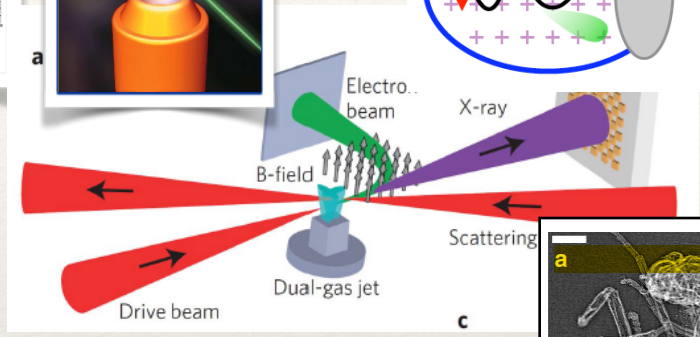
Laser-plasma interaction: applications

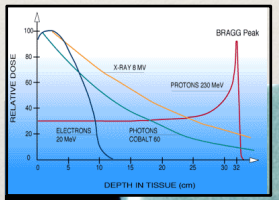
- Laser driven acceleration
  - Particles acceleration
  - X-ray generation.
- Applications
  - Radiotherapy
  - Bio-imaging
- HED physics
  - LabAstro
  - ICF

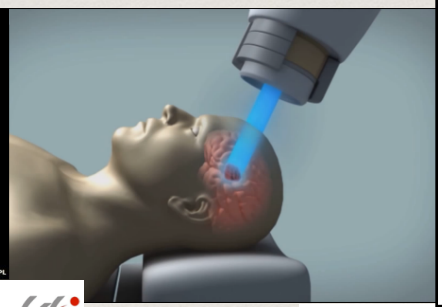


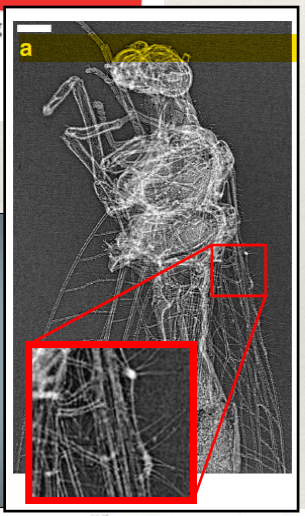


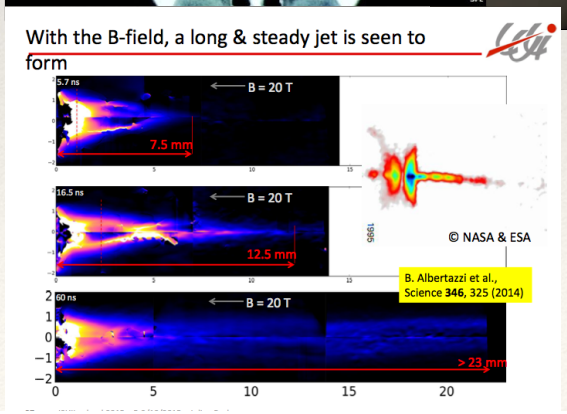


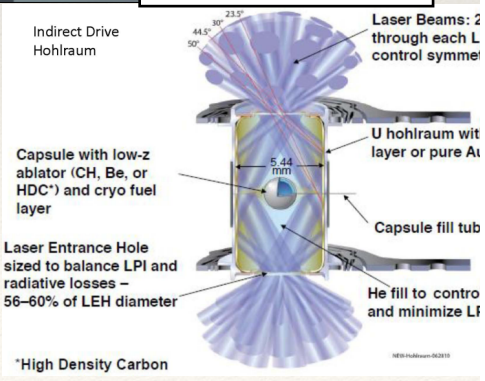






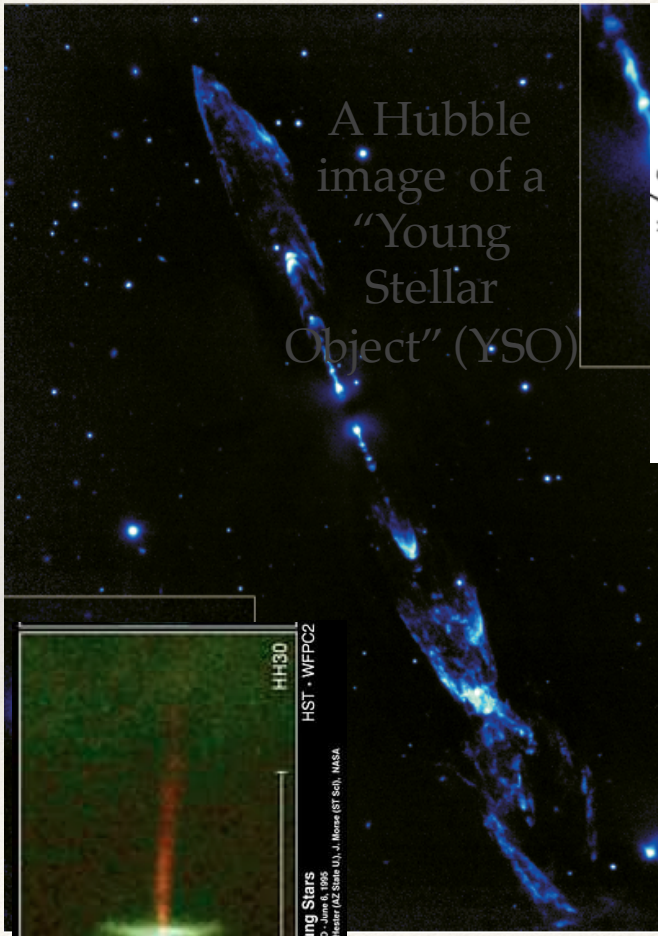


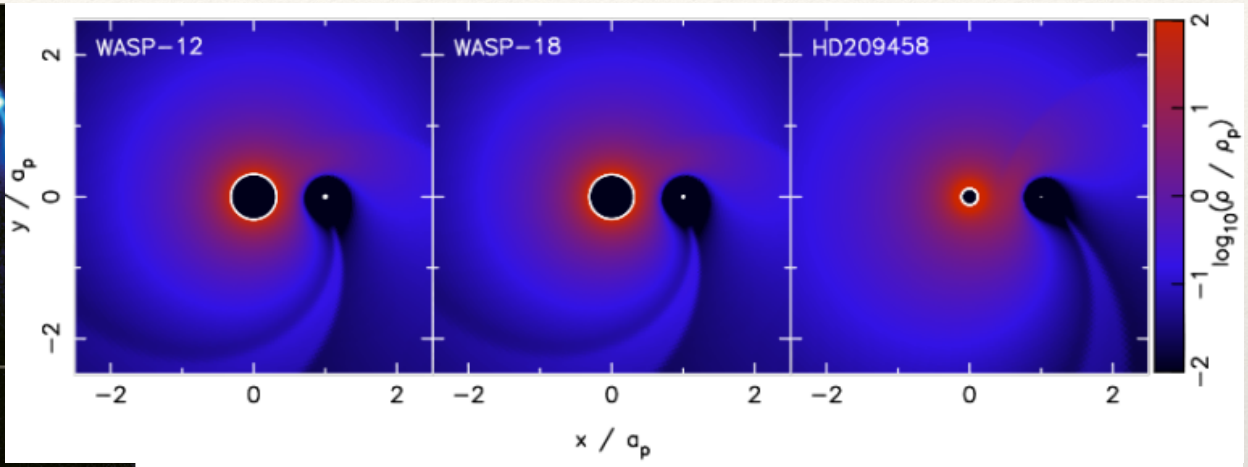


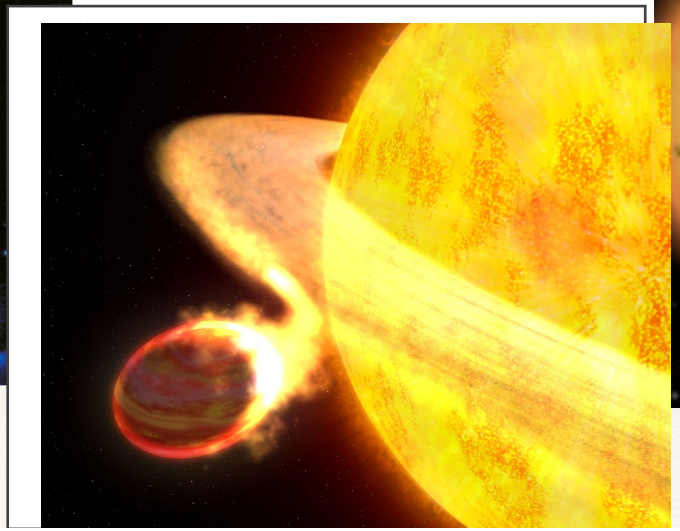


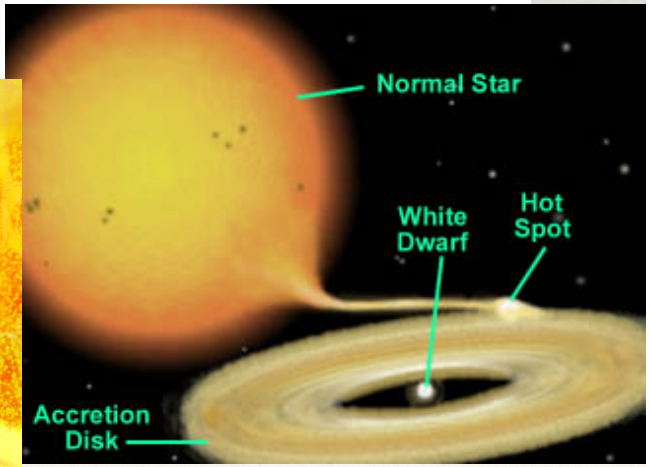
Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

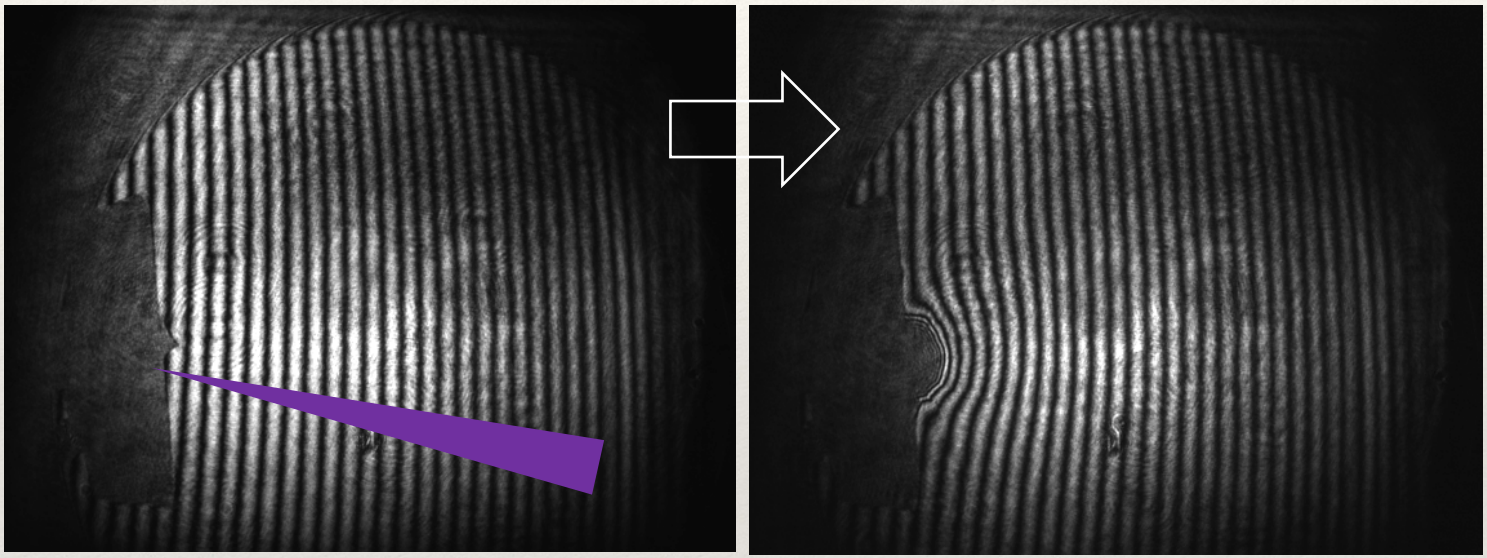








Initial laser-plasma conditions



Initial laser-plasma conditions

Ne = 3e18 cm-3, Z = 6.3, Te = 200 eV, Ti = 200 eV, B0 = 13.5 T, V = 600 km/s, L = 0.4 cm

'v_s(km/s) = ' [104.2111]

'v_A(km/s) = ' [104.4661]

'lambda_e(um) = ' [43.3147]

'lambda_i(um) = ' [1.4920]

'rho_e(um) = ' [2.4975]

'rho_i(um) = ' [69.1992]

'M(Mach) = ' [5.7575]

'M_A(Afven Mach) = ' [5.7435]

'beta(p_th/p_b) = ' [1.5259]

'beta_dy(p_dynamic/p_b) = ' [65.5693]

'Pe_heat (Peclet) = ' [4.3136]

'Re (Reynolds) = ' [1.7794e+005]

'ReM (magnetic Reynolds) = ' [2.2529e+003]

'Hall_e = ' [17.3433]

'Hall_i = ' [0.0216]

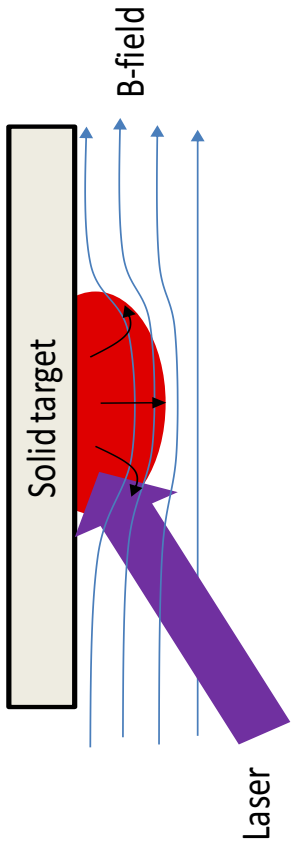
'Pr (Prandtl) = ' [0.0379]

'p_b(magn. press., MPa) = ' [72.9000]

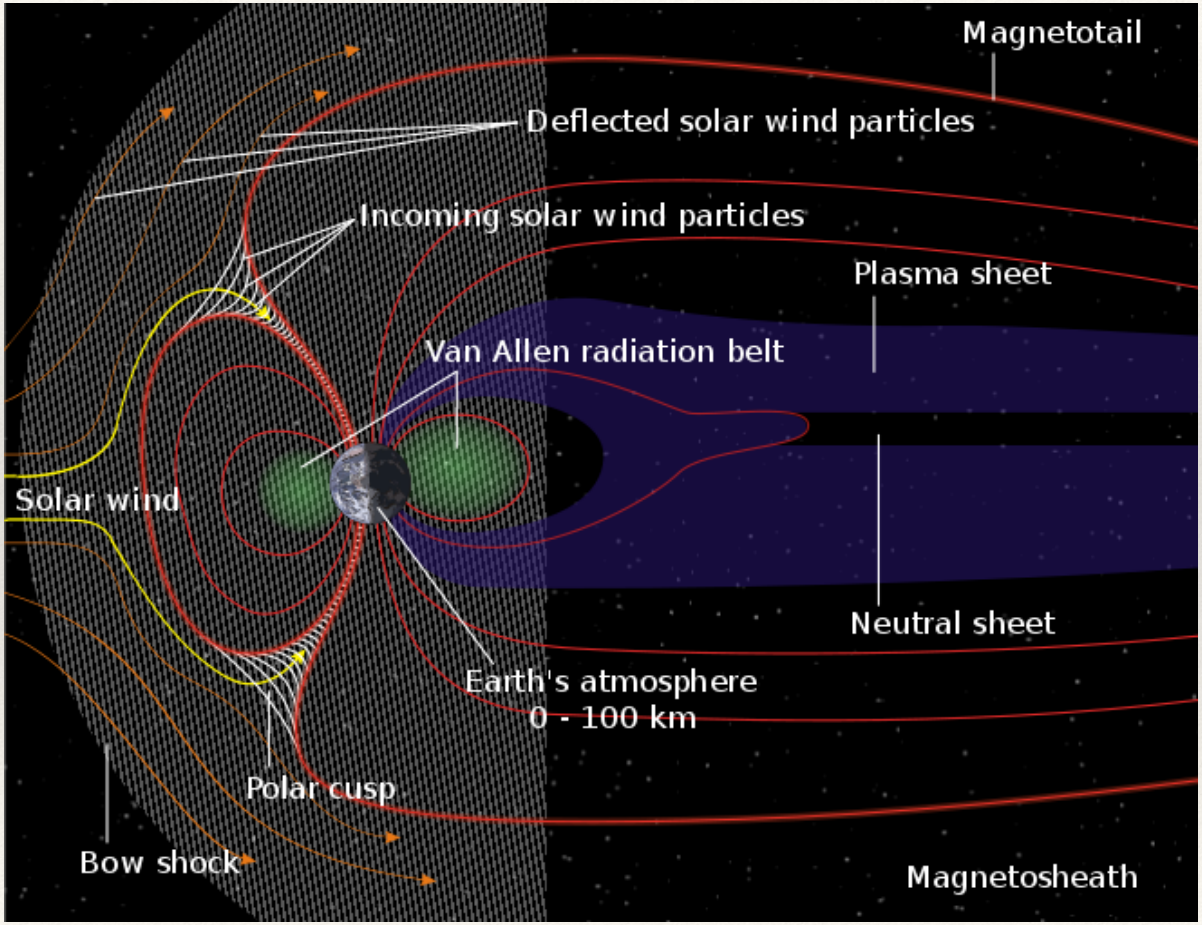
'p_th(kin. press., MPa) = ' [111.2381]

'p_dy(ram press., MPa) = ' [3.6875e+003]

'c/omega_pi(um) = ' [545.7387]



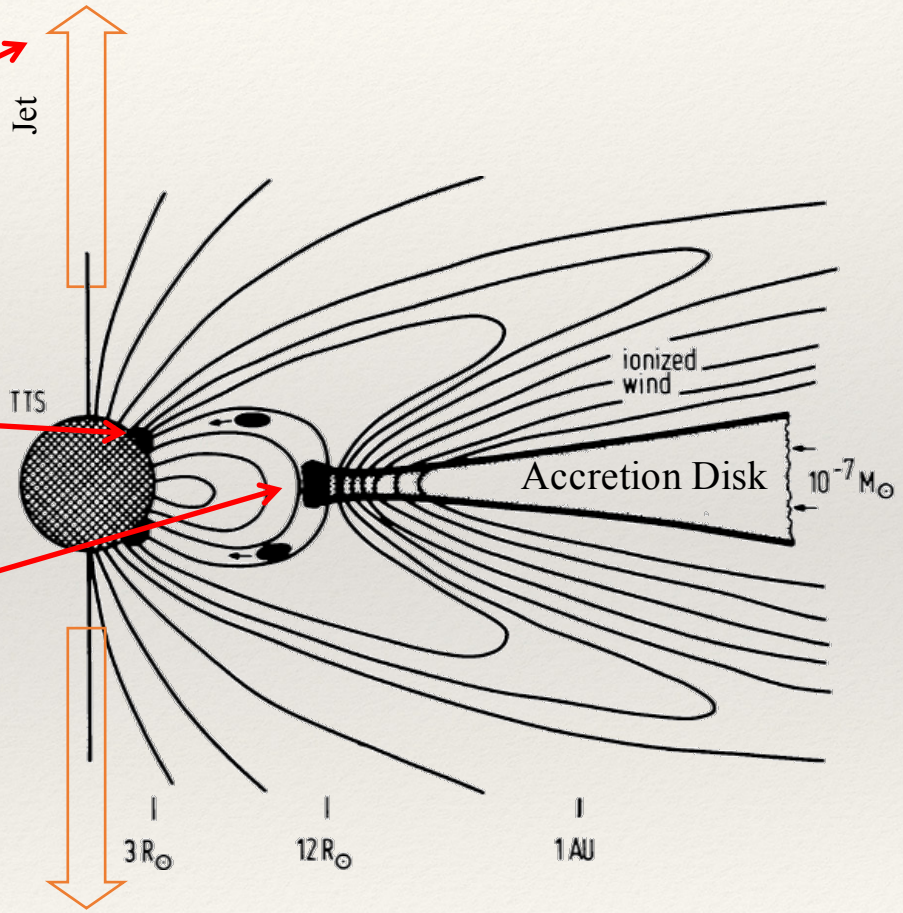
Space plasma processes



Space plasma processes

- Modeling of magneto-hydrodynamic plasma phenomena

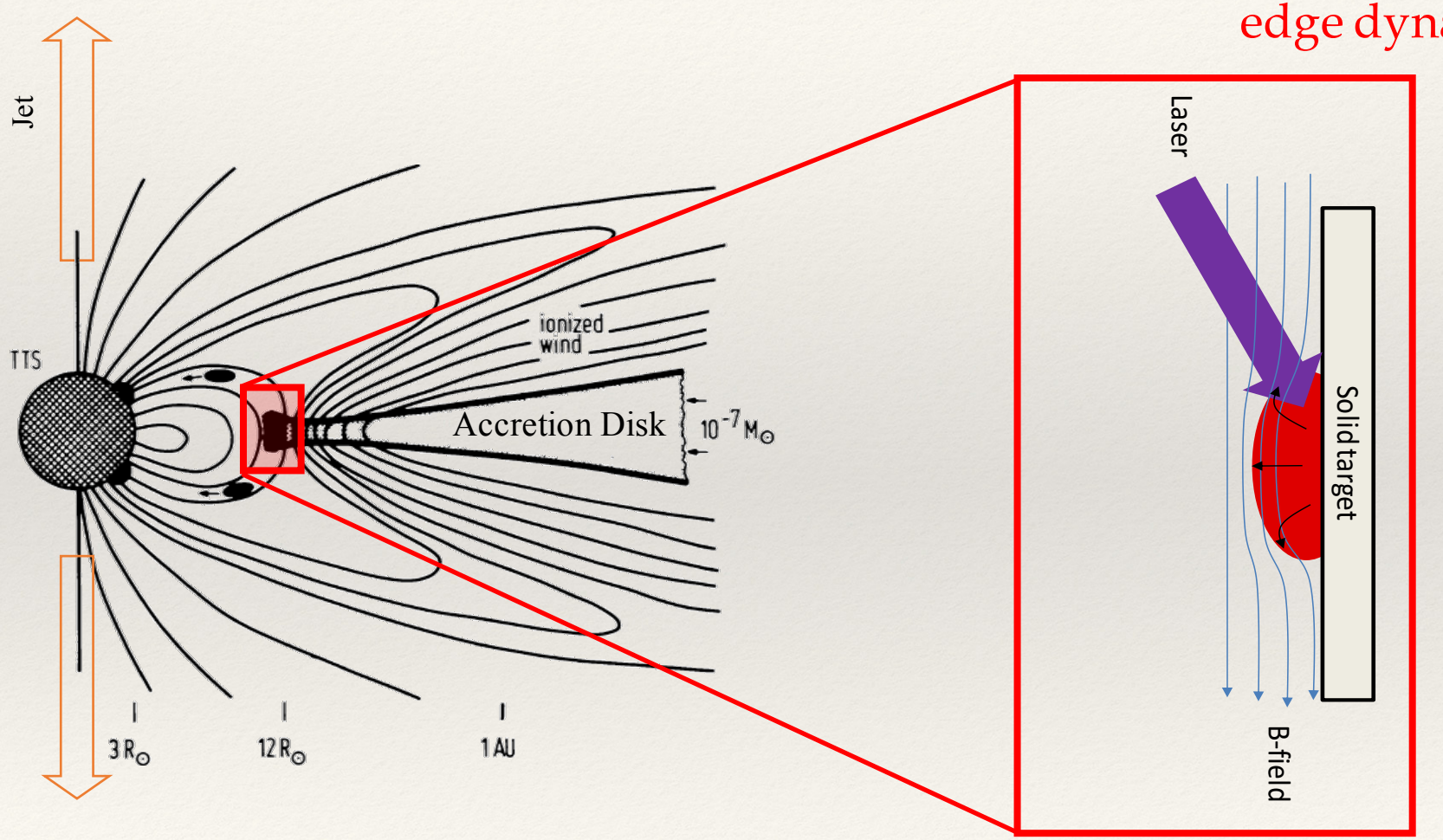
- ❑ Jet formation:
  effect of poloidal magnetic field.
- ❑ Accretion column:
  magnetized plasma flow interaction with surface.
- ❑ Accretion disc dynamics
  in the vicinity of β~1.



Adapted from Camenzind, (1990).

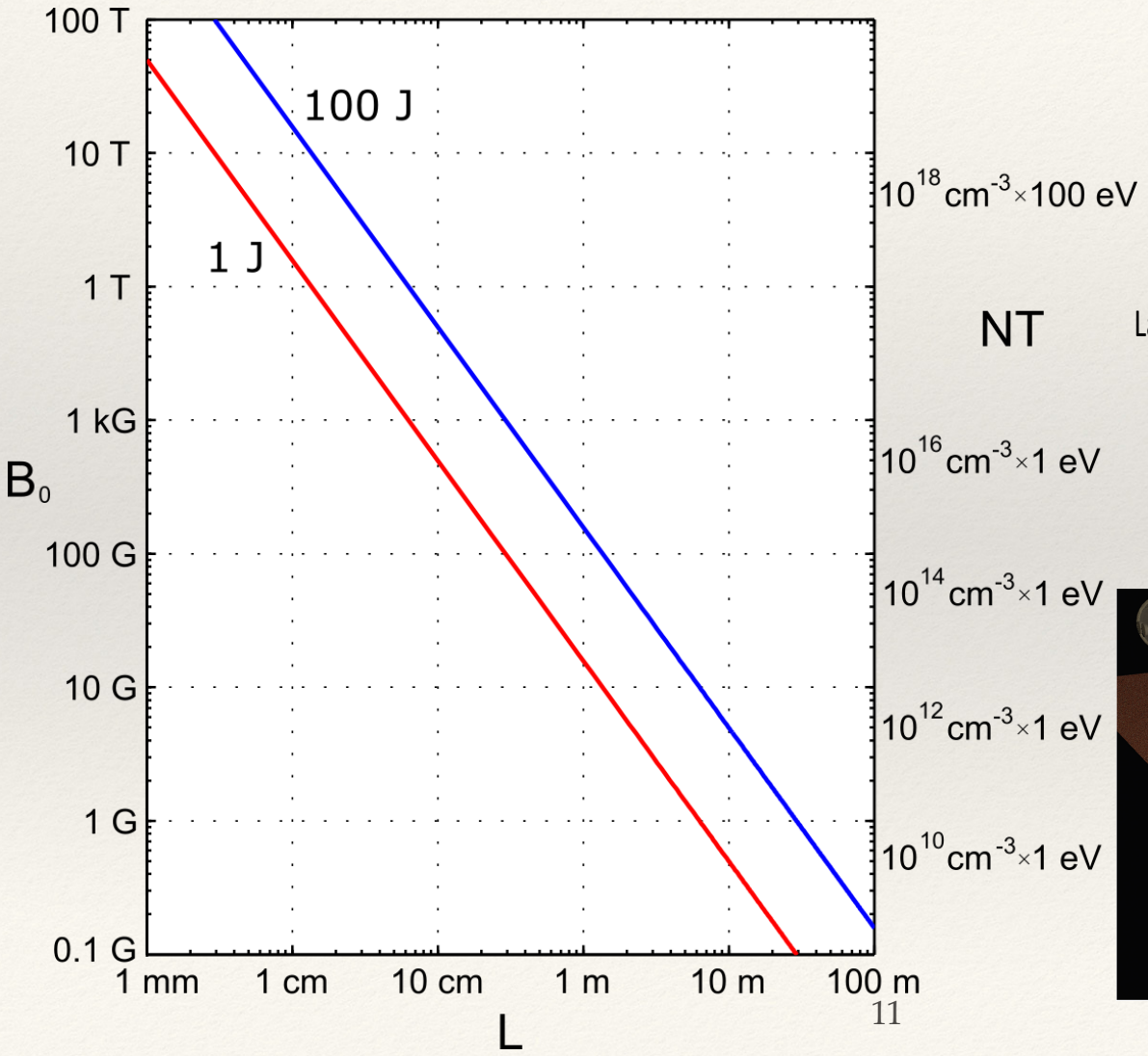
Space plasma processes

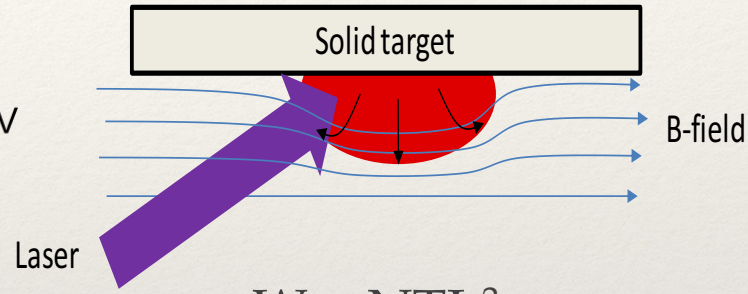
- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc edge dynamics



Adapted from Camenzind, (1990).

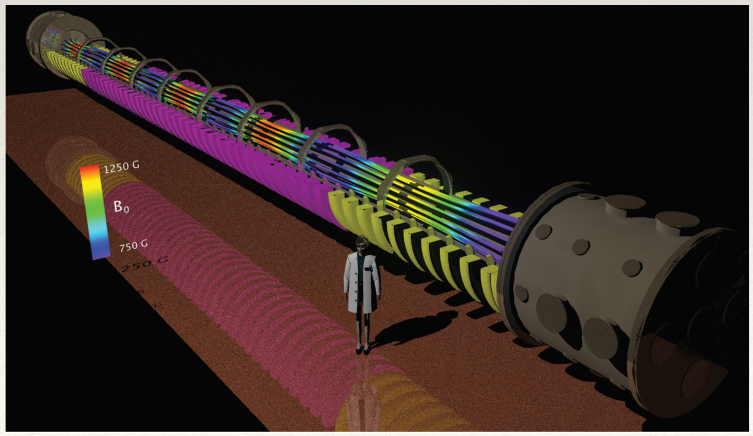
Modeling of MHD processes: scaling



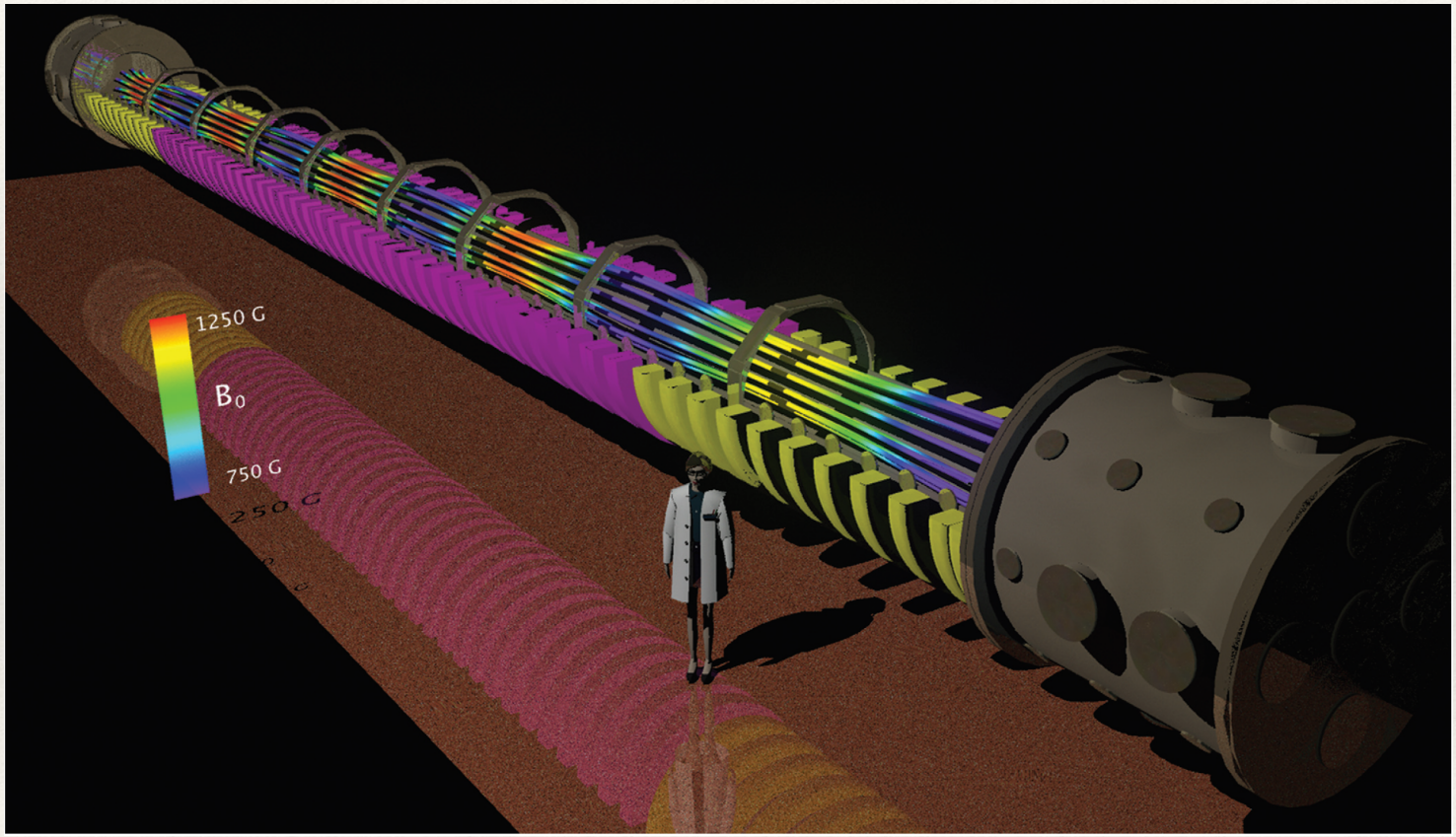


$$W = NTL^3$$

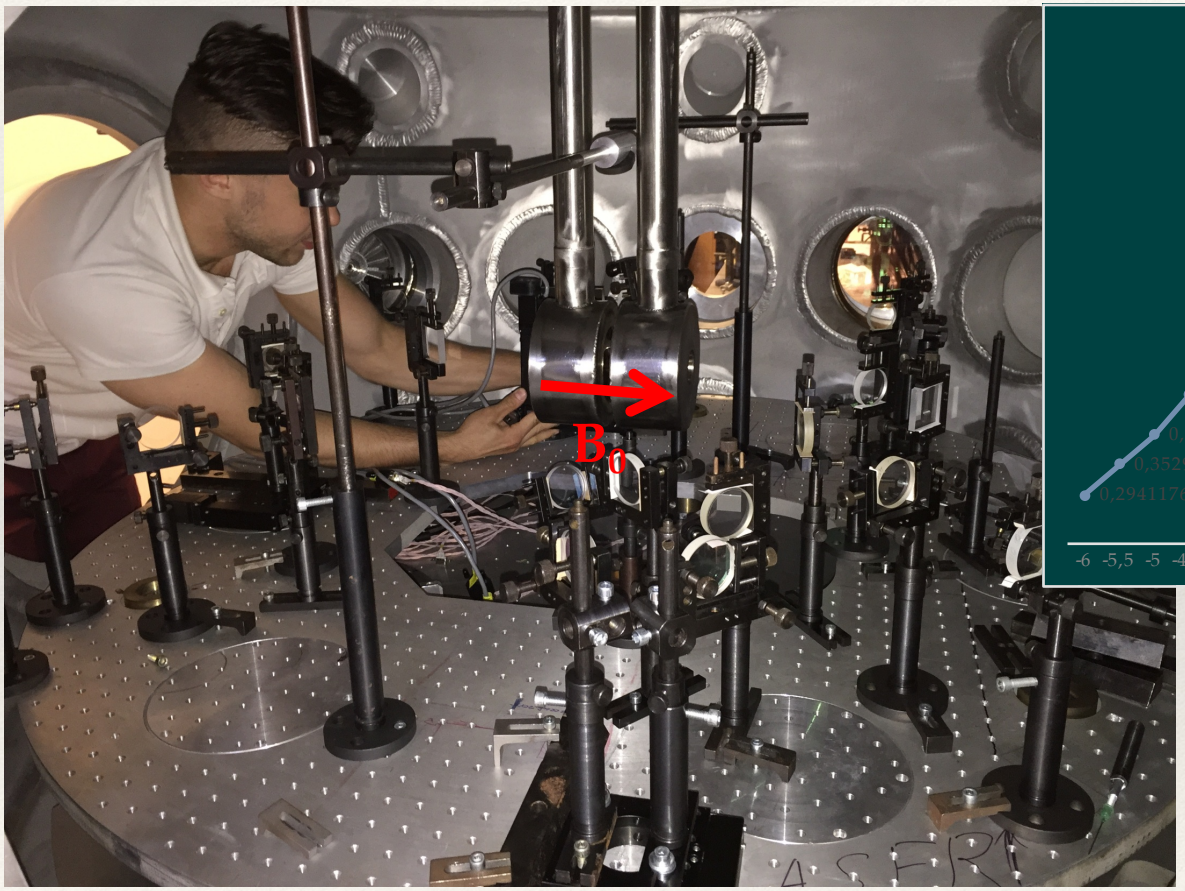
$$NT = B^2/8\pi$$

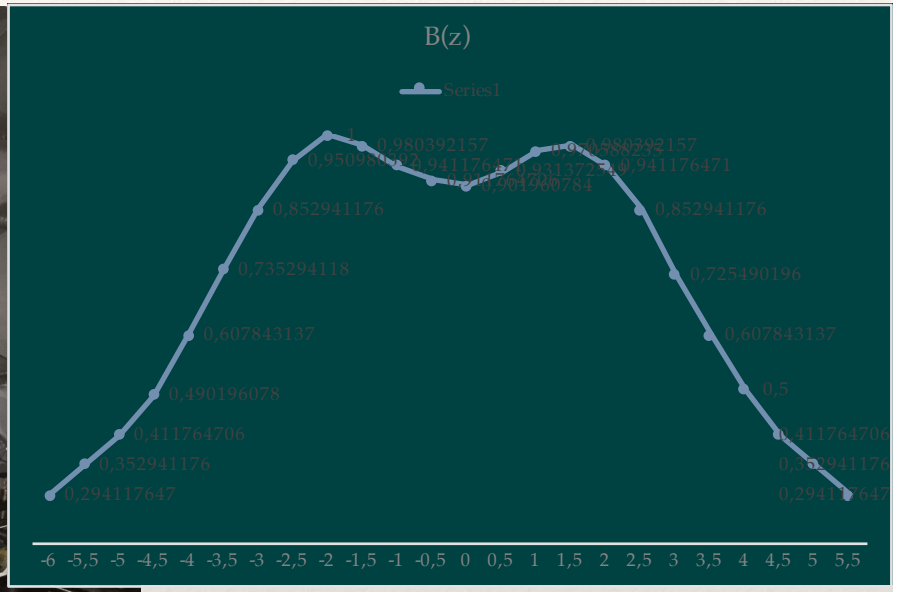


LAPD (UCLA)



Modeling of MHD processes: experiment

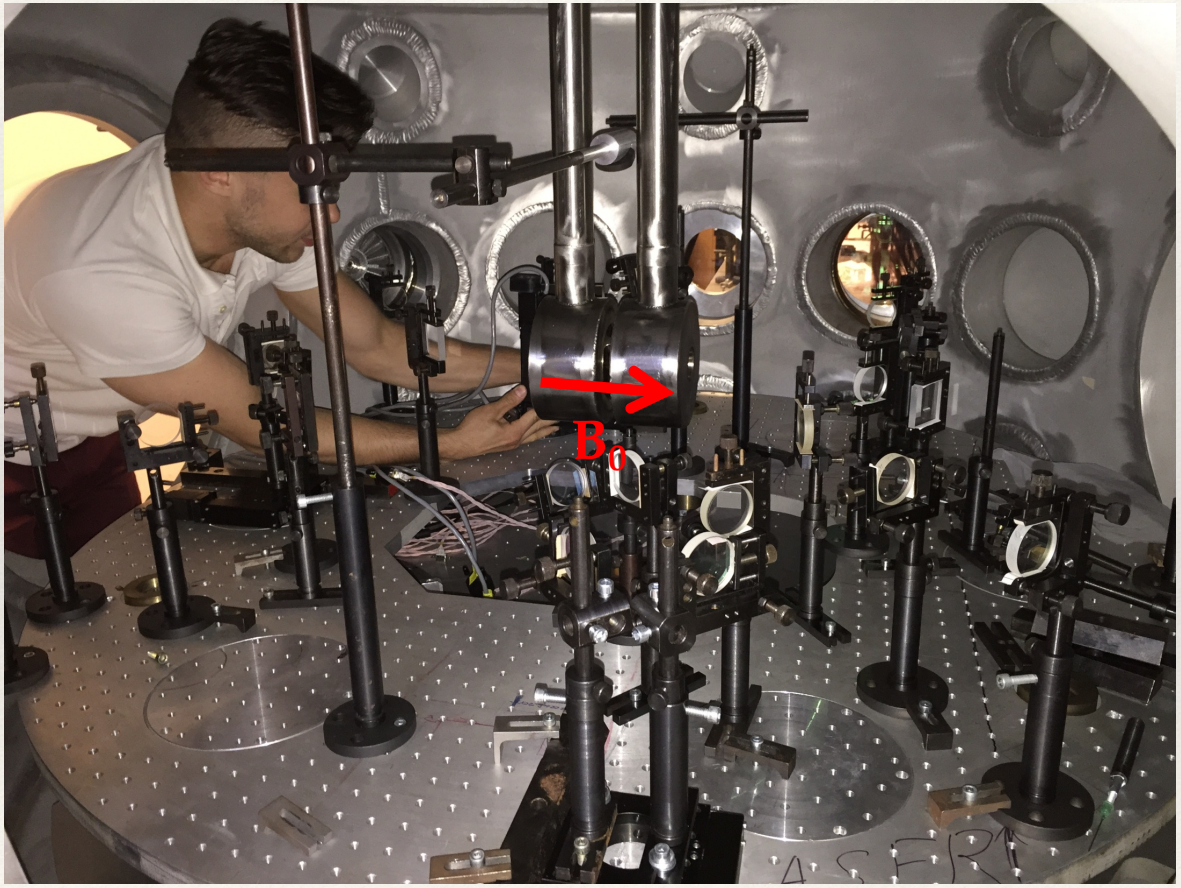


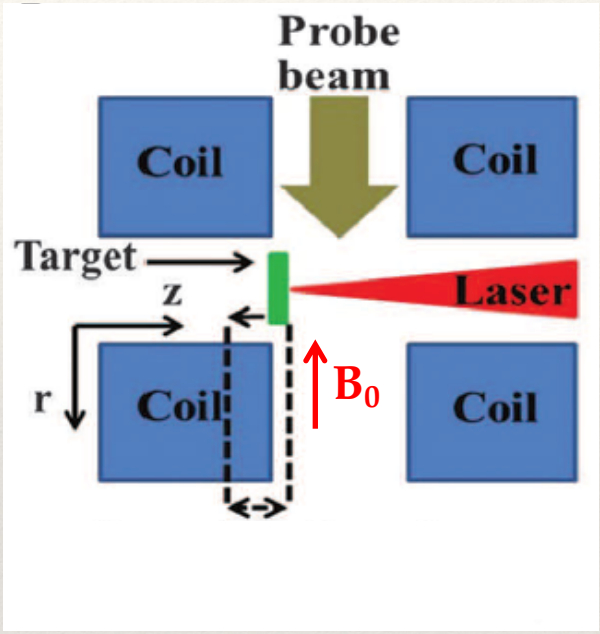


Ambient magnetic field

- Split pulsed solenoid
- Uniform configuration (15 T)
- “Zero-point” configuration

Modeling of MHD processes: experiment





Ambient magnetic field

- Split pulsed solenoid
- Uniform configuration (15 T)
- "Zero-point" configuration

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

- Jet formation:
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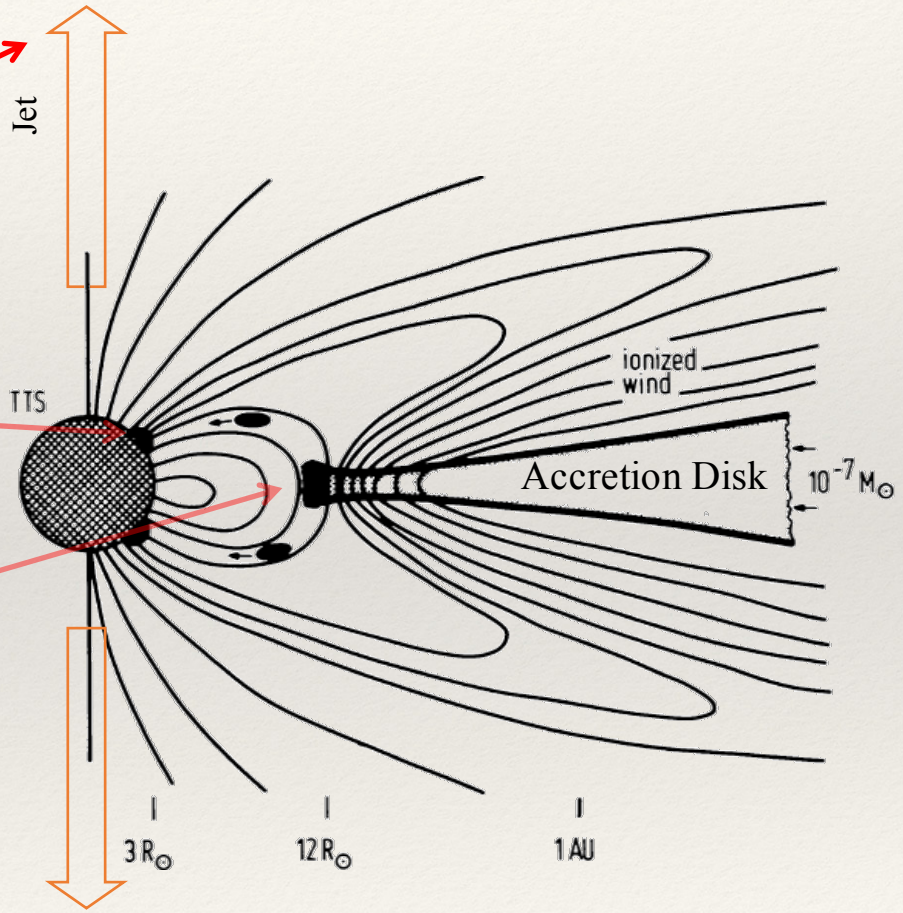
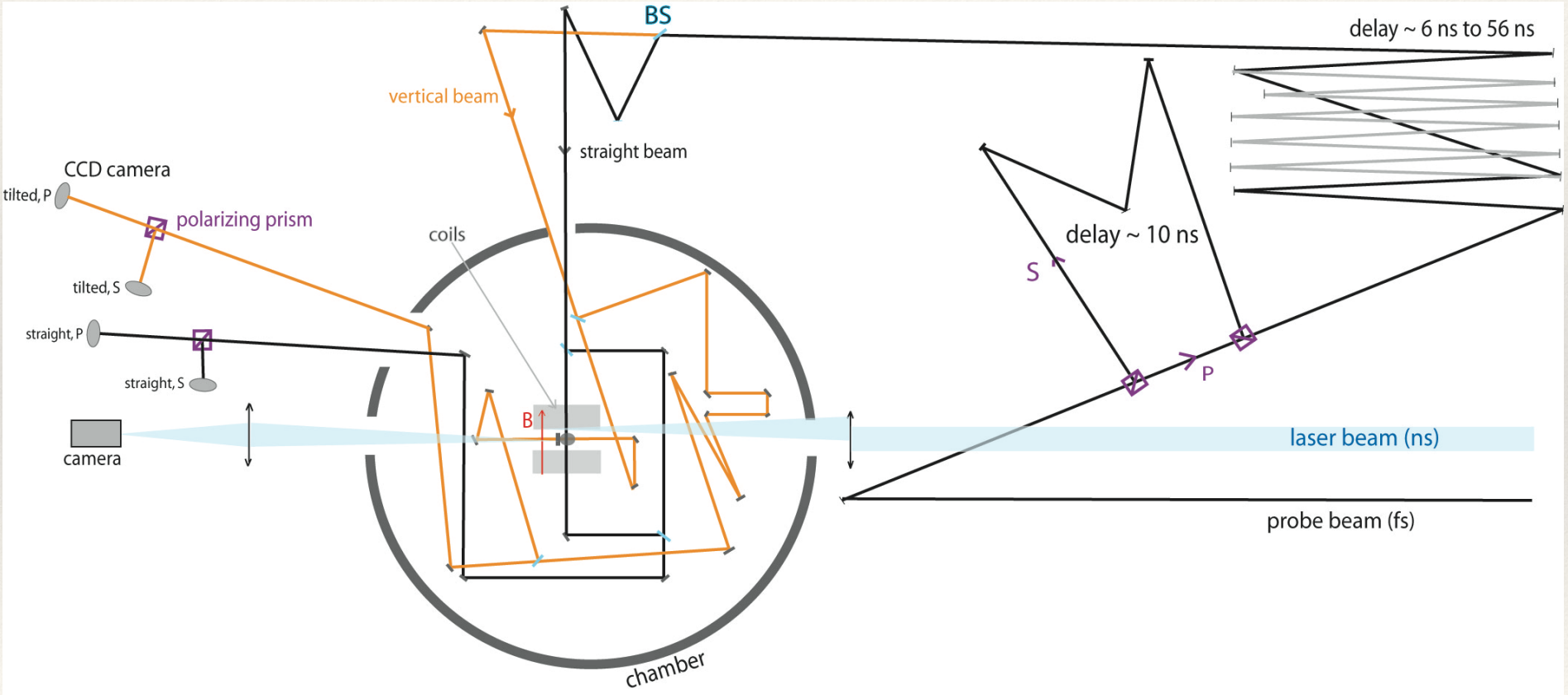


Adapted from Camenzind, (1990).

Laboratory astrophysics

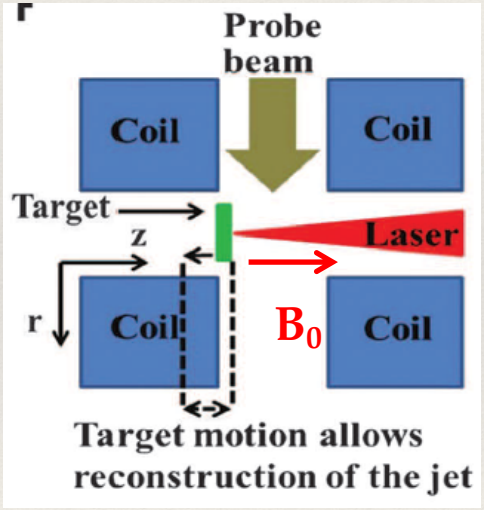
- Modeling of magneto-hydrodynamic plasma phenomena

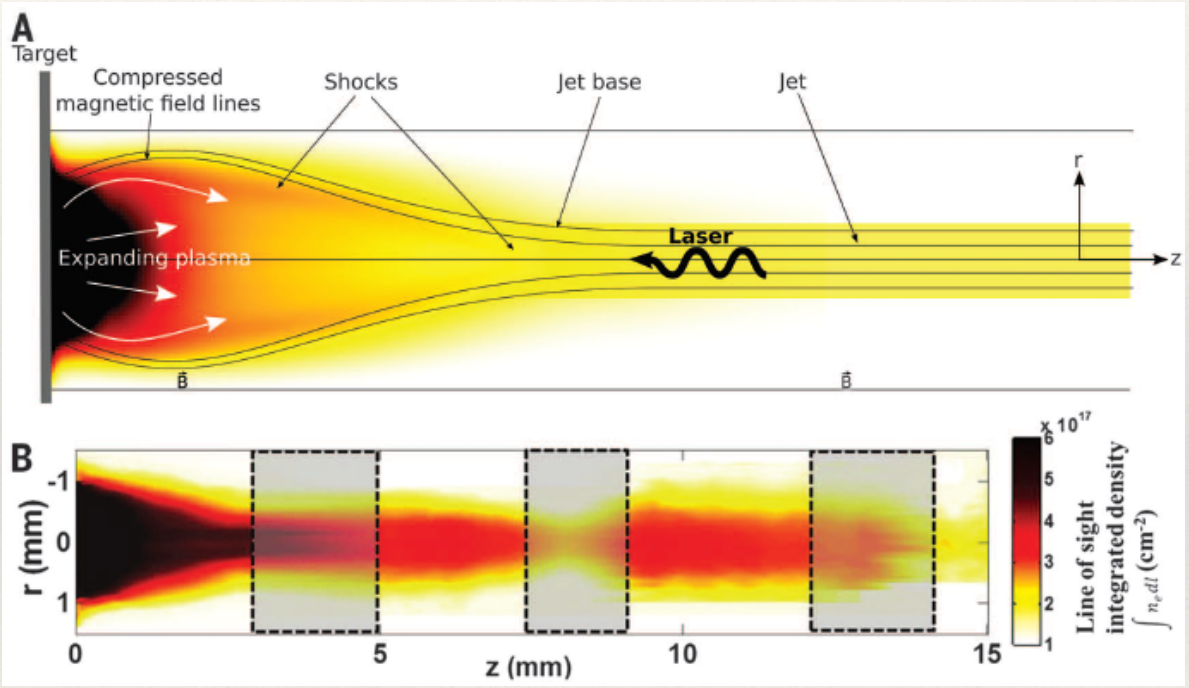


Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: jet formation mechanisms

Laser-plasma plume propagating along the ambient magnetic field



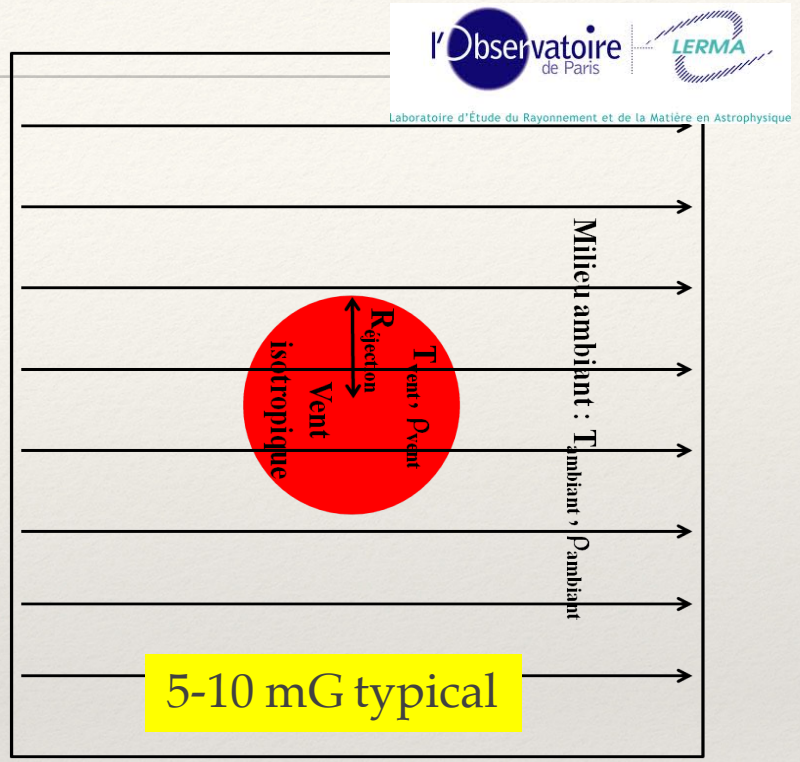


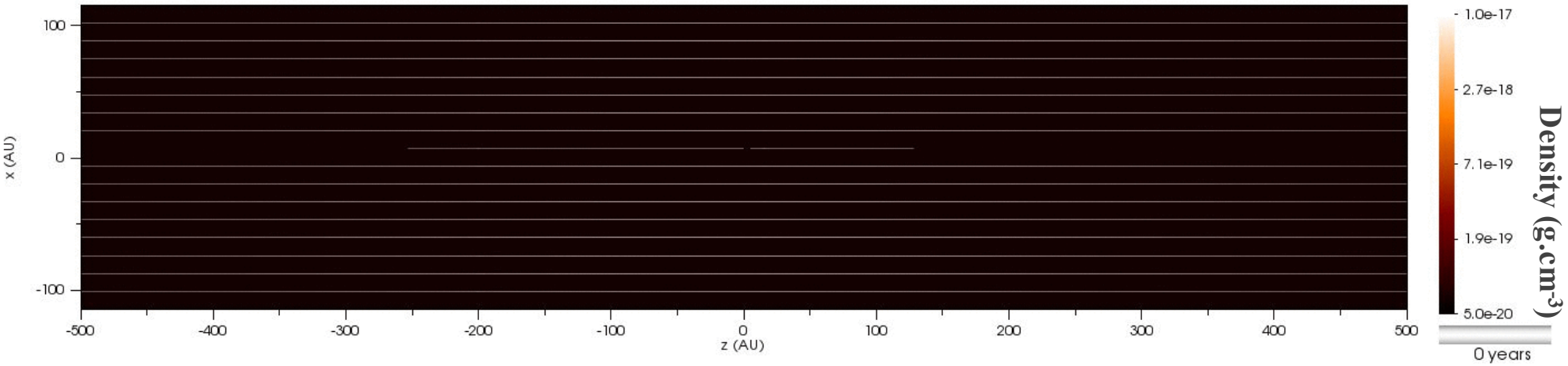
Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field
B. Albertazzi *et al.*
Science **346**, 325 (2014);
DOI: 10.1126/science.1259694

Full-scale astrophysical simulation

Simulations performed by A. Ciardi (code RAMSES)

Objet	cas 1	cas 2	cas 3
Champ magnétique (mG)	5	20	10
Taux de masse éjecté ($M_{solaire}$/an)	10^{-8}	5.10^{-7}	10^{-7}
$T_{ambiant}$ (K)	100	500	100
T_{vent} (K)	10000	500	10000
ρ_{vent} (part.cm^{-3})	10^5	10^7	10^6
$\rho_{ambiant}$ (part.cm^{-3})	4.10^3	4.10^5	4.10^4
$R_{éjection}$ (U.A)	8	10	10
vitesse d'éjection (km.s^{-1})	200	70	130
Perturbation en vitesse (%)	5	10	5





Laser / astrophysical plasma scaling

Quantity	Laser-plasma	YSO
	10^{13} W/cm^2	
B_0	20 T	~1e-3 G
Peclet	3.5	1.0e11
Reynolds	1.0e4-1.0e5	1.0e13
Magnetic Reynolds	50-5000	1.0e15
Mach (v_{jet}/c_s)	1-50	10-50
$\beta=p_{plasma}/p_{magnetic}$	>>1 near source <<1 away	Same, <<1 from ~10s AU

$P_e > 1$: close to 1, thermal conduction plays a minor role

$R_e >> 1$: viscosity negligeable

$R_{em} > 1$: magnetic field lines frozen in the outflow

$M > 1$: outflow supersonic

β: plasma varies from kinetic to magnetically dominated

- Time: 20 ns → 6 years
- Space: 1 mm → 300 AU, or 4.5 10^{13} m
- Magnetic field: 20 T → 1 μT

Both are ideal MHD plasmas

D. D. Ryutov et al., The Astrophysical J. Suppl. **127**, 465 (2000)

Laser / astrophysical plasma scaling

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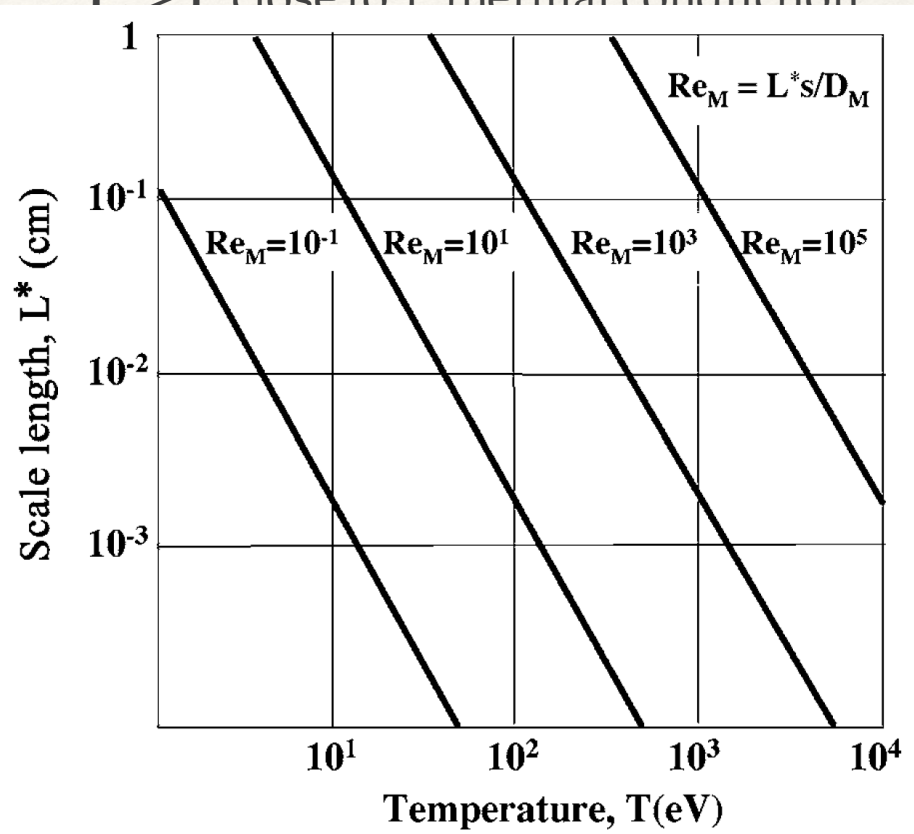

- Time: 20 ns → 6 years
- Space: 1 mm → 300 AU, or 4.5 10^{13} m
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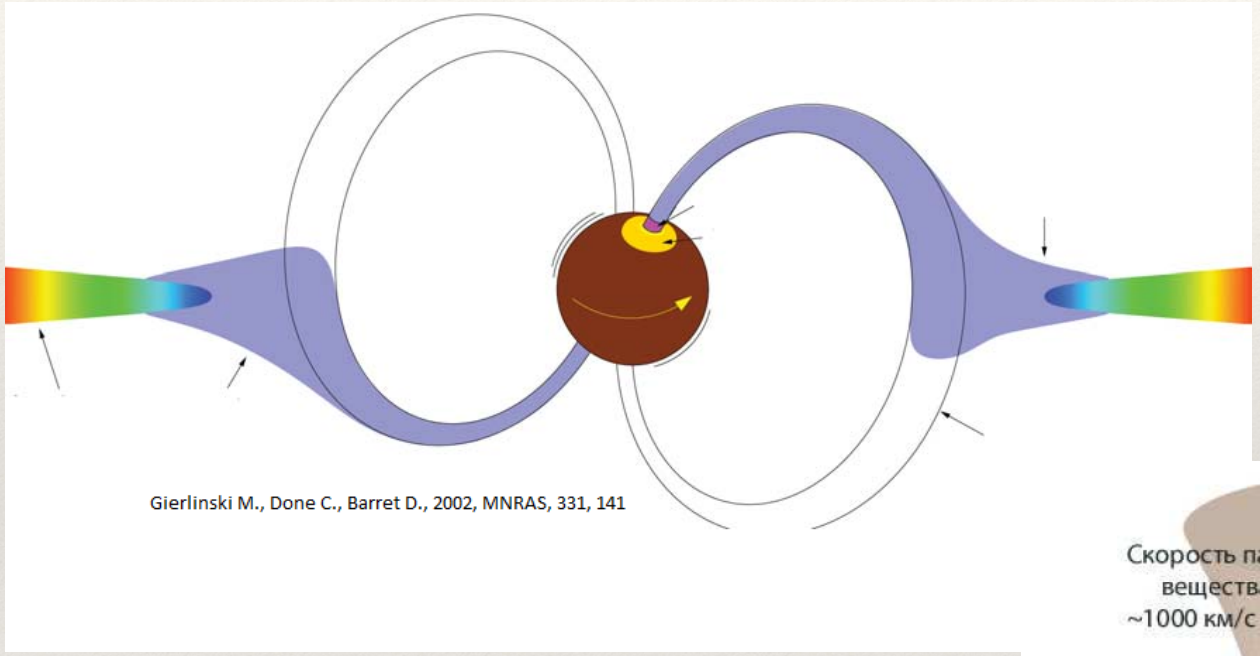
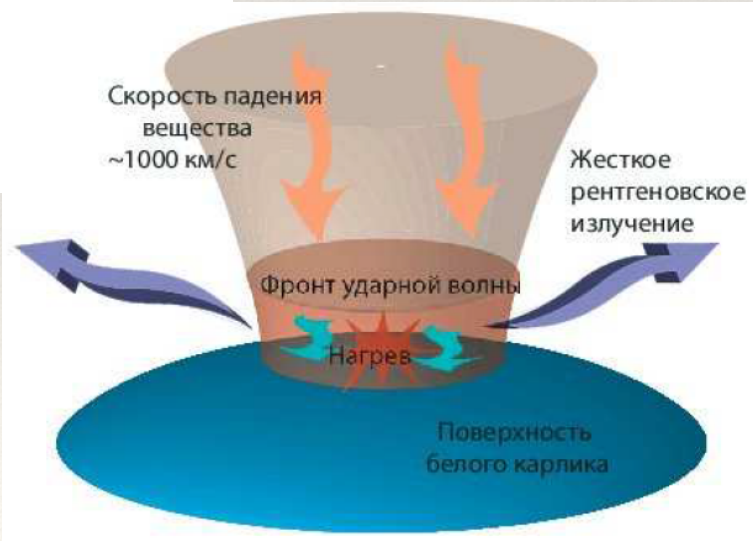
B. Remington et al., Rev. Mod. Phys. **78**, 755 (2006)

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena



Gierlinski M., Done C., Barret D., 2002, MNRAS, 331, 141



Laboratory astrophysics

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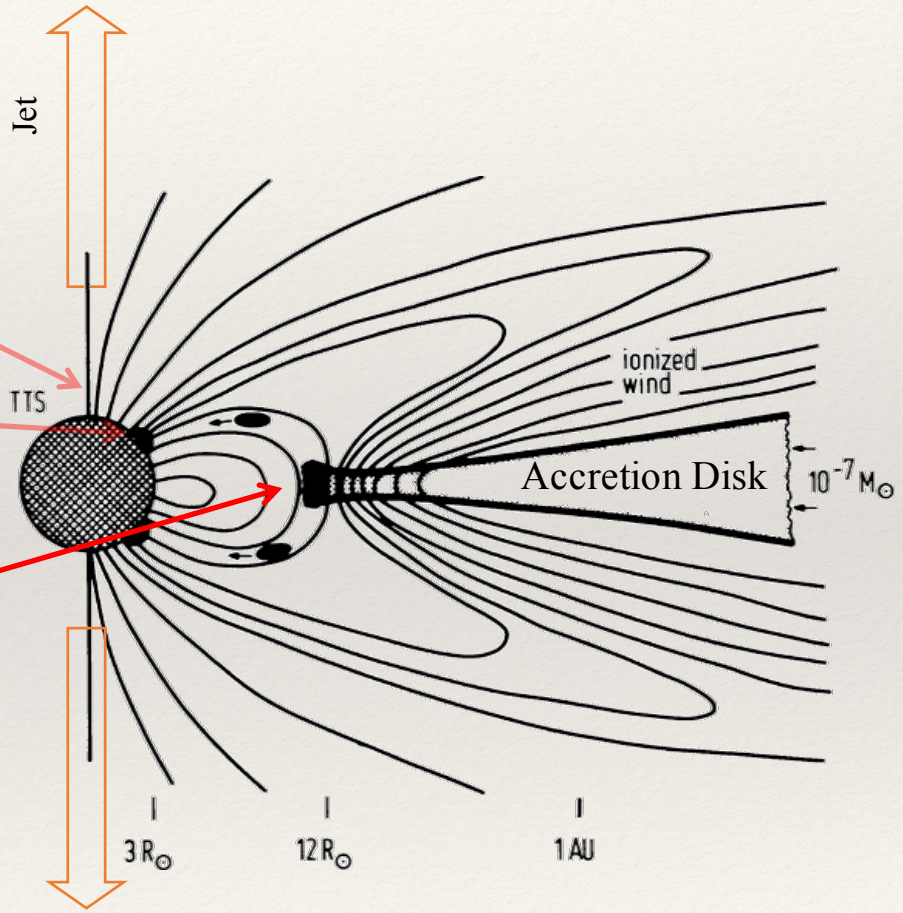
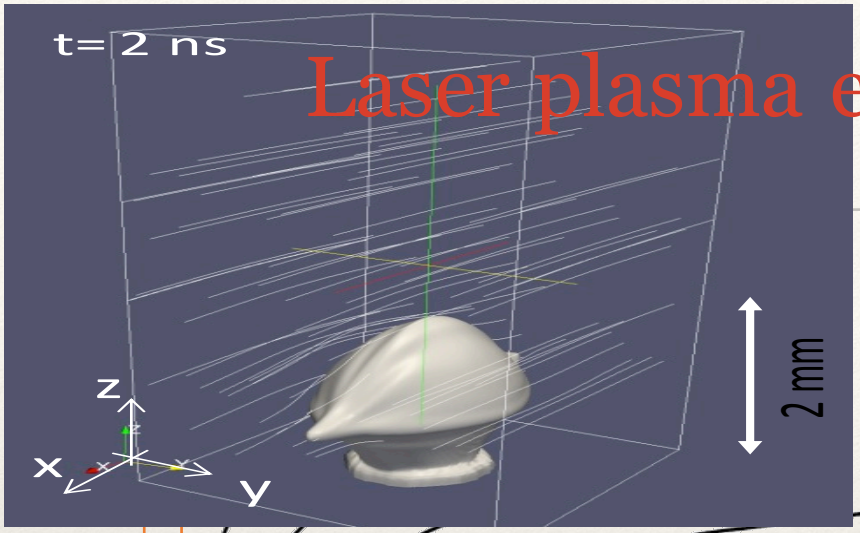
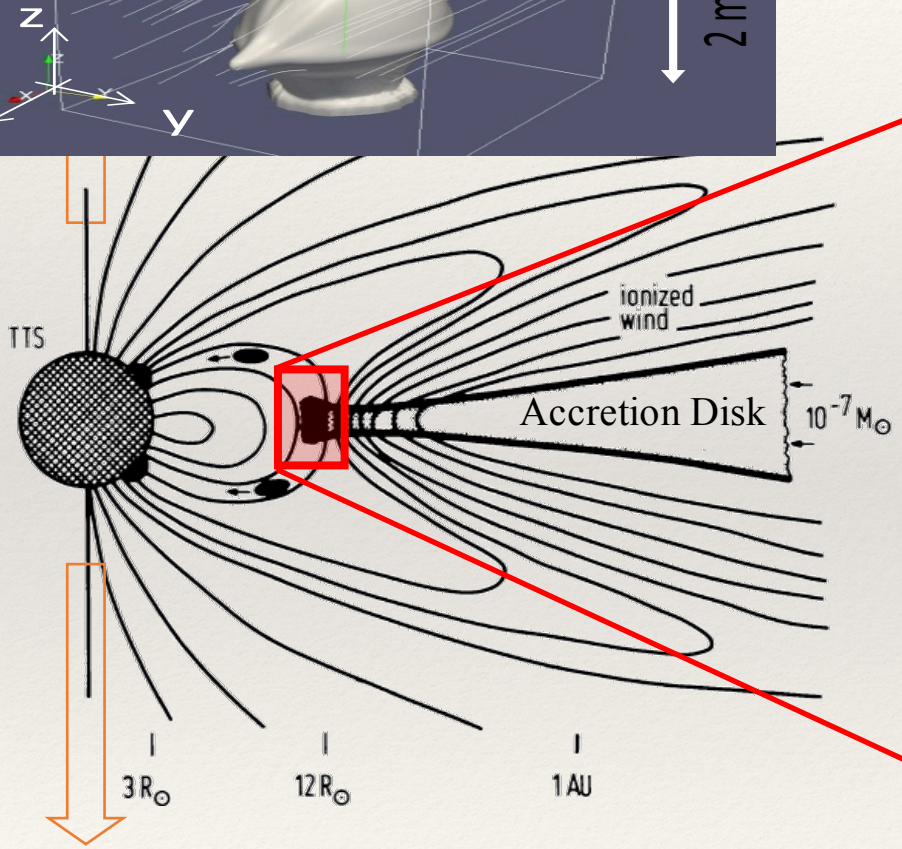
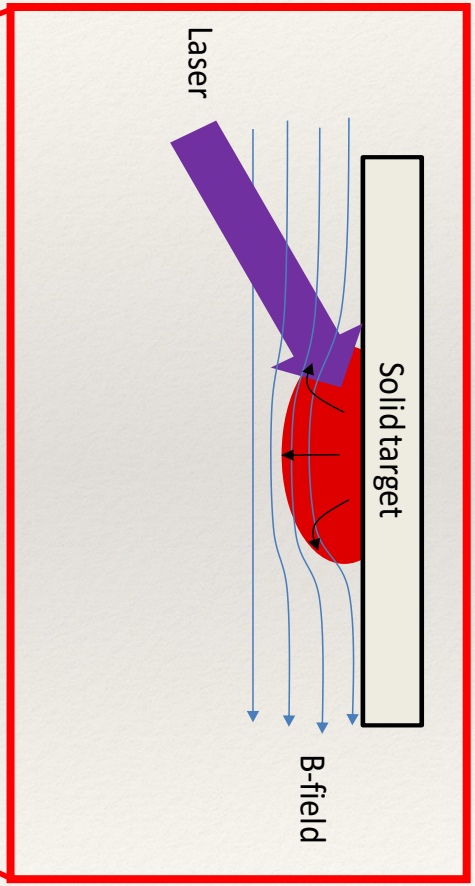


Adapted from Camenzind, (1990).

Laser plasma expansion across $\mathbf{B}_o$





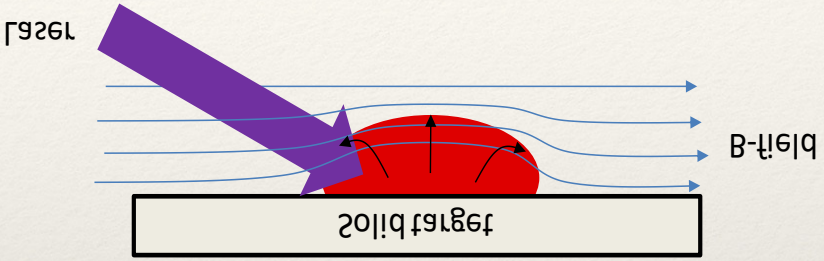


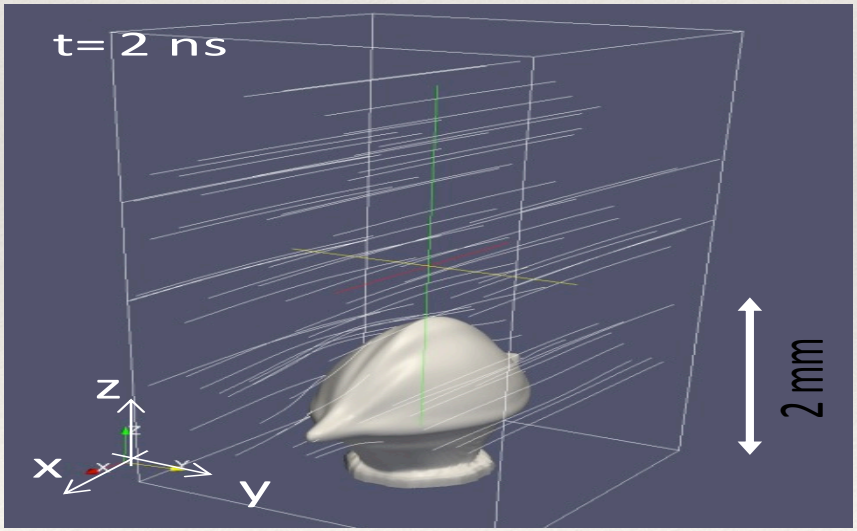
Adapted from Camenzind, (1990).

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc edge dynamics

Laser-plasma plume propagating across the ambient magnetic field





Andrea Ciardi (2016)

expect:

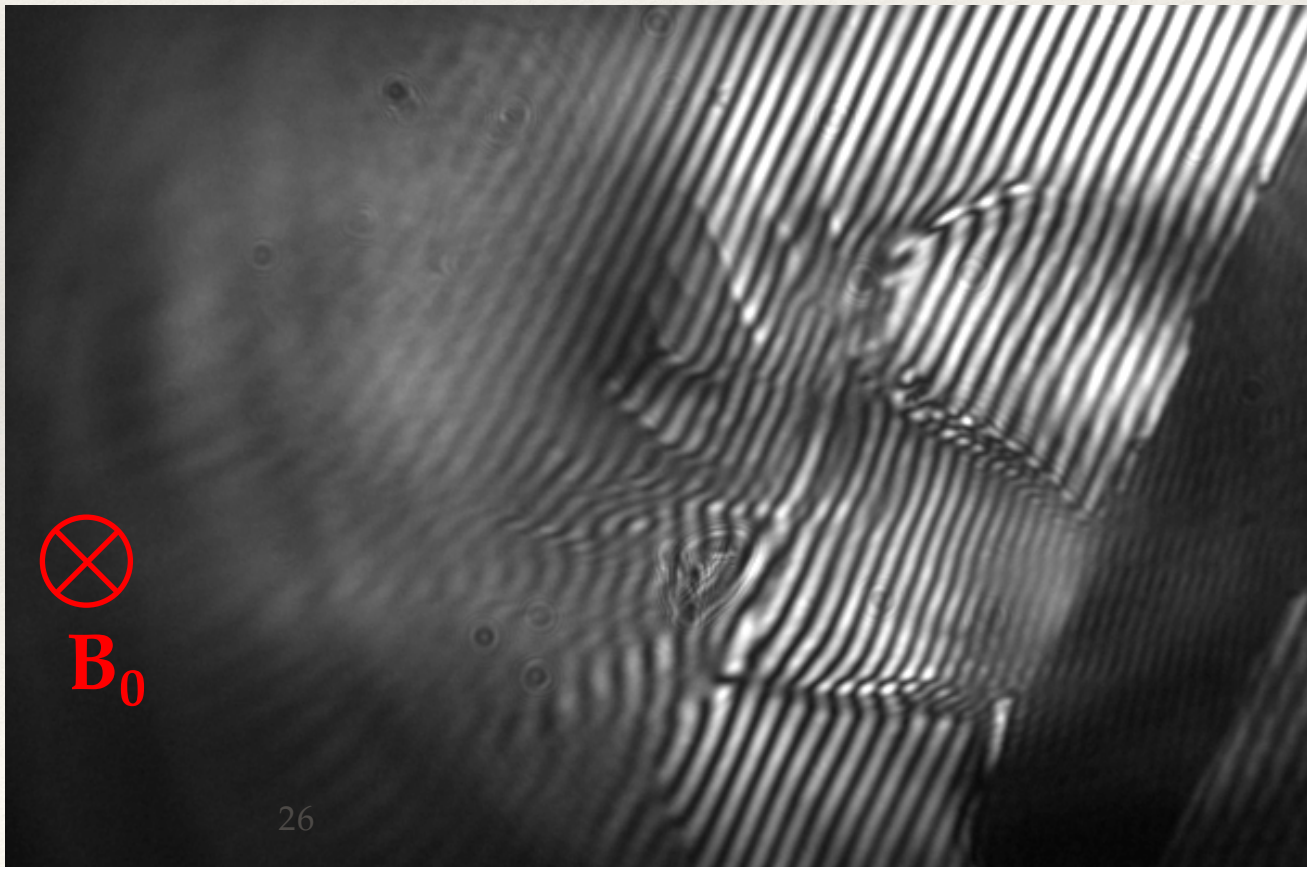
plasma expansion across $\mathbf{B}_0$
is limited by magnetic pressure

further plasma expansion
is along $\mathbf{B}_0$

Laser plasma expansion across $\mathbf{B}_0$: experiment

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc

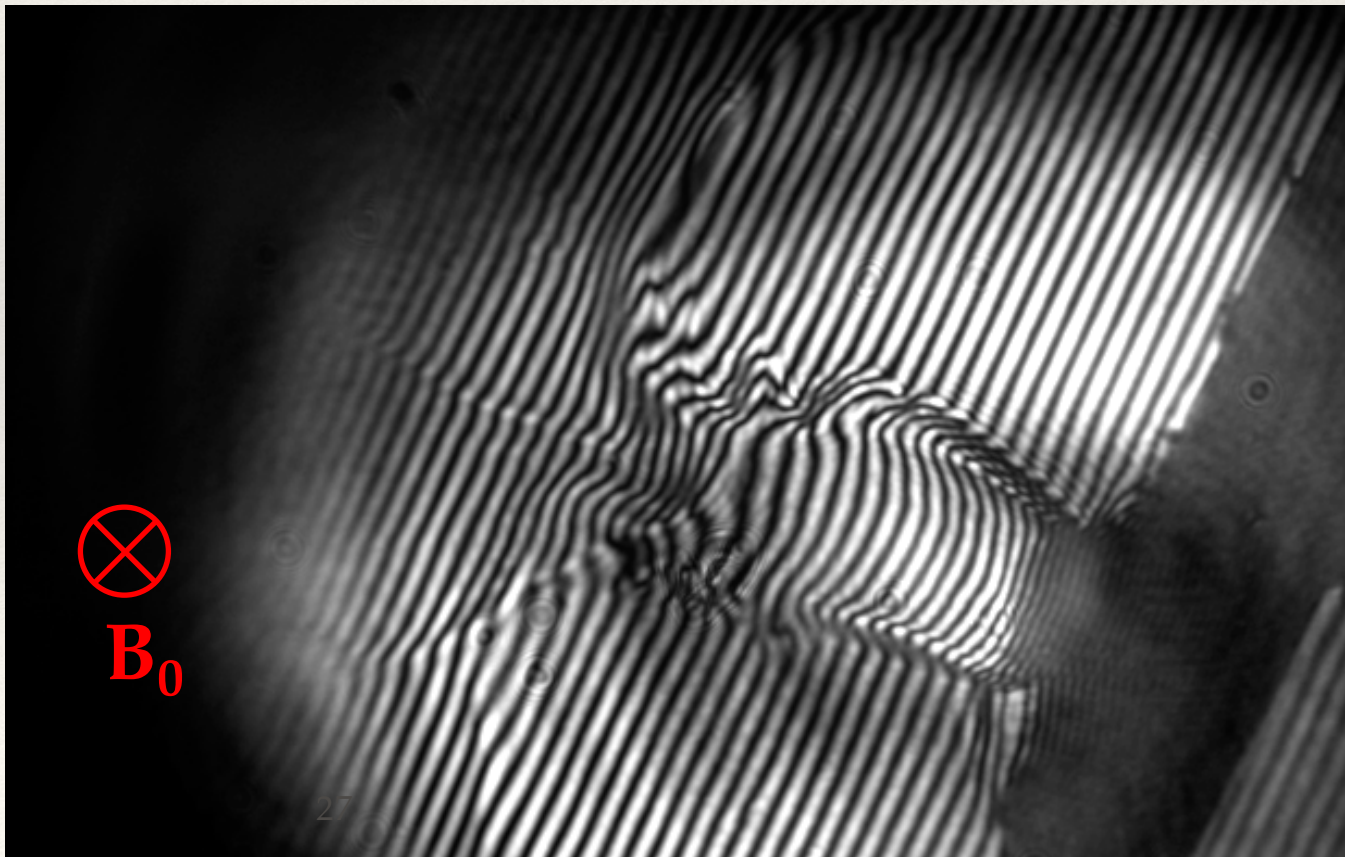
16ns, **25J**



Laser plasma expansion across $\mathbf{B}_0$: experiment

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc

26ns, **25J**

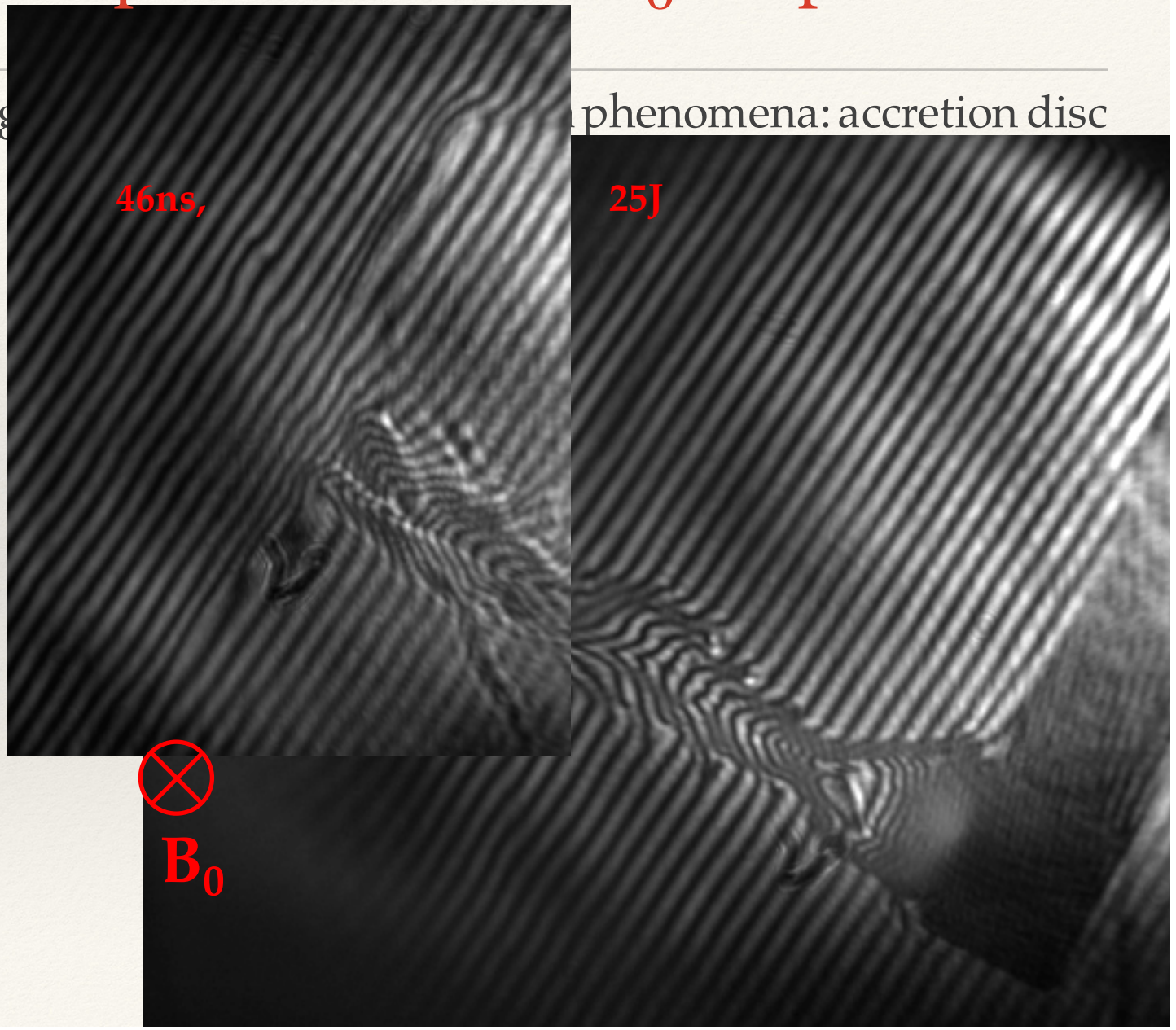


Laser plasma expansion across $\mathbf{B}_0$: experiment

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc

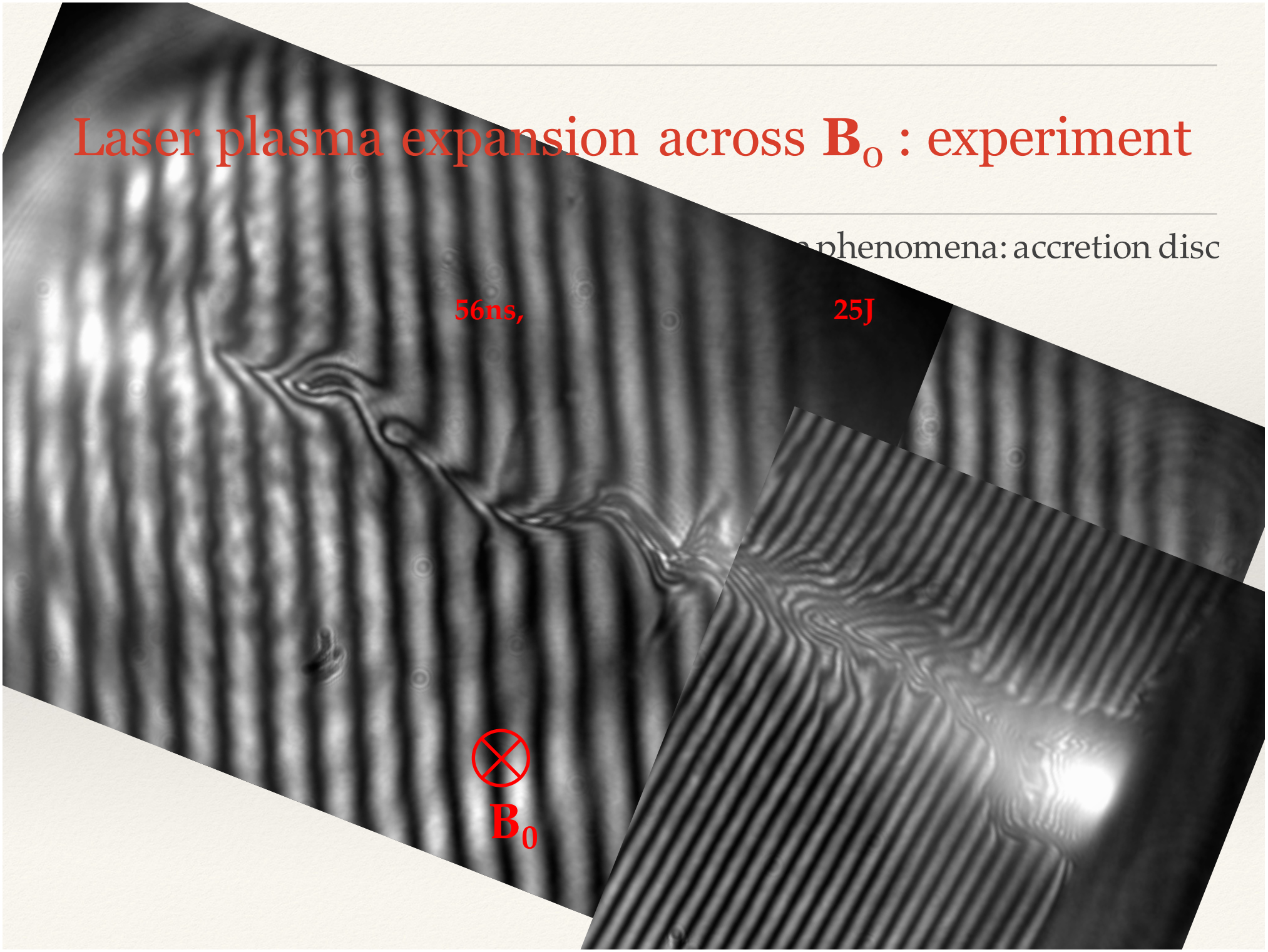
Laser plasma expansion across $\mathbf{B}_0$: experiment

- Modeling of mag phenomena: accretion disc



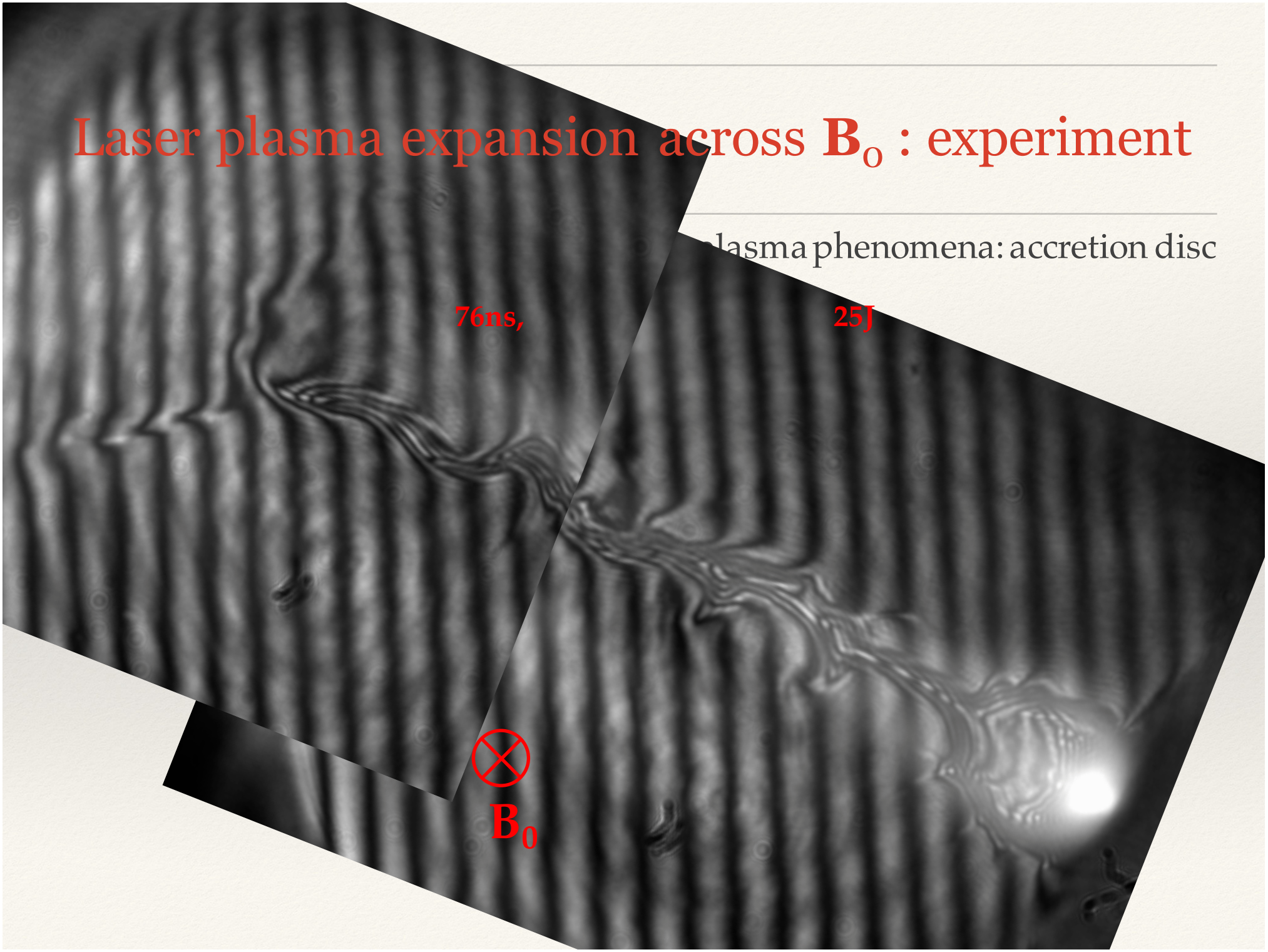
Laser plasma expansion across $\mathbf{B}_0$: experiment

phenomena: accretion disc

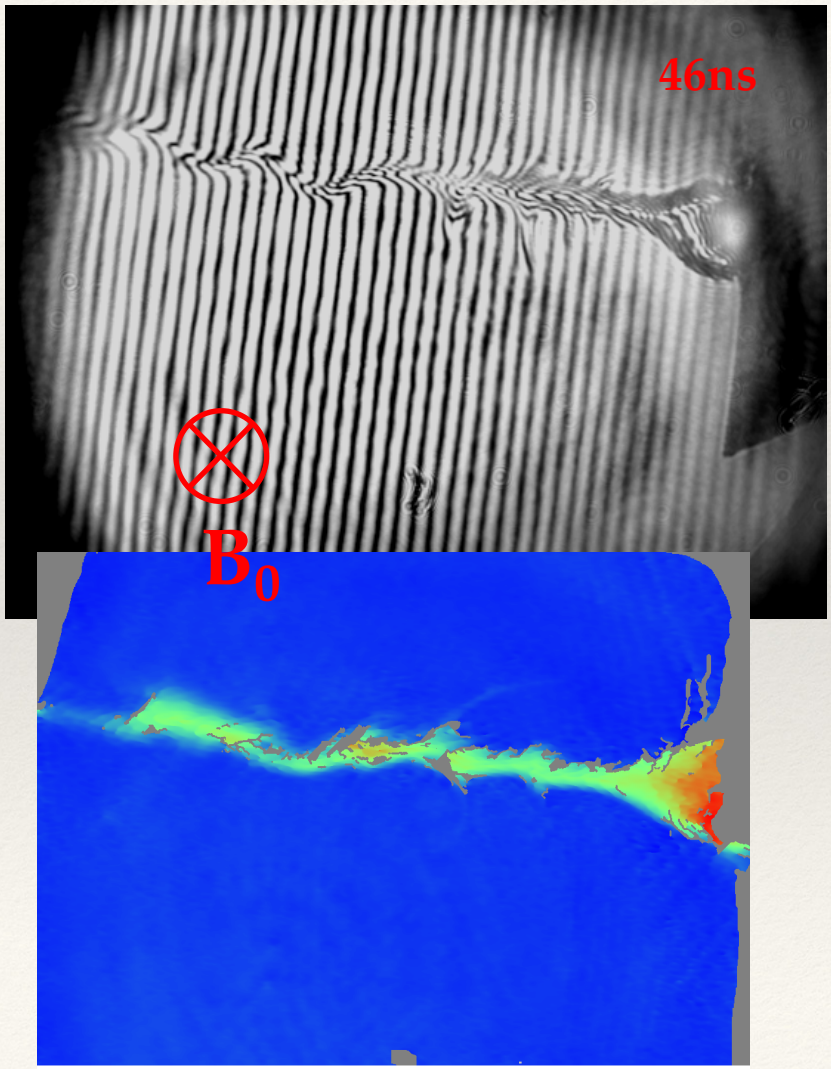


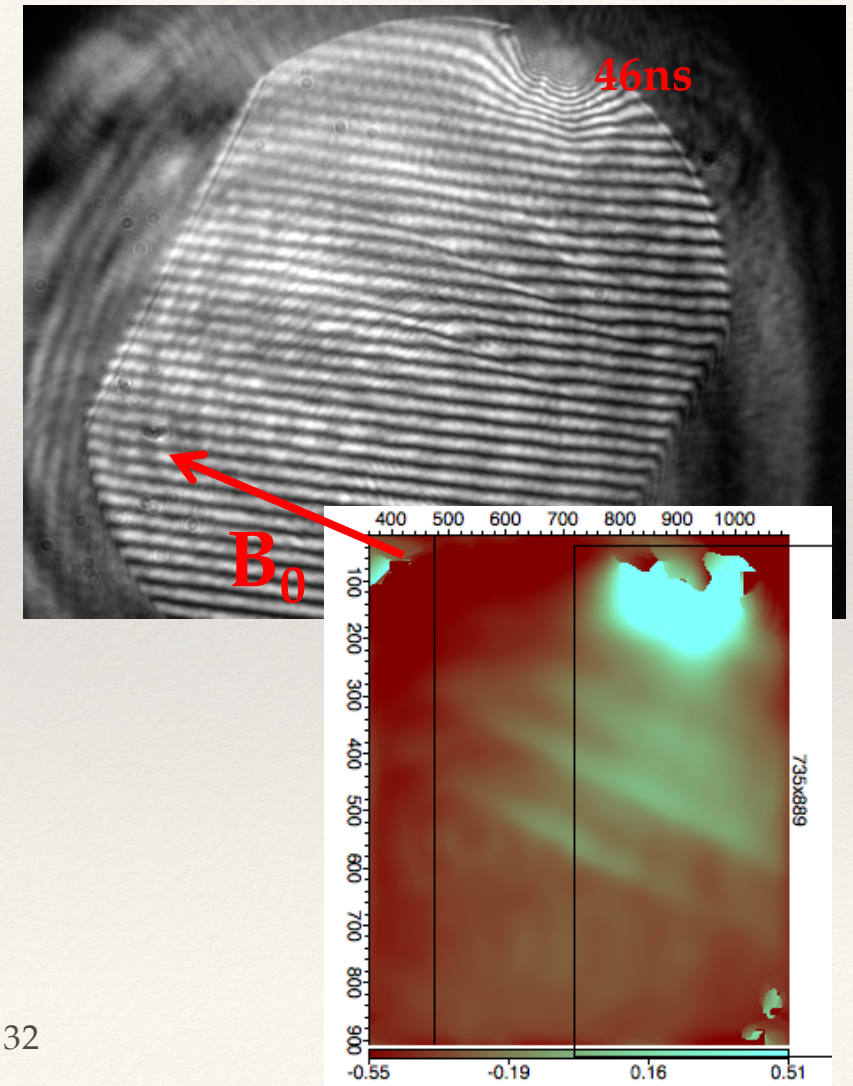
Laser plasma expansion across $\mathbf{B}_0$: experiment

lasma phenomena: accretion disc

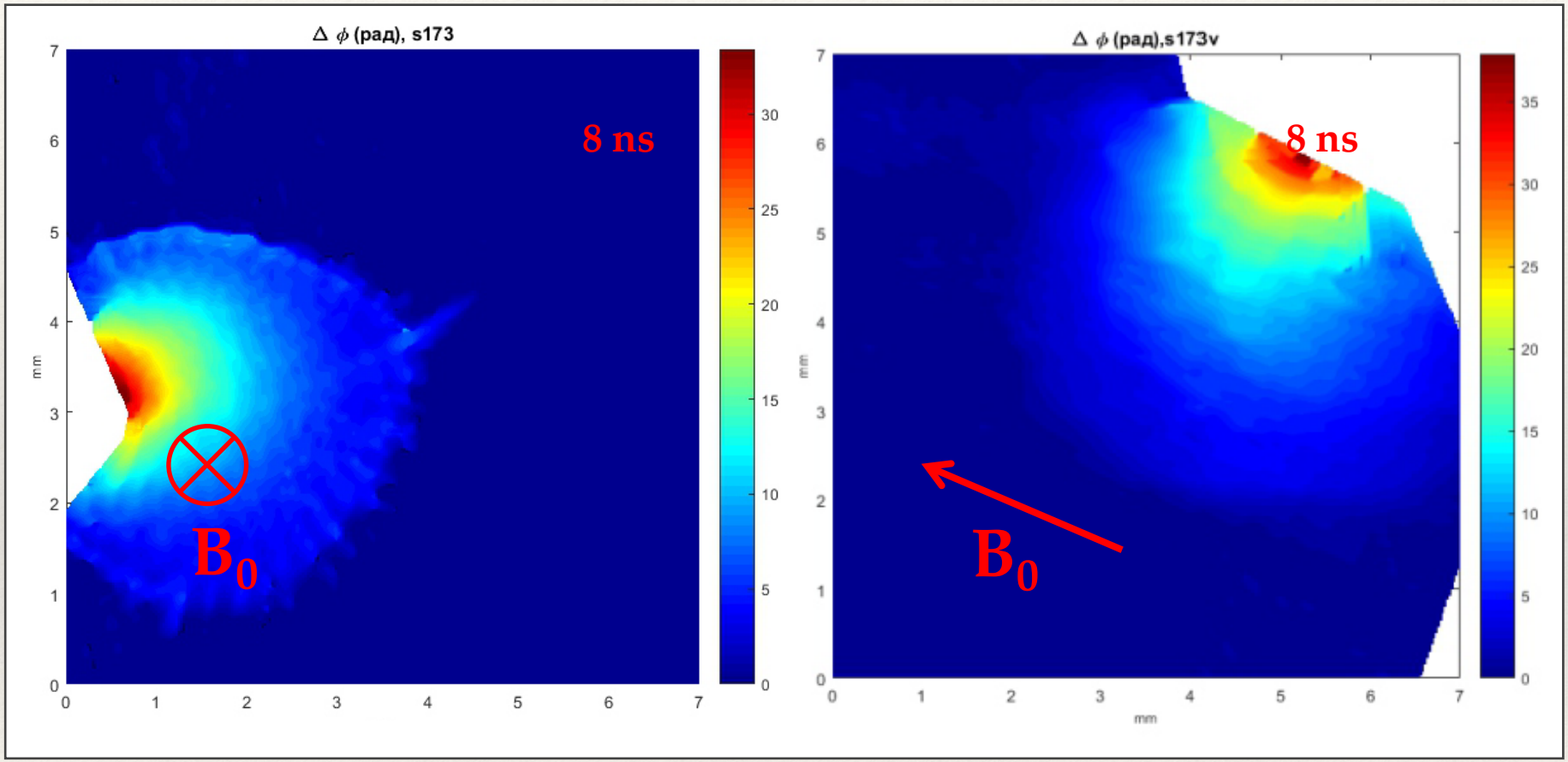


Laser plasma expansion across $\mathbf{B}_0$: experiment

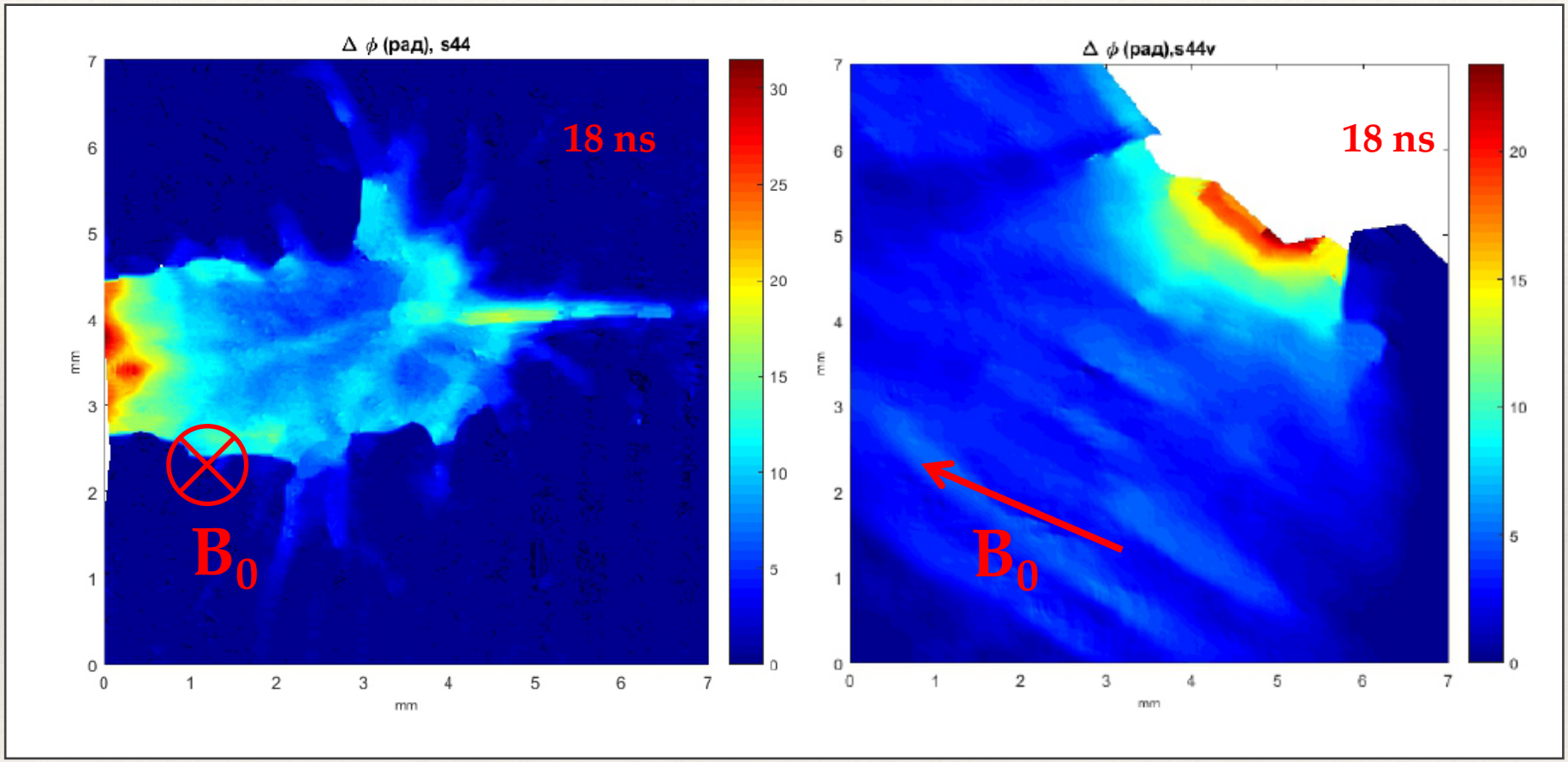




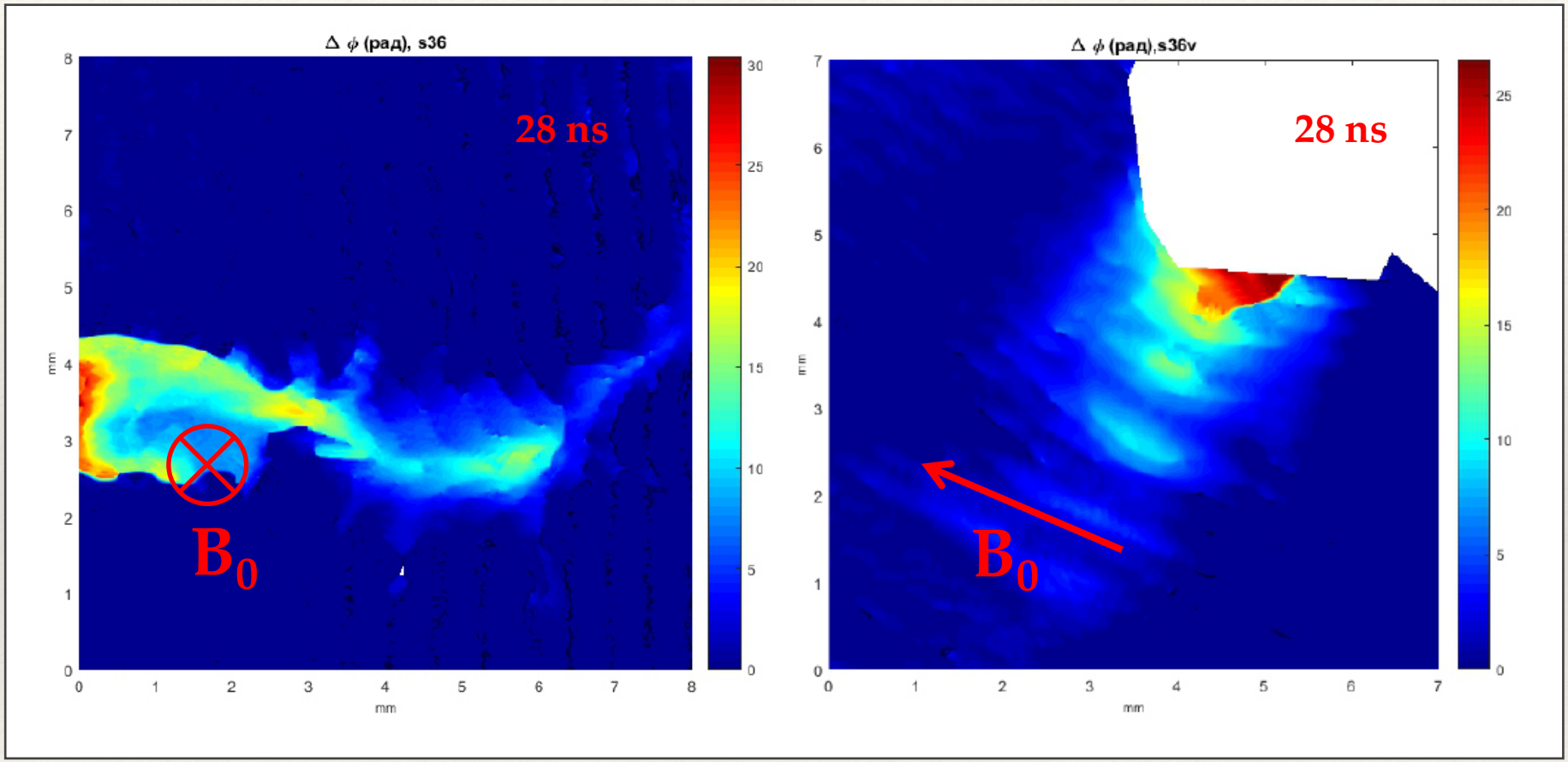
Laser plasma expansion across $\mathbf{B}_0$: experiment



Laser plasma expansion across $\mathbf{B}_0$: experiment



Laser plasma expansion across $\mathbf{B}_0$: experiment



Laser pla riment

Ne = 1e18 cm-3, Z = 6.3, Te = 30 eV, Ti = 30 eV, B0 = 13.5 T, V = 600 km/s, L = 0.1 cm

'v_s(km/s) = ' [40.3608]

'v_A(km/s) = ' [180.9407]

'lambda_e(um) = ' [4.2320]

'lambda_i(um) = ' [0.1458]

'lambda_p(c/f_p, um) = ' [33.9292]

'rho_e(um) = ' [0.9673]

'rho_i(um) = ' [26.8007]

'M(Mach) = ' [14.8659]

'M_A(Afven Mach) = ' [3.3160]

'beta(p_th/p_b) = ' [0.0763]

'beta_dy(p_dynamic/p_b) = ' [21.8564]

'Pe_heat (Peclet) = ' [22.7988]

'Re (Reynolds) = ' [9.4045e+005]

'ReM (magnetic Reynolds) = ' [37.8895]

'Hall_e = ' [4.3752]

'Hall_i = ' [0.0054]

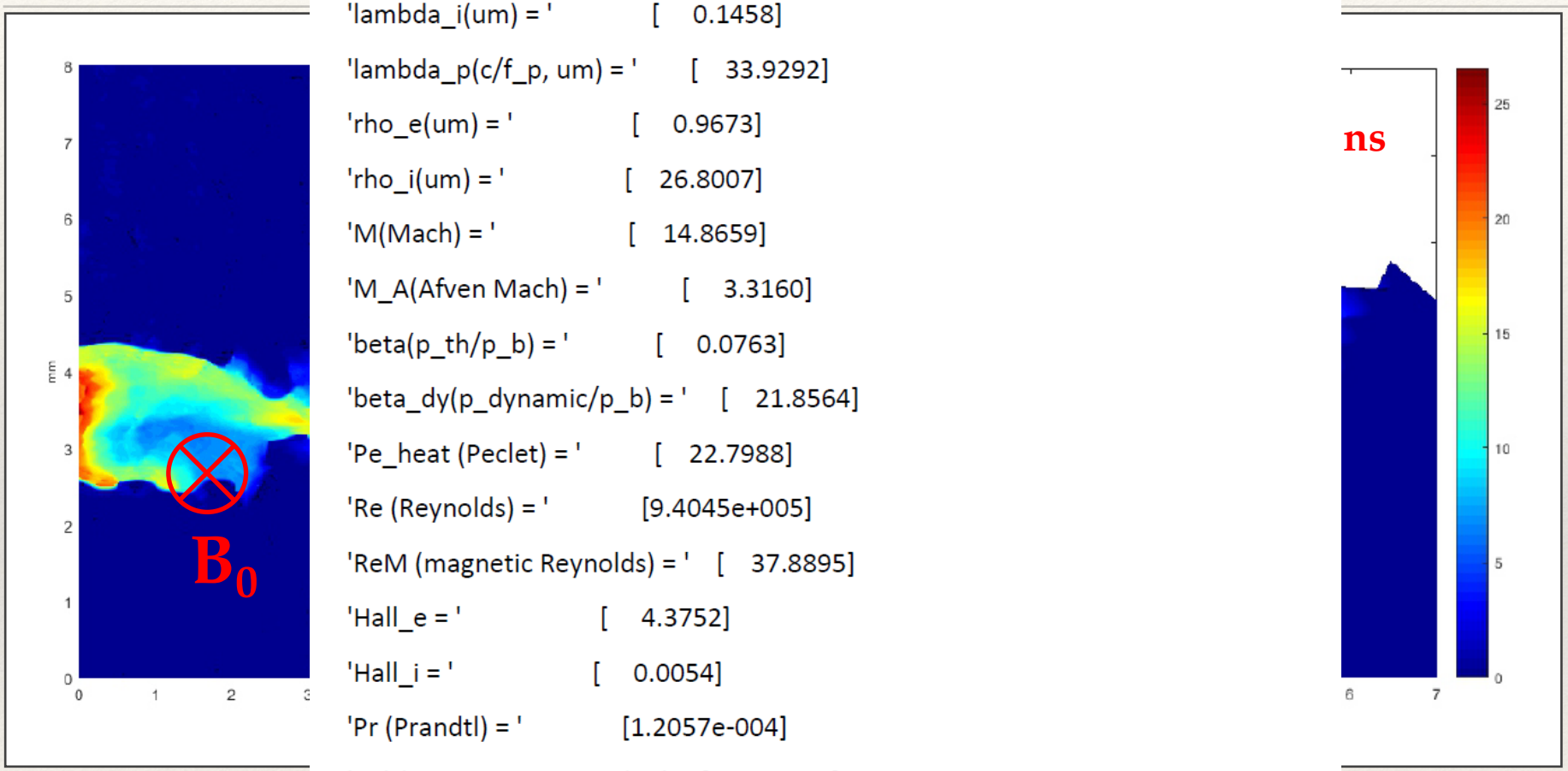
'Pr (Prandtl) = ' [1.2057e-004]

'p_b(magn. press., MPa) = ' [72.9000]

'p_th(kin. press., MPa) = ' [5.5619]

'p_dy(ram press., MPa) = ' [1.2292e+003]

'c/omega_pi(um) = ' [945.2472]

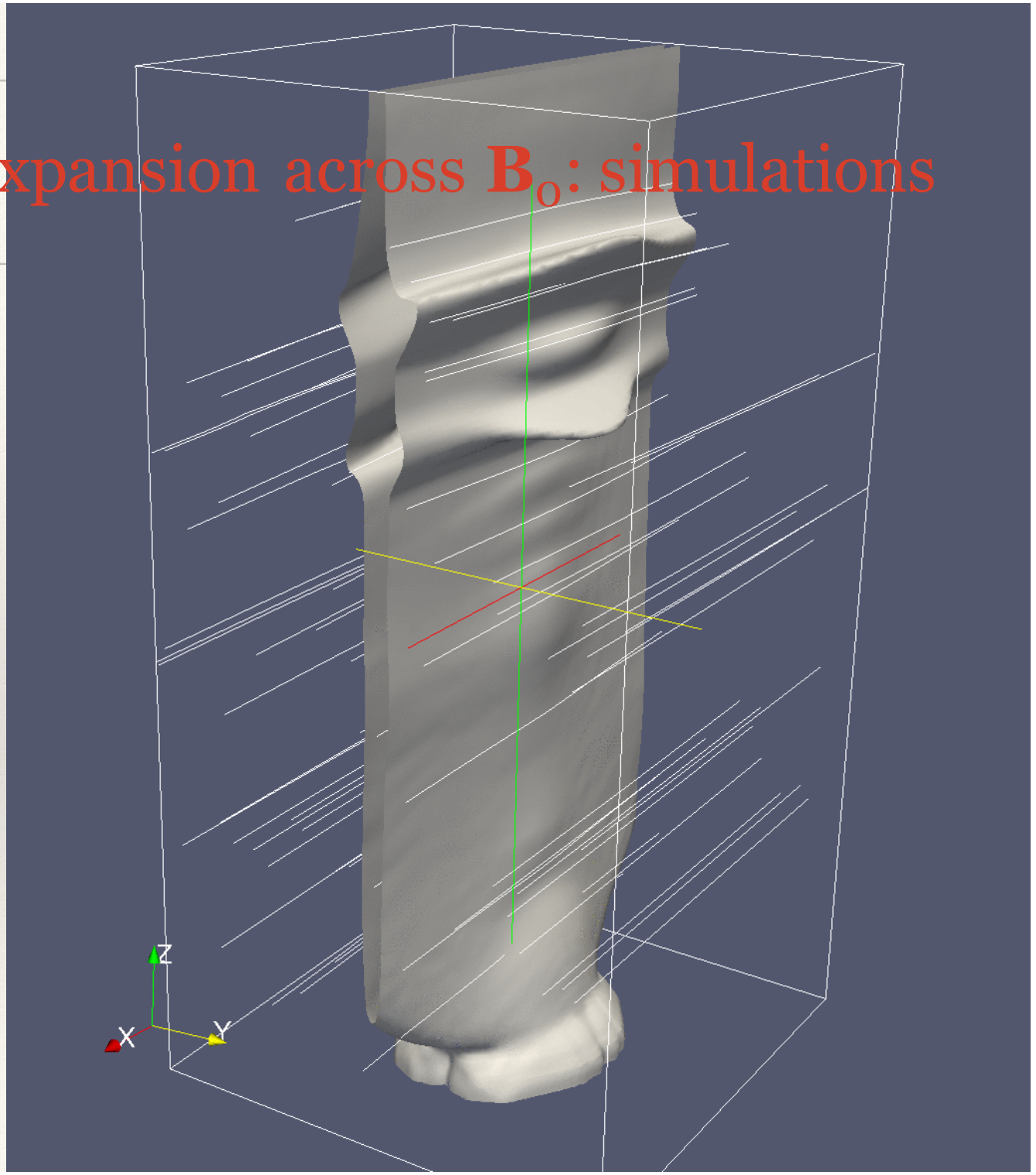


Laser plasma expansion across B_0: simulations

Main dynamics:
RT instability ?

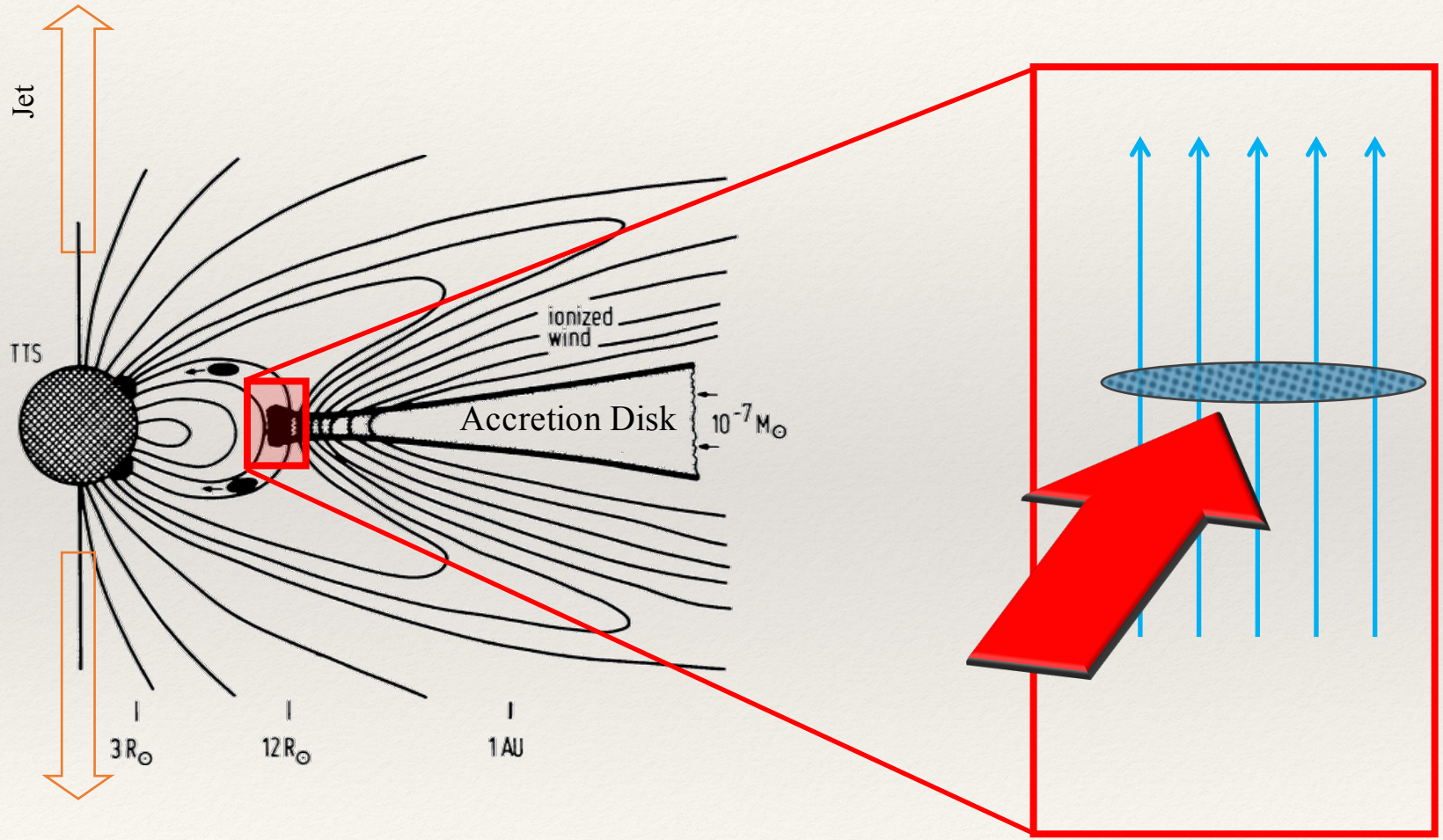
Side oscillations:
KH instability ?

Where are the accretion columns ?
Are the astrophysical accretion models correct ?



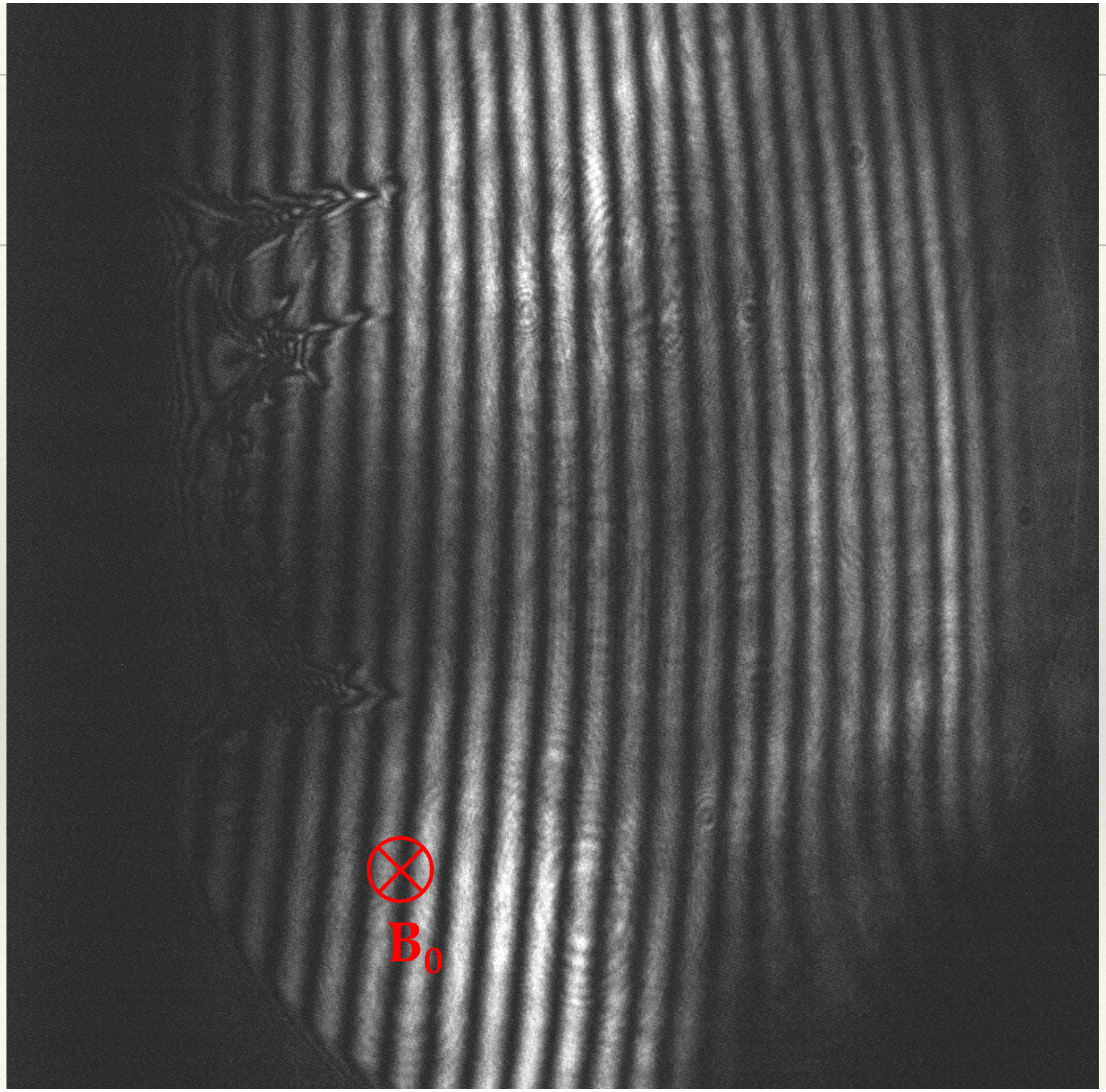
Andrea Ciardi (2016)

Laser plasma expansion across $\mathbf{B}_0$: modeling of accretion disc

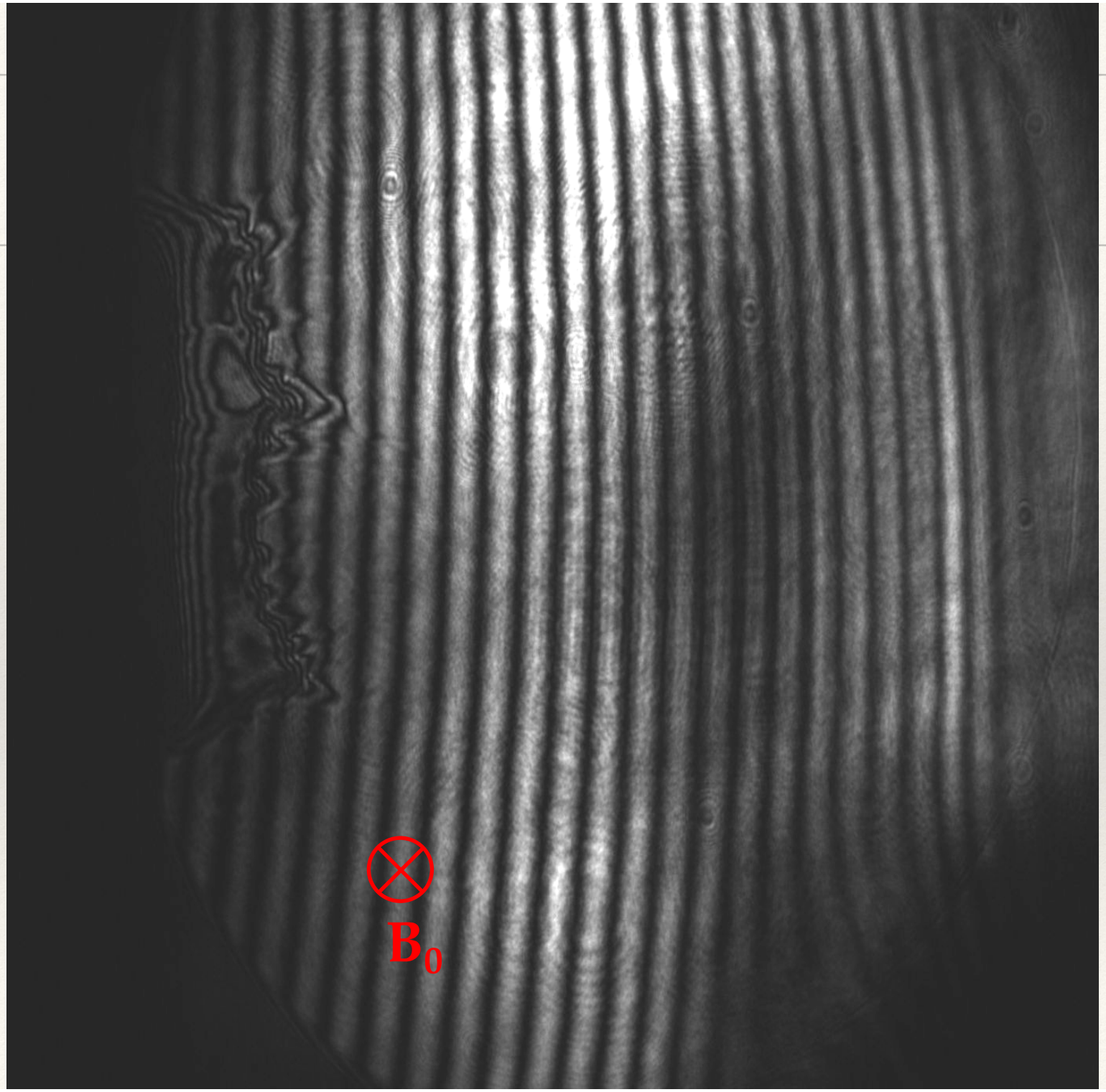


Adapted from Camenzind, (1990).

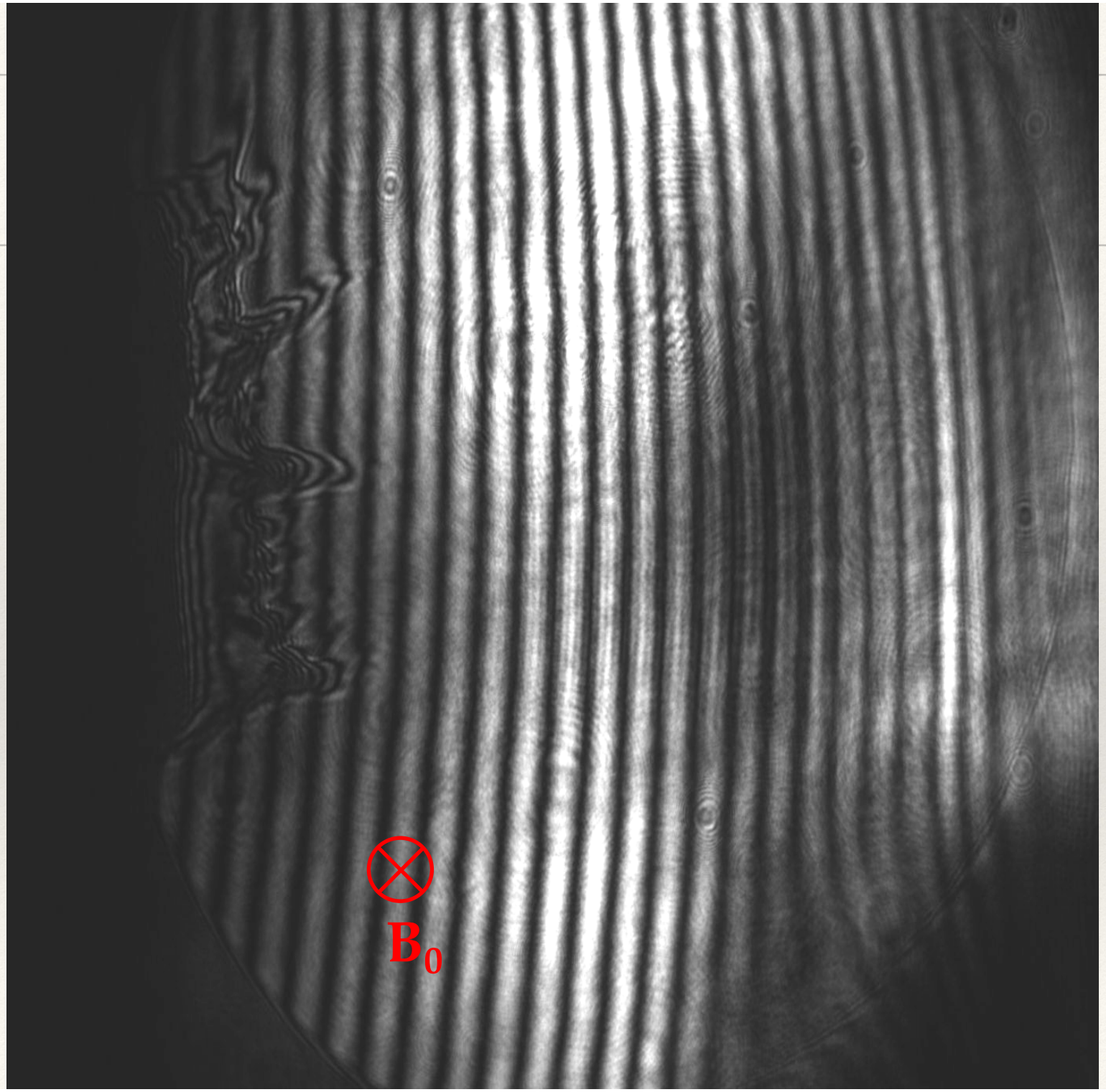
s089
28 ns
13 J



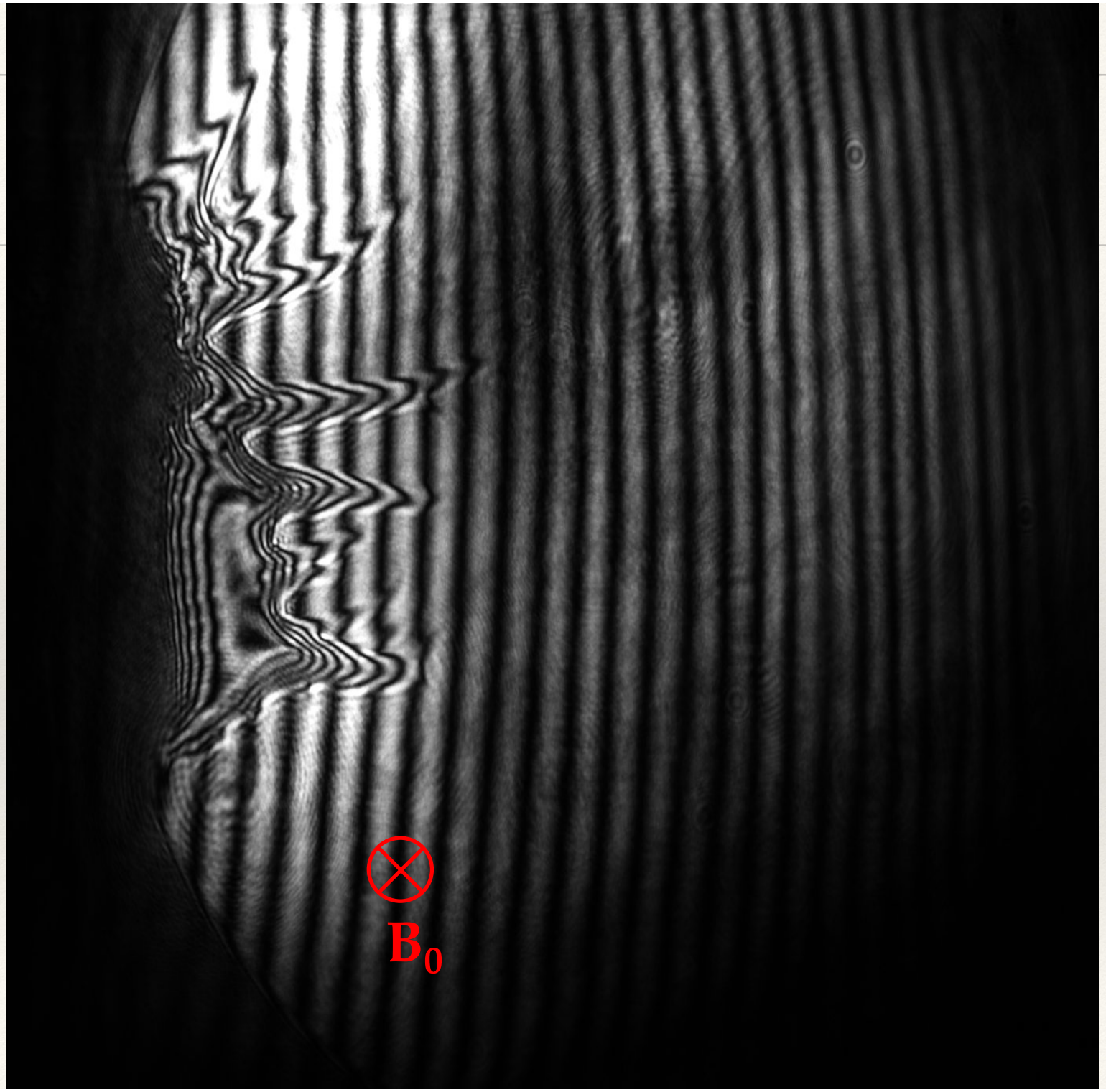
s090
28 ns
16.4 J



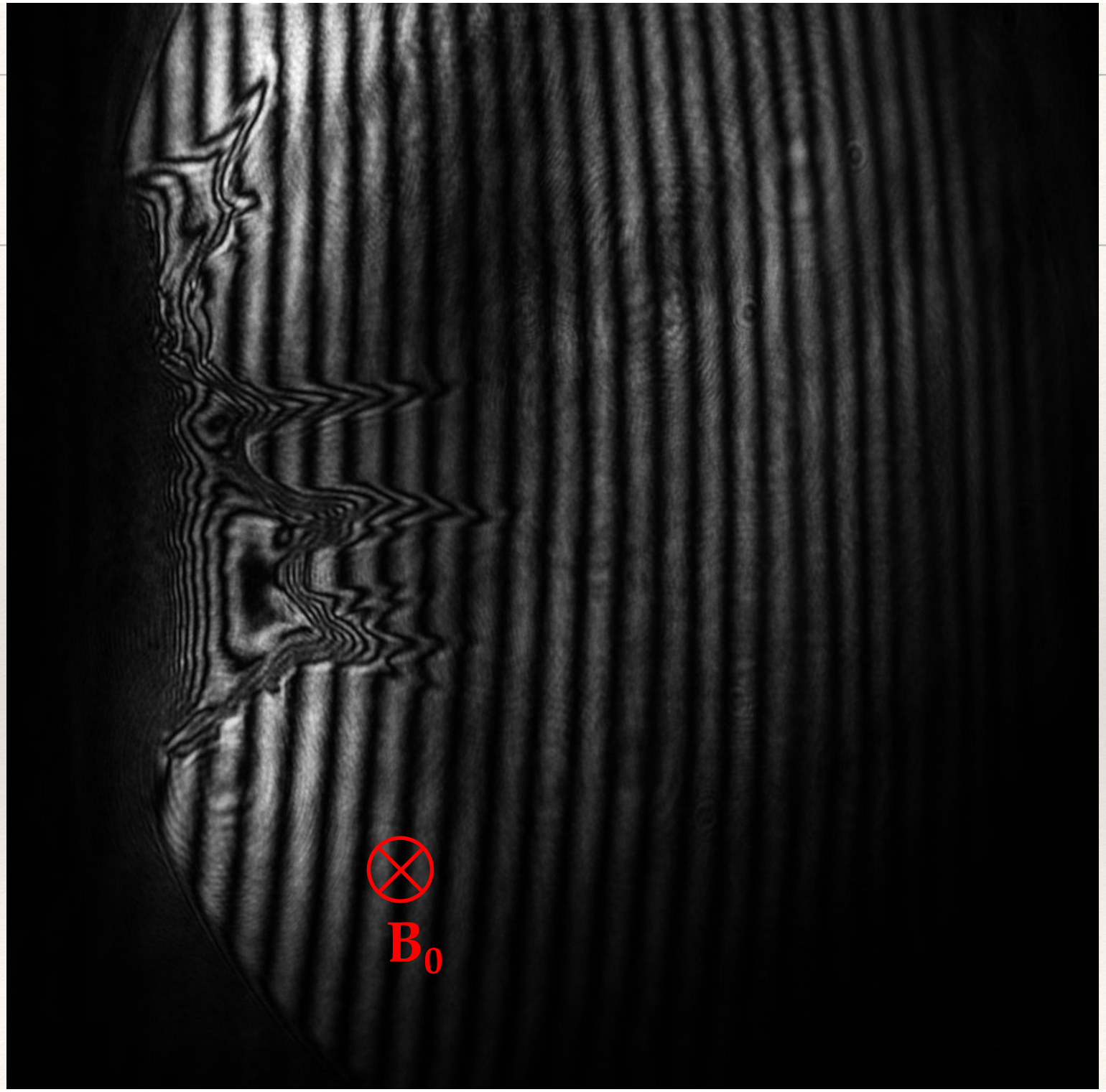
s091
28 ns
22.6 J



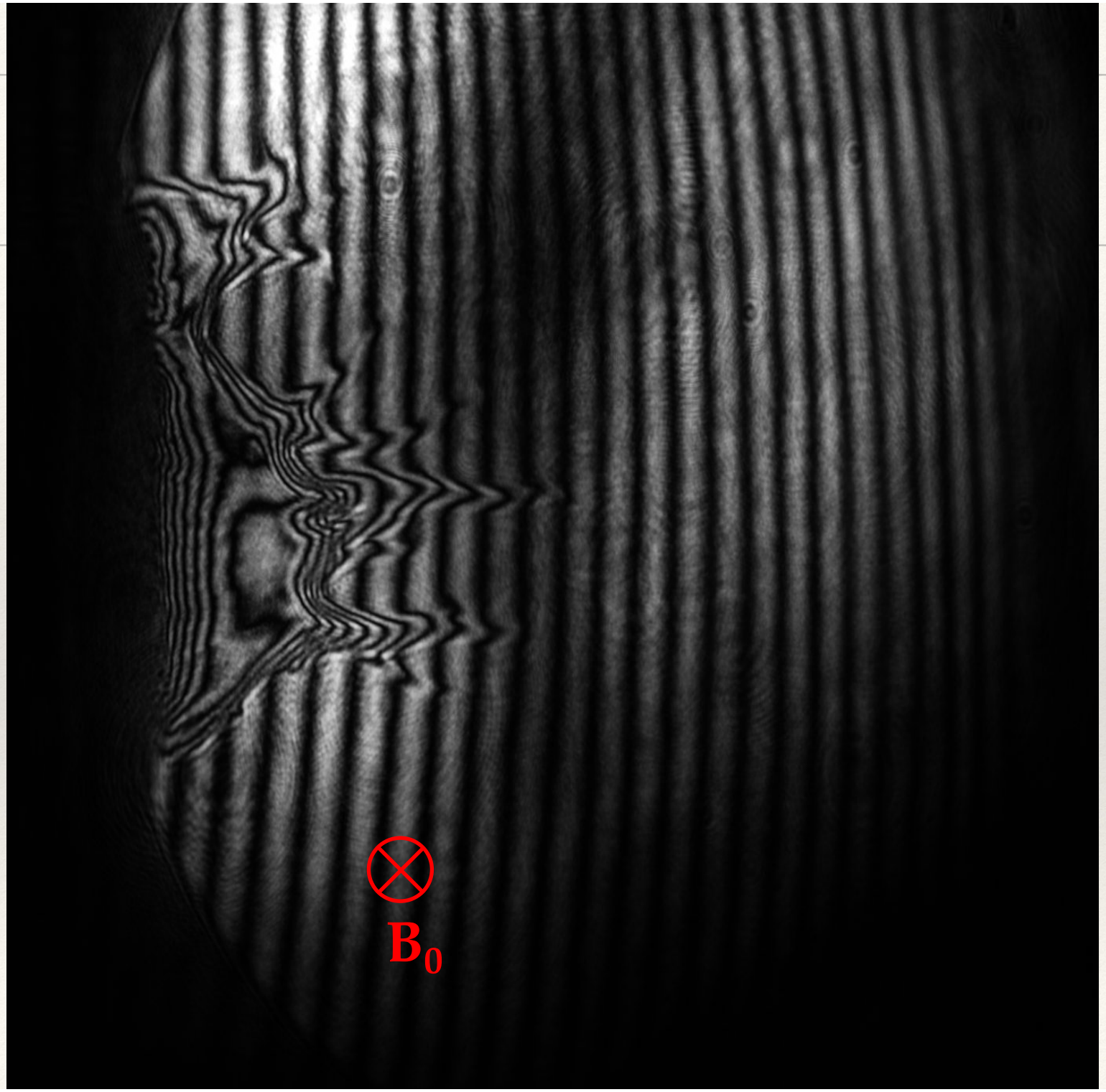
s092
38 ns
21.5 J



s093
38 ns
28 J

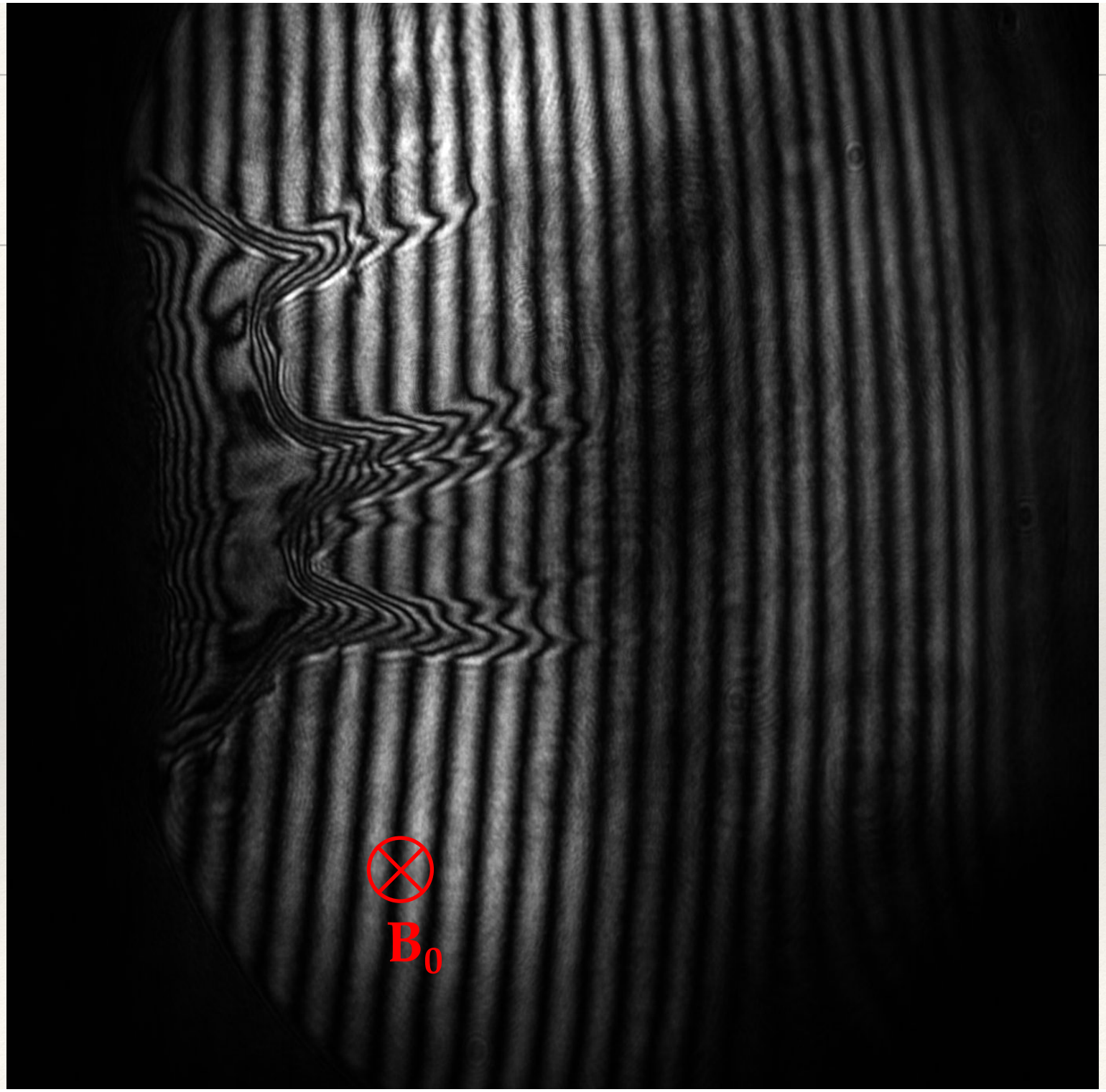


s094
48 ns
26.4 J

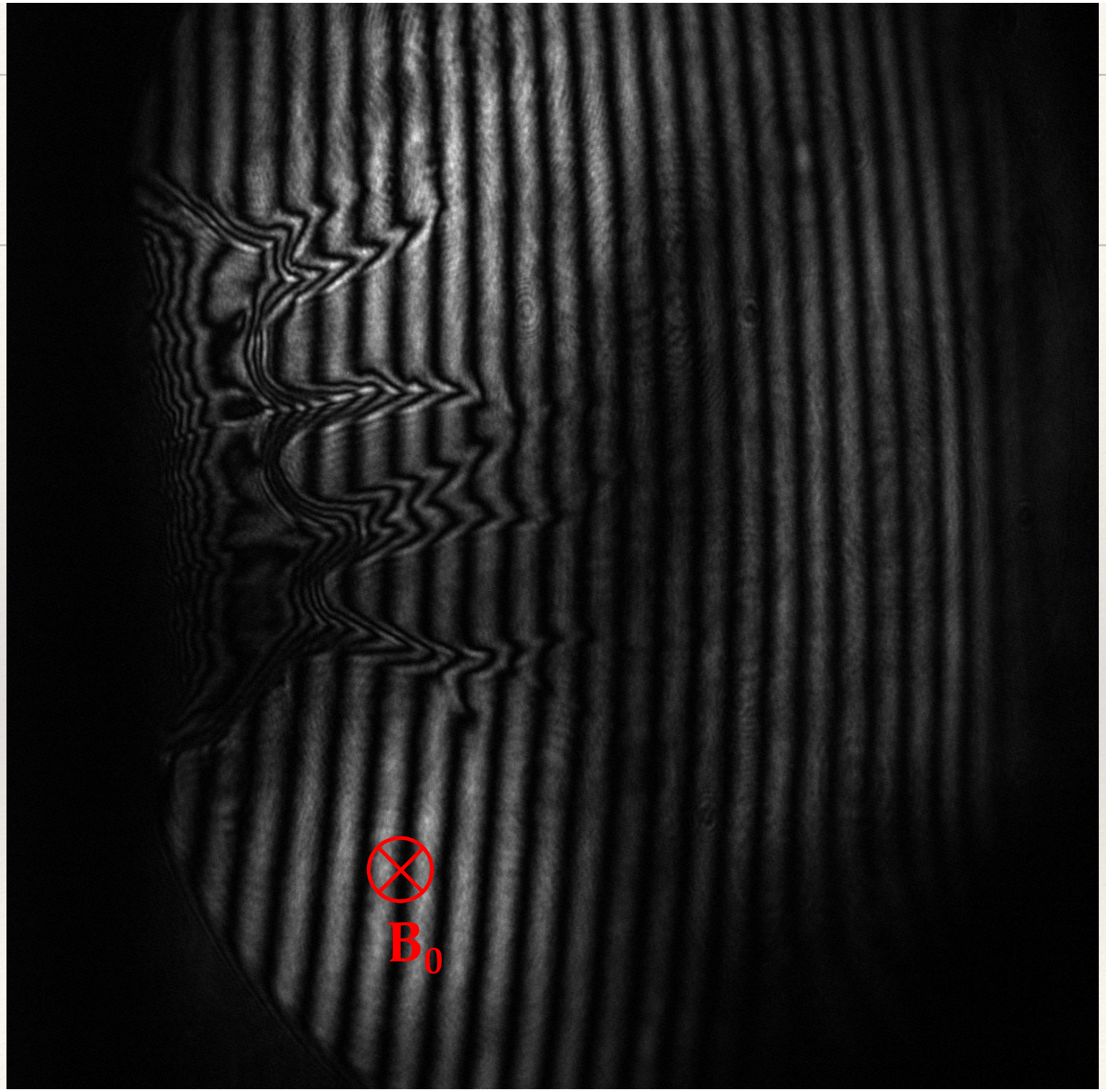


s095
48 ns
26.4 J

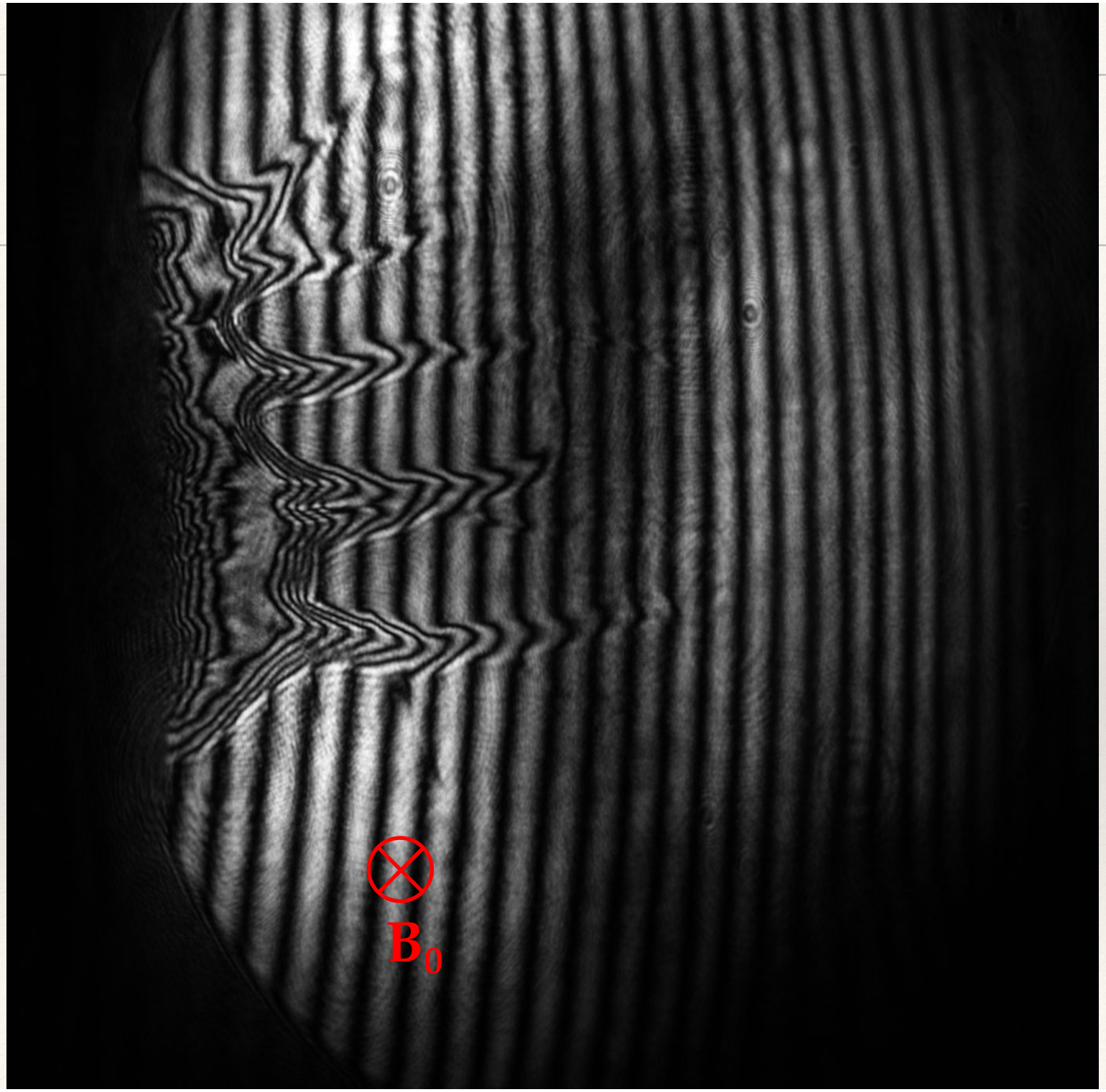
s096
58 ns
28.3 J



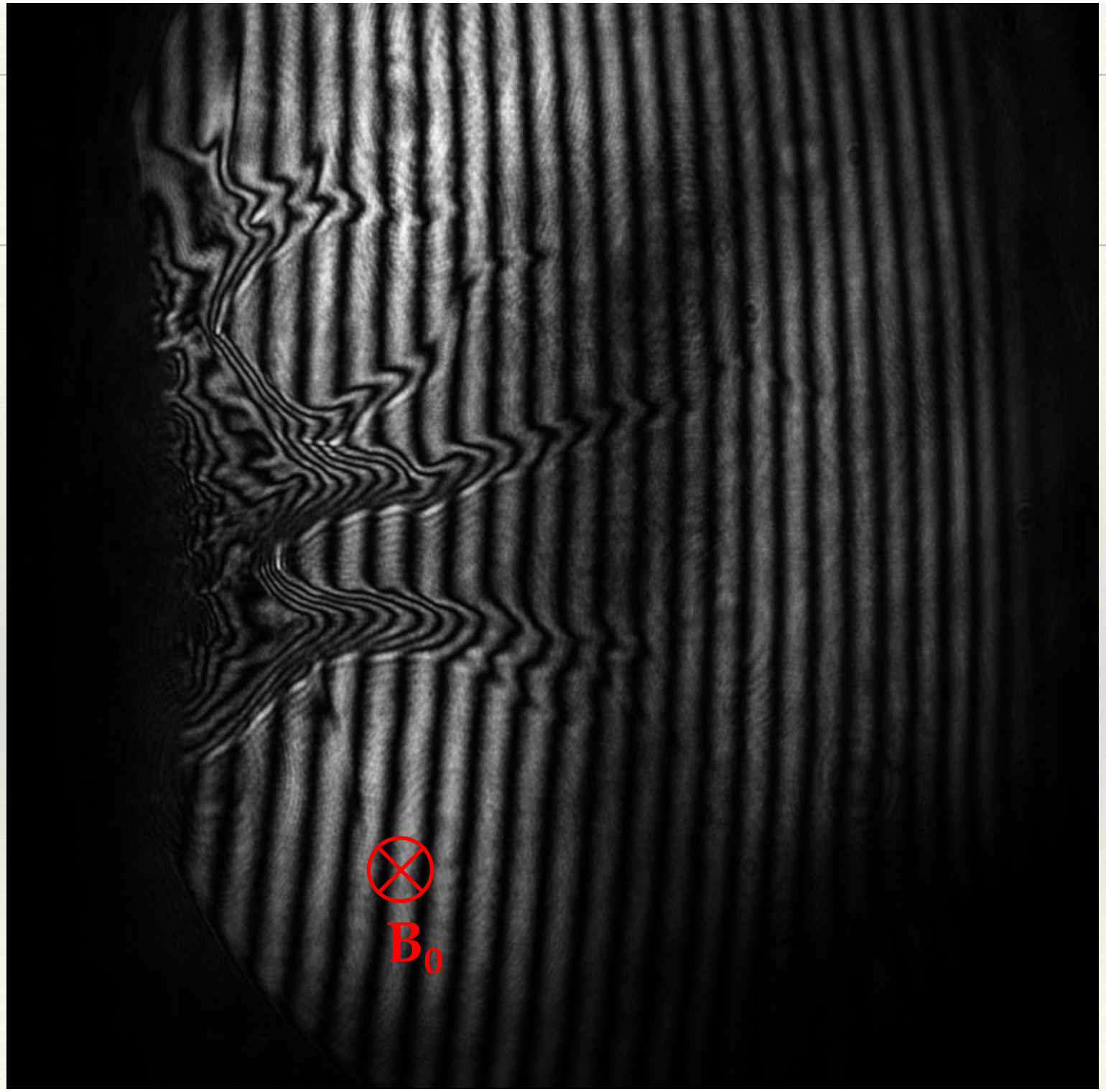
s097
58 ns
28.6 J



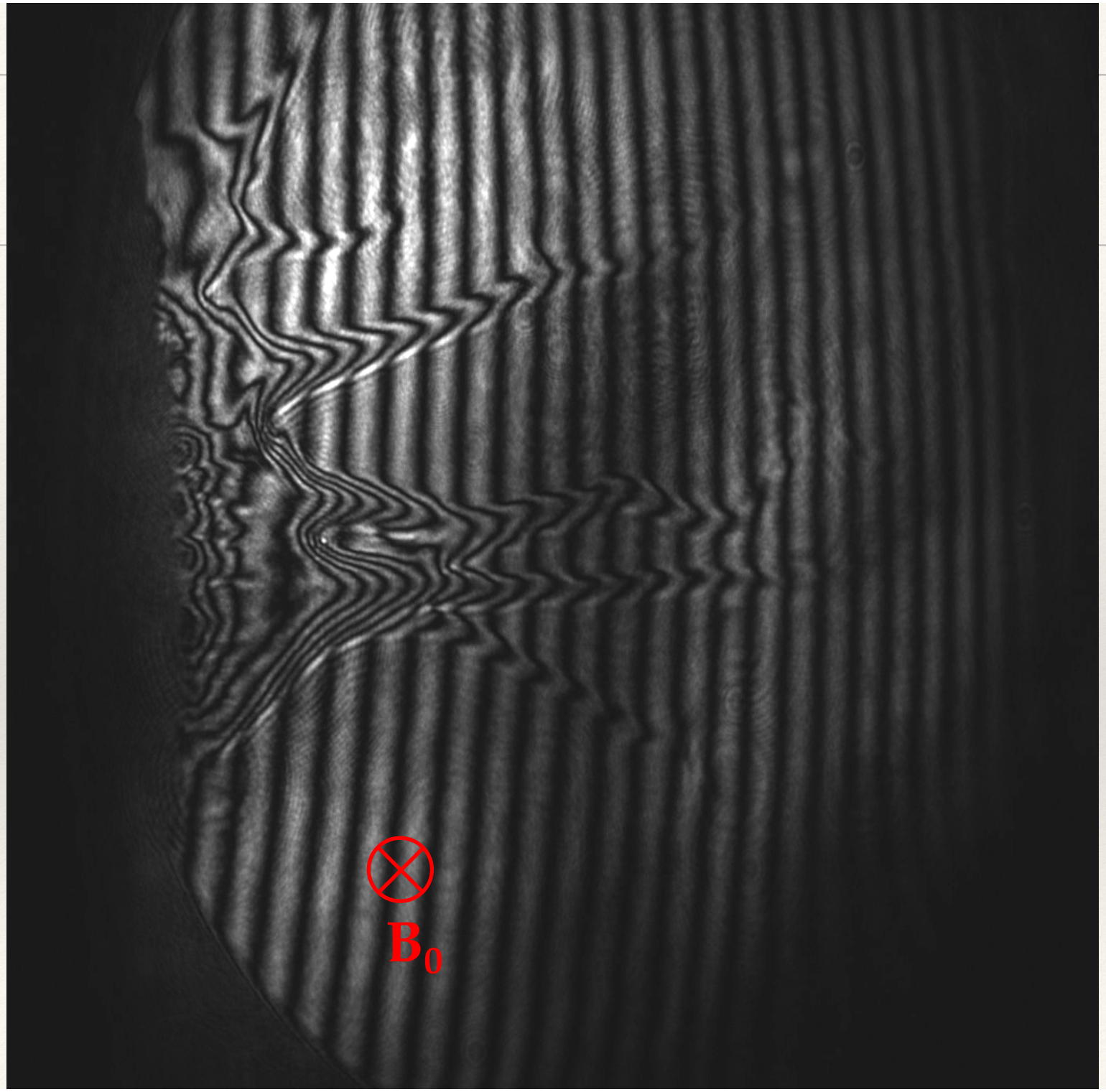
s098
68 ns
27.8 J



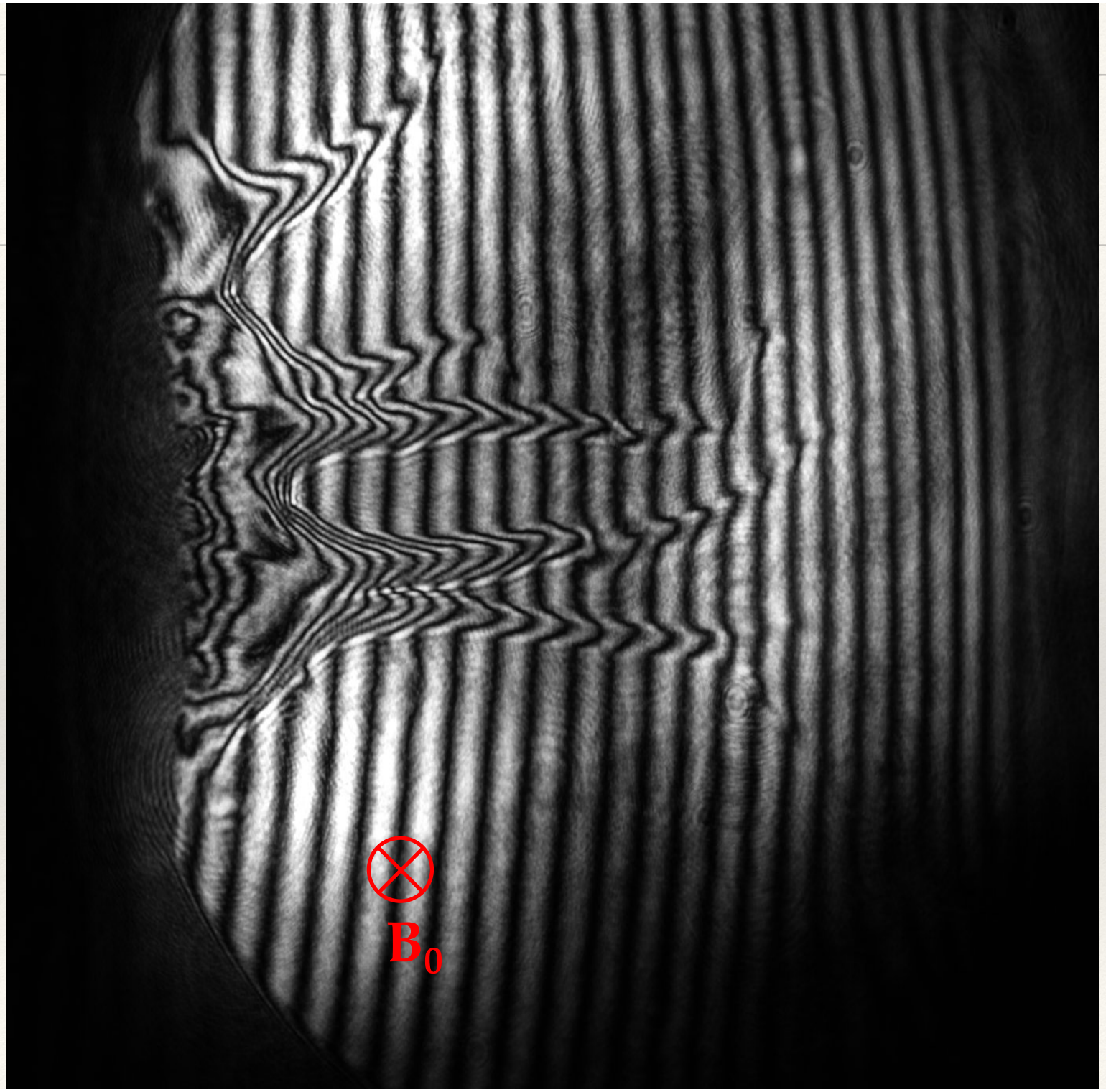
s099
78 ns
28.6 J



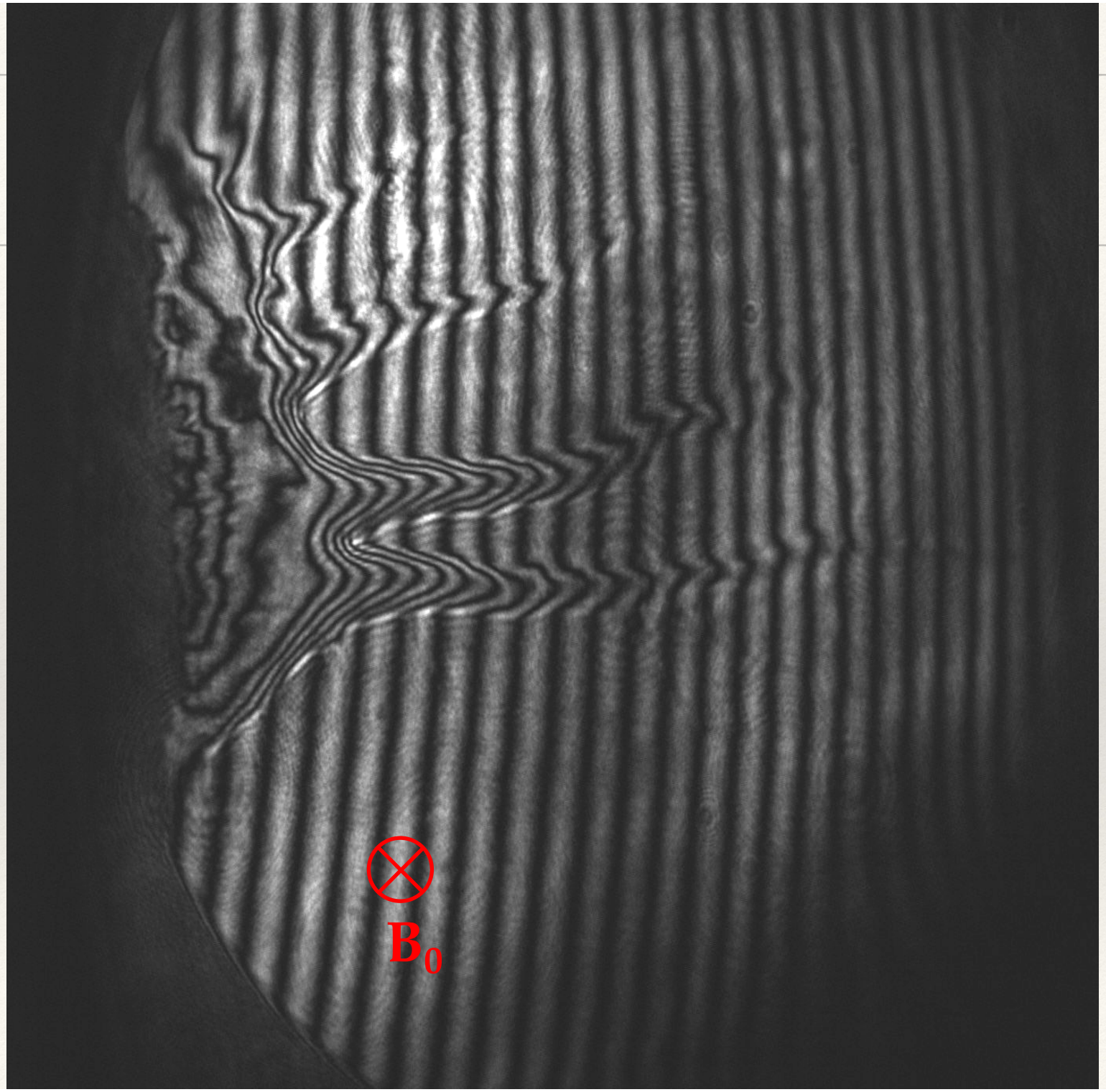
s100
88 ns
26.9 J



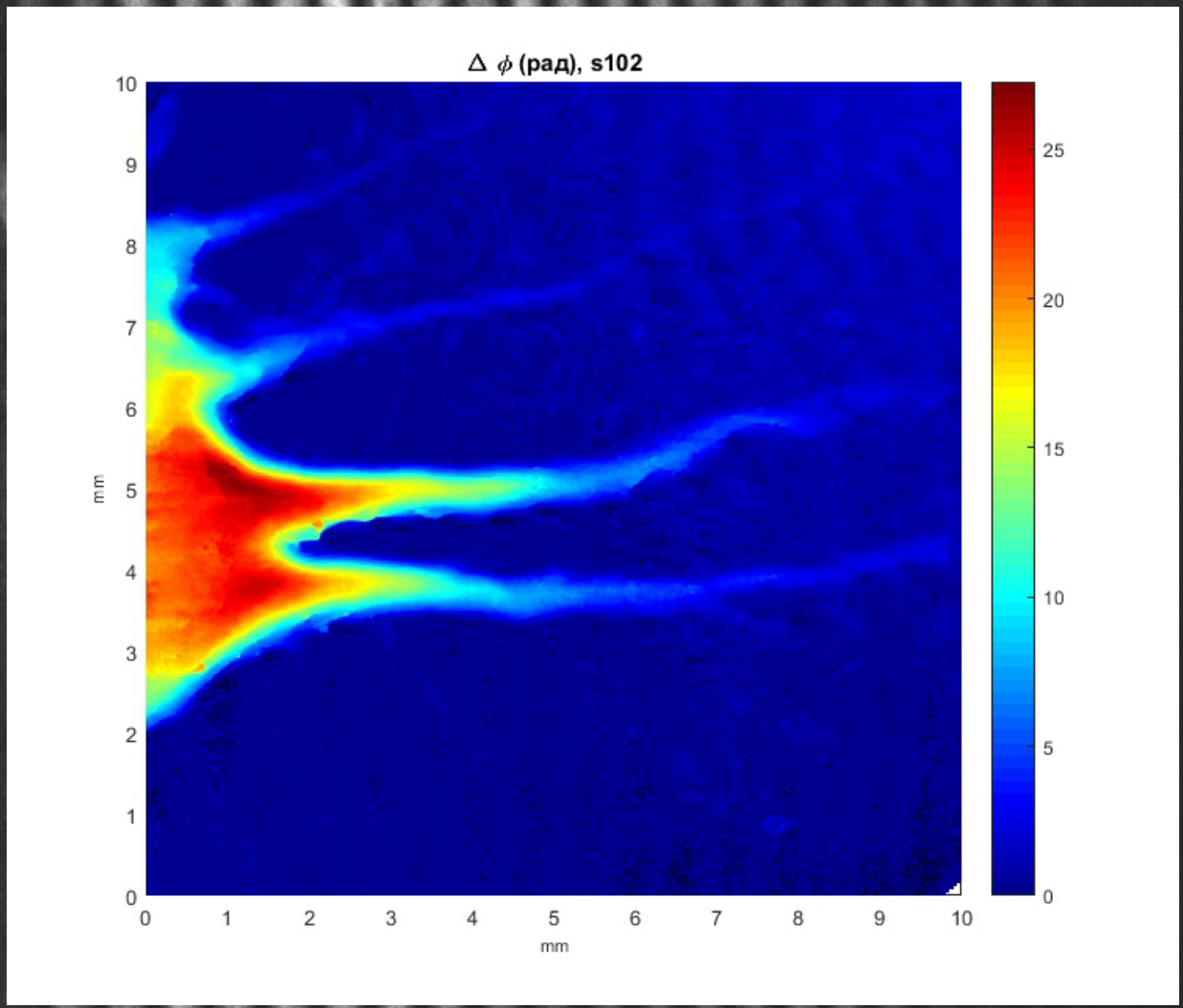
s101
98 ns
28.6 J



s102
108 ns
26.2 J



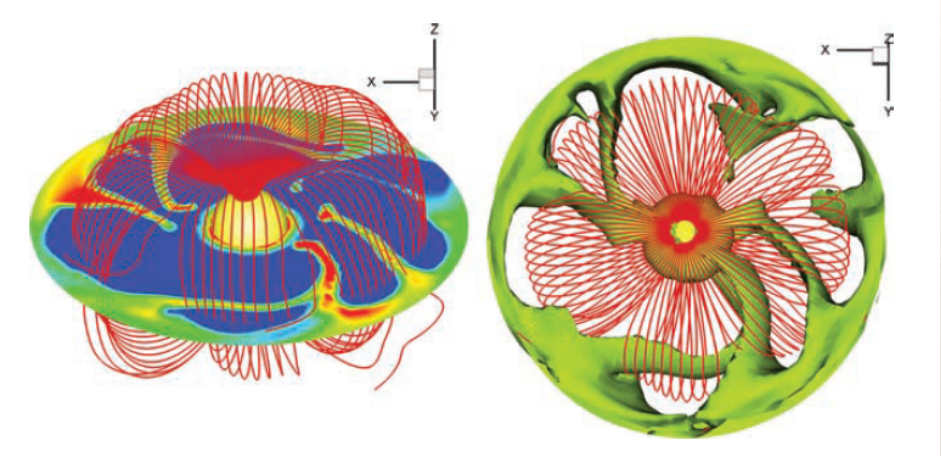
s102
108 ns
26.2 J



B_0

Summary

Kulkarni and Romanova MNRAS. **386, 673–687 (2008)**



- Small-scale RT instability at the edge of an accretion disc
- The source of the turbulence in accretion discs (α-models)
- Structure of plasma flows in the vicinity of different astrophysical objects (hot Jupiters etc.)