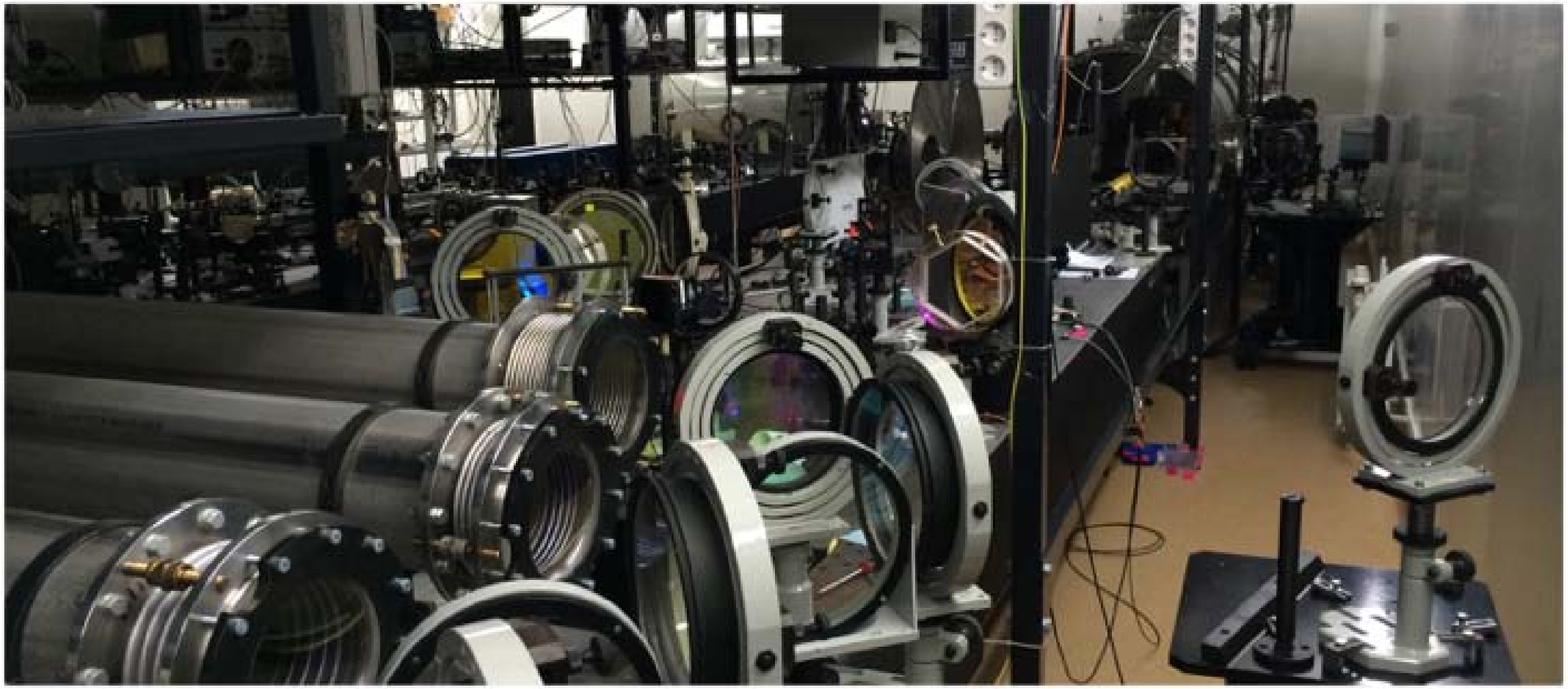

Стародубцев М.В.
Институт прикладной физики РАН
(ИПФ РАН, Нижний Новгород)

Экспериментальное исследование процессов с высокой плотностью электромагнитной энергии

Collaborators

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Коробейникова А.П.[1]
Кочетков А.А.[1]
Кузьмин А.А.[1],
Шайкин И.А.[1]
Шайкин А.А.[1]
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Рязянцев С.Н.[3]
Алхимова М.А.[3]
Филиппов Е.Д.[3]
Пикуз Т.А.[3]

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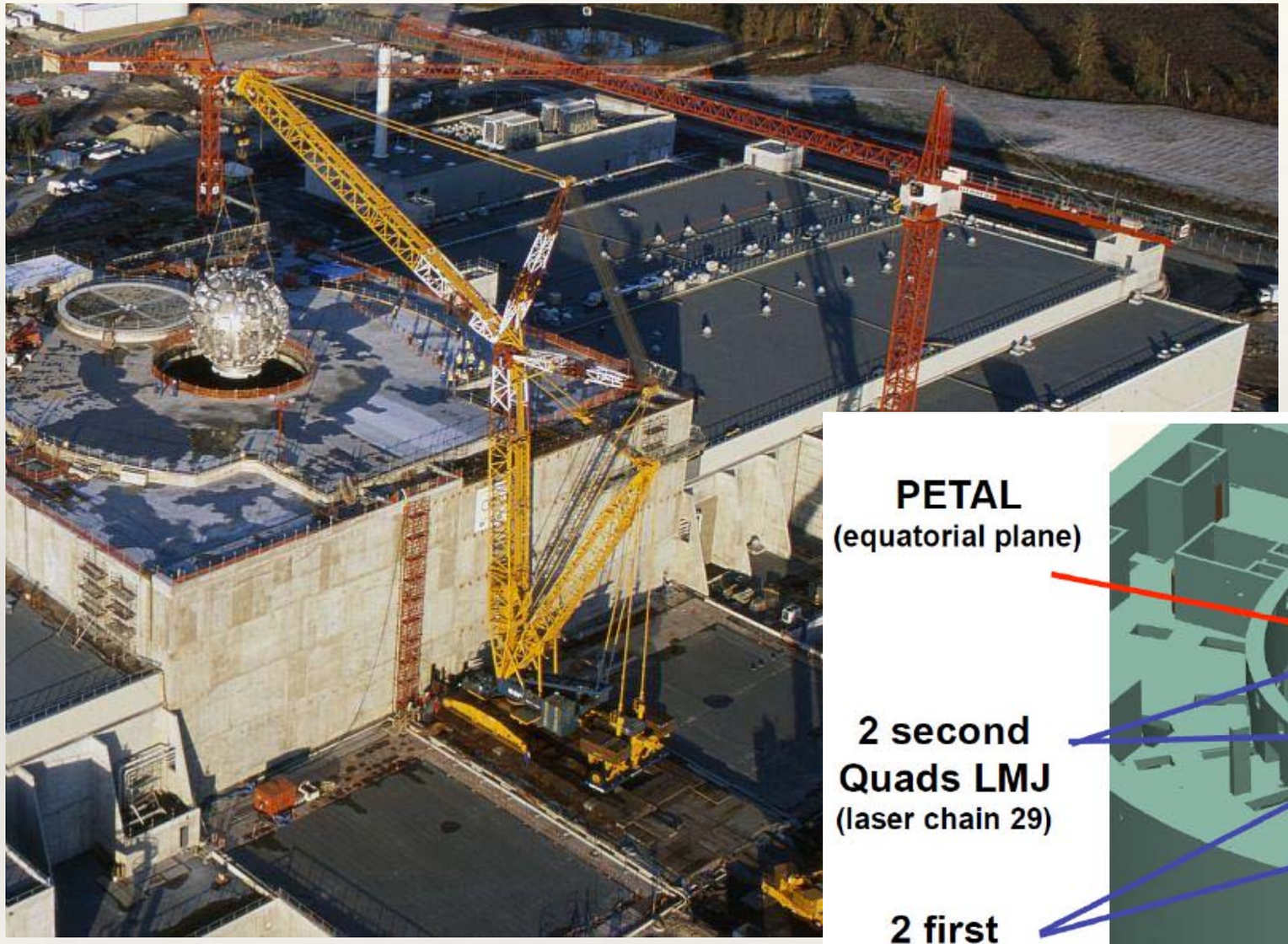
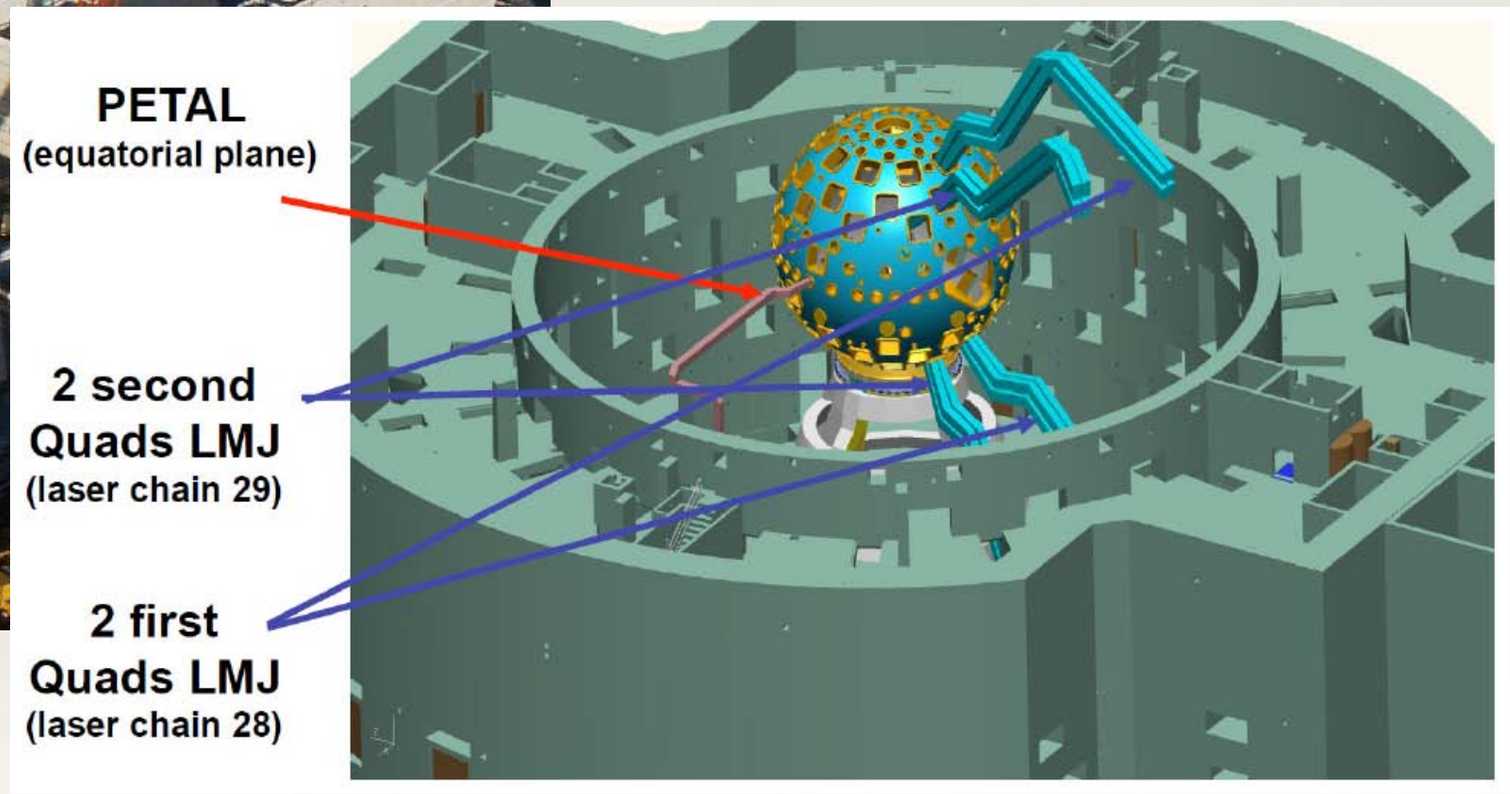
B. Khiar[4]

Бисикало Д.В.[5]
Курбатов Е.П.[5]

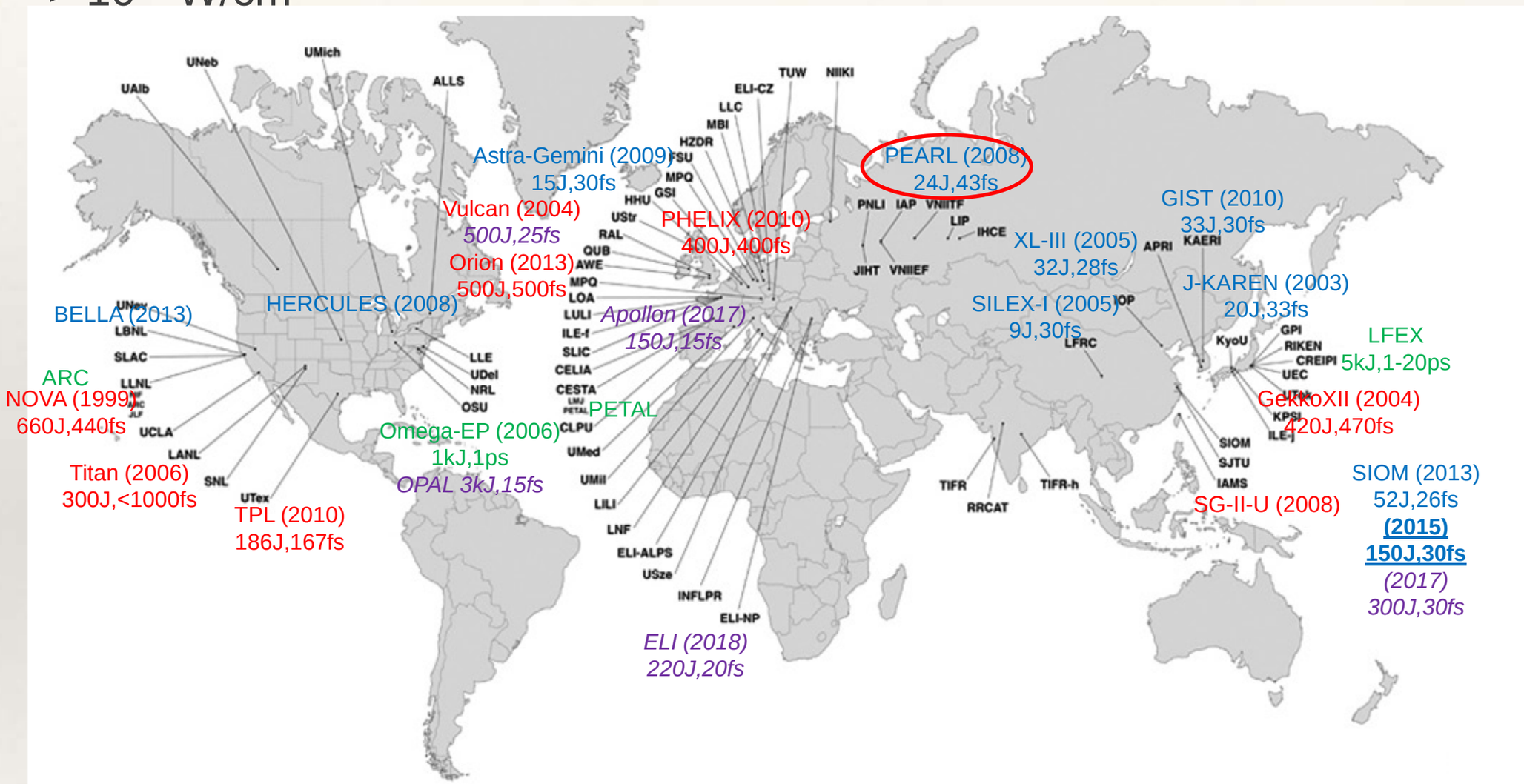
PETAL-LMJ




PETAL
(equatorial plane)
2 second
Quads LMJ
(laser chain 29)
2 first
Quads LMJ
(laser chain 28)

Ultra-high intensity lasers

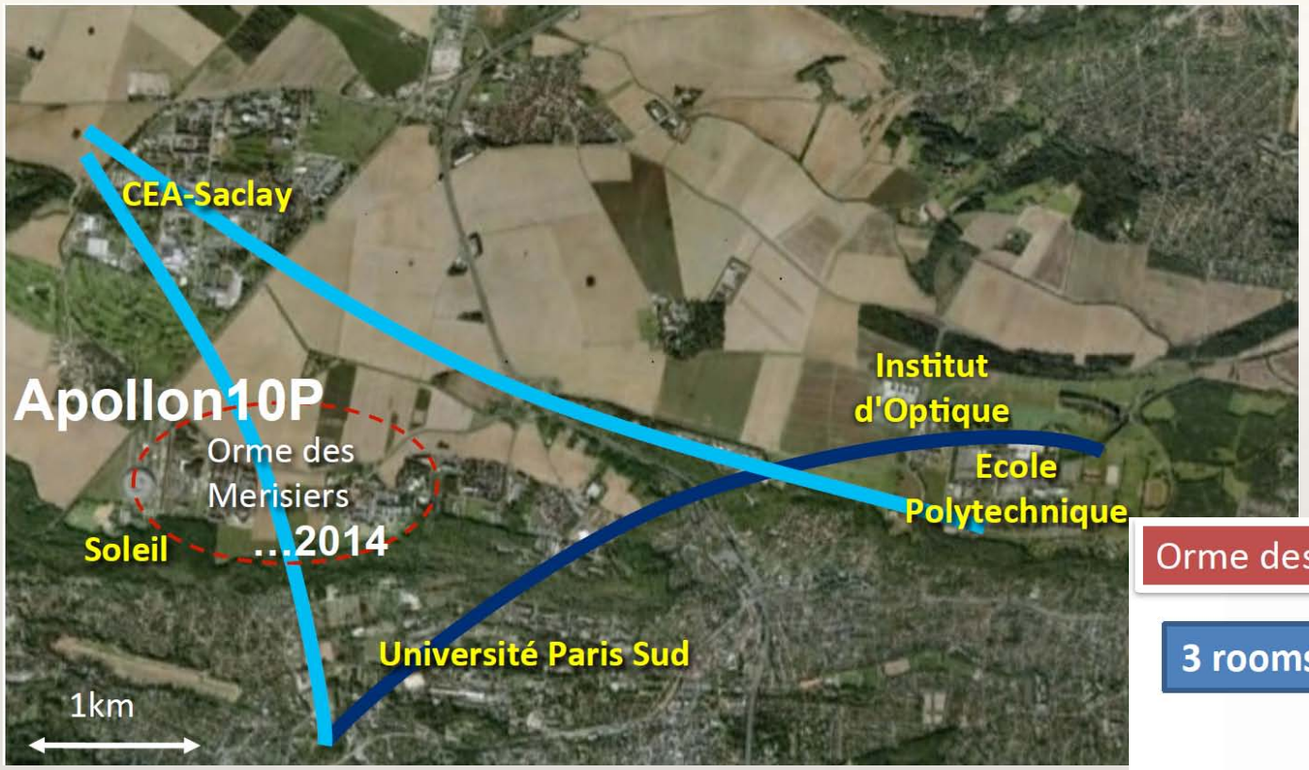
> 10^{19} W/cm^2

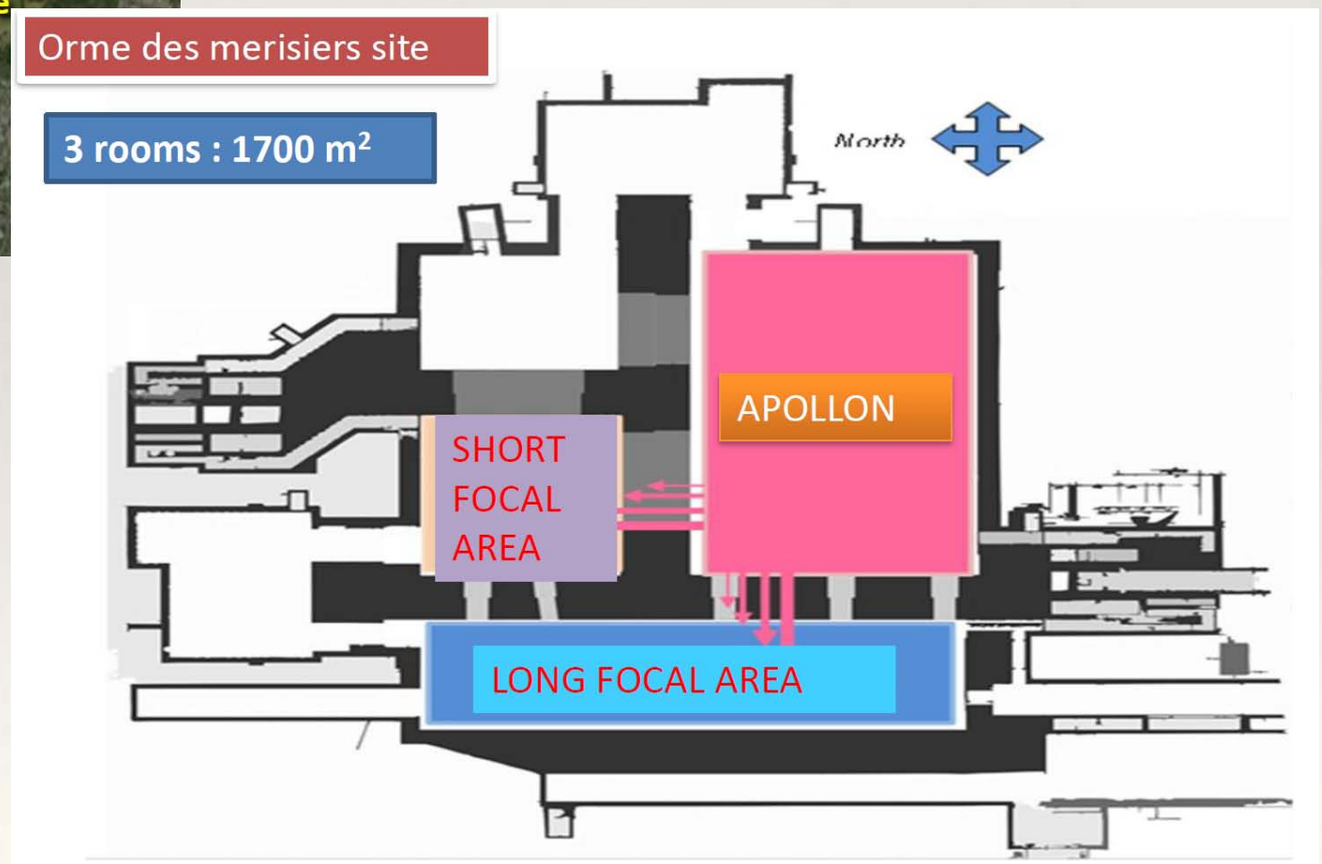


ICUIL World Map of Ultrahigh Intensity Laser Capabilities

Terry Kessler, ICUIL Secretary ICUIL *News* – June 2016 – **3**

Apollon project





- 10 PW: 150 J, 15 fs
- + 1 PW, + diagnostic fs,
- + high-energy ns

ELI-NP project

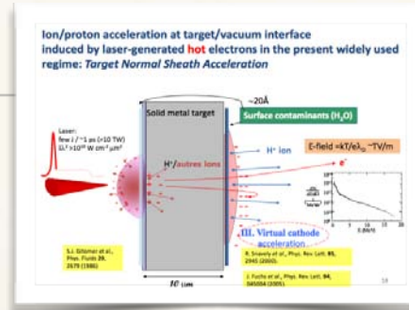
Лето 2016 г.

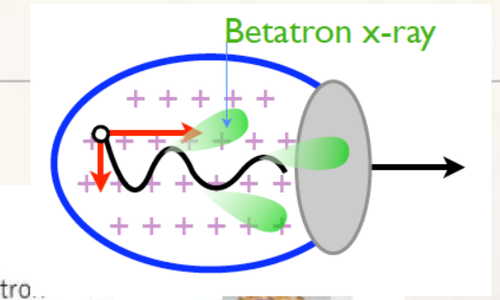
- 2×10 PW (200 J, 20 fs)
- 3 PW
- LINAC (720 MeV)

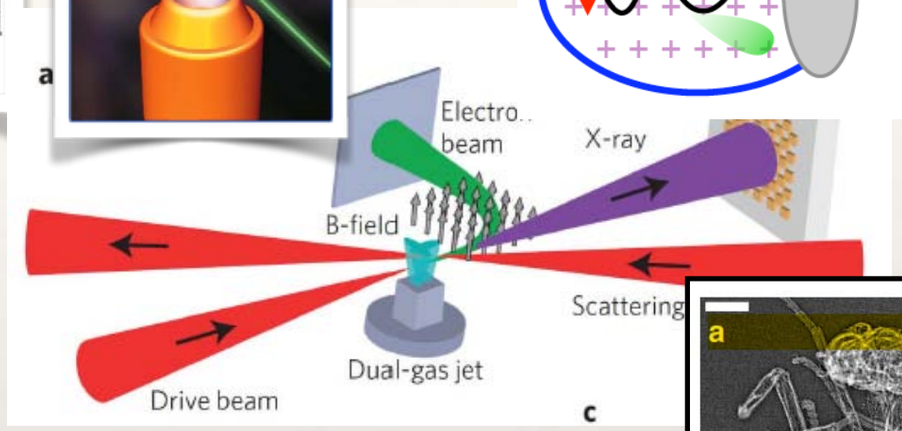
Proton/ion acceleration
Nuclear physics
Gamma beam system

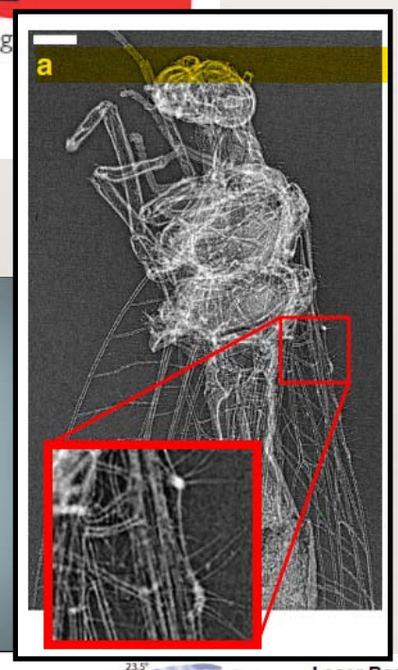
Laser-plasma interaction: applications

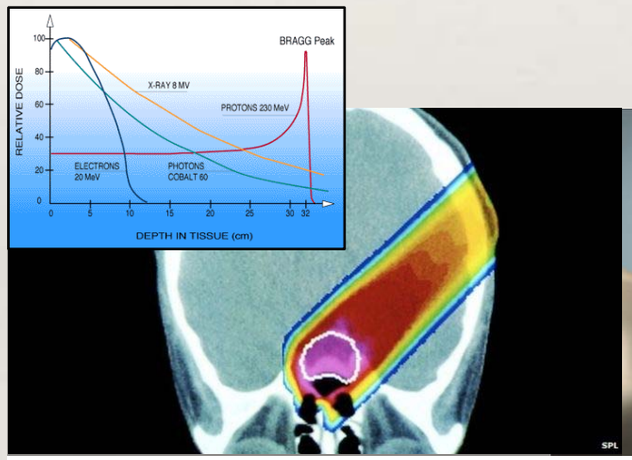
- Laser driven acceleration
  - Particles acceleration
  - X-ray generation.
- Applications
  - Radiotherapy
  - Bio-imaging
- HED physics
  - LabAstro
  - ICF

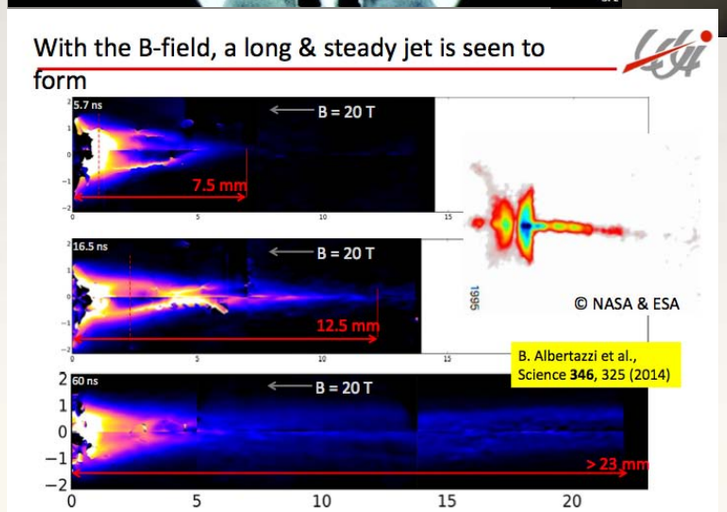


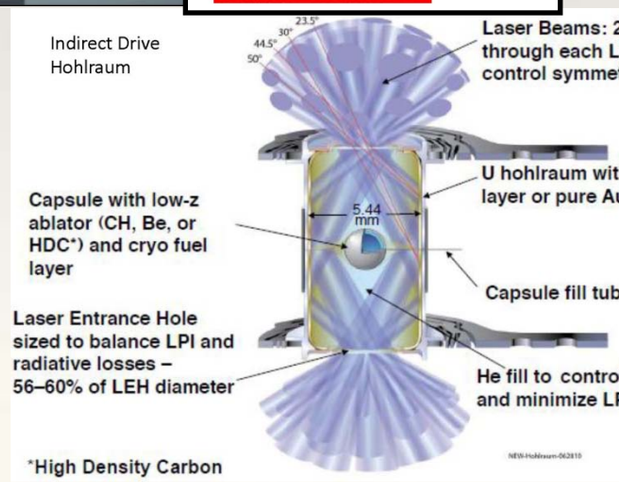








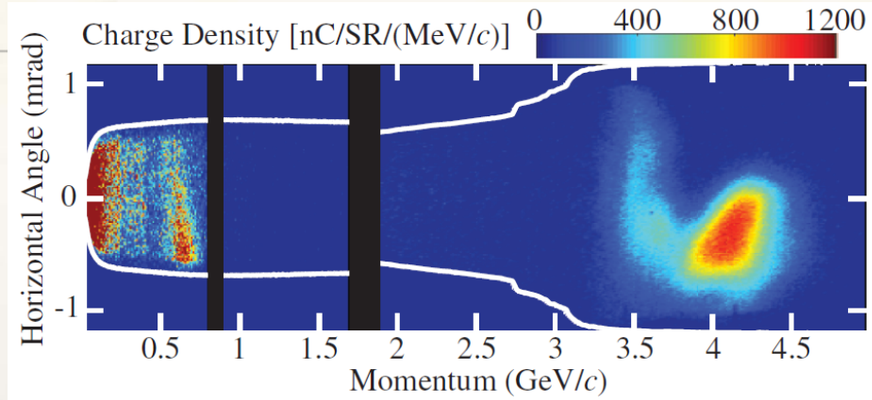




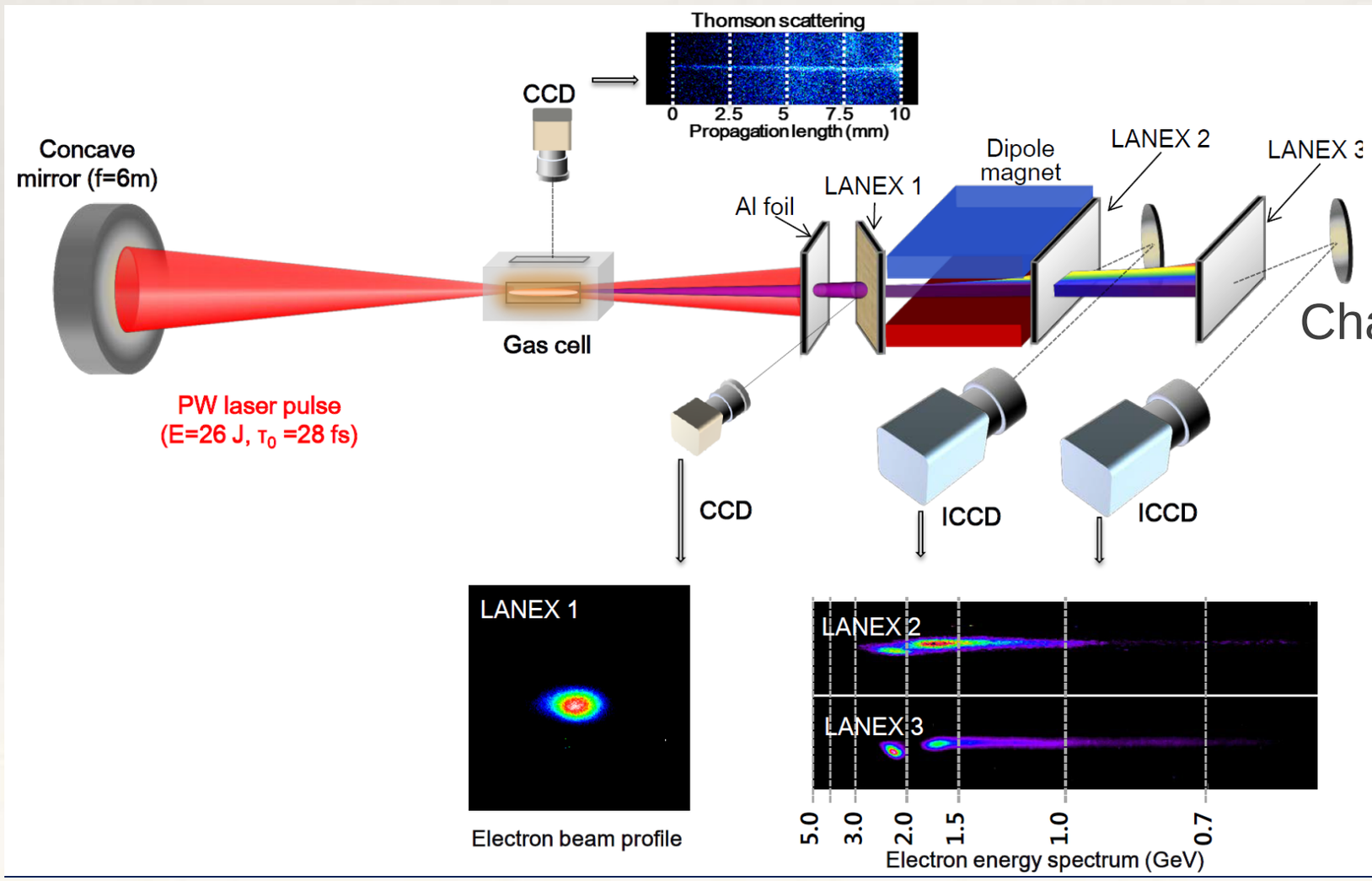
LPA: records

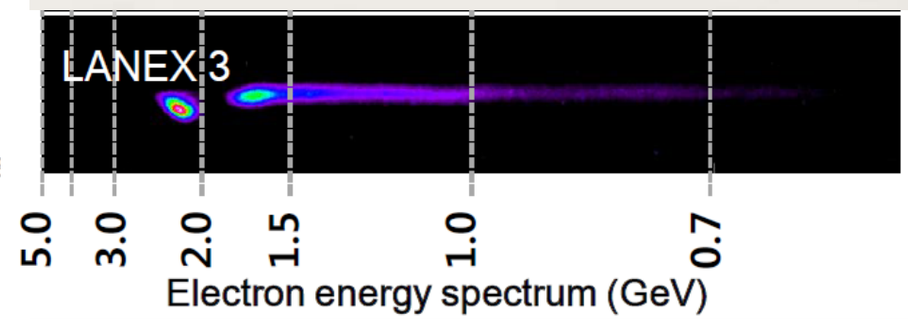
Ускорение электронов:

прозрачная плазма (газовые мишени)
плавная фокусировка лазерного излучения (≥10 м)
длинная область взаимодействия (до нескольких см)

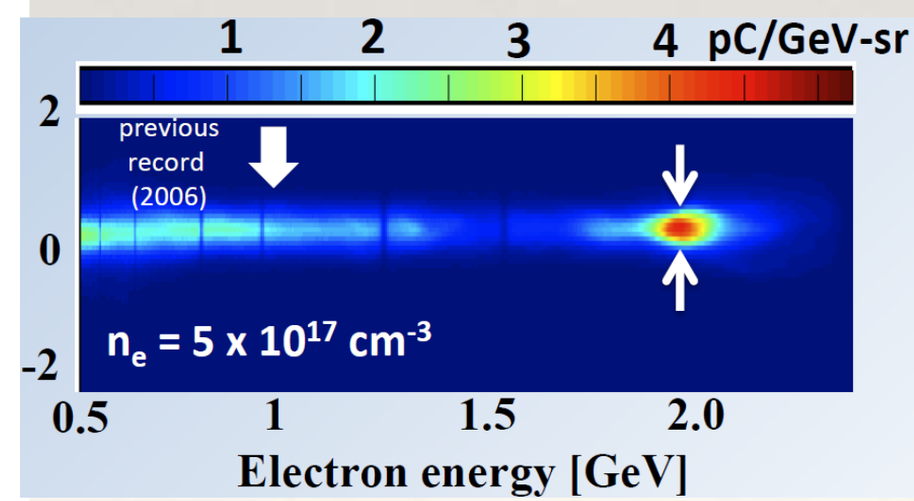


Leemans et al. (2014) / BELLA





Chang Hee Nam et al. (2014) / GIST

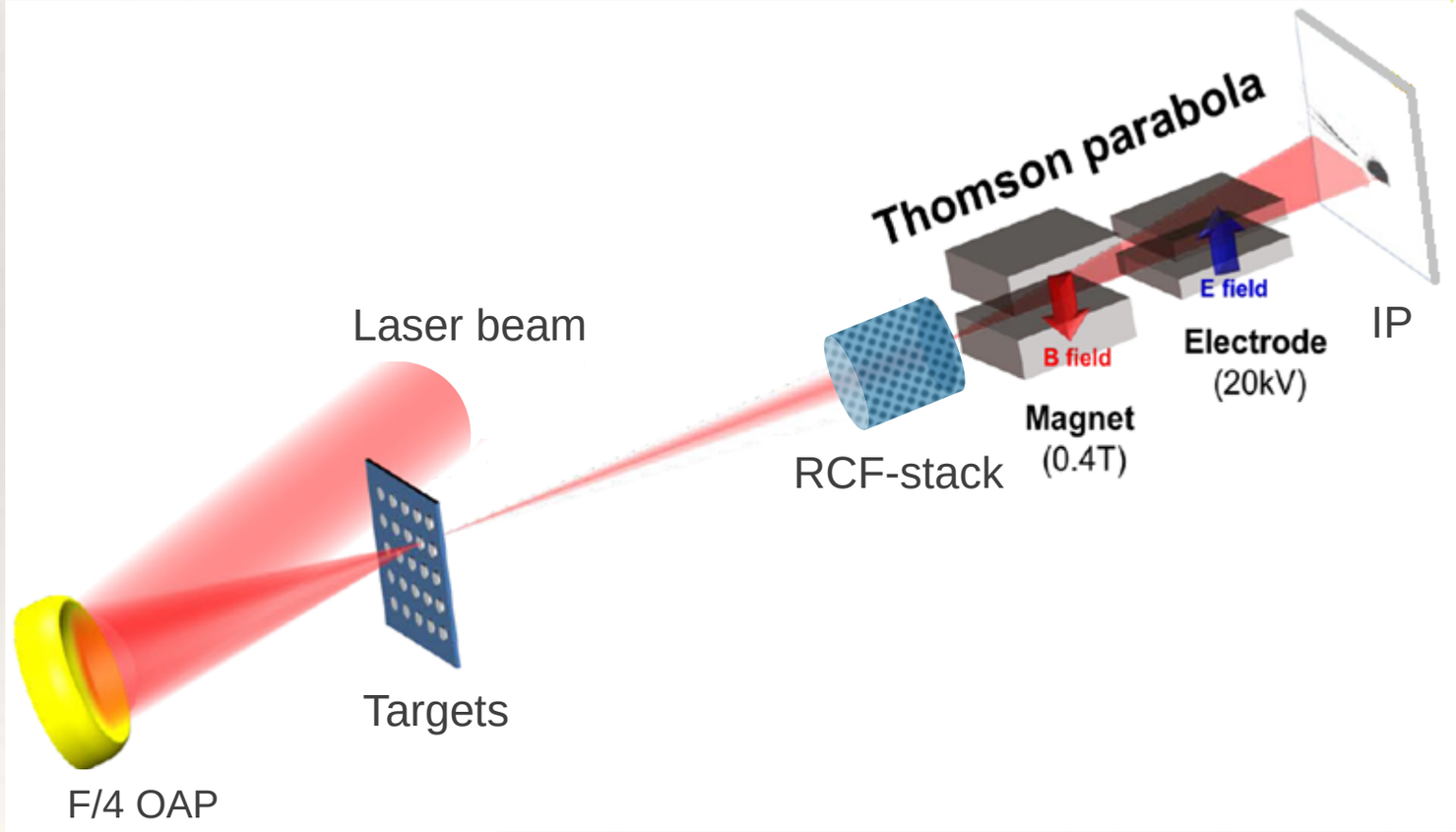


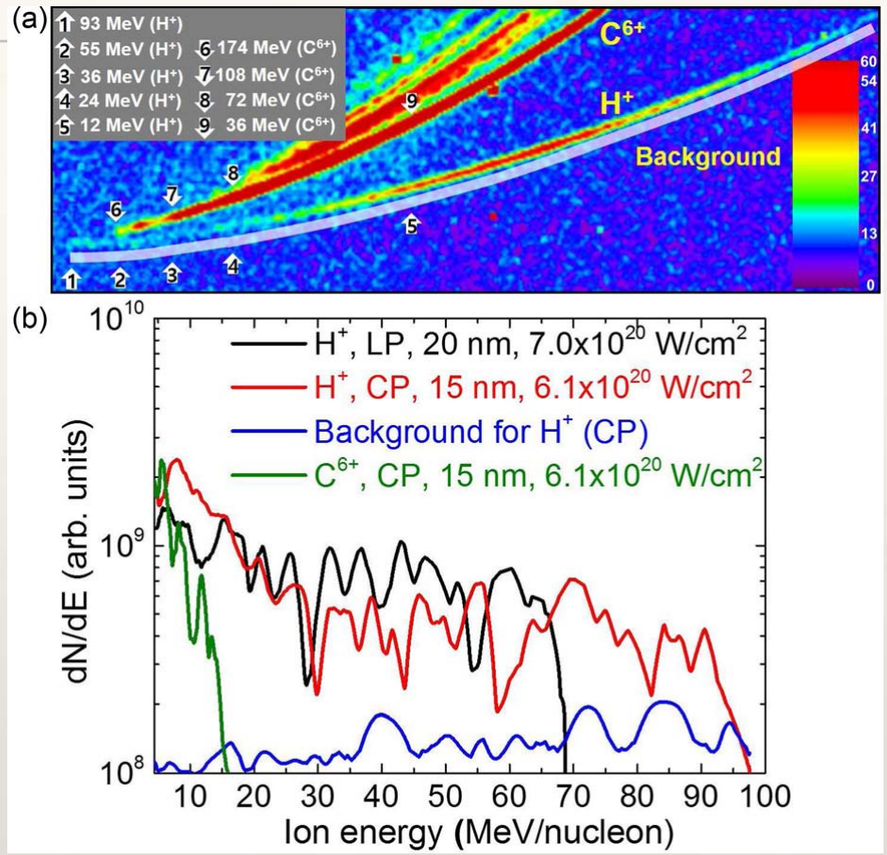
Wang et al. (2013) / TPL

LPA: records

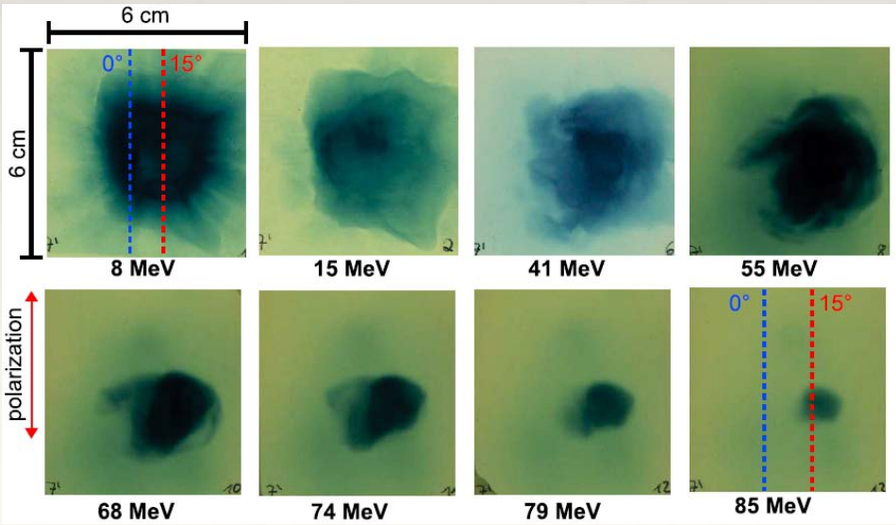
Ускорение протонов/ионов:

непрозрачная плазма (твердотельные мишени)
острая фокусировка лазерного излучения (высокая I)
высокий контраст лазерного излучения



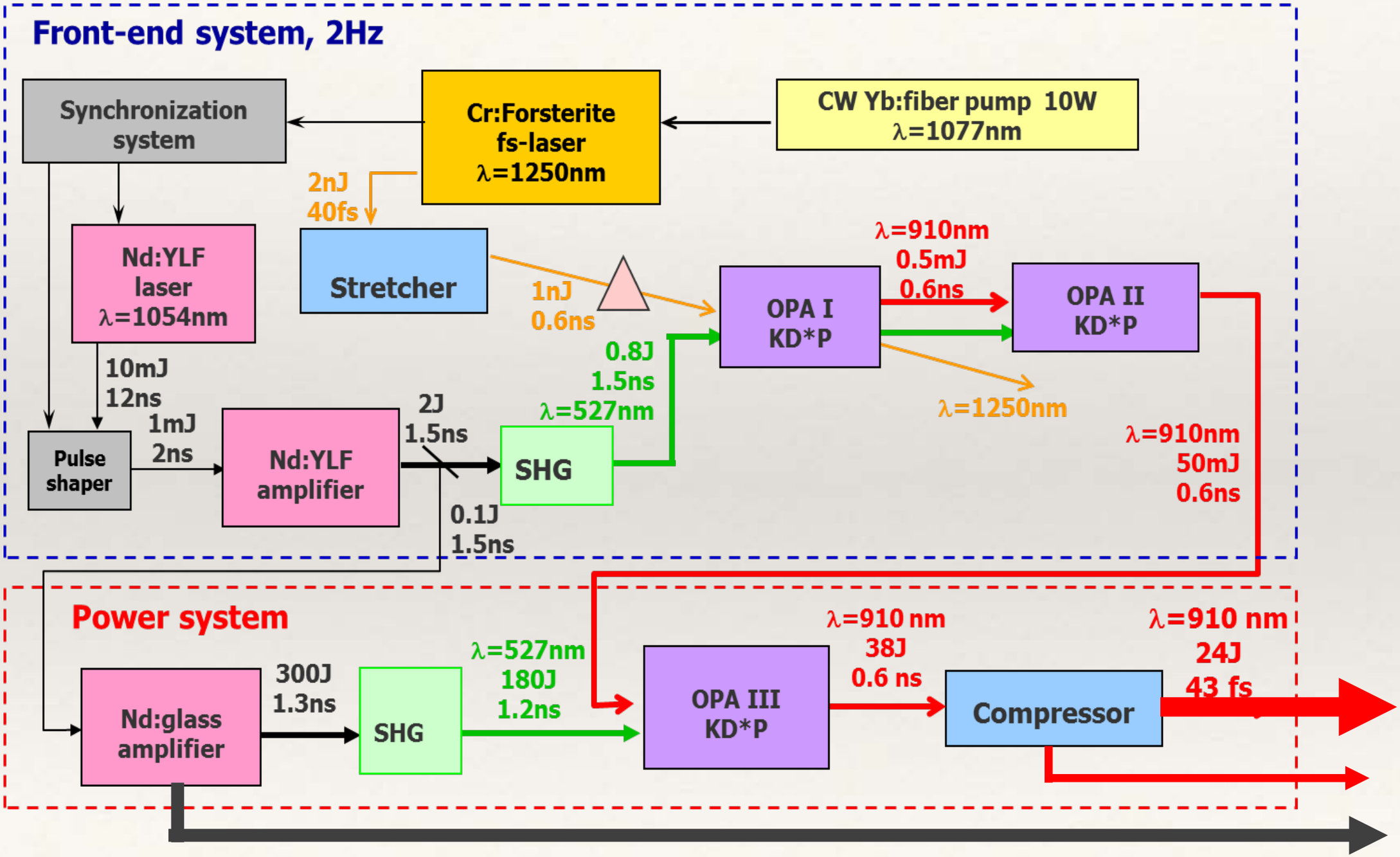


Kim et al. PoP (2016) / GIST



Wagner et al. PRL (2016) / PHELIX

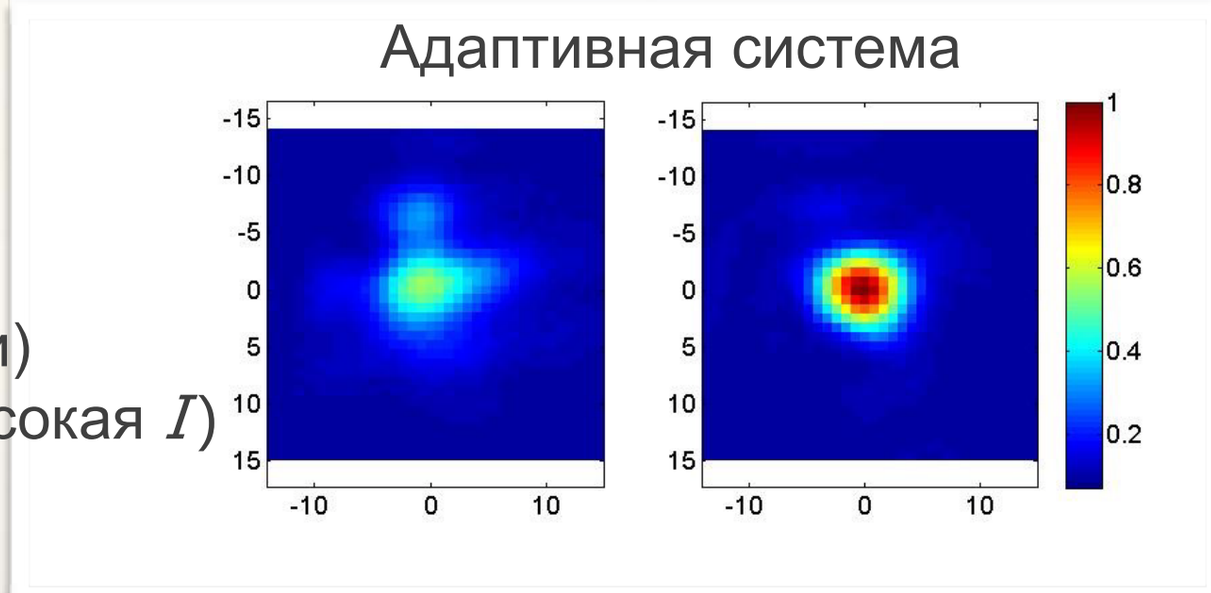
Sub-PW OPCPA PEARL laser facility

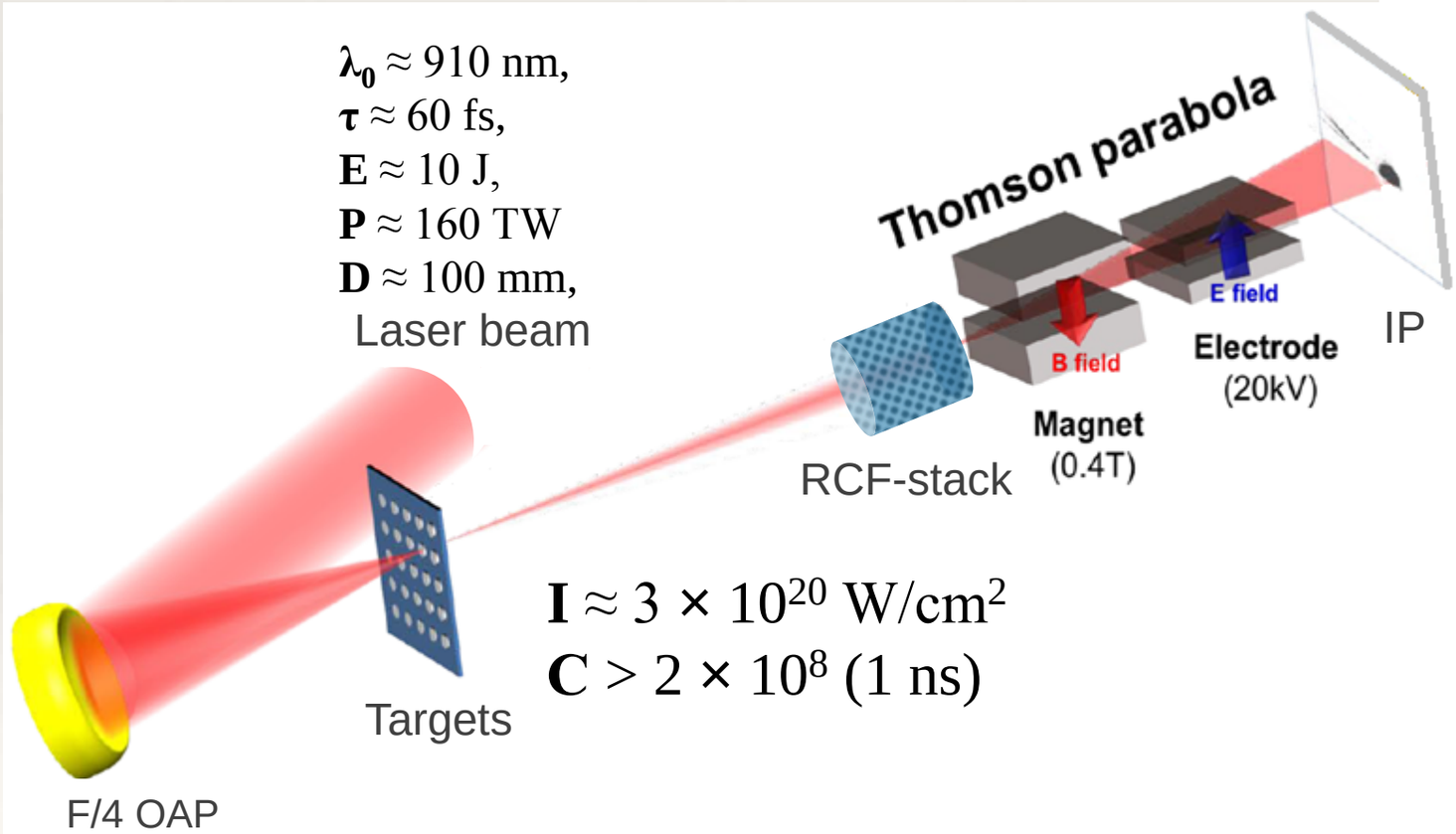


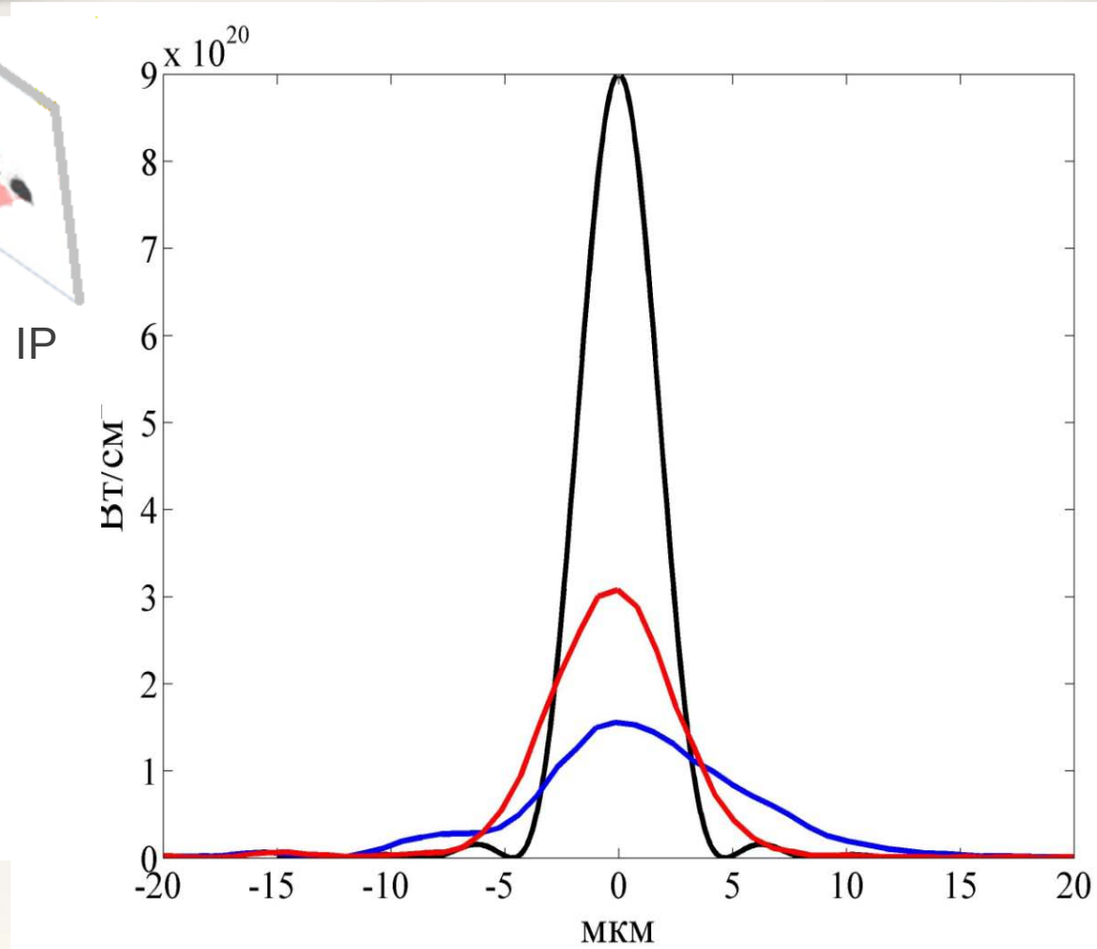
PEARL
Ion acceleration

Ускорение протонов/ионов:

непрозрачная плазма (твердотельные мишени)
острая фокусировка лазерного излучения (высокая I)
высокий контраст лазерного излучения

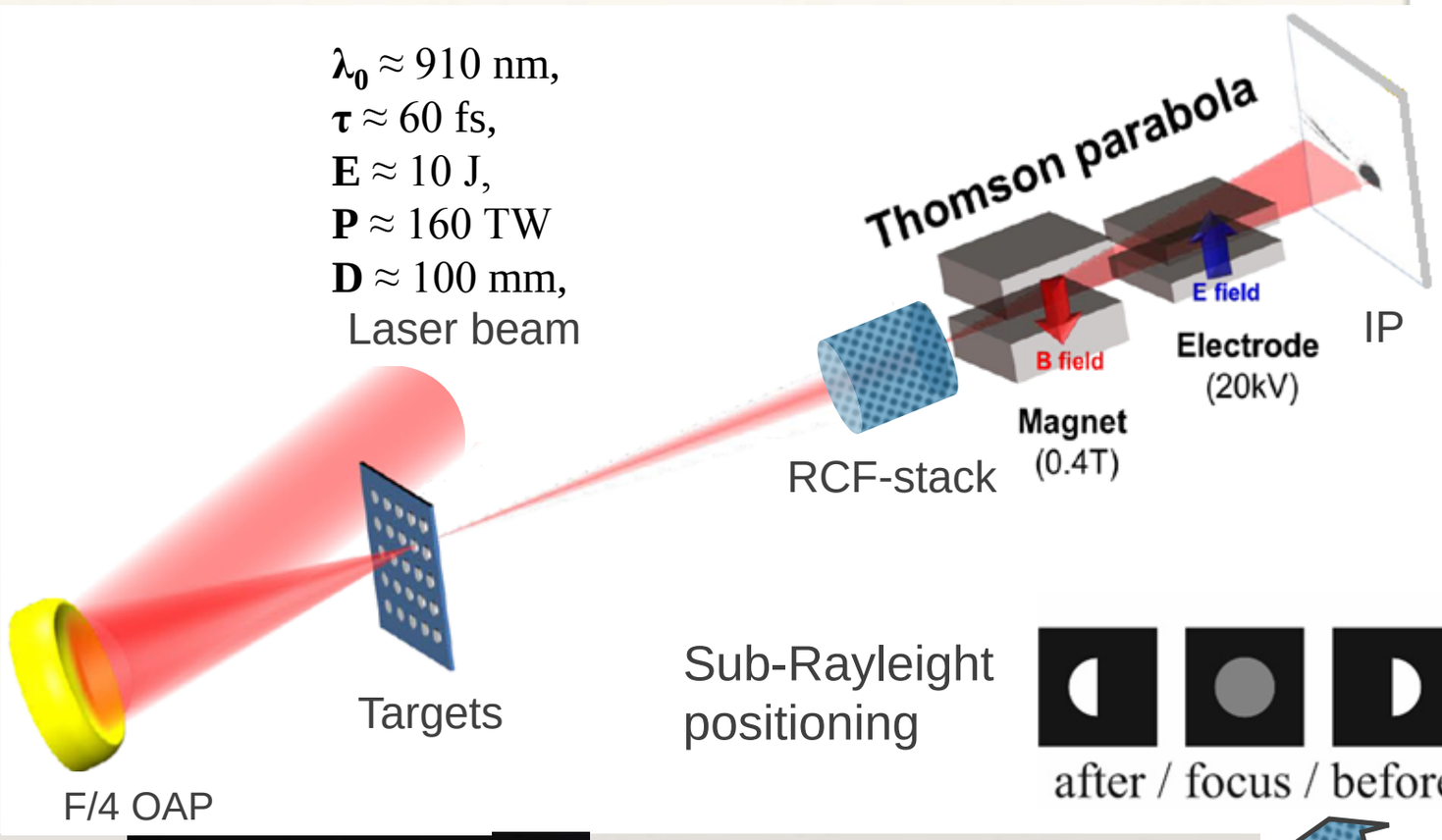






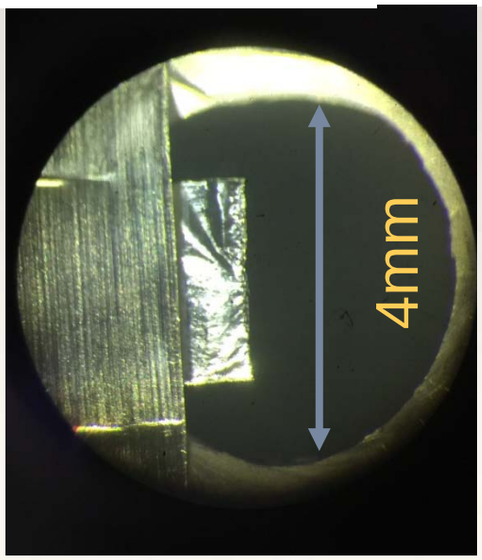
Ion acceleration

$\lambda_0 \approx 910$ nm,
$\tau \approx 60$ fs,
$E \approx 10$ J,
$P \approx 160$ TW
$D \approx 100$ mm,

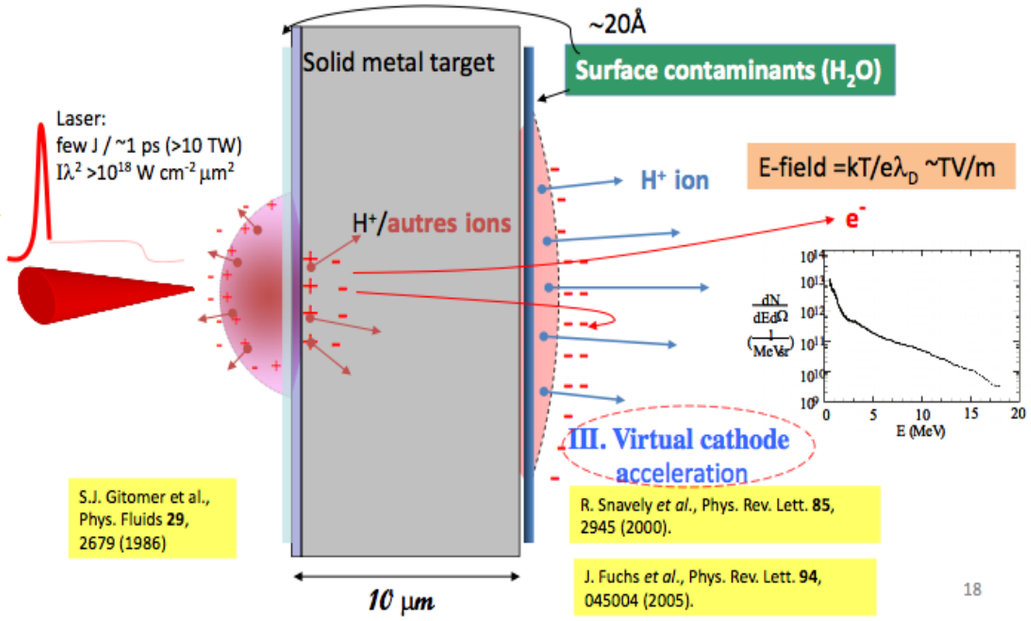


Sub-Rayleight positioning

after / focus / before



Ion/proton acceleration at target/vacuum interface induced by laser-generated hot electrons in the present widely used regime: *Target Normal Sheath Acceleration*

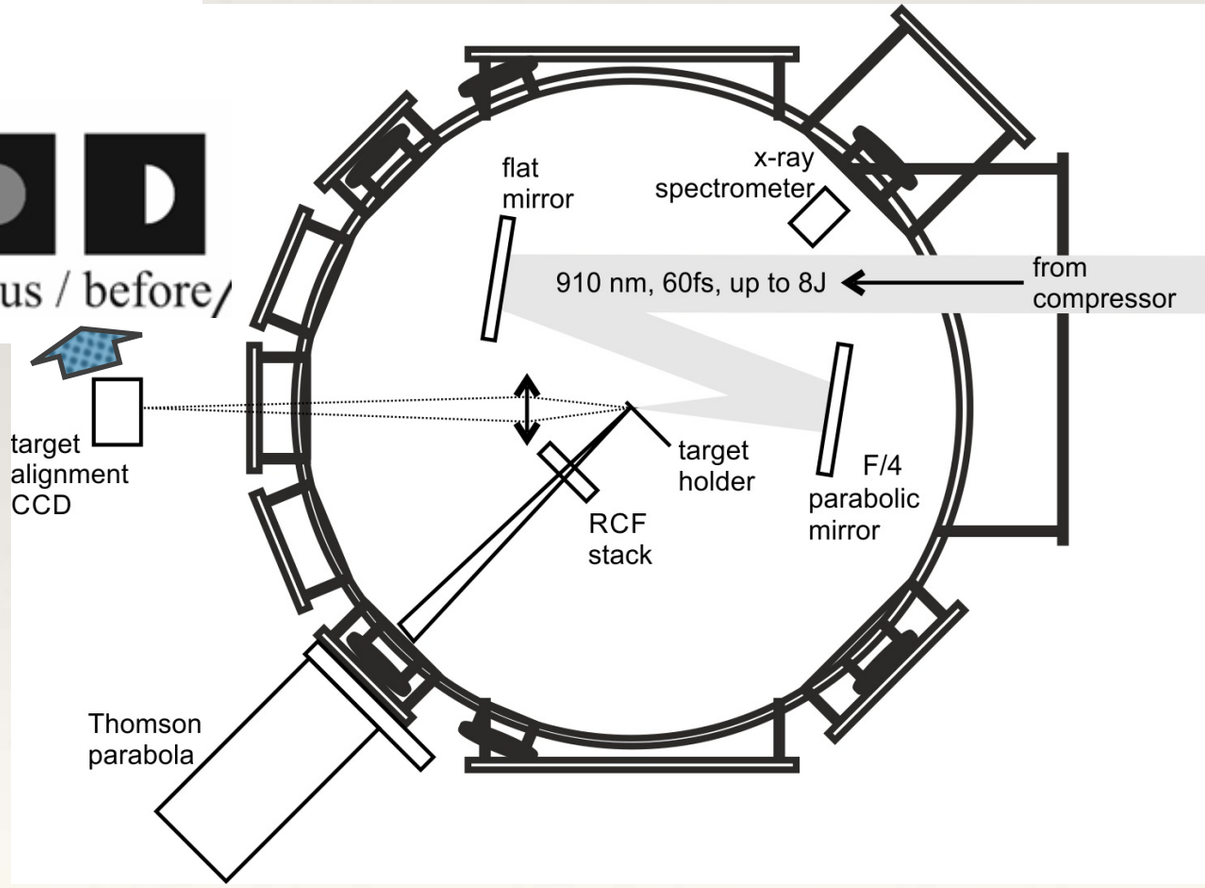


S.J. Gitomer et al., Phys. Fluids **29**, 2679 (1986)

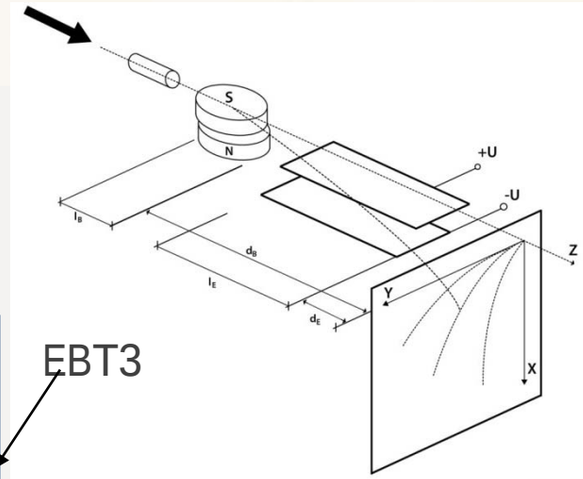
R. Snavely *et al.*, Phys. Rev. Lett. **85**, 2945 (2000).

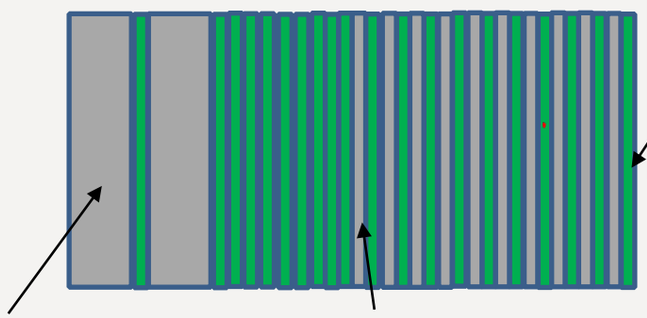
J. Fuchs *et al.*, Phys. Rev. Lett. **94**, 045004 (2005).

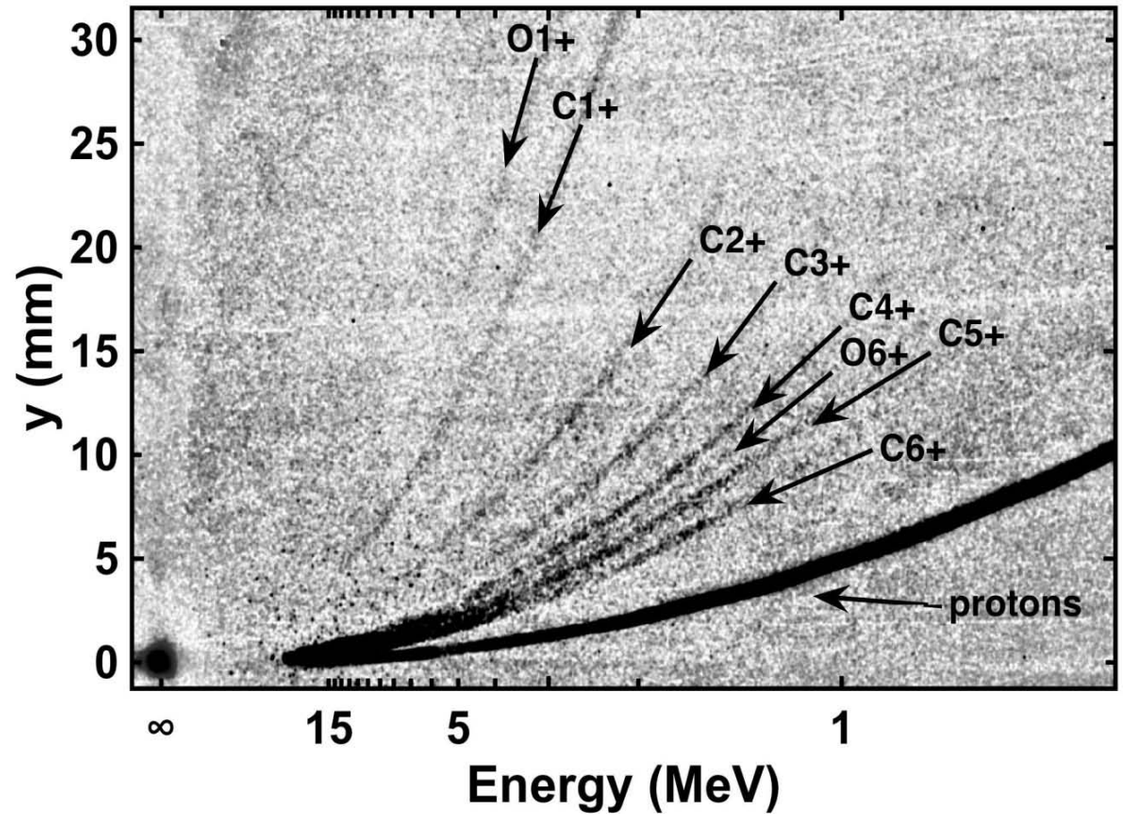
18



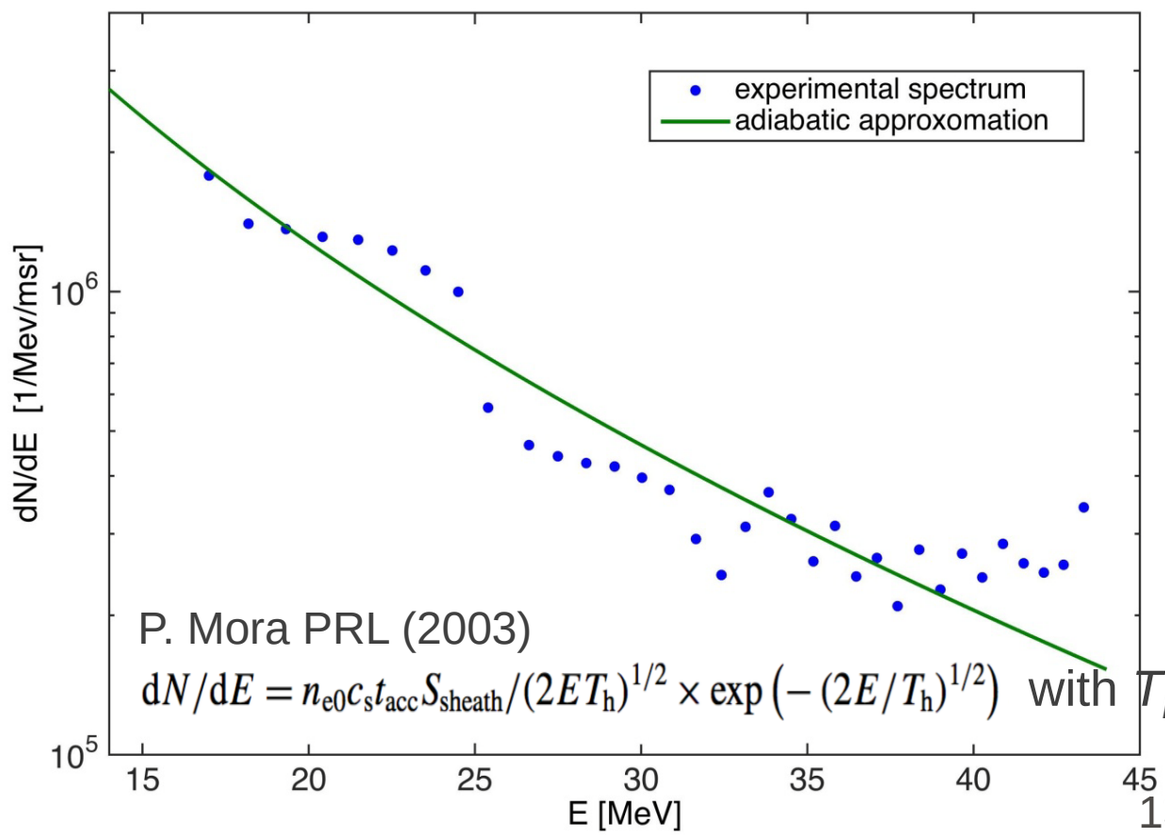
Ion acceleration





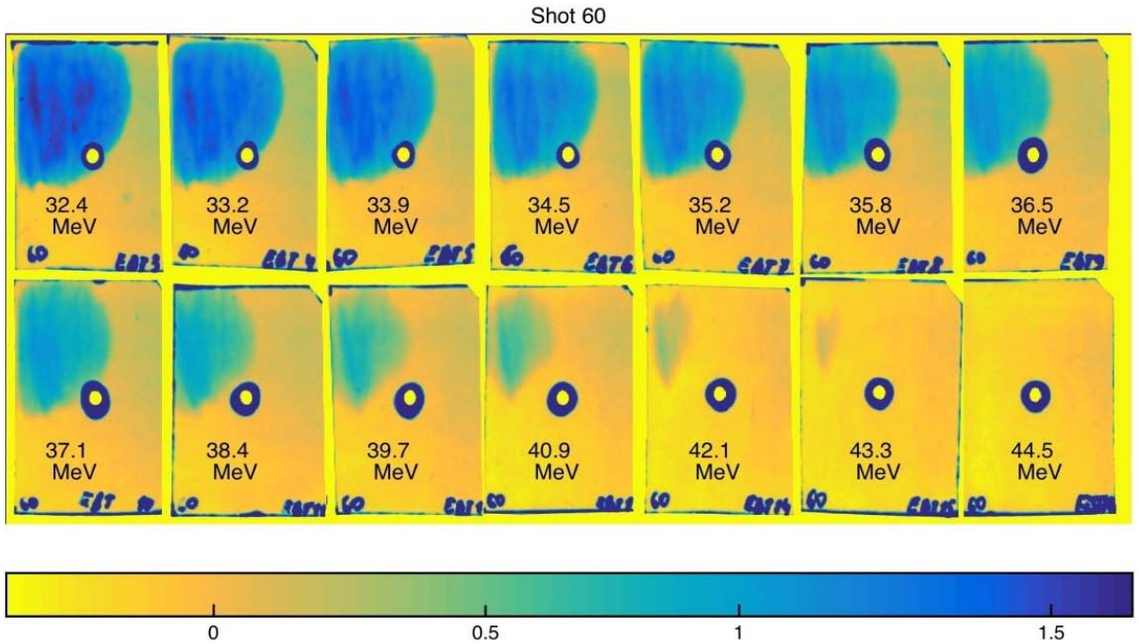


Experimental data:



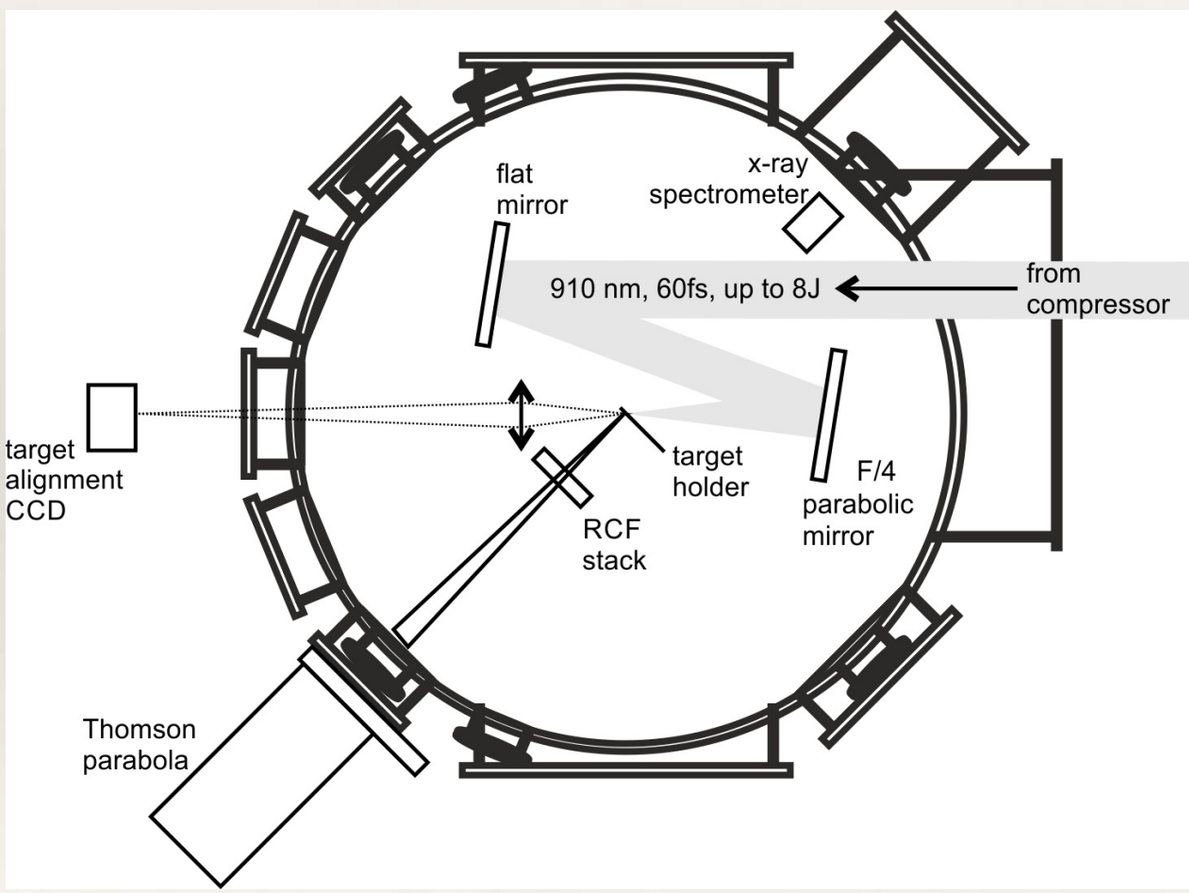
P. Mora PRL (2003)

$$dN/dE = n_{e0} c_s t_{acc} S_{sheath} / (2ET_h)^{1/2} \times \exp\left(-(2E/T_h)^{1/2}\right)$$ with T_h= 3.5 MeV

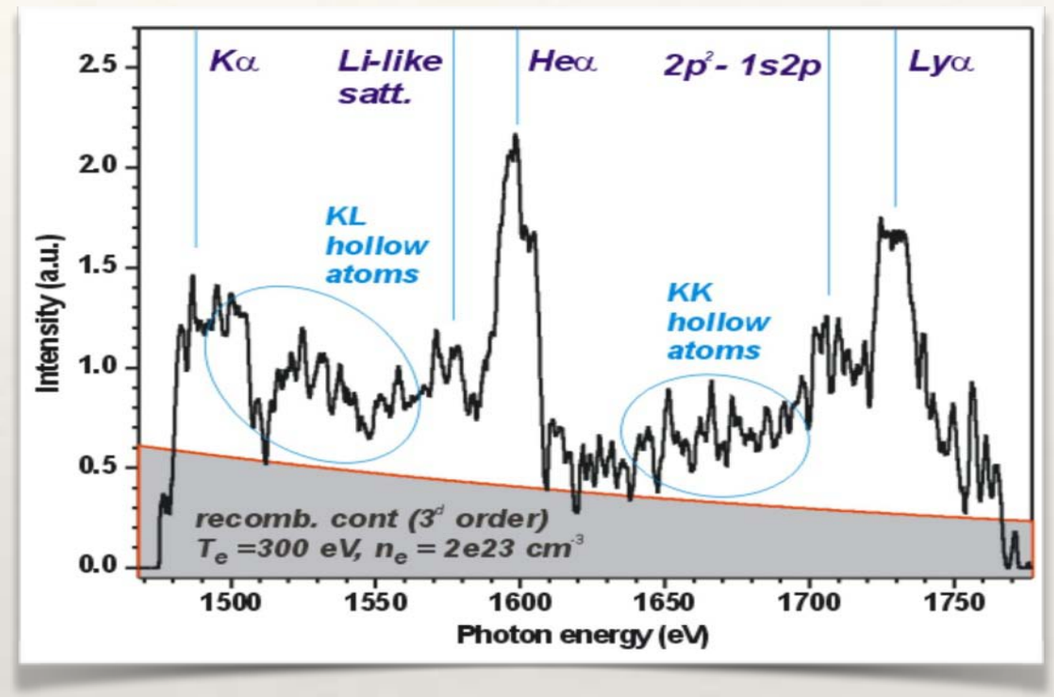


Accomplished experiments

Ion acceleration: X-ray spectrometry

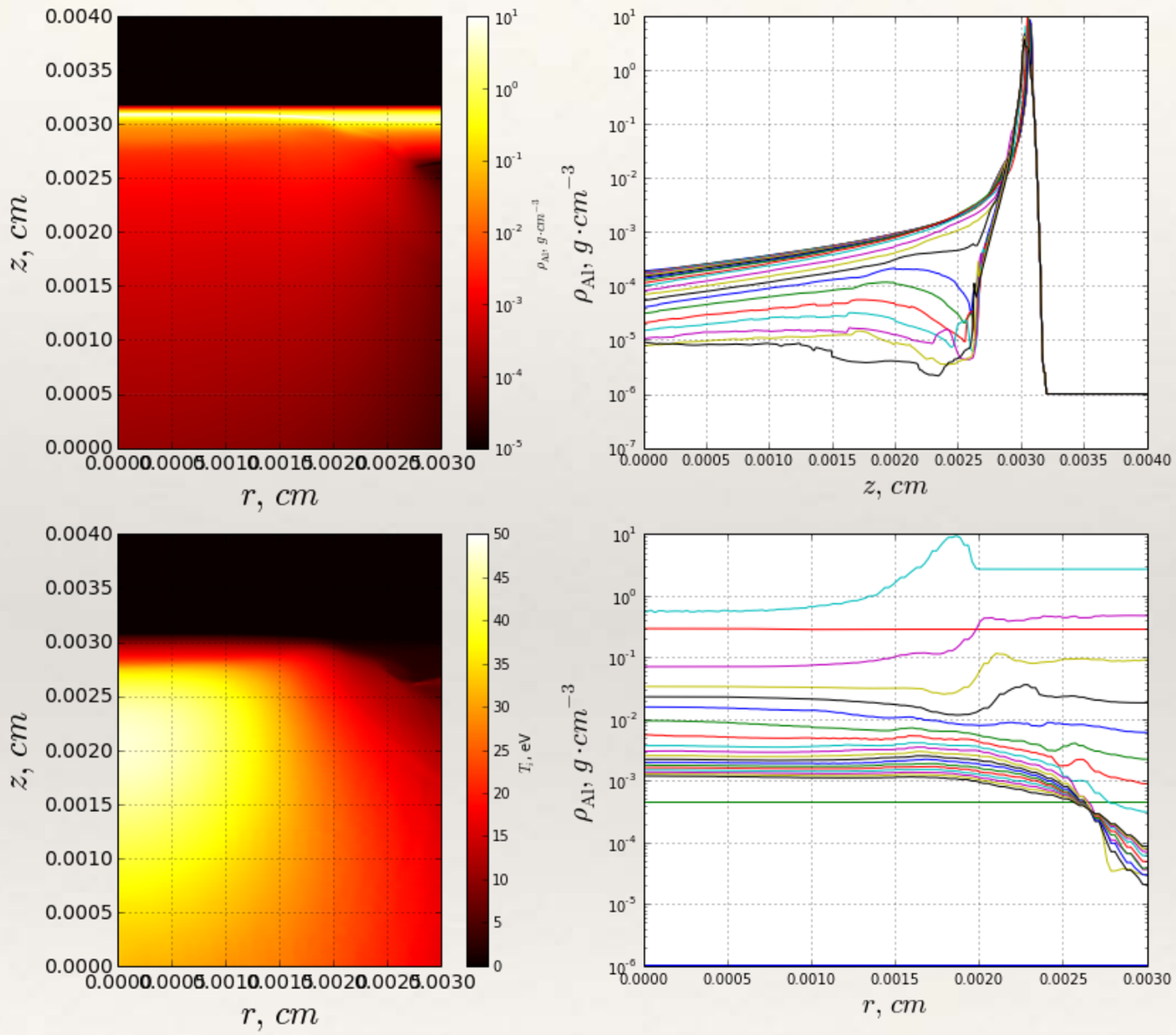


Focusing Spectrometer with Spatial Resolution (FSSR)

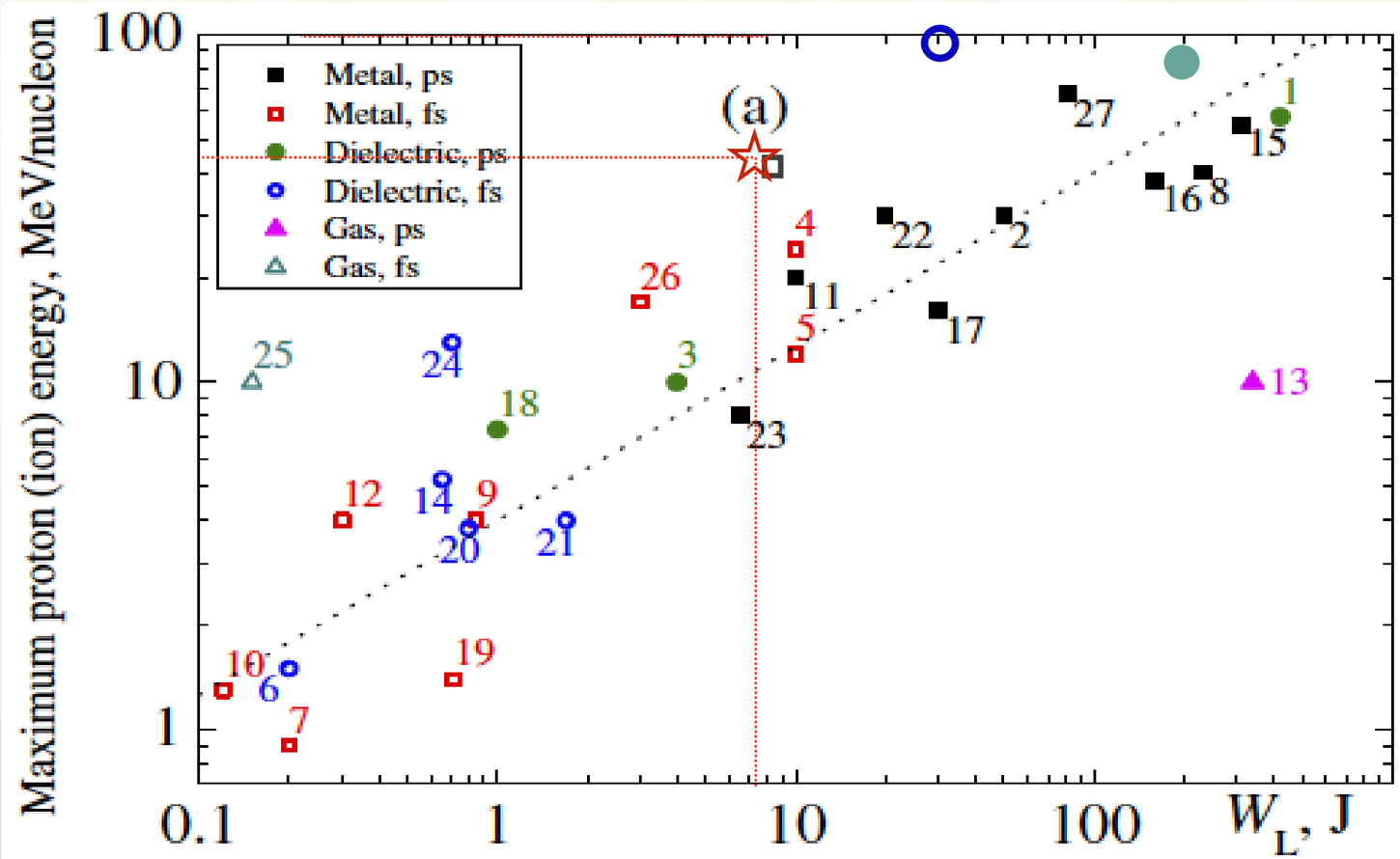


No signature of a significant preplasma at the target front:
the target remains at solid density by the time the main laser pulse arrives

Численное моделирование образования предплазмы



43.3 MeV proton beam



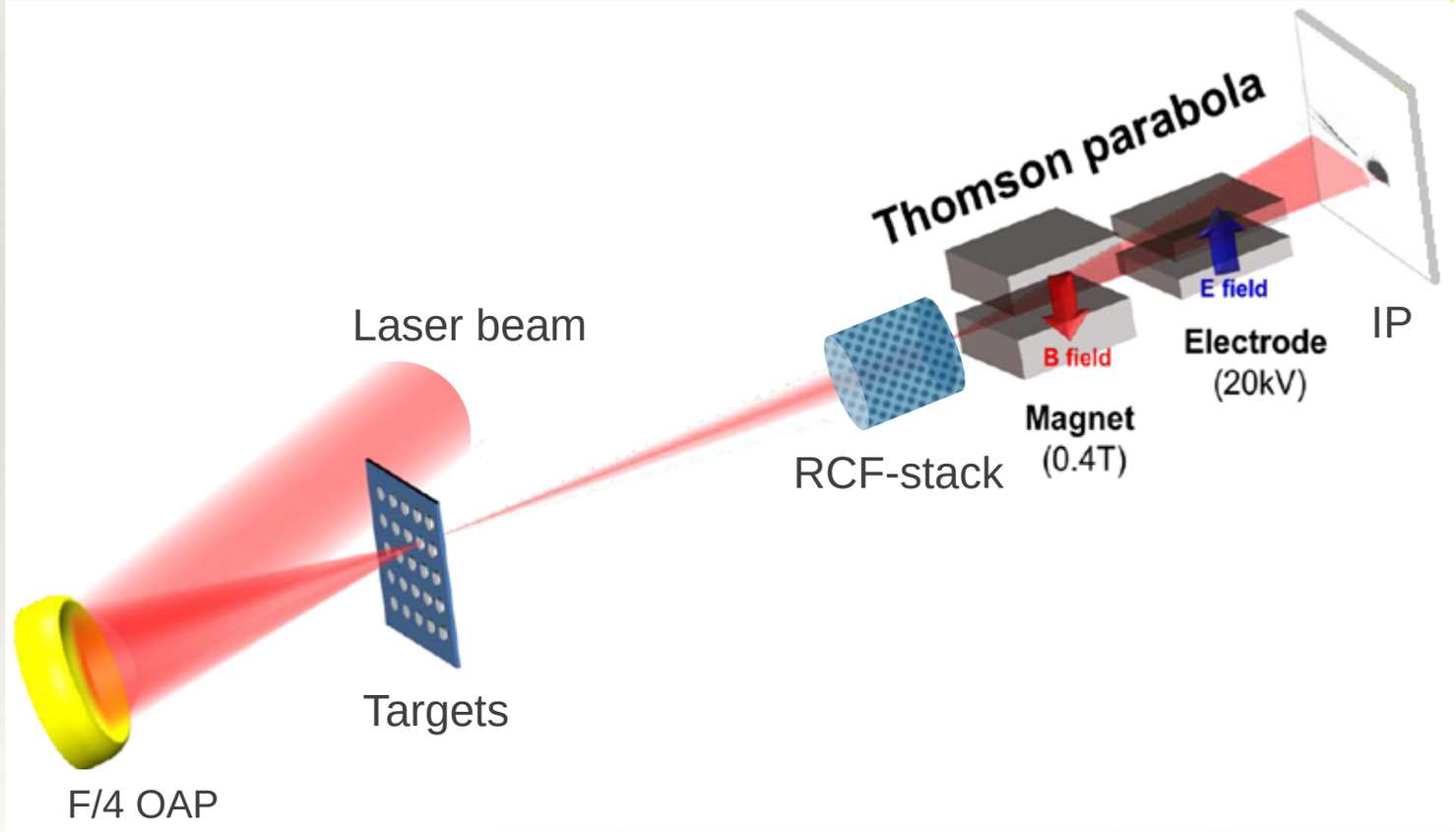
- Ogura et al., Optics Letters 37 14 (2012)
  41 MeV - TNSA
- ☆ IAP RAS summer 2015 (SR)
  43 MeV - TNSA
- Wagner et al, Phys Rev Letters 116 205002 (2016)
  85 MeV - TNSA
- Jong Kim et al, Physics of Plasmas 23 070701 (2016)
  93 MeV – RPA (world record for today)

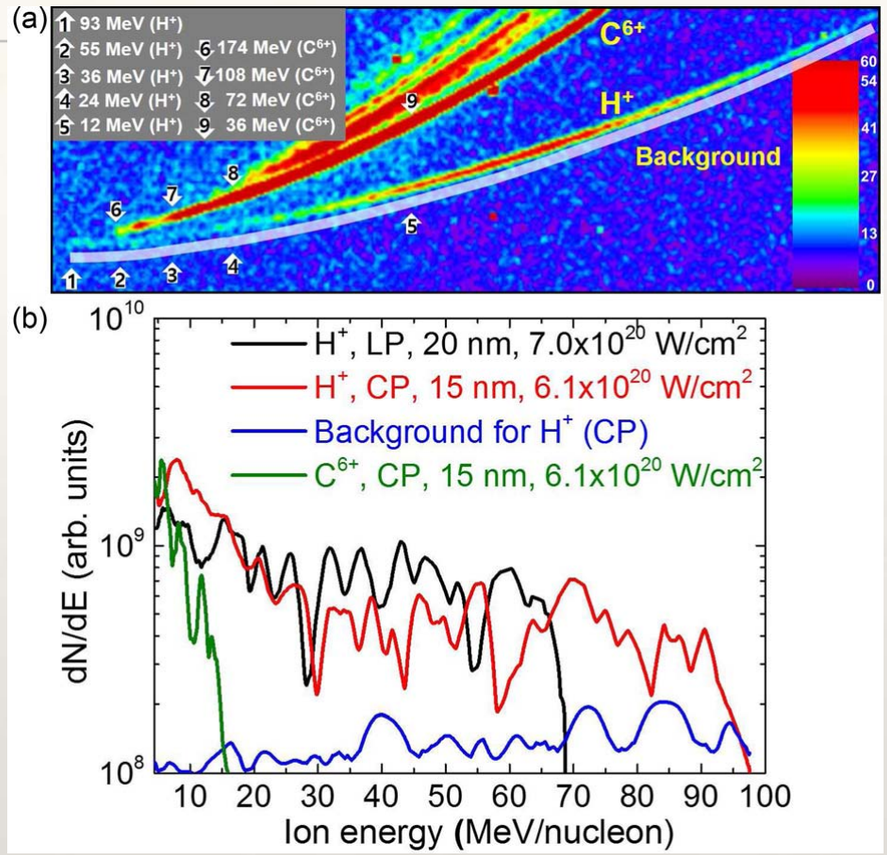
No.	Reference	Pulse energy W_L (J)	Pulse duration τ (fs)	Irradiance I_0 (W cm^{-2})[a]	Contrast	Target and thickness (μm)	Incidence angle (°)	Proton/ion energy $\mathcal{E}_{p(i)}$, (MeV/nucleon)
1	Snavely *et al* (2000)	423	500	3×10^{20}	1×10^{4}	CH 100	0	58
2	Krushelnick *et al* (2000b)	50	1000	5×10^{19}		Al 125	45	30
3	Nemoto *et al* (2001)	4	400	6×10^{18}	5×10^{5}	Mylar 6	45	10
4	Mackinnon *et al* (2002)	10	100	1×10^{20}	1×10^{10}	Al 3	22	24
5	Patel *et al* (2003)	10	100	5×10^{18}		Al 20	0	12
6	Spencer *et al* (2003)	0.2	60	7×10^{18}	1×10^{6}	Mylar 23	0	1.5
7	Spencer *et al* (2003)	0.2	60	7×10^{18}	1×10^{6}	Al 12	0	0.9
8	McKenna *et al* (2004)	233	700	2×10^{20}	1×10^{7}	Fe 100	45	40
9	Kaluza *et al* (2004)	0.85	150	1.3×10^{19}	2×10^{7}	Al 20	30	4
10	Oishi *et al* (2005)	0.12	55	6×10^{18}	1×10^{5}	Cu 5	45	1.3
11	Fuchs *et al* (2006)	10	320	6×10^{19}	1×10^{7}	Al 20	0 and 40	20
12	Neely *et al* (2006)	0.3	33	1×10^{19}	1×10^{10}	Al 0.1	30	4
13	Willingale *et al* (2006)	340	1000	6×10^{20}	1×10^{5}	He jet 2000		10
14	Ceccotti *et al* (2007)	0.65	65	5×10^{18}	1×10^{10}	Mylar 0.1	45	5.25
15	Robson *et al* (2007)	310	1000	6×10^{20}	1×10^{7}	Al 10	45	55
16	Robson *et al* (2007)	160	1000	3.2×10^{20}	1×10^{7}	Al 10	45	38
17	Robson *et al* (2007)	30	1000	6×10^{19}	1×10^{7}	Al 10	45	16
18	Antici *et al* (2007)	1	320	1×10^{18}	1×10^{11}	Si_3N_4 0.03	0	7.3
19	Yogo *et al* (2007)	0.71	55	8×10^{18}	1×10^{6}	Cu 5	45	1.4
20	Yogo *et al* (2008)	0.8	45	1.5×10^{19}	2.5×10^{5}	Polyimide 7.5	45	3.8
21	Nishiuchi *et al* (2008)	1.7	34	3×10^{19}	2.5×10^{7}	Polyimide 7.5	45	4
22	Flippo *et al* (2008)	20	600	1.1×10^{19}	1×10^{6}	Flat-top cone Al 10	0	30
23	Safronov *et al* (2008)	6.5	900	1×10^{19}		Al 2	0	8
24	Henig *et al* (2009b)	0.7	45	5×10^{19}	1×10^{11}	DLC 0.0054	0	13
25	Fukuda *et al* (2009)	0.15	40	7×10^{17}	1×10^{6}	CO_2+He cluster jet 2000		10
26	Zeil *et al* (2010)	3	30	1×10^{21}	1×10^{8}	Ti 2 μm	45	17
27	Gaillard *et al* (2011)	82	670	1.5×10^{20}	1×10^{9}	Flat-top cone Cu 12.5	0	67.5

LPA: records

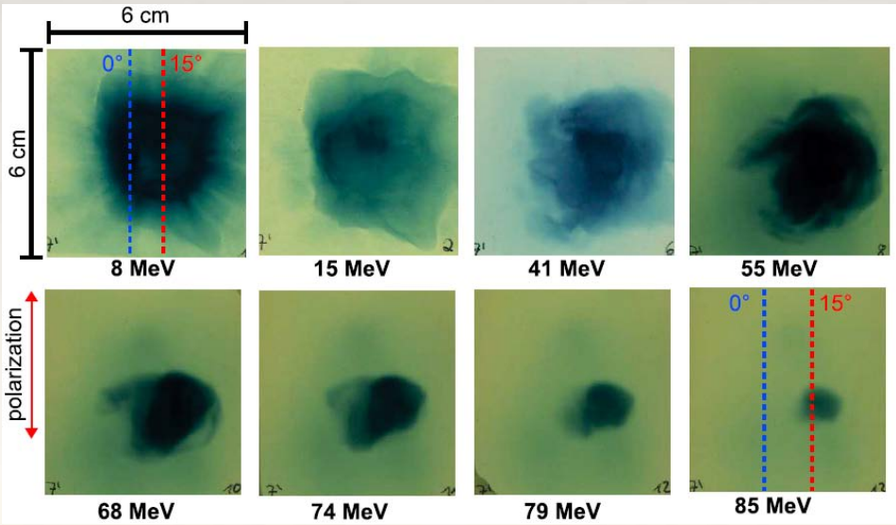
Ускорение протонов/ионов:

непрозрачная плазма (твердотельные мишени)
острая фокусировка лазерного излучения (высокая I)
высокий контраст лазерного излучения





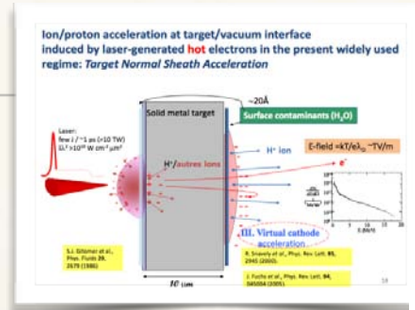
Kim et al. PoP (2016) / GIST

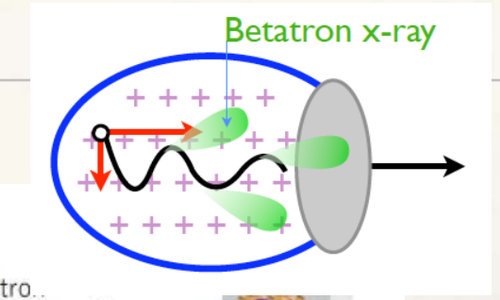


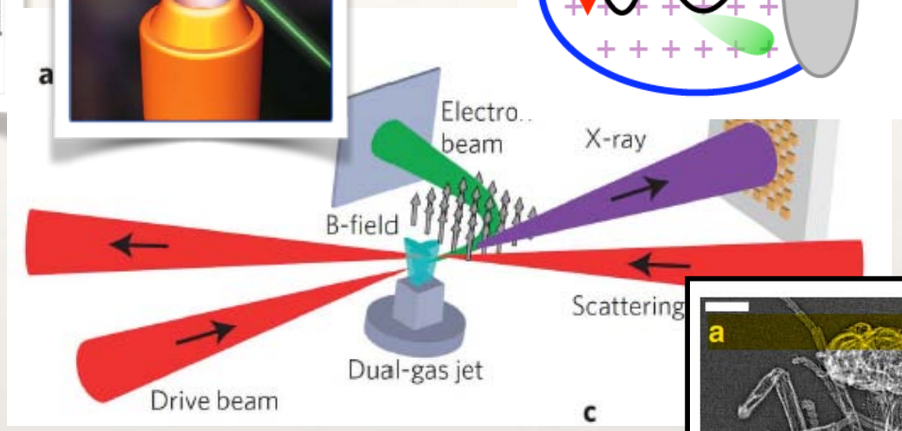
Wagner et al. PRL (2016) / PHELIX

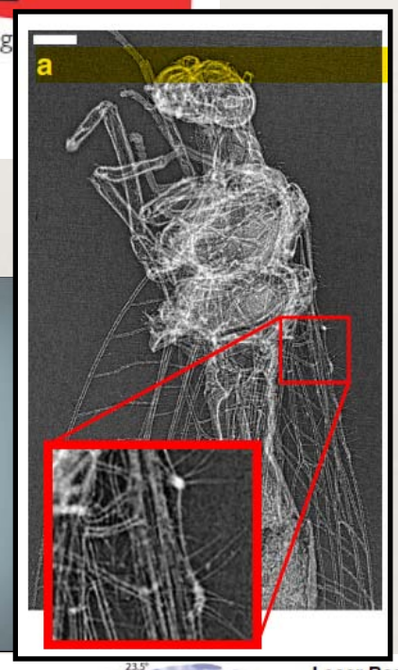
Laser-plasma interaction: applications

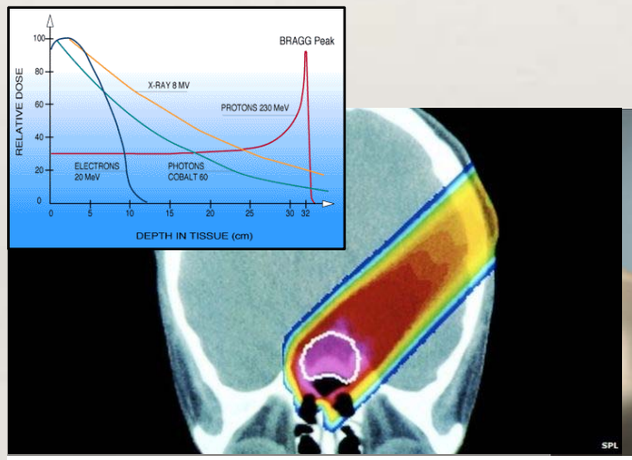
- Laser driven acceleration
  - Particles acceleration
  - X-ray generation.
- Applications
  - Radiotherapy
  - Bio-imaging
- HED physics
  - LabAstro
  - ICF

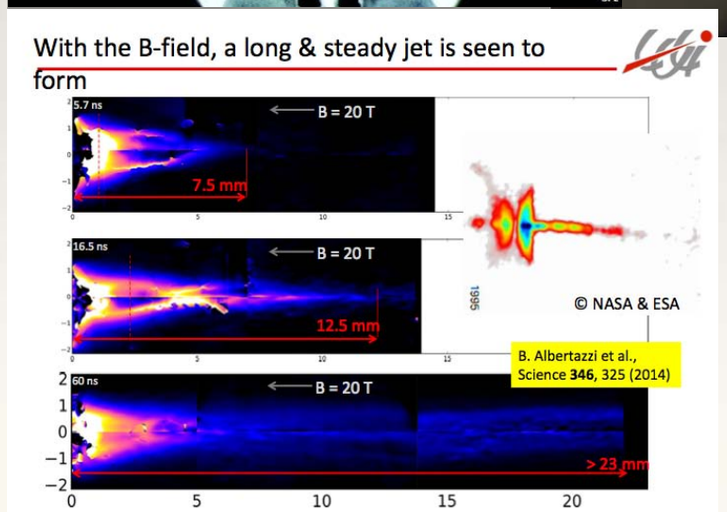


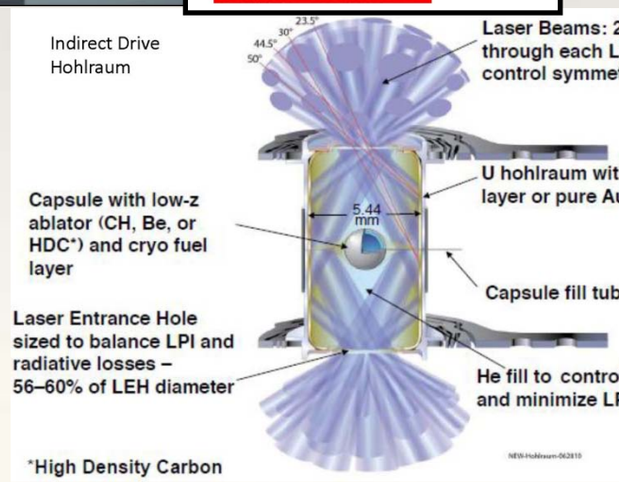












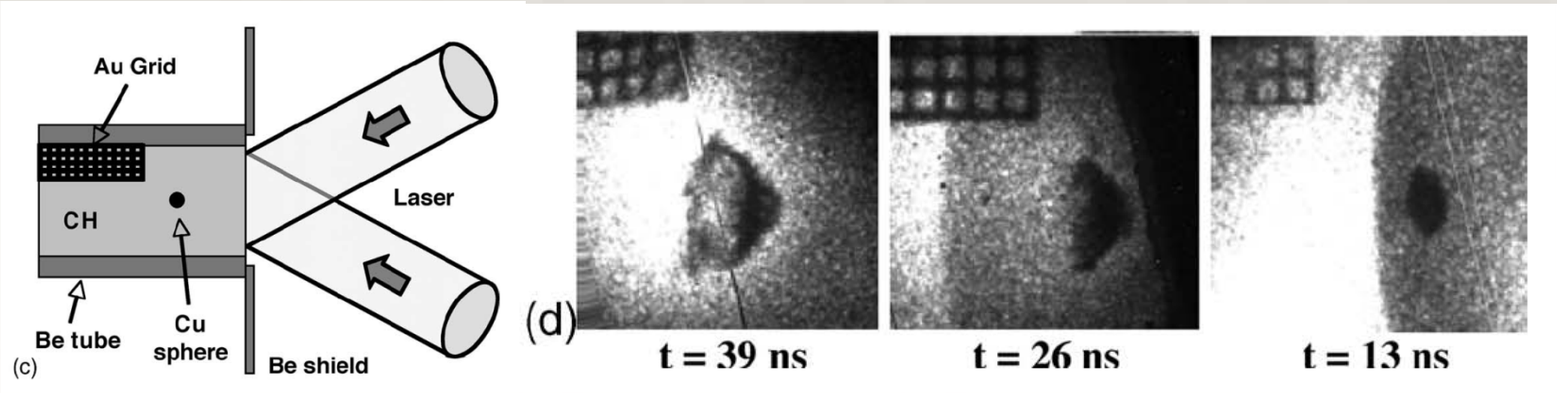
Laser-plasmas are great tool to investigate“laboratory astrophysics”

→ what can be realistic goals?

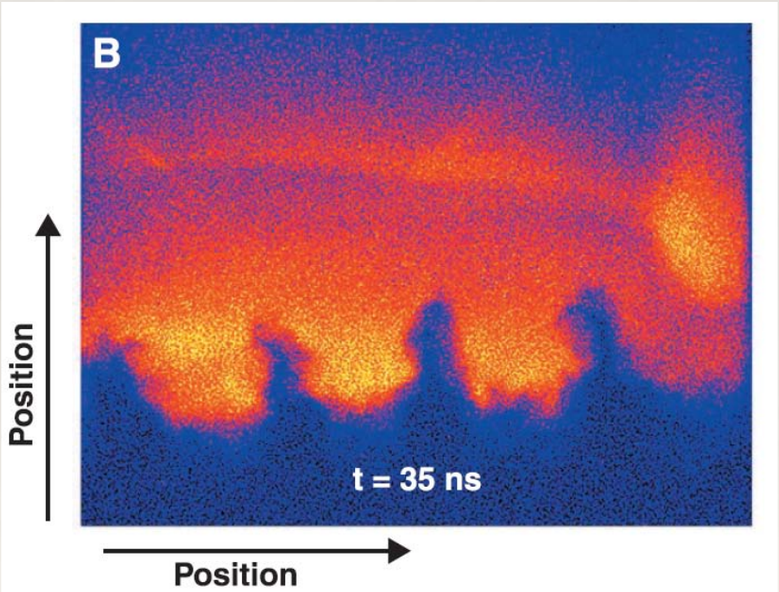
1. Observe the dynamics of a directly+fully scalable phenomenon

2. Investigate physics (even if non fully scalable system) that is out of reach of present-day codes

3. Test a segment of a model/code (e.g. EoS)



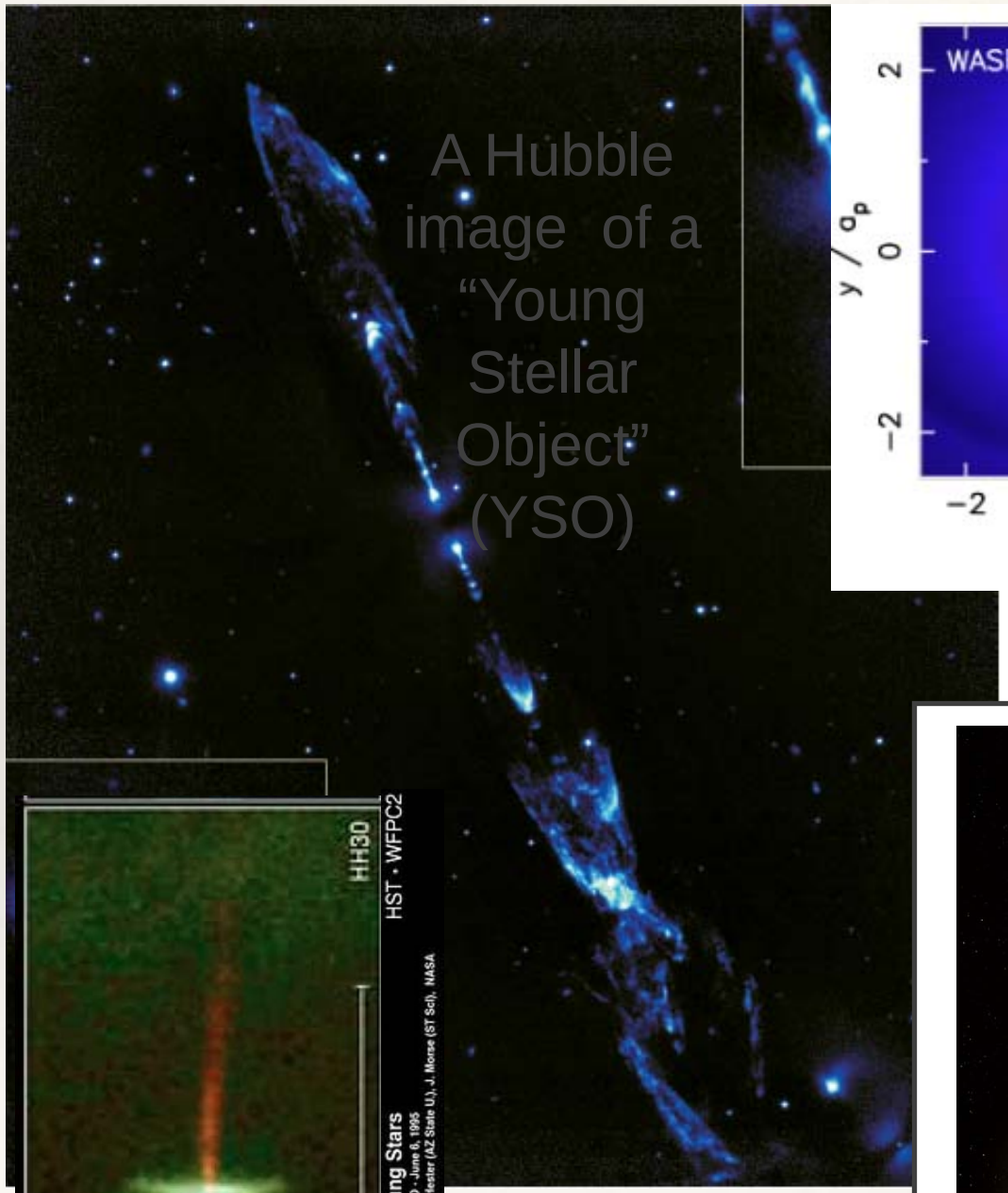
Robey et al (2002)

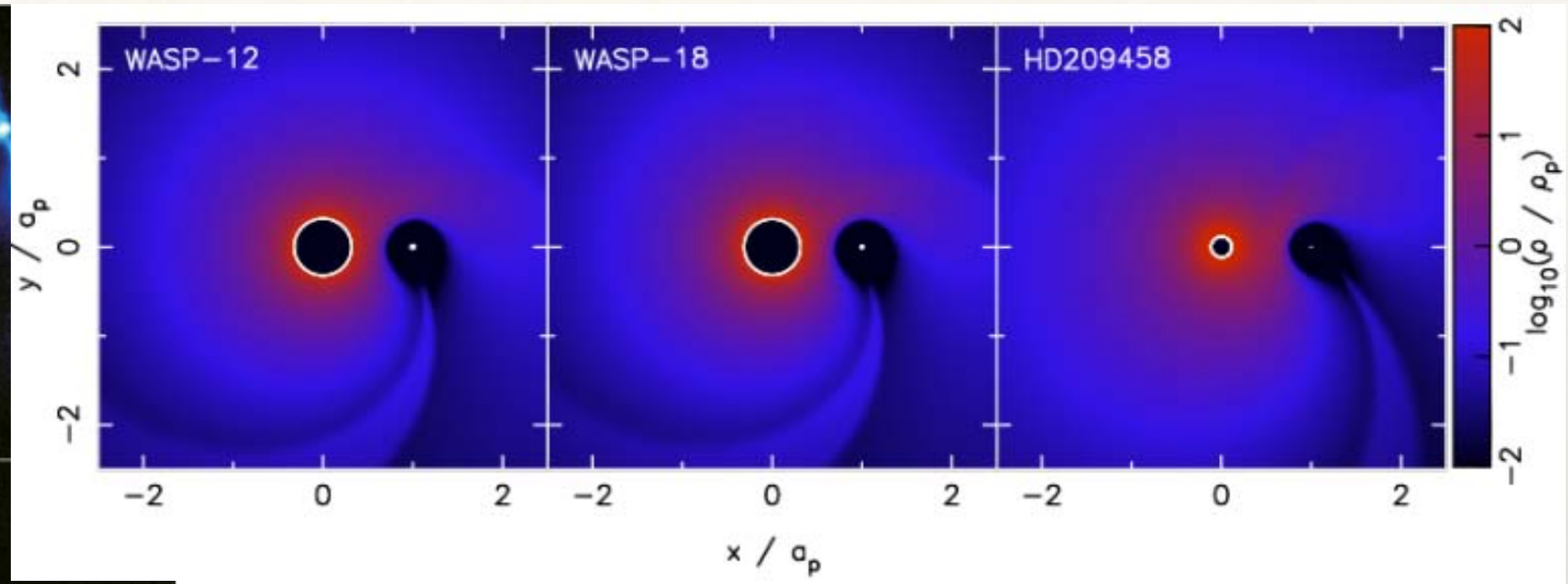


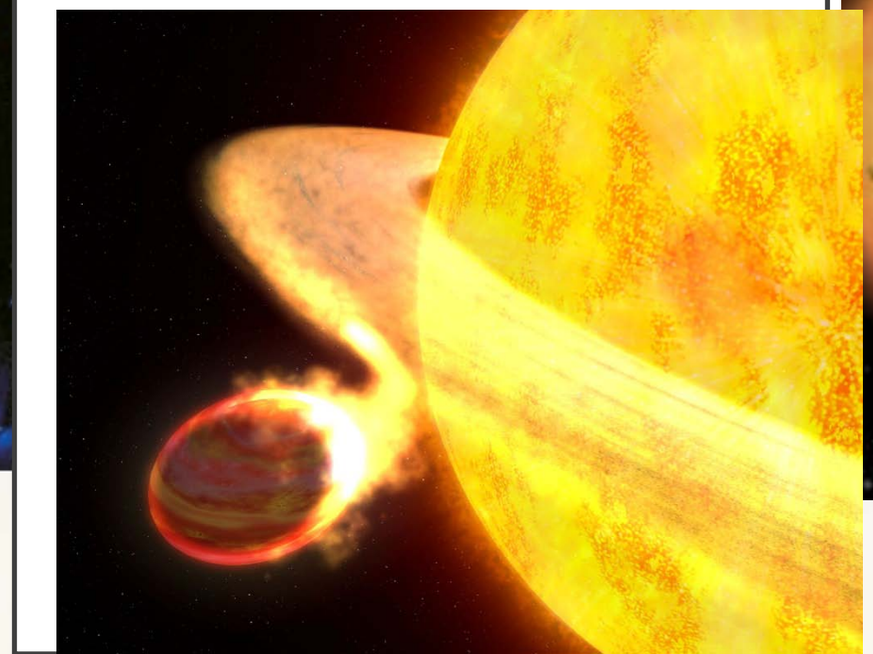
Glanz (1997)

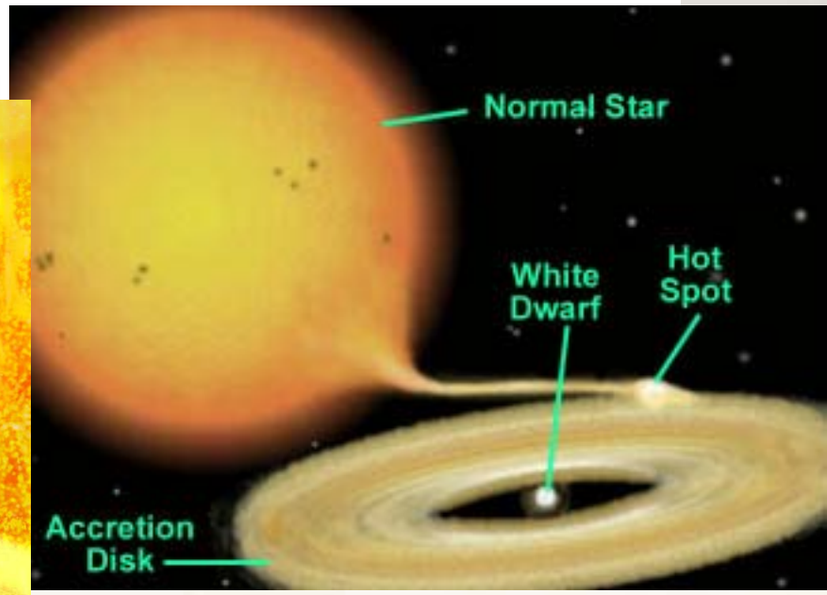
Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena





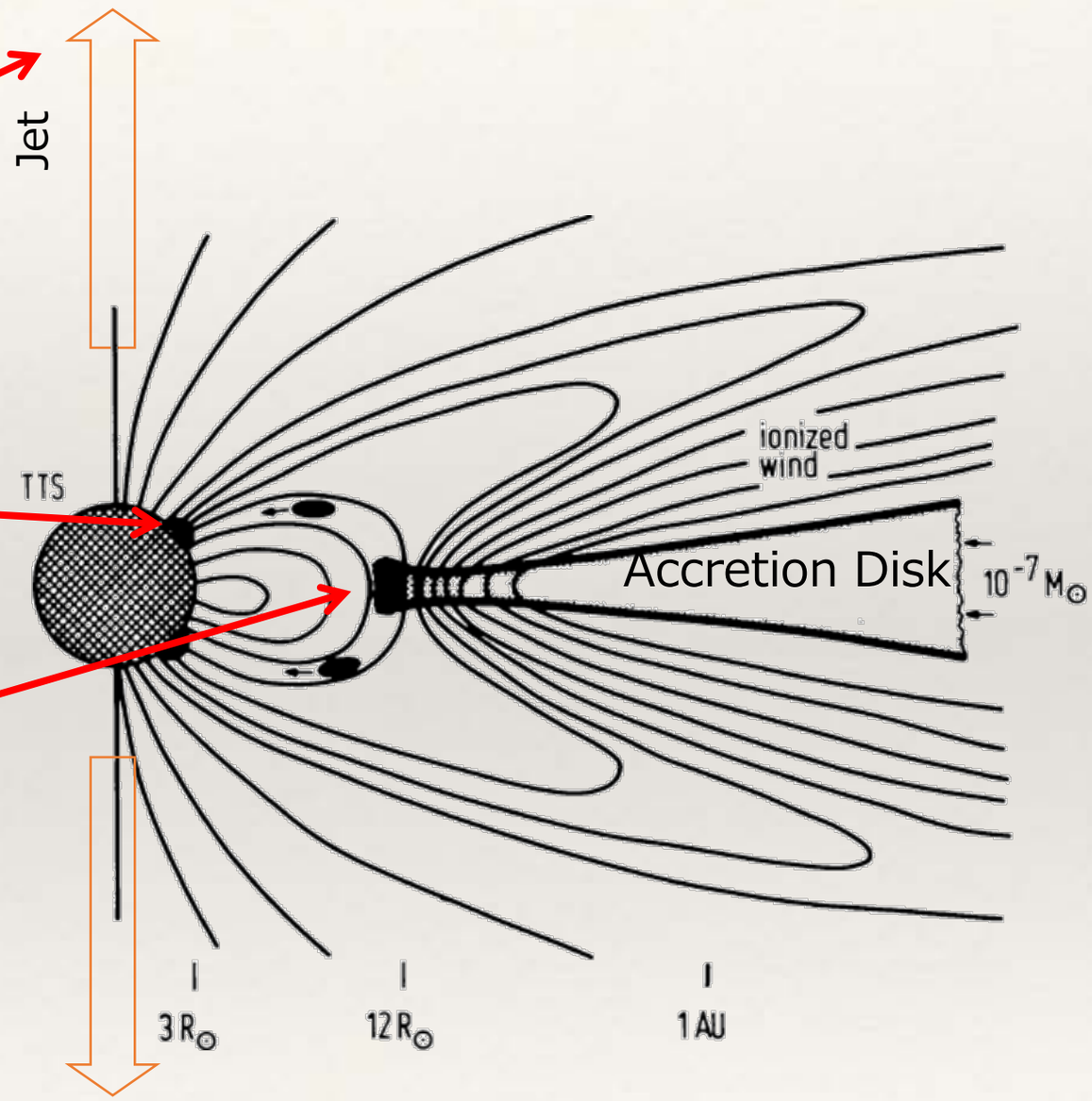




Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

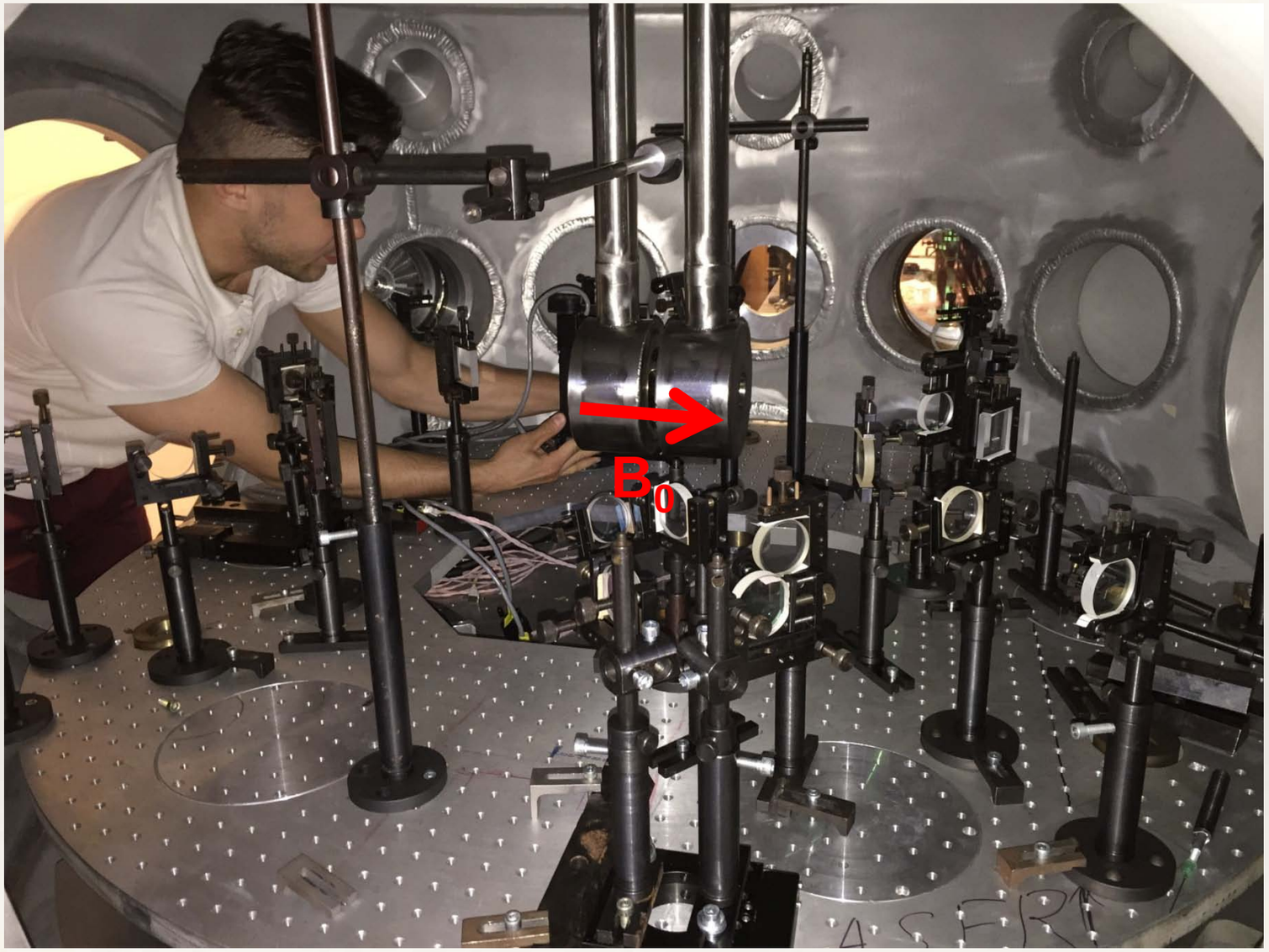
  - ❑ Jet formation:
    effect of poloidal magnetic field.
  - ❑ Accretion column:
    magnetized plasma flow interaction with surface.
  - ❑ Accretion disc dynamics
    in the vicinity of β~1.



Adapted from Camenzind, (1990).

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena



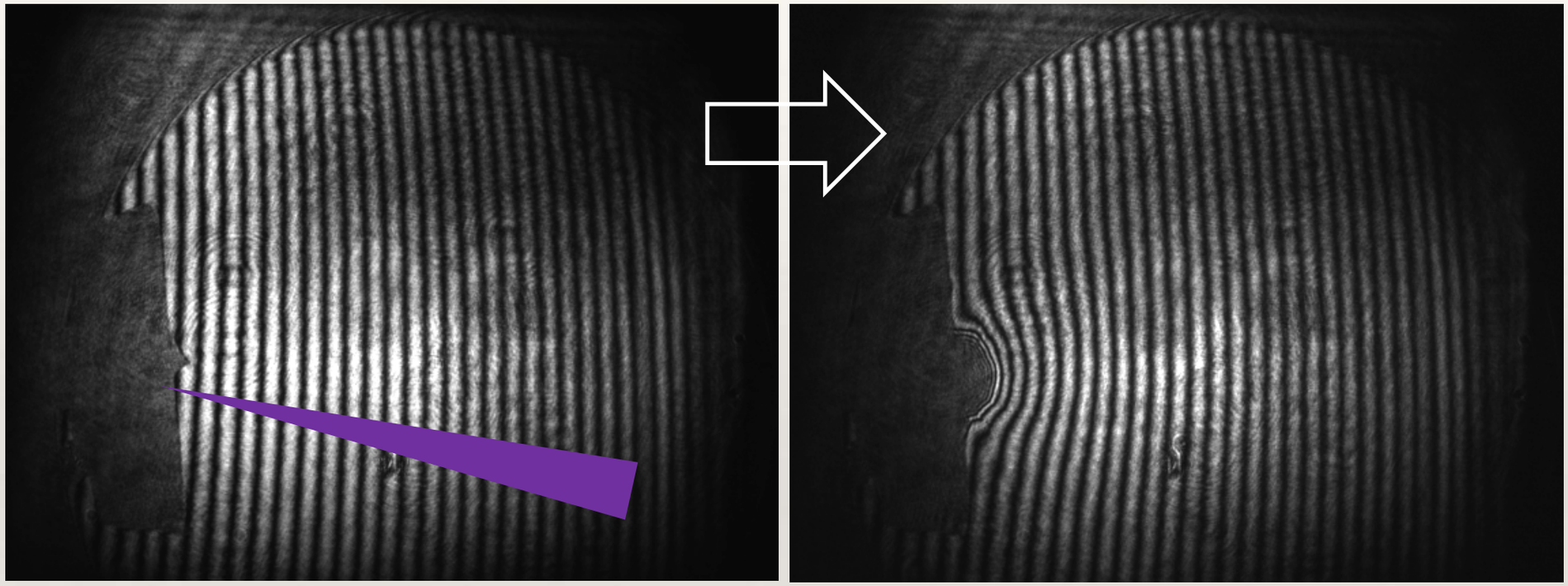
Ambient magnetic field

- Split pulsed solenoid
- Uniform configuration (20 T)
- “Zero-point” configuration

Laser plasma production

- PEARL pump laser (~100 J, 1 ns, 1054 nm)
- Solid-state targets

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]

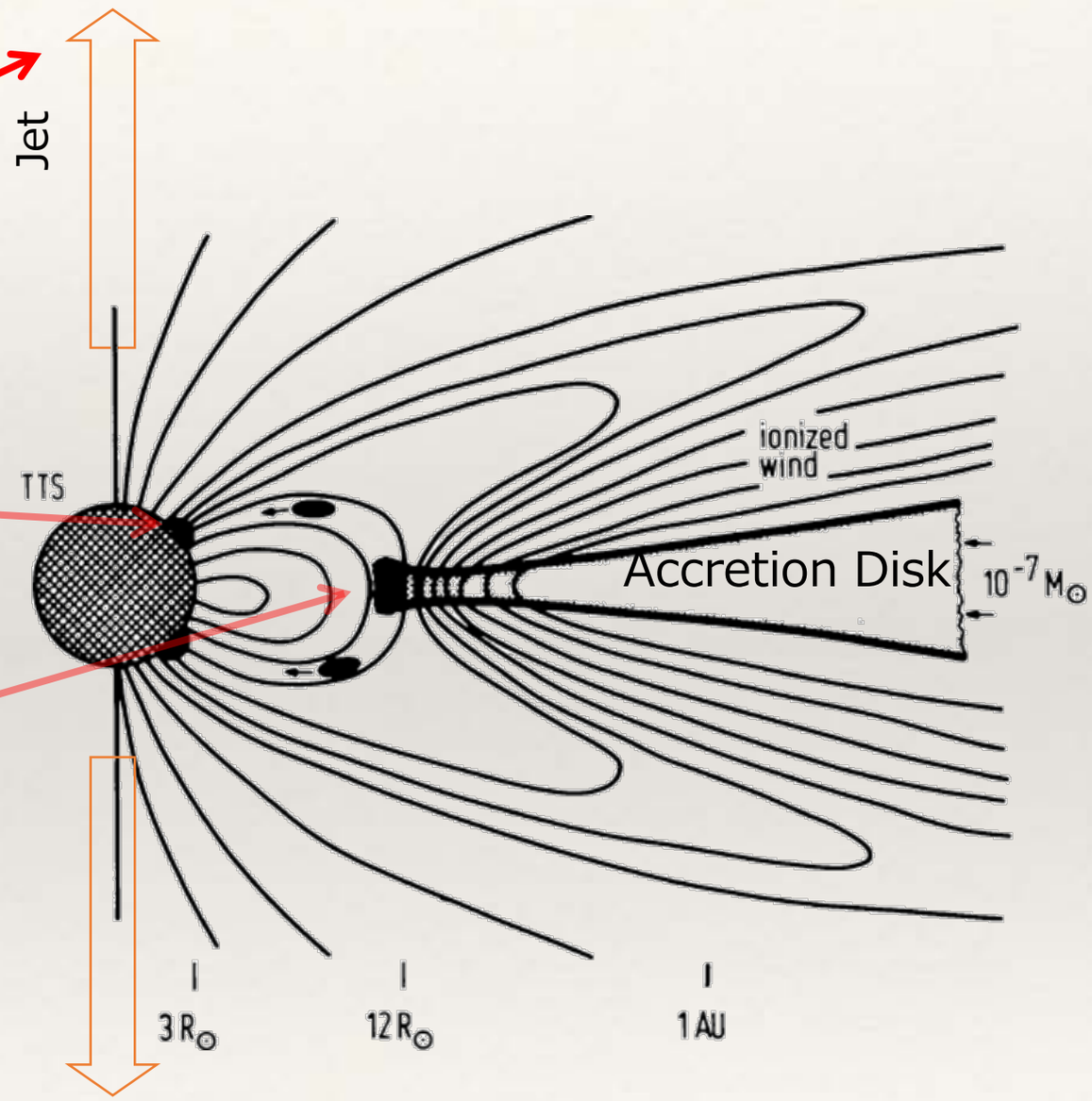
Laboratory astrophysics

- 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 $\beta \sim 1$.

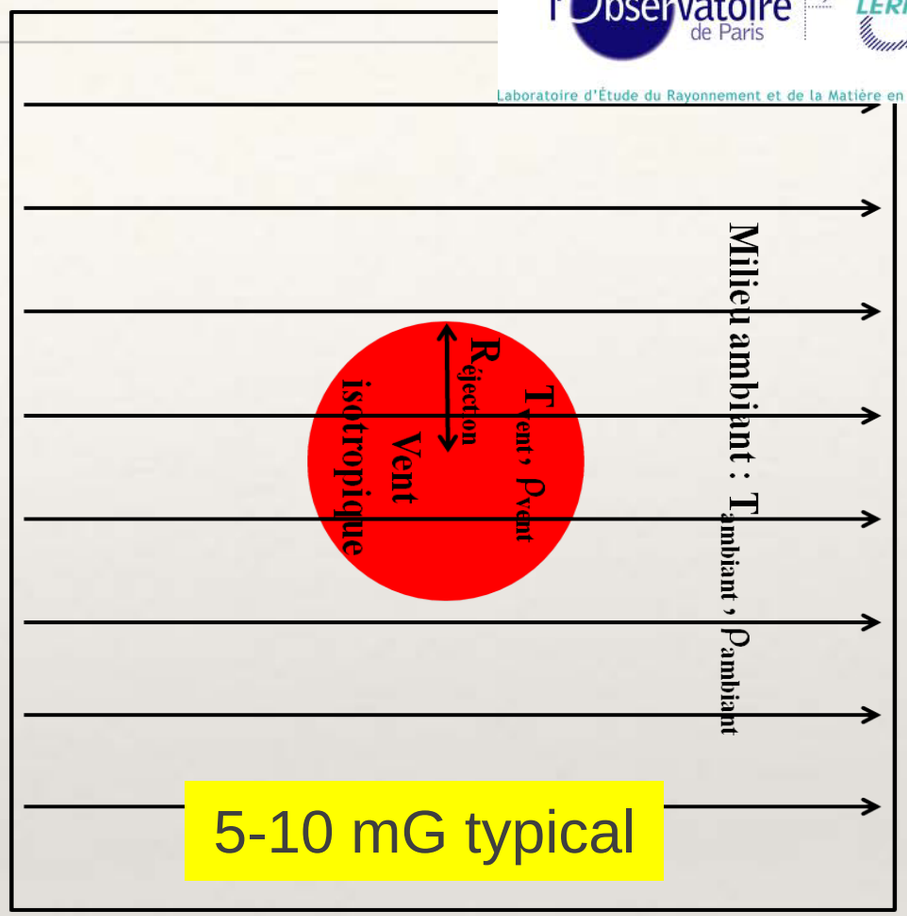


Adapted from Camenzind, (1990).

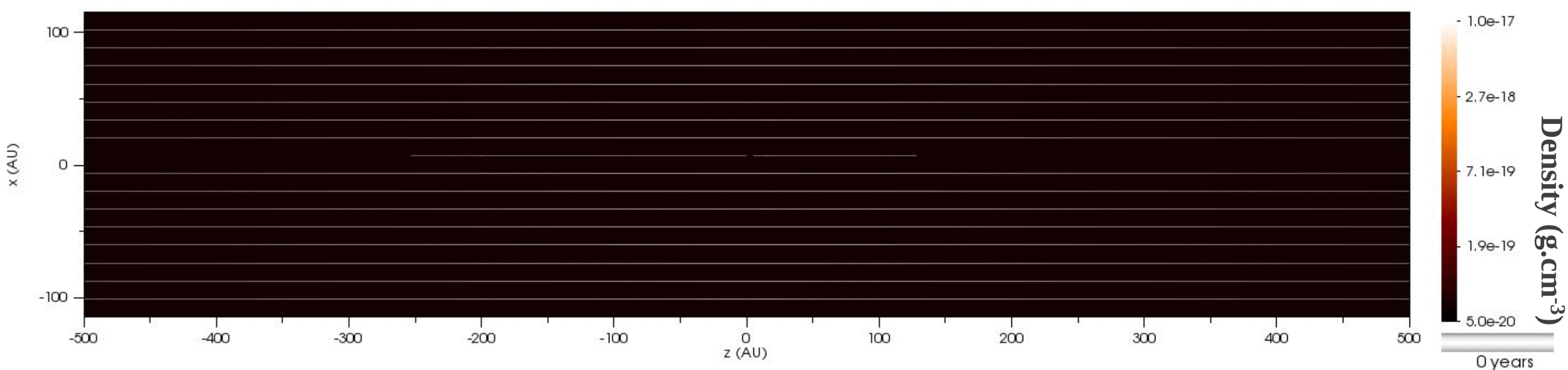
Full-scale astrophysical simulation

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



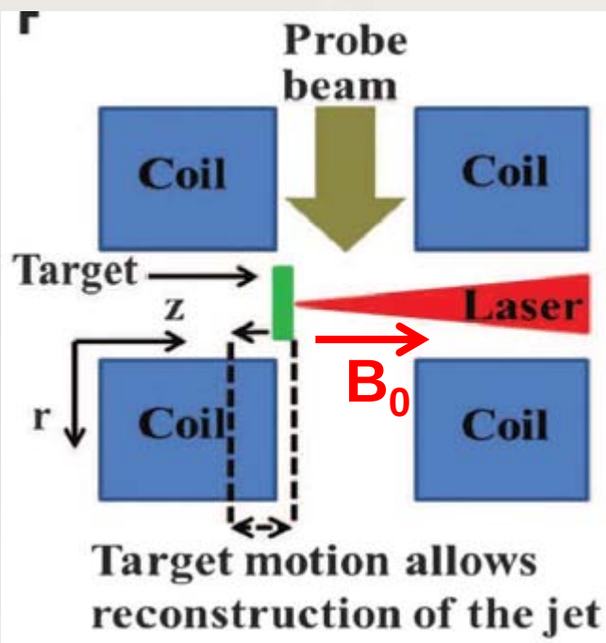
5-10 mG typical

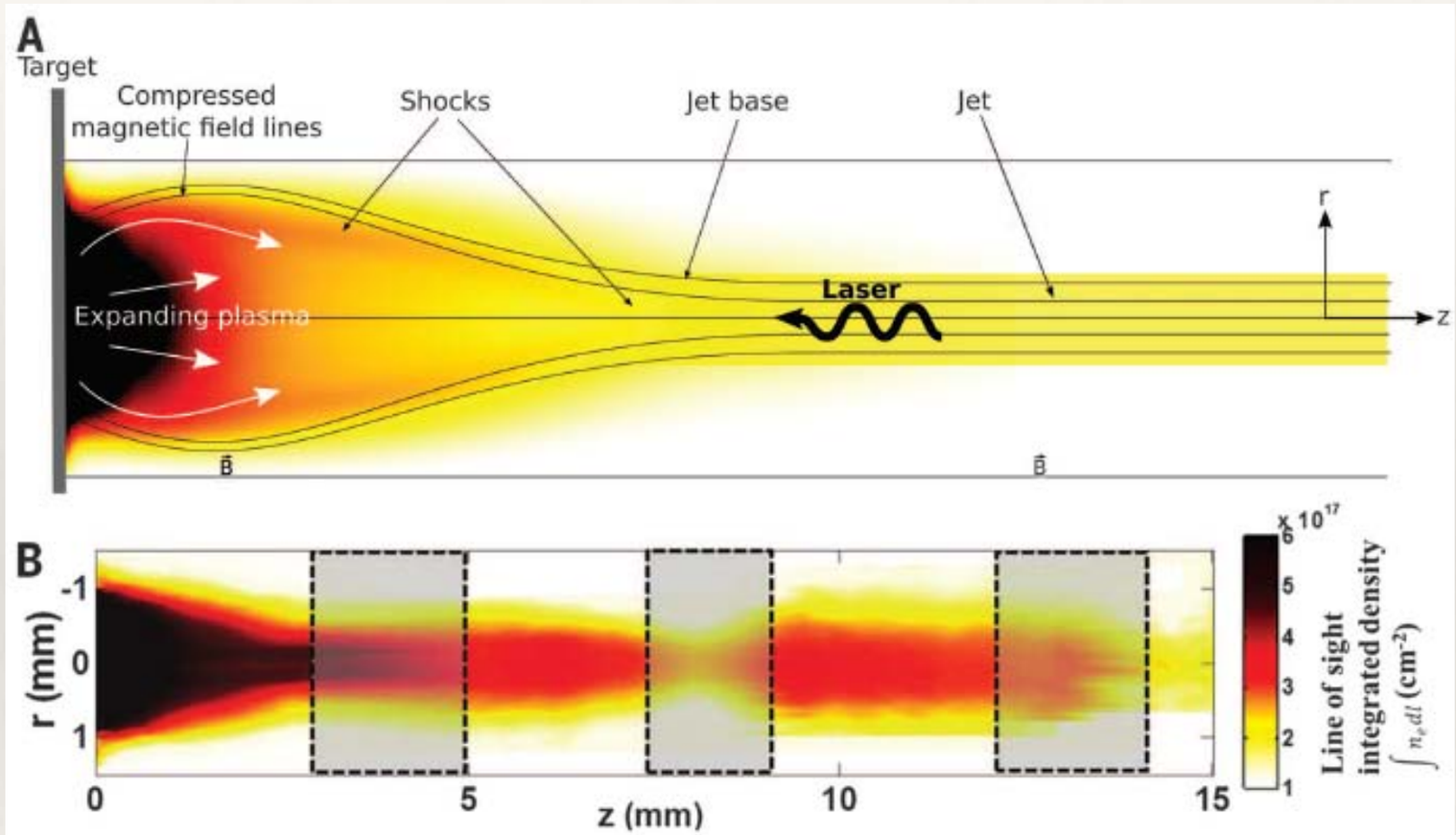


Laboratory astrophysics

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

Laser-plasma plume propagating along the ambient magnetic field

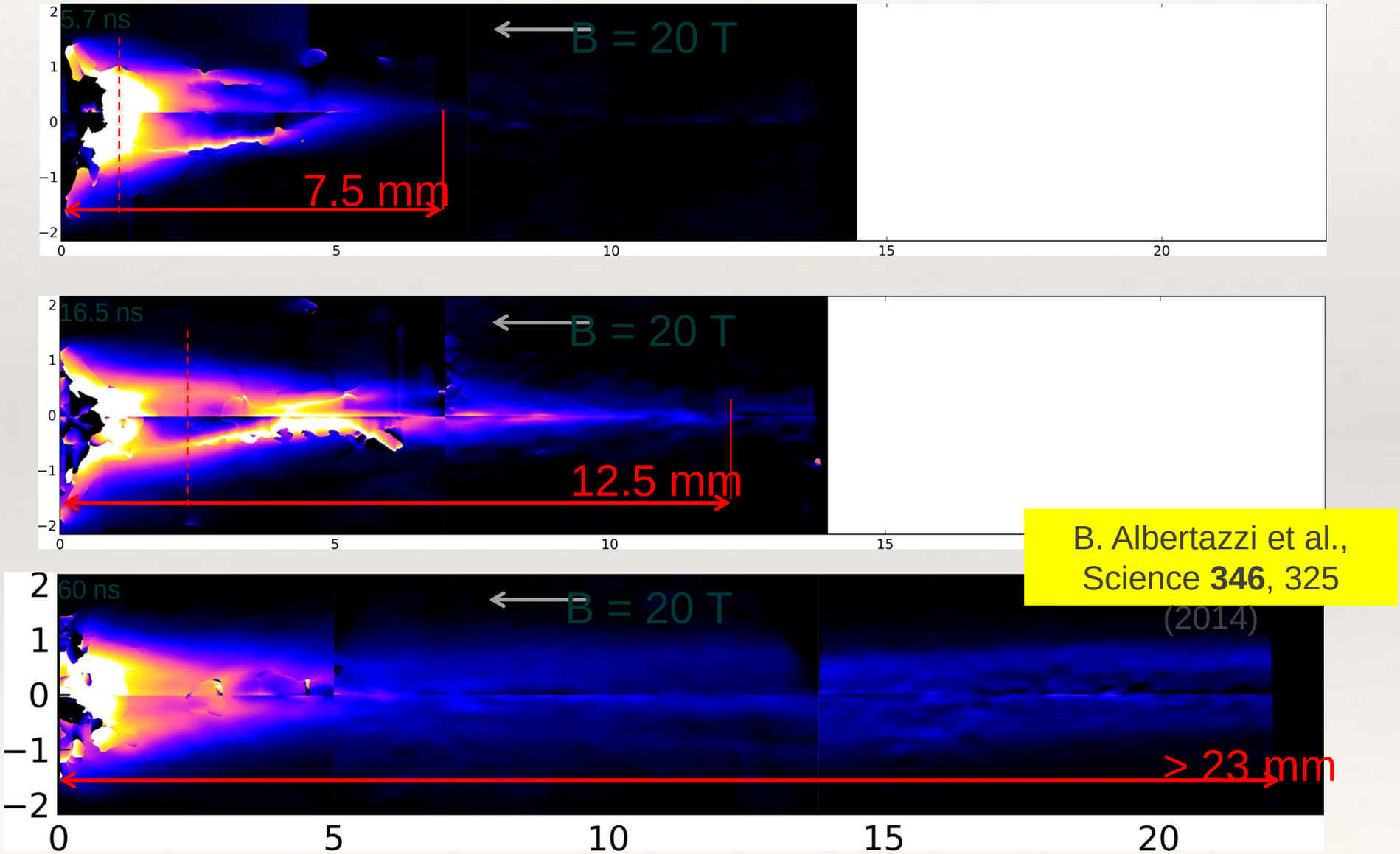




Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field
B. Albertazzi *et al.*
Science **346**, 325 (2014);
DOI: 10.1126/science.1259694

Laboratory astrophysics

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



B. Albertazzi et al., Science **346**, 325 (2014)

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

Both are ideal MHD plasmas

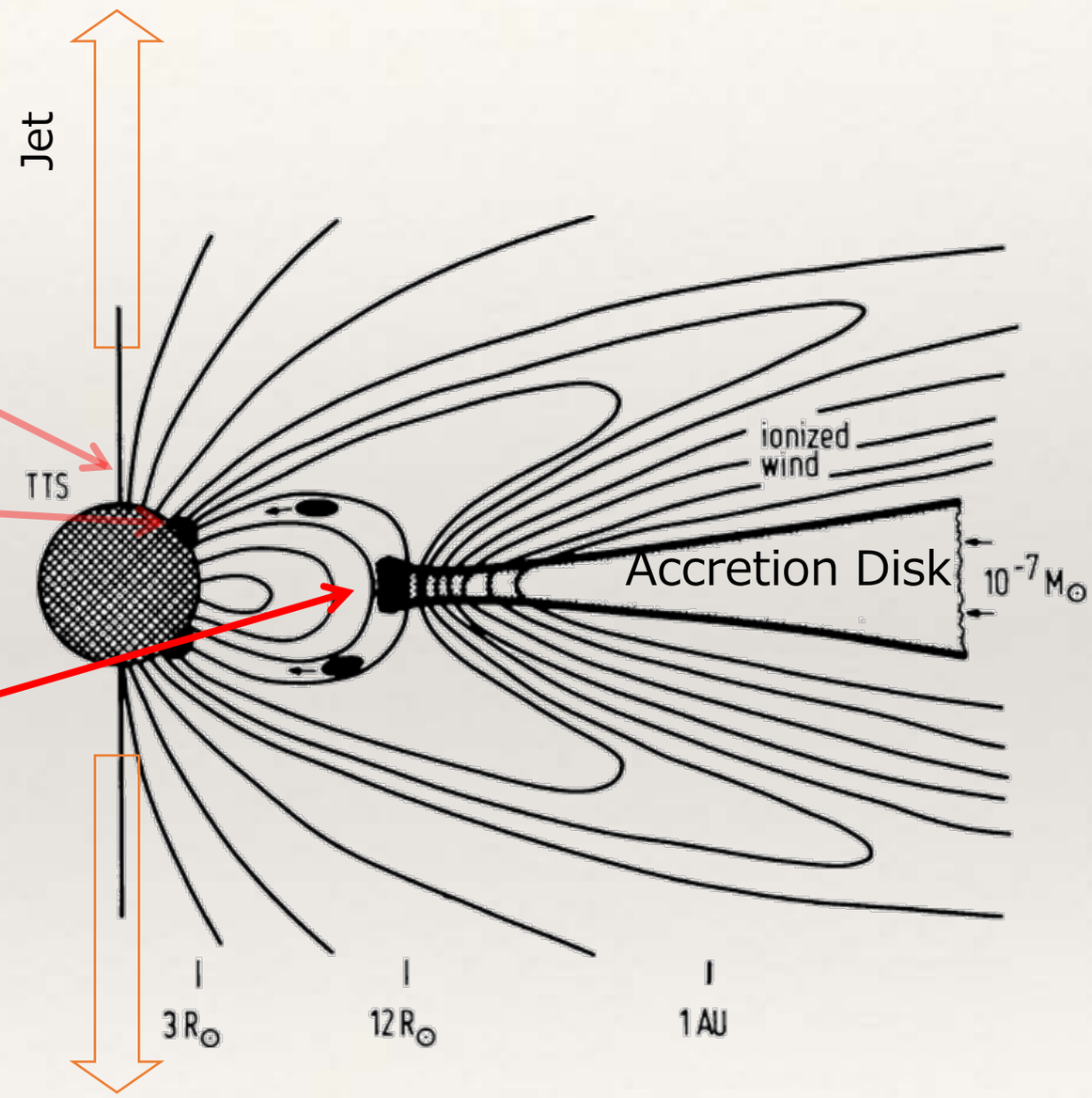
- ❖ Time: 20 ns → 6 years
- ❖ Space: 1 mm → 300 AU, or 4.5 10^{13} m
- ❖ Magnetic field: 20 T → 1 μT

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

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

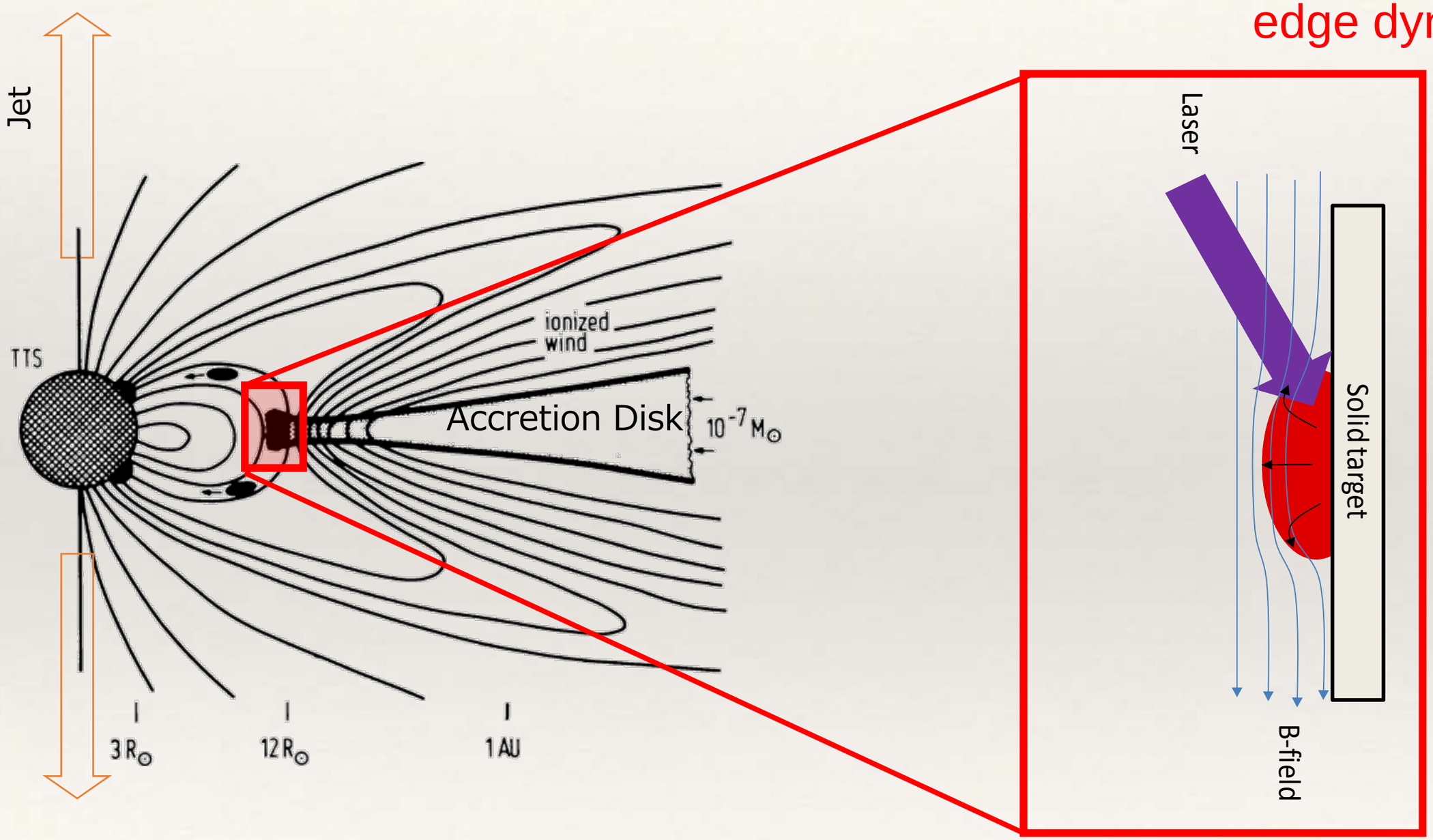
  - Jet formation:
    effect of poloidal magnetic field.
  - Accretion column:
    magnetized plasma flow interaction with surface.
  - Accretion disc dynamics in the vicinity of β~1.



Adapted from Camenzind, (1990).

Laboratory astrophysics

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

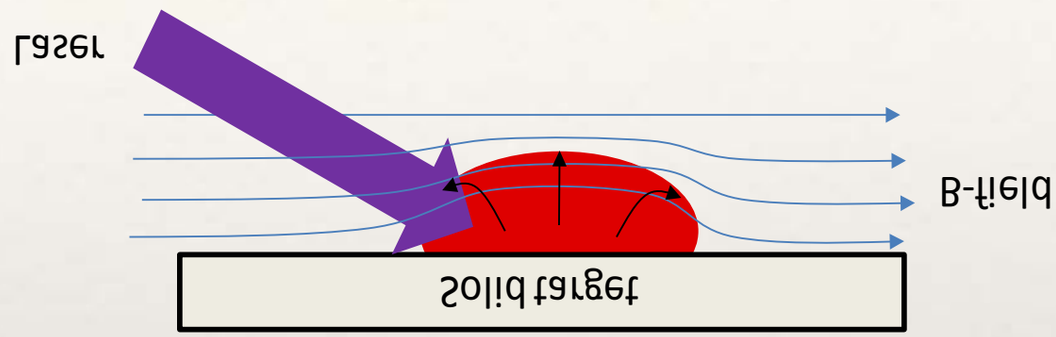


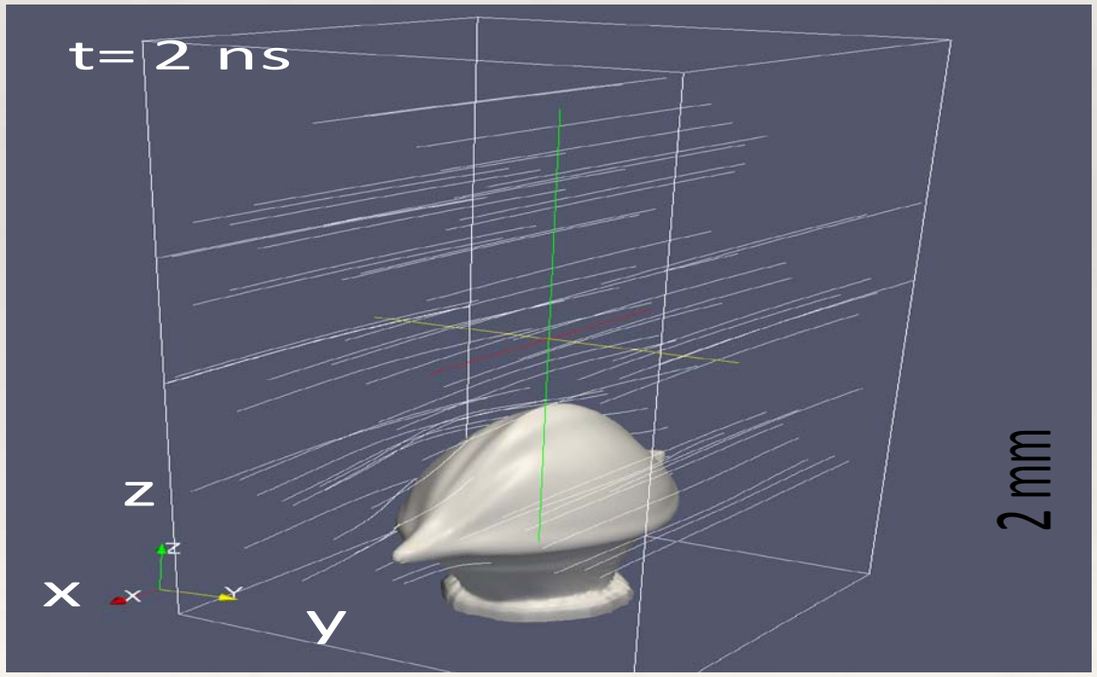
Adapted from Camenzind, (1990).

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:

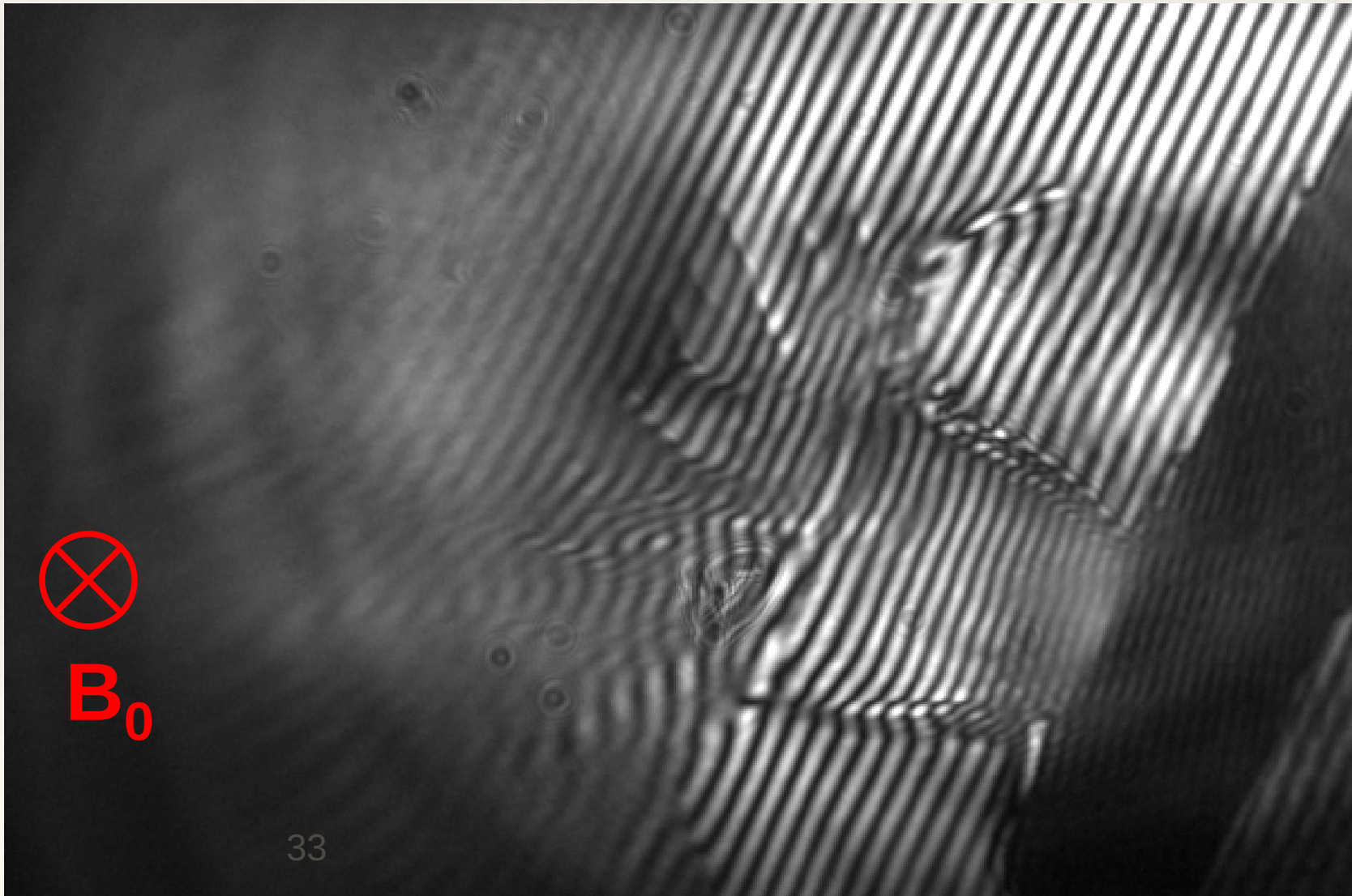
plasma expansion across $\mathbf{B}_0$ is limited by magnetic pressure

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

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc

16ns, **25J**



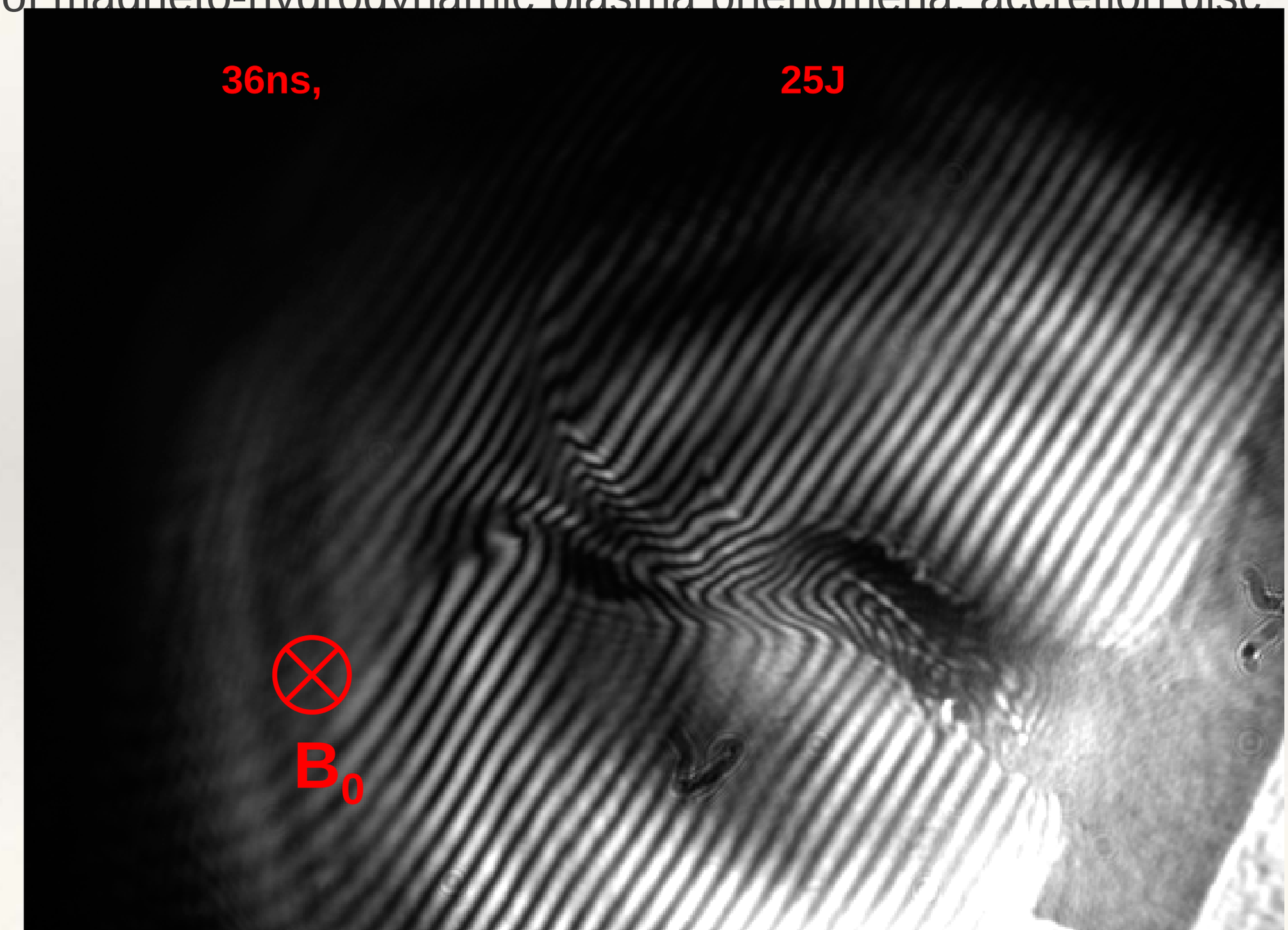
Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc

26ns, **25J**

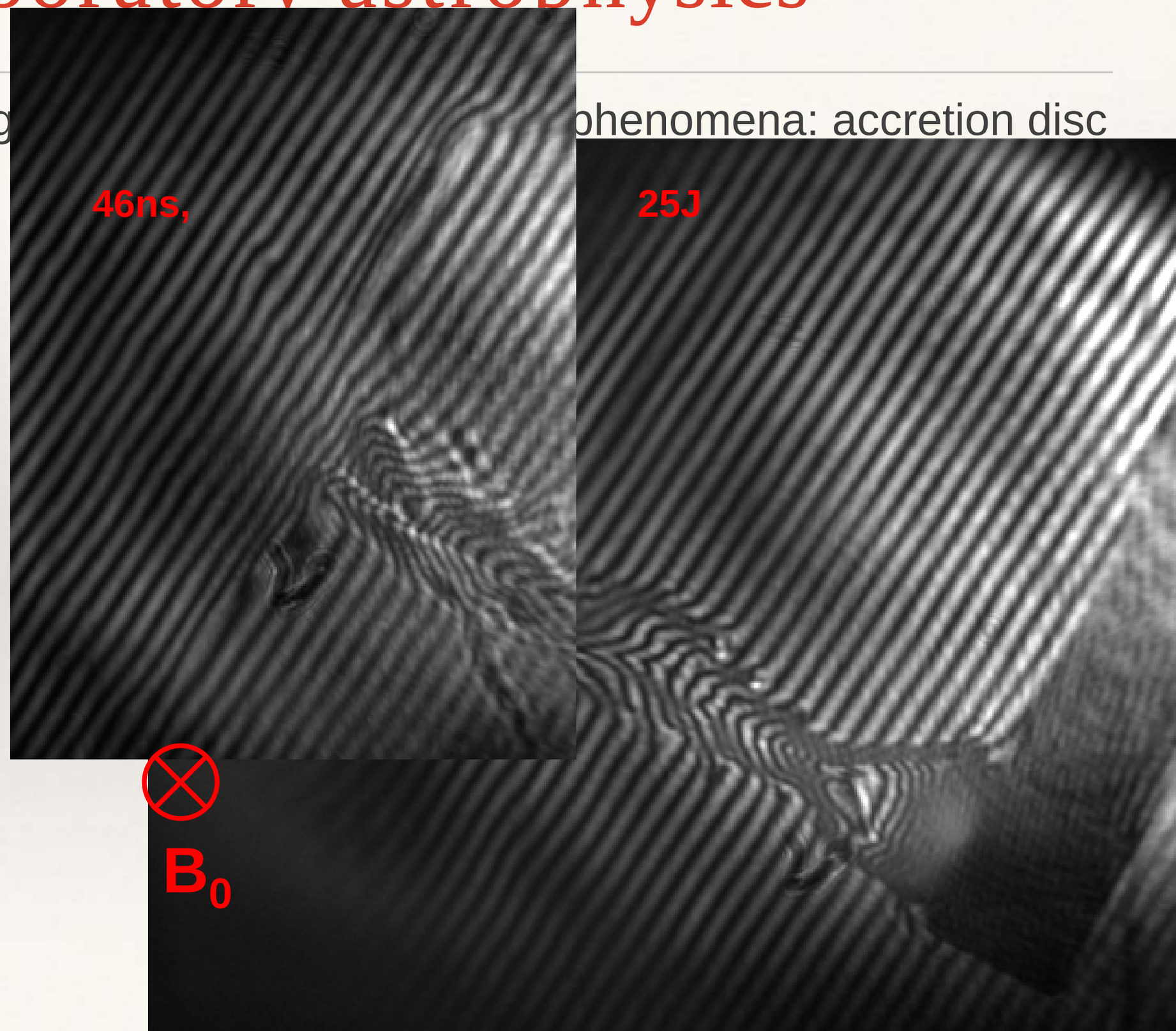
Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc



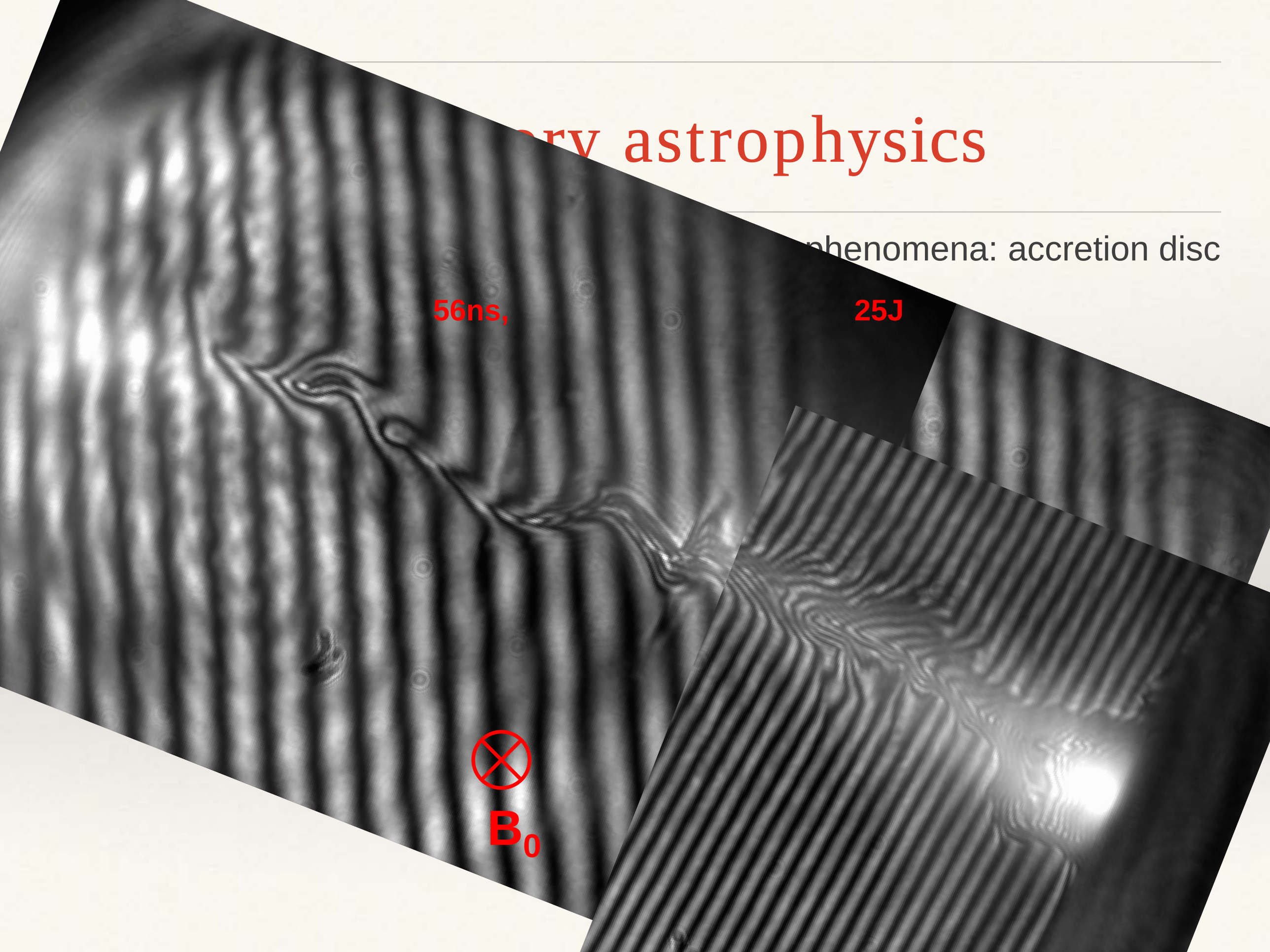
Laboratory astrophysics

- Modeling of mag phenomena: accretion disc



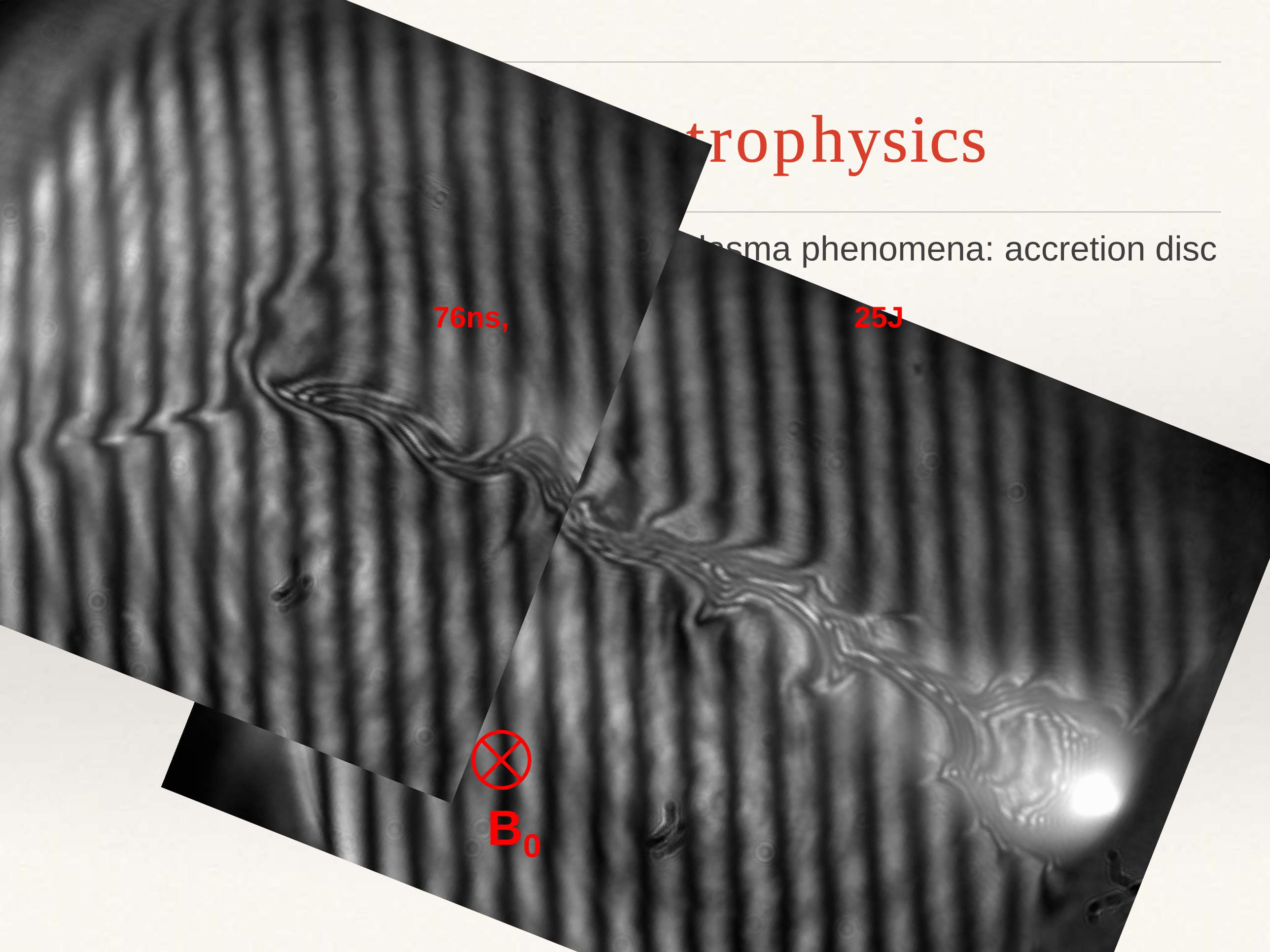
ory astrophysics

phenomena: accretion disc



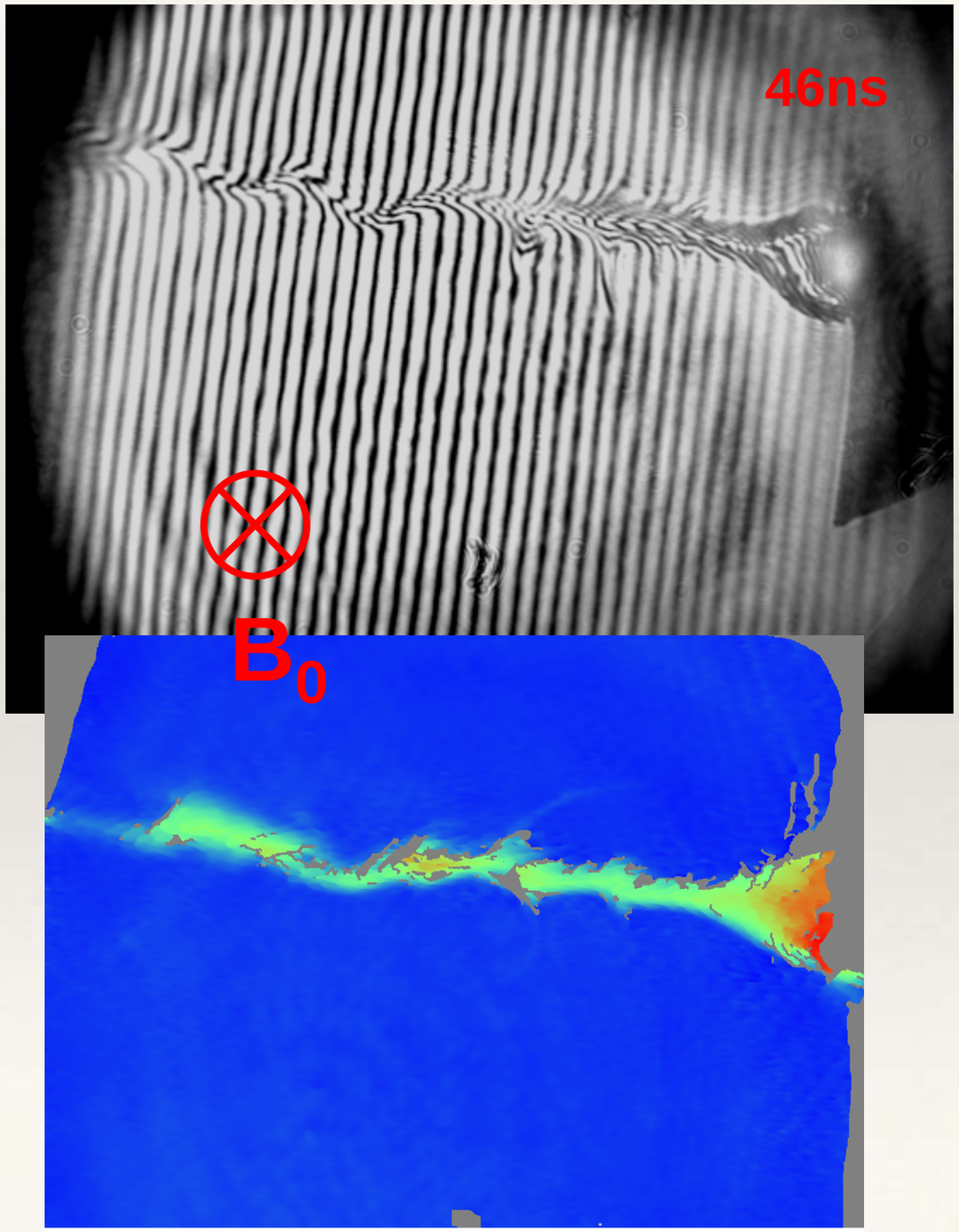
trophysics

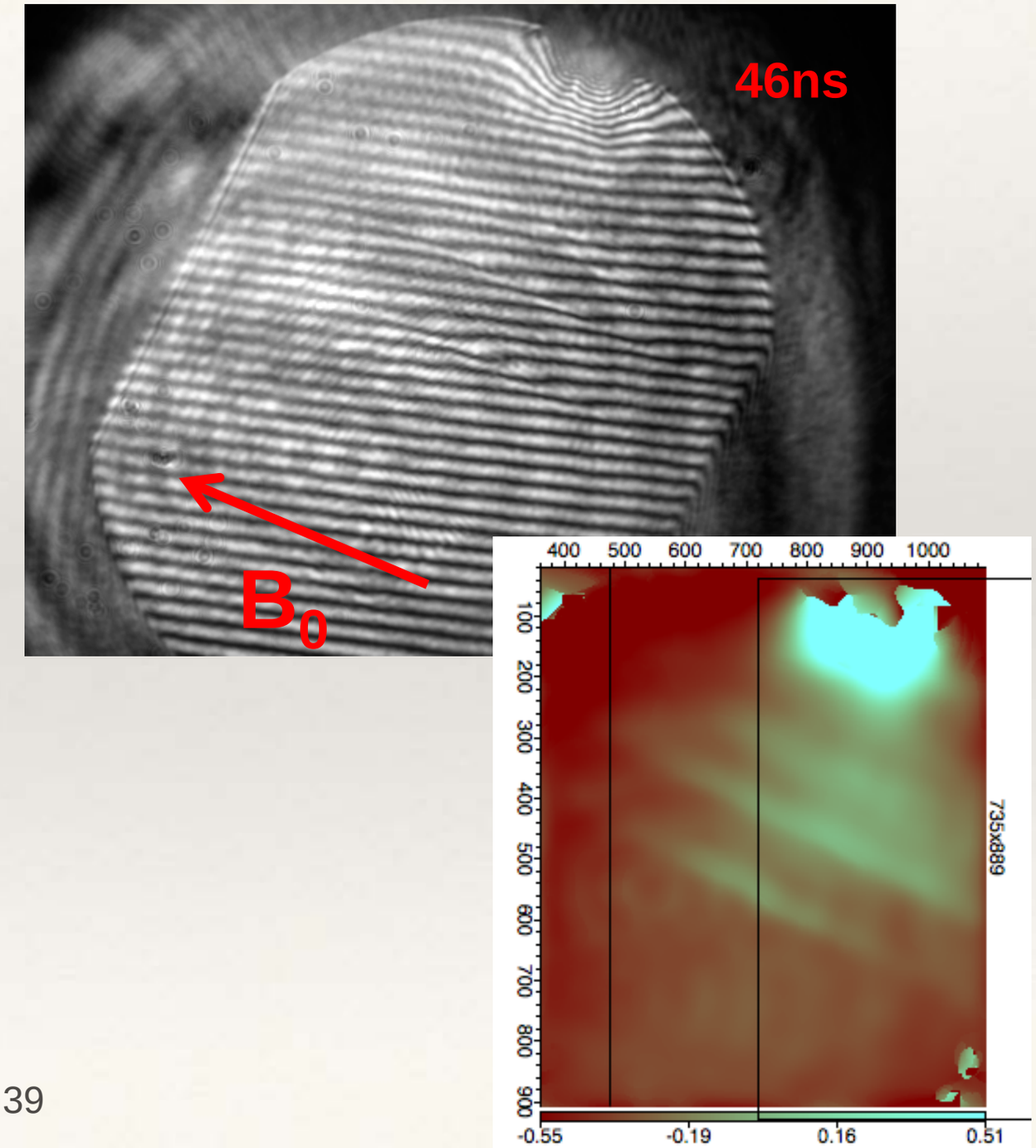
asma phenomena: accretion disc



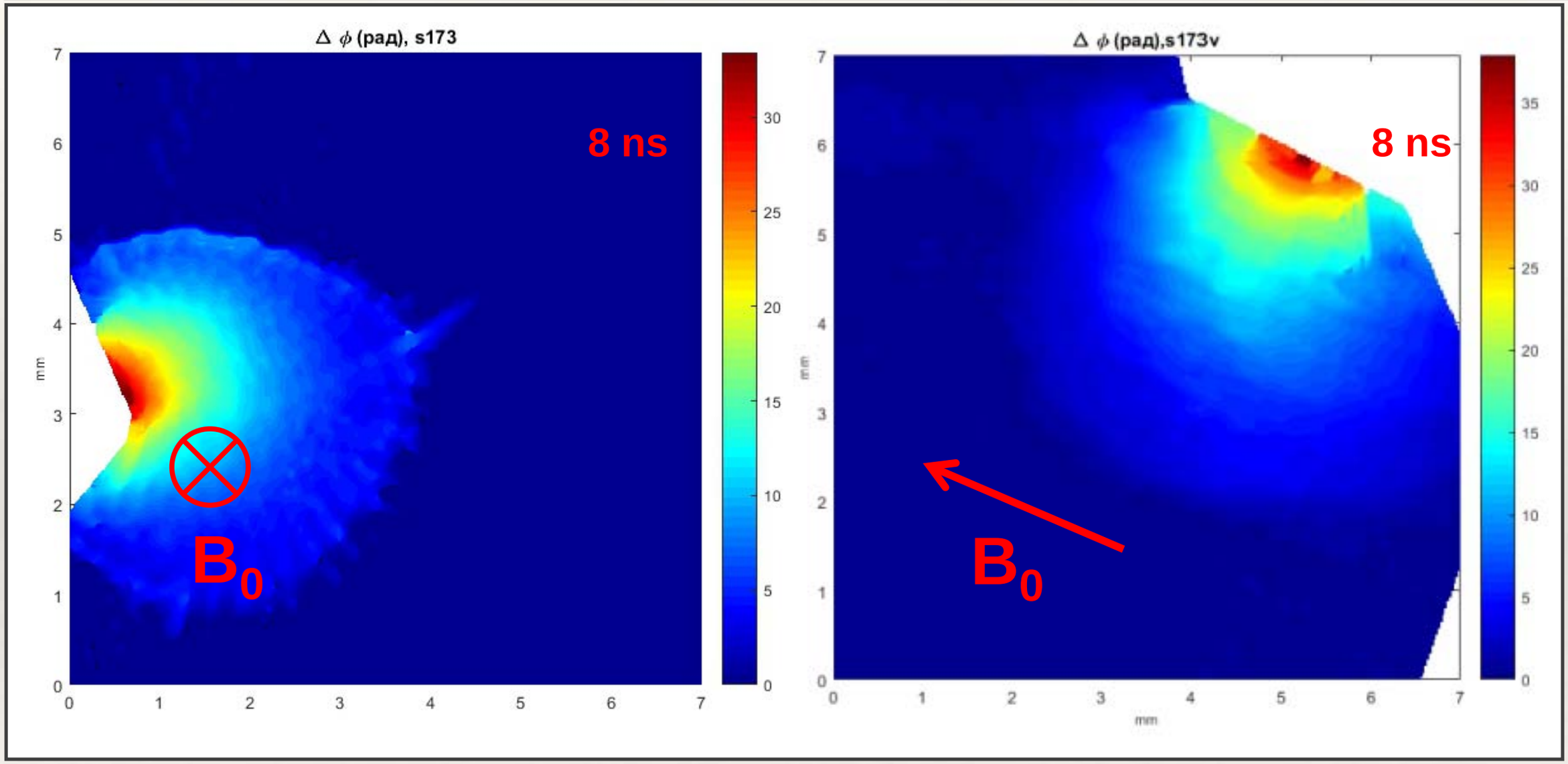
Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc





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



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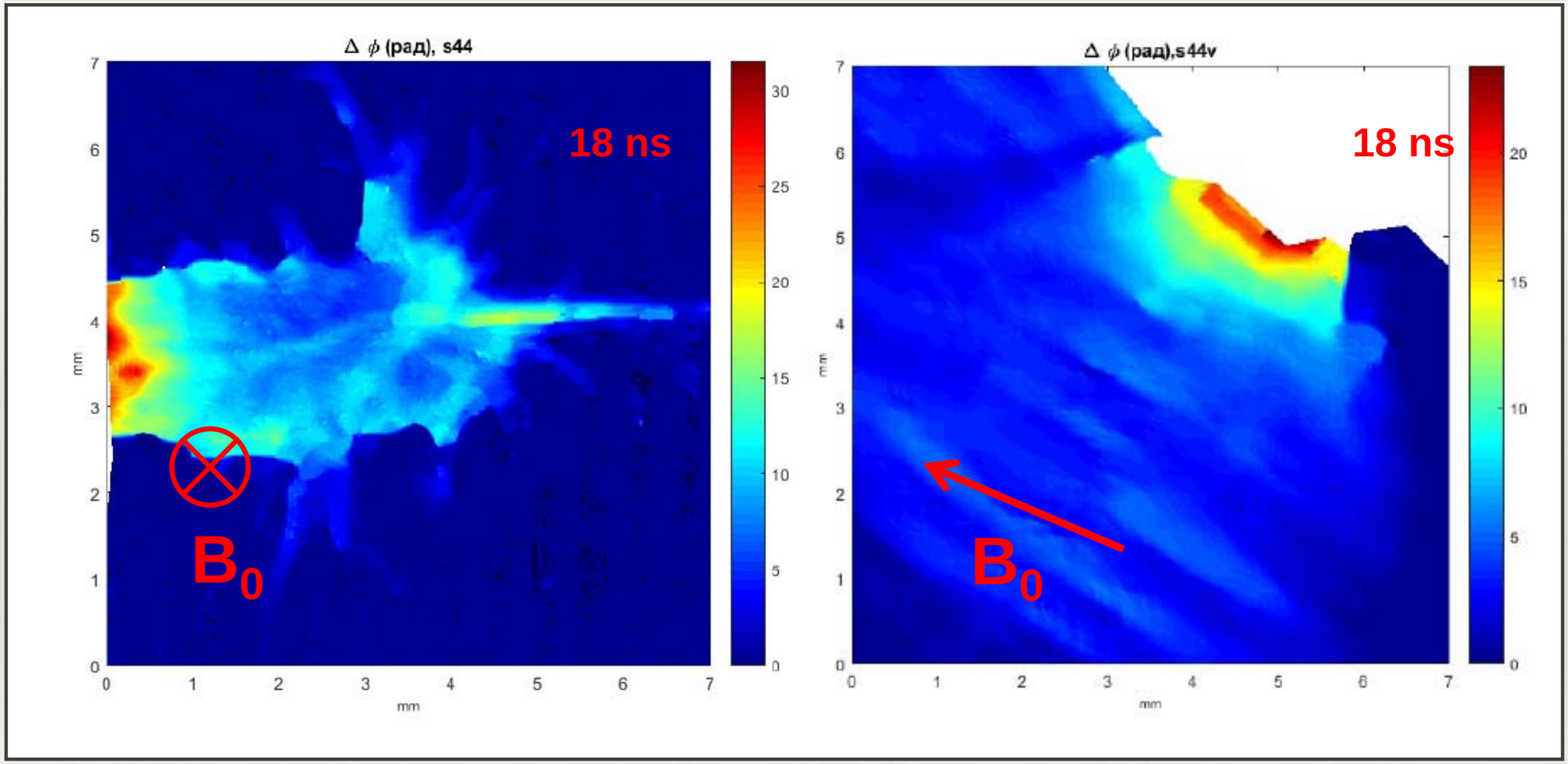
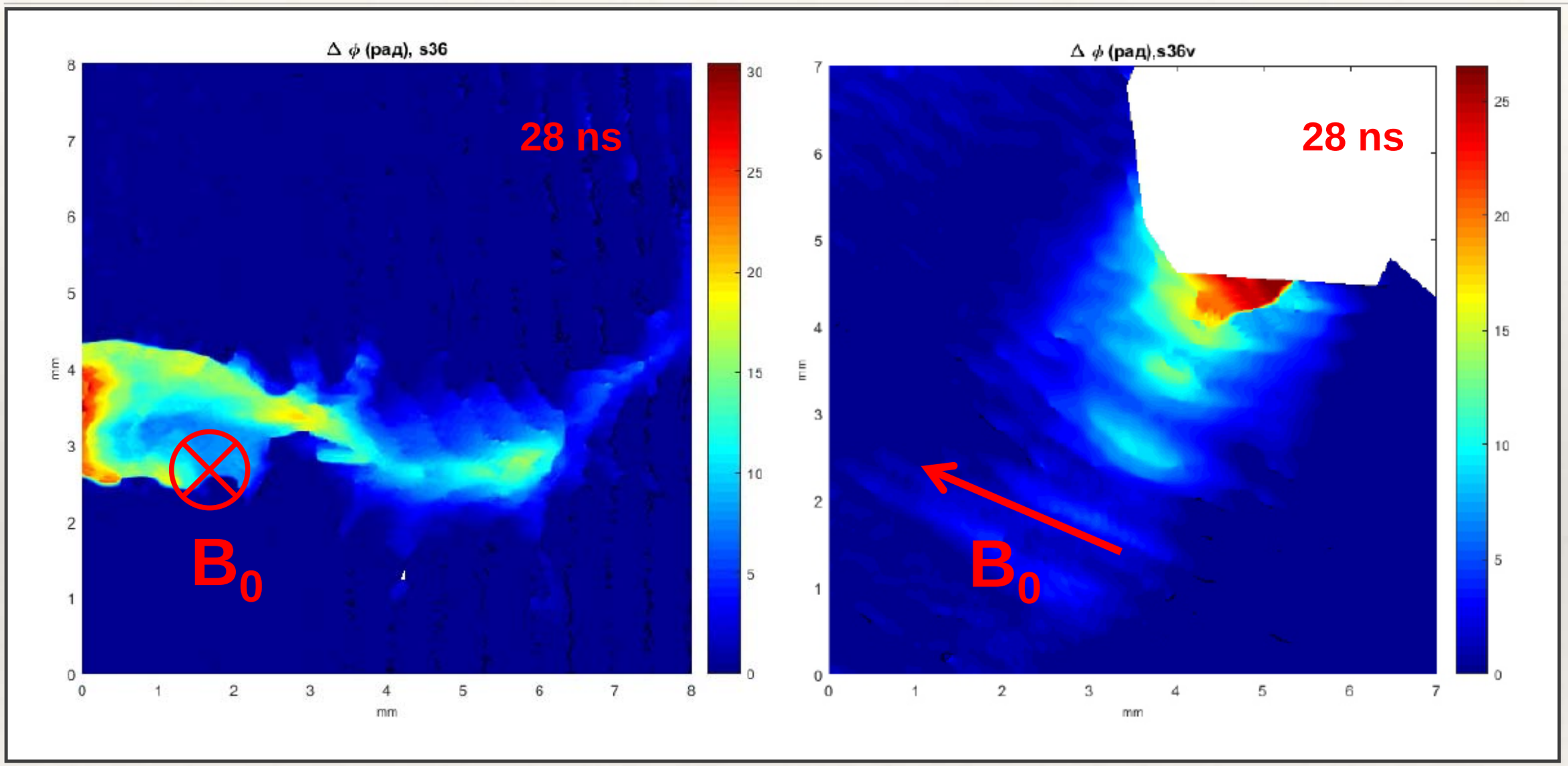
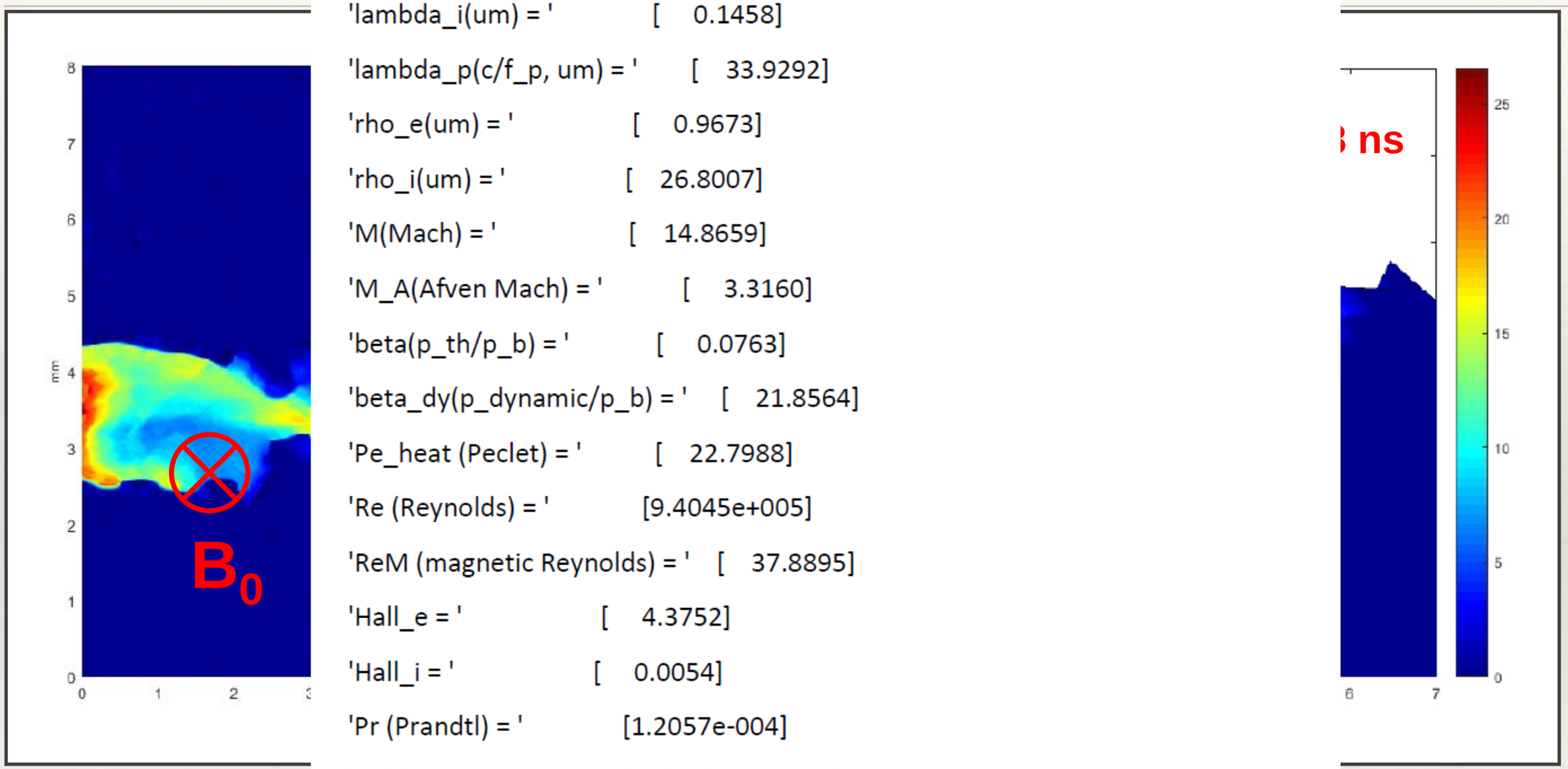


Laser plasma expansion across $\mathbf{B}_0$: experiment



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]

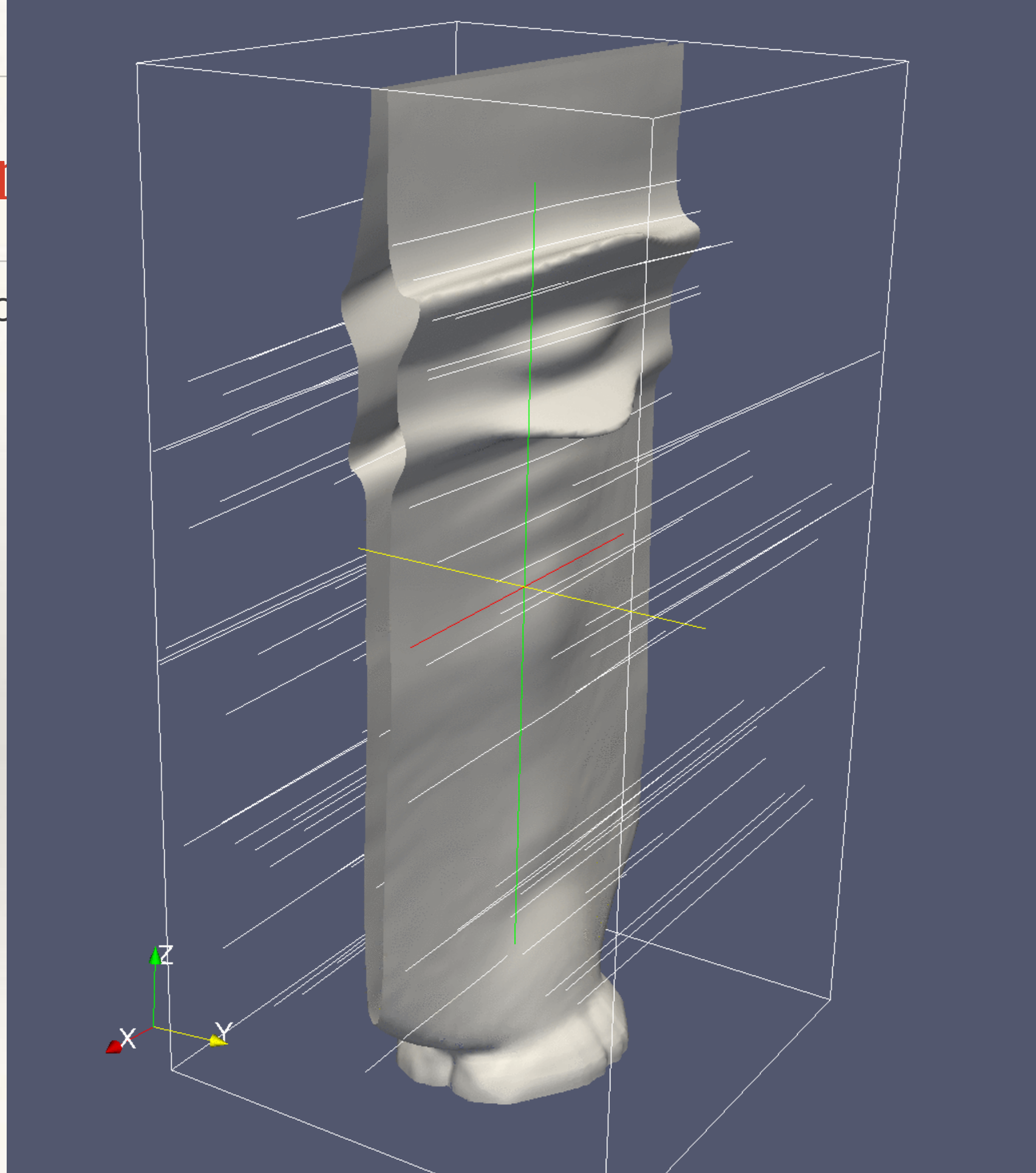
Labor

- Modeling of magneto

Main dynamics:
RT instability ?

Side oscillations:
KH instability ?

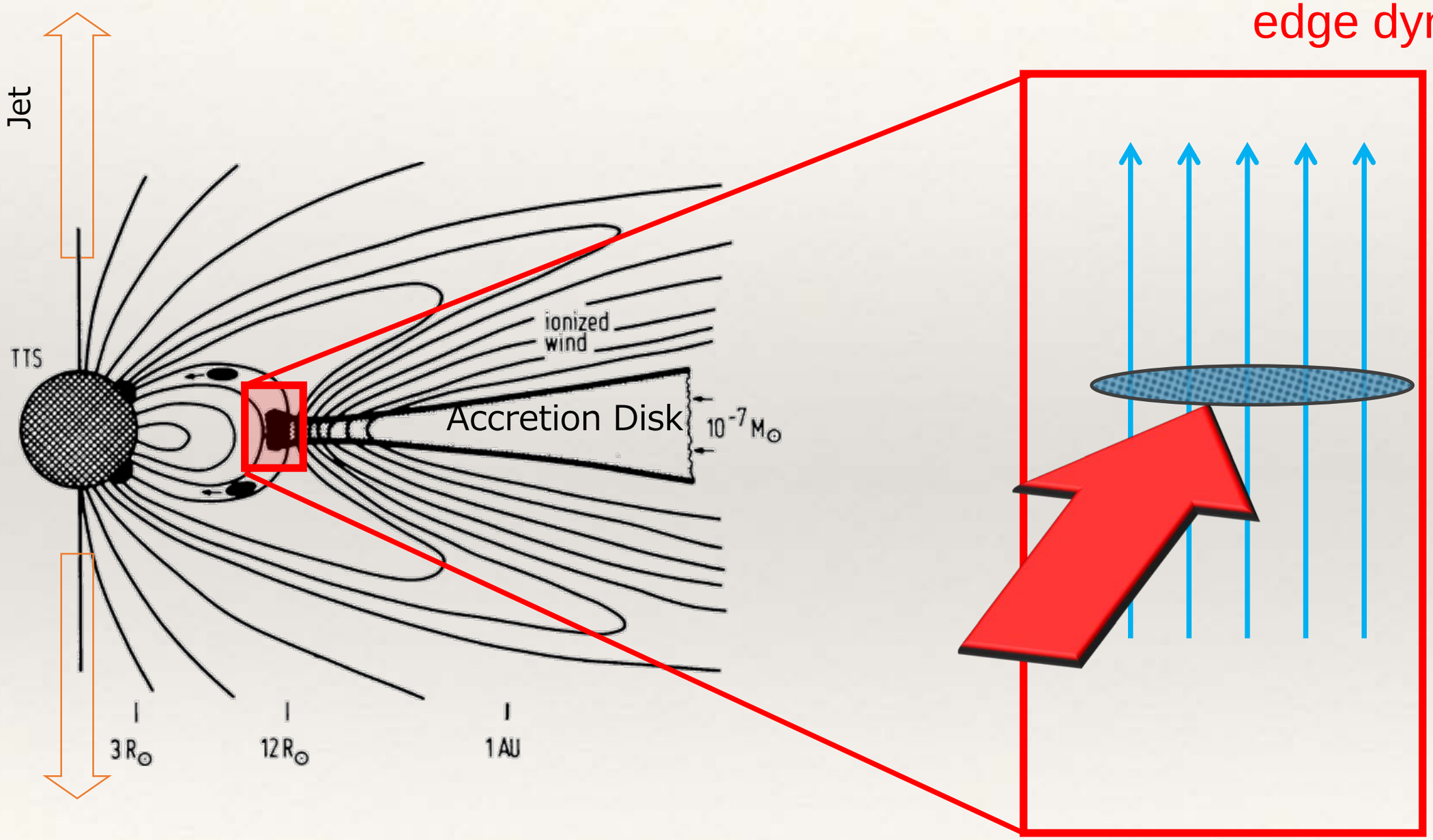
Where are the accretion columns ?
Are the astrophysical accretion models correct ?



Andrea Ciardi et al (2016)

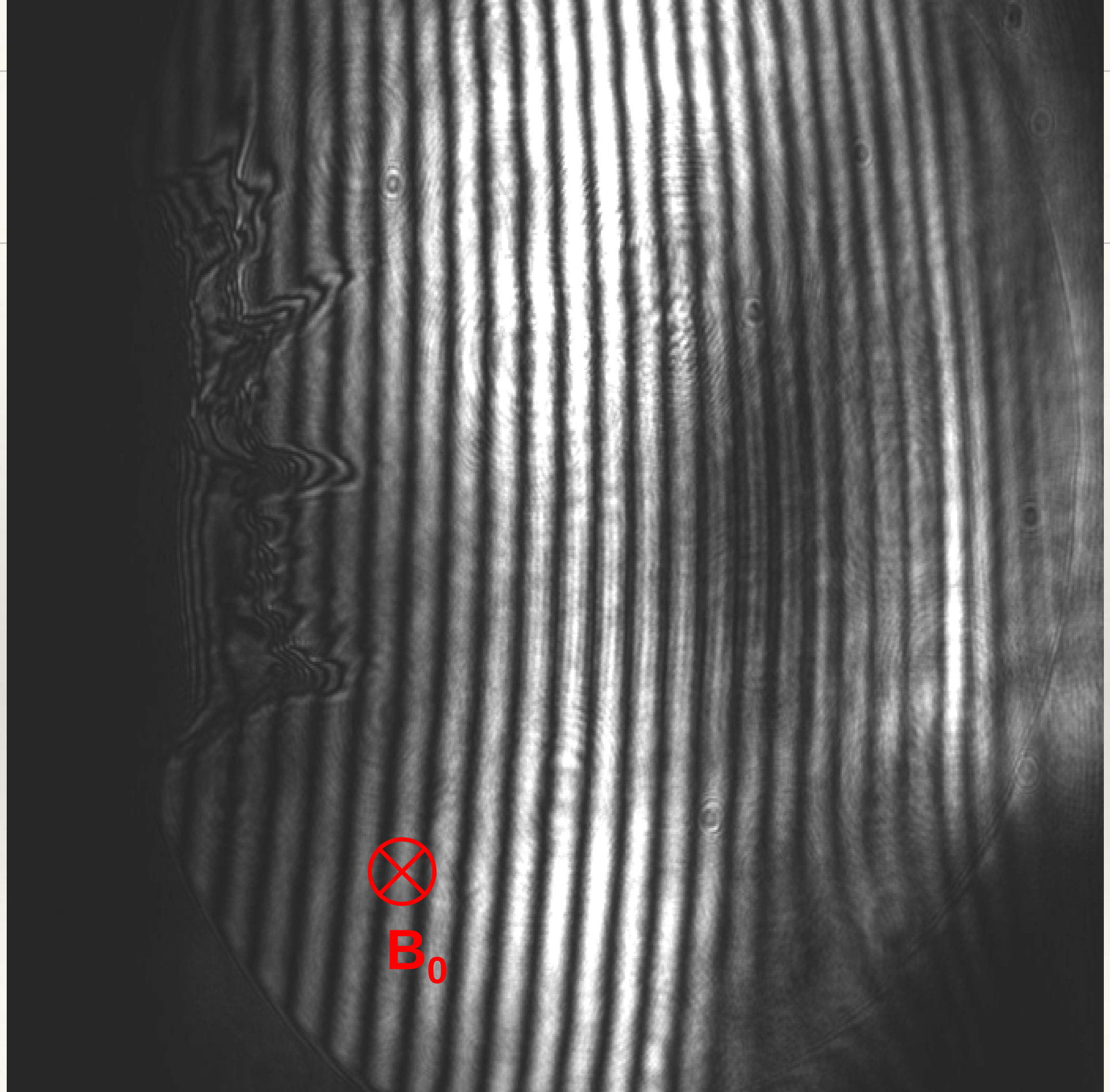
Laboratory astrophysics

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

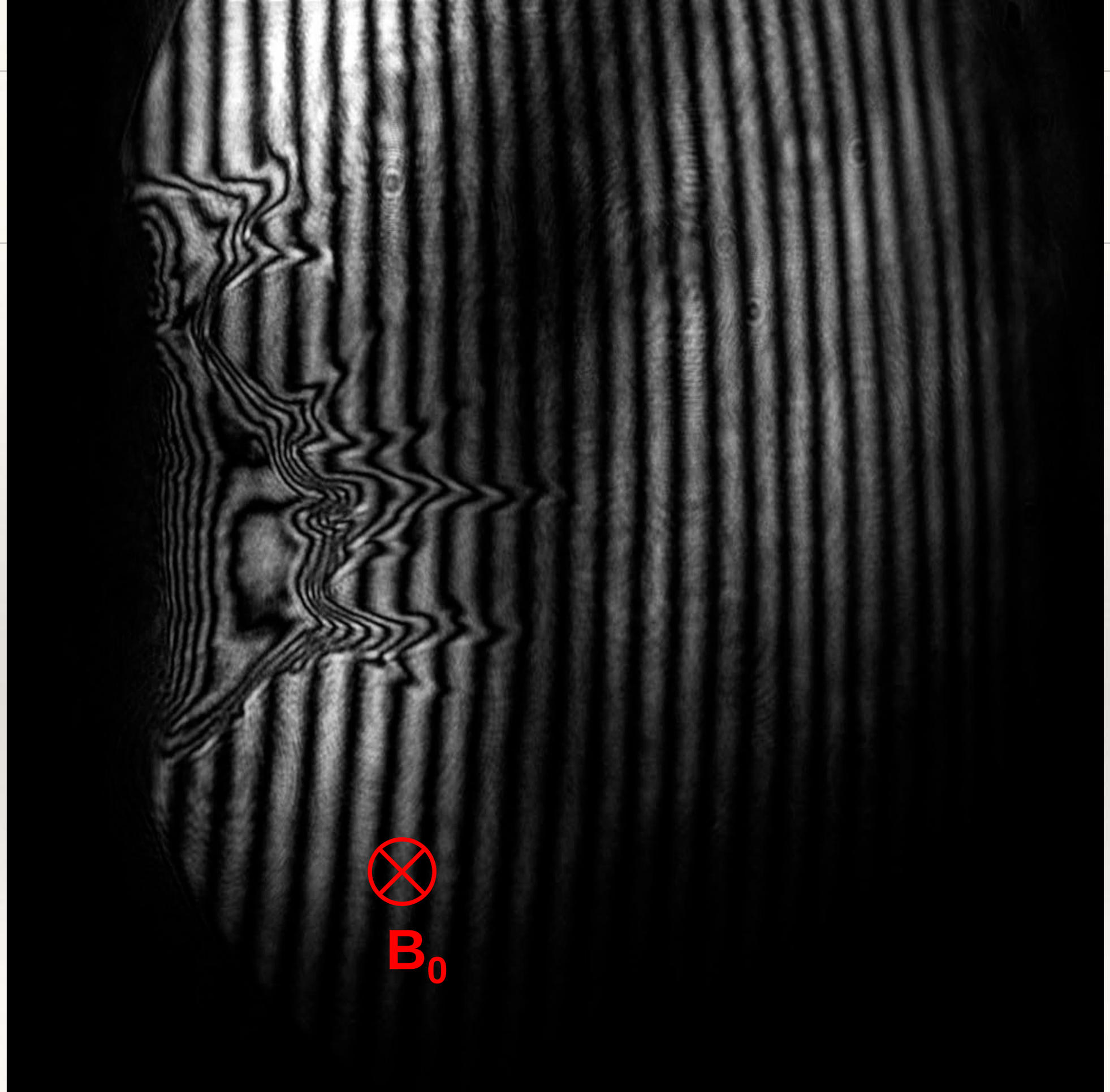


Adapted from Camenzind, (1990).

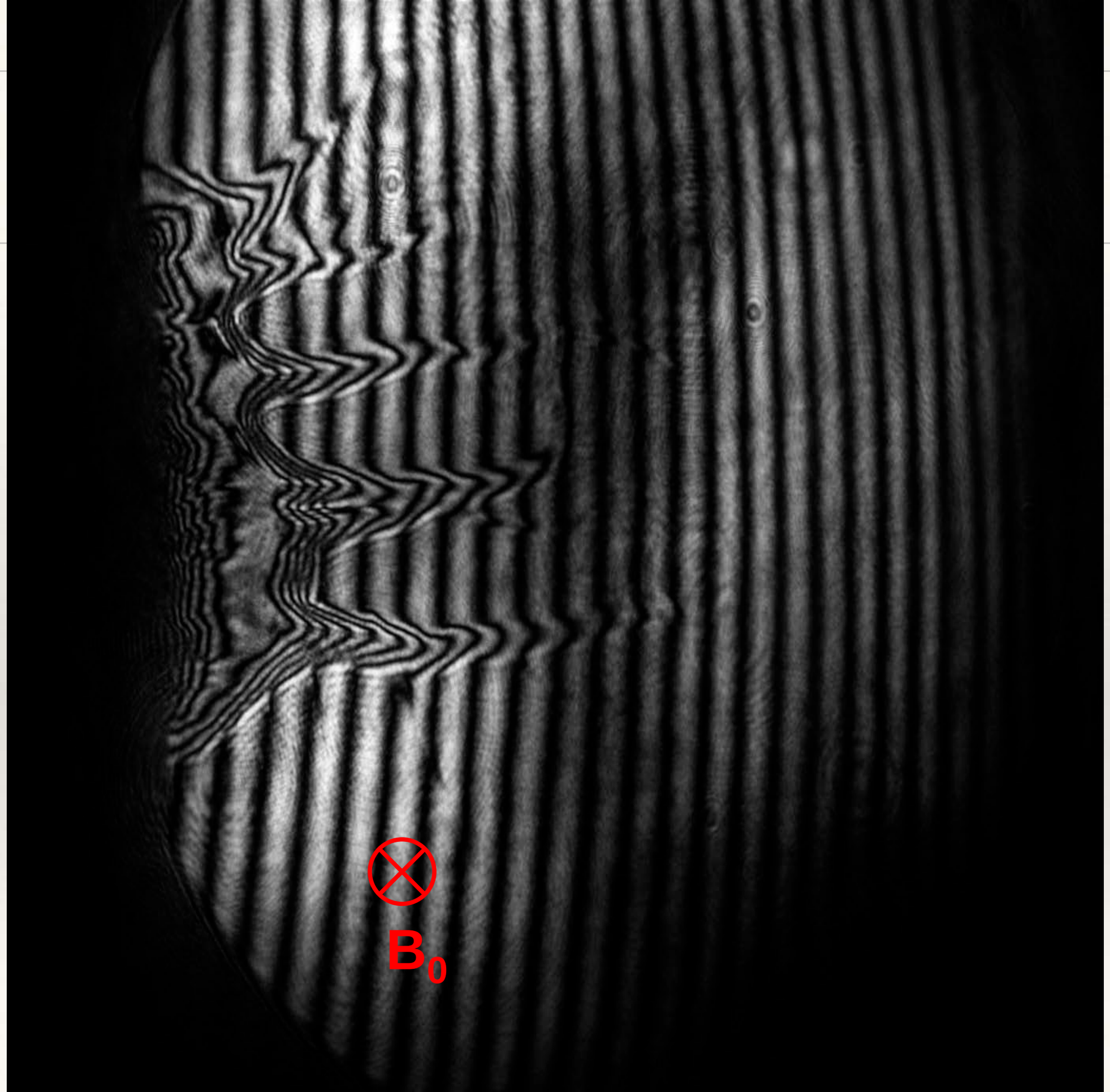
s091
28 ns
22.6 J



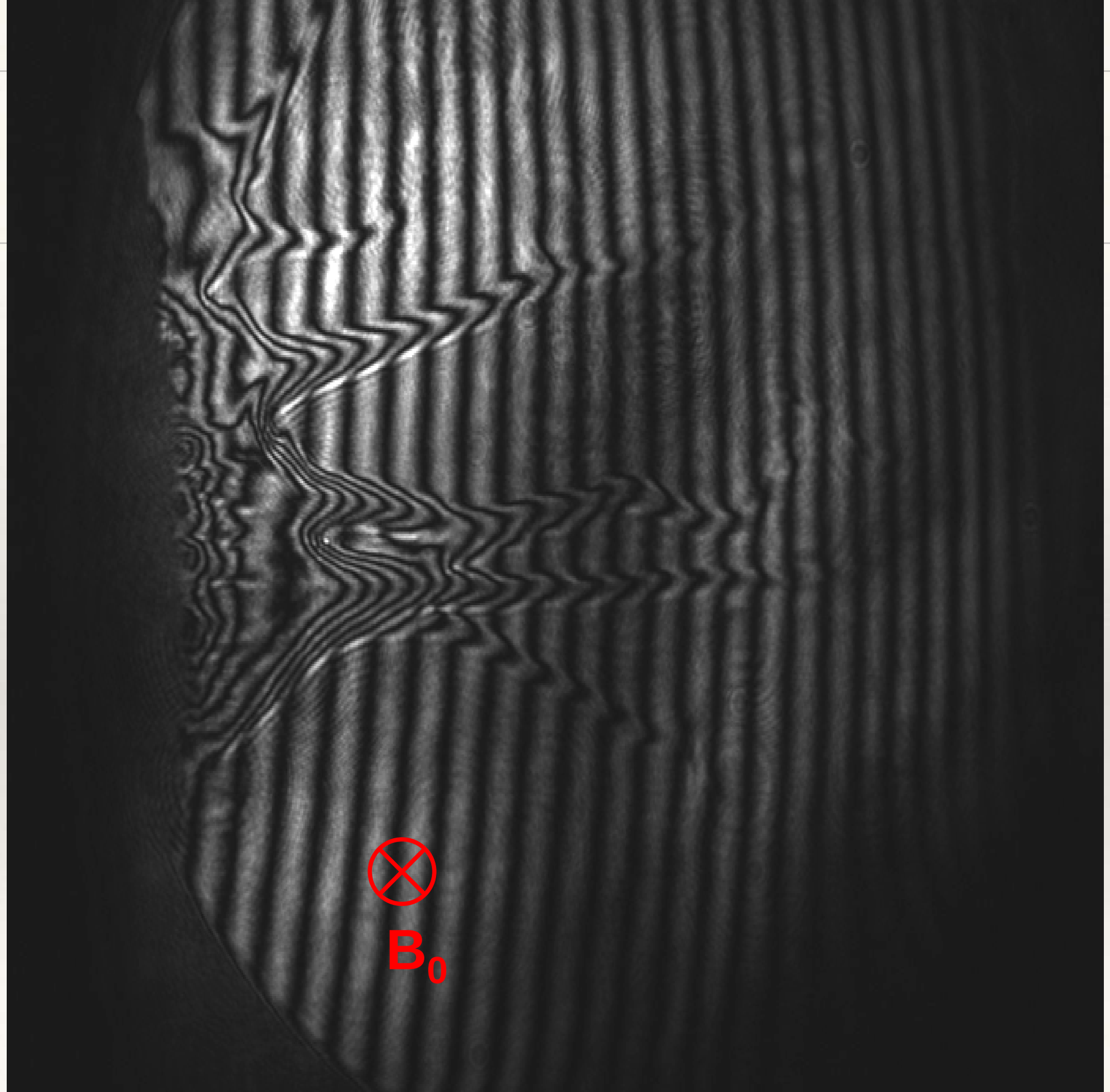
s094
48 ns
26.4 J



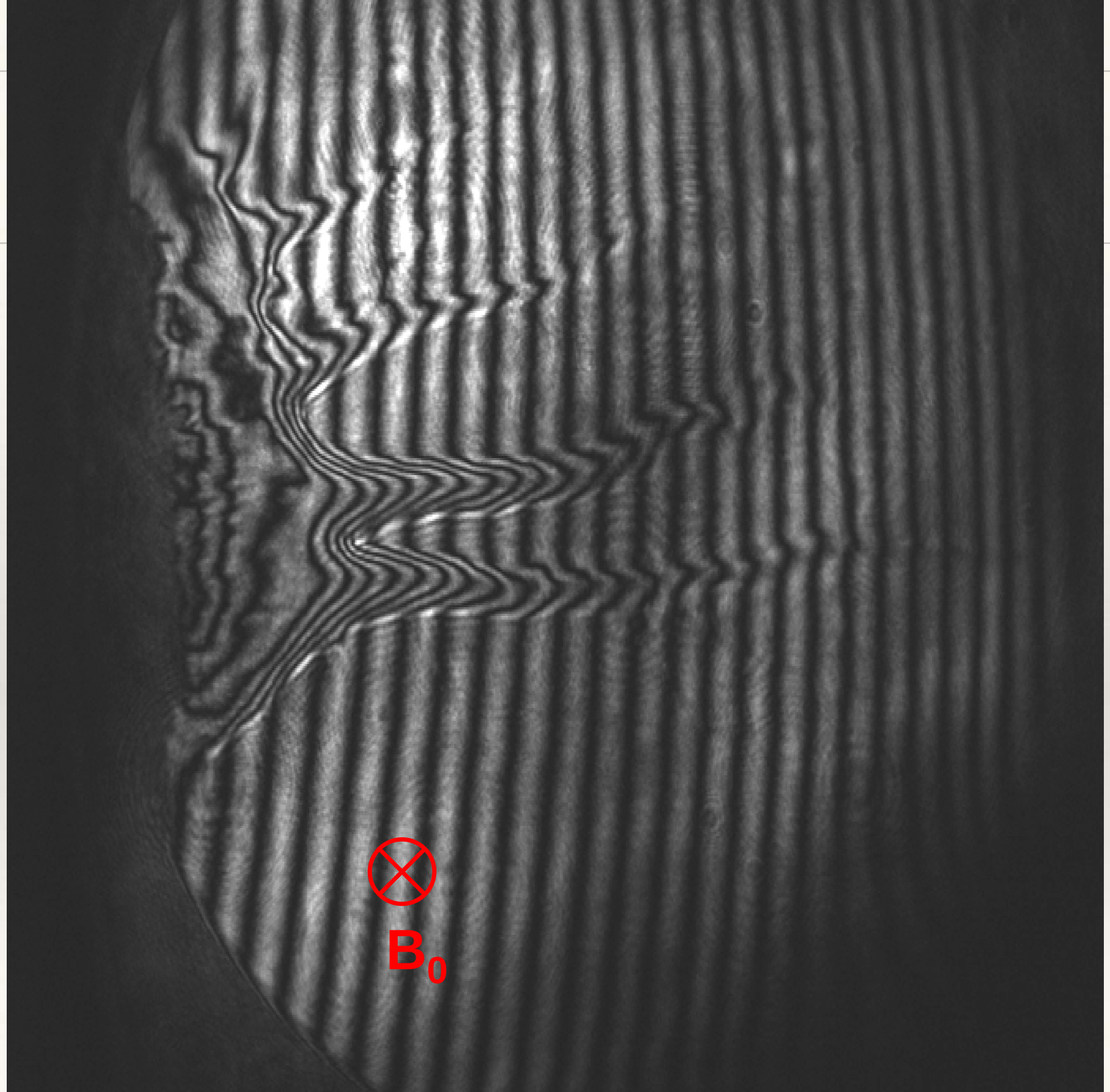
s098
68 ns
27.8 J



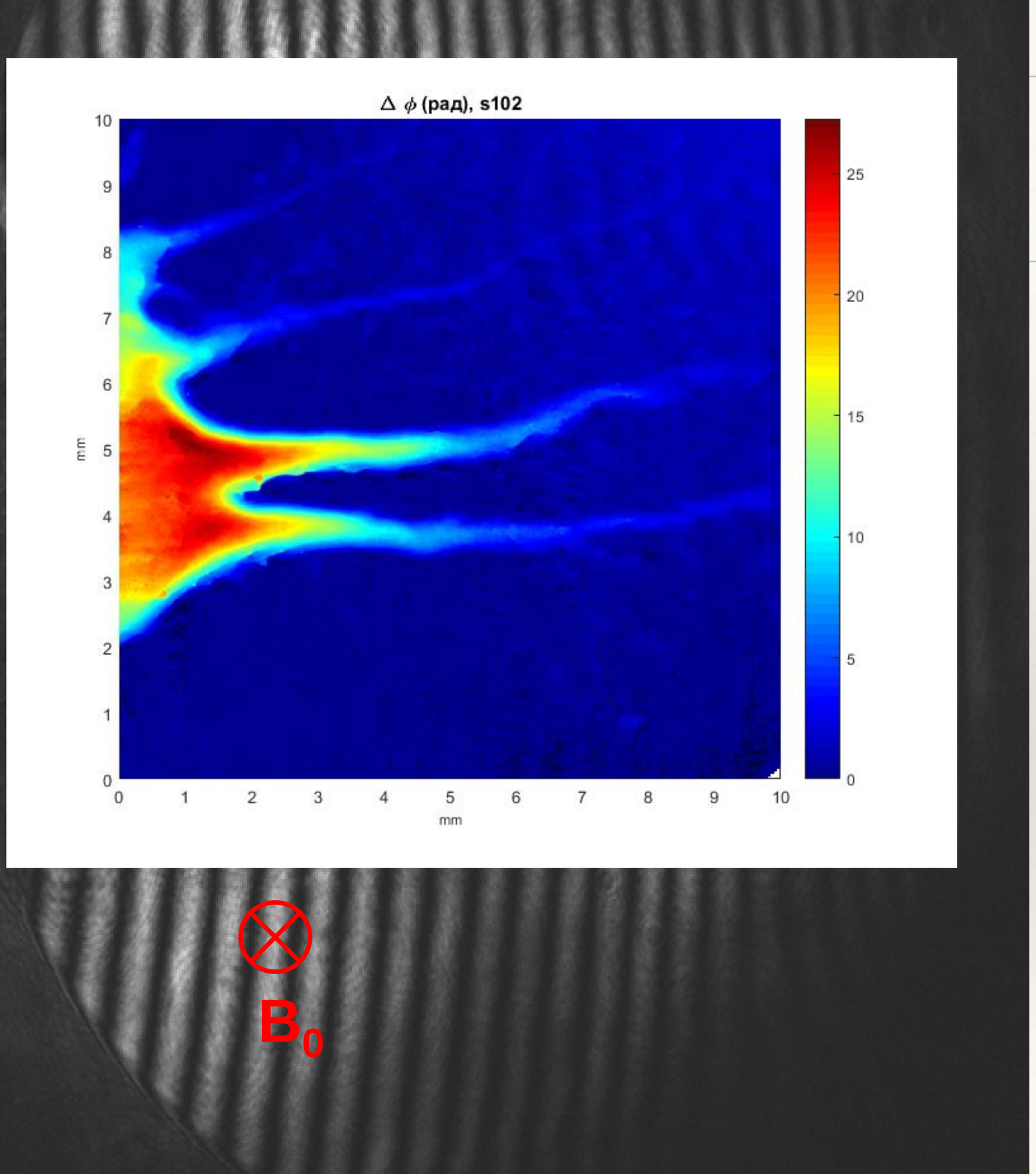
s100
88 ns
26.9 J



s102
108 ns
26.2 J



s102
108 ns
26.2 J



Summary

- Прогресс в лазеростроении:
  - 1 PW уверенно пройден
  - 10 PW ожидается в ближайшем будущем
- Лазерно-плазменное ускорение заряженных частиц:
  - Квазимоноэнергетичные электронные пучки (до 4 ГэВ)
  - Протонные пучки до 100 МэВ
- Широкие возможности для приложений и исследований в области лабораторной астрофизики