AE98 progress report

(Probing electron Weibel instability in optical-field ionized plasmas)

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Collaborators:

- *Yipeng Wu, Audrey Farrell, Mitchell Sinclair, Ken Marsh, Warren B. Mori (UCLA)*
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- *Rotem Kupfer, Karl Kusche, Mikhail Fedurin, Igor Pogorelsky, Mikhail Polyanskiy, Mark Palmer (ATF)*
  Thank you!

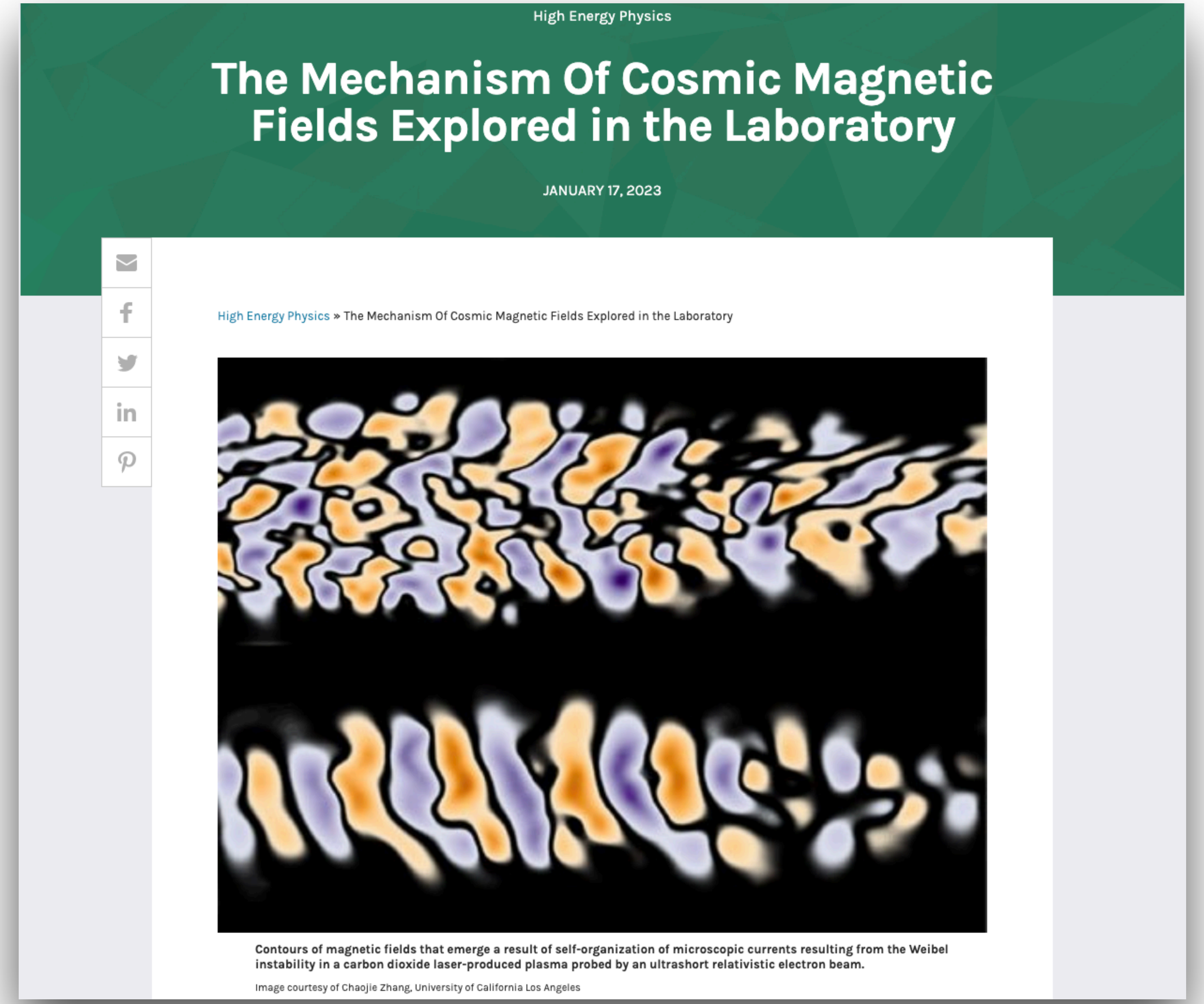
UCLA Stony Brook University

Supported by NSF and DOE-NNSA, DOE-HEP (received)

NSF U.S. DEPARTMENT OF ENERGY

The 25th annual ATF User Meeting, Mar 1st, 2023

Our experiment done in 2021 is published in PNAS and highlighted on the DOE website



High Energy Physics

The Mechanism Of Cosmic Magnetic Fields Explored in the Laboratory

JANUARY 17, 2023

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Contours of magnetic fields that emerge a result of self-organization of microscopic currents resulting from the Weibel instability in a carbon dioxide laser-produced plasma probed by an ultrashort relativistic electron beam.

Image courtesy of Chaojie Zhang, University of California Los Angeles

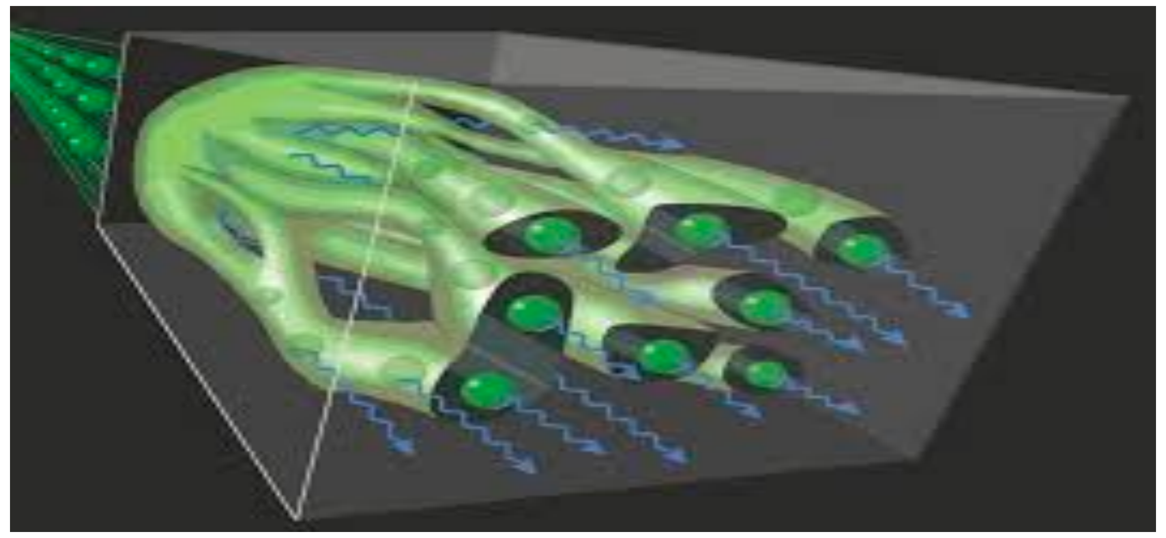
Weibel instability is relevant in many lab. and astrophysical plasmas

- **An important mechanism for self-magnetization of many laboratory and astrophysical plasmas**
- **its unambiguous demonstration remains a challenge**
  - **Mediate collisionless shocks (possible accelerator for cosmic rays)**
  - **Generate bright gamma ray flashes (novel light sources)**
  - **Affect energy deposition in the fast ignition scenario (energy)**

Acceleration: Collisionless shock[1]

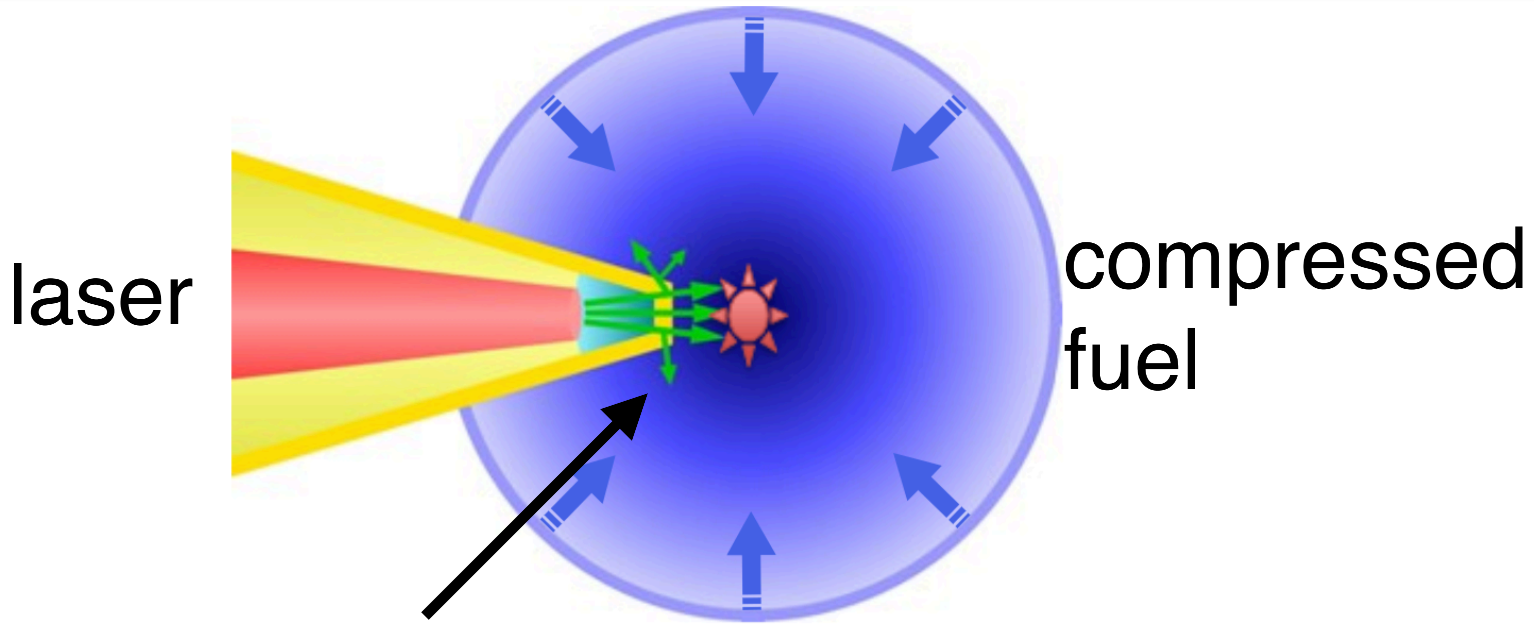
colliding plasma creates collisionless shocks

Light source: Gamma ray flash[2]



filamentation of dense e- beam in plasma generates bright γ-ray flashes

Energy: Laser-driven fusion[3]



electron/proton tranport in dense plasma

1, J. Meinecke et al., Nat. Phys. 2014; C. M. Huntington et al., Nat. Phys. 2015, etc.

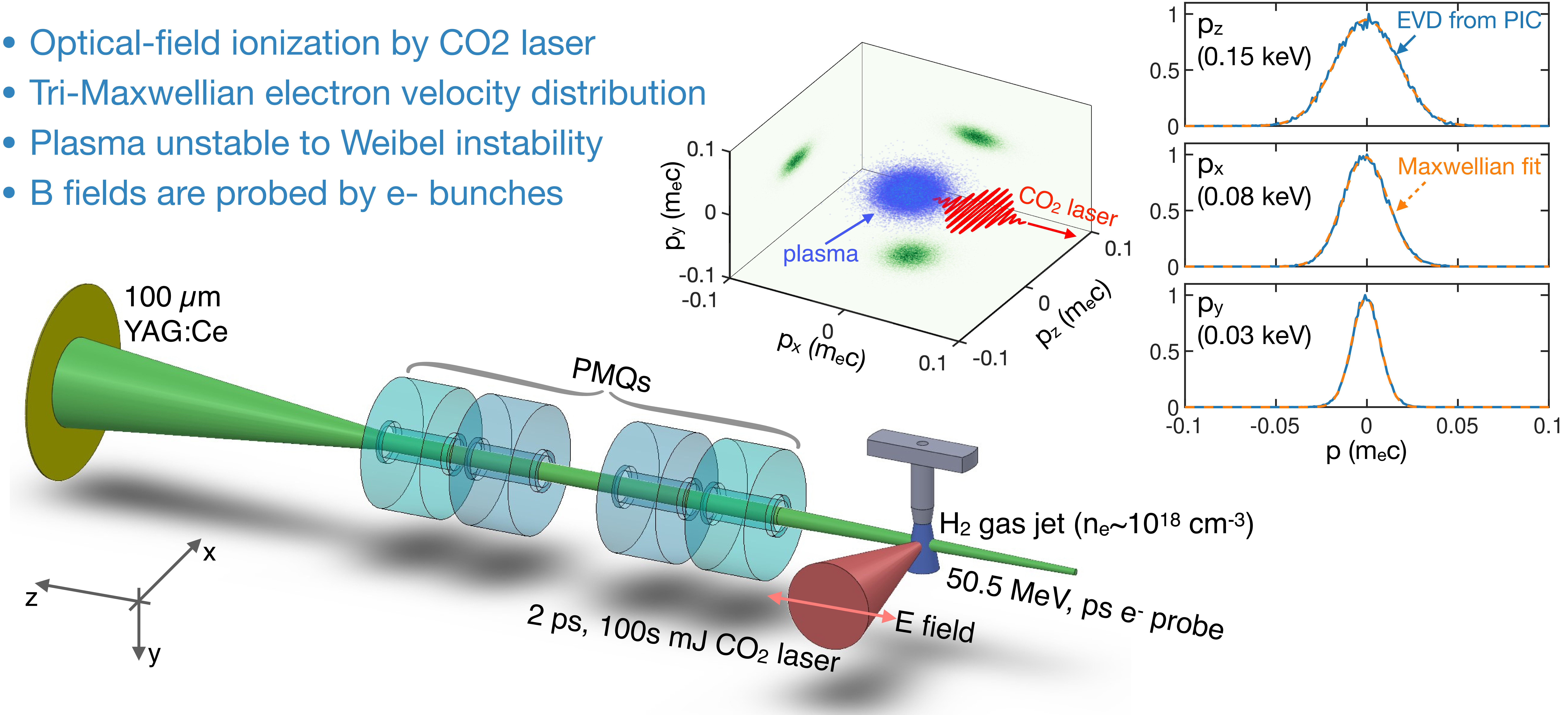
2, A. Benedetti et al., Nat. Photonics 2018, etc.

3, M. Tabak et al., PoP 1994; A. Pukhov et al., PRL 1997; M. Honda et al., PRL 2000; M. Roth et al., PRL 2001, etc.

Experiment was successfully done in 2021, results published in PNAS

UCLA

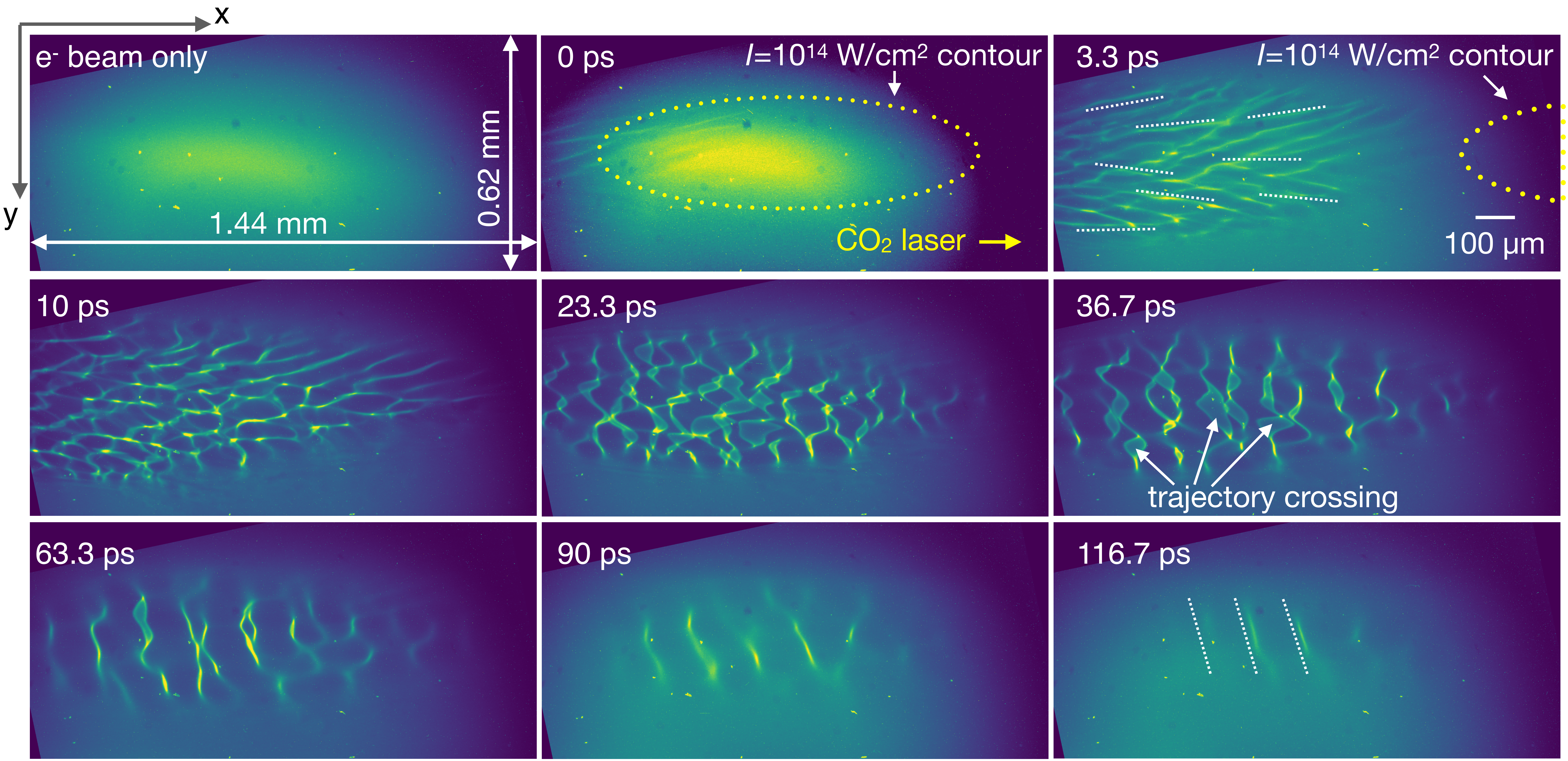
- Optical-field ionization by CO2 laser
- Tri-Maxwellian electron velocity distribution
- Plasma unstable to Weibel instability
- B fields are probed by e- bunches



C. Zhang et al, PNAS 50, 119 (2022)

First direct observation of 2D evolution of the Weibel B fields

UCLA

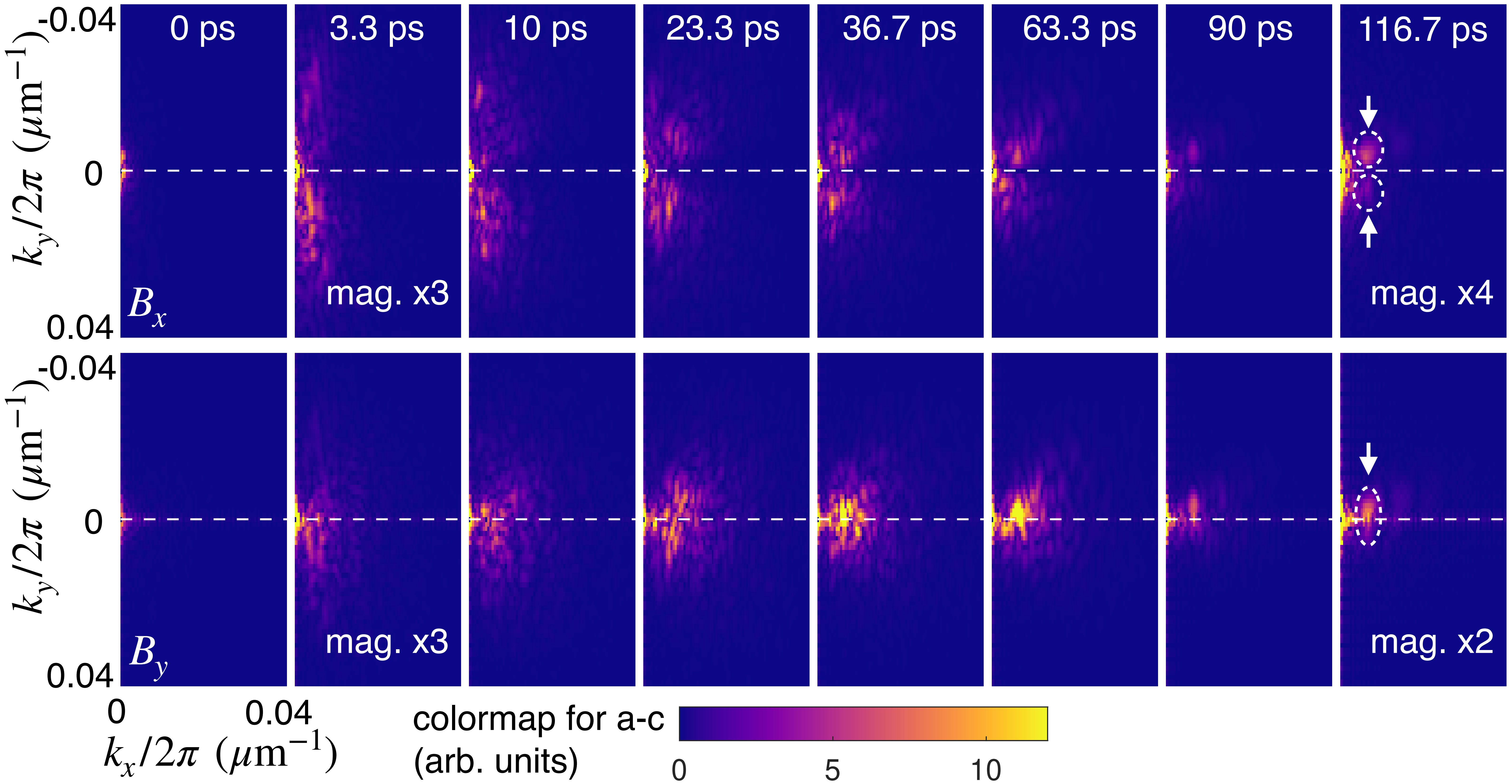


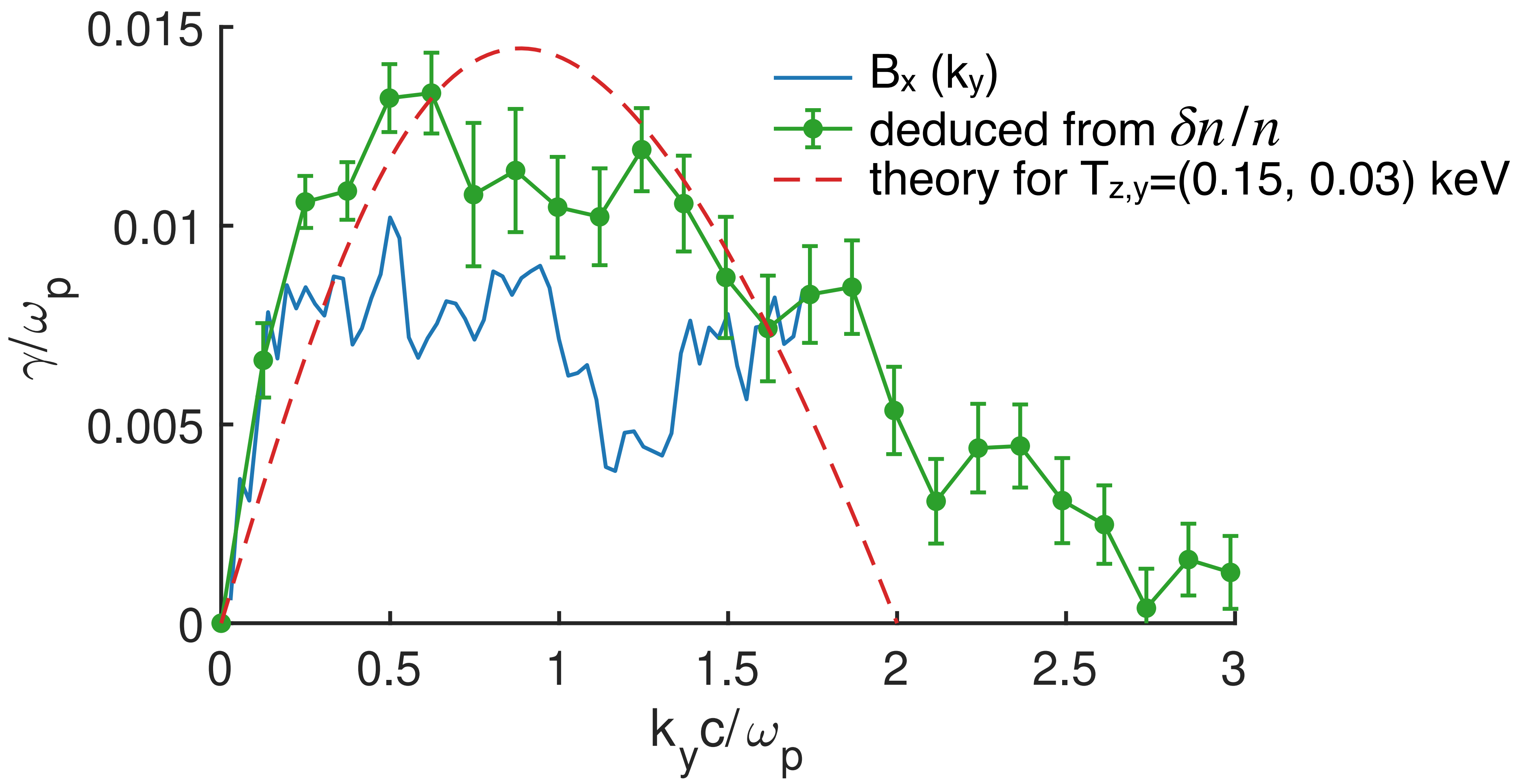
C. Zhang et al, PNAS 50, 119 (2022)

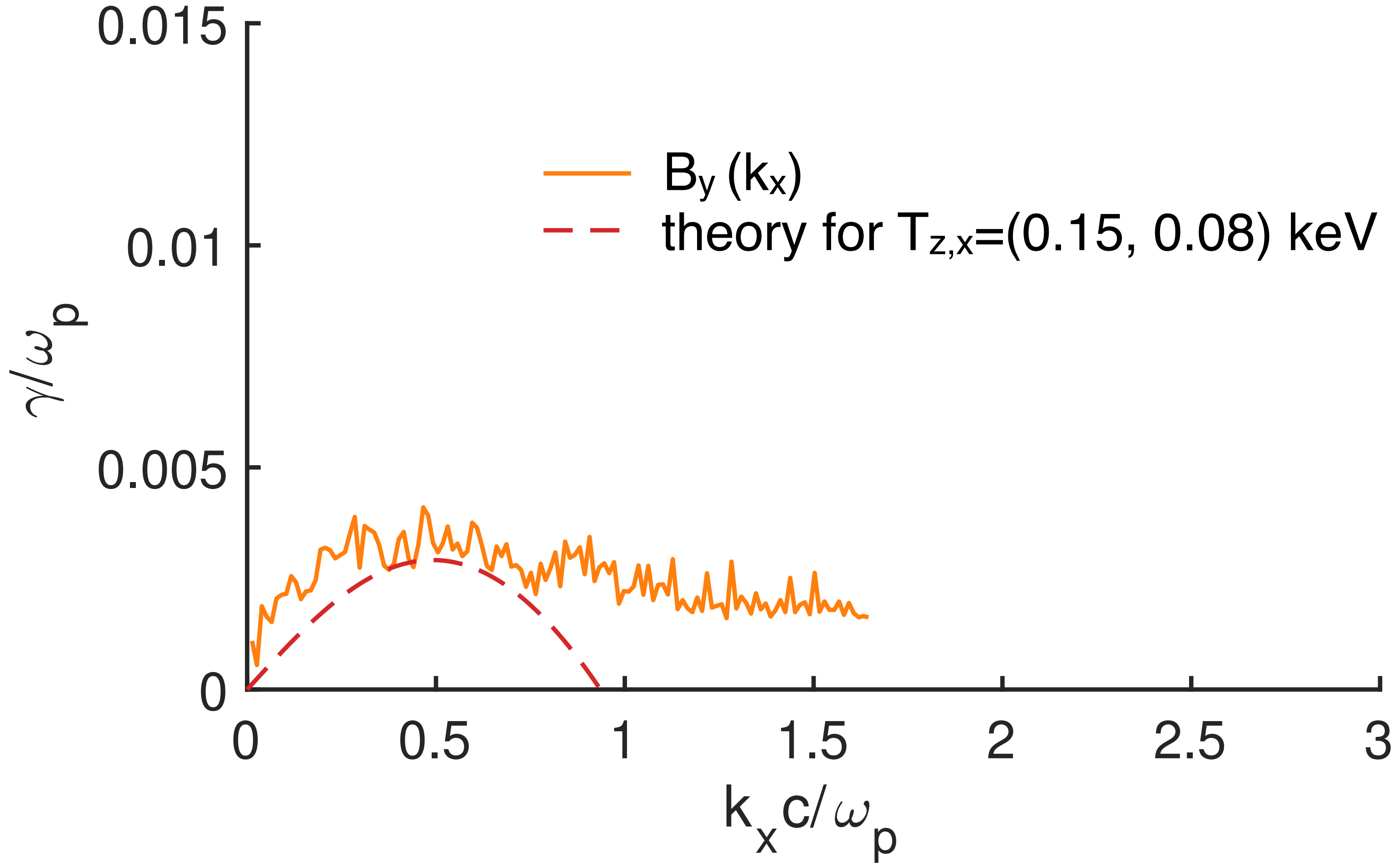
High spatiotemporal resolution e- probing demonstrated

First measurement of the k-resolved growth rate

UCLA







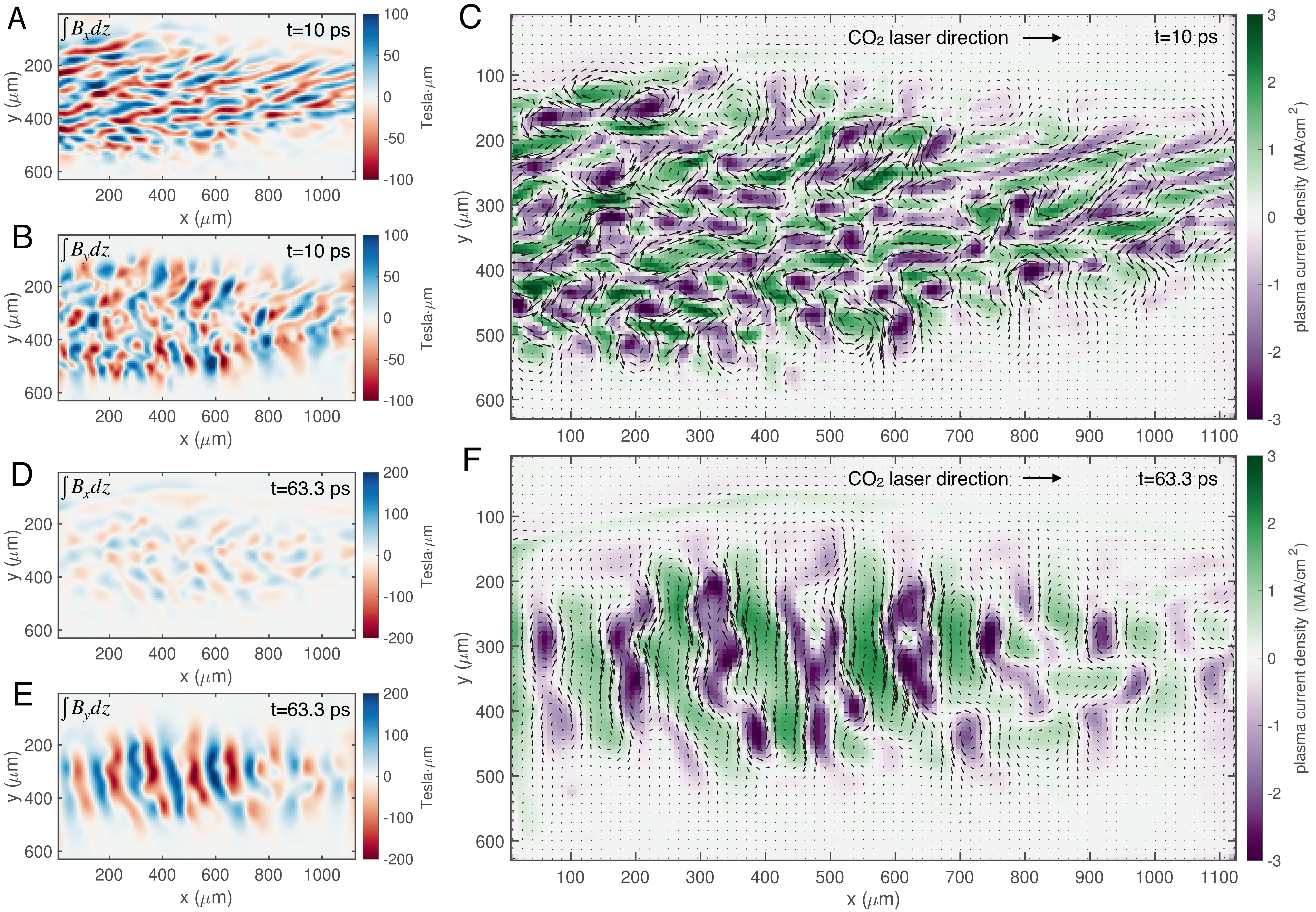
- The unstable mode starts with narrow k_x and broad k_y and then spreads in the 2D k space;
- The dominating k redirects from y to x;
- Eventually a quasi-single mode forms;

C. Zhang et al, PNAS 50, 119 (2022)

- Time-resolved measurements of the k spectra allows us to calculate the k-resolved growth rate
- Measured growth rates agree with theory

Self-organization of OFI plasma by Weibel instability

UCLA

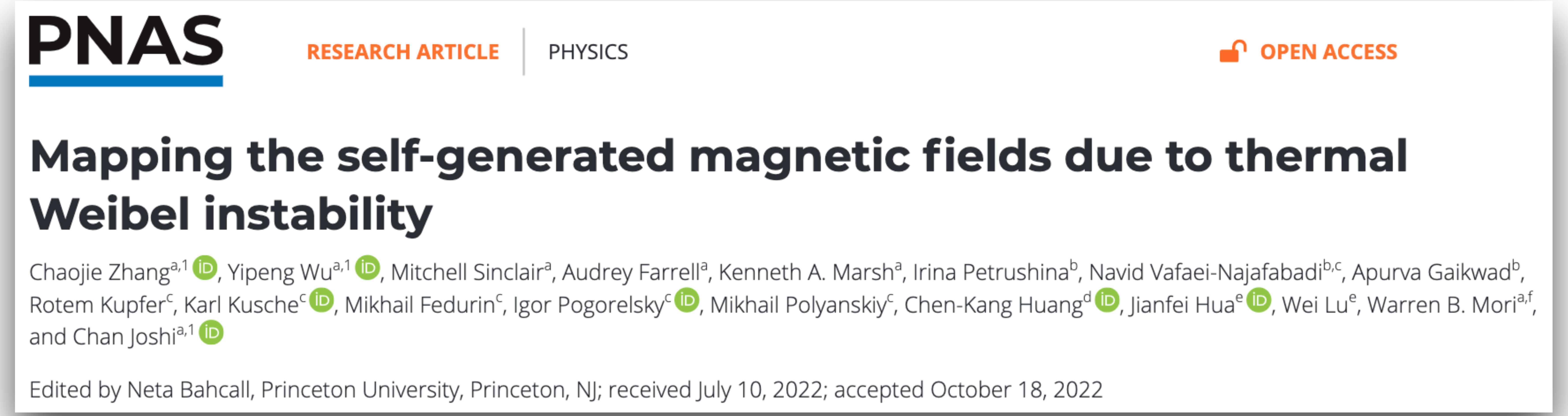


- significant amount (~1%) of thermal energy was converted to magnetic energy
- supports the hypothesis that the Weibel instability may provide the seed for galactic dynamo to produce ~μG magnetic fields that exist in the cosmos

C. Zhang et al, PNAS 50, 119 (2022)

Summary of results

- Self-generated magnetic fields due to Weibel instability were measured
  - with unprecedented ps, μm resolution
  - first k-resolved growth rate measurements
  - conclusively demonstrated the thermal Weibel instability driven by anisotropic EVD
- ~1% of the thermal energy was converted to magnetic energy
  - agrees with theoretical prediction
  - supports that Weibel instability may be able to provide a seed for the galactic dynamo

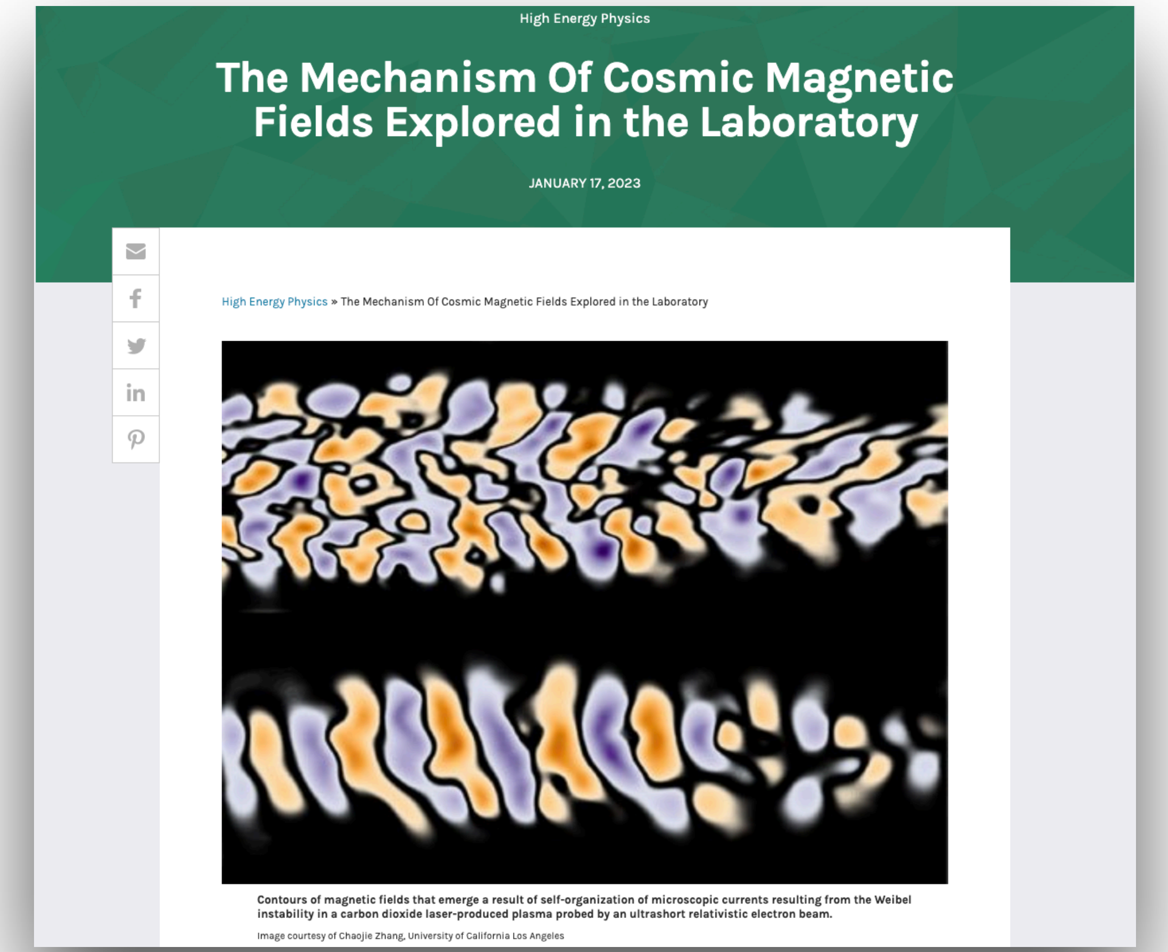


PNAS RESEARCH ARTICLE | PHYSICS OPEN ACCESS

Mapping the self-generated magnetic fields due to thermal Weibel instability

Chaojie Zhang[a,1], Yipeng Wu[a,1], Mitchell Sinclair[a], Audrey Farrell[a], Kenneth A. Marsh[a], Irina Petrushina[b], Navid Vafaei-Najafabadi[b,c], Apurva Gaikwad[b], Rotem Kupfer[c], Karl Kusche[c], Mikhail Fedurin[c], Igor Pogorelsky[c], Mikhail Polyanskiy[c], Chen-Kang Huang[d], Jianfei Hua[e], Wei Lu[e], Warren B. Mori[a,f], and Chan Joshi[a,1]

Edited by Neta Bahcall, Princeton University, Princeton, NJ; received July 10, 2022; accepted October 18, 2022



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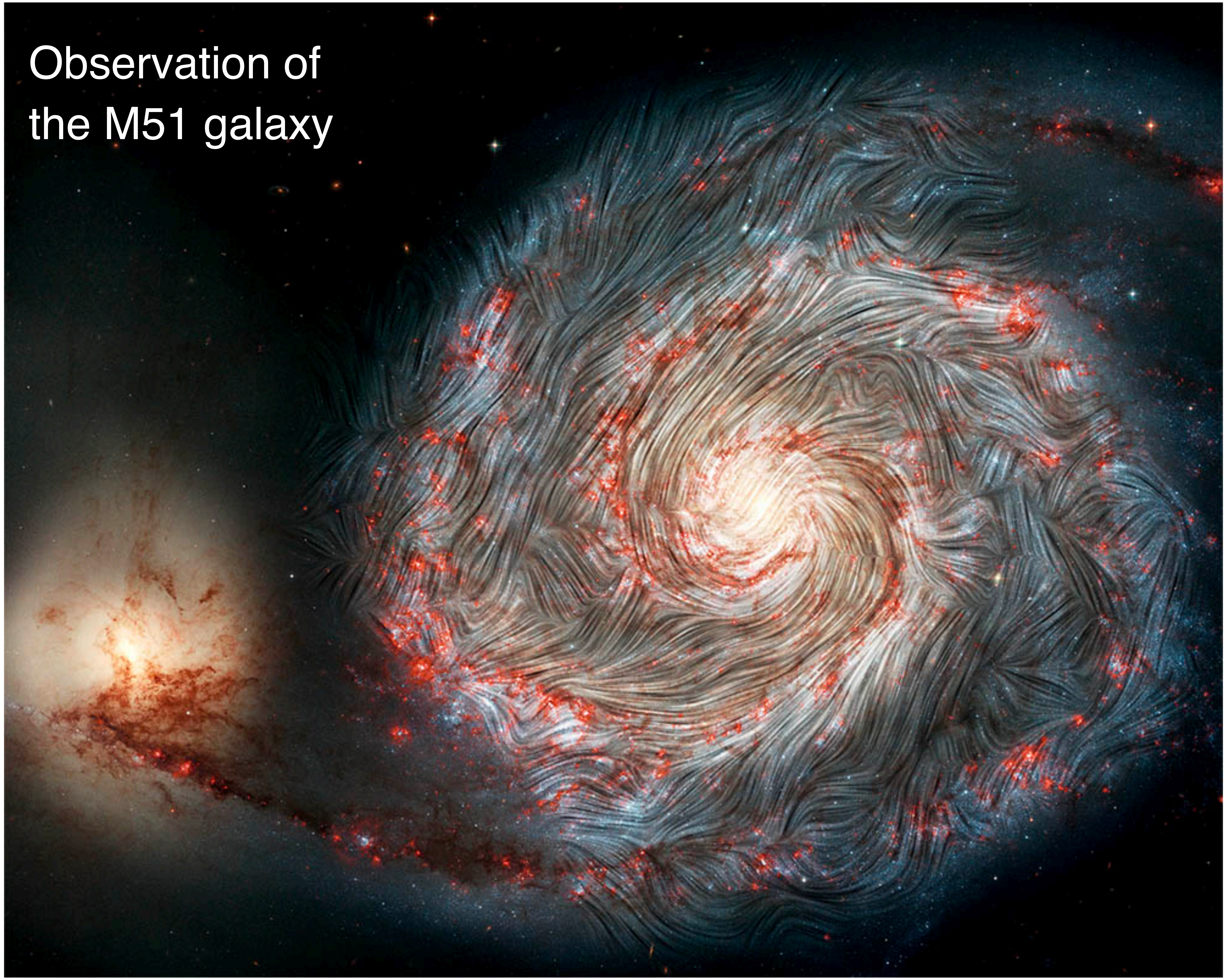
Contours of magnetic fields that emerge a result of self-organization of microscopic currents resulting from the Weibel instability in a carbon dioxide laser-produced plasma probed by an ultrashort relativistic electron beam.

Image courtesy of Chaojie Zhang, University of California Los Angeles

The origin of galactic magnetic fields



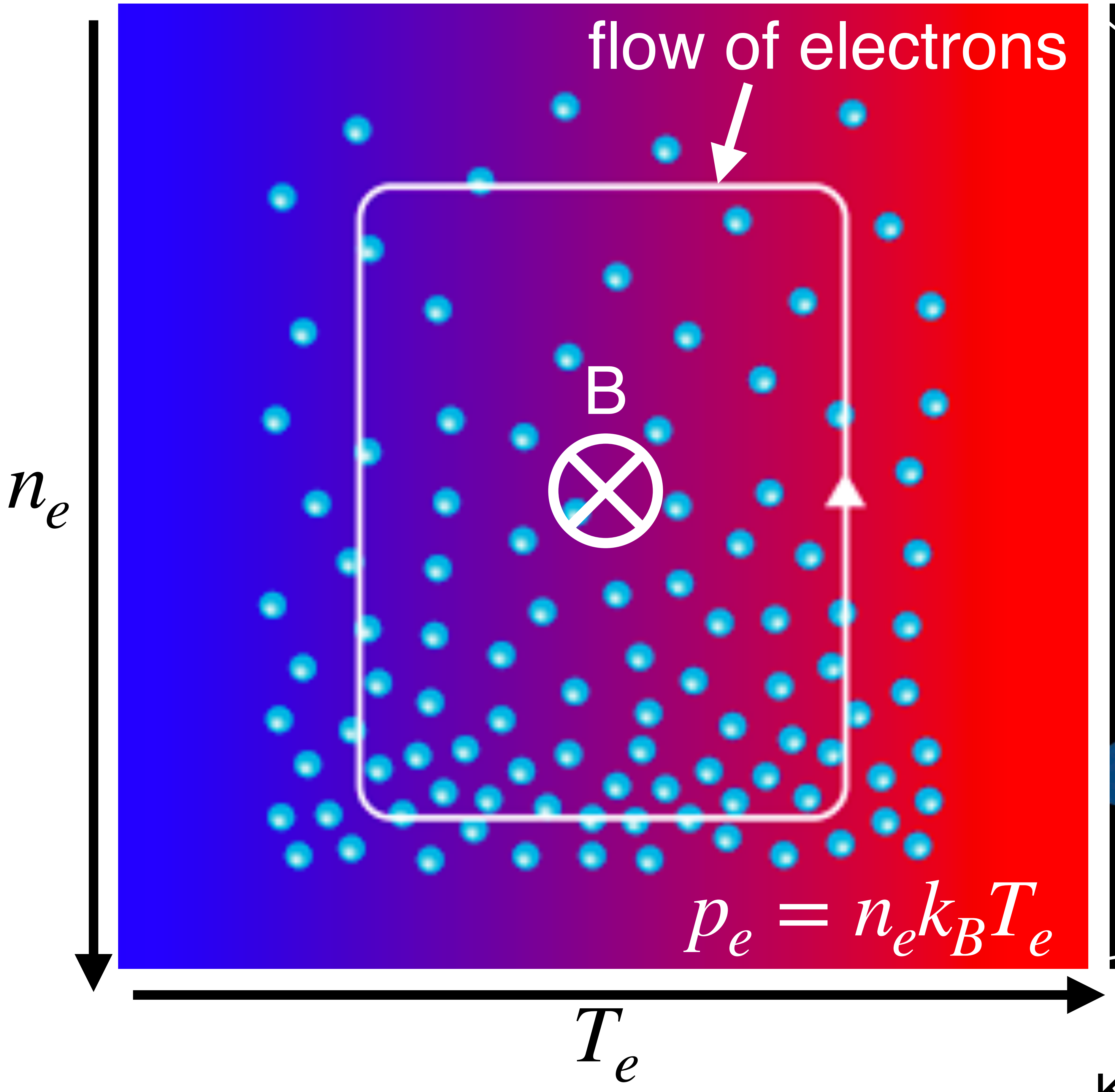
Observation of the M51 galaxy

- Streamlines
  - ~μG magnetic fields detected by SOFIA
- Background
  - optical image taken by Hubble Space Telescope

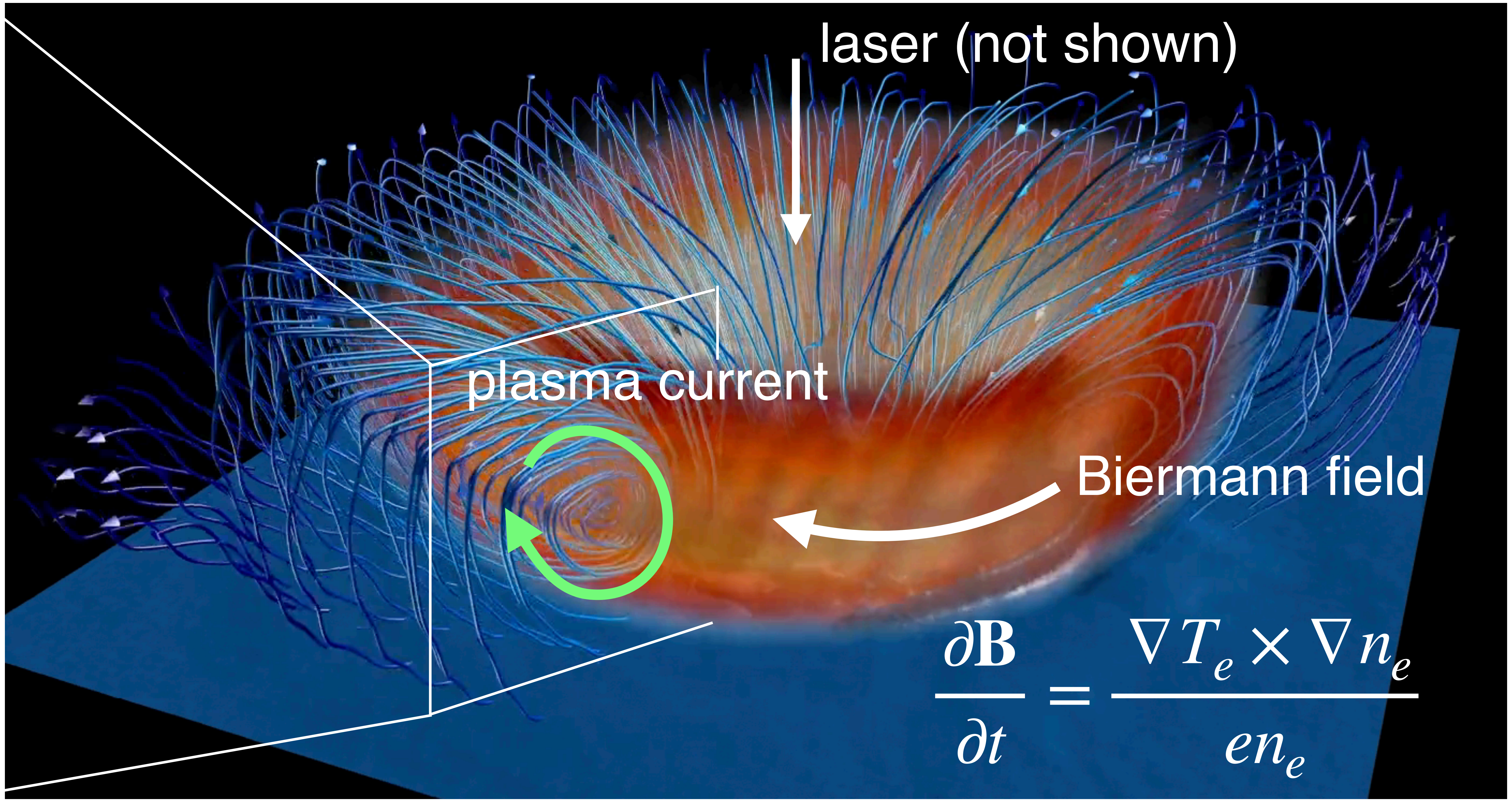
- **What is the origin of these fields?**
  - **Primordial** (fG - nG) + compression during structure formation (NOT our interest)
  - **Weak seeds by plasma mechanisms + dynamo amplification**
    - Weibel instability (AE98)
    - Biermann battery

Biermann battery effect

- Biermann battery: a process that can generate a weak seed magnetic field from zero initial condition discovered by German astronomer Ludwig Biermann in 1950.
- A possible source for seeding the galactic dynamo to created the observed ~μG B fields



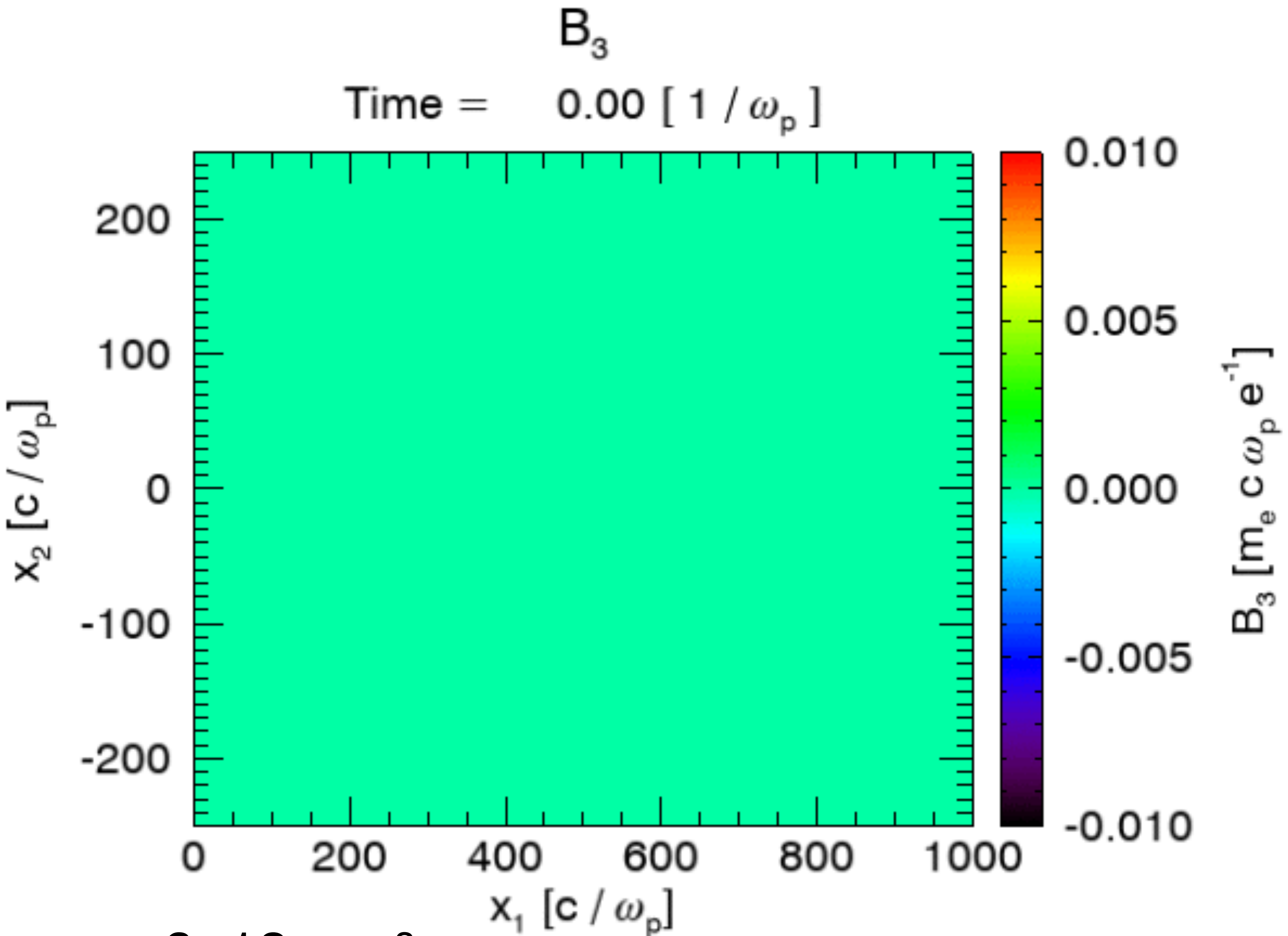
Ellen Zweibel, “The seeds of a magnetic universe." *Physics* 6 (2013)

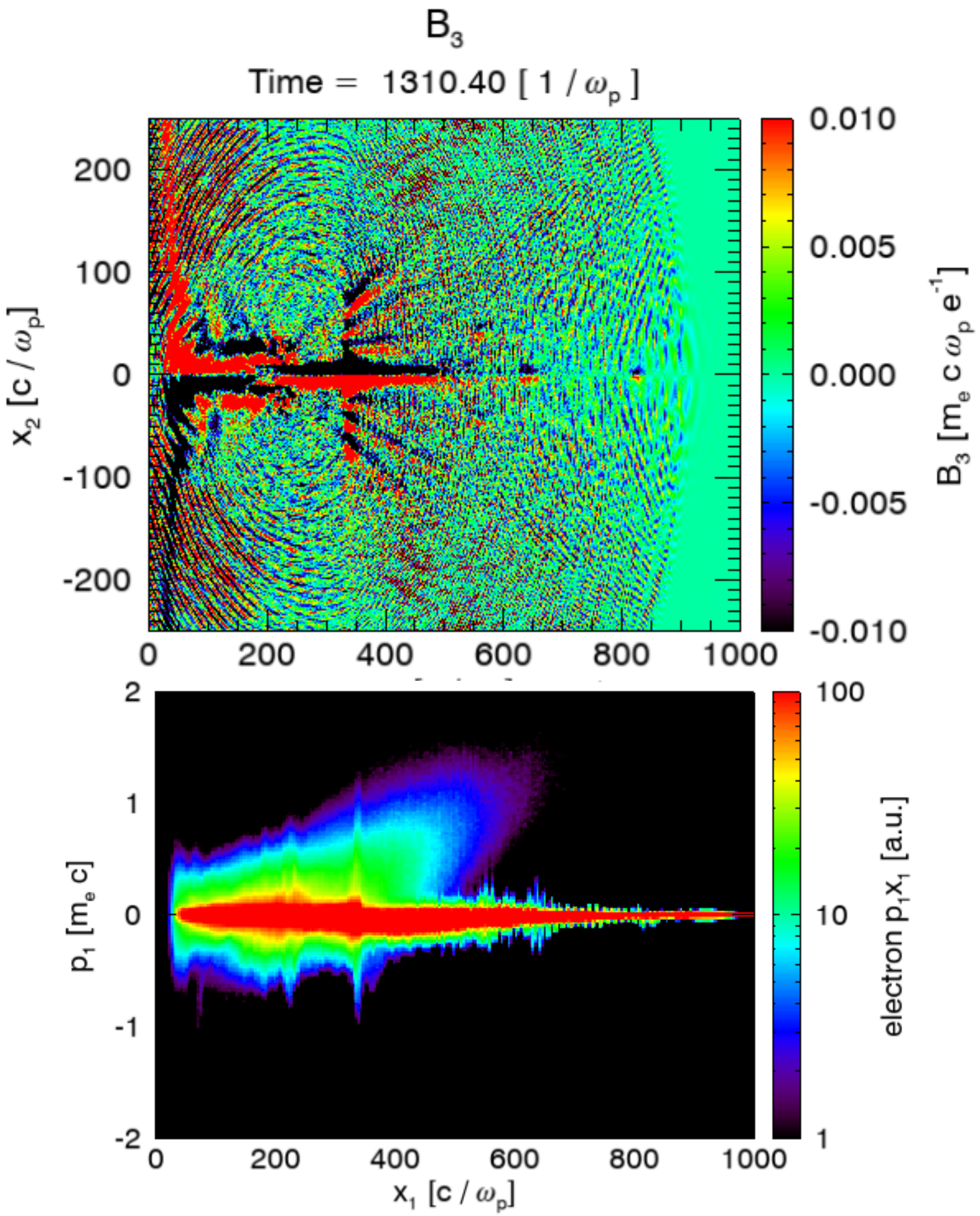


Kinetic simulation and visualization by the IST group; http://epp.tecnico.ulisboa.pt/fountain-currents-and-biermann-fields-at-target-surface/

Plan: Simultaneous measurement of Biermann and Weibel fields

2D simulation parameters:
laser: CO2, λ=10 μm, a0=0.6, w0=80 μm, s polarized
P=0.5 TW
plasma: cold hydrogen plasma





Quasi-relativistic CFI/Weibel instability

e- energy increasing →

non-relativistic CFI or Weibel instability
$E \lesssim 1\ \mathrm{keV}$

CFI/Weibel in optical-field ionized plasmas,

UCLA:
Zhang et al. Sci Advances (2019)
UCLA-ATF:
Zhang et al. PNAS (2022)

quasi-relativistic CFI
$E \sim 0.1 - 1\ \mathrm{MeV}$

UCLA-ATF:
CO2 interacting with near-critical-density plasmas
+
e- and/or optical probing

relativistic CFI
$E \sim 10 - 100\ \mathrm{MeV}$

Expt. done at ATF:
B. Allen el al, "Experimental Study of Current Filamentation Instability", PRL (2012)

ultra-relativistic CFI
$E = 10\ \mathrm{GeV}$

E305 at Facet-II
10 GeV dense e-beam interacts with foils

Summary of products delivered from the work to date

- **Conference**
  - Invited talk at the 63rd APS-DPP meeting (2021)
  - talk at the 64th APS-DPP meeting (2022)

- **Two Papers**
  - **Electron Weibel instability induced magnetic fields in optical-field ionized plasmas**, ***invited paper***, Physics of Plasmas 29, 062102 (2022), **Editor's pick**
  - **Mapping the self-generated magnetic fields due to thermal Weibel instability**, ***PNAS*** 119 (50) e2211713119 (2022), **Highlighted on the DOE website**

- See the next a few slides for the beam parameter requirements

Electron beam requirements

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	***50.5 MeV***
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	***<0.1 for best compression***
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to*	***<1 ps***
Transverse size at IP (s)	mm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	***>1 mm (horizontal)*** ***>0.5 mm (vertical)***
Normalized Emittance	mm	1 (at 0.3 nC)	*Variable with bunch charge*	***<1 mm mrad***
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	***1.5 Hz***
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	***single bunch***

CO_2 laser requirements

Configuration	**Parameter**	**Units**	**Typical**	**Comments**	**Requested Values**
CO_2 Regenerative Amplifier	Wavelength	mm	9.2	*Wavelength determined by mixed isotope*	***9.2 μm***
	Peak Power	GW	~3		***3***
	Pulse Mode	---	Single		***single***
	Pulse Length	ps	2		***2***
	Pulse Energy	mJ	6		***6***
	M^2	---	~1.5		***OK***
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	***OK***
	Polarization	---	Linear	*Circular polarization available at slightly*	***linear***
CO_2 CPA Beam	Wavelength	mm	9.2	*Wavelength determined by mixed isotope*	***9.2 μm***
Note that delivery of full power	Peak Power	TW	2	*~5 TW operation is planned for FY21*	***2***
	Pulse Mode	---	Single		***single***
	Pulse Length	ps	2		***2***
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will*	***<5***
	M^2	---	~2		***OK***
	Repetition Rate	Hz	0.05		***OK***
	Polarization		Linear	*Adjustable linear polarization along with circular polarization will become available in FY20*	***Linear***

Other Experimental Laser Requirements

Ti:Sapphire Laser System	**Units**	**Stage I Values**	**Stage II Values**	**Comments**	**Requested Values**
Central Wavelength	nm	800	800	*Stage I parameters have been delivered, while Stage II parameters will be available for user experiments once*	***800 nm***
FWHM Bandwidth	nm	20	13		***OK***
Compressed FWHM Pulse Width	fs	<55	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction*	***OK***
Chirped FWHM Pulse Width	ps	^{3}50	^{3}50		***OK***
Chirped Energy	mJ	>30	200		***Stage I OK***
Compressed Energy	mJ	>14	100		***Stage I OK***
Energy to Experiments	mJ	>10	>80		***<10 mJ***
Power to Experiments	GW	>250	>1067		***OK***

Nd:YAG Laser	**Units**	**Typical**	**2021**	**Comments**	**Requested Values**
Wavelength	nm	1064	1064	*Single pulse*	
Energy	mJ	5	100		
Pulse Width	ps	14	<20		
Wavelength	nm	532		*Frequency doubled*	
Energy	mJ	0.5			
Pulse Width	ps	10			

Special Equipment Requirements and Hazards

- **Electron beam**
  - same as AE99 except the location of the beam profile screen is different
- **CO_2 laser**
  - start with linear polarization (LP, p-polarized)
  - circular polarization is optional
- **Ti:Sapphire laser**
  - improved beam quality and pointing stability
- **Hazards and special Installation Requirements**
  - none

Experimental Time Request

CY2023 Time Request (3 weeks combined with AE99)

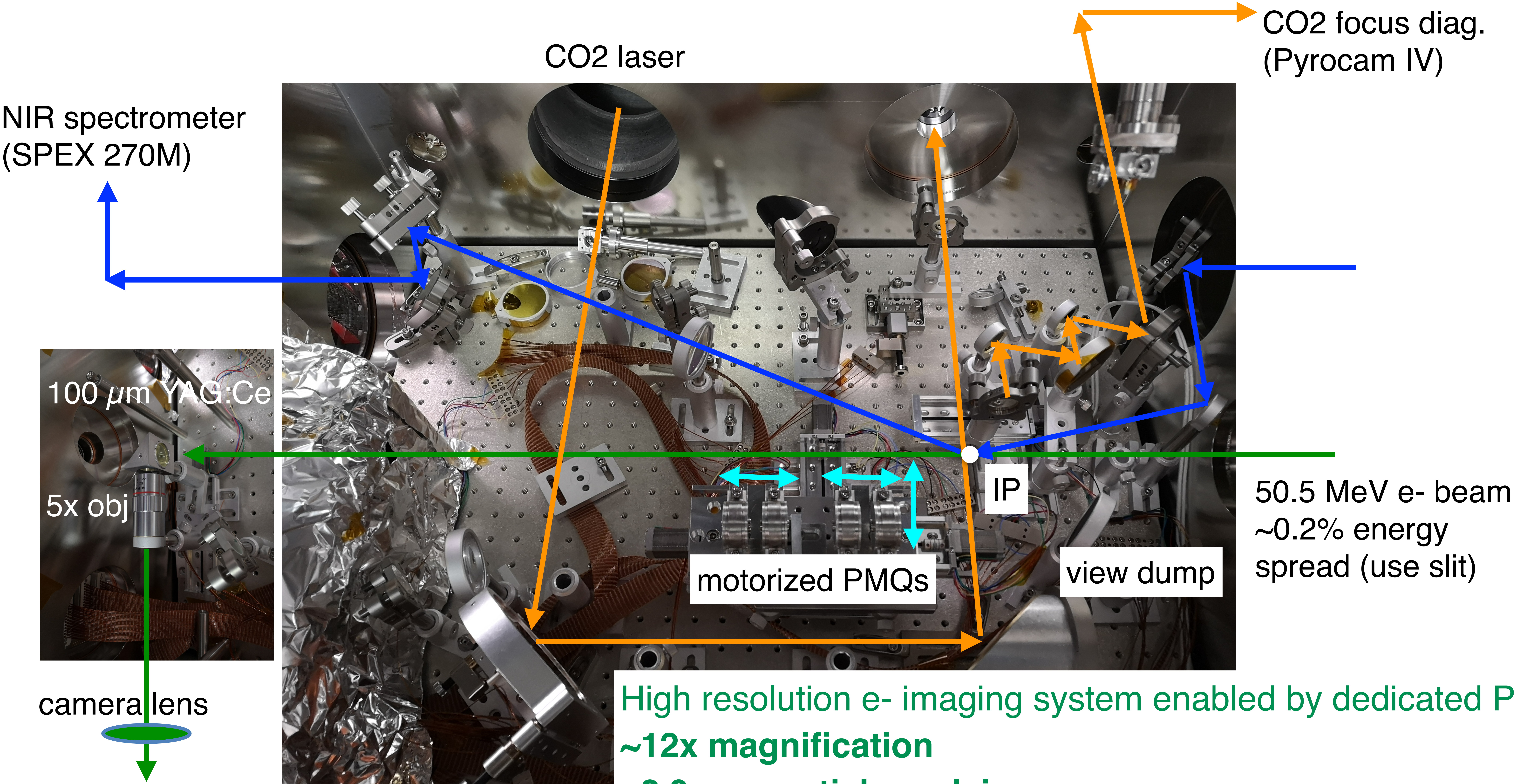
4 days setup, 11 days run

Capability	Setup Hours	Running Hours
Electron Beam Only	***16***	***24***
Laser* Only (in Laser Rooms)	***currently unknown***	***currently unknown***
Laser(s)* + Electron Beam	***16***	***64***

Time Estimate for Remaining Years of Experiment (6 weeks including FY2023)

Capability	Setup Hours	Running Hours
Electron Beam Only	***32***	***48***
Laser* Only (in FEL Room)		
Laser(s)* + Electron Beam	***32***	***128***

Experimental layout



CO2 laser

CO2 focus diag.
(Pyrocam IV)

NIR spectrometer
(SPEX 270M)

100 μm YAG:Ce

5x obj

camera lens

CCD (GPOP10)

IP

motorized PMQs

view dump

50.5 MeV e- beam
~0.2% energy
spread (use slit)

High resolution e- imaging system enabled by dedicated PMQs

~12x magnification

~2.9 μm spatial resolving power

(see more details in Yipeng's talk)