Probing electron Weibel instability in optical-field ionized plasmas (AE98)

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UCLA

Collaborators:

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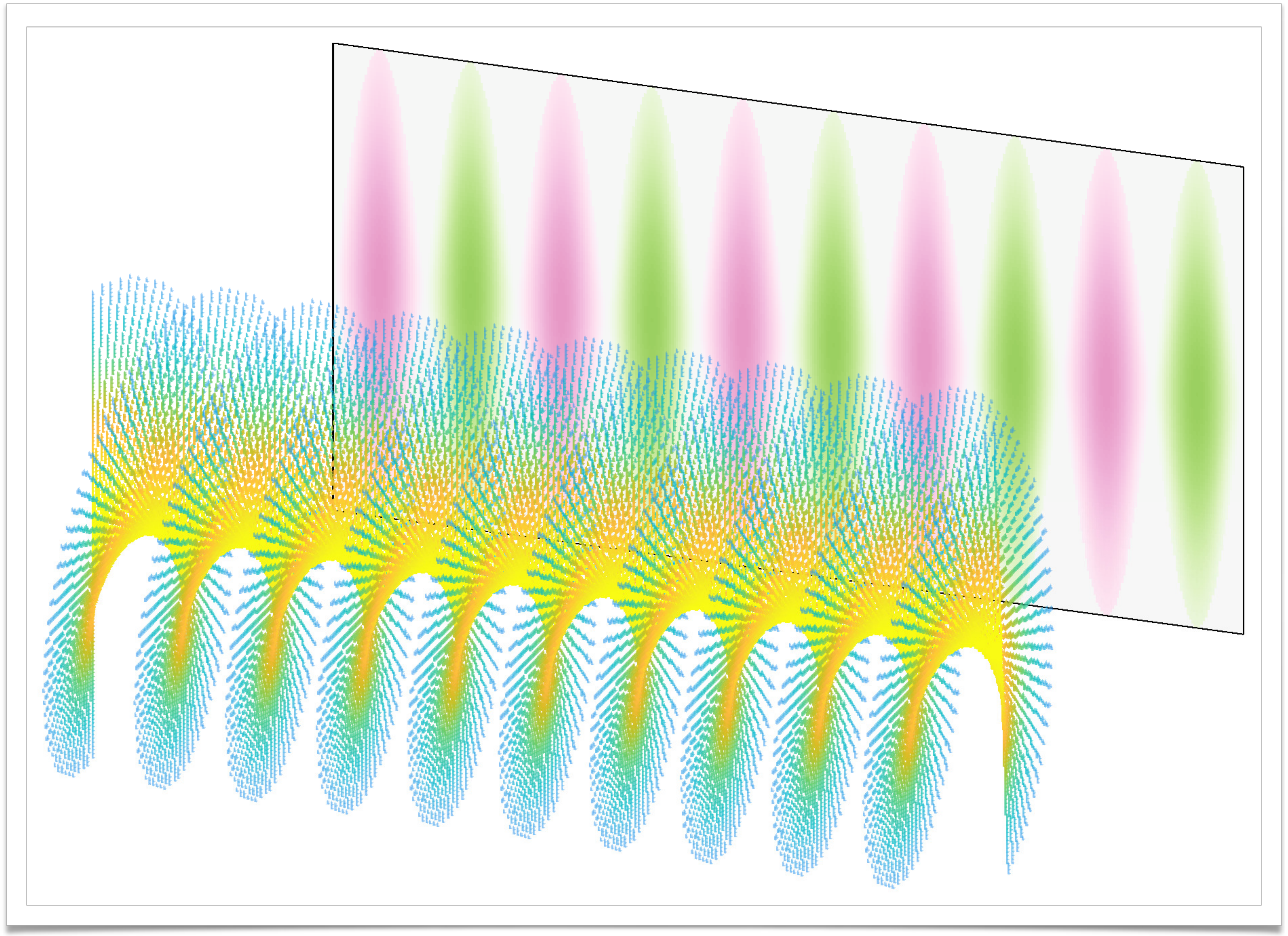

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UCLA Stony Brook University 清華大學 Tsinghua University

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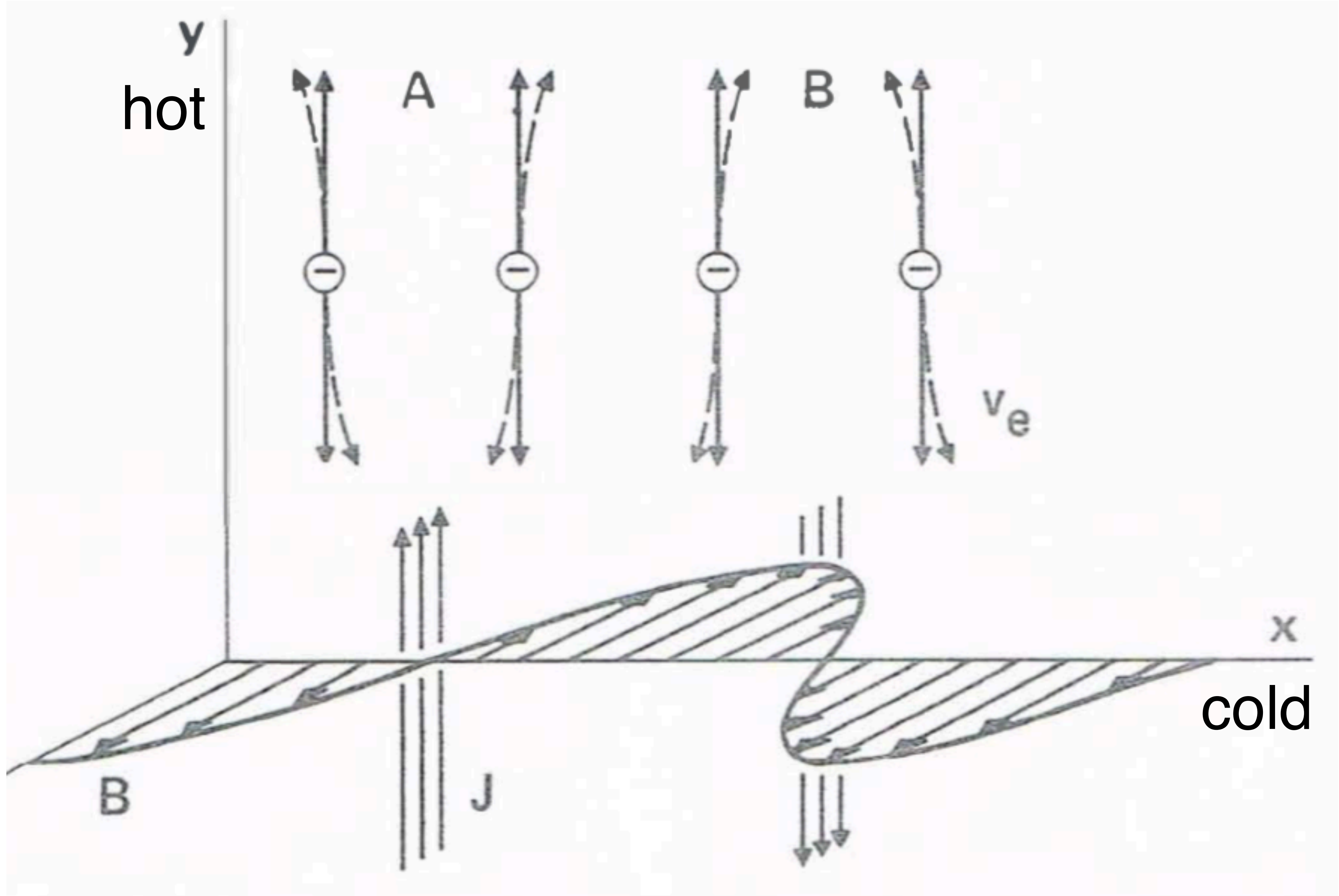
NSF U.S. DEPARTMENT OF ENERGY

Introduction: electron thermal Weibel instability

- Weibel instability is one of the earliest kinetic instability discovered in plasma theory (E. S. Weibel, 1959)

- It is driven by temperature anisotropy
- Relaxation of the anisotropic plasma causes self-organization (coalescence) of the currents which leads to the generation and amplification of magnetic fields
- It is primarily an electromagnetic mode
- Quasi-static B fields
- One of the major candidates responsible for seeding magnetic fields in laboratory and astrophysical plasmas

Many theoretical work; few experiments;



Physical mechanism of the Weibel instability.

- Initialize anisotropic EVD;
- Accurate measurement of B field (10s μm, ~Tesla, 10s ps)

Review of the proposal

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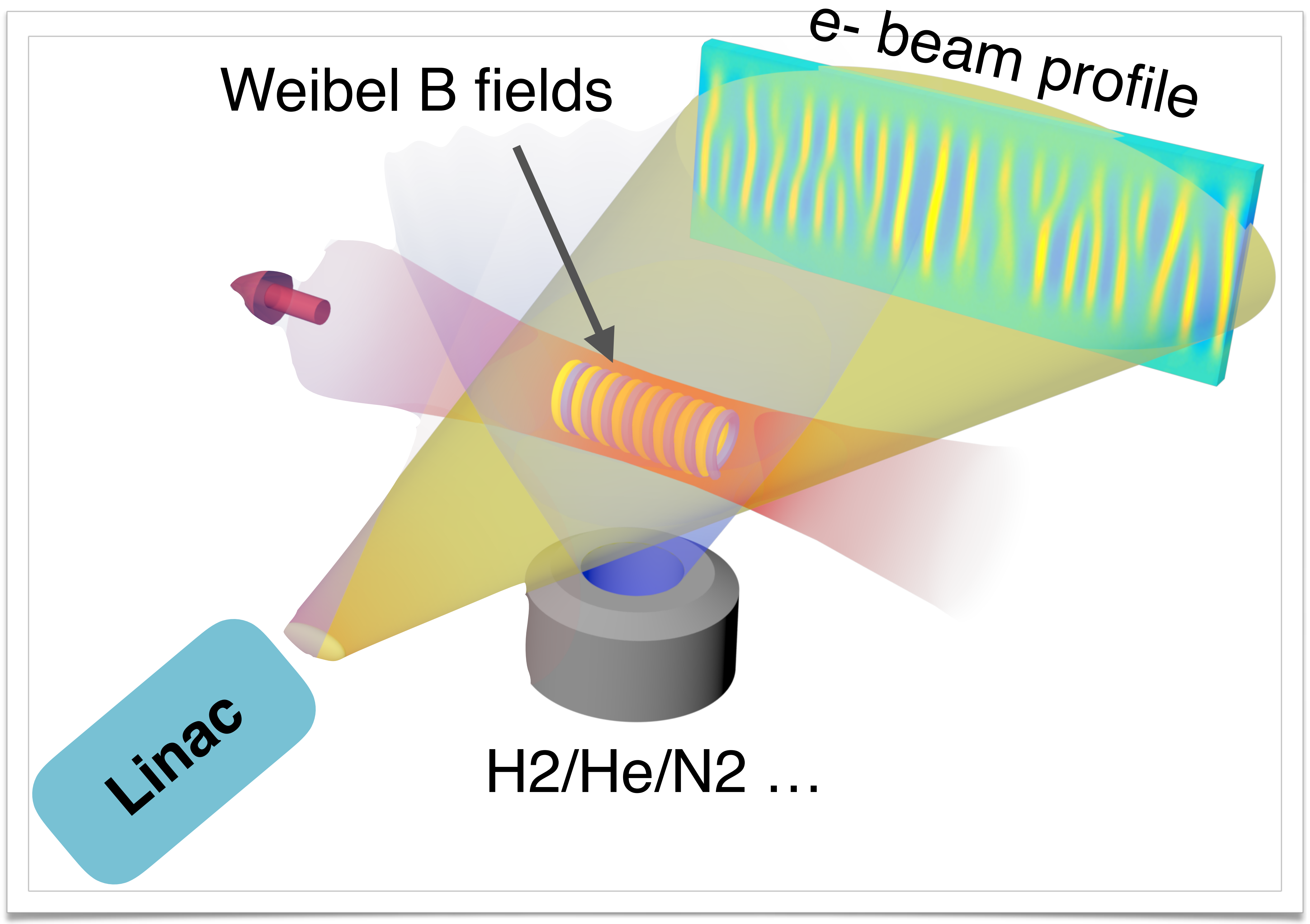
Sketch of the experiment



- CO2 laser: 1-2 TW, both LP and CP
- e- beam: 50-60 MeV, >0.1 nC, <0.3 ps, large spot size

- **Concepts:**
  - Initialize anisotropic plasmas using optical field ionization
  - Take snapshots of Weibel magnetic fields using e- beams
- **Physics we can explore:**
  - growth rate, k-spectrum evolution
  - different plasma temperatures/densities
  - effect of collisions
  - effect of finite width plasma
  - etc

Progress: proof-of-principle experiment performed (using a 0.8-μm laser driver and a 45-MeV electron probe)

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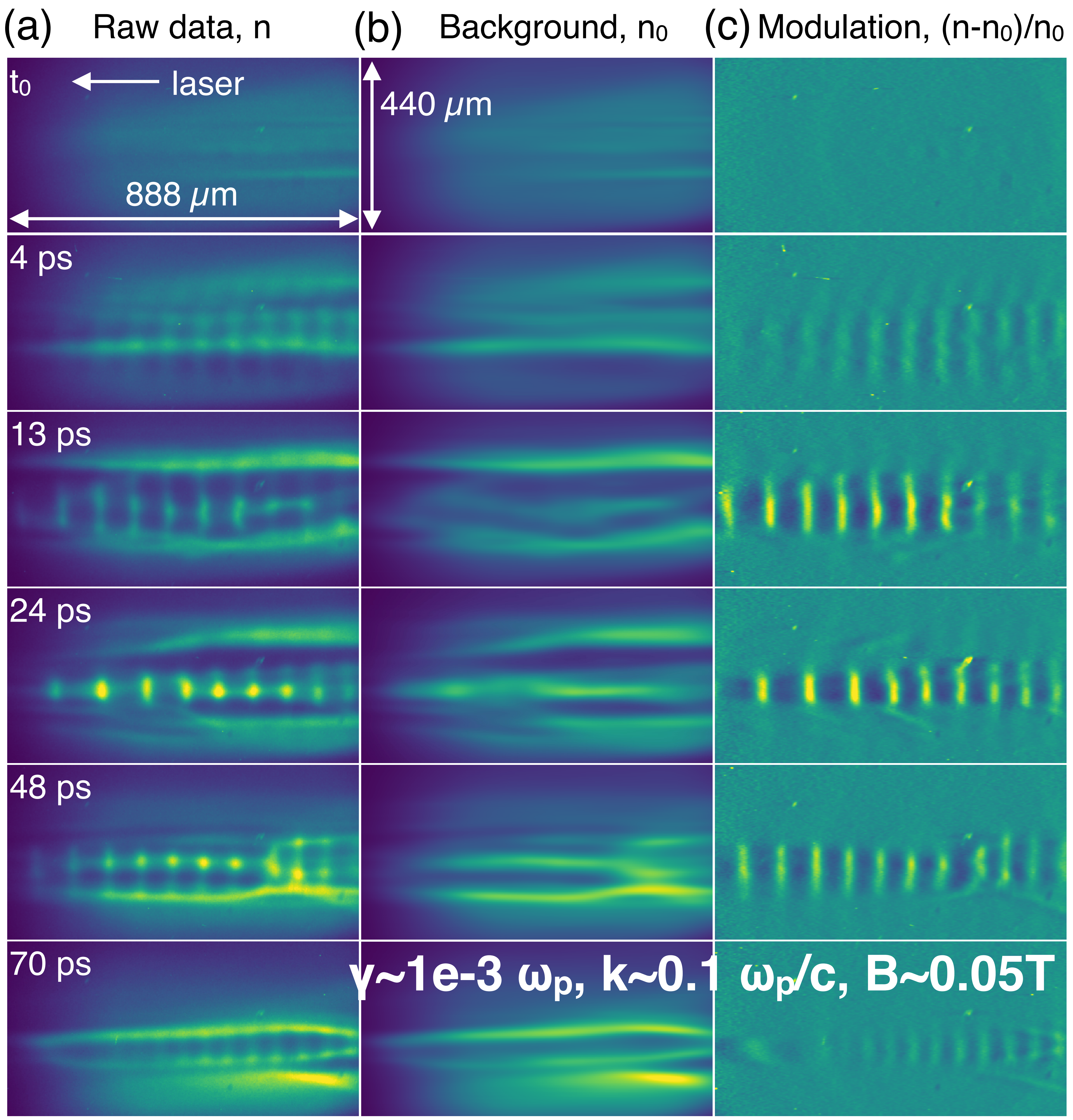
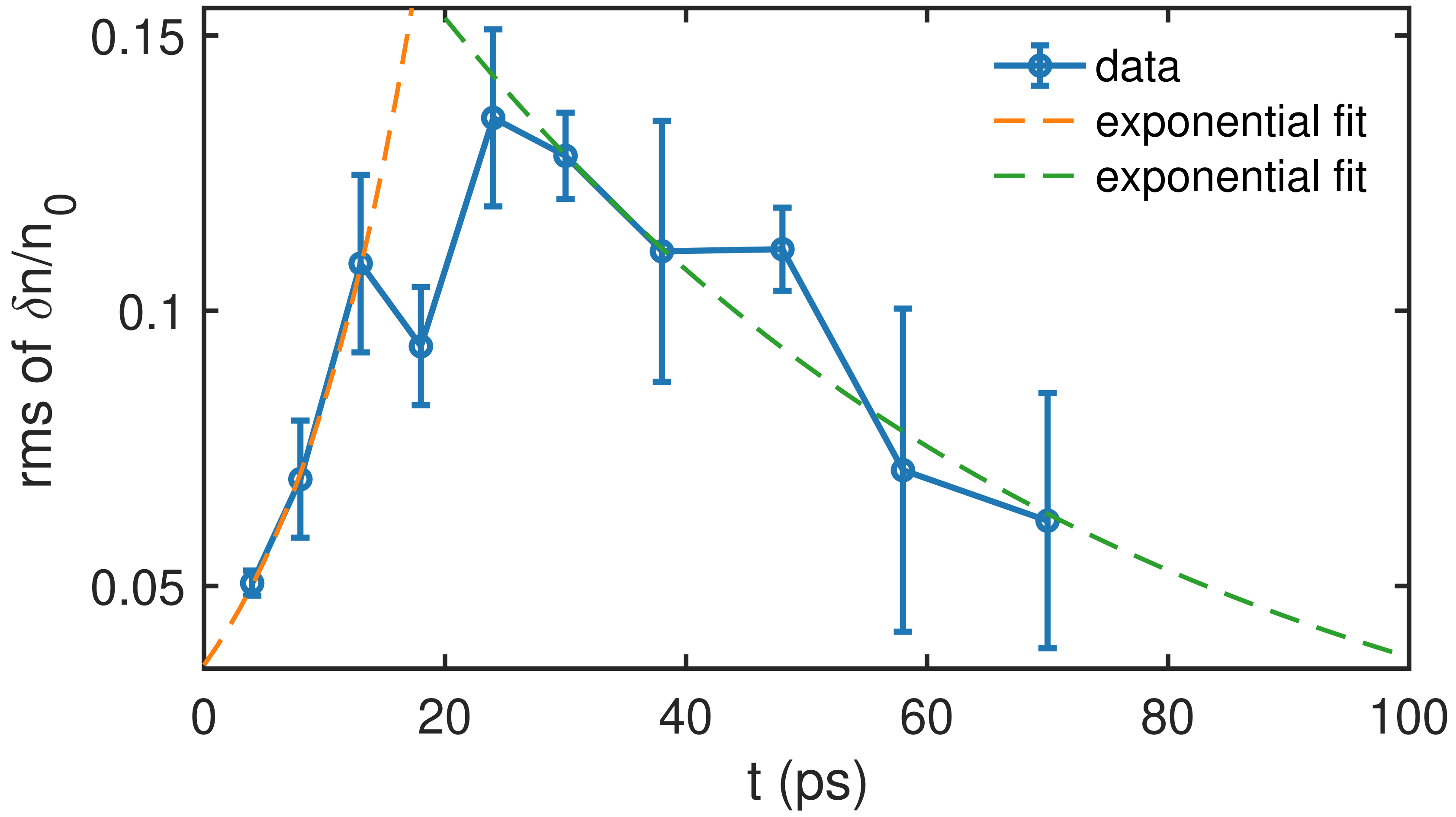


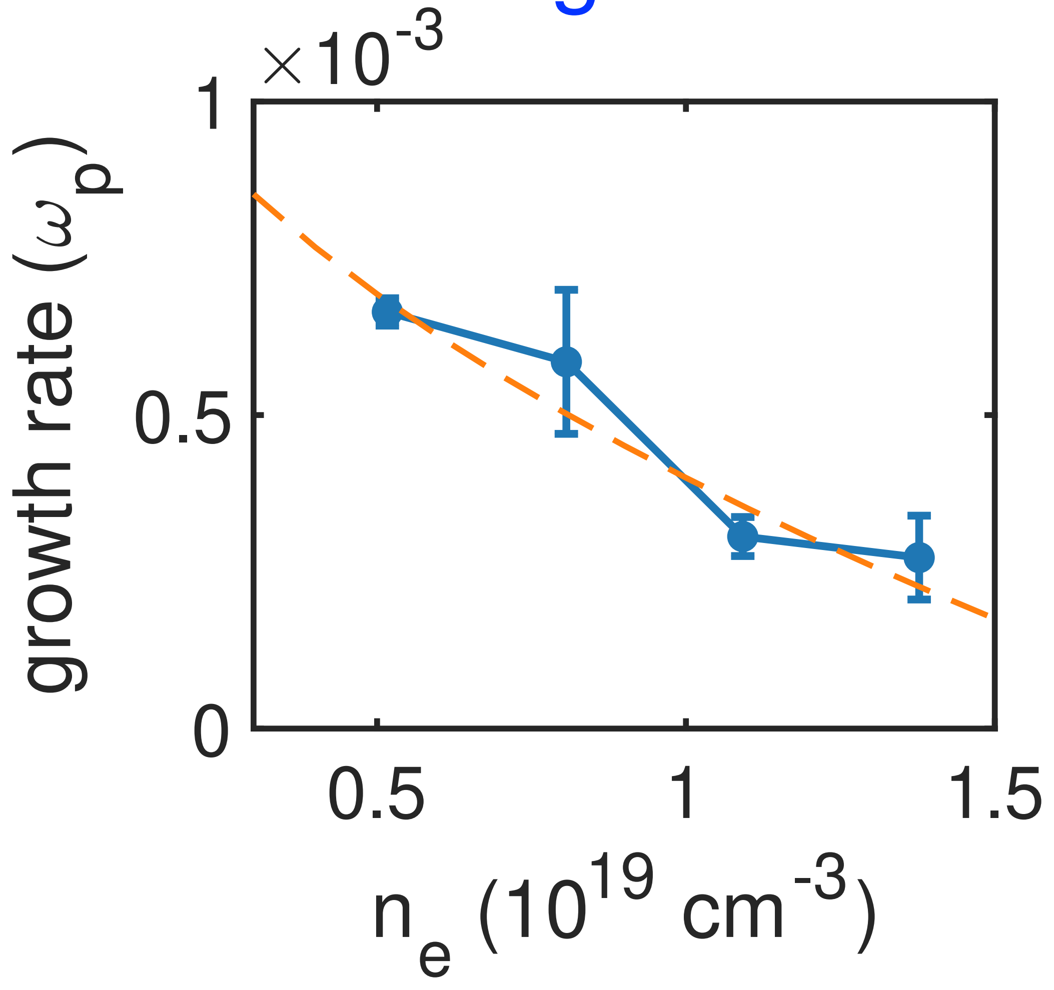
The paper has been accepted by PRL and is available at https://arxiv.org/abs/2011.09979

- **We have demonstrated the feasibility of the proposed experiment**

evolution Weibel B field



collisional growth rate



- **Major findings:**
  - confirmed existence of detectable Weibel magnetic fields in anisotropic OFI plasmas
  - measured the **collisional** growth rate (Te~260 eV, n_e~1e19 cm^{-3})
  - the quasistatic Weibel B field lasts for tens of ps

New physics expect to explore at ATF

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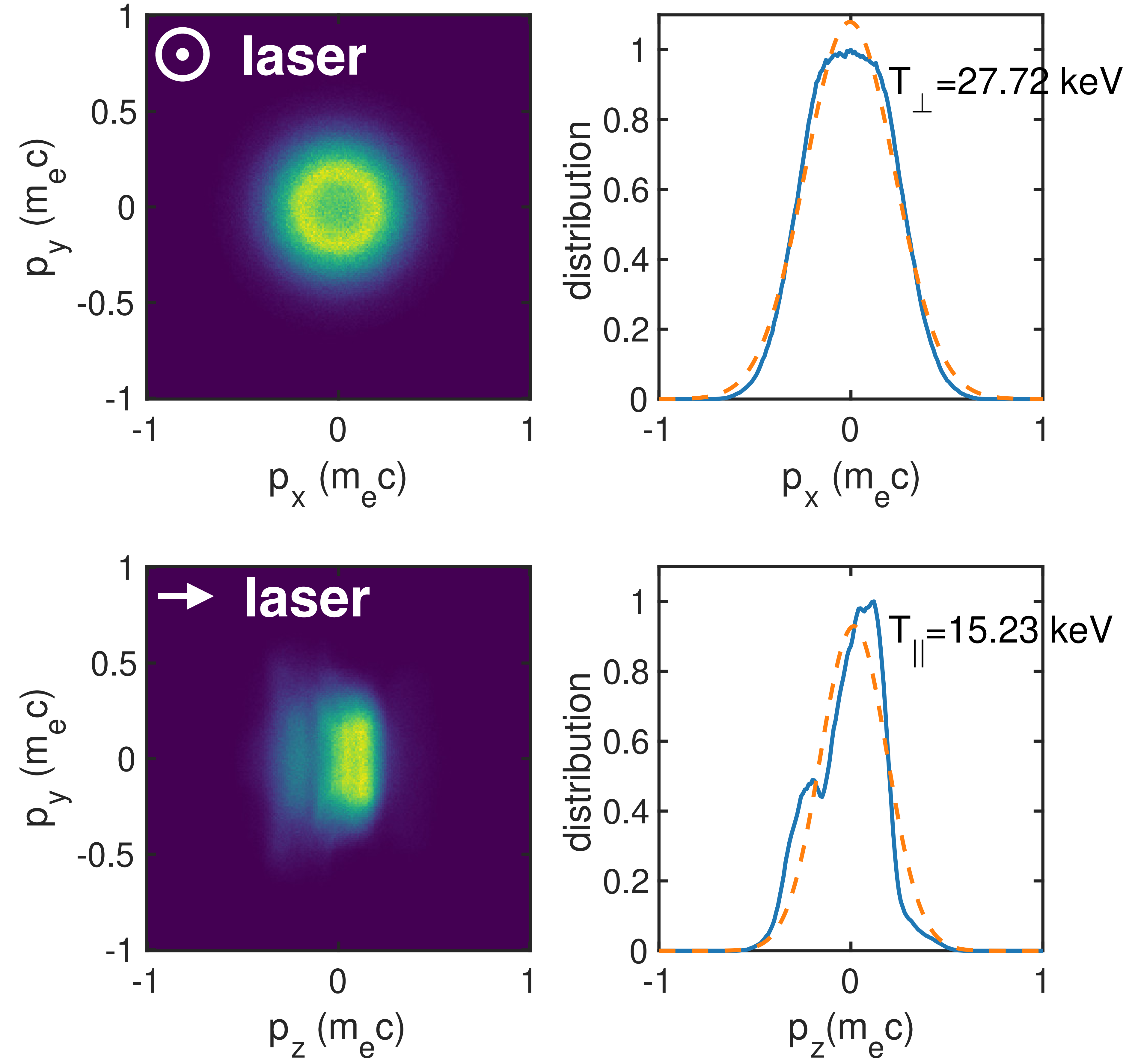
1) Collisionless, quasi-relativistic regime due to the much hotter CO_2-driven plasma ($I\lambda^2$ scaling)

EVD from self-consistent 3D PIC simulations

Laser: CO_2 laser, 3 ps (FWHM), w_0=50 μm, P=0.8 TW,
Peak intensity 2e16 W/cm² (CP), a0=0.86, ne=1e17 cm^{-3}



- **Plasma temperatures from 3D PIC simulations**

λ_0	τ	a_0	gas	T⊥ (keV)	T∥ (keV)
0.8 μm	50 fs	0.2	He	0.5	0.04
10 μm	3 ps	0.86	He	28	15
10 μm	3 ps	1.22	N2	16.5	17.1
10 μm	3 ps	0.1	H2	1.5	0.3
10 μm	0.3 ps	0.86	He	47	8

New physics expect to explore at ATF

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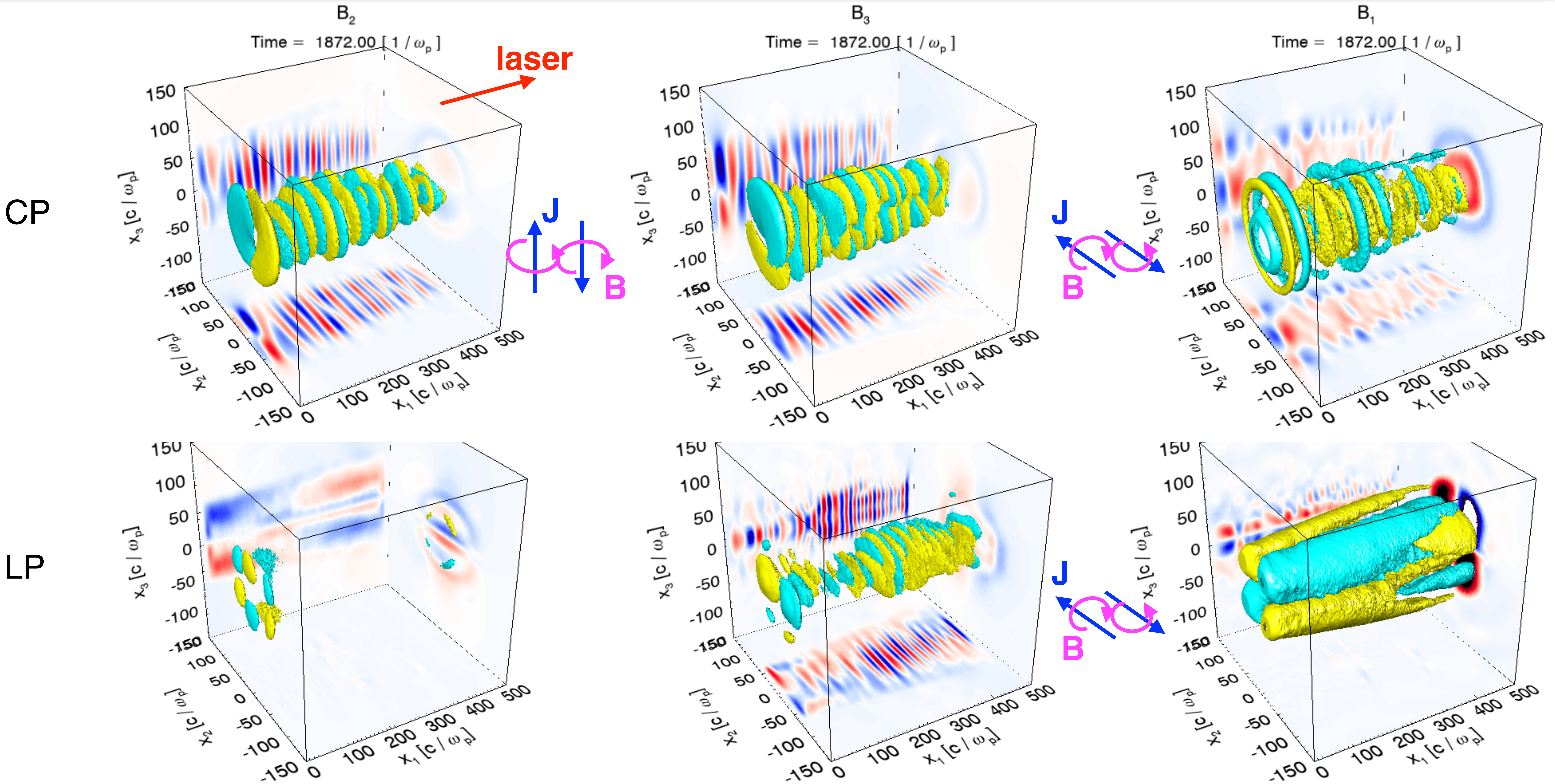
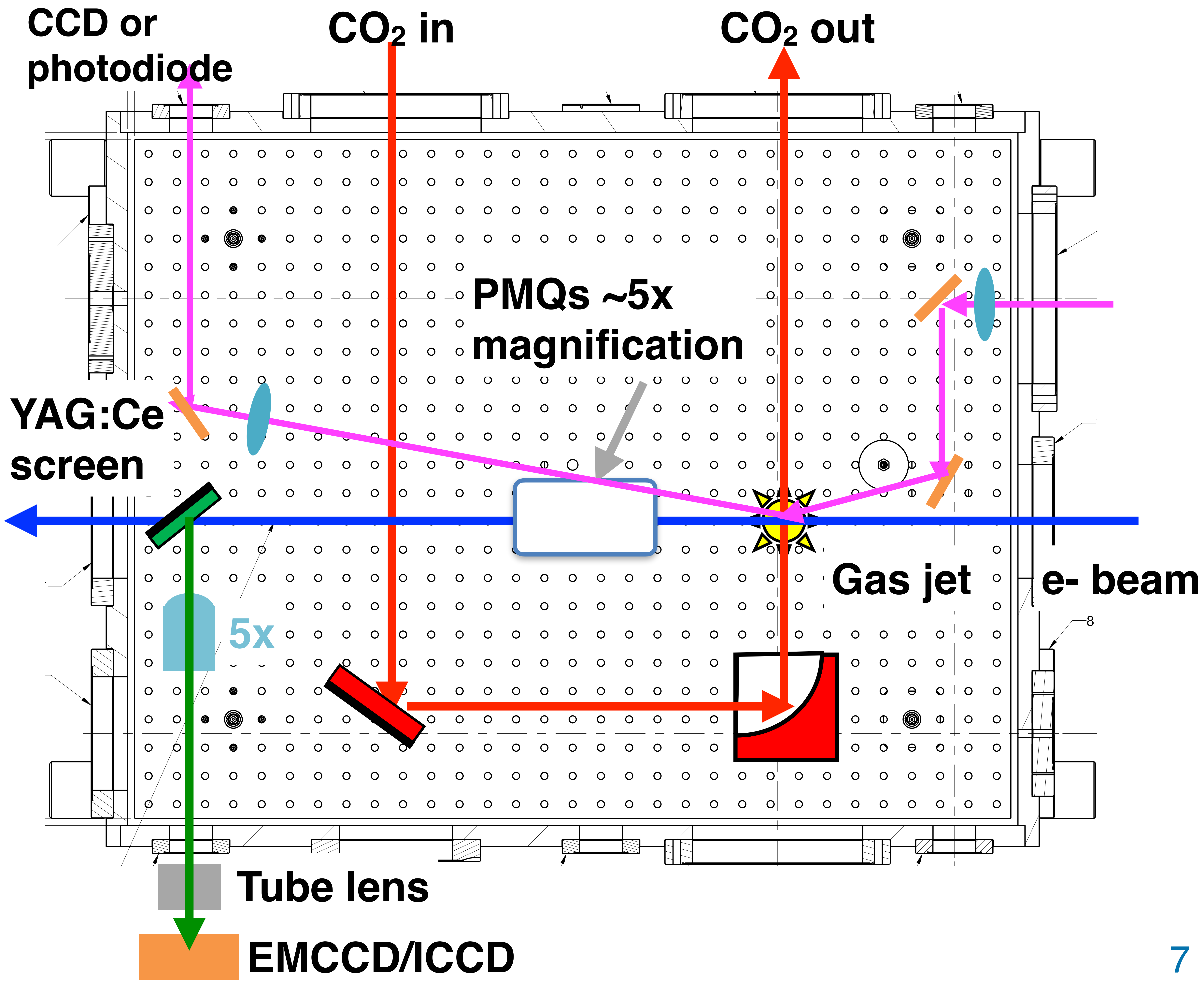
2) dependence of the B field topology on anisotropy (controlled by CO_2 laser polarization)



Experimental layout with upgraded diagnostics

- **Compatible with AE93 and AE99**
- **upgraded diagnostics**
  - a compact PMQ-based imaging system for the e- probe
  - Thomson scattering to measure possible (ion) density fluctuation associated with the B field (also useful for AE99)

Requirements at the IP:	
e- beam	*CO_2 laser*
E=60 MeV	*P~1-2 TW*
τ<0.2 ps	*τ~2-3 ps*
Q>50 pC	*w0~50-200 μm*
εn<10 mm.mrad	*Jitter<0.3 ps*
σr~1 mm	***LP and CP (reduced power <0.5TW is OK)***



Upgraded probing technique: PMQ-based electron imaging

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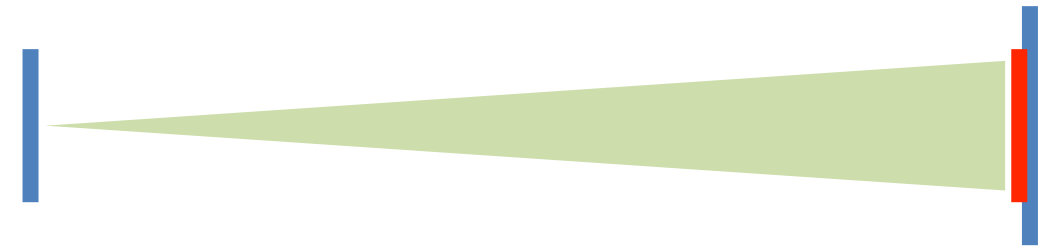


plasma detector

shortest wavelength observed in the experiment: ~30 μm

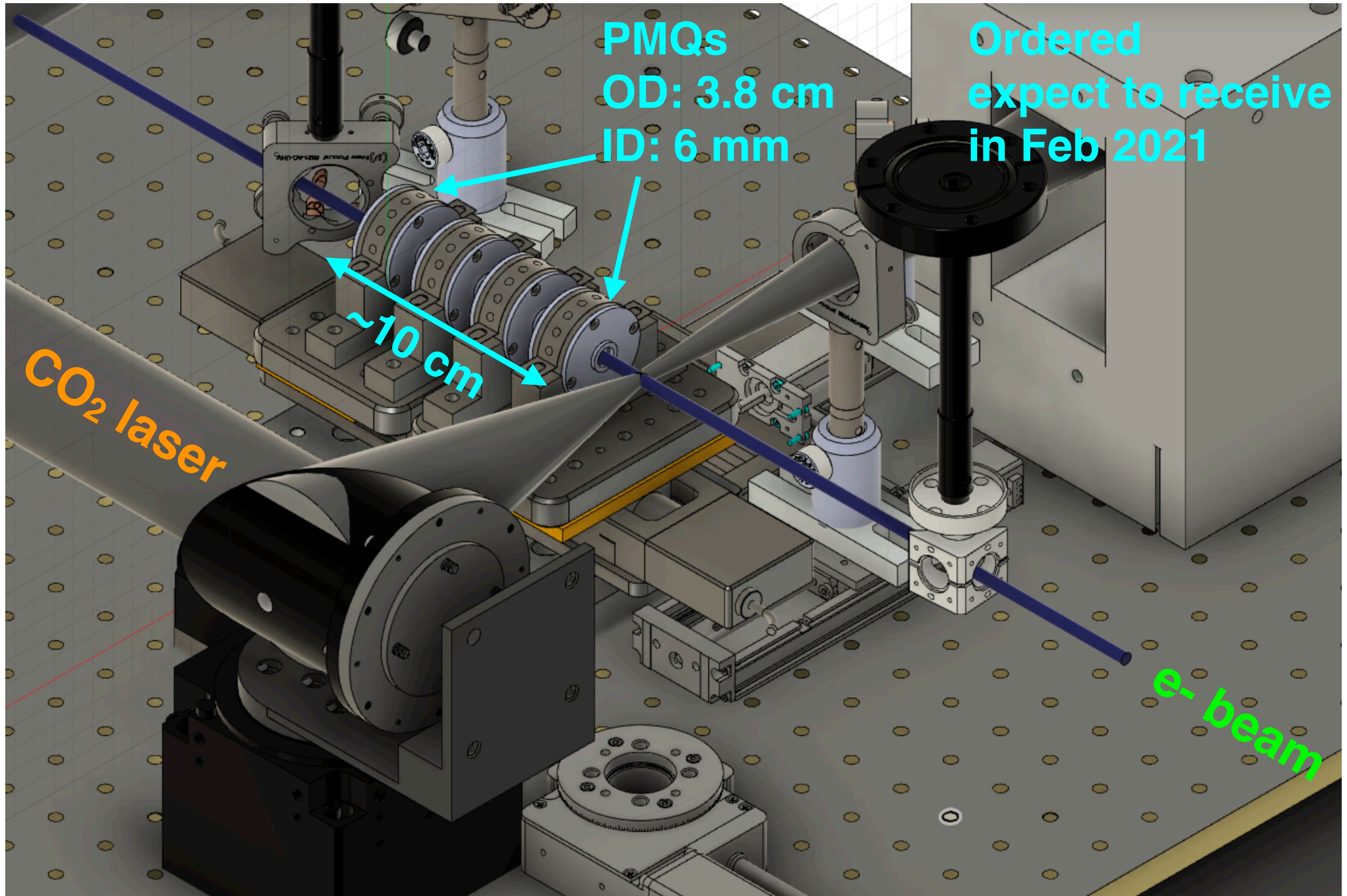
a PMQ system is useful for measuring stronger magnetic fields with shorter wavelength, therefore useful for both AE98 and AE99.

object plane

plasma PMQ detector

(permanent magnet quadrupoles)

- 2D point-to-point imaging
- 5-10x magnification
- allow to put the object plane very close (overlap) to the plasma to measure stronger fields (also useful for AE93)



CAD drawing of the PMQs (designed by Dr. Yipeng Wu)

Summary: goals for the first run and timeline

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- **Repeat the proof-of-principle experiment with focuses on**
  - measure the evolution of the B field in the collisionless, quasi-relativistic regime
  - show the magnetic field topology of LP case (and its dependence on polarization if CP is available)
  - resolve shorter wavelength using the PMQs (this may enable us to observe the initial broad k spectrum predicted by kinetic theory)

- **Timeline**
  - Now — March 2021, testing of diagnostics (e.g., PMQ) at UCLA
  - Now — May 2021, discussions with Navid and ATF staff to sort out the installation plan
  - run plan: see Chan’s talk

2020 Activities & Impacts Associated with this Experiment

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- Experiment officially approved in June 2020
- A proof-of-principle experiment using 0.8-μm laser performed
- Manuscripts
  - The results of the proof-of-principle experiment is available at
  - https://arxiv.org/abs/2011.09979 **(accepted by PRL)**

COVID-19 Pandemic Impacts

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- Travel to ATF was not possible
- Established collaboration with local user team (Navid's group and the ATF staff)
- Simulation work continued
- Hardware development (in house) continued

Electron beam requiremnets

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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*	***50-60 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* [illegible]	***<0.5 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

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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 and Circular (OK to reduce power)***

Near IR Experimental Laser Requirements

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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

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- **Electron beam**
  - save as AE93 and AE99 except the location of the beam profile screen is different
  - likely to bring in a compact assembly of permanent magnet quadrupoles
- **CO_2 laser**
  - can start with linear polarization (LP) but circular polarization (CP) is highly desired
  - ok to reduce the power to <0.5 TW for CP
- **Ti:Sapphire laser**
  - need to be synchronized to the CO2 laser and e- beam
- **Hazards and special Installation Requirements**
  - none

Experimental Time Request

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CY2021 Time Request (combined with AE99)

Capability	Setup Hours	Running Hours
Electron Beam Only	***30***	***30***
Laser* Only (in Laser Rooms)	***currently unknown***	***currently unknown***
Laser(s)* + Electron Beam	***15***	***90***

Time Estimate for Remaining Years of Experiment (including FY2021)

Capability	Setup Hours	Running Hours
Electron Beam Only	***50***	***60***
Laser* Only (in FEL Room)		
Laser(s)* + Electron Beam	***40***	***250***