Workshop Magnetic Fields in Laboratory High Energy Density Plasmas (LaB)

Low-beta Magnetic Reconnection Experiments Driven by Intense Lasers

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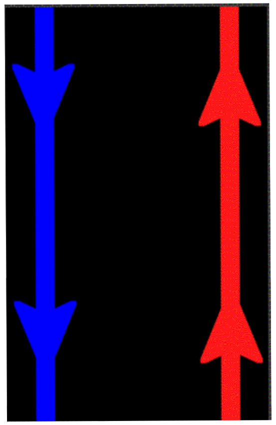
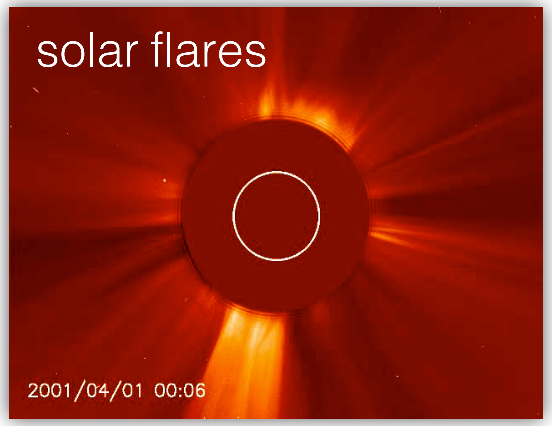
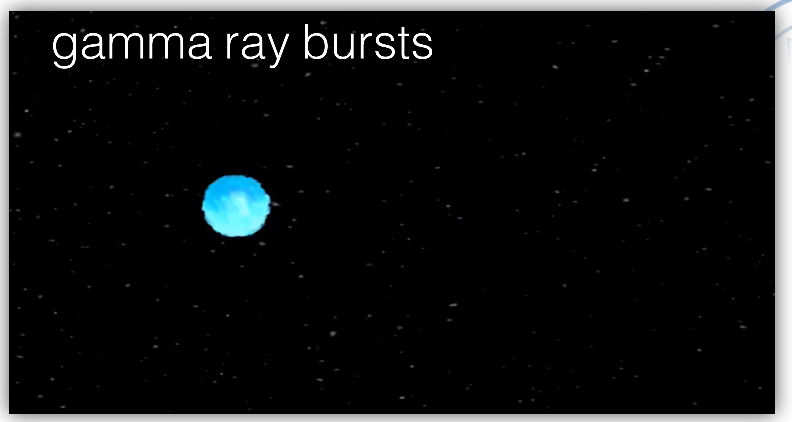
Magnetic Reconnection







Magnetic reconnection is a fundamental feature of astrophysical and laboratory plasmas, which creates a sudden release of magnetic energy, occurs in solar flares, Earth's magnetosphere, gamma ray bursts, and laboratory-produced fusion plasma et al.

Many Fundamental Reconnection Problems are still open…

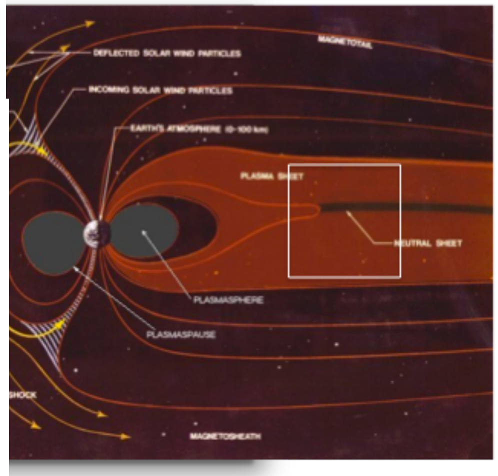
- How is reconnection rate determined? **(The rate problem)**
- How does reconnection take place in 3D? **(The 3D problem)**
- How does reconnection start? **(The onset problem)**
- How are particles energized? **(The energy problem)**
- How do boundary conditions affect reconnection process? **(The boundary condition problem)**
- How does reconnection take place in relativistic and strongly magnetized plasmas? (**The relativity problem)**
- How to apply local reconnection physics to a large system? **(The scaling problem)**

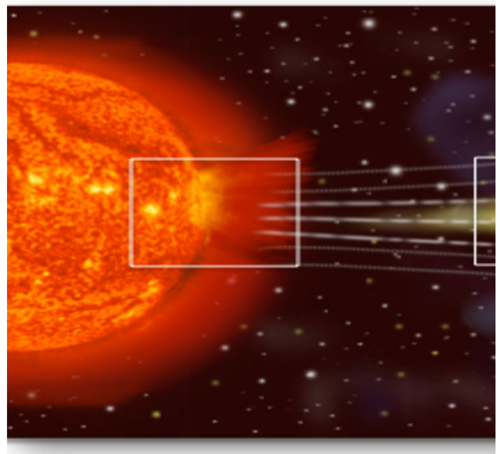
Plasma Beta

The **beta** of a plasma, symbolized by β, is the ratio of the plasma pressure to the magnetic pressure.

$$\beta = \frac{P}{B^2/2\mu_0} = 4.03 \times 10^{-11} n T B^{-2}$$

Location	Plasma	Size (m)	T_e (eV)	n_e (m^{-3})	B_T (Tesla)	S	λ	Notes	β
Lab	MRX[75]	0.8	10	1×10^{19}	0.1	3×10^{3}	1.5×10^{2}	$\epsilon=1/4, T_i=T_e/2, B_R=0.3B_T$	$4.03*10^{-3}$
	VTF[14]	0.4	25	1.5×10^{18}	0.044	3×10^{2}	4×10^{0}	$\epsilon=1/4, T_i=5$ eV, Ar^{+}	$7.806*10^{-3}$
	Laser plasma[76]	2×10^{-4}	10^{3}	5×10^{25}	100	2×10^{1}	1×10^{1}	$Al^{+13}, B_R=B_T$	2.015
	MST[77]	1.0	1.3×10^{3}	9×10^{18}	0.5	3×10^{6}	6.2×10^{1}	$T_i=350$ eV, $D^{+}, B_R=0.05B_T$	$1.88604*10^{-2}$
	TFTR[78]	0.9	1.3×10^{4}	1×10^{20}	5.6	1×10^{8}	2.3×10^{2}	$T_i=36$ keV, $D^{+}, B_R=0.01B_T$	$1.6706*10^{-2}$
	ITER[79]	4	2×10^{4}	1×10^{20}	5.3	6×10^{8}	5×10^{2}	$D^{+}, B_R=0.01B_T$	$2.86935*10^{-2}$
	NGRX[80]	1.6	25	1×10^{19}	0.5	1×10^{5}	1×10^{3}	$\epsilon=1/4, T_i=T_e/2, B_R=0.3B_T$	$4.03*10^{-4}$
Solar system	Magnetopause[81]	6×10^{7}	300	1×10^{7}	5×10^{-8}	6×10^{13}	9×10^{2}	$B_R=B_T$ (p. 267)	$4.836*10^{-1}$
	Magnetotail[81]	6×10^{8}	600	3×10^{5}	2×10^{-8}	4×10^{15}	1.3×10^{3}	$B_R=B_T, T_i=4.2$ keV (p. 233)	$1.8135*10^{-1}$
	Solar wind[81]	2×10^{10}	10	7×10^{6}	7×10^{-9}	3×10^{12}	2×10^{5}	(p. 92)	$5.757143*10^{-1}$
	Solar corona[81]	1×10^{7}	200	1×10^{15}	2×10^{-2}	1×10^{13}	4×10^{7}	(p. 79)	$2.015*10^{-4}$
	Solar chromosphere[82]	1×10^{7}	0.5	1×10^{17}	2×10^{-2}	1×10^{8}	3×10^{8}	Neutral particle effects are weak[82]	$5.0375*10^{-5}$
	Solar tachocline[83,84]	1×10^{7}	200	1×10^{29}	1	1×10^{9}	5×10^{10}		$8.06*10^{6}$
Galaxy	Protostellar disks[85]	9×10^{9}	3×10^{-2}	6×10^{8}	2×10^{-5}	8×10^{3}	1×10^{9}	$L=2h(R=1AU)$, e-n collisions included,[82] Mg^{+}	$1.8135*10^{-8}$
	X-ray binary disks[86,87]	4×10^{4}	75	1×10^{27}	36	3×10^{7}	9×10^{8}	$M=10M_{\odot}, L=2h(R=10^2R_S)$, $\alpha=10^{-2}, \dot{M}=10^{16}g/s$	$2.3323*10$
	X-ray binary disk coronae[88]	3×10^{4}	5×10^{5}	1×10^{24}	1×10^{4}	1×10^{16}	9×10^{7}	$M=10M_{\odot}, R=R_S, T_i=(m_p/m_e)T_e$, $\eta_{Compton}$ included (Ref. 88)	$2.015*10^{-3}$
	Crab nebula flares[89–91]	1×10^{14}	130	10^{6}	10^{-7}	5×10^{20}	2×10^{11}	Pair plasma, T from $B_R{}^2/2\mu_0=2nT$	$5.239*10^{-3}$
	Gamma ray bursts[92]	10^{4}	3×10^{5}	2×10^{35}	4×10^{9}	6×10^{17}	2×10^{16}	Pair plasma	$1.51125*10^{-3}$
	Magnetar flares[92,93]	10^{4}	5×10^{5}	10^{41}	2×10^{11}	6×10^{16}	5×10^{17}	Pair plasma, SGR 1806-20	$5.0375*10^{-1}$
	Sgr A* flares[94,95]	2×10^{11}	7×10^{6}	10^{13}	10^{-3}	2×10^{24}	5×10^{8}	$L=2R=20R_S$	$2.821*10$
	Molecular clouds[96,97]	3×10^{16}	10^{-3}	10^{9}	2×10^{-9}	1×10^{11}	7×10^{12}	Neutral particle effects included,[82] HCO^{+}	$1.0075*10^{-1}$
	Interstellar media[96,97]	5×10^{19}	1	10^{5}	5×10^{-10}	2×10^{20}	1×10^{14}	$L=$ magnetic field scale height	$1.612*10^{-1}$
Extra-galactic	AGN disks[86,87,98]	2×10^{11}	24	8×10^{23}	0.5	2×10^{13}	1×10^{14}	$M=10^8M_{\odot}, L=2h(R=10^2R_S)$, $\alpha=10^{-2}, \dot{M}=10^{26}g/s$	$3.09504*10$
	AGN disk coronae[88]	3×10^{11}	5×10^{5}	1×10^{17}	4	10^{23}	3×10^{11}	$M=10^8M_{\odot}, R=R_S, T_i=(m_p/m_e)T_e$, $\eta_{Compton}$ included (Ref. 88)	$1.259375*10^{-3}$
	Radio lobes[69]	3×10^{19}	100	1	5×10^{-10}	2×10^{25}	8×10^{12}		$1.612*10^{-4}$
	Extragalactic jets[99]	3×10^{19}	10^{4}	3×10^{1}	10^{-7}	6×10^{29}	1×10^{14}	3C 303	$1.209*10^{-5}$
	Galaxy clusters[100]	6×10^{18}	5×10^{3}	4×10^{4}	2×10^{-9}	2×10^{25}	6×10^{11}	A1835	$2.015*10$

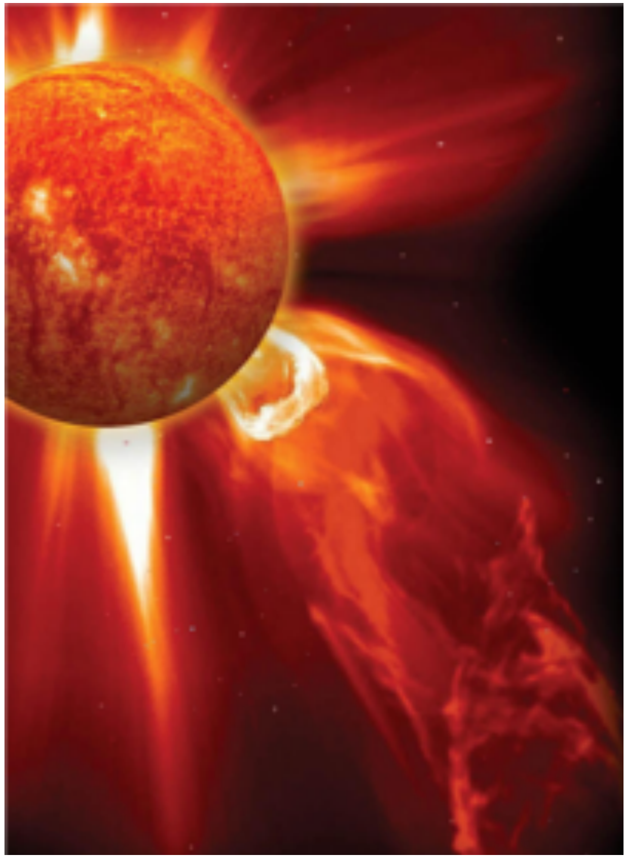


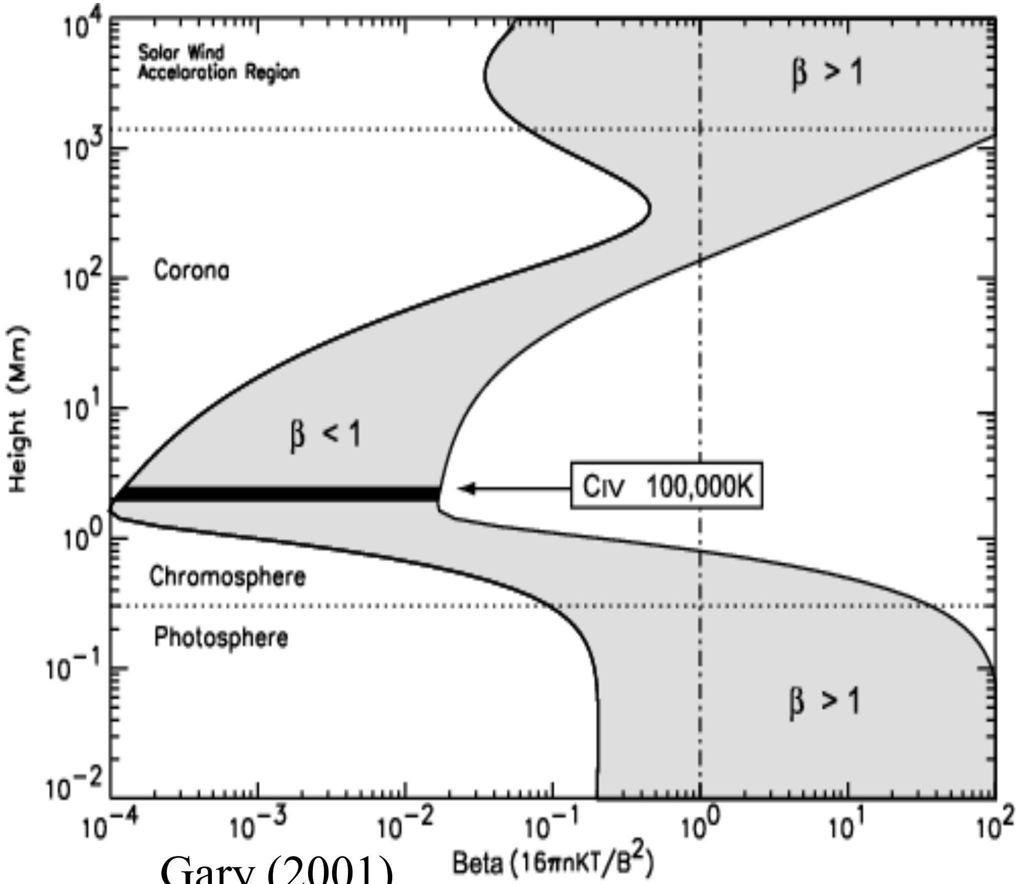


Ji, et al., 2011

Plasma beta in the solar atmos.

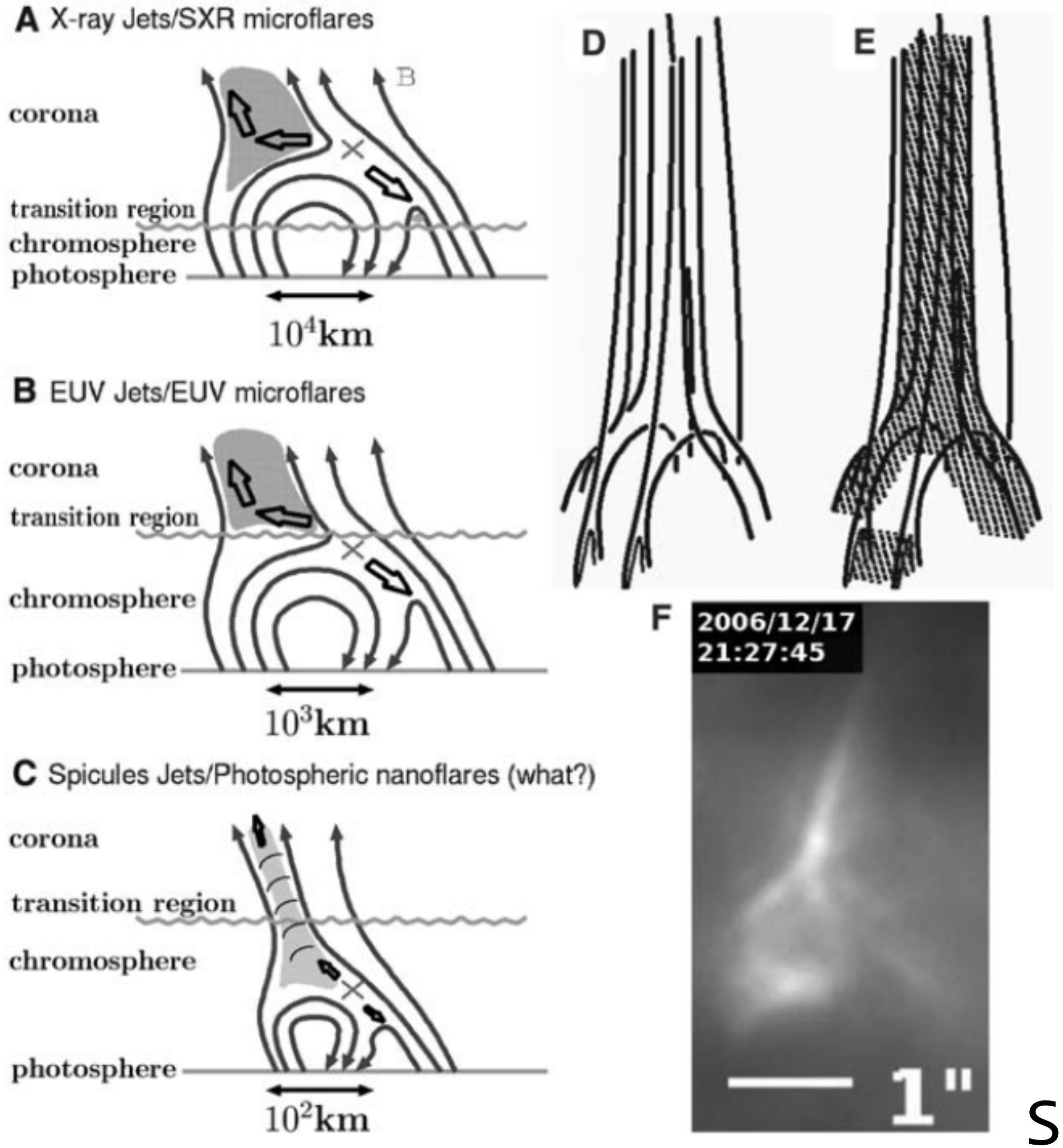
the plasma β value changes with height in the solar atmosphere. As one can see a region with β ≪ 1 is sandwiched between the photosphere and the upper corona, where β is about unity or larger.





Gary (2001).

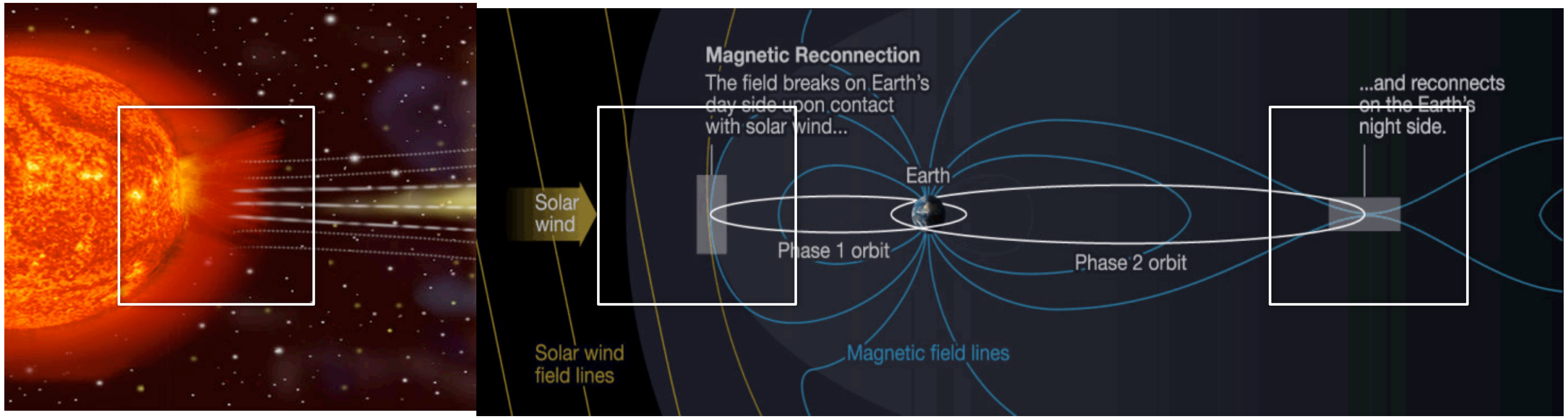
Schematic illustration of magnetic reconnections that occur at various altitudes



A model of Ca jets. (D) shows the three-dimensional magnetic-field configuration, and the hatched area in (E) shows the heated plasmas in the jet and bright point. (**F**)A typical example of an observed Ca jet.

Shibata (2007)

Magnetic reconnection in Earth's magnetoshpere

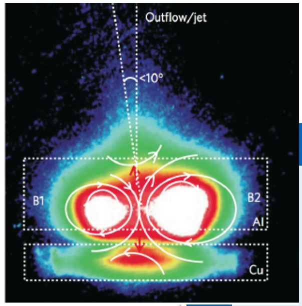


Magnetic reconnection occurs in two primary locations in Earth's magnetosphere in response to driving from solar wind, where β is about unity or smaller.

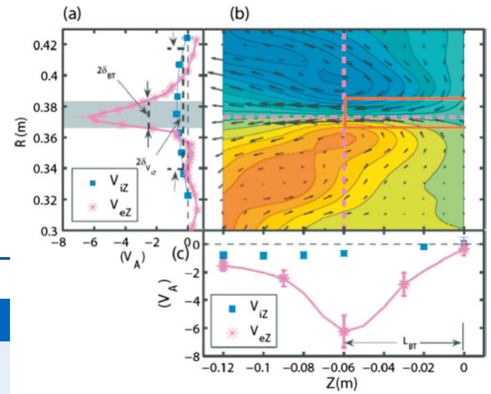
- Dayside magnetopause: solar wind plasma reconnecting with magnetospheric plasma
- Nightside Magnetotail: in response to magnetic energy building up in lobes due to solar wind driving

Why MR in laser Plasma

Solar Flares Reconnection models



Global



Local

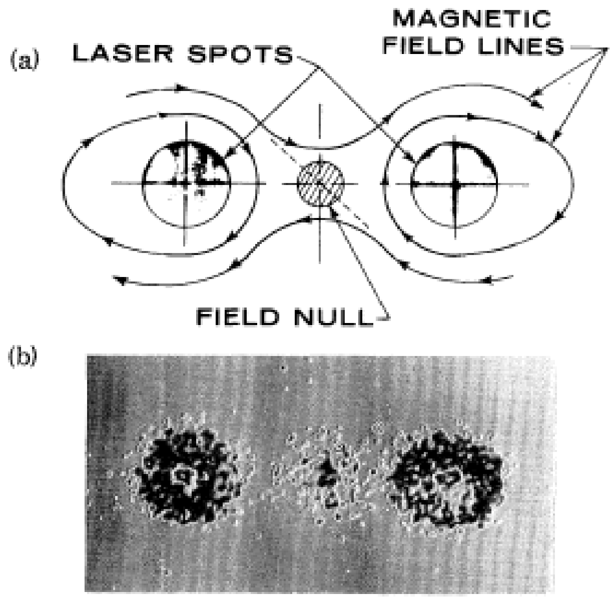
Direct comparison with global structures and dynamics observed by Yohkoh, SOHO, TRACE

No internal consistency

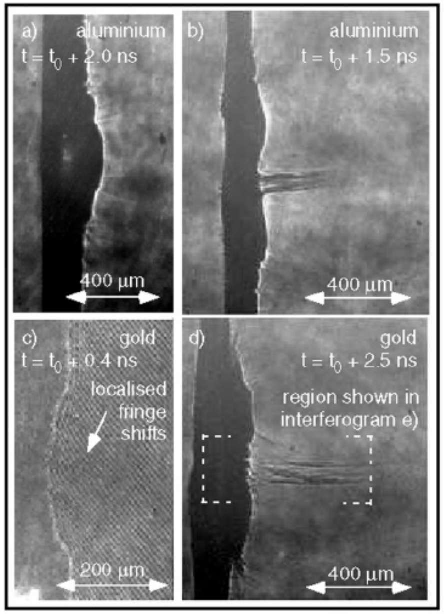
Plasma physics of reconnection and acceleration of electrons and ions

No incorporation in global models

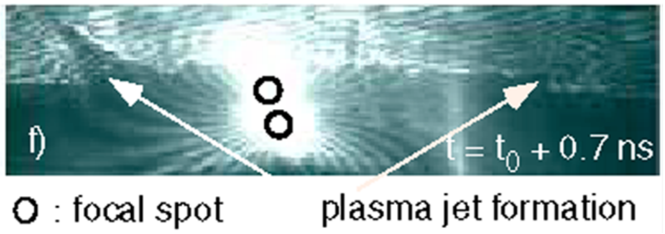
Why low beta MR in laser Plasma



Yates et al., PRL, **49**,1702 (1982)



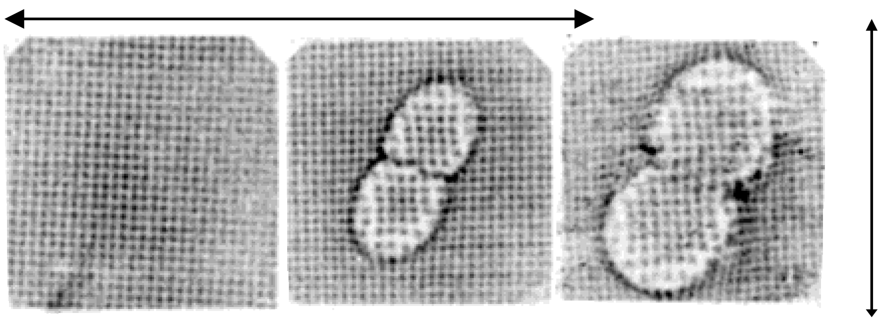
Vulcan



Nilson et al., PRL **97**, 255001 (2006)

Willingale et al., PoP **17**, 043104 (2010)

Laser on from 0 – 1 ns



5 mm

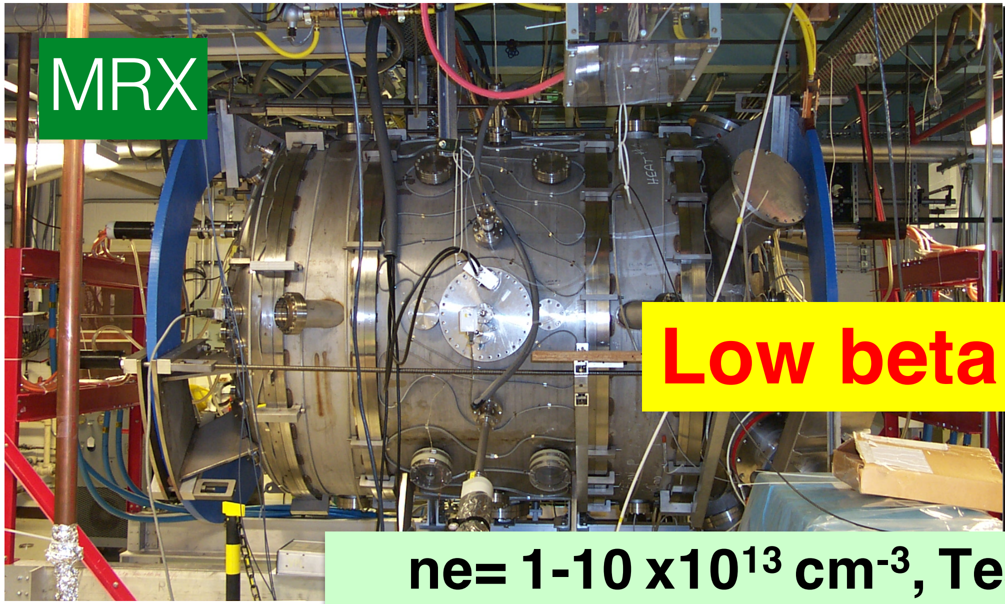
0.04 ns **0.67 ns** **1.42 ns**

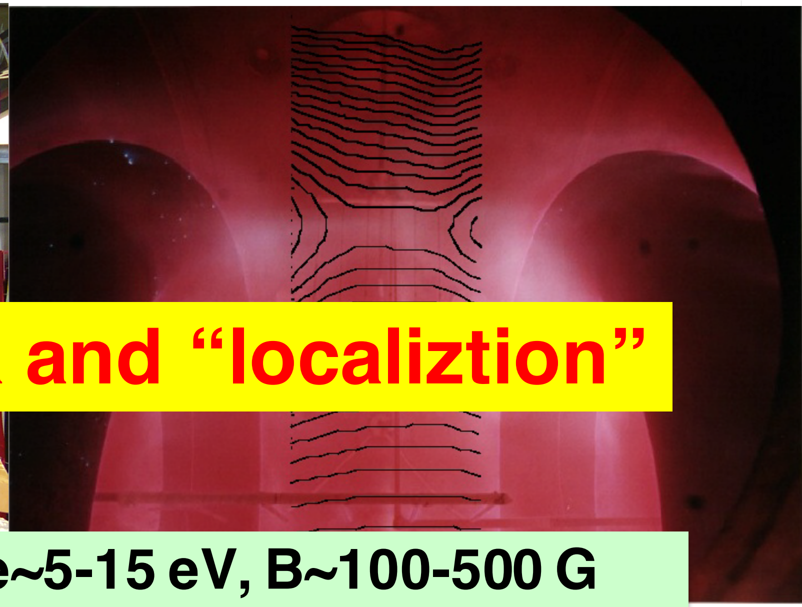
C. K. Li et al., PRL **99**, 055001 (2007)

Omega

Previous MR experiments are high beta, larger than unit

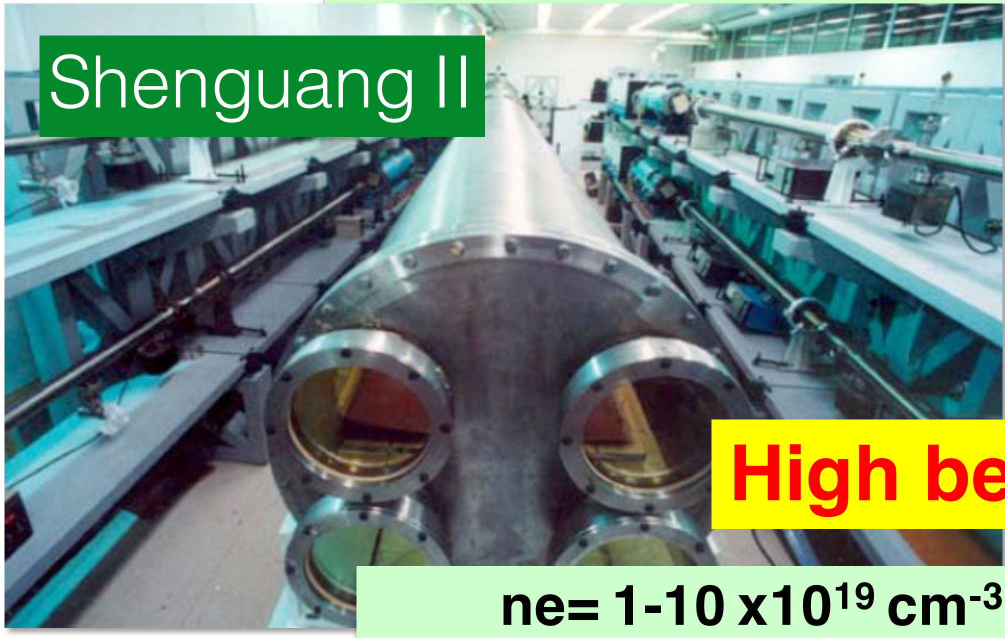
Reconnection from Lab plasmas

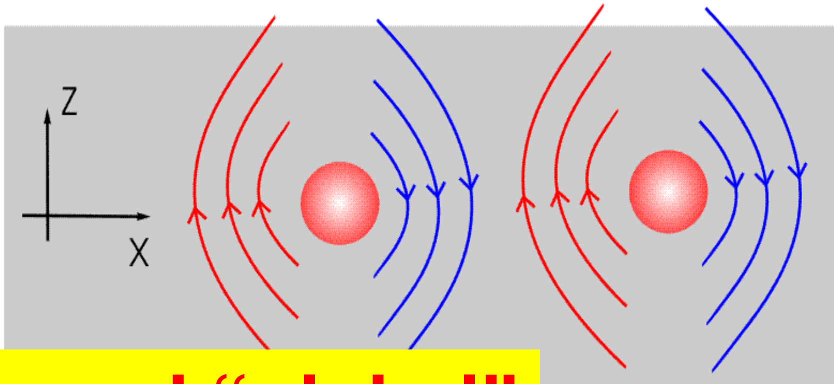




Low beta and "localiztion"

ne= 1-10 x10^{13} cm^{-3}, Te~5-15 eV, B~100-500 G



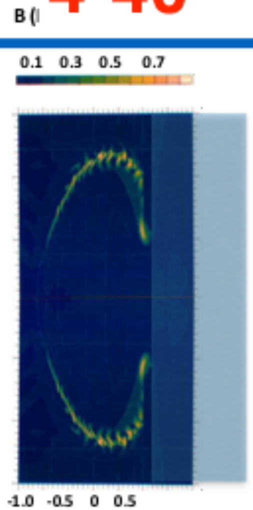


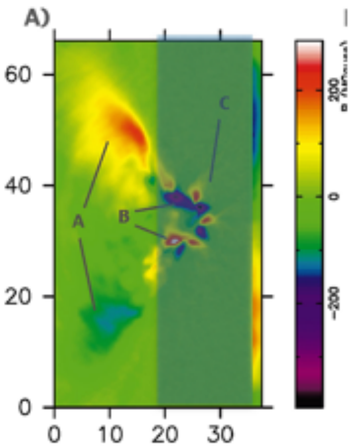
High beta and "global"

ne= 1-10 x10^{19} cm^{-3}, Te~1keV, B~10^{6} G

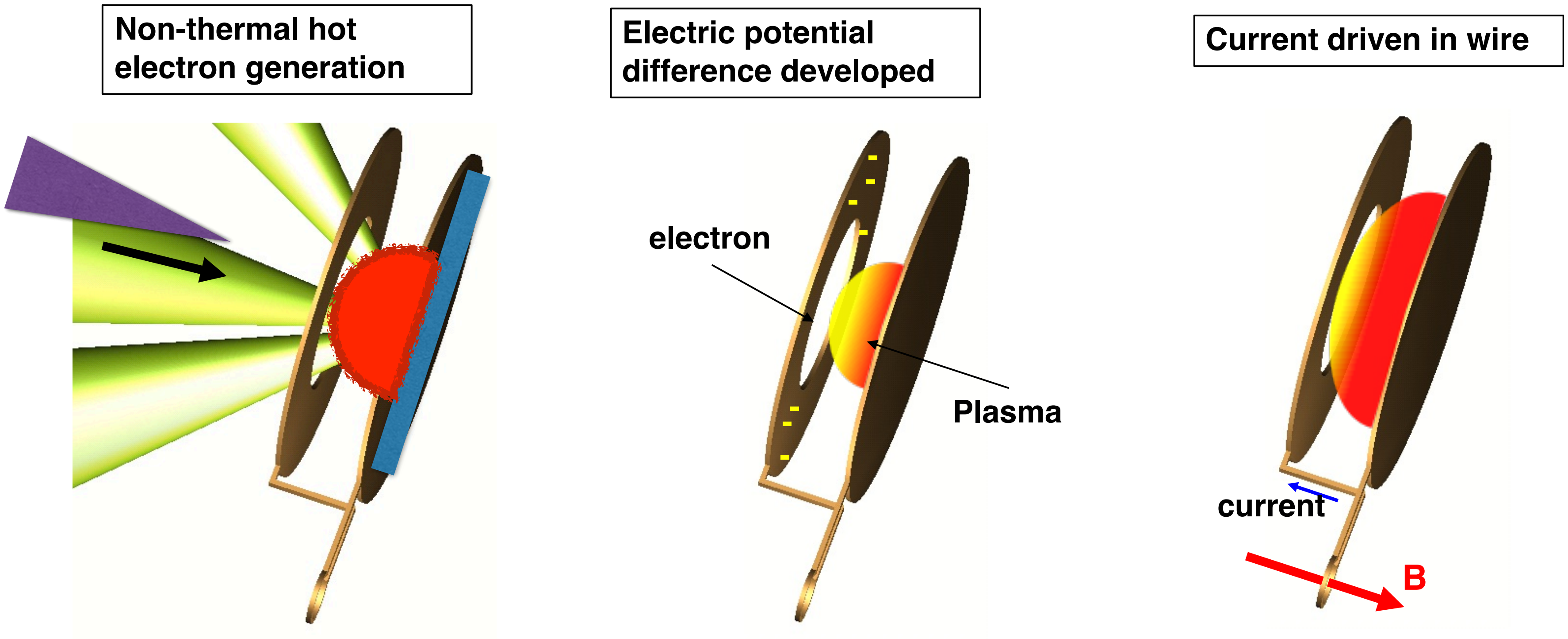
SUMMARY FOR MAGNETIC FIELDS IN LASER PLASMAS

	Long pulse lasers	Short pulse lasers	Coil target
B	0.1-1MG	10-100MG	1-10MG
Te	keV	keV-10 keV	eV-100 eV
Ne	10^20	10^20	10^18
β	4-40	<1	<0.004





-MAGNETIC FIELDS WITH A COIL TARGET



Courtesy Fujioka

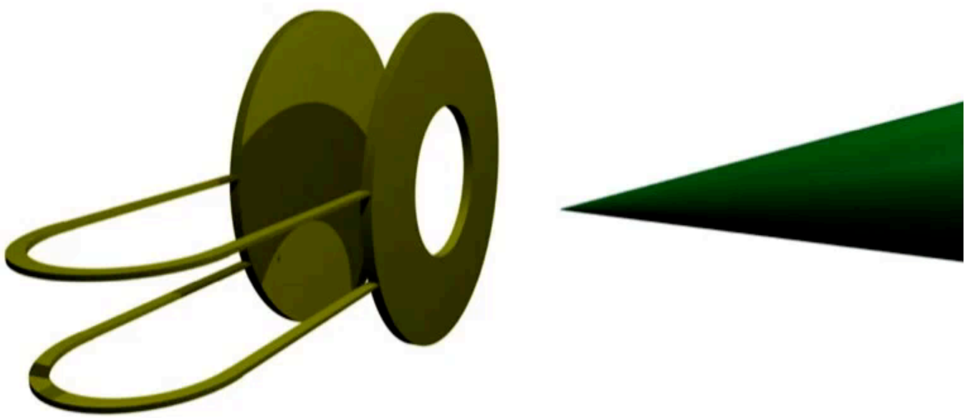
Movement of non-thermal hot electrons between the disks drives electric current in the wire.

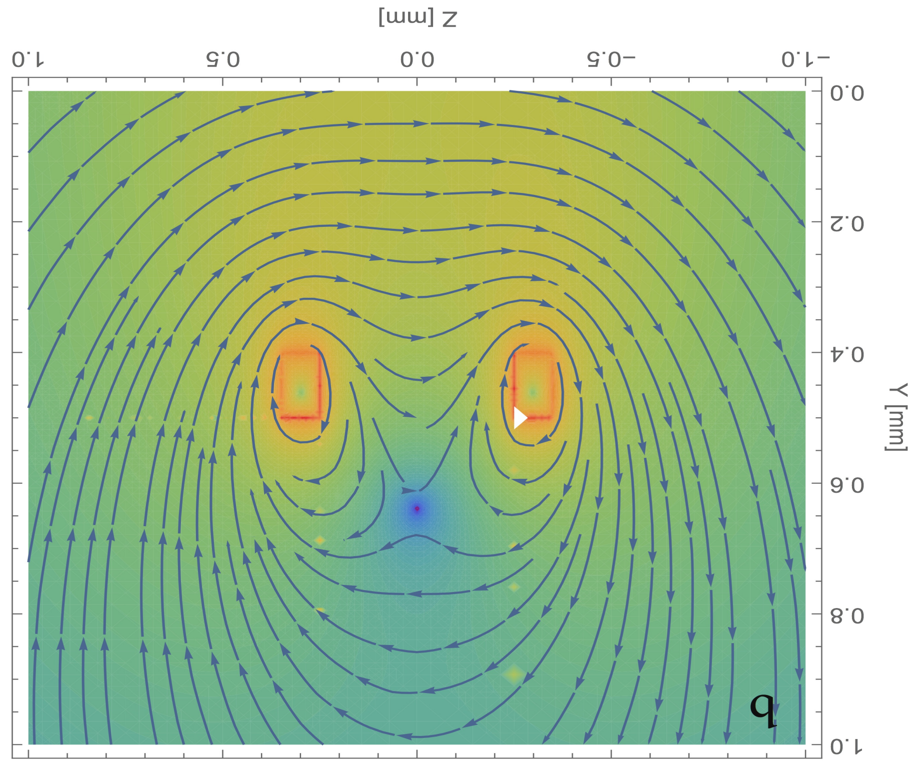
1 kT B-field from the coil
was obtained with the laser-driven capacitor-coil target

H. Daido *et al.*, PRL (1985), C. Courtois *et al.*, JAP (2005). S. Fujioka *et al.*, Sci. Rep. (2013).

Low beta MR experiment with Capacity target

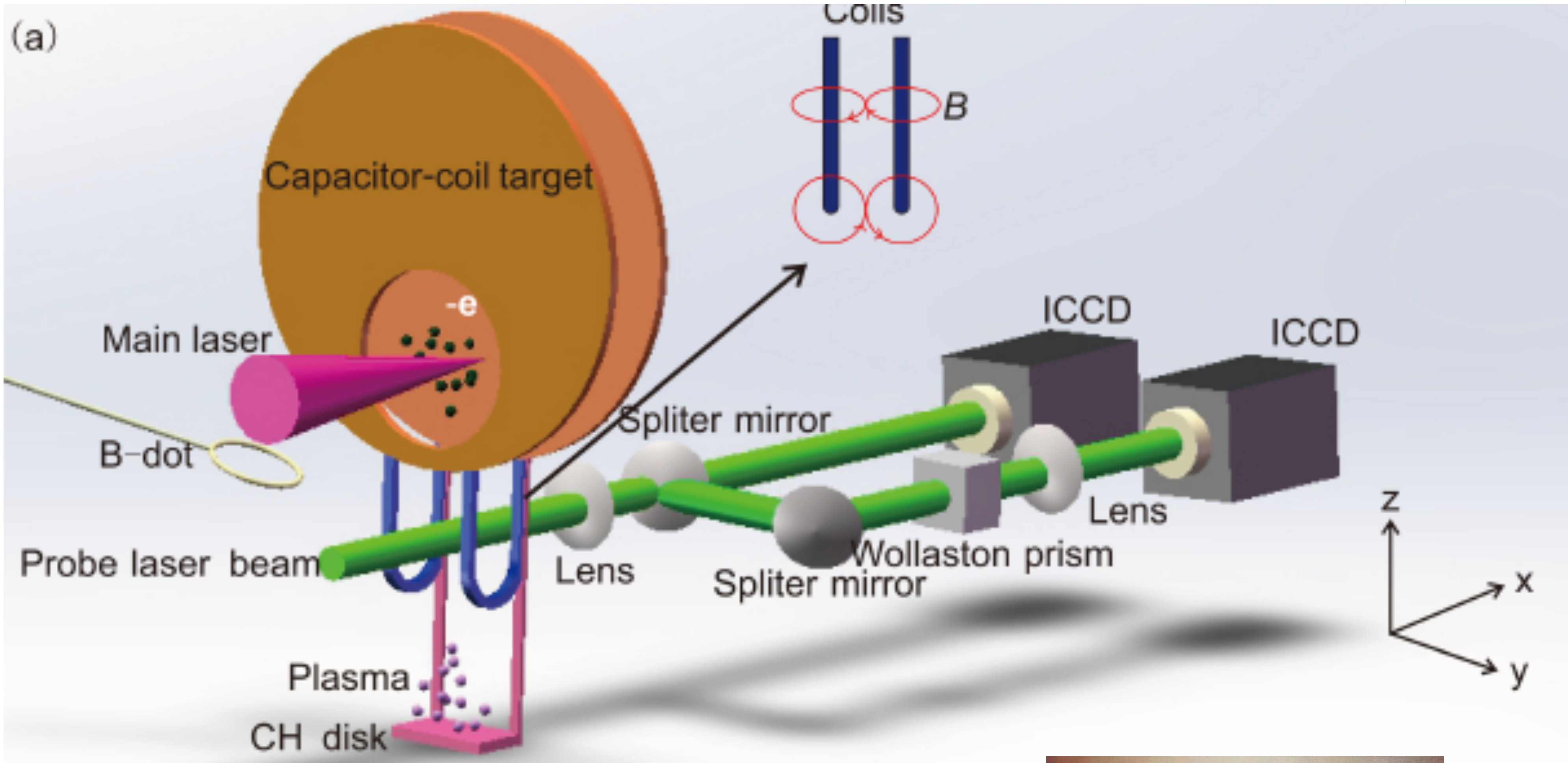
a Helmholtz like capacitor-coil target is used to obtain an Uniform B field

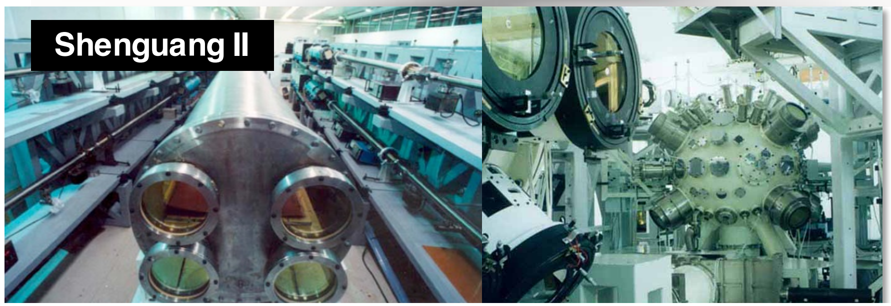




Magnetic Field Map

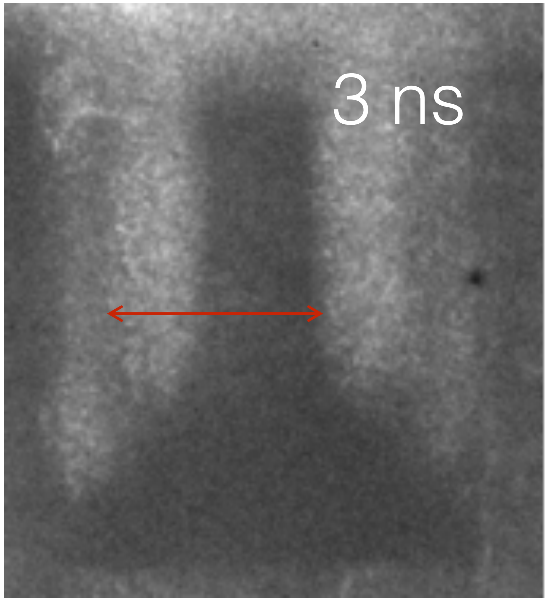
Low beta MR experiment with Capacity target



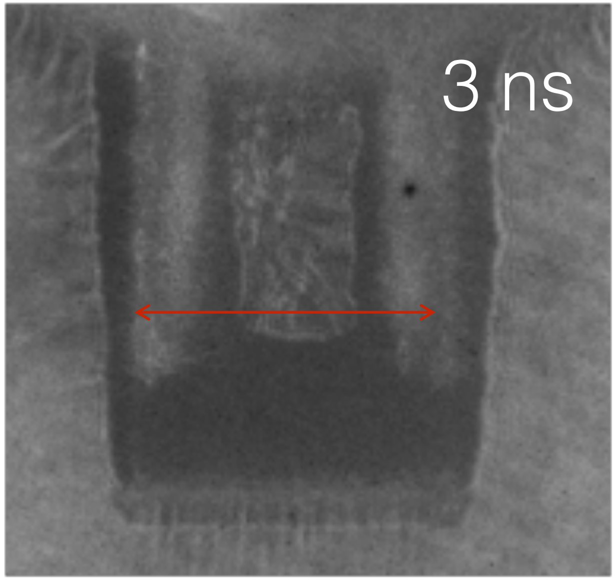


SG II Lasers
Beams: 8
Pulse: 1 ns
Energy: 260 J/beam for 3w
Focus spot: 50-100 υm
Intensity: 1-5$*10^{15}$ W/cm^2

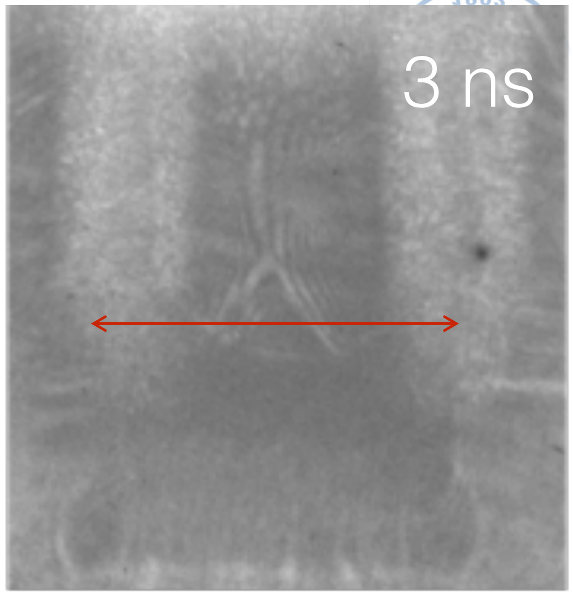
Optimized MR experiment with Capacity target



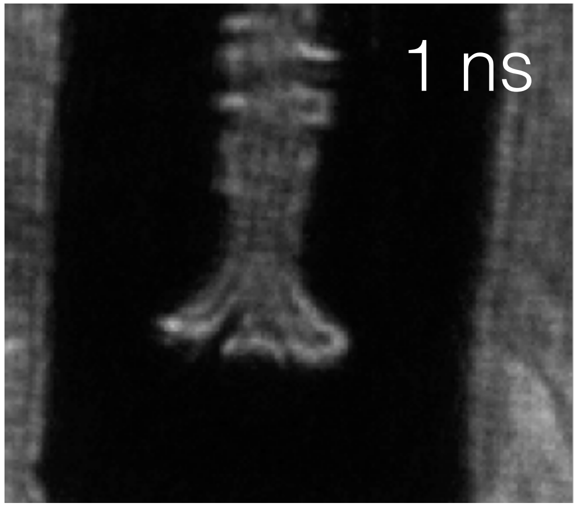
400 um



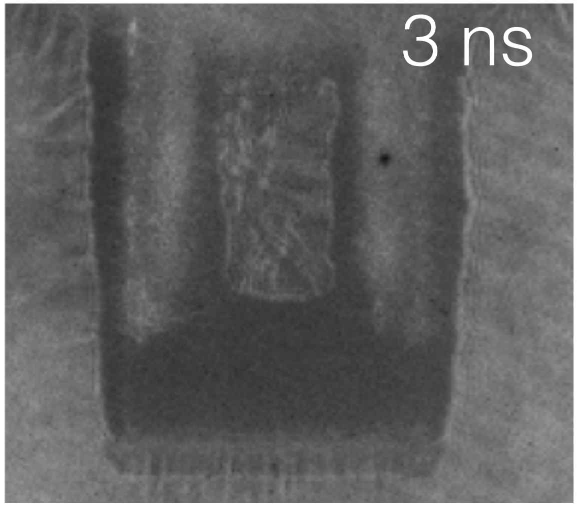
600 um



800 um



600 um



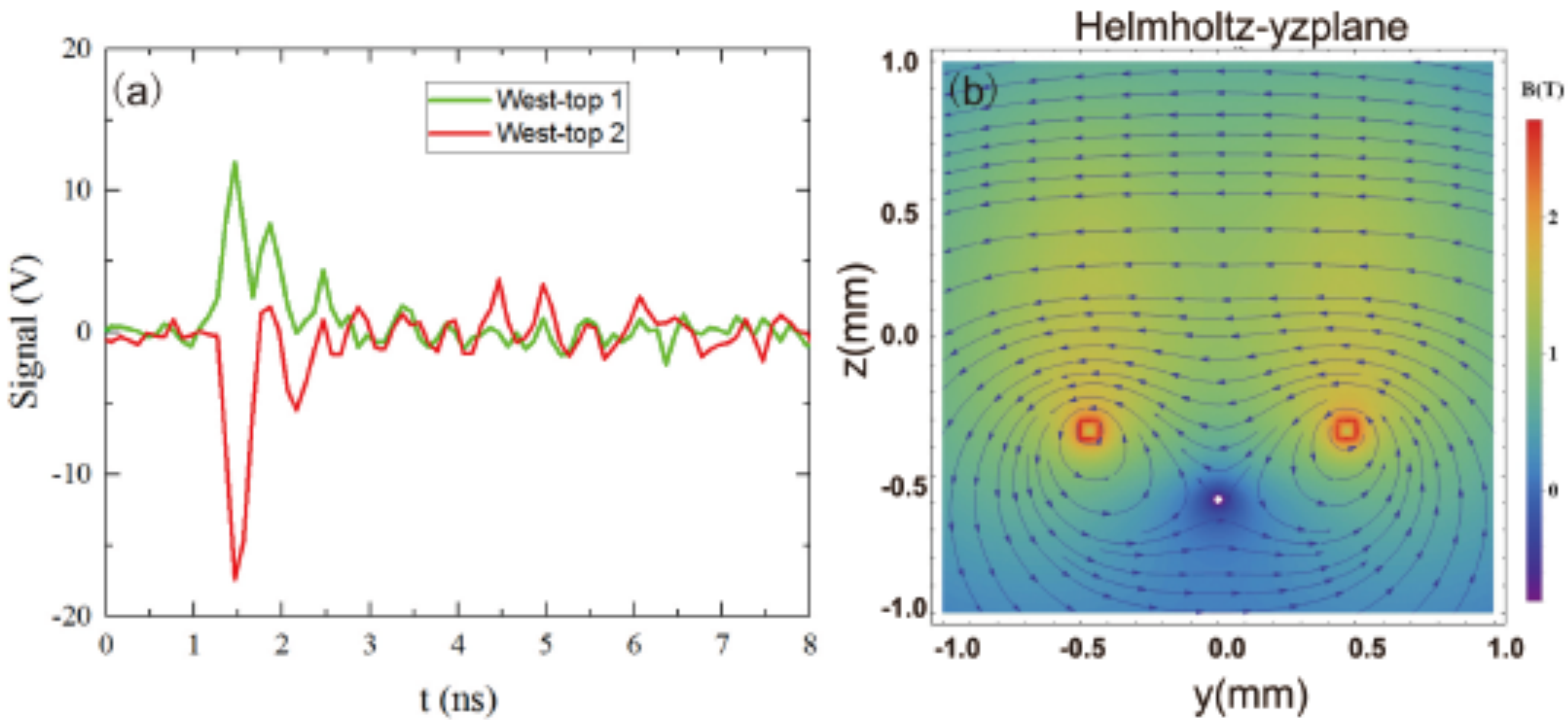
600 um

we optimized the plasma for the Helmholtz target by changing the distance of two coils, and delay of probing beam

Magnetic field measurement

With B-dot

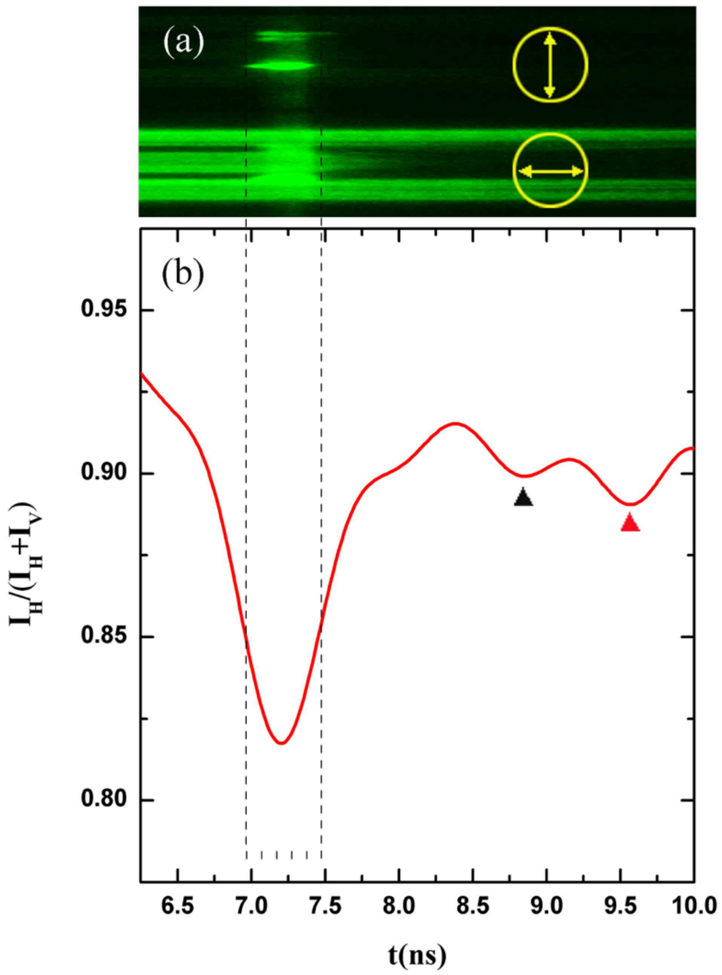
B-field is around 50 T



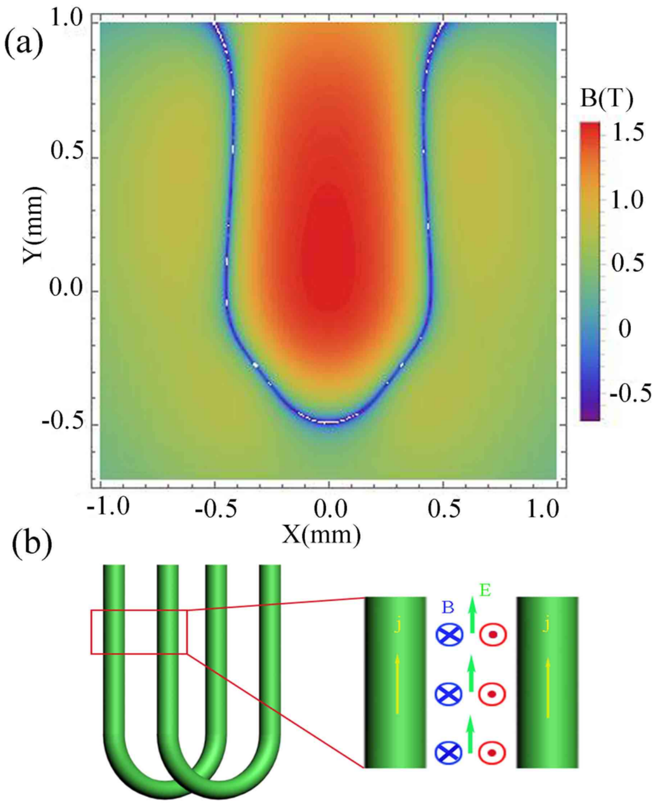
Typical magnetic probe signals measured by the two differential induction coils of the B-dot which is response to a time-varying magnetic field (dB/dt).

Magnetic field measurement

With Optical Faraday rotation



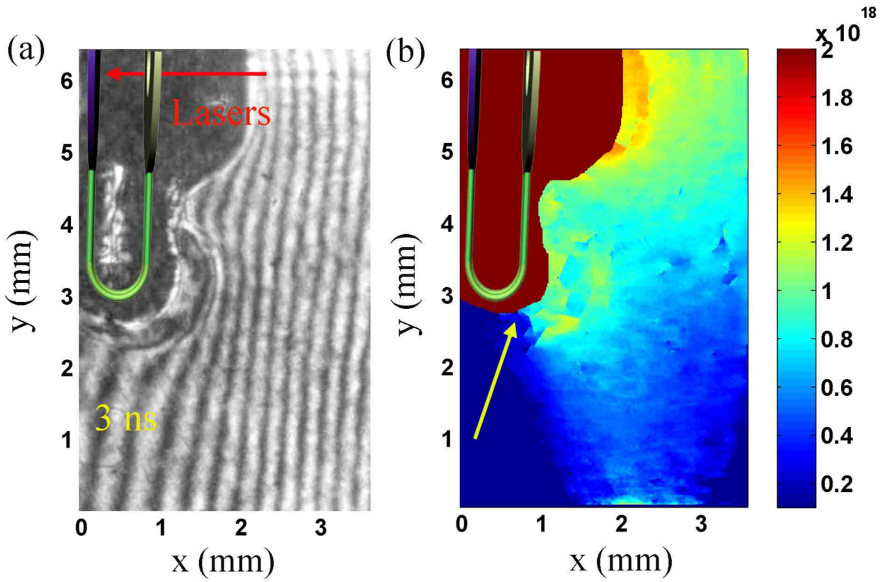
Pei et al., Pop (2016)

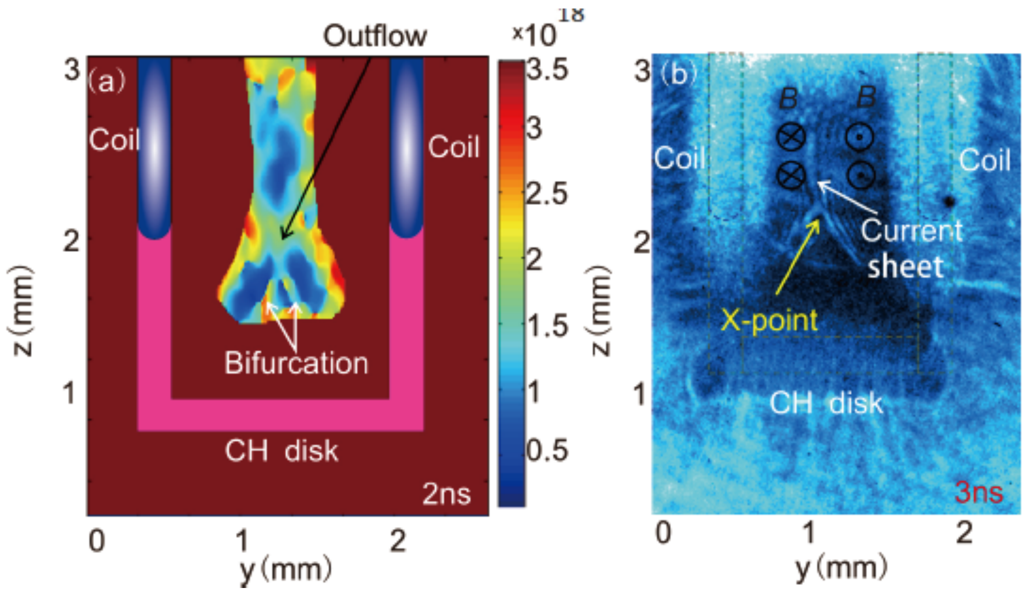


Shadow image from the optical streak camera, showing the evolution of the horizontal component and vertical component of the probe beam.

Density measurement

Density is around few10^{18} cm^{-3}

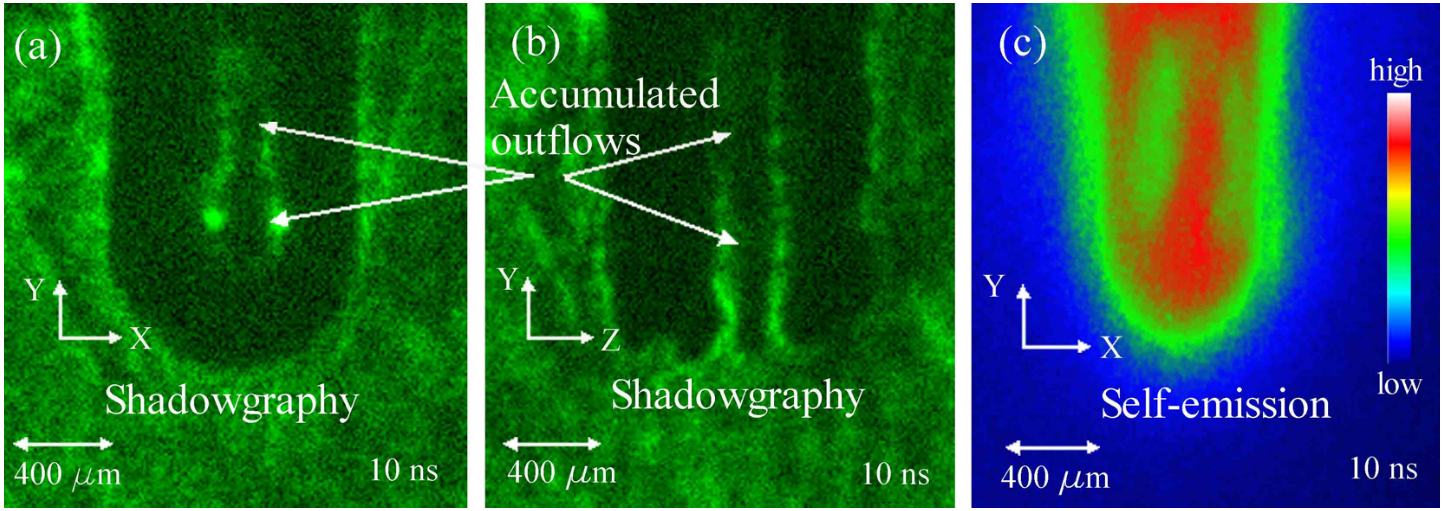




An interferogram taken at 3 ns after laser irradiation; (b) distribution of the electron density outside the coils.

Pei et al., (2016), Yuan et al.,(2017)

Low beta MR experiment with Capacity target



(a) and (b) Shadow images taken from two orthogonal directions at a delay of 10 ns;(c) self-emission image taken at a delay of 10 ns.

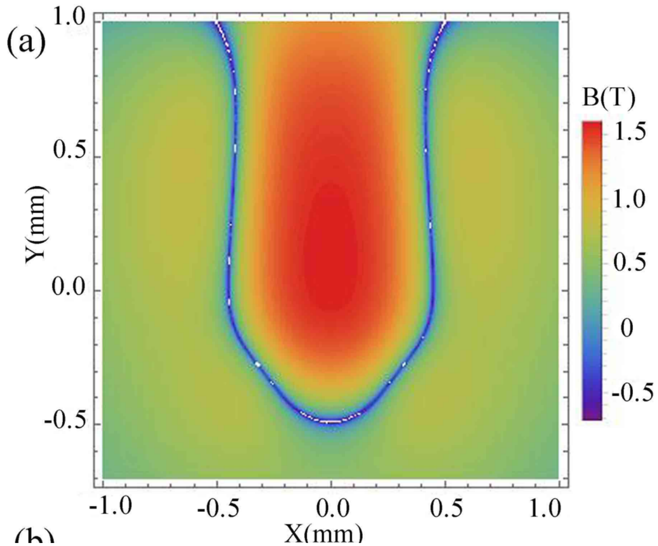
we estimate the plasma beta value near the coil as $\beta = p_e/(B^2/2\mu_0) = n_e k T_e/(B^2/2\mu_0)$, where the electron density is $n_e = 10^{24}\,\mathrm{m}^{-3}$, the Boltzmann constant is $k = 1.38\times10^{-23}$ J/K, and generally the electron temperature from the coils is <100eV. Even if we choose an electron temperature of $T_e = 100\mathrm{eV} = 1.16\times10^6\mathrm{K}$ and a **B**-field of 50 T, the estimated plasma beta value is ~0.016, and it will be even smaller at a lower electron temperature.

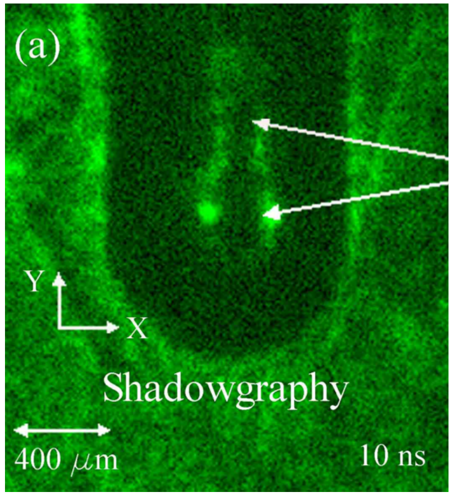
Pei et al., (2016)

SUMMARY

1. **Low beta magnetic reconnection experiments are successfully realized with a Helmholtz coil target both in SGII, Gekko and Xinguang laser facilities**

2. **For laser driven a Helmholtz coil target, the magnetic field between the coils is not uniform due to the magnetic reconnection.**





3. **The present low beta device is much smaller, and the global plasma evolution can be observed more easier, which can also be applied to study particle acceleration and simulate the magnetosphere plasma**