Internal magnetic field measurements on MagLIF using pulsed polarimetry

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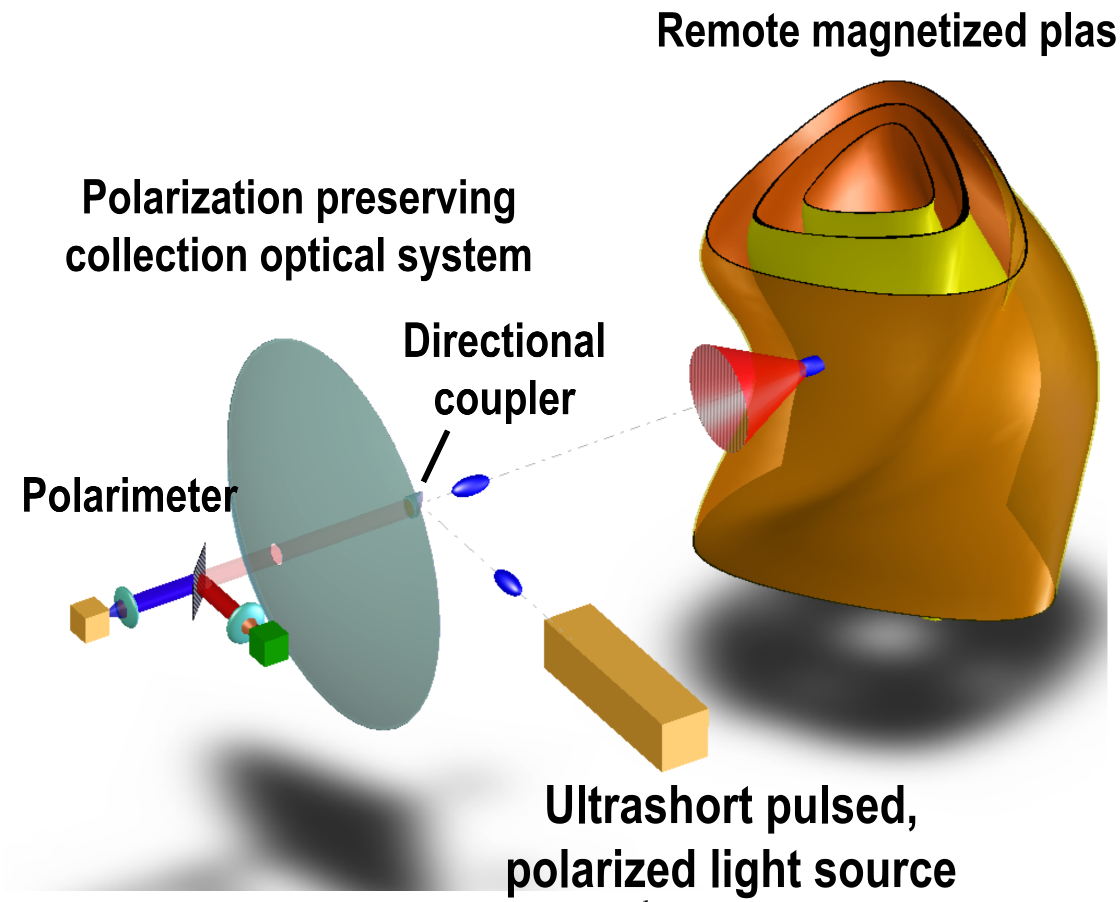
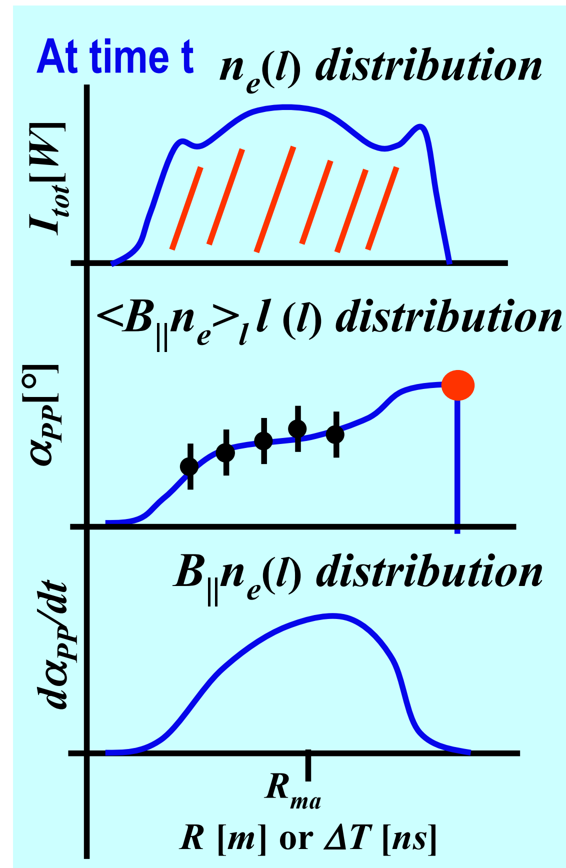
A Pulsed Polarimeter





$$\alpha_{PP}(l) = \mathbf{2}\cdot 2.63x10^{-13}\ \lambda_o^{2}\int_0^l n_e B_{\|}(s,t)\ ds$$

"Nonperturbative measurement of the local magnetic field using pulsed polarimetry for fusion reactor conditions" R J Smith, *Rev Sci Instrum.* 2008 Oct;79(10):10E703

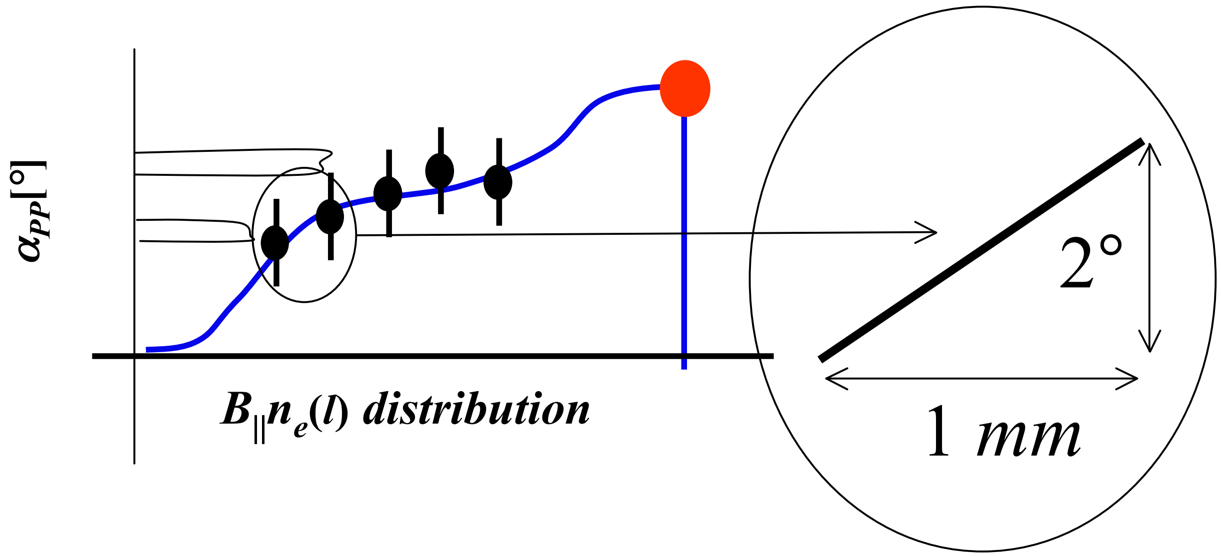
Combines

Lidar Thomson scattering with polarimetry to provide

local n_e and $B_{||}$ along sightline

Can also provide T_e along sightline, though collective TS (low T_e, high n_e) is a problem

How it works: Seems to be universal, tokamaks to MHED



$\Delta\alpha_{pp}/\Delta s \propto n_e B_{||}$

$2° \Leftrightarrow (n_e = 10^{25}\ m^{-3}) \times (B = 20\ \text{T}) \times (\lambda = 0.532)^2 \times (\Delta s = 1\ mm)$

x100 x10 ÷100 ÷10

$2° \Leftrightarrow (n_e = 10^{27}\ m^{-3}) \times (B = 200\ \text{T}) \times (\lambda = 0.050)^2 \times (\Delta s = 100\mu m)$

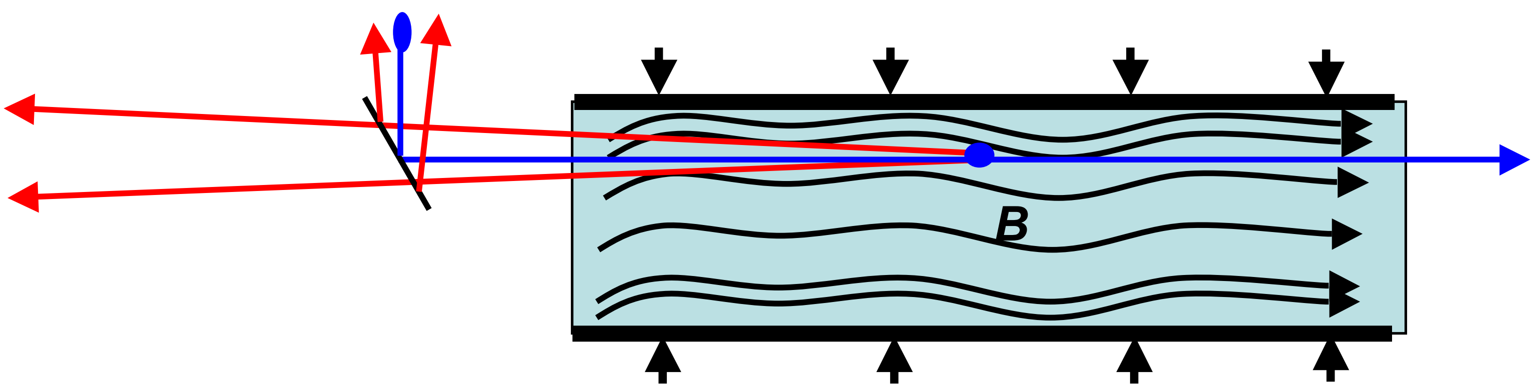
TS: can reduce pulse energy by 10, so better!

Pulsed polarimetry on MagLIF

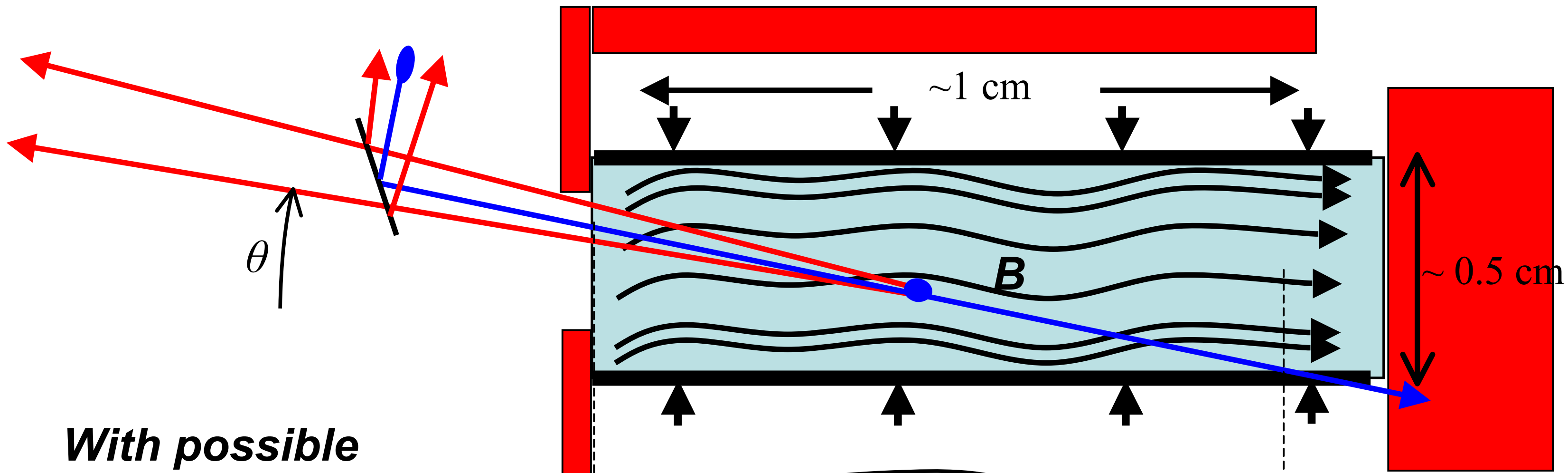
I) High spatial and temporal resolution of $\mathbf{B}_{||}(t,s)$ field

- Spatial resolutions of Δs < 500 μm (1 *ps*)
- Temporal resolutions of Δt ~70 *ps/cm* of plasma
- Field resolutions of a $\Delta B_{||}/B_{||}$ ~ a few percent

Resilient to refraction and non-perturbing Aim-and-shoot, single diagnostic access port



A measurement scenario, addresses Key issues



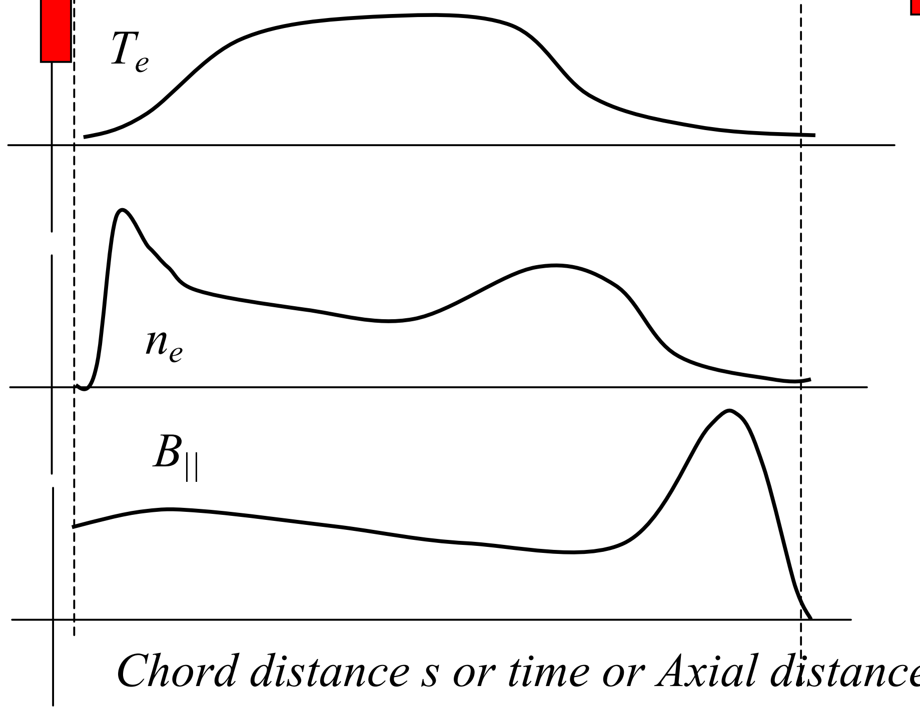
With possible measurement goals:

$n_e T_e$ or electron pressure

Peak n_e and peak T_e

Edge distributions of n_e, T_e

Internal magnetic field



The parameters (wire Z pinch, pre-cursor phase for example):

Plasma: n_e =1.4x10^{25} m^{-3}; T_e = 100 eV; Z_{eff} = 7; B = 80 T; L_p = 2 cm

Instrument: E_{laser} =1 J; Δs= 0.5 *mm*; λ_{laser}= 532 *nm*; A=$\pi(1000\lambda)^2$; ΔΩ = 0.005 sr; η = 5%

I. **Δα** (for 500 *μm*)= 4 degrees! (***healthy***) ∝ (B, n_e, Δs, λ_{laser}^2)

II. Inv. Brems abs. length (**α_{IB}**) = 5 *cm* (***large***) ∝ (T_e, $1/n_e^2$, Δs, $1/\lambda_{laser}^2$, $1/Z_{eff}$)

III. **Cutoff λ** = 9 *μm* (***high***) ∝ ($1/\sqrt{n_e}$)

IV. **N_{TS}** = 7x10^8 *ph* per Δs (***huge***) ∝ (n_e, ΔΩ, E_{laser}, Δs, λ_{laser})

V. **δB** ~0.4 mT or **δB/B** <1% (***obviously too good***) ∝ (1/*SNR*(shot limited), η)

VI. N_{brems} = 8x10^6 *ph* per Δs ∝ (n_e^2, AΔΩ, L_p, Δs, Z_{eff}, Δs/*c*)

but **$N_{brems\ noise}$** ∝ ($\sqrt{N_{brems}}$) ~ 3x10^3*ph* (***exceedingly small***)

Very positive but how to carry it out?

Instrumental considerations

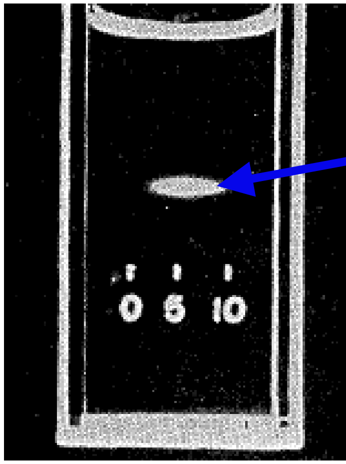
Detection: 1 *ps* bandwidth is needed: ~~streak cameras (170k$)~~ cannot provide useful dynamic range and they have low QE

(***use OKE method, high dynamic range, cheaper, high QE***)

Material costs? CCD camera(30k$),
scattering cell(2k$)
optical Kerr cell(4k$),
collection optics, polarimeter and port(10k$).

Laser: Sub-*ps* pulsed lasers are needed with ~ 1 J output energy
λ can be 1060, 530, 353, 265, or 800, 400, 200 *nm* etc.
(***Available***)

Imaging of a laser pulse



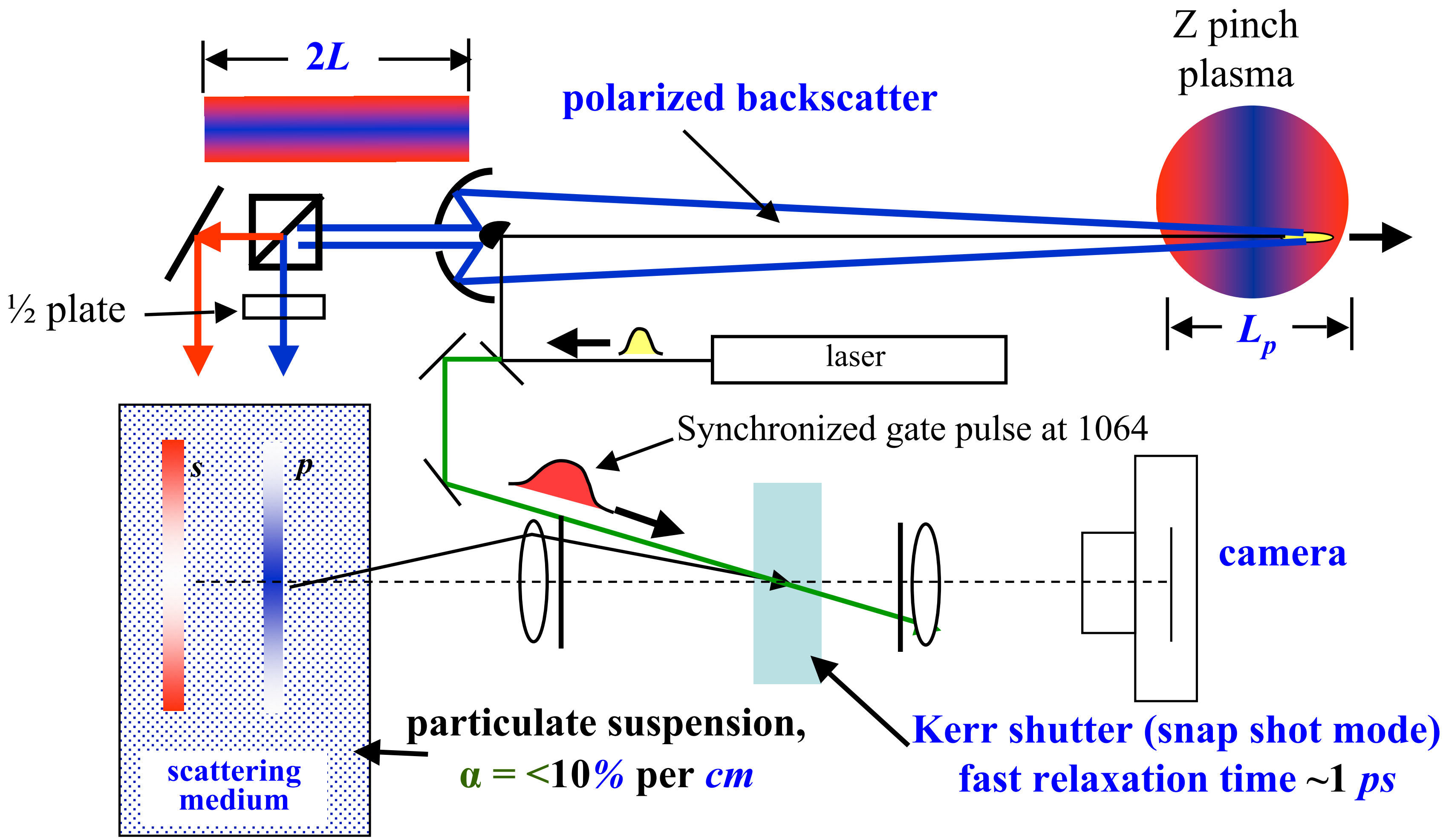
Still image of the intensity of a pulse of light frozen in flight (*cm* scale)

'Ultrahigh Speed Photography of Picosecond Light Pulses and Echoes'

M.A Duguay and A.T. Mattick, *App. Optics, V10, 9, 1971*

A 2 *cm* plasma produces a 2 *cm* image for direct imaging and 4 *cm* image for **Pulsed Polarimetry**. Best and only method for plasmas of this size, I believe.

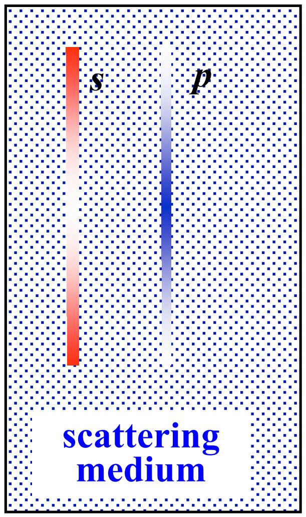
Pulsed Polarimetry using ultra-fast photography



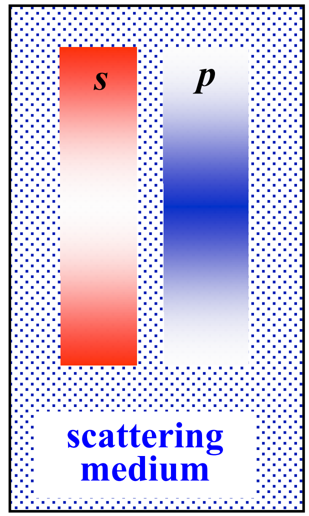
Pulsed Polarimetry diagnostic using OKE shutter showing the two *s*, *p* intensity profiles

"Imaging of the magnetic field structure in megagauss plasmas by combining pulsed polarimetry with an optical Kerr effect shutter technique" R J Smith *Rev Sci Instrum.* 2010 Oct 81(10):10D530.

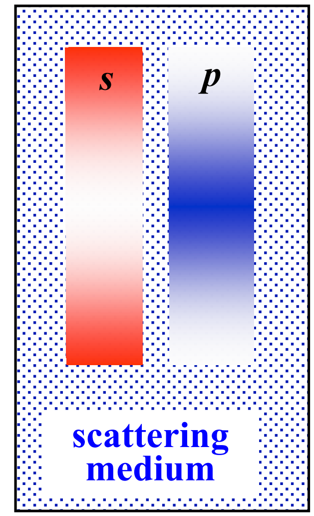
Scattering cell can do everything a Streak camera can do



n_e and $B_{||}$ vs (s)



n_e and $B_{||}$ vs (s and y)



n_e, $B_{||}$ and T_e vs (s)

It may be possible to achieve a Kerr cell technique with 100 femtosec response and a 100 femtosec laser pulse gives $\Delta s \sim 30\ \mu m$

Doesn’t end there

Use a surrogate medium for a plasma:

(fiber pulsed polarimetry),

Ingredients: 1) Faraday effect in a medium

2) Rayleigh backscatter

Provides complementary information:

Boundary conditions

Fiber optic Pulsed Polarimeter Option

A. Plasma pulsed polarimetry as above – requires a 'good' magnetized plasma to work.

B. Fiber optic pulsed polarimetry – always works! provides local field sensing as boundary conditions:

1) **current distributions** in conductors from external fields

2) coupling efficiency of **pulsed power drivers** to plasma

3) **Boundary fields** adjacent to and in plasmas

4) Time resolved field profiles (**Dynamics!!**).

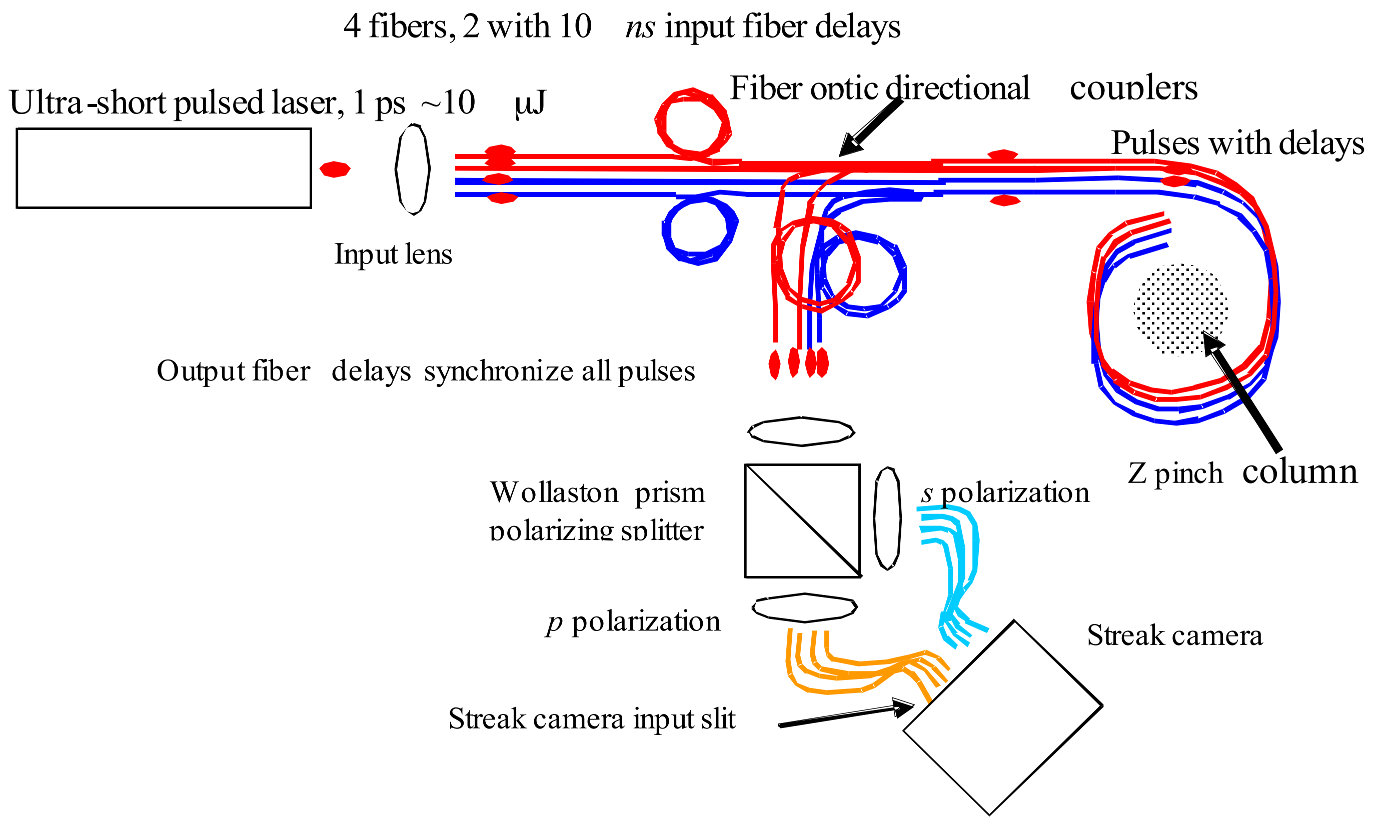
Fiber pulsed polarimetry

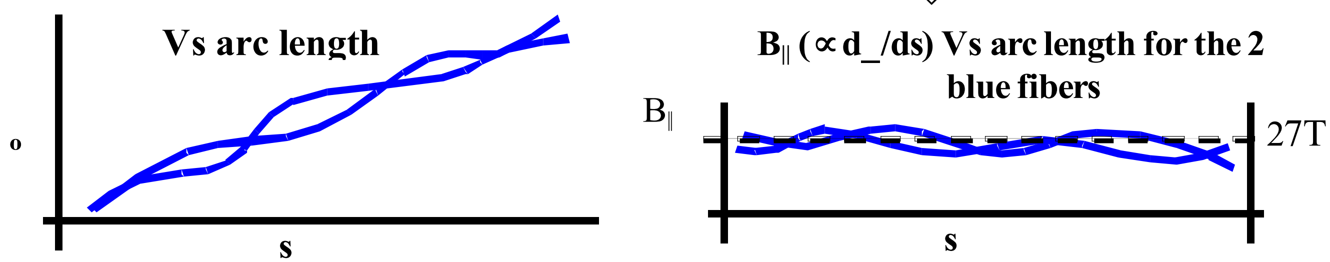
- measures *local* field along the fiber and seems to be a single shot but

  - *several fibers with delays multiplexed into a streak camera provide dynamics* -

Many optical fibers with delays easily gives :

- Plasma Dynamics -





Detector for fiber option

- Why would a streak camera work for fibers and not for plasma?

- light slows in fiber by 2/3rds
- light is easier to manipulate to a narrow slit (good time resolution 10 *ps*)
- pulse can be very narrow-100 *fs* (little dispersion)

Δs can be around ~ 1 *mm*, (the Lidar minimum)

Silica fibers are sufficient at 20T

How to develop these techniques?
no lack of interest

Univ. of Washington (pulsed polarimeter for MTF, ~*cm* resolution under development)

NTF Reno (Zebra and more important the laser, Radu P.)

NTF Reno (polarimetry using 266 nm, Vladimir I.)

Cornell (Cobra, interest in Faraday techniques, John G.)

LANL/AFRL (MTF spans the full range of HED, interest in Faraday techniques, Tom I.)

These techniques have promise across all of MHED science

Conclusions

- Pulsed polarimetry is appropriate for a good starting range of MagLIF plasmas and can mature to high n_e and B.
- There are no other '*local*' field sensing diagnostics outside of pulsed polarimetry for HED science.
- Pulsed polarimetry provides distributions of *internal* n_e, $B_{||}$ and T_e in one 'snap shot' and is single port aim-and-shoot.
- Fiber pulsed polarimetry can provide several distributions of *local* $B_{||}$ external to plasma and plasma dynamics.