

Internal magnetic field measurements in dense transient plasmas using Pulsed Polarimetry

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Outline

- Introduction to the Pulsed Polarimetry technique
- Measurement details
- Pulsed Polarimetry applied to the FRX-L experiment
- Prospects for Pulsed Polarimetry on HED plasmas
- A brief summary of the advantages of Pulsed Polarimetry

Introduction to Pulsed Polarimetry

A non-perturbative remote sensing technique
combining the Faraday effect and optical scattering

Measures: *local* B_{\parallel} , n_e , T_e along the trajectory of a light pulse

Application: all Magnetic Fusion Energy (MFE) plasmas
but especially dense, transient plasmas (MTF& Z-pinch plasmas)
and future burning plasmas

Principles of the Pulsed Polarimetry technique

- I) Induced *backscatter* is identical in nature to light produced by a partial retro-reflection by a plane mirror at that location along the inducing light beam.

More to the point, induced optical backscatter *inherits* the polarization of the inducing probe beam.

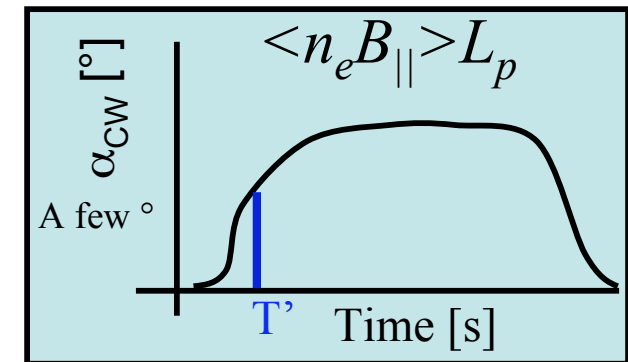
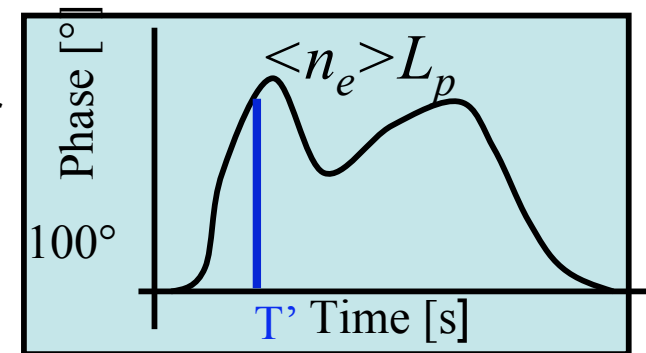
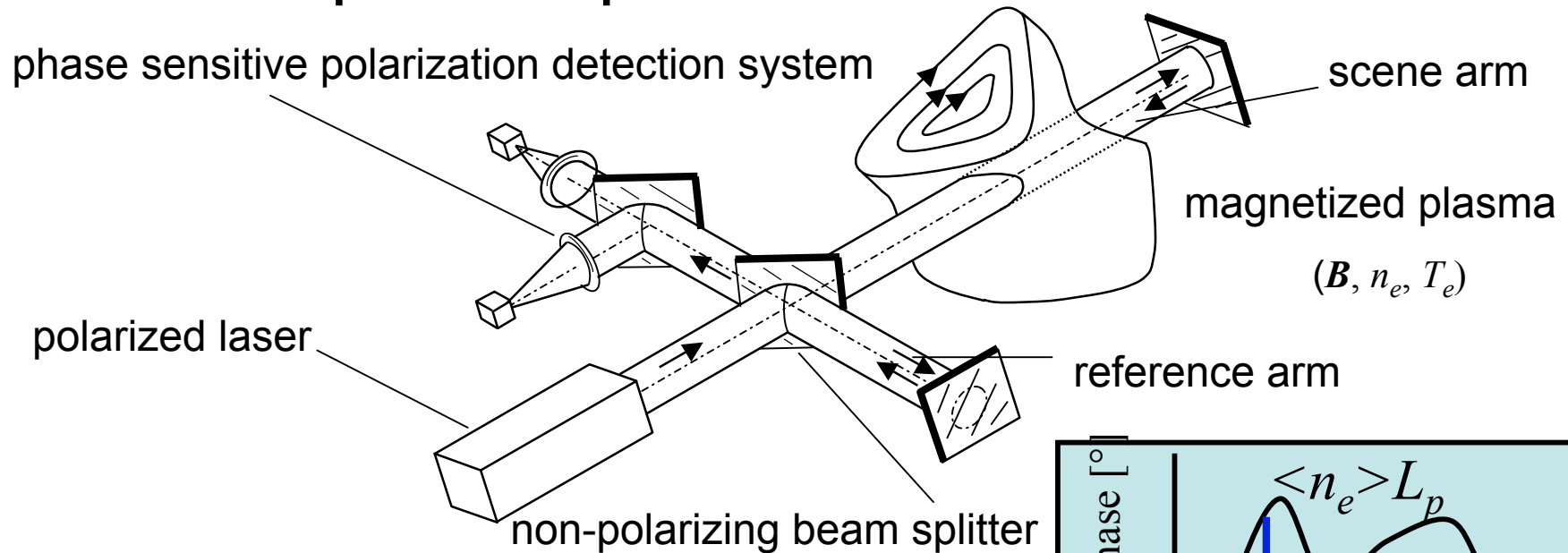
- II) The Faraday effect is *non-reciprocal*: The sense of rotation of the polarization of light propagating in a plasma is independent of the direction of propagation.

Combines two well known Plasma Diagnostics:

CW Polarimetry

and *LIDAR Thomson scattering*

CW plasma polarimeter/interferometer



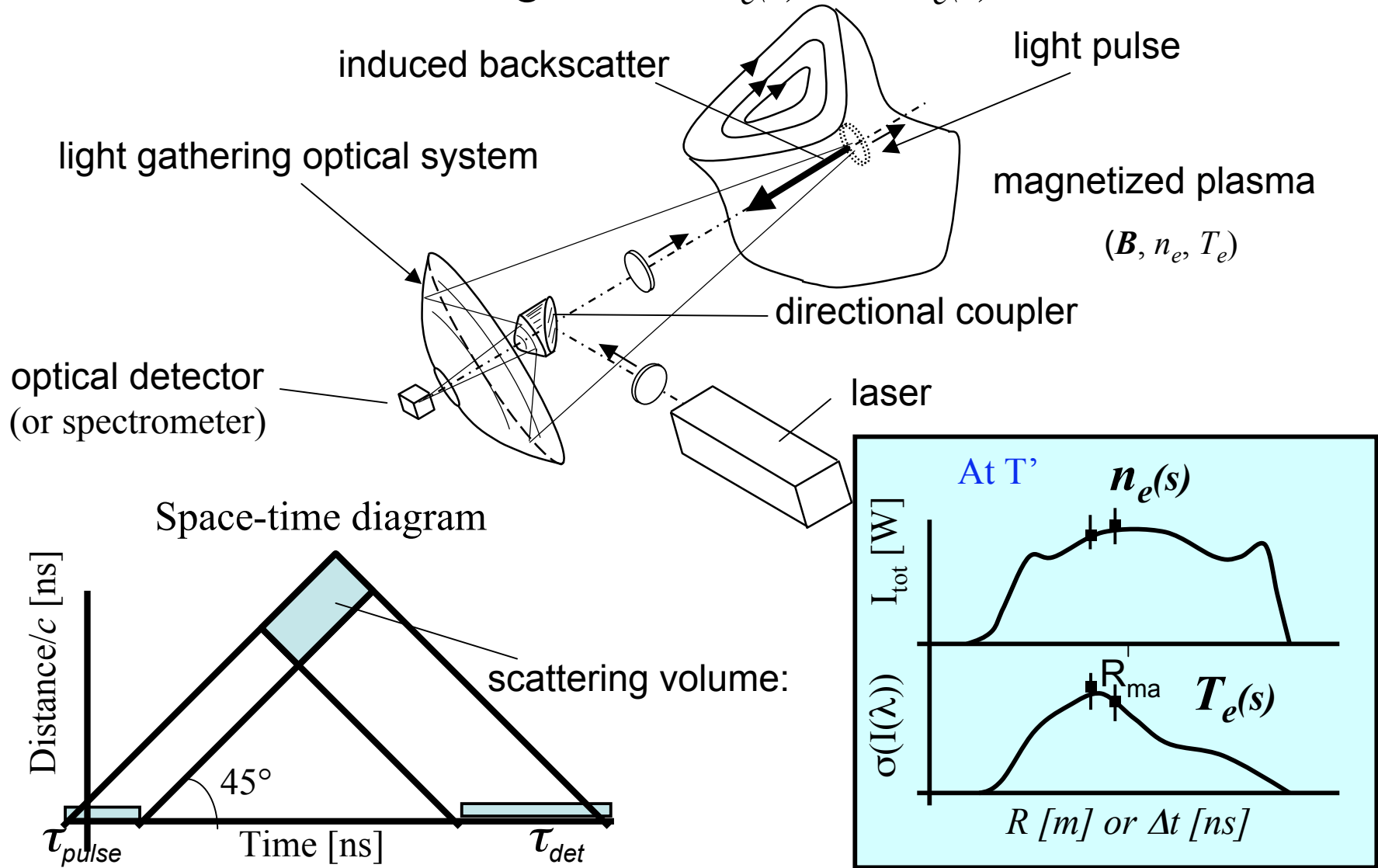
$$\phi_{CW}(T) = 2 \times 4.5 \times 10^{-16} \lambda_o \int_0^{L_p} n_e(s, t(s)) ds$$

$$\alpha_{CW}(T) = 2 \times 2.63 \times 10^{-13} \lambda_o^2 \int_0^{L_p} (n_e B_{\parallel})(s, t(s)) ds$$

double pass

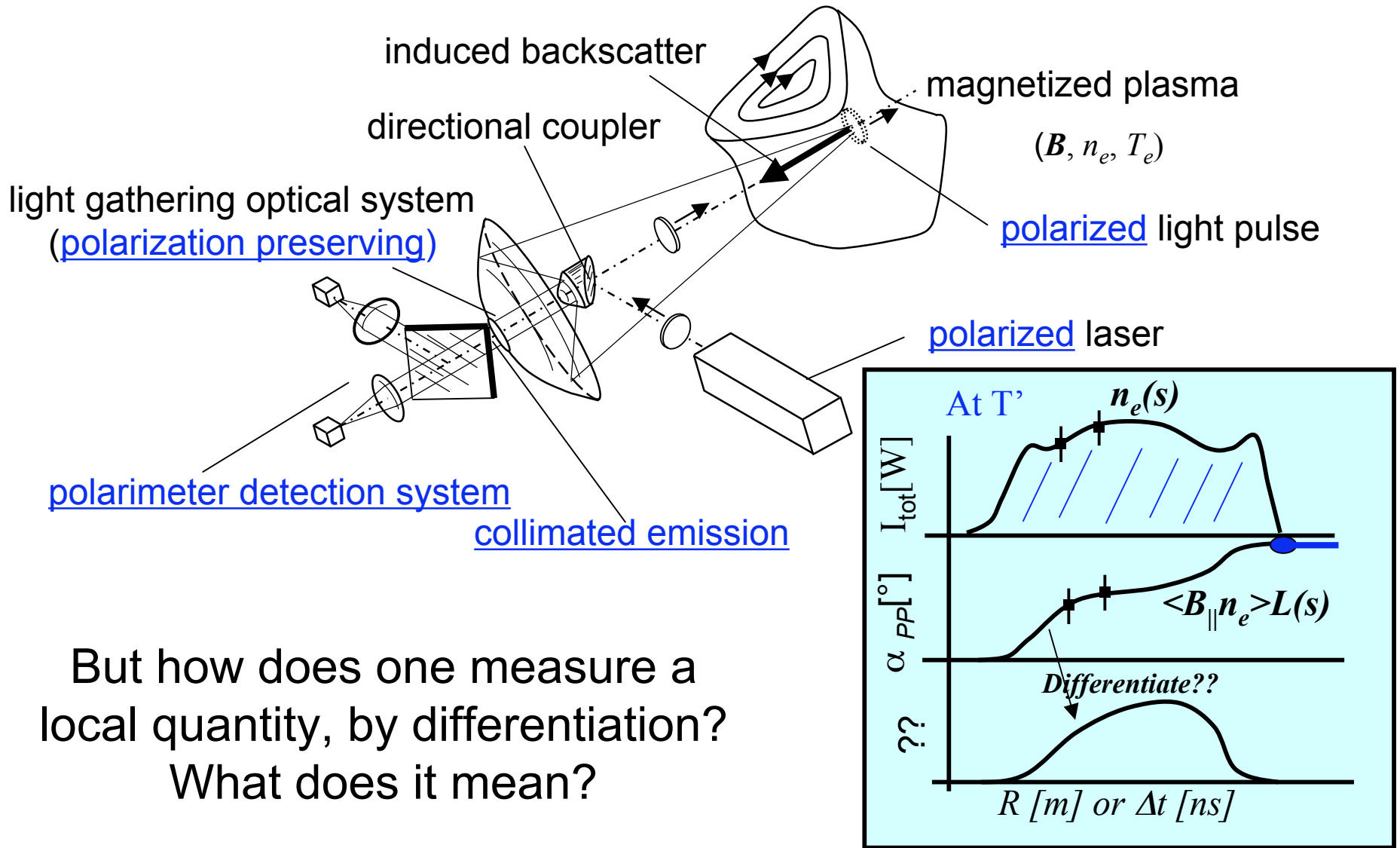
LIDAR Thomson Scattering

remote sensing of local $n_e(s)$ and $T_e(s)$



Pulsed Polarimeter

remote sensing of local $n_e(s)$ and $n_e B_{\parallel}(s)$ (and $T_e(s)$)

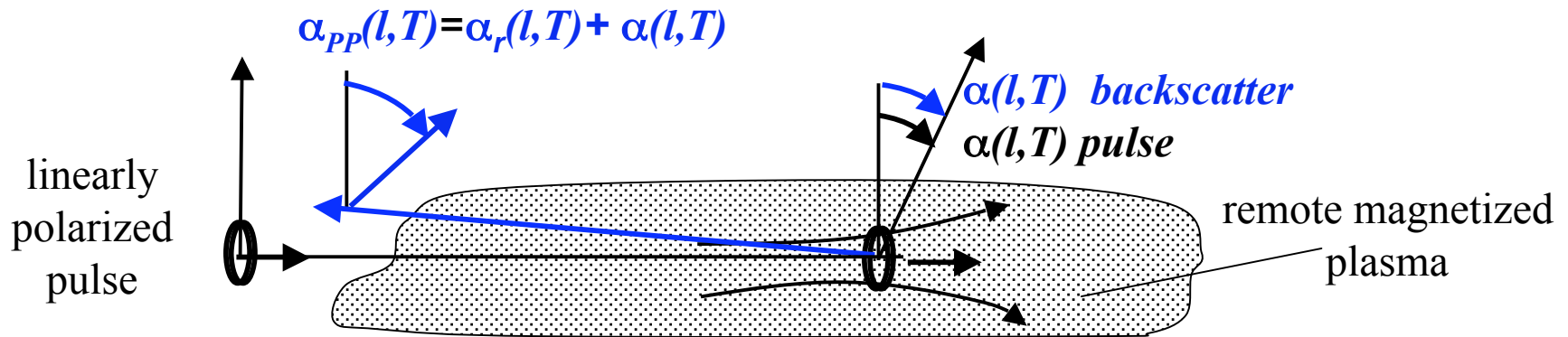


But how does one measure a local quantity, by differentiation?
What does it mean?

Combining the two principles

In plasma

$$\alpha_{PP}(l, T) = (2x) 2.63 \times 10^{-13} \lambda_o^2 \int_0^l (n_e B_{\parallel})(s, t) ds$$



From I) $\alpha(l, T) = \alpha(l, T)$ at l

From II) $\alpha_r(l, T)$ adds to $\alpha(l, T)$

From a *quasi-static* assumption: $\alpha_r(l, T) = \alpha(l, T)$ (6.6 ns/m)

Result: $\alpha_{PP}(l, T) = 2 \alpha(l, T)$

Measurement Process

Density:

$$n_e(l)[m^{-3}] = \frac{I_o(l)}{7.8 \times 10^{-30} \Delta\Omega(l) E_{pulse} c/2}$$

Density-field product:

$$n_e B_{\parallel}(l)[Tm^{-3}] = \frac{1.9 \times 10^{12}}{\lambda_o^2} \left(\frac{\partial \alpha_{PP}(s, T)}{\partial s} \right) \Big|_l$$

B_{\parallel} field:

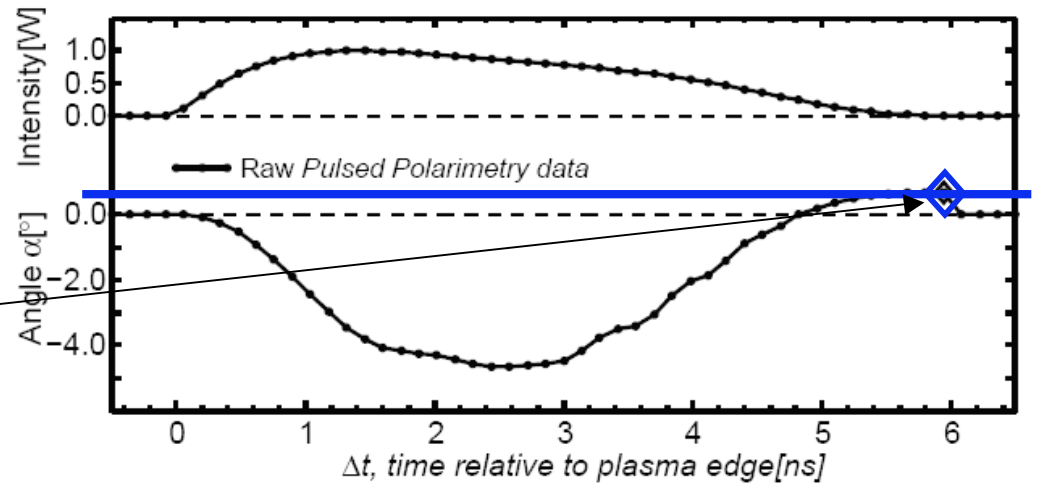
$$B_{\parallel(2j+1)/2}[T] = \frac{1.9 \times 10^{12}}{\lambda_o^2 (n_{e_{j+1}} + n_{e_j})/2} \left(\frac{\alpha_{PP_{j+1}} - \alpha_{PP_j}}{\delta L} \right)$$

Where j is the time index and δL is the distance for one time step:
 $\delta t = 2\delta L/c$.

Illustration of data from a Pulsed Polarimeter

- $I_o[W]$ and $\alpha_{pp}[^\circ]$ Vs Δt

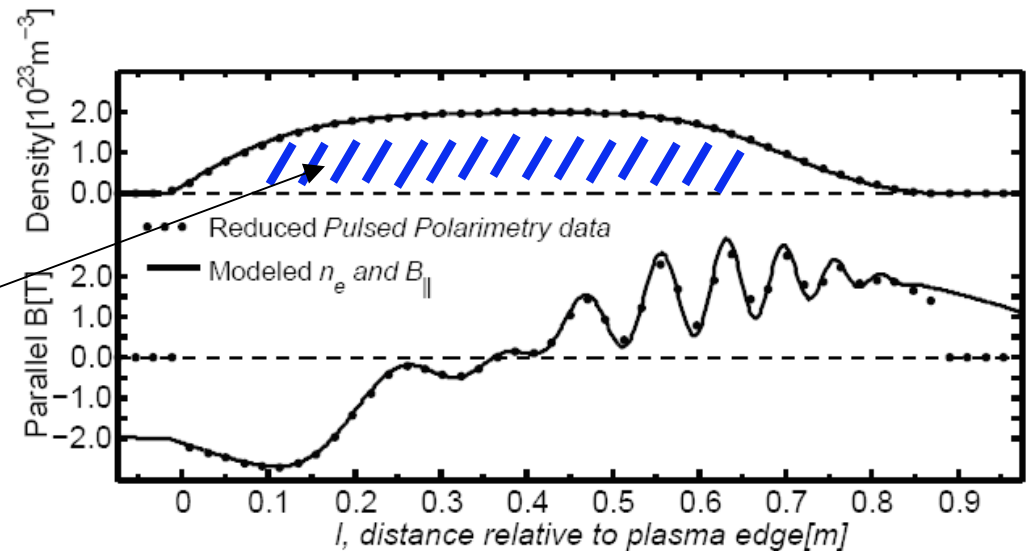
- Diamond point is the only data from the CW plasma polarimeter at a time T .



- $B_{||}[T]$ and $n_e [m^{-3}]$ Vs l ,

- Spatial resolution enough to resolve fluctuations

- CW interferometry measures area at time T .



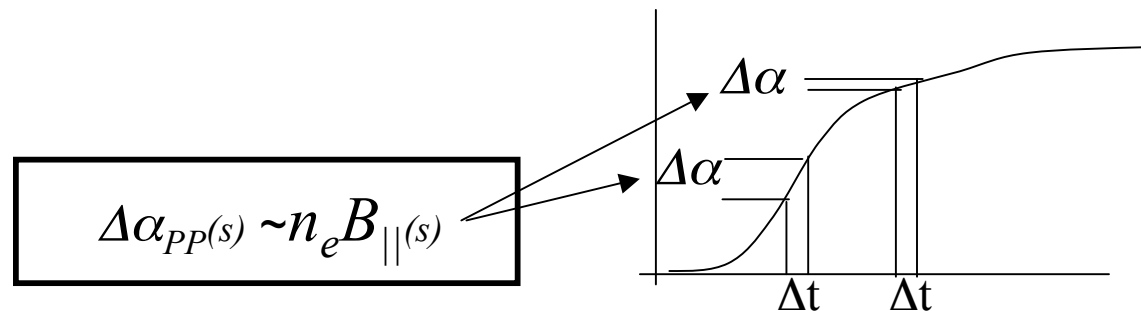
Why the name 'Pulsed Polarimetry'?

$\alpha_{PP(s)}$ is a non-local measurement, determined by the intervening plasma

- Requires: A *quasi-static* condition (as with CW polarimetry)
- The Faraday effect is dispersive which produces a rotation α spread

$$\delta\alpha/\Delta\alpha = 2\lambda_o N_m^2/L_p \text{ (0.7\% for FRX-L)}$$

- α is the difference of two non-local double-pass path integrals
- $n_e(s), T_e(s), \sim$ from intensity of backscatter – are 'truly' local measurements
 - intervening plasma does not interfere with measurement
 - *quasi-static* condition is not necessary



Measurement details

Rules of Pulsed Polarimetry

- $\alpha(L_p)$ is to be set relatively small, ~ 0.5 (30°)
$$V_s - V_p \sim 2 \alpha_{PP} I_o \quad \text{differential detection}$$
- The method improves with smaller λ_0 which means plasmas with a high $n_e B_{\parallel}$ product are better
- high n_e is needed to achieve good accuracy in resolving small rotation angles

Noise sources

I) Intrinsic backscatter photon noise:

$$N_{TS} \sim E_{pulse} \lambda_0 \Delta\Omega n_e \tau_{det}$$

II) Bremsstrahlung emission

$$N_{br} = E_{br}/h\nu_0 \sim Z_{eff} n_e^2 L_p A_{beam} \Delta\Omega \tau_{det} \lambda_0$$

III) Blackbody photon noise

$$SNR = \sqrt{\eta N_{TS}} / \sqrt{(N_{TS} + N_{br} + N_{bb})}$$

$$FRX-L: \quad N_{TS} = 4.4 \times 10^9$$

$$N_{br} = 3.9 \times 10^6$$

$$N_{bb} = \textit{negligible}$$

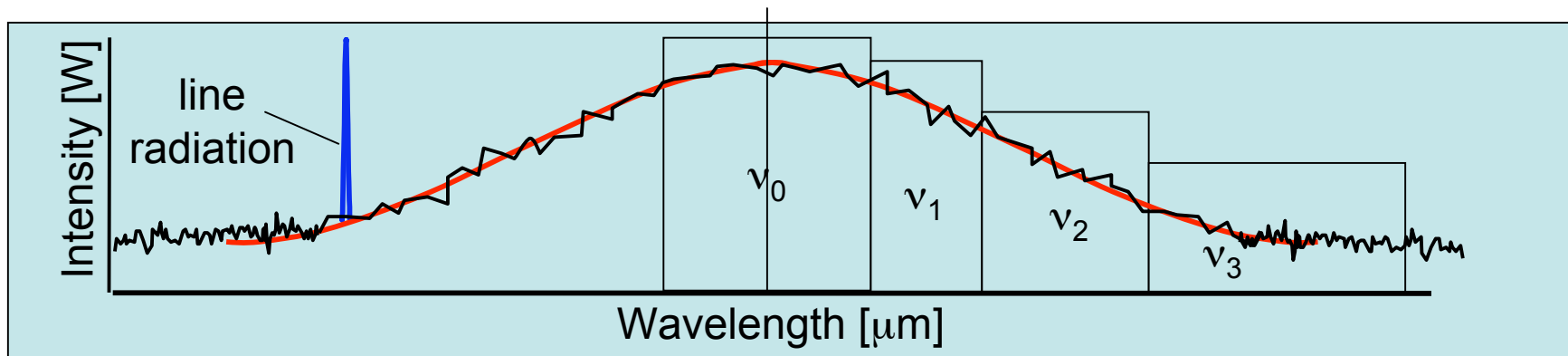
Optical Filtering

- For polarimetry a band-pass filter of width $\Delta\nu_{\text{filter}}$ centered on ν_0 is used to pass induced backscatter and reject (block) out-of-band plasma emission.

$$\Delta\nu_{\text{filter}}/\nu_0 = 2\nu_{th}/c = 1.4 \times 10^{-3} \sqrt{T_e [eV]}$$

($\pm 1\%$ for 300eV plasma(FRX-L), $\pm 7\%$ for a 10keV plasma, ITER)

However each filtering window, offset from ν_0 , will introduce a frequency dependent rotation in polarization. [It's a good thing](#) and can be used to gain more information specific to the location l .



Resolution of the Pulsed Polarimeter

$$SNR = 1/\varepsilon$$

Then $\delta n_e/n_e = \varepsilon$ and $\delta T_e/T_e = \varepsilon$

But $\delta B_{||}/B_{||} = \varepsilon / (2\Delta\alpha_{PP})^*$

***One trades off accuracy, $\delta B_{||}/B_{||}$, for spatial resolution: $2\Delta\alpha_{PP}$.**

Polarimeter angular resolution is taken to be $\sim 0.005^\circ$

When if ever is the background plasma emission too large?

$$\frac{E_{sc}}{\langle E_{br} \rangle} = \frac{1.2 \times 10^{26} E_{pulse}}{n_e Z_{eff} \lambda_o [\mu m] L_p} > 1$$

Using $r_{beam} \sim 1000 \lambda_o = 1mm$ for a NdYag source and $\Delta v_{filter}/v_o = 2v_{th}/c$

For $\lambda_o = 1\mu m$, $E_{pulse} = 1J$, $L_p = 4cm$, and $Z_{eff} = 2$, then $n_e = 1.5 \times 10^{27} m^{-3}$!. T
This gives a cutoff frequency of $350THz$ or $\lambda_{cutoff} = 0.86\mu m$.

Pulsed Polarimetry applied to the FRX-L experiment

Pulsed Polarimetry is just the tool for these dense and high $n_e B_{||}$ plasmas.

Conventional TS and CW polarimetry are very difficult to make work

FRX-L: **peak $n_e = 10^{23} m^{-3}$** **peak $B = 5T$** **$L_p = 36cm$**

Wavelength : $\lambda_o = 1.064\mu m,$

Pulse energy $E_{pulse} = 1J$

Time resolution $cdL = 200ps$ with $BW_{det} = 2.25GHz$

SNR = 5000:1 because max intensity = 5mW
NEP = 1 μW @2.25GHz

Spatial resolution $dL = 3cm$ 12 measurements

Solid angle $\Delta\Omega = 0.035sr$ ($\theta_{1/2} = 6^\circ$)

Incremental $\Delta\alpha_{pp} = 0.009(0.52^\circ)$ in 3cm

Intensity $I_o = 4W,$ $E_{sc} = 0.83nJ$

Plasma details: the scattering is incoherent Thomson scattering

Kirtland FRC $\Delta\alpha_{pp} = 15,400^\circ$ in 3cm at 500T and $300 \times 10^{23} m^{-3}$

A proposed Pulsed Polarimeter for FRX-L

$$\text{SNR} = 5000:1$$

(Detector limitation: $1\mu\text{W}$ and 5mW)

$$I_o = 4\text{W is too high by } 1000\text{x} !$$

So add more detectors and measure T_e , drop $\Delta\Omega$, etc.

With a $1\mu\text{W}$ NEP corresponding to $\tau_{\text{det}} = 200\text{ps}$:

$$n_e \text{ accuracy} \quad 0.02\%$$

$$B_{\parallel} \text{ accuracy} \quad \delta B_{\parallel}/B_{\parallel} = \varepsilon/2\Delta\alpha_{\text{pp}} \text{ or } 1\%$$

$$\text{Spatial localization} \quad 3\text{cm}$$

$$3\text{cm}: 5000 = 0.52^\circ (1:50) \text{ to } (\delta B_{\parallel}/B_{\parallel} 1\% \text{ accuracy})$$

With a $2\mu\text{W}$ NEP corresponding to $\tau_{\text{det}} = 50\text{ps}$:

$$8\text{mm}: 2500 = 0.13^\circ (1:200) \text{ to } (\delta B_{\parallel}/B_{\parallel} 8\% \text{ accuracy})$$

Prospects for Pulsed Polarimetry on HED plasmas

One must ask the following:

- 1) What λ range is needed for polarimetry?
- 2) Is there a laser in this range that is suitable for LIDAR?

Lasers: NdYag , TiSapphire, CO₂, FELs (1J, 10ps, 1ps, 100ps)

Detectors: InGaAs & Si photodiodes, IR HgCdTe detectors and PMTs

(400-1400nm, as fast as 60GHz)

Real time digitization: 60 GHz

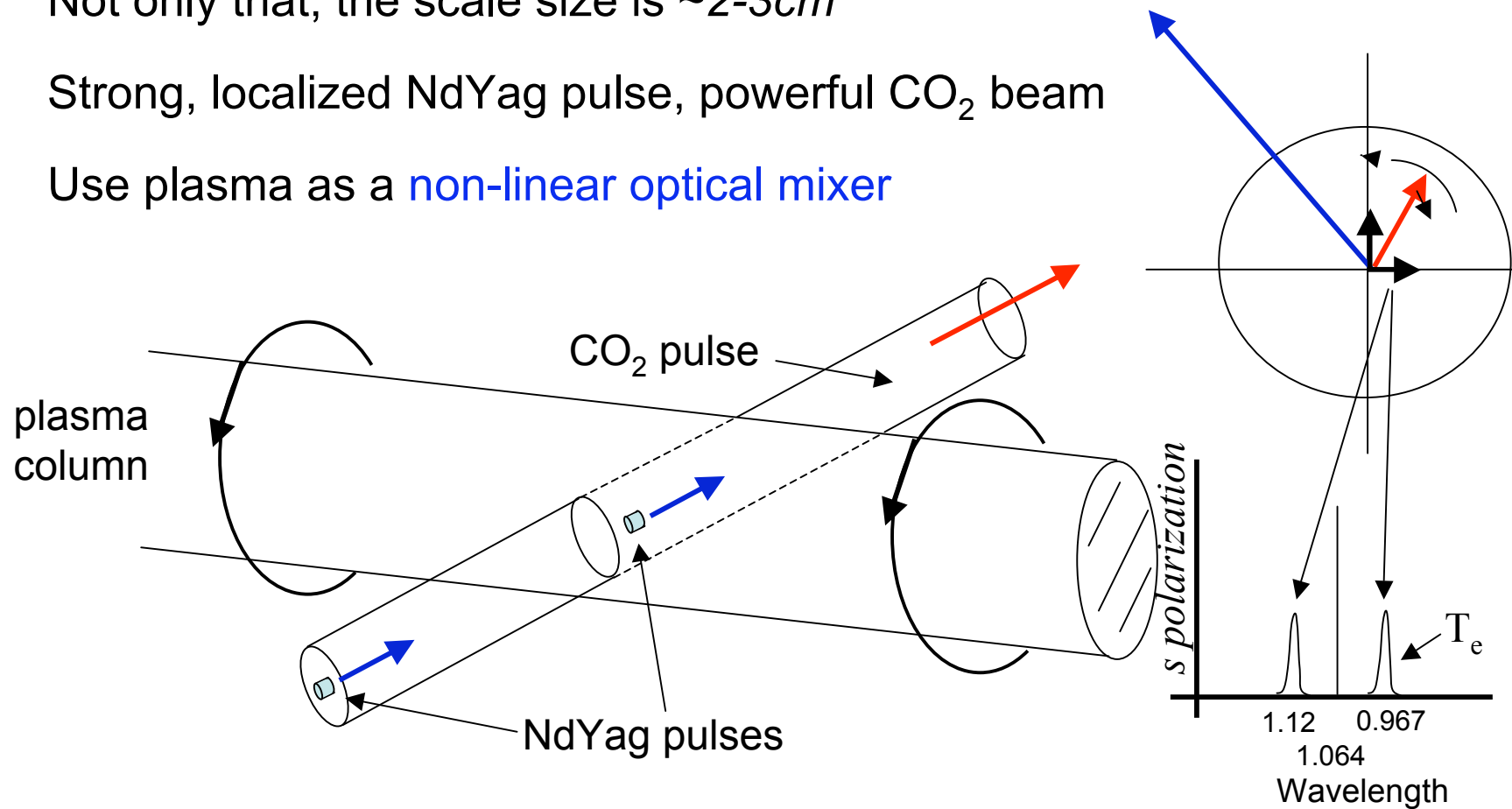
(200ps, 3cm, 2.25GHz and 8ps, 1.3mm, 60GHz)

Not to despair: $100\text{nm} - 1.5\mu\text{m}$, is ideal for lasers and detectors
for *mm-cm* resolution

Hybrid scheme ($n_e \sim 10^{23} \text{m}^{-3}$ and $B \sim 1 \text{T}$)

(work in progress)

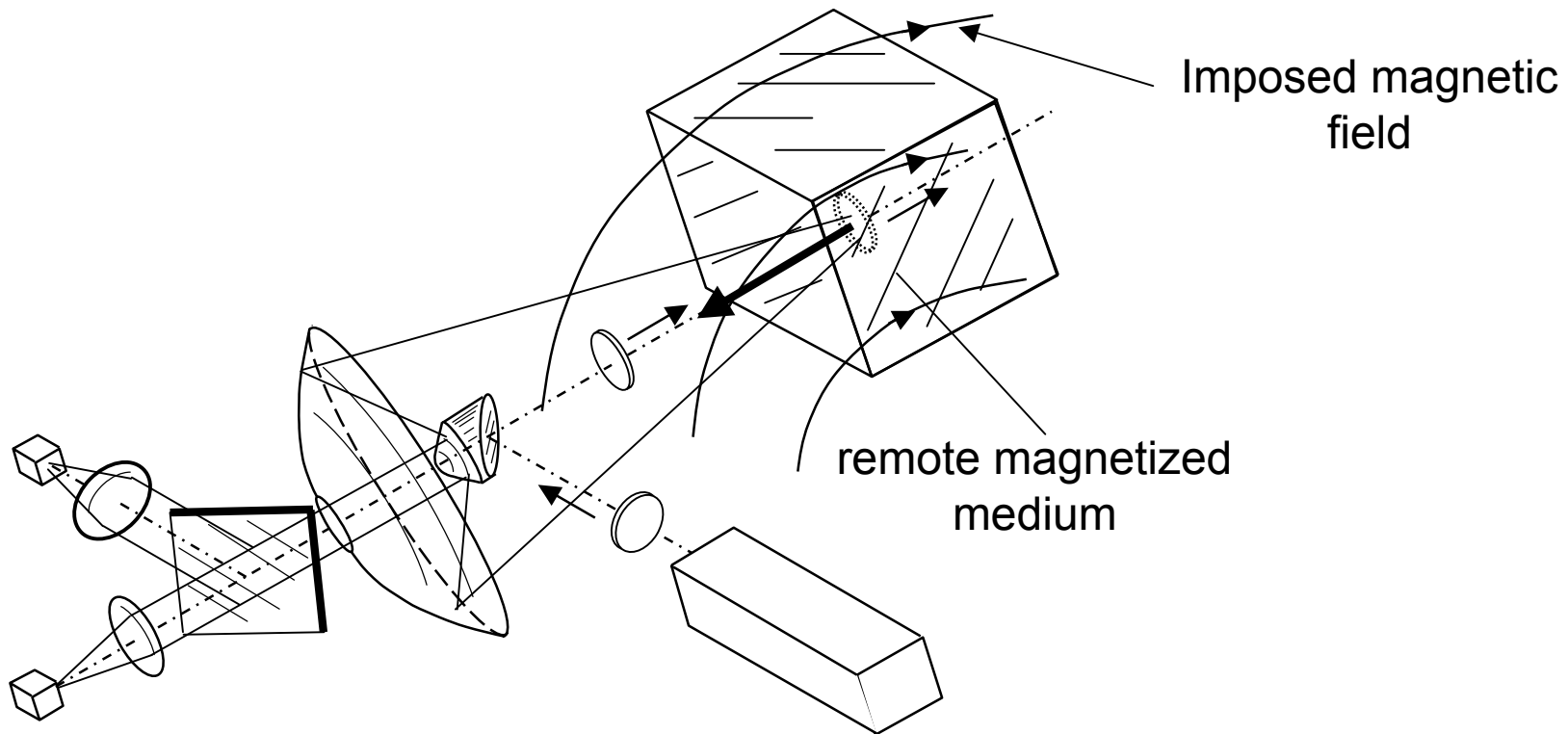
- CO₂ and NdYag lasers, $10.6 \mu\text{m}$ and $1.06 \mu\text{m}$
- $\alpha_{\text{co}_2} = 100 \times \alpha_{\text{NdYag}}$ **but** $\lambda_{\text{co}_2} = \lambda_{\text{NdYag}} / 10$ and low T_e
- Not only that, the scale size is $\sim 2\text{-}3 \text{cm}$
- Strong, localized NdYag pulse, powerful CO₂ beam
- Use plasma as a **non-linear optical mixer**



Ideas- I: Substitute medium

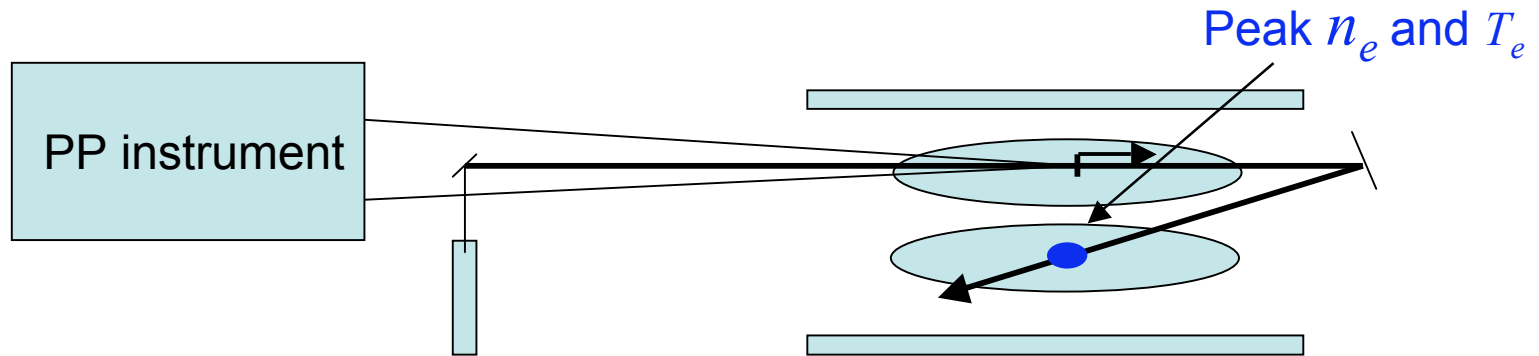
Faraday rotator glass medium

To align, calibrate and evaluate a Pulsed Polarimeter

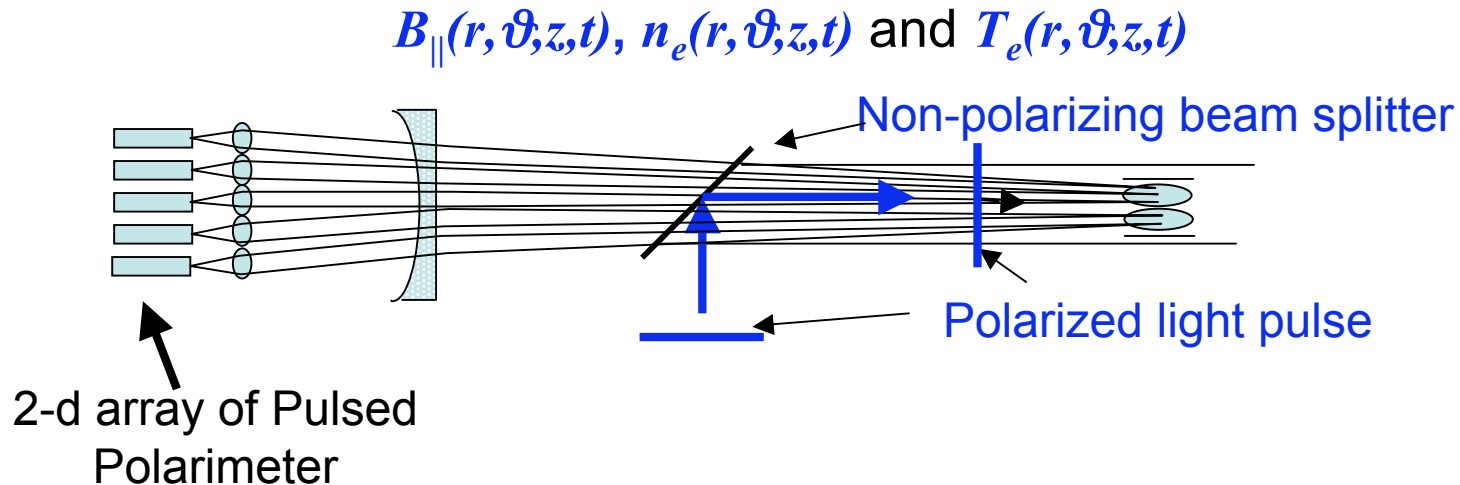


Ideas- II&III

Multi-pathing: pulse direction is redirected after one pass through the plasma. The second path might pass through the sightline where B_{\parallel} is weak but T_e peaks.



Imaging PP on AFRX-L: The plasma is smaller than the light pulse!



Advantages of Pulsed Polarimetry

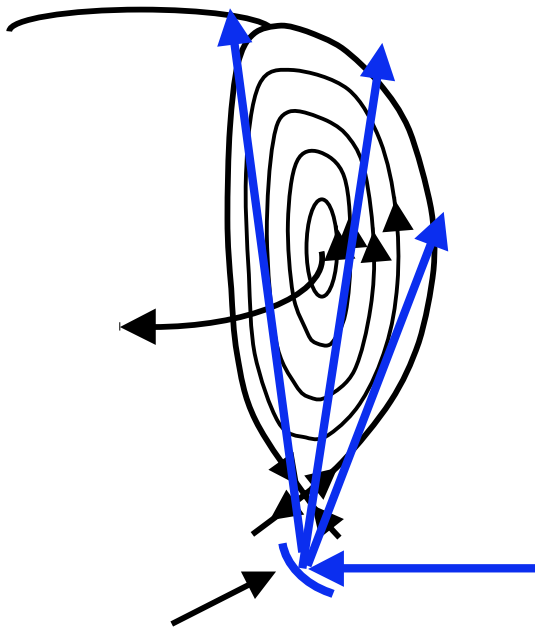
1. Measures local $B_{||}(s)$, $n_e(s)$ and $T_e(s)$ profiles in a [general purpose](#) diagnostic technique ([as opposed to a Carolan-like experiment or MSE](#)). Applies to ITER, burning plasmas and HEDLP experiments. *****
2. Nearly instantaneous profile measurement. ***66ps/1cm of plasma!********
3. Real-time feedback for mitigating MHD instabilities in tokamaks, provides time and [location](#).*****

4. Better interpretation of results ****

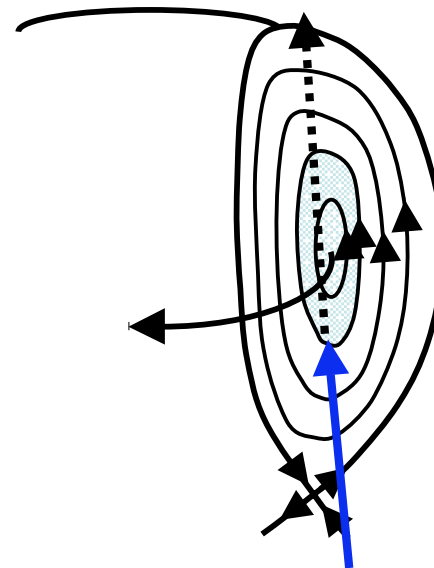
$$\alpha_{PP}(l, T) \sim \lambda_o^2 \int_0^l \frac{n_e B_{\parallel}(s)}{\sqrt{1 - \lambda_o^2 / \lambda_{cutoff}(s)^2}} ds$$

Allows a wavelength range right down to cutoff.

5. Unbounded sightline: Every CW polarimeter sightline is a possible Pulsed Polarimeter sightline, conversely, there are many more sightlines available to a Pulsed Polarimeter than for a CW polarimeter.*****



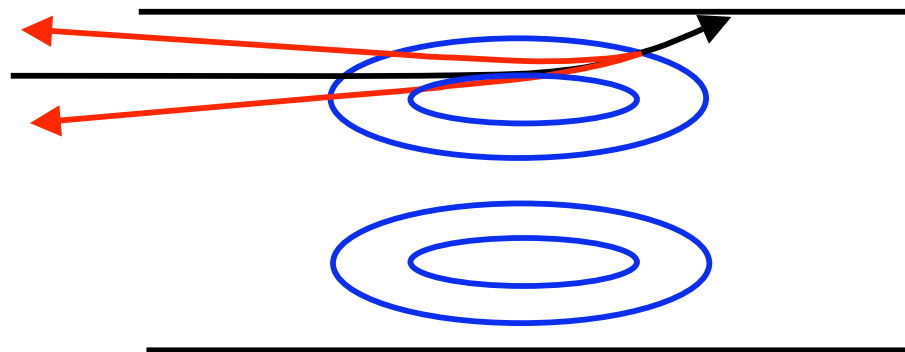
A steering mirror can be used to steer the pulse and collect light



If cutoff is present along the trajectory, the diagnostic still works, in principle

6. Radiation compatible. As a remote sensing optical diagnostic, it ranks with the best. No radiation sensitive equipment is needed in close proximity to the tokamak.*****

7. Refraction is reciprocal: The measurement is insensitive to refractive curving of the trajectory. However one must know the location of the measurement. ***



8. The best of all, the diagnostic works better on future plasmas that:

are denser

have higher fields

are more challenging

possibly changing the worst diagnosed plasmas
into the best diagnosed plasmas.

The End