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*** $B_{||}$, 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.

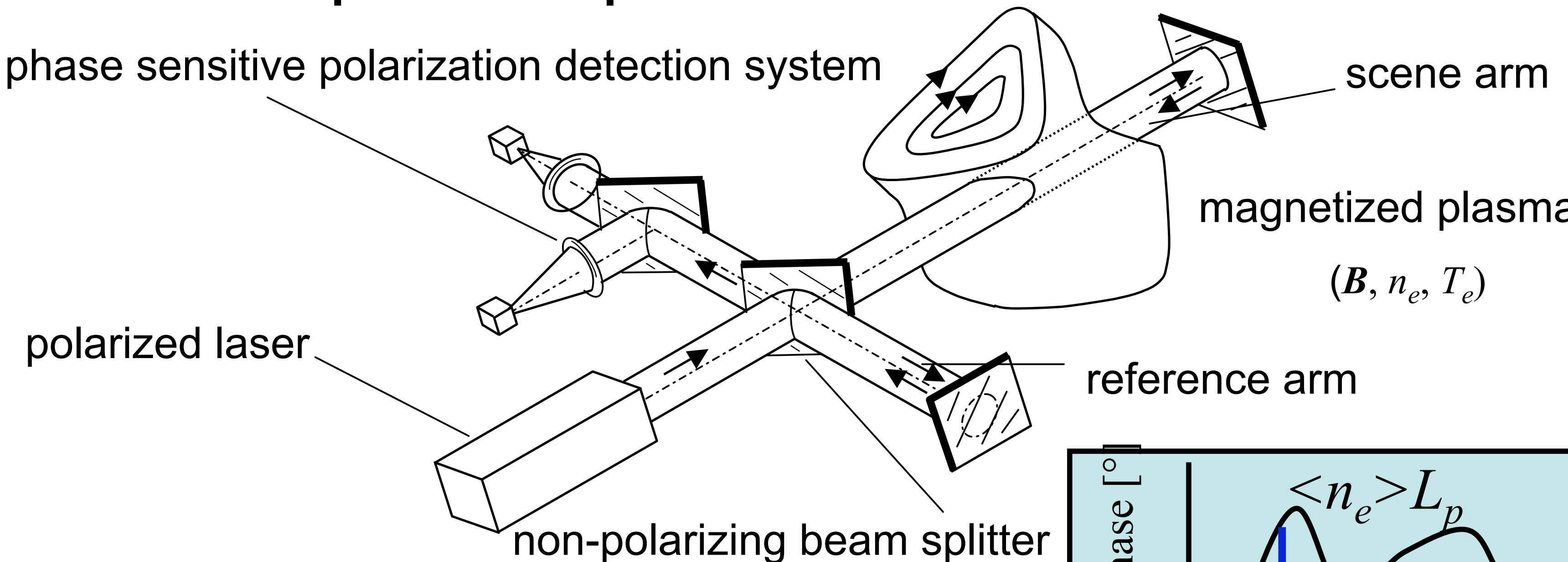
II) The Faraday effect is *non-reciprocal:* The sense of rotation of the polarization of light propagating in a plasma is independent of the direction of propagation.

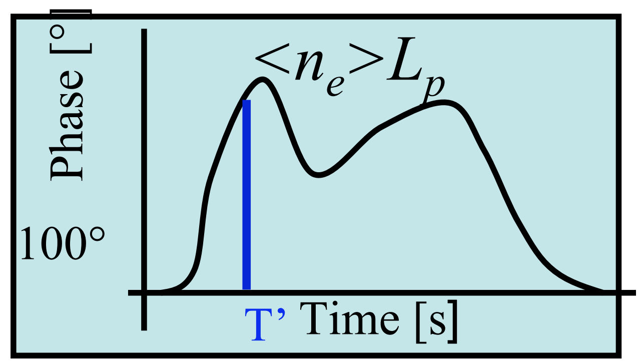
Combines two well known Plasma Diagnostics:

CW Polarimetry

and LIDAR Thomson scattering

CW plasma polarimeter/interferometer

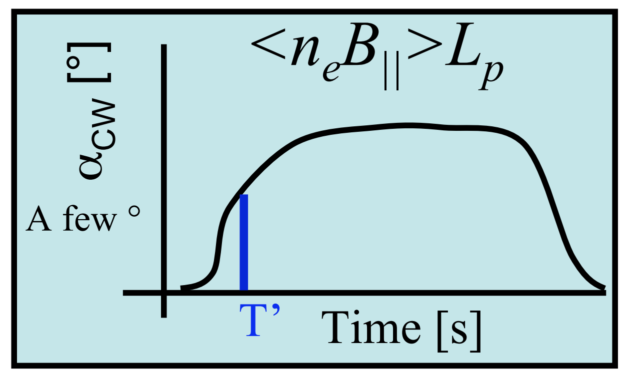




$$\phi_{CW}(T) = 2\; x4.5x10^{-16}\;\lambda_o \int_0^{Lp} n_e(s,t(s))\, ds$$

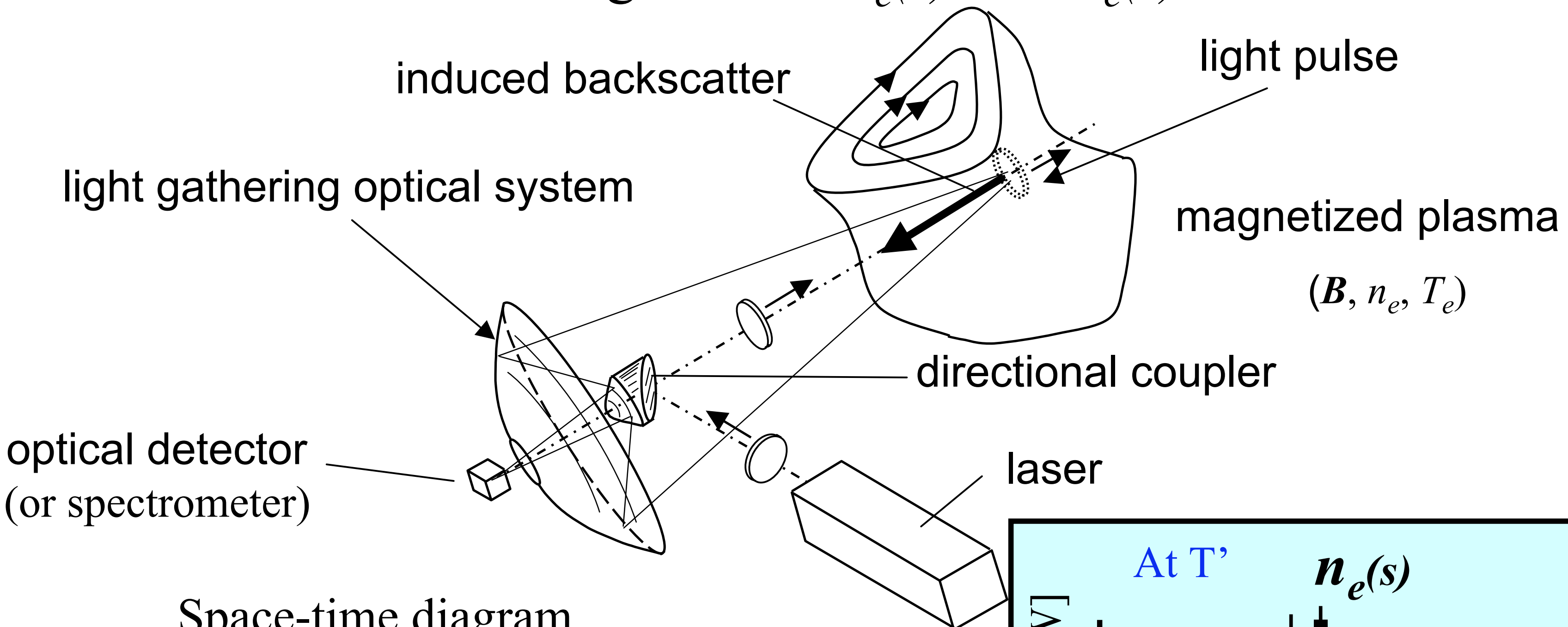
$$\alpha_{CW}(T) = 2\; x2.63x10^{-13}\;\lambda_o^{2} \int_0^{Lp} (n_e B_{\parallel})(s,t(s))\, ds$$

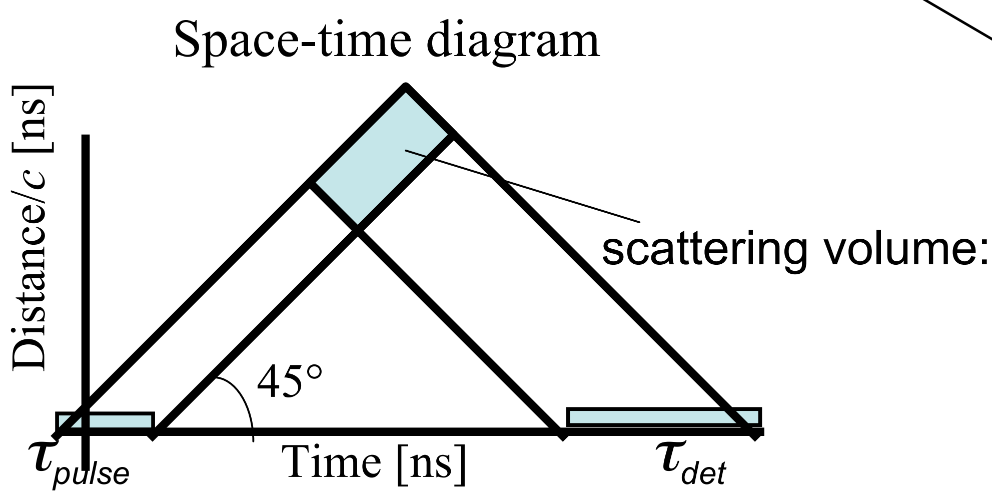
double pass

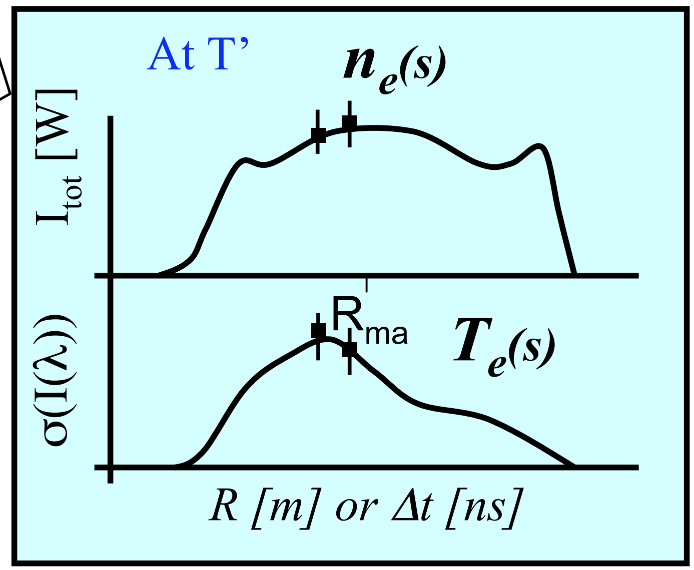


LIDAR Thomson Scattering

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

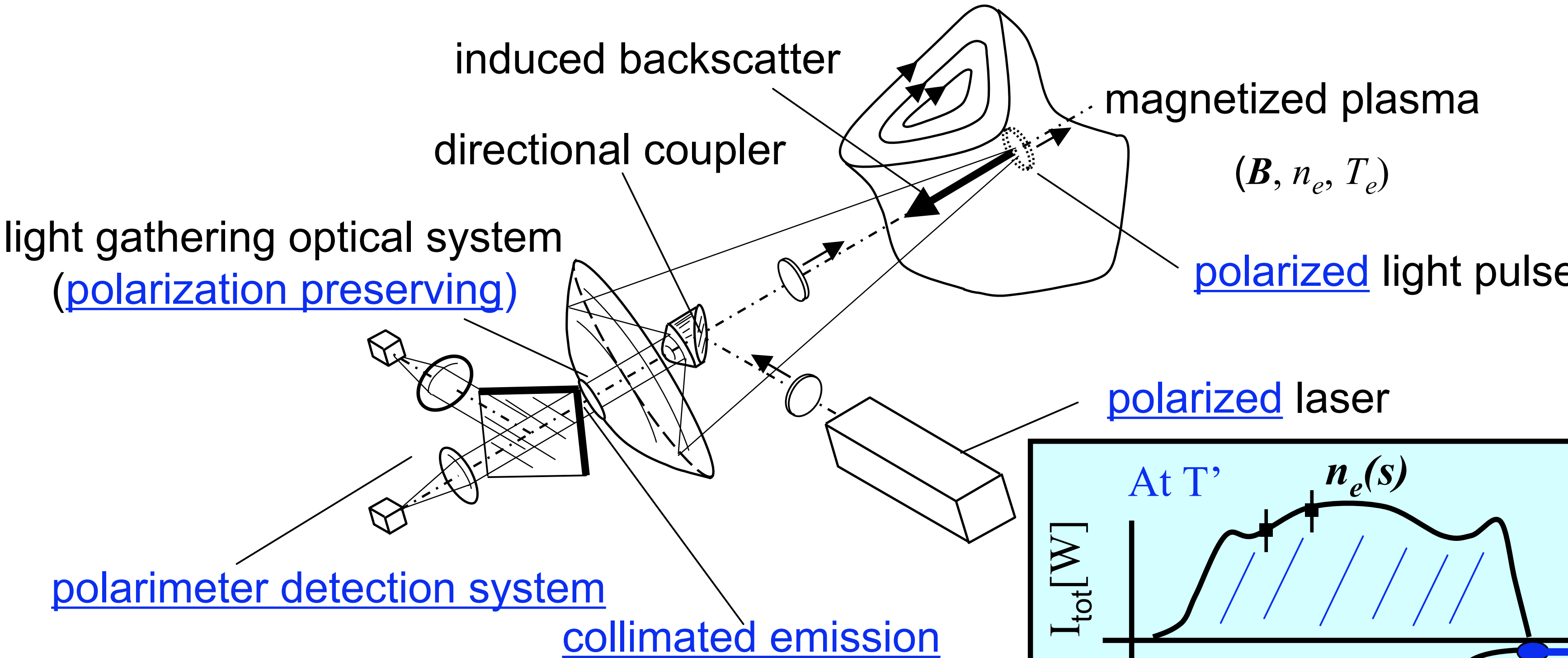


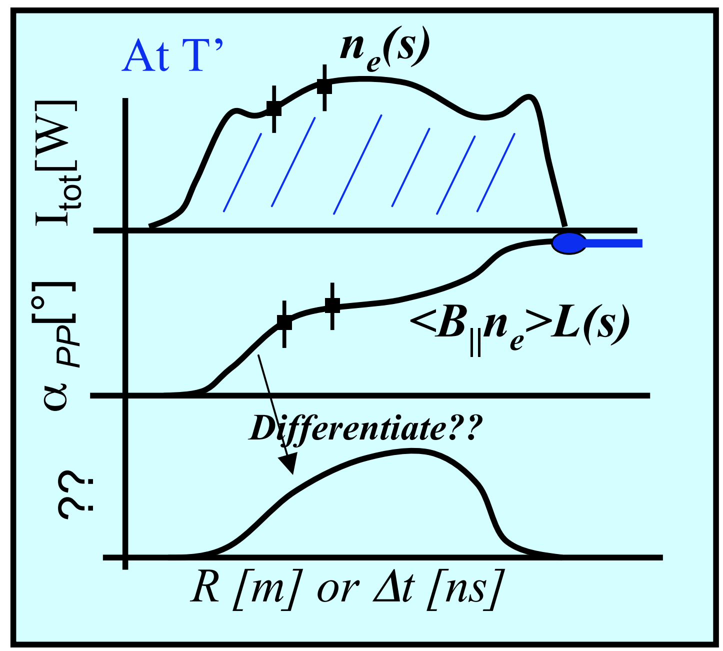




Pulsed Polarimeter

remote sensing of local $n_{e(s)}$ and $n_e B_{||(s)}$ (and $T_{e(s)}$)



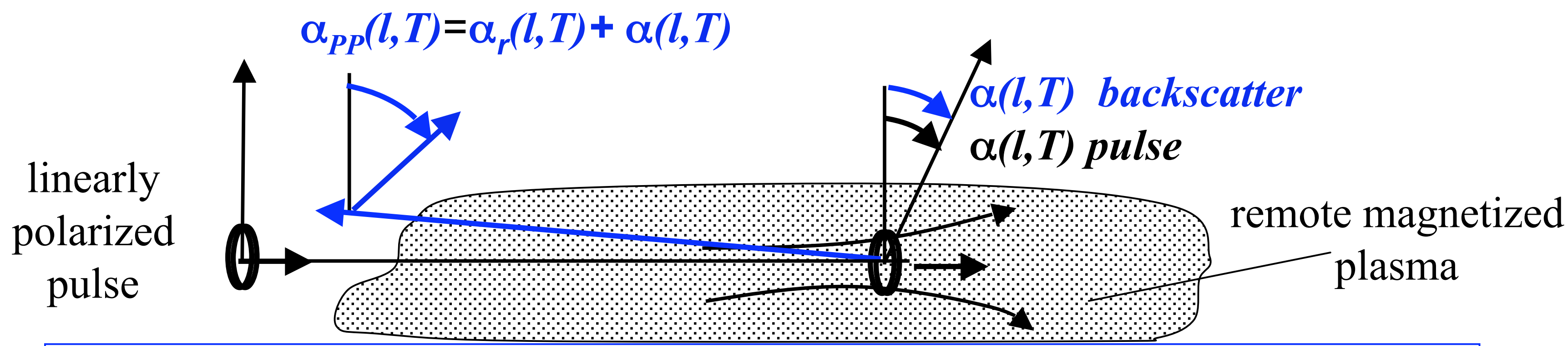


But how does one measure a local quantity, by differentiation? What does it mean?

Combining the two principles

In plasma

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



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: $\alpha_r(l,T) = \alpha(l,T)$ *(6.6ns/m)*

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

Measurement Process

Density:

$$n_e(l)[m^{-3}] = \frac{I_o(l)}{7.8x10^{-30}\ \Delta\Omega(l)\ E_{pulse}c/2}$$

Density-field product:

$$n_e B_{||}(l)[Tm^{-3}] = \frac{1.9x10^{12}}{\lambda_o^{\ 2}} \left(\frac{\partial \alpha_{PP}(s,T)}{\partial s} \right) \Bigg|_l$$

$B_{||}$ field:

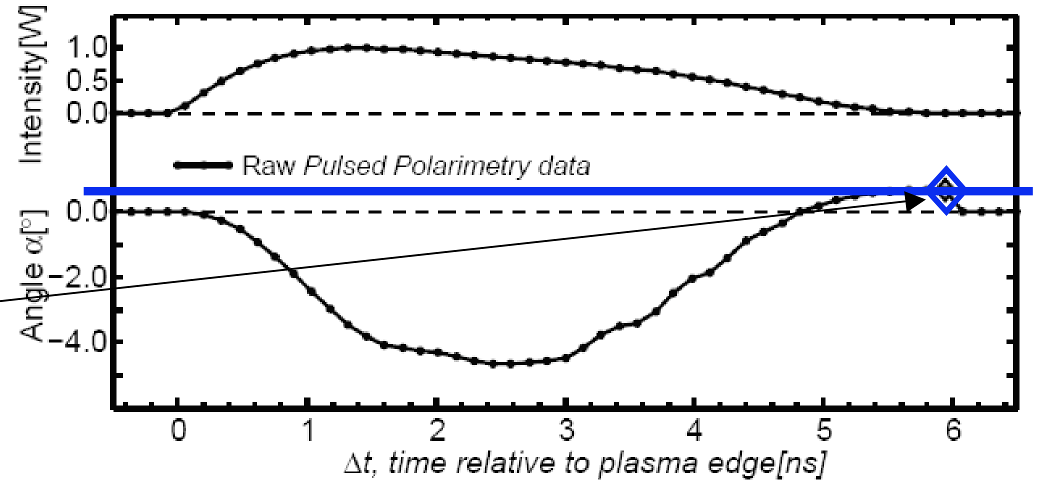
$$B_{||_{(2j+1)/2}}[T] = \frac{1.9x10^{12}}{\lambda_o^{\ 2}\left(n_{e_{j+1}} + n_{e_j}\right)/2} \left(\frac{\alpha_{PP_{j+1}} - \alpha_{PP_j}}{\delta L} \right)$$

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 $\alpha_{pp}[°]$ Vs Δt

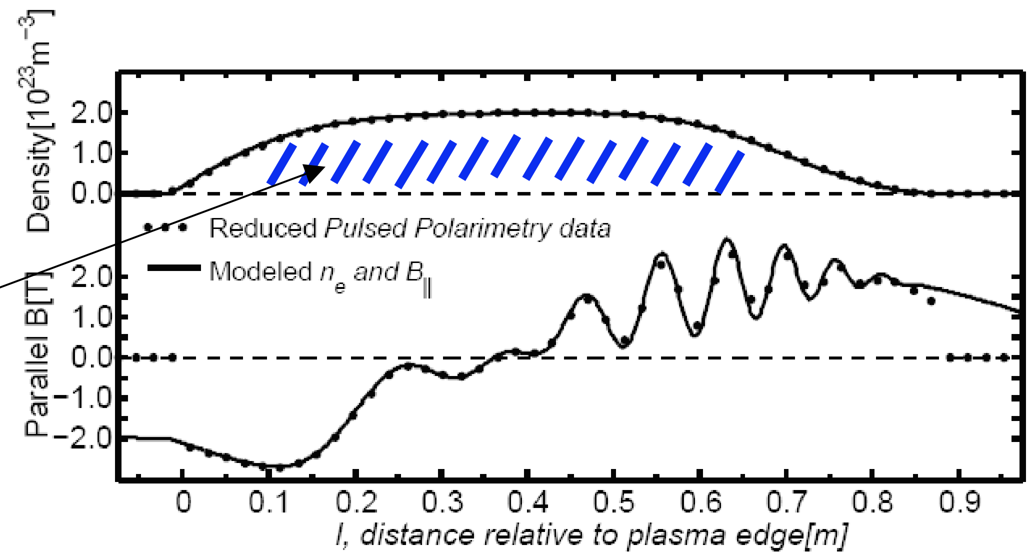
- Diamond point is the <u>*only*</u> data from the CW plasma polarimeter at a time T.



- $B_{||}[T]$ 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

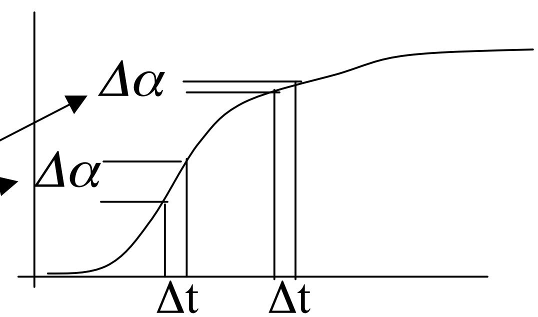
- Requires: A ***quasi-static*** condition (as with CW polarimetry)
- The Faraday effect is dispersive which produces a rotation α spread

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

- α is the difference of two ***non-local*** double-pass path integrals

- $n_e(s)$, $T_e(s)$, ~ from intensity of backscatter – are '***truly' local*** measurements
  - intervening plasma does not interfere with measurement
  - ***quasi-static*** condition is not necessary

$$\Delta\alpha_{PP}(s) \sim n_e B_{||}(s)$$



Measurement details

Rules of Pulsed Polarimetry

- $\alpha(L_p)$ is to be set relatively small, ~0.5 **(*30°*)**

  V_s-V_p ~2 $\alpha_{PP} I_o$ *differential detection*

- The method improves with smaller λ_o which means plasmas with a high $n_e B_{||}$ product are better

- high n_e is needed to achieve good accuracy in resolving small rotation angles

Noise sources

I) Instrinsic backscatter photon noise:

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

II) Bremsstrahlung emission

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

III) Blackbody photon noise

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

FRX-L:

$N_{TS} = 4.4x10^9$

$N_{br} = 3.9x10^6$

$N_{bb} = negligible$

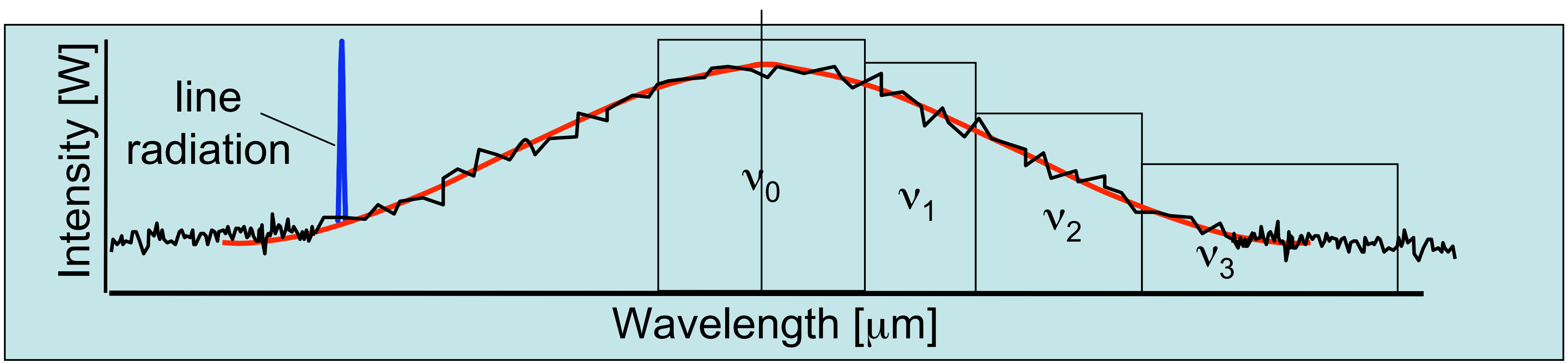
Optical Filtering

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

$$\Delta\nu_{filter}/\nu_o = 2v_{th}/c = 1.4\times10^{-3}\sqrt{T_e[eV]}$$

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

However each filtering window, offset from ν_o, 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 $\sim 0.005°$

When if ever is the background plasma emission too large?

$$\frac{E_{sc}}{\langle E_{br} \rangle} = \frac{1.2\text{x}10^{26}\ E_{pulse}}{n_e\, Z_{eff}\, \lambda_{o\,[\mu m]}\, L_p} > 1$$

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

For $\lambda_o = 1\mu m$, $E_{pulse} = 1J$, $L_p = \underline{4cm}$, *and* $Z_{eff} = 2$, then $n_e = 1.5x10^{27} m^{-3}$!. 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=*1μW@2.25GHz*
Spatial resolution dL = 3cm *12 measurements*
Solid angle $\Delta\Omega = 0.035sr$ ($\theta_{1/2} = 6°$)
Incremental $\Delta\alpha_{pp}$ = *0.009*(0.52°) 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° in 3cm at 500T and $300 \times 10^{23} m^{-3}$

A proposed Pulsed Polarimeter for FRX-L

SNR = *5000:1*

(Detector limitation: 1μW and 5mW)

I_o = ***4W is too high by 1000x !***

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

With a 1μW NEP corresponding to τ_{det} = 200ps:

n_e accuracy	*0.02%*
$B_{\|\|}$ accuracy	$\delta B_{\|\|}/B_{\|\|} = \varepsilon/2\Delta\alpha_{pp}$ *or 1%*
Spatial localization	*3cm*

3cm: 5000 = 0.52º (1:50) to ($\delta B_{||}/B_{||}$ 1% accuracy)

With a 2μW NEP corresponding to τ_{det} = 50ps:

8mm: 2500 = 0.13º (1:200) to ($\delta B_{||}/B_{||}$ 8% 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, CO_2, 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)

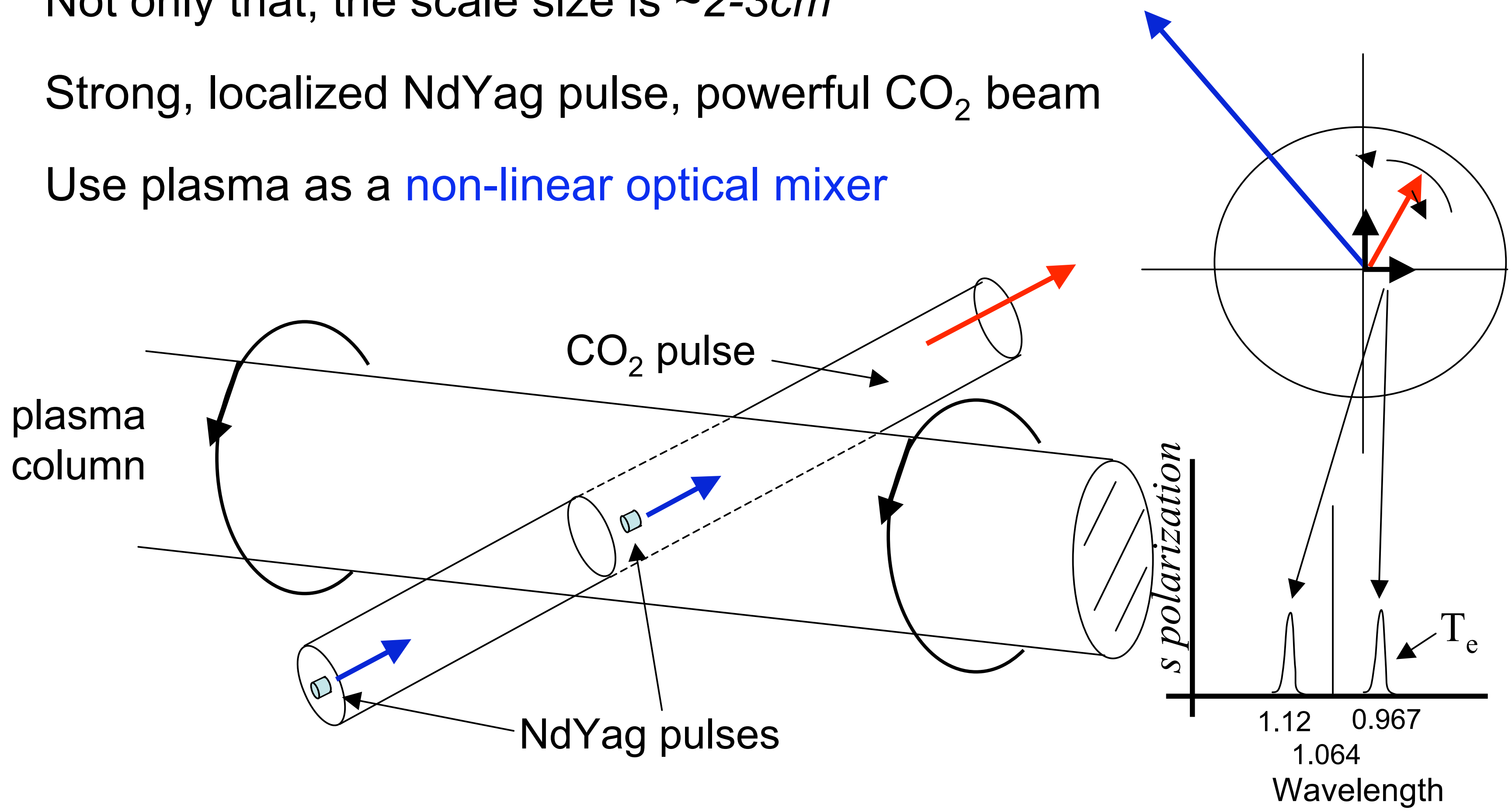
Not to despair: 100nm – 1.5μm, is ideal for lasers and detectors

for ***mm-cm*** resolution

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

(work in progress)

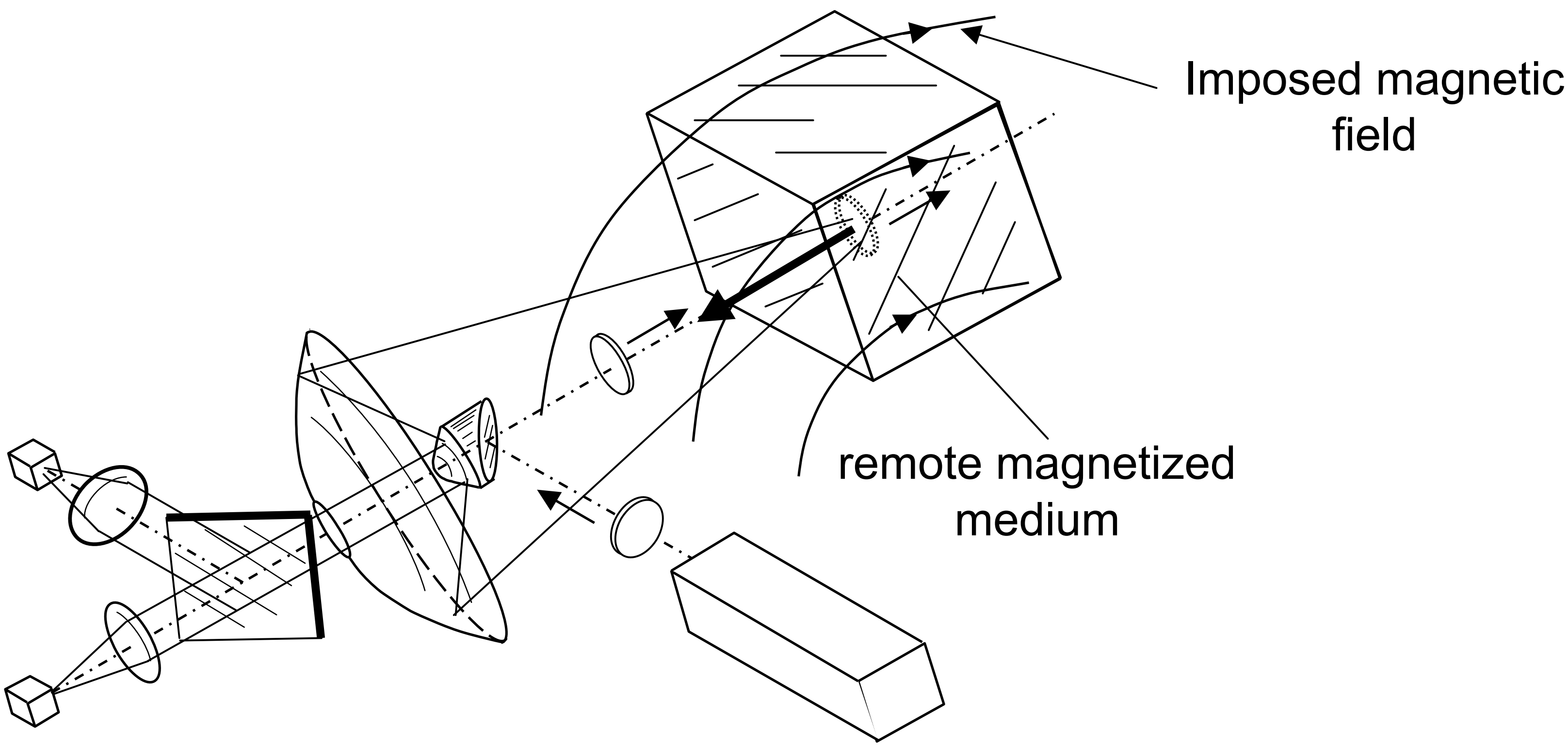
- CO2 and NdYag lasers, 10.6μm and 1.06μm
- $\alpha_{co2}=100x\alpha_{NdYag}$ **but** $\lambda_{co2}= \lambda_{NdYag}/10$ and low T_e
- Not only that, the scale size is ~*2-3cm*
- Strong, localized NdYag pulse, powerful CO_2 beam
- Use plasma as a non-linear optical mixer



Ideas- I: Substitute medium

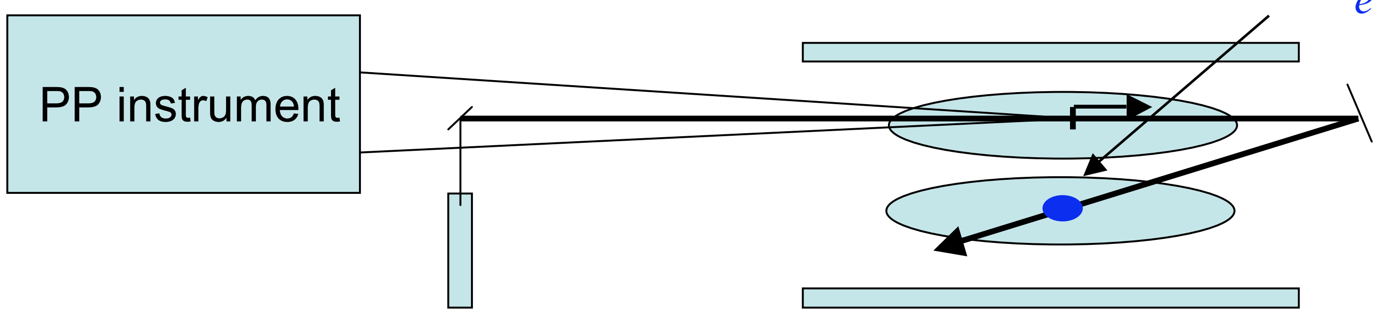
Faraday rotator glass medium

To <u>align</u>, <u>calibrate</u> and <u>evaluate</u> a Pulsed Polarimeter



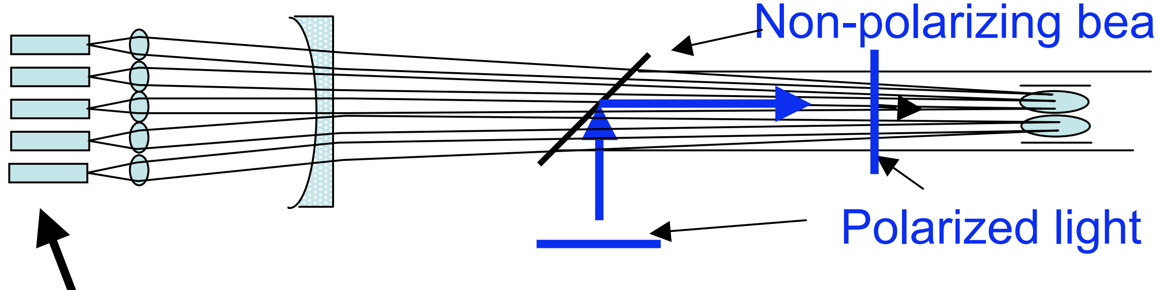
Ideas- II&III

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



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

$B_{||}(r,\vartheta,z,t)$, $n_e(r,\vartheta,z,t)$ and $T_e(r,\vartheta,z,t)$



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,

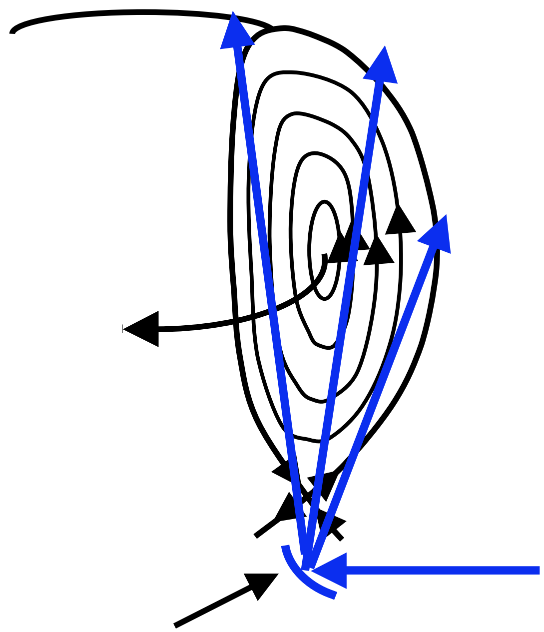
provides time and location.*****

4. <u>Better interpretation of results</u> ****

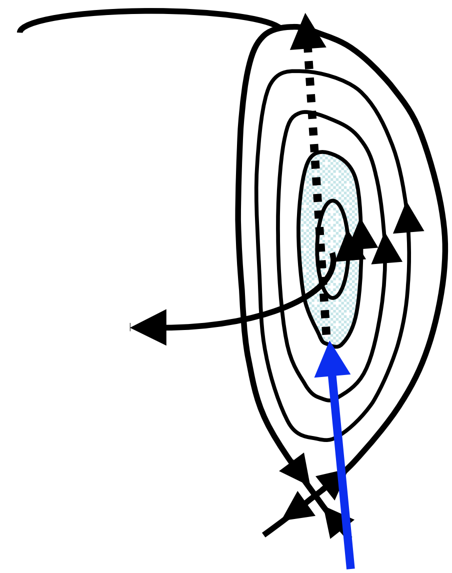
$$\alpha_{PP}(l,T) \sim \lambda_o^{\,2} \int_0^l \frac{n_e B_{\parallel}(s)}{\sqrt{1-\lambda_o^{\,2}/\lambda_{cutoff}(s)^2}}\, ds$$

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.*****



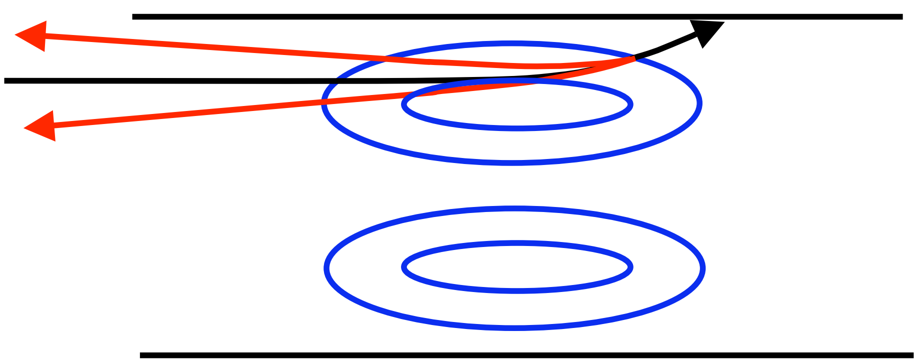
A steering mirror can be used to steer the pulse and collect light



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

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

7. <u>Refraction is reciprocal:</u> 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