IPP INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

THOMSON SCATTERING

PETRA BÍLKOVÁ

Institute of Plasma Physics of the Czech Academy of Sciences

OUTLINE

☐ Introducing me
☐ Thomson scattering – Principles
☐ Thomson scattering – Experimental setup
☐ Main instrumental strategies how to measure profiles of T_e and n_e
☐ Examples of TS diagnostics at fusion devices
☐ Good to think of
☐ Challenges
☐ New trends

INTRODUCING MYSELF

- Mathematic – Physics Faculty, Charles University, Prague. PhD in Experimental physics – Low temperature plasma, thin layers
- NATO grant – magnetron sputtering, producing ZnO and BN layers and its characterization
- Institute of Physics – Liquid crystals
- Institute of Plasma Physics – High temperature plasma physics and fusion. Task: build Thomson scattering
- First trip was to TEXTOR tokamak – supervision of Mikhail Kantor and Roger Jaspers
- Second trip was to MAST – supervised by Mike Walsh and Rory Scannell
- I met many great Thomson scattering people through the years – conferences, experiments
- I came to the IPP to do a research but I was asked to build the diagnostics system first
- Instrumentation is an important art. There is no perfect fusion research without good diagnostics.
- Thomson scattering can be simple but it is not easy (no big mistakes allowed on the road …)
- Therefore, life of “Thomsonists” is never boring

PRINCIPLES

Acknowledgement:

M.Leyland (University of YORK & CCFE, Culham Science Centre – MAST and JET)
M.J.Walsh (ITER, Head of Diagnostics)
R.Scannell (CCFE, Culham Science Centre, MAST, Thomson scattering)

PRINCIPLES

Gas in thermal equilibrium (f.e. in a room) – most probable **velocity distribution** of the particles is Maxwellian

1D **Maxwellian** velocity distribution:

$f(v_x) = A.e\text{-}((1/2mv_x{}^2)/k_BT)$

Normalisation: density $n = {}_{-\infty}{}^{\infty} \int f(v)dv$

$A=n(m/(2\pi k_BT))^{1/2}$

PRINCIPLES

Typical velocity of N_2 at 300K:

$1/2m\mathbf{v}^2 = 1/2k_B\mathbf{T}$

at 300 K : v = 0.30 kms^{-1}

Different temperature would change the velocity.

PRINCIPLES

Maxwellian can be generically expressed as a Gaussian:

$$f(x) = 1/(\sigma(2\pi)^{1/2}).e\text{-}(1/2(x\text{-}x_0)^2/\ \sigma^2)$$

x_0 mean

σ standard deviation

related to width of Gaussian

1D: $\sigma = (k_BT/m)^{1/2}$, $x_0 = 0$

$1/2mv^2 = 1/2k_BT \quad \Rightarrow \quad v = \sigma$

Can determine σ from Gaussian and relate the width to temperature, i.e.

width of the Maxwelian is determined by the constant T called temperature.

Temperature quoted in energy units:

T_e = 1keV ≈ 10 000 000 K

PRINCIPLES

Plasma – quasi neutral gas of ions, electrons, neutrals

We assume a **Maxwellian distribution of electron velocities**

PRINCIPLES

(Just remind):

Wave: $A(\theta) = B. \cos(\theta)$

θ phase, A amplitude, B constant

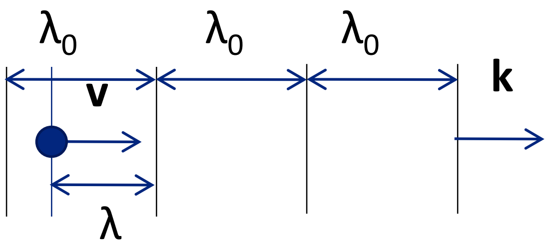
k vector: $k=d\,\theta/dx$

$A(x)=B.\cos(kx+\varphi)$

1 cycle $\Delta\,\theta=2\pi$, $x=\lambda$ $\qquad$ $k= =2\pi/\,\lambda$

$\omega = 2\pi/T = 2\pi f$

Doppler shift:



$\lambda = \lambda_0 - v.T$

Source emitting wave (λ_0) is moving at a velocity **v**
λ is compressed by the distance the source travels in 1 period

shortening λ – blue shift
extending λ – red shift

PRINCIPLES

Doppler shift:

$\lambda = \lambda_0 - v.T = \lambda_0 - v.\ \lambda_0/c = \lambda_0\,(1-v/c),\ \ T=1/f = \lambda_0/c$

$\Delta\lambda = \lambda - \lambda_0 = \lambda_0\,(1-v/c) - \lambda_0$

$\Delta\lambda/\ \lambda_0 = -v/c$ $\Delta\ \omega/\omega_0 = v/c$

Positive shift in λ results in negative shift in ω.

$\Delta\ \omega = \omega_0\ .v/c = (2\pi/\ \lambda).v = k.v$

More generically $\Delta\ \omega = \mathbf{k.v}$

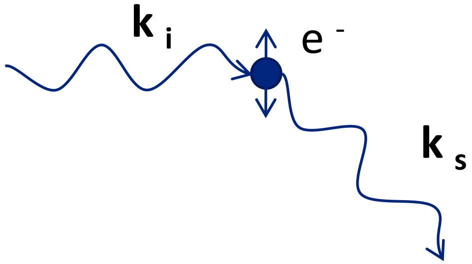
The frequency change due to Doppler shift is equal to the dot product of the k vector and the velocity of the source.

PRINCIPLES

Scattering:

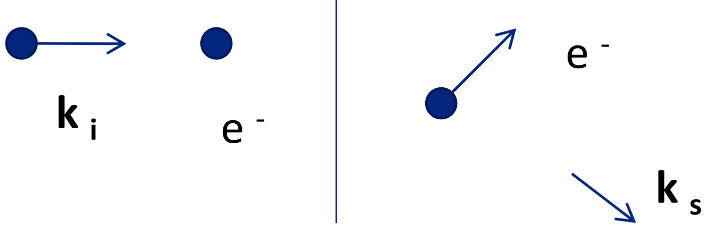
Classical – absorption & re-emission $\hbar\,\omega << mc^2$

THOMSON SCATTERING



Quantum – collision of particles $\hbar\,\omega >> mc^2$

COMPTON SCATTERING



PRINCIPLES

Scattering regimes on free electrons:

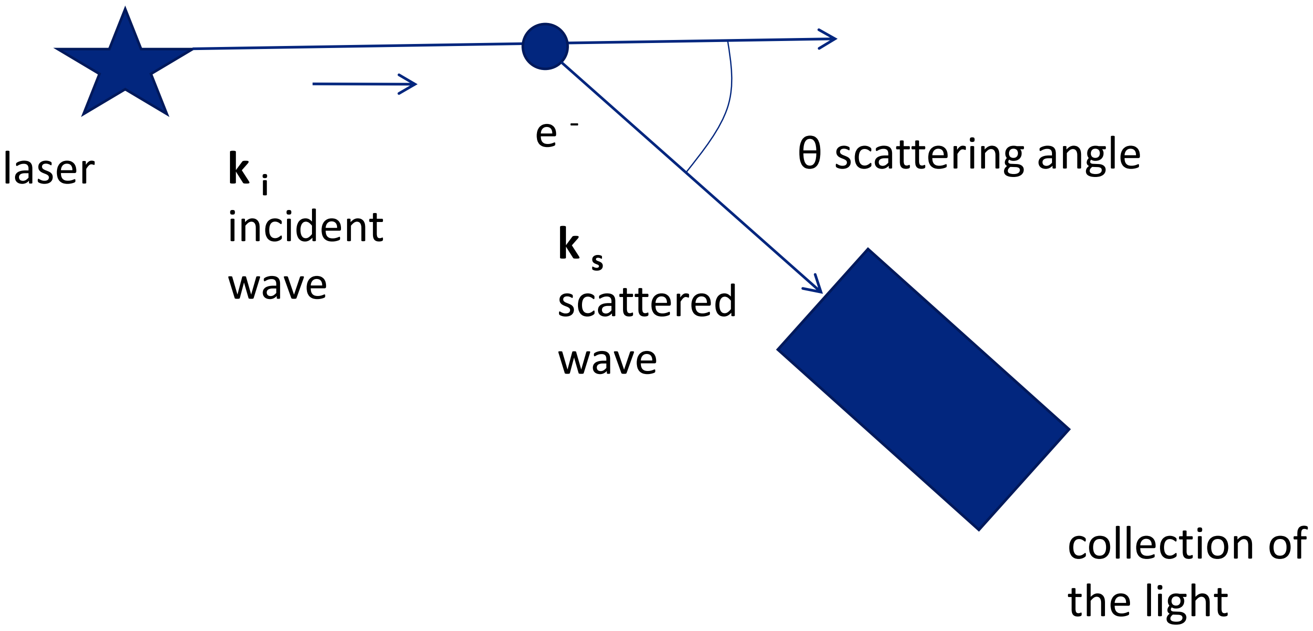
e^- : $mc^2 = 0.51$ MeV

Nd:YAG lasers ($\lambda = 1064$ nm) : $\hbar\,\omega = 1.17$ eV

Ruby lasers ($\lambda = 694.3$ nm) : $\hbar\,\omega = 1.79$ eV

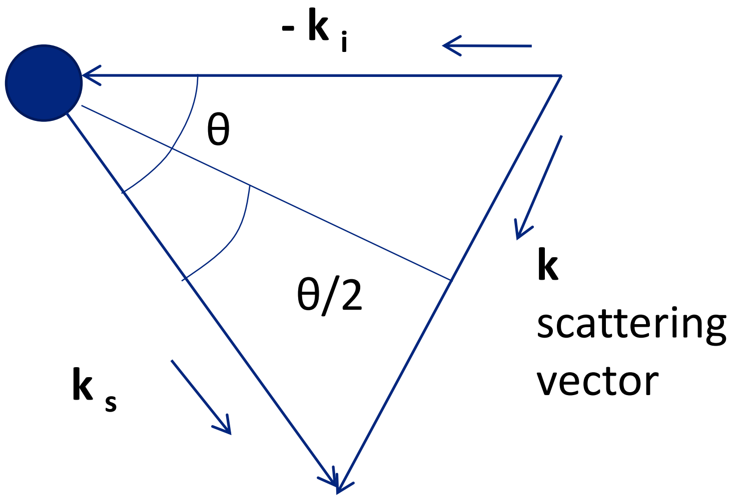
Both Thomson scattering regimes.

Typical exprimental setup for Thomson scattering



GEOMETRY

Geometry:



$\mathbf{k} = \mathbf{k_s} - \mathbf{k_i}$

$k_s = k_i = 2\pi/\lambda_0$

$\sin \theta/2 = (k/2)/k_s$

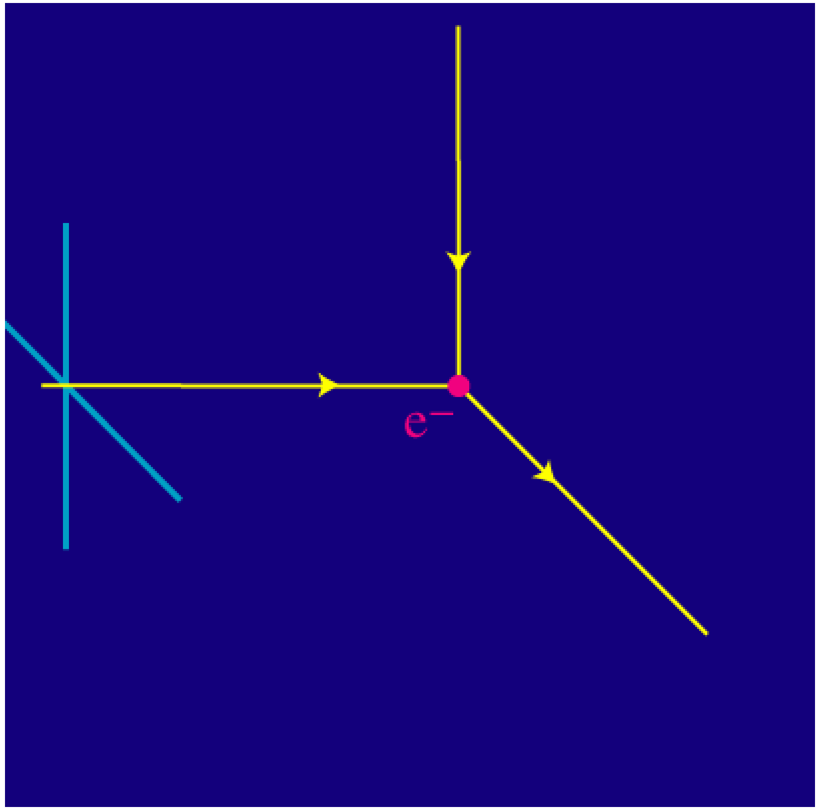
$k = 2.k_s.\sin \theta/2$

remind:

$\Delta\omega = k.v$

$\Delta\omega \approx \sin \theta/2$

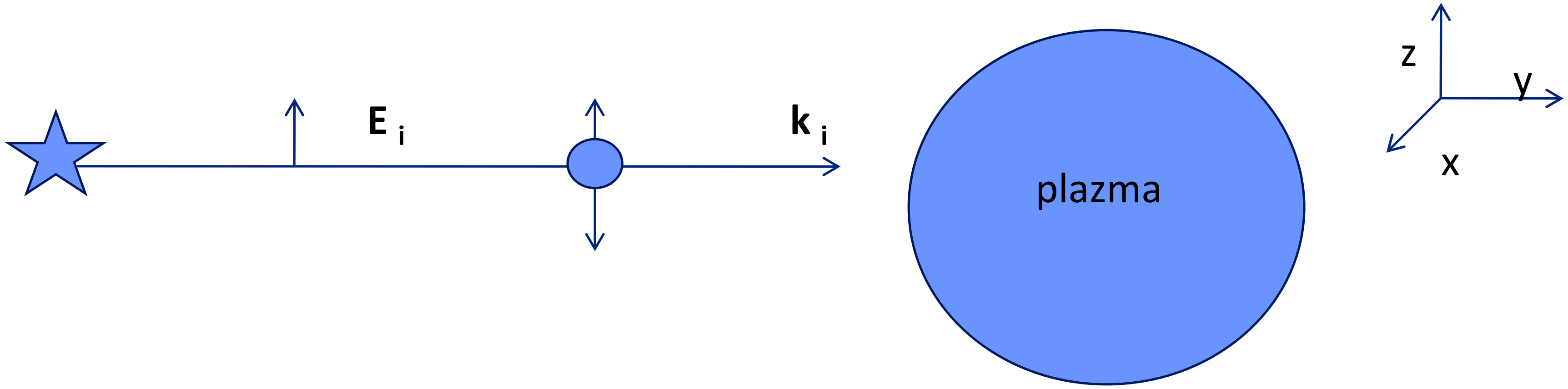
POLARIZATION



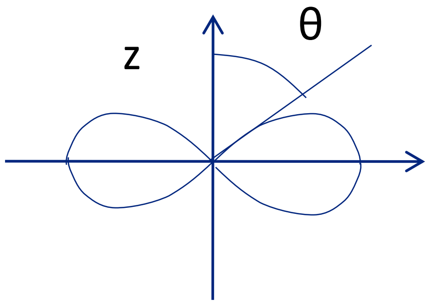
http://bolo.berkeley.edu/~rogero/I_eat_bugers/slide2.html

POLARIZATION

Laser light is polarized:

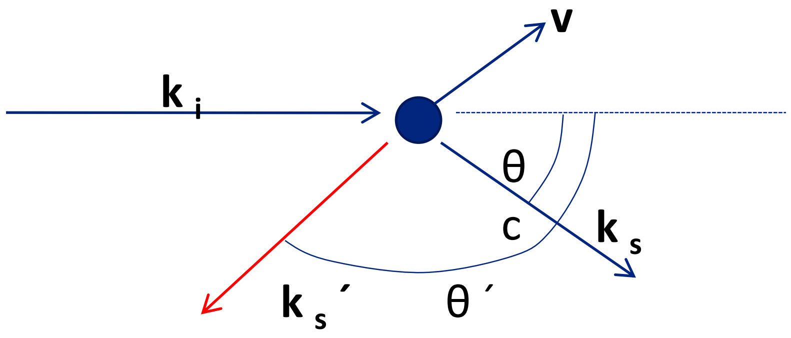


E_i oscilates in a z direction
electron oscilation also in a z direction
re-emitted wave not in direction of oscillation,
defined by **differential scattering cross-section**
$d\sigma/d\Omega = r_e^2 \sin^2 \theta$



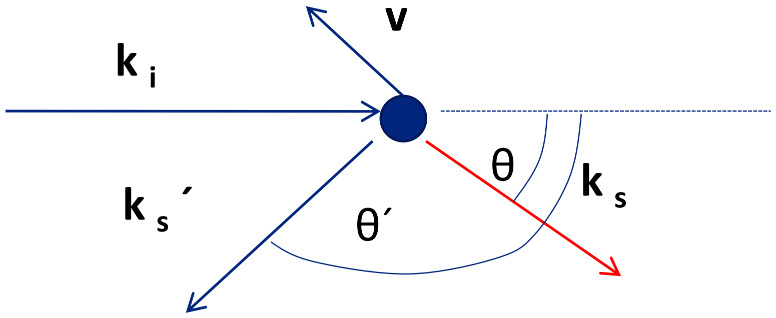
DOPPLER SHIFT

v.k$_i$ > 0



incident wave red shift on absorption
scattered wave blue or red shift on re – emission
dep. on θ
remind: $\Delta\lambda \sim \sin\theta/2$
θ = 0° no shift, θ = 180° double red shift

v.k$_i$ < 0



incident wave blue shift on absorption
scattered wave blue or red shift on re-emission
dep. on θ
θ = 0° no shift, θ = 180° double blue shift

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WHAT DO WE MEASURE

remind $\Delta\omega = \mathbf{k.v} = k.v_k$

$-\Delta\lambda/\lambda_0 = \Delta\omega/\omega_0$

$-\Delta\lambda/\lambda = 2.(v_k/c).\sin(\theta/2)$

Maxwellian in k vector:

$f(v_k) = (m/(2\pi k_B T)^{1/2})e((-1/2mv_k^2)/k_B T)$

$v_k = -c(\lambda-\lambda_0)/(2\ \lambda_0 \sin(\theta/2))$

Experiment to measure scattered signal as a function of λ. Map velocity space to wavelength space.

WHAT DO WE MEASURE

Looking for distribution function in terms of λ

$f(\lambda) = A.e((-1/2(\lambda - \lambda_0)^2/\sigma^2))$

Standard deviation :

$\sigma = 2\lambda_0/c(k_BT/m)^{1/2}.\sin(\theta/2)$

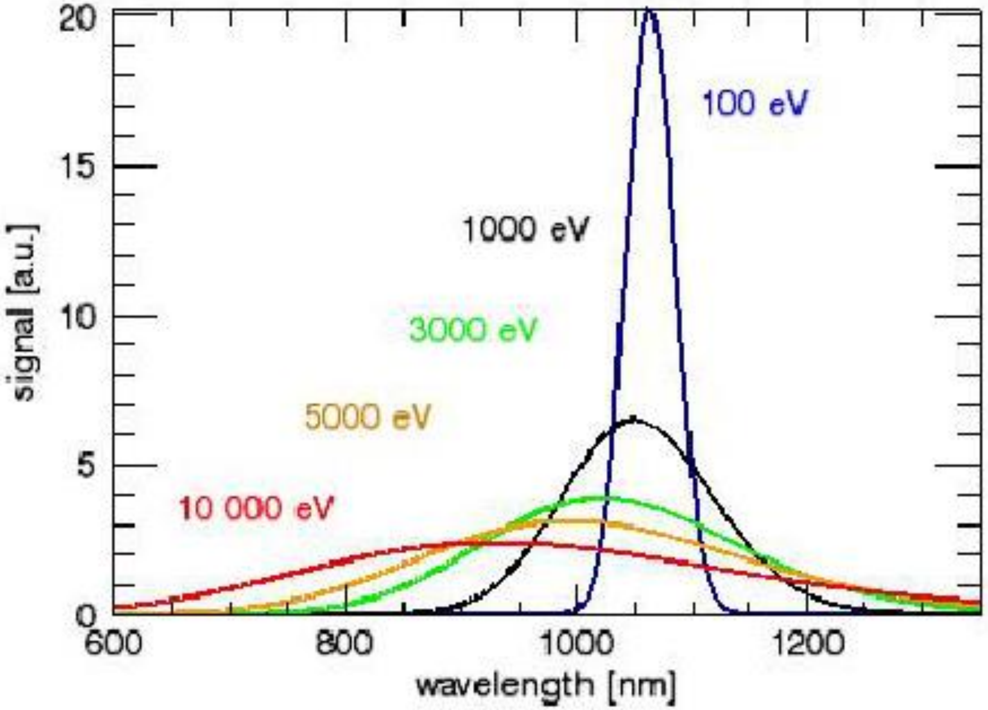
width of scattered peak – temperature T

f.e. 90°, T_e = 100eV, λ=1064 nm …….. σ = 36 nm

ANOTHER COMPLICATION

High temperatures – high velocities – relativistic effects

Propper code has to be used – Selden Matoba



SeldenMatoba code, MAST, UK

SUMMARY

Thomson scattering diagnostics is widely used in the fusion community to measure profiles of electron temperature and electron density simultaneously.

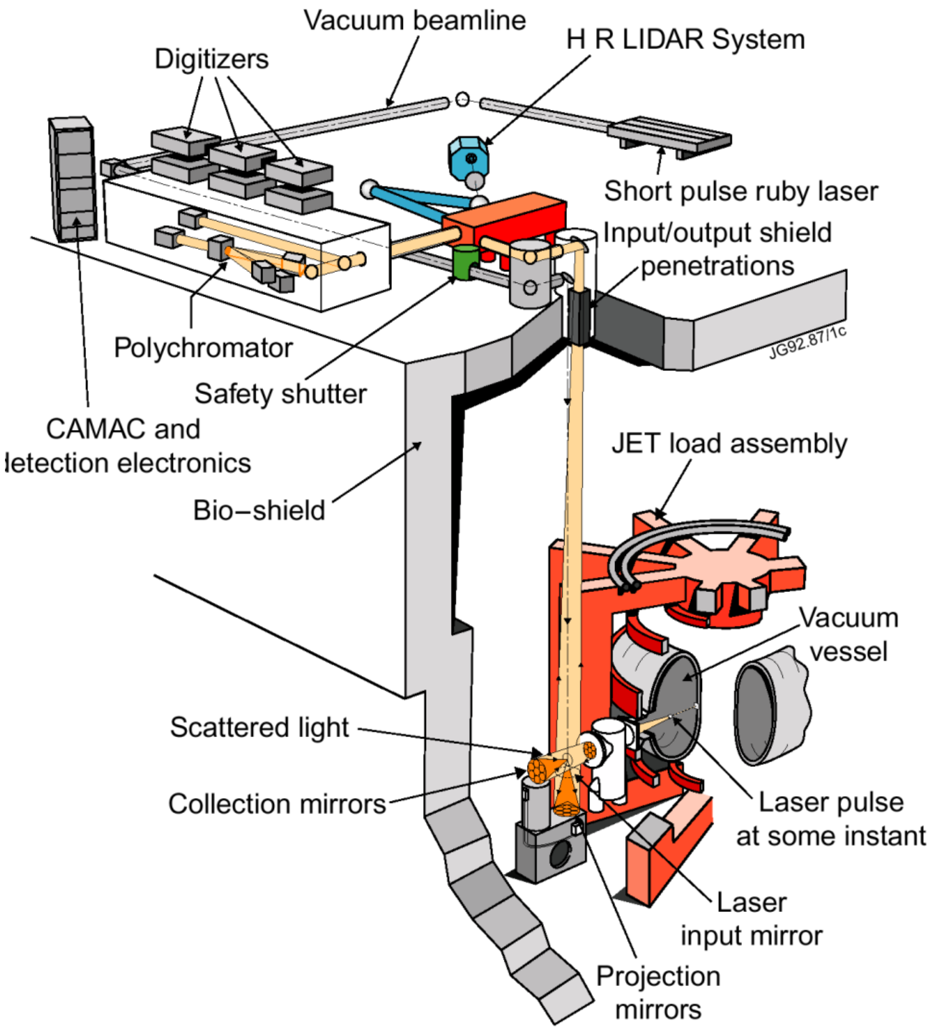
The temperature (of electrons) can be calculated from the width of a scattered signal.

The density can be evaluated after comparing scattered signal on free electrons in plasma with scattered signal of radiation by gas molecules

WAYS OF GETTING SPECTRA

- **Conventional diagnostics**
  - Signal from a laser scattered in a plazma passing a series of spectral filters, Avalanche photodiodes and fast digitizers (GS/s as a laser pulse is only 7 ns long)
  - Signal from a laser scattered in a plasma is lead to a large spectrometer and CCD camera
- **LIDAR diagnostic**

LIDAR



JET’s LIDAR – TS Diagnostics on the roof of the Torus HAll

„LIght Detection And Ranging“

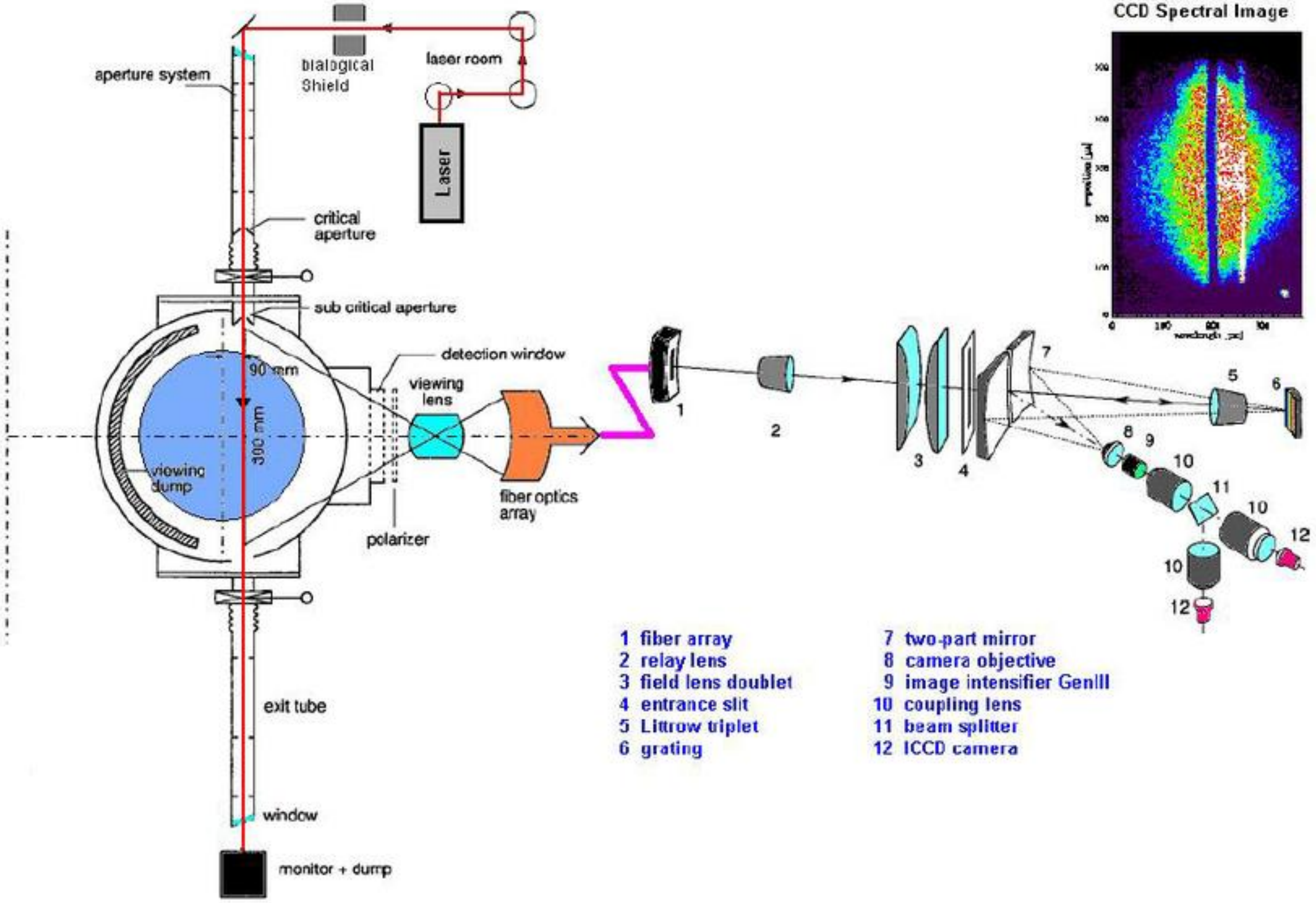
180° scattering

Short pulses (300 ps $\propto$ 9 cm)

Time-of-flight

→ position information

CONVENTIONAL TS - CCD BASED SETUP

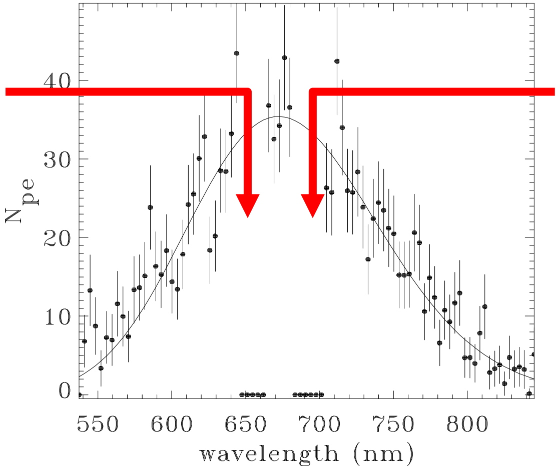


1 fiber array
2 relay lens
3 field lens doublet
4 entrance slit
5 Littrow triplet
6 grating
7 two-part mirror
8 camera objective
9 image intensifier GenIII
10 coupling lens
11 beam splitter
12 ICCD camera

Schematic layout of the double-pulse Thomson scattering at the TEXTOR tokamak

H_α-emission is cut away

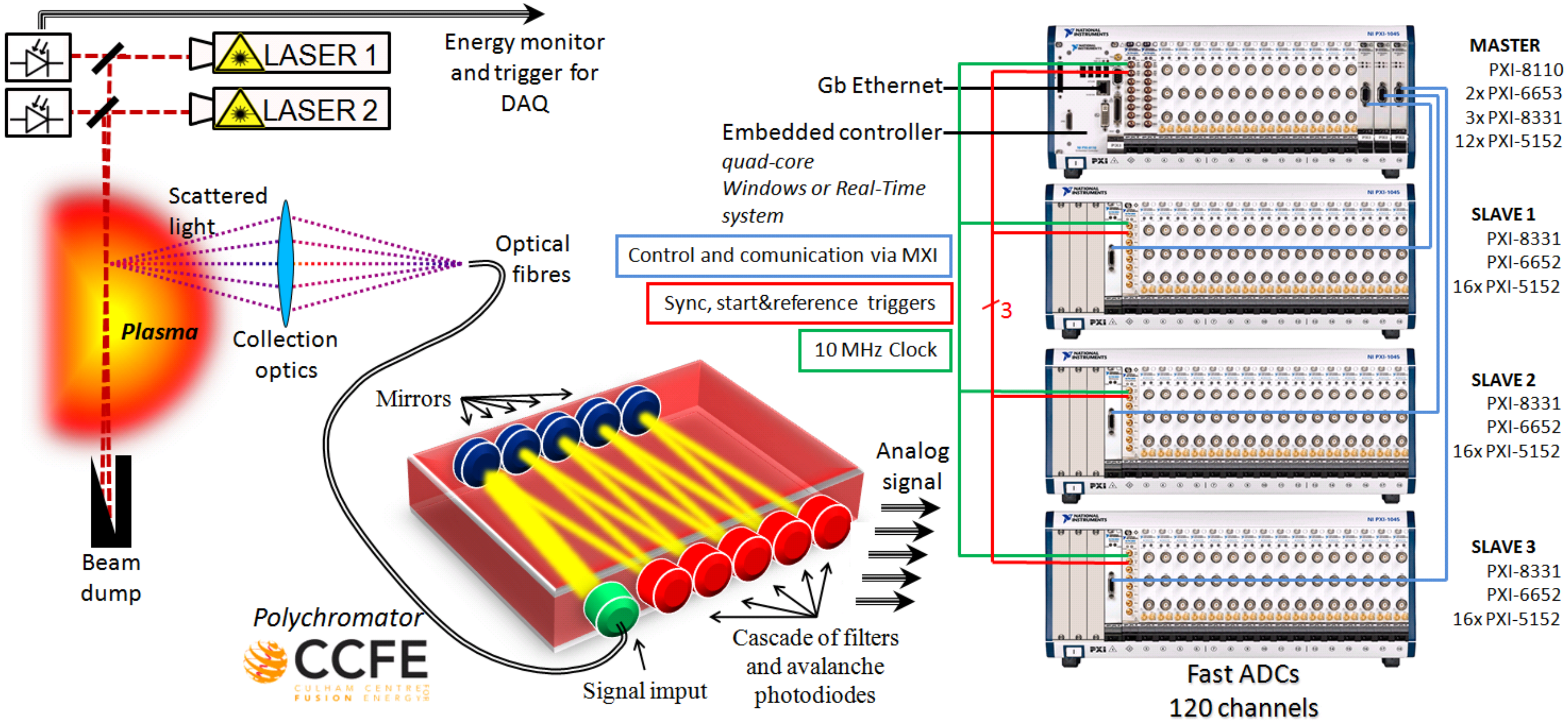
Laser wavelenght is cut out



[R. Jaspers, M. Kantor, TEXTOR]

CONVENTIONAL TS - APD BASED SETUP

Filters and APDs solution, laser 1064 nm @ 1.5 J
This system is used at tokamaks COMPASS, MAST, JET



LASER 1
LASER 2
Energy monitor and trigger for DAQ
Scattered light
Plasma
Collection optics
Optical fibres
Beam dump
Mirrors
Analog signal
Polychromator
CCFE
CULHAM CENTRE FOR FUSION ENERGY
Signal imput
Cascade of filters and avalanche photodiodes
Gb Ethernet
Embedded controller
quad-core
Windows or Real-Time system
Control and comunication via MXI
Sync, start&reference triggers
10 MHz Clock
3

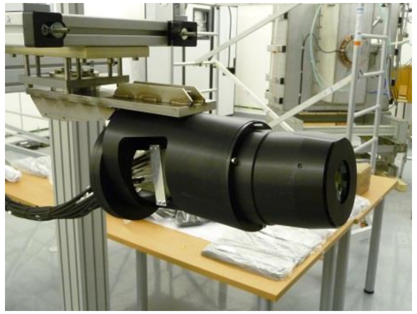
MASTER
PXI-8110
2x PXI-6653
3x PXI-8331
12x PXI-5152

SLAVE 1
PXI-8331
PXI-6652
16x PXI-5152

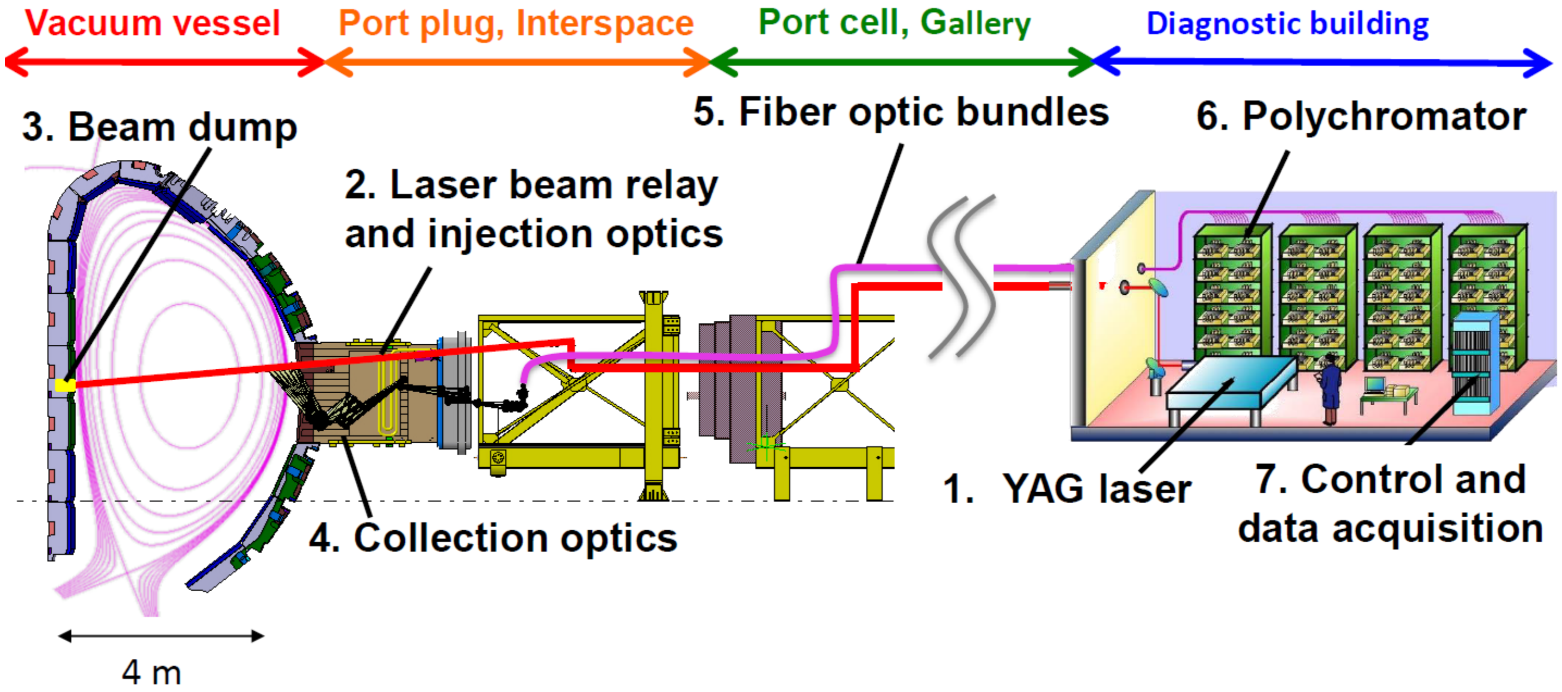
SLAVE 2
PXI-8331
PXI-6652
16x PXI-5152

SLAVE 3
PXI-8331
PXI-6652
16x PXI-5152

Fast ADCs
120 channels



ITER TS DIAGNOSTICS FOR EDGE PLASMA



- Nd:YAG laser, fiber optical bundles, polychromators
- Final design review of the laser beam dump 2022
- Next FDR about components in tokamak building planned for June 2025
- Beam dump – extreme heat load 2,4 kW – plasma spray coating of ceramic applied on stainless steel (20 micrometer Al_2O_3-TiO_2 coating samples tested)

[Courtesy: Eichii Yatsuka, ITER Japan Domestic Agency]

DESIGN CHOICES OF TS DIAGNOSTICS & TRADES OFF

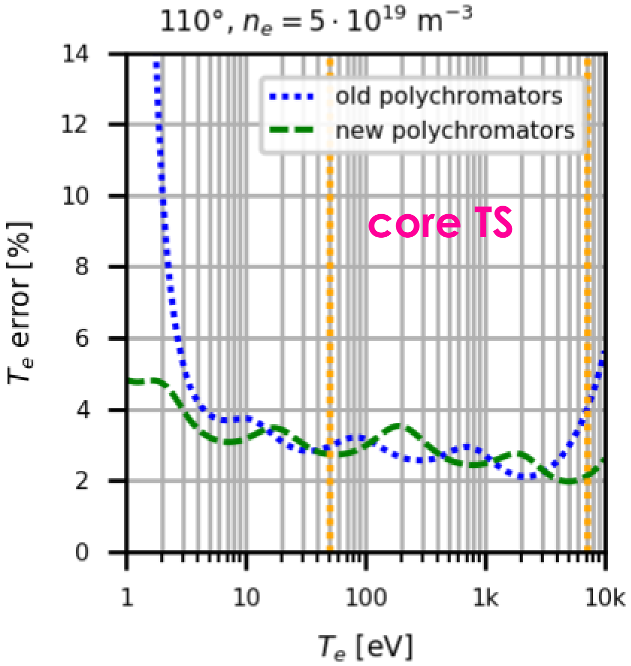
- **Choice between conventional TS and LIDAR**
  - LIDAR – simpler optics and more robust but requires more advanced detectors
  - Conventional TS based on Avalanche photodiodes detection more common
- **Fiber bundle cross-section** dimensions at the tokamak side
  - Dimension alongside the laser line – smaller one gives better spatial resolution but lower signal (critical for TS)
  - Dimension across the laser line – bigger one provides a better clearance in case of laser misalignment but collects more background light (worse signal/noise ratio)
- **Choice of spectral filters**
  - To cover the requested spectral range
  - To optimize error curve versus range of measured Te, ne
  - More filters – smoother curve but higher losses through the system. Usually not more than 6 filters are used for that reason.

DESIGN CHOICES – SPECTRAL FILTERS

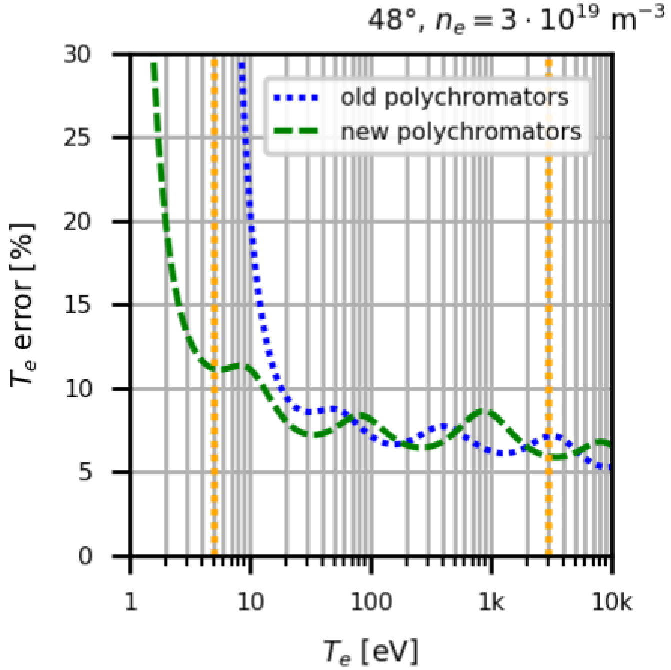
Example – Optimization of spectral filters choice for COMPASS Upgrade

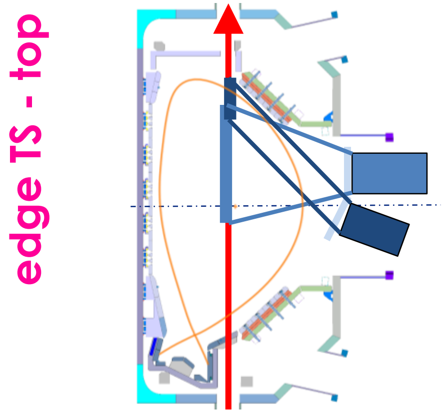
- optimization of filters for both
    - edge TS
        - low T_e
        - orientation of optics

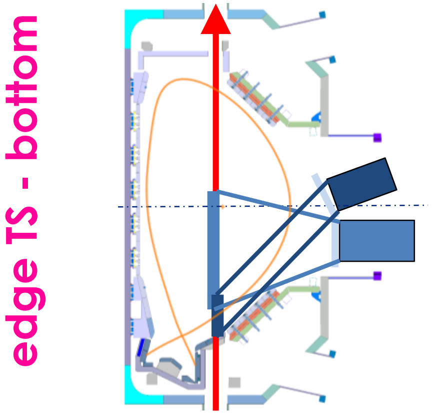
        -> variable scattering angle
    - core TS – high T_e

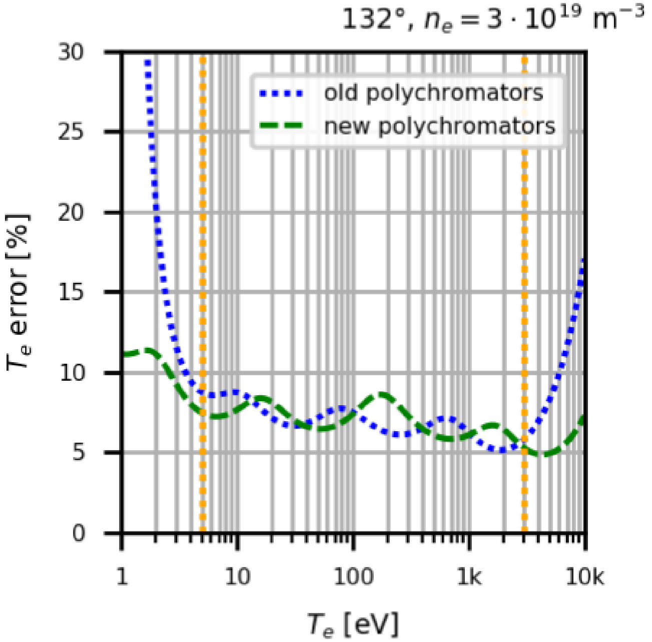


[P. Böhm, IPP.CR]







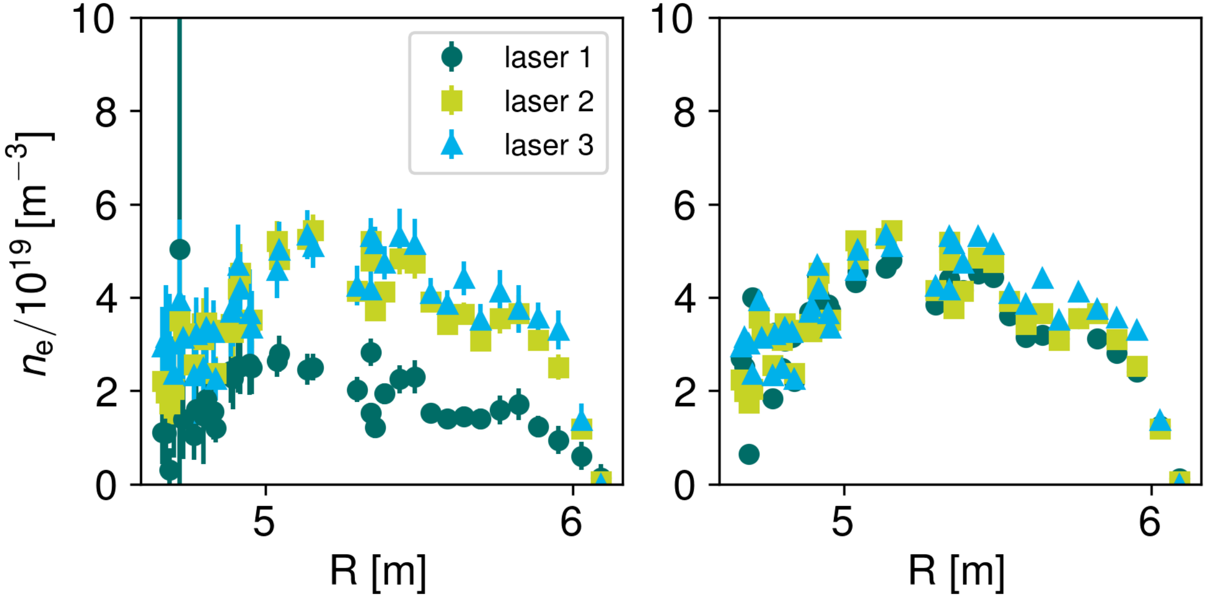


GOOD TO THINK OF

- Laser line stability, laser position monitoring
- Alignment – misalignment leads to an incorrect n_e calculation
- Calibrations – absolute, spectral
- Strategy how to maintain a good quality of measured data when access to the experimental device during experimental campaign is limited:
  - Remote alignment
  - Calibration during experimental campaign
  - Using neural network
- Real time

NICE EXAMPLE

- Absolute Raman calibration depends on laser position.
- Varying the laser position during the calibration → ideal calibration for every position.
- Position monitoring during TS operation allows choice of correct calibration factor.
- Effect can also be learned from the profile data using machine learning.



[Fuchert et al., JINST **17** (2022)]

CHALLENGES

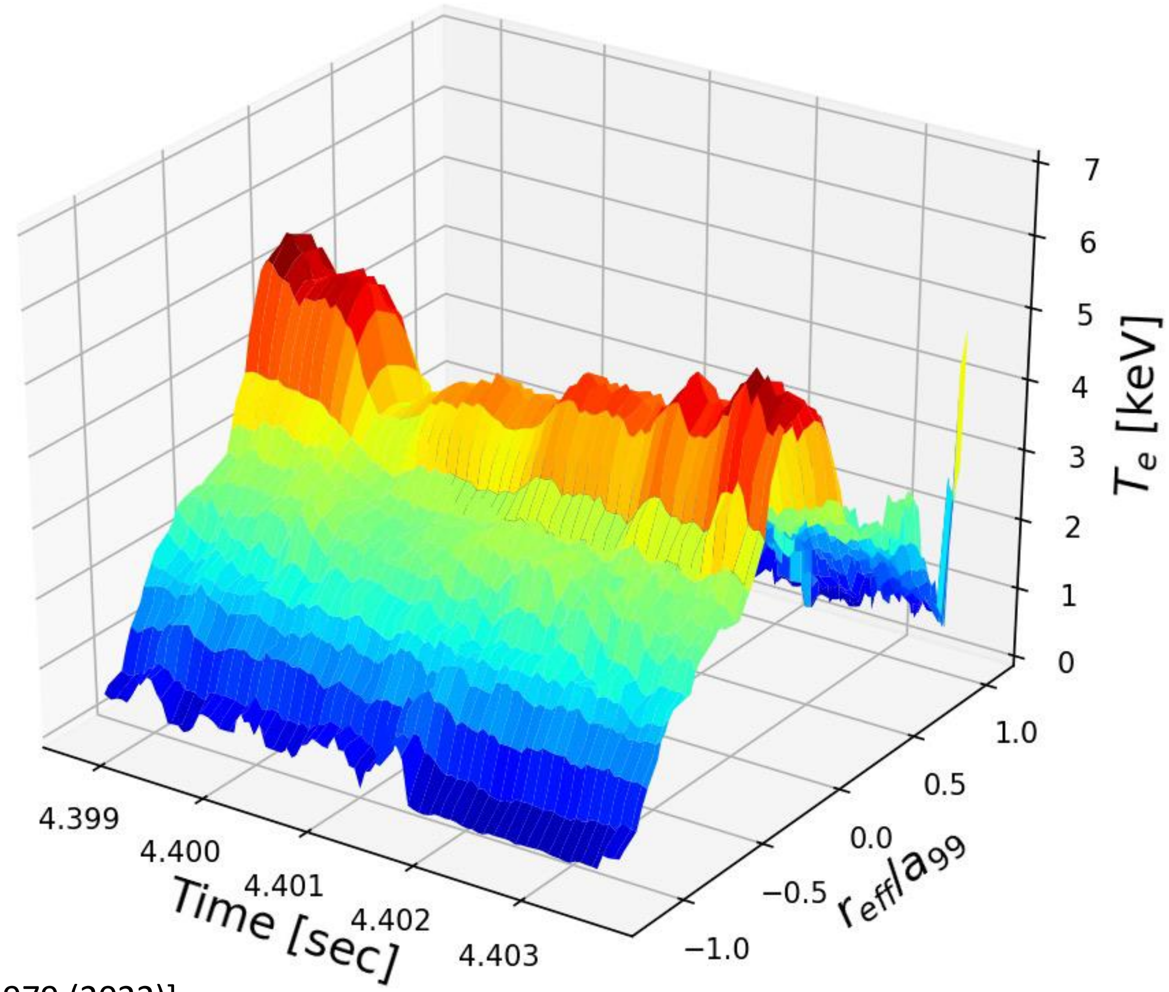
- **Temporal resolution of the TS diagnostics**
  - Laser has to have a high power output – conventional lasers off the shelf offer only tens of Hz repetition rate which is not sufficient to capture fast events in the plazma
  - What to do?
  - Sequence of lasers firing with a very short time delay (MAST-U, COMPASS, …) – microsecond delay
  - Development of a special High repetition TS system allowing burst mode (Univerzity of Wisconsin @ Daniel Hartog) – up to 100 kHz

HIGH REPETITION TS MEASUREMENTS

High repetition laser system has been built for LHD by Daniel Hartog & team

Heat-capacity laser operation – burst of pulses is of limited duration • burst length ≤100 ms • pulse rep rate ≥1 kHz

High-rep-rate lasers enable detailed measurements of plasma dynamics Example 20 kHz Thomson scattering electron temperature measurement in LHD stellarator (Japan) – captured Te evolution during minor collapse of e-ITB N. Kenmochi



[N. Kenmochi *et al.*, *Sci. Rep.* **12**, 6979 (2022)]

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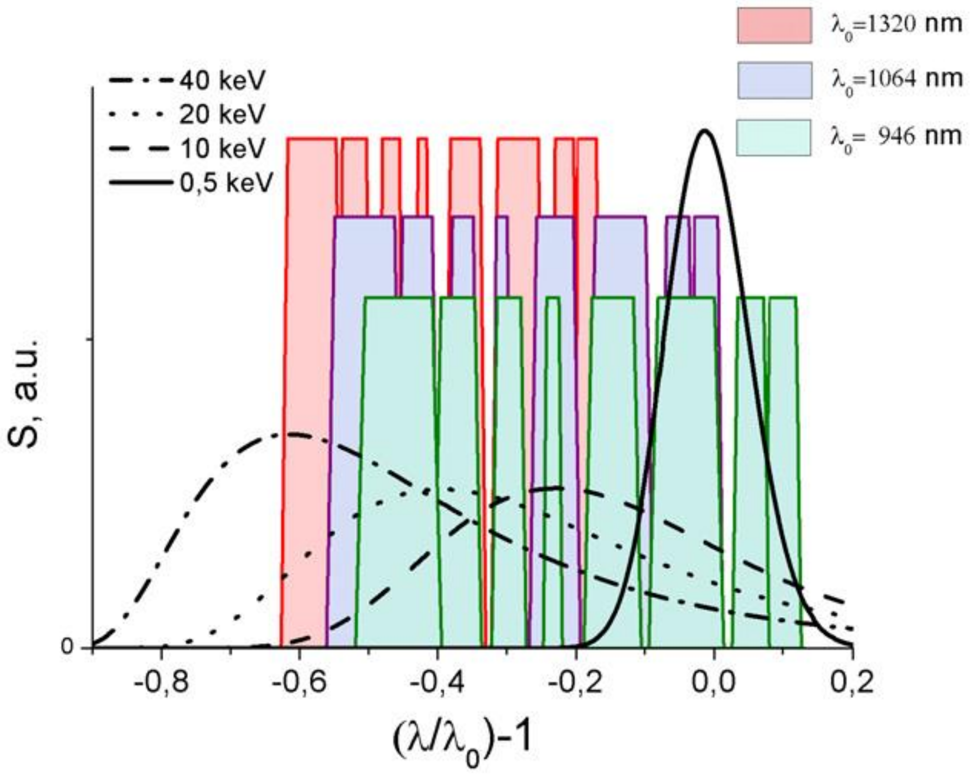
CHALLENGES

- **Too wide a range of measured T_e**



See [G.S. Kurskiev et al 2015 Nucl. Fusion 55 053024]

At **high temperatures** (T_e > 10 keV, expected to be regularly achieved in **ITER**), the TS **spectrum spans** a **wide** region of **wavelengths**.

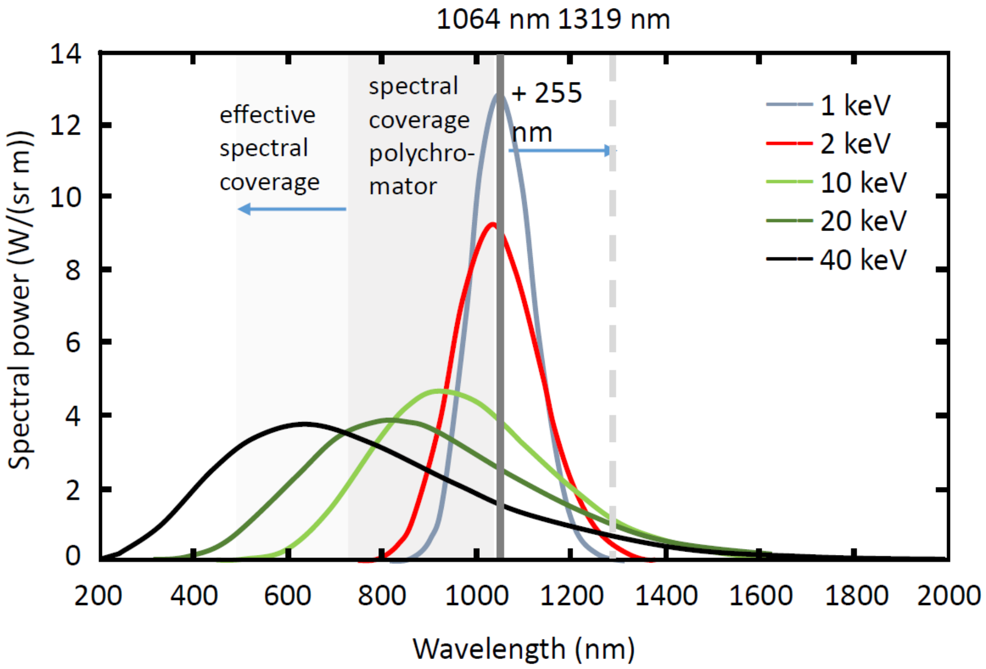
Spectra widening will be particularly **problematic** in the **core** region, where the **highest temperatures** are expected.

Depolarization effect plays the non-negligible role

What to do?

CHALLENGES

1) High T_e measurements using dual-wavelength TS



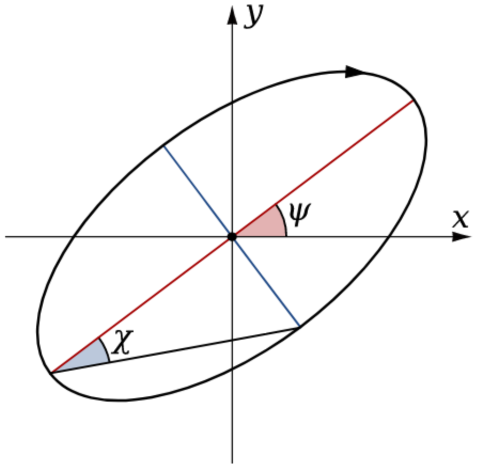
[E. Pasch et al, *Rev. Sci. Instrum*. 89, 10C115 (2018)] and [E. Pasch et al, Recent progress of dual-laser wavelength Thomson scattering, poster contribution at HTPD24]

- This technique allows to **expand** the **detectable spectrum** by using **two lasers** at **different wavelength**.
- **1064 nm** and **1319 nm** lasers (5 J and 2 J, respectively)
- Allows for **in-situ calibrations** by **measuring** the **relative sensitivities** of **spectral channels** with two-lasers
- **Higher temperature** can be measured
- This system is **currently** being **tested** in **W7-X** (see, for instance, [F.A. D'Isa et al 2023 JINST 18 C11025])

CHALLENGES

2) Polarimetric TS

- Measures depolarization of the scattered light
- Degree of depolarization as a function of T_e
- When a completely polarised source (such as the TS input laser) is injected into a high temperature plasma, the scattered radiation collected by TS systems will be partially depolarised.
- This is a relativistic effect (see [V. V. Mirnov, D. J. Den Hartog, and E. Parke, Phys. Plasmas 23, 052108 (2016)]), i.e. it is non-negligible only at high temperatures (see also [R. Scannell et al, Rev. Sci. Instrum. 94, 013506 (2023)], where recent measurements of depolarisation in JET are reported).
- Using Mueller matrices formalism, the degree of depolarisation can be written as a function of multiple factors (scattering angle, orientation and ellipticity of the polarisation ellipse, electron temperature)
- The choice of θ_{scat}, χ, ψ, T_e strongly affects the system feasibility



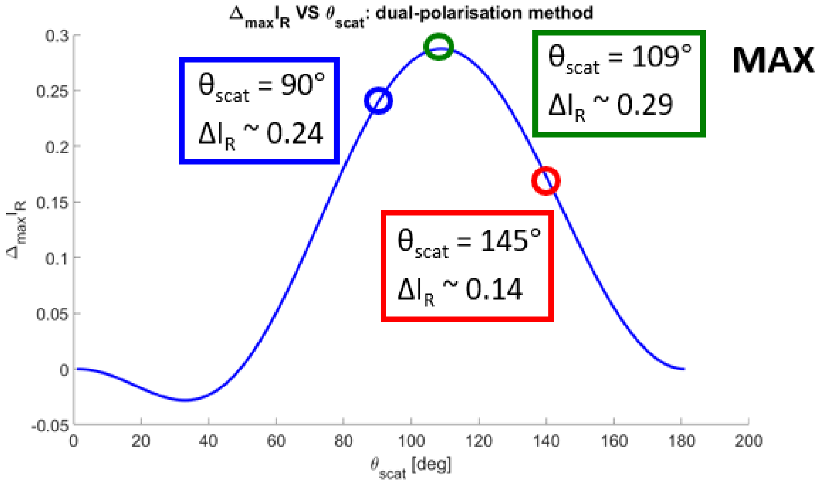
$$D = D(\theta_{scat}, \chi, \psi, T_e)$$

[courtesy: Filippo Bagnato, ITPA TG, ITER Organization], [F. Bagnato et al., *Rev. Sci. Instrum.* 95, 083506 (2024)]

CHALLENGES

3) Dual polarization technique

- Technique first proposed by L. Giudicotti and then reported in [H. Tojo Fusion Engineering and Design 191 (2023) 113511]
- injecting a sequence of two laser pulses, one with linear horizontal polarisation (s-laser, linear horizontal polarization), the other vertical (p-laser, linear vertical polarization).
- As the two lasers share the same optics, the optical transmission cancels out in the ratio.
- The ratio between the p and s-laser intensities is measured in output: $\mathbf{I_R = S_{out}^{(ver)}/S_{out}^{(hor)}}$
- The s-laser produces a large amount of scattered light. On the other hand, the p-laser produces a significant amount of scattered light only at high temperature.
- Using Stokes vectors formalism and the Mueller matrix derived in [V. V. Mirnov, D. J. Den Hartog, and E. Parke, *Phys. Plasmas* 23, 052108 (2016)]), the output ratio I_R is obtained in the form from which T_e and scattering angle can be obtained



Variation of I_R (**ΔI_R**) between 0 and 50 keV **as a function of θ_{scat}**

[courtesy: Filippo Bagnato, ITPA TG, ITER Organization], [F. Bagnato et al., *Rev. Sci. Instrum.* 95, 083506 (2024)]

NEW TRENDS

- Using **forward and backward models** to help both diagnostics design process and an efficient data processing (checking for errors, speed – real time)
- Fully **data driven models** can be alternative to avoid uncertainties of physics-based models
- Synthetic diagnostics
- Combining TS and other diagnostics for **synthetic "super resolution" diagnostics**
  - Correlations among diagnostics can be learned using historical data
  - find hidden physics with AI-based multi-modal super resolution
  - ***TS measurements can be created at points where it was not done!***
  - example: evidence of RMP induced island mechanism on the plasma boundary in DIII-D [Jalalvand, arXiv:2405.05908v3 [physics.plasm-ph] 27 Jun 2024]

Thank you for your attention.