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# *Measurement of Electron and Ion temperature in tokamaks*

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- **Electron temperature and density measurements by Thomson scattering**
- **Ion temperature measurements by Neutral Particle analyzer**

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# Thomson scattering for local measurement of electron temperature and density in tokamaks

**I will not focus on background physics of TS (it is describe in detail in any textbook on plasma diagnostics – e.g. J Hutchinson,…), but rather on specific features of TS complex on the COMPASS tokamak**

# *Wavelength spectrum of scattered light*

- Laser beam is injected into the plasma
- Photons scattered by the angle ~ 90 degrees are registered
- Wavelength spectrum of scattered light is significantly broader than the spectrum of the laser beam
- The width of the spectrum is proportional to the electron temperature
- Intensity of the scattered light is proportional to electron density

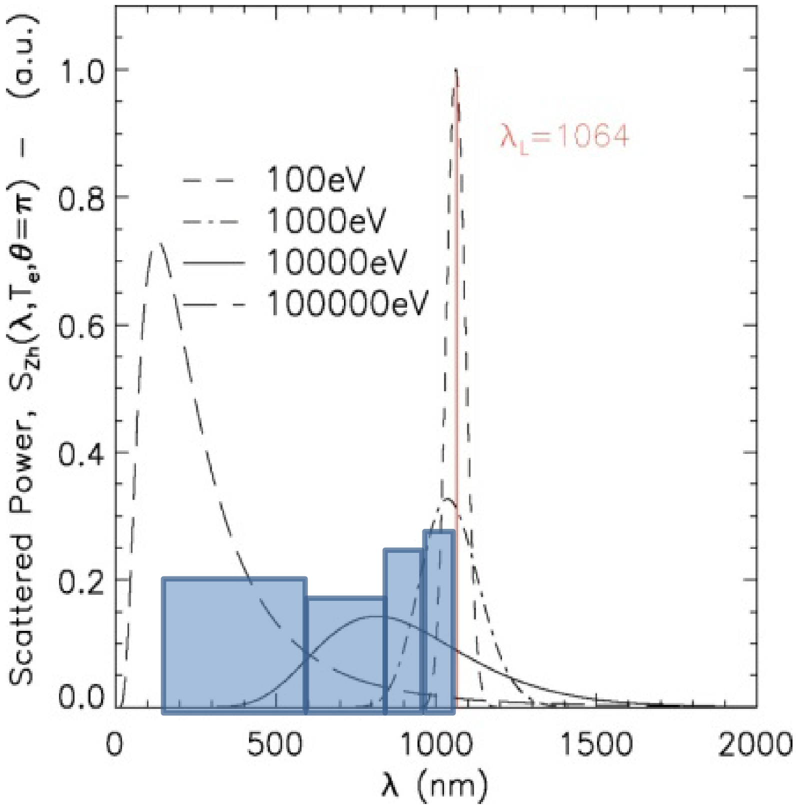

$$I \sim ne$$

# *Wavelength spectrum of scattered light*

**How to measure the spectrum of scattered light?**

- **The cross section for Thomson scattering on free electrons is extremely low**
- **Standard spectrometers can not be used – too low intensity**
- **The only way is to integrate the scattered spectrum over a range of wavelength**
- **Use sensitive detectors to collect a sufficient number of scattered photons**

**Simulated spectrum of scattered laser light at λ = 1064 nm for several electron temperatures**
(Selden-Matoba)



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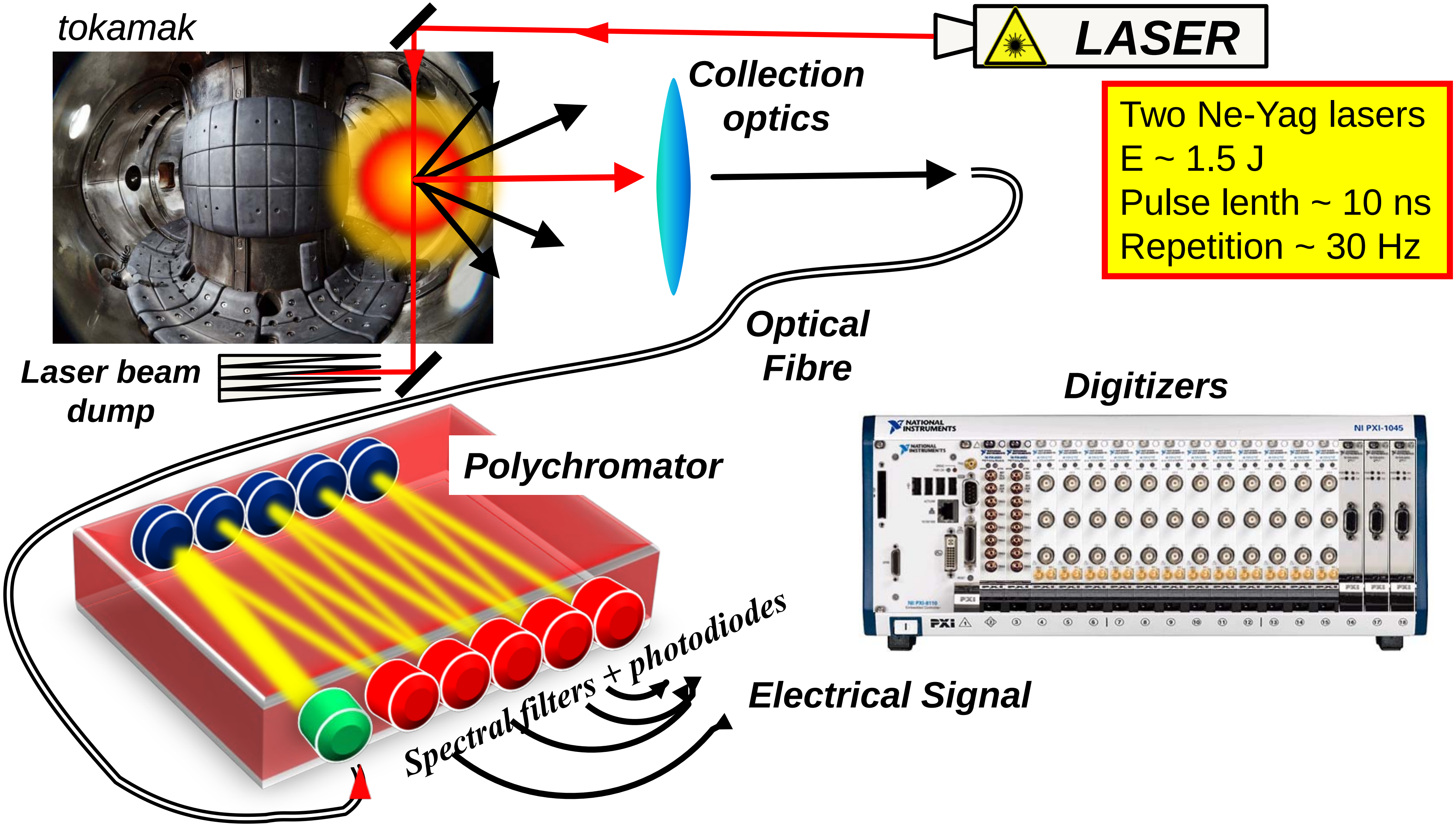
# *Schematic layout of TS on COMPASS*



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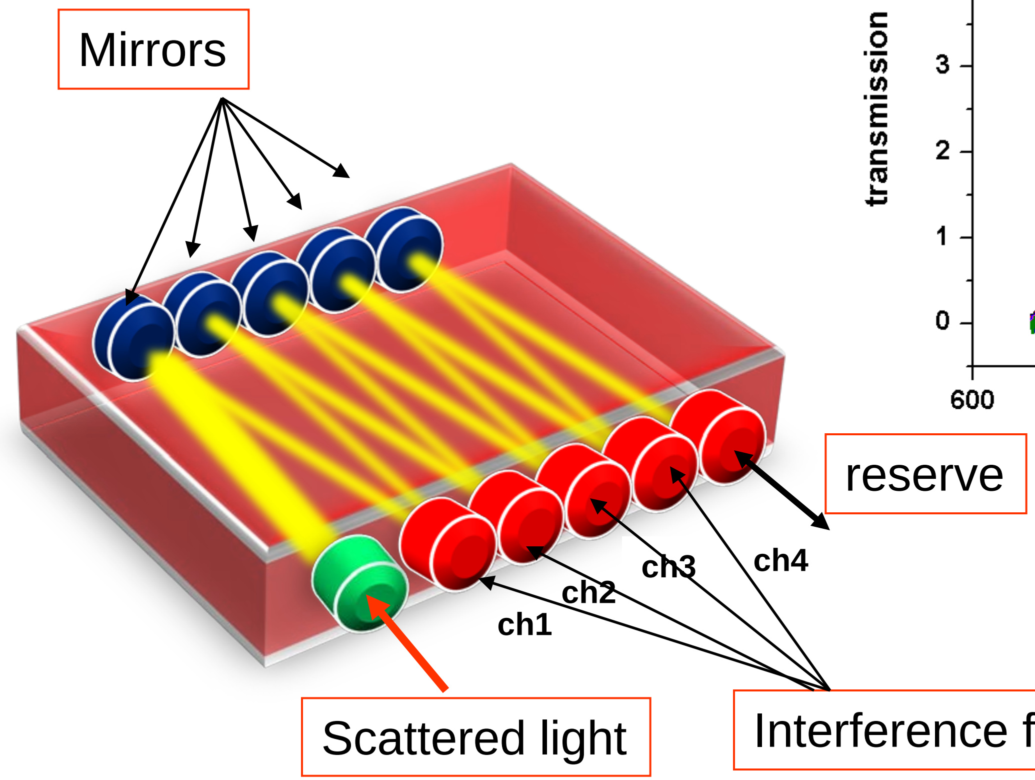
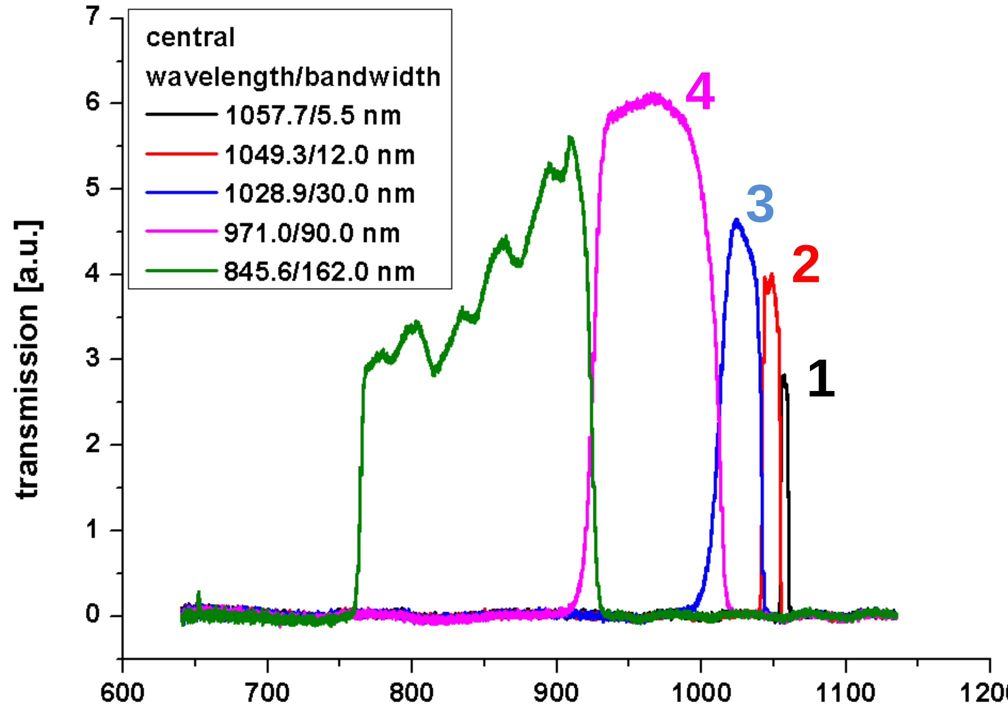
# *4 channel polychromator*

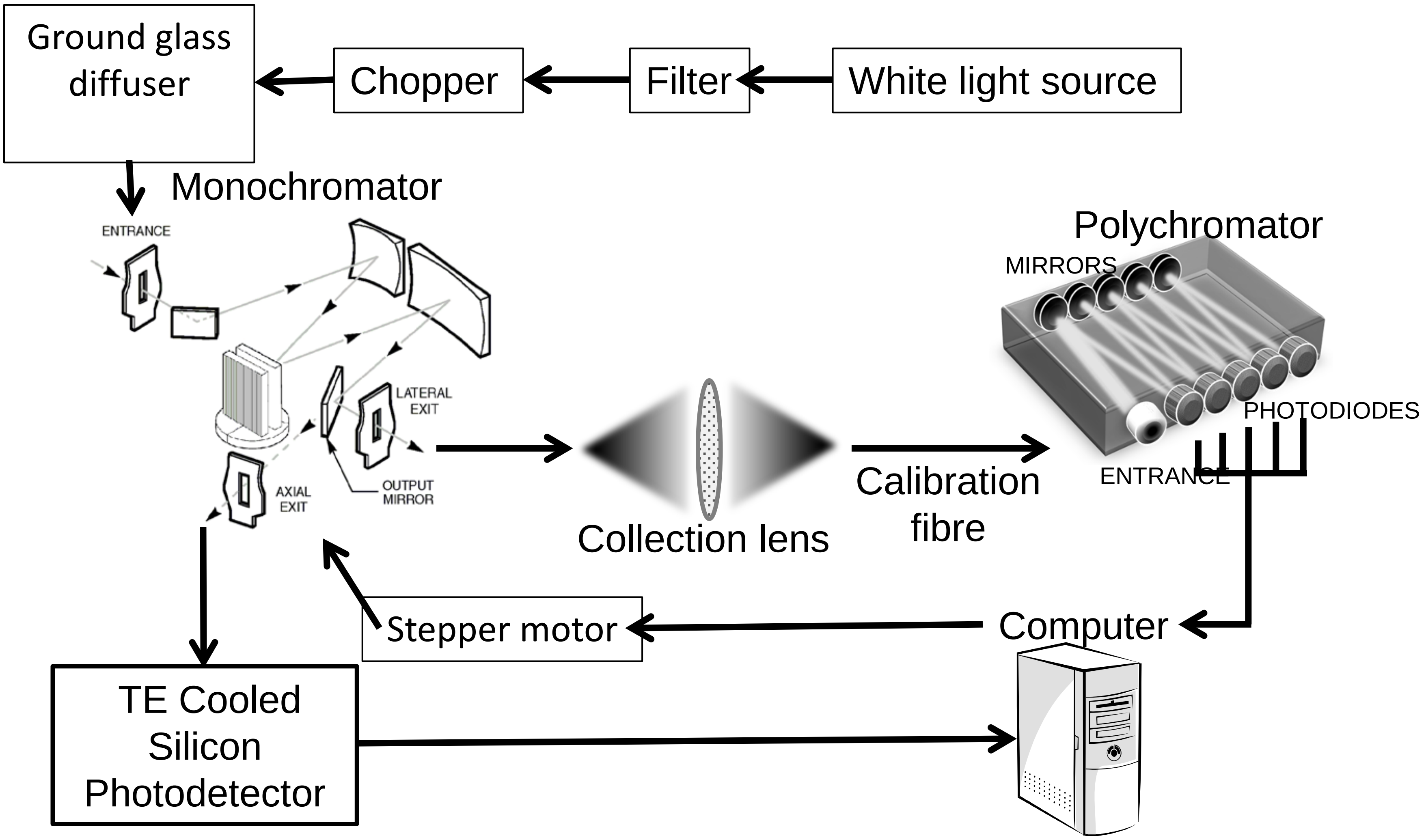
**Relative transmission of individual channels has to be precisely calibrated!!!!**



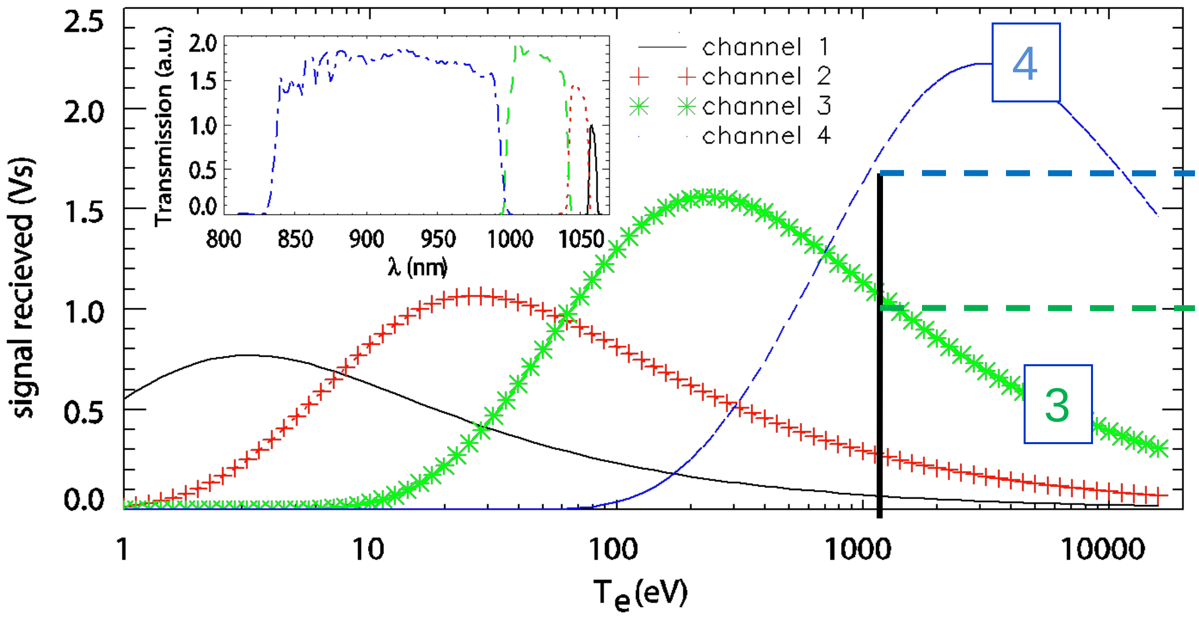

**Designed by British colleagues in Culham laboratory**

# *Apparatus for precise spectral calibration*



# *Spectral sensitivity of individual channels*

Relative amplitude of signals from individual channels versus the electron temperature



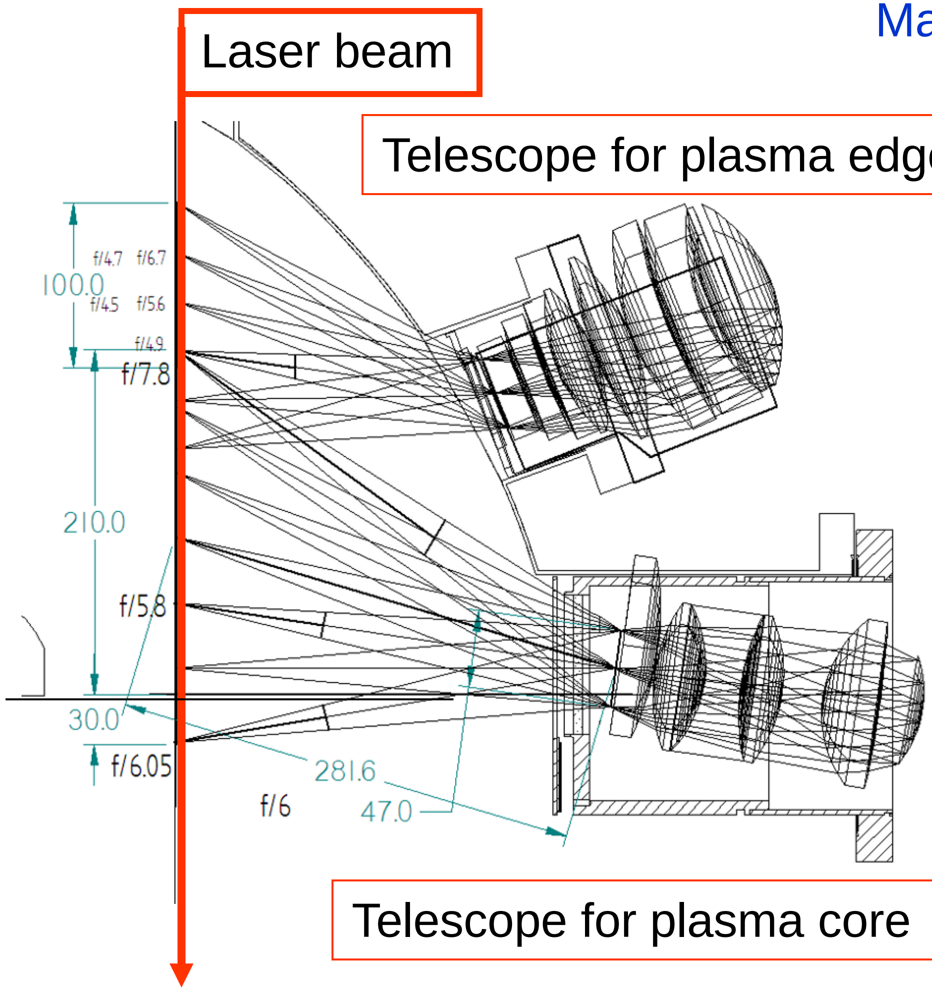

Electron temperature is derived from the ratio of signals from individual channels

<u>For example:</u>
If the ratio of signals from the channels 4 and 3 is
Ch4/Ch3 = 1.7/1 = 1.7 =>

Te = 1100 eV

# *Multichannel optical system*

Many points along the laser beam is required?
More is better!




**Edge TS - 32 spatial points, resolution ~ 3 mm**

**Core TS - 25 spatial points, resolution ~ 6 mm**

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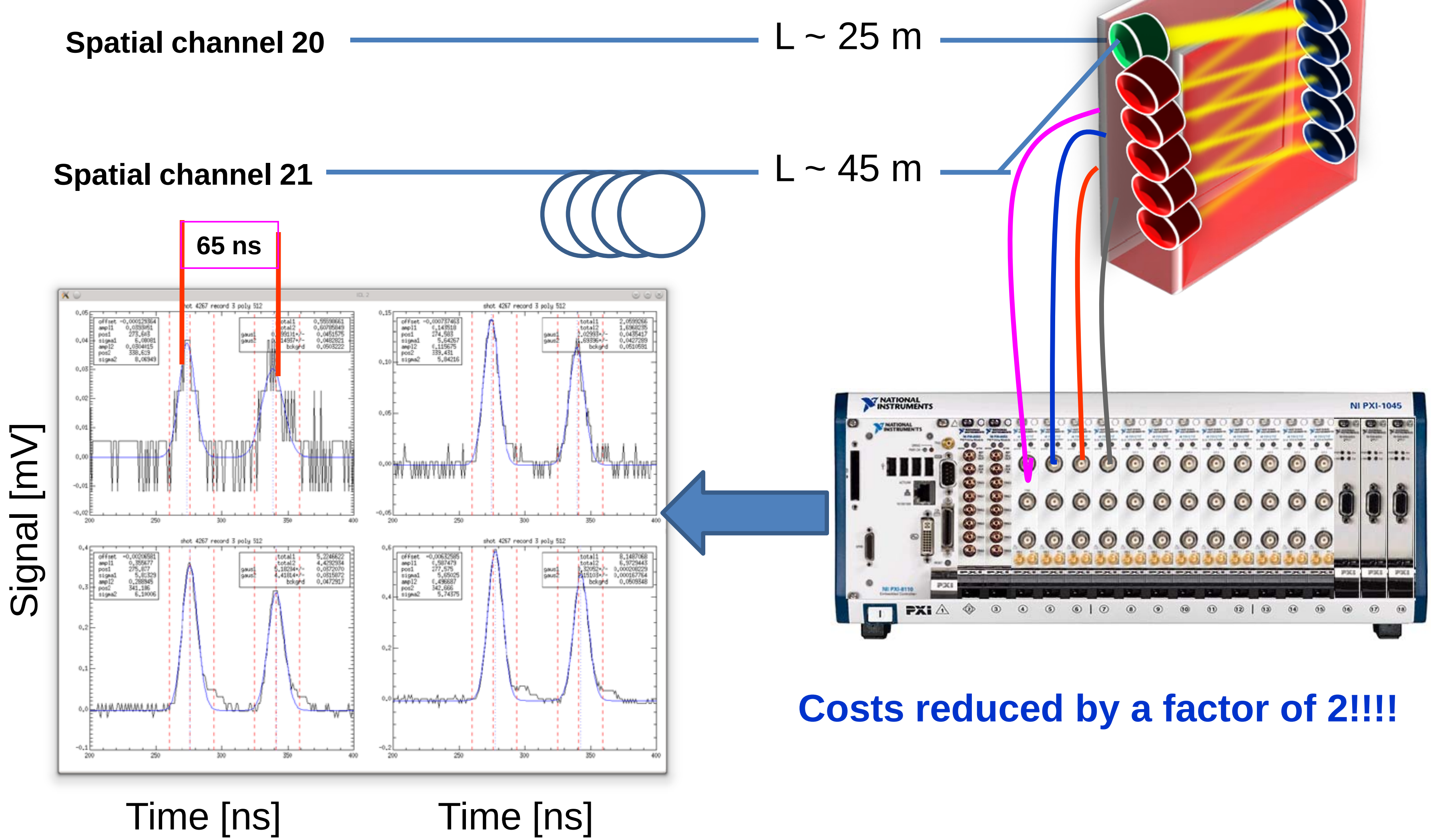
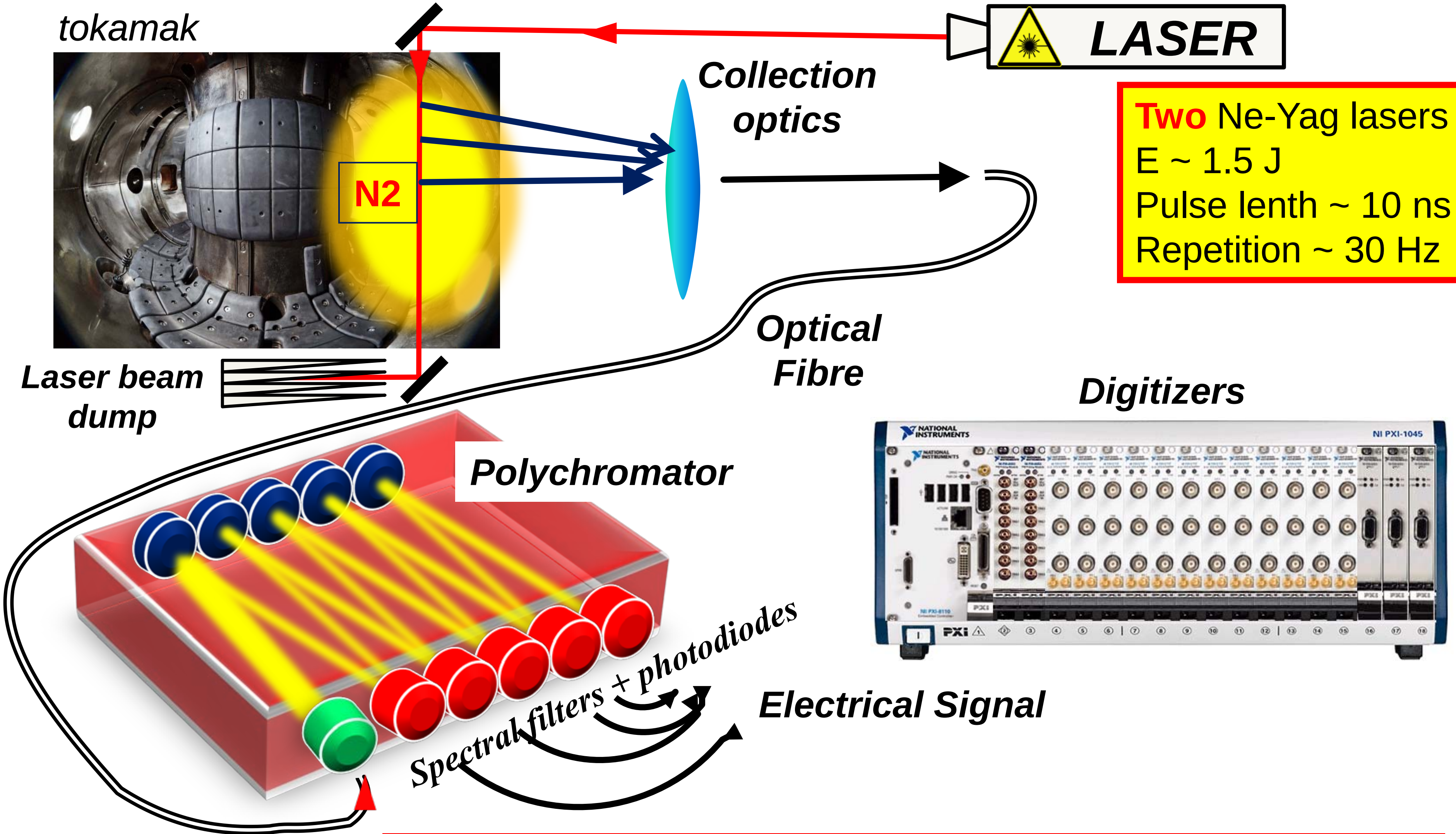
# *Cost reduction of the TS system*

**How to reduce the number of polychromators and DA channels, and consequently reduce costs of equipment?**




**Costs reduced by a factor of 2!!!!**

# Absolute calibration of intensity - measurement of electron density




**Two** Ne-Yag lasers
E ~ 1.5 J
Pulse lenth ~ 10 ns
Repetition ~ 30 Hz

**Rayleigh scattering – well known scattering cross section**

# *Radial profiles measured by HR TS*

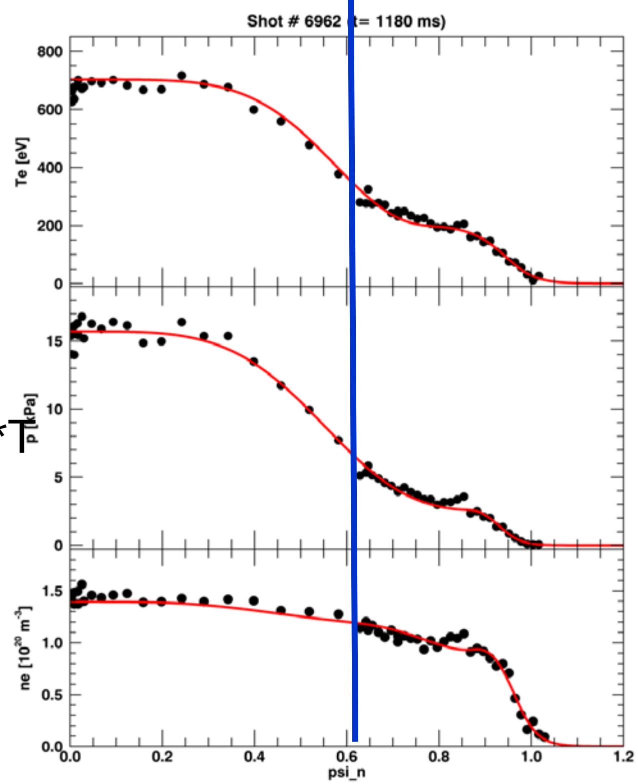
## A reasonable spatial resolution of Edge TS is evident

Core TS | Edge TS

Profile of electron temperature

Profile of electron pressure ~ n*T

Profile of electron density




Normalized radius

**Steep gradients at the plasma edge are signature of a discharge with improved confinement.**

## H mode regime

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# In summary of HR Thomson scattering

- One of the most essential diagnostics in tokamaks

- Radial profiles of Te and ne with a high spatial resolution

- However, expensive > 1 MEuro)!!

- Requires permanent care of  2-3 experts (alignment of the laser beam with detection optics, absolute calibration by Raylaigh scattering, data processing and their validation, …)

# Measurement of central ion temperature by the Neutral Particle Analyzer
# NPA

# *Density of neutral atoms in tokamaks*

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**Statement that tokamak plasma is fully ionized is not true! There is an influx of neutral hydrogen (gas puff, recycling, NBI,..). This "slow" hydrogen influx is attenuated by collisions with charged particles:**

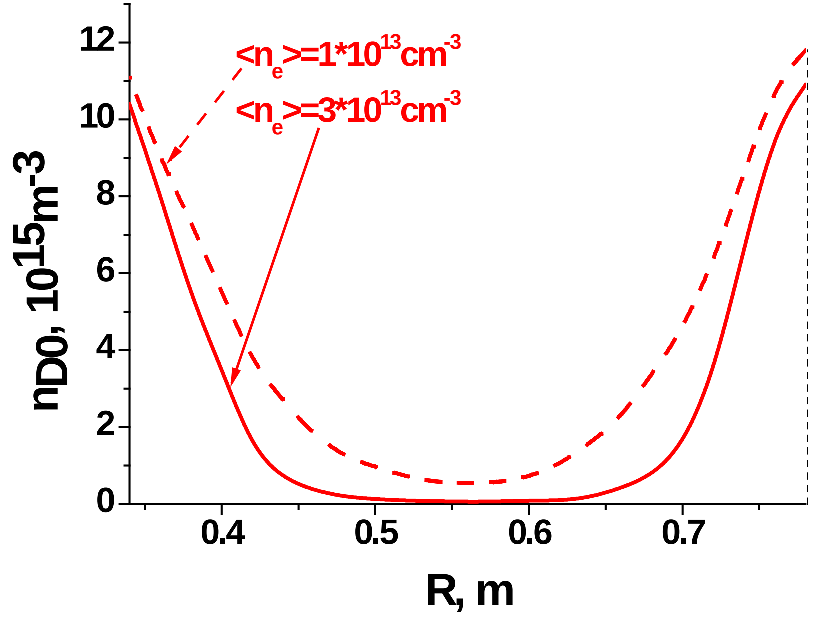
- **ionization (dissociation) by electrons**
- **ionization plasma ions**
- **charge exchange collisions**

**fast p + slow $H^0$ => fast $H^0$ + slow p**

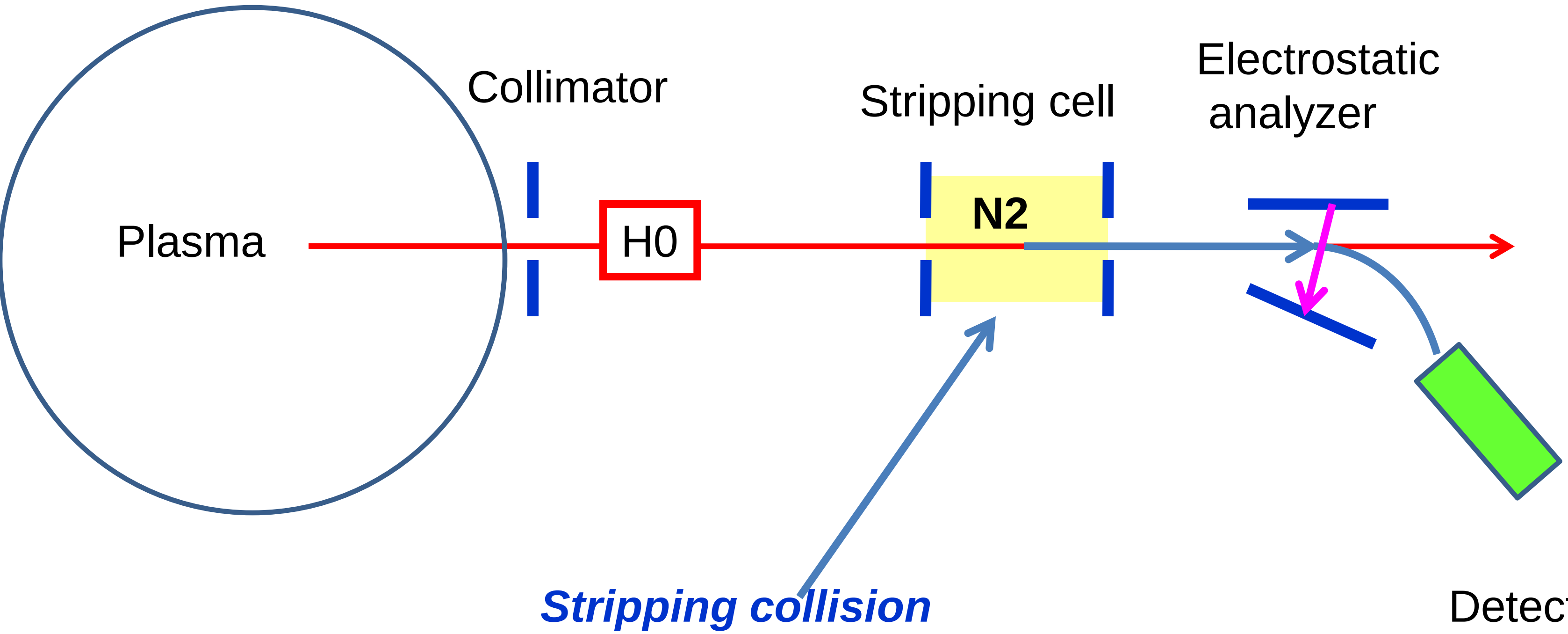
**The mean free path of resulting fast CHX neutrals can be comparable with minor radius under some conditions.**

**On the other hands, these fast neutrals (in thermal equilibrium with ion component) escape plasma**

**Density of neutral hydrogen calculated by the numerical code DOUBLE (MC) developed by IOFFE institute.**



# *How to measure energy distribution of fast atoms?*




**fast $H^0$ + slow N2 => fast p + ........**

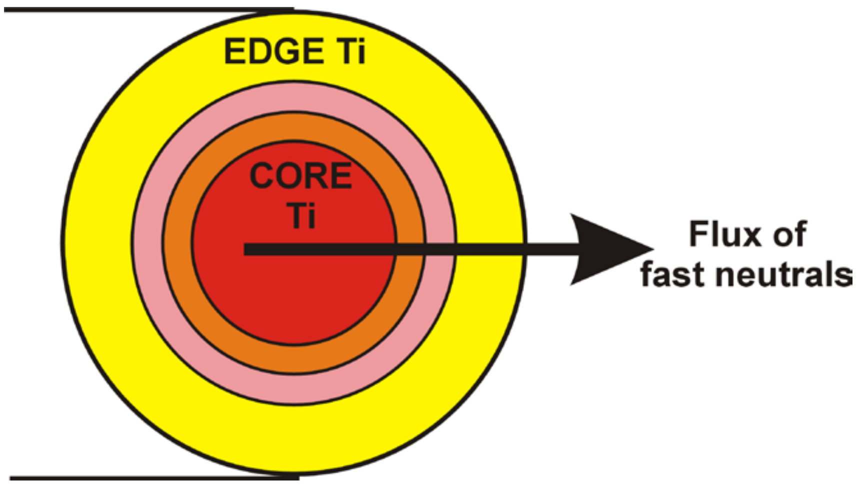
***Resulting fast proton has almost the same energy and momentum as primary fast neutral***

## *Pasive measurement of central Ti*

**Experimental spectrum is superposition of energy spectra of fast atoms emerging from different slabs of the plasma column**

**Central ion temperature is determined from the slope of the tail of the experimental spectrum**

$$dN/dE \sim \exp -[E/T_i(0)]$$



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# *Multichannel measurements of the energy spectrum*

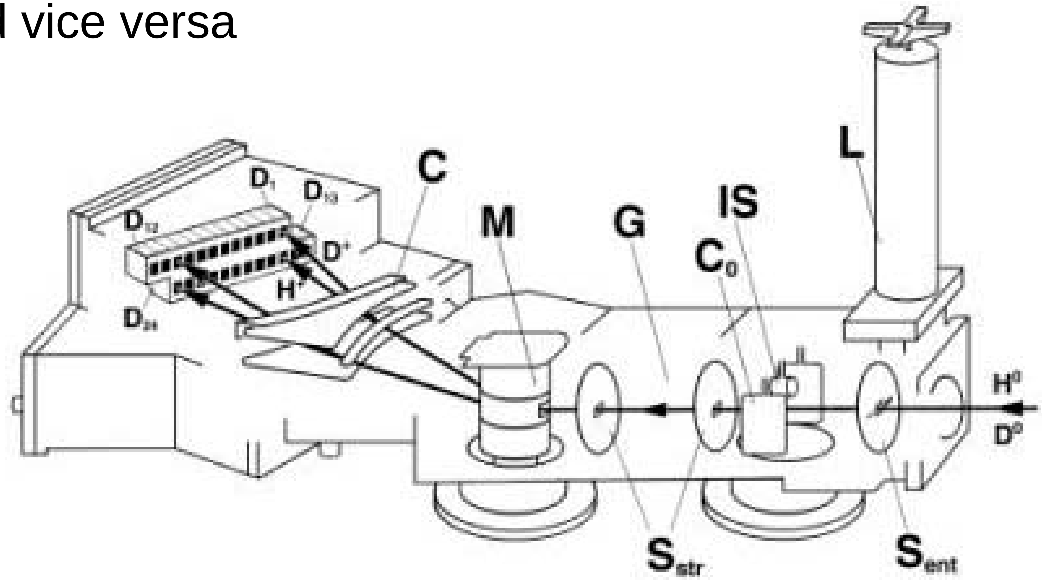
**Energy analyzer of fast neutral atoms escaping from tokamak with 5 energy channels**

**A part of the is measured during i singke tokamak discharge**

**Passive diagnostics!!**
**Energy spectrum is averaged along the observation chord**

# NPA on COMPASS – ACCORD-24

Resolution according momentum (mass if the ions) is required, if discharges with Hydrogen and Deuterium are executed (e.g Hydrogen neutral beam to Deuterium plasma and vice versa

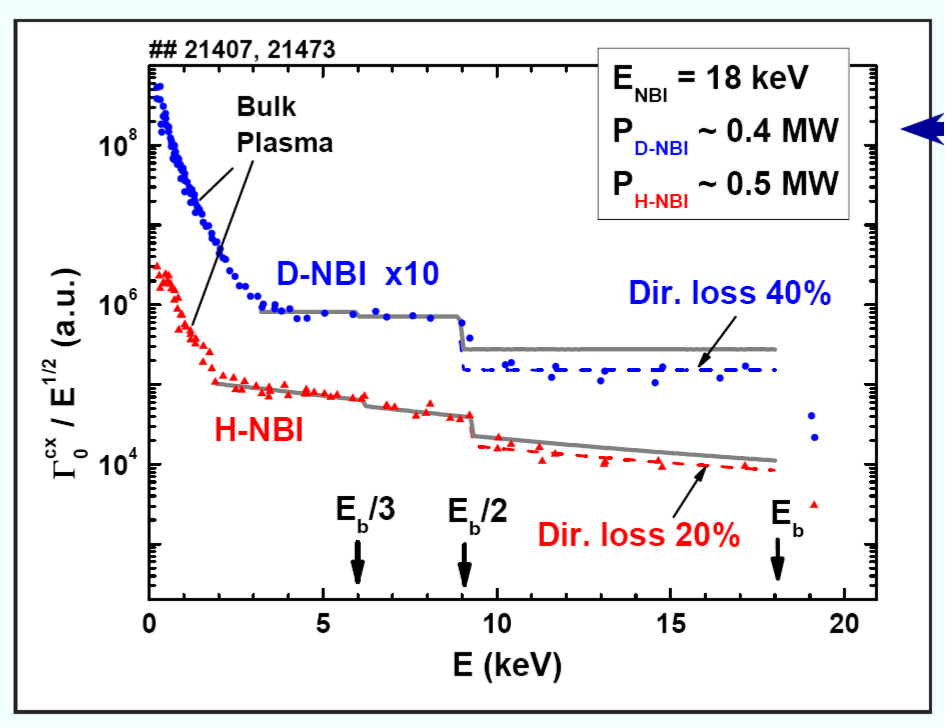



**12 channels for hydrogen atoms, 12 channels for Deuterium atoms**
**Energy spectrum of hydrogen and deuterium atom is measured simultaneously!**

**Energy resolution 0.2 – 70 keV (high energies are important for NBI studies)**

# *Expected energy spectra with NBI*

## Example of results from the GLOBUS tokamak




**NPA views plasma in the tangential direction**

**Direct losses of beam ions at NBI can be determined**

# *Energy and mass analysis*

$v_H/v_D = 2$

$$\frac{\text{Energy of protons}}{\text{Energy of deuterons}} = 2$$