Introduction to plasma diagnostics

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Outline

- **Motivations**
- **Diversity of plasma diagnostics**
- **General classification**
- **How to choose the right one:** plasma parameters and physics are the starting point
- **Magnetic field and current measurements**
  - RSX -> invasive
  - TCV -> non-invasive
- **Electron Temperature measurement**
  - Active diagnostic: Thomson scattering
  - Passive diagnostic: two foil method

Why study plasma diagnostics?

1. Necessary for practical control of the plasma: (plasma current, position feedback, impurity content, fusion power)
2. Necessary for a precise understanding of physical phenomena (reality check for plasma theory, avoid cold-fusion mistakes)
3. Discoveries made by improved diagnostics (sawtooth instabilities from soft x-ray, advanced tokamaks from current profile measurements)
4. Spin-off in other fields (laser scattering for textile fiber analysis, …)

Plasma diagnostics: How many ?
Too many!!!

Diagnostics →	Measured parameter
Magnetics: >200 pick-up coils 62 flux loops Diamagnetic Loop	Equilibrium & shape, stored energy MHD modes
Thomson scattering: 30 channels (vert.) 3 Nd-Yag lasers, 20 Hz	Electron temperature profile Electron density profile
FIR interferometer 215 μm, 14 channels	Electron density profile (continuous)
microwave interferometer	Back-up for FIR at low n_e
Infrared cameras	Tile temperatures, power load
Instrumented tiles (36 Langmuirs, thermocouples)	T_e and n_e at tiles, tile temperature
Reciprocating Langmuir probe	T_e, n_e profiles up to 2cm inside LCFS
Multibolometer(64 chans, 5 cams)	P_{rad} distribution (sensitive to neutrals)
XUV bolometer cameras (16 chan, 3	P_{rad}, insensitive to neutrals, fast
X-ray tomography 200 channels in 10 pinhole cameras **Multiwire X-ray camera** (64 chan) **X-ray monitor diodes** (8) **Hard-X monitor,** **Hard-X camera**	Plasma shape MHD phenomena, plasma purity MHD phenomena, ECH power deposition $T_e(0)$ from foils, mode n-numbers, Suprathermal electrons (>0.2 MeV) Suprathermal elc.

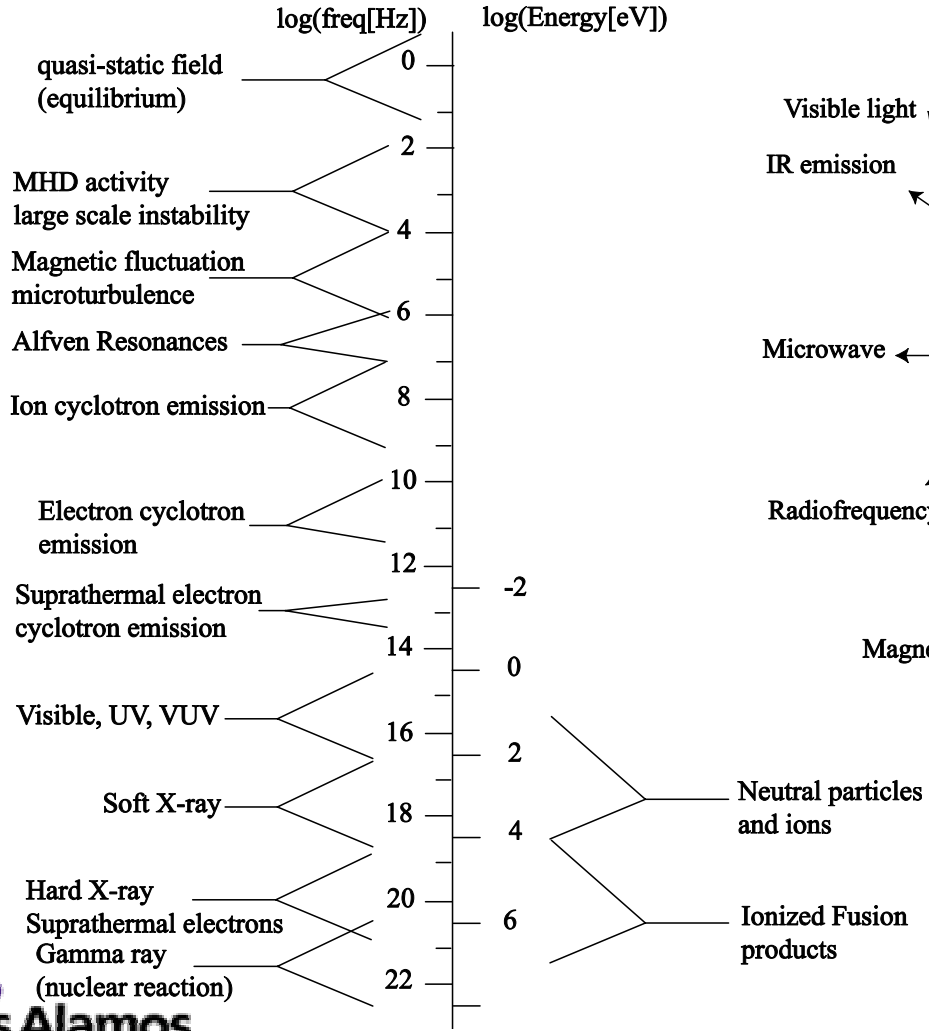
Diagnostics →	Measured parameter
Visible tangential cameras (4)	Plasma position & boundary shape, areas of plasma-wall interaction, visible radiation from in divertor area
Neutral particle analyser	$T_i(0)$
Visible light monitors 20	Dα and impurity lines,particle flux
H-α camera (128 diodes)	H/Dα emission profile
Spectroscopy **visible** **VUV** (Vacuum Ultraviolet) **USX** (Ultrasoft X-rays) **SPRED** XUV spectrometer **X-ray pulse height analyser**	 Plasma purity, Edge lines Edge and some bulk lines He & H-like stages of B,C,N,O Bulk lines of virtually all impurities E>1keV, metals
Laser ablation of trace impurities	Impurity transport
Charge exchange spectroscopy	$T_i(r)$ using diagnostic neutral beam light impurity densities
Neutron counter	D-D neutrons
Electron cyclotron emission (ECE)	$T_e(r,t)$ (fast,high spatial resolution) suprathermal ECE

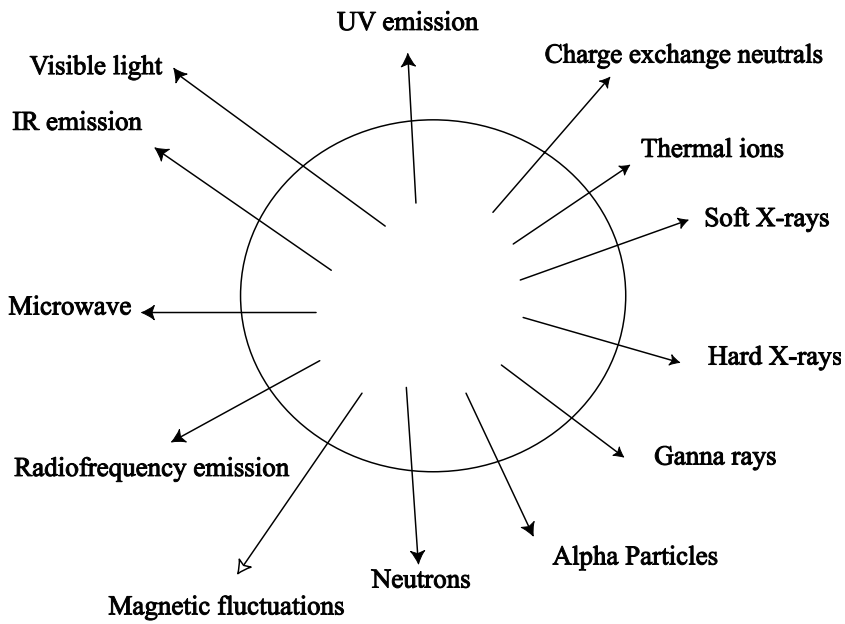
List of TCV diagnostics

Why are they so many?

1. Plasmas are extremely complex media (lots of chemical and physical phenomena: dissociation, recombination, ionization, waves, instabilities, shocks)
   - lots of parameters to measure (n_e, T_e, n_i, T_i, B, visible, VUV, IR, soft X, hard X emission, neutrons)
   - lots of physical phenomena providing the background for measurements (scattering, interference, emission of electromagnetic radiation, …)
2. Plasmas span a wide range of parameters
   - Different technologies, constraints and implementations of diagnostics to measure the same quantity $\Rightarrow$ choose the right one!!!

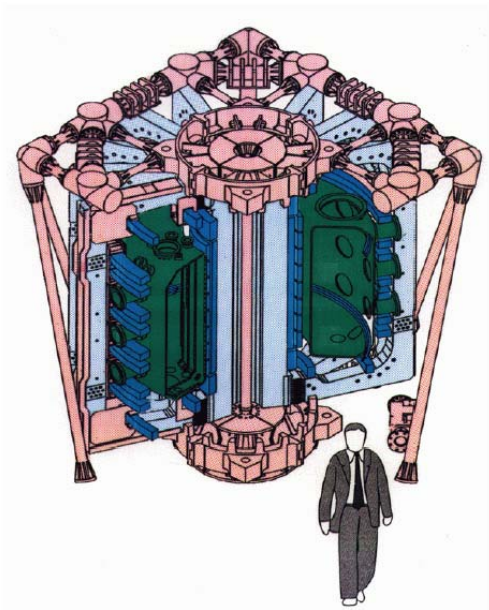
An example of complexity: spectrum of emission of a fusion plasma





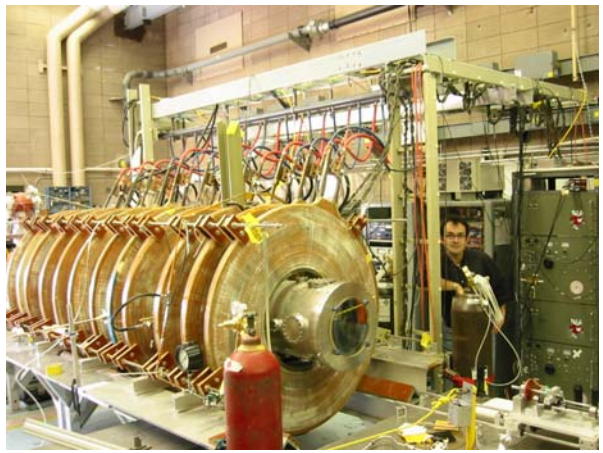
Plasmas span a wide range of parameters

TCV tokamak



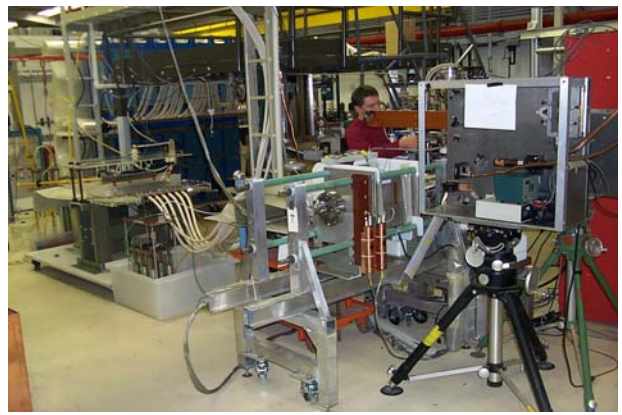
T_e~15KeV, n_e~$10^{20}m^{-3}$, τ~4s,m size, I_P~1MA, B~1T

RSX



T_e~10eV, n_e~$10^{19}m^{-3}$, τ~10ms,cm size, I_P~1kA, B~0.1T

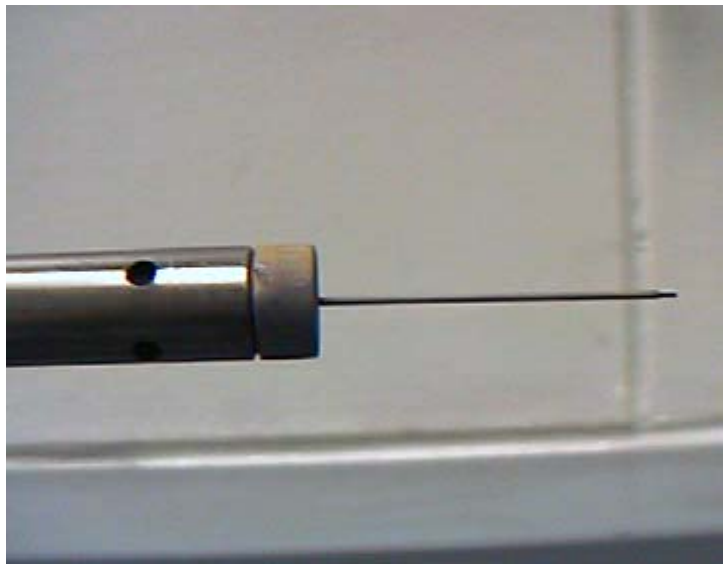
FRX-L



T_e~200eV, n_e~$10^{22}m^{-3}$, τ~12μs,cm size, I_P~1MA, B~3T

Different plasmas have different constraints

Langmuir probes are commonly used in small lab plasmas with small heat flux to the probe



An attempt of using a Langmuir probe into a too hot plasma…

Lesson learned: choose the right diagnostic!

An attempt to classify plasma diagnostics

Active diagnostics or "probing the plasma" (ex: a laser beam is injected in the plasma and the scattered wave is detected. The electron density and temperature can be calculated.)

Invasive: perturb the plasma

Non-Invasive: do not perturb the plasma

Passive diagnostics or "looking at the plasma" (ex: soft X-rays are emitted from the plasma and detected by photodiodes through different filters. The ratio of the two signals can provide T_e)

How to choose: physics first!!!

1. **Space and time resolution** (determined by the size and the timescale of the physical phenomenon in which we are interested) $\Rightarrow$ **good knowledge of the physics an plasma parameters in order to choose the good diagnostic!**

2. **Signal/noise level** (could be a factor that determines the choice of the diagnostic)

3. **Calibration** (can be done on a workbench, or diagnostics can be cross-calibrated)

4. **Good understanding of the physics that is beyond the measurement** (two classes: 1) easy measurements, difficult interpretation, ex. Langmuir; 2) difficult measurement, easy interpretation, ex. Thomson scattering)

Magnetic measurements: different plasma parameters and physics ⇒ different constraints

RSX

Plasma: T_e~10eV, n_e~$10^{19}m^3$, τ~10ms, cm size, I_P~1kA, B~0.1T

Physics: magnetic reconnection (μs)

1. **B probe can be placed inside the plasma: thermal, electrical shielding**
2. **Small B, I_P,**
3. **Need to the very small (1mm)**
4. **Need to be very fast (f > 5MHz)**

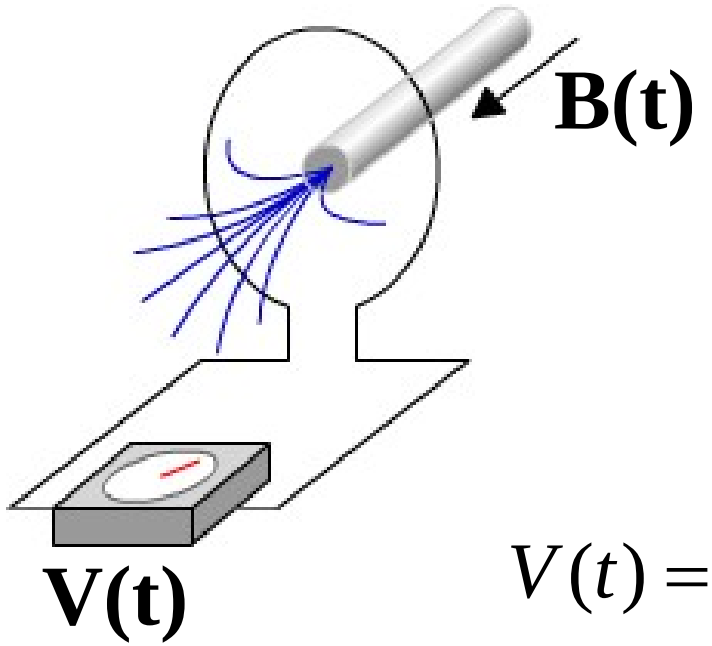
TCV

Plasma: T_e~15KeV, n_e~$10^{20}m^{-3}$, τ~4s, m size, I_P~1MA, B~1T

Physics: control of the plasma (ms), MHD instability (1/10 ms)

1. **No physical contact of B probe with the plasma**
2. **High B, I_P, high signal-to-noise ratio, no electrostatic shielding**
3. **Can be fairly big (few cm)**
4. **Not particularly fast** (f~100kHz)

Passive diagnostics: magnetic field

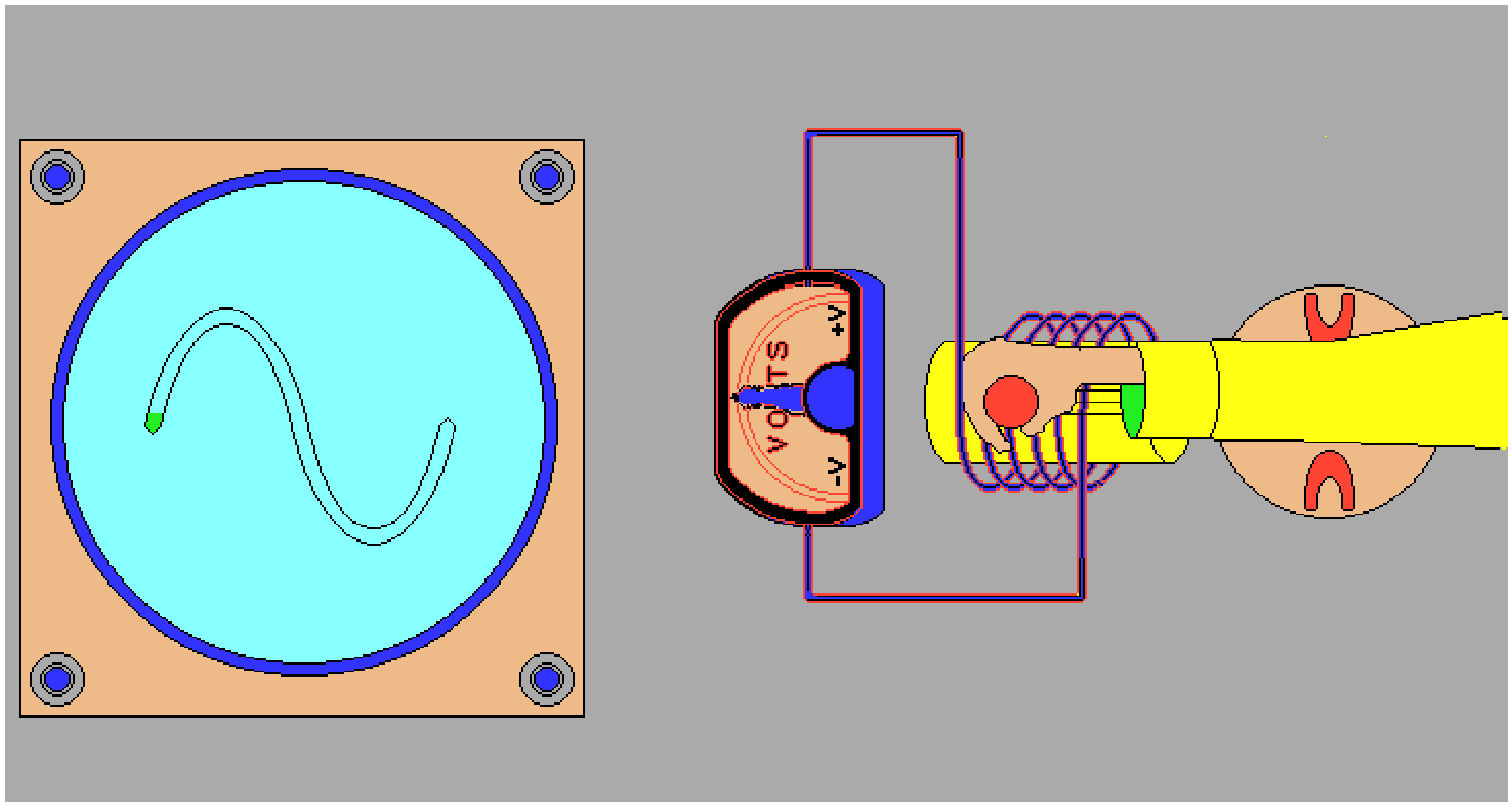


Faraday's law

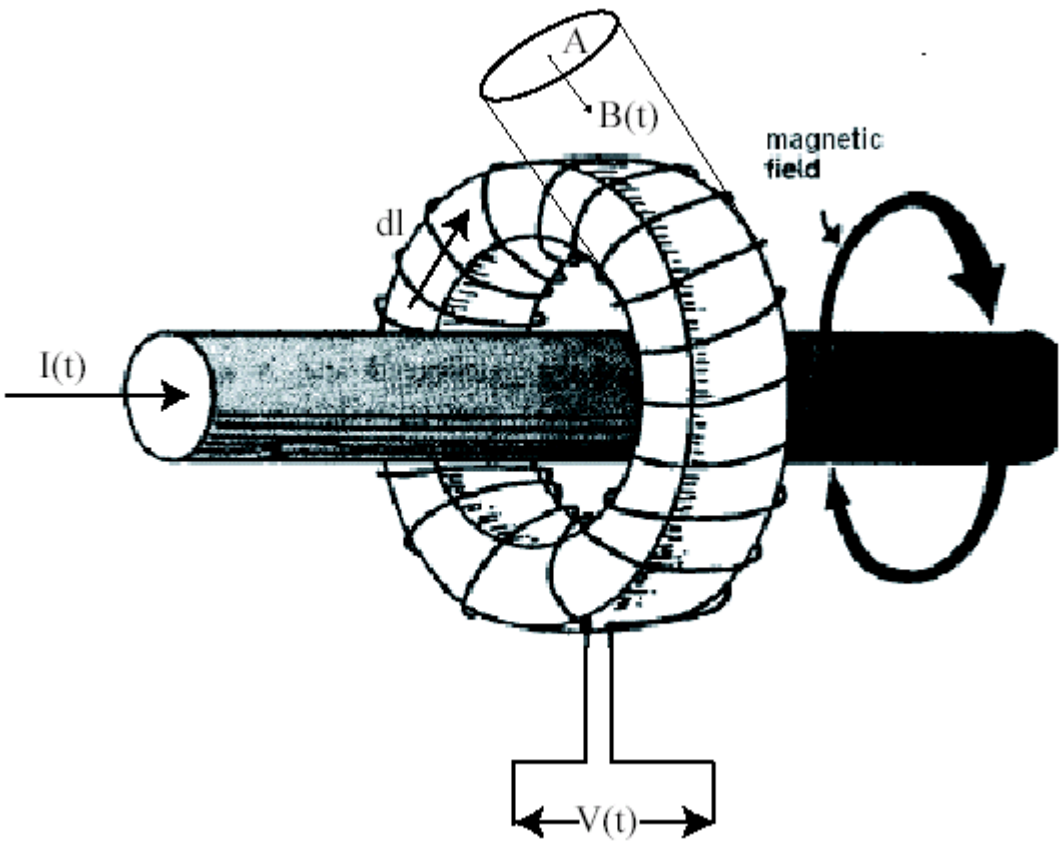
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \longrightarrow \oint \vec{E} \cdot d\vec{\ell} = -\frac{d}{dt}\int \vec{B} \cdot d\vec{A}$$

$$V(t) = -A\frac{dB(t)}{dt} \longrightarrow B(t) = -\frac{1}{A}\int_0^t V(t)dt$$

Animated demonstration of Faraday's law



Passive diagnostics: Rogowski coil for plasma current measurements



$$V(t) = -\frac{d\Phi}{dt}$$

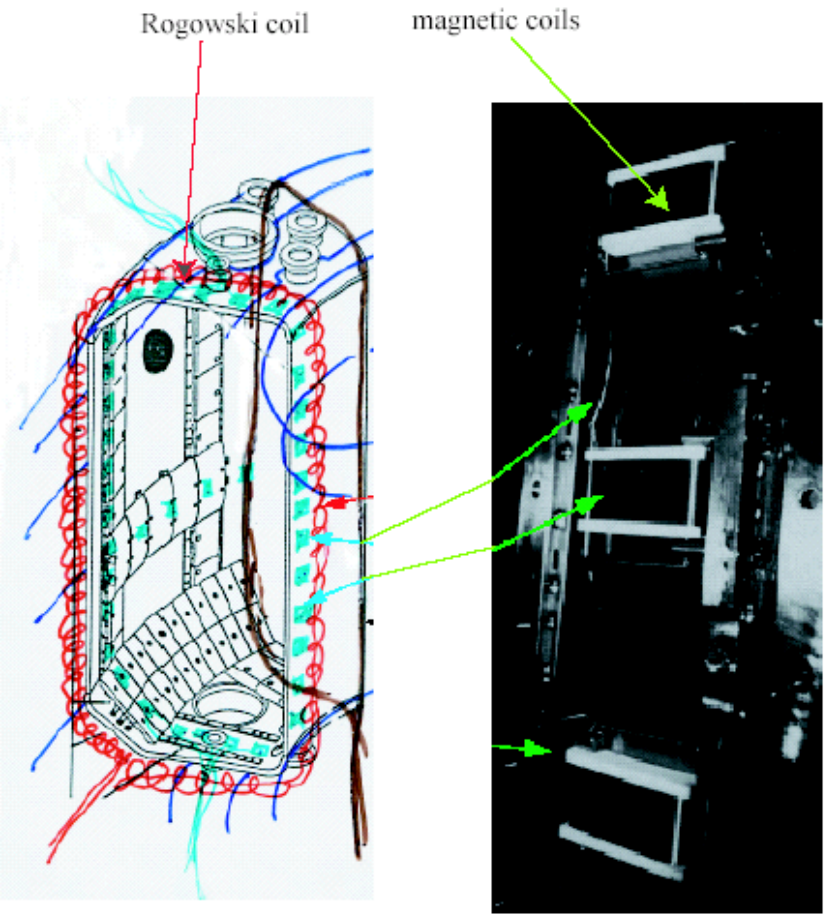
$$\Phi = BAnl$$

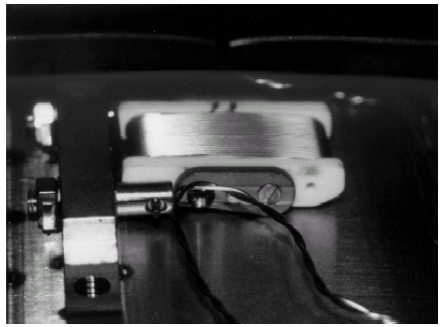
$$\Phi = AnBl = An\oint Bdl$$

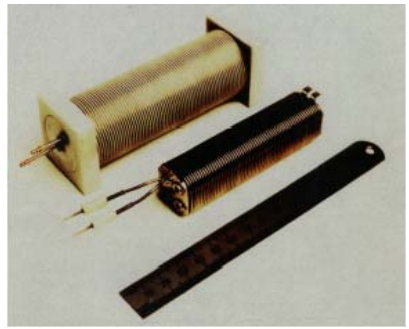
$$An\oint Bdl = An\mu_0 I$$

$$V(t) = -An\mu_0 \frac{dI}{dt}$$

Implementation on TCV







200 magnetic coils (cm size)

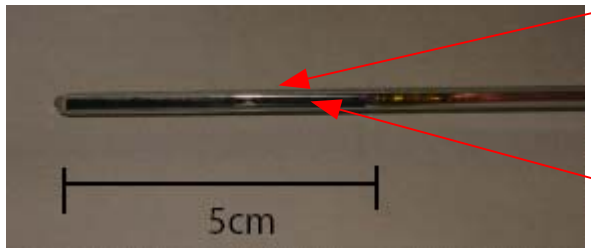
1. **Control of plasma**
2. **Shape of plasma**
3. **MHD mode identification**

Single Rogowski coil

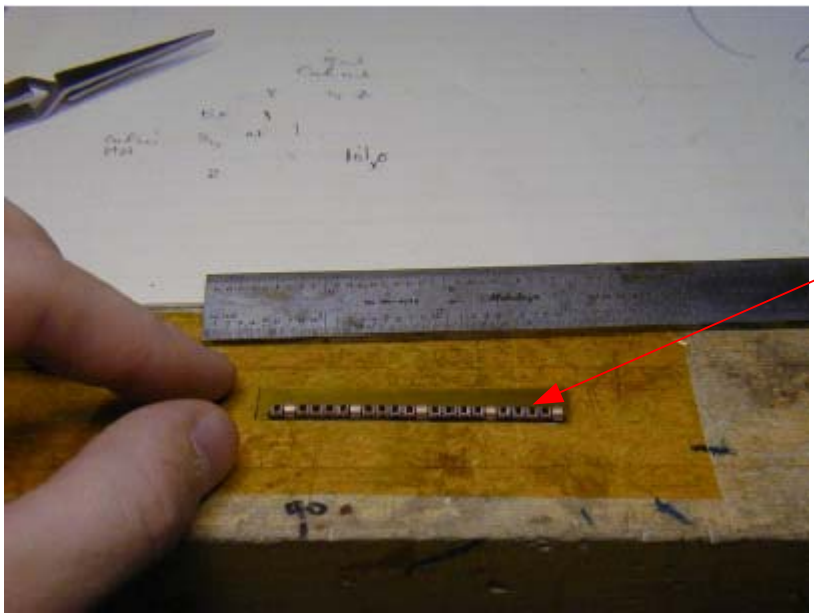
1. **Total plasma current**

Implementation on RSX: 2D magnetic probes

Pirex tubing for thermal and electrical insulation (heat load ~ 30J)

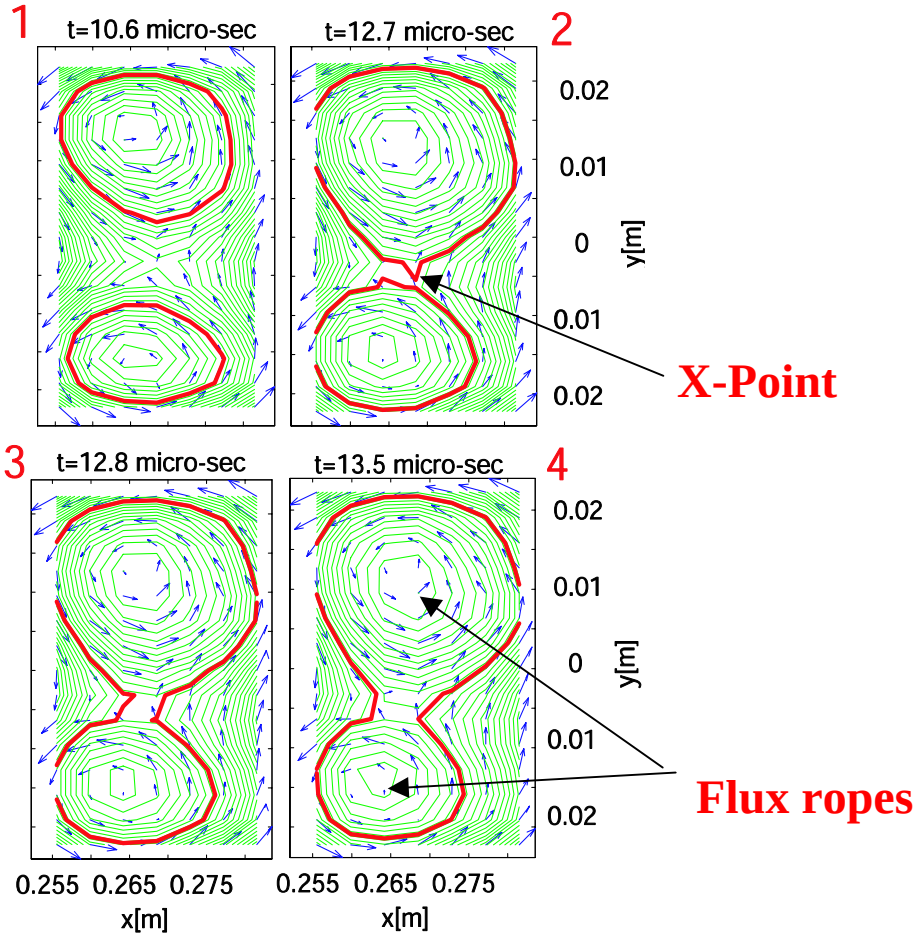


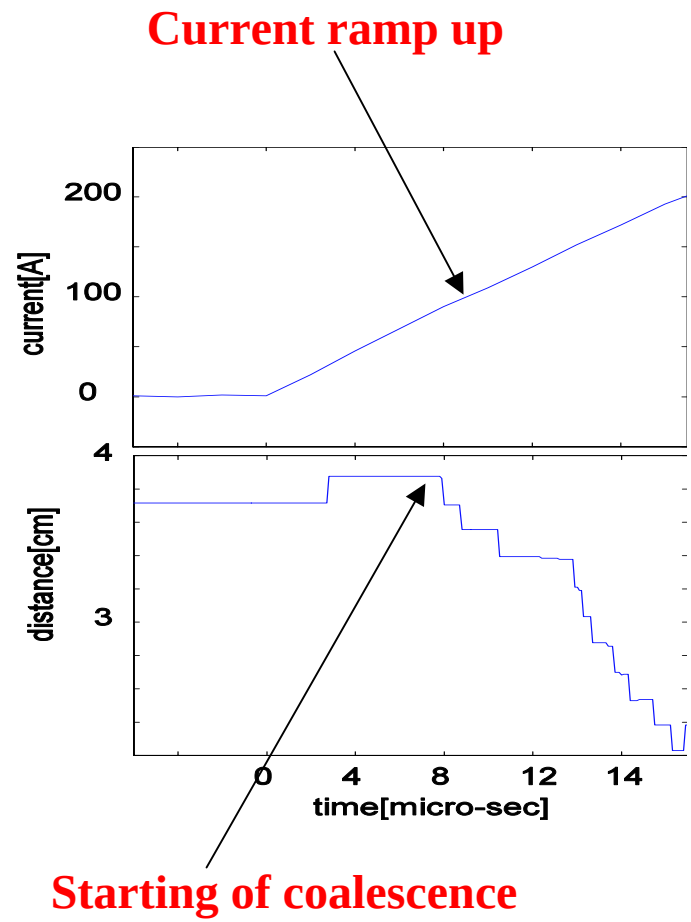
Ele



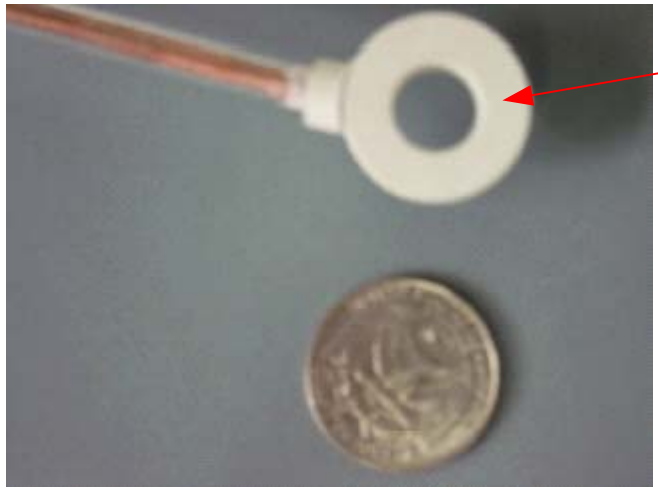
12 ns
20MHz

The probe is inserted into the RSX plasma and provide time and space resolved data

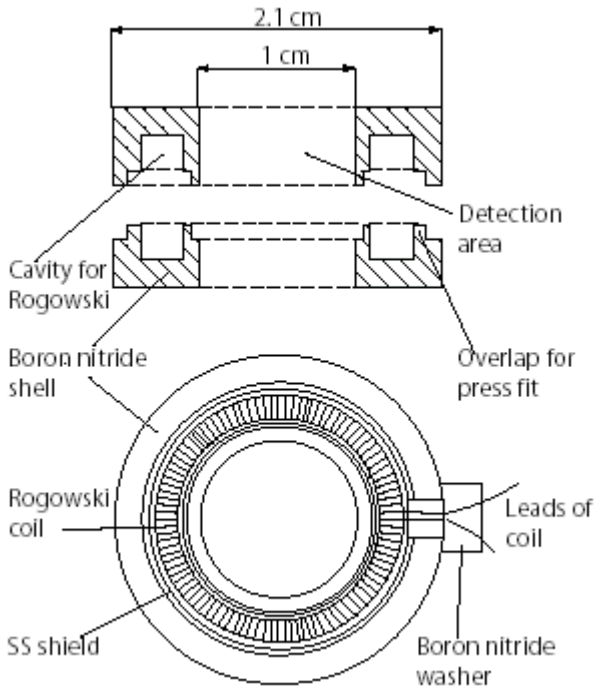




Implementation on RSX: Rogowski probe



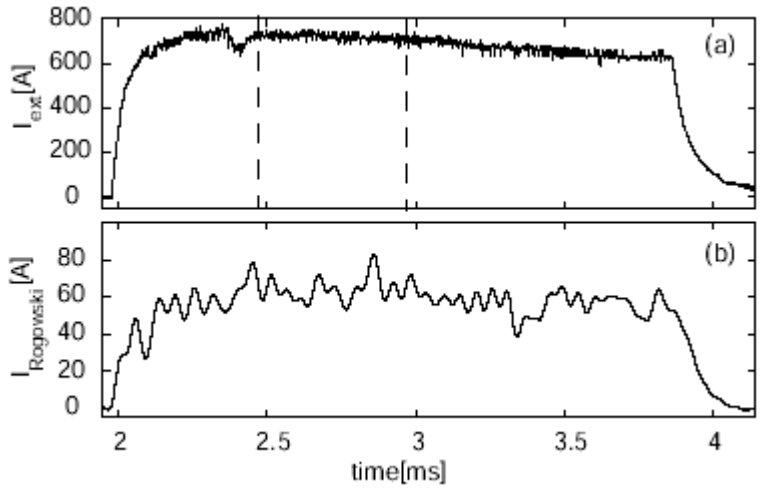
BN shell



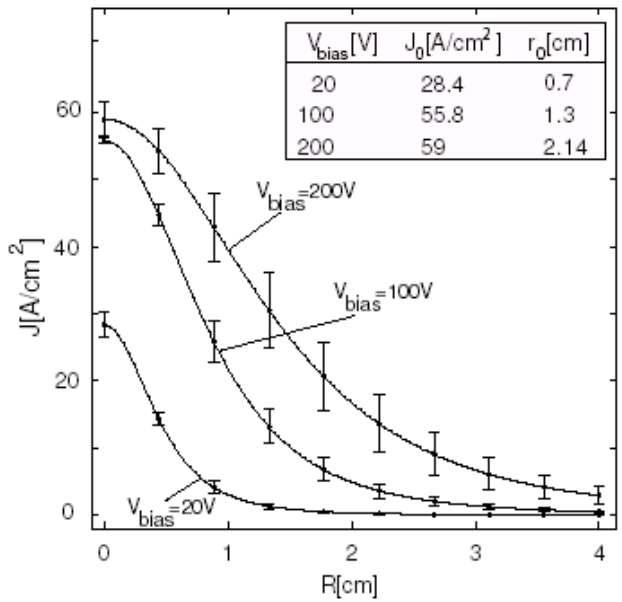
1. **High heat flux~100 J**
2. **Thermal, electrical insulation (BN)**
3. **Electrostatic shield (SS)**
4. **High freq. response ~ 5 MHz**

The probe has adequate time response and spatial resolution ⇒ good diagnostic

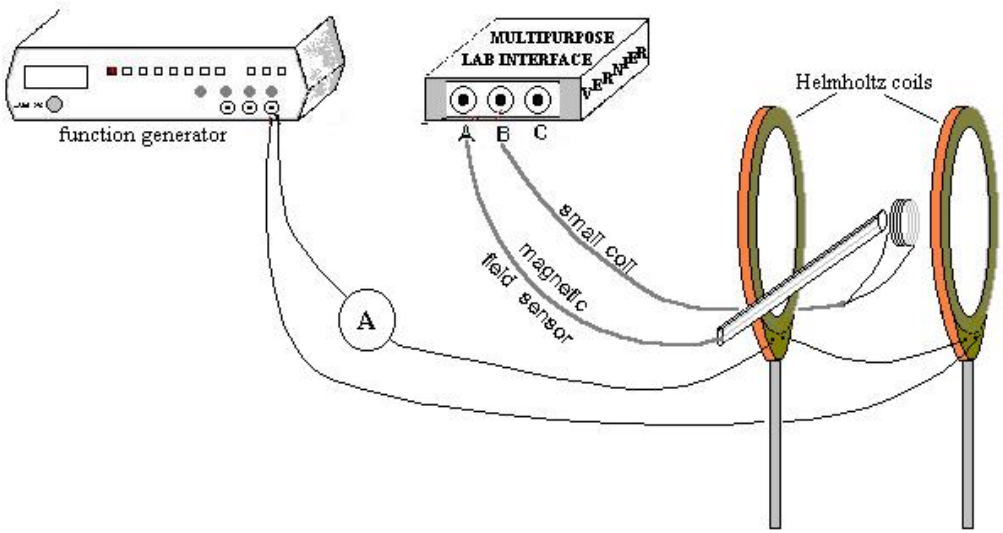
Plasma current time evolution



Plasma current profiles



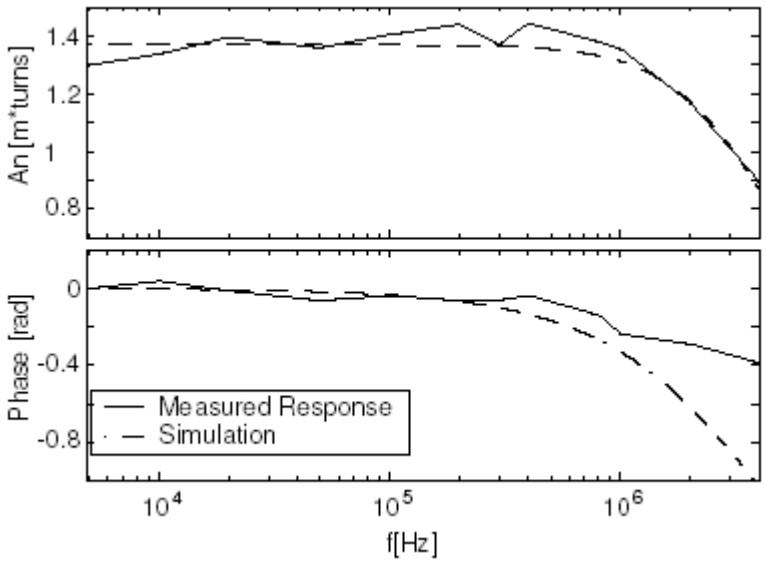
A common issue: the calibration



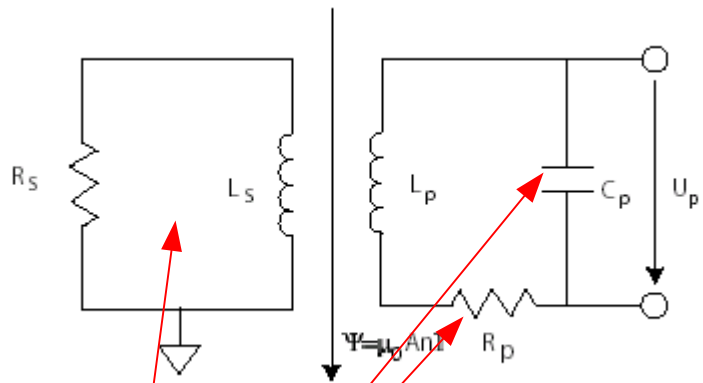
1. Need to know absolute calibration: Gauss/Volts, A/Volts
2. Non-ideal effects of the probe: resistivity, capacity of the wire, coupling to the shield
3. Build equivalent circuit of the probe: frequency response
4. Extremely difficult procedure at high and low frequency

Calibration may reveal important non-ideal effects

Frequency response

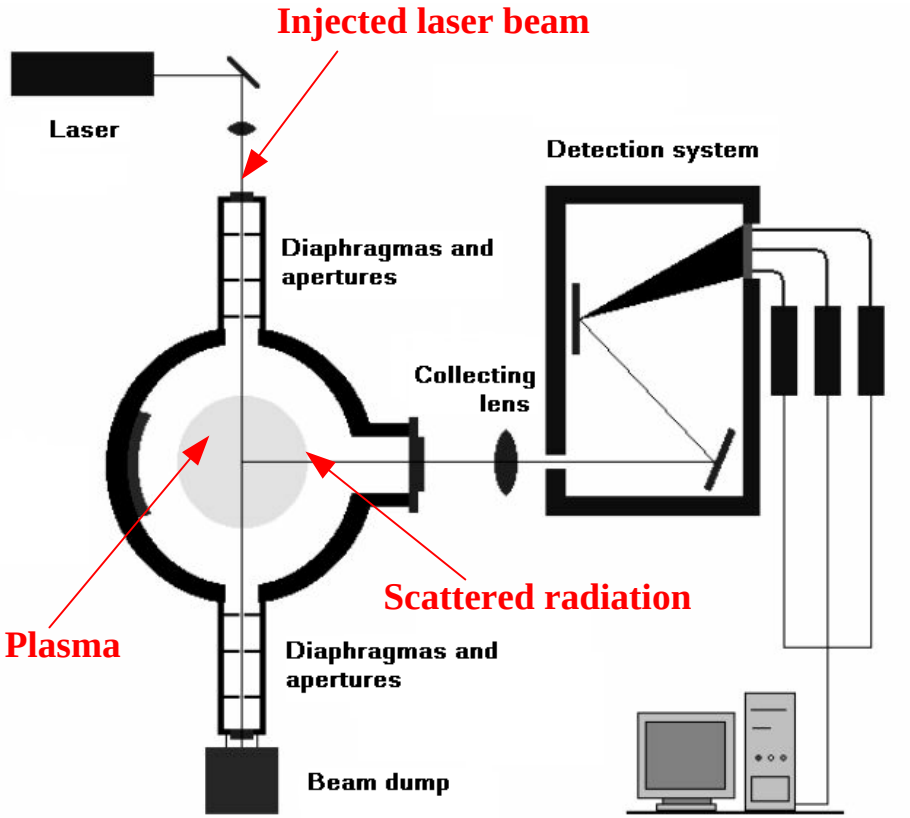


Equivalent circuit



Non-ideal effects

T_e measurement: brief tutorial on Thomson scattering (I)



Principle: inject a laser beam through the plasma and measure the scattered laser radiation

Brief tutorial on Thomson scattering (II)

Provided the following conditions are satisfied:

1. $\omega_{laser} >> \omega_{pe}=(n\varepsilon^2/e_0 m_e)^{1/2}$ => incoherent Thomson scattering
2. Classical approximation => no relativistic effects (T_e<1 keV)
3. Electron Maxwellian distribution => $f(v)$

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = 2.82e^{-15} m$$

$$\frac{d^2P}{d\Omega d\omega} = P_0 n_e r_e^{\,2} (\sin\vartheta)^2 L f(v)$$

P_0 total incident laser power

θ angle between incident and scattered rad.

Ω unit solid angle

n_e electron density

L interaction length

Few practical considerations

$$\frac{d^2P}{d\Omega d\omega} = P_0 n_e r_e^{\,2} (\sin\vartheta)^2 L f(v)$$

total scattered power ~ n_e
spectral distribution ~ $f(v_e)$
HWHM ≈ 16 $T_e^{1/2}$ Å (T_e in eV)

$$P_{tot} = P_0 n_e \frac{8\pi}{3} r_e^{\,2} L$$

$$\sigma_{Th} = \frac{8\pi}{3} r_e^{\,2} = 6.65e^{-29} m^2$$

n_e~10^{20}m^{-3}, L=1 cm, Ω~10^{-2} sr ⇒ Only 10^{-13} photons are collected

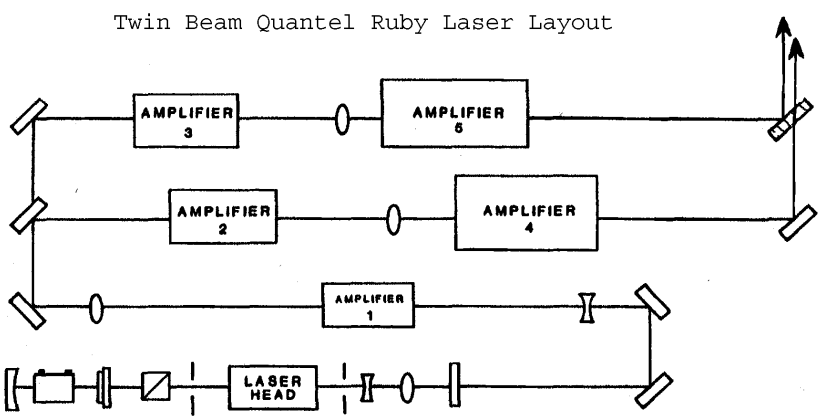
MW → μW ⇒ Need for powerful lasers

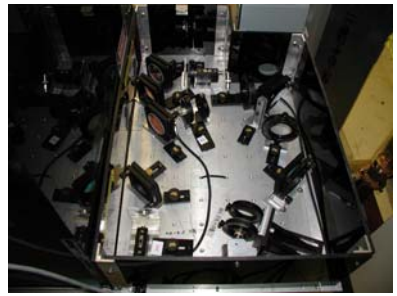
Good design is crucial for SNR

Serious issues to take into account

- Minimization of stray laser light
  - Long entrance and exit ports with baffles
  - Laser exit dump
- Alignment
  - Accurate intersection of laser beam with focal point of collection optics
  - Avoid contact of laser beam with stray-light reducing components (*e.g.,* baffles) along beam transport path
- Calibration
  - Absolute wavelength position (using neon lamp)
  - Absolute calibration for n_e determination using known Rayleigh scattering cross section in nitrogen gas (few hundred Torr)
- Must contend with plasma background light
  - Best possible SNR limited by bremmstrahlung
  - other line radiation, especially D_α at 656.2 nm, may also be important

Thomson scattering on FRX-L

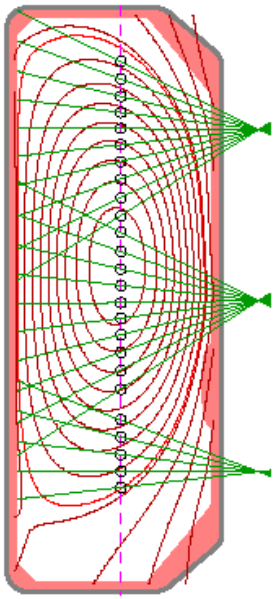




- Quantel ruby laser (694.3 nm, 12 J/beam)
- DEP gated intensifier (10% QE, 75 mm, 30 ns exposure)
- PixelVision 512 × 512 16-bit cooled CCD
- Holographic grating spectrometer 1650 mm^{-1}, f/5 with coverage from 694.3–656.1 nm
- Up to 6 viewing chords w/fiber bundles each with three 2 mm diameter quartz fibers and a *f*/4, 1.7 cm diameter lens

Thomson scattering on TCV

Geometrical setup

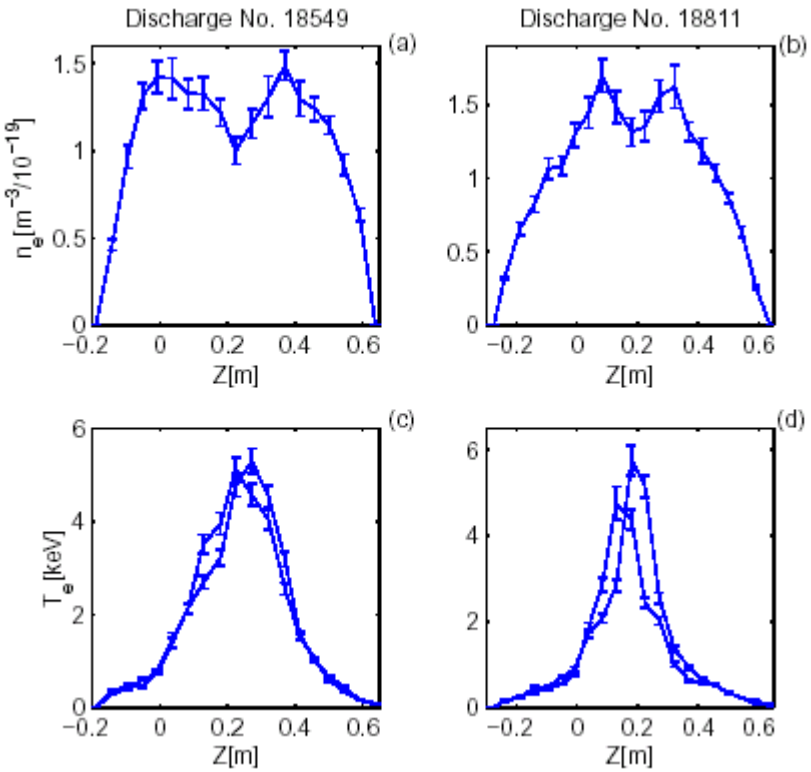


Collection optics

Polychromators

1. Three Nd-Yag lasers (1.04mm, 20Hz, 1J)
2. 25 point measurements (4 cm resolution)
3. Polychromators with 3 or 4 interference filters
4. Si-avalanche photodiodes
5. Optimized for T_e>50eV, n_e>1e18m^{-3}

Thomson scattering data on TCV



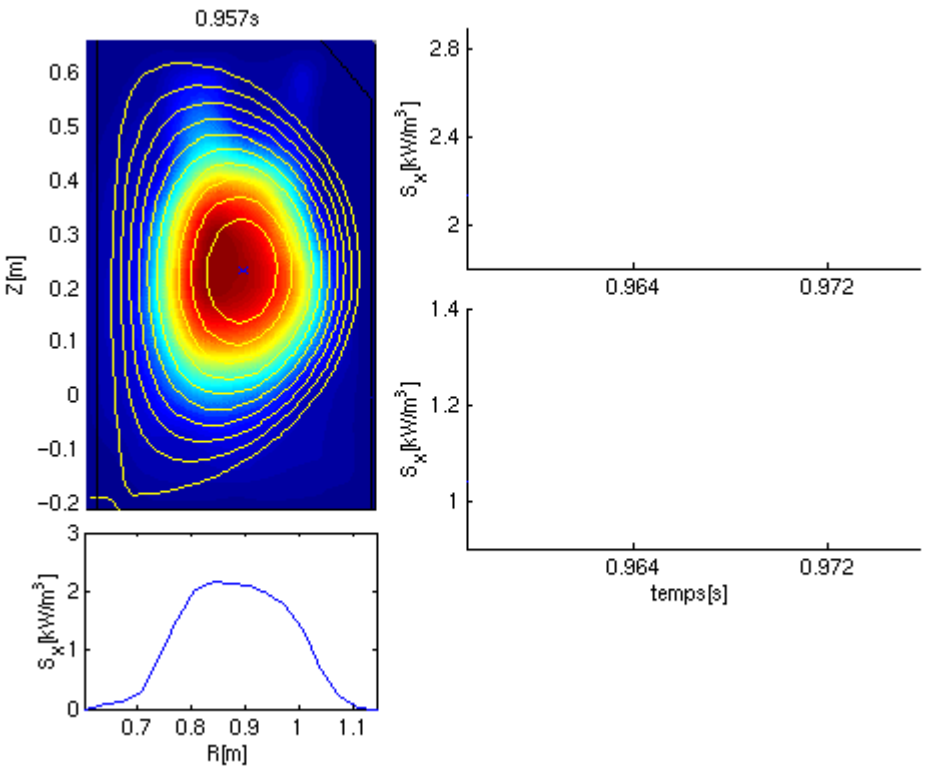
Advantages:

- Easy interpretation
- T_e and N_e profiles

Disadvantages:

- Needs powerful lasers ($$)
- Difficult measurement
- Small rep. Rate -> only small time scale phenomena

Thomson scattering is inadequate to study fast MHD phenomena (sawteeth)



Sawtooth activity time scale

1. Ramp: >1 ms
2. Crash: <100 ns

Thomson Rep. Rate=60Hz

Need another diagnostic!

Brief tutorial on radiation from plasmas

Bremsstrahlung

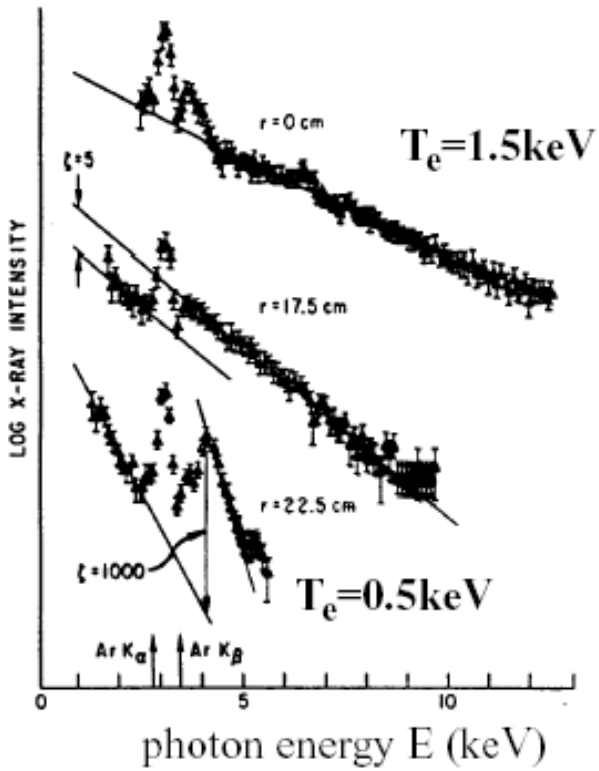
$$e(\nu) \propto n_e n_Z Z^2 \frac{e^{-h\nu/T_e}}{\sqrt{T_e}}$$

Recombination

$$e(\nu) \propto n_e n_Z Z^2 \frac{e^{-h\nu/T_e}}{\sqrt{T_e}} \left(\frac{Z^2}{n^3 T_e} e^{-Z^2 R_y / n^2 T_e}\right)$$

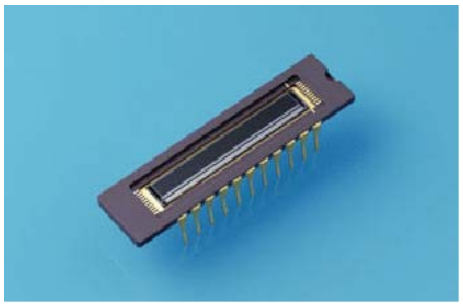
Line radiation

$$I_{p,q} = n_Z(p) A(p,q) h\nu_{p,q}$$



Soft X-rays are detected by photodiodes

Si photodiodes

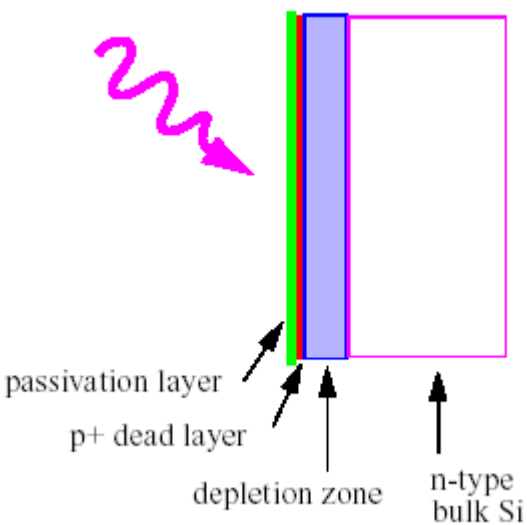


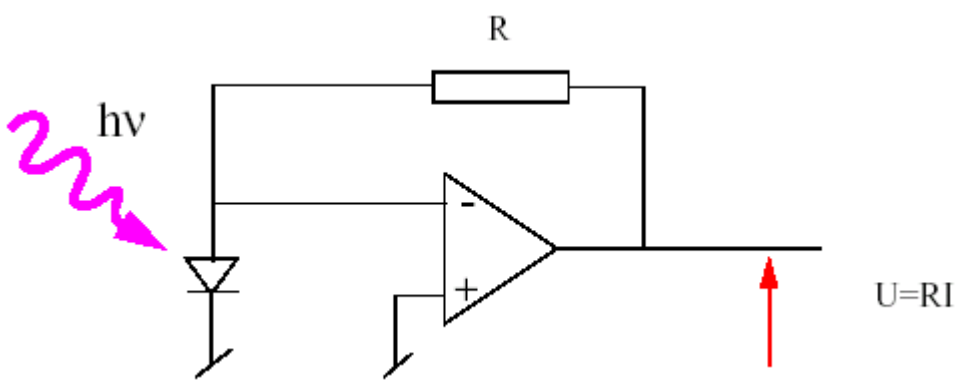
- Si photodiodes (PIN type, same as for visible light), Si bandgap energy 3.6eV
- Photon energy E is converted to N electron-hole pairs

$$N = \frac{E(eV)}{3.6eV}$$

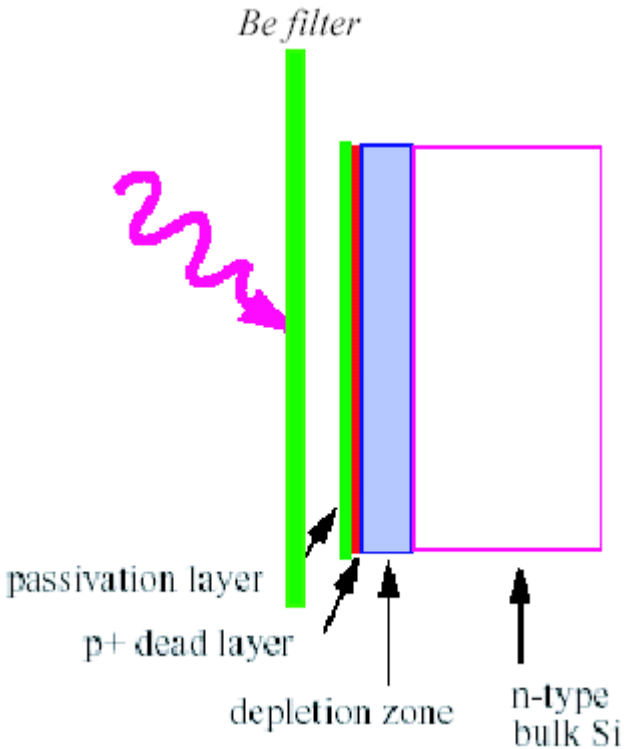
- Resulting photocurrent is

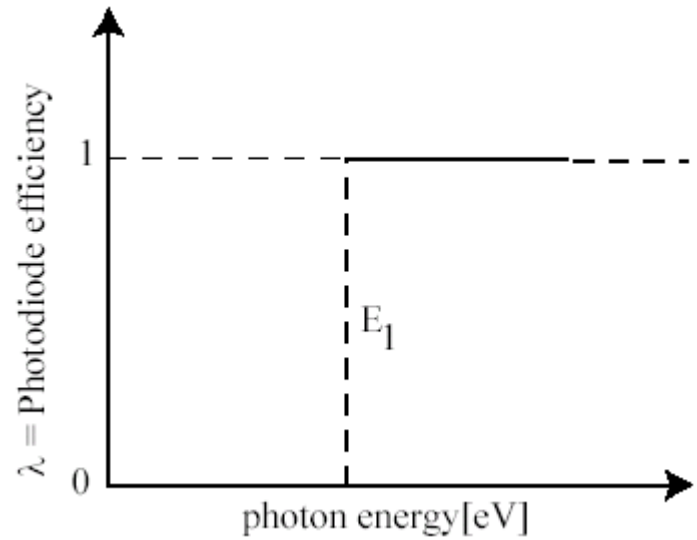
$$I[A] = \frac{P_{det}[W]}{3.6}$$





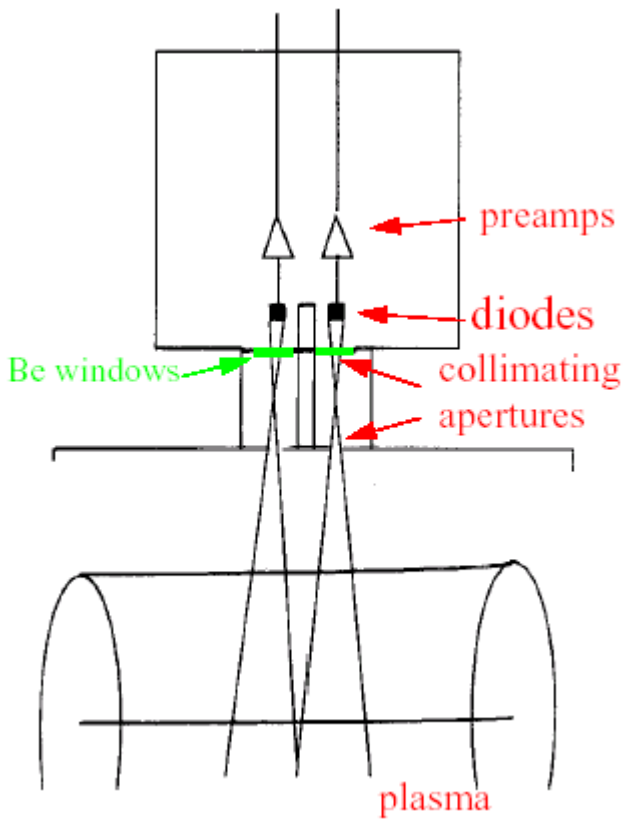
Photodiodes can be filtered to stop high energy photons: ideal case





$$P = \int_0^\infty e(E)\lambda(E)dE = \int_{E_1}^\infty e(E)dE$$

If only Bremss is important and n_e, n_Z, Z are constant, it is easy to extract T_e from two-foil measurements



Bremsstrahlung

$$e(\nu) \propto n_e n_Z Z^2 \frac{e^{-h\nu/T_e}}{\sqrt{T_e}}$$

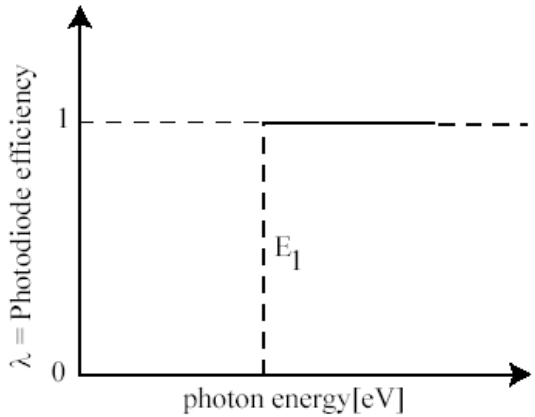
$$P_1 \propto \int_{E_1}^{\infty} n_e n_Z Z^2 \frac{e^{-E/T_e}}{\sqrt{T_e}} dE = n_e n_Z Z^2 \sqrt{T_e} e^{-E_1/T_e}$$

$$P_2 \propto \int_{E_2}^{\infty} n_e n_Z Z^2 \frac{e^{-E/T_e}}{\sqrt{T_e}} dE = n_e n_Z Z^2 \sqrt{T_e} e^{-E_2/T_e}$$

$$\frac{P_2}{P_1} = \frac{e^{-E_2/T_e}}{e^{-E_1/T_e}} \longrightarrow T_e = \frac{E_1 - E_2}{\log(\frac{P_2}{P_1})}$$

Real world is more complicated…

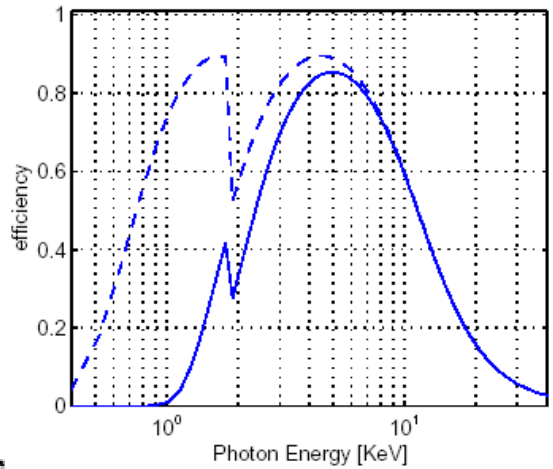
Ideal

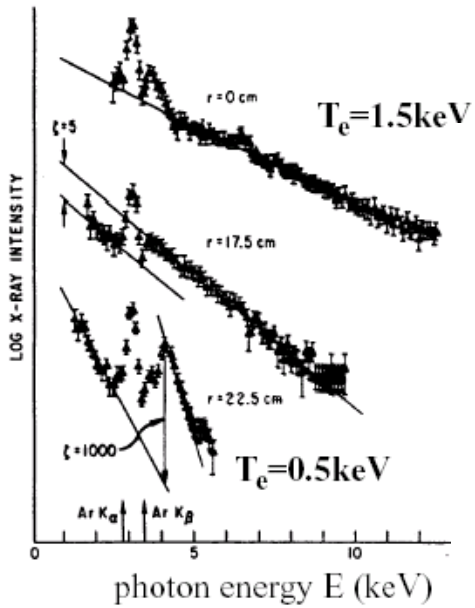


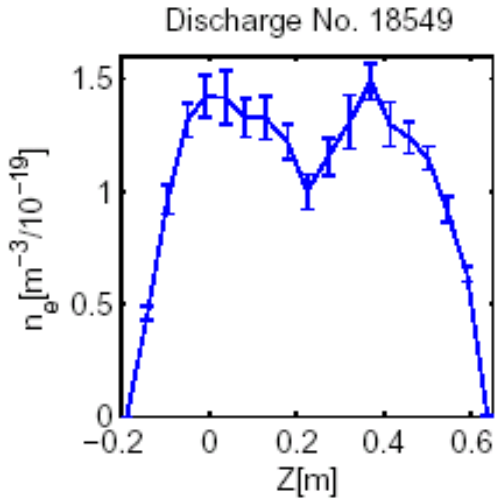
Only Bremss is important: not true!!!

Profiles are constant: not true!!!

Reality

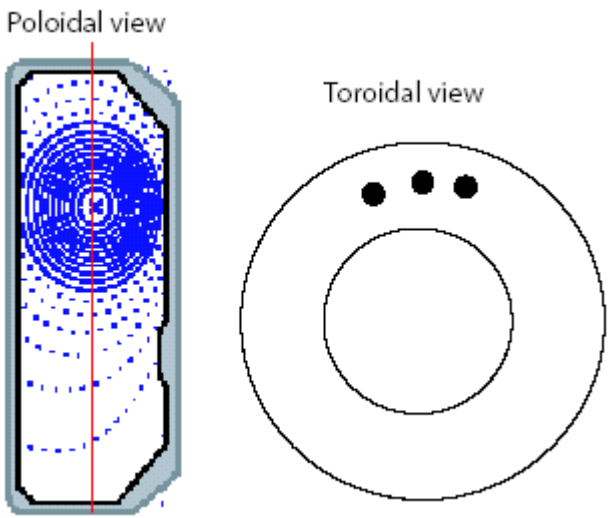


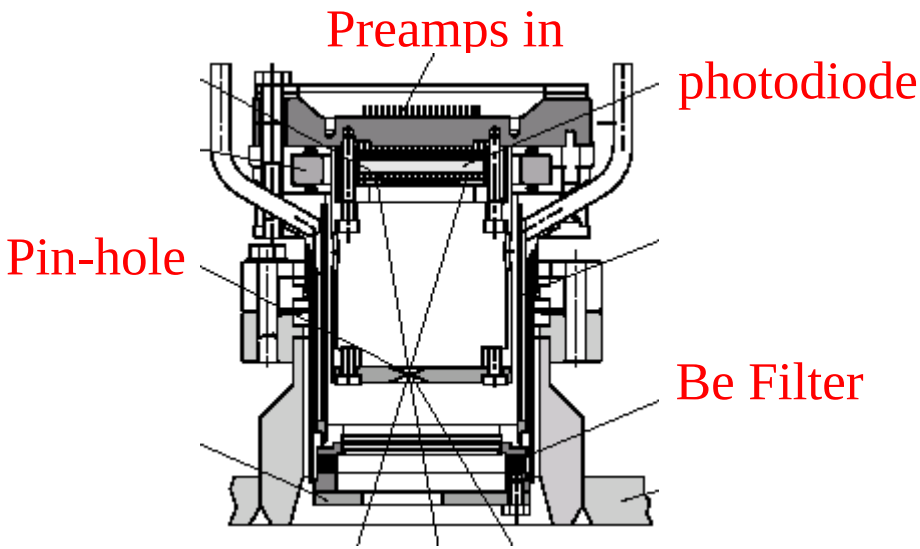




Two foil system setup on TCV

Photodiode setup





Three Si photodiodes filtered by 50, 150, 650 μm Be filter, 250 kHZ acquisition frequency (very fast)

Reality: a perfect example of easy to make and difficult to interpret measurements

$$E(r) = \sum_Z n_e(r) n_Z(r) \varepsilon_Z(r)$$

$$P = \frac{A\Omega}{4\pi} \int_{L_t} \sum_Z n_e(r) n_Z(r) \varepsilon_Z(r) dl_i \propto \int_{L_t} n_e^2 \sum_Z \varepsilon_Z(r) dl_i$$

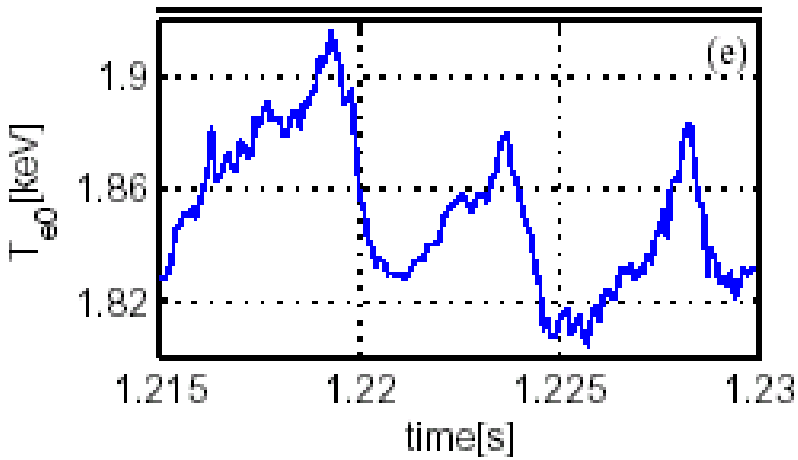
$$n_e = n_{e0}\left(1 - \frac{r^2}{a^2}\right)^\alpha$$

$$T_e = T_{e0}\left(1 - \frac{r^2}{a^2}\right)^\beta$$

$$P \propto \int_{L_t} n_e^2 \sum_Z \varepsilon_Z(T_e) dl = n_{e0}{}^2 f(\alpha, \beta, T_{e0})$$

A strong modeling of the plasma is required to derive the electron temperature

T_e can be calculated with a lot of work and the time resolution is adequate to study ST activity



Advantages:

1. Inexpensive
2. Fast (250kHz)

Disadvantages:

1. Difficult to interpret
2. Only T_{e0} provided
3. Requires inversion procedure

References

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