IPP Summer University for Plasma Physics and Fusion Research

Greifswald, Sept. 2016

Wendelstein project W7-X

DIAGNOSTICS FOR FUSION PLASMAS

with contributions from many colleagues
and some textbooks (see reference list at the end)

J. Baldzuhn, Greifswald 2016

Outline of this talk:

1) Basics, measured quantities, principles and some physics
(here we stick to the magnetic field, electrons and protons)

2) Techniques, practical considerations and some results

Challenges in a fusion relevant plasma:

- It is extremely hot

- Impurities can pollute it
  (anything heavier than H,D,T)

➔Nothing made of material
can touch it

- Radiation and fast particles

- Intense EM background

- Wide range of timescales:
Several seconds τ_Z, L/R,…
⇔ GHz-range: fast MHD,…

$T > 10^8$ K
(about 10 keV)

Only H+, D+, e-
(ideally); reactor: T+

In reality: also
traces (!!) of
C, Fe,…….

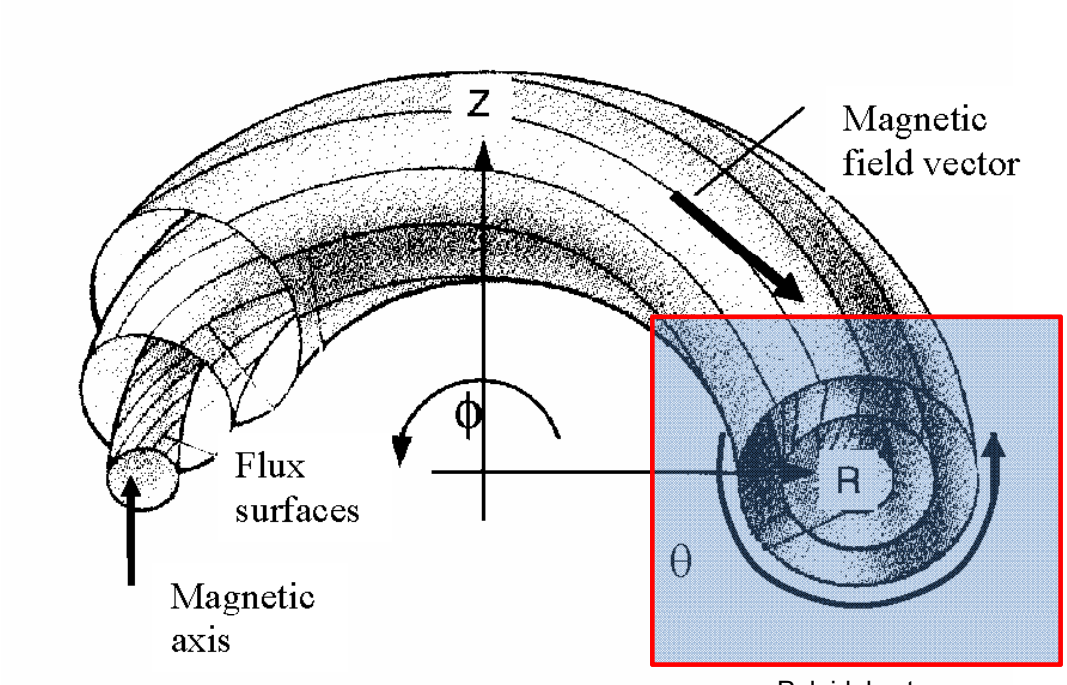
The most important ingredient for plasma fusion: the magnetic field

The concept of nested magnetic flux surfaces:

Almost all quantities are constant on one and the same flux surface

Problem: how can we map from magnetic coordinates { Z, θ, ϕ}
to „real-space“ coordinates [x, y, z]?

The situation is relatively „simple“
in a tokamak:
there we have axisymmetry !



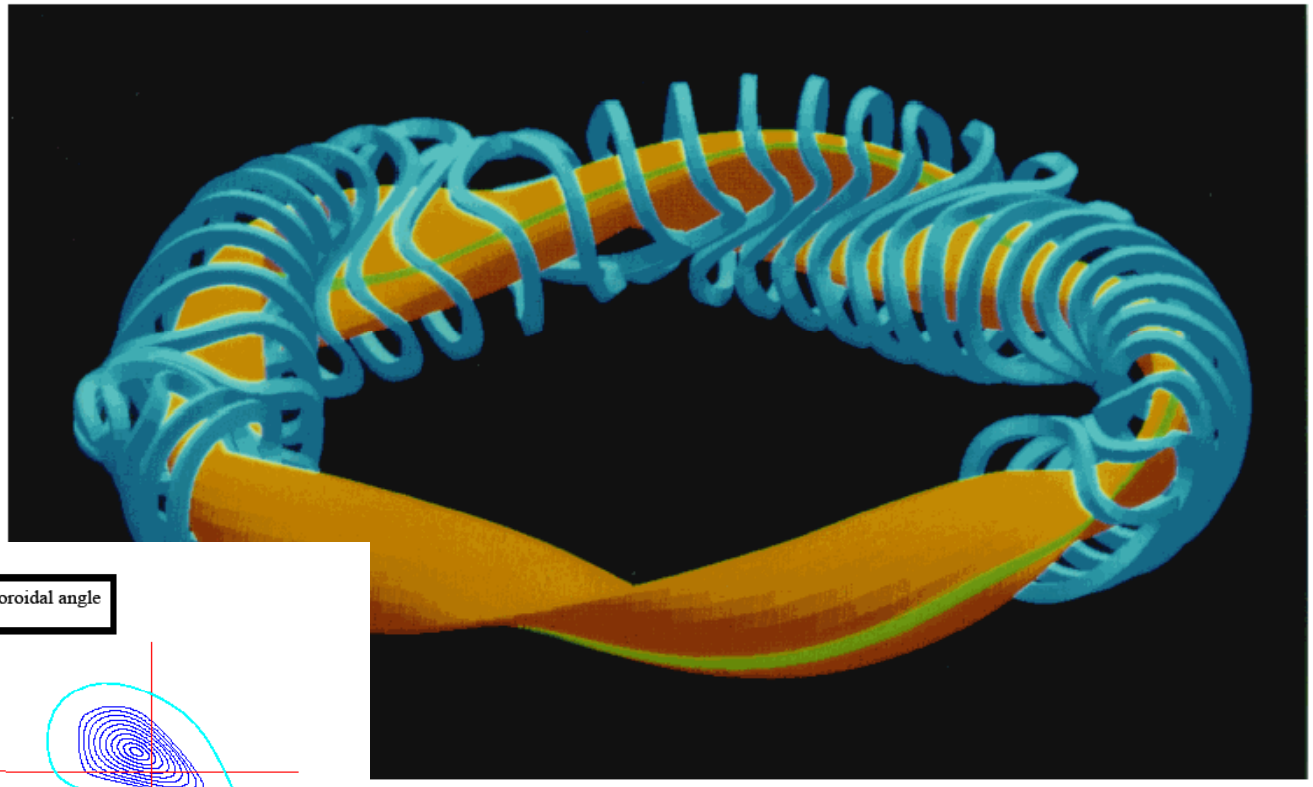
Poloidal cut

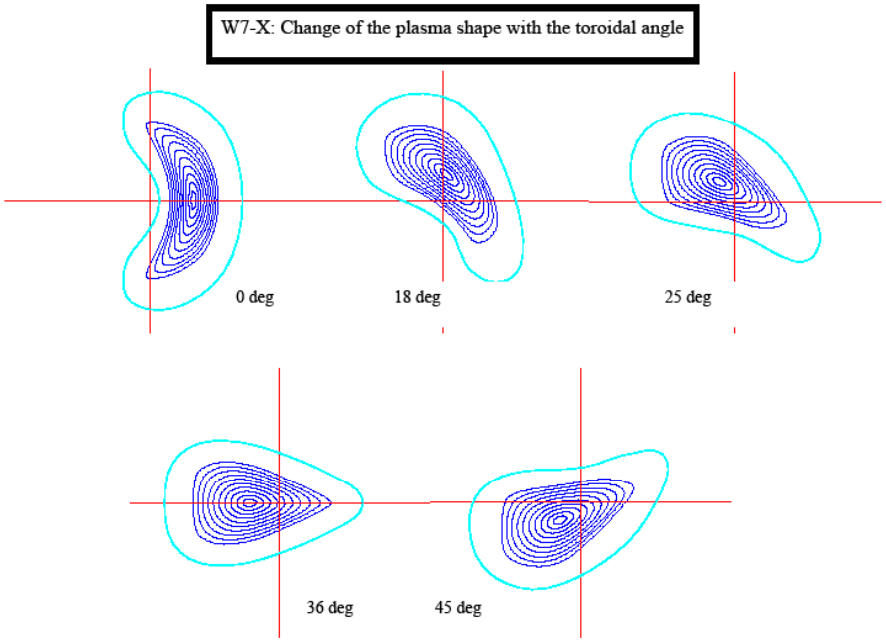
Hutchinson: Principles of plasma diagnostics

Unternehmung
Wendelstein 7-X

The situation is more complex in a stellarator: full 3-D !

W7-X: an artist's view





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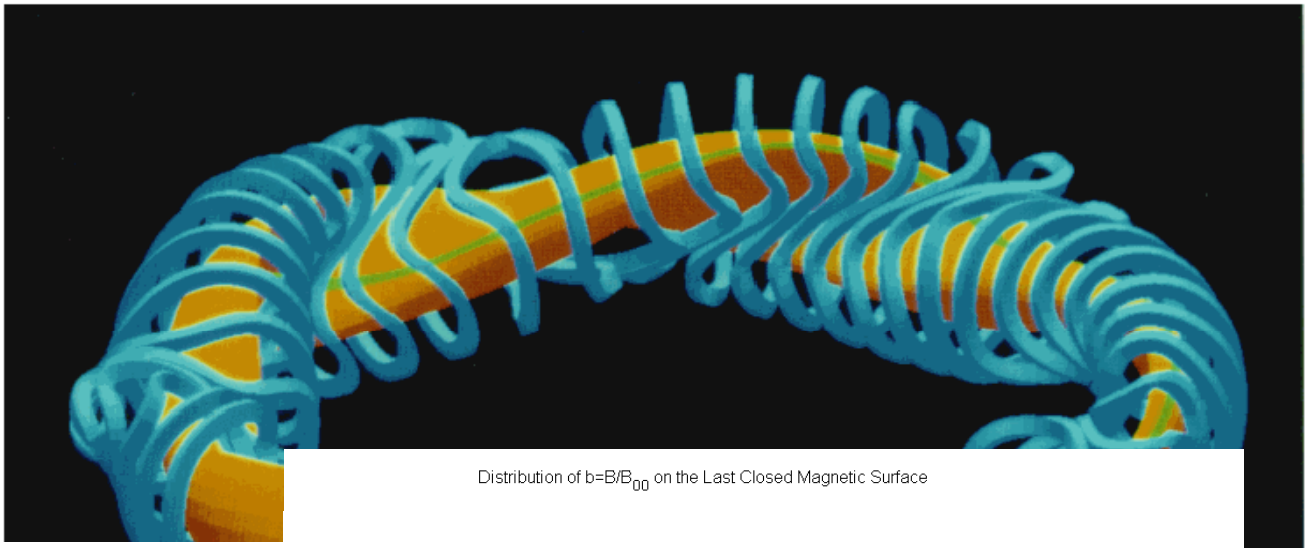
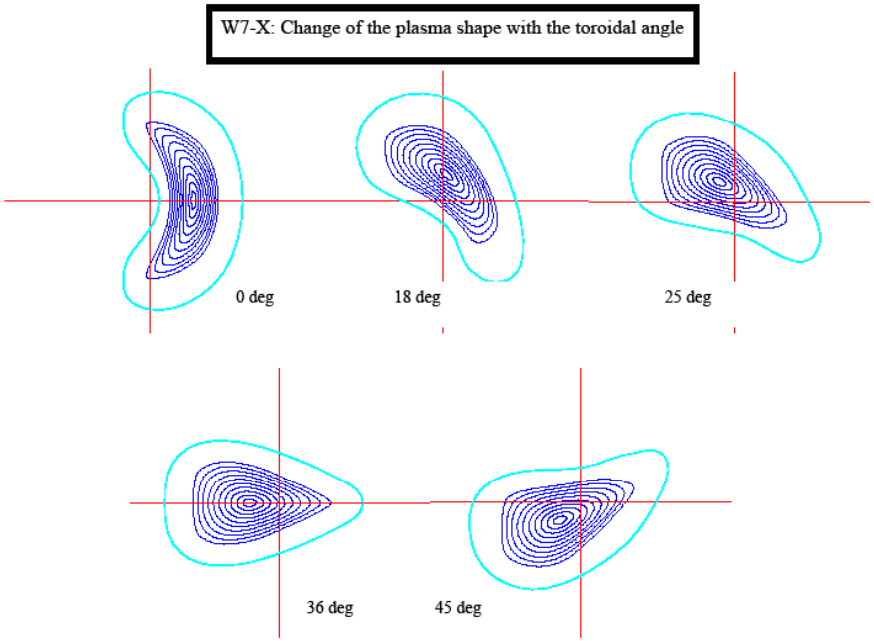
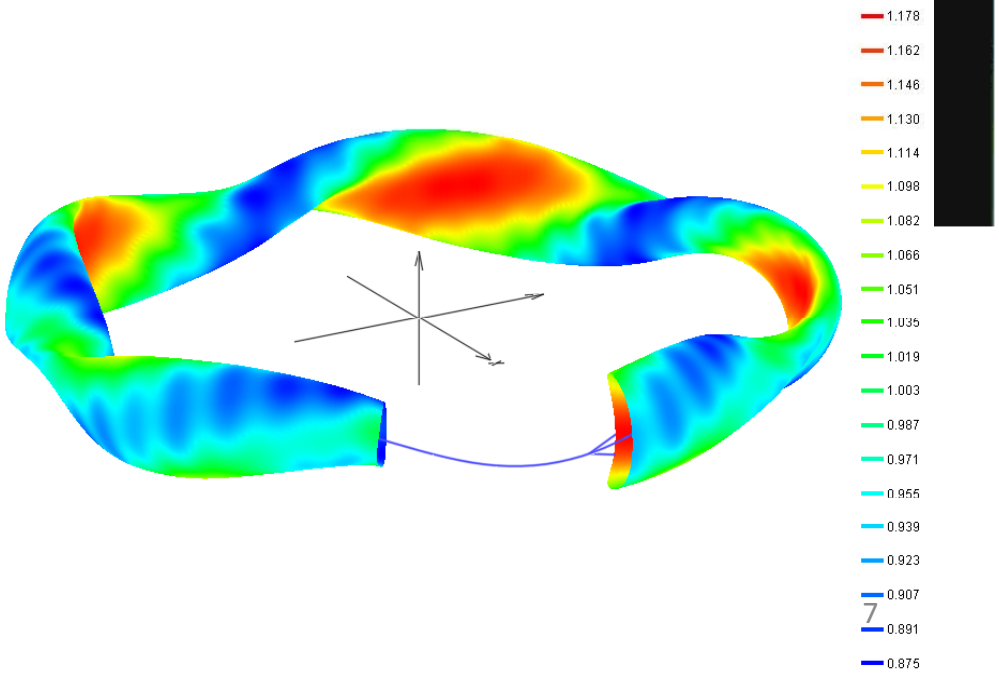
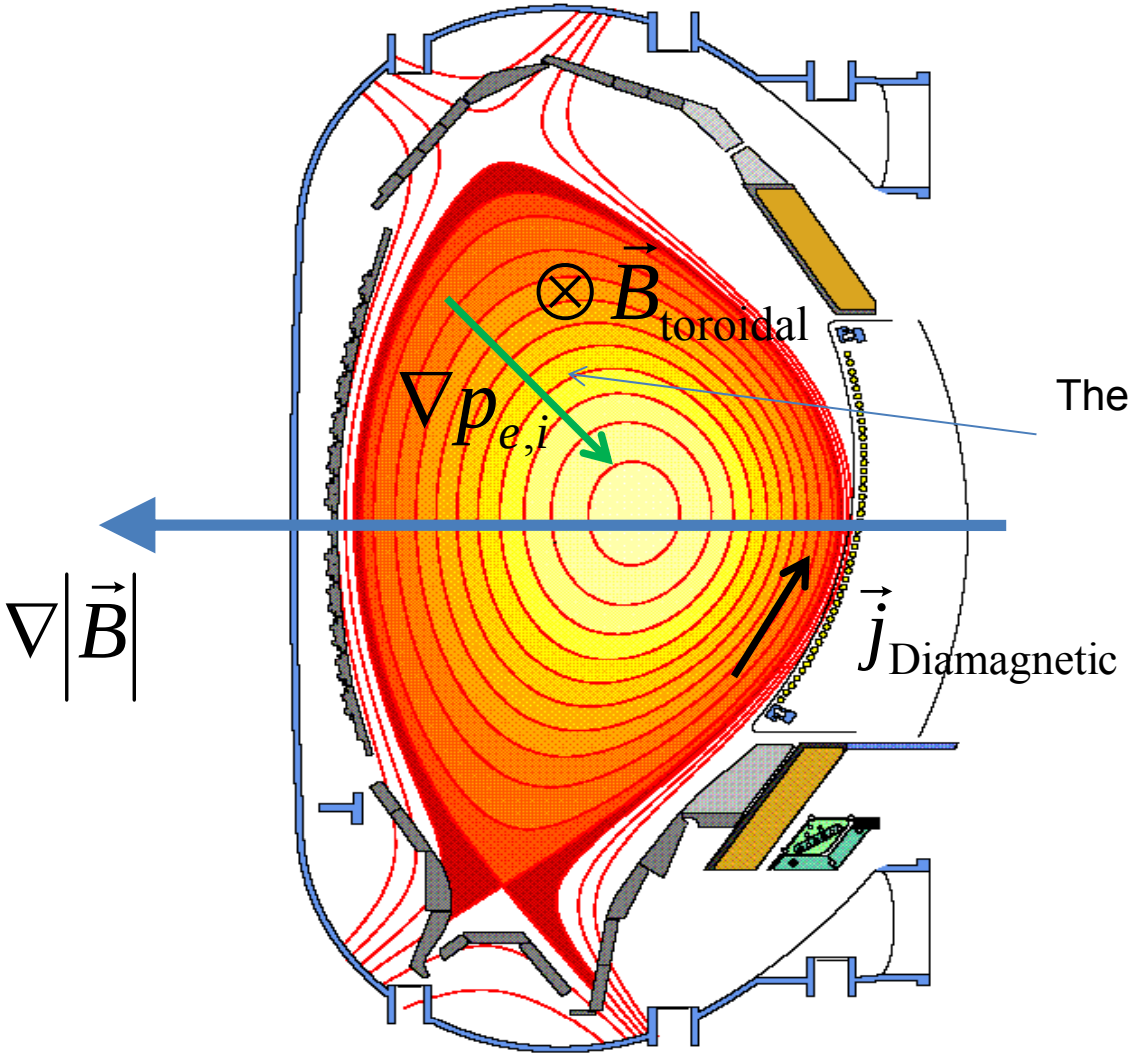


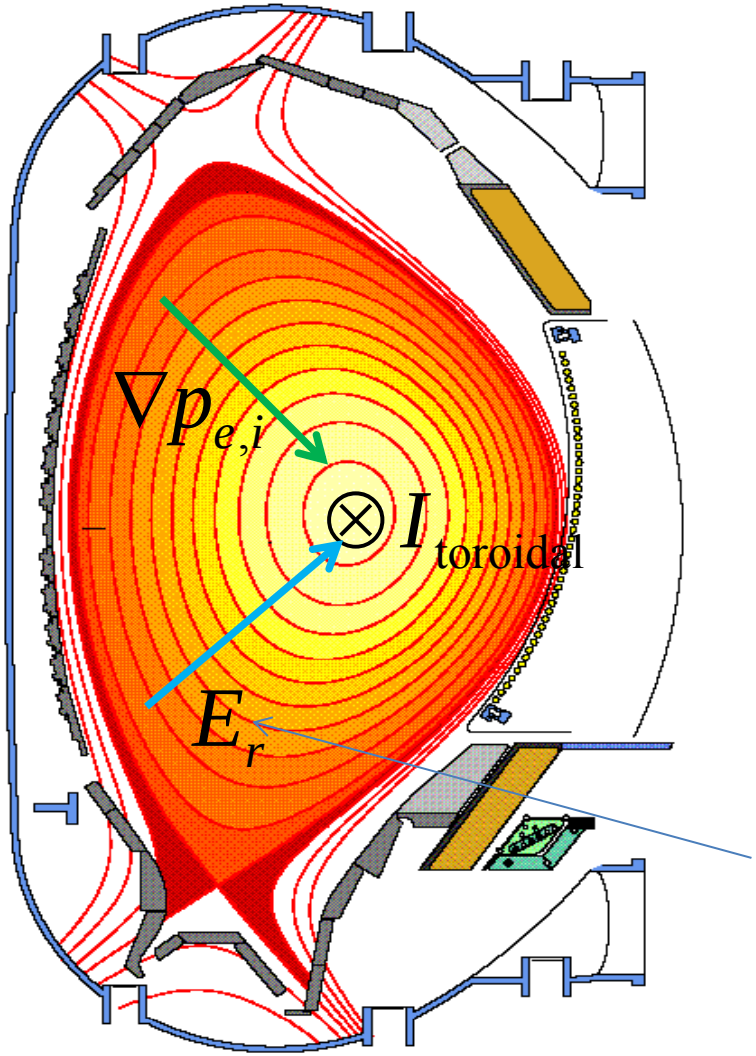






The famous pressure equilibrium:

$$\nabla p = \vec{j} \times \vec{B}$$



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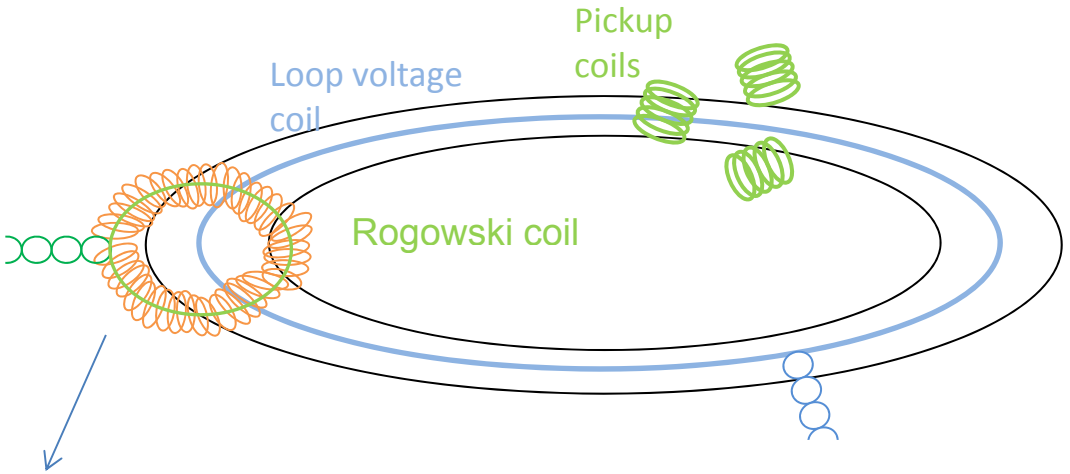
Typically, the radial ion transport is not exactly equal to the electron transport
➔a radial electric field E_r builds up until an equilibrium is maintained

Talking about the magnetic field (variation)



Ampères law provides the toroidal plasma current

$$I = \int \vec{j} \cdot d\vec{A} = \frac{1}{\mu_0} \oint B_\theta dl$$

$$\Rightarrow I_{plasma} = \frac{2\pi a}{NA\mu_0} \int U\, dt$$

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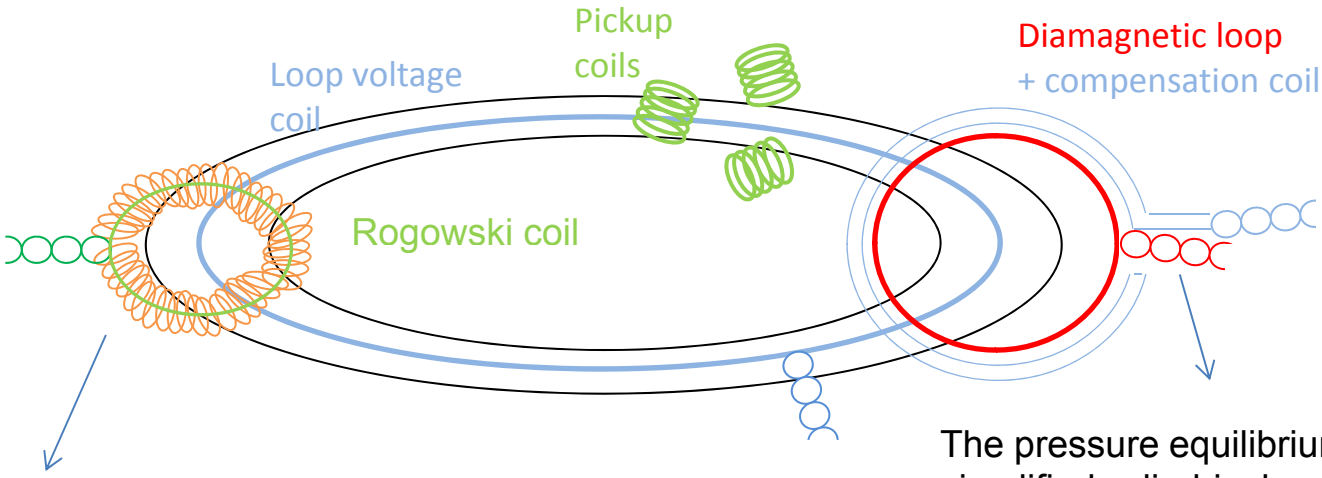

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The pressure equilibrium provides in simplified cylindrical geometry:

$$\nabla p = \vec{j} \times \vec{B}$$

$$\mu_0 \frac{dp}{dr} + \frac{d}{dr}\left(\frac{B_\phi^2}{2}\right) + \frac{B_\theta}{r}\frac{d}{dr}\left(rB_\theta\right) = 0$$

$$\Phi = -\frac{2\pi\mu_0}{B_0}\int_0^a prdr + \frac{\mu_0^2 I_z^2(a)}{8\pi B_0} + \frac{\pi\mu_0}{B_0}\int_0^a j_z B_\phi r^2 dr$$

$$= -\frac{\mu_0 W}{3\pi R B_0} + \frac{\mu_0^2 I_{plasma}^2}{8\pi B_0} + \frac{\pi\mu_0 \iota_{vac}}{R}\int_0^a j_z r^3 dr$$

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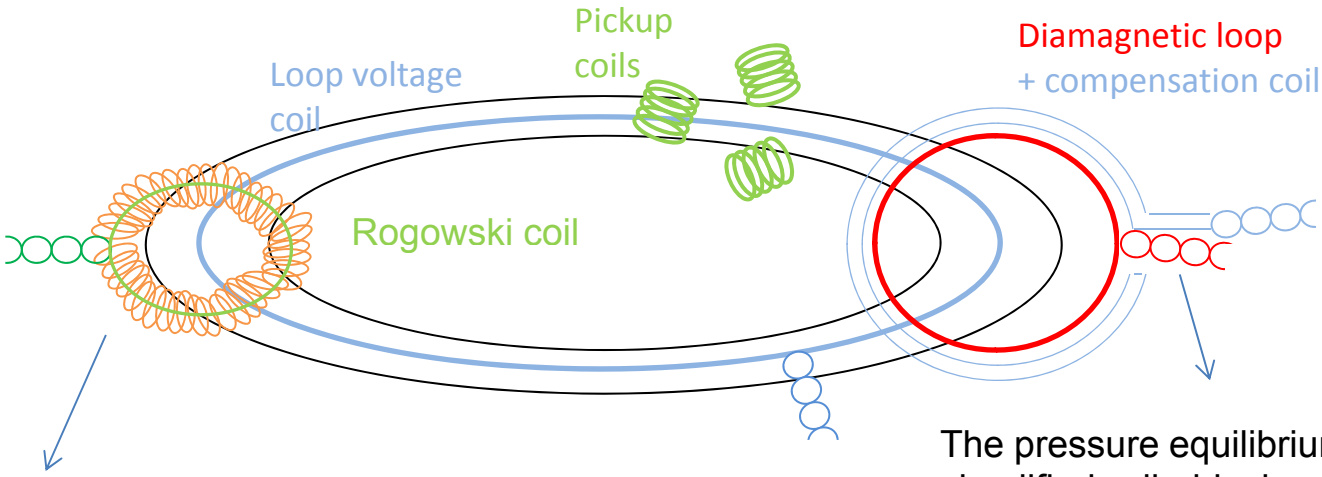

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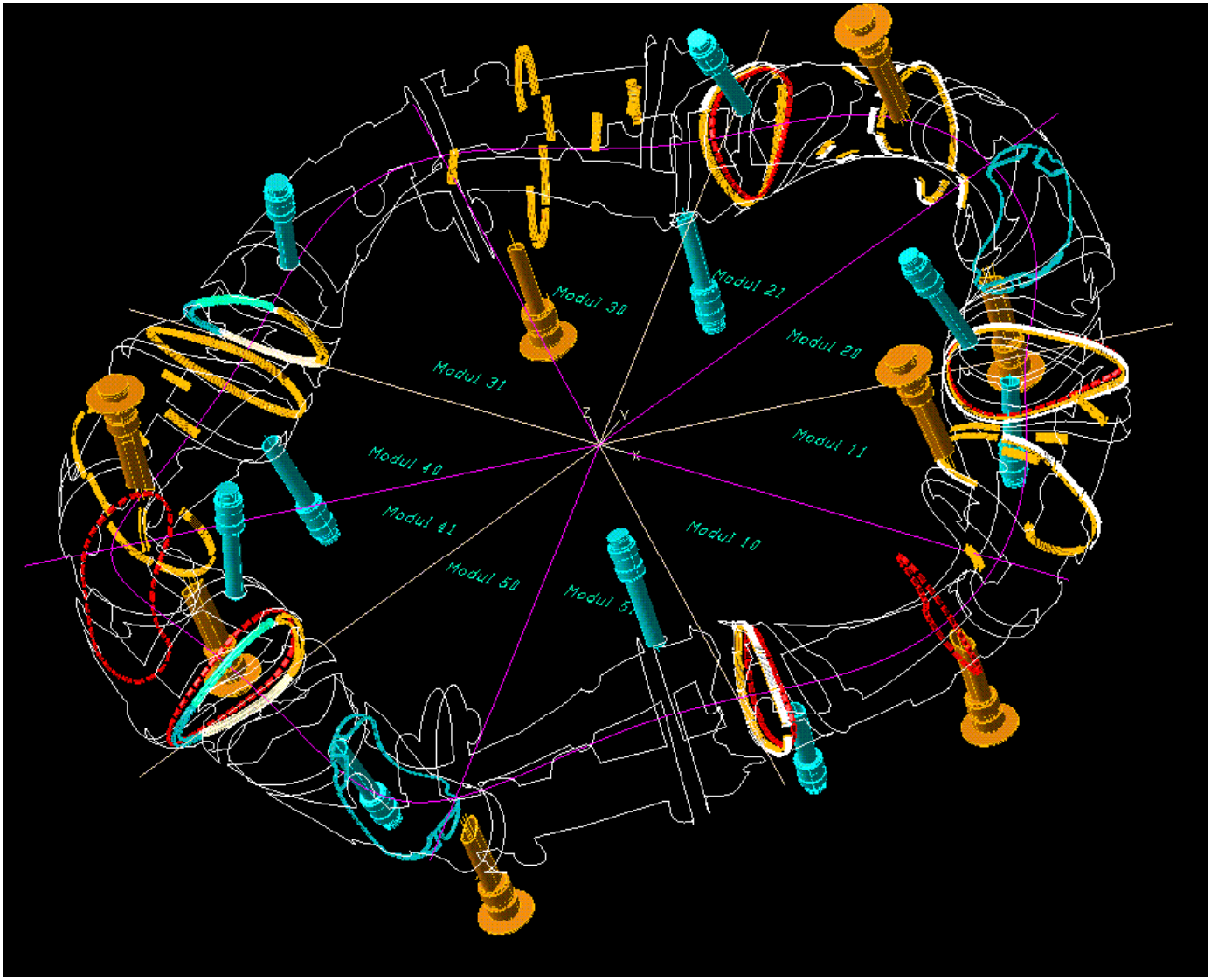
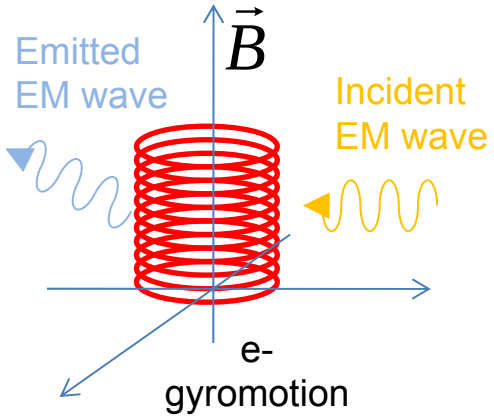
$$p_{plasma} = k(n_e T_e + n_i T_i) \Rightarrow W_{\text{kinetic}} = \int k(n_e T_e(\vec{r}) + n_i T_i(\vec{r}))\, d^3 r$$

The location of the magnetic coils in W7-X



…..then we continue with the magnetic field and the electrons…..

EM-emission and the B-field



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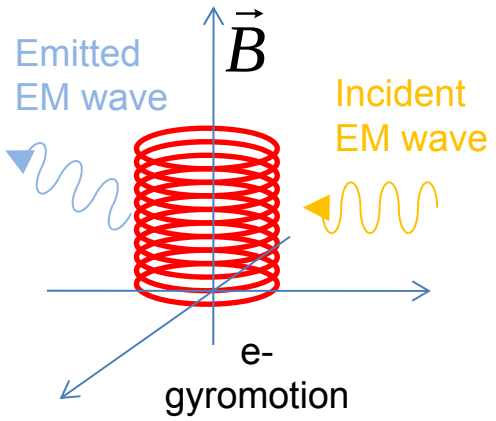

Frequency of the emitted wave $\omega = l \cdot \omega_{cyclotron} = l \cdot \frac{eB}{m_e}$

Emission parallel to B ➔ no harmonics (l = 1)

Emission perpendicular to B: ➔ polarization perpendicular to B: X-mode

➔ polarization parallel to B: O-mode

$$\frac{d^2P}{d\omega\, d\Omega} = const \cdot \omega^2 \sum_{l=1}^{\infty} \left\{ \frac{V_{II}^2}{c^2} J_l\left(\frac{\omega V_{II}}{\omega_c c}\right) + \frac{V_{\perp}^2}{c^2} J_l\left(\frac{\omega V_{\perp}}{\omega_c c}\right) \right\} \cdot \partial(\omega - l\omega_c)$$

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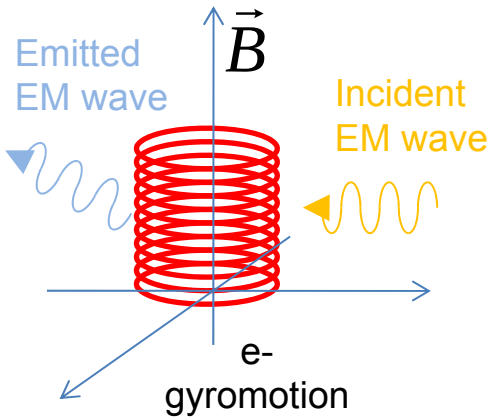

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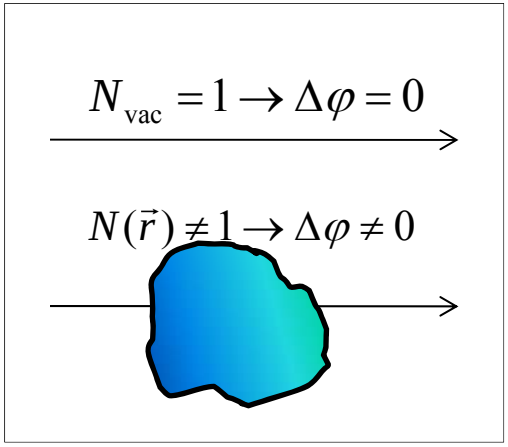


The EM-waves experience a refractive index N for $\omega > \omega_{cyclotron}$

$$N^2 \approx 1 - \frac{\omega_p^2}{\omega^2} \; ; \; \omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

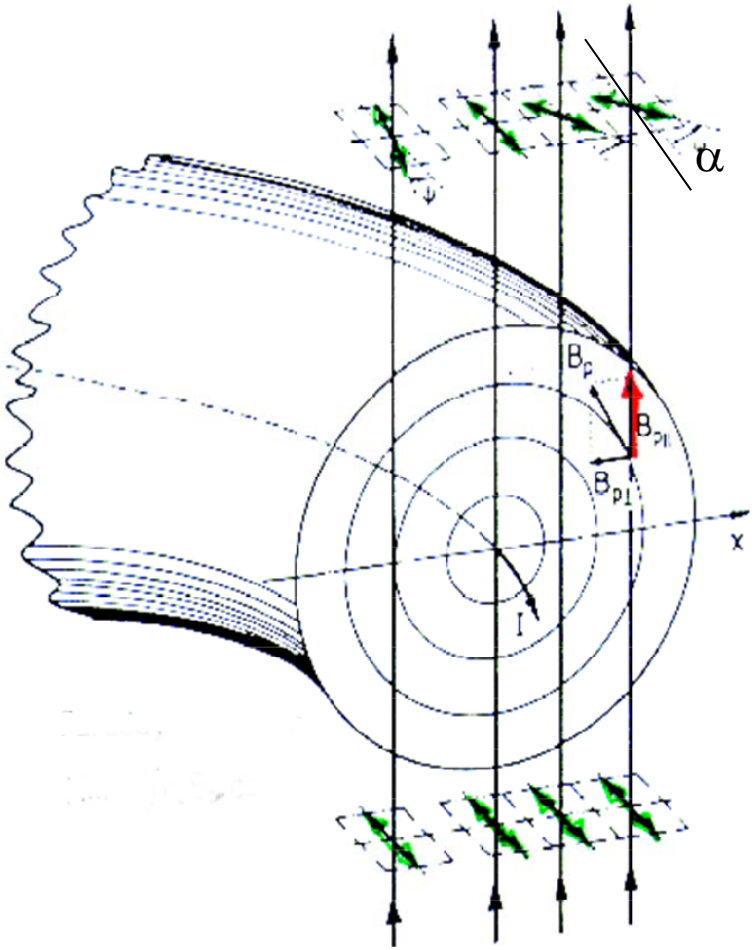
Below the (electron) plasma frequency the plasma becomes conductive

➔EM-waves are absorbed (reflected) ➔ cut-off density (for X-mode !)

➔ N approaches 0 ➔ waves are reflected

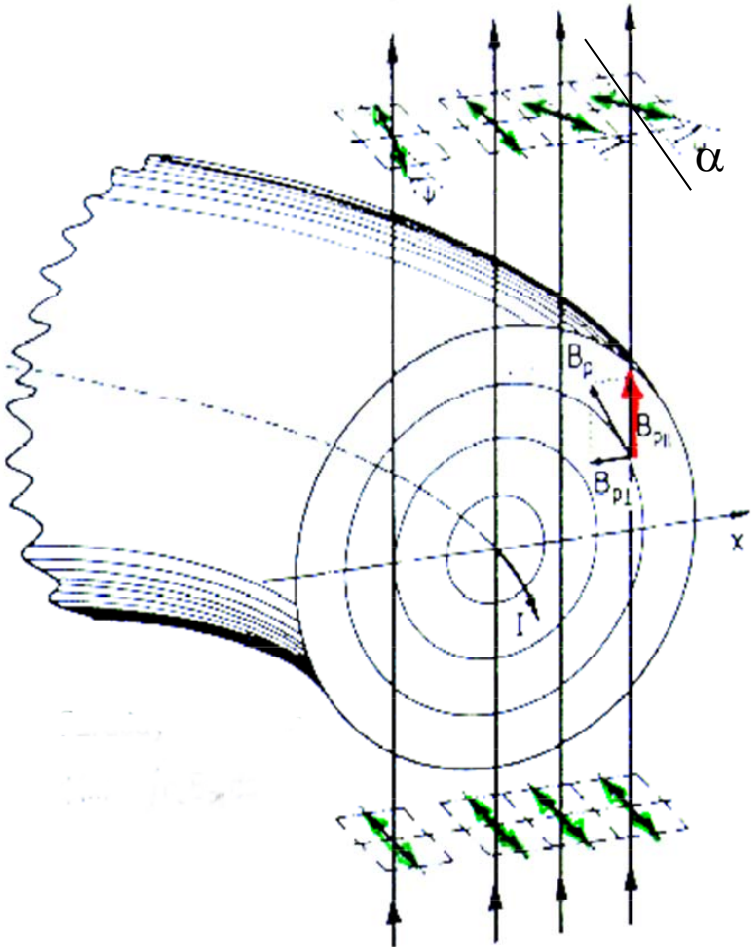
➔ higher EM-frequencies can travel freely but experience a phase shift

And more about the magnetic field…..



Array of microwave senders on the bottom and receivers / polarizers / interferometers on the top

And more about the magnetic field…..



Array of microwave senders on the bottom and receivers / polarizers / interferometers on the top

Interferometry: measure the phase shift

$$\Delta\varphi \propto \lambda \int_{l1}^{l2} n_e dl$$

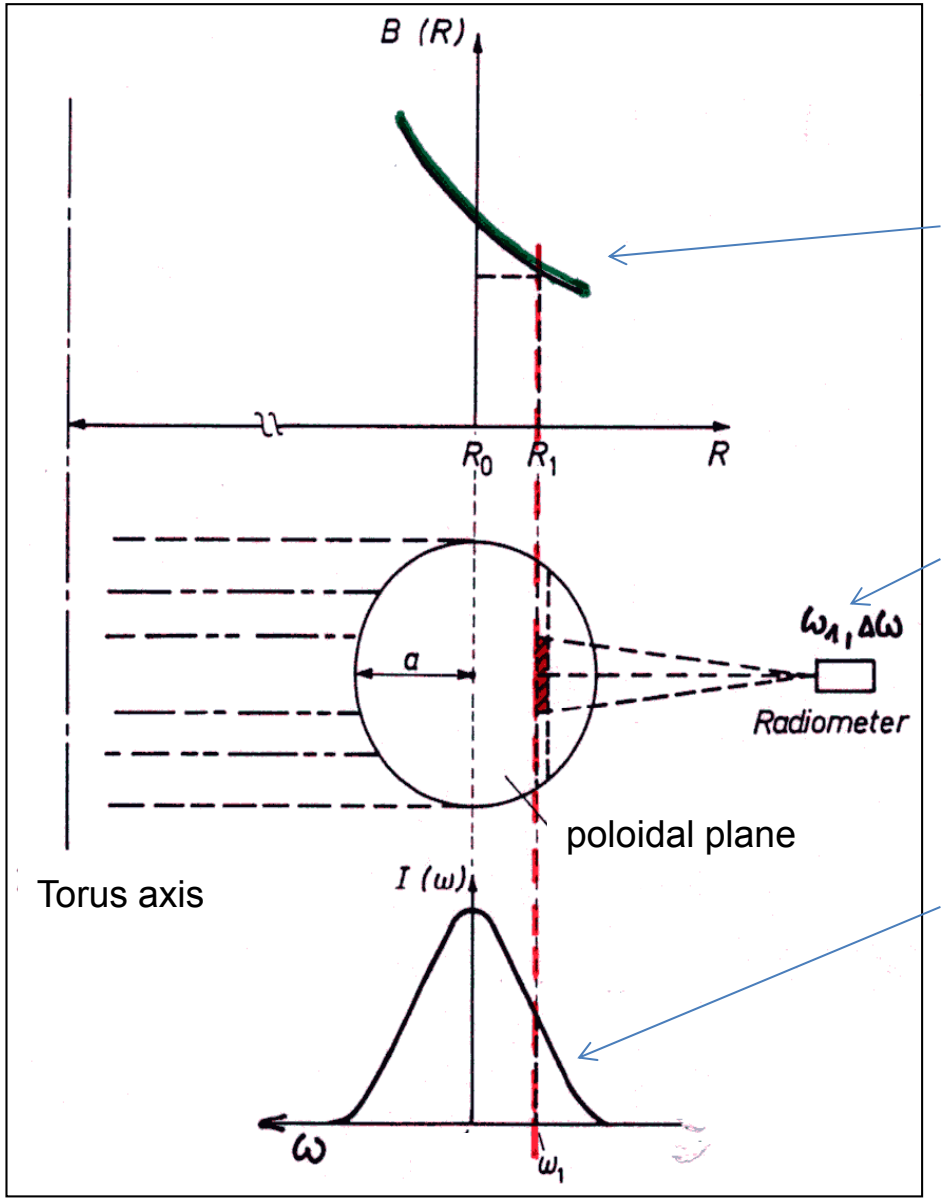
Faraday rotation: measure the polarization angle

$$\alpha \propto \lambda^2 \int_{l1}^{l2} B_{II} n_e dl$$

The Cotton-Mouton-effect: see Faraday-rotation

$$\alpha \propto \lambda^3 \int_{l1}^{l2} B_{\perp} n_e dl$$

ECE, electron temperature



In a toroidal fusion experiment holds roughly:

$$B(R) \propto 1/R$$

The emitted frequency ω from gyrating electrons is localized:

$$I(\omega) = \frac{\omega^2}{8\pi^3 c^2} \cdot T_e \cdot \left(1 - e^{-\tau}\right)$$

With the optical thickness τ for (ideal) blackbody radiation (τ ➔ infinity at cut-off n_e) it follows:

$$I(\omega) \propto T_e(R)$$

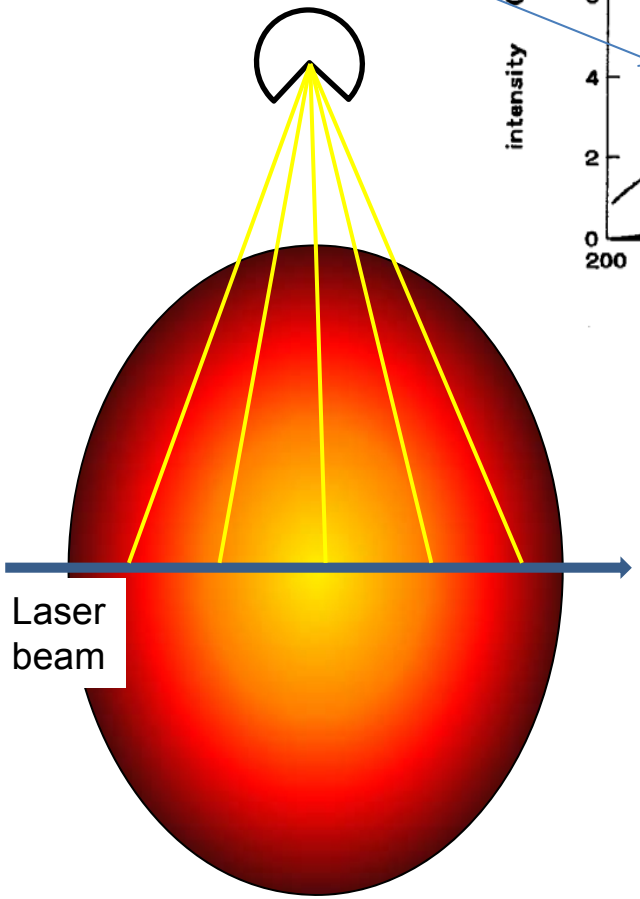
At the cutoff-layer the blackbody-limit is reached, here the plasma is optically thick

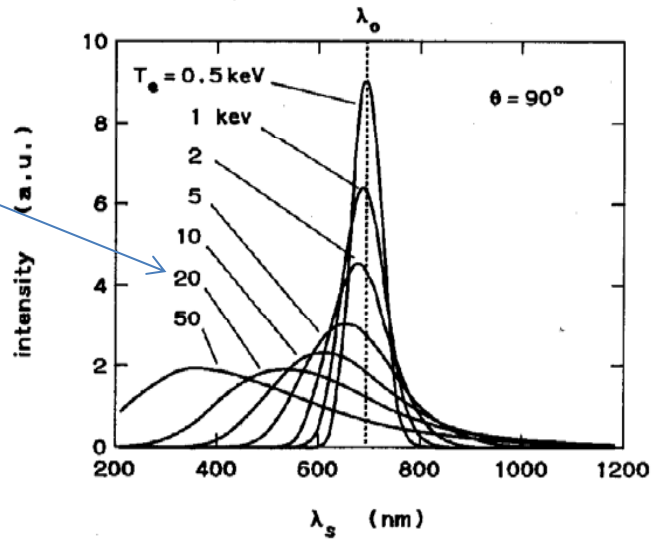
…..and some (beam assisted) active diagnostics.

Thomson scattering: n_e , T_e

Hutchinson: Principles of plasma diagnostics

Spectroscopic observation





The moving electrons scatter the laser light. Their thermal velocity produces a Doppler shift (line broadening).

At higher temperatures a relativistic blue shift occurs.

The Thomson cross section:

$$\sigma_{\text{Thomson}} = \frac{8\pi}{3}\left(\frac{e^2}{4\pi\varepsilon_0 m_e c^2}\right)^2$$

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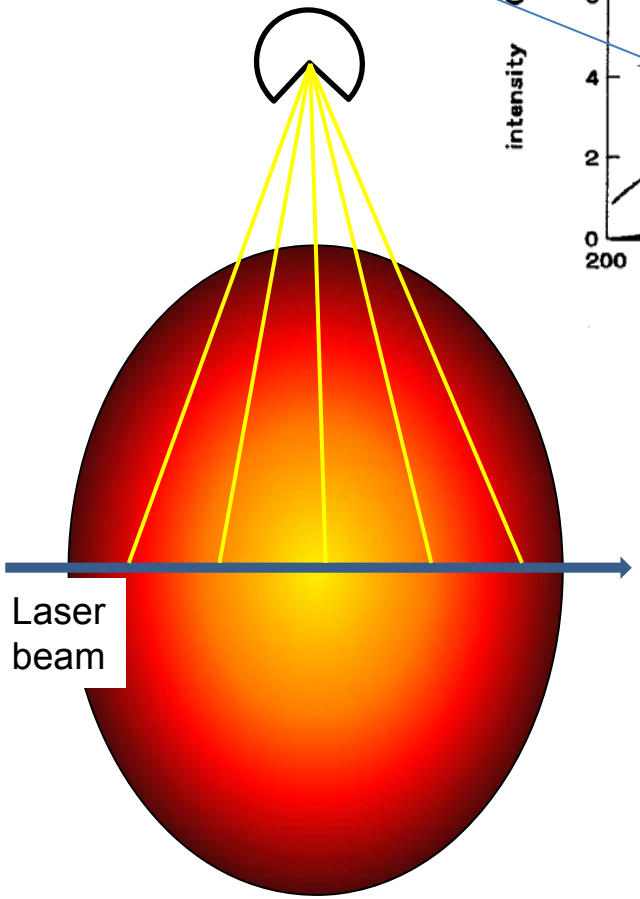

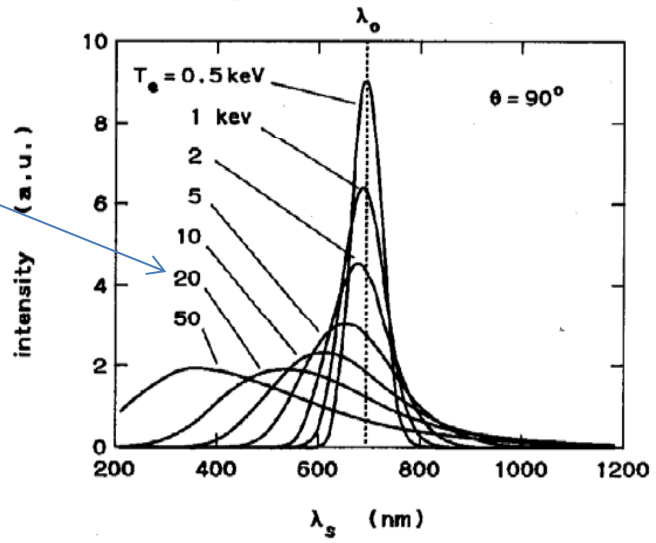

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The Thomson cross section:

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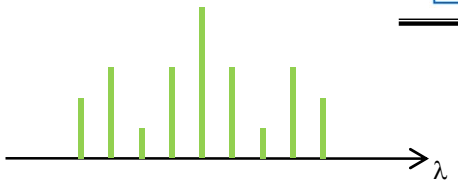
The scattered light intensity is proportional to n_e :

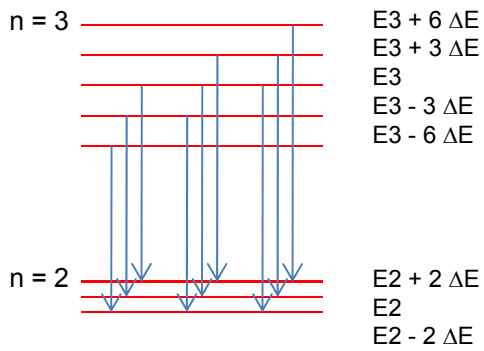
$$d\,I_z(\lambda) \propto n_e(r)\sqrt{\frac{m_e}{2\pi kT_e}}\cdot\exp\left\{-\frac{m_e V_z^2}{2kT_e}\right\}dV_z$$ z – line of sight

according to a Maxwellian distribution with a mean velocity

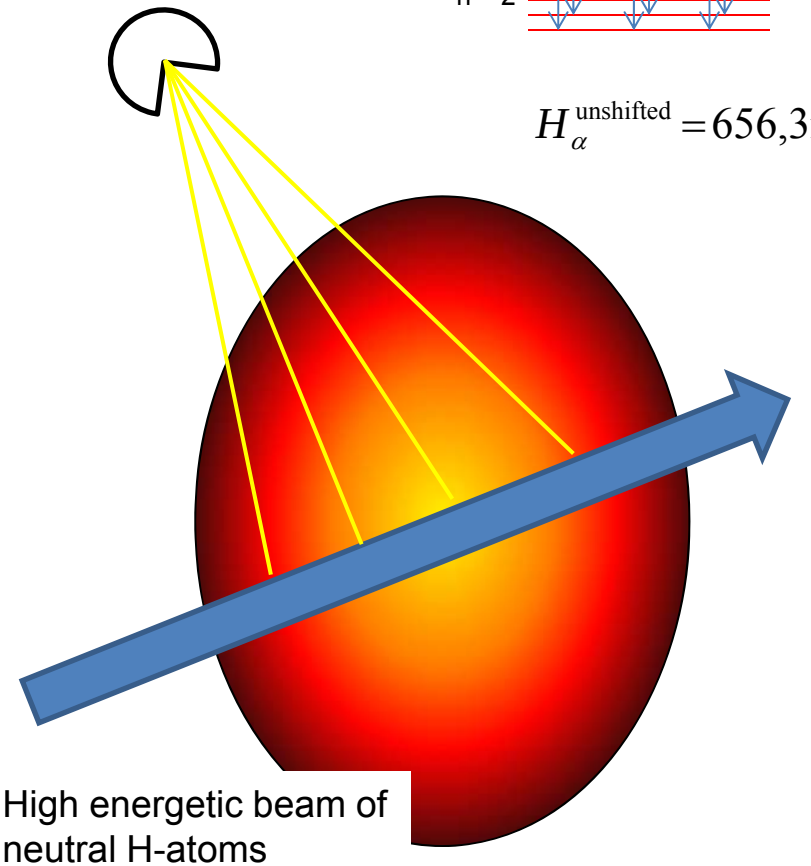
$$\left|\hat{V}_z^e\right| = \sqrt{\frac{8kT_e}{\pi\, m_e}} \;\Rightarrow\; \Delta\lambda_{\text{Broad}} = \lambda_{\text{Laser}}\cdot\frac{\left|\hat{V}_z^e\right|}{c} = \text{f}(T_e)$$



Spectroscopic
+ polarimetric
observation



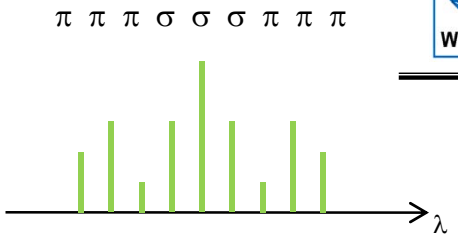
$$H_{\alpha}^{\text{unshifted}} = 656{,}3\text{nm}$$



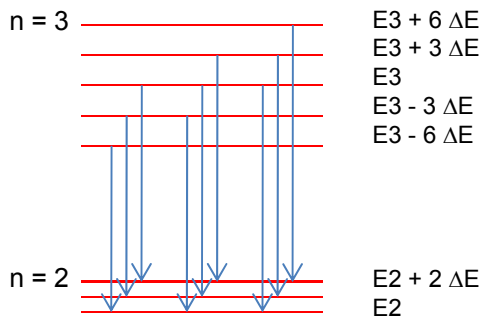
High energetic beam of
neutral H-atoms

The motional Stark effect: Beam Emission Spectroscopy

Max-Planck-Institut
fuer Plasmaphysik
EURATOM Assoc.



Spectroscopic + polarimetric observation



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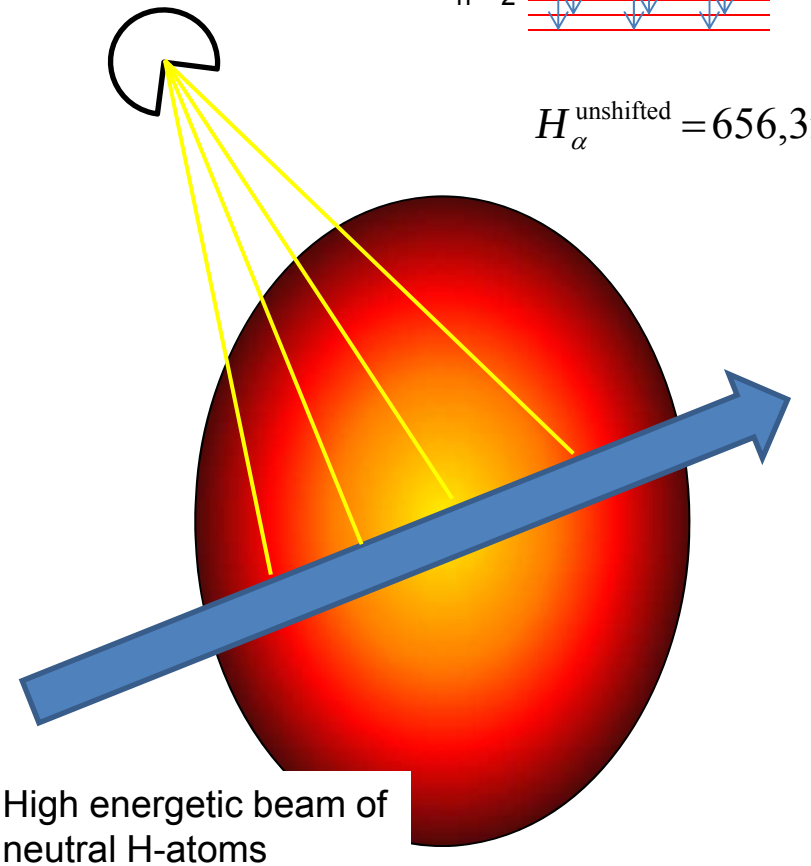


High energetic beam of neutral H-atoms

The neutrals experience a relativistically transformed E-field from B by:

$$\vec{E}_{\text{motional}} = \vec{V} \times \vec{B} \quad (= V_{\text{beam}} \cdot B_{\perp})$$

leading to a Stark line splitting of the Hα line

$$\Delta\lambda_S = \frac{3a_0 e \lambda_a V_{\text{beam}}}{2hc} \sqrt{B_\phi^2 \sin^2\Omega + B_\theta^2}$$

with the σ to π line intensities I and the definition equations:

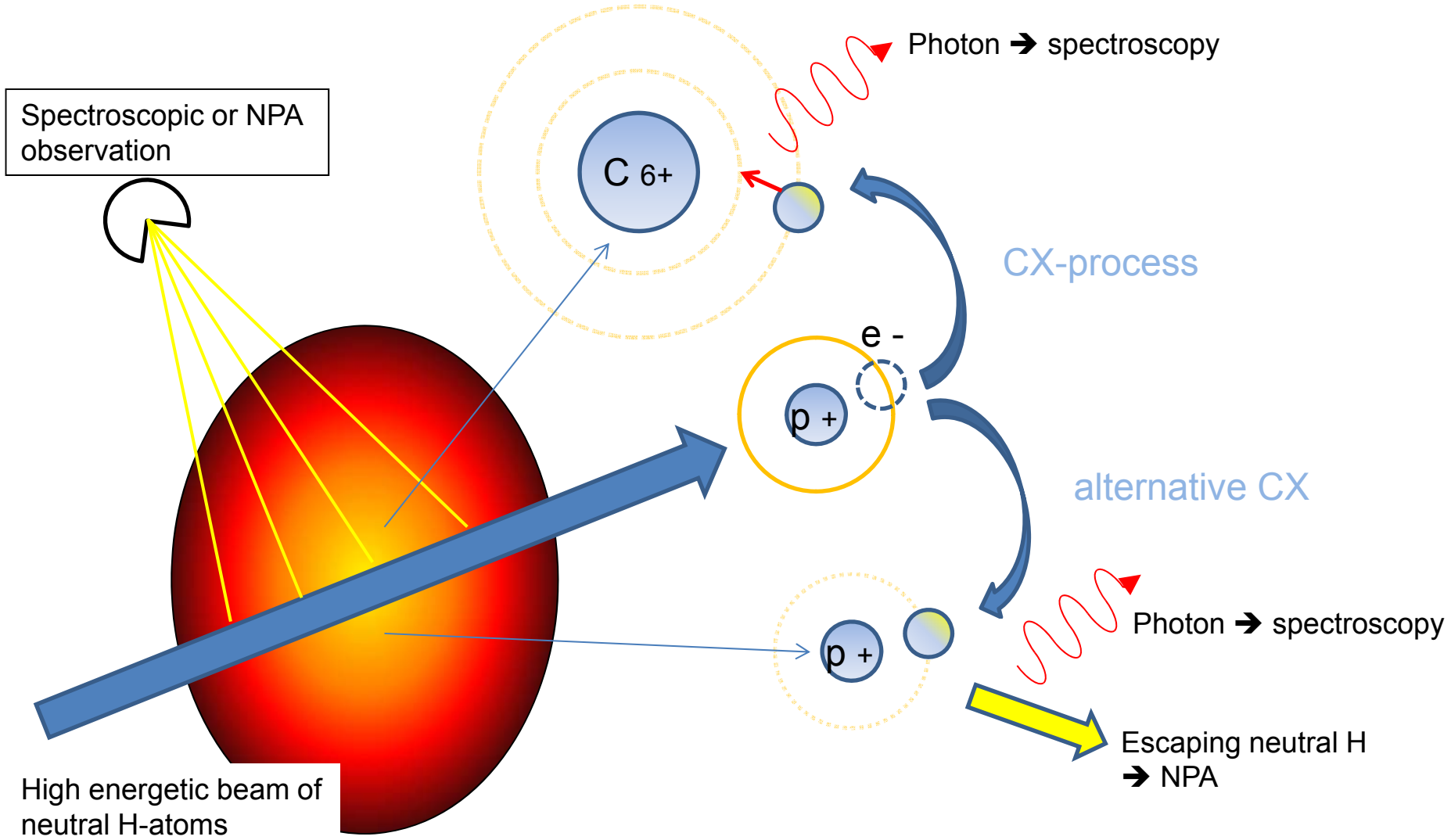
$$\tan\theta = \pm\sqrt{\frac{2I_\pi}{I_\sigma - I_\pi}} \; ; \quad \tan\varepsilon = \tan\gamma\left(\frac{\cos[\Omega - a]}{\sin\Omega}\right)$$

one can evaluate *q* by: $\tan\gamma = \frac{r}{Rq}$

$$\theta, \alpha, \Omega, \varepsilon, \phi$$

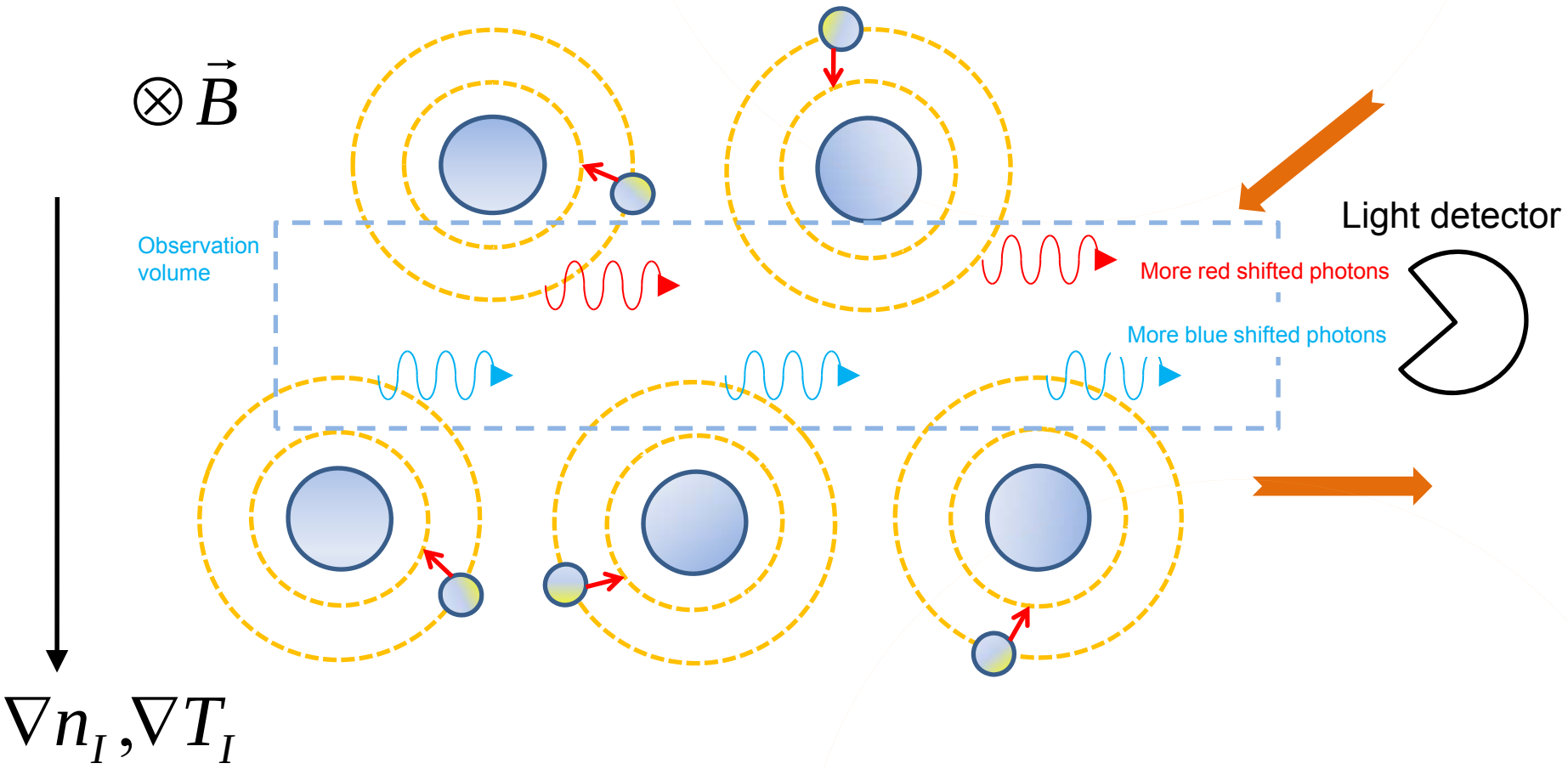
are angles between the electric field and the viewing line, line of sight and the toroidal direction, between beam and toroidal direction, the measured polarisation angle, the toroidal angle

The Charge eXchange process CX



A graphic „explanation“ for the diamagnetic effect

Guiding centre



➔Spectral line shift even with „fixed“ guiding centres
➔ diamagnetic current (drift)

Guiding centre

Within the moving reference frame of the ion´s Larmor orbit guiding centre holds the equation:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{-T_I}{ceZ_{I+1}B} \cdot \nabla\left\{\ln\left(n_{I+1} \cdot T_I \cdot \zeta_I^{\gamma}\right)\right\} \quad , \quad \gamma = \frac{\left(\omega_I \tau_I\right)^2}{1+\left(\omega_I \tau_I\right)^2}$$

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The ion pressure balance equation together with inertial forces reads:

$$\nabla p_{\mathrm{I}}=\vec{j}_I\times\vec{B}\Rightarrow$$

$$m_I n_I\left(\frac{\partial\vec{V}}{\partial t}+\left(\vec{V}\cdot\nabla\right)\vec{V}\right)=-\nabla p_I-\left\langle\nabla\vec{\vec{\Pi}}\right\rangle+n_I eZ_I\left(\vec{V}\times\vec{B}+\vec{E}\right)+\sum\vec{F}_{\mathrm{external}}$$

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$$m_I n_I\left(\frac{\partial\vec{V}}{\partial t}+\left(\vec{V}\cdot\nabla\right)\vec{V}\right)=-\nabla p_I-\left\langle\nabla\vec{\vec{\Pi}}\right\rangle+n_I eZ_I\left(\vec{V}\times\vec{B}+\vec{E}\right)+\sum\vec{F}_{\mathrm{external}}$$

this provides for stationary conditions and small friction forces:

$$E_r(r)=\frac{\partial\left\{n_{\mathrm{I+1}}(r)\cdot T_I(r)\right\}/\partial r}{eZ_{\mathrm{I+1}}n_{\mathrm{I+1}}(r)}+\frac{T_I(r)\cdot\gamma}{eZ_{\mathrm{I+1}}}\cdot\frac{\partial\zeta_I/\partial r}{\zeta_I}+\left[B_\theta V_\varphi(r)-B_\varphi V_\theta(r)\right]$$

Within the moving reference frame of the ion´s Larmor orbit guiding centres holds the equation:

$$\frac{\Delta\lambda}{\lambda_0}=\frac{-T_I}{ceZ_{\mathrm{I+1}}B}\cdot\nabla\left\{\ln\left(n_{\mathrm{I+1}}\cdot T_I\cdot\zeta_I^{\gamma}\right)\right\}\quad,\quad\gamma=\frac{\left(\omega_I\tau_I\right)^2}{1+\left(\omega_I\tau_I\right)^2}$$

The ion pressure balance equation together with inertial forces reads:

$$\nabla p_{\mathrm{I}}=\vec{j}_I\times\vec{B}\Rightarrow$$

$$m_I n_I\left(\frac{\partial\vec{V}}{\partial t}+\left(\vec{V}\cdot\nabla\right)\vec{V}\right)=-\nabla p_I-\left\langle\nabla\vec{\vec{\Pi}}\right\rangle+n_I eZ_I\left(\vec{V}\times\vec{B}+\vec{E}\right)+\sum\vec{F}_{\mathrm{external}}$$

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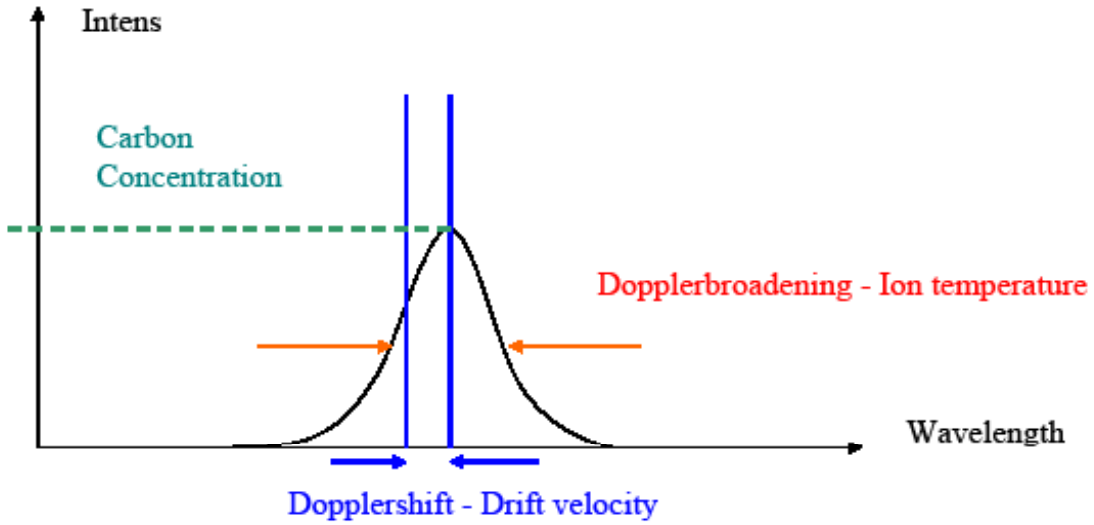
and the normalized radial gradient of the excitation probability

$$\frac{\partial\zeta_I/\partial r}{\zeta_I}=\frac{\sum_{j=1}^{3}\left\langle\sigma_j^{rad}\cdot V_j^{beam}\right\rangle\cdot\partial n_j^{beam}(r)/\partial r}{\sum_{j=1}^{3}\left\langle\sigma_j^{rad}\cdot V_j^{beam}\right\rangle\cdot n_j^{beam}(r)}$$

The principle of CXRS (Charge Exchange Recombination Spectroscopy) and the NPA (Neutral Particle spectral Analysis)

$$\overline{H}_{beam} + H^{+}_{plasma} \rightarrow \overline{H}^{+}_{beam} + (H_{plasma} \Rightarrow Detektor)$$

$$\overline{H}_{beam} + C^{6+}_{plasma} \rightarrow \overline{H}^{+}_{beam} + (C^{5+}_{plasma} + h\nu \Rightarrow Spektrometer)$$



The principle of CXRS (Charge Exchange Recombination Spectroscopy) and the NPA (Neutral Particle spectral Analysis)

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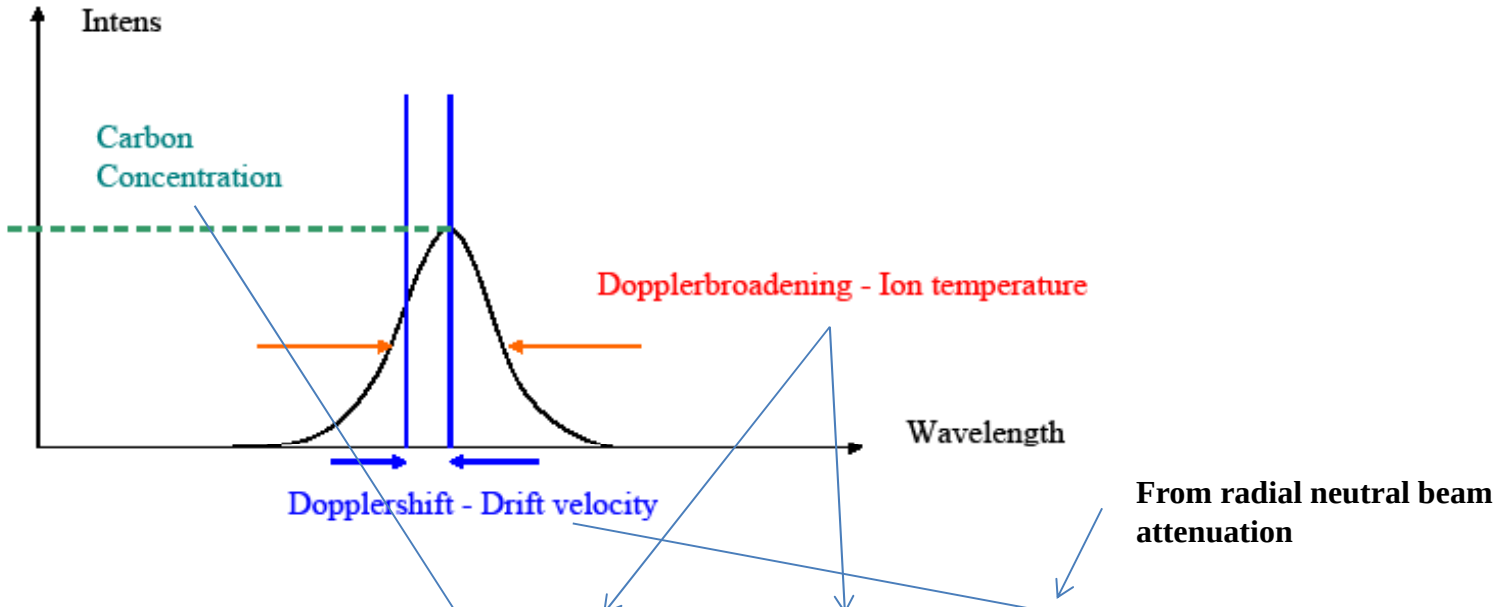


Using the formula from above:

$$E_r(r) = \frac{\partial\{n_{I+1}(r)\cdot T_I(r)\}/\partial r}{eZ_{I+1}n_{I+1}(r)} + \frac{T_I(r)\cdot\gamma}{eZ_{I+1}}\cdot\frac{\partial\zeta_I/\partial r}{\zeta_I} + \left[B_\theta V_\varphi(r) - B_\varphi V_\theta(r)\right]$$

Outline of this talk:

1) Basics, measured quantities, principles and some physics
(here we stick to the magnetic field, electrons and protons)

2) Techniques, practical considerations and some results
(and now we see that (fusion) life has even more aspects….)

Technical problem: how to get access to the plasma ?

Restricted space situation, narrow and long ports, restrictions by strong power densities, laser beams, high voltage, neutron radiation, magnetic field, …….

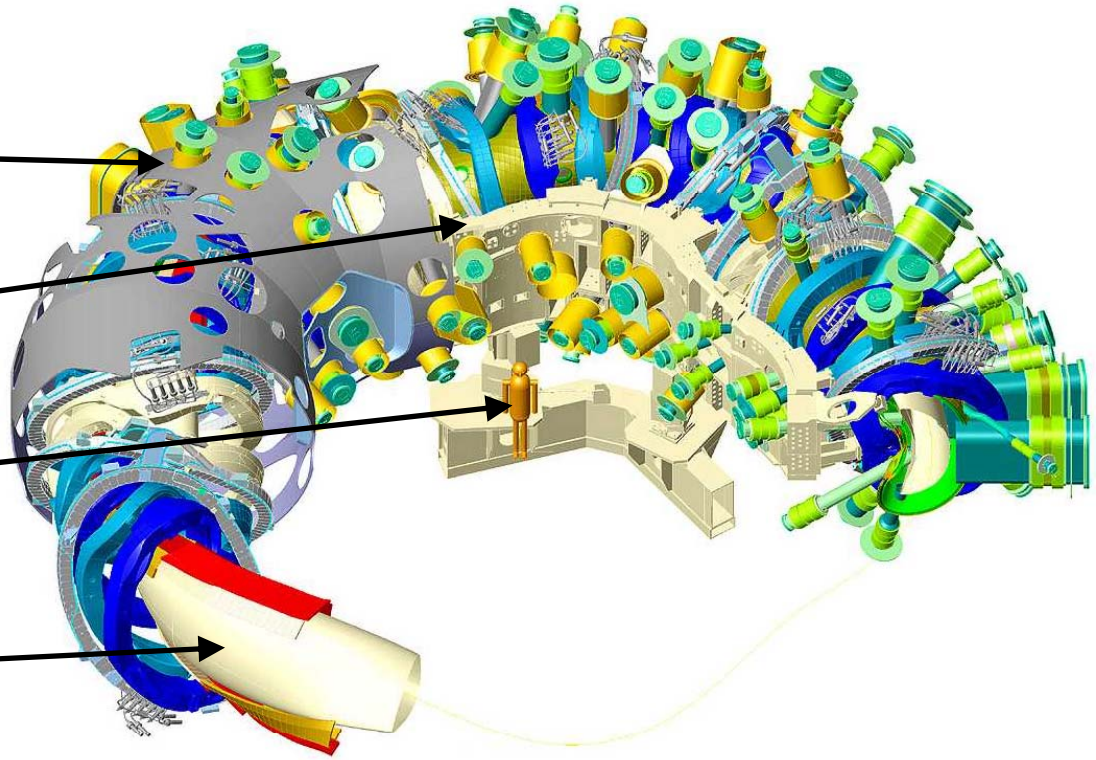
Example: W7-X

Cryostat

Mechanical supports

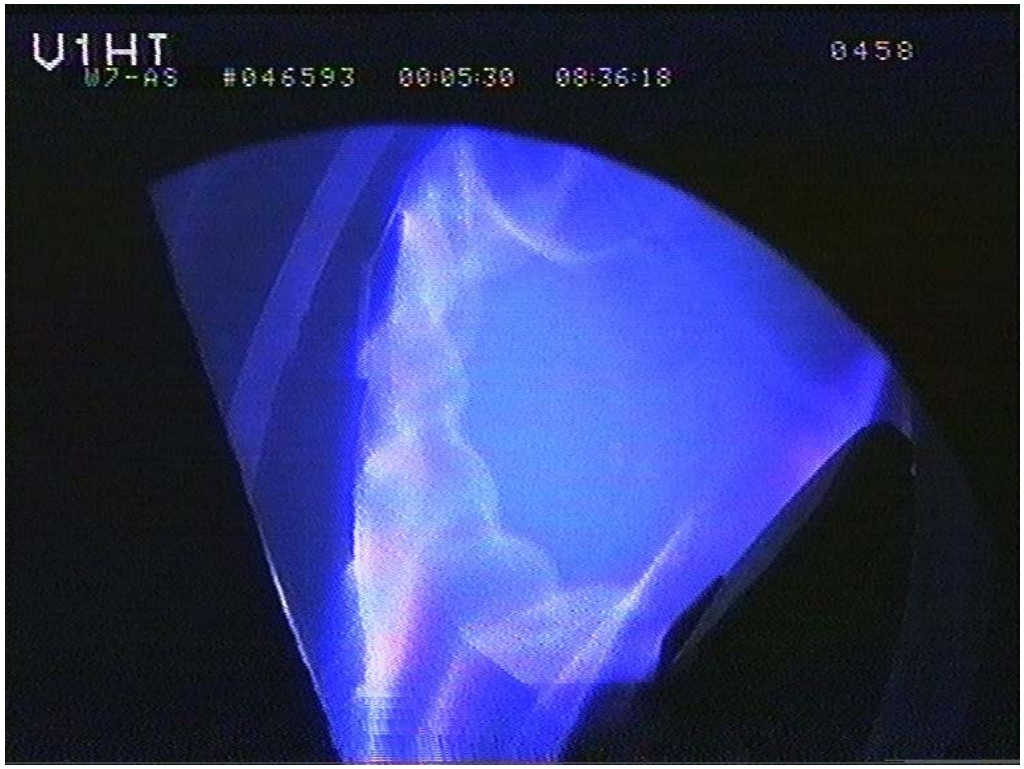
1 human being

And, finally, the plasma…..

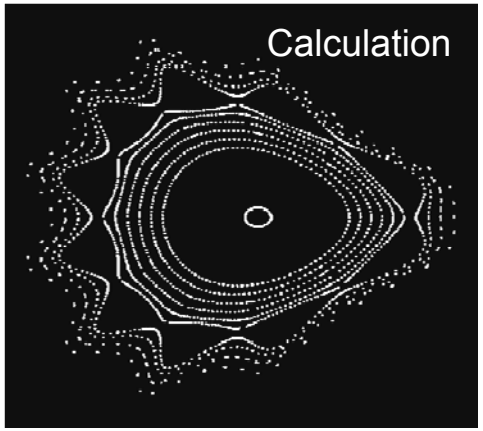


……and again, the magnetic field…….

Imaging techniques for the magnetic field



Video screenshot of a W7-AS plasma with magnetic islands at the plasma edge



T. S. Pedersen_Stell. News 2004

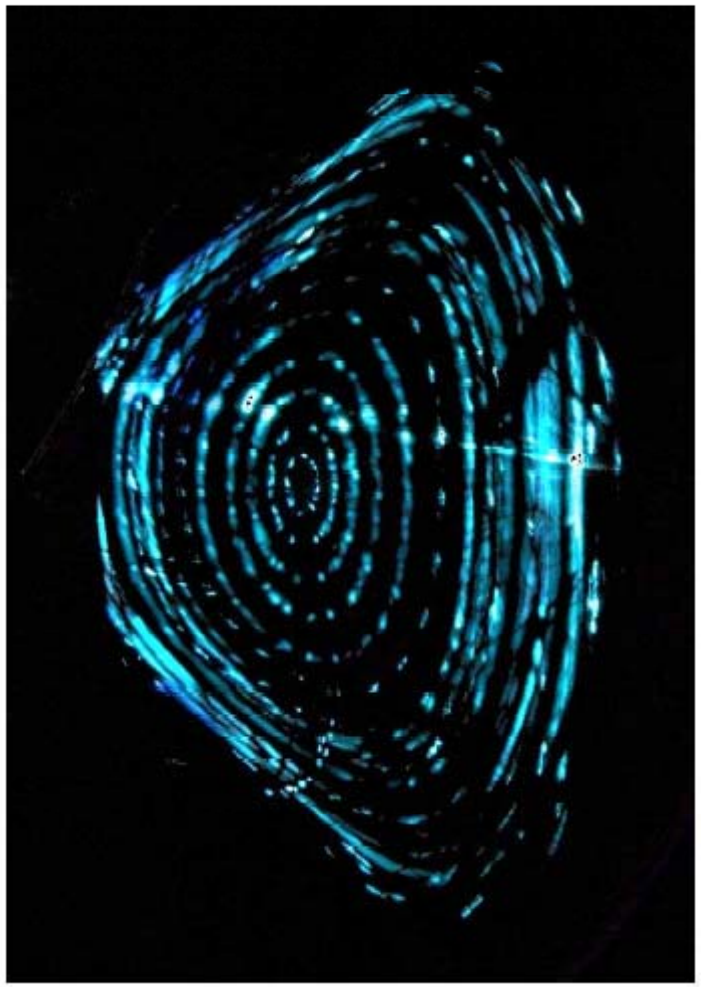
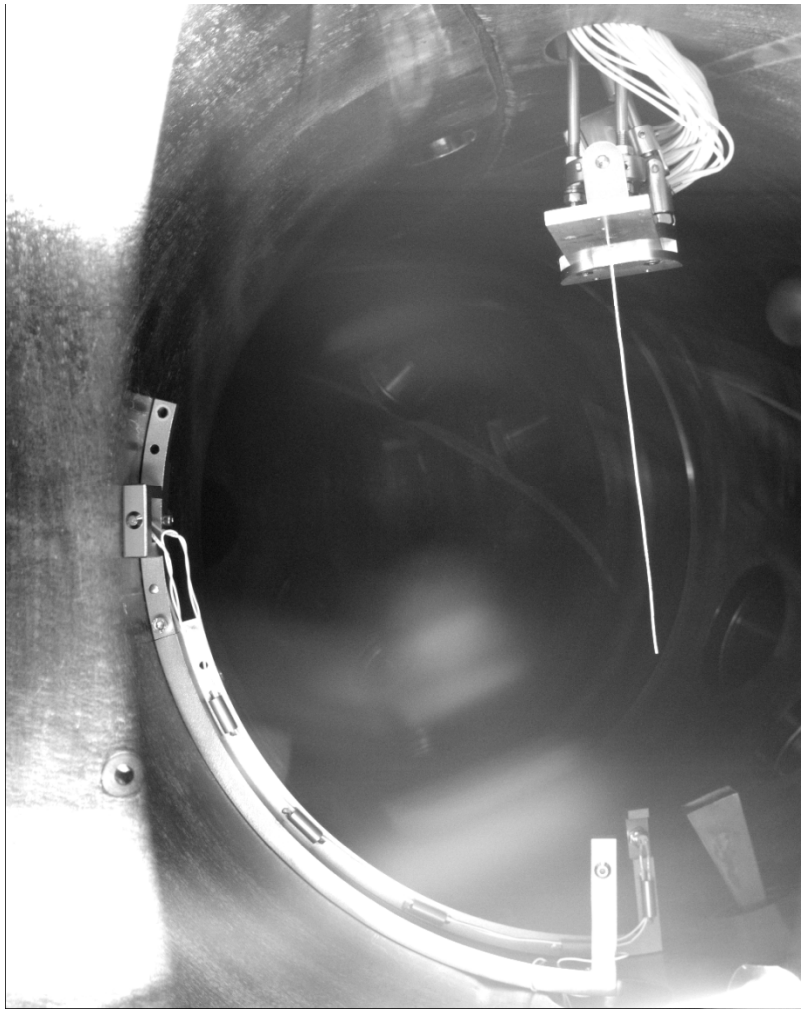


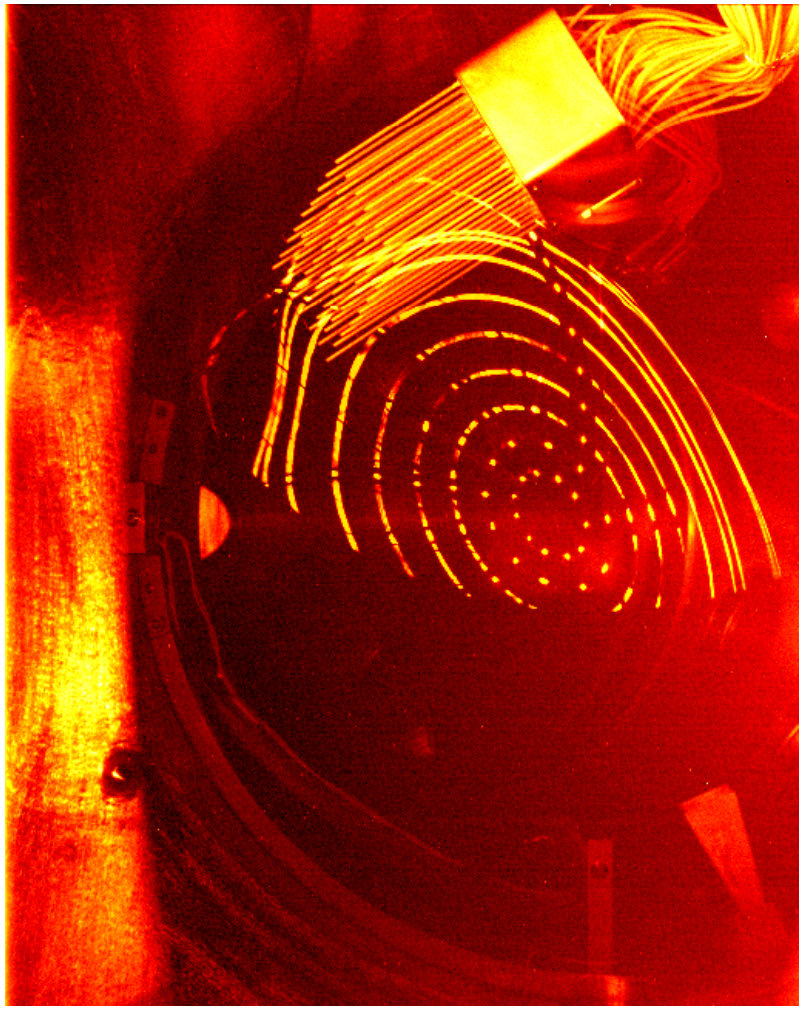
Fig. 3. Nested magnetic surfaces in CNT, mapped out using an electron beam and two rotatable ZnO-coated rods.

Imaging techniques for the magnetic field

Demonstration examples from WEGA: the fluorescence rod (ZnS) and the electron beam together with the Langmuir probe array

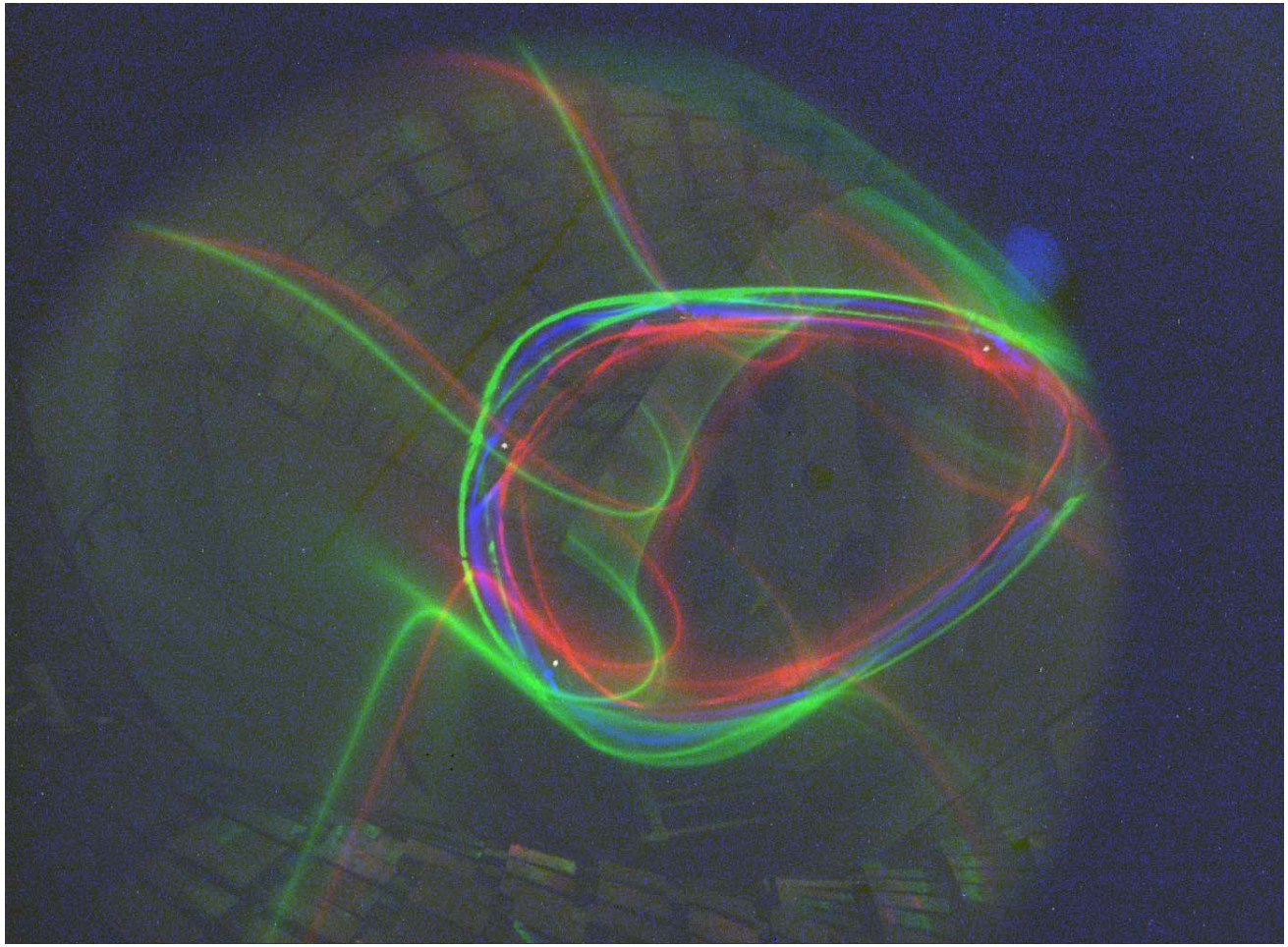
M. Otte, W7-X Team



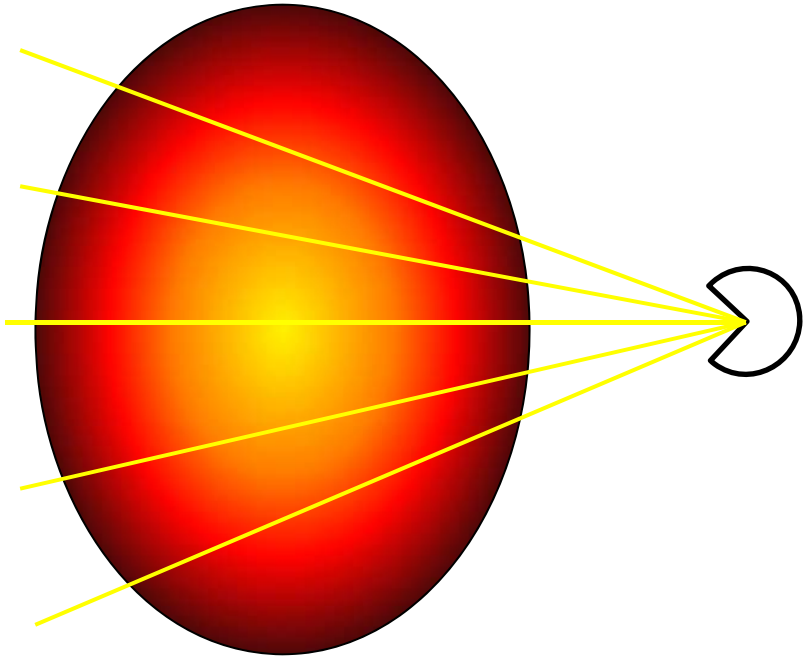


Imaging techniques for the magnetic field

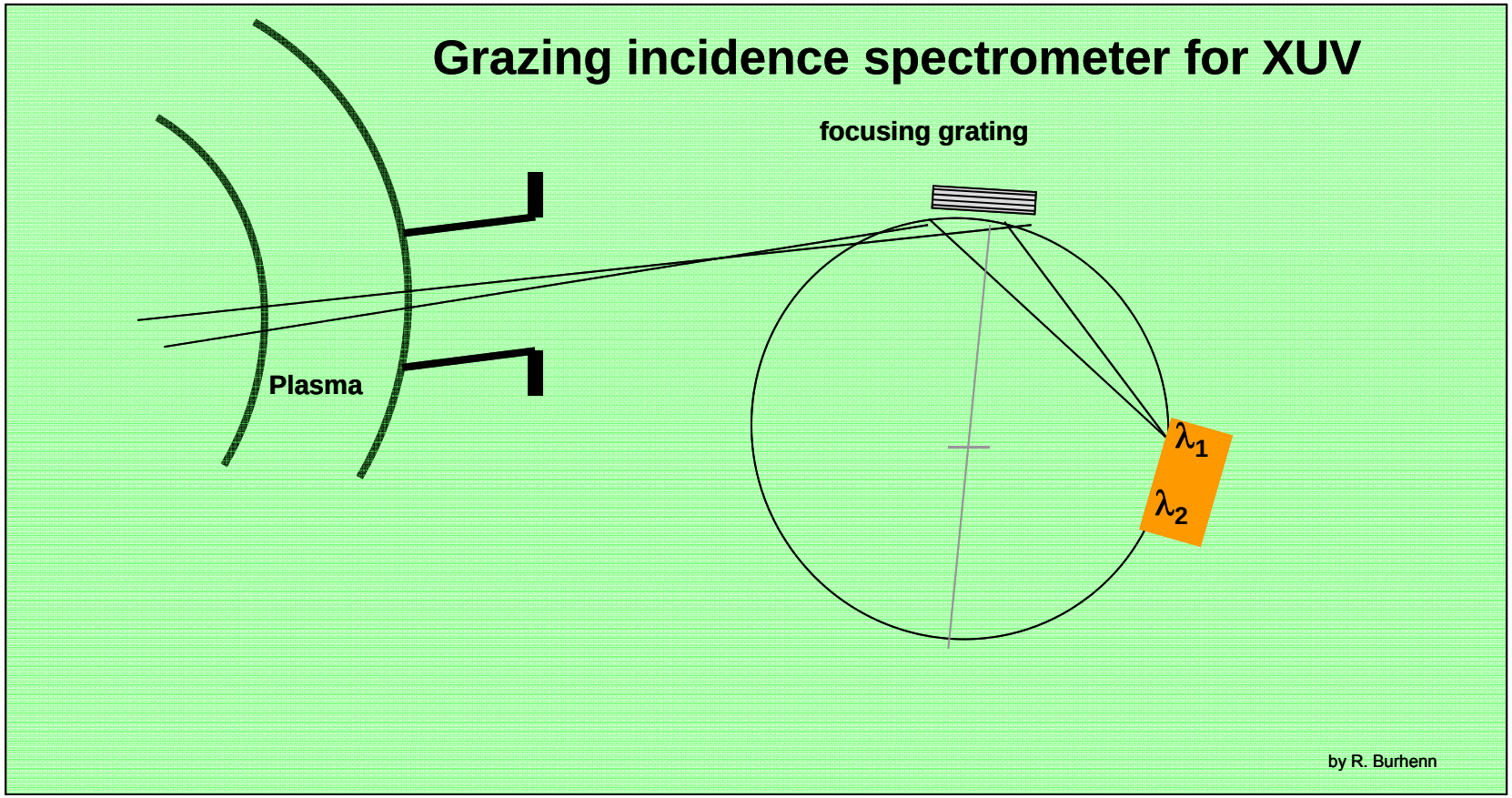
Example from W7-X: the 5/6 edge island. Green = 12kA, blue = 10kA, red = 2 kA nominal coil current.



Fan of chords

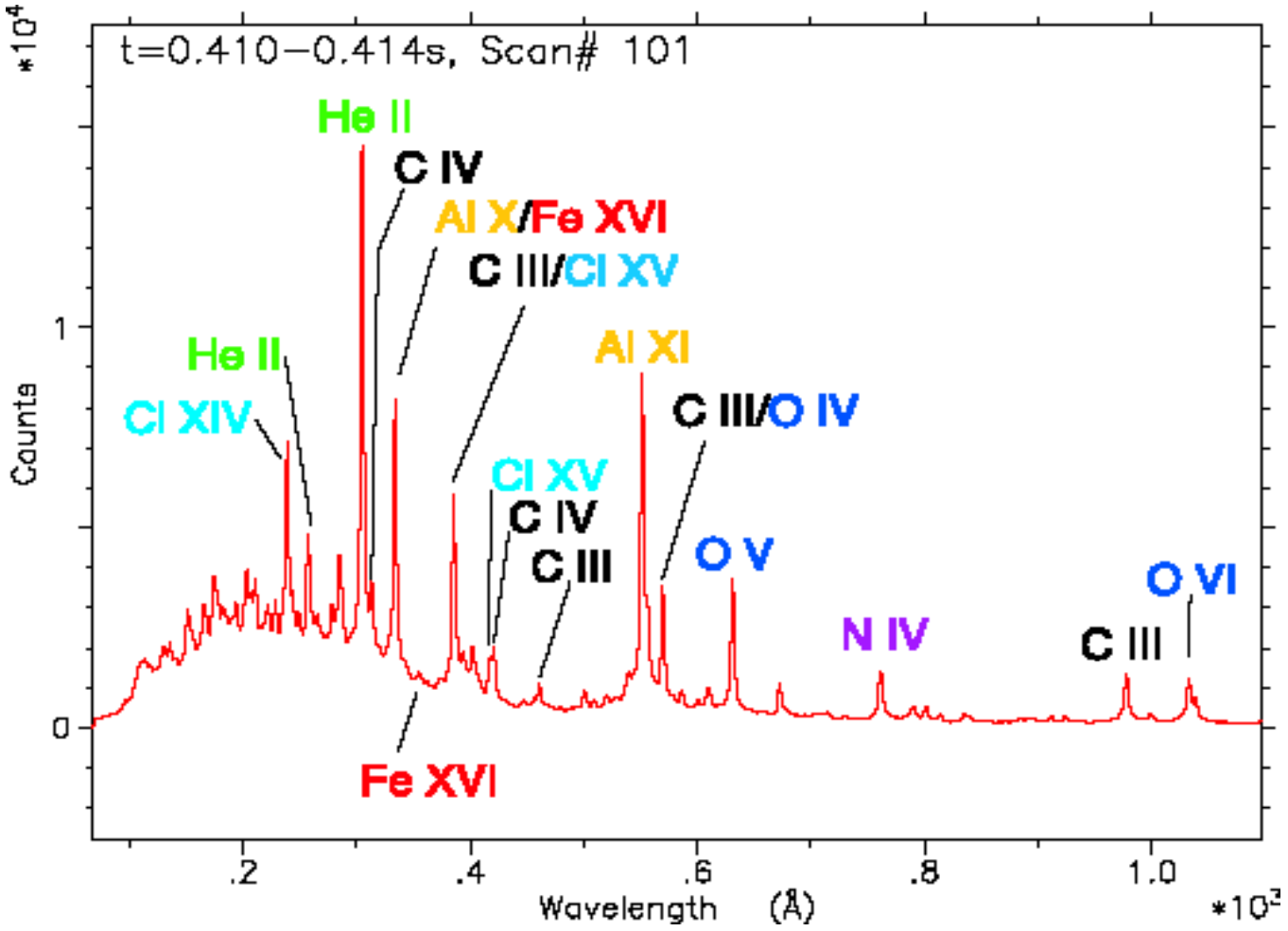


Detector



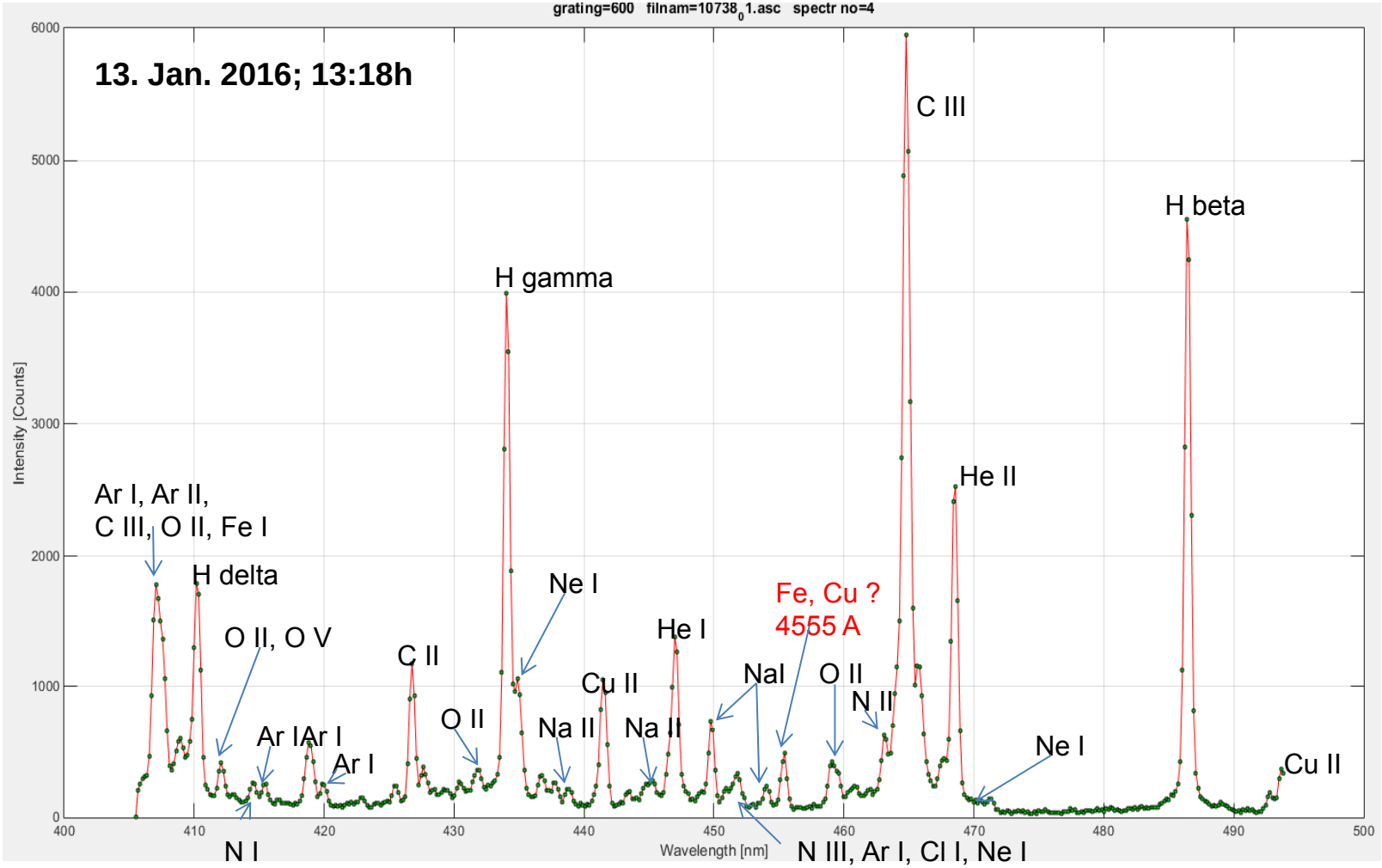
In the VUV-range: observation of highly ionized, heavy impurities

A typical VUV-spectrum

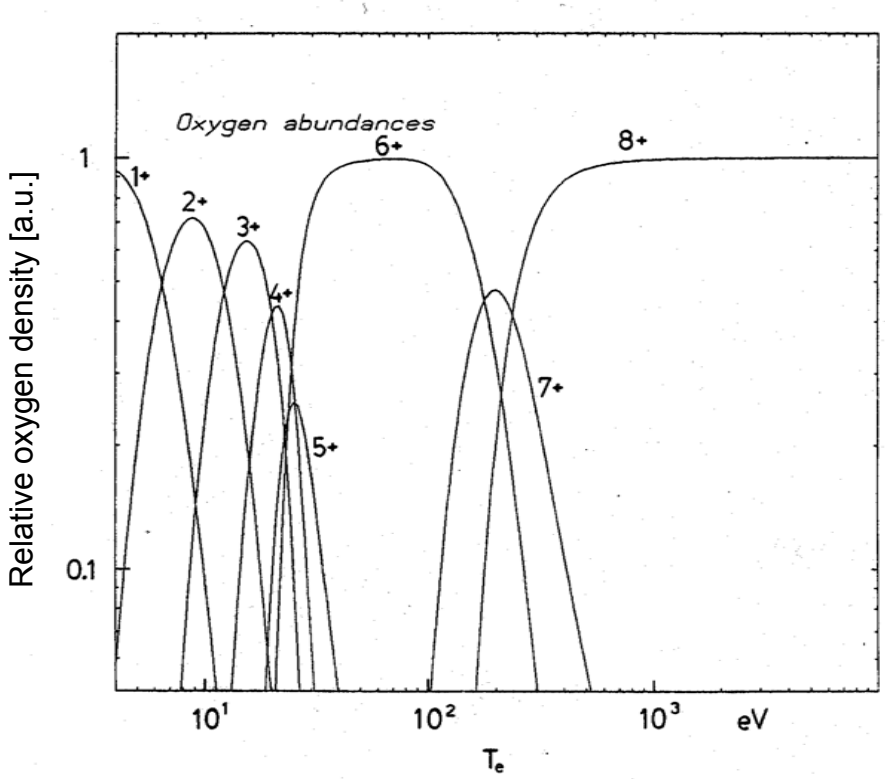


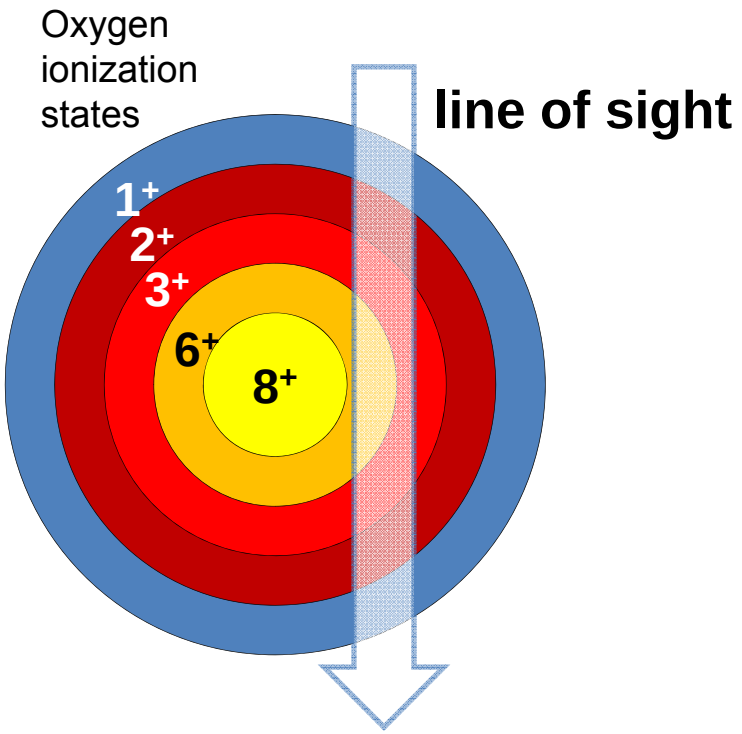
Dominating lines of Fe, C, N, Al, ……..

A typical visible spectrum in W7-X



Dominating lines of Ar, C, Ne, Na, ……..





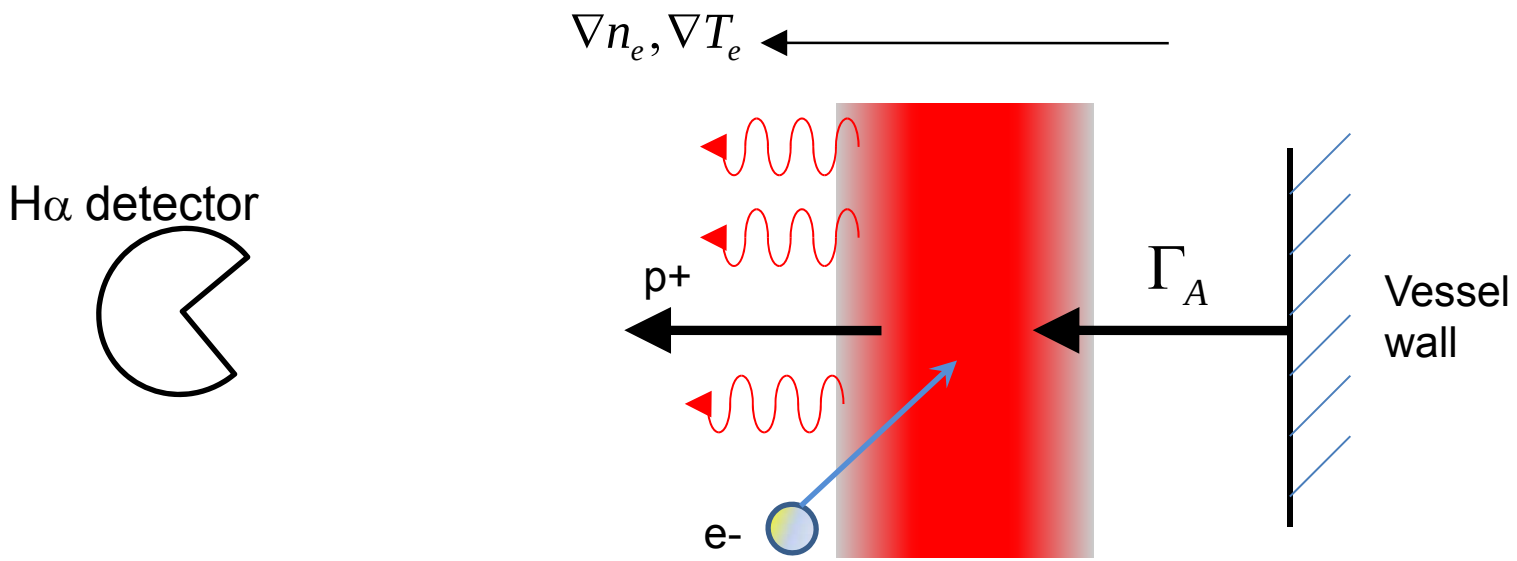
Principle of the line-of-sight integration

Passive Hα observation
➔ neutral particle fluxes

For transitions p➔q

$$I_A^{H\alpha} = \Gamma_A \cdot \frac{h\upsilon \cdot \left(A_{pq} / \sum_{q<p-1} A_{pq} \right)}{4\pi} \cdot \frac{\int_{r1}^{r2} n_e(r) n_A(r) \langle \sigma_{impact} V_e \rangle dr}{\int_{r1}^{r2} n_e(r) n_A(r) \langle \sigma_{ionizat} V_e \rangle dr} = \Gamma_A \cdot \frac{h\upsilon \cdot \{\text{Branch.}\}}{4\pi} \cdot \frac{\{\text{Excit.}\}}{\{\text{Ioniz.}\}}$$

For fusion plasma edges: $n_e = 10^{19}$ m^{-3} and $T_e = 10$ eV holds as a „good value“: $\frac{\text{Branch} * \text{Excit}}{\text{Ioniz}} \approx \frac{1}{15}$



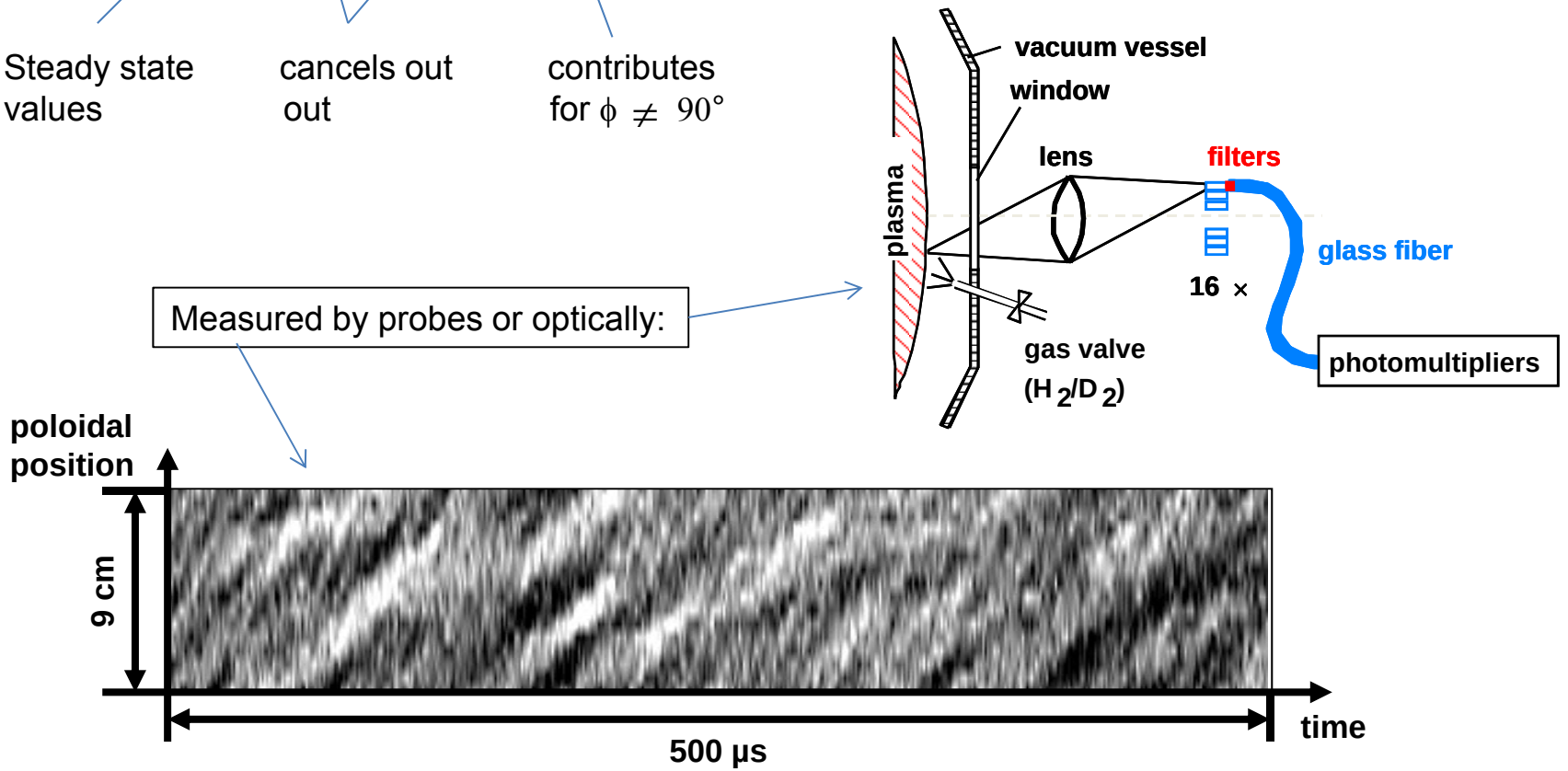
The net radial particle transport driven by fluctuation:

$$\Gamma_r = \left\langle \bar{n}\bar{V}_r + \bar{n}\tilde{V}_r + \tilde{n}\bar{V}_r + \tilde{n}\tilde{V}_r \right\rangle_{time}$$

Steady state values

cancels out out

contributes for $\phi \neq 90°$

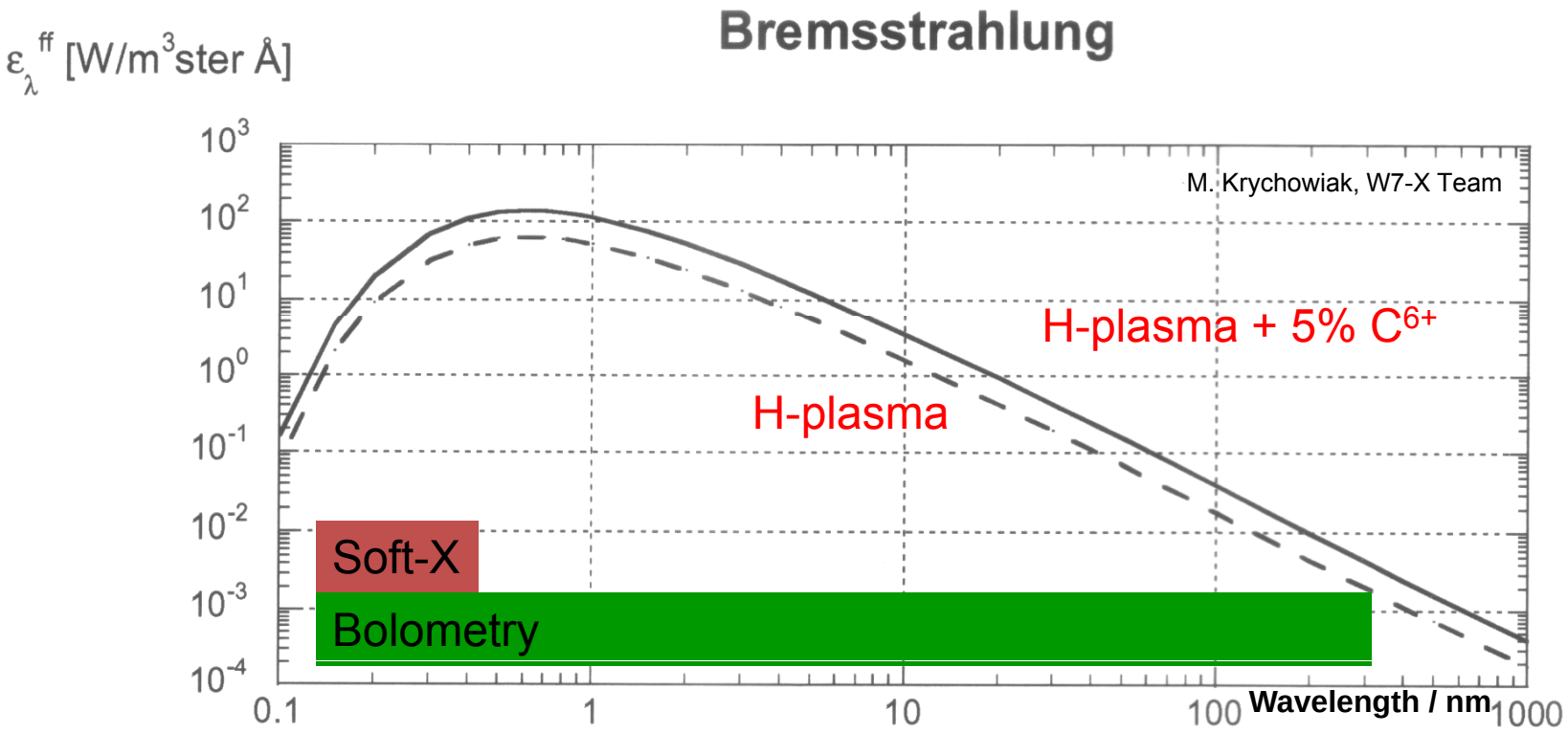


Z_{eff} from the Bremsstrahlung of the thermal electrons in the Coulomb field of the impurity ions

$$Z_{eff} = \frac{\sum n_e n_I Z_I^2}{n_e^2} \Rightarrow Z_{eff} \geq 1$$

$$\frac{dP}{d\omega} = 1{,}02 \cdot 10^{-33} \cdot n_e^2 \cdot \bar{g}_{ff} \cdot Z_{eff} \cdot \frac{\exp\{-\hbar\omega / kT_e\}}{\sqrt{kT_e}}$$

T-averaged free-free Gaunt factor summarized for all impurities



Important for bolometry and soft-X diagnostics: the high energy emission. The sources are:

- Bremsstrahlung (scattered electrons in the ion Coulomb field)
- line radiation (radiating excited electron states in impurity ions)
- thermal plasma emission (blackbody radiation, minor contribution)

-The number of photons per time, per volume and per energy interval into 4π reads:

$$\frac{dN}{dE_x} = \alpha \cdot n_e \cdot \frac{\exp\{-E_x / T_e\}}{E_x \sqrt{T_e}} \cdot \left[n_{prot} g_{ff} + Z_{eff}^2 n_Z g_{ff}^Z + n_Z g_{fb} F(n_e, T_e) \right], \quad \alpha = 9{,}6 \cdot 10^{-20}\ eV^{1/2} m^3 s^{-1}$$

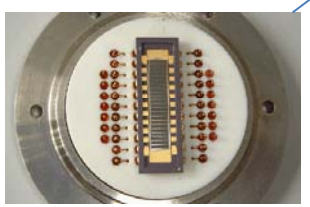
Bremsstrahlung - electrons-protons

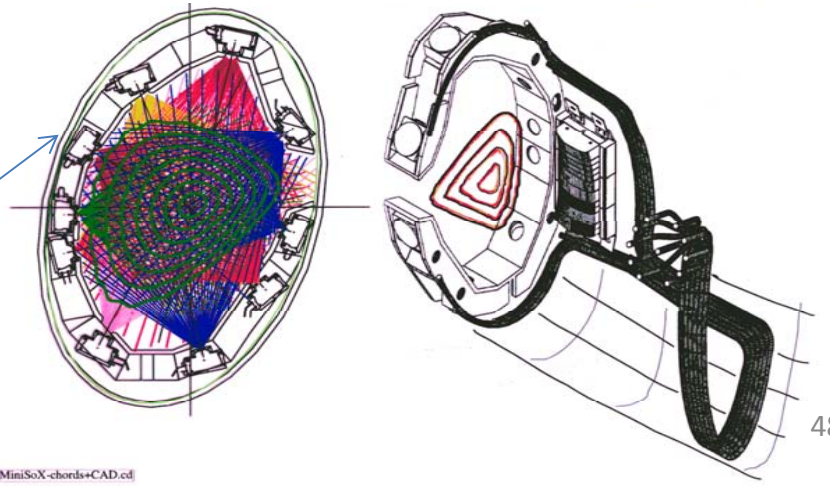
electrons-impurities

line radiation impurities/recombination

The W7-AS soft-X tomography system

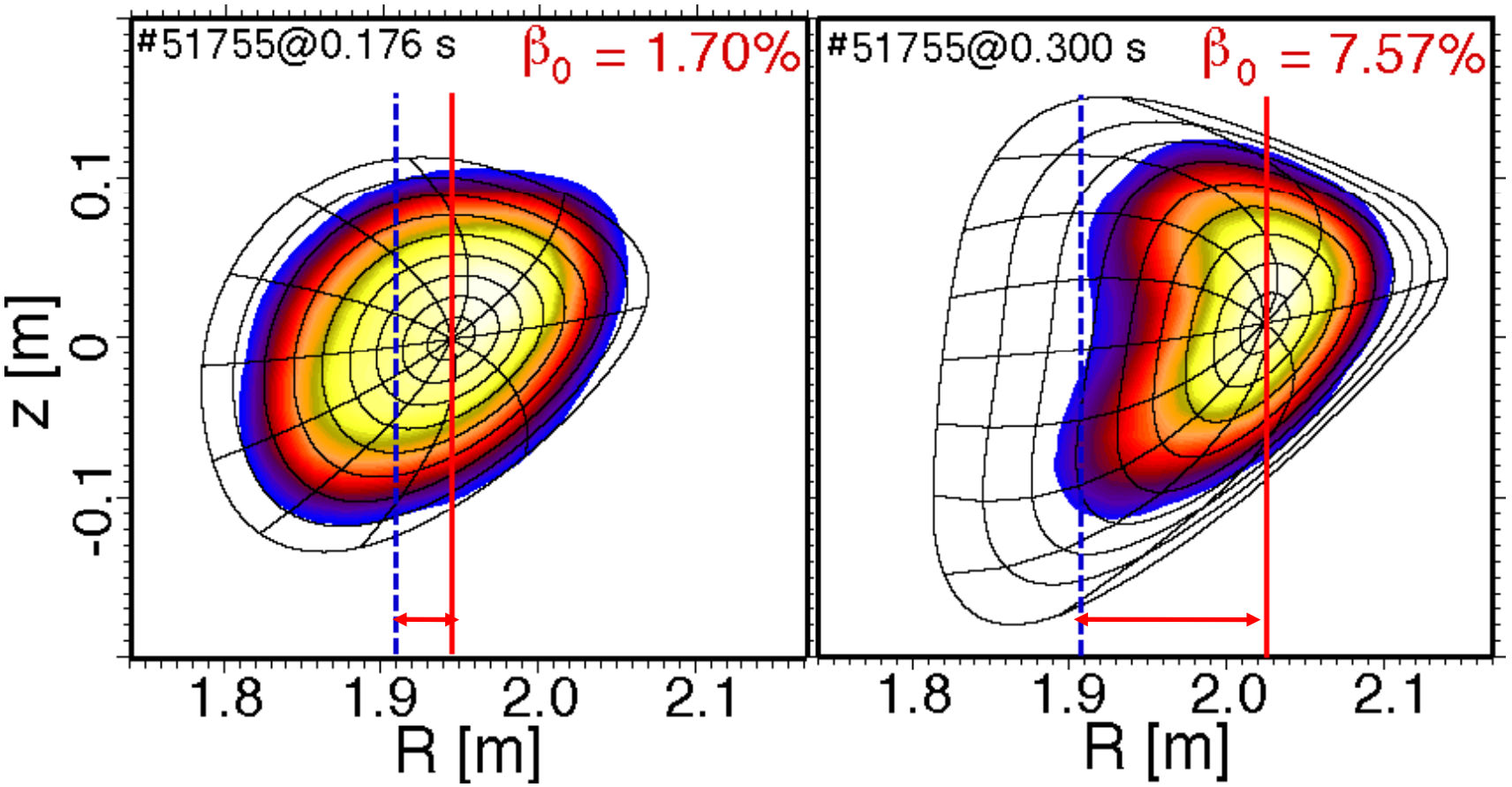
Si- Photodiode arrays



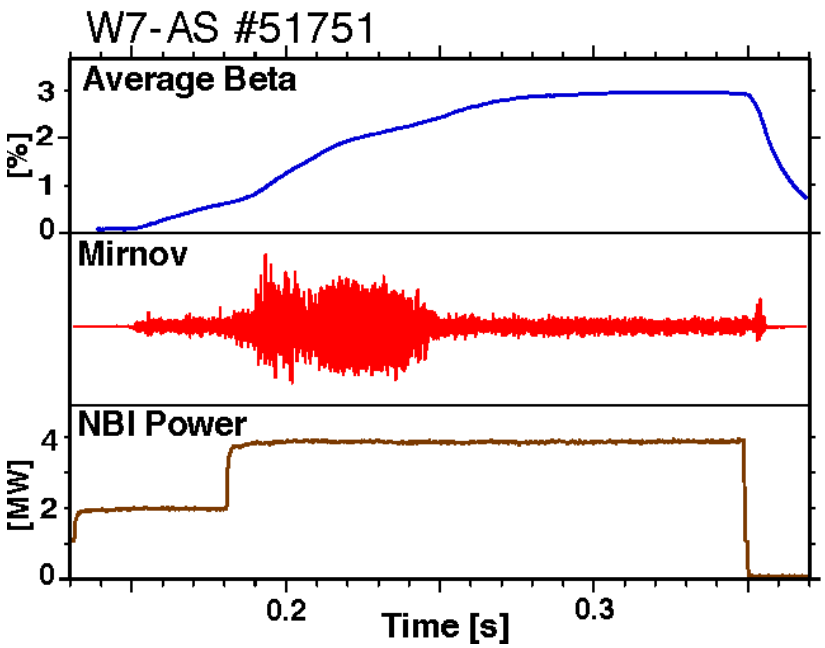


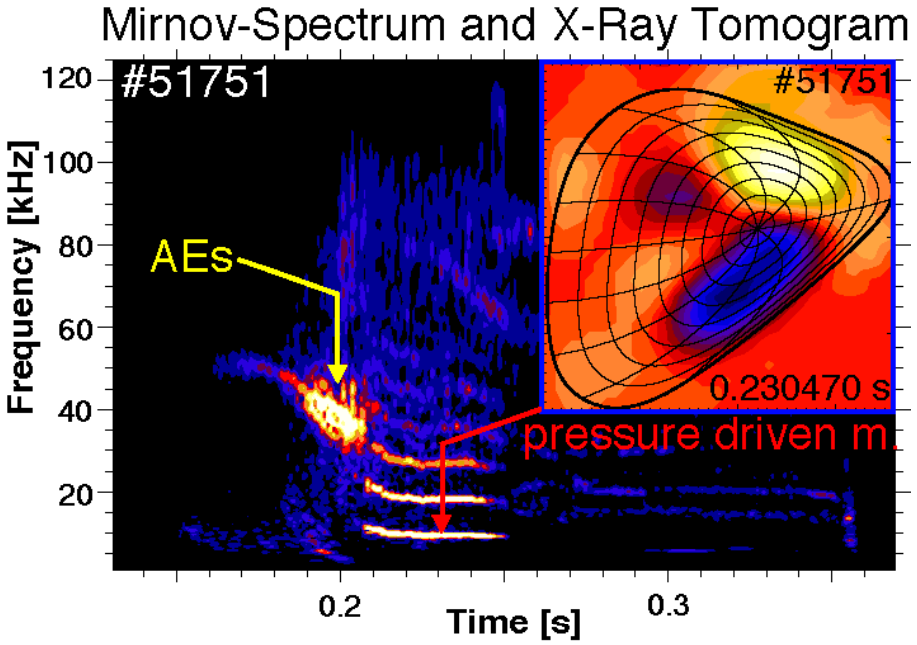
A. Weller, ASDEX-U Team

Soft-X diagnostics is sensitive to line radiation, Z_{eff} , n_e and T_e , the emissivity is a function of the magnetic flux



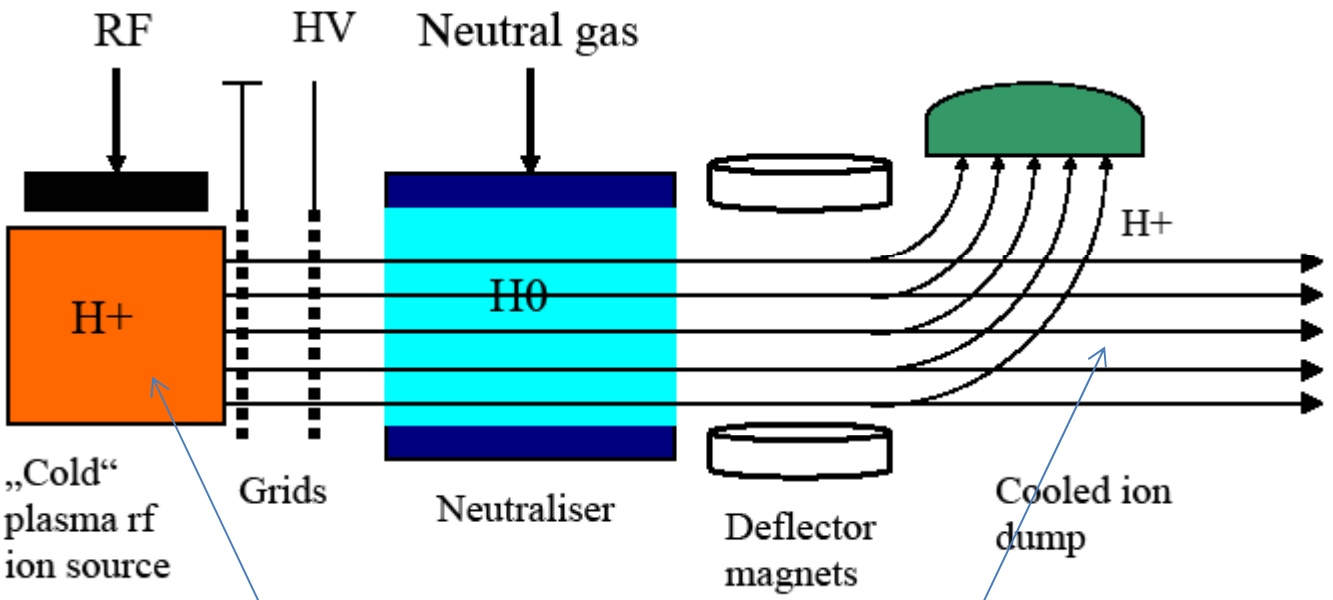
W7-AS: demonstration of the Shafranov shift due to the plasma pressure





Within a certain pressure-window Alfvén eigenmodes can survive,
for higher plasma pressure they vanish

Neutral Beam Injection NBI: Sketch of the arrangement

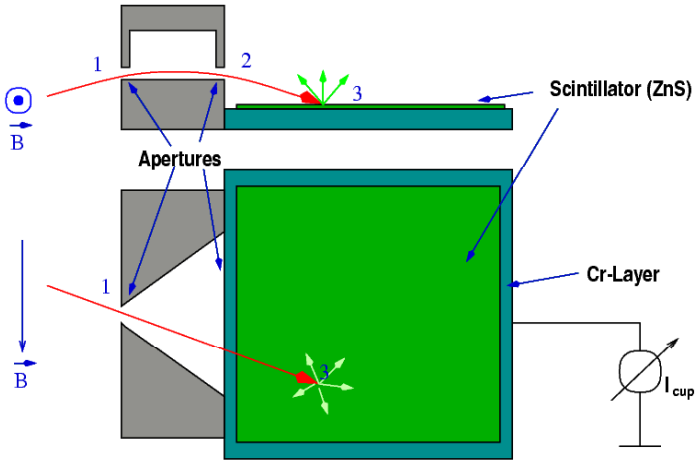


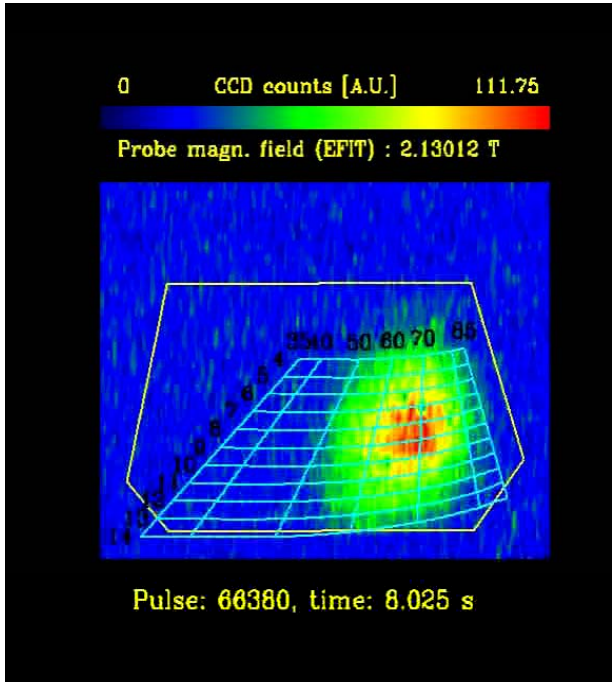
Plasma

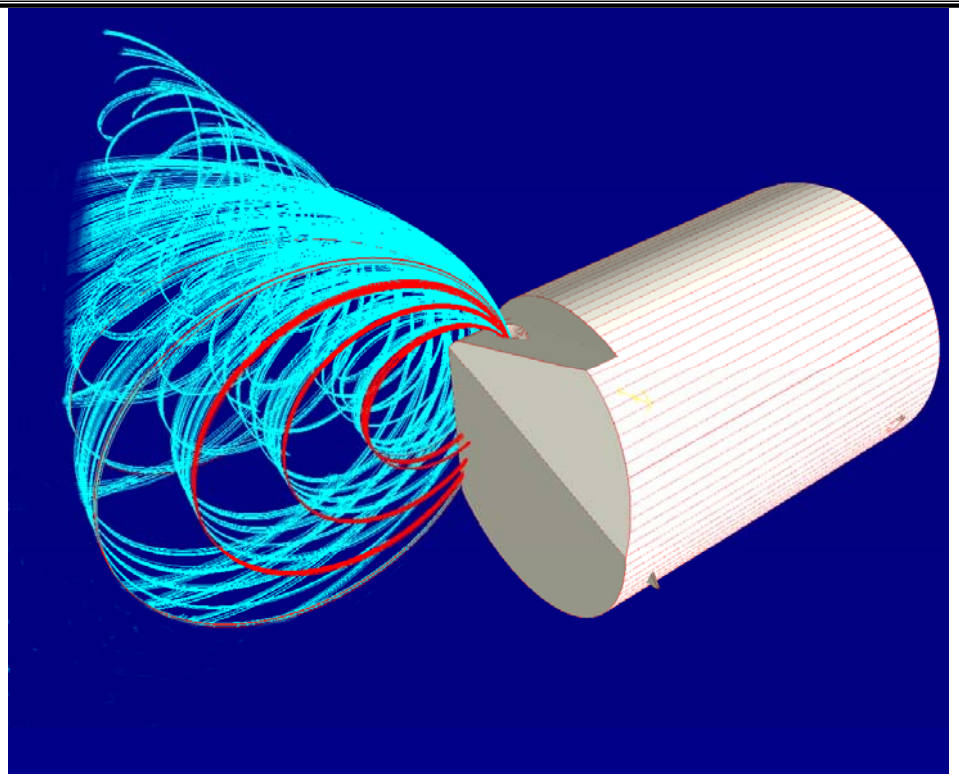
p^+ protons
H_2^+ , H_3^+ molecules
H_2O^+ molecules

➔Energy-mix in the beam:
U_{acc} , 1/2 U_{acc} , 1/3 U_{acc}, 1/18 U_{acc}

Fast ion loss detector – energy and pitch angle resolution







Scintillator light yields ion fluxes

Important for confinement studies

Heavy ion beam probe: the principle

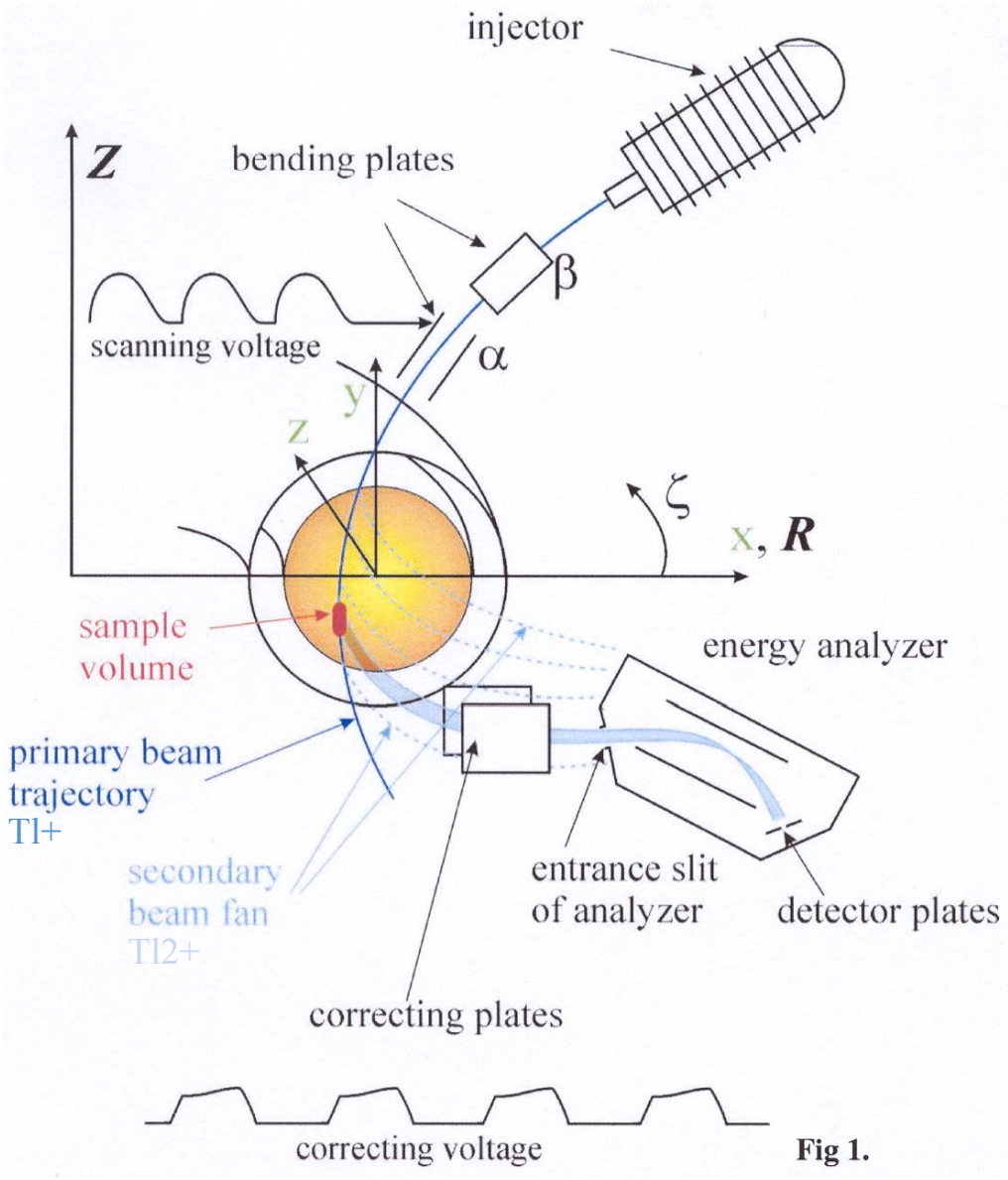
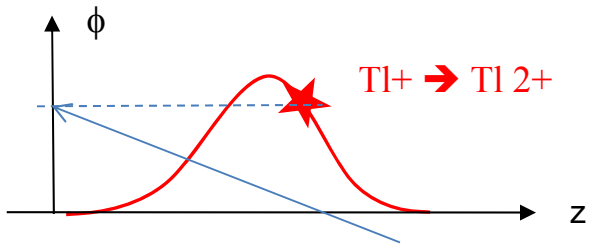


Fig 1.



$$E_{end} = U_{accel} + e \cdot \phi_z$$

The measurement of $E_r(r,\theta,\varphi)$ becomes accessible

High time resolution
➔ $\widetilde{E}_r$ becomes accessible

U_{accel} typically 1-2 MeV (W7-X)
I_{prim} typically 100 μA
I_{second} typically 300 nA
Time resolution typ. MHz

Fusion diagnostic challenges for the future

The way to ITER:

-Huge and long ports

-Very difficult diagnostic access to the plasma

-High neutron/gamma radiation level

-No human access to the operating machine

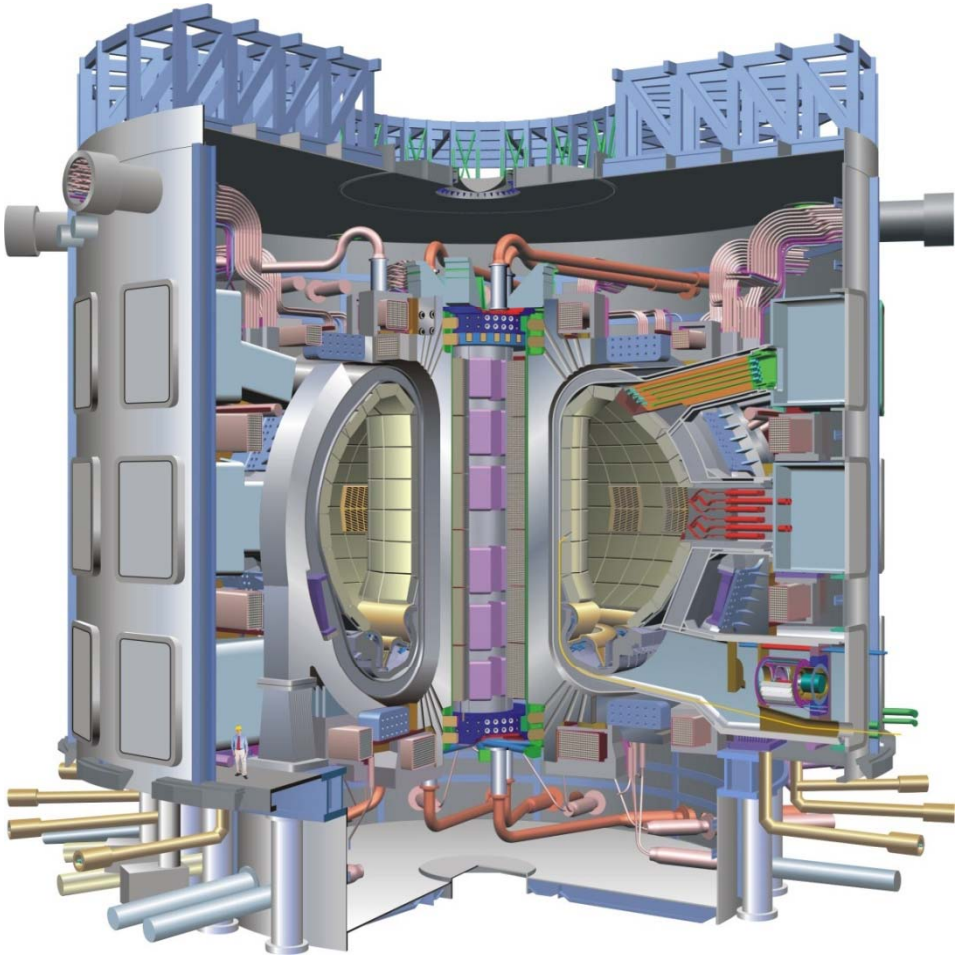
-Long pulse operation

-Huge amount of measurement data

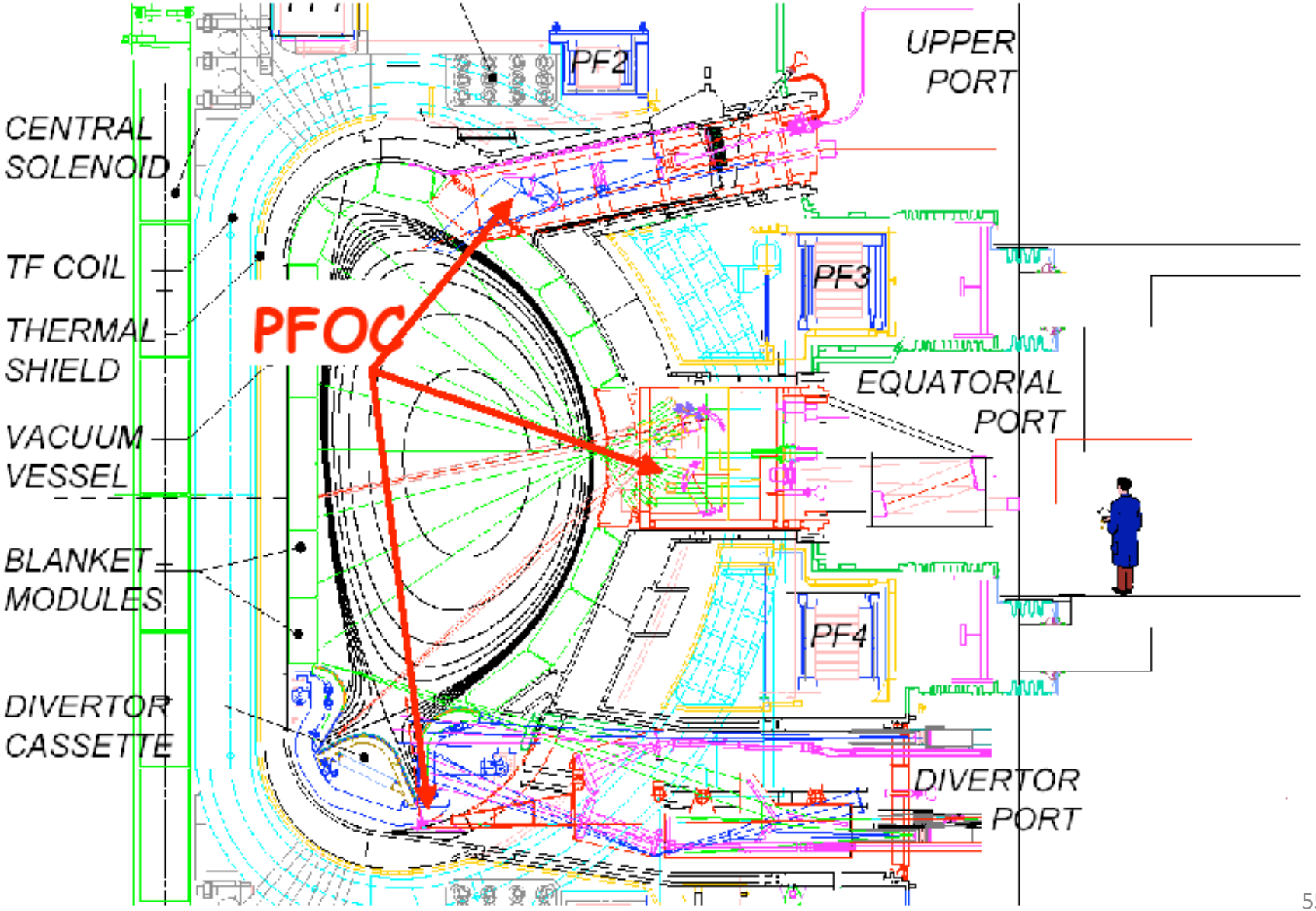
-High thermal radiation load

-Long operation lifetimes for components required

-Large, very specialized + expensive components
➔ first design must fit



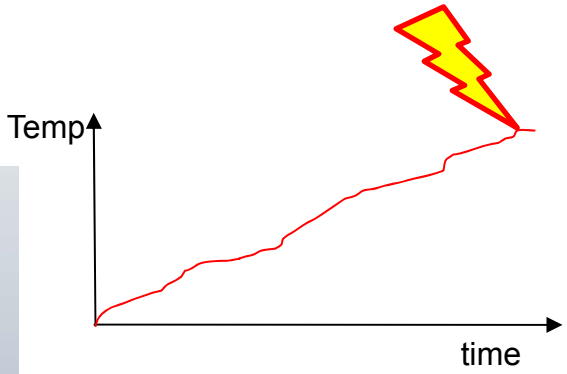
The ITER cross section



Temperature control of all plasma facing components (graphite, tungsten, steel)

➔ safety interlock becomes mandatory

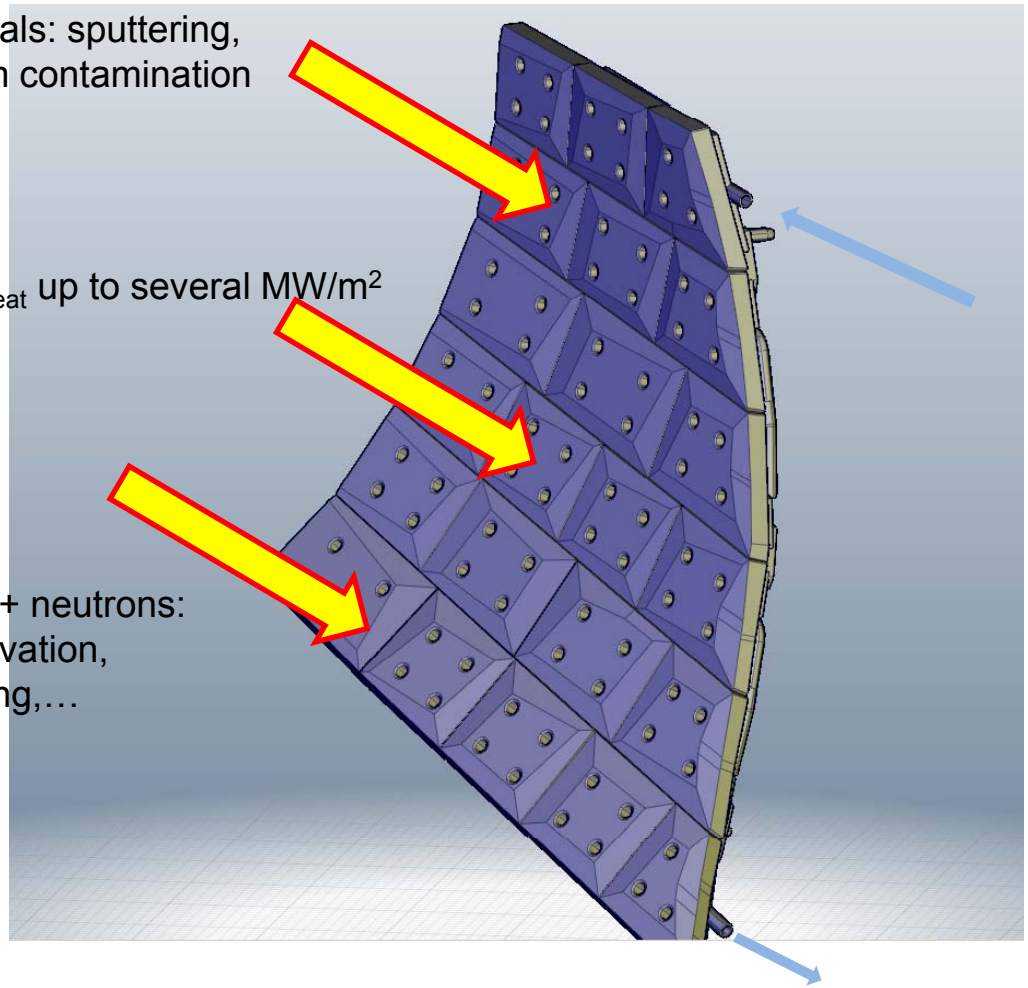
➔ active cooling is required for all plasma facing components



Neutrals: sputtering,
tritium contamination

P_{heat} up to several MW/m^2

Fusion alphas + neutrons:
sputtering, activation,
erosion, swelling,…



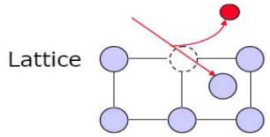
Cooling water:

-requirement of water flow + temperature control

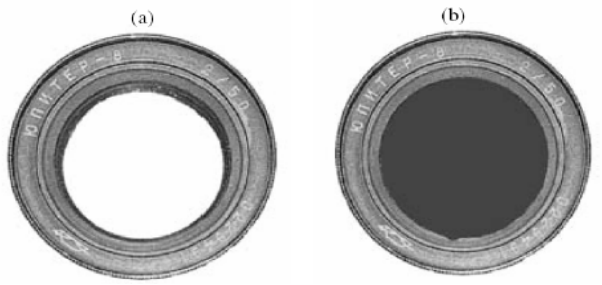
-control of possible tritium contamination

- activation of Na after neutron capture

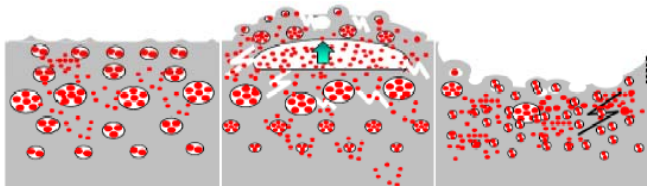
High neutron fluxes
in ITER $8 \times 10^{17} m^{-2} s^{-1}$



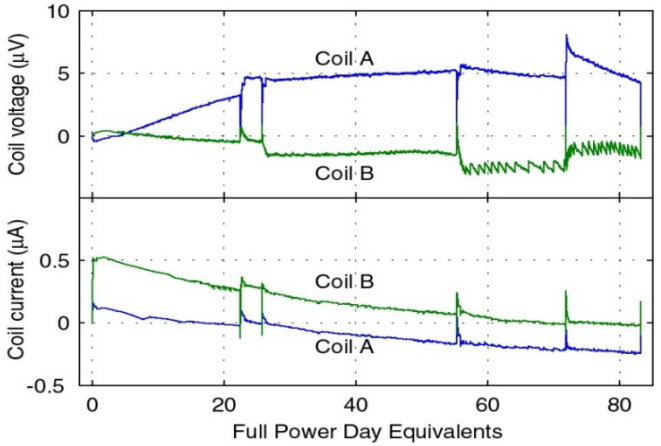
Optical systems are getting dark
+ radio-luminescence occurs



Mirrors are better suited,
but swelling by neutrons and
CX atoms happens
+ plasma erosion + particle deposition



Cables (impact on magnetics), capacitors:
- RIC – radiation induced conductivity
-RIEMF – RI electromotive forces
- radiation induced change of the dielectric constant ε_r



Compiled material by T.Donné,Ch.Ingesson, Costley and many others, talk by H. Weisen CRPP-EPFL

- John Wesson: *Tokamaks*, Oxford Science Publications, Clarendon Press

- Richard Dendy: *Plasma Physics*, Cambridge University Press

- R.D. Hazeltine, J.D. Meiss: *Plasma Confinement*, Addison-Wesley Pub. Comp.

- I.H. Hutchinson: *Principles of Plasma Diagnostics*, Cambridge University Press

-W. Lochte-Holtgreven, *Plasma Diagnostics,* AIP, New York

-H.J. Hartfuss, R. König, A. Werner: *Steady-state diagnostics for fusion plasmas*, Plasma Phys. Contr. Fusion **48** (2006) , p. R83

…….thank you very much for your attention

(and sorry for the rather inhomogeneous, incomplete collection of bits and pieces)

Types of diagnostics:

-„Passive“ line-of-sight integrated, and „active“ supported by beams

- „Local“ and „global“ diagnostics

Looking at:

- Electromagnetic emission (light, microwaves, radio-waves, X-ray, B-fields, …..

- Particle + power fluxes (neutrals, impurities, neutrons, heating power,……

- ……..

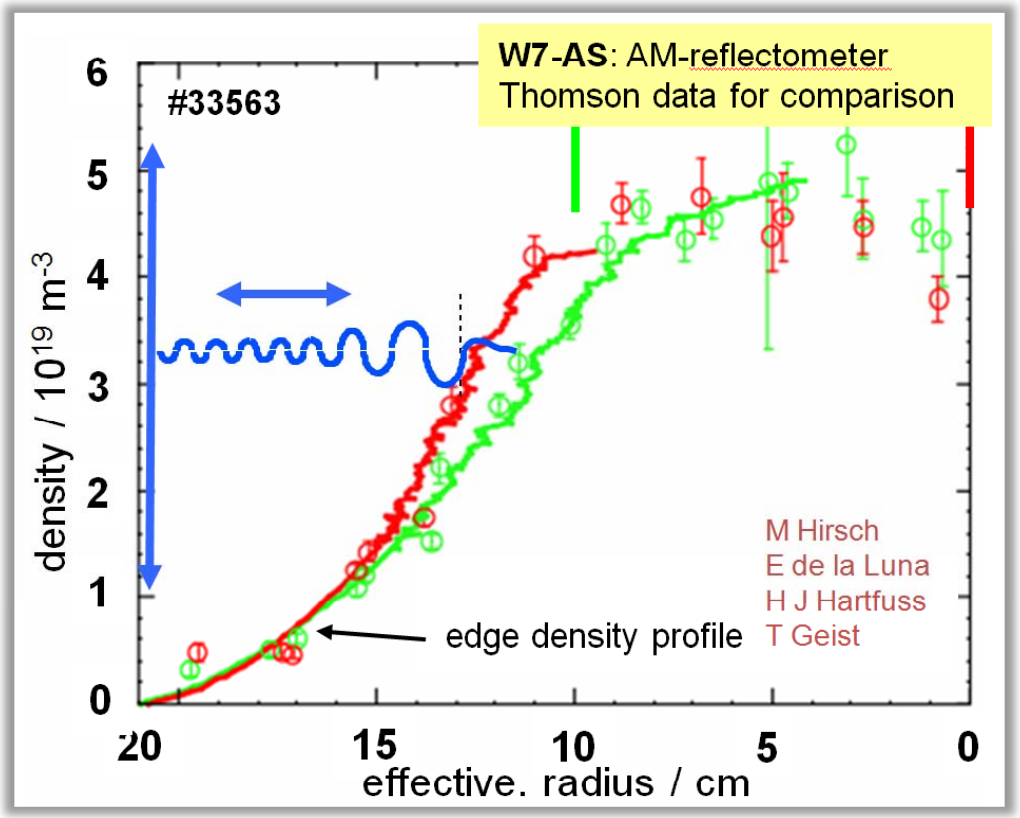
Some of the plasma parameters we want to observe

Energy content	W_{dia}
Temperatures	T_i , T_e
Densities	$n_{i,}$ n_e , n_Z , $n_{neutrals}$
Currents	$J_{toroidal}$, $j(r)$
Power fluxes	$P_{heating}$, $P_{radiation}$, P_{wall}
Fields	E_r , $B_{toroidal}$, $B_{poloidal}$,
Fluctuations, oscillations	$\widetilde{B}, \widetilde{E}, \widetilde{n}_e$
Particle fluxes	$\Gamma_{neutrals}$, $\Gamma_{impurities}$, $\Gamma_{fast\ ions}$
Others	$V_{toroidal}$, $V_{poloidal}$, $f(r)$, ...

$$N^2 \approx 1 - \frac{\omega_p^2}{\omega^2} \; ; \; \omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

Reminder: EM-waves are reflected when N ➔ 0

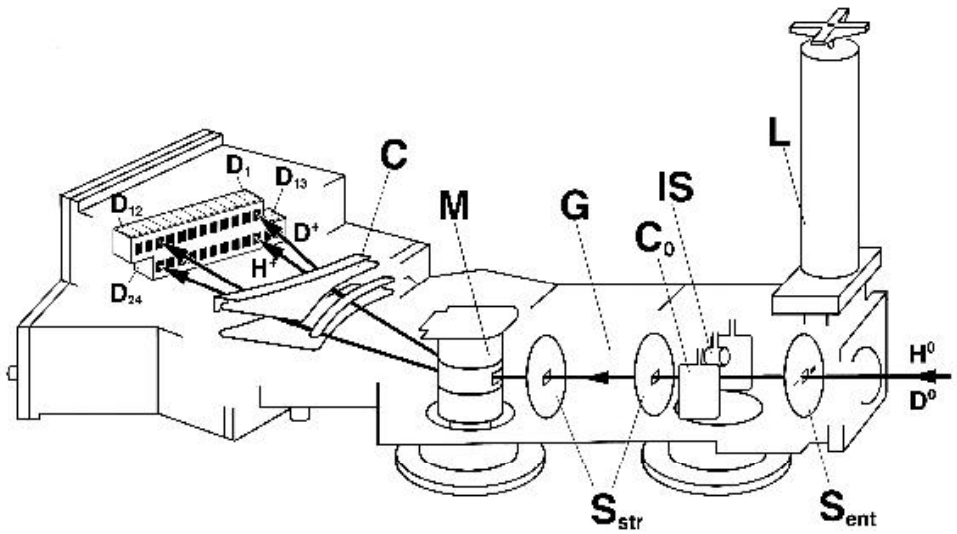
This provides a tool for the measurements of n_e (RADAR principle)



Prerequiste: n_e must be monotonically increasing

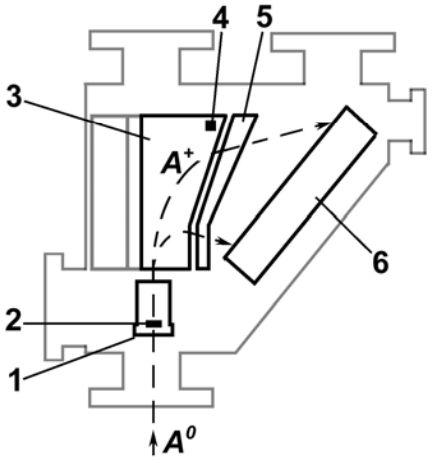
Broadband data evaluation provides information about electron density fluctuations $\tilde{n}_e$

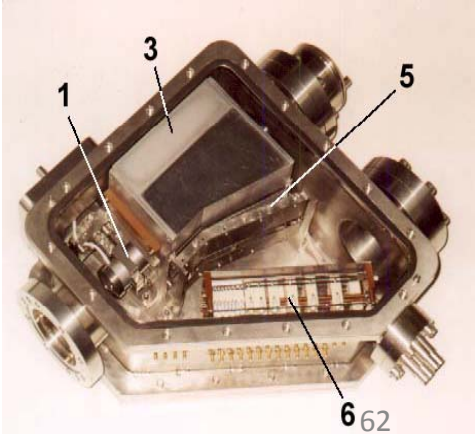
Principle of NPA: ACORD-24



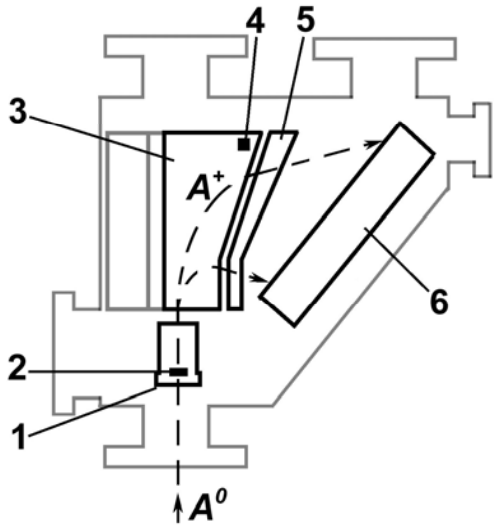
(L) vacuum shutter; (S_{ent}) "step like" entrance slit; = 1
(C_o) "cleaning" electrostatic condenser, removing charged particles from the flux; = 2
(G) stripping cell chamber; = 2
(S_{str}) stripping chamber slits;
(M) electromagnet; = 3
(C) analysing electrostatic condenser; = 5
(D_1 - D_{24}) two rows of detectors;
(IS) auxiliary ion source for NPA testing; (H^0, D^0) atoms emitted by the plasma; (H^+, D^+)secondary ions.
Hall probe = 4
Detector = 6

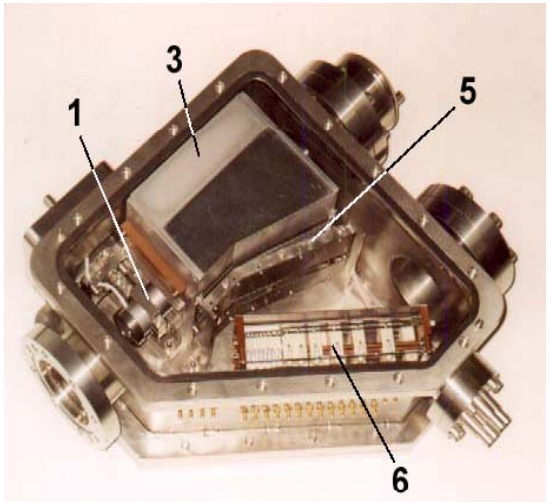
Absolutely calibrated single chord Neutral Particle Analyzer (NPA)
H/D discrimination
Energy range up to 100 keV
24 channeltron detectors (dual mass)





NPA- the principle



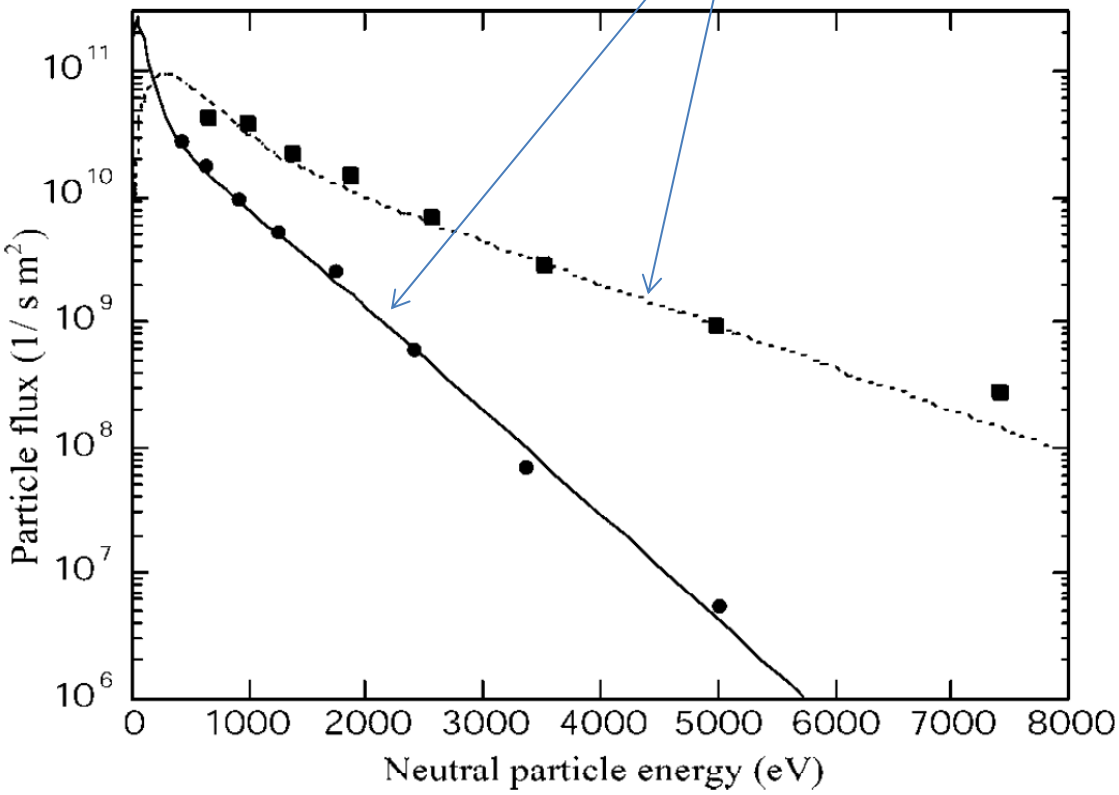


(1) acceleration/stripping unit
(2) stripping foil
(3) analysing magnet
(4) Hall probe
(5) analysing electrostatic condenser
(6) detector array

Energy range	**0.8-80 keV (H), 0.8-40 keV (D)**
Size	**169 × 302 × 326 mm**
Weight	**42.5 kg**
Stripping	**Carbon foil (100 Angstrom)**
Acceleration of secondary ions	**+ 5 kV**
Permanent magnets	**NdFeB, B_r ~ 1 T**
Number of energy channels	**14 × 2 rows**
Purpose	**Measurements of thermal and suprathermal CX-fluxes (H and D – simultaneously)**

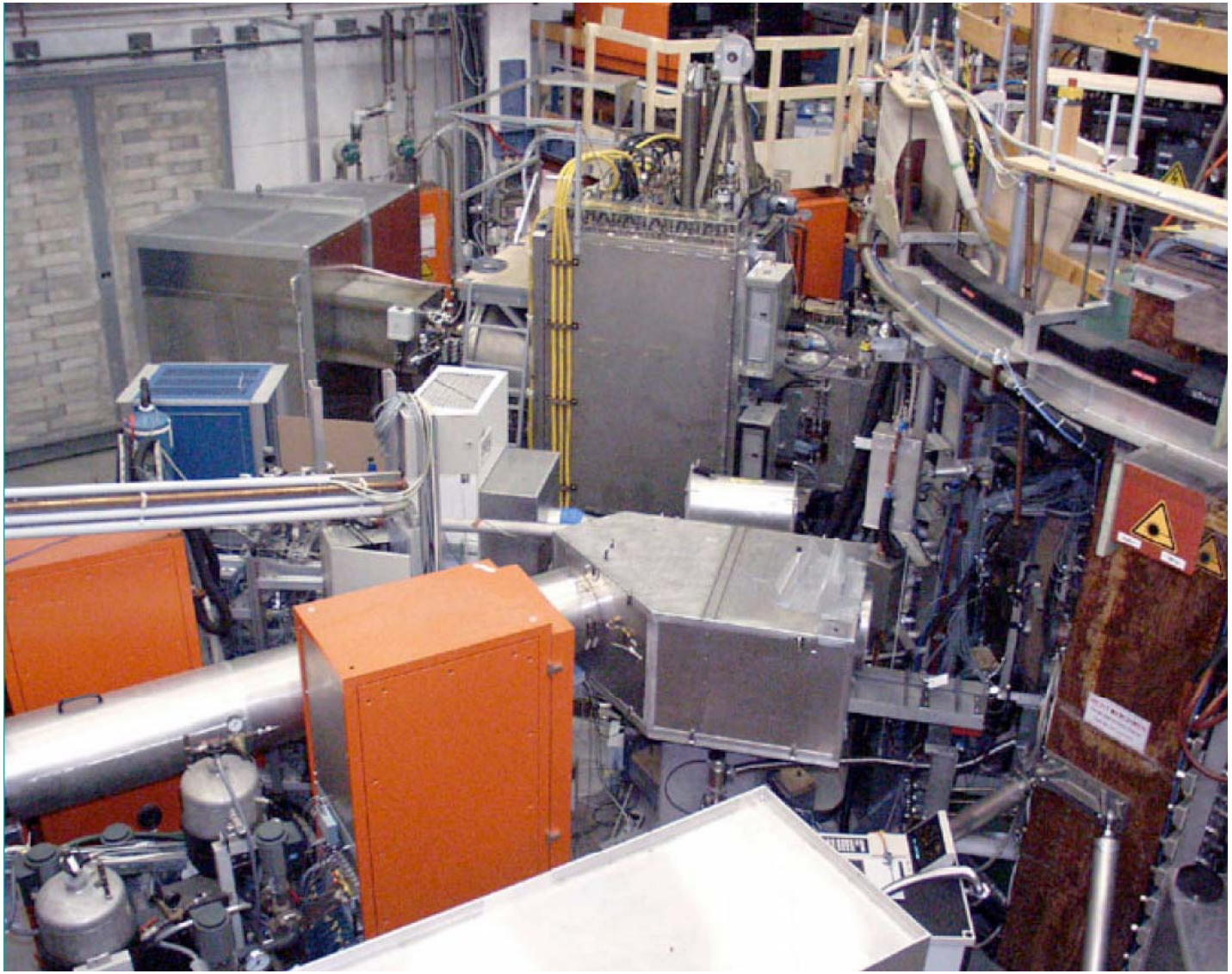
NPA flux spectrum example

$$d\,n_0 = N_0 \cdot n_i(r) \cdot \sqrt{\frac{m_i}{2\pi k T_i}} \cdot \exp\left\{-\frac{E_i^{kin}}{kT_i}\right\} dV_z$$



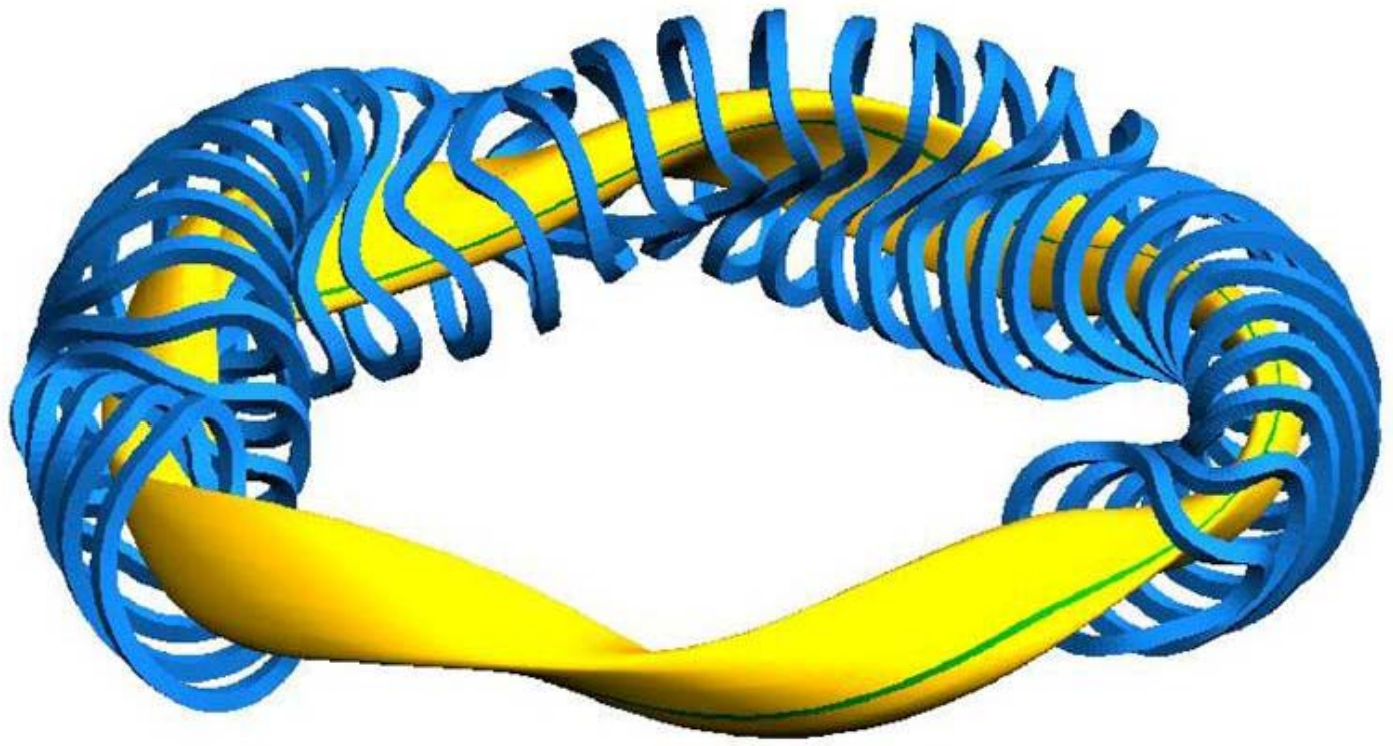
Example: two discharges with different energy confinement (different T_i)

…even the close-up doesn‘t make things much clearer…..

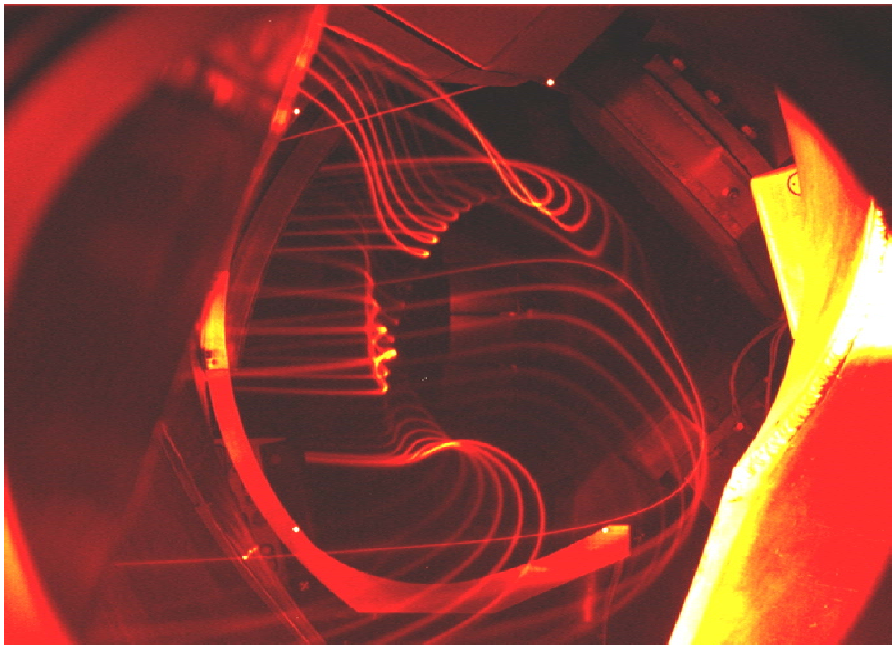


Real life: the stellarator W7-AS

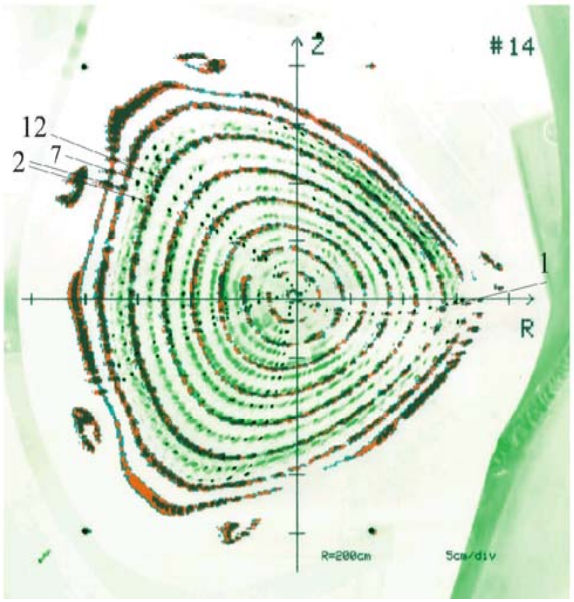
Sketch of the toroidal facility W7-X: only the plasma and some nonplanar coils



Imaging techniques for the magnetic field



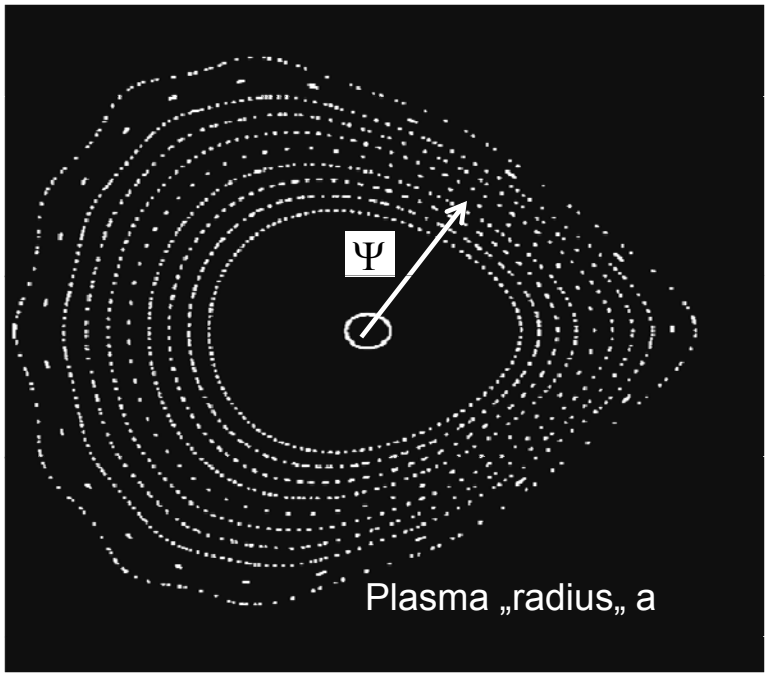
W7-AS:
Field-line tracing with an electron beam using fluorescence in hydrogen gas (false colour).



W7-AS:
flux surface measurements before operation (dark) and after 56000 discharges (green)

M. Otte, R. Jaenicke, Stell. News (2006)

The concept of nested magnetic flux surfaces



Poincaré - plot

Simplifying assumption:

Plasma parameters are (more or less) constant on magnetic flux surfaces (label Ψ)

Distribution function $f(\vec{r},\vec{V},t) = f(\Psi,\vec{V},t)$
with the (toroidal magnetic flux) function Ψ

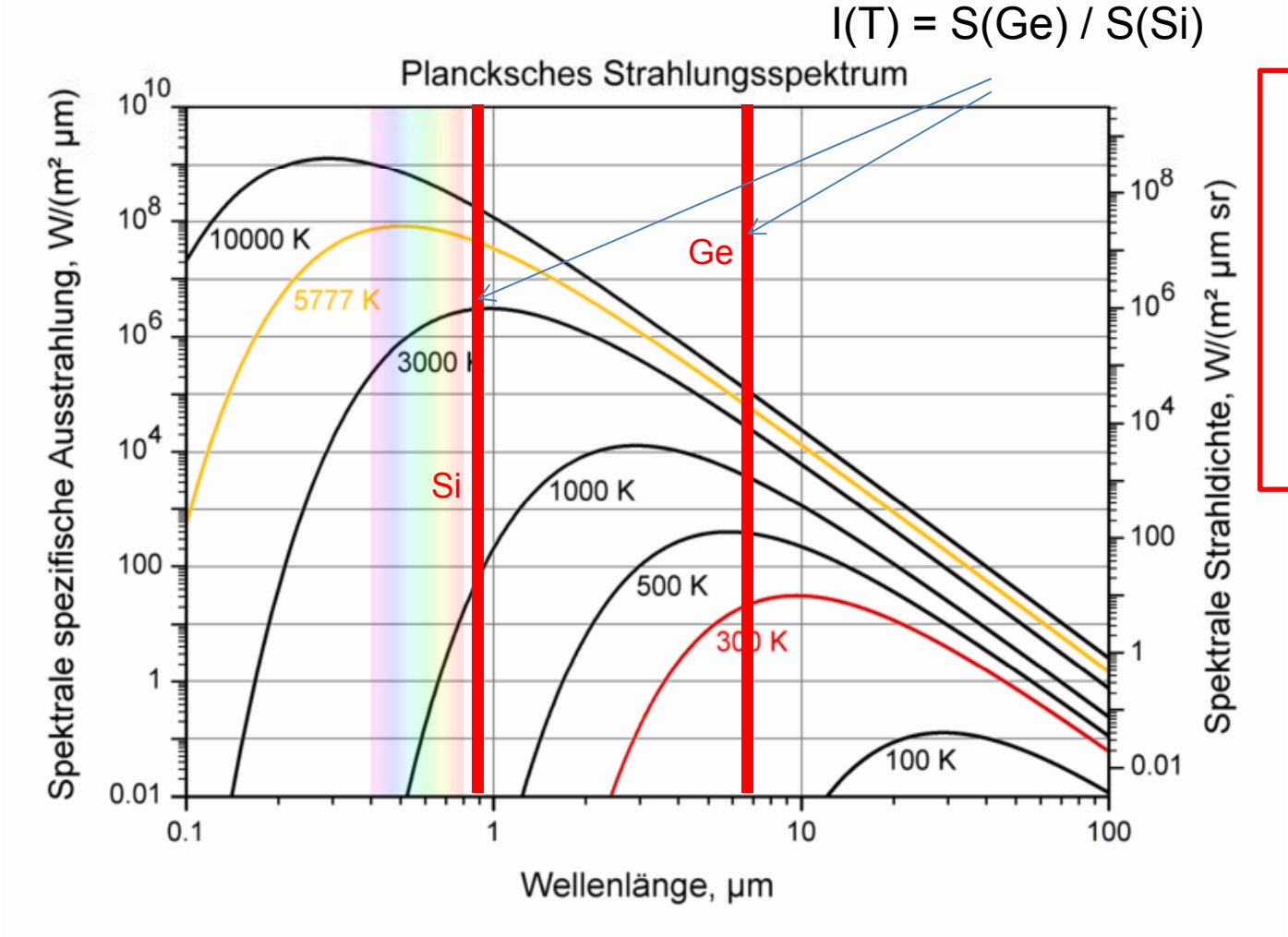
Plasma parameters $g(r) = g(\Psi) = g(\rho)$; $\rho = r/a$

Due to the fast transport parallel to the magnetic lines, this holds mainly for the quantities:

$\phi(\rho)$, $T_e(\rho)$, $T_i(\rho)$

……can reveal, by passive observation, the surface temperature of wall components

I(T) = S(Ge) / S(Si)



With Planck's law:

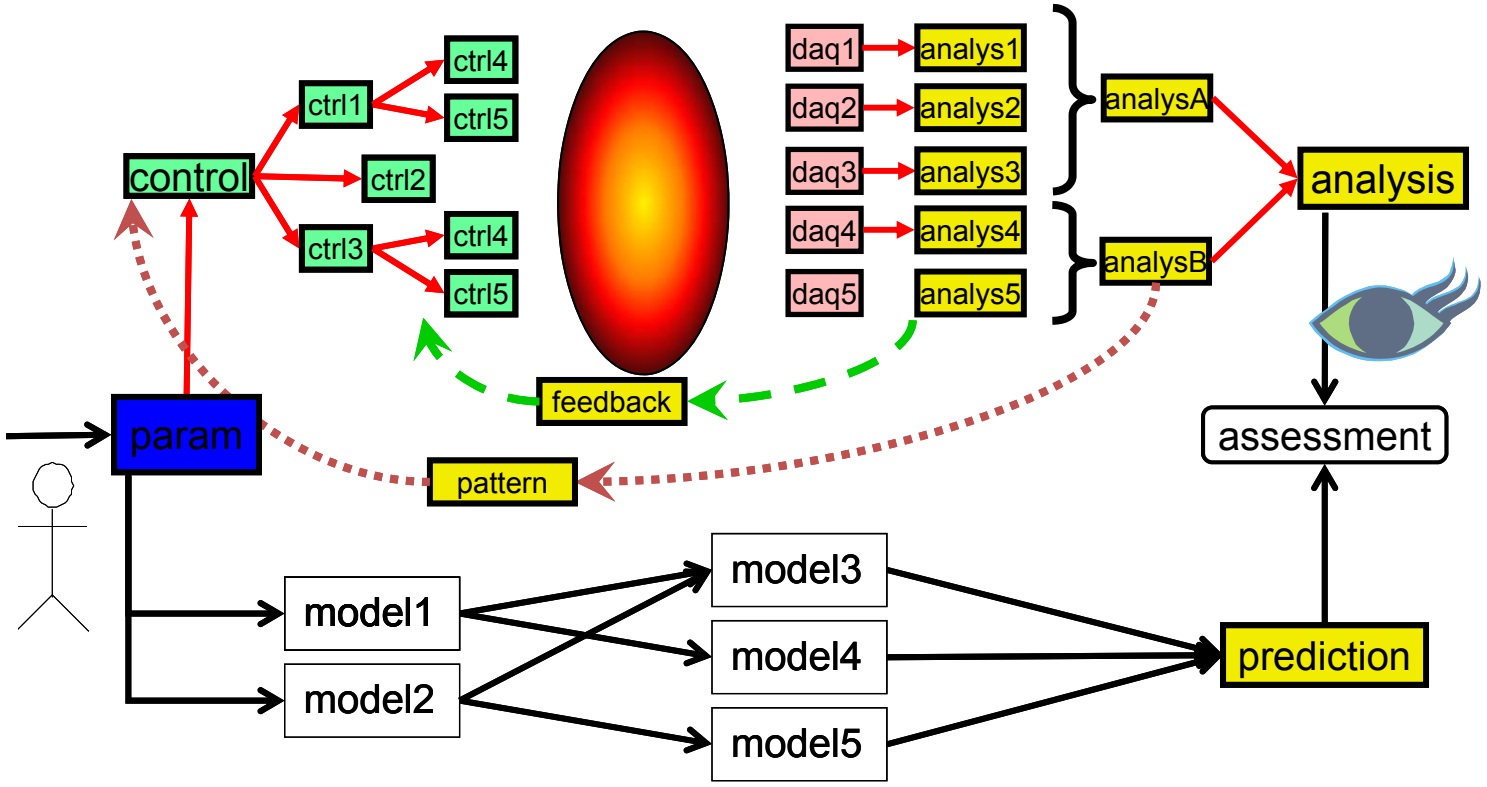
$$\frac{dP}{d\lambda} = \frac{2\pi hc^2}{\lambda^5}\left(\exp\left\{\frac{hc}{\lambda kT}\right\} - 1\right)^{-1}$$

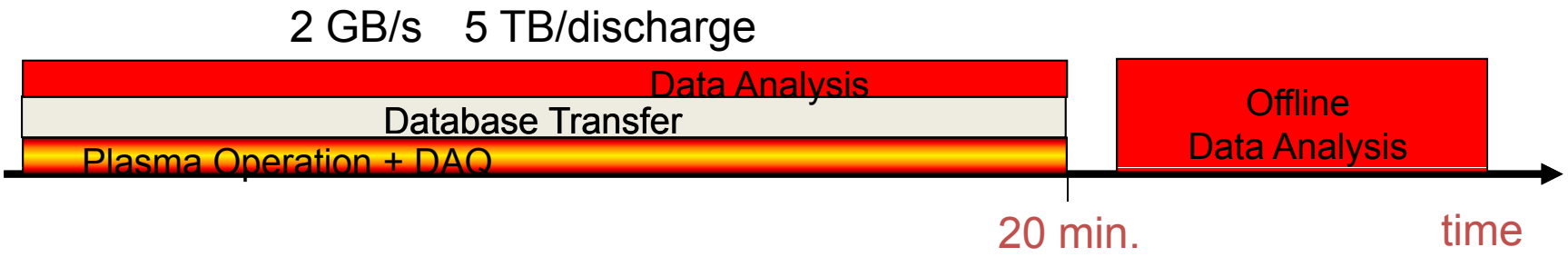
and Stefan-Boltzmann:

$$P_{total} = \varepsilon \sigma_{SB} T^4 A$$

Plot from Wikipedia

……and finally a brief outlook to the future……..


control
ctrl1
ctrl2
ctrl3
ctrl4
ctrl5
ctrl4
ctrl5
daq1
daq2
daq3
daq4
daq5
analys1
analys2
analys3
analys4
analys5
analysA
analysB
analysis
feedback
param
pattern
assessment
model1
model2
model3
model4
model5
prediction


2 GB/s 5 TB/discharge
Data Analysis
Database Transfer
Plasma Operation + DAQ
Offline
Data Analysis
20 min.
time

Inference

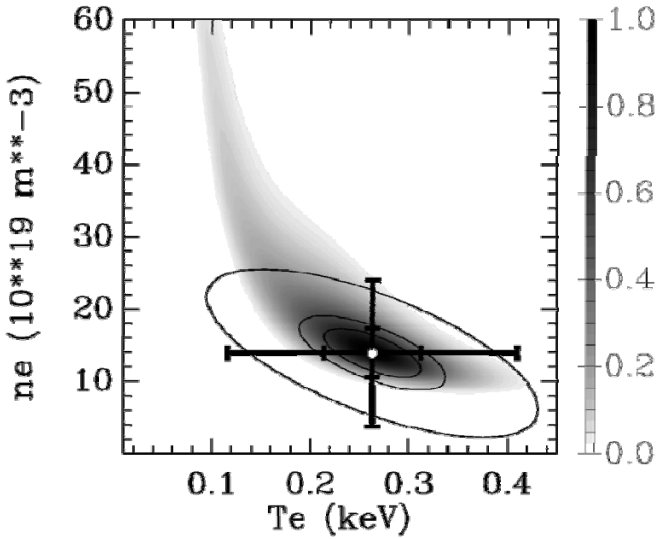
How likely do we find results ***H*** GIVEN data ***D*** with background information ***I*** ?

Bayes Theorem

learning

$$\Rightarrow \quad p(\mathrm{H}|\mathrm{D},\mathrm{I}) \sim p(\mathrm{H}|\mathrm{I}) \times p(\mathrm{D}|\mathrm{H},\mathrm{I})$$

posterior pdf | prior pdf | likelihood



Posterior of Thomson scattering
new: full error propagation
$n_e\uparrow \leftrightarrow T_e\downarrow$
'… measures P_e'

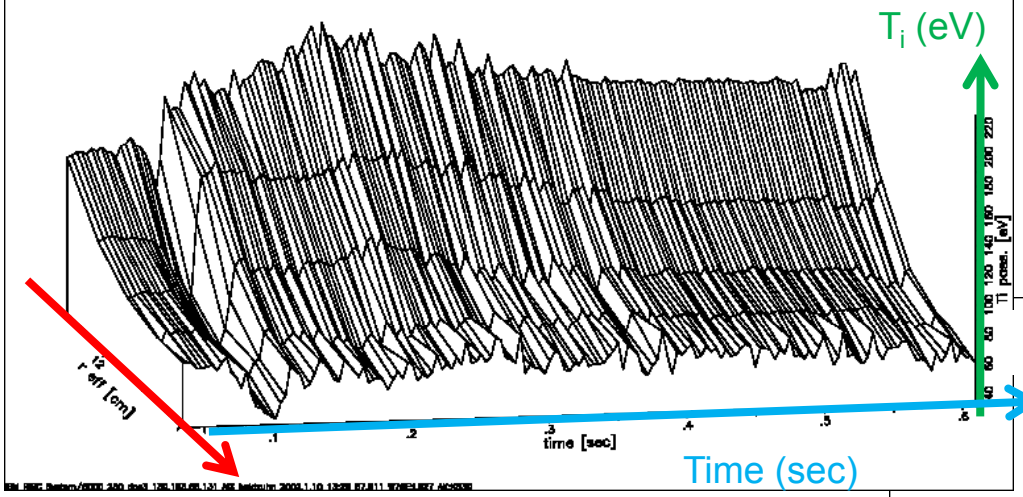
measurement | inference

knowledge → data → updated knowledge

A. Dinklage: Integrated data analysis; Varenna 2007

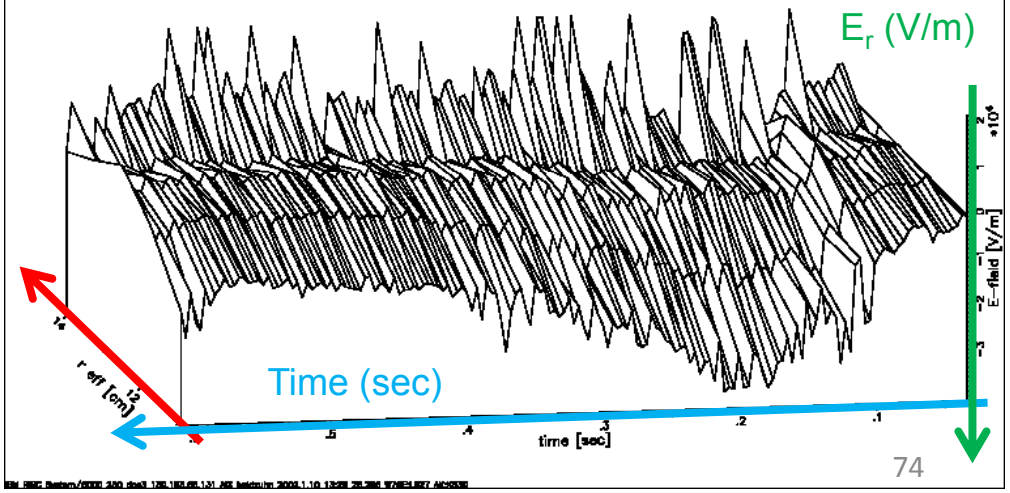
Line integrated measurements on B IV in the near-UV

Edge ion temperature profile

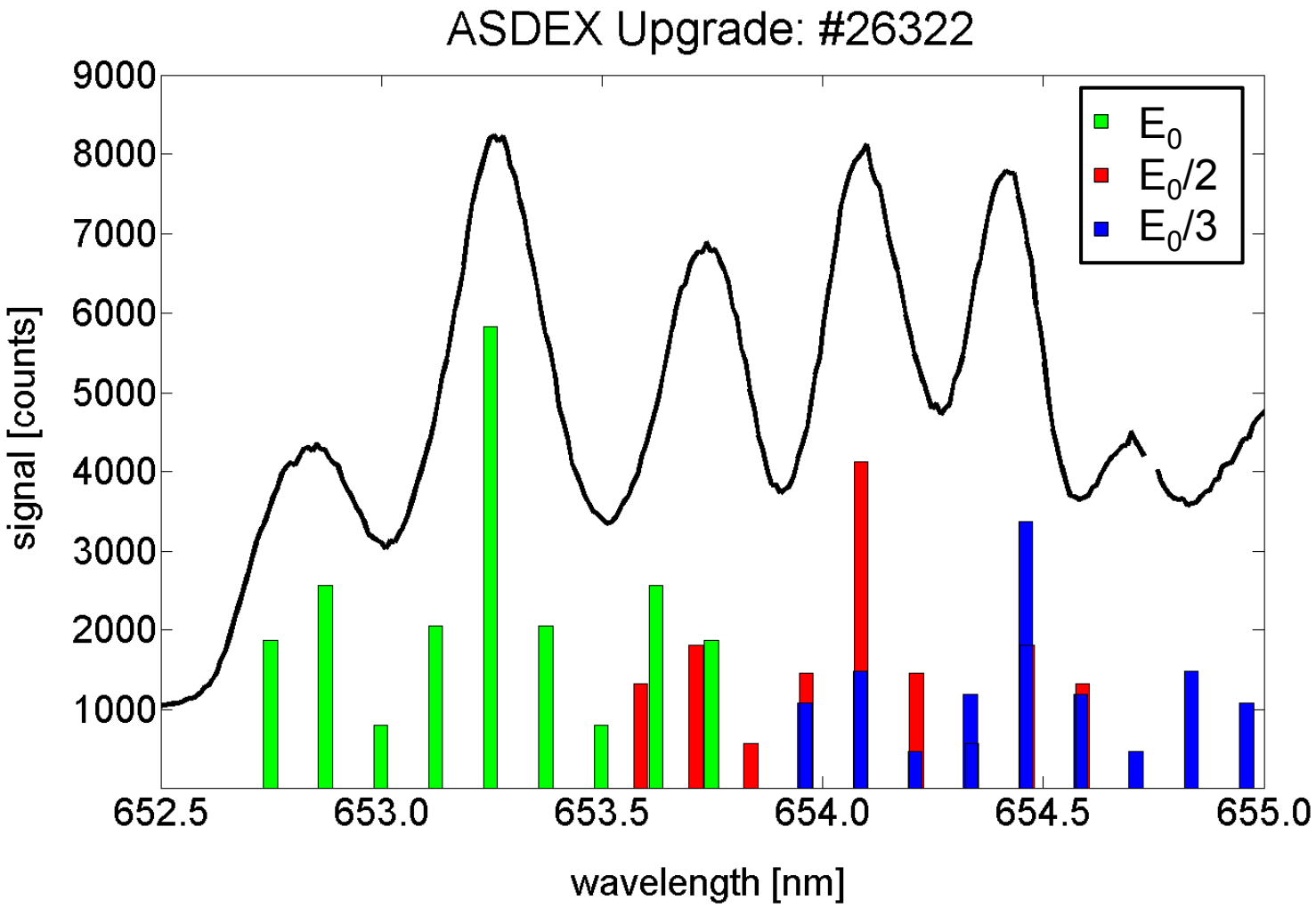


Examples of time traces for passively measured T_i, E_r

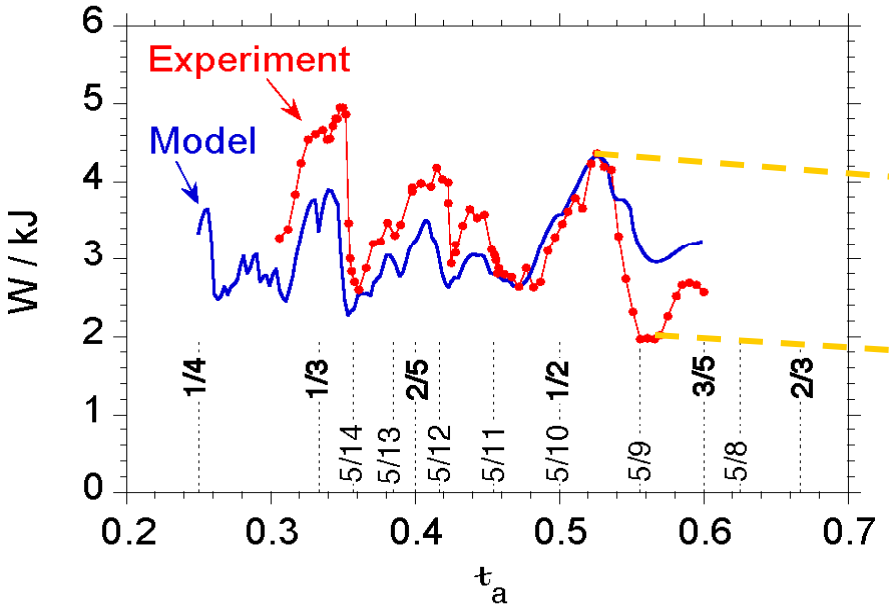
Edge radial electric field profile

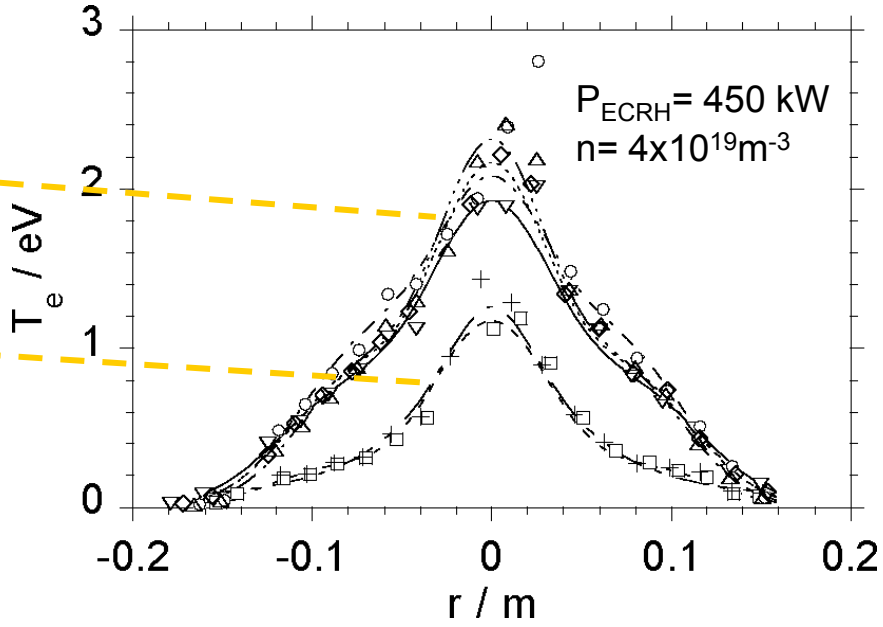


An example of a BES spectrum



The impact of the magnetic field (iota) on the plasma in W7-AS





The plasma confinement in a low-shear stellarator depends strongly on the edge Rotational transfrom iota (via the anomalous, turbulence driven) transport

➔ At rational iota-values it drops

➔ In close vicinity to low-order rationals it increases

$$\tau_E = W_{dia} / P_{heat}$$

$$\iota = \frac{2\pi}{q} = R \oint \frac{B_\theta}{B\phi} ds \approx \frac{R}{r} \frac{B_\theta}{B_\phi}$$

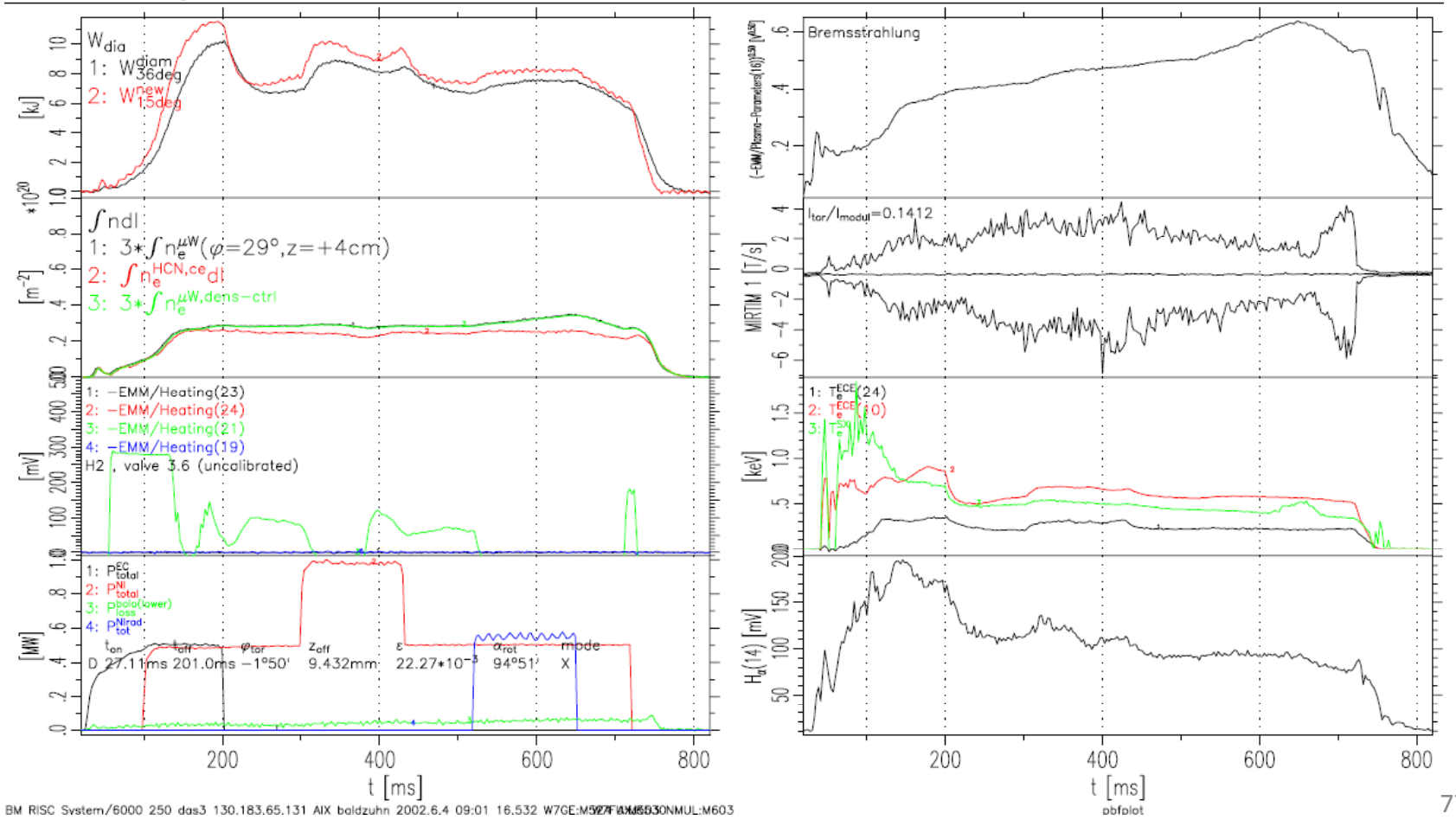
R. Brakel, Nucl. Fusion (2002)

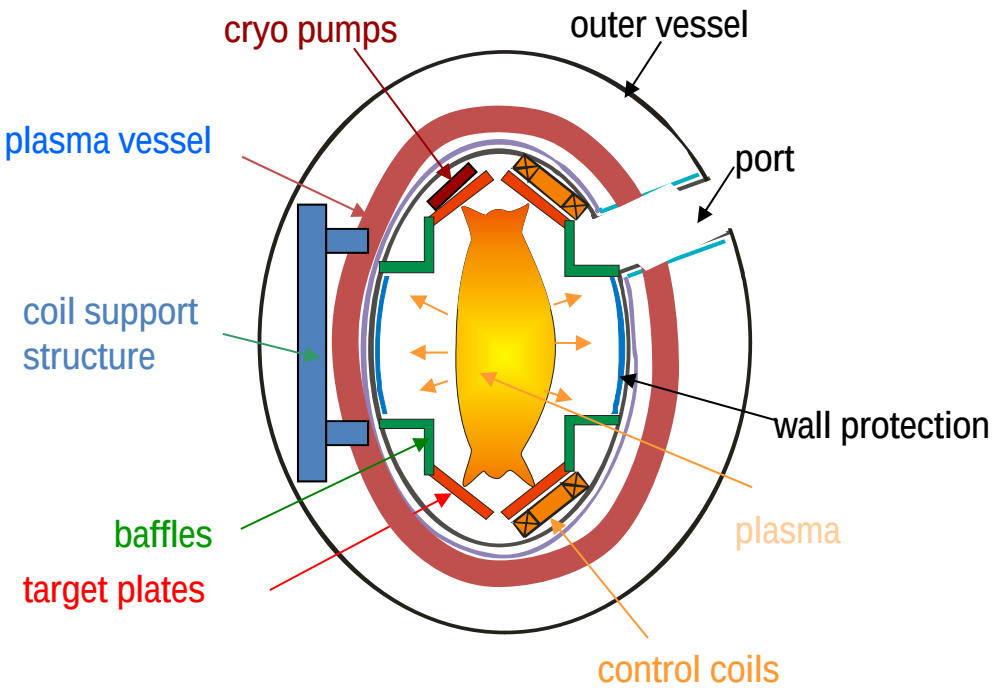
W7-AS Shot 55774 (2002.5.29 10:57) $B_o^{36deg,new}=-2.520T$

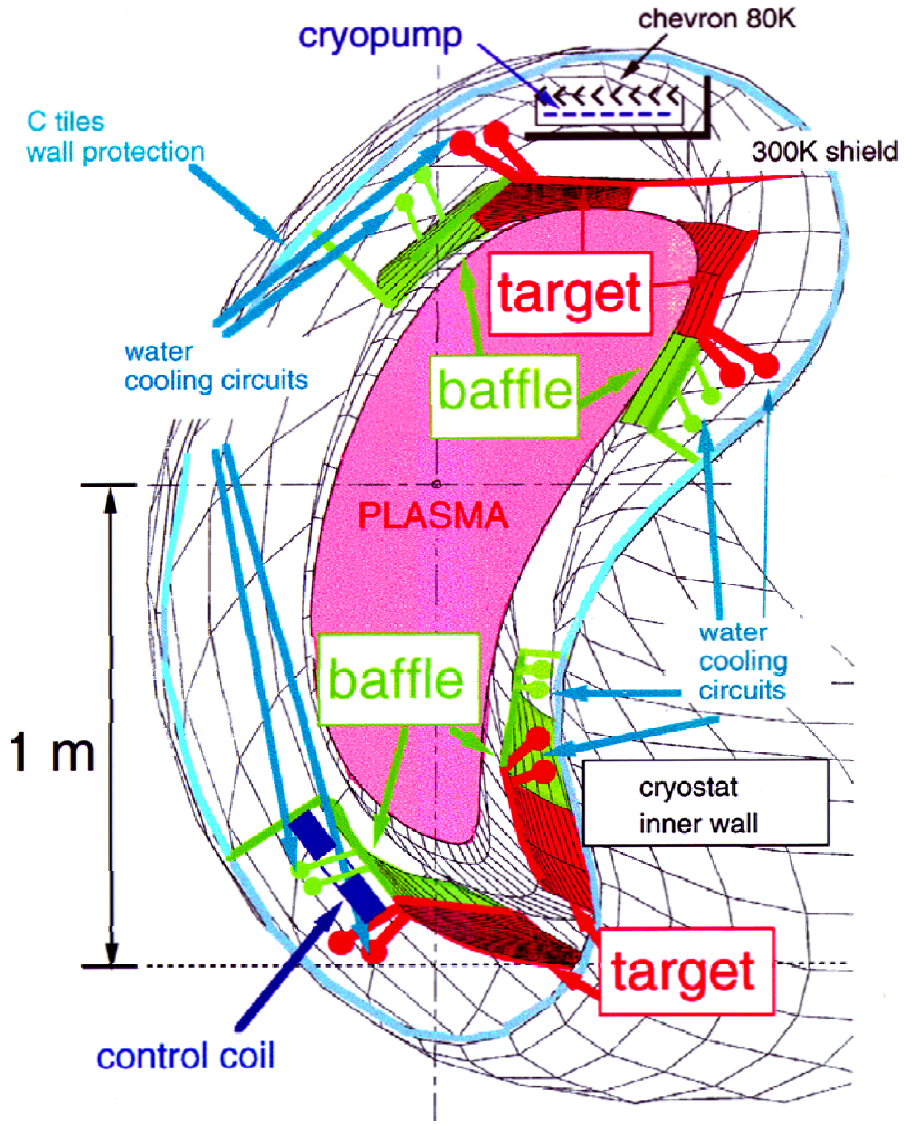
$a_P=15.70cm$ $B_z=-19.87mT$ $\iota_a=0.3416$ $\iota_a^{old}=0.3424$ $t_{TH}=599.9ms$

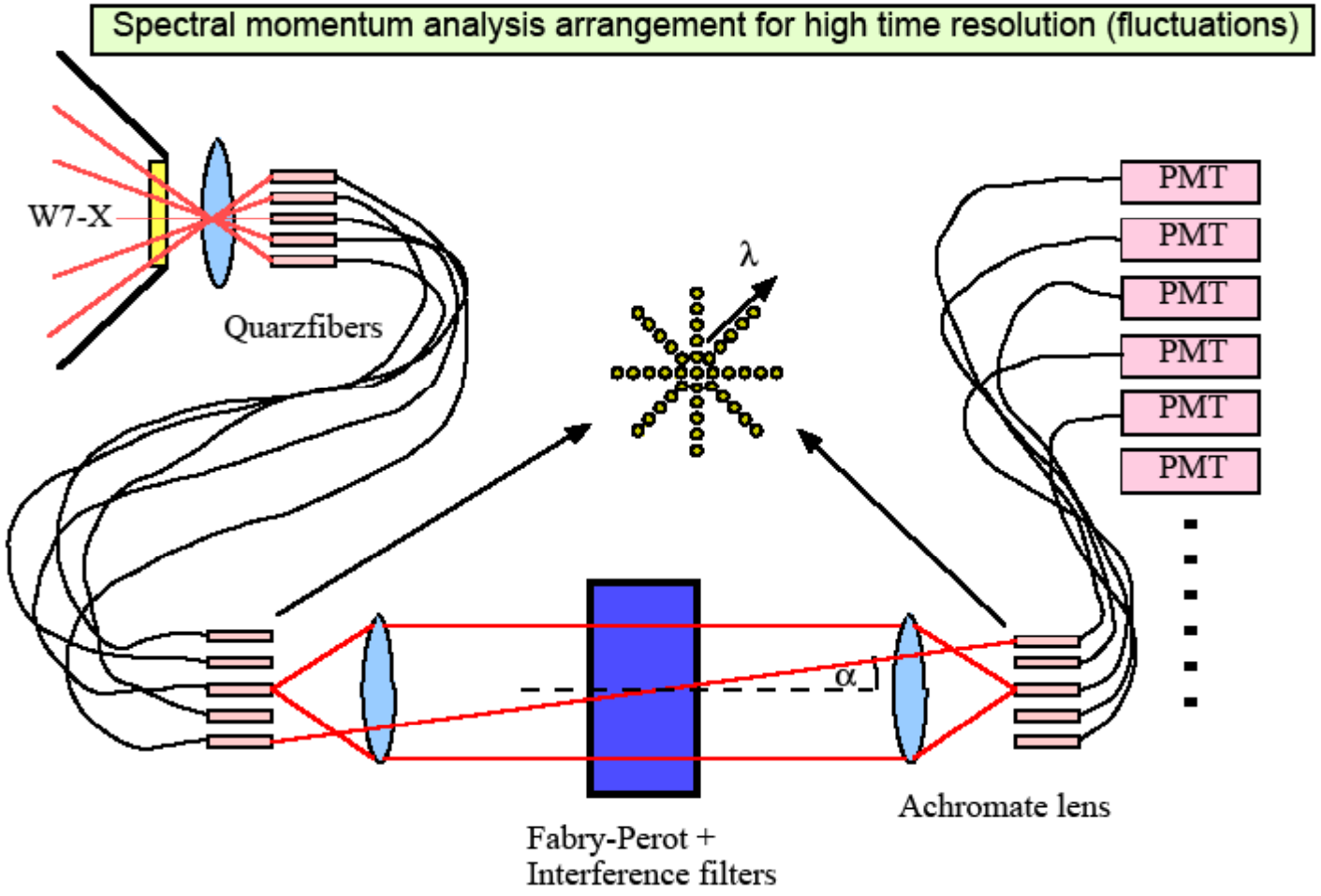
ECRH: 140 GHz, NBI $I_{cc1}/I_{modul}=0.0$

Radialinjektion mit Deuterium

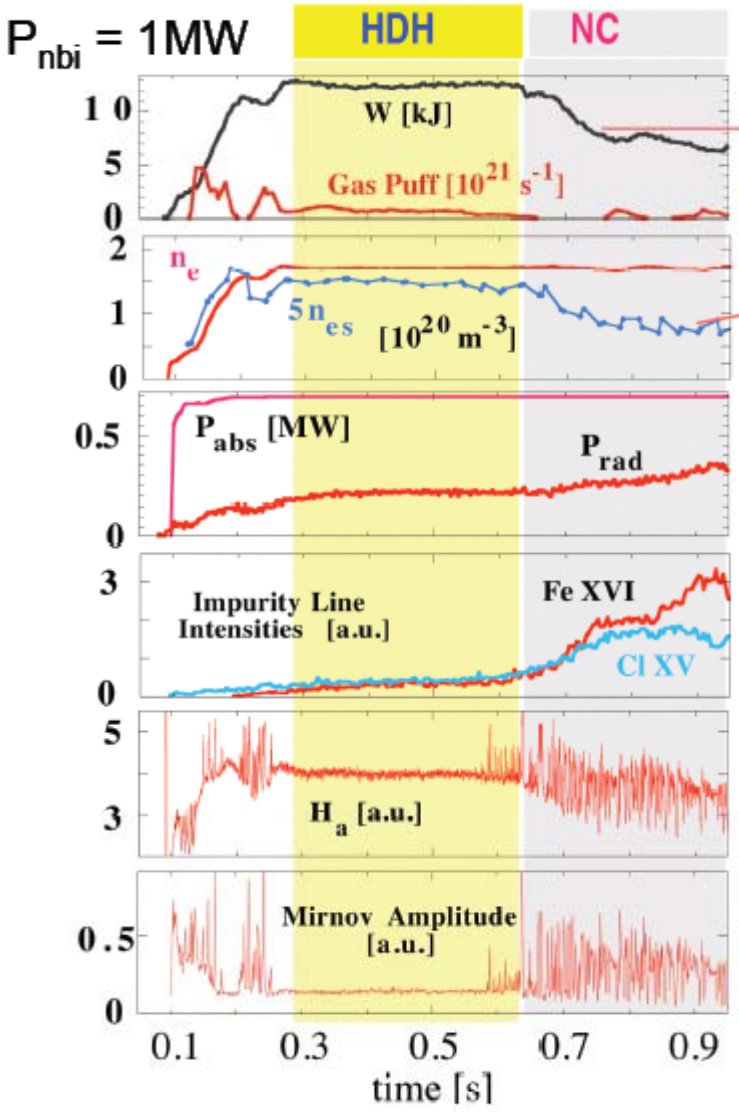



cryo pumps
outer vessel
plasma vessel
port
coil support
structure
wall protection
baffles
plasma
target plates
control coils


cryopump
chevron 80K
C tiles
wall protection
300K shield
target
water
cooling circuits
baffle
PLASMA
baffle
water
cooling
circuits
cryostat
inner wall
1 m
target
control coil


Spectral momentum analysis arrangement for high time resolution (fluctuations)
W7-X
Quarzfibers
λ
PMT
PMT
PMT
PMT
PMT
PMT
α
Achromate lens
Fabry-Perot +
Interference filters

A plasma discharge „fingerprint“



Results Stellarator W7-AS

Stored Energy is lower in NC

Separatrix density n_{es} is lower in NC
- for the same line-averaged density

P_{rad} increases in NC

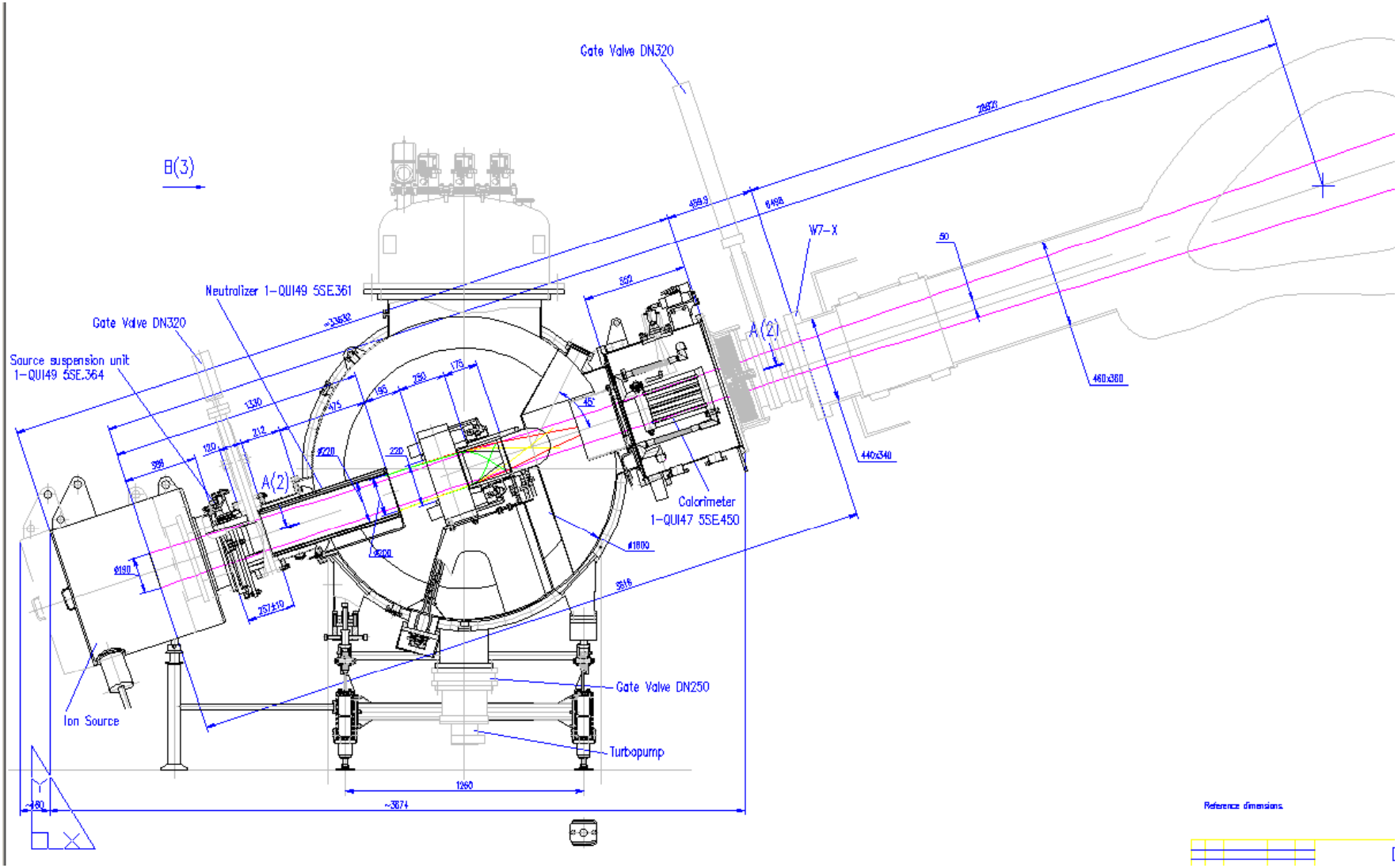
Impurity line intensity increases in NC

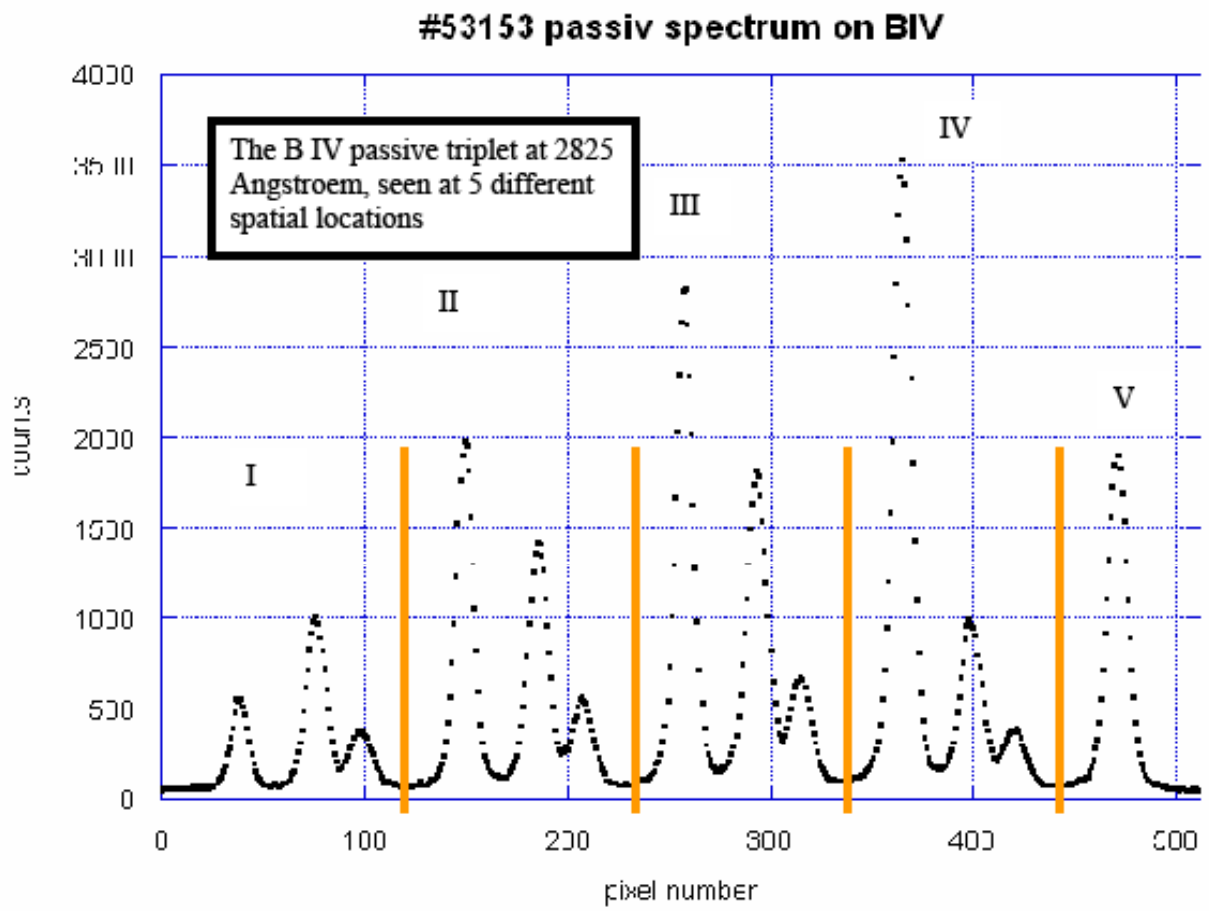
HDH shows no evident ELM activity

HDH shows reduced MHD activity

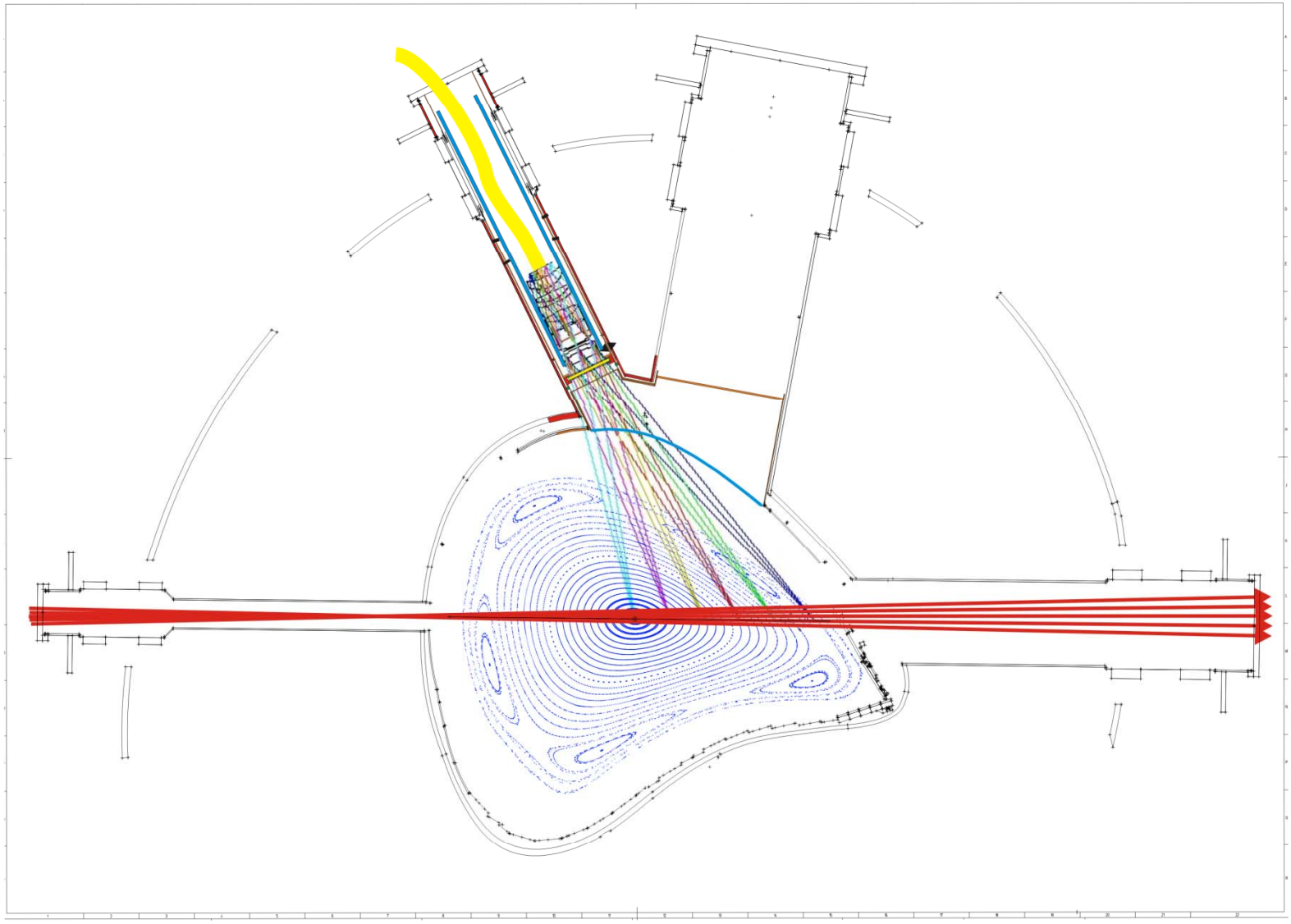
McCormick et al. 2004

Technical drawing of the diagnostic beam injector

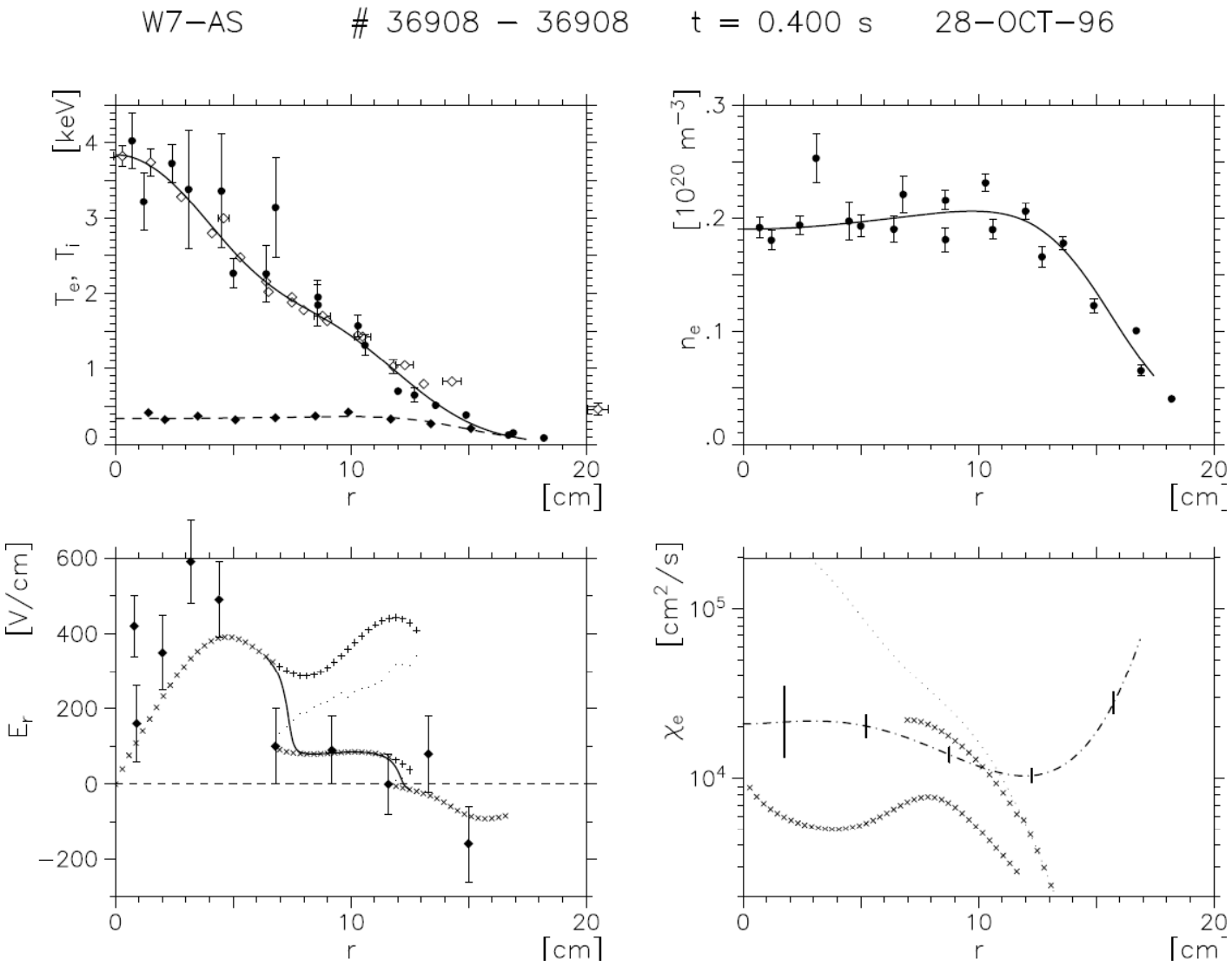



#53153 passiv spectrum on BIV
The B IV passive triplet at 2825 Angstroem, seen at 5 different spatial locations
I
II
III
IV
V
counts
pixel number
0
500
1000
2000
2500
4000
0
100
200
300
400

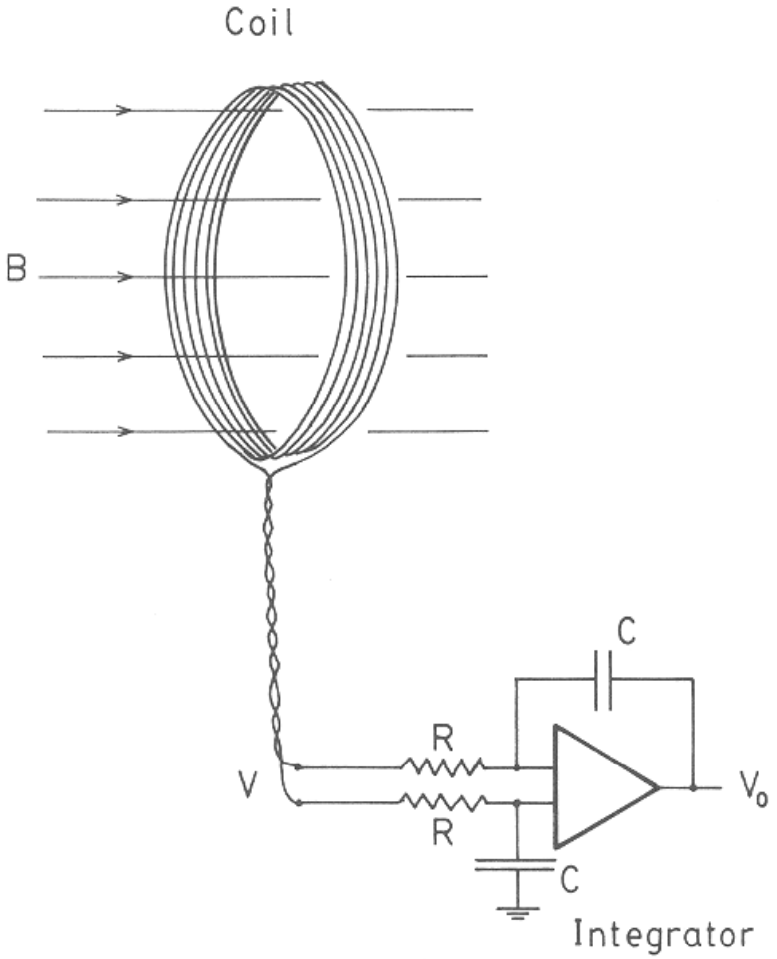
The W7-X Thomson scattering geometry



➔ Important plasma parameters can be simply plotted versus an (effective) minor radius



A technical problem: the drift of the integrator



$$U_{ind} = -N\frac{d}{dt}\left(\vec{B}\cdot\vec{A}\right)$$

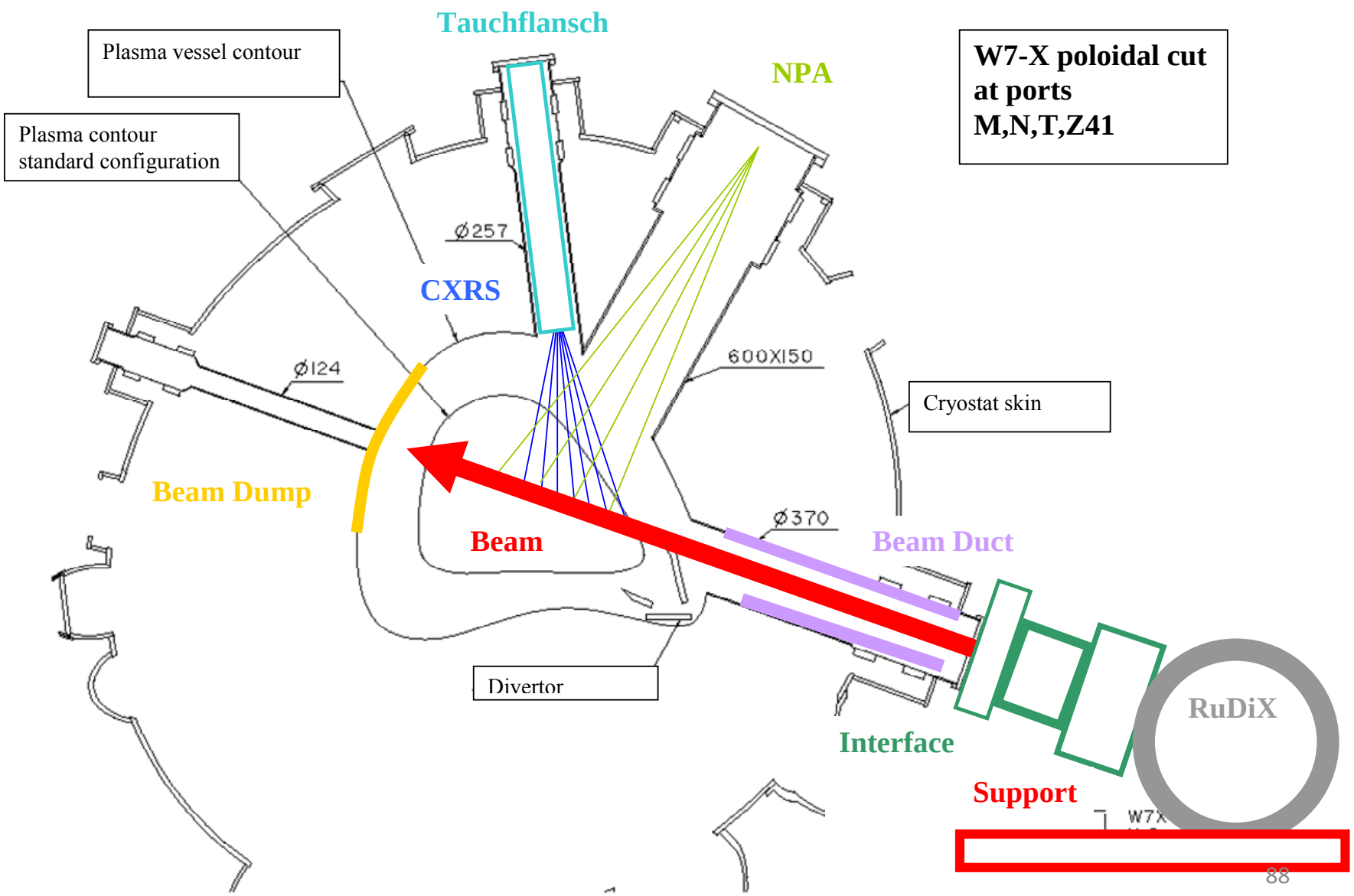
$$B_{meas} \propto V_{out} = -\frac{1}{RC}\int_{t0}^{t1} U_{ind}(t')dt'$$

Hutchinson: Principles of plasma diagnostics

CXRS active lines of interest in order of wavelength

Wavelength nm	transition	Ion species
252.4	7 → 6	N VII
297.5	9 → 8	O VIII
298.1	6 → 5	B V
343.4	7 → 6	C VI
388.8	8 → 7	N VII
436.6	14 → 13	Ar XVI
468.6	**4 → 3**	**He II**
494.5	7 → 6	B V
522.4	16 → 15	Ar XVIII
524.9	11 → 10	Ne X
529.1	8 → 7	C VI
566.9	9 → 8	N VII
606.9	10 → 9	O VIII
656.3	3 → 2	H α

The RuDI-X geometry



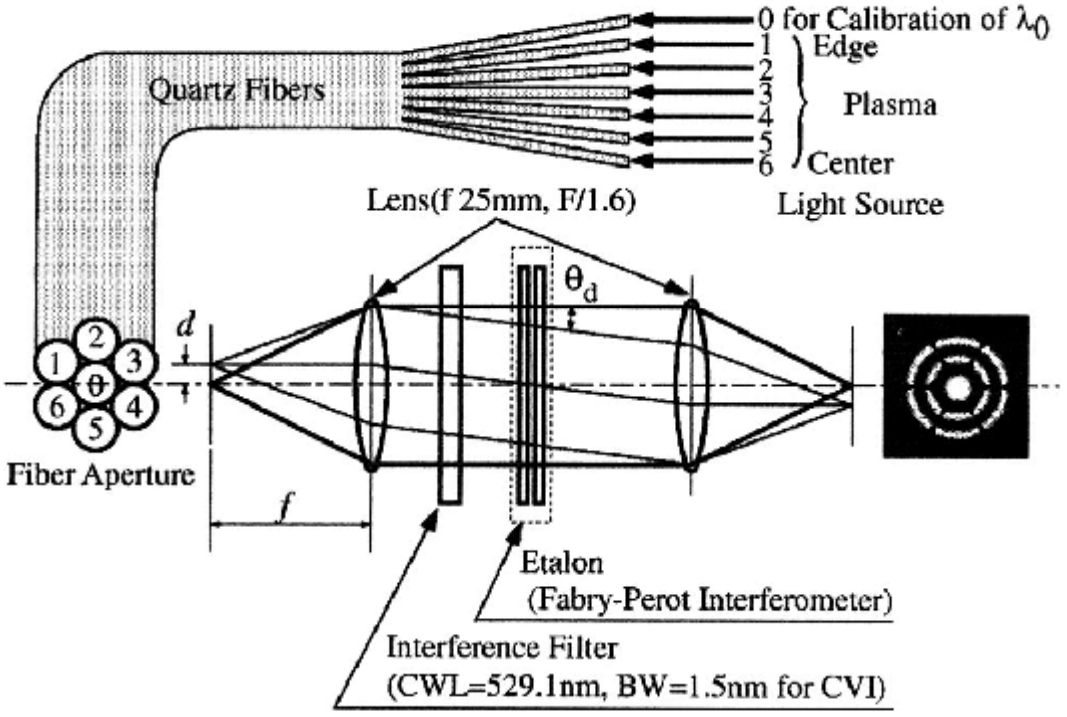
Project
Wendelstein 7-X

Project Wendelstein W7-X
Die CXRS Diagnostik

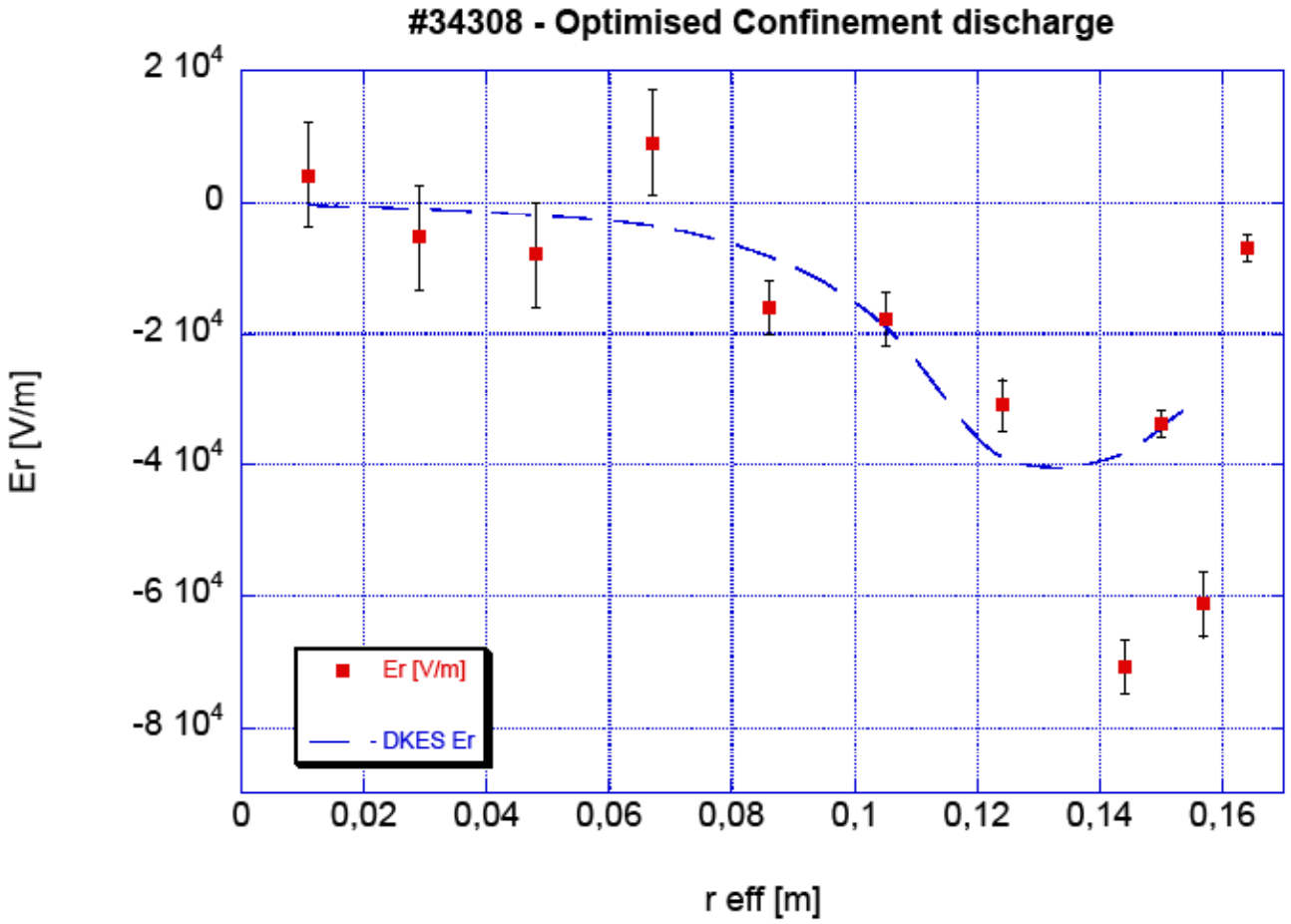
Max-Planck-Institut
fuer Plasmaphysik
EURATOM Assoc.

Arrangement of the W7-AS Fabry-Perot spectrometer

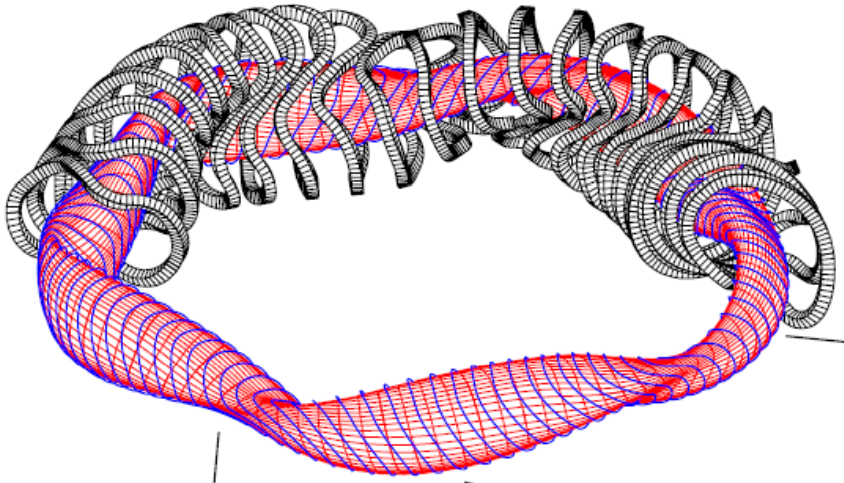
(see M. Yoshinuma NIFS, Japan: M. Yoshinuma, J. Baldzuhn, K. Ida, Rev. Sci. Instr. Vol. 75, (2004), p. 4136)

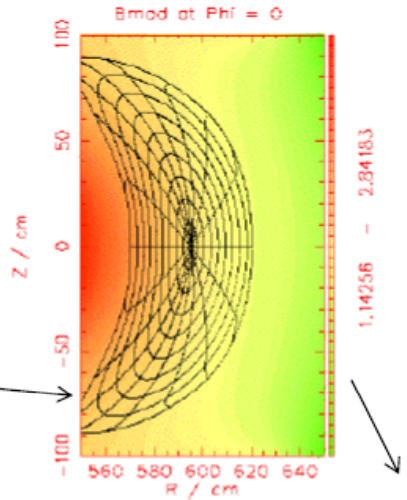


An example of an actively measured E_r – profile from CXRS



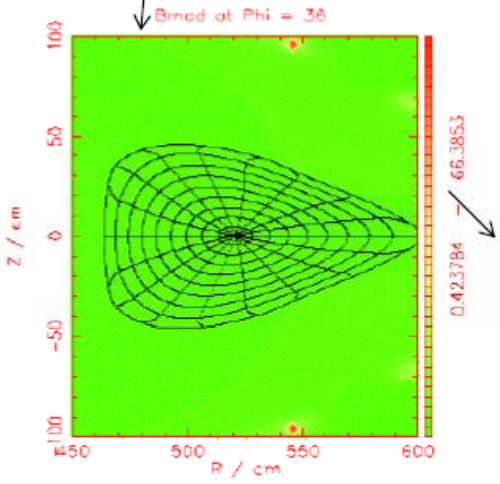
W7-X Stellarator Optimisation concept: drift optimisation + reduced parallel currents



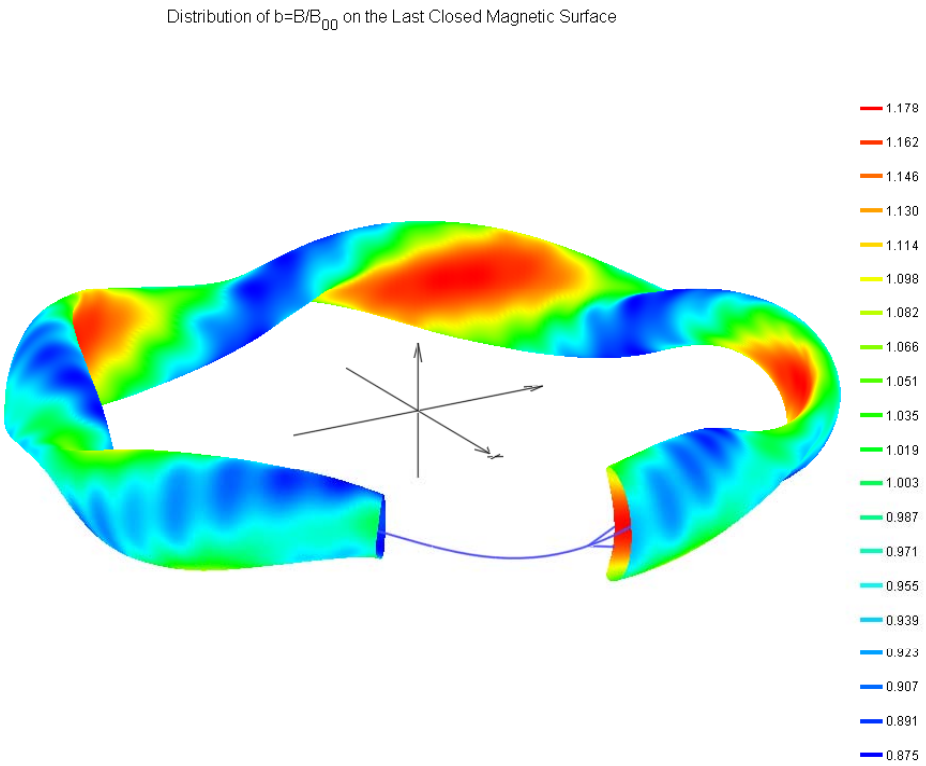


diamagnetic + PS
current paths:
reduced PS currents !

grad(B) high ⇒ high grad(B) drift. BUT:
B-field high: trapped particle population reduced
⇒ net reduced drift losses. AND:
High "tokamak" elongation ⇒ reduced mean ripple



grad(B) low ⇒ low grad(B) drift. AND:
B-field low: trapped particle population enhanced
⇒ drift losses play only a minor role.


Distribution of b=B/B00 on the Last Closed Magnetic Surface
1.178
1.162
1.146
1.130
1.114
1.098
1.082
1.066
1.051
1.035
1.019
1.003
0.987
0.971
0.955
0.939
0.923
0.907
0.891
0.875

The plasma emission spectrum

Radio Frequency *(RF, IC, ICRF, ICE)*

Micro Wave *(μw, ECE, mm-waves)*

Infra-Red *(IR, Far IR)*

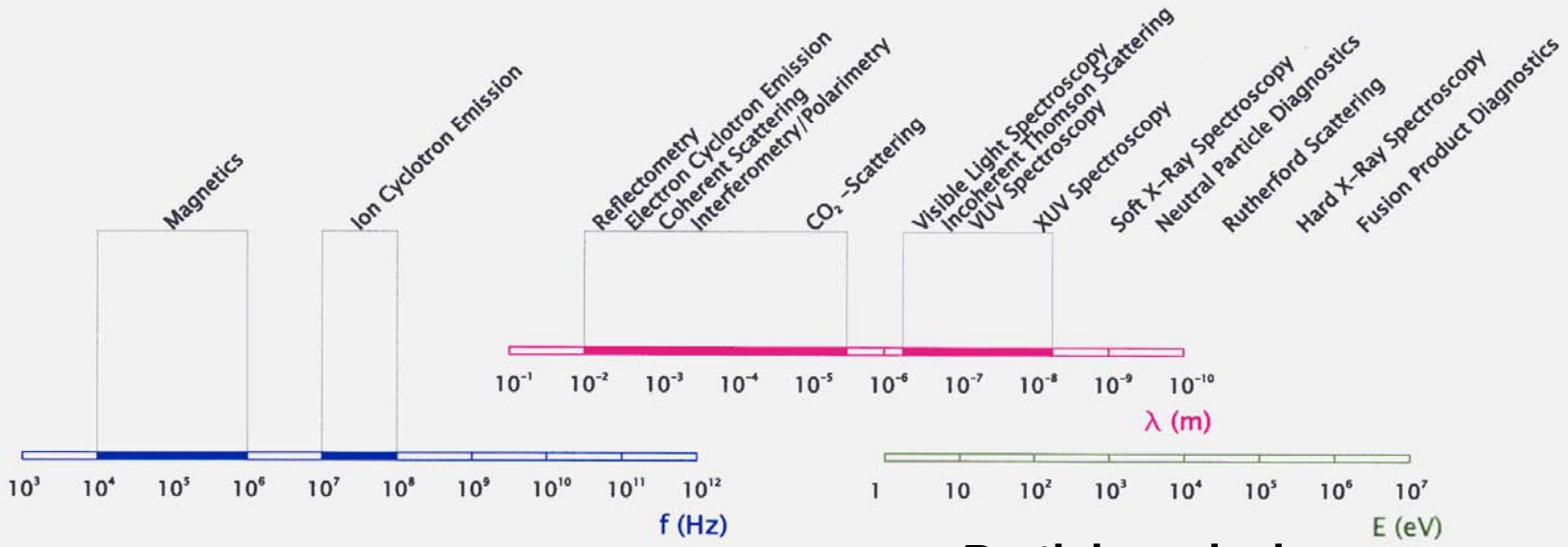
Visible Light

Vacuum Ultra Violet *(VUV, EUV, XUV)*

X-Rays *(Soft, Hard)*

γ

EM emission



Particle emission

Thermal Particles *(H, H_2, H^+,H_2^+,e^-,Z^+)*

Heated Particles *(H^+,e^-)*

Fusion Products *(α, n)*