

Concept of an Atomic Beam Probe diagnostic on COMPASS tokamak

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Introduction

In this paper the concept of a new method for the measurement of poloidal magnetic field and its fluctuations in the outer regions of COMPASS tokamak plasmas is described. The diagnostic will be an extension of the Lithium Beam Emission Spectroscopy (BES) system by collecting the ions stemming from beam ionization. Therefore we call it Atomic Beam Probe diagnostics (ABP). The BES system for COMPASS is already being manufactured by KFKI RMKI, and it is planned to be operated by Li and Na beams. The extension will require operating at higher energies.

The main aims of this diagnostics:

- Measurement of magnetic field fluctuations in order to assess the relevance of electromagnetic turbulence.
- Get information on the plasma current profile.
- Complement density fluctuation measurement by standard BES.

Basics of the diagnostics

The idea of the ABP system is to overcome the most serious difficulty of Heavy Ion Beam Probe (HIBP) systems, namely the difficulty in accessing the plasma by an ion beam. In the proposed scheme neutral atoms are injected, therefore they can easily be lead along a straight horizontal diagnostics port. After ionization ions will be collected in a vertical diagnostic port located at the same poloidal cross-section. Using alkali atoms the second ionization potential is much higher than the first one, therefore second ionization of the ion beam can in many cases be negligible. The typical current of an alkali diagnostic beam [1, 2] is about 3 orders of magnitude higher than the conveniently measurable ion currents.

In BES the neutral beam is produced by neutralization of an ion beam using a charge exchange gas cell. The efficiency of this process decreases sharply above a certain energy (50% for 100 keV Lithium), therefore the beam energy cannot be increased arbitrarily as in HIBP. This restricts the use of ABP to smaller machines and not too high magnetic fields. However, initial calculations show that COMPASS plasmas with 1.5 T toroidal field should be accessible.

The beam atoms ionized at different radii along the beam arrive at different positions in the exit port, where, at the first approximation, the ion current is proportional to the local plasma density at the point of ionization. The poloidal magnetic field moves the ion beam toroidally, therefore the two – dimensional measurement of the ion current in the exit port can theoretically reveal information on both the density and magnetic field profiles. Additionally, the density profile can also be determined from the standard BES measurement [1, 2].

Theoretical background

Starting from the Lagrangian description of charged particle motion in a given $\mathbf{B} = (B_r, B_\phi, B_z)$ magnetic field one gets for the toroidal component of the canonical momentum as [6]:

$$mr^2\dot{\phi} = q \int_0^t r(\dot{z}B_r - \dot{r}B_z)dt \equiv q\Pi(t),$$

here cylindrical coordinates are used and it is clear that the angular momentum (canonical momentum in Lagrangian formalism) can be changed by the time integrated toroidal torque $\Pi(t)$. Integrating along the ion path:

$$\phi_D = \frac{q}{m} \Pi(t_i) \int_{t_i}^{t_D} \frac{1}{r^2} dt + \frac{q}{m} \int_{t_i}^{t_D} \frac{\Pi(t)}{r^2} dt.$$

The linear manipulations in the expression for the toroidal displacement ϕ_D allow us to use it unchanged for small fluctuations about an equilibrium displacement caused by the equilibrium magnetic field. The time points along the beam path in the plasma at the ionization point and at the detector position are t_i and t_D , respectively. From the known beam energy the velocity of beam particles can be estimated and for the present calculation it is thought to be constant along the beam path: $s = v_b t$. This gives a new parameterization of the beam trajectory. In the equation above the first term is the ‘local’ (at the ionization point) integrated magnetic torque and the second one is the path integral of the integrated torque. This later one under some circumstances such as well localized low frequency modes can be neglected (see [6]). From the local term the perpendicular magnetic field B_{\perp} component (perpendicular to the velocity at the place of ionization) can be easily extracted if we have multichannel detection of particles ionized at adjacent locations. The difference between the beam displacements on the neighbouring detectors is:

$$\Delta\phi_D = \frac{\partial\phi_D}{\partial\hat{s}} \Delta\hat{s} = G(\hat{s}_i) \frac{\partial\hat{\Pi}_i}{\partial\hat{s}} \Delta\hat{s} = G \cdot \frac{M_{\phi,i}}{R_L B v_b} \cdot \Delta\hat{s},$$

where $M_{\phi,i} = B_{\perp} \cdot v_{\parallel} \cdot R_i$ is the magnetic torque at the ionization point and the normalized variables are: $\hat{s} = s/R_L$, $\hat{\Pi}_i = \Pi_i/B R_L^2$, here R_L is the Larmor radius of the beam and B is the characteristic strength of the magnetic field. Finally we can get:

$$B_{\perp} = \frac{1}{G} \frac{R_L}{R_i} \frac{R_L v_b}{\Delta s v_{\parallel}} B \Delta\phi_D \equiv \alpha \cdot \Delta\phi_D.$$

The proportionality factor α can be directly evaluated from the trajectory calculations. It is important to note that in our case when the ionization points are aligned almost radially B_{\perp} gives us essentially the poloidal component of the magnetic field.

Conceptual design of the diagnostics

Figure 1 shows the conceptual design of the ABP system. The basic of this diagnostics is the BES system. Positively charged thermal alkali (Li, Na or K) ions are emitted (~ 1 mA) continuously during the tokamak discharge from a resistively heated ion emitter and accelerated by an ion optic up to 100 keV. Ions are neutralized in a gas cell filled with Sodium vapour. The beam can be chopped with deflection plates thus allowing background measurement.

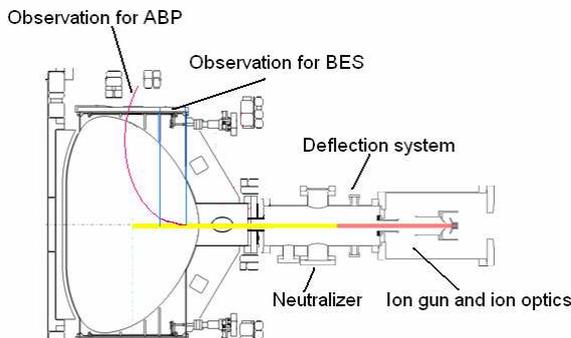


Figure 1. Conceptual design of the ABP system.

The neutral beam enters the plasma and subsequently it becomes ionized. The ionized particles are deflected by the magnetic field.

Calculation of trajectories in magnetic field

Motion of the charged beam particles was followed by numerical integration of equation of motion. The trajectory of a 54 keV Rb beam and a 100 keV Li beam ionized at $x=0.71$ m can be seen on Figure 2. The toroidal magnetic field is 1.2 T, the plasma current is 170 kA. Equilibrium magnetic field was reconstructed by EFIT code on the base of magnetic measurements on COMPASS – D.

Rb ions with 54 keV energy can reach a detector at the top of the tokamak, while Li ions with 100 keV get out from confined plasma region a bit above the midplane. From the current and from toroidal displacement of these ions it is possible to extract information on the electron density at the place of ionization and on the poloidal magnetic field. [3, 5, 6]

Effect of the second ionization

Although it looks like heavier alkalis would be more appropriate for this diagnostics because of the bigger Larmor radius, by calculating the effect of the secondary ionization one gets the result that for alkali ions other than Li the second ionization effect becomes unacceptably high (see last column of Table 1.), which means that heavier alkalis cannot be used for this diagnostics. The same effect using Li

	First ionization potential	Second ionization potential	R ₂ /R ₁
Li	5,42 eV	76,02 eV	~ 5 %
Na	5,16 eV	47,52 eV	~ 18 %
K	4,36 eV	31,79 eV	~ 41 %
Rb	4,20 eV	27,43 eV	~ 100 %
Cs	3,91 eV	23,27 eV	~ 100 %

Table 1. First and second ionization energies.

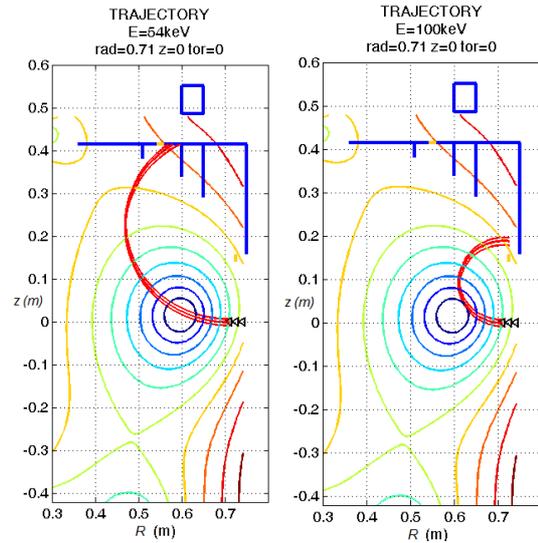


Figure 2. Trajectories of Rb and Li ions at the COMPASS geometry (toroidal magnetic field: 1.2 T, plasma current: 170 kA.

ions is only about 5 %. Table 1 shows the first and second ionization energies for five different alkalis. Last column of Table 1 shows estimated ratio of current after first ionization to current from second ionization. Rate coefficients were estimated on the base of next formula ([4]):

$$R = 10^{-11} \cdot n_e \cdot \frac{(kT_e/\chi)^{1/2}}{(\chi)^{3/2}(6.0 + kT_e/\chi)} \cdot \exp\left(-\frac{\chi}{kT_e}\right).$$

Plasma edge current measurement

The effect of plasma current perturbations on the poloidal component of the magnetic field of a tokamak can be modelled as the sum of additional magnetic fields (B_{pert}) generated by “elementary” toroidal currents (I_{pert}) and calculated on the base of Biot – Savart law:

$$B_{pert} = \mu_0 \frac{I_{pert}}{2\pi r'}.$$

I_{pert} – current perturbation, r' – distance from the place of current perturbation to the given point of equilibrium magnetic field. We assume that plasma current change is radially localized and poloidally equally distributed along the separatrix. [3, 5]

Perturbative magnetic field modifies the toroidal shift of the ion trajectories. This provides the possibility of edge current perturbation measurement using the ABP diagnostics. [3, 5]

On Figure 3 the set of current filaments can be seen at the LCFS. The perturbed magnetic field will shifts the ion trajectories toroidally. This modification is approximately proportional to the

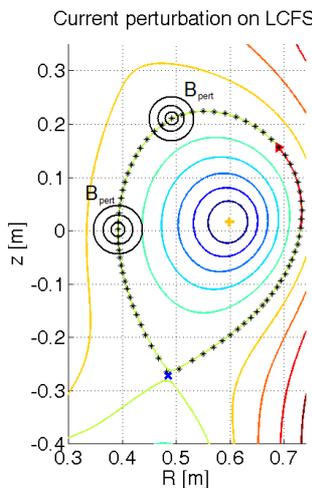


Figure 3. Current perturbation at the LCFS.

total current perturbation and from the trajectory calculations one can conclude that 1 kA total toroidal current perturbation, distributed - as said - evenly on the separatrix, results about 0.5 mm toroidal displacement.

Detector concept

For the detection of the ion beam and its displacement a segmented multichannel system seems to be applicable. An entrance slit could be located in front of the detector. It will be biased to reduce background noise (electrons or ions) and to prevent secondary electrons from escaping. The beam trajectories and the slit locations will be arranged in a way to avoid direct X-ray and UV radiation by the plasma.

The background noise can be measured by chopping (removing) the beam. It is possible up to 400 kHz using a fast high voltage switch, but the proper background noise level has to be measured by a test detector.

In standard BES measurements 1–2 cm beam diameter is used, but for ABP only a small central fraction of the beam will be cut out by a diaphragm before the beam enters the plasma. Therefore the beam diameter on the detector would be determined by the diameter of the diaphragm, the beam divergence and the place of the ionization. The divergence is maximum 1–2 mrad. The whole length of the ion beam trajectory in COMPASS would be about 1 m, which results in 1–2 mm widening of the beam. A few mm beam diameter seems to be easily achievable on the detector, thus the size of one channel toroidally can be about 0.5 mm. Accordingly to the relative movement, resolution is expected to be in the few 0.1 mm range corresponding to a 1 kA current filament, which is considerably less than 1% of the total plasma current. The beam will cover more than one toroidal segment at the same time and small beam movements can be detected from the ratio of currents detected on neighbouring segments. [3, 6]

In radial direction the number of segments determines the radial resolution of the measurement therefore 5–10 channels with about 5 mm size is a reasonable number.

Using a few mm diameter beam diaphragm the ion equivalent neutral beam current will be around 1mA. If this is distributed on 5 radial detector channels and at each radial location ~10 collectors will see the beam at the same time, the ion current per channel will be about tens of μA . This can easily be amplified at 1 MHz bandwidth (for fluctuation measurement), although noise sources might impose some limitation.

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