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# Feasibility of a motional Stark effect system on the TCV tokamak

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This paper presents a feasibility study for a motional Stark effect (MSE) [F. M. Levinton *et al.*, Phys. Rev. Lett. **63**, 2060 (1989)] diagnostic on the TCV tokamak. A numerical simulation code has been used to identify the optimal port arrangement and geometrical layout. It predicts the expected measurement accuracy for a range of typical plasma scenarios. With the existing neutral beam injector (NBI) and a detection system based on current day technology, it should be possible to determine the safety factor with an accuracy of the order of 5%. A vertically injected beam through the plasma center would allow one to measure plasmas which are centered above the midplane, a common occurrence in connection with electron cyclotron resonance heating and electron cyclotron current drive experiments. In this case a new and ideally more powerful NBI would be required.
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## I. INTRODUCTION

The scientific program of the TCV tokamak[1] could greatly benefit from a *q*-profile measurement based on the motional Stark effect (MSE). There are basically two main features which make TCV unique in its category: the coil system and vacuum vessel which allow to produce plasma cross sections with very flexible shapes and the powerful electron cyclotron resonance heating (ECRH) and electron cyclotron current drive (ECCD) system. The former renders profile reconstruction more challenging than usual and the constraints imposed by MSE data could greatly improve the reliability of the procedure. Concerning the latter the interpretation of barrier formation in ECRH heated plasmas would certainly benefit.

Budgetary limitations and the fact that a neutral beam injector (NBI)[2] system (albeit of limited power) is already available on TCV were the main reasons for the decision to perform a detailed feasibility study for a MSE diagnostic on TCV. The numerical code PERF developed at JET[3] allowed us to investigate the effect of different geometries and plasma and equipment parameters on the expected precision of such a measurement.

The existing neutral particle injector on TCV is mounted horizontally and emits particles in the midplane of the machine, in roughly radial direction, resulting in a vertical Lorentz field. For maximum detection sensitivity the lines of sight (LOS) should therefore be in a horizontal plane. The Doppler shift which separates the observed spectral lines from the unshifted $H_\alpha$ line emitted mainly from charge exchange and plasma edge is largest for radial LOSs. However, this results in a complete loss of spatial resolution, which would be optimum with a tangential LOS arrangement. Hence a compromise has to be found for these two conflicting requirements.

In toroidal direction the ports in the midplane of TCV are separated by an angle of 22.5° and with the injector left in its current position the detection system could be placed in a neighboring port or either two or three ports away, hence forming angles of 22.5°, 45°, and 67.5°, respectively with the injector port. With some rearrangement of other diagnostics, ports above or below the midplane (at heights ±45 cm) could also be used for the detection system, but simulations showed that this would not produce any performance improvement.

Figure 1 shows the port arrangement in the midplane. The injector can be tilted horizontally by about 11° in either direction. For larger angles it is no longer possible to inject the whole beam diameter through the port arrangement. Twenty observation points along the beam line determine the LOS fan.

## II. SIMULATIONS

The code used simulates the spectrum and the intensities of the harmonics of the polarimeter output from which the expected measurement error in the polarization angle is obtained. In the code the following assumptions are made:

(1) the $H_\alpha$ or $D_\alpha$ emission only is considered;
(2) a simple elliptical equilibrium is assumed;
(3) beam attenuation by protons and carbon is included, assuming a fixed $Z_{\rm eff}$;

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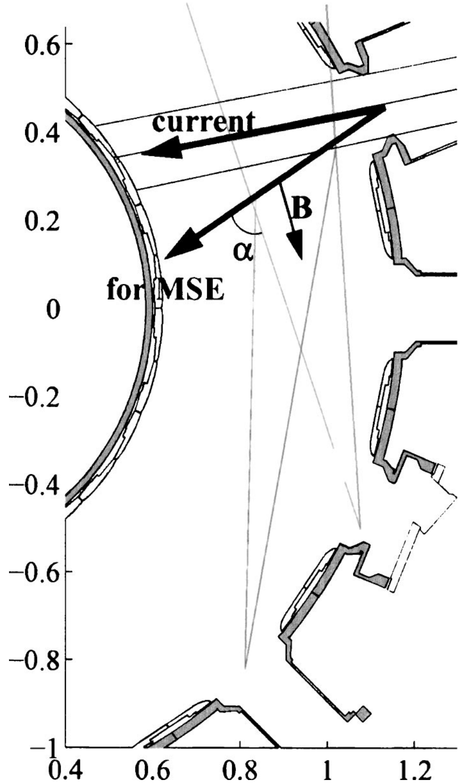


FIG. 1. Port arrangement in the midplane with NPI and possible diagnostic ports. The current injector angle is +11°.

(4) the calculations are only done for the linear Stark regime, which is well satisfied; and
(5) the Zeeman splitting is ignored.

A description of the code algorithm is given in Ref. 4.

The measurement precision is inversely proportional to the square root of the diagnostic sensitivity, the beam power and the integration time. The diagnostic sensitivity was treated as a fixed input parameter, based on the TCV geometry and assuming typical values (size, transmission) for the optical elements (lenses, fibers etc.). The relevant plasma parameters were varied around the typical values of: $n_e=2\times10^{19}$ m$^{-3}$, $B_T=1.43$ T, $\kappa=1.5$, and $\tau=10$ ms. Apart from normal shear cases, some more detailed simulations were carried out for reversed shear profiles with $q=2$ in the center, $q=1$ at $\rho=0.25$, and $q=8$ at the edge.

The injector voltage (52 kV) and power (65 kW) were held constant in all simulations, based on the assumption that the existing NBI[2] would be used.

## III. SIGNAL TO NOISE RATIO CONSIDERATIONS

Based on the injector power reduced by plasma absorption, the Lorentz field at the point of observation, the Stark emission for the assumed plasma parameters and all the geometrical factors involved, the spectrally resolved intensity incident on the detection system is calculated by the code. The most important source of undesirable background radiation is line radiation due to impurities or unshifted $H_\alpha$. Fortunately these are features of narrow spectral width which can be avoided by a judicious choice of the Stark line used for the measurement and the measurement geometry. With a measured emission spectrum in the vicinity of the $H_\alpha$ line it was shown that no line radiation rising above the noise level is observed above 659 nm and below 654 nm. Based on this measurement the signal to noise ratio at the input to the detection system is of the order of 1%.

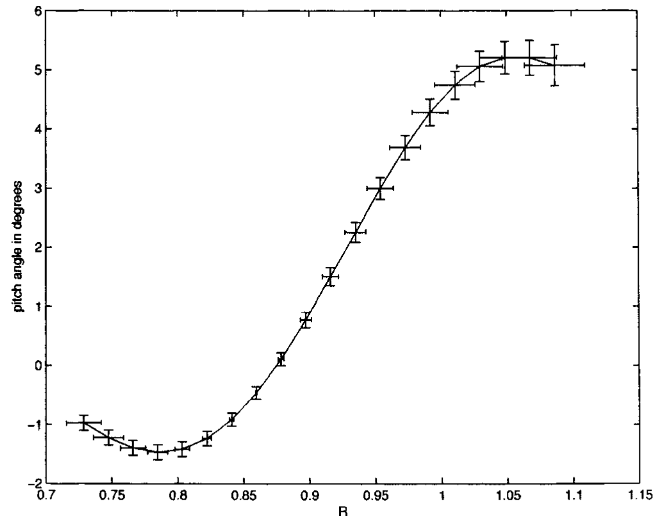


FIG. 2. Simulated pitch angle measurement for a normal shear profile. The angle between beam and detection port is 45° and the injector angle −11.25°. Plasma center at 0.875 m.

A first optimization step involves the geometry. Larger angles between beam and observation ports offer higher Doppler shifts and projection factors at the expense of spatial resolution. Note that "spatial resolution" does not describe the aiming accuracy of the beam and LOSs, both of which can be made quite precise with a careful alignment procedure. It is the uncertainty concerning the distance along the LOS over which light is collected from because of the finite width of the particle beam, leading to a smearing out of the measured pitch angle.

A further optimization step concerns the placement of the spectral channel. It must be outside the region where line radiation is observed. Furthermore it should be placed on top of an intense Stark line, but one which is sufficiently separated from other lines, in particular those with different polarization. It is found that the purity of the polarization is more important than the spectral intensity within the channel. Hence the channel is normally placed on the Stark lines with the largest shift, because these do usually not or only weakly overlap with other lines. The code produces emission spectra for each LOS which are used as guidelines for the placement of the channel and the selection of the channel width.

## IV. NORMAL AND REVERSED SHEAR SCENARIOS

For quadratic density and $q$ profiles with central values of $2\times10^{19}$ m$^{-3}$ and 0.9, respectively, and edge values of $10^{18}$ m$^{-3}$ and 2.7, respectively, the "measured" polarization angle $\gamma_m$ with error bars and the space resolution are shown in Fig. 2 ($B_o=1.43$ T, $\tau=0.01$ s, $\kappa=1.5$). The Stark lines are on the low wavelength side and the filters have been placed on the Stark line farthest from the $H_\alpha$ line. The error bars shown suggest that the accuracy for this (normal shear) case is reasonable for all LOS. From this procedure it follows that

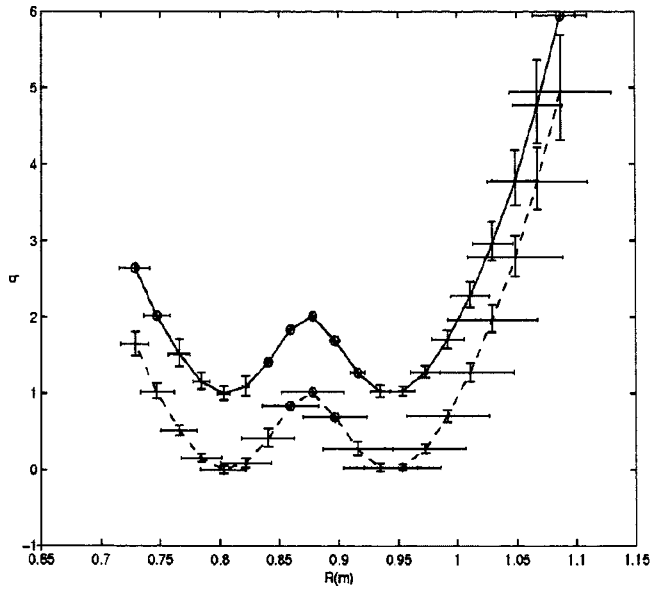


FIG. 3. Reversed shear case for port separation angles of 45° (solid curve) and 67.5° (dashed curve, lowered by $q=1$). $\Delta q$ exceeds ±15% if no error bar shown.

$q$ at the outside up to almost the center can be determined with typically ±6% precision with a space resolution around ±2 cm, whereas the accuracy of $q$ is around ±10% on the inside. The error in $q$ for the three centermost points exceeds 15%. In principle this shows that a pitch angle measurement is possible over the whole plasma cross section. However, with the particular choice of the spectral channels interference from the broadened unshifted $H_\alpha$ background cannot be excluded for the five innermost points.

With normal and reversed shear it is found that only two geometries look promising: beam and observation port in the same horizontal plane and separated either by 45° or 67.5°. The larger port separation angle (67.5°) gives better accuracy in $q$, but less precise space resolution, whereas for the angle of 45° the opposite is true. We compare these two geometries in Fig. 3 for a reversed shear case.

The conditions on TCV are such that during high power ECR/ECCD plasmas with centers of up to 21 cm above the median plane are preferred, with typical values of 10 and 21 cm. No ports for the beam injector exist at these levels: the next horizontal plane with ports is 45 cm above the median plane, which is not suitable. Without access to the plasma center, distinction between normal and reversed shear becomes difficult. With the plasma center at 10 cm this is still possible for high elongation ($\kappa=2.4$), but not at 21 cm height.

## V. VERTICAL INJECTOR

With a vertical beam line it would be possible to sample the plasma independently of its height above the median plane, provided the detection system can be placed appropriately. A preliminary study has shown that an injector could be installed below the machine. It would have to be an additional injector, contrary to all cases studied so far where it was assumed that the existing one[5] would be used.

An almost ideal arrangement is found to be a separation of beam and detector by a toroidal angle of 45°. This is not only a good compromise as far as the spatial accuracy is concerned, but since the LOS fan is almost tangential to the toroidal field, the precision of the pitch angle measurement is also good. However, the diagnostic port has to be either above or below the midplane. In the midplane the spatial resolution is better, but the precision of $\gamma_m$ is much worse.

For a LOS fan in a vertical plane there is a limited spatial accuracy in both $R$ and $z$ direction. For $R$ the resolution is better than ±0.5 cm in all cases, but in the vertical direction $z$ it is only ±4 cm. The accuracy of $q$ is quite good over the whole range. Geometries can be found where $\Delta z$ is better, but then the $q$ errors are larger. Again, as in the case of a horizontal beam, good space resolution and $q$ accuracy are mutually exclusive and a good compromise has to be found in each case. Space resolution is proportional to the beam size and could thus be improved with a smaller beam diameter.

## VI. DISCUSSION

The MSE simulation code "PERF" has been an invaluable tool to investigate certain aspects of the feasibility of an MSE diagnostics on TCV. In particular, it allowed us to determine which geometrical arrangements are most promising. This seems to be an arrangement with beam port and diagnostic port in the same horizontal plane and displaced by two or three ports, viz. angles of 45° and 67.5°, respectively. In the first case the spatial resolution is better and in the second case the $q$ measurement accuracy looks more promising.

Geometries with vertical beam injection look promising. This would require a new injector with at least comparable—but ideally better—power than the present one. Because of the larger distance from the plasma the beam divergence should be equal to or better than the existing injector and the beam diameter smaller to improve spatial resolution.

## ACKNOWLEDGMENT

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