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JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

* *See Annex*

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Plasma physics

Turbulence

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Dominique BOUCHER, Paul-Henri REBUT. Michael WATKINS

JET - Joint Undertaking, Abingdon, Oxon., OX14 3EA, U.K.

Abstract:

The study of steady electron density profiles in the absence of external sources provides a convenient way of assessing the particle transport properties of the tokamak plasmas. Indeed, such a study in JET suggests a link between the ratio V/D (particle convective speed over particle diffusivity) and the safety factor (q) profile which represent the pitch of the magnetic field lines around magnetic surfaces. This result is in agreement with a recent theoretical work [1]. The evidence for this relation is given, together with a model of particle transport, including ions, which is compared with experimental results.

I)Definitions and method used:

The well known conservation equation for particles of species α is $\frac{\partial}{\partial t}n_\alpha+\nabla\Gamma_\alpha=s_\alpha$ and, in the tokamak geometry, the radial particle flux across a magnetic surface of area A may be written in the form: $\Gamma = -D \nabla n + nVp$ with D particle diffusivity and Vp particle convective speed where s_α is the particle source density. It is easy to obtain an expression for the ratio V/D:

$$\frac{V_\alpha}{D_\alpha} = \frac{\nabla n_\alpha}{n_\alpha} + \frac{\Gamma_\alpha}{n_\alpha D_\alpha} - \frac{1}{n_\alpha D_\alpha A}\int \frac{\partial n}{\partial t}\,dV \text{ with } \Gamma_\alpha = \frac{1}{A}\int s_\alpha dV$$

By carefully selecting steady state conditions in the absence of external particle sources, we can neglect the last two terms on the right hand side of equation (1) and relate directly the ratio V/D to the density profile expressed by the ratio $\nabla n/n$.

Since in a large tokamak such as JET recycling neutrals penetrate only a few percent of the minor radius, particle sources are indeed negligible over most of the plasma volume. As for the steady state condition, we select periods during the pulse where the volume averaged density is held constant and we superimpose the available measured density profiles in order to estimate the uncertainties in the measurements.
In JET, three separate diagnostics are used to measure the electron density profiles: LIDAR Thomson scattering, seven chords interferometer and reflectometer for edge density profiles.

II) Results of the investigation of density profiles:

We will now compare various reference steady profiles from pulses which have different global parameters such as volume averaged density, current, magnetic field and additional heating power.
First, we notice that we can divide the density profiles into three regions: an outermost one dominated by sources due to the penetration of the recycling neutrals; an intermediate region characterized by a slope $\nabla n/n$ indicative of the ratio V/D; and a central region affected by an M.H.D. instability which periodically flattens density as well as temperature profiles on a very short time scale (typically 100 μs in JET) and whose period varies between few tens of millisecond to several seconds. We have observed that in this central region the density shows little evolution between two successive redistributions indicative a small V/D ratio.

Secondly, the slope of the intermediate region once we've normalized the profiles to their central density value, appears to be independent of averaged density or temperature profiles when total current and magnetic field are kept constant.

Fig. 1 illustrates this for three different profiles corresponding to three different densities at 5MA and 3 Tesla. Note also that the flattening of the central region is clearly visible. A similar resilience in normalized density profiles is also shown in Fig. 2. This time temperature profiles are varied by using different levels of additional heating power.

III)A model for particle transport:

The above observations suggest a dependence of the ratio V/D on plasma current and magnetic field. By varying these parameters independently, it would appear that a dependence on q only is sufficient. Furthermore, the clear difference in the ratio V/D between the central and intermediate regions is consistent with the fact that the q profile is also flattened during the instability and evolves only on a resistive time scale between successive redistributions, however the details of this redistribution are not very well understood. We therefore suggest an empirical expression for V/D in the form $\frac{\nabla q}{q}$ which gives a steady electron density profile described by $\frac{\nabla n_e}{ne} = - \alpha \frac{\nabla q}{q}$ or $n_e q^\alpha$=constant (in pure plasma). An estimation of the dimensionless parameter α is made possible by computing $f = \frac{n_e(r)q(r)^\alpha}{n_e(0)q(0)^\alpha}$ for the various reference density profiles discussed previously. A value of $\frac{1}{2}$ if found to agree with experimental results when the q profile is taken from the magnetic equilibrium constructed from experimental measurements.

We propose a generalized expression for the radial flow of particles of the form:

$$\Gamma_{e,a}=-D_e\left[\nabla n_e+\frac{e\,n_e\,E}{kT_e}+\alpha\left[n_e+\sum n_i\right]\frac{\nabla q}{q}\right]$$

$$\Gamma_{i,a}=-D_i\left[\nabla n_i-\frac{Z_i e\,n_i\,E}{kT_i}\right]$$

To these flows should be added the neoclassical flows which are themselves functions of the radial electric field required to maintain ambipolarity in presence of turbulent fluctuations as discussed by T.Stringer [3]. The anomalous diffusivities D_e and D_i are linked to the anomalous heat diffusivity as described in [2] with the anomalous energy transport coefficients being given by the Rebut-Lallia-Watkins critical electron temperature gradient model [4].

Fig. 3 shows various simulations of temperature, particle and q profiles using this model, we have also included plots of the quantity (1 - f).

IV)Discussion:

A theoretical expression based on the properties of magnetic turbulence has been derived by Taylor [1] where the ratio V/D is related to the current density profile. Using the usual definition of the safety factor q in cylindrical geometry ($q=\frac{r\,Bz}{R\,Bp}$) the theoretical expression for the ratio V/D in a pure plasma with $n_e = n_i = n$, gives the same dependence on q: $\frac{\nabla n}{n}=\frac{V}{D}=-2\frac{\nabla q}{q}$. Note that the coefficient α=2 is different from that deduced from observations of JET density profiles and can therefore be excluded.

It should also be noted that in some cases density profiles show normalized slopes considerably flatter than expected by the present model. This may imply that M.H.D. activity can also affect the intermediate region. This thesis is endorsed by the fact that as soon as additional heating is applied the density becomes peaked again, even though the density is sometimes even higher. This is seen in fig. 4 where about 8 MW of either ICRH or NBI (sources being taken into account) are applied.

V) Conclusion:

Experimental observations suggest that a model where the ratio V/D would depend only on the q profile would apply to a large range of the JET tokamak discharges.

This result is extended to a general expression for radial particle transport both for ions and electrons. Simulations using these expressions show good agreement with JET experimental data. But in some cases additional M.H.D. effects might have to be taken into account.

Validation of the model for other tokamaks than JET together with its testing for high Z impurities (Nickel injection in JET) is under way.

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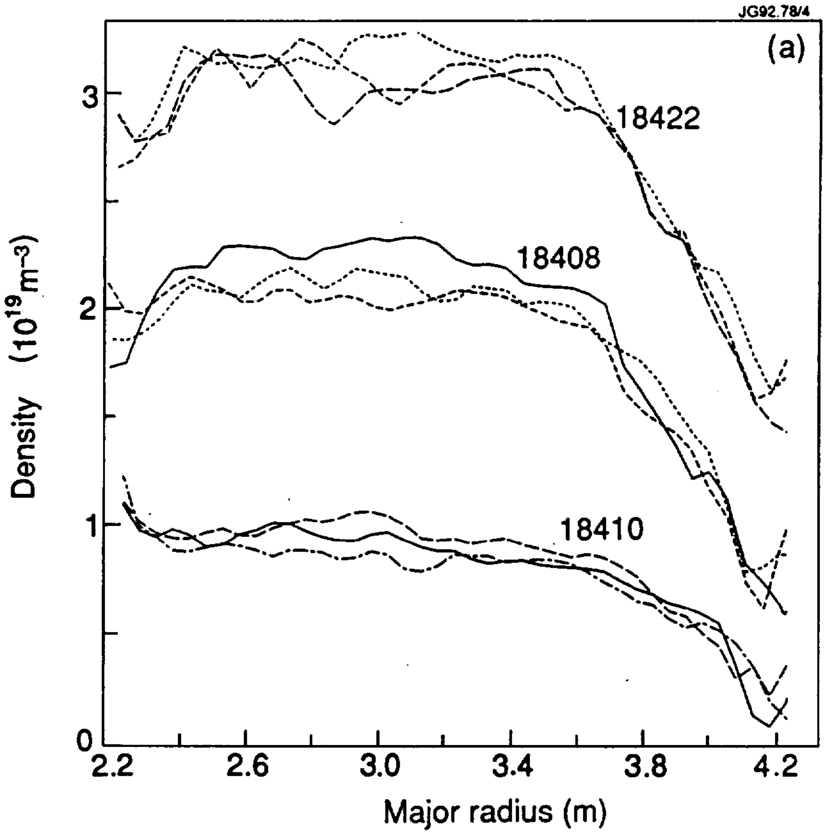


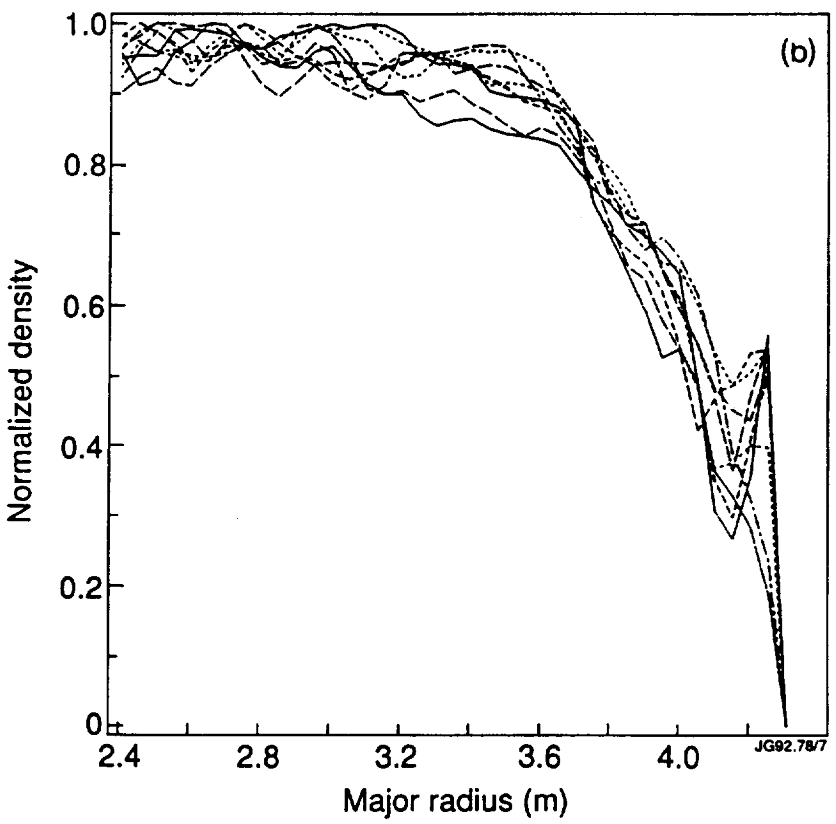
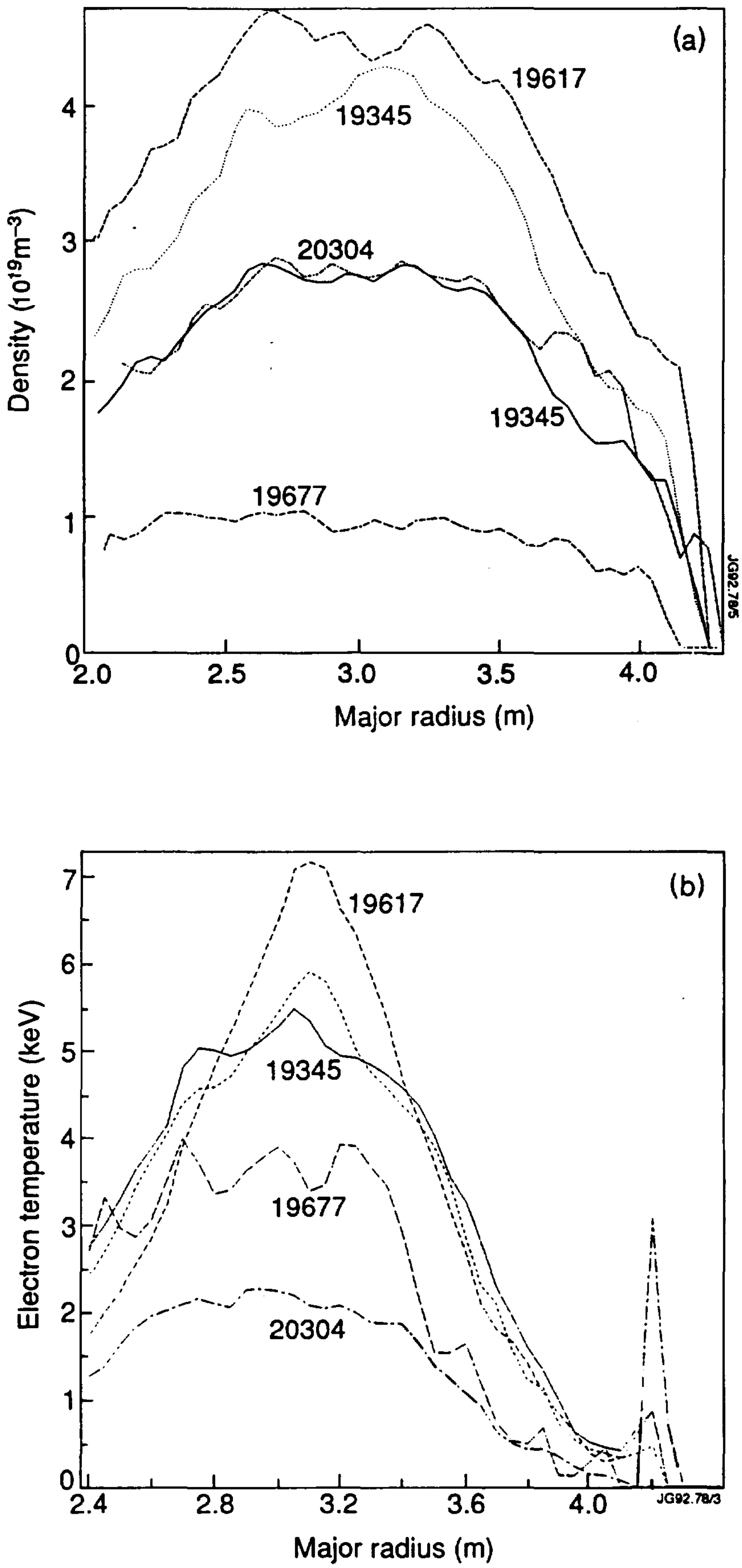


Fig. 1:Comparison of density profiles for three different pulses (#18408, #18410, #18422: 5MA, 3T) is seen in (a). These profiles normalized to their central value are shown in b).



(a)
Density ($10^{19}m^{-3}$)
19617
19345
20304
19345
19677
0
1
2
3
4
2.0
2.5
3.0
3.5
4.0
Major radius (m)
JG92.78/5
(b)
Electron temperature (keV)
19617
19345
19677
20304
0
1
2
3
4
5
6
7
2.4
2.8
3.2
3.6
4.0
Major radius (m)
JG92.78/3

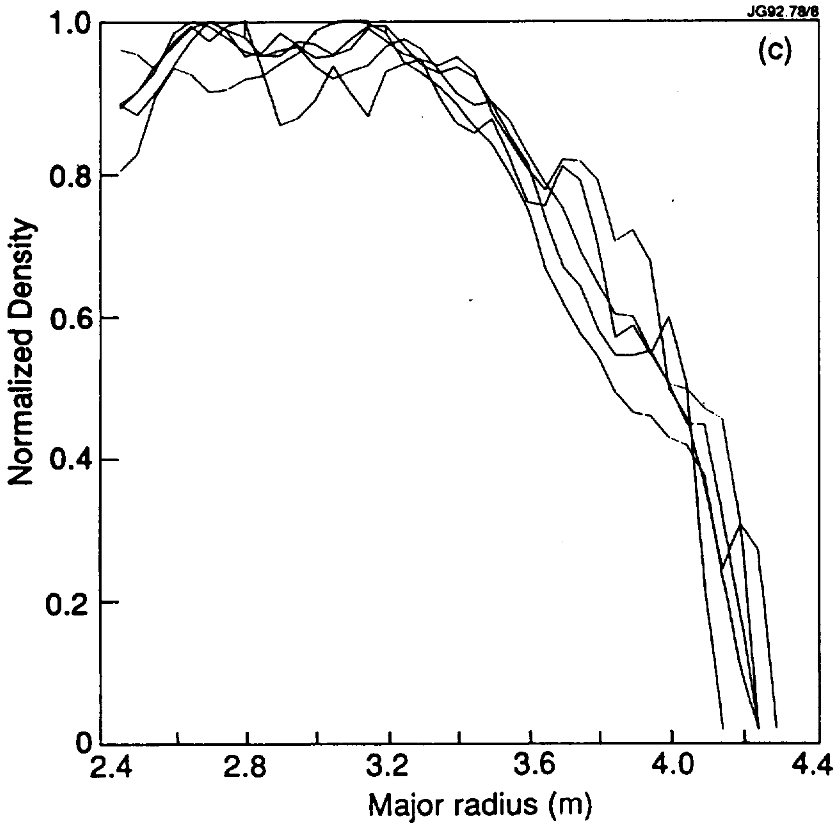


Fig. 2: Comparison between four different pulses: (a) density profiles, (b) corresponding temperature profiles and (c) the normalized density profiles.

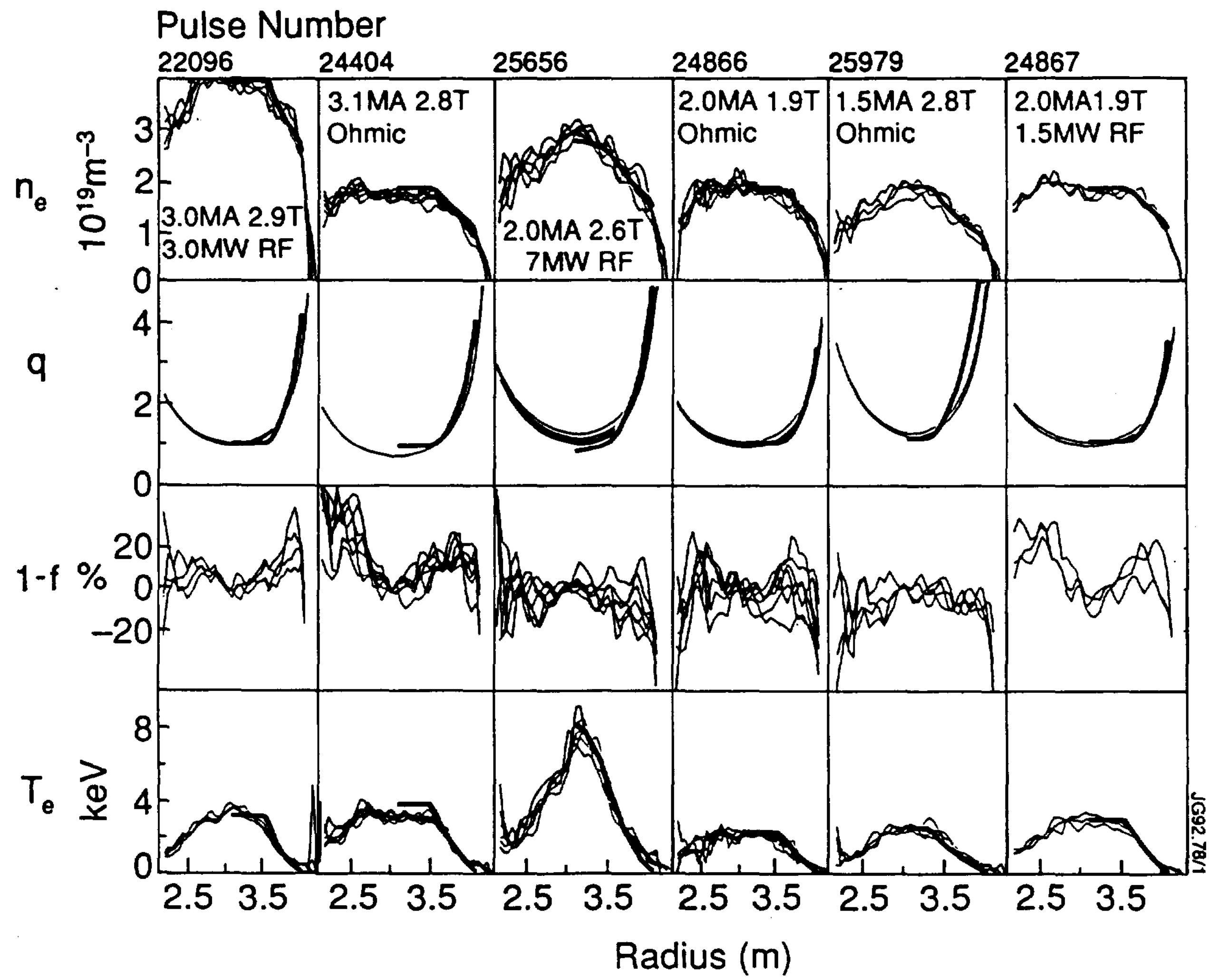
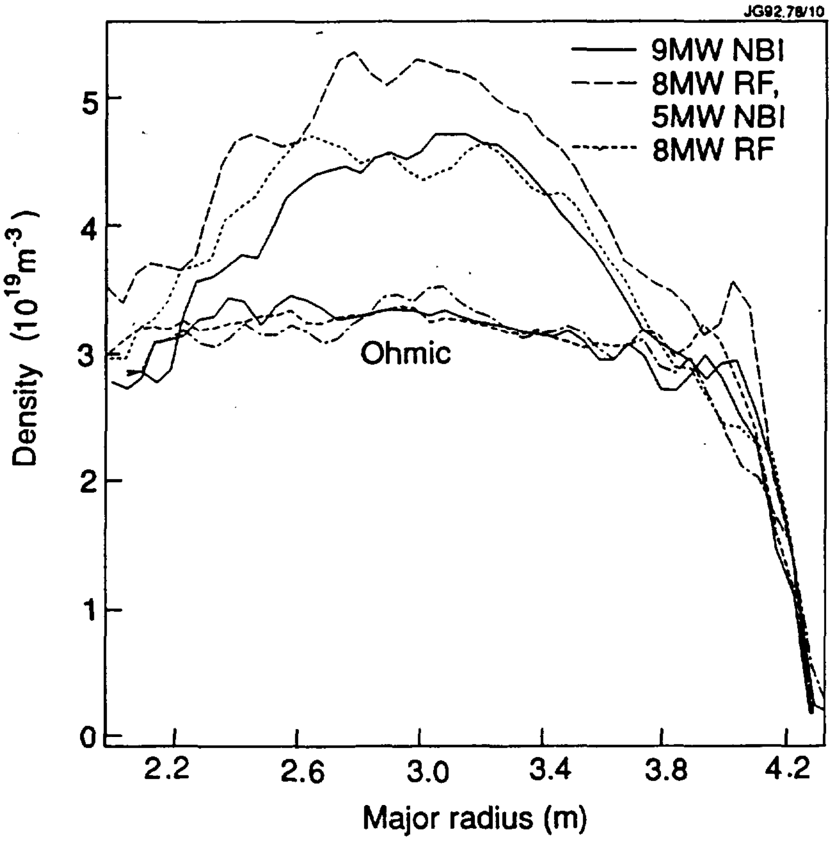


Fig.3: Experimental (thin lines) and simulated (thick lines) density, safety factor and temperature profiles for six different pulses. The (1 - f) quantity is also shown for α=1/2.



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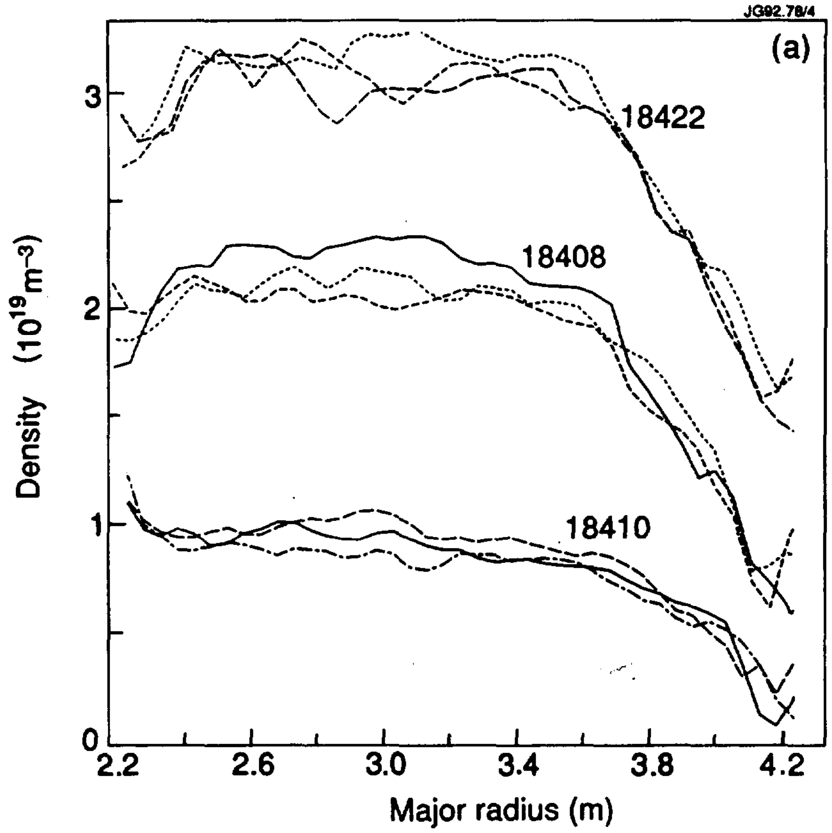

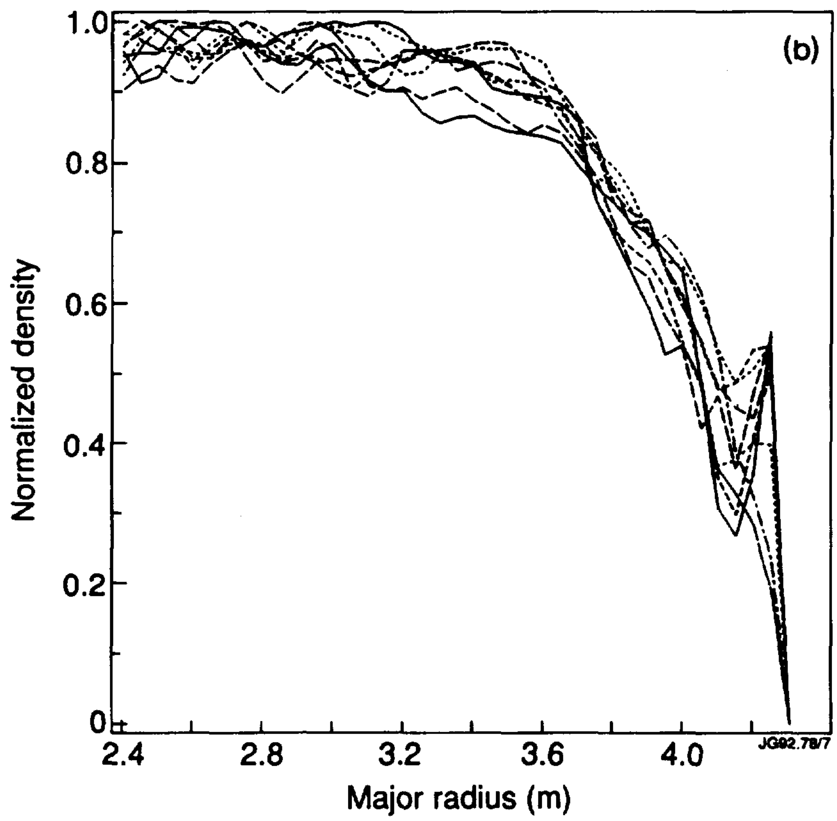

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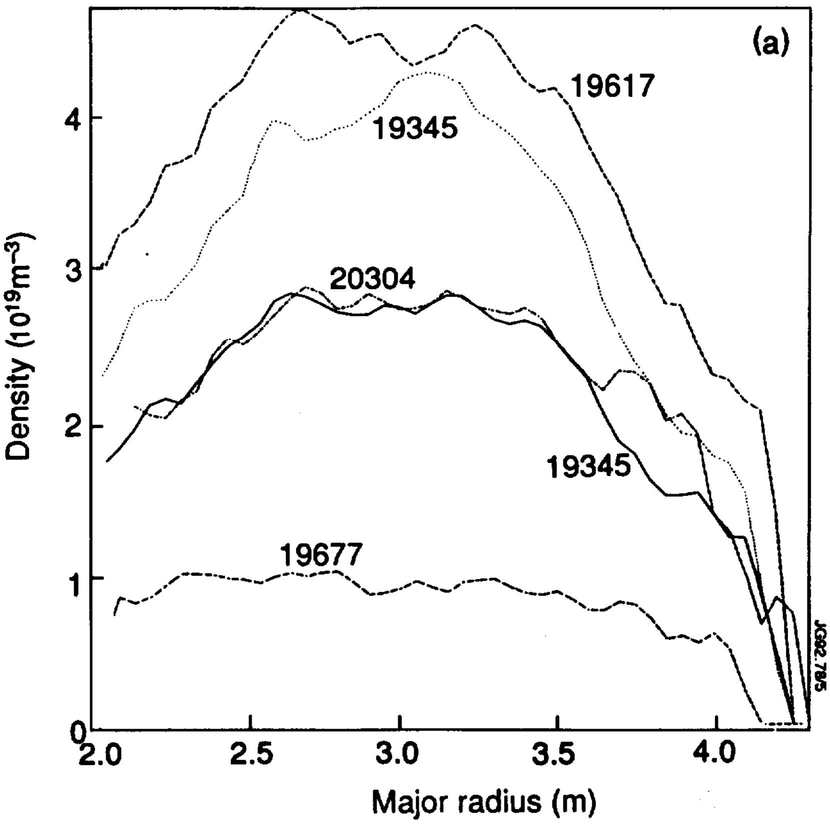

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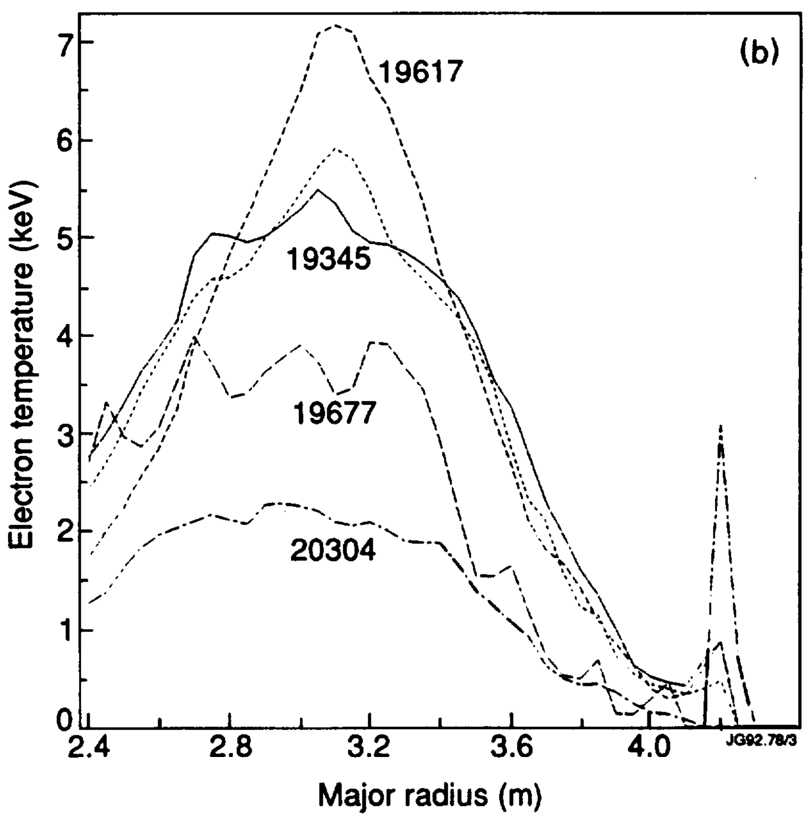
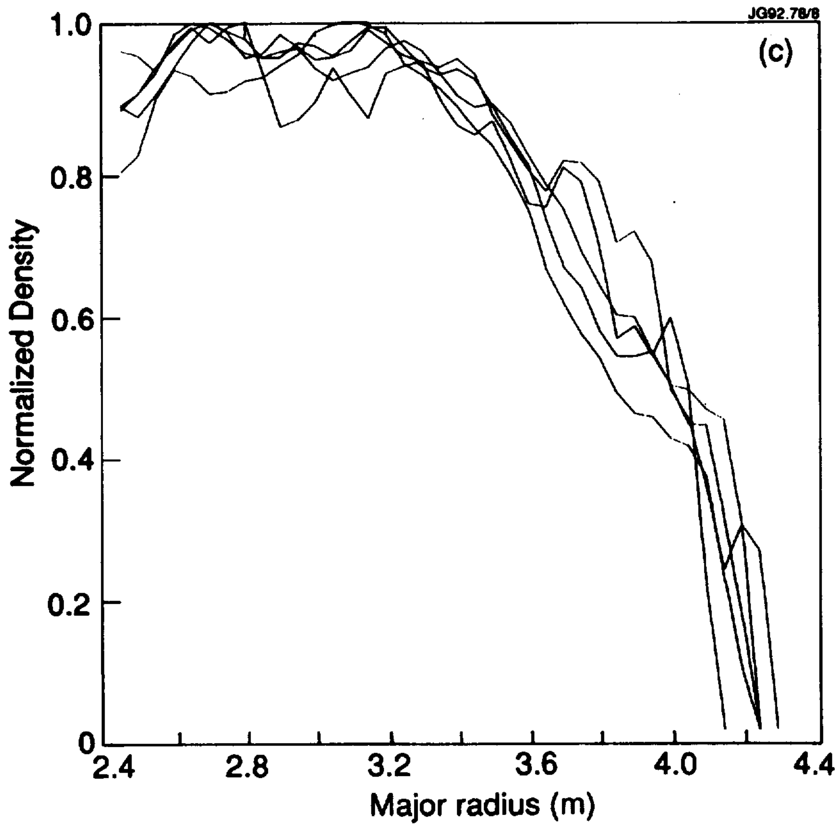
19617
19345
20304
19345
19677
Density ($10^{19}m^{-3}$)
Major radius (m)
JG92.78/5



(b)
19617
19345
19677
20304
Electron temperature (keV)
Major radius (m)
JG92.78/3



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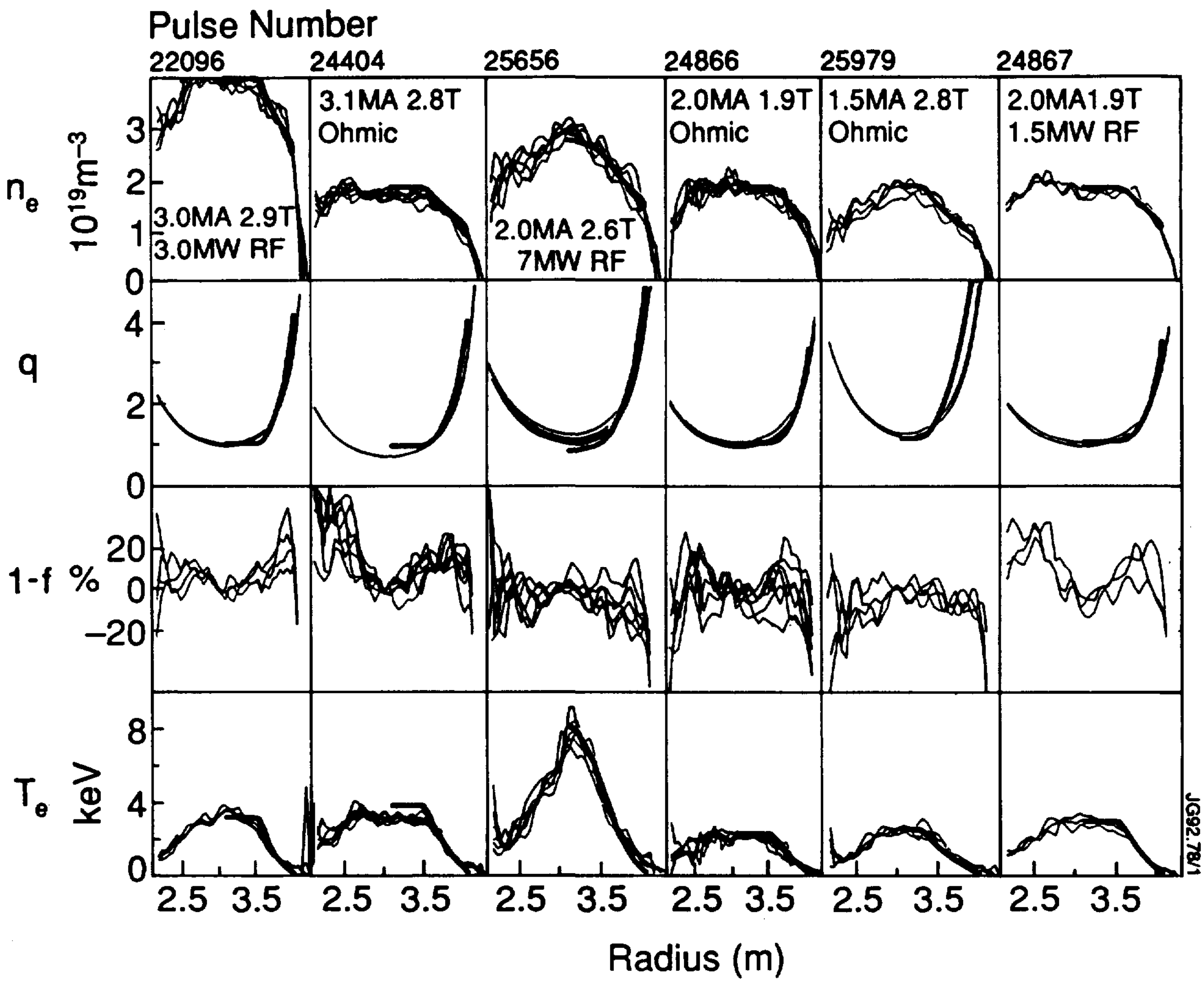

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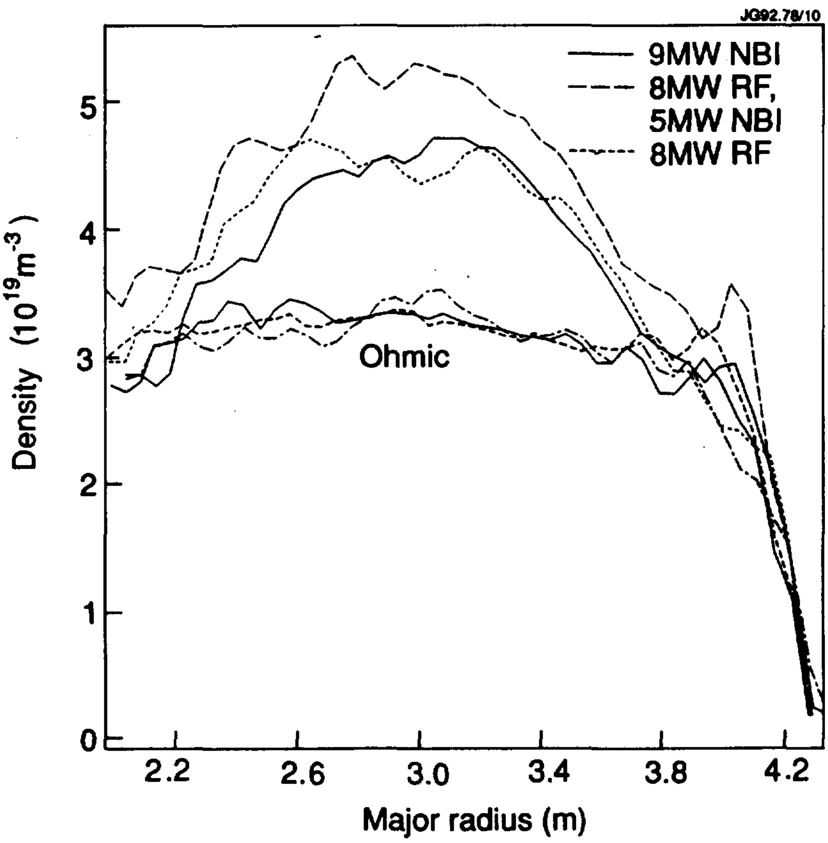

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#19617 (8 MW RF), #19646 (8 MW RF + 5 MW NBI) and #19649 (9 MW NBI).

ANNEX

P.-H. REBUT, A. GIBSON, M. HUGUET, J.M. ADAMS[1], B. ALPER, H. ALTMANN, A. ANDERSEN[2], P. ANDREW[3], M. ANGELONE[4], S. ALI-ARSHAD, P. BAIGGER, W. BAILEY, B. BALET, P. BARABASCHI, P. BARKER, R. BARNSLEY[5], M. BARONIAN, D.V. BARTLETT, L. BAYLOR[6], A.C. BELL, G. BENALI, P. BERTOLDI, E. BERTOLINI, V. BHATNAGAR, A.J. BICKLEY, D. BINDER, H. BINDSLEV[2], T. BONICELLI, S.J. BOOTH, G. BOSIA, M. BOTMAN, D. BOUCHER, P. BOUCQUEY, P. BREGER, H. BRELEN, H. BRINKSCHULTE, D. BROOKS, A. BROWN, T. BROWN, M. BRUSATI, S. BRYAN, J. BRZOZOWSKI[7], R. BUCHSE[22], T. BUDD, M. BURES, T. BUSINARO, P. BUTCHER, H. BUTTGEREIT, C. CALDWELL-NICHOLS, D.J. CAMPBELL, P. CARD, G. CELENTANO, C.D. CHALLIS, A.V. CHANKIN[8], A. CHERUBINI, D. CHIRON, J. CHRISTIANSEN, P. CHUILON, R. CLAESEN, S. CLEMENT, E. CLIPSHAM, J.P. COAD, I.H. COFFEY[9], A. COLTON, M. COMISKEY[10], S. CONROY, M. COOKE, D. COOPER, S. COOPER, J.G. CORDEY, W. CORE, G. CORRIGAN, S. CORTI, A.E. COSTLEY, G. COTTRELL, M. COX[11], P. CRIPWELL[12], O. Da COSTA, J. DAVIES, N. DAVIES, H. de BLANK, H. de ESCH, L. de KOCK, E. DEKSNIS, F. DELVART, G.B. DENNE-HINNOV, G. DESCHAMPS, W.J. DICKSON[13], K.J. DIETZ, S.L. DMITRENKO, M. DMITRIEVA[14], J. DOBBING, A. DOGLIO, N. DOLGETTA, S.E. DORLING. P.G. DOYLE, D.F. DÜCHS, H. DUQUENOY, A. EDWARDS, J. EHRENBERG, A. EKEDAHL, T. ELEVANT[7], S.K. ERENTS[11], L.G. ERIKSSON, H. FAJEMIROKUN[12], H. FALTER, J. FREILING[15], F. FREVILLE, C. FROGER, P. FROISSARD, K. FULLARD, M. GADEBERG, A. GALETSAS, T. GALLAGHER, D. GAMBIER, M. GARRIBBA, P. GAZE, R. GIANNELLA, R.D. GILL, A GIRARD, A. GONDHALEKAR, D. GOODALL[11], C. GORMEZANO, N.A. GOTTARDI, C. GOWERS, B.J. GREEN, B. GRIEVSON, R. HAANGE, A. HAIGH, C.J. HANCOCK, P.J. HARBOUR, T. HARTRAMPF, N.C. HAWKES[11], P. HAYNES[11], J.L. HEMMERICH, T. HENDER[11], J. HOEKZEMA, D. HOLLAND, M. HONE, L. HORTON, J. HOW, M. HUART, I. HUGHES, T.P. HUGHES[10], M. HUGON, Y. HUO[16], K. IDA[17], B. INGRAM, M. IRVING, J. JACQUINOT, H. JAECKEL, J.F. JAEGER, G. JANESCHITZ, Z. JANKOVICZ[18], O.N. JARVIS, F. JENSEN, E.M. JONES, H.D. JONES, L.P.D.F. JONES, S. JONES[19], T.T.C. JONES, J.-F. JUNGER, F. JUNIQUE, A. KAYE, B.E. KEEN, M. KEILHACKER, G.J. KELLY, W. KERNER, A. KHUDOLEEV[21], R. KONIG, A. KONSTANTELLOS, M. KOVANEN[20], G. KRAMER[15], P. KUPSCHUS, R. LÄSSER, J.R. LAST, B. LAUNDY, L. LAURO-TARONI, M. LAVEYRY, K. LAWSON[11], M. LENNHOLM, J. LINGERTAT[22], R.N. LITUNOVSKI, A. LOARTE, R. LOBEL, P. LOMAS, M. LOUGHLIN, C. LOWRY, J. LUPO, A.C. MAAS[15], J. MACHUZAK[19], B. MACKLIN, G. MADDISON[11], C.F. MAGGI[23], G. MAGYAR, W. MANDL[22], V. MARCHESE, G. MARCON, F. MARCUS, J. MART, D. MARTIN, E. MARTIN, R. MARTIN-SOLIS[24], P. MASSMANN, G. MATTHEWS, H. McBRYAN, G. McCRACKEN[11], J. McKIVITT, P. MERIGUET, P. MIELE, A. MILLER, J. MILLS, S.F. MILLS, P. MILLWARD, P. MILVERTON, E. MINARDI[4], R. MOHANTI[25], P.L. MONDINO, D. MONTGOMERY[26], A. MONTVAI[27], P. MORGAN, H. MORSI, D. MUIR, G. MURPHY, R. MYRNÄS[28], F. NAVE[29], G. NEWBERT, M. NEWMAN, P. NIELSEN, P. NOLL, W. OBERT, D. O'BRIEN, J. ORCHARD, J. O'ROURKE, R. OSTROM, M. OTTAVIANI, M. PAIN, F. PAOLETTI, S. PAPASTERGIOU, W. PARSONS, D. PASINI, D. PATEL, A. PEACOCK, N. PEACOCK[11], R.J.M. PEARCE, D. PEARSON[12], J.F. PENG[16], R. PEPE DE SILVA, G. PERINIC, C. PERRY, M. PETROV[21], M.A. PICK, J. PLANCOULAINE, J.-P POFFÉ, R. PÖHLCHEN, F. PORCELLI, L. PORTE[13], R. PRENTICE, S. PUPPIN, S. PUTVINSKII[8], G. RADFORD[30], T. RAIMONDI, M.C. RAMOS DE ANDRADE, R. REICHLE, J. REID, S. RICHARDS, E. RIGHI, F. RIMINI, D. ROBINSON[11], A. ROLFE, R.T. ROSS, L. ROSSI, R. RUSS, P. RUTTER, H.C. SACK, G. SADLER, G. SAIBENE, J.L. SALANAVE, G. SANAZZARO, A. SANTAGIUSTINA, R. SARTORI, C. SBORCHIA, P. SCHILD, M. SCHMID, G. SCHMIDT[31], B. SCHUNKE, S.M. SCOTT, L. SERIO, A SIBLEY, R. SIMONINI, A.C.C. SIPS, P. SMEULDERS, R. SMITH, R. STAGG, M. STAMP, P. STANGEBY[3], R. STANKIEWICZ[32], D.F. START, C.A. STEED, D. STORK, P.E. STOTT, P. STUBBERFIELD, D. SUMMERS, H. SUMMERS[13], L. SVENSSON, J.A. TAGLE[33], M. TALBOT, A. TANGA, A. TARONI, C. TERELLA, A TERRINGTON, A TESINI, P.R. THOMAS, E. THOMPSON, K. THOMSEN, F. TIBONE, A. TISCORNIA, P. TREVALION, B. TUBBING, P. VAN BELLE, H. VAN DER BEKEN, G. VLASES, M. VON HELLERMANN, T. WADE, C. WALKER, R. WALTON[31], D. WARD, M.L. WATKINS, N. WATKINS, M.J. WATSON, S. WEBER[34], J. WESSON, T.J. WIJNANDS, J. WILKS, D. WILSON, T. WINKEL, R. WOLF, D. WONG, C. WOODWARD, Y. WU[35], M. WYKES, D. YOUNG, I.D. YOUNG, L. ZANNELLI, A. ZOLFAGHARI[19], W. ZWINGMANN

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