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Joint research using small tokamaks

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Abstract
Small tokamaks have an important role in fusion research. More than 40 small tokamaks are operational. Research on small tokamaks has created a scientific basis for the scaling-up to larger tokamaks. Well-known scientific and engineering schools, which are now determining the main directions of fusion science and technology, have been established through research on small tokamaks. Combined efforts within a network of small and medium size tokamaks will further enhance the contribution of small tokamaks. A new concept of interactive coordinated research using small tokamaks in the mainstream fusion science areas, in testing of new diagnostics, materials and technologies as well as in education, training and broadening of the geography of fusion research in the scope of the IAEA Coordinated Research Project, is presented.

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1. Introduction

Much of the world-wide effort on magnetic fusion is devoted to the present and future generations of large tokamaks. At the same time, in many countries (Brazil, Canada, People's Republic of China, Czech Republic, Egypt, Germany, India, Iran, Japan, Portugal, Republic of Korea, Russian Federation, Turkey and USA) more than 40 small tokamaks are operational. On these tokamaks, research is carried out mostly on the basis of domestic programmes and only in a few cases also in the frame of an international cooperation.

Small tokamaks have played a very important role in fusion research. They have created a scientific basis for the scaling-up to larger tokamaks and established the well-known scientific and engineering schools, which are now determining the main directions of fusion science and technology.

Because of the compactness, flexibility, low operation costs and high skill of their personnel, the small tokamaks may significantly contribute to a better understanding of phenomena in a wide range of fields such as plasma confinement and energy transport; plasma stability in different magnetic configurations; plasma turbulence and its impact on local and global plasma parameters; dimensionless scaling, processes at the plasma edge and plasma–wall interaction; scenarios of additional heating and noninductive current drive; new methods of plasma profile and parameter control; development of novel plasma diagnostics; benchmarking of new numerical codes and so on.

Furthermore, small tokamaks are very convenient for developing and testing new materials and technologies, which because of the risky nature cannot be done in large machines without preliminary studies. Small tokamaks are suitable and important for broad international cooperation, providing the necessary environment and manpower to conduct dedicated joint research programmes. In addition, the experimental work on small tokamaks is very appropriate for education of students, scientific activities of post-graduate students and for training of personnel for large tokamaks. All these tasks are well recognized and reflected in ITER documents and understood by the teams of large tokamaks.

In the past, assessment of the output from the small tokamak research programmes has shown the need for stronger links between the small and large tokamaks and better coordination of the collaboration between small tokamak research projects [1]. A new concept of interactive coordinated joint research using small tokamaks in the scope of the IAEA Coordinated Research Project (CRP), which started in 2004, should be a new step in better coordination of this collaboration and in improvement of links between the small and large tokamaks.

The overall objective of this approach is to achieve a network of fusion research using the innovative possibilities of small tokamaks. This will result in the deeper integration of small tokamaks in national, regional and international fusion activities and an increase in the number of collaborative experiments. This will also help us to promote fusion research in developing countries and open wider possibilities for young scientists. Work packages for the different research activities can be carried out under the supervision of the members of the CRP, thus providing a clear future perspective for small tokamaks in a coordinated approach. This will help us to improve the quality of the scientific output from small tokamak research activities.

The specific objectives of this coordinated joint research fall into the following groups:

- Direct contribution of small tokamaks to mainstream fusion research.
- A test-bed of new tools, materials and technologies for large machines.
- Improvement and development of diagnostics.
- Expertise development and capacity building of students and post-graduate students and training of personnel, in particular in developing countries. These may be achieved through promotion of mobility, exchange of equipment, joint experiments, training courses, schools, etc.

In this paper we present an overview of the main activities involving small tokamaks participating in the CRP. With the increasing number of participants, other research activities on small tokamaks, not covered in this paper, will be included in the research network and presented in the future.

2. Small tokamak database

As one of the first CRP activities, the small tokamak database has been established, table 1. There were several attempts in the past to create a small tokamak database [1]. Some information can be found in the IAEA Nuclear Fusion World Survey (presently the 2001 version is available), http://epub.iaea.org/fusion/public/ws01/index.html, and in the DMOZ ODP database, see http://dmoz.org/Science/Physics/Nuclear/Fusion/Magnetic. The new updated database covers 52 presently or recently active small tokamaks and devices under construction. The selection criteria for the database were chosen based not exclusively on the device size, but on the scale of a project as a whole, including the budget and staff considerations. However, there are many joint experiments between tokamaks of all sizes, including medium and large ones, that use results of research and developments on small tokamaks. These tokamaks could also participate in the CRP and contribute to its activities. The database only includes information which was supplied to the authors or is available in publications. It is one of the objectives of the CRP to complete and update it on a regular basis. Numbers after a slash in table 1 give design values if they have not yet been achieved. Information in italic is provisional.

3. Description of main activities with small tokamaks participating in the project

Nine participants have joined the CRP in 2004. Some of them are from well-developed projects which make a direct contribution to mainstream fusion research (T-10, ISTTOK, STOR-M, CASTOR, TCABR), and others are relatively new projects (GUTTA, SUNIST, ETE, EGYPTOR). The number of collaborators is increasing. During the first Research Coordination Meeting at Lisbon, 7–10 November 2004, the status of all ongoing activities with these tokamaks was presented, which is described in the next section, and summarized in the classification table (table 2). The list of currently proposed CRP research topics has been classified accordingly and is presented in the individual activity matrix (IAM) (table 3) for each participating tokamak. This list can be upgraded as new opportunities or topics for collaboration appear. In addition, joint research activities were identified from the IAM and a joint activity matrix (JAM) was established for the first year of the CRP project presented in table 4. Each activity number in these two matrices is identified in table 2. The working plan consists of joint and individual activities, which will be carried out under the framework of the CRP. The main activities are described below. Details of the described research and references can be found on the CRP Web page, www-crp.iaea.org.

3.1. Direct contribution of small tokamaks to mainstream fusion research

Contribution to mainstream fusion research from CRP participants is foreseen in several areas. On T-10 [2], these include transport barrier investigation; investigation of the role of the q profile in ITB formation, including the role of resonant q surfaces; investigations of plasma turbulence and its impact on local and global plasma parameters using correlation reflectometry; analysis of short wavelength plasma instabilities using ECE scattering and FIR; measurements of stationary and fluctuating electric fields using the heavy ion beam probe (HIBP) diagnostic; investigation of energy and particle transport in the vicinity of the Greenwald density limit; investigation of edge plasma behaviour; analysis of electron transient transport during auxiliary heating and in transient processes (pellet-injection, ITB formation, etc); investigation of particle transport under RF heating and of the density pump-out effect and impurity behaviour under ECRH.

Table 1. List of small tokamaks.

		Name	Organization	R (m)	a (m)	Elon	I_p (kA)	B_t (T)	Config.	τ_{pulse} (ms)	Aux. heating (MW)	Project start, end, status
	Europe											
1	Russia	Globus-M	Ioffe, St Petersburg	0.36	0.24	1.6/2.2	350/500	0.5/0.62	DND, SND, L	300/500	NB 1.5/0.8; ICRH 1	1999
2	Russia	TUMAN-3M	Ioffe, St Petersburg	0.55	0.24	1.0	180	1.0/3.0	L	150	NB 0.5; ICRH 0.4/1.0	1985
3	Russia	FT2	Ioffe, St Petersburg	0.55	0.08	1.0	22	2.5	L	60	LH 0.3	1979
4	Russia	T-11M	TRINITY, Troitsk	0.7	0.2	1.0	150	1.2	L	250	ICRH 1.0	1996
5	Russia	GUTTA	St Petersburg University, St Petersburg	0.16	0.084	2	150	1.5	L, DND	10	No	1984, restarted in 2002
6	Russia	T-10	RRC ‘Kurchatov Institute’, Moscow	1.5	0.36	1.0	400/820	2.5/5.0	L	1 s	ECRH 3.0	1975
7	Czech Republic	CASTOR	IPP, Praha	0.4	0.085	1.0	20	1.5	L	50	LH	1985
8	Portugal	ISTTOK	ICT CFN, Lisbon	0.46	0.078	1.0	8	0.6	L	70	No	1992
9	Italy	Proto-Sphera (START)	ENEA, Frascati	0.18	0.14	1.6	240	0.6	DND	—	No	Under construction
10	UK	Compass-D	UKAEA, Culham	0.557	0.232	1.66	350	2.1	SND	1 s	ECRH 2.0, LH 0.2	1992–2001
	Asia											
11	Japan	TST-2	University of Tokyo, Tokyo	0.38	0.25	1.8	120/200	0.3/0.4	DND, L	200	EBW 0.2	1999
12	Japan	LATE	Kyoto University, Kyoto	0.25	0.2	1.34	4	0.12	L	4.5 s	ECRH 0.2	2000
13	Japan	HIST	University, of Hyogo, Himeji	0.3	0.24	2	100	0.2	L	5	No	1998
14	Japan	TS4	University of Tokyo, Tokyo	0.55	0.45	3.0	300	0.5	L	5	No	2000
15	Japan	TS3	University of Tokyo, Tokyo	0.2	0.14	2.0	80	0.2	L	0.05	No	1986
16	Japan	CSTN-IV	Nagoya University, Nagoya	*0.4*	*0.1*	*1.0*	*1*	*0.12*	*L*	*20*	*No*	*1998*
17	Japan	HYBTOK-II	Nagoya University, Nagoya	*0.4*	*0.11*	*1.0*	*15*	*1.5*	*L*	*15*	*No*	*1991*
18	Japan	NUCTE-ST	Nihon University, Nihon	*0.062*	*0.052*	*10.0*	*340*	*0.45*	*L*	*0.12*	*No*	*1998*
19	Japan	TODOROKI-II	Tokyo Institute of Technology, Tokyo	*0.3*	*0.08*	*1.0*	*11*	*1.0*	*L*	*10/4*	*No*	*2002*
20	Japan	TRIAM	Kyushu University, Fukuoka	0.84	0.13	1.5	430	8	L, SND	>5 h	LH 0.45, ECRH 0.2,	Ops. till 2005
21	Japan	HT-2	Hitachi Res. Lab., Ibaraki-ken	0.41	0.11	1.0	50	2	L	50	LH	1989–2001
22	Japan	WT-3	Kyoto University, Kyoto	0.65	0.2	1.0	150	1.75	L	150	ECRH 0.2, LH 0.35	1985–2000
23	China	HT-6M	ACIPP, Hefei	0.65	0.2	1.0	150	1.5	L	60	ICRH, LH	1985
24	China	HT-7	ACIPP, Hefei	1.22	0.35	1.0	400/350	3/2.5	L	4 min	ICRH 1.0/0.5, LHCD 1.0	1995
25	China	SUNIST	SUNIST Lab., Beijing	0.3	0.22	1.6	50	0.08/0.15	DND, L	13	EBW 0.1, HHFW	2003
26	China	HL-2A (ASDEX)	SWIP, Chengdu	1.64	0.4	1.6	480	2.8	SND, DND	750	NBI 10, LHCD 3, ECRH 1, ICRH 3	2002
27	China	KT-5C	USTC, Hefei	*0.325*	*0.095*	*1.0*	*20*	*0.7*	*L*	*2*	*No*	*1985*
28	China	CT-6B	IOP AS, Beijing	0.45	0.125	1.0	30	0.75	L	30	ECRH	1995–2002
29	China	HL-1M	SWIP, Chengdu	1.02	0.26	1.0	350	3	L	100	NBI 1, LHCD 1, ECRH 0.5, ICRH 1	1989–2001
30	Korea	KT-1	KAERI, Daejeon	0.27	0.05	1.0	15	1.5	L	20	No	1988

Table 1. (Continued).

		Name	Organization	R (m)	a (m)	Elon	I_p (kA)	B_t (T)	Config.	τ_{pulse} (ms)	Aux. heating (MW)	Project start, end, status
31	Korea	KAIST-TOKAMAK	KAIST, Daejeon	0.53	0.14	1.0	40	0.5	L	100	No	1992–2002
32	India	ADITYA	IPR, Bhat	0.75	0.25	1.0	80	0.5	L	60	No	1992
33	India	SINP	SAHA, Kolkata	*0.3*	*0.075*	*1.0*	*75*	*2*	*L*	*20*	*No*	*1987*
34	Turkey	STPC-EX	TAEA, Ankara	0.084	0.056	4.0	6.5	0.12	L	9.5	No	1992
35	Iran	DAMAVAND	PPL, Tehran	0.36	0.07	2.8	35/40	1.0/1.2	DND	25/50	No	1995
36	Iran	ALVAND-IIC	PPL, Tehran	*0.455*	*0.126*	*1.0*	*30*	*0.8*	*L*	*10*	*No*	*1981*
37	Iran	IR-T1	PPRC IA University, Tehran	0.45	0.125	1.0	40	1.2	L	25/10	No	1994
38	Kazakhstan	KTM	IEA NNC, Kurchatov	0.9	0.45	1.7	750	1	SND	4 s	RF 7.0	Under construction
39	Kirgyzstan	TF-2	IHT RAS, Bishkek	0.225	0.041	1.0	15	2	L	15	No	On hold 1998
	Australia											
40	Australia	Flinders Tokamak	Flinders University, Adelaide	0.1	0.06	2.5	17	0.024	L	5	RMF 0.4	1998–2001
	America											
41	USA	CDX-U/ LTX	PPPL, Princeton	0.335	0.225	1.7	70	0.23	DND, L	25	FW	1993
42	USA	Pegasus	University of Wisconsin, Madison	0.45	0.41	3.7	160/300	0.15	DND, L	50	EBW, HHFW	1996
43	USA	ET	UCLA	5	1	2.0	40/100	0.25	L	5 s	ICRH 5.0, NB 1.0	1999
44	USA	HBT-EP	Columbia University, New York	0.92	0.15	1.0	30/40	0.35/0.5	L		ICRF 5.0	1993
45	USA	HIT-II	University of Washington, Seattle	0.3	0.2	1.9	370	0.5	L	0.06	None	1997–2004
46	Brazil	ETE	INPE, SP	0.3	0.2	1.6/1.8	60/400	0.4/0.8	L	10.0/25.0	No	2000
47	Brazil	TCABR	University of São Paulo, SP	0.61	0.18	1.0	110	1.1	L	100/120	Alfvén 1.0	1999
48	Brazil	NOVA	University of Campinas, SP	0.30	0.06	1.0	10.0	0.8/1.5	L	12.0	No	1998
49	Mexico	NOVILLO Tokamak	ININ, Mexico City	*0.23*	*0.06*	*1.0*	*12*	*0.47*	*L*	*5*	*No*	*1983*
50	Canada	STOR-M	PPL University of Saskatchewan	0.46	0.12	1.0	30	0.7	L	50 ms or ac	No	1987
	Africa											
51	Egypt	EGYPTOR	NRC, EAEA, Cairo	0.3	0.1	1.25	45/100	1.2	L	60/45	No	2002
52	Libya	LIBTOR (TM4-A)	Tajoura Nuclear Research Center, Tajoura	0.53	0.115	1.0	120	4	L	20	No	1982

Enhanced confinement regimes have been identified in several small tokamaks. In STOR-M [3], H-modes have been triggered using several methods such as plasma biasing and compact torus (CT) injection. Several models to explain the mode switching from L-mode to H-mode invoke the role of the plasma flow and its structure in the edge. The proposed research project aims at measuring directly the edge plasma toroidal and poloidal velocities in STOR-M to study its evolution before and after the onset of the H-mode, thereby identifying the most appropriate model and contributing to the understanding of the processes involved in switching mechanisms. For the biasing experiments, a voltage is applied, with respect to the vessel chamber, either to a movable electrode inserted into the tokamak edge region ($r = 8.2$–10.5 cm) or to a segmented limiter consisting of four segments on each side of a ceramic base. There are small gaps between adjacent segments, and each segment can be biased independently. For the CT injection experiments, hydrogen CTs can be formed and accelerated between coaxial electrodes with typical densities of the order of 10^{15} cm^{-3}. The measured velocity is approximately 120–200 km s^{-1}. The inner and outer radii of the CT ring are 1.8 cm and 5 cm, respectively. The estimated CT length is 15 cm. The CT mass is of the order of 1 μg, representing 50% of the particle inventory in STOR-M.

Emissive electrode biasing experiments are also carried out on the ISTTOK tokamak [4]. In small tokamaks with a relatively low plasma density, the current collected by negative biased standard electrodes is not sufficient to decrease the plasma potential due to the limitation imposed by the ion saturation current. Emissive electrodes produce a much larger current, allowing therefore a more efficient way of controlling the edge radial electric field. A movable emissive electrode has been developed for biasing experiments on ISTTOK and has proved to be a valuable tool for control of the edge radial electric field, allowing a detailed investigation of its importance in plasma confinement. Biasing experiments revealed that a large radial electric field is induced in the edge plasma for both polarities (up to ± 12 kV m^{-1}) together with a significant increase in the plasma density. However, positive bias tends to increase recycling, and therefore the improvement in particle confinement is much larger for a negative bias. In order to understand this different behaviour, the edge

Table 2. CRP research topics.

Topic	Subtopic	Tokamaks
1. Core transport and turbulence	1.1. H-mode studies, L/H transition, improved confinement	TCABR, T-10, ISTTOK, CASTOR, STOR-M, ETE (modelling)
	1.2. ITB formation, control	T-10, TCABR
	1.3. Nonlocal transport (transient phenomena)	T-10
	1.4. Turbulence, ITG, ETG, GAM, zonal flows, plasma rotation	T-10, STOR-M, TCABR
	1.5. Contribution to confinement DB	T-10
	1.6. Contribution to pedestal DB	
	1.7. Impurity and particle transport	CASTOR, T-10
2. Edge physics, PSI and technology	2.1. Edge turbulence	CASTOR, ISTTOK, T-10, STOR-M, TCABR, ETE, SUNIST
	2.2. Biasing	CASTOR, ISTTOK, T-10, STOR-M, TCABR
	2.3. Cross-field transport, blobs	CASTOR, ISTTOK, T-10, TCABR
	2.4. Plasma surface interaction	T-10
	2.5. Plasma facing components and materials, dust	ETE, T-10, CASTOR
	2.6. Liquid wall, limiter	ISTTOK, T-10
	2.7. Divertor plasma parameters, detachment	
	2.8. Fuelling, recycling, wall conditioning	STOR-M, ETE, T-10, CASTOR, EGYPTOR
3. Heating, CD and plasma formation	3.1. Heating power source development	ETE
	3.2. Heating methods developments, EBW, Alfvén wave	SUNIST, TCABR, CASTOR, T-10
	3.3. Nonsolenoid plasma formation	SUNIST, GUTTA, STOR-M
	3.4. Steady state operations, ac discharges	ISTTOK, STOR-M, GUTTA
	3.5. Startup	ETE, EGYPTOR, SUNIST, GUTTA, T-10, STOR-M
4. MHD and control	4.1. Error fields, RWM	T-10, ISTTOK
	4.2. NTM control	T-10
	4.3. ELMs and mitigation	
	4.4. TAE and energetic particle modes	
	4.5. Runaway and mitigation	TCABR, ISTTOK, EGYPTOR, T-10
	4.6. Disruptions, mitigation	T-10, TCABR
	4.7. Plasma control	GUTTA
	4.8. MHD instabilities	ETE (modelling), TCABR, STOR-M
5. Diagnostics improvement and development	5.1. Core diagnostics	ISTTOK, STOR-M, T-10, ETE, TCABR
	5.2. Edge diagnostics	ISTTOK, STOR-M, T-10, ETE, TCABR, CASTOR
	5.3. Magnetic diagnostics, eq. reconstruction	ETE, ISTTOK, SUNIST, GUTTA, EGYPTOR
	5.4. Calibration, test-bed, methodology, burning plasma diagnostic R&D	CASTOR, T-10
6. Control, data acquisition, remote participation	6.1. Control and data acquisition	ISTTOK, GUTTA, T-10, TCABR
	6.2. Real time processing and control	GUTTA, ISTTOK, STOR-M
	6.3. Remote control and collaboration	ISTTOK, CASTOR, T-10
	6.4. Clusters, grids, networking and parallel processing	TCABR, ISTTOK, T-10
7. Excellency education, knowledge transfer, capacity building	7.1. Plasma physics schools	CASTOR, T-10
	7.2. Post-graduate programmes	GUTTA, ISTTOK, SUNIST, CASTOR, TCABR, STOR-M, T-10
	7.3. Undergraduate	ISTTOK, TCABR, CASTOR, GUTTA, ETE, T-10, STOR-M, SUNIST
8. Expertise exchange	8.1. Joint experiments	Everyone
	8.2. Joint database	

Table 3. CRP individual activity matrix.

<table>
<tr><th>Tokamak</th><th colspan="2">1. Core transport and turbulence</th><th colspan="2">2. Edge physics, PSI and technology</th><th colspan="2">3. Heating, CD and plasma formation</th><th colspan="2">4. MHD and control</th></tr>
<tr><td>T-10</td><td>1.2, 1.3, 1.7</td><td>1.3</td><td>2.1, 2.5</td><td>2.1</td><td></td><td></td><td>4.5</td><td></td></tr>
<tr><td>GUTTA</td><td></td><td></td><td></td><td></td><td colspan="2">3.3, 3.5</td><td>4.7</td><td>4.7</td></tr>
<tr><td>SUNIST</td><td></td><td></td><td></td><td></td><td></td><td>3.3, 3.5</td><td></td><td></td></tr>
<tr><td>EGYPTOR</td><td></td><td></td><td>2.8</td><td></td><td>3.5</td><td></td><td></td><td></td></tr>
<tr><td>ETE</td><td></td><td></td><td>2.8</td><td></td><td>3.1, 3.5</td><td>3.1, 3.5</td><td></td><td>4.8</td></tr>
<tr><td>TCABR</td><td>1.4</td><td>1.4</td><td>2.1, 2.2</td><td></td><td></td><td></td><td>4.5, 4.6, 4.8</td><td>4.5</td></tr>
<tr><td>ISTTOK</td><td></td><td></td><td colspan="2">2.1, 2.2, 2.6</td><td></td><td></td><td colspan="2">4.1, 4.8</td></tr>
<tr><td>CASTOR</td><td>1.7</td><td></td><td>2.1, 2.2</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>STOR-M</td><td>1.1, 1.4</td><td>1.1, 1.4</td><td colspan="2">2.1, 2.2, 2.8</td><td colspan="2">3.3, 3.4, 3.5</td><td>4.8</td><td>4.8</td></tr>
<tr><td></td><td>exp</td><td>th</td><td>exp</td><td>th</td><td>exp</td><td>th</td><td>exp</td><td>th</td></tr>
</table>

<table>
<tr><th>Tokamak</th><th colspan="2">5. Diagnostics development</th><th colspan="2">6. Control, data acquisition, remote participation</th><th colspan="2">7. Excellency education, knowledge transfer, capacity building</th><th colspan="2">8. Expertise exchange</th></tr>
<tr><td>T-10</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>GUTTA</td><td></td><td></td><td>6.2</td><td></td><td>7.2, 7.3</td><td>7.2, 7.3</td><td></td><td></td></tr>
<tr><td>SUNIST</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>EGYPTOR</td><td>5.3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>ETE</td><td>5.1, 5.2, 5.3</td><td>5.3</td><td></td><td></td><td></td><td></td><td>8.1</td><td>8.1</td></tr>
<tr><td>TCABR</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>ISTTOK</td><td colspan="2">5.1, 5.2</td><td>6.2</td><td></td><td colspan="2">7.2, 7.3</td><td colspan="2">8.1, 8.2</td></tr>
<tr><td>CASTOR</td><td>5.2</td><td>5.2</td><td></td><td></td><td>7.1, 7.2</td><td>7.2</td><td>8.1, 8.2</td><td>8.1, 8.2</td></tr>
<tr><td>STOR-M</td><td colspan="2">5.1, 5.2</td><td>6.2</td><td>6.2</td><td></td><td></td><td>8.1</td><td>8.1</td></tr>
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</table>

exp, experiment; th, theory.

turbulent transport will be investigated. The behaviour of edge fluctuations is clearly modified by the emissive electrode bias. Low frequency fluctuations are suppressed for a negative bias and even amplified for a positive bias, suggesting that the different behaviour of the particle confinement for positive and negative bias may be related to the edge turbulent transport. The fast modification of the plasma rotation (induced by biasing) has indicated that the viscosity is dominated by anomalous processes. To clarify the importance of neoclassical effects on the viscosity, the same experiments will be performed in plasmas with a larger magnetic ripple. The larger ripple will be achieved using only 12 of the 24 toroidal field coils.

Studies of physical processes in improved plasma confinement regimes induced using the electrode biasing technique have been performed on the TCABR tokamak [5]. Detailed studies have been carried out on the physical processes involved in the transport barrier formation at the plasma edge. Temporal and radial profiles of plasma parameters with and without bias have been measured. A comparison of the profiles shows an increase in the density, up to a maximum factor of 2.6, while the H-alpha hydrogen spectral line intensity decreases and the CIII impurity remains at the same level. An analysis of the temporal and radial profiles of the plasma parameters indicates that the confined plasma entered the H-mode regime. Data analysis shows a maximum enhanced confinement factor of 1.95, decaying to 1.5 at the maximum of the density, in comparison with the predicted Neo-Alcator scaling law values. Indications of a transient increase in the density gradient near the plasma edge were obtained with measurements of density profiles. Calculations of the turbulence and transport at the plasma edge, using measured floating potentials and ion saturation currents, show a strong decrease in the turbulence power spectra and transport.

Biasing experiments have been performed in several tokamaks, with different and sometimes even contradictory results obtained. This justifies the need for joint research in this area. The emissive electrode will be used in different devices (e.g. ISTTOK, STOR-M, CASTOR [6] and TCABR) to establish a set of comparable data from different small tokamaks and to compare these with those of nonemissive electrodes, contributing therefore to our understanding of the role of the electric field in plasma confinement as well as the role of the edge plasma–wall interaction effects.

Heating, current drive and generation of sheared fluxes by Alfvén waves are under investigation on the TCABR tokamak. Extensive theoretical investigations have been carried out to find the best conditions for the Alfvén wave excitation, including toroidal and impurity effects. A new antenna system has been developed. In spite of the preliminary character of the experiments that have been carried out, it has been possible to determine conditions for good antenna–plasma coupling and to obtain an indication of plasma heating and current drive by the Alfvén waves. Another important possibility is utilization of the Alfvén waves to trigger the H-mode.

Instabilities that occur in different discharge scenarios when Alfvén waves are used for heating and current drive will be investigated on TCABR. Experimental and theoretical studies of the ideal kink instabilities and resistive tearing instabilities will be carried out, performing detailed studies of

Table 4. CRP joint activity matrix.

Topics	Subtopics	T-10	GUTTA	SUNIST	EGYPTOR	ETE	TCABR	ISTTOK	CASTOR	STOR-M	Activity description
1. Core transport and turbulence	1.4										
	1.7	●							●		Joint studies of impurity transport in CASTOR and T-10
2. Edge physics, PSI and technology	2.1	●					●	●	●	●	Joint studies of edge turbulence in different tokamaks
	2.2						●	●	●	●	Joint studies of the effects of the biasing induced electric field on plasma performance
	2.8				●	●				●	Optimization of discharge parameters by fuelling and wall conditioning in small tokamaks
3. Heating, CD and plasma formation	3.3		●	●						●	Comparative studies and development of different nonsolenoid plasma formation method
	3.5		●	●	●	●				●	Modelling and experimental studies of startup in tokamaks
4. MHD and control	4.5	●					●	●			Theoretical and experimental investigations of runaway and disruptive discharges in tokamaks
	4.8						●	●		●	Theoretical and experimental investigations of the influence of edge biasing on MHD activity
5. Diagnostics improvement and development	5.1					●	●	●		●	Collaboration on development and improvement of core diagnostics
	5.2					●		●	●	●	Collaboration on development and improvement of edge diagnostics
	5.3				●	●					Improved methods of equilibrium reconstruction and plasma position determination using magnetic diagnostics
6. Control, data acquisition, remote participation	6.2		●					●		●	New approaches for real time plasma position control
7. Excellency education, knowledge transfer, capacity building	7.2		●					●	●		Participation of CRP members, PhD students in joint studies
	7.3		●					●			Participation of CRP members, undergraduate students in joint studies

the disruptive instability including toroidal asymmetry effects, in collaboration with the Kurchatov Institute in Russia.

Two projects are under development on the TCABR tokamak with the objective of investigating the magnetic fluctuations associated with the MHD instabilities and to find ways of controlling them. The first one is based on a magnetic limiter, which will be used to apply resonant magnetic fields with well-defined helicities. The second one is based on the injection of impurity pellets to modify locally and globally the plasma parameters, mainly the effective charge, Z_{eff}, which changes the plasma transport properties and increases the emission of bremsstrahlung radiation. By analysing the experimental magnetic fluctuation and signals from some other diagnostic systems, such as H_α and soft x-ray emission, an artificial neural network will be trained to forecast the exact instant that the instability may occur. An external command signal, in real time, will be used to turn on one or two defence mechanisms in an attempt to control the instability. The success of such a system may represent significant help towards mitigating the effects of major disruptions in tokamaks.

Investigation of the MHD stability and its control by ECH/ECCD is proposed on T-10. HIBP and reflectometry diagnostics at T-10 together with ECRH/ECCD give information about the behaviour of instabilities.

Investigation of generation of suprathermal electrons under ECRH/ECCD, analysis of suprathermal electron generation during plasma disruption and measurement of thermal and nonthermal SXR spectra using an SXR spectrometer will also be carried out on the T-10 tokamak. Nonthermal electrons ($E \sim 40$–$100\,\mathrm{keV}$) represent one of the most important features of the disruption instability.

Studies of plasma and runaway electron parameters in runaway dominated discharges using measurements of hard x-ray emission, magnetic diagnostics, plasma spectroscopy and reflectometry are a part of the TCABR programme. Production of runaway electrons by the avalanche mechanism has been investigated. In this regime, runaway electrons are produced by close-encounter collisions of energetic electrons in the tail of the distribution function. This mechanism has attracted attention because it can explain the production of runaway electrons in conditions where the standard Dreicer mechanism, based upon multiple small-angle scattering, is not effective. An important result of this work has been the identification of a new regime of runaway discharges, in which the discharge current is almost completely maintained by a relativistic electron beam ($E \sim 5\,\mathrm{MeV}$), in a background plasma of low temperature ($T_\mathrm{e} \sim 5\,\mathrm{eV}$). This regime is characterized by a strong increase in the relaxation instability associated with runaway electrons, which is manifested by strong spikes in the temporal traces of H_α emission, electron cyclotron radiation, total power radiated by the plasma, MHD activity, etc. This strong nonlinear instability is clearly associated with some type of energy relaxation of the relativistic electron beam.

Fluctuations of the magnetic field will be studied using arrays of magnetic sensors based on the Hall effect in the CASTOR tokamak [6]. Probe arrays oriented in the poloidal and/or radial direction will be used to measure turbulent structures simultaneously in many locations in the plasma column. The electric fields in the edge plasma of the CASTOR tokamak will be modified by biasing an electrode immersed in the edge plasma. The resulting changes in turbulent structures will again be measured using probe arrays. Furthermore, the transport of impurity ions, injected into the edge plasma from outside under these conditions, will be studied using the VUV spectrometer with wavelength and spatial resolution and compared with results of numerical simulations. The probe measurements of the density fluctuations will be accompanied by the contactless method—microwave reflectometry.

A systematic measurement and study of plasma edge parameters will be carried out in the ETE spherical tokamak [7]. The project includes the implementation and upgrading of the diagnostics (Thomson scattering, neutral lithium beam probe, electrostatic probes, spectroscopic and magnetic measurements and ultra-soft x-ray photodiode arrays, among others) that will be used to study the plasma boundary properties. Several aspects of the edge physics will be considered, including issues of plasma fuelling and density control, impurity effects and wall conditioning, and power and particle handling. Activities related to upgrading the Thomson scattering system as well as implementation of a data acquisition system in ETE have been carried out in collaboration with the Centro de Fusão Nuclear (CFN) of the Instituto Superior Técnico (IST) in Lisbon, Portugal.

Measurements of plasma rotation will be continued on TCABR to get results for the temporal profile of the toroidal rotation in the ohmic regime, in the H-mode regime with an electrically biased electrode and Alfvén waves and in the runaway regime.

3.2. Small tokamaks as a test-bed for new tools, materials and technologies

Small tokamaks can be a good test-bed of new tools, materials and technologies for large machines. On T-10, plasma control under lithium gettering and the use of lithium elements as plasma-facing components is under investigation. Effects due to plasma–wall interactions on different materials will be investigated on ETE simultaneously with the development of plasma assisted surface treatment processes. Implementation of the liquid metal limiter and evaluation of liquid gallium limiters as a new plasma facing device for fusion applications are being carried out on the ISTTOK tokamak.

The tritium balance research in JET and particle balance investigations on different tokamaks show the dominant role of deposited films in hydrogen isotope absorption. Different structures of carbon films were observed in T-10, which differ in the deuterium fraction. A study of film deposition conditions, film structure and hydrogen isotope content is one of the priority problems of plasma–surface interaction research on T-10. Analysis of the peculiarities of generation of thin films and dust during operating regimes and wall conditioning processes, studies on the dependence of film structure on formation conditions and studies on the partition of hydrogen isotopes in films and other plasma–surface interactions will be performed.

Testing of control algorithms developed for large tokamaks and ITER at low aspect ratio may provide important benchmarking of the methods developed. Here the contribution of GUTTA [8], with low aspect ratio, may be highly valuable. For these areas of fusion research, the GUTTA tokamak has the advantages of a flexible poloidal field configuration, good vacuum conditions, excellent availability and good access for diagnostics.

Design studies of Next Step spherical tokamaks (STs) show that the optimum aspect ratio for a burning ST, ST component test facility or ST power plant lies between 1.4 and 2. With aspect ratio $A = 1.9$, GUTTA fills the gap between spherical and conventional aspect ratio tokamaks. Plasma startup is an important issue in ST research due to the reduced space for the central solenoid. Experiments with the ECRH/EBW startup on GUTTA will contribute to this area.

Another method of noninductive (without use of the central solenoid) plasma current startup and sustainment will be tested on the SUNIST spherical tokamak [9]. The plan is to produce a seed current using ECR with electrode discharge assistance and to investigate how to transfer that current into a typical spherical tokamak discharge.

3.3. Improvement and development of diagnostics

Development of new plasma diagnostics was traditionally an important part of small tokamak activities and is expected to be a valuable output of the CRP. A new diagnostic system based on the scanning probe microscope (STM-AFM) will be developed and applied for analysis of thin films and dust during the operating regime and wall conditioning processes on T-10. On this tokamak, the development of new diagnostics of nonthermal emission in a wide energy range, $E = 3$–$200\,\mathrm{keV}$, is also foreseen.

Recent experiments in tokamaks have indicated that localized beams of nonthermal electrons can be induced during reconnection of the magnetic field lines at the initial stage of disruptions. Beams can affect the growth of tearing modes and in some cases can lead to avalanches of runaway electrons during plasma current collapse. The analysis is complicated by the fact that the x-ray emission produced by nonthermal electrons is distributed in a limited forward cone along the electron lines of flight. Measurements of the x-ray intensity in the direction tangential to the plasma column (close to the toroidal direction) are required in order to provide enhanced sensitivity to suprathermal electrons. A new diagnostic system based on CdTe detectors with orthogonal and tangential views of the plasma column is installed on the T-10 tokamak. The system will be used for studies of nonthermal electrons in future experiments.

Development and testing of advanced tools for edge plasma diagnostics is included in the CASTOR proposal. In particular, a so-called tunnel probe for fast measurements of the electron temperature will be used to determine the level of electron temperature fluctuations. Its modifications (the segmented and Katsumata tunnel probe) appeared to be sensitive to the ion temperature. Finally, the ball-pen probe was designed to take direct measurements of the plasma potential and its fluctuations. The design of an oriented electric probe (the Gundestrup probe) for ion flow measurements has been optimized. The experimental work will be accompanied by numerical simulations in order to interpret correctly the experimental results achieved. Implementation of these advanced probes in other small tokamaks which participate in the CRP is envisaged. The design and fabrication of the Gundestrup probe to measure the poloidal and toroidal components of the velocity of the plasma ions in different operating regimes has also been proposed on the STOR-M tokamak.

The ISTTOK proposal includes the development of a soft x-ray tomography diagnostic based on commercial CCD cameras and optimization of the time-of-flight energy analyser for plasma potential measurements using a heavy ion beam diagnostic that will be used to study the plasma core electric field. Activities in data acquisition and plasma control are also foreseen on ISTTOK, including (i) upgrading the ISTTOK data acquisition system; (ii) collaboration in the upgrades of the TCABR, ETE and EGYPTOR [10] data acquisition systems; and (iii) development of real-time systems in collaboration with TCABR for plasma control and long pulse operation including ISTTOK alternative plasma current operation.

On ETE, it is proposed to use the fast lithium beam probe to measure the particle influx from a gas puff, and the density fluctuations at the boundary. The probe ($10\,\mathrm{kV}$; $1\,\mathrm{mA\,cm^{-2}}$ equivalent current) has been developed in a continuing collaboration with the lithium beam probe group of the Compact Helical System of the National Institute for Fusion Science (NIFS) in Toki, Japan.

3.4. Training, expertise development and capacity building

A very important goal of small tokamaks is to provide the necessary facilities for education of students, scientific activities of post-graduate students and training of personnel for large tokamaks. On CASTOR, an annual practical training course on tokamak operation has been organized, and in 2003 the summer training course (SUMTRAIC) hosted 12 Hungarian graduate and PhD students. The CASTOR tokamak was completely available for them for one week. The students were divided into three experimental groups (probe diagnostics, fluctuation measurements and plasma spectroscopy), supervised by Czech and Hungarian supervisors. Students participated in measurements and data analysis in different regimes. The course was concluded with a workshop, where students presented the results achieved. In 2004, the SUMTRAIC was organized on a more international basis (Hungary, Slovakia, Belgium and Egypt). The next experimental training course on the CASTOR tokamak (SUMTRAIC-III) for graduate and PhD students will be organized in June 2005. Participation in the course will be preferably offered to members of the CRP.

ISTTOK has been and will be used to support the experimental part of Master and PhD programmes on plasma physics and engineering.

Joint research on the EGYPTOR tokamak [10] will help improve links and deeper integration of EGYPTOR in national and international fusion activities. This will promote fusion research in Egypt and other developing countries and open wider possibilities for young scientists from these countries to participate in fusion research.

On GUTTA, a laboratory project for undergraduate students on ‘Plasma equilibrium control in a tokamak’ will be introduced as a part of the academic programme.

4. Summary

In summary, this interactive joint research project will provide coordination and guidance for integration of small tokamak projects. The output will also consist of:

(a) an established informational network of small tokamak projects resulting in improvements in communication among small tokamak groups working world-wide;

(b) practical advice and assistance via IAEA on further integration with the national programmes of large tokamaks, ITER and other international projects as well as contribution to mainstream nuclear fusion R&D;
(c) a coordinated plan of collaboration between small tokamak projects to support and promote free exchange of scientific and technical personnel, equipment and diagnostics;
(d) joint presentations of the scientific results obtained on small tokamaks under international collaboration.

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