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by tracer impurity technique in the tokamak TEXTOR

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Tracer injection technique for studies of material transport

First wall material erosion and deposition are of importance for reactor availability

- Limited lifetime of first wall
- Increased inventory of tritium due to co-deposition
- Dust formation and exfoliation of deposited layers
- Reduced performance of diagnostics (i.e. first mirrors)

Techniques mainly used for studying material transport in tokamaks

Post-mortem analysis

- Can be done once per experimental campaign
- Analysis averaged over plasma conditions of the entire campaign
- Complex analysis of multi-layered structure of deposits

Tracer impurity injection

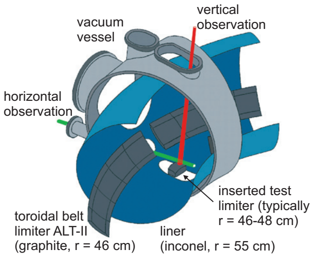
- Can be performed during a campaign, if material samples can be extracted
- Performed in well defined experimental conditions (reproducible discharges)
- Simpler surface analysis: focused on specific, easy to detect element on the very surface of material samples

Application of tracer impurity technique

- Injection of tracer impurity in reproducible plasma discharges with pre-selected conditions
- Investigation of local transport → Analysis of samples located near injection
- Investigation of long range transport → Analysis of first wall tiles (Vessel intervention necessary)
- Injected species should be representative for wall materials and plasma constituents and be detectable by analysis techniques: $^{13}CH_4$, $^{13}C_2H_4$, $^{15}N_2$, $^{18}O_2$, WF_6, MoF_6
- Analysis of distribution of tracer elements on the wall surface by surface analysis techniques, i.e. Nuclear Reaction Analysis (NRA), Rutherford Backscattering (RBS), Elastic Recoil Detection Analysis (ERDA), Secondary Ion Mass Spectrometry (SIMS), Electron Probe Microanalysis (EPMA)

Tracer impurity injection in TEXTOR

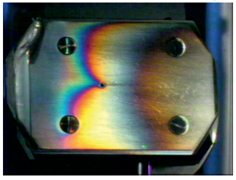
Limiter lock system in TEXTOR



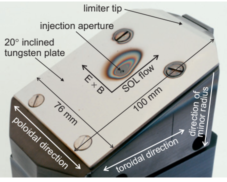
- Versatile facility for exposing test limiters without breaking vacuum in TEXTOR [1]
- Test limiters of up to ~100 mm typical size (CF 150 limiter exchange window)
- Electrical connections
- Heating and temperature control by thermocouples
- Gas injection through test limiter
- Spectroscopic observation from two directions
- Two limiter lock systems available
  - LL1 on bottom of toroidal section 10/11
  - LL3 on top of toroidal section 15/16

Review of tracer injection experiments performed in TEXTOR

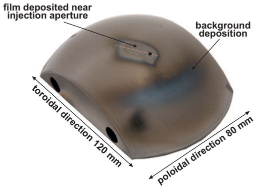
^{13}C on roof-like limiter with Al plate



^{13}C on roof-like limiter with W plate



^{13}C on spherical graphite limiter



Technique of $^{13}CH_4$ tracer injection was pioneered in TEXTOR

experiment on 24/06/1997 roof-like limiter with aluminium plate [2]

Crucial parameter: **local deposition efficiency**

$$\frac{\underline{\text{Amount of 13C deposited on limiter}}}{\text{Amount of injected }^{13}\text{CH}_4}$$

Deposition efficiency in this 1997 experiment ≈0.2% (low!)

Experiments in TEXTOR under variation of

- Injected species: $^{13}CH_4$, $^{13}C_2H_4$, SiH_4, $^{15}N_2$, $^{18}O_2$, WF_6, MoF_6
- Substrate material: graphite, aluminium, tungsten, molybdenum
- Substrate roughness: 0.1 - 1 μm
- Substrate temperature: 150 - 2700°C
- Increased incident ion energy by negative limiter biasing of -300 V
- Discharge conditions: Ohmic and NBI heated discharges, without and with resonant magnetic perturbations (RMP)

Typically, the local ^{13}C deposition efficiency was in a range between 0.1% and 10%.

Local ^{13}C deposition efficiency is

- Higher for spherical limiters with a grazing angle of incidence of the magnetic field lines comparing to the roof-like geometry
- Higher on the graphite than on the tungsten substrate
- Higher in Ohmic than NBI heated discharges
- Higher for higher incident ion energy (negatively biased limiter)
- Higher when decreasing the puffing rate
- Higher for ethene than methane

Modelling by ERO code

[6, 7, 9, 13, 15, 18]

- "Standard" assumptions: simulated deposition efficiency of ~50%
- Agreement with experiment with assumption of enhanced (factor ~10) re-erosion of deposited carbon

Overview of impurity injection experiments performed in TEXTOR

Date of experiment	Limiter geometry	Substrate material	Special experimental conditions	Injected species	Limiter temperature [°C]	Surface roughness [um]	Discharge heating	Radial position [cm]	Injected amount [x10^{20} atoms]	Deposition efficiency [%]	References
1993	spherical	graphite		SiD4	220	n/a	ohmic	46.5	0.24	4.5	[3]
02.03.1995	spherical	steel		SiD4	n/a	n/a	ohmic	46.8	0.7	5	[4,5]
03.02.1997	roof	Al/ graphite		SiH4	150	n/a	ohmic	46	12.7	0.1	[6]
24.06.1997	roof	Al		13CH4	150	n/a	ohmic	46	17	0.2	[2,7]
03.02.2004	spherical	graphite	rough graphite	13CH4	450	1	ohmic	47	2.2	9	[10]
04.02.2004	spherical	W		13CH4	450	0.1	NBI	48	5.7	0.3	[8-10]
15.06.2004	spherical	graphite	rough graphite	13CH4	450	1	NBI	48	5.5	4	[8-10]
27.10.2005	roof	W		13CH4	150	0.1	ohmic	46	6.3	0.11	[11]
03.11.2005	roof	Mo		13CH4	150	0.1	ohmic	46	3.8	0.14	[11]
07.03.2006	roof	graphite		13CH4	150	0.1	ohmic	46	4.1	0.3	[11]
13.12.2006	spherical	graphite		13CH4	450	0.1	NBI	48	1.7	1.3	[10]
13.03.2007	spherical	graphite		13C2H4	450	0.1	ohmic	47	8.1	2.1	[12,13]
13.03.2007	spherical	W		13C2H4	450	0.1	ohmic	47	7.7	1.2	[12,13]
14.03.2007	spherical	graphite		13CH4	450	0.1	ohmic	47	2.8	1.7	[10]
15.03.2007	spherical	W		13CH4	450	0.1	ohmic	47	2.7	0.8	[10]
05.03.2008	roof	graphite		WF6	150	0.1	NBI	47.5	1.9	1	[6,14]
30.06.2009	roof	graphite	stepped limiter	13CH4	150	0.1	ohmic	45.5	13	0.45	[15]
15.06.2010	spherical	graphite	no RMP (LL1)	13CH4	2700	0.1	NBI	46	n/a	14	[16,17]
15.06.2010	spherical	graphite	no RMP (LL3)	13CH4	900	0.1	NBI	46	n/a	0.7	[16,17]
16.06.2010	spherical	graphite	static RMP (LL1)	13CH4	1900	0.1	NBI	46	n/a	18	[16,17]
16.06.2010	spherical	graphite	static RMP (LL3)	13CH4	900	0.1	NBI	46	n/a	0.8	[16,17]
16.06.2010	spherical	graphite	sweep RMP (LL1)	13CH4	2300	0.1	NBI	46	n/a	6	[17]
16.06.2010	spherical	graphite	sweep RMP (LL3)	13CH4	500	0.1	NBI	46	n/a	0.6	[17]
10.02.2011	roof	graphite	biased limiter -300 V	13CH4	500	0.1	ohmic	47	3.2	1.7	[18]
16.02.2011	roof	graphite	low injection rate	13CH4	150	0.1	ohmic	46.2	0.7	0.7	[18]
09.06.2011	roof	graphite	high Z transport	WF6	150	0.1	NBI	48	1.93	2.5	[14]
19.11.2011	roof	graphite	stepped limiter	WF6	150	0.1	NBI	48	3.3	1.9	[15]
18.04.2012	roof	Mo	low flux ('cave') limiter	13CH4	400	0.1	ohmic	46.8	4.6	9.2	[19]
05.02.2013	roof	graphite	high amount of injection	13CH4	150	0.1	ohmic	47	70	11	here
14.11.2013	roof	graphite	multi aperture limiter	13CH4	150	0.1	ohmic	46.5	t.b. analysed	t.b. analysed	[19]
04.12.2013	roof	graphite	long range high Z transport	MoF6	150	0.1	NBI	47.5	14	1.5	[20]

New experiment with high injected amount of $^{13}CH_4$

Background

- Significantly higher amount of injected $^{13}CH_4$ in comparison with previous experiments in TEXTOR: 7×10^{21} vs. typically $\sim10^{20}$ - 10^{21}
- Higher injected amount achieved by larger number of pulses, 118 pulses vs. typically 10 or less (608 s of plasma vs. typically 50 s or less)
- Puffing rate in flattop similar to most of previous experiments: 2×10^{19} $^{13}CH_4/s$

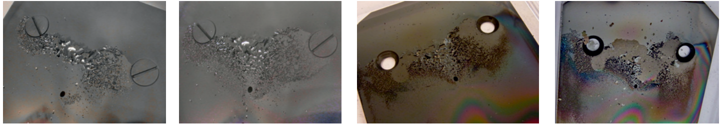
Goals of experiment

- Investigate local carbon deposition for higher carbon turnover, relevant to long-term experiments
- Investigate long range transport of injected ^{13}C
  - Towards distant collector probe at LL3 located toroidally on opposite top side of TEXTOR
  - Measure toroidal distribution of ^{13}C on the belt limiter ALT-II

Results

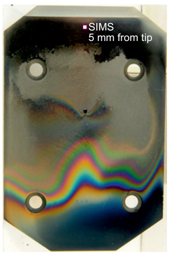
Roof-like limiter with graphite plate and injection aperture
Back side with graphite and molybdenum collector plates
Distant collector with graphite and molybdenum plates

Peeling off of deposited layer during storage on air

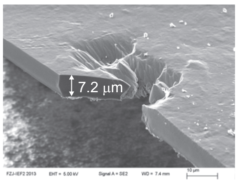


After 7 days
After 17 days
After 2.5 months
After 4 months

After 6 months flakes were removed and analysed

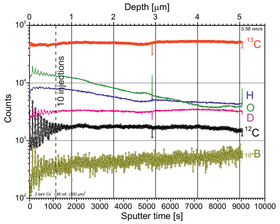


SEM of a flake



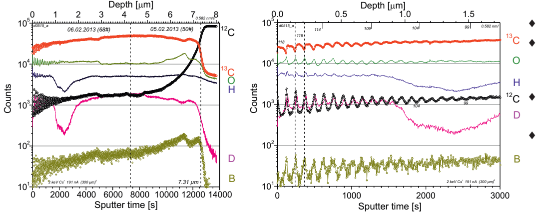
6.4 mg of flakes were collected
≈2.5×10^{20} ^{13}C assuming 85% $^{13}C/C$
→ 3.6% of injected ^{13}C in flakes

SIMS of a flake



- $^{13}C/C$ = 97%
- Last 10 injections visible (oscillations)
- 60 nm/pulse
- 7.4 μm for 118 pulses

SIMS depth profiling of remaining deposit, 5 mm from limiter tip

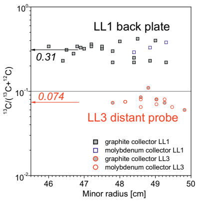


- $^{13}C/C$ = 97%
- Last 20 injections visible as equidistant oscillations ≈70 nm/pulse
- 7.3 μm total layer, matches well 70 nm × 118 ≈ 8.2 μm
- Takes 1-2 μm or 15-30 pulses to get ^{13}C signal stationary, probably due to roughness of SIMS crater

Conclusions for local ^{13}C deposition

- 7.4×10^{20} (±20%) ^{13}C atoms were locally deposited on top plate of 7×10^{21} ^{13}C injected
- Local deposition efficiency **<u>11%</u>** (to be compared with 0.3% in reference case [11,18])
- Thickness growth rates near maximum deposition are similar: (new) 70-80 vs. (ref) 80-90 nm/pulse
- Higher deposition efficiency is mainly due to bigger affected area: (new) ≈50 vs. (ref) ≈3 cm^2
- Limiter in new experiment is further outside LCFS than in reference experiment
  - Injection aperture is in deposition dominated region → Increased deposition
  - Returning ^{13}C particles are distributed over larger area (lower flux) → Increased deposition
- Area of local detectable deposition increases pulse-by-pulse → Apparent increase of deposition

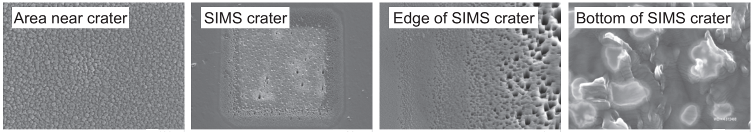
$^{13}C/C$ on back plate and in distant location



Conclusions for long range ^{13}C transport

- $^{13}C/C$ = 31% on back plate, $^{13}C/C$ = 7.4% on distant probe (cf. 1.1% natural abundance of ^{13}C)
- ^{13}C is distributed radially uniformly on both collector locations
- Transport of ^{13}C to back plate in LL1 is presumably not direct from injection, but via other obstacles in vessel, e.g. main limiter ALT-II (intermediate range transport)
- On main limiter ALT-II, up to ~10^{17} $^{13}C/cm^2$ was estimated by NRA
- Distribution of ^{13}C on ALT-II was nor measurable, as 10^{17} $^{13}C/cm^2$ is at the detection limit of NRA
- ~10^{21} ^{13}C is deposited on ALT-II (assuming ~1 m^2 of deposition dominated area)

Roughening of SIMS crater



Area near crater
SIMS crater
Edge of SIMS crater
Bottom of SIMS crater

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