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Thermal and Electrostatic Analyses of One Dimensional CFC Diagnostic Calorimeter for SPIDER Beam Characterisation

CONSORZIO RFX Ricerca Formazione Innovazione
Euratom-ENEA Association

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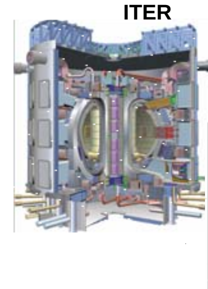
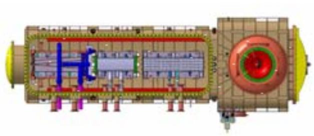
ELECTROSTATIC stationary analysis. THERMAL transient, non-linear analyses

ITER



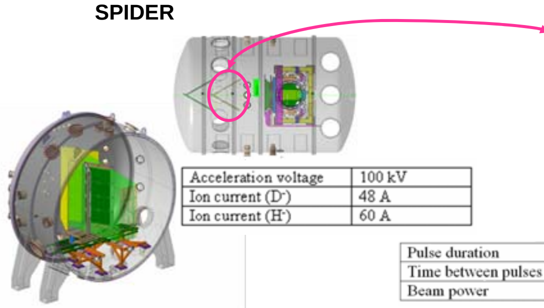
Major radius of plasma	6.2 [m]
Minor radius of plasma	2 [m]
Volume of plasma	840 [m³]
Density	10^{20}m^{-3}
Peak temperature	17 keV
Plasma current	15 [MA]
Toroidal field on the axis	5.3 [T]
Fusion power	500 [MW]
Pulse duration	> 400 [s]
Gain factor	Q > 10

NBI



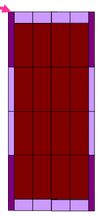
Number	2 (3) H&CD
Power/NBI	16.7 MW
Operation time	1 hour
Current density	200 A/m² (D⁻)
Acceleration voltage	1 MV

SPIDER



Acceleration voltage	100 kV
Ion current (D⁻)	48 A
Ion current (H⁻)	60 A

STRIKE



Pulse duration	10 s
Time between pulses	1200 s
Beam power	5 MW

STRIKE PURPOSES

ITER Requirements: Uniformity ≤ ±10 %

Measure of:

Beam Uniformity → Power dwposition / Negative ion current

Beam divergence

Stripping losses in SPIDER

STRIKE REQUIREMENTS

- Observation of rear side
- Several seconds pulses
- Energy flux uniformity measurements
- Current uniformity measurements
- Divergence measurements
- 2 positions (open-close)
- 2 axial distances
- 2 converging panels

PHYSICAL PHENOMENA IN SPIDER

Beam particle with the same charge → Beam divergence
Stripping within the accelerator → Beam divergence
Stripping between the accelerator and STRIKE: $D^- \rightarrow D^0$, $D^- \rightarrow D^+$
Beam interaction wjth background gas → Plasma formation → Radiating sheet

Particles impact to STRIKE → Secondary electrons emission / Sublimation → Radiating sheet

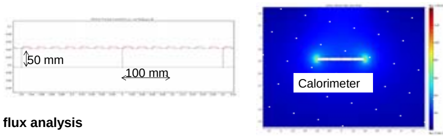
Preliminary specifications and feasibility study

Electrostatic analysis

Hp: D+, D-, D⁰ extract secondary electrons at 3 eV

Scope: prevent secondary electrons extracted from a tile from being collected by another tile to measure the beam current distribution

Cases simulated: starting angle 30°, **45°** 60°, 90°
biasing voltages 60V, 100V, **200V**



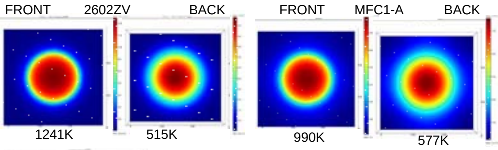
Heat flux analysis

Simulated material : Graphite
Carbon Fibre Composites (CFC):
— MFC-1A by Mitsubishi
—2602ZV by SGL CARBON GROUP
—1501G by SGL CARBON GROUP

Modelled system: part of a sector around the area hit by one beamlet. The surface where heat is deposited is 30 mm × 30 mm

Simulated cases: thicknesses : 5 mm, 20 mm and 30 mm
different pulse durations: 0.1 s, 1 s and 2 s
heat fluxes: 10 MW/m² 20 MW/m² and 100 MW/m²

20 mm thickness, 20 MW/m² and 1 s pulse duration; observation performed when heat load ends

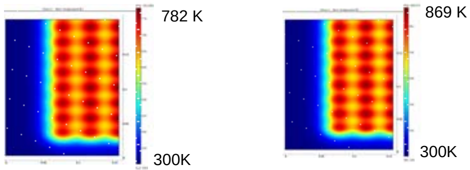


Temperature profile along middle line of the simulated sample MFC1-A 20 mm

Conclusion: MFC1-A is the material for future simulations; 20 mm thickness

Uniformity

0.02m thickness, MFC1-A
Rear side; g = 60°; t = 5 s; t = 5s; d = 3 mrad; d = 1 m



Power per Beamlet - 15 % Power per beamlet + 5 %

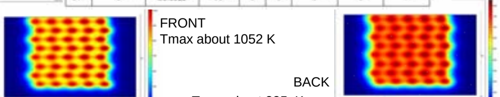
Reference case: 848 K

Conclusion: ~ 20° every 5%

Assessment of sensitivity to beamlet deflection

Beam characteristic: Gaussian distribution
Modelled system: half bemalet group (0.396/2)x(0.32) m²
0.02m thickness, MFC1-A
Vertical misalignment is negligible
5 s pulse duration and observation when heat load ends

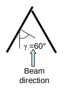
Case	Vertical misalignment α [rad]	Horizontal misalignment β [rad]	Exposure angle γ [degree]	X-width σ_x [mm]	Y-width σ_y [mm]	X-divergence δ_x [mrad/m]	Y-divergence δ_y [mrad/m]	Distance between calorimeter and GG [m]
017	0	±0.0025	60°	3	3	3	3	1



Conclusion: all beamlets are contained within the sector and clearly identified

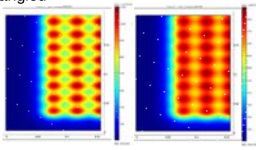
Assessment of calorimeter position

Beam characteristic: Gaussian distribution
Modelled system: (0.396/2)×(0.16/2) orthogonal, (0.396/2)x(0.32/2) angled
0.02m thickness, MFC1-A
Simulated cases:

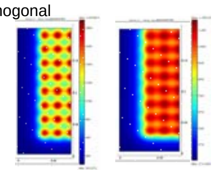


Case	Vertical misalignment α [rad]	Horizontal misalignment β [rad]	Exposure angle γ [degree]	X width σ_x [mm]	Y width σ_y [mm]	X divergence δ_x [mrad/m]	Y divergence δ_y [mrad/m]	Distance between calorimeter and GG [m]
015	0	0	0°	3	3	0	0	1
016	0	0	0°	3	3	3	3	1
017	0	0	60°	3	3	3	3	1
018	0	0	0°	3	3	5	5	1
019	0	0	60°	3	3	5	5	1

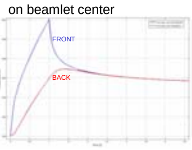
τ= 5s; δ = 3 mrad; d = 1m; t = τ; RT = 300 K
observation when heat load ends
angled



τ= 5s; δ = 3 mrad; d = 1m; t = τ; RT = 300 K
observation when heat load ends
orthogonal



Temperature vs Time on beamlet center



Summarized results

Case		Tmax front [K]	T back [K]	T asymptotic [K]
015 1s	(t=1s)	2808	662	
016 1s	(t=1s)	890	531	446 (500 s)
017 1s	(t=1s)	601	448	379 (900 s)
018 1s	(t=1s)	710	496	446 (800 s)
019 1s	(t=1s)	511	419	380 (900 s)
016 5s	(t=5s)	1880	1160	846 (900 s)
017 5s	(t=5s)	1102	848	621 (900 s)
018 5s	(t=5s)	1478	1067	823 (900 s)
019 5s	(t=5s)	917	769	604 (1100 s)

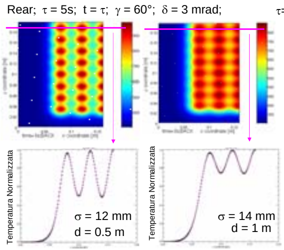
Conclusion:An angle of 60 degrees between the beam direction and the normal to the calorimeter surface should be sufficient to avoid too high superficial temperature, to allow 5 s pulses and at the same time to provide a good IR cameras image.

Measurement of divergence

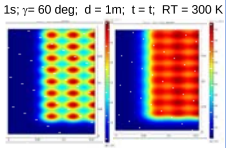
Modelled system: a quarter of a bemalet group (0.396/2)x(0.32/2) m²
0.02m thickness, MFC1-A
Simulated cases:

Case	Horizontal misalignment α [rad]	Vertical misalignment β [rad]	Exposure angle γ [degree]	X width σ_x [mm]	Y width σ_y [mm]	X divergence δ_x [mrad]	Y divergence δ_y [mrad]	Distance between calorimeter and GG [m]
016	0	0	0	3	3	3	3	1
017	0	0	60°	3	3	3	3	1
018	0	0	0	3	3	5	5	1
019	0	0	60°	3	3	5	5	1
020	0	0	0°	3	3	3	3	0.5
021	0	0	60°	3	3	3	3	0.5
022	0	0	0°	3	3	5	5	0.5
023	0	0	60°	3	3	5	5	0.5
024	0	0	60°	3	3	3	3	1
025	0	0	60°	3	3	3	3	1

Rear; τ = 5s; t = τ; γ = 60°; δ = 3 mrad;



τ= 1s; γ= 60 deg; d = 1m; t = t; RT = 300 K



δ = 3 mrad
T_{max} front ≈ 600 [K]
δ = 5 mrad
T_{max} front ≈ 510 [K]

Case	Exposure angle γ [degree]	divergence $\delta_x=\delta_y$ [mrad]	expected beamlet width [mm]	Distance between STRIKE and GG [m]	Front 1st peak [mm]	Front 2nd peak [mm]	Front 3rd peak [mm]	Back 1st peak [mm]	Back 2nd peak [mm]	Back 3rd peak [mm]
016 1s	0	3	6	1	6.57	6.48	6.5	8.2	7.17	8.15
020 1s	0	3	4.5	0.5	4.92	5	4.94	6.76	6.21	6.72
017 1s	60	3	12	1	13.03	12.67	12.62	14.52	13.24	14.22
021 1s	60	3	9	0.5	9.9	9.71	9.48	11.45	10.97	11.01
018 1s	0	5	8	1	8.7	8.35	8.41	10.1	8.57	9.78
022 1s	0	5	5.5	0.5	6.02	6	5.98	7.72	6.83	7.68
019 1s	60	5	16	1	17.47	16.53	16.68	18.81	16.51	18.14
023 1s	60	5	11	0.5	12.29	11.86	11.68	13.8	12.96	13.23

Summarized results

Conclusion: indications of the divergence can be obtained

Thermal simulation with radiation

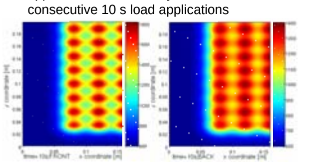
Beam characteristics: Gaussian-shaped beamlets, with peak heat flux 20 MW/m², half-width 3 mm and divergence 3 mrad

Simulated cases: 0.02m thickness, MFC1-A

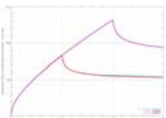
(1) after flux application, all tile faces are thermally insulated; three consecutive 5 s load applications

(2) after flux application, all tile faces are thermally insulated; at all times the face opposite the one hit by the beam radiates towards a surface at 300 K; four consecutive 5 s load applications

(3) after flux application, all tile faces are thermally insulated; at all times the face opposite the one hit by the beam radiates towards a surface at 300 K; three consecutive 10 s load applications



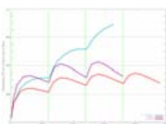
Case (3) at the end of third pulse



First pulse, X=160, Y=187

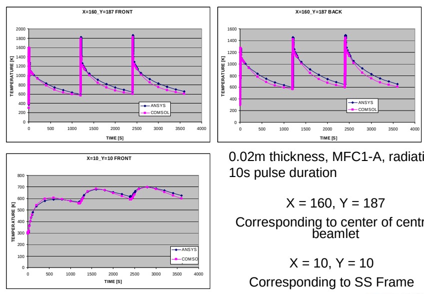
	case (1)		case (2)		case (3)	
no.	T before pulse[°C]	ΔT [°C]	T before pulse[°C]	ΔT [°C]	T before pulse[°C]	ΔT [°C]
0	27		27		27	
1	316	289	215	188	285	258
2	514	199	264	48	320	35
3	690	176	277	13	326	6.7
4			281	4		

Conclusion: operational range of IR cameras
10 s pulse duration
1200 s time between pulses
no active cooling



Successive pulses, X=10, Y=10

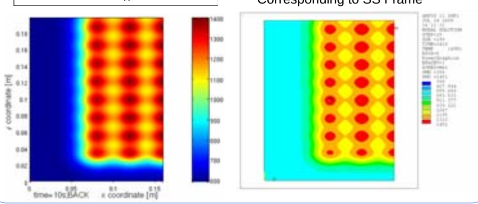
Comparison with ANSYS: successful



0.02m thickness, MFC1-A, radiation, 10s pulse duration

X = 160, Y = 187
Corresponding to center of central beamlet

X = 10, Y = 10
Corresponding to SS Frame



Conclusions: on the basis of COMSOL results, decision taken about:

- Reference material 1-D CFC
- 60° angle between beam direction and the normal to the calorimeter
- Observation of the rear side by IR cameras (2x2)
- No active cooling
- Tiles electrically insulated
- 2 axial distances
- 2 position (open-close)
- 10s pulse duration
- 1200 s

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