Automated Magnetic Divertor Design for Optimal Power Exhaust

Maarten Blommaert



Energie & Umwelt/ Energy & Environment Band/Volume 365 ISBN 978-3-95806-216-0



Forschungszentrum Jülich GmbH Institute of Energy and Climate Research Plasma Physics IEK-4

Automated Magnetic Divertor Design for Optimal Power Exhaust

Maarten Blommaert

Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt / Energy & Environment

Band / Volume 365

ISSN 1866-1793

ISBN 978-3-95806-216-0

Contents

Li	st of	Figur	es	xi
Li	st of	Table	S	xiii
Li	st of	\mathbf{Symb}	ols	xv
1	Intr	oduct	ion	1
	1.1	Nucle	ar fusion: confining the energy of stars	. 1
	1.2 Th		ivertor: a tokamak exhaust system	5
		1.2.1	Why today's tokamaks are equipped with divertors	6
			Impurity transport	. 6
			Pumping	. 7
			New plasma and divertor regimes	. 8
			Power exhaust limitations	. 9
		1.2.2	How to prevent excessive target erosion in DEMO?	10
	1.3	Comp	utational divertor design	. 12
	1.4 Optimal design		nal design	. 14
	1.5	Goals	and outline of the thesis	16
2	Opt	imal N	Magnetic Divertor Design	21
	2.1	Divert	tor design as an optimization problem	21
		2.1.1	First order necessary conditions for optimality	23
		2.1.2	Gradient calculation	26
			The forward approach to gradient calculation	26
			The adjoint approach to gradient calculation	. 27
			Discretization and adjoint approaches	. 28

CONTENTS

	2.2	2.2 Optimization algorithms		
		2.2.1	Nested optimization methods	32
		2.2.2	SQP, rSQP and one-shot methods	33
	2.3	Globa	lization	35
	2.4	Summ	nary	36
3	Inte	egral N	Agnetic Divertor Model	39
3.1 Magnetic field modelling				41
		3.1.1	Quasi-static magnetic field equations	41
		3.1.2	Exploiting toroidal (quasi-)symmetry	42
		3.1.3	Towards a free boundary equilibrium problem	44
		3.1.4	A simple and fast perturbation approach	45
	3.2	Plasm	a edge grid generation	48
		3.2.1	Continuous	49
		3.2.2	Discrete	52
3.3 Plasma edge modelling		a edge modelling	55	
		3.3.1	Plasma model equations	55
			Ion continuity equation	55
			Ion parallel momentum equation	56
			Neutral pressure diffusion equation	57
			Total internal energy equation	57
			Rate coefficients, radiative loss function and transport co-	
			efficients	58
			Remarks on the model choice	59
		3.3.2	Plasma model equations in convection-diffusion form \ldots	59
		3.3.3	Boundary conditions	61
			Target boundaries	61
			Core boundary	62
			Wall and private flux boundaries	63
		3.3.4	Discretizing and solving the plasma edge equations \ldots .	64
			Solving a correction equation $\ldots \ldots \ldots \ldots \ldots \ldots$	64
			Boundary conditions	65
	3.4	Concl	usions	66

4	Automated Design of a JET Configuration			
	4.1	A suitable objective functional formulation	38	
	4.2	Introducing a core shape constraint	72	
	4.3	Projection onto the design constraints	74	
	4.4	Solving the optimization problem	75	
	4.5	Automated design procedure applied to a JET configuration		
		4.5.1 Test case specification $\ldots \ldots $	78	
		4.5.2 Results	31	
		Optimization with low wall heating penalty 8	31	
		Optimization with high wall heating penalty 8	34	
	4.6	Conclusion	35	
5	5 In-Parts Adjoint Sensitivities for Efficient Magnetic Divertor De			
	sign			
	5.1	Motivation	90	
	5.2	A problem-adapted efficient computation of the objective gradient 9	92	
	5.3	Introducing the continuous adjoint plasma edge model 9)5	
		5.3.1 Linearization	96	
		5.3.2 Integration by parts $\ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots $	97	
		5.3.3 Adjoint boundary conditions	99	
	5.4	Derivation of a semi-discrete approach to in-parts adjoint sensitiv-		
		ity calculation $\ldots \ldots \ldots$)0	
		Towards a semi-discrete approach to sensitivity calculation 10)1	
		Finding the correct boundary multipliers 10)2	
	5.5	Sensitivity verification with a grid refinement study $\ldots \ldots \ldots \ldots 10$)5	
	5.6	Application to optimal current design)7	
	5.7	Conclusions	1	
6	Inte	gration of Free-Boundary Equilibrium Magnetic Model 11	3	
	6.1	CEDRES++ free-boundary equilibrium calculations 11	15	
	6.2	Comparison of magnetic models	8	
		6.2.1 Analysis of model assumptions	8	
		6.2.2 Comparison of sensitivities	21	

CONTENTS

	6.3	Adapt	ing the FBE calculations for automated target heat load	
		evalua	$tions \dots \dots$	5
		6.3.1	Estimation of contour line errors 128	5
		6.3.2	Introducing adaptive grid refinement 127	7
	6.4	Sensit	ivity calculation and verification	3
		6.4.1	Test case description)
		6.4.2	Sensitivity calculation and results)
		6.4.3	Setting up design constraints	3
		6.4.4	Optimal design results	5
	6.5	Conclu	usions $\ldots \ldots 138$	3
7	One	e-shot	Optimization 141	L
	7.1	Litera	ture review on one-shot approaches	3
	7.2	A first	t attempt to one-shot magnetic divertor design 140	3
		7.2.1	One-shot approach	3
		7.2.2	Set-up of an unconstrained WEST test case 14	7
		7.2.3	Discussion of first results	3
	7.3	Accele	eration of the one-shot procedure	3
		7.3.1	Grid deformation method $\ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 154$	1
		7.3.2	Adapted test case)
		7.3.3	Results and discussion)
			Convergence behaviour)
			Optimization efficiency)
			Conclusions	3
	7.4	A nov	el one-shot strategy with a practical augmented Lagrangian	
		global	ization $\ldots \ldots 165$	5
		7.4.1	One-shot optimization using a doubly augmented La-	
			grangian function	3
			Optimization with fixed-point solvers	3
			Doubly augmented Lagrangian theory	3
			Discussion)
		7.4.2	Derivation of a practical augmented Lagrangian merit func-	
			tion	1

CONTENTS

Bi	Bibliography 201			
	8.2	Sugges	stions for further research	197
			Development of optimal design algorithms $\ldots \ldots \ldots$	195
			Modelling and magnetic divertor designs $\ . \ . \ . \ .$	194
	8.1	Genera	al conclusions	193
8	Dis	cussion	and Conclusions	193
	(.(Discus	sion and conclusions	190
	77	1.0.2 D:	Giobalization of the constrained one-shot method	190
		700	Clabeling of the constrained and also with a l	180
		7.6.1	Constrained one-shot optimization based on an active set	100
	7.6	One-sl	not optimization for constrained magnetic divertor design .	185
		7.5.4	Results	181
		7.5.3	Overview of the applied one-shot algorithm	180
		7.5.2	Notes on sensitivity calculation	179
		7.5.1	From theory to practice	178
	test problem			177
	7.5	5 Application of the globalized one-shot method to the unconstrain		
		7.4.4	A robust approach to Hessian estimation	175
		7.4.3	A simple line search procedure for globalization $\ . \ . \ .$	174
			A practical augmented Lagrangian merit function $\ . \ . \ .$	172
			Considerations on the adjoint feasibility penalty	171

Energie & Umwelt/ Energy & Environment Band/Volume 365 ISBN 978-3-95806-216-0

