

Contents

Acknowledgements *xv*

Nomenclature *xvii*

Introduction *1*

Oleg B. Malyshev

References *3*

1	Vacuum Requirements	5
	<i>Oleg B. Malyshev</i>	
1.1	Definition of Vacuum	5
1.2	Vacuum Specification for Particle Accelerators	6
1.2.1	Why Particle Accelerators Need Vacuum?	6
1.2.2	Problems Associated with Beam–Gas Interaction	8
1.2.2.1	Beam Particle Loss	8
1.2.2.2	Background Noise in Detectors	8
1.2.2.3	Residual Gas Ionisation and Related Problems	9
1.2.2.4	Contamination of Sensitive Surfaces	9
1.2.2.5	Safety and Radiation Damage of Instruments	10
1.2.3	Vacuum Specifications	11
1.2.4	How Vacuum Chamber Affects the Beam Properties	12
1.3	First Considerations Before Starting Vacuum System Design	13
1.3.1	What Is the Task?	13
1.3.2	Beam Lattice	14
1.3.3	Beam Aperture and Vacuum Chamber Cross Section	15
1.3.3.1	Required Mechanical Aperture	15
1.3.3.2	Magnet Design	17
1.3.3.3	Mechanical Engineering	17
1.3.3.4	Other Factors Limiting a Maximum Size of Beam Vacuum Chamber	17
1.3.4	Vacuum Chamber Cross Sections and Preliminary Mechanical Layout	18
1.3.5	Possible Pumping Layouts	19
1.4	First and Very Rough Estimations	20
1.5	First Run of an Accurate Vacuum Modelling	22
1.6	Towards the Final Design	22

1.7	Final Remarks	25
	References	25
2	Synchrotron Radiation in Particle Accelerators	29
	<i>Olivier Marcouillé</i>	
2.1	Emission of a Charged Particle in a Magnetic Field	29
2.1.1	Radiated Energy Density and Power Density	31
2.1.2	Angular Flux	32
2.2	SR from Dipoles	32
2.2.1	Emission Duration and Critical Energy	33
2.2.2	Photon Flux	34
2.2.3	Vertical Angular Distribution of Photon Flux	37
2.2.4	Photon Power	39
2.2.5	Vertical Angular Distribution of Power	41
2.3	SR from Quadrupoles	42
2.4	SR from Insertion Devices	43
2.4.1	Motion of Charged Particles Inside a Planar Insertion Device	44
2.4.2	Resonance Wavelength	45
2.4.3	Radiation from Undulators and Wigglers	46
2.4.4	Angular Aperture of ID at Resonant Wavelength	51
2.4.5	Estimation of Power Distribution Radiated in a Wiggler	52
2.4.6	Estimation of the Power Collected by Simple Geometry Aperture	54
2.4.7	Method for Estimation Absorbed Power on the Complex Shapes	54
2.5	Software Dedicated to Evaluation of the Photon Flux and Power Distribution from the Insertion Devices	55
2.5.1	XOP	56
2.5.2	Synchrotron Radiation Workshop (SRW)	56
2.5.3	SPECTRA	57
2.5.4	SYNRAD	58
2.5.5	OSCARS	59
	Acknowledgements	59
	References	60
	Further Reading	60
3	Interaction Between SR and Vacuum Chamber Walls	61
	<i>Vincent Baglin and Oleg B. Malyshev</i>	
3.1	Photon Reflectivity	61
3.2	Photoelectron Production	69
3.2.1	Total Photoelectron Yield	69
3.2.2	Effect of the Photon Energy	72
3.2.3	Effect of the Incidence Angle	76
	References	76
4	Sources of Gas in an Accelerator Vacuum Chamber	79
	<i>Oleg B. Malyshev and Junichiro Kamiya</i>	
4.1	Residual Gases in Vacuum Chamber	79

4.2	Materials Used for and in Vacuum Chambers and Built-In Elements	81
4.2.1	Stainless Steel	82
4.2.2	Aluminium Alloys	83
4.2.3	Copper and Its Alloys	84
4.2.4	Titanium and Its Alloys	85
4.2.5	Ceramics	85
4.2.6	Other Vacuum Materials	86
4.3	Thermal Outgassing	87
4.3.1	Thermal Outgassing Mechanism During Pumping	88
4.3.2	Equilibrium Pressure	89
4.3.3	Vapour Pressure	91
4.3.4	Thermal Outgassing Rate of Materials	93
4.3.5	Outgassing Rate Measurements	97
4.3.5.1	Throughput Method	97
4.3.5.2	Conductance Modulation Method	98
4.3.5.3	Two-Path Method	98
4.3.5.4	Gas Accumulation Method	99
4.3.6	Thermal Desorption Spectroscopy	100
4.4	Surface Treatments to Reduce Outgassing	102
4.4.1	Cleaning	102
4.4.2	Bakeout	105
4.4.3	Air Bake	106
4.4.4	Vacuum Firing	106
4.4.5	Surface Coatings	108
4.4.5.1	Coating the Surface by Thin Films of Material with Low Hydrogen Permeability and Low Outgassing	108
4.4.5.2	Coating the Surface by Thin Film of Getter Materials	108
4.5	Electron-Stimulated Desorption	109
4.5.1	ESD Definition and ESD Facilities	109
4.5.2	ESD for Different Materials as a Function of Dose	112
4.5.3	ESD as a Function of Amount of Desorbed Gas	113
4.5.4	Effect of Pumping Duration	114
4.5.5	ESD as a Function of Electron Energy	119
4.5.6	Effect of Bakeout on ESD	122
4.5.7	Effectiveness of Surface Polishing and Vacuum Firing on ESD	123
4.5.8	A Role of Oxide Layer on Copper	125
4.5.9	Effect of Surface Treatment	125
4.5.10	Effect of Vacuum Chamber Temperature	125
4.6	Photon-Stimulated Desorption	128
4.6.1	PSD Definition and PSD Facilities	128
4.6.2	PSD as a Function of Dose	131
4.6.3	PSD for Different Materials	131
4.6.4	PSD as a Function of Amount of Desorbed Gas	135
4.6.5	PSD as a Function of Critical Energy of SR	136
4.6.6	Effect of Bakeout	137
4.6.7	Effect of Vacuum Chamber Temperature	140

4.6.8	Effect of Incident Angle	142
4.6.9	PSD versus ESD	144
4.6.10	How to Use the PSD Yield Data	145
4.6.10.1	Scaling the Photon Dose	145
4.6.10.2	Synchrotron Radiation from Dipole Magnets	145
4.6.10.3	PSD Yield and Flux as a Function of Distance from a Dipole Magnet	148
4.6.10.4	PSD from a Lump SR Absorber	151
4.6.10.5	Combining PSD from Distributed and Lump SR Absorbers	153
4.7	Ion-Stimulated Desorption	155
4.7.1	ISD Definition and ISD Facilities	155
4.7.2	ISD as a Function of Dose	156
4.7.3	ISD Yield as a Function of Ion Energy	158
4.7.4	ISD Yield as a Function of Ion Mass	159
4.7.5	ISD for Different Materials	160
4.7.6	Effect of Bakeout and Argon Discharge Cleaning	161
4.7.7	ISD versus ESD	161
4.7.8	ISD Yield as a Function of Temperature	161
4.7.9	ISD Yields for Condensed Gases	163
	Acknowledgements	166
	References	166
5	Non-evaporable Getter (NEG)-Coated Vacuum Chamber	175
	<i>Oleg B. Malyshev</i>	
5.1	Two Concepts of the Ideal Vacuum Chamber	175
5.2	What Is NEG Coating?	177
5.3	Deposition Methods	179
5.4	NEG Film Characterisation	181
5.5	NEG Coating Activation Procedure	182
5.6	NEG Coating Pumping Properties	188
5.6.1	NEG Coating Pumping Optimisation at CERN	188
5.6.2	NEG Coating Pumping Optimisation at ASTeC	190
5.7	NEG Coating Lifetime	193
5.8	Ultimate Pressure in NEG-Coated Vacuum Chambers	195
5.9	NEG-Coated Vacuum Chamber Under SR	196
5.10	Reducing PSD/ESD from NEG Coating	200
5.10.1	Initial Considerations	200
5.10.2	ESD from Vacuum Chamber Coated with Columnar and Dense NEG Films	201
5.10.3	Dual Layer	202
5.10.4	Vacuum Firing Before NEG Deposition	204
5.11	ESD as a Function of Electron Energy	204
5.12	PEY and SEY from NEG Coating	204
5.13	NEG Coating Surface Resistance	206
5.14	NEG at Low Temperature	207
5.15	Main NEG Coating Benefits	207

5.16	Use of NEG-Coated Vacuum Chambers	208
	References	209
6	Vacuum System Modelling	215
	<i>Oleg B. Malyshev</i>	
6.1	A Few Highlights from Vacuum Gas Dynamics	215
6.1.1	Gas in a Closed Volume	216
6.1.1.1	Gas Density and Pressure	216
6.1.1.2	Amount of Gas and Gas Flow	217
6.1.2	Total Pressure and Partial Pressure	218
6.1.3	Velocity of Gas Molecules	218
6.1.4	Gas Flow Rate Regimes	220
6.1.5	Pumping Characteristics	221
6.1.6	Vacuum System with a Pump	223
6.1.7	Vacuum Conductance	223
6.1.7.1	Orifice	224
6.1.7.2	Vacuum Conductance of Long Tubes	224
6.1.7.3	Vacuum Conductance of Short Tubes	225
6.1.7.4	Serial and Parallel Connections of Vacuum Tubes	226
6.1.8	Effective Pumping Speed	226
6.2	One-Dimensional Approach in Modelling Accelerator Vacuum Systems	228
6.2.1	A Gas Diffusion Model	229
6.2.2	A Section of Accelerator Vacuum Chamber in a Gas Diffusion Model	231
6.2.3	Boundary Conditions	232
6.2.4	Global and Local Coordinates for Each Element	238
6.2.5	Using the Results	240
6.2.6	A Few Practical Formulas	241
6.2.6.1	Gas Injection into a Tubular Vacuum Chamber	241
6.2.6.2	Vacuum Chamber with Known Pumping Speed at the Ends	241
6.2.6.3	Vacuum Chamber with Known Pressures at the Ends	244
6.3	Three-Dimensional Modelling: Test Particle Monte Carlo	245
6.3.1	Introduction	245
6.3.2	A Vacuum Chamber in the TPMC Model	246
6.3.3	TPMC Code Input	246
6.3.4	TPMC Code Output	248
6.3.4.1	Gas Flow Rate	248
6.3.4.2	Gas Density and Pressure	250
6.3.4.3	Transmission Probability and Vacuum Conductance	250
6.3.4.4	Pump-Effective Capture Coefficient	251
6.3.4.5	Effect of Temperature and Mass of Molecules	251
6.3.5	What Can Be Done with TPMC Results?	251
6.3.5.1	A Direct Model with a Defined Set of Parameters	252
6.3.5.2	Models with Variable Parameters	253
6.3.6	TPMC Result Accuracy	256

6.4	Combining One-Dimensional and Three-Dimensional Approaches in Optimising the UHV Pumping System	257
6.4.1	Comparison of Two Methods	257
6.4.2	Combining of Two Methods	258
6.5	Molecular Beaming Effect	260
6.6	Concluding Remarks	265
6.A	Differential Pumping	265
6.B	Modelling a Turbo-Molecular Pump	266
	Acknowledgements	267
	References	267
7	Vacuum Chamber at Cryogenic Temperatures	269
	<i>Oleg Malyshev, Vincent Baglin, and Erik Wallén</i>	
7.1	Pressure and Gas Density	269
7.2	Equilibrium Pressure: Isotherms	272
7.2.1	Isotherms	273
7.2.2	Cryotrapping	279
7.2.3	Physisorption on Gas Condensates	281
7.2.4	Temperature Dependence of the H ₂ Isotherms	282
7.2.5	Choice of Operating Temperature for Cryogenic Vacuum Systems	286
7.3	Gas Dynamics Model of Cryogenic Vacuum Chamber Irradiated by SR	289
7.3.1	Infinitely Long Vacuum Chamber Solution	291
7.3.1.1	Vacuum Chamber Without a Beam Screen	292
7.3.1.2	Vacuum Chamber with Holes in the Beam Screen	292
7.3.2	Short Vacuum Chamber Solution	294
7.3.2.1	Solution for a Short Vacuum Chamber with a Given Pressure at the Ends	296
7.3.2.2	Solution for a Short Vacuum Chamber with a Given Pumping Speed at the Ends	298
7.4	Experimental Data on PSD from Cryogenic Surface	300
7.4.1	Experimental Facility for Studying PSD at Cryogenic Temperatures	301
7.4.2	Discovery of Secondary PSD	301
7.4.3	Calculation of the Desorption Yields from Experimental Data	306
7.4.4	Primary PSD Yields	308
7.4.5	Secondary PSD Yields	310
7.4.6	Photon-Induced Molecular Cracking of Cryosorbed Gas	312
7.4.6.1	Experimental Measurements	312
7.4.6.2	How to Include Cracking into the Model	315
7.4.6.3	Example	316
7.4.7	Temperature of Desorbed Gas	318
7.5	In-Depth Studies with COLDEX	321
7.5.1	COLDEX Experimental Facility	321
7.5.2	PSD of Cu as a Function of Temperature	324
7.5.3	Secondary PSD Yields	325

7.5.4	PSD of a BS with Sawtooth for Lowering Photon Reflectivity and PEY	326
7.5.5	Vacuum Transient	328
7.5.6	Temperature Oscillations	329
7.6	Cryosorbers for the Beam Screen at 4.5 K	331
7.6.1	Carbon-Based Adsorbers	333
7.6.1.1	Activated Charcoal	333
7.6.1.2	Carbon Fibre	334
7.6.2	Amorphous Carbon Coating Absorption Properties	337
7.6.3	Metal-Based Absorbers	338
7.6.3.1	Aluminium-Based Absorbers	338
7.6.3.2	Copper-Based Absorbers	340
7.6.3.3	LASE for Providing Cryosorbing Surface	341
7.6.4	Using Cryosorbers in a Beam Chamber	341
7.7	Beam Screen with Distributed Cryosorber	342
7.8	Final Remarks	343
	References	344
8	Beam-Induced Electron Multipacting, Electron Cloud, and Vacuum Design	349
	<i>Vincent Baglin and Oleg B. Malyshev</i>	
8.1	BIEM and E-Cloud	349
8.1.1	Introduction	349
8.1.2	E-Cloud Models	351
8.2	Mitigation Techniques and Their Impact on Vacuum Design	356
8.2.1	Passive Methods	357
8.2.2	Active Methods	363
8.2.3	What Techniques Suit the Best	365
8.3	Secondary Electron Emission (Laboratory Studies)	365
8.3.1	SEY Measurement Method	365
8.3.2	SEY as a Function of the Incident Electron Energy	367
8.3.3	Effect of Surface Treatments by Bakeout and Photon, Electron, and Ion Bombardment	367
8.3.4	Effect of Surface Material	368
8.3.5	Effect of Surface Roughness	369
8.3.6	'True' Secondary Electrons, Re-Diffused Electrons, and Reflected Electrons	371
8.3.7	Effect of Incidence Angle	374
8.3.8	Insulating Materials	374
8.4	How the BIEM and E-Cloud Affect Vacuum	376
8.4.1	Estimation of Electron Energy and Incident Electron Flux	376
8.4.2	Estimation of Initial ESD	378
8.5	BIEM and E-Cloud Observation in Machines	379
8.5.1	Measurements in Machines	379
8.5.1.1	Vacuum Pressure	381
8.5.1.2	Vacuum Chamber Wall Properties	382
8.5.1.3	Specific Tools for BIEM and Electron Cloud Observation	386

8.5.2	Machines Operating at Cryogenic Temperature	390
8.5.2.1	Surface Properties at Cryogenic Temperature	391
8.5.2.2	Observations with Beams	394
8.5.2.3	The CERN Large Hadron Collider Cryogenic Vacuum System	401
8.6	Contribution of BIEM to Vacuum Stability	405
8.7	Past, Present, and Future Machines	407
	Acknowledgements	409
	References	409
9	Ion-Induced Pressure Instability	421
	<i>Oleg B. Malyshev and Adriana Rossi</i>	
9.1	Introduction	421
9.2	Theoretical	422
9.2.1	Basic Equations	422
9.2.2	Solutions for an Infinitely Long Vacuum Chamber	425
9.2.2.1	Room Temperature Vacuum Chamber	425
9.2.2.2	Cryogenic Vacuum Chamber	426
9.2.2.3	Summary for an Infinitely Long Vacuum Chamber	427
9.2.3	Short Vacuum Chamber	428
9.2.3.1	Solution for a Short Vacuum Chamber with a Given Gas Density at the Ends	428
9.2.3.2	Solution for a Short Vacuum Chamber with a Given Pumping Speed at the Ends	431
9.2.3.3	Solution for a Short Vacuum Chamber Without a Beam Screen Between Two Chambers With a Beam Screen	434
9.2.3.4	Some Remarks to Solutions for Short Tubes	437
9.2.4	Multi-Gas System	437
9.2.5	Two-Gas System	438
9.2.5.1	Solutions for an Infinitely Long Vacuum Chamber	439
9.2.5.2	Solution for a Short Vacuum Chamber in the Equilibrium State	439
9.2.6	Some Comments to the Analytical Solutions	440
9.2.7	Effect of the Ion-Stimulated Desorption on the Gas Density	441
9.2.7.1	Infinitely Long Vacuum Chamber (One Gas)	441
9.2.7.2	Vacuum Chamber with a Given Pumping Speed at the Ends (One Gas)	441
9.2.7.3	Two-Gas System	443
9.2.8	Some Numeric Examples from the LHC Design	443
9.2.8.1	The Critical Current for an Infinitely Long Vacuum Chamber	444
9.2.8.2	Short Vacuum Chambers	445
9.2.8.3	Effect of the Ion-Stimulated Desorption on the Gas Density	445
9.3	VASCO as Multi-Gas Code for Studying the Ion-Induced Pressure Instability	447
9.3.1	Basic Equations and Assumptions	447
9.3.2	Multi-Gas Model in Matrix Form and Fragmentation in Several Vacuum Chamber Elements	448
9.3.2.1	Boundary Conditions	449
9.3.3	Transformation of the Second-Order Differential Linear Equation into a System of First-Order Equations	450

9.3.3.1	Boundary Conditions	451
9.3.4	Set of Equations to be Solved	451
9.3.5	'Single Gas Model' Against 'Multi-Gas Model'	452
9.4	Energy of Ions Hitting Vacuum Chamber	455
9.4.1	Ion Energy in the Vacuum Chamber Without a Magnetic Field	455
9.4.1.1	Circular Beams	455
9.4.1.2	Flat Beams	458
9.4.2	Ion Energy in a Vacuum Chamber with a Magnetic Field	460
9.4.2.1	Vacuum Chamber in a Dipole Magnetic Field	461
9.4.2.2	Vacuum Chamber in a Quadrupole Magnetic Field	461
9.4.2.3	Vacuum Chamber in a Solenoid Magnetic Field	462
9.5	Errors in Estimating the Critical Currents I_c	464
9.5.1	Beam-Gas Ionisation	465
9.5.2	Ion Impact Energy	465
9.5.3	Ion-Stimulated Desorption Yields	465
9.5.4	Pumping	466
9.5.5	Total Error in Critical Current	466
9.6	Summary	467
	References	467
10	Pressure Instabilities in Heavy Ion Accelerators	471
	<i>Markus Bender</i>	
10.1	Introduction	471
10.2	Pressure Instabilities	472
10.2.1	Model Calculations of the Dynamic Pressure and Beam Lifetime	476
10.2.1.1	Closed System (Vessel)	476
10.2.1.2	Vessel Including Collimation	478
10.2.1.3	Longitudinal Profile	478
10.2.2	Consequences	479
10.3	Investigations on Heavy Ion-Induced Desorption	480
10.3.1	Desorption Yield Measurements	481
10.3.2	Materials Analysis	483
10.3.3	Dedicated Set-ups to Measure Ion-Induced Desorption Yields	485
10.3.4	Results	489
10.3.4.1	Materials	490
10.3.4.2	Surface Coatings	493
10.3.4.3	Cleaning Methods	494
10.3.4.4	Energy Loss Scaling	495
10.3.4.5	Angle Dependence	496
10.3.4.6	Conditioning	497
10.3.4.7	Cryogenic Targets	498
10.3.5	Theoretic	499
10.3.5.1	Interaction of Ions with Matter	499
10.3.5.2	Inelastic Thermal Spike Model	501
10.4	Conclusion: Mitigation of Dynamic Vacuum Instabilities	505
	Acknowledgement	507
	References	507