

---

# Contents

Preface	xiii
Acknowledgments	xv
Author	xvii
Symbols	xix
1 Historical Introduction and Survey	1
1.1 The Discovery in Fall 1895	1
1.2 The Early Days of X-Rays	6
1.2.1 Industrialization from 1896	6
1.2.2 Victims and Casualties	10
1.3 Major Steps of Progress	12
1.3.1 Crookes Tubes	12
1.3.2 Two-Pulse Generators	13
1.3.3 Legacy of Heat Units	14
1.3.4 Coolidge's Thermionic Electron Production—1913	15
1.3.5 Goetze's Line Focus—1918	17
1.3.6 Bouwers Commercializes the Rotating Anode Tube—1929	18
1.3.7 Metal-Ceramics and Spiral-Groove Bearing Tubes in the 1980s	21
1.3.8 Electron Beam Computed Tomography—Mid-1980s	23
1.3.9 Rotating Frame Tubes—2003	24
1.3.10 The Largest Commercial Anode—2005	25
1.3.11 CT Requirements on the Move	26
1.3.12 The Highest Power Density CT Tube—2007	27
References	29
2 Physics of Generation of Bremsstrahlung	31
2.1 Acceleration of Electrons	32
2.2 Efficiency of Energy Conversion	34
2.3 The X-Ray Continuum Spectrum	37
2.4 Characteristic Radiation	44
2.5 Characteristic Radiation and Discontinuous Attenuation	48

2.6	Theory of the Angular Distribution of the Continuum Radiation	54
2.7	Angular Distribution of Characteristic Radiation	60
2.8	Polarization	61
2.9	Theory of Electron Scatter in the Anode	61
2.10	Electron Backscatter	65
2.11	The Thomson–Whiddington Law in More Detail	70
2.12	Measured and Simulated Isotropic X-Ray Intensity Distribution	74
2.13	The Heel Effect	76
	References	78
3	The Interaction of X-Rays with Matter	81
3.1	Basics of the Attenuation of X-Rays	82
3.2	X-Ray Refraction and X-Ray Lenses	89
3.3	Thomson Scattering	94
3.4	Rayleigh Scattering	95
3.5	Compton Scattering	98
3.6	Photoelectric Absorption	101
	References	106
4	More Background on Medical Imaging	109
4.1	Non-X-Ray Methods	109
4.2	X-Ray Imaging	111
4.2.1	Attenuation Imaging	111
4.2.2	Linear Systems Theory	118
4.2.3	Modulation Transfer Function	123
4.2.4	Stating the MTF	125
4.3	Spectral Imaging	132
4.4	Phase-Contrast Imaging	135
4.5	Fluorescence Imaging	137
4.6	Polarized X-Rays	137
	References	138
5	Imaging Modalities and Challenges	139
5.1	Computed Tomography	141
5.1.1	Basics of CT	141
5.1.2	CT Application	145
5.1.3	Changing Requirements for CT Sources	147
5.1.4	Dedicated X-Ray Source Features for CT	150
5.1.4.1	In-Plane Focal Spot Deflection	150
5.1.4.2	Axial Focal Spot z-Deflection	151



5.1.4.3	Fighting Beam-Hardening Artifacts	154
5.1.4.4	Reducing Off-Focal Radiation	155
5.1.5	Dual-Source CT	156
5.1.6	Spectral CT	157
5.1.7	Comparing Tubes in CT Systems	160
5.2	Cardio and Vascular Imaging	161
5.3	Radiographic Systems	169
5.4	Radiography/Fluoroscopy (R/F) Systems	171
5.5	Mammography Systems	172
5.6	Surgical C-Arm Systems with Monoblocks	174
	References	175
6	Diagnostic X-Ray Sources from the Inside	177
6.1	Working Principle and Types of Medical X-Ray Tubes	177
6.1.1	Stationary Anode Tubes	182
6.1.2	Miniature Stationary Anode Tubes for Electronic Brachytherapy	183
6.1.3	Rotating Anode Tubes	186
6.1.4	Rotating Frame Tubes	187
6.2	Tube Components in Detail	190
6.2.1	The Cathode	190
6.2.1.1	Energy Required for Electron Production—Work Function	191
6.2.1.2	Mechanisms of Electron Emission	193
6.2.1.3	Robustness of the Tungsten Emitter	199
6.2.1.4	Cathode Characteristics—The Emission Chart	201
6.2.1.5	Filament Heating	202
6.2.1.6	Electron Beam Focusing and Metric for the Focal Spot Size	207
6.2.1.7	Off-Focal Radiation	214
6.2.1.8	Special Cathode Features	215
6.2.1.9	Grid Switching for Fluoroscopy Application	219
6.2.1.10	Advanced Electron Optics in Medical X-Ray Tubes	222
6.2.1.11	Alternatives to Tungsten Emitters	226
6.2.1.12	Charge Balance Inside the X-Ray Tube	232
6.2.2	The Anode	233
6.2.2.1	Stationary Anode Targets	235
6.2.2.2	Rotating Anode Targets	238
6.2.2.3	Thermal Balance	240
6.2.2.4	Cooling Channels	252
6.2.2.5	Temperatures in CT Application	260

6.2.2.6	Temperatures in Interventional and General Radiography Application	262
6.2.2.7	Metric of Anode Heat Storage Capacity Abandoned	263
6.2.2.8	Stating Thermal X-Ray Tube Performance	263
6.2.3	Rotor Systems, Drives, and Vacuum Bearings	269
6.2.3.1	Rotor Drive	270
6.2.3.2	Rotor Dynamics, Moment of Inertia, and Start-Up Time	271
6.2.3.3	Vibration and Noise	274
6.2.3.4	Gyroscopic Momentum	277
6.2.3.5	Ball Bearing Systems	277
6.2.3.6	Spiral Groove Bearings	280
6.2.3.7	Magnetic Bearings	284
6.3	The Tube Frame	284
6.4	Maintaining Vacuum	288
6.5	Vacuum Discharges and High-Voltage Stability	293
	References	305
7	Housings, System Interfacing, and Auxiliary Equipment	309
7.1	X-Ray Source Assembly	309
7.2	Radiation Shield	312
7.3	Beam Quality	315
7.4	Beam Limitation	316
7.5	Protection Against Implosion and Explosion	319
7.6	Cooling	320
7.6.1	Air Convection and Limits	321
7.6.2	Enforced Cooling	322
	References	325
8	The Source of Power	327
8.1	Basic Functionality of the X-Ray Generator	328
8.2	High-Voltage Chain	330
8.3	Sensing Tube Voltage and Current	333
8.4	Energy Quantization	336
8.5	Voltage Ripple	337
8.6	Dual-Energy (Dual-X-Ray Color) Imaging	338
8.7	Filament Heating and Emission Control	339
8.8	Grid and Electrostatic Deflection Supply	340
8.9	Multiple Tubes	340
8.10	Other Auxiliary Supplies	340
8.11	Tube Temperature Supervision	342
8.12	Dose Control	342



8.13	Matching Generator and Tube	343
8.14	Monoblocks	345
	References	346
9	Manufacturing, Service, and Tube Replacement	347
9.1	Manufacturing of X-Ray Tubes	348
9.1.1	Cleanliness	348
9.1.2	Basic Logistics	349
9.1.3	Production Lines	349
9.1.4	Final Testing	351
9.2	Process-Oriented versus Assembly-Oriented Production	352
9.3	Production Yield	353
9.4	Installation and Service	354
9.4.1	Reconditioning	354
9.4.2	Warm Up	355
9.5	Tube Replacement and Recycling	356
9.5.1	Average Tube Lifetime	356
9.5.2	Warranty and Costs of Ownership	360
9.6	Recycling	361
	Reference	362
10	X-Ray Source Development for Medical Imaging	363
10.1	Application Trends for the Development of Medical X-Ray Sources	364
10.1.1	Trends for Computed Tomography	364
10.1.2	Trends for Interventional X-Ray and General Radiography	365
10.2	Developments Which Have Not (Yet?) Made it to the Marketplace	365
10.2.1	High-Throughput Rotating Frame Tube	365
10.2.2	Fourth-Generation CT Torus	365
10.2.3	Stationary CT Tube with Carbon Nanotube Field Emission Cathodes	366
10.2.4	Other Dedicated Sources for Three-Dimensional-Like Imaging	367
10.2.5	Sources for Inverse Geometries	368
10.3	Candidates for Next-Generation Bremsstrahlung Sources	368
10.3.1	Enhanced Brilliance: Liquid Metal Anodes	368
10.3.2	Alternative High-Voltage Generation	370
10.3.3	Microfabricated Dielectric Laser Electron Accelerator	371
10.4	Dream and Reality: Deficits of Bremsstrahlung Sources	371
10.5	Nonbremsstrahlung Sources of X-Rays for Imaging	373
10.5.1	Synchrotron Radiation	373
10.5.2	Free Electron Lasers	373
10.5.3	Laser-Wakefield X-Ray Sources	373
10.5.4	Other Selected Physical Processes of X-Ray Generation	375

10.6	Industrial Development of Novel X-Ray Sources	376
10.6.1	Evolution or Game Changers?	376
10.6.2	Development Process	378
10.6.3	Value Engineering	382
	References	
	Index	385