



UNIVERSITI PUTRA MALAYSIA

**TIME-RESOLVED CHARACTERISTICS OF SOFT X-RAY AND HARD
X-RAY EMITTED FROM NITROGEN AND NEON GAS MIXTURES IN 4 kJ
PLASMA FOCUS DEVICE**

AFSHIN ROOMI

FS 2011 44

TIME-RESOLVED CHARACTERISTICS OF SOFT X-RAY AND HARD X-RAY EMITTED FROM NITROGEN AND NEON GAS MIXTURES IN 4 kJ PLASMA FOCUS DEVICE

By
AFSHIN ROOMI

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfillment of the Requirements for the Degree of Doctor of Philosophy**

September 2011

This Thesis Is Dedicated To

Professor Reza Amrollahi

*Who Has Had a Unique Contribution to the Development of Nuclear Science and Technology in
Iran.*

Abstract of thesis presented to the Senate of Universiti Putra Malaysia, in fulfillment of the Requirement for the degree of Doctor of Philosophy

TIME-RESOLVED CHARACTERISTICS OF SOFT X-RAY AND HARD X-RAY EMITTED FROM NITROGEN AND NEON GAS MIXTURES IN 4-kJ PLASMA FOCUS DEVICE

By

AFSHIN ROOMI

September 2011

Chairman : Professor Elias Saion, PhD

Faculty : Science

Plasma focus (PF) is a pulsed plasma producing device which consists of two coaxial electrodes separated by an insulator sleeve, a vacuum chamber filled with working gas at low pressure, and an electrical circuitry. Upon discharging a capacitor bank, a plasma column is created in nanosecond rise time. The Lorentz force accelerates the plasma sheath along the anode towards the anode tip and compressed magnetically to form a dense plasma column. As a result of electrons interaction with atoms of the anode and working gas, Soft X-rays (SXR) and hard X-rays (HXR) are produced. The effects of applied voltage, operating pressure and working gas composition on SXR and HXR emitted from a 4 kJ plasma focus device which is called 'APF' have been investigated. Nitrogen (N_2) and Nitrogen: Neon (N_2 : Ne) admixture with three volumetric ratios of (90: 10), (75: 25), and (50: 50) were used as the working gas in order to study the effect of gas composition on X-ray emission from the device. To investigate the effect of

applied voltage and operating pressure on the behavior of SXR and HXR emissions, four voltages of 10, 11, 12, and 13 kV with a range of pressures of 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 torr were applied. The diagnostic devices employed during the experiments were a scintillation detector for HXR detection, an array of five filtered PIN-diodes for SXR detection with different energies, a Pin-hole camera with two different filtered apertures for analyzing the dense plasma column, a Rogowski coil for measuring the discharge current, a voltage probe to measure the tube voltage and four oscilloscopes for getting the signals obtained by the different detectors. The results of HXR signals obtained by the scintillation detector showed that the intensity of HXR decreases with an increase of neon gas in the working gas admixture. On the other hand the signals obtained by three PIN-diodes filtered by Al + Mylar (12 μ m), Al + Mylar (24 μ m), and Be (230 μ m) which were for SXR, illustrated that the intensity of SXR increases with an increase of neon percentage in the admixture. Also the signals detected by two PIN-diodes covered by Al + Mylar (150 μ m), and Cu (10 μ m) which are for HXR, were in agreement with the results of the scintillation detector. For all compositions of the working gases, it was observed that the intensity of both SXR and HXR increased with increase of the applied voltage. For applied voltages used on every working gas, the optimum pressures for maximum intensity of SXR and HXR emitted were obtained. The results showed that the optimum conditions for maximum emissions of SXR and HXR using nitrogen (N₂) and neon (Ne) mixture are different. Therefore, it was found that the APF is in the optimum condition either for SXR or HXR emission. Our results concluded that the mixing neon (Ne) and nitrogen (N₂) as the working gas in the APF is a power source of SXR emission.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PENCIRIAN PELERAIAN MASA SINAR-X LEMBUT DAN SINAR-X KERAS
DIPANCARKAN DARIPADA CAMPURAN GAS NITROGEN DAN NEON
DALAMPERANTI PLASMA FOKUS 4-KJ**

Oleh

AFSHIN ROOMI

September 2011

Pengerusi : Profesor Elias Saion

Fakulti : Sains

Plasma fokus (PF) adalah peranti pengeluar plasma yang terdiri daripada dua elektrod sepaksi yang dipisahkan oleh lapisan penebat, satu ruang vakum diisikan dengan gas tindak balas pada tekanan rendah, dan satu litar elektrik. Selepas kapasitor discas, plasma dihasilkan dalam tempoh beberapa nano saat peningkatan masa. Daya Lorentz memecutkan plasma sepanjang anod ke hujung anod dan plasma dimampatkan secara magnet kepada lanjur plasma mampat. Hasil daripada tindakbalas electron dengan atom anod dan gas maka terhasillah sinar-X lembut (SXR) dan sinar-X keras (HXR). Kesan daripada voltan digunakan, tekanan operasi, dan komposisi gas tindakbalas terhadap pengeluaran SXR dan HXR dipancarkan daripada peranti plasma focus APF 4-kJ telah dikaji. Nitrogen (N_2) dan campuran Nitrogen: Neon ($N_2:Ne$) dengan nisbah (90: 10), (75: 25), and (50: 50) telah digunakan sebagai gas tindakbalas untuk mengetahui kesan komposisi gas terhadap sinar-X yang dihasilkan oleh peranti ini. Untuk mengkaji kesan

voltan digunakan dan tekanan operasi terhadap perlakuan SXR dan HXR, empat voltan digunakan iaitu 10, 11, 12, and 13 kV dengan tekanan operasinya 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 torr telah dikaji. Peranti diagnostik yang digunakan semasa eksperimen terdiri daripada pengesan sentilator untuk mengesan HXR, susunan lima PIN-diod berturas untuk mengesan SXR pada tenaga berbeza, satu kamera Pin-aperture celah dua berturas untuk menganalisis lanjur plasma tumpat, satu gelong Rogowski untuk mengukur arus discas, sebuah meter voltan untuk mengukur voltan, dan empat osiloskop untuk mendapatkan isyarat daripada pengesan yang berbeza. Keputusan isyarat HXR yang diukur dengan pengesan sentilator menunjukkan bahawa keamatan HXR berkurangan dengan pertambahan gas neon dalam campuran gas tindakbalas. Pada masa yang sama isyarat SXR yang diukur dengan tiga PIN-diod dituraskan oleh Al + Mylar (12 μ m), Al + Mylar (24 μ m), dan Be (230 μ m), menunjukkan keamatan SXR bertambah dengan pertambahan neon dalam campuran gas. Juga isyarat yang dikesan oleh dua PIN-diod disaluti dengan Al + Mylar (150 μ m), and Cu (10 μ m) untuk isyarat HXR adalah setuju dengan keputusan daripada pengesan sentilator. Untuk semua komposisi gas tindakbalas didapati bahawa keamatan kedua SXR dan HXR bertambah dengan pertambahan voltan. Untuk voltan digunakan terhadap setiap gas tindakbalas, tekanan optimum untuk keamatan maksimum dipancarkan oleh SXR dan HXR telah diperolehi. Keputusan kajian menunjukkan bahawa keadaan optimum pancaran SXR dan HXR maksimum dengan menggunakan nitrogen (N₂) dan neon (Ne) adalah berbeza. Oleh itu didapati bahawa operasi APF berada dalam keadaan optimum untuk kedua SXR dan HXR. Kita boleh membuat keputusan disini bahawa campuran nitrogen (N₂) dan neon (Ne) sebagai gas tindakbalas dalam APF adalah sumber kuasa pemancaran SXR.

ACKNOWLEDGMENTS

It is a great pleasure that at the last step of my graduate period, I have the chance to express my deep appreciation to the many people who have contributed to both my work and my life during this period of time.

I would like to express my full thanks and sincere gratitude to my dear supervisor Prof. Dr Elias Saion for all of guidance, discussions, unlimited assistance consultations and support, without which it would not have been possible for me to complete this work. It has been a pleasant experience to work under his supervision.

I would also like to express my deepest gratitude and thanks to my worthy advisor Prof. Dr Reza Amrollahi, Dean of Faculty Engineering and Physics, Amirkabir University of Technology in Tehran, for his kind directions, inspiring guidance, and invaluable discussions throughout the entire course of this project. Without his patience and encouragement, this work would never be fulfilled. I am very grateful to have such a fulfilling and enriching experience of working under him. I also express my sincere gratitude my committee members, Prof. Dr Wan Mahmood and Assoc. Prof. Dr M. Iqbal.

Also I would like to express my especial thanks and sincere gratitude to Assoc. Prof. Dr Morteza Habibi for his invaluable suggestions, beneficial advices and his endless helps which made this work possible. I am also grateful to my dear co-labs; Dr. Gholam Reza Etaati, Reza Baghdadi, Mohsen Mardani and Dr. Reza Zamiri.

Finally, I would like to express my full thanks and sincere gratitude to my dear family for their encouragements, emotional supports and fortitude efforts in my life time.

Afshin Roomi
October 2011

Appendix D1 Approval Sheet 1

I certify that an Examination Committee has met on **29/09/2011** to conduct the final examination of Afshin Roomi on his thesis entitled **“Time-Resolved Characteristics of Soft X-Ray and Hard X-Ray Emitted from Nitrogen and Neon Gas Mixtures in A 4-kJ Plasma Focus Device”** in accordance with the Universities and University Colleges Act 1971 and the constitution of the Universiti Putra Malaysia [P.U.(A)] 15 March 1998. The Committee recommends that the student be awarded the PhD.

Members of the Examination Committee were as follows:

Jumiah Hassan, PhD

Assoc. Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Mansor Hashim, PhD

Assoc. Professor
Faculty of Science
Universiti Putra Malaysia
(Internal Examiner)

Chen Soo Kien, PhD

Assoc. Professor
Faculty of Science
Universiti Putra Malaysia
(Internal Examiner)

M. Zakauallah, PhD

Professor
Department of Physics
Quiad-i-Azam University
45320 Islamabad
Pakistan
(External Examiner)

HASANAH MOHD. GHAZALI, PhD

Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Elias Saion, PhD

Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Wan Mahmood Mat Yunus, PhD

Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

M Iqbal, PhD

Assoc. Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Reza Amrollahi, PhD

Professor
Faculty of Nuclear Engineering and Physics
Amirkabir University of Technology, Tehran, Iran
(Member)

BUJANG KIM HUAT

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia
Date:

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

AFSHIN ROOMI

Date: 29 September 2011

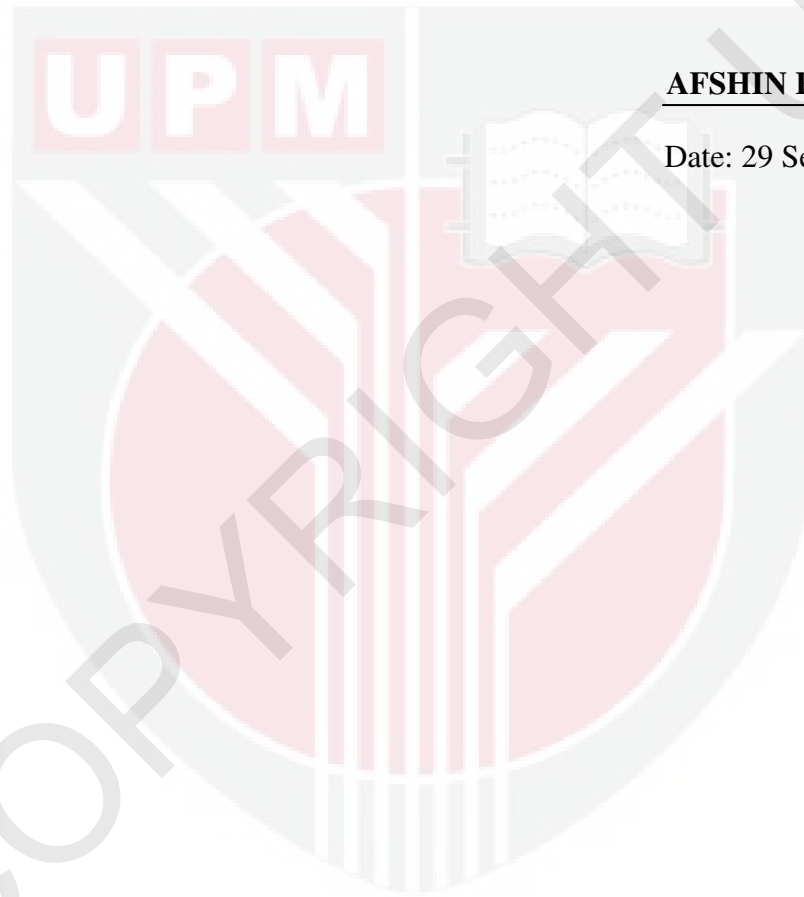


TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENTS	vii
APPROVAL	viii
DECLARATION	x
LIST OF TABLES	xv
LIST OF FIGURES	xvi

CHAPTER

1	INTRODUCTION	
1.1	Research background	1
1.2	X-rays from the PF	2
1.3	Problem statement	4
1.4	Scope of research	5
1.5	Objectives	5
1.6	Layout of the thesis	7
2	LITERATURE REVIEW	
2.1	History of the plasma focus	9
2.1.1	State of the art	9
2.1.2	The PF as a power source of X-ray	11
2.2	Research on soft X-ray and hard X-ray emitted from the PF	14
3	THEORETICAL	
3.1	Structure and working elements of plasma focus device (PF)	34
3.2	Plasma focus dynamics	35
3.2.1	The breakdown phase	36
3.2.2	The axial rundown phase	38
3.2.3	The radial phase	39
3.2.3.1	The compression phase	40
3.2.3.2	The quiescent phase	42
3.2.3.3	The unstable phase	43
3.2.3.4	The decay phase	45
3.3	Instabilities and turbulence	45
3.3.1	Rayleigh-Taylor instability	47
3.3.2	The $m=0$ instability	47
3.3.3	The $m=1$ instability	49
3.3.4	Micro-instabilities and turbulence	50
3.4	Plasma focus models and voltage measurements	52
3.4.1	Simplified evolution process in plasma focus in the Lee model on PF	52

	3.4.1.1 The axial phase	54
	3.4.1.2 The radial inward shock phase	54
	3.4.1.3 The radial reflected shock phase	55
	3.4.1.4 The slow compression phase	55
3.5	Circuit equations and electrical properties	56
	3.5.1 Equivalent circuit equations	56
	3.5.2 Voltage computation	58
	3.5.3 Plasma resistance	58
	3.5.4 Driving parameter	59
3.6	X-ray radiation from the PF	60
	3.6.1 X-ray emission	61
	3.6.1.1 The Bremsstrahlung radiation	62
	3.6.1.2 The recombination radiation	63
	3.6.1.3 The de-excitation radiation	64
4	METHODOLOGY	
4.1	Experimental set up and diagnostics	65
	4.1.1 APF (Amirkabir Plasma Focus) device	67
	4.1.2 Parameters of APF device	70
4.2	Experimental layout	70
	4.2.1 Switching system	70
	4.2.2 APF tube	71
	4.2.3 The vacuum system	75
4.3	Basic electrical diagnostic methods	79
	4.3.1 Rogowski coil	79
	4.3.2 Measurement of tube voltage	82
4.4	Experiments and used diagnostics for X-rays emitted from the APF	83
	4.4.1 Set up for hard X-ray emitted from the APF	85
	4.4.2 Set up for time-resolved soft X-ray emitted from the APF	90
	4.4.3 Set up for time-integrated X-ray emitted from the APF	95
	4.4.4 Set up for record the visible light emitted from the APF	96
5	RESULTS AND DISCUSSION	
5.1	Plasma focus dynamics and parameter correlation	98
	5.1.1 General characteristics of the discharge current	98
	5.1.2 The effect of gas composition on discharge current	108
	5.1.3 Focusing time	111
	5.1.4 The effect of applied voltage and operating pressure on focusing time	111
	5.1.5 The effect of working gas composition on focusing time	115
5.2	Hard X-ray (HXR) emitted from the APF plasma focus device	121
	5.2.1 General characteristics	121
	5.2.2 Variation of HXR intensity with pressure using different working gas at low applied voltage of 11 kV	124
	5.2.3 Variation of HXR intensity with pressure using different working gas at higher applied voltages of 12 kV and 13 kV	126
	5.2.4 Time-resolved of HXR signals at different applied voltages and optimum pressures using pure nitrogen	130
	5.2.5 Time-resolved of HXR signals at different operating	133

	pressures using pure nitrogen	
5.2.6	Time-resolved of HXR signals using different working gases	136
5.3	Soft X-ray (SXR) emitted from the APF plasma focus device	139
5.3.1	General characteristics	139
5.3.2	The energy response of different filtered pin-diodes	142
5.4	Variation of SXR intensity with pressure for different working gases	144
5.4.1	Obtaining optimum pressure for SXR emission from pure nitrogen (N ₂) gas at low applied voltages of 10 and 11 kV	144
5.4.2	Obtaining optimum pressure for SXR emission from volumetric ratio (90: 10) of (N ₂ : Ne) admixture at applied voltage of 11 kV	151
5.4.3	Obtaining optimum pressure for SXR emission from volumetric ratio (75: 25) of (N ₂ : Ne) admixture at applied voltage of 11 kV	154
5.4.4	Obtaining optimum pressure for SXR emission from volumetric ratio (50: 50) of (N ₂ : Ne) admixture at applied voltage of 11 kV	155
5.4.5	Obtaining optimum pressure for SXR emission from pure nitrogen (N ₂) gas at applied voltages of 12 and 13 kV	158
5.4.6	Obtaining optimum pressure for SXR emission from volumetric ratio (90: 10) of (N ₂ : Ne) admixture at voltages of 12 and 13 kV	163
5.4.7	Obtaining optimum pressure for SXR emission from volumetric ratio (75: 25) of (N ₂ : Ne) admixture at voltages 12 and 13 kV	165
5.4.8	Obtaining optimum pressure for SXR emission from volumetric ratio (50: 50) of (N ₂ : Ne) admixture at applied voltages 12 and 13 kV	167
5.5	Time- resolved of SXR signals obtained by different filtered PIN-diodes	170
5.5.1	SXR time-resolved at applied voltage 12 kV and pressure 3 torr using pure nitrogen	171
5.5.2	SXR time-resolved at applied voltage 12 kV and pressure 4 torr using pure nitrogen	181
5.5.3	SXR time-resolved at applied voltage 11 kV and pressure 3.5 torr using nitrogen gas	191
5.5.4	SXR time-resolved at applied voltage 12 kV and operating pressure 4.5 torr using volumetric ratio (50: 50) of (N ₂ : Ne) admixture	200
5.6	X-ray time-integrated at different voltages and optimum pressures for SXR and HXR emission by Pin-hole camera	211

6	CONCLUSION AND FUTURE WORK	
6.1	Conclusions	215

6.2 Some suggestion for future work

221

REFERENCES

223

