Open Access **Baghdad Science Journal** **P-ISSN: 2078-8665**
Published Online First: Suppl. November 2022 **2022, 19(6): 1536-1543** **E-ISSN: 2411-7986**

DOI: https://dx.doi.org/10.21123/bsj.2022.6883

Electron lens Optimization for Beam Physics Research using the Integrated Optics Test Accelerator

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Received 30/12/2021, Accepted 26/7/2022, Published Online First 25/11/2022, Published 5/12/2022

Abstract:

This study proposed control system that has been presented to control the electron lens resistance in order to obtain a stabilized electron lens power. This study will layout the fundamental challenges, hypothetical plan arrangements and development condition for the Integrable Optics Test Accelerator (IOTA) in progress at Fermilab. Thus, an effective automatic gain control (AGC) unit has been introduced which prevents fluctuations in the internal resistance of the electronic lens caused by environmental influences to affect the system's current and power values and keep them in stable amounts. Utilizing this unit has obtained level balanced out system un impacted with electronic lens surrounding natural varieties.

Keywords: Accelerator modeling, Accelerator Subsystems, Beam dynamics, Electron lens, IOTA.

Introduction:

Beam focusing has produced scientific revolution in the acceleration units through presenting the standard for dynamic inclination (moreover familiar as solid)[1]. It has been found that a course of action of exchanging (centering unabsorbing) quadruple as well dipole magnets might preserve the charging molecule zeroed in by and large. On a very basic level, this is conceivable on the grounds that the molecule cross over movement, notwithstanding being time subordinate, has two invariants of movement, referred to instantly as Courant-Snyder undeviating. The presence of movement undeviating consistently works on the movement, presenting requirements upon molecule activities. In the event that two driving integrals of movement exist, the molecule's movement (in the event that limited) might become decreased to movement on tori in 4D phase surface [1-3].

Every current gas pedals with solid centering has the succeeding setting: molecule cross over wavering (betatron) frequency is by plan autonomous of molecule adequacy. The molecule dynamics can be perceived by presenting the supposed standardized phase-space organizes[4,5]:

$$z_N = \frac{z}{\sqrt{\beta(s)}},$$

$$P_N = P\sqrt{\beta(s)} - \frac{\acute{\beta}(s) z}{2\sqrt{\beta(s)}} \qquad 1$$

Where z represents either x or y molecule arranges, p is essentially either px or py, and β(s) is either the level or vertical beta-work. For such standardized directions the molecule movement is indistinguishable from that of a direct oscillator[4,5] :

$$\frac{d^2 z_N}{d\Psi^2} + \omega^2 z_N = 0 \qquad 2$$

Where Ψ is the new "time", which is the betatron phase:

$$\acute{\Psi} = \frac{1}{\beta(s)} \qquad 3$$

In this research, we will introduce a few instances of centering models, that are nonlinear through plan, beside the molecule frequencies become subject to adequacy, up to now steady also integrable. The advantages of the alike structure are dual-overlay. In the early place, the expanded betatron spreading frequencies provide further developed Landau damping. In the other place, a nonlinear scheme is better steady to annoyances of the straight kind [6].

There are just a modest bunch of nonlinear schemes along single then again dual logical integrals for movement of gas pedals. The deduction can be explained such that the nonlinear schemes along scientific undeviating parts are extremely uncommon in an immense ocean of nonlinear schemes. Moreover, concerning the centering components we need to utilize, as it were, the electromagnetic fields submitting to the Maxwell conditions. This, hence, radically diminishes the assortment for schemes along undeviating parts of reasonable utilize. Through the following section of this paper, processing development in integrative nonlinear gas pedal cross-area tracking induced a proposition to advance a test gas pedal at Fermi lab with nonlinear strong centering which sustains an essential separation from reverberation too tempestuous molecule movement. In this paper, a proposed control system is presented to deal with the electron focal point internal obstruction from ecological impacts in request to obtain a balanced out electronic focal point power. A viable AGC regulator has been introduced which prevents vacillations in the internal opposition of the electronic focal point brought about by natural influences to influence the system's current and power esteems and keep them in stable sums. This idea has recognized the center difficulties, speculative arrangement plans and improvement situation of the Integrated Optical Test Accelerator (IOTA) in the works at Fermilab. [7-13].

1. Methodology of IOTA Scheme

IOTA ring has been intended for the confirmation of-rule examination of the nonlinear integrable optics thought[3] at the ASTA office[4]. The underlying variant for the ring configuration depicted in [5]has included 4 occasional cells that had total 8-overlap reflect evenness. We have next distinguished that it is attractive to oblige further tests, like the nonlinear centering along electron bar focal point [6] as well as optical stochastic stimulation. Such decisions requested joining of a 5 m-length directly area. The exploratory lobby measurements permit to oblige the extended ring, Fig. 1, saving the four 2 m nonlinear magnet additions with the e-shaft power of 150 MeV. Table 1 sums up the fundamental boundaries of Particle. The direct segment inverse to the remote exploratory addition will become utilized for infusion, RF hole as well apparatuses. The ring grid involves 50 customary water-cooled quadrupole with eight dipole magnets. The pipe bar opening is 50 mm.

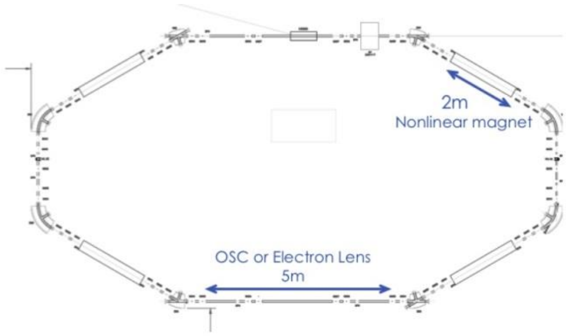


Figure 1. The IOTA ring Structure[2].

Table 1. Basic 10 nations of wind beside sun oriented force introduced limit in 2019[2].

Parameter	**Value**
Nominal beam energy	150 MeV (γ=295)
Nominal beam intensity	1×10^9 (single bunch)
Circumference	38.7 m
Bending field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum β-function	3 ÷ 6 m
Momentum compaction	0.015 ÷ 0.1
Betatron tune	3.5 ÷ 7.2
Natural chromaticity	-5 ÷ -15
Transv. Emittance, rms	0.02 ÷0.08 µm
SR damping time	0.5 s (5×10^6 turns)
RF V,f, harmonic	75 kV, 162.5 MHz, 21
Synchrotron tune	0.005 ÷ 0.01

The objective of trials at IOTA is to show the plausibility to carry out nonlinear integrable model in a sensible gas pedal plan. The undertaking will think on the logical part of the single-molecule movement dependability in the nonlinear integrable scheme, departing the investigations of aggregate impacts as well as achievement of huge bar flow to further exploration[7]. We plan to accomplish the adequacy subordinate nonlinear tune transmit surpassing 0.25 beyond debasement of dynamic opening.

1. Nonlinear Electron Lenses

Dual species of nonlinear concentrating components might become planned for the functional application:

1- a charge column (an electron lens) kind also;

2- an exterior static field kind. The former is much abstractive due to the static voltages in vacuum must to argue the Laplace formula.

An electron lens [6] applies the space charge implies of a small-power electrons beam which intercepts amongst the high-power particle along an expansive distance, L_e. The lens might become utilized as all linear with nonlinear concentrating component

relying upon the electron current-density reallocation $j_e(r)$ also the electron-beam radius a_e.
The earliest evidence of such kind is the what-named McMillan slim lens. A 1-dimensional lens of such kind was initially defined with E. McMillan[8] also was next extensive towaeds 2-d by Danilov with Perevedentsev [9]. Concerning a slim lens is likely to become logical, the coming terms should be satisfied: $Le<\beta$, where β is the beta-function applied on the electron lens position. The electron lens current density has the coming arrangement [8,10,16]:

$$J_e(r)\alpha \frac{I_e}{(r^2+a_e^2)^2} \qquad 4$$

Where, I_e, is the electron current in Ampere. Hence, from Eq.4, we could find the complete expression of the electron current as a function of the electron lens radius, r, by evaluating the integral of $J_e(r)$ with respect to r, so that:

$$I_e(r) = \int \frac{I_e}{(r^2+a_e^2)^2}\, dr \qquad 5$$

$$I_e(r) = \frac{I_e}{2a_e^3}\left(\tan^{-1}\frac{r}{a_e} + \frac{ra_e}{(r^2+a_e^2)}\right) \qquad 6$$

For integrable nonlinear system, the IOTA ring should have the coming one-revolution linear transformation matrix:

$$\begin{pmatrix} cI & sI \\ -sI & sI \end{pmatrix} = \begin{pmatrix} 0 & \beta & 0 & 0 \\ \frac{-1}{\beta} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{\beta} & 0 \end{pmatrix} \qquad 7$$

Where,

$$c = \cos(\emptyset), s = \sin(\emptyset) = I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad 8$$

Also, $\emptyset$ is random constant. Fig. 2 represents an illustration of the tune footprint, resulted using the Frequency Map Analysis[10, 11]. The achievable ultimate impart of frequencies of betatron for a unique electron lens is ~0.3.

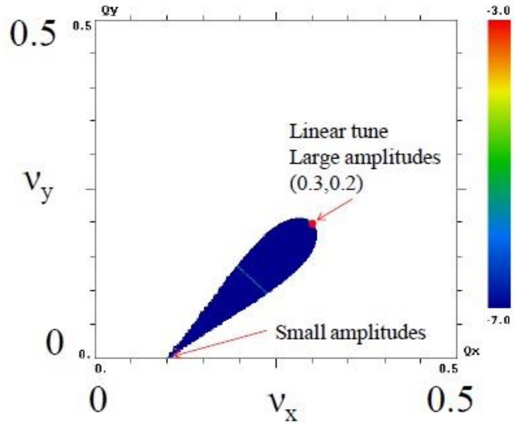


Figure 2. A thin-lens a likeness of fractional tune footprint in ($L<<\beta$). With such emulation the 150-MeV IOTA beam was supposed to counter-propagate the electron lens beam current of $I_e \times L$ = 0.5 A-m with a_e = 1 mm [5].

The other exercise of a nonlinear scheme applying an electron lens does not need a slim-lens likeness. Instead, it needs an axially-compatible electron lens with acurrent density allocation. We have utilized the distribution [4] for this emulation. The concept depends upon the succeeding fundament: the electron lens directing solenoidal domain (5 kG) is satisfactorily huge to focus the 150-MeV IOTA beam also. Demonstration test of ring beta-formulas is illustrated in Fig. 3.

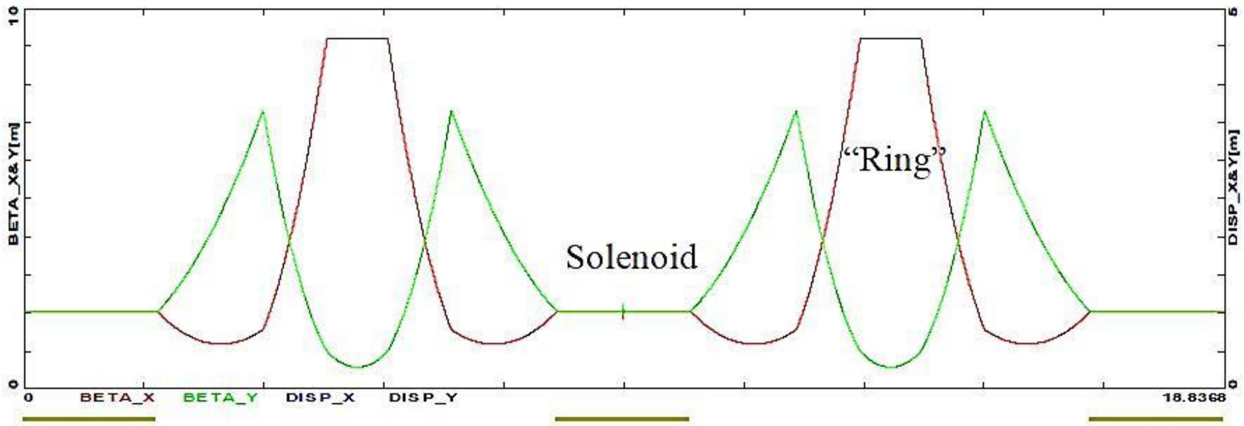


Figure 3. An illustration of “ring” beta- formulas equivalent to a solenoid (5-kG) to find a portion of fixed beta- formulas (2-m) through the solenoid distance [2]

Fig. 3 demonstrates too uncomplicated “ring” formulae. Actually, the unique restriction upon the Ω optics function with the ring (regardless for the solenoid) should have the betatron phase firstly of $n\pi$, in which n is an integer, that is simply implemented in IOTA [12, 13, 14].
Consequently, the electron power across R, Ω resistor could be also derived from Eq.6 such as:

$$P_e(r) = \frac{I_e^2}{4Ra_e^6}\left(\tan^{-1}\frac{r}{a_e} + \frac{ra_e}{(r^2+a_e^2)}\right)^2 \qquad 9$$

Where, R is the internal electron lens resistance in Ohms.

Actually, R might usually be affected by the environmental influences such as temperature changes, magnetic and electromagnetic fields, electronic vibration and other external factors which affect the amount of the internal resistance, R and hence the values of current and the resulting power. These environmental factors could be related with R in a mathematical equation:

$$R(T, H, E) \propto f(T, H, E) \qquad 10$$

Where, T, H, and E, are the temperature changes, magnetic and electromagnetic fields respectively [12,15].

The Proposed Scheme

In order to sustain stability in the resulting electron lens power, $P_e(r)$, a control system unit has been presented as a compensation system to prevent variations in the electron lens power and current. The block diagram of the proposed control system (also named compensation unit) has been shown in Fig. 4.

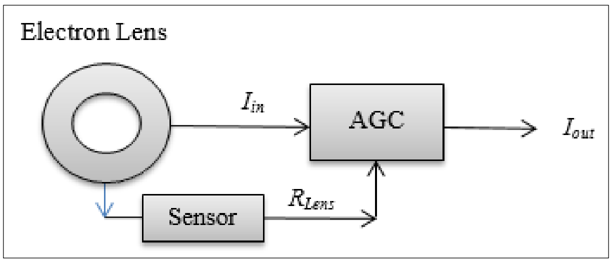


Figure 4. Block diagram of the proposed control system, compensator unit.

The principle of operation of the proposed compensation unit might be explained by measuring the electron lens inherent resistance signal, R_{Lens} from the sensor and entered its value to the automatic gain control, AGC unit. The AGC unit will have two input signals, the IOTA electron lens current, I_{in} and the measured electron lens inherent resistance signal, R_{Lens} from the sensor. The action of the AGC unit is to changing the gain of the internal amplifier according to the variations in the measured R_{Lens} signal, so that the amplitude of the IOTA electron lens current, I_{in} could be sustained in the constant value. By so doing, the resulting power P_e (r) will also remain a province on a constant value.

Hence, and through the introduction of this proposed system, a process of self-control was provided for the changes in the resistance of the electron beam lens from various influences such as temperature changes, electromagnetic waves, electronic vibration and other external factors that affect the value of the internal resistance and thus the amount of current and the resulting power.

Simulation Results and Discussion:

Concerning the practical part of the research, the electron current density described in Eq.5 has been simulated utilizing MatLab2020 simulation program for varying values of the electron lens radius, r. Furthermore, the effective IOTA electron current $I_e(r)$, which has been derived and explained by Eq. 6, has been simulated for the same varying r vector.

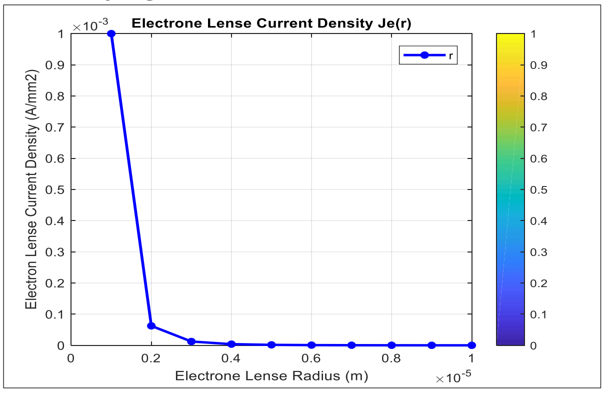


Figure 5. Calculating the electron current density as function of r, $J_e(r)$.

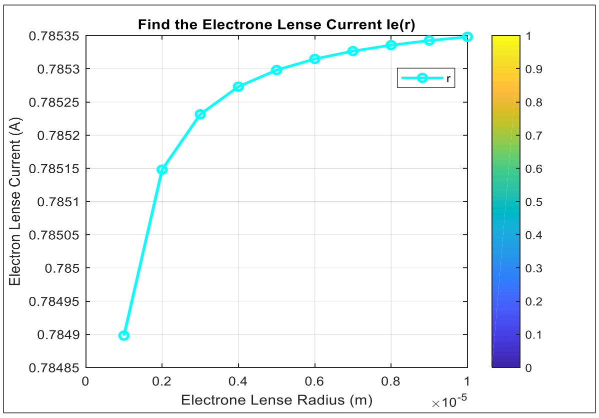


Figure 6. Calculating the electron lens current as function of r, $I_e(r)$.

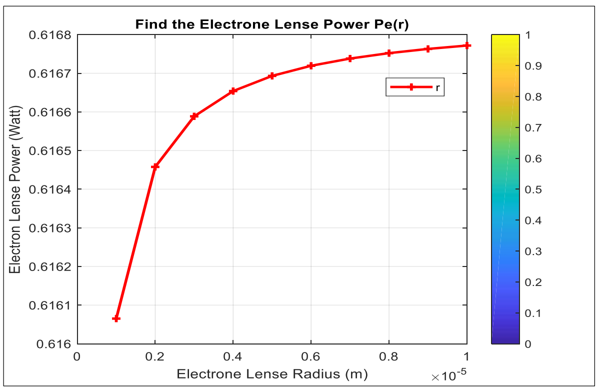


Figure 7. Calculating the electron lens power as function of *r*, $P_e(r)$.

From the Figures above, we might conclude that as the electron lens radius, *r* increased, the effective IOTA electron lens current density $J_e(r)$ will decrease until zero Ampere/m^2 as has been shown in Fig.5, where $J_e(r)$ =0 A/m^2 at r=4 μ m. On the other hand, and by referring to Figs. 6 and 7 we can see the increasing values of IOTA electron lens current $I_e(r)$, as well power, $P_e(r)$ with respect to *r*. This increasing value is actually due to the increased amount of the electronic lens radius, *r*.

Now, by concerning the proposed system, we implement the variation of the inherent resistance *R*, in Eq.9 and the results of the simulation are plotted in Figs.8 and 9 for IOTA electron current $I_e(r)$, as well power, $P_e(r)$.

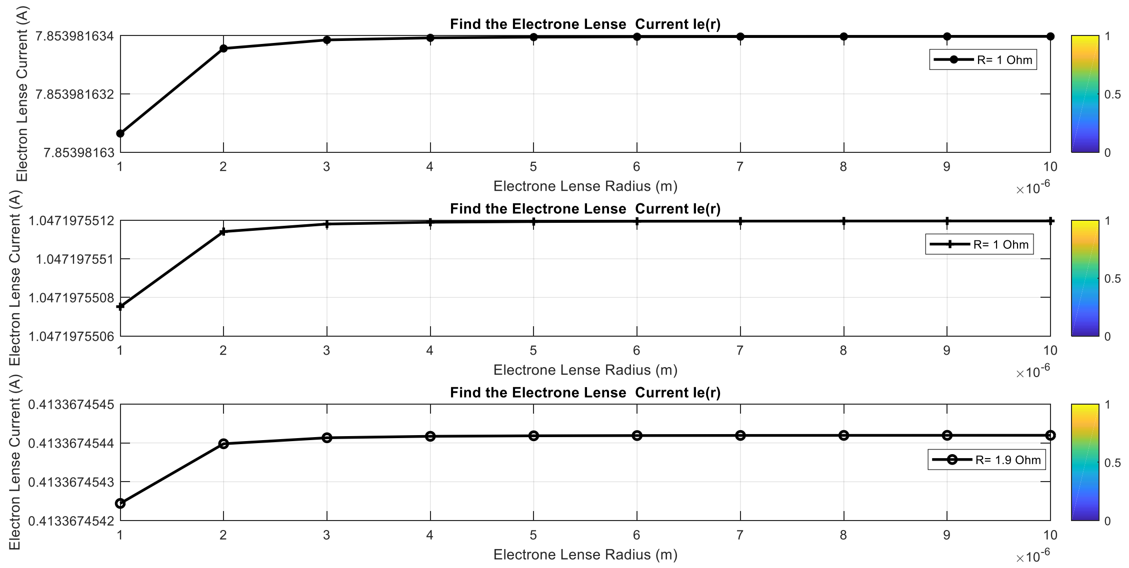


Figure 8. Calculating the electron lens current under inherent resistance *R* effect, $I_e(r)$.

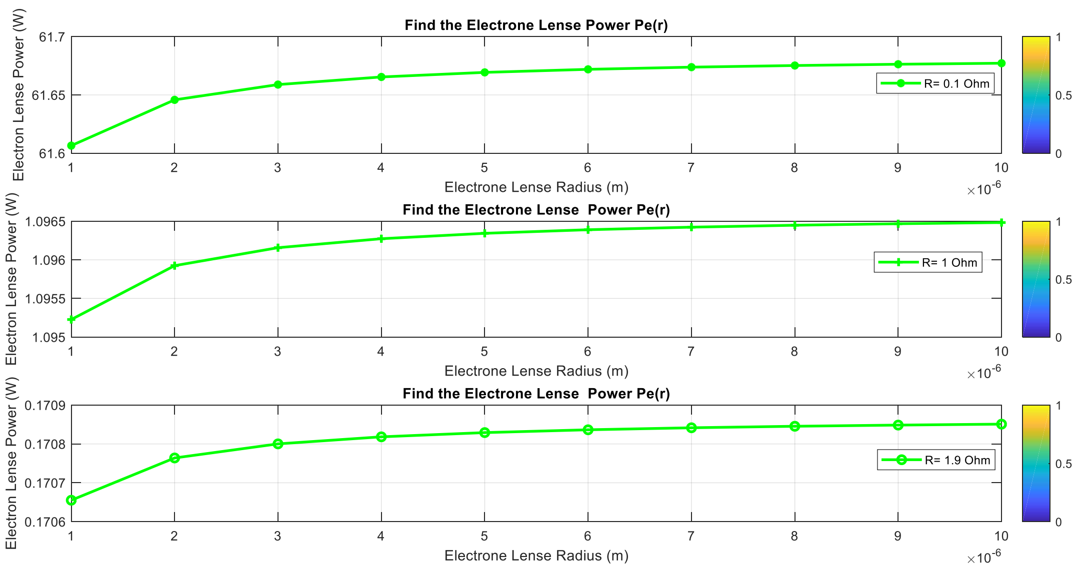
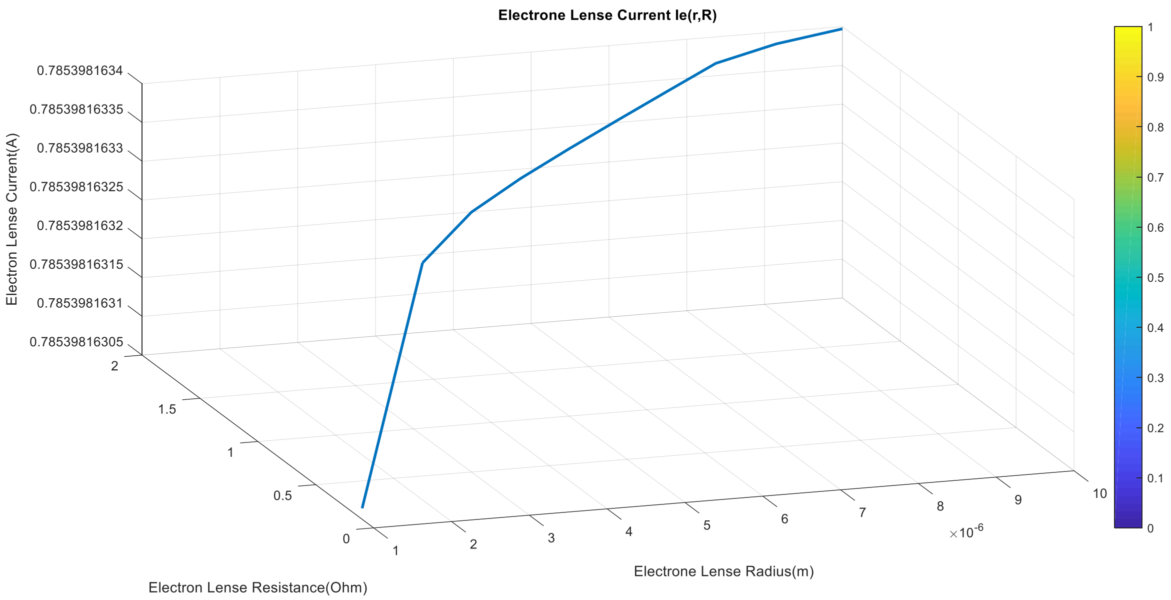
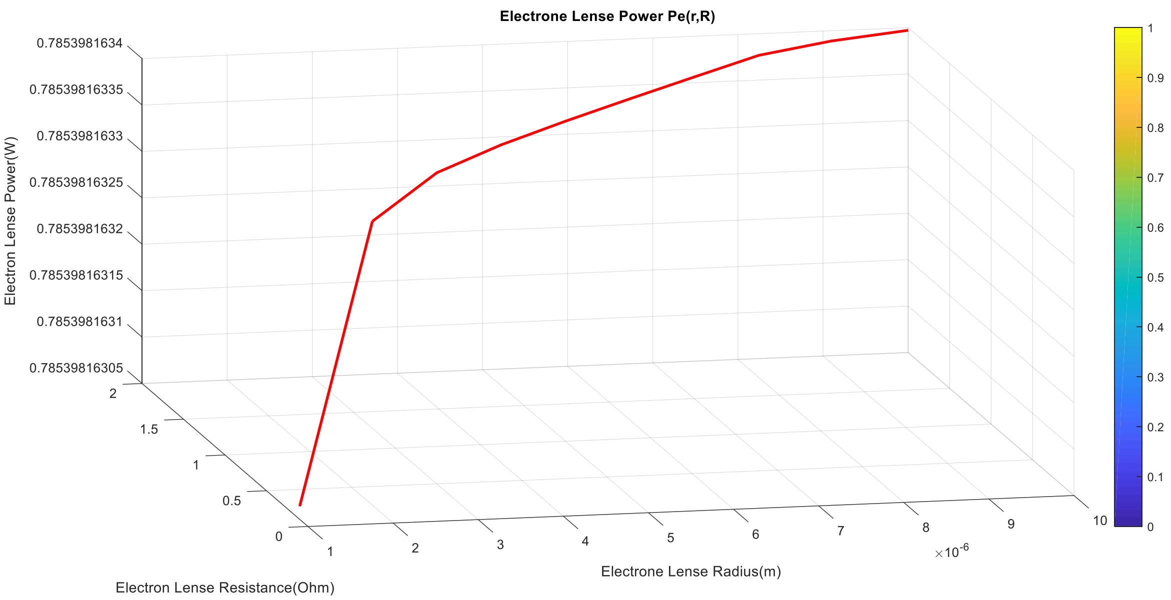


Figure 9. Calculating the electron lens power under inherent resistance *R* effect, $P_e(r)$.

From the previous Figures, it is clear that a simple change in the value of the electron lens inherent resistance *R* will result with a moderate change in the amounts of $I_e(r)$. and $P_e(r)$. Finally, the effect of including the compensator AGC unit include the IOTA electronic lens system has been illustrated in Fig. 10.



(a)



(b)

Figure 10. 3D plot of the compensator control effect on electron lens inherent resistance *R*, (a) Stabilized $I_e(r, R)$, (b) Stabilized $P_e(r, R)$.

Referring to Fig. 10, it is obvious that the stability of both the IOTA electronic lens current and power, $I_e(r)$. and $P_e(r)$ with the fluctuations of the electron lens inherent resistance, R. hence, by utilizing the compensator AGC control unit we have obtained amore stabilized system unaffected with electronic lens surrounding environmental variations

Conclusions:

Processing evolution in integrative nonlinear gas pedal cross-section tracking induces a proposal to progress a test gas pedal at Fermilab with nonlinear solid centering which sustains a strategic distance from resonance as well turbulent particle motion. In this paper, a proposed control system is presented to manage the electron lens internal resistance from environmental effects in order to obtain a stabilized electronic lens power. An effective AGC controller has been introduced which prevents fluctuations in the internal resistance of the electronic lens caused by environmental influences to affect the system's current and power values and keep them in stable amounts. This suggestion has identified the core challenges, hypothetical plan arrangements and development status of the Integrated Optical Test Accelerator (IOTA) in progress at Fermilab. Referring to the results, it can be concluded that as the radius of the electron lens increases, the density of the electron lens decreases, reaching IOTA zero amperes / m 2. On the other hand, the values of power and variance of the intrinsic resistance as well as the power of the lens are affected due to the increase in the amount of electronic lens radius

Authors' declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for re-publication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in Al-Nahrain University.

Authors' contributions statement:

O. S.A. conceived of the presented idea. O. S.A, T. J.H. and A. S.S. developed the theory and verified the analytical methods. O. S.A and T.J.H. supervised the findings of this work. O. S.A and A. S.S. wrote the manuscript. All authors discussed the results and contributed to the final manuscript.

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تحسين العدسة الإلكترونية لإجراء بحوث فيزياء الاشعة باستخدام مسرع اختبار البصريات المتكامل

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الخلاصة:

في هذا البحث تم تقديم نظام تحكم مقترح للتحكم في مقاومة عدسة الإلكترون من أجل الحصول على قدرة عدسة إلكترونية مستقرة. سيحدد هذا البحث التحديات الأساسية وترتيبات الخطة الافتراضية وحالة التطوير لمسرع اختبار البصريات القابلة للتكامل (IOTA) قيد التقدم في مختبر فيرمي Fermilab. وبالتالي، تم إدخال وحدة تحكم الآلي الفعال بتقنية الكسب AGC تمنع التقلبات في المقاومة الداخلية للعدسة الإلكترونية الناجمة عن التأثيرات البيئية للتأثير على قيم التيار والطاقة للنظام والحفاظ عليها بكميات مستقرة. من خلال الاستفادة من هذه الوحدة تم الحصول على مستوى متوازن خارج النظام غير متأثر مع عدسة إلكترونية تحيط بالأصناف الطبيعية

الكلمات المفتاحية: نمذجة ومحاكاة المسرعات، أنظمة وتقنيات التسريع الفرعية، ديناميات الشعاع، عدسة الكترون ,IOTA