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PIC Simulation With Uniform Transverse Magnetic Fields And Axial Magnetic Fields Re-Distribution For The Generation of 35GHz FEL Amplifiers

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This work explored the investigation about beam wave interaction of Free Electron Laser (FEL) Amplifiers through code driven algorithm. The modelling of proposed novel structure is done through the simulation of particle-in-cell (PIC) in CST particle studio. The results are observed for the re-distribution of axial and transverse magnetic field in helix round cross section, and validated using magnetostatic solver. For simulation, the 60ns pulse is excited by electron beam having energy of 164.99 keV with beam voltage 164.99 kV, and beam current of 103.04 A. The beam radius is taken as 0.3 cm with 1% of velocity spreads by neglecting the impact of space charge effect. Moreover, this FEL Amplifier offers maximum amplification at 35 GHz frequency in TM01 mode at DC magnetic field B_o=1.175 Tesla with wiggler field (B_w) of 0.115 Tesla. Further, it is observed that EM power approaches to saturation level after the pulse duration with radio-frequency (RF) power approximately 17 MW and electronic efficiency of 20%.
Keywords— FEL Amplifiers, Wiggler magnetic field, Axial magnetic field, Helix core, and RF wave.

I. INTRODUCTION

This study about transverse and axial magnetic field at 35GHz is carried out by applying relativistic electron beam concept with 1% velocity spreading[1-2]. In [3-6], the authors have practically proposed a THz FEL operating between 1-5GHz by employing the negative-mass instability (NMI) effect. In general, a very short bunches and small wiggler periods are used to radiate 10-20 THz frequencies and 6 MeV electron energy. For instance in [7], it is shown that electron cyclotron frequency is much higher than its wiggler frequency. In addition authors in [8-12] have studied the importance of wiggler in transportation of electron beam as well as generation of super radiance regime.

Madey attains signal amplification in a large size wiggler [13] and it is done by several metrics such as wiggler period, Lorentz factor, and gamma factor of the electron beam [14-17]. Danley et al. [18] proposed the scheme of gyrotron pumped FELs to produced radiation at optical frequencies and produces much shorter wavelengths, like X-rays. Pant and Tripathi [19] have examined whistler pumped FELs and explored the possible operations when axial field and wiggler are used. Freund et al. [20] have developed a nonlinear theory and simulation approaches in collective regime, employing a uniform wiggler, with an efficiency of 27% at 33.4GHz, while the tapered wiggler operation had a 35% efficacy for the same wavelength at 3.5MeV/850A electron beam energy.

First time, in 1984, S. H. Gold et al., utilizing relativistic electron beams (REBs), a high power FEL was experimentally accomplished and studied the impact of the axial magnetic field tapering to increase the device's effectiveness and power [21-23]. In [24], an experiment is conducted to study the impact of space charge and electron beam quality by utilizing guiding field, a helical wiggler, and low-energy high beam current. Authors in [25] have experimentally examined super radiant FEL amplifier that produces 35MW power with an efficiency of 2.5%. In [25-26], authors have studied the efficacy of tapered strong magnetic field in the improvement of efficiency and reduction of interaction region. Moreover in [27], the study of dispersive nature over FEL in whistler mode over efficiency and amplification is done comprehensively [28-31].

This work, explored the investigation about beam wave interaction of Free Electron Laser (FEL) Amplifiers through code driven algorithm. The modelling of proposed novel structure is done through the simulation of particle-in-cell (PIC) in CST particle studio. The results are observed for the re-distribution of axial and transverse magnetic field in helix round cross section, and validated using magnetostatic solver. This device proposed maximum amplification at 35 GHz frequency in TM_{01} mode at DC magnetic field=1.175 Tesla with wiggler field of 0.115 Tesla. It is also observed that EM power approaches to saturation level after the pulse duration with radio-frequency (RF) power 17 MW approximately and electronic efficiency of 20%.

In this work, Section II gives the design analysis of magnetostatic behaviour of FEL amplifiers. The result discussion of device simulation in beam absent case and beam present case In section III, a brief discussion of employing PIC simulation in "CST Particle Studio" occurs, and section IV draws its conclusion.

II. DESIGN ANALYSIS OF MAGNETOSTATIC BEHAVIOUR

The design of this helical wiggler based FEL has been done through comprehensive theoretical as well CST simulation. This simulation presumes beam absence in the development of negative-mass instability (NMI) under combined strong uniform and helical wiggler fields, which enables the creation of intense and narrowband radiation by providing a continuum of consistent sizes of short- and long-living bunches. In contrast, Negative-mass stabilisation (NMS) regimes, at wiggler lengths, coherent spontaneous emission is offered, while the emitted frequency is reduced than in the regime with the zero guiding field, this results in a large increase in the power and duration of the pulse that is radiated [1]. The value of the wiggler field (Bw), which is ten times less than the guiding field for typical THz source characteristics (particle energy of 5–6 MeV with up to 1 nC charges and 1-2 THz radiated frequency), should be in the range of 0.1–0.2 T [2].

Accordingly, it is suggested that a relatively thin steel helix can provide the appropriate amount of the wiggler field (Bw). In an endless solenoid with a uniform field, let's determine the field of a helical insertion. Considering here, the magnetization $\bar{J}$ of an infinite ferromagnetic cross sectional view of helix with wiggler period λ_w , inner and outer radius 'r_1' and 'r_2', respectively, thickness $t = r_2 - r_1$, and axial size 'd' shown below Fig. 1.

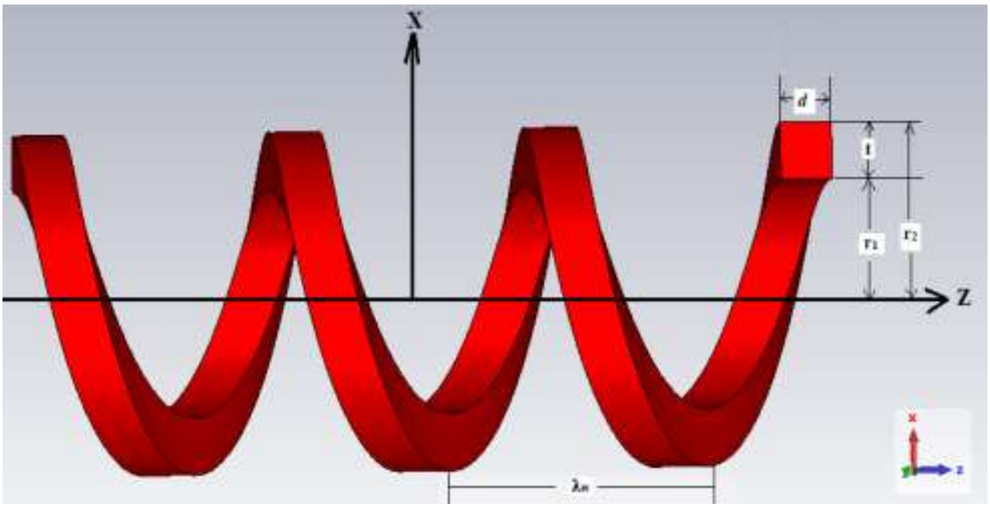


Fig. 1. Cross sectional view of the helical wiggler

When, there is a highly strong guiding field, the helix's magnetization reaches saturation, that is $\bar{J} = \bar{J}_\infty$, therefore its value are independent on B_o. The static wiggler magnetic field at the system's axis is represented as cylindrical surface boundary conditions where $r = R$ (mean radius) correspond to field strengths is given as,

$$B_w = \frac{1}{\pi} k_w^2 t R \sin(k_w d / 2) K_1(k_w R) \mu_o J_\infty . \qquad (1)$$

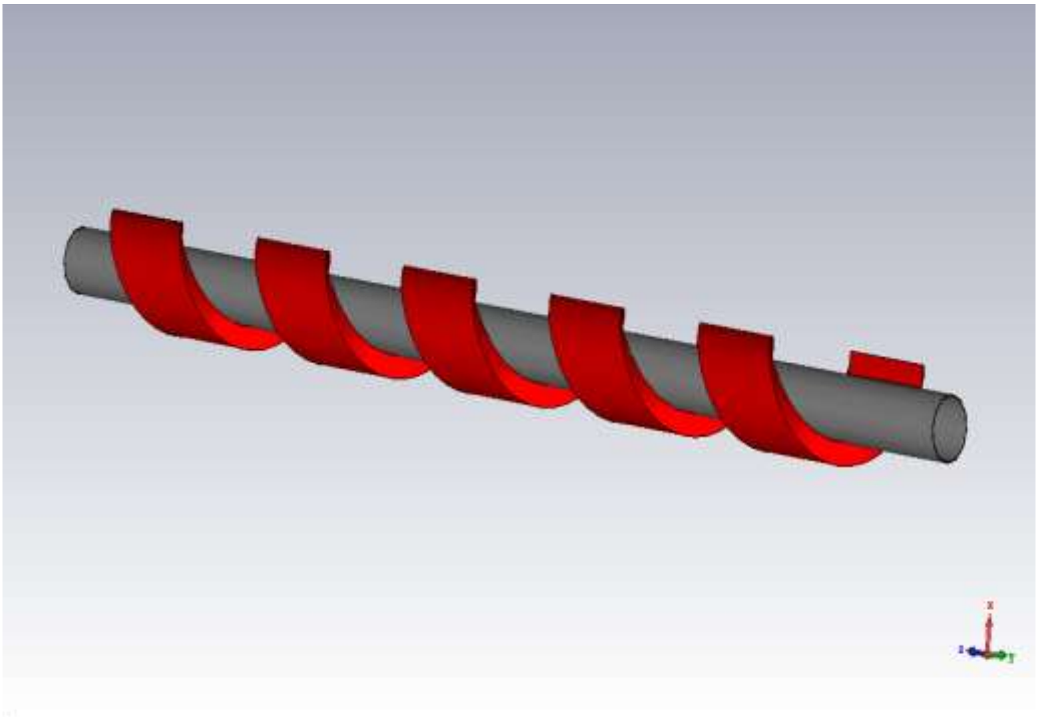
Where μ_o is the permeability for the ferromagnetic materials and $K_1(k_w R)$ is McDonald constant for first order Bessel function. The transverse field is maximized when the helix's axial dimension is equal to half of its period, i.e., $d = \lambda_w / 2$. Additionally, if one takes parameters '$d = t$' and '$r = R$', the aforementioned equation works well for thin helices with rounded cross sections. Equation (1) is validated with the help of magnetostatic solver equations using CST Particle Studio for partial re-distribution of transverse magnetic fields and axial magnetic fields amplitude with a finite thickness of the helix with rectangular cross section as well as round cross section with nonlinear permeability of Iron and Steel ferromagnetic materials [1].

III. RESULT AND DISCUSSION

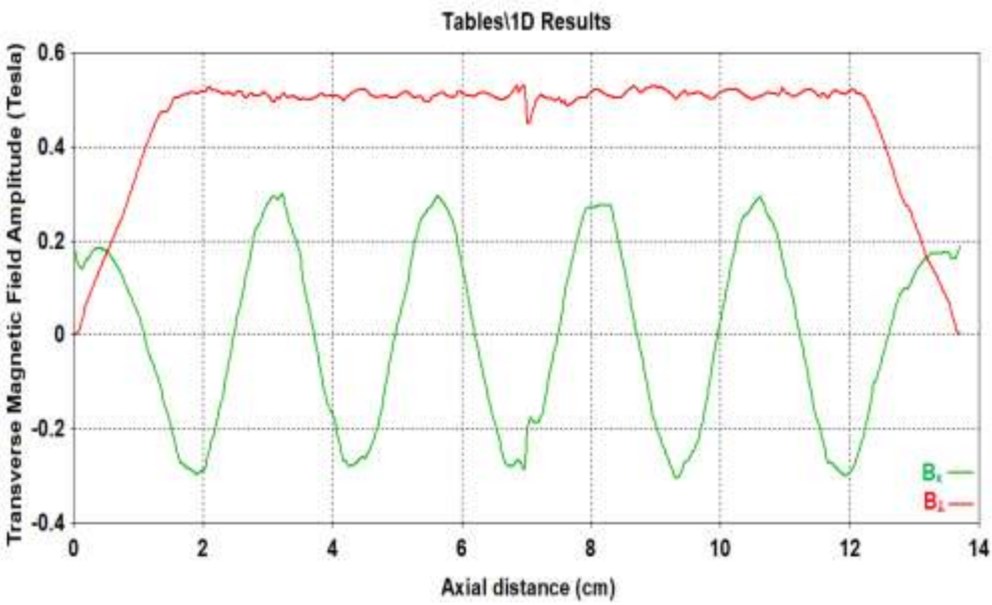
Based on the analytical method, high power microwave- FEL Amplifiers is studied. A computer friendly numerical code is written to analyze the device beam mechanism. To validate the optimized FEL Amplifiers design obtained by following the device design methodology, the PIC simulation results obtained by modeling the device through CST Particle Studio are validated with the analytical results.

A. PIC SIMULATION IN THE ABSENT OF ELECTRON BEAMS

Simulation results of re-distributed transverse magnetic field amplitude $B_x(T)$ & $B_\perp(T)$ for the case of Iron helix and Steel helix with rectangular cross section and round cross section are shown in Fig. 2 and Fig. 3.

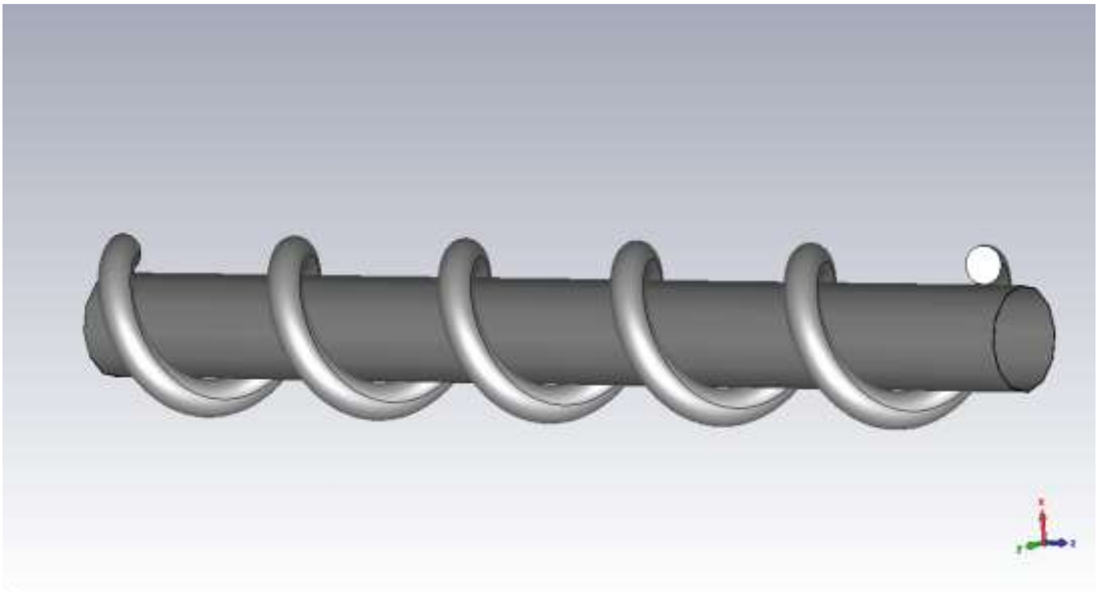


(a)

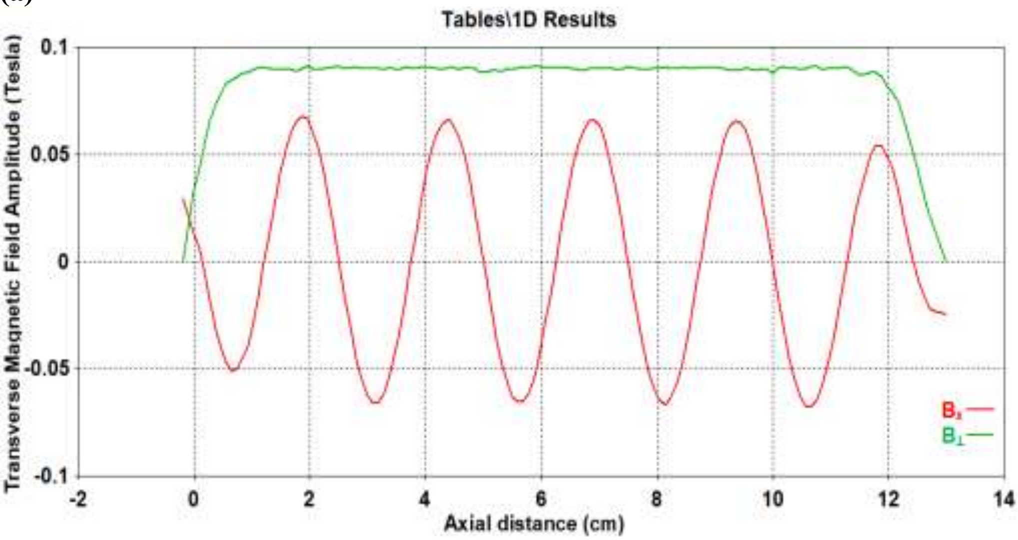


(b)

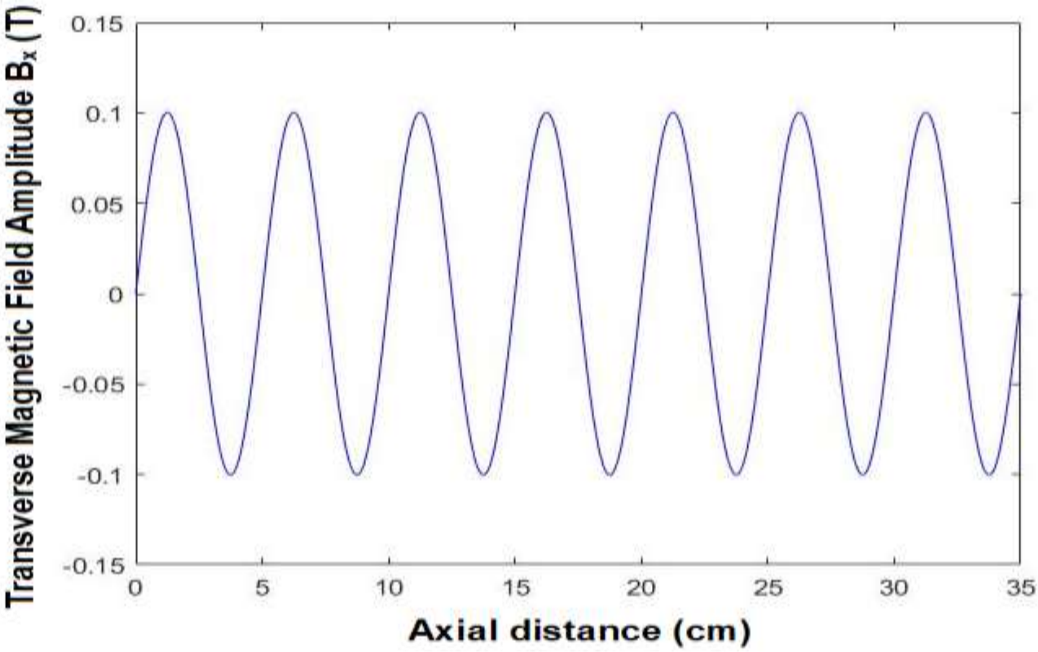
Fig. 2. Simulation results for Iron helix with rectangular cross section of B_x(T) & $B_\perp$(T) in drift tube



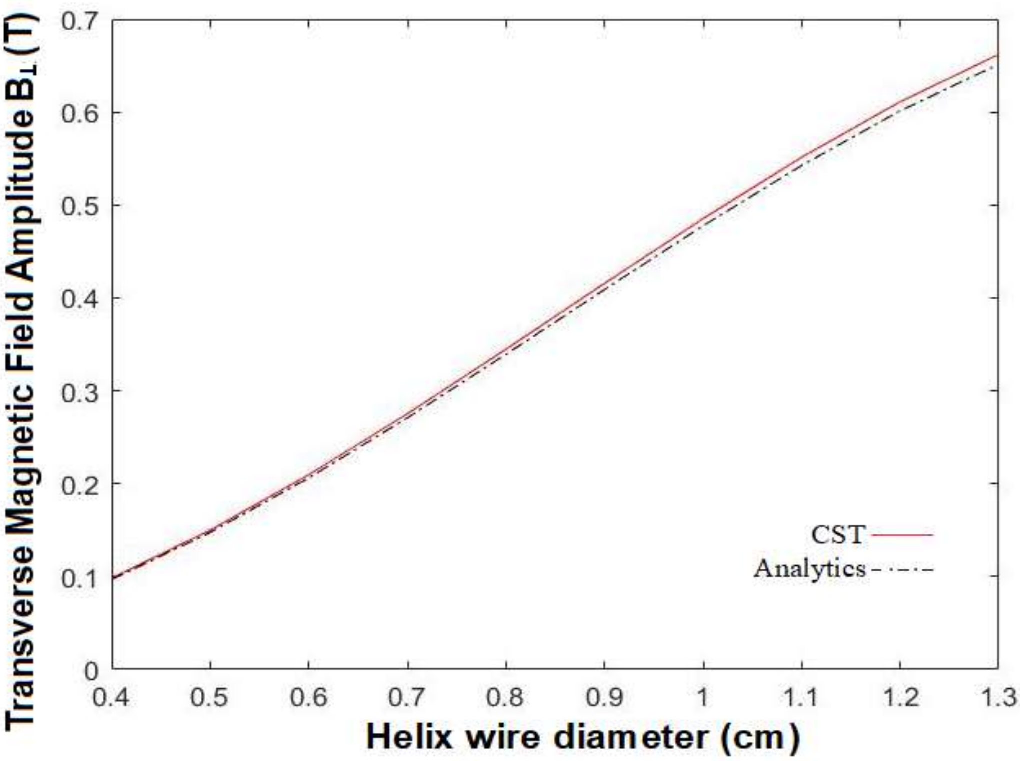
(a)


Tables\1D Results
Transverse Magnetic Field Amplitude (Tesla)
0.1
0.05
0
-0.05
-0.1
-2
0
2
4
6
8
10
12
14
Axial distance (cm)
B
$B_\perp$

(b)


Transverse Magnetic Field Amplitude Bx (T)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
5
10
15
20
25
30
35
Axial distance (cm)

(c)


Transverse Magnetic Field Amplitude B⊥ (T)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Helix wire diameter (cm)
CST
Analytics

(d)
Fig. 3. Simulation results of steel helix with round cross section of $B_x(T)$ & $B_\perp(T)$ with drift tube

B. PIC SIMULATION IN THE PRESENCE OF ELECTRON BEAMS

The PIC simulation is presented here to extend for the beam-present case. Additionally, electrons have been regarded as being equally dispersed in drift tubes with electron bunch forms for the PIC simulation in the beam current situation. As a result, they consequently synchronise their energy transfer to the RF wave. This enables electromagnetic wave amplification at the cyclotron frequency of the FEL amplifiers and the wiggling of electron bunches during beam present case PIC simulation are shown in Fig. 4.

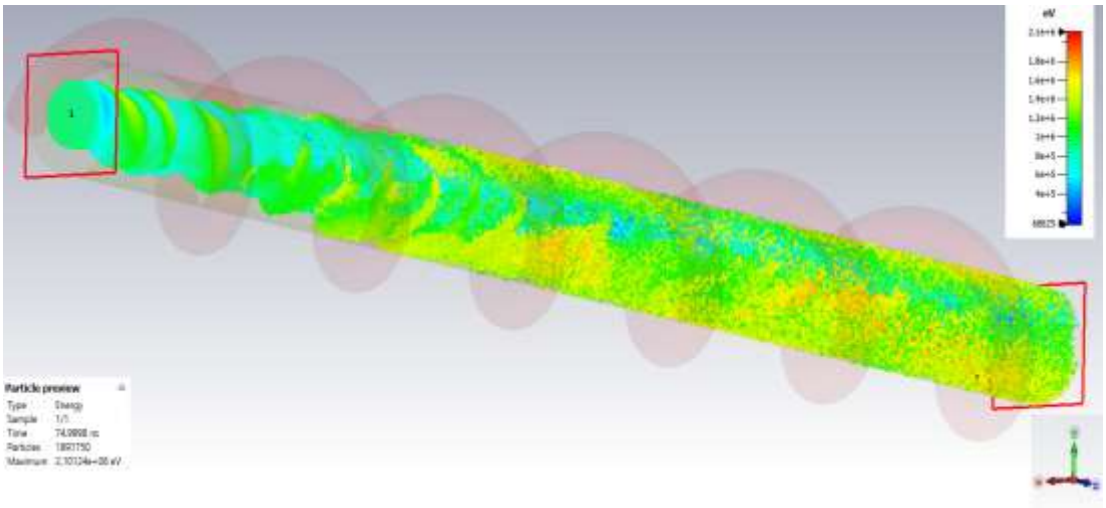


Fig.4. Wiggling view of the electron beams during PIC Simulations

By obtaining the electric field's Fourier transform and calculating the frequency spectrum of the amplitude, as shown in Fig. 5, it is possible to determine the FEL amplifier's working frequency. The largest frequency peak is clearly seen at about 35 GHz to TM_{01} mode, and validates the FEL amplifiers frequency of operation as a result.

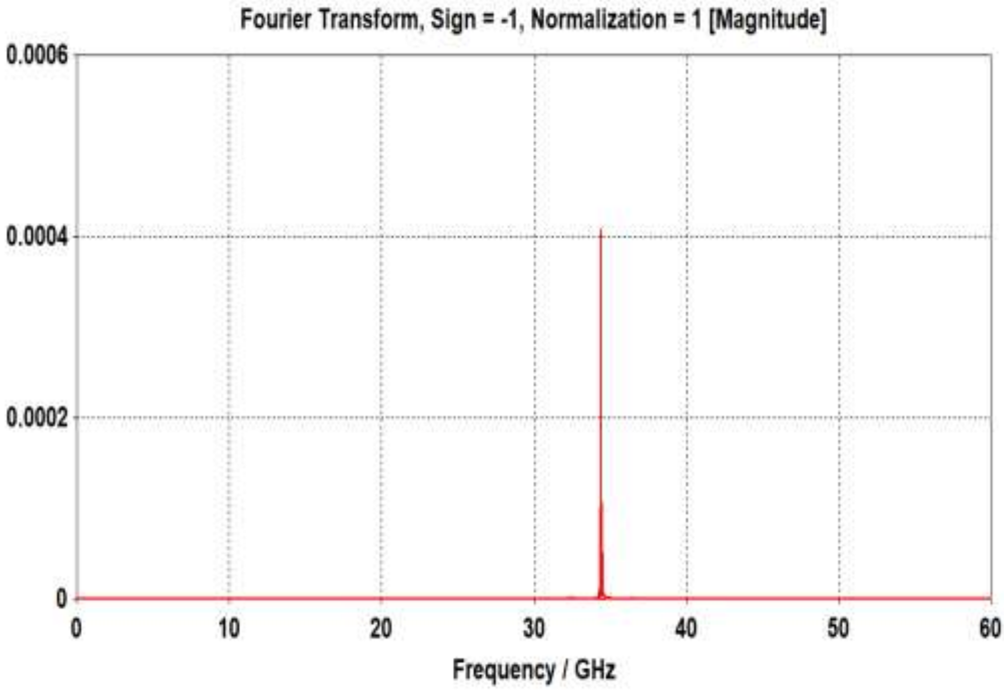


Fig. 5. Frequency spectrum of the TM_{01} mode

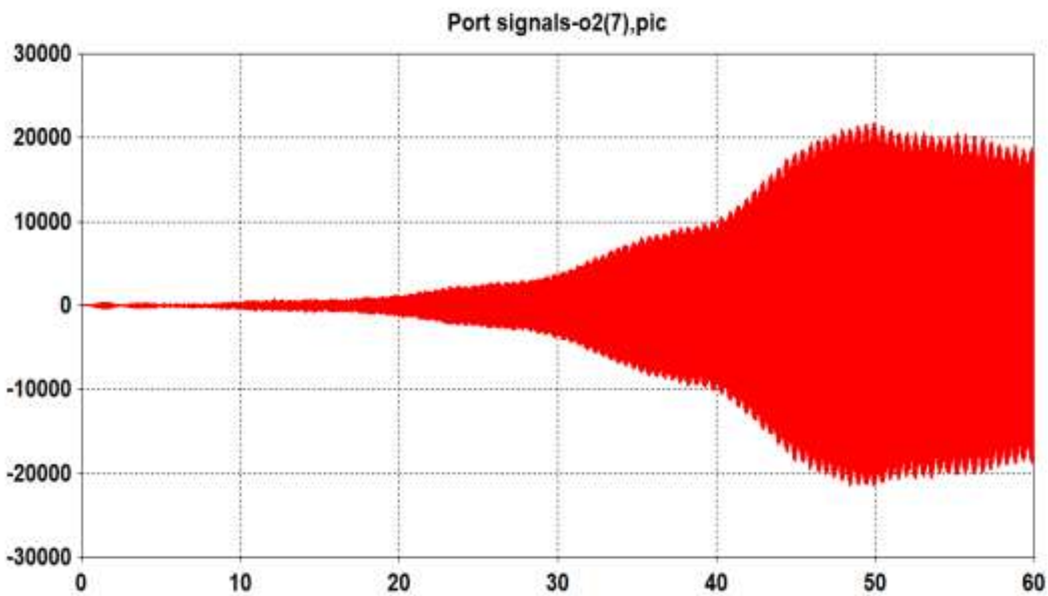


Fig. 6. Temporal amplitude curve of the TM_{01} mode

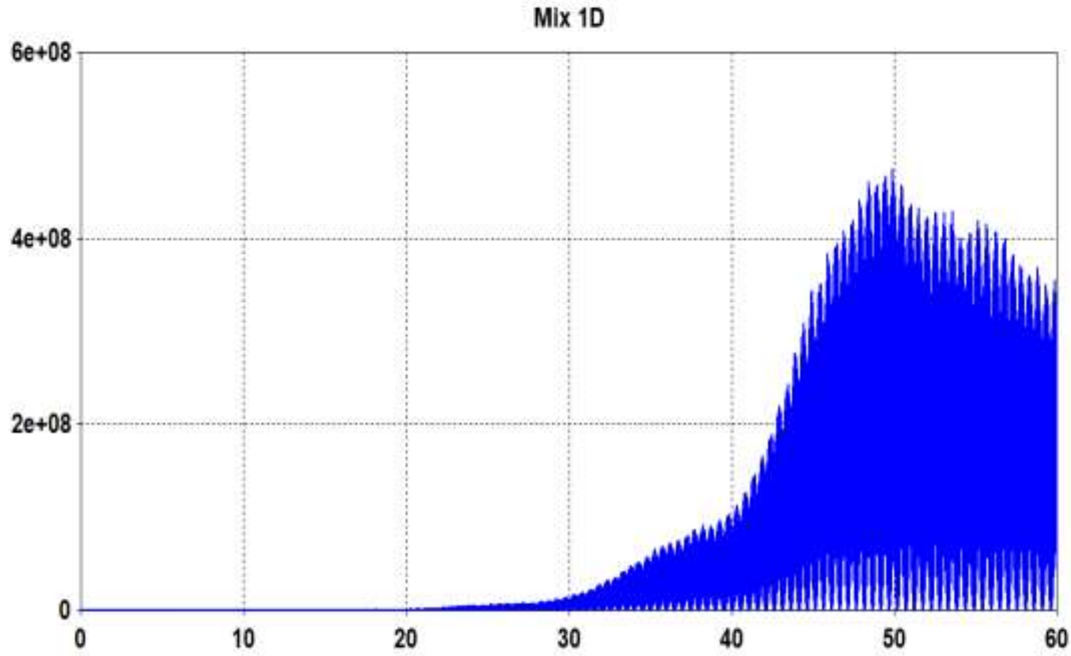


Fig. 7. Temporal power plot of the TM_{01} mode

At DC magnetic field B_o = 1.175 Tesla with wiggler field (B_w) of 0.115 Tesla, the output associated for TM_{01} mode with maximum amplitude as compared to others. The saturated RF output power has been estimated in CST as around 17 MW (Fig. 7) with an electronic efficiency of 20% for The electron beam energy of 164.99 keV with beam voltage of 164.99 kV, and beam current of 103.04 A, 100 ns pulse duration, which is exited in the input port of the device.

IV. CONCLUSION

This work explored the investigation about beam wave interaction of FEL Amplifiers through code driven algorithm. The modelling of proposed novel structure is done through the simulation of particle-in-cell (PIC) in CST particle studio. The results are observed for the re-distribution of axial and transverse magnetic field in helix round cross section, and validated using magnetostatic solver. For simulation, the 60ns pulse is excited by electron beam having energy of 164.99 keV with beam voltage 164.99 kV, and beam current of 103.04 A. The beam radius is taken as 0.3 cm with 1% of velocity spreads by neglecting the impact of space charge effect. Moreover, this FEL Amplifier offers maximum amplification at 35 GHz frequency in TM_{01} mode at DC magnetic field B_o = 1.175 Tesla with wiggler field (B_w) of 0.115 Tesla. Further, it is observed that EM power approaches to saturation level after the pulse duration with radio-frequency (RF) power approximately 17 MW and electronic efficiency of 20%.

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