Updates on kinetic modeling of resonant nanoantennas towards laser induced fusion

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#### **Inertial Confinement Fusion**

Two ways Radiation Dominated Implosion Absorptivity by nano-technology

#### Nanoplasmonic Laser Fusion Research Laboratory



Kőszeg, September 14, 2019 - Int. Workshop on Collectivity First meeting on the NAPLIFE project (12 people)

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#### Nanoplasmonic Laser Fusion Research Laboratory

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#### Inertial Confinement Fusion

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#### Thermo-nuclear Fusion

•  $\eta E_f$  is the usable energy

• The loss is 
$$(1 - \eta)(E_0 + E_b)$$

- $E_0 = 3nkT$ ,  $E_b = bn^2 \tau \sqrt{T}$  (thermal bremsstralung)
- Giving the gain factor:  $Q = \frac{\eta \epsilon n \tau v \sigma}{4(1-\eta)(3kT+bn\tau\sqrt{T})}$
- Q must be Q > 1 for energy production

• This also means 
$$n au > rac{3kT(1-\eta)}{rac{1}{4}\epsilon\eta\langle v\sigma 
angle - b(1-\eta)\sqrt{T}} 
ightarrow \mathsf{LC}$$

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#### Lawson criterion

Fulfilling the Lawson criterion

- Magnetically confined plasmas: increase confinement time
- Inertial confinement fusion: increase density of fusion plasma

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#### News on fusion

Home / News / Lawrence Livermore National Laboratory achieves fusion ignition



Lawrence Livermore National Laboratory achieves fusion ignition

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The of <u>U.S. Department of Energy</u> (DOE) and DOE's of <u>National Nuclear Security</u> <u>Administration</u> (NNSA) today (Dec. 13) announced the achievement of fusion ignition



Dec. 14, 2022

#### News on fusion

Article

https://doi.org/10.1038/s41467-023-36655-1

Inertial Confinement Fusion

**Radiation Dominated Implosion** 

Absorptivity by nano-technology

Two ways

# First measurements of p<sup>11</sup>B fusion in a magnetically confined plasma

Received: 4 November 2022	R. M. Magee® <sup>1</sup> ⊠, K. Ogawa® <sup>2</sup> , T. Tajima <sup>1,3</sup> , I. Allfrey® <sup>1</sup> , H. Gota® <sup>1</sup> , P. McCarroll <sup>1</sup> , S. Ohdachi® <sup>2</sup> , M. Isobe <sup>2</sup> , S. Kamio® <sup>1,3</sup> , V. Klumpe <sup>1,3</sup> , H. Nuga <sup>2</sup> , M. Shoj <sup>2</sup> , S. Ziael <sup>1</sup> , M. Binderbauer <sup>2</sup> & M. Osakabe® <sup>2</sup>
Accepted: 10 February 2023	
Published online: 21 February 2023	
Check for updates	Proton-boron (p <sup>11</sup> B) fusion is an attractive potential energy source but tech- nically challenging to implement. Developing techniques to realize its poten- tial requires first developing the experimental capability to produce p <sup>13</sup> B fusion in the magnetically-confined, thermonuclear plasma environment. Here we report clear experimental measurements supported by simulation of p <sup>14</sup> B fusion with high-energy neutral beams and boron powder injection in a high- temperature fusion plasma (the Large Helical Device) that have resulted in diagnostically significant levels of alpha particle emission. The injection of boron powder into the plasma edge results in boron accumulation in the core. Three 2 MW, 160 kV hydrogen neutral beam injectors create a large population of well-confined, high -energy protons to react with the boron plasma. The fusion products, MeV alpha particles, are measured with a custom designed particle detector which gives a fusion rate in verg good relative agreement with calculations of the global rate. This is the first such realization of p <sup>18</sup> B fusion in a magnetically confined plasma.

While the challenges of producing the fusion core are greater for

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#### News on fusion



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#### Direct vs Indirect drive





#### Hohlraum

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#### Hohlraum 2014



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#### Hohlraum 2022



Fig. 1: Schematic of the indirect-drive inertial confinement approach to fusion.

Centre, A typical indirect-drive target configuration with key engineering elements labelled. Laser beams (blue) enter the hohlraum through laser entrance holes at various angles. Top left, A Schematic pie diagram showing the radial distribution and dimensions of materials in diamond (high-density carbon, HDC) ablator implosions. Bottom left, The temporal laser power pulse-shape (blue) and associated hohlraum radiation temperature (green). Right, At the centre of the hohlraum, the capsule

[A.B, Zylstra, O.A. Hurricane et al., Nature, 601, 542-548 (2022)]

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## Rayleigh-Taylor instabilities



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## Rayleigh-Taylor instabilities



# Energy must be delivered as sysmmetric as possible!

Different levels of corrugation of the shell surfaces :

Stiking similarities exist between tydrodynamic Instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* 2, 275 (1990); image (b) is from Hachisu et al. Astrophysical Journal 366, L27 (1991)]



Left: same roughness of inner and outer surface as specified for the NIF target Center: outer surface roughness is twice the NIF level

**Right:** DT inner surface roughness three times larger than NIF specifications

[S. Atzeni et al., Nucl. Fusion 54, 054008 (2014).]

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Latest (January 2023) news 3.15MJ kinetic energy at NIF with burning time of 89-137 ps(?)

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#### RFD



[Csernai, L.P. (1987). Detonation on a time-like front for relativistic systems. Zh. Eksp. Teor. Fiz. 92, 379-386.]

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#### RFD



Figure 5.9: Space-like (a) and time-like (b) surfaces of discontinuity [Csernai, L.P. (1987). Detonation on a time-like front for relativistic systems. Zh. Eksp. Teor. Fiz. 92, 379-386.]

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#### RFD



Figure 5.10: Smooth change from spacelike to timelike detonation [Csernai, L.P. (1987). Detonation on a time-like front for relativistic systems. Zh. Eksp. Teor. Fiz. 92, 379-386.]

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#### Constant absorptivity



#### [L.P. Csernai & D.D. Strottman, Laser and Particle Beams 33, 279 (2015)]

 $\alpha_{k_{middle}} = \alpha_{k_{edge}}$ 

# Simultaneous volume ignition is only up to 12%

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#### Changing absorptivity



[Csernai, L.P., Kroo, N. and Papp, I. (2017). Procedure to improve the stability and efficiency of laser-fusion by nano-plasmonics method. Patent P1700278/3 of the Hungarian Intellectual Property Office.]

 $\alpha_{k_{middle}} \approx 4 \times \alpha_{k_{edge}}$ 

Simultaneous volume ignition is up to 73%

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### Flat target



Schematic view of the cylindrical, flat target of radius, R, and thickness, h.  $V = 2\pi R^3$ ,  $R = \sqrt[3]{V/(2\pi)}$ ,  $h = \sqrt[3]{4V/\pi}$ .

[L.P. Csernai, M. Csete, I.N. Mishustin, A. Motornenko, I. Papp, L.M. Satarov, H. Stöcker & N. Kroó, Radiation- Dominated Implosion with Flat Target, *Physics and Wave Phenomena*, **28** (3) 187-199 (2020)]

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#### Varying absorptivity



**Deposited energy** per unit time in the space-time plane across the depth, h, of the flat target. (a) without nano-shells (b) with nano-shells To increase central absorption we used the following distribution:

$$\alpha_{ns}(s) = \alpha_{ns}^{C} + \alpha_{ns}(0) \cdot \exp\left[4 \times \frac{\left(\frac{s}{100}\right)^2}{\left(\frac{s}{100} - 1\right)\left(\frac{s}{100} + 1\right)}\right]$$

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#### Similar Configuration with success

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Nuclear probes of an out-of-equilibrium plasma at the highest compression Phys. Lett. A 383 (2019) 2285-2289. G. Zhang<sup>a,b,\*</sup>, M. Huang<sup>c</sup>, A. Bonasera<sup>d,e,\*</sup>, Y.G. Ma<sup>f,b,i,\*</sup>, B.F. Shen<sup>g,h,\*</sup>, H.W. Wang<sup>a,b</sup> W.P. Wang<sup>g</sup>, J.C. Xu<sup>g</sup>, G.T. Fan<sup>a,b</sup>, H.J. Fu<sup>b</sup>, H. Xue<sup>b</sup>, H. Zheng<sup>j</sup>, L.X. Liu<sup>a,b</sup>, S. Zhang<sup>c</sup>, W.I. Li<sup>b</sup>, X.G. Cao<sup>a,b</sup>, X.G. Deng<sup>b</sup>, X.Y. Li<sup>b</sup>, Y.C. Liu<sup>b</sup>, Y. Yu<sup>g</sup>, Y. Zhang<sup>b</sup>, C.B. Fu<sup>k</sup>,

4 (up) + 4(down) lasers Target thickness, h (3.6µm-1mm) & radius, R, (150-400µm) were varied.

X.P. Zhang<sup>k</sup>

Total pulse energy 1.2kJ (2ns) for 8 beams. Shortest (250ps) pulses -> 100s MeV ions > non-thermal distr. = directed ion acceleration



Typical fusion neutron energies were measured & used to extract the target density.



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Transmission Electronmicroscopy photos of 75x25 nm gold nano-rod antennas [Judit Kámán, A. Bonyár et al. (NAPLIFE Collab.)., Gold nanorods .... 10th ICNFP 2021, Kolymbari]

FEM approach PIC approach

#### Nanorod

Field solver:  $\epsilon(\omega) = 1 - \frac{\omega_p^2}{(\omega^2 + i\gamma\omega)}$ where  $\omega_p$  is the plasma frequency:  $\sqrt{\frac{n_e e^2}{m'\epsilon_0}}$   $\gamma$  is the damping factor or collision frequency:  $\gamma = \frac{1}{\tau}$  and  $\tau$  is the average time between collisions Particle simulation:

$$\frac{\partial \boldsymbol{E}}{\partial t} = \frac{1}{\mu_0 \epsilon_0} \nabla \times \boldsymbol{B} - \frac{\boldsymbol{J}}{\epsilon_0}, \ \frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$$

 $\gamma_i m_i \boldsymbol{v}_i = q_i (\boldsymbol{E}_i + \boldsymbol{v}_i \times \boldsymbol{B}_i), \ \gamma_i$  is the relativistic factor

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#### Nanorod



[W. J. Ding, et al., Particle simulation of plasmons Nanophotonics, vol. 9, no. 10, pp. 3303-3313 (2020)]

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#### Particle In Cell methods



Figure 2: The Yee grid in 2D

[F.H. Harlow (1955). A Machine Calculation Method for Hydrodynamic Problems. Los Alamos Scientific Laboratory report LAMS-1956]

[T.D. Arber et al 2015 Plasma Phys. Control. Fusion 57 113001]

A **super-particle** (marker-particle) is a computational particle that represents many real particles.

Particle **mover** or **pusher** algorithm as (typically Boris algorithm).

Finite-difference time-domain method for solving the time evolution of Maxwell's equations.

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## General layout of the EPOCH code





- (input) deck
- housekeeping
- o io
- parser
- physics\_packages
- user\_interaction

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## FDTD in EPOCH

• 
$$\boldsymbol{E}_{n+\frac{1}{2}} = \boldsymbol{E}_n + \frac{\Delta t}{2} \left( c^2 \nabla \times \boldsymbol{B}_n - \frac{\boldsymbol{j}_n}{\epsilon_0} \right)$$
  
•  $\boldsymbol{B}_{n+\frac{1}{2}} = \boldsymbol{B}_n - \frac{\Delta t}{2} \left( \nabla \times \boldsymbol{E}_{n+\frac{1}{2}} \right)$   
• Call particle pusher which calculates  $\boldsymbol{j}_{n+1}$   
•  $\boldsymbol{B}_{n+1} = \boldsymbol{B}_{n+\frac{1}{2}} - \frac{\Delta t}{2} \left( \nabla \times \boldsymbol{E}_{n+\frac{1}{2}} \right)$   
•  $\boldsymbol{E}_{n+1} = \boldsymbol{E}_{n+\frac{1}{2}} + \frac{\Delta t}{2} \left( c^2 \nabla \times \boldsymbol{B}_{n+1} - \frac{\boldsymbol{j}_{n+1}}{\epsilon_0} \right)$ 

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#### Particle pusher

 Solves the relativistic equation of motion under the Lorentz force for each marker-particle

$$\boldsymbol{p}_{n+1} = \boldsymbol{p}_n + q\Delta t \left[ \boldsymbol{E}_{n+\frac{1}{2}} \left( \boldsymbol{x}_{n+\frac{1}{2}} \right) + \boldsymbol{v}_{n+\frac{1}{2}} \times \boldsymbol{B}_{n+\frac{1}{2}} \left( \boldsymbol{x}_{n+\frac{1}{2}} \right) \right]$$

**p** is the particle momentum **q** is the particle's charge **v** is the velocity. **p** =  $\gamma m \mathbf{v}$ , where **m** is the rest mass  $\gamma = [(\mathbf{p}/mc)^2 + 1]^{1/2}$ 

 Villasenor and Buneman current deposition scheme [Villasenor J & Buneman O 1992 Comput. Phys. Commun. 69 306], always satisfied: ∇ · E = ρ/ε<sub>0</sub>, where ρ is the charge density.

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#### Particle shape



Figure 3: Second order particle shape function

#### First order approximations are considered

$$F_{part} = \frac{1}{2}F_{i-1}\left(\frac{1}{2} + \frac{x_i - X}{\Delta x}\right)^2 + \frac{1}{2}F_i\left(\frac{3}{4} - \frac{(x_i - X)^2}{\Delta x^2}\right)^2 + \frac{1}{2}F_{i+1}\left(\frac{1}{2} + \frac{x_i - X}{\Delta x}\right)^2$$

[EPOCH 4.0 dev manual]

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#### Metal Nanoparticles as Plasmas

The conduction band electrons in metals behave as strongly coupled plasmas.

For golden nanorods of 25nm diameter in vacuum this gives an effective wavelength of  $\lambda_{\rm eff}=266\rm{nm}$ 

$$rac{\lambda_{ ext{eff}}}{2R\pi}=13.74-0.12[arepsilon_{\infty}+141.04]-rac{2}{\pi}+rac{\lambda}{\lambda_{
ho}}0.12\sqrt{arepsilon_{\infty}+141.04}$$

[Lukas Novotny, Effective Wavelength Scaling for Optical Antennas, Phys. Rev. Lett. **98**, 266802 (2007).]

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## Kinetic Modelling of the Nanorod

#### Nanorod inside a PIC simulation box



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## Kinetic Modelling of the Nanorod

#### Evolution of the nanoantenna



Number density of electrons in the middle of a nanorod of size  $25 \times 130$  nm at different times. The nanorod is orthogonal to the beam direction, *x*.

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(a)

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#### Kinetic Modelling of the Nanorod in Vacuum



- Evolution of the E field's y component from 42.4 till 45.7 fs, around a nanorod of 25x130 nm.

- The direction of the E field at the two ends of the nanorod does not change.

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#### In Vacuum



energy in the box without nanorod antenna  $3 \times 10^{-8}$  J (black line) nanorod absorbs EM energy reducing it to  $2.3 \times 10^{-8}$  J (red line) deposited energy in the nanorod (green line) results in light absorption cross section highest

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#### In UDMA-TEGDMA copolymer comparison



Optical response of the gold nanorod with different numerical methods and lengths,  $L = \lambda_{eff}/2$ ,  $\lambda_{eff}/3$  and  $2\lambda_{eff}$  eff/3. (a) PIC, (b) FEM and (c) FEM with normalized values to unit antenna length.

[I. Papp, L. Bravina, M. Csete, et al.(NAPLIFE Collaboration), Kinetic model of resonant nanoantennas in polymer for laser induced fusion, Frontiers in Physics, **11**, 1116023 (2023).]

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#### In UDMA-TEGDMA copolymer comparison



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#### In UDMA-TEGDMA copolymer comparison



Electrons leaving the nanorod. Figure (a) indicates the **maximum momentum** in time, Figure (b) shows the distribution of electrons at different momentum values.

[I. Papp, L. Bravina, et al. Frontiers in Physics, **11**, 1116023 (2023),]

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#### Capping in the experiment



The gold nanorods in the polymer matrix are coated with dodecanethiol (DDT) capping.  $CH_3(CH_2)_{11}SH$ [Bonyár A, et al. The Effect of Fem- tosecond Laser Irradiation and Plasmon Field on the Degree of Conversion of a UDMA-TEGDMA Copoly- mer

Nanocomposite Doped with Gold Nanorods. Inter- national Journal of Molecular Sciences 23(21), 13575 (2022).]

Introduction Modelling the Nanorod

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Considerations for the simulation box:  $S_{CB} = 530 \times 530 \text{ m}^2 = 2.81 \times 10^{-9} \text{ cm}^2$  and length of  $L_{CB} = 795 \text{ nm}$ 

beam crosses the box in T = 795 nm/c = 2.65 fs

Nanorod size: 25 nm diameter with 85 nm length

Pulse length:  $40 \times \lambda/c = 106$  fs Intensity:  $4 \times 10^{15}$  W/cm<sup>2</sup>

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#### Ionisable surrounding



We consider a laser pulse of intensity  $I = 4 \cdot 10^{15} \text{W/cm}^2$  and  $I = 4 \cdot 10^{17} \text{W/cm}^2$  and duration of 106fs.

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#### Ionisable surrounding



We consider a laser pulse of intensity  $I = 4 \cdot 10^{15} \text{W/cm}^2$  and  $I = 4 \cdot 10^{17} \text{W/cm}^2$  and duration of 106fs.

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#### Kinetic Modelling of the Nanorod in Hydrogen medium



- Evolution of the E field's y component from 42.4 till 45.7 fs, around a nanorod of 25x85 nm.  $I = 4 \cdot 10^{15} \text{W/cm}^2$ 

- The direction of the E field at the two ends of the nanorod does not change.

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#### Kinetic Modelling of the Nanorod in Hydrogen medium



- Evolution of the E field's y component from 42.4 till 45.7 fs, around a nanorod of 25x85 nm.  $I = 4 \cdot 10^{17} \text{W/cm}^2$ 

- The direction of the E field at the two ends of the nanorod does not change.

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#### Ionisable surrounding



The number of electrons and protons when they leave the nano antennas or their surrounding at intensity  $I = 4 \times 10^{15} \text{ W/cm}^2$ .

FEM approach PIC approach

#### Ionisable surrounding



The number of electrons and protons when they leave the nano antennas or their surrounding at intensity  $I = 4 \times 10^{17} \text{ W/cm}^2$ .

Conclusions Acknoledgements

## Conclusions, Looking forward

- The model is in good agreement with currently available widely accepted methods
- Quantitative differences mainly come at different resonant lengths
- The model is less idealized than before
- Ionization in the medium is now included, nuclear reactions are on the way
- Target pre-compression in the next step can be estimated

Conclusions Acknoledgements

#### Acknoledgements

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