A non-thermal laser-driven mixed fuel nuclear fusion reactor concept

Hartmut Ruhl and Georg Korn
Marvel Fusion, Blumenstrasse 28, Munich, Germany

Abstract
We propose a laser-driven non-thermal near-solid density fast reactor concept with mixed nuclear fusion fuels that is capable of transforming external laser energy efficiently into fusion energy and secondary particles. The reactor is capable of making use of a range of neutronic and aneutronic fuels. Its core part consists of an integrated nanoscopic nuclear fusion fuel based laser-driven accelerator that is capable of producing non-thermal ionic distributions within fuel mixes.

Keywords: integrated accelerator, nanoscopic reactor, nanoscopic converter, nonlinear optics, secular field generator, non-thermal Lawson criteria

Contents
1 Introduction to the concept 1
2 The abstraction model 2
3 Rate equations for reactions 3
4 The integrated nano-accelerator 4
5 Burn fraction and efficiency 7
6 Nonlinear optics and confinement 9
7 Radiative energy loss 10
8 Summary 11
9 Acknowledgements 12

1. Introduction to the concept
In recent years there has been an abundance of papers in the field of ultra-short ultra-intense laser-matter interaction with nano-structures. We quote [1, 2, 3] and the literature therein to give examples. In case the laser and the nano-structures are tailored towards each other the interaction of ultra-short ultra-intense laser pulses interacting with nano-structures promise an efficient way of transferring laser energy into a target.

Many of the papers in the field discuss nano-structures that are either extremely small and randomly oriented or the structures are so large that they cannot be called nano-structures anymore. Here, we propose a nano-structured nuclear micro-reactor with comparatively small structures sizes for non-thermal operation, which is entirely composed of nuclear fuels. It comprises an integrated nano-structured accelerator consisting of boron or lithium rods with a radius of \( R \approx 30 \text{ nm} \) or smaller. The nuclear fuels can have a range of Gamov energies and \( S \)-factors. They can be neutronic or aneutronic or any mix of the latter.

Since lasers represent the fastest macroscopic energy sources we propose that the reactor is powered by ultra-short ultra-high intensity laser pulses with VUV wavelengths. The laser couples to the reactor via the boron or lithium nano-structures.

If both, the nano-structures and the laser pulses are tailored towards each other it is possible to engineer controlled nonlinear optical properties into the system consisting of the nano-structured reactor and the driver laser. Optical instabilities might be avoided. It might be possible to engineer near complete laser energy deposition and in addition to deploy nearly limitless energy to the reactor in the fastest possible way.

The boron or lithium nano-rods are supposed to ionize rapidly leading to subsequent Coulomb explosions propagating at the speed of light along the laser pulse. Coulomb explosions are efficient if electronic recurrence into the ionizing nano-structures is avoided on the time scale of the Coulomb explosions. This is possible for sufficiently small nano-structures and sufficiently energetic electrons.

If the nano-structures are sufficiently small and sufficiently far apart from each other the laser drivers interacting with the nano-structures might be capable of capturing electrons from ionizing nano-structures by which process large electronic currents are generated that lead to secondary electric and magnetic fields in the reactor. As a consequence, large confining magnetic fields might emerge that are strong enough to form an efficient confinement system for the nuclear fuel of the proposed reactor. The proposed reactor would the become an ultra-strong magnetic field generator.

Since it is the laser pulse energy that is expensive reactor concepts that rely on scalable ultra-short pulse laser technology might have a competitive edge and a commercial advantages. If in addition external energy consuming compression schemes could be avoided or at least mitigated and if a larger range of nuclear fuels could be envisioned within an ignition concept a wider range of applications of the proposed reactor at lower
cost levels might be possible. To this end the design of ultra-fast and brilliant neutron sources is conceivable by embedding deuterated boron or lithium nano-accelerators into tritium.

- The proposed nano-structured micro-reactor can be operated with pure nuclear fuels and with nuclear fuel mixes. For example, it is possible to make use of neutronic fuels like DT and \( n^7Li \) and aneutronic ones like \( p^{11}B \) and \( p^9Li \).

- The integrated nano-accelerator can be made of boron or lithium. Both, boron and lithium can be nuclear fuel constituents. They enhance efficiency since the heating of materials that are not part of fusion cycles can be avoided.

- A range of nano-morphologies are possible in order to tailor the reactor towards the fuel mix under consideration and the limitations of nano-fabrication.

- It is possible to dope the embedded boron or lithium based nano-accelerator with nuclear fuel mixes. For example, D, p, or lithium can be implanted into boron or visa versa p can be implanted into lithium while the gaps between the nano-accelerator structures can be filled in with a broad range of matching fuel constituents. We note that it is possible to take advantage of chemical compounds like LiH. Moreover, it is possible to combine boron and lithium based nano-accelerators inside the micro-reactor.

- Since non-thermal reactivities are large the proposed reactor concept might enable near solid fuel density operation for a range of fuels.

- The operation of the nano-structured micro-reactor with ultra-short laser pulses minimizes the required laser pulse energy for triggering efficient nuclear fusion reactions. Hence, rep-rated reactor operation might be possible. In addition, ultra-short laser pulse technology might be scalable. Hence, multiple ultra-short laser pulse drivers could be used instead of a single system enabling tailored drive profiles for the reactor.

- The form factors of the nano-structures of the integrated accelerator are approximately 30 nm. They are too small to allow for electronic recurrence within the Coulomb explosion time. As a consequence, efficient Coulomb explosions in a mixed fuel context can be triggered that propagate close to speed of light.

- External fuel compression might not be necessary since the proposed reactor concept has two intrinsic compression schemes. One is due to the exploding nano-accelerator and the other is due to the large scale ultra-strong pinching magnetic field, which forms a global confinement system.

In the paper some of the consequences of the hypotheses outlined in the introduction are discussed. There are assumptions and uncertainties that have to become subjects of deeper investigations. The paper is structured in the following way. In section 2 the abstraction model is outlined. In section 3 simplified transport equations are discussed with the help of which the relevant parameters for best fusion efficiency can be identified. In section 4 the concept of the integrated mixed fuel nano-accelerator is introduced. In section 5 the conversion fraction and efficiency as a function of the fuel mix are addressed. In section 6 the optical properties of ultra-short ultra-intense laser pulses interacting with nano-rods are discussed. In section 7 energy loss processes are addressed.

2. The abstraction model

We start from an effective quantum field theory with electromagnetic interactions \([4, 5, 6, 7]\). An expansion into a quantum BBGKY-hierarchy up to binary correlation order in the presence of electromagnetic fields leads to

\[
\left( \frac{\partial^\mu}{\partial x^\mu} + m_k \frac{\partial}{\partial p_i^\mu} \right) f(x, \vec{p}_k) = \sum_{l, k} \int \frac{d^3 p_l}{p_l^0} \frac{d^3 p_{\mu}}{p_{\mu}^0} \frac{d^3 p_{\nu}}{p_{\nu}^0} \times A(p_l p_k, p_{\mu} p_{\nu}) f(x, \vec{p}_{\mu}) f(x, \vec{p}_{\nu})
\]

\[
- \sum_{l, k} \int \frac{d^3 q_l}{q_l^0} \frac{d^3 q_{\mu}}{q_{\mu}^0} \frac{d^3 q_{\nu}}{q_{\nu}^0} \times A(q_l q_{\mu} q_{\nu}, p_l p_{\mu} p_{\nu}) f(x, \vec{q}_l) f(x, \vec{q}_{\mu}) f(x, \vec{q}_{\nu})
\]

where the invariant transition amplitude is given by

\[
A(p_l p_k, p_{\mu} p_{\nu}) = \delta^3 (p_l + p_k - p_{\mu} - p_{\nu}) \langle p_l p_k | T_{in} | q_{l} q_{\mu} q_{\nu} \rangle^2.
\]

The binary \( T_{in} \)-matrix in (2) has to be calculated in the context of ultra-strong electromagnetic fields. Hence, appropriately dressed states are required. Calculations of that kind in a somewhat different context are found in \([14]\). The \( T_{in} \)-matrix is obtained with the help of the self-energy \( S_{in} \)-matrix, which is to lowest order

\[
S_{in} = 1 + \frac{1}{\hbar c} \int^\infty_{-\infty} dx L^*_m (x) : .
\]

This implies

\[
in \langle q_1 q_2 | S - 1 | p_2 p_1 \rangle_{in} = \frac{i}{\hbar c} (2\pi \hbar)^4 \delta^3 (p_1 + p_2 - q_1 - q_2) \times \langle q_1 q_2 | L^*_m : | p_2 p_1 \rangle_{in}
\]

and hence

\[
in \langle q_1 q_2 | T_{in} | p_2 p_1 \rangle = \frac{2\pi}{c} (2\pi \hbar)^4 \langle q_1 q_2 | L^*_m : | p_2 p_1 \rangle_{in}.
\]

In section 3 we give details of the abstraction model based on the general structure of the transport equations stated here.
the electric field strength tensor. Maxwell’s equations are given

\[
\begin{align*}
\nabla \times E &= -\frac{\partial B}{\partial t} , \\
\nabla \times B &= \mu \nabla \times E , \\
\n\nabla \cdot E &= \rho_f , \\
\n\nabla \cdot B &= 0 ,
\end{align*}
\]

where the \( q \) and \( \rho_f \) particles embedded in a self-consistent electromagnetic field context inside the convertor as depicted in Fig. 1.

The abstraction model (1) - (5) contains the dynamics of all particles embedded in a self-consistent electromagnetic field context inside the convertor as depicted in Fig. 1.

A fusing kl-system can be approximately described by the following kinetic equations

\[
p_k' \frac{\partial f_k}{\partial \mathbf{p}_k} + m_k F^{\mu}_{\nu} \frac{\partial f_k}{\partial p_k^{\mu}} = \sum_{l,k',l'} \int d^3 p_l \int d^3 p_{l'} \int d^3 p_k' \int d^3 p_k \\
\times \frac{F^{\mu}_{\nu} f_k f_{l'} f_{l} f_k'}{W_{l'kl}^{C}} = - \sum_{l,k',l'} \int d^3 p_l \int d^3 p_{l'} \int d^3 p_k' \int d^3 p_k W_{kl'lk}^{R} f_{l'} f_l f_k f_k',
\]

and

\[
F^{\mu}_{\nu} = \frac{q_k}{m_k} F^{\mu}_{\nu} p_k,
\]

where the \( q_k \) are the electric charges of particles \( k \) and \( F^{\mu}_{\nu} \) is the electric field strength tensor. Maxwell’s equations are given by

\[
\frac{\partial F^{\mu}_{\nu}}{\partial x^\mu} = \frac{\partial J^\mu}{\partial x^\mu} , \quad \frac{\partial F^{\mu}_{\nu}}{\partial x^\nu} = 0 ,
\]

where \( F^{\mu}_{\nu} \) is the dual of \( F^{\mu}_{\nu} \). The total four current is

\[
J^\nu = \sum_k q_k \int d^3 p 2 \Theta(p_0) \delta(p^2 - m_k^2 c^2) c p^\nu f_k,
\]

where the collisional and reactive invariant transition amplitudes \( W^C \) and \( W^R \) can be mapped onto invariant collisional and reactive cross sections \( \sigma_C \) and \( \sigma_R \) provided the underlying system is sufficiently dilute and weakly coupling with the help of

\[
W^C_{l'kl'k} = W^C_{l'kl} ,
\]

\[
W^C_{l'kl} = s \sigma_C(s, \psi) \delta^3 \left( p_{l'} + p_l - p_k - p_l' \right) ,
\]

\[
W^R_{l'kl} = s \sigma_R(s, \psi) \delta^3 \left( p_{l'} + p_l - p_k - p_l' \right) ,
\]

\[
s = \left( p_{l'}^2 + p_l^2 \right)^{3/2} .
\]

The kinematics of the reactions in the kl-system is best analyzed in the center of mass frame

\[
\begin{align*}
\tilde{p}_k^{cm} &= \tilde{p}_k + \frac{1}{\beta^2} (\gamma - 1) (\tilde{p}_k \cdot \tilde{\beta}) \tilde{\beta} - \gamma \tilde{\beta} \tilde{p}_k^0 , \\
\tilde{p}_l^{cm} &= \tilde{p}_l + \frac{1}{\beta^2} (\gamma - 1) (\tilde{p}_l \cdot \tilde{\beta}) \tilde{\beta} - \gamma \tilde{\beta} \tilde{p}_l^0 ,
\end{align*}
\]

where

\[
\tilde{\beta} = \frac{\tilde{p}_k + \tilde{p}_l}{\tilde{p}_k^0 + \tilde{p}_l^0} ,
\]

\[
\gamma = \frac{1}{\sqrt{1 - \beta^2}} ,
\]

\[
\tilde{p}_k^0 = \sqrt{m_k^2 c^2 + \tilde{p}_{l'}^2} ,
\]

\[
\tilde{p}_l^0 = \sqrt{m_l^2 c^2 + \tilde{p}_l^2} .
\]

The quantity \( p \) is the length of the CM-frame momenta \( \tilde{p}_k^{cm} \) and \( \tilde{p}_l^{cm} \). It is given by

\[
p = \frac{1}{2 N^s} \sqrt{(s - (m_k^2 + m_l^2) c^2)^2 - 4 m_k^2 m_l^2 c^4} .
\]

To define the post-collision momenta we introduce a right-handed coordinate system in the CM-frame, the \( \tilde{e}_1 \)-axis of which is along \( \tilde{p}_k^{cm} \). The CM frame coordinate system is embedded into a right-handed coordinate system in the lab frame. The \( z \)-axis of the latter is along \( \tilde{e}_z \). For the parametrization of

\[
\tilde{e}_1 = \frac{\tilde{p}_k^{cm}}{|\tilde{p}_k^{cm}|} ,
\]

\[
\tilde{e}_2 = \frac{\tilde{p}_l^{cm} \times \tilde{e}_z}{|\tilde{p}_l^{cm} \times \tilde{e}_z|} ,
\]

\[
\tilde{e}_3 = \frac{\tilde{p}_k^{cm} \times \tilde{e}_z \times \tilde{p}_l^{cm}}{|\tilde{p}_k^{cm} \times \tilde{e}_z \times \tilde{p}_l^{cm}|} .
\]

If \( s \geq (m_k c + m_l c)^2 \) holds, where \( m_k \) and \( m_l \) denote either the post-collisional masses or the masses of the binary nuclear

Figure 1: Cylindrical boron nano-rods with \( R \leq 30 \text{ nm} \) are placed inside the micro-reactor. The nano-rods contain protons or deuterons. Between the nano-rods the low \( Z \) nuclear fuel constituent \( T \) is placed. An ultra-short high intensity UV laser pulse impinges the reactor from the left and couples efficiently to the boron nano-rods.

Figure 2: Release angles of nuclear fusion products for binary decays.
fusion products, we can calculate the post-collisional or post-fusion momenta in the CM-frame

\[ p_{k}^{0,cm} = \sqrt{m_k^2 c^2 + q_k^2} \]  

\[ \vec{p}_{k}^{cm} = q \cos \psi \vec{e}_1 + q \sin \psi \sin \nu \vec{e}_2 + q \sin \psi \cos \nu \vec{e}_3 \]  

\[ p_{l}^{0,cm} = \sqrt{m_l^2 c^2 + q_l^2} \]  

\[ \vec{p}_{l}^{cm} = -\vec{p}_{k}^{cm} \]  

where \( q \) is given by

\[ q = \frac{1}{2 \sqrt{s}} \sqrt{(s - (m_k^2 + m_l^2) c^2)^2 - 4 m_k^2 m_l^2 c^4} \]  

Finally we transform back into the lab-frame. Since the CM frame moves with the velocity \( c\beta \) we can go back to the lab frame by boosting the CM frame with the velocity \(-c\beta\). We obtain for the post-collisional variables in the lab frame

\[ p_{k}^{0} = \gamma (p_{k}^{0,cm} + \vec{p}_{k}^{cm}) \]  

\[ \vec{p}_{k} = \vec{p}_{k}^{cm} + \frac{1}{\beta} (p_{k}^{0,cm} \cdot \vec{p}_{k}^{cm}) \beta + \gamma \beta p_{k}^{0,cm} \]  

\[ p_{l}^{0} = \gamma (p_{l}^{0,cm} + \vec{p}_{l}^{cm}) \]  

\[ \vec{p}_{l} = \vec{p}_{l}^{cm} + \frac{1}{\beta} (p_{l}^{0,cm} \cdot \vec{p}_{l}^{cm}) \beta + \gamma \beta p_{l}^{0,cm} \]  

At this point we have the momenta of the nuclear fusion products in the \( k' l' \)-system in the lab frame again. We note that the masses of the products are typically different. However, total energy and momentum are conserved.

The transport equations in three notation are obtained by performing the integration over \( \vec{p}_{l'} \) in (6). We obtain \( \vec{p}_{l'} = \vec{p}_{l} + \vec{p}_{l} - \vec{p}_{k} \). Making use of the center of mass frame we find

\[ \frac{\partial}{\partial t} \left( \begin{array}{c} p_{k}^{0,cm} + p_{l}^{0,cm} - p_{k}^{0,cm} - p_{l}^{0,cm} \\ p_{k}^{cm} + p_{l}^{cm} - p_{k}^{cm} - p_{l}^{cm} \\ \end{array} \right) \\
\delta \left( \begin{array}{c} (p_{k}^{0,cm} - p_{l}^{0,cm}) \\ (p_{k}^{cm} - p_{l}^{cm}) \\ \end{array} \right) = \frac{1}{|\vec{p}_{k}^{cm}| \sqrt{s}} \left( \begin{array}{c} \frac{\partial f_{k}}{\partial \vec{v}_{k}} + \frac{\partial f_{k}}{\partial \vec{x}_{k}} + q_{k} (\vec{E} + \vec{v}_{k} \times \vec{B}) \cdot \frac{\partial f_{k}}{\partial \vec{v}_{k}} \\ \frac{\partial f_{l}}{\partial \vec{v}_{l}} + \frac{\partial f_{l}}{\partial \vec{x}_{l}} + q_{l} (\vec{E} + \vec{v}_{l} \times \vec{B}) \cdot \frac{\partial f_{l}}{\partial \vec{v}_{l}} \\ \end{array} \right) \\ \right) \\
\sum_{l} \int d^3 p_{l} v_{rel}^{kl} \int d\Omega_{\phi} \sigma_{e}^{kl} (s, \psi) (f_{f} f_{k'} - f_{f} f_{k}) \\
- \sum_{l} \int d^3 p_{l} v_{rel}^{kl} \int d\Omega_{\phi} \sigma_{e}^{kl} (s, \psi) f_{l} f_{l} , \\
\]  

This leads to

\[ \frac{\partial f_{k}}{\partial \vec{v}_{k}} + \frac{\partial f_{k}}{\partial \vec{x}_{k}} + q_{k} (\vec{E} + \vec{v}_{k} \times \vec{B}) \cdot \frac{\partial f_{k}}{\partial \vec{v}_{k}} = \sum_{l} \int d^3 p_{l} v_{rel}^{kl} \int d\Omega_{\phi} \sigma_{e}^{kl} (s, \psi) (f_{f} f_{k'} - f_{f} f_{k}) \\
- \sum_{l} \int d^3 p_{l} v_{rel}^{kl} \int d\Omega_{\phi} \sigma_{e}^{kl} (s, \psi) f_{l} f_{l} , \\
\]  

where fuel breeding is excluded.

In section 4 we discuss the integrated nanoscopic accelerator concept.

4. The integrated nano-accelerator

As preliminary investigations by Belloni et al. [8] show auto-catalytic enhancement of ultra-fast nuclear fusion by collisional energy transfer from fusion products to fuel constituents is inefficient, in particular at near solid density and for aneutronic fuels.

However, energy transfer to fuel constituents by electromagnetic fields has a chance to be efficient and fast for almost all nuclear fusion fuels. The required electromagnetic fields can in principle be generated by external laser drivers in case they can interact with the nuclear fuel.

The convertor concept discussed in the present paper consists of a laser-powered integrated nano-structured accelerator. For reasons of efficiency it consists exclusively of very small nuclear fuel based nano-structures that allow Coulomb explosions. Fuel mixes with different fuel masses, fuel densities, and fusion resonances are possible.

The integrated nano-accelerator is assumed to be an efficient design for the generation of large ionic currents at low ion energies. It is powered by ultra-short ultra-high energy laser pulses in the UV to the VUV wavelength range. The integrated accelerator is expected to absorb the driver laser energy almost completely avoiding parametric optical instabilities.

Nano-structures can be efficient laser energy converters into ionic motion if the electrons in the nano-structures can be overheated by the driver laser. Over-heated electrons are those that cannot be recaptured by the ionized nano-structures. Hence, positive ions are exposed to their own electric space-charge field for long enough and Coulomb explode, leaving behind after some time, a nearly homogeneous ionic distribution in configuration space and a non-thermal one in the momentum space that is peaked at the resonances of the provided nuclear fuel mix.

Specifically, we consider cylindrical nano-rods that form the accelerator as sketched in Fig. 1, which is composed of rigid fuel constituents \( l \) into which lighter fuel constituents \( k \) are embedded. We assume \( e_l/m_l \ll e_k/m_k \) for the involved effective charges and fuel masses. Between accelerator nano-rods low Gamov energy fuel ions can be places in form of foams. Since we propose UVV driver laser wavelengths we assume that the laser is still capable of propagating through the proposed convertor.
The VUV laser driver ionizes the nano-rods partially. The ionizing electrons occupy the space inside and between the nano-rods in such a way that individual nano-rods are partially shielded from each other. Still they provide an ion accelerating electric field strong enough to obtain the required relative energies between the fuel constituents for the provided fusion resonances of the fuel mix.

For reasons of simplicity we make the following assumption for the electric field of a single nano-rod composed of the high density fuel constituent $l$

$$E_l(r) = \begin{cases} C r_l, & 0 \leq r < R \\ 0, & r \geq R \end{cases}, \quad C = \frac{e n_l}{2\varepsilon_0},$$

where the field $E_l$ is radial and $n_l$ represents the average positive charge density inside the rods. The parameter $r_l$ is the radial position of an ion of sort $k$ inside the nano-rod composed of ions of sort $l$ and $R$ is the nano-rod radius.

Since collisions and fusion reactions are rare on the fs time scales, which the postulated Coulomb explosions require, we neglect the collision and fusion operators in (33) during the Coulomb explosion phase. In addition, we assume that the light ions only expand radially, while the heavy ones stand still. Hence, for $r_k \leq R$ the acceleration of the $k$-ions is approximated by the following radial Vlasov equation

$$\left( \partial_t + v_k \partial_{v_k} + \frac{e_k}{m_k} C r_k \partial_r \right) (r_k v_k f_k) (r_k, v_k, t) = 0.$$  (35)

The above approximation is justified for the $\text{p}^{11}\text{B}$ fuel for example. For $r_k > R$ the light ions undergo further acceleration. Also the heavy ions $l$ are ultimately subject to acceleration. However, for simplicity we neglect secondary forces on all fuel ions $kl$. This implies for the light ions of sort $k$ for $r_k > R$

$$\left( \partial_t + v_k \partial_{v_k} \right) (r_k v_k f_k) (r_k, v_k, t) = 0$$

until they collide or fuse.

According to (35) the light ions fulfill the following equations of motion during the Coulomb explosion phase

$$\frac{dr_k}{dt} = v_k \quad \frac{dv_k}{dt} = \frac{e_k}{m_k} C r_k,$$

while the solution of (35) is

$$(r_k v_k f_k) (r_k, v_k, t) = (r_{k0} v_{k0} f_k) (r_{k0}, v_{k0}, 0),$$

where due to (37) we have

$$\begin{pmatrix} r_{k0} \\ v_{k0} \end{pmatrix} = \begin{pmatrix} \cosh \left( \sqrt{\frac{e_k C}{m_k}} t \right) - \frac{1}{\sqrt{e_k C}} \sinh \left( \sqrt{\frac{e_k C}{m_k}} t \right) & r_k \\ -\frac{1}{\sqrt{e_k C}} \sinh \left( \sqrt{\frac{e_k C}{m_k}} t \right) & \sqrt{\frac{e_k C}{m_k}} \cosh \left( \sqrt{\frac{e_k C}{m_k}} t \right) \end{pmatrix} \begin{pmatrix} r_k \\ v_k \end{pmatrix}.$$  (39)

The parameter $r_{k0} \leq R$ is the initial radial position of the light ions and $v_{k0} > 0$ their initial radial velocity. The parameters $r_k$ and $v_k$ are the radial position and velocity at times $t > 0$.

To estimate the energy distribution of the light ions we consider a layer $s$ of the latter with initial radial position $0 < r_s^k \leq R$ and a radial velocity distribution given by

$$\begin{pmatrix} r_{k0} v_{k0} f_k \end{pmatrix} (r_{k0}, v_{k0}, 0) = N^k_s \frac{N_k}{4\pi} \frac{r_k}{r_s^k} \delta \left( r_k - r_s^k \right) \delta \left( v_k - v_s^k \right),$$

where $N^k_s$ is the number of particles $k$ at the radial position $r_s^k$. Plugging $r_{k0}$ and $v_{k0}$ given by (39) into (40) gives for $t \leq t_s^k$

$$r_k v_k f_k (r_k, v_k, t) = \frac{N^k_s(t)}{4\pi} \frac{1}{r_s^k} \delta \left( r_k - r_s^k \right) \delta \left( v_k - g_s^k(t) \right),$$

where

$$t_s^k = \sqrt{\frac{m_k}{e_k C}} \cosh \left( \frac{R}{r_s^k} \right),$$

$$r_s^k(t) = r_s^k \sqrt{\frac{e_k C}{m_k t}},$$

$$g_s^k(t) = \frac{r_k}{m_k} r_s^k \left( \sqrt{\frac{e_k C}{m_k t}} \right).$$

After rapid acceleration during the Coulomb explosion phase the light ion layer is assumed to move on ballistically. At $t = t_s^k$ we obtain

$$r_k v_k f_k (r_k, v_k, t) = \frac{N^k_s(t)}{2\pi} \frac{1}{r_s^k} \delta \left( r_k - r_s^k \right) \delta \left( v_k - g_s^k \right).$$

It holds

$$(2\pi)^2 \int_{0}^{\infty} dv_k \int_{0}^{\infty} dr_k r_k f_k (r_k, v_k, t) = N^k_s(t).$$

Next, we rewrite the distribution functions in the following way

$$f_k (\vec{r}_k, \vec{v}_k, t) \approx N^k_s(t) \delta \left( \vec{r}_k - \vec{r}_s^k \right) \delta \left( \vec{v}_k - \vec{g}_s^k \right),$$

$$N^k_s(t) = N_k(t) n^k_s, \quad n^k_s = \frac{2 r_s^k \Delta r_k}{R^2},$$

$$N_k(t) = \int_{V} \frac{N(t)}{V} N_k(t),$$

where $V$ is the reactor volume and $N$ the number of nano-rods in the reactor, that can be reached during the reactor runtime, and $\Delta r_k$ is the thickness of the layer $s$ in the nano-rod. We assume that all velocity directions are uniformly distributed. In addition, each velocity group has its own density group. All densities groups add up to the total density. To ease calculations we assume

$$f_k (\vec{r}_k, \vec{v}_k, t) \approx \sum_{s=1}^{\infty} f_k^s (\vec{r}_k, \vec{v}_k, t),$$

$$f_l (\vec{r}_l, \vec{v}_l, t) \approx \frac{N}{V} N_k(t) \delta^3 (\vec{v}_l).$$
Simulations confirm that an approximately homogeneous and isotropical light ion distribution in configuration space is obtained after the interaction with the laser pulse, while a peaked non-thermal light ion distribution in momentum space remains. Figure 3 shows the proton momentum and Fig. 4 the boron momentum distribution obtained from a simulation. The distribution function $f_p$ of the protons is peaked at small momenta mainly due to rods not interacting with the laser pulse and at $|\vec{p}_p| \approx 0.03 m_p c$ due to nano-acceleration and periodic boundaries used in configuration space. There are also many protons at $|\vec{p}_p| > 0.05 m_p c$.

Fuel mixes can offer advantages. While technically difficult it is conceivable to accelerate deuterons in boron nano-rods and immerse tritium between the deuterated boron rods. Many spatio-temporal configurations and fuel mixes are possible. The nonlinear optical properties of a nano-structured accelerator embedded into the fuel composite have to be engineered such that nano-acceleration is efficient and tailored to the fuel mix and its spatio-temporal configuration.

Numerical and experimental campaigns are required to characterize the proposed integrated nanoscopic accelerator concept on a more advanced level. In particular, the laser energy conversion efficiency of the nanoscopic accelerator into relative ionic motion with the desired relative velocities is of great interest. We expect that the energy conversion efficiency of the integrated nanoscopic accelerator strongly depends on the size of the nano-rods, the laser intensity, the laser pulse length, and the laser frequency. There is a lower and an upper limit for the nano-rod radii for best laser energy conversion efficiency into the ionic subsystem as a function of the laser parameters. In
addition, a range of different nano-structures and fuel compositions have to be investigated.

In the next section we discuss the basics of the conversion fraction $\eta^k$ and efficiency $Q^k$.

5. Burn fraction and efficiency

To derive a relation for the burn fraction we make use of (33) and of the ionic distribution functions (53) - (54). Obtaining the lowest and first velocity moments of (33) we obtain approximately for the $k$ ions of a single rod

$$\frac{dN_k(t)}{dt} \approx -(N_k(t))^2 \sum q_k N_k(t) \sum s \alpha_k^q g_{sb}^{\text{ab}}(t) \sigma_{kl}^q \left( g_{kl}^{\text{ab}}(t) \right),$$

where

$$\frac{d}{dt} \left( \sum_{s} \alpha_k^q g_{sb}^{\text{ab}}(t) \right) \approx q_k N_k(t) \sum s \alpha_k^q \left( \frac{1}{4} + \sum_{s} \alpha_k^q \sum_{kl} g_{sb}^{\text{ab}}(t) \sigma_{kl}^q \left( g_{kl}^{\text{ab}}(t) \right) N_k(t) \sum_{s} \alpha_k^q \right)$$

and

$$\frac{d}{dt} g_{kl}^{\text{ab}}(t) = g_{sb}^{\text{ab}}(t).$$

In the end we have to sum over all nano-rods. The quantities $\dot{E}$ and $\dot{B}$ are electromagnetic fields and $\nu_{kl}^q$ are the collision frequencies

$$\nu_{kl}^q \left( g_{kl}^{\text{ab}}(t) \right) \approx \frac{g_k^2 \sigma_{kl}^q N}{4\pi\epsilon_0 m_k^2} \left( g_{kl}^{\text{ab}}(t) \right) \ln \Lambda_{kl}.$$  

Mean field and binary level radiation loss is neglected for simplicity in (55) - (57). The electromagnetic fields $\dot{E}$ and $\dot{B}$ can be the laser fields as well as secondary slowly varying fields. The collision frequencies are modified by radiation loss. A solution of the system (55) - (57) would lead to an advanced Lawson criterion. However, since a solution is complicated we leave it to integrated kinetic simulations.

Equation (55) neglecting (56) and (57) can be solved. We find

$$N_k(\Delta t) \approx \frac{N_k(0)}{1 + \frac{g_k^2 \sigma_{kl}^q N}{4\pi\epsilon_0 m_k^2} \left( g_{kl}^{\text{ab}}(t) \right)}$$

where $\Delta t$ is an effective reactor runtime, which depends on the field context and the radiative and collisional energy loss. The conversion fraction is

$$\eta^k = \frac{\Delta N_k(\Delta t)}{N_k(0)}$$

and

$$\eta^k = 1 - \frac{N_k(\Delta t)}{N_k(0)}$$

With the help of an approximate function for $\sigma_{kl}^q$ we have

$$\sum_{s} \alpha_k^q \int_{0}^{\Delta t} dt g_{sb}^{\text{ab}}(t) \sigma_{kl}^q \left( g_{kl}^{\text{ab}}(t) \right)$$

where

$$\epsilon_{\text{am}}^k = \frac{\epsilon_{\text{am}}^k}{\beta_{\text{am}}^k} = \frac{1}{2} m_k \left( \frac{g_k^{\text{am}}}{m_k} \right)^2,$$

$$\epsilon_{\text{am}}^k = 2 \left( \frac{\pi e^2 Z_k Z_l}{4\pi\epsilon_0 hc} \right)^2 m_k c^2,$$

$$m_{kl} = \frac{m_k m_l}{m_k + m_l}.$$  

The parameter $g_{kl}^{\text{am}}$ is a free parameter, that links the kinetic energy $\epsilon_{\text{am}}^k$ to the Gamov energy $\epsilon_{\text{am}}^k$ of the underlying nuclear fusion process. The parameter $g_{kl}^{\text{am}}$ is the effective relative velocity between the $k$ and $l$ ions in the reactor. The factor $S_{kl}$ is the astrophysical parameter for the underlying nuclear fusion process. According to [9] the cross section used in (61) underestimates the reactivity. An illustration is given in Fig. 7.

$$\frac{\text{d}N_k(t)}{\text{d}t} \approx -(N_k(t))^2 \sum_{s} \alpha_k^q g_{sb}^{\text{ab}}(t) \sigma_{kl}^q \left( g_{kl}^{\text{ab}}(t) \right),$$

$$\frac{d}{dt} \left( \sum_{s} \alpha_k^q g_{sb}^{\text{ab}}(t) \right) \approx q_k N_k(t) \sum s \alpha_k^q \left( \frac{1}{4} + \sum_{s} \alpha_k^q \sum_{kl} g_{sb}^{\text{ab}}(t) \sigma_{kl}^q \left( g_{kl}^{\text{ab}}(t) \right) N_k(t) \sum_{s} \alpha_k^q \right)$$

and

$$\frac{d}{dt} g_{kl}^{\text{ab}}(t) = g_{sb}^{\text{ab}}(t).$$

In the end we have to sum over all nano-rods. The quantities $\dot{E}$ and $\dot{B}$ are electromagnetic fields and $\nu_{kl}^q$ are the collision frequencies

$$\nu_{kl}^q \left( g_{kl}^{\text{ab}}(t) \right) \approx \frac{g_k^2 \sigma_{kl}^q N}{4\pi\epsilon_0 m_k^2} \left( g_{kl}^{\text{ab}}(t) \right) \ln \Lambda_{kl}.$$  

Mean field and binary level radiation loss is neglected for simplicity in (55) - (57). The electromagnetic fields $\dot{E}$ and $\dot{B}$ can be the laser fields as well as secondary slowly varying fields. The collision frequencies are modified by radiation loss. A solution of the system (55) - (57) would lead to an advanced Lawson criterion. However, since a solution is complicated we leave it to integrated kinetic simulations.
There are many interesting fuel cycles. The most relevant neutronic fuel cycles are given in Table 1. They have small Gamov energies $\epsilon_{G}^{ij}$ and large $S_{kl}$. Advanced fuel cycles are summarized in Table 2. They have larger Gamov energies $\epsilon_{G}^{ij}$ than the neutronic fuel cycles. Hence, the cross sections are very small at low energies. At high energies, however, aneutronic fuel cycles become attractive as well. In particular, boron is a material that can be nano-machined to form an integrated nano-accelerator. At the same time boron can be a nuclear fuel constituent. The burn fraction $\eta_{B}$ becomes

$$
\eta_{B} = \frac{\frac{N}{N} R_{k} \frac{S_{kl}}{S_{kl}} \beta_{pB}^{ij} e^{-\sqrt{\beta_{pB}^{ij}}} \left(1 + \frac{S_{kl}}{S_{kl}} \frac{R_{k}}{R_{k}} e^{-\sqrt{\beta_{pB}^{ij}}}ight)}{1 + \frac{S_{kl}}{S_{kl}} \frac{R_{k}}{R_{k}} e^{-\sqrt{\beta_{pB}^{ij}}}}, \quad R_{k} = \Delta t g_{kv}^{av}.
$$

(65)

where electric fields can exponentially enhance or suppress the reactivity depending on the polarity of the latter with respect to the directions of the velocities of the light ions. Magnetic fields can compress the reacting fuels.

Equation (65) shows that large average velocities $g_{kv}^{av}$ and energy confinement time $\Delta t$ are capable of mitigating low fuel densities. For a given conversion fraction we have

$$
\frac{N}{N} R_{k} \approx n_{f} R_{k} < \eta_{B}^{ij} \frac{S_{kl}}{S_{kl}} \frac{1}{\beta_{pB}^{ij}} e^{-\sqrt{\beta_{pB}^{ij}}}.
$$

(66)

We define the conversion efficiency $Q^{ij}$ as

$$
Q^{ij} = \frac{\epsilon_{ij}^{k}}{S_{ij}^{k}} \eta^{ij} = \frac{\epsilon_{ij}^{k}}{S_{ij}^{k}} \beta_{pB}^{ij} \eta^{ij},
$$

(67)

where $\epsilon_{ij}^{k}$ is the energy release of an elementary nuclear fusion reaction.

To give an example we consider $p^{11}B$. An illustration of the conversion fraction $\eta_{B}^{11}$ as a function of $\beta_{pB}^{11}$ and $n_{B} R_{p}$ is shown in Fig. 8. The conversion efficiency $Q^{11}$ as a function of $\beta_{pB}^{11}$ and $n_{B} R_{p}$ is shown in Fig. 9. To give another example we consider a boron nano-accelerator embedded into DT. The natural density of deuterium is about $n_{0} \approx 10^{24} m^{-3}$. An illustration of the conversion fraction $\eta_{DT}$ as a function of $\beta_{DT}$ and $n_{T} R_{D}$ is shown in Fig. 10. The conversion efficiency $Q^{DT}$ as a function of $\beta_{DT}$ and $n_{T} R_{D}$ is shown in Fig. 11.

In case the nano-structured reactor is operated with VUV laser pulses the electron plasma density of the deuterium - tritium content in the reactor remains sub-critical during external energy charging of the reactor.

Auto-catalytic amplification of nuclear fusion via collisional or collective energy transfer between fuel constituents, nanoscopic as well as large scale magnetic fuel compression, and radiative loss have been neglected in the analytical estimate of $Q^{ij}$ given in (67) since (56) and (57) have been disregarded.

Many of the deficits addressed above can be mitigated. Large $Q^{ij}$ for the proposed reactor are desirable but would not be necessary if the proposed reactor could become an embedded ignitor that is capable of overcoming energy thresholds required for the ignition of secondary amplifiers.
The gap $D$ between the nano-rods can be estimated from the critical plasma density for a given $\lambda$ of the laser since the average plasma density in the reactor should be subcritical. We find for the gap between the nano-structures

$$D \geq \sqrt{\frac{e^2 n_i R^2}{4\pi \varepsilon_0 m_e c^2} \lambda}.$$  (70)

Figure 12 below shows the radius $R$ of the rods for various wavelengths $\lambda$ for half ionized $^1$H$^1$B required for the relative energy of $e_i \approx 0.5$ MeV between protons and boron ions. For a given rod radius $R$ and half ionized $^1$H$^1$B the required gap $D$ between nano-rods for stable laser pulse propagation is shown in Fig. 13.

6. Nonlinear optics and confinement

Efficient embedded nano-acceleration of ions depends on specific optical properties of the laser driver interacting with the nano-structures.

The lower threshold for the electric field strength required to ionize the nano-rods to the charge density $e_i n_i$ is approximately

$$E \geq \frac{R}{e_i} \left( m_e \omega^2 + e_i C \right).$$  (68)

The implication for the laser intensity

$$I_c = \frac{1}{2} \varepsilon_0 c E^2 \geq \frac{\varepsilon_0 c R^2}{2 e_i^2} \left( \frac{4\pi e_i^2 m_e}{P} + e_i C \right)^2.$$  (69)

The gap $D$ between the nano-rods can be estimated from the critical plasma density for a given $\lambda$ of the laser since the average plasma density in the reactor should be subcritical. We find for the gap between the nano-structures

$$D \geq \sqrt{\frac{e^2 n_i R^2}{4\pi \varepsilon_0 m_e c^2} \lambda}.$$  (70)

Figure 12 below shows the radius $R$ of the rods for various wavelengths $\lambda$ for half ionized $^1$H$^1$B required for the relative energy of $e_i \approx 0.5$ MeV between protons and boron ions. For a given rod radius $R$ and half ionized $^1$H$^1$B the required gap $D$ between nano-rods for stable laser pulse propagation is shown in Fig. 13.
ing almost the complete protonic content of the $p^{11}$B fuel to the relative velocities required for optimal reactivity.

Next, we have a closer look at the optical properties of an ultra-short ultra-intense laser pulse interacting with nano-structured matter. Since the required intensities and charge densities are high the power of the required laser pulses might exceed the critical power for self-focusing.

However, self-focusing is suppressed for sufficiently short laser pulses with $L \leq \lambda_p$ according to \cite{10,11,12}

$$P_{c,sp} \approx \frac{2P}{k^2 n_p^2} \gg P_c,$$  

where $\zeta$ is the pulse length in the laser pulse frame. The time required to ionize the nano-rods increases $P_{c,sp}$ further and hence allows for laser pulses with $L > \lambda_p$. The details have to be obtained with the help of numerical campaigns.

Since ultra-short laser pulses are capable of capturing ionizing electrons from the nano-rods large electronic currents along the z-axis are generated, which reduce the average electron density in the convertor along this axis and produce a strong azimuthal magnetic field that works as a separatrix between electron current and return current along the z-axis. We have neglecting collisional and radiative resistivities

$$\frac{\partial n_e}{\partial t} + \frac{\partial }{\partial x_e}(n_e \vec{v}_e) = 0,$$  

$$n_e \left( \frac{\partial }{\partial t} + \vec{v}_e \cdot \frac{\partial }{\partial x_e} \right) \vec{v}_e = \frac{e}{m_e} \vec{j}_e \times \vec{B} - \frac{e}{m_e} \frac{\partial P}{\partial x_e},$$  

$$\frac{\partial }{\partial x_e} \times \vec{B} = \frac{1}{\epsilon_0 c^2} \vec{j}_e, $$  

$$\frac{\partial }{\partial t} \vec{B} = -\frac{\partial }{\partial x_e} \times \vec{E},$$  

$$\vec{E} = - \vec{v}_e \times \vec{B},$$  

$$\frac{\partial }{\partial x_e} \cdot \vec{B} = 0, $$

where $P$ is the electronic plasma pressure. Under the assumptions (72) - (77) the magnetic field is slowly varying as simulations confirm. Assuming $d\vec{v}_e/dt \approx 0$ we obtain with the help of (73)

$$\vec{j}_e \times \vec{B} - \frac{\partial P}{\partial x_e} \approx 0,$$  

$$\frac{\partial }{\partial t} \vec{B} = \frac{\partial }{\partial x_e} \times (\vec{v}_e \times \vec{B}) \approx 0.$$  

The strength of the magnetic fields can be estimated if the electronic current densities are known. Given the topology of the electronic currents in the convertor we find

$$B_0 = \begin{cases} \frac{2e_0 c^2}{2 \epsilon_0 c} n_e r, & r \leq R_L \\ \frac{2e_0 c^2}{2 \epsilon_0 c} \leq \frac{2e_0 c^2}{2 \epsilon_0 c} n_e R_L, & r > R_L \end{cases},$$

where $j_0$ is the strength of the electronic current density and $R_L$ is the effective laser pulse radius. The magnetic field $B_0$ required to force a proton into an orbit with radius $r_0$ at the velocity $v_0 \ll c$ is

$$B_0 \approx \frac{m_p v_0}{e r_0}.$$

This implies for

$$r_0 \approx 10^{-6} \, \text{m}, \quad v_0 \approx 10^7 \, \text{m/s}, \quad R_L \approx 10^{-5} \, \text{m},$$

the current density and magnetic field

$$j_0 \approx \frac{2e_0 c^2 m_p v_0}{e r_0 R_L} \approx 10^{16} \, \text{A/m}^2,$$  

$$B_0 \approx 10^5 \, \text{V/m}^2.$$  

Magnetic fields of the required topology and magnitude can indeed be generated as simulations show. They pinch the ions. The stability and the lifetime of the magnetic fields have to be analyzed in detail.

In section 7 we discuss radiative energy loss. Radiative energy loss is important since it impacts electron - ion collisions. The latter become efficient if electrons and ions propagate at about the same velocity. The driver laser is capable of capturing electrons, of over-heating them, and of depleting the average electron density in the reactor along the path of the laser pulse due to a magnetic separatrix that emerges. During this phase of the reactor operation collisions between electrons and fuel ions are rare as is radiative loss.

However, eventually the fuel constituents will loose their relative energy and the reactor stops. The analysis of effective reactor runtimes is an important problem, that requires integrated simulations based on the abstraction model outlined in the present paper. Autocatalytic processes can then be incorporated.

## 7. Radiative energy loss

Since we consider a transport framework up to binary correlation order we have radiative contributions to the equations of motion of charged particles by mean-field radiation, which is traditionally called radiation reaction \cite{13} and by radiative collisions in binary correlation order in external field contexts as
conceptually outlined in [14]. The latter are obtained with the help of the \( T \)-matrix in (5).

Both contributions modify the equations of motion of an electron. While electrons are subject to self-radiation, binary level radiative collisions, and the impact of external fields ions are mainly subject to radiation-free collisions and the impact of secondary collective fields. Their reactive dynamics is given by (55) - (57) or the underlying kinetic equations.

Ions with large spreads in their masses mainly lose their energy via collisions with electrons. As long as electrons are hot they cannot collide efficiently with cold ions. However, due to radiative energy loss electrons will eventually collide with ions thus draining the energy contained in the ionic subsystem. As long as radiative binary collisions are rare radiation reaction accounts for most of the radiative energy loss of electrons and hence the effective lifetime \( \Delta t \) of the externally heated convertor.

The radiation loss per single electron can be estimated to be

\[
\frac{dp}{dt} \approx \frac{2\tau_0 m_e a^2 u^2}{3 c^3}, \quad \tau_0 = \frac{e^2}{4\pi\epsilon_0 m_e c^3}.
\]  

(85)

The radiation power loss per electron is given by

\[
d \left( c^3 p^0 - m_e c^2 \right) dt \approx \frac{2\tau_0 m_e a^2 u^2 e^2}{3 c^3},
\]  

(86)

where

\[
\frac{dx^\nu}{dt} = u^\nu, \quad \frac{du^\mu}{dt} = a^\mu = \frac{e}{m_e} F^{\mu\nu} u_{\nu}.
\]  

(87)

According to Landau and Lifshitz [16] we have

\[
a^\nu a_{\nu} \approx \frac{m_e^2 e^2}{\hbar^2} \chi_e^2, \quad \chi_e = \frac{eh}{m_e c^3} \sqrt{\left( F^{\mu\nu} p_{\nu} \right)^2}.
\]  

(88)

The strongest field in the fast micro-reactor is the laser field. We approximate

\[
\chi_e \approx \frac{\gamma E}{E_e} \approx 10^{-5}, \quad E_e = \frac{m_e^2 c^3}{e\hbar} \approx 10^{18} \frac{V}{m}.
\]  

(89)

This implies for the electronic radiation loss power density

\[
I_{el} \approx \frac{1}{6\pi} \frac{e^2 m_e^3 c^3 n_e}{e_0 \hbar^2} \chi_e^2 \approx 3.2 \cdot 10^{-7} n_e \chi_e^2 \frac{J}{ps}.
\]  

(90)

It is also possible to calculate the quantum corrections to radiation including the impact of the nonlinear Compton effect according to the papers by Ritus and Nikishov [15]. The emitted integrated radiation loss power density for \( \chi_e \ll 1 \) according to [15] is

\[
I_{RN} \approx I_{el} \left( 1 - \frac{55 \sqrt{3}}{16} \chi_e + 48 \chi_e^2 \pm \ldots \right) \leq I_{el}.
\]  

(91)

For the parameters of the fast convertor concept a temporal window \( \Delta t \approx (50 - 100) \text{ ps} \) might be possible. In case of p\textsuperscript{11}B in the non-thermal regime this implies a large effective \( n_B \mathcal{R}_p \) after magnetic compression.

The magnitude of radiative collisions can be estimated with the help of the radiation-free collision frequencies given by

\[
\nu_{el} \approx \frac{e^2}{4\pi\epsilon_0 m_e c^3} \ln \Lambda_{el}.
\]  

(92)

Electrons are also the lightest particles with the highest density. This implies that all electron - electron and electron - ion collision frequencies have to be estimated. We have approximately

\[
\nu_{el} \approx \left( 10^{11} - 10^{10} \right) \frac{1}{s}.
\]  

(93)

Collisional energy exchange in the fast micro-reactor at near solid density via electrons takes about \( 10 - 100 \text{ ps} \). Hence, it might be possible to reach effective reactor run-times in the range of 100 ps.

To promote the estimates given here to the next level integrated simulation have to be done.

8. Summary

We propose a convertor concept for triggering efficient nuclear fusion reactions with the help of ultra-short ultra-high energy laser pulses in the UV to the VUV wavelength range interacting with an embedded nanoscopic fuel-based accelerator.

We believe that ultra-short laser pulses can be used as efficient, rep-rateable, and scalable drivers for the proposed reactor implying that multiple laser systems can replace a single large laser system.

We suggest that nano-structures can be used to integrate specific nonlinear optical properties for ultra-intense ultra-short laser pulses into the reactor.

We believe that energy transfer into low energy ions can be very efficient if the nano-structures and laser parameters match. We believe that the ionic distribution functions can be engineered.

With the help of stable laser pulse propagation in the reactor due to nano-structures tailored to the laser pulse parameters magnetic fields can be generated that are capable of confining and pinching the laser-accelerated ionic subsystem in the reactor. We believe that the exploding embedded nano-accelerator can drive multiple nanoscopic shocks in the fuel. External compression might be unnecessary.

The proposed reactor can operate with fuel mixes in a non-thermal regime. It might be possible to optimize for neutron yield, energy output or magnetic fields. Since the reactor we propose is ultra-fast the concept might be appropriate for embedding it into an amplifier. Radiation shielding measure might mitigate radiation loss and extend the effective reactor runtime. In this case a small igniter \( Q^\text{ff} \) or a low wall plug efficiency of the laser drivers might be mitigated.

Integrated numerical simulations and support experiments have to be conducted in order to assess the individual processes required and their interplay for successful reactor operation. We note that the present paper is conceptual in nature.
9. Acknowledgements

The present work has been motivated and funded by the Marvel Fusion GmbH. Particular credit has to be given to Moritz von der Linden for his promotion of the underlying investigations.

References

[1] L. Fedeli, A. Formenti, L. Cialfi, A. Pazzaglia, M. Passoni, Ultra-intense laser interaction with nanostructured near-critical plasmas, Scientific reports 8 (1) (2018) 1–10.

[2] D. Margarone, J. Bonvalet, L. Giumfreda, A. Morace, V. Kantarelou, M. Tosca, D. Raffestin, P. Nicolau, A. Piccotto, Y. Abe, et al., In-target proton–boron nuclear fusion using a pw-class laser, Applied Sciences 12 (3) (2022) 1444.

[3] A. Curtis, C. Calvi, J. Tinsley, R. Hollinger, V. Kaymak, A. Pukhov, S. Wang, A. Rockwood, Y. Wang, V. N. Shlyaptsev, et al., Micro-scale fusion in dense relativistic nanowire array plasmas, Nature communications 9 (1) (2018) 1–7. doi:https://doi.org/10.1038/s41467-018-03445-z.

URL https://www.nature.com/articles/s41467-018-03445-z.

[4] C. G. Van Weert, W. Van Leeuwen, S. De Groot, Elements of relativistic kinetic theory, Physica 69 (2) (1973) 441–457. doi:https://doi.org/10.1016/0031-8914(73)90082-7.

URL https://doi.org/10.1016/0031-8914(73)90082-7.

[5] D. Vasak, M. Gyulassy, H.-T. Elze, Quantum transport theory for abelian plasmas, Annals of Physics 173 (2) (1987) 462 – 492. doi:http://dx.doi.org/10.1016/0003-4916(87)90169-2.

URL http://www.sciencedirect.com/science/article/pii/0003491687901692.

[6] P. Zhuang, U. Heinz, Relativistic quantum transport theory for electrodynamics, Annals of Physics 245 (2) (1996) 311 – 338. doi:http://dx.doi.org/10.1006/aphy.1996.0011.

URL http://www.sciencedirect.com/science/article/pii/S0003491696900111.

[7] C. G. van Weert, W. de Boer, On the derivation of quantum kinetic equations. i. collision expansions, Journal of Statistical Physics 18 (3) (1978) 271–280. doi:http://dx.doi.org/10.1007/BF01018093.

URL https://doi.org/10.1007/BF01018093.

[8] F. Belloni, D. Margarone, A. Picciotto, F. Schillaci, L. Giumfreda, On the enhancement of p-11b fusion reaction rate in laser-driven plasma by α→p collisional energy transfer, Physics of Plasmas 25 (2) (2018) 020701. doi:http://dx.doi.org/10.1063/1.5007923.

URL https://aip.scitation.org/doi/abs/10.1063/1.5007923.

[9] W. Nevins, R. Swain, The thermonuclear fusion rate coefficient for p-11b reactions, Nuclear fusion 40 (4) (2000) 865.

[10] E. Esarey, P. Sprangle, J. Krall, A. Ting, Self-focusing and guiding of short laser pulses in ionizing gases and plasmas, IEEE journal of quantum electronics 33 (11) (1997) 1879–1914. doi:http://dx.doi.org/10.1109/3.641305.

URL https://ieeexplore.ieee.org/abstract/document/641305.

[11] P. Sprangle, E. Esarey, J. Krall, G. Joyce, Propagation and guiding of intense laser pulses in plasmas, Physical review letters 69 (15) (1992) 2200. doi:http://dx.doi.org/10.1103/PhysRevLett.69.2200.

URL https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.69.2200.

[12] J. Faure, V. Malka, J.-R. Marquès, P.-G. David, F. Amiranoff, K. Ta Phuoc, A. Rousse, Effects of pulse duration on self-focusing of ultra-short lasers in underdense plasmas, Physics of Plasmas 9 (3) (2002) 756–759. doi:http://dx.doi.org/10.1063/1.1447556.

URL https://aip.scitation.org/doi/abs/10.1063/1.1447556.

[13] C. Bied, D.-A. Deckert, H. Ruhl, Radiation reaction in classical electrodynamics, Physical Review D 99 (9) (2019) 096001. doi:10.1103/PhysRevD.99.096001.

URL https://doi.org/10.1103/PhysRevD.99.096001.