A laser-driven mixed fuel nuclear fusion reactor concept

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Abstract
We propose a laser-driven near-solid density fast reactor concept with mixed nuclear fusion fuels that is capable of transforming external laser energy into fusion energy and secondary particles. The reactor is capable of making use of a range of neutronic and aneutronic fuels. Its core parts consists of an integrated nanoscopic nuclear fusion fuel based laser-driven accelerator that is capable of producing non-thermal ionic distributions within the fuel mixes almost instantly and of a secular electric and magnetic field generator capable of enhancing fusion yield after nano-acceleration.

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

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

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 promises 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, which is entirely composed of nuclear fuels. It comprises an integrated nano-structured accelerator consisting of boron or lithium rods with structure radii of \( R \leq 30 \text{ nm} \) doped with further constituents of nuclear fuel cycles. 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. There are interesting chemical compounds like lithium borohydrate, that have very high natural densities.

Since lasers represent the fastest macroscopic energy sources we propose that the reactor is powered by ultra-short ultra-high intensity laser pulses with UV to VUV wavelengths.

Simulations show that near complete laser deposition in nano-structured targets is possible. Hence, If both the nano-structures and the laser pulses are tailored towards each other it might be possible to engineer controlled non-linear 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 in the reactor.

The 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. In addition, ultra-short high energy laser pulses are capable of over-heating electrons thus reducing electronic collisionality. In addition, simulations show that secular electric and magnetic fields are generated. They are capable of impacting fusion yield in the reactor.

The purpose of the present paper it is to outline the nano-structured micro-reactor concept, the abstraction model, and to estimate some of its properties and limitations on a parametric level only. Future papers will go deeper into the details of the concept.

The paper is structured in the following way. In section 2 the abstraction model is outlined for future reference. In section 3 simplified relativistic transport equations are discussed.
in preparation of the numerical model in future versions of this paper. With the help of the relativistic transport equations the parameters required for high fusion efficiency can be identified. In section 4 the concept of the embedded nano-accelerator is introduced. In section 5 the conversion fraction and efficiency are addressed. In section 6 the laser parameters required for the desired optical properties of the laser pulses interacting with nano-rods are sketched. In section 7 radiative energy loss processes are addressed.

2. The abstraction model

Since the required laser pulse radiation is ultra-intense electrons will become relativistic. There might also be positrons. Hence, we refer to [4, 5, 6, 7]. For further reference we state an expansion into a quantum BBGKY-hierarchy up to binary correlation order in the presence of electromagnetic fields leads to

\[
\left(p_k^\mu \frac{\partial}{\partial x^\nu} + m_k F^\mu_\nu \frac{\partial}{\partial p_k^\nu} \right) f(x, \tilde{p}_k) = \sum_{l,k,l'} \int \frac{d^3 p_1}{p_1^0} \frac{d^3 p_{l'}}{p_{l'}^0} \frac{d^3 p_{l'}}{p_{l'}^0} \frac{d^3 q_{l'}}{q_{l'}^0} \frac{d^3 q_{l'}}{q_{l'}^0} \times \mathcal{A}(p_l, p_k, p_{l'}, p_{l'}) f(x, \tilde{p}_{l'}) f(x, \tilde{p}_{l'})
\]

and

\[
\mathcal{A}(p_l, p_k, p_{l'}, p_{l'}) = \delta^4(p_l + p_k - p_{l'} - p_{l'}) \left| \left( p_l, p_k | T_m | q_{l'}, q_{l'} \right) \right|^2 .
\]

The binary \( T_m \)-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 [8]. The \( T_m \)-matrix is obtained with the help of the \( S_m \)-matrix, which is lowest order

\[
S_m = \mathbb{1} + \frac{1}{\hbar c} \int_{-\infty}^{\infty} d^4 x : L_m^{in}(x) :.
\]

This implies

\[
\langle q_1 q_2 | S_m | p_2 p_1 \rangle = \frac{i}{\hbar c} (2\pi \hbar)^3 \delta^4(p_1 + p_2 - q_1 + q_2) \times \langle q_1 q_2 : L_m^{in} : | p_2 p_1 \rangle.
\]

and hence

\[
\langle q_1 q_2 | T | p_2 p_1 \rangle = \frac{2\pi}{c} (2\pi \hbar)^3 \langle q_1 q_2 : L_m^{in} : | p_2 p_1 \rangle.
\]

In section 3 we give details of the abstraction model based on the general relativist structure of the transport equations stated here.

3. Rate equations for reactions

The abstraction model (1) - (5) contains the dynamics of all particles embedded in a self-consistent electromagnetic field context inside the converter as depicted in Fig. 1. It is also the basis of the numerical abstraction model in future papers. This is one reason why we state the details of it here. We will also make use of it later in the paper.

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

\[
p_k^\mu \frac{\partial f_k}{\partial x^\nu} + m_k F^\mu_\nu \frac{\partial f_k}{\partial p_k^\nu} = \sum_{l,k,l'} \int \frac{d^3 p_1}{p_1^0} \int \frac{d^3 p_{l'}}{p_{l'}^0} \int \frac{d^3 p_{l'}}{p_{l'}^0} \times \mathcal{A}(p_l, p_k, p_{l'}, p_{l'}) f(x, \tilde{p}_{l'}) f(x, \tilde{p}_{l'})
\]

and

\[
F^\mu_k = \frac{q_k}{m_k c} F^\nu_{\mu} p_{k\nu},
\]

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

\[
\frac{\partial}{\partial x^\nu} F^\nu_{\mu} = \frac{j^\nu}{c^2 \epsilon_0}, \quad \frac{\partial}{\partial x^\mu} \tilde{F}^\nu_{\mu} = 0,
\]

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

\[
j^\nu = \sum_k q_k \int d^4 p \Theta(p_0) \delta(p_r^2 - m_k^2 c^2) c p_r f_k,
\]

where the collisional and reactive invariant transition amplitudes \( W^C \) and \( W^R \) can be mapped onto invariant collisional and
The kinematics of the reactions in the $kl$-system is best analyzed in the center of mass frame

$$\begin{align*}
\vec{p}^c_{k} &= \frac{1}{\beta k} (\vec{p}_k + \vec{p}_l) \beta - \gamma \beta p^0_k, \\
\vec{p}^c_l &= \frac{1}{\beta l} (\vec{p}_l + \vec{p}_l) \beta - \gamma \beta p^0_l,
\end{align*}$$

where

$$\begin{align*}
\beta &= \frac{\vec{p}_k + \vec{p}_l}{\vec{p}^c_k + \vec{p}^c_l}, \\
\gamma &= \frac{1}{\sqrt{1 - \beta^2}}, \\
p^0_k &= \sqrt{m^2_k + \vec{p}^c_k}, \\
p^0_l &= \sqrt{m^2_l + \vec{p}^c_l}.
\end{align*}$$

The quantity $p$ is the length of the CM-frame momenta $\vec{p}^c_{k}$ and $\vec{p}^c_{l}$. It is given by

$$p = \frac{1}{2 \sqrt{s}} \sqrt{s - (m^2_k + m^2_l) c^2} - 4 m^2_k m^2_l c^4.$$  

To define the post-collision momenta we introduce a right-handed coordinate system in the CM frame, the $\vec{e}_l$-axis of which is along $\vec{p}^c_{k}$. 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 $\vec{e}_l$. For the parametrization of the nuclear fusion products in the $k' l'$-system the angles $\psi$ and $\nu$ are introduced as indicated in Fig. 2. We construct three orthonormal vectors for all three coordinate axes as follows

$$\vec{e}_1 = \frac{\vec{p}^c_{k}}{|\vec{p}^c_{k}|},$$

$$\vec{e}_2 = \frac{\vec{p}^c_{l} \times \vec{e}_1}{|\vec{p}^c_{l} \times \vec{e}_1|},$$

$$\vec{e}_3 = \frac{(\vec{p}^c_{k} \times \vec{e}_1) \times \vec{p}^c_{l}}{|(\vec{p}^c_{k} \times \vec{e}_1) \times \vec{p}^c_{l}|}.$$  

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 fusion products, we can calculate the post-collisional or post-fusion momenta in the CM-frame

$$\begin{align*}
p^0_{k'} &= \sqrt{m^2_k c^2 + q^2}, \\
p^0_{l'} &= q \cos \psi \vec{e}_l + q \sin \psi \sin \nu \vec{e}_2 + q \sin \psi \cos \nu \vec{e}_3, \\
p^0_{l'} &= \sqrt{m^2_l c^2 + q^2}, \\
p^0_{l'} &= -\vec{p}^c_{l}.
\end{align*}$$

where $q$ is given by

$$q = \frac{1}{2 \sqrt{s}} \sqrt{s - (m^2_k + m^2_l) c^2} - 4 m^2_k m^2_l c^4.$$  

Finally we transform back into the lab-frame. Since the CM frame moves with the velocity $c \vec{e}_3$ we can go back to the lab frame by boosting the CM frame with the velocity $-c \vec{e}_3$. We obtain for the post-collisional variables in the lab frame

$$\begin{align*}
p^0_{k'} &= \gamma \left(\vec{p}^0_{k'} \cdot \vec{e}_3 + \beta \vec{p}^c_{k'} \right), \\
\vec{p}_k &= \vec{p}^c_{k} + \frac{1}{\beta k} (\vec{p}^0_{k'} + \vec{p}^c_{k}) \beta + \gamma \beta p^0_{k'}, \\
p^0_{l'} &= \gamma \left(\vec{p}^0_{l'} \cdot \vec{e}_3 + \beta \vec{p}^c_{l'} \right), \\
\vec{p}_l &= \vec{p}^c_{l} + \frac{1}{\beta l} (\vec{p}^0_{l'} + \vec{p}^c_{l}) \beta + \gamma \beta p^0_{l'}.
\end{align*}$$

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.

Since electrons are relativistic and to derive simple scaling laws for nuclear fusion efficiency at a later point in this paper three notations are helpful. The three notation are obtained by performing the integration over $\vec{p}_l$ in (6). We obtain $\vec{p}_l = \vec{p}_l + \vec{p}_l - \vec{p}_l$. Making use of the center of mass frame we find

$$\begin{align*}
\delta \left(\vec{p}^0_{k'} + \vec{p}^0_{l'} - \vec{p}^0_{k'} - \vec{p}^0_{l'} \right) \\
= \frac{\delta (|\vec{p}^c_{k'}| - \vec{T}_u)}{|\vec{p}^c_{k'}| \sqrt{s}},
\end{align*}$$

where the quantity $\mathcal{F}_{kl}$ is given by

$$\mathcal{F}_{kl} = (p_k \cdot p_l)^2 - m^2_k m^2_l c^4.$$  

Figure 2: Release angles of nuclear fusion products for binary decays.
In the velocity space this leads to

\[
\frac{\partial f_k}{\partial t} + \mathbf{\ddot{v}}_k \cdot \frac{\partial f_k}{\partial \mathbf{x}_k} + q_k (\mathbf{E} + \mathbf{v}_k \times \mathbf{B}) \cdot \frac{\partial f_k}{\partial p_k} = \sum_l \int d^3 \mathbf{p}_l v_{rel}^{kl} \int d\Omega \sigma_C^{kl} (s, \psi) (f_l f_k - f_l f_k) - \sum_l \int d^3 \mathbf{p}_l v_{rel}^{kl} \int d\Omega \sigma_k^{kl} (s, \psi) f_l f_k ,
\]  

(30)

where

\[
v_{rel}^{kl} = \frac{e F_{kl}}{p_k \mathbf{p}_l} = \frac{1}{\sqrt{m_k c^2 + p_k^2}} \sqrt{\left| \mathbf{v}_k - \mathbf{v}_l \right|^2 - \frac{1}{c^2} (\mathbf{v}_k \times \mathbf{v}_l)^2} ,
\]

(31)

\[
\tilde{v}_k = \frac{e \mathbf{p}_k}{\sqrt{m_k c^2 + p_k^2}} .
\]

(32)

We finally find

\[
\frac{\partial \tilde{v}_k}{\partial t} + \mathbf{\ddot{v}}_k \cdot \frac{\partial \tilde{v}_k}{\partial \mathbf{x}_k} + \frac{q_k}{m_k} (\mathbf{E} + \mathbf{v}_k \times \mathbf{B}) \cdot \frac{\partial \tilde{v}_k}{\partial \mathbf{p}_k} = \sum_l \int d^3 \mathbf{v}_l \tilde{v}_{rel}^{kl} \int d\Omega \sigma_C^{kl} (s, \psi) (f_l f_k - f_l f_k) - \sum_l \int d^3 \mathbf{v}_l \tilde{v}_{rel}^{kl} \int d\Omega \sigma_k^{kl} (s, \psi) f_l f_k ,
\]

(33)

where fuel breeding is excluded.

In section 4 we parametrically discuss the integrated nanoscopic accelerator concept. It relies on the assumption that the driver laser is capable of removing sufficiently many electrons from the nano-rods in the micro-reactor in a predictable way. We will not investigate the details in this paper and leave it for future numerical analysis.

4. The integrated nano-accelerator

We assume that energy transfer to fuel constituents takes place with the help of the electromagnetic fields of the driver laser. This energy delivery system has a chance to be efficient and fast for almost all nuclear fusion fuels.

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.

The integrated nano-accelerator is assumed to be an efficient design for the generation of large ion 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 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 within the time window the Coulomb explosions take. Hence, positive ions are exposed to their own electric space-charge field for long enough and Coulomb explode, leaving behind some time, a nearly homogeneous ionic distribution in configuration space and a non-thermal one in the momentum space that can be engineered such that it is peaked at the resonances of the provided nuclear fuel mix.

Specifically, we consider cylindrical nano-rods that form the embedded nano-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 effective charges and fuel masses involved. Between accelerator nano-rods low Gamov energy fuel ions can be placed in form of foams. Since we propose UV to VUV driver laser wavelengths we assume that the laser is still capable of propagating through the proposed convertor in a stable and predictable way.

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 \( l \)

\[
E_r (r) = \begin{cases} 
C_f r_k , & 0 \leq r_k < R \\
0 , & r_k \geq R
\end{cases} ,
\]

(34)

where the nanoscopic field \( E_r \) is radial and \( n_i \) represents the average positive charge density inside the rods. The parameter \( r_k \) 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

\[
\left( \frac{\partial}{\partial t} + v_k \frac{\partial}{\partial r_k} + \frac{e_k}{m_k} C_f r_k \frac{\partial}{\partial r_k} \right) (r_k v_k f_k) (r_k, v_k, t) = 0 .
\]

(35)

The above approximation is justified for the \( ^{11} \)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 \( r_k > R \)

\[
\left( \frac{\partial}{\partial t} + v_k \frac{\partial}{\partial r_k} \right) (r_k v_k f_k) (r_k, v_k, t) = 0
\]

(36)

until they collide or fuse.

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

\[
\frac{dr_k}{dt} = v_k , \quad \frac{dv_k}{dt} = \frac{e_k}{m_k} C_f r_k ,
\]

(37)

while the solution of (35) is

\[
(r_k v_k f_k) (r_k, v_k, t) = (r_\infty v_\infty f_k) (r_\infty, v_\infty, 0) ,
\]

(38)
where due to (37) we have

\[
\begin{pmatrix}
  r_{k0} \\
  v_{k0}
\end{pmatrix} =
\begin{pmatrix}
  \cosh\left(\sqrt{\frac{eCl}{m_k}} t\right) & -\frac{1}{\sqrt{\frac{eCl}{m_k}}} \sinh\left(\sqrt{\frac{eCl}{m_k}} t\right) \\
  -\frac{1}{\sqrt{\frac{eCl}{m_k}}} \sinh\left(\sqrt{\frac{eCl}{m_k}} t\right) & \cosh\left(\sqrt{\frac{eCl}{m_k}} t\right)
\end{pmatrix}
\begin{pmatrix}
  r_k \\
  v_k
\end{pmatrix}.
\]  

(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 \( 0 < r_{k0}^s(0) \leq R \) and a radial velocity distribution given by

\[
\begin{pmatrix}
  r_{k0} v_{k0} f_k^s(0, r_{k0}, v_{k0}, 0) \\
  v_{k0}
\end{pmatrix} = \frac{N_k^s(0)}{4\pi^2} \delta\left(r_{k0} - r_k^s(0)\right) \delta\left(v_{k0} - v_k^s(0)\right),
\]

where \( N_k^s(0) \) is the initial number of particles \( k \) at the radial position \( r_k^s(0) \). Plugging \( r_{k0} \) and \( v_{k0} \) given by (39) into (40) gives for \( t \leq t_k^s \)

\[
r_k v_k f_k^s(r_k, v_k, t) = \frac{N_k^s(t)}{4\pi^2} \delta\left(r_k - r_k^s(t)\right) \delta\left(v_k - v_k^s(t)\right),
\]

(41)

where

\[
t_k^s = \sqrt{\frac{m_k}{eCl}} \cosh^{-1}\left(\frac{R}{r_k^s(0)}\right),
\]

(42)

\[
r_k^s(t) = r_k^s(0) \cosh\left(\sqrt{\frac{eCl}{m_k}} t\right),
\]

(43)

\[
g_k^s(t) = \sqrt{\frac{eCl}{m_k}} r_k^s(0) \sinh\left(\sqrt{\frac{eCl}{m_k}} t\right).
\]

(44)

After rapid acceleration during the Coulomb explosion phase the light ion layer is assumed to move on ballistically. At \( t = t_k^s \) we obtain

\[
r_k v_k f_k^s(r_k, v_k, t_k^s) = \frac{N_k^s(t)}{2\pi} \delta\left(r_k - r_k^s(0)\right) \delta\left(v_k - v_k^s(0)\right),
\]

(45)

where

\[
r_k^s(0) = R,
\]

(46)

\[
g_k^s(0) = \sqrt{\frac{eCl}{m_k}} \sqrt{R^2 - \left(r_k^s(0)\right)^2}.
\]

(47)

It holds

\[
(2\pi)^2 \int_0^\infty dv_k \int_0^\infty dr_k v_k f_k(r_k, v_k, t) = N_k^s(t).
\]

(48)

Next, we rewrite the distribution functions in the following way

\[
f_k^s(\vec{r}_k, \vec{v}_k, t) \approx N_k^s(t) \delta^3(\vec{r}_k - \vec{r}_k^s(t)) \delta^3(\vec{v}_k - \vec{g}_k^s(t)),
\]

(49)

\[
N_k^s(t) = N_k(t) \alpha_k^s,
\]

\[
\alpha_k^s = \frac{2r_k^s(0)}{R^2} \Delta r_k
\]

(50)

\[
N_k(t) = \sum_l N_l^k(t),
\]

(51)

\[
n_l(t) = \frac{N_B}{V} N_l(t),
\]

(52)

where \( V \) is the reactor volume, \( \beta \) the ratio between \( k \) and \( l \) ions, \( N \) 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

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

(53)

\[
f_l(\vec{r}_l, \vec{v}_l, t) \approx \frac{N}{V} N_l(t) \delta^3(\vec{u}_l).
\]

(54)

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 \( |\vec{p}_p| > 0.05 m_p c \).

Single fuel cycles may have low efficiency. 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. We will not analyze coupled fuel mixes in the present version of this paper. Instead, we will analyze the principal limitations of single fuel cycles in a parametric way.

Figure 3: Proton momentum distributions integrated over the configuration space after the laser pulse has exited the nano-structures. The proton momenta are normalized to \( m_p c \). The simulation has lateral periodic boundaries, while the laser pulse is a central disk with 10fs pulse length and \( \lambda = 250 \) nm. The polarization is circular.
Figure 4: Boron momentum distributions integrated over the configuration space after the laser pulse has exited the nano-structures. The boron momenta are normalized to $m_B c$. The simulation has lateral periodic boundaries, while the laser pulse is a central disk with 10 fs pulse length and $\lambda = 250$ nm. The polarization is circular.

Figure 5: The laser impinges the nano-reactor from the left. Two time frames are shown. The box size is $8 \mu m \times 8 \mu m \times 32 \mu m$. The nano-rods are 30 nm wide and about 800 nm apart. The laser wavelength is 250 nm. The laser is circularly polarized. The laser driver has nearly constant loss of energy per unit of propagation length. The laser does not self-focus. It captures electrons forming a magnetic field that separates electron current and return currents. The plot shows that the plasma starts to pinch.

Figure 6: Coulomb explosions in the body of the laser pulse. The explosion front propagates with almost the speed of light.

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. It is unclear at present to which extent this is possible.

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 has to be investigated.

In the next section we discuss the basics of the conversion fraction $\eta$ and efficiency $Q$ in a parametric way. We will incorporate binary collisions by making the simple assumption that the light ion constituents propagate ballistically until they collide the first time. How this assumption impacts the performance of the micro-reactor as we will see in the next section.

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

$$\frac{dN_k(t)}{dt} \approx - (N_k(t))^2 N \sum_i a_{ik} g_{ik}^i(t) \sigma_{ik}^i (g_{ik}^i(t)),$$

where

$$\frac{d\tilde{g}_{ik}^j(t)}{dt} \approx \frac{e_k}{m_k} \left[ \tilde{E} \left( \tilde{r}_{ik}^j(t), t \right) \right] + \tilde{B} \left( \tilde{r}_{ik}^j(t), t \right) \times \tilde{g}_{ik}^j(t) \right]$$

$$- c_k \tilde{v}_{ik} \left( g_{ik}^j(t) \right) \tilde{g}_{ik}^j(t)$$
\[ \frac{dE^e(t)}{dt} = \vec{g}^e_k(t). \] (57)

In the end we have to sum over all nano-rods. The quantities \( E^e \) and \( B \) are electromagnetic fields and \( \nu_{ke}^e \) are the collision frequencies

\[ \nu_{ke}^e \left( g^e_k(t) \right) \approx \frac{\epsilon^k_{sl} e^2}{4\pi \epsilon_0 m^e_{ke} \left| \vec{g}^e_k(t) - \vec{v}_e(t) \right|^2} \ln \Lambda_{ke}. \] (58)

Making the assumptions explained in section 6 and for simplicity the assumptions

\[ \vec{E}(\vec{r}, t) = -E \hat{e}_r, \] (59)

\[ \vec{B}(\vec{r}, t) = -B \hat{e}_\phi \] (60)

for the secular electric and magnetic fields in the micro-reactor we obtain for (56) - (57) on a perturbative parametric level

\[ g^{11}_k(t) \approx -\frac{e_k E}{m^e_{ke}} \left( 1 - e^{-\nu_{ke}^e t} \right) \hat{e}_r + \frac{e_k E}{m^e_{ke}} \vec{g}^{11}_k(0) \times B \hat{e}_\phi, \] (61)

\[ g^{22}_k(t) \approx -\frac{e_k E}{m^e_{ke}} \left( 1 - e^{-\nu_{ke}^e t} \right) \left( \frac{e_k E}{m^e_{ke}} \vec{g}^{11}_k(0) \times B \hat{e}_\phi \right) + \frac{e^2 E B}{m^e_{ke} c^2} \left[ 1 - \frac{1}{\nu_{ke}^e} \left( 1 - e^{-\nu_{ke}^e t} \right) \right] \hat{e}_r, \] (62)

\[ g^i_k(t) \approx \vec{g}^{11}_k(t) + \vec{g}^{22}_k(t), \] (63)

where we assume that \( \nu_{ke}^e \) does not depend on the velocity. Equations (61) - (63) do not reflect the true motion of an ion in the presence of the fields given by (59) and (60). The initial velocity \( \vec{g}^{11}_k(0) \) is obtained by rapid nano-acceleration. Mean field and binary level radiation loss is neglected in (56) - (57). Estimates of both levels of radiation loss indicate that they have about the same rate as the binary collisions. The details of this problem will be investigated in detail in another paper.

In what follows we neglect the impact of the secular electric and magnetic fields but assume that there is magnetic field confinement, which is described by the first line of (62). The second line of (62) is a drift leading to jets along the \( z \)-axis. The mechanism of jet production along \( z \) leads to auto-catalysis via collective fields in the micro-reactor. It implies, that two head on micro-reactors enable colliding jets of nuclear fuel ions.

Here, we make the simple assumption that the range of the ions \( k \) is given by their nano-accelerator exit velocities divided by their collision frequencies. We essentially neglect the collective auto-catalysis implied in (61) - (63) in the reactor and leave the detailed analysis of it to a future paper. Equation (55) can now be solved. We find

\[ N_k(\Delta t) \approx \frac{N_k(0)}{1 + \frac{\gamma_k}{\nu_k} \int_{0}^{\Delta t} dt \sum_s \alpha_k^s g_k^s(t) \sigma^{kl}_k \left( g_k^e(t) \right)}. \] (64)

where \( \Delta t \) is an effective reactor runtime, which depends on the field context and the radiative and collisional energy loss. The parameter \( N_k(0) \) is to some extent a free parameter. The conversion fraction is

\[ \eta_k^{kl} = \frac{\Delta N_k(\Delta t)}{N_k(0)} \] (65)

\[ = 1 - \frac{N_k(\Delta t)}{N_k(0)} \]

\[ = \frac{\beta_N}{\nu_k} \sum_s \alpha_k^s \int_{0}^{\Delta t} dt \left( g_k^s(t) \sigma^{kl}_k \left( g_k^e(t) \right) \right). \]

By changing the morphology of the nano-structures the energy spread of the light ions \( k \) can become very small. Then almost all \( k \) ions are at the same exit velocity. With the help of an approximate function for \( \sigma^{kl}_k \) we have

\[ \sum_s \alpha_k^s \int_{0}^{\Delta t} dt \left( g_k^s(t) \sigma^{kl}_k \left( g_k^e(t) \right) \right) \]

\[ \approx \Delta t g_k^{av} \sigma^{kl}_k \left( g_k^{av} \right) \]

\[ \approx \Delta t g_k^{av} \left( \frac{m_k}{\epsilon_G} \right) \rho_k^{kl} e^{-\sqrt{\frac{m_k}{\epsilon_G}}}, \] (66)

where

\[ \rho_k^{kl} = \frac{\epsilon_k^{sl} E}{\beta_k \gamma_k} \approx \frac{1}{2} m_k \left( \epsilon_k^{av} \right)^2, \] (67)

\[ \epsilon_k^{av} = \left( \frac{\pi c^2 Z_k^2}{4 \pi \epsilon_0 \hbar c} \right)^{2/3} m_k c^2, \] (68)

\[ m_{kl} = m_k m_l / (m_k + m_l). \] (69)

The parameter \( \rho_k^{kl} \) is a free parameter, that links the kinetic energy \( \epsilon_k^{av} \) to the Gamov energy \( \epsilon_k^G \) of the underlying nuclear fusion process. The parameter \( g_k^{av} \) is the effective relative velocity between the \( k \) and \( l \) ions in the reactor. The factor \( S_{kl} \) is the astro-physical parameter for the underlying nuclear fusion process. According to [9] the cross section used in (66) underestimates the reactivity. An illustration is given in Fig. 7.

![Figure 7: Comparison between the cross sections of pB and DT as quoted in reference [9].](image)

There are many interesting fuel cycles. The most relevant neutron fuel cycles are given in table 1. They have small Gamov energies \( \epsilon_k^G \) and large \( S_{kl} \). Advanced fuel cycles are summarized in table 2. They have larger Gamov energies \( \epsilon_k^G \).
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 $\eta^d$ becomes

$$\eta^d = \frac{N_B}{V} \frac{S_{kl}}{S_{kl} + S_{kl - p}} e^{-\sqrt{\frac{S_{kl}}{S_{kl - p}}}}$$ (70)

$$R_e = \Delta g_{kl} \approx \frac{g_{kl}^0}{\nu_x}$$ (71)

Equation (70) shows that large average velocities $g_{kl}^0$ and low collisionality are capable of mitigating low fuel densities. Since the collision frequencies scale like the density and the conversion fraction contains the product between density and range there can only be a weak scaling with density for the proposed single pass micro-reactor operation. A detailed analysis is left for a future paper. However, if the micro-reactor is operated with a fuel cycle that can become auto-catalytic in the course of its operation there will be a strong density scaling for $\eta^d$. The DT fuel cycle is such a candidate.

For a given conversion fraction we have

$$\frac{N_B}{V} R_e \approx n_i \beta R_e > \frac{\eta^d}{1 - \eta^d} \frac{S_{kl}}{S_{kl - p}} \frac{1}{\beta_{av}} e^{-\sqrt{\frac{S_{kl - p}}{S_{kl}}}}.$$ (72)

We define the conversion efficiency $Q^d$ as

$$Q^d = \frac{\eta^d}{S_{kl}^d} \eta^d = \frac{S_{kl}}{S_{kl - p}} \beta_{av} \eta^d,$$ (73)

where $S_{kl}^d$ is the energy release of an elementary nuclear fusion reaction. It is of course clear that there are further primary driver energy consuming processes. We will discuss this in a future paper.

Since we plan to work with a nano-structured LiDTpB composite with structures at near solid density we first consider $p^{11}B$. For an average fuel density of about $n_B = n_p \approx 5.0 \cdot 10^{28}$ m$^{-3}$, an average velocity of $g_{kl}^0 \approx 2.0 \cdot 10^7$ m s$^{-1}$ according to Fig. 46, and a collision frequency of $\nu_x \approx 10^{10}$ s$^{-1}$ the range is $R_p \approx 2 \cdot 10^3$ m$^{-3}$ yielding $n_B R_p \approx 10^{26}$ m$^{-2}$. An illustration of the conversion fraction $\eta^d$ as a function of $\beta_{av}$ and $n_B R_p$ is shown in Fig. 9 for $\beta = 1$. The parameter $\beta$ can be modified for better conversion in the micro-reactor. It has to be investigated, which fuel constituent ratio $\beta$ is best, since higher proton concentration implying $\beta > 1$ requires more energy.

![Figure 9: The expected conversion fraction $\eta^d$ as a function of $\beta_{av}$ and $n_B R_p$ for $\beta = 1$ based on the cross section given in Fig. 7. Changing $\beta$ will enhance or lower $\eta^d$. This is a well-known effect.](image)

At the same time we have very high deuterium and tritium densities within a boron - lithium nano-matrix. The embedded nano-accelerator is then capable of generating energetic high density deuterons, which can impinge high density tritium. Again, we consider single-pass operation of the micro-reactor. There is almost no benefit from external compression for this mode of operation. The DT fuel is a neutrino fuel cycle allowing for a fast energy extraction mechanism via neutrons and radiation.

The average density of the deuterium leaving the boron nano-rods can be as high as $n_D \approx 5.0 \cdot 10^{28}$ m$^{-3}$, while tritium immersed into the reactor is assumed to have about the same density. The exit velocity of D is assumed to be $2 \cdot 10^7$ m s$^{-1}$, while the collision frequency is approximately $\nu_{Dx} \approx 10^{10}$ s$^{-1}$. We obtain approximately $n_T R_D \approx 10^{26}$ m$^{-2}$. As Fig. 7 shows the cross

| Standard fuels | $\epsilon^d$ MeV | $S_{kl}$ keV barn | $\sqrt{\frac{\epsilon^d}{\epsilon^d}}$ $\sqrt{\nu_x}$ |
|----------------|----------------|-----------------|----------------|
| D + T $\rightarrow$ $^4$He + n | 17.39 | 1.2 $\cdot$ 10$^8$ | 34.38 |
| D + D $\rightarrow$ T + p | 4.04 | 56.0 | 31.4 |
| D + D $\rightarrow$ $^4$He + n | 3.27 | 54.0 | 31.4 |
| D + D $\rightarrow$ $^4$He + y | 23.85 | 4.3 $\cdot$ 10$^{-3}$ | 31.4 |
| T + T $\rightarrow$ $^4$He + 2n | 11.33 | 138.0 | 38.45 |

Table 1: Standard fuel cycles. They are typically producing neutrons at high rates but are better suited for thermal nuclear fusion concepts.

| Advanced fuels | $\epsilon^d$ MeV | $S_{kl}$ keV barn | $\sqrt{\frac{\epsilon^d}{\epsilon^d}}$ $\sqrt{\nu_x}$ |
|----------------|----------------|-----------------|----------------|
| D + $^3$He $\rightarrow$ $^4$He + p | 18.35 | 5.9 $\cdot$ 10$^7$ | 68.75 |
| p + $^3$Li $\rightarrow$ $^4$He + $^3$He | 4.02 | 5.5 $\cdot$ 10$^7$ | 87.2 |
| p + $^3$Li $\rightarrow$ 2$^2$He | 17.35 | 80.0 | 88.1 |
| p + $^{11}$B $\rightarrow$ 3$^2$He | 8.68 | 2.0 $\cdot$ 10$^4$ | 150.3 |

Table 2: Advanced fuel cycles. They are typically producing less neutrons but have larger Gamov energies. Hence, cross sections are small at low energies making the fuel cycles difficult to trigger in a thermal context.
section of DT is large over an extended energy range. Hence, the deuterons can loose a lot of their energy keeping their reactivity almost constant in the course of it. This property implies the need for a bottom up integration of (55) - (57). An optimistic estimate of the conversion fraction $\eta^{DT}$ as a function of $\beta^{DT}$ and $n_f R_D$ is shown in Fig. 10. The physics behind it will be analyzed in a future paper.

We assume that the laser irradiated form factor of the micro-reactor and range of the fuel constituents decouple. The confinement problem might find a solution via self-generated magnetic fields in the micro-reactor. The details of this problem will be investigated in a separate paper.

We repeat that the single pass operation regime of the micro-reactor does not benefit from compression.

In section 6 some aspects of the nonlinear electron optical properties of the micro-reactor are addressed.

### 6. Nonlinear optics

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 $\epsilon_i n_f$ is approximately

$$E \geq \frac{R}{\epsilon_i} \left( m_i \omega^2 + e_r C_i \right).$$

The implication for the laser intensity is

$$I_c = \frac{1}{2} \epsilon_0 c E^2 \geq \frac{\epsilon_0 c R^2 \left( 4 \pi e^2 m_i + e_r C_i \right)}{2 \epsilon_i^2}.$$  \hspace{1cm} (75)

The gap $D$ between the nano-rods is estimated from the critical plasma density for a given $\lambda$ of the laser

$$D \geq \frac{\epsilon_i^2 n_f R^2}{4 \pi \epsilon_0 m_i c^2 \Lambda}.$$ \hspace{1cm} (76)

Figure 11 below shows the approximate radius $R$ of the rods for various wavelengths $\lambda$ for half ionized $p^{11}$B required for the relative energy of $\epsilon_p^{11}B \approx 0.5$ MeV between protons and boron ions. For a given rod radius $R$ and half ionized $p^{11}$B the required gap $D$ between nano-rods for stable laser pulse propagation is shown in Fig. 12.

The gap $D$, the radius $R$, and the charge state $n_i$ of the rods can be engineered to match the laser driver for optimal nano-acceleration of ions. It is the goal to convert a large share of the external laser energy into ionic motion. Laser-optical instabilities have to be avoided.

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 [10, 11, 12]

$$P_{c,sp} \approx \frac{2 P_c}{L^2 \sigma^2} \Rightarrow P_c,$$ \hspace{1cm} (77)

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 $L > \lambda_p$.

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 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
\[ \frac{\partial n_e}{\partial t} + \frac{\partial}{\partial x} (n_e \bar{v}_e) = 0, \quad (78) \]
\[ \left( \frac{\partial}{\partial t} + \bar{v}_e \cdot \frac{\partial}{\partial x} \right) \bar{v}_e = \frac{e}{m_e n_e} j_e \times \vec{B} - \frac{e}{m_e n_e} \frac{\partial p}{\partial t}, \quad (79) \]
\[ \frac{\partial}{\partial x} \vec{B} = \frac{1}{\varepsilon_0} j_e, \quad (80) \]
\[ \frac{\partial B}{\partial t} = \frac{\partial}{\partial x} (\bar{v}_e \times \vec{B}), \quad (81) \]
\[ \vec{E} = -\bar{v}_e \times \vec{B}, \quad (82) \]
\[ \frac{\partial}{\partial x} B = 0, \quad (83) \]

where \( P \) is the electronic plasma pressure. Under the assumptions (78) - (83) the magnetic field is slowly varying as simulations confirm. Assuming \( d\bar{v}_e/dt \approx 0 \) we obtain with the help of (79)
\[ \bar{J}_e \times \vec{B} - \frac{\partial P}{\partial x} \approx 0, \quad (84) \]
\[ \frac{\partial \vec{B}}{\partial t} = \frac{\partial}{\partial x} (\bar{v}_e \times \vec{B}) \approx 0. \quad (85) \]

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 assume
\[ \vec{B}(r,t) = \begin{cases} \frac{\bar{J}_e}{2 \pi \sigma r^2} \bar{r} e \phi, & r \leq R_L \\ \frac{\bar{J}_e}{2 \pi \sigma r^2} \bar{r} e \phi, & r > R_L \end{cases}, \quad (86) \]

where \( J_e = e_e n_e v_e \) is the strength of the electronic current density and \( R_L \) is the effective laser pulse radius. The electric field associated to \( J_e \) and \( B \) is according to (82)
\[ \vec{E}(r,t) = -\frac{1}{e_e n_e} \bar{J}_e \times \vec{B}(r), \quad (87) \]

The electric field (87) stabilizes the electron current. It points towards the center of the reactor. For the ion motion we have according to (56) - (57) on a perturbative parametric scale
\[ \frac{d\vec{g}_{1e}(t)}{dt} \approx \frac{e_e}{m_e} \bar{E} (\vec{r}_e(t), t) - \nu_e \bar{g}_{1e}(t) \bar{g}_{1e}(t), \quad (88) \]
\[ \frac{d\vec{g}_{2e}(t)}{dt} \approx \frac{e_e}{m_e} \bar{g}_{1e}(t) \times \vec{B} (\vec{r}_e(t), t), \quad (89) \]
\[ \frac{d\vec{g}_e(t)}{dt} \approx \bar{g}_{1e}(t) + \bar{g}_{2e}(t). \quad (90) \]

To simplify further we assume radially and temporally constant fields with the correct directionalities according to (86) and (87)
\[ \bar{E}(r,t) = -\bar{E} \bar{e}_\phi, \quad (91) \]
\[ \vec{B}(r,t) = -B \bar{e}_\phi. \quad (92) \]

The correct solution is quite complicated. On a perturbative parametric scale we obtain
\[ \bar{g}_{1e}(t) \approx -\frac{e_e E}{m_e v_{le}^2} \left( 1 - e^{-\nu_e t} \right) \bar{e}_\phi + \bar{g}_{1e}(0) e^{-\nu_e t}, \quad (93) \]
\[ \bar{g}_{2e}(t) \approx -\frac{e_e}{m_e v_{le}^2} \left( 1 - e^{-\nu_e t} \right) \bar{g}_{1e}(0) \times \vec{B} \bar{e}_\phi \]
\[ + \frac{e_e^2 E B}{m_e^2 v_{le}^4} \left[ t - \frac{1}{v_{le}} \left( 1 - e^{-\nu_e t} \right) \right] \bar{e}_\phi, \quad (94) \]
\[ \bar{g}_e(t) \approx g_{1e}(t) + g_{2e}(t). \quad (95) \]

It is clear that (93) - (95) only hold if the \( E \)- and \( B \)-fields are constant, unidirectional, not rotating, and as long as the electric and magnetic fields are not too strong. The drift velocities are quite significant in that case. In reality, the electric and magnetic fields are space and time dependent. To understand the full scope of the problem equations (56) - (57) have to be solved numerically. We will do this in a future paper.

Let us now estimate the required secular field strengths. The magnetic field \( B \) required to force a \( k \)-ion into an orbit with radius \( r_k^1 \) at the velocity \( g_k^1 \) is c is
\[ B \approx \frac{m_k g_k^1}{e_k r_k^1}. \quad (96) \]

This implies for
\[ r_k^1 \approx 10^{-6} \text{ m}, \quad g_k^1 \approx 10^7 \text{ m/s}, \quad R_L \approx 10^{-5} \text{ m}, \quad (97) \]

where \( R_L \) is the effective laser spot size the current density, magnetic field, and electric field
\[ j_e \approx 2 \frac{e_k c^2 m_k g_k^1}{e_k r_k^1 R_L} \approx 10^{16} \text{ A/m}^2, \quad (98) \]
\[ B \approx 10^5 \text{ V/m}, \quad (99) \]
\[ E \approx 10^{10} \text{ V/m}, \quad (100) \]

Since the electric and magnetic fields scale with radius we make the assumption that the electric and magnetic fields are effectively much weaker than what is predicted as peak values in from simulations. For \( E \approx 10^7 \text{ V/m} \) and \( B \approx 10^4 \text{ T} \) we have
\[ \frac{e_k E}{m_k v_{le}^2} \approx 10^7 \text{ ms}^{-1}, \quad \frac{e_k^2 E B}{m_k^2 v_{le}^4} \approx 10^8 \text{ ms}^{-1}, \quad (101) \]

implying that the parametric solutions in (93) - (95) have to be improved.

Simulations shown in Fig. 13 indicate that electric and magnetic fields of the required topology and magnitude can be generated that are large enough to enable confinement and to overcome collisional resistivity. The magnetic field strength in the simulation is \( B \approx 10^3 \text{ T} \), the laser spot size is \( R_L \approx 2 \cdot 10^{-6} \text{ m} \), the current density is \( j_e \approx 10^{17} \text{ A/m}^2 \), and the electron density is \( n_e \approx 10^{20} \text{ m}^{-3} \). The implication is that almost all electrons move at about the speed of light.

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 magnetic field strength obtained is laser pulse interacting with nano-rods. The simulation parameters are those of Figure 13: Azimuthal magnetic field obtained in a simulation for an ultra-short pulse. They contain radiation reaction [13]. The elevation of radiation reaction accounts for most of the radiative energy loss of electrons. While electrons are subject to self-radiation, binary electron - ion collision frequencies have to be estimated. We have approximately $v_k e \approx (10^9 - 10^{11})$ s$^{-1}$. Collisonal energy exchange in the fast micro-reactor at near solid density via electrons takes about 10 – 1000 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 nuclear fusion for a range of nuclear fuels. It is based on a nano-structured micro-reactor driven by advanced ultra-short ultra-high energy laser pulses in the UV to the VUV wavelength range. The embedded nanostructures represent an integrated nano-accelerator.

Provided, the nonlinear electron optical part of the concept works out as suggested the concept should be capable of reaching high conversion fractions. Since the reactor has two intrinsic mechanisms of catalysis multiple nuclear fuel cycles are required.
While collective electric fields trigger the initial nano-acceleration of the nuclear fuel leading to high fuel velocities and spreads of relative energies all over the reactor volume, secondary secular electric and magnetic fields emerge implying jet formation and the compensation of resistive energy loss by drift motion. During this phase of the reactor cycle preferentially aneutronic fuels are desirable and there is little to no benefit from fuel compression. Reduced confinement times due to jets can be counteracted by head on reactor pairs powered by at least two laser drivers.

At a later stage resistive energy loss dominates. The reactor might transition into a resistive mode of operation ultimately leading to thermo-nuclear fusion based on auto-catalysis via collisions. In this phase there is potentially a benefit from high fuel densities.

Fuels allowing collisional-auto-catalysis are low Gamov energy nuclear fuels like DT. In addition, most of them produce neutrons that carry most of the nuclear fusion energy. Neutrons and radiation form a fast and robust energy extraction system for the proposed micro-reactor.

It is clear that the present paper can only represent an introduction into a potentially powerful micro-reactor concept. We will follow up with this paper by a number of more detailed papers that focus on the many scientific subtopics implies by this paper. In addition, fully integrated simulations are required that are under preparation.

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