BEAM DRIVEN PLASMA ACCELERATION for LINEAR COLLIDER (physics & development stage)

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Suggestions and attempts to higher gradients were made by many people through decades and for many times.

For us, at Novosibirsk, the main drive in the direction, since 1960s, was always *Linear Collider* hope for hundreds of GeV electron-positron collisions.

When we first presented publicly (1978) the VLEPP project, which incorporates 100 MeV/m accelerating gradient for normal conducting short pulse linacs, this "high gradients problem" was considered by the majority as a main one in linear collider business (even obstacle!).

Additionally to VLEPP project, we have discussed at that time the possibility to use the huge energy, stored at existing and - especially - planned proton beams of super-accelerators. This option was called the "proton klystron", and the way was shown to excite by such beams 1 cm wave length range linear accelerating structures up to the limit of accelerating gradients.

Since that time, in our Lab and in many other labs this level was proved practical for GHz (cm wave) range, short pulse, normal conducting accelerator structures - just have enough RF power and use proper technology for structures!

But it was (more or less) evident from the beginning - 100 MeV/m is close to the ultimate limit for metallic accelerating structures: electric field at the surface is additionally few times higher, and it starts to produce "cold currents", and occasional discharges degrade the surface instead of improving it (training process fails!).

Hence, to reach much higher gradients (above 300 MeV/m) we need to shift from the solid materials transforming/shaping of electromagnetic fields to plasma based structures.

(At really high electric fields, the exposed surface in any case converts into something close to plasma.)

To "pump-in" such plasma based high gradient accelerators the natural (may be - the only) option is to use high energy charged particle beams - higher? much higher than 1 GeV

(not lasers, not low energy beams)

- we need to arrange proper fields at km length and with precision of fine machined metallic structures!
And to prevent all the instabilities.

{100% ionized (hydrogen) plasma should be prepared in advance - the action of driver beams is not efficient enough}.

First of all - the answer for the simplest question: why we need something, like plasma, at all to generate accelerating fields by driver beams?

1. Acceleration is provided by the longitudinal electric field only. Longitudinal electric field of the co-moving relativistic driver (in rest frame, where a bunch is gamma times longer) is much, much lower than its transversal field. In lab system, transversal electric field is additionally gamma times higher, while longitudinal field remains the same as in rest frame. Hence, the direct use of driver bunch longitudinal electric field is extremely inefficient.

2. The driver bunch traveling through plasma excites plasma electron oscillations with its transversal electric field. Plasma electric fields reach the level of transversal driver field (and even much higher in case of resonant pumping!).

In proper case, longitudinal electric field in plasma oscillation is of the level of its transversal field (even few times higher).

3. The above mentioned property justifies the use of plasma, already. But additionally, we can excite useful plasma oscillations by train of micro-bunches resonantly, obtaining proportional gain in driver peak current requirement.

Inside plasma, plasma electrons and electro-magnetic fields oscillate coherently. More or less universal limit (if we intend to use efficient "resonant excitation") can be evaluated in such a way:

electric field energy density should be less than (rest frame) energy density of plasma electrons.

In equations:

$$E_{ultim} = \sqrt{\frac{4\pi e^2}{r_e} \cdot n_e}\,.$$

hence

$$E_{ultim} = \sqrt{4\pi \cdot n_e mc^2} = \sqrt{\frac{4\pi \cdot e^2}{r_e} \cdot n_e}$$

The realizable field is around 3 times lower. Hence, the plasma density needed is

$$n_e = \frac{9}{4\pi} \cdot \frac{r_e}{e^2} \cdot E_{acc}^2\,.$$

Hence, for to reach

1 GeV/m

we need to use plasma density

10^{15} cm^{-3}.

The obvious example for plasma oscillations: longitudinally homogenous cylinder in plasma with radial excitation of plasma electrons velocities:

E_{radial} - only!

Magnetic field = 0

For the needed high fields, short time periods and "modest" plasma density -

- **plasma temperature - zero,**
- **kinetic pressure - zero,**
- **plasma is collision-less,**
- **only electrons can move.**

Electric field and plasma electrons oscillate coherently.

And no influence of these oscillations on plasma outside of excited cylinder!

<u>The oscillations do not propagate and its energy do not dissipate!</u>

Oscillation frequency is electron plasma frequency:

$$\omega_e = \sqrt{\frac{4\pi e^2 n_e}{m_e}}\,.$$

But in such an excited plasma cylinder there is no longitudinal electric field - <u>witness beam acceleration is zero!</u>

To accelerate relativistic witness beam the "radial" plasma oscillations should be excited "locally" with proper phase shift - to arrange phase velocity equal to the light velocity **c**.

The most natural way - relativistic <u>driver beam</u> excitation.

(Compensating "backward" electron current in plasma!)

Zero temperature and no collisions - no "plasma break-down"!

(no capture of plasma electrons in continuous acceleration, no "Landau damping")

And "excitement confinement" - remains!

The best excitation option - a train of ultrarelativistic micro-bunches, spaced resonantly:

$$\lambda_{pl} = \sqrt{\frac{\pi}{r_e n_e}} \; .$$

What is the minimal driver particles number to excite accelerating field E?

Let the excited plasma cylinder radius to be "minimal"

$\lambda_{pl}/2\pi$.

Stored energy vs. transferred energy balance (per cm):

$$\frac{E^2}{8\pi} \cdot \pi \cdot \frac{\lambda^2}{(2\pi)^2} \cdot 2 = e N_{need} E \cdot \frac{1}{2} \; .$$

Hence

$$N_{need} = \frac{1}{8\pi^2} \cdot \frac{E\lambda^2}{e} \; .$$

To reach 1 GeV/m = 30 kGs at wave length 1 mm :

$$N_{need} = 1 \cdot 10^{10}$$

(if all the driver particles travel at maximum of decelerating field!)

To minimize the driver peak current it is worth to distribute them along the train of (10 ?) micro-bunches separated by λ_{pl}.

Plasma density

$$\underline{1*10^{15}}\ \text{cm}^{-3}$$

corresponds to the micro-bunches spacing

$$\underline{\lambda_{pl}=1\text{mm}}.$$

For the driver train of 1 cm length with 10 micro-bunches, to excite 1 GeV/m <u>the mean train current</u> should be

$$\frac{1\cdot 10^{10}\cdot 3\cdot 10^{10}}{6\cdot 10^{18}} = 50\ \text{A}$$

The micro-bunch peak current shall be 10-15 times higher - still not too high!

The computer code was developed:

axial symmetry;

electron temperature - zero;

the hierarchy of characteristic time periods and lengths:

plasma oscillations - 0.15 mm,
(de)focusing length of beams - 10 cm to 10 m,
длина торможения возбуждающего пучка - 1 м - 100 м;

plasma electrons are considered hydrodynamically;

driver/witness beams are considered as ensembles of macro-particles.

Using estimations and computer code, we understood:

* Optimal radius for driver beam - close to

$$\lambda_{pl}/2\pi$$

(for bigger radius - "filamentation" instability, for smaller - strong field distortions lead to inefficiency)

* It is really possible to use up to 10 driver micro-bunches.

* The driver micro-bunches should be positioned non-equidistantly (closer for higher amplitudes), and the positioning should be rigid.

* The amplitude of transversal (de)focusing forces in the excited channel is much stronger than any external focusing.

Hence, we need to take care to place all the particles at correct phases - decelerating for driver, accelerating for witness - and with plasma focusing - simultaneously!!

* External focusing is necessary to direct and focus the leading driver microbunch - the rest follow the leader and are focused by plasma field.

* At high gradients the "coherent monopole instability" (the growing over-focusing) is essential.
To cure it, we need to match <u>local</u> emittance and <u>local</u> plasma focusing - to keep driver beam radius continuously at optimum.

* Transverse coherent dipole stability is not analyzed yet.

The hope is:
the gradient of transverse oscillations frequencies along micro-bunches and the frequency difference between micro-bunches are so high (order of 100%) - the coherent stability is guaranteed.

Higher transversal modes are even more stable.

*Of course, longitudinal coherent stability is of no problem at all.

*Energy losses for ultra-narrow intense witness micro-bunch could not be calculated in hydrodynamical approximation;
but it was shown, at parameters of interest these additional losses are less than 100 MeV - not disastrous!

*The correct use of extremely strong plasma focusing (maximum of transversal force corresponds to 1/3 of accelerating field and gives gradient up to 700 kGs/cm!) in spite of multiple scattering on plasma particles, keeps the final transversal emittance of witness small enough even for linear collider application.

* Pre-arranged ("fully" ionized) plasma density should be very homogeneous along the accelerator - to prevent dangerous phase shifts of plasma oscillations at witness position.

Some "technical" findings:

* "Transversal" density modulator to prepare the properly positioned driver micro-bunches: the use of extremely small emittance of "good" high energy beams.

* The same device gives possibility to excite the proper local emittance for every slice of the driver beam - by placing of appropriate scattering matter at the modulator slots.

* The "pre-microbunching" by "inverse FEL" device gives possibility to make the efficiency of the "incoming driver bunch - to - driver train" transformation several times higher.

The other attractive option to reach the same goal is to use the appropriate time structure for the laser gun.

{But the use of transversal modulator for the final positioning, shaping and local emittance excitation of driver micro-bunches seems inevitable!}

* It is possible (with the use of helical delay-lines) to arrange acceleration of the same witness by sequence of bunches of the single driver accelerator.

Consequently, the final energy of the witness can be many (hundreds) times higher than the driver accelerator energy.

$$\rho_{helix} = 2 \cdot \frac{E_{acc}}{H_{bend}} \cdot \delta L$$

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For 10 GeV, 10 cm driver:

$$2 \cdot \frac{3 \cdot 10^4}{1.5 \cdot 10^4} \cdot 0.1 = 0.4 \quad m$$

Transversal forces.

A very important problem is related to the transversal forces acting on driver and accelerated beam particles in the excited plasma channel.

These (de)focusing forces are strongly dependent on the phase of plasma oscillations; they are minimal ("almost zero") at maximums of accelerating (decelerating) fields and grow at channel radius up to fraction (around one third) of longitudinal force maximum.

And, of course, its action is higher if the beam energy is lower.

This problem makes life a lot more difficult and, in particular, pushes to **higher driver beam energy.**

The maximum of radial force, acting on driver or accelerating beam particles (the sum of eE_{rad} and eB_{az}) is proportional to the electric longitudinal field - accelerating or decelerating. In linear regime of plasma oscillation, this effective transversal field is about 1/3 of the longitudinal field maximum. The rise radius is about $\lambda/2\pi$ (excited plasma channel assumed to be minimal!).

So, the equation for transversal single particle motion will be:

$$\frac{d^2}{ds^2}r+\frac{2\pi}{3}\cdot\frac{gradE_{eV}\kappa}{E_{eV}\lambda}r=0 \quad ,$$

where s is the longitudinal coordinate, and κ is the fraction of transversal force maximum at the current phase.

If the coefficient is negative (defocusing), the accelerating field about 1 GeV/m leads to incurable defocusing and, hence, to the loss of particles at this phases - no matter how strong, albeit realizable, is the external focusing system.

If this coefficient is positive, effective "plasma beta-function" will be

$$\beta_{pl}=\sqrt{\frac{3}{2\pi}\cdot\frac{E_{eV}\cdot\lambda}{gradE_{eV}\cdot\kappa}} \quad .$$

To direct the drive beam properly, we need appropriate external focusing - by quadrupoles (the drive beam energy is high!).

So, drive micro-bunches - #2 (and even the tail of the first one!) and the following - as well, as witness bunch, travel under combined action of the homogeneous (for given slice) focusing of plasma oscillations and alternating focusing of quadrupoles.

Hence, we need to take care on stability of incoherent transversal oscillations of all the useful particles of very different energy and at very different plasma focusing - in a time!

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The phase structure of accelerating and transversal forces is quite complicated.

At the initial, linear stage, their maximums are shifted almost at $\pi/2$.

At the developed stage, which is of the main interest, this shift is going down and it is necessary to play with driver and witness bunches phasing and lengths - and even with their angular spreads! - very carefully.

Proper matching of emittances (in size and shape) in every slice of driver and witness - is the must.

<u>"Transversal" micro-bunching.</u>

To find the way to introduce a proper micro-bunch structure in the bunches of driver beam (and, also, to prepare a proper witness micro-bunch to be accelerated) is one of the crucial elements of the whole approach.

The problem looks non-trivial, because we need 0.1 mm range length of each "very high" energy micro-bunch and its positioning should take into account plasma frequency variation (non-linear regime!), hence - micro-bunches should be non-equidistant.

This positioning should prevent parts of driver micro-bunches from entering the accelerating phases, what would "eat" the plasma oscillations energy instead of to pump it in, and the plasma defocusing phases.

The way we proposed to solve this problem is: to use <u>very low emittance</u> beams

and "transversal cutting".

The general layout looks as following.

At some part of the (future driver) beam channel with high beta value, say, in vertical direction, we arrange local RF structure acting on the traveling bunch with the vertical force linearly depending on the position along the bunch (zero action at the bunch center).

The resulting transversal vertical momentum should be much higher than due-to-emittance internal momenta in the bunch.

Upon passing long enough free space, the different head-to-tail constituents of each bunch will be positioned differently in vertical direction.

At this stage, a target-cutter is placed, the slots in which are transparent but the other parts of the target destroy beam components completely.

At the same place a vertically focusing lens is placed (focal length is 2 times smaller than RF section-to-target distance).

At the same distance after the target the same RF structure is located, which compensates the vertical momenta of bunch components.

Hence, at the exit of this section, each driver beam bunch will be transformed in a series of micro-bunches - properly (longitudinally) shaped and properly positioned!

Placing appropriate thin foils in the slots, we can give each micro-bunch a proper angular spread (and even proper dependence of this spread on slice position along the micro-bunch) - in correspondence to the future local plasma focusing (local beta-value).