Presented at AAC Workshop, Stony Brook, NY June 21-26 CBN 04-6

Physical Foundations for Acceleration by Traveling Laser Focus[1]

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Abstract. In this method called Traveling Laser Focus (TLF), multi-cell microstructures scaled down to the laser wavelength-size. Each cell in these structures has an opening from the side. Special Electro-Optical device controllably sweeps focused laser spot along these openings in accordance with instant position of accelerated micro-bunch inside the structure. This arrangement reduces the illuminating time for every point on the structure's surface and power required from the laser. Physical limitations considered for mostly important components of the TLF scheme.

INTRODUCTION

The way of acceleration we are defending for many years based on scaling down dimensions of accelerating structure so, that it becomes resonant with electromagnetic (EM) radiation having micrometer wavelength. Fabrication of such tiny structures is possible due to nano-technology, which demonstrates remarkable achievements. One can see this visiting web-site of any Nano-Factory (Cornell Nano-Scale Science & Technology Facility, CNF, for example, http://www.cnf.cornell.edu/). So accelerating structure made with this technology can work with a Laser source of EM Radiation.

Of cause our method is not as trivial as just scaling down the structure. Some tricks are thought here. Namely, excitation of the structure is going locally from the side, *following the bunch* during its way inside the structure. By this arrangement the surface of the structure becomes illuminated locally for extremely short time. This time comes to be even shorter, than the time between electron-electron collisions in material of structure. High gradient required not only by desire to make accelerator more compact but also by necessity to keep the ratio of wakes to acceleration field at reasonable level. Acceleration rate required brings the laser power close to destruction limit for the structure. So the proper arrangement of excitation of accelerating structure becomes *first* crucial moment of all acceleration strategy. *Second* crucial moment is a necessity to prepare and keep tiny emittance required for free pass through structure having dimensions comparable with laser wavelength. Emittance required comes to be $\gamma\varepsilon \leq 6\pi \cdot 10^{-8}\, cm \cdot rad$. IP phenomenon is *third* moment here. Physical limitations could manifest itself in sweeping device, material damage, in preparation and keeping tiny emittance and at IP. In this paper we considered some of these limitations. Let us remind on TLF first.

THE TLF METHOD

In Traveling Laser Focus method, laser radiation focused onto a spot covering the side openings in accelerating structure. Excitation of each cell of the structure is going from this side opening. This laser spot is *swept* in longitudinal direction so it is running

[1] Electronic version available at http://www.lns.cornell.edu/public/CBN/2004/CBN04-6/phys_found.pdf

synchronously with the bunch inside the accelerating structure [1]. Special Electro-optical device does this sweep. As the motion of the focused laser spot along the structure is going with the speed of particle, this yields the picture, shown in Fig.1. Evidently, $\tan\alpha = c/v$ where c is the speed of light, and v is the speed of the bunch. For electrons or positrons $\alpha \cong \pi/4$. Radiation applied to every point of structure during $\tau \sim l_t/c$, where l_t is the instant height of the sloped laser bunch, Fig. 1. Electric field in each point of the laser bunch is perpendicular to the line, connecting this point with the center of the sweeping device. The number of cells excited simultaneously is $\sim l_f/\lambda_{ac}$, l_f is a spot size, Fig.1. The focal point is following the beam *in average*. Some mismatches allowable, as the *phase* of the laser radiation is synchronized once with the particle's bunch motion. Due to this arrangement, all laser pulsed power acts for generation of accelerating field at the instant particle's location only. Power reduction and shortening of illuminating time is equal numerically to the *number of resolved spots* (*pixels*), associated with the sweeping device. Let us consider what limitations might occur here.

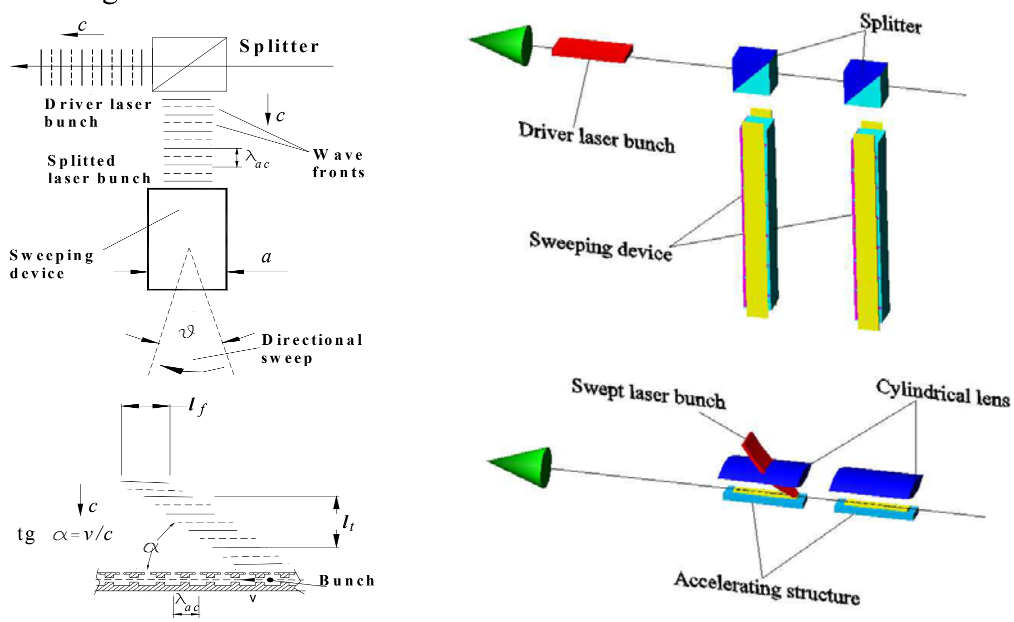

FIGURE 1. The concept of illumination by TLF, left. Beam has a speed $\vec{v} \sim c$ to the left. At the right – two sections are shown. Cylindrical lens serves for transverse focusing of the laser bunch.

Sweeping device could be characterized by deflection angle ϑ and by the angle of natural diffraction $-\vartheta_d \cong \lambda/a$, where a –is aperture of the sweeping device (Fig.1). *The ratio of deflection angle to diffraction angle is fundamental measure of the quality for any deflecting device.* This ratio defines the *number of resolved spots (pixels)* placed along the structure, $N_R = \vartheta/\vartheta_d$. The last number is an invariant under optical transformations. *Electro-optical* sweeping device uses dependence of refractive index on electrical field strength applied to some crystals. When electric field applied to such crystal, refractive index n changes its value. For a prism-based device, Fig.2, this yields the change in deflection angle. To arrange such a change, the basements of the prism covered by metallic foils and high voltage applied to them.

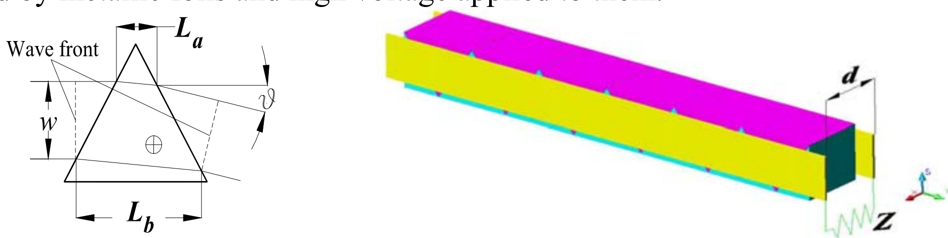

FIGURE 2. The prism deflection device concept, left. Cross marks direction of optical axis. At the right-prisms with *oppositely directed optical axes* installed in series between two parallel strip–line electrodes, Electromagnetic pulse $E_x(t-y/c)$ propagates with laser bunch to the right.

When $E(t)$ applied to the crystal, the refractive index changes $\Delta n = \Delta n(E(t))$, so

$$\Delta\vartheta \cong \Delta n \cdot (L_a - L_b)/w\,. \qquad (2)$$

where w –is the width of incident laser beam, L_a and L_b –are the distances from Fig.2. So the number N_R becomes

$$N_R \cong \Delta\vartheta/(\lambda/a) = \Delta n \cdot (L_a - L_b)\cdot a/(\lambda \times w) \cong \Delta n \cdot l/\lambda\,, \qquad (3)$$

where $l = L_a - L_b$ and $a/w = 1$ in our case. To increase the numbers ($N_R, \Delta\vartheta$), *multiple-prism* deflectors were developed. We recognized that for angular sweep of short laser bunch, electric field must be applied as a *traveling wave slop* [2]. Multi-prism deflector, Fig.2 right, has oppositely oriented optical axes in neighboring prismatic crystals. In this case *full length* of deflecting device serves as *l.* For *l*=50*cm*, $w \cong 1cm$, one can expect that deflection angle can be $\Delta\vartheta \cong 10^{-2}$ and $N_R \cong 100$ for $\lambda \cong 1\mu m$. For $\lambda \cong 10\,\mu m$ $N_R \cong 10$, angle is the same. So these numbers satisfy TLF method and there are no physical limitations here.

ACCELERATING STRUCTURE

Accelerating structure serves for *confinement* of EM field in space. Its precise location defined by accuracy of fabrication, accuracy of positioning, how far from equilibrium the fields are and by physical limitations. Each part of the structure is illuminated by duration, which is defined by longitudinal size l_t , Fig.1. For example, if $l_t \cong 100\,\lambda$, $\lambda = 1\mu m$, then $l_t/c \cong 3\cdot 10^{-13}$*sec*. This time is less than the time between electron-electron collisions $\tau \approx l_{free}/v_F \cong 10^{-12}$ *sec*, where l_{free} is the free path length, v_F is the electron velocity at Fermi-surface. The time of illumination still longer, however, than the reaction time of electron plasma in metal: $\tau \cong 2\pi/\sqrt{4\pi n_e r_0 c^2} \approx 3\cdot 10^{-16}$ *sec*, where n_e is the electron density in a metal. The tunneling probability brings a limit to the surface field as high as $E \approx 4\pi\varepsilon_0 U_F^2/e$ [2]. For Fermi-energy $U_F \approx 5V$ this gives $E \approx 17 GeV/m$. Dielectric coating helps to increase the field strength $\sim \varepsilon$.

The latest measurements show that the damage threshold increases while the illumination time is shortening. This was explained by saturation of impact ionization rate per unit distance. *Measured* threshold for 0.3 *ps* pulse was about 10 J/cm^2. For 1 *ps* the threshold measured was 6 J/cm^2. In Figs 4, 5, covers adjust the coupling between the cell and outer space. The last defines a quality factor Q_{RF} of the structure. With these covers the height h is about $h \cong \lambda_W / 2$ and the cells have *inductive* coupling with outer space. Table below summarizes results on the power density. One can see that sweeping drastically reduces the power density on the surface.

Wavelength	Energy/length	Gradient	Power density	Time of Illumination
$\lambda \cong 1\mu\ m$	3 *mJ/cm*	30 *GeV/m*	30 J/cm^2	0.1*ps*
$\lambda \cong 10\mu\ m$	3 *mJ/cm*	3 *GeV/m*	3 J/cm^2	0.3*ps*

Calculations carried with **GdfidL**. Example of a structure with round passing holes and smoothed passing holes are represented in Fig.5. The final shape is a trade between technology and optimal filling properties.

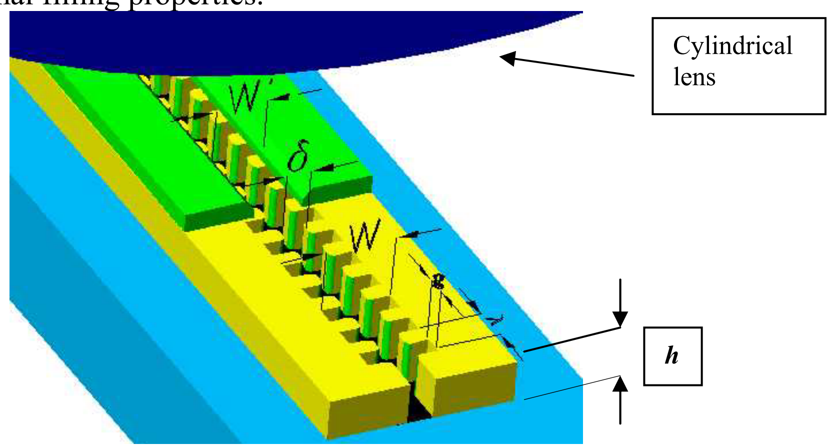

FIGURE 4. Accelerating structure. Height $h \cong \lambda_W / 2$, where λ_W –is a wavelength of laser radiation inside the cell. $g/\lambda \cong 1/2$, $W \cong 0.7\lambda$, $\delta \cong 0.2\lambda$. The masks used for trimming the coupling (Q_{RF}-factor). The beam is going at height ~h/2.

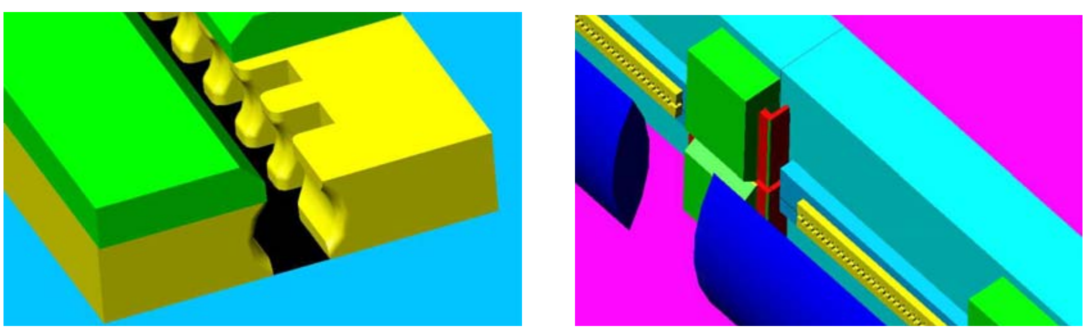

FIGURE 5. Structure with round passing holes, left, and the quadrupole design, right.

The wake is slightly inductive. The ratio of calculated wake drop $\approx 7kV/pC \times 0.16pC \cong 1.12kV$ to the energy gain per one cell~30 *kV*, (see lower) is about ~$1.12/30 \cong 3.7\%$. Nano-technological possibilities advanced far beyond the requirements associated with this structure, scaled down to $\lambda_{ac} \cong 1\mu m$. Each structure is installed on a nano-table moved by a piezoelectric. Structures are cooled down to keep the mechanical tolerances within the margins allowed. Monocrystall of Silicon with different types of conductivity is best here. The final conclusion could be made after experimental work in this field.

Angular alignment $\Delta\vartheta$ each individual structure must be within $(\Delta\vartheta)_y \leq 2\cdot10^{-5}$, and $\Delta\vartheta_x \leq 7\cdot10^{-4}$. *The focusing system* includes the quadrupole lenses of appropriate dimensions and a *RF focusing* [2]. The biggest size goes along the slit. Example of a quadrupole design is represented in Fig. 5, right. RF forces are quadrupole types for the particles out of the crest of RF. The effective focusing factor of the RF lens can be evaluated as

$$k_x = -\tfrac{1}{pc}\partial\langle F_x\rangle/\partial x \cong -e\lambda_{ac}E_m Sin\,\varphi/mc^2\gamma W^2\,, \qquad k_y \cong -e\lambda_{ac}E_m Sin\varphi/mc^2\gamma h^2\,. \qquad (4)$$

Substitute here $\lambda_{ac} = 10\mu m$, $\gamma = 2\cdot10^4$ (*pc*=10 *GeV*), $W \approx 5\mu m$ (see Fig.4), $E_m \approx 10^{10}V/m$, one obtains $k_x \approx 10^5\cdot Sin\varphi[m^{-2}]$. So manipulating by phase, focusing in both directions could be obtained here.

General conclusion is that there is a structure, acceptable for particle acceleration with wavelengths $\lambda_{ac} \cong 1-10\mu m$.

BEAM PARAMETERS AND IP PHENOMENA

For wiggler dominated cooler equilibrium emittance could be obtained as small as $(\gamma\varepsilon_x) \cong 2.5\cdot10^{-8}cm\cdot rad$, $(\gamma\varepsilon_y) \cong 9.5\cdot10^{-10}cm\cdot rad$, what satisfy requirements, mentioned in introduction [2]. If laser flash lasts τ *sec* and caries energy *Q Joules* then maximal field strength goes to

$$E_m \cong 2\sqrt{Q/(\varepsilon_0 c\tau\lambda g)}\times\sqrt{r/l_f}\ . \qquad (5)$$

This formula for *Q*=0.01*J*, $\tau \cong 0.1$ *ns*, $\lambda \cong 1\mu m$, $g \cong \lambda/2 = 0.5\mu m$s gives $E_m\cdot\sqrt{g/l_f} \approx 11.2GeV/m$. For $Q_{RF} \approx 9$ it could reach again ~33*GeV/m* in conservative estimation. So TLF method promises up to 30 *TeV/km* or 300 *TeV* on 10 *km* with 3 *kJ* per pulse total for the 10 *km*. Laser amplifier could be sectioned, [2]. So for 1 *km,* the total output power of the laser must be within 0.5 *MW* with repetition rate about 160 *Hz* for $\lambda_{ac} \cong 1\mu m$. *Nd-Glass* lasers can be used here. For pumping the driving lasers the *diode laser arrays* (efficiency ~30%) could be used for the wavelengths indicated. This brings efficiency of the laser up to 10% level.

Minimal number of particles required for obtaining desirable Luminosity can be estimated as a $N^2 \geq 4\pi\lambdabar_C^2 L/n\,f$, where $\lambdabar_C = \hbar/mc$, *f* is a repetition rate, *n* is a number of bunches per train. For $L \cong 10^{34}$, *f*=100Hz, *n*=10, $N \geq 4\cdot10^5$. We also mentioned in [2] that the lowered emittance with reduced number of particles could be obtained by scrapping all extra particles obtained from usual beam injectors. Considering the balance of energy, accepted from the field, one can obtain for *N* estimation

$$N \cong \eta/2eI(g)\sqrt{\varepsilon_0\lambda^3 Q/(c\tau g)}\,. \qquad (6)$$

$I(g)$ –an analog of the transit time factor, With $I(g)$= 0.5, $\eta \approx 0.05$ (i.e. only 5% of energy stored in one cell carried out by the bunch), this yields $N \cong 1\cdot10^6$ for

$\lambda_{ac} \cong 1\mu m$. For $\lambda_{ac} \cong 10\mu m$ this number will be $N \cong 3 \cdot 10^7$, what is much bigger, than minimal number.

Effect of synchrotron radiation in a quadrupole lens was considered first in [3]. In [4] there was considered focusing in plasma with adiabatically changing strength for reduction of final quad phenomena. We suggested an arrangement of the final focus as *a multiplet* of FODO structures. The number of (RF) lenses in such a multiplet $\approx 10^3$ [2]. We also called this *Adiabatic Final Focus*. The gradient in these RF lenses varies from very strong at the side closest to IP, to a weak one at opposite side. For 1 *TeV*, according to (4), k could be as big as 10^3 1/m^2. Focal distance F goes to be $F \cong 1/kg \cong 1/10^3 \cdot 5 \cdot 10^{-6} = 200$ [*Meters/cell*] (g-from Fig.4). So the lens with $\approx 10^3$ cells reaches the focal distance $F \approx 20$ *cm*.

Formula for *luminosity* $L = N^2 fH_B / 4\pi\sigma_x\sigma_y$, where f–is a repetition rate, $\sigma_{x,y}$ are the Gaussian widths for x and y directions respectively, H_B – is the enhancement parameter. N_B –is the number of bunches per train, gives for $\gamma\varepsilon_x \cong 2.5 \cdot 10^{-8} cm \cdot rad$, $\gamma\varepsilon_x \cong 9.5 \cdot 10^{-10} cm \cdot rad$ and for $\beta_x \approx \beta_y \approx 0.3\lambda_{ac}$, $\lambda_{ac} \cong 10\mu m$, $\gamma = 6 \cdot 10^6$ (pc=3*TeV*), $N \cong 10^7$, $f \cong 160 Hz$, H_B=1, N_B=*1* the value $L \approx 1.7 \cdot 10^{34} cm^{-2} s^{-1}$. For $\lambda_{ac} \cong 1\mu m$ result will be about the same. The transverse Gaussian size will be $\sigma_x \cong \sqrt{(\gamma\varepsilon_x)\beta_x^* / \pi\gamma} \cong 1.1 \cdot 10^{-9} cm$ and $\sigma_y \cong 2.2 \cdot 10^{-10} cm$. So the aspect ratio in this case is about $\sigma_x / \sigma_y \cong 5$, what looks reasonable. Operation with high repetition rate, up to *few kHz* is possible here.

Radiation can be characterized by Y_0 parameter, $Y_0 \equiv 2\hbar\omega_c / 3E = \gamma H / H_c$, where H is the magnetic field, $H_c = m^2c^3 / e\hbar \cong 4.4 \cdot 10^{13}\, G$, ω_c is critical frequency of classical synchrotron radiation. For E~1TeV, this parameter goes to be ~10^3. *There is one peculiarity, however.* Formation length for the boundary particles goes to $l_F \cong \lambda\!\!\!^{-}_C \gamma / (Y_0^{2/3}\sigma_b)$. Critical frequency of radiated photons goes to $\omega_c \cong mc^2\gamma / Y_0\hbar$, and corresponding wavelength is $\lambda\!\!\!^{-}_{cr} \cong c / \omega_c = cY_0\hbar / mc^2\gamma$. So the transverse size of coherence goes to $\sigma_\perp^{coh} \cong \sqrt{\lambda\!\!\!^{-}_{cr} l_F \sigma_b} \cong Y_0^{1/6} \lambda\!\!\!^{-}_C \sim 3\lambda\!\!\!^{-}_C \cong 1.15 \cdot 10^{-10} cm$. So the radiation from the incoming bunch formally *could not* be described as a dipole radiation of a single particle in coherent field of oncoming bunch. In this case the particles on opposite vertical sides of the bunch have opposite accelerations. This yield opposite polarizations of electromagnetic fields, radiated by these oppositely located particles. In it's turn this yields a destructive interference of radiation in forward direction. So the resulting radiation looks like a quadrupole one. This type of radiation has zero intensity in forward direction. For peripheral coordinate the size $\sigma_\perp \equiv \sigma_{x,y} / \sqrt{N}$, where N –is a bunch population, needs to be taken for estimations of magnetic field strength. So the radiation is strongly suppressed here $\sim 1/N$. This is a peculiarity of a laser driven accelerator [2].

General parameters of Linear Laser Collider (LLC) complex with TLF are represented in Table below. The laser and particle's bunch run first apart from the IP.

On this way all parameters (laser, electron/positron) picked up, processed with appropriate algorithms locally and applied to correcting elements on the back way to IP. One can imagine that LLC has *two stages* with two wavelengths. Small crossing angle required for preventing illumination of the final lenses by used beam. Repetition rate up to few *kHz*, allows easy manipulation with the beams. Interaction of beams at IP is going in deep quantum regime. The beams of electrons and positrons can be *polarized* what gives the effective gain in luminosity and reduces the background. Neighboring platforms aligned with help of sensors, installed at the end of each platform. The sensors are similar to that used in tunneling microscope technique.

Parameter	$\lambda_{ac} \cong 10\mu m$	$\lambda_{ac} \cong 1\mu m$
Energy of $e^{\pm}$ beam	3×3 *TeV*	30×30 *TeV*
Total two-linac length	2×1 *km*	2×1 *km*
Main linac gradient	3 *GeV/m*	30 *GeV/m*
Luminosity/bunch	$10^{34} cm^{-2} s^{-1}$	$10^{34} cm^{2} s^{-1}$
No. of bunches/pulse	10 (≤ 100 max)	30 (≤ 300 max)
Laser flash energy/Linac	300*J*	300*J*
Repetition rate	160 *Hz*	160 *Hz*
Beam power/Linac	2.3 *kW*	760*W*
Bunch population	10^7	10^6
Bunch length	$1\mu m$	$0.1\mu m$
$\gamma\,\varepsilon_x \,/\, \gamma\,\varepsilon_y$	$\approx 10^{-8}/10^{-9} cm\cdot rad$	$5\cdot 10^{-9}/1\cdot 10^{-10} cm\cdot rad$
Damping ring energy	2 *GeV*	2 *GeV*
Length of section/Module	3*cm*	3*cm*
Wall plug power**	2×0.5 *MW*	2×0.5 *MW*

** Without supplementary electronics.

CONCLUSION

Nano–technology available creates solid base for accelerator with *Travelling Laser Focus*. Illuminating time and total laser power reduction in this method defined by the number of resolved spots (pixels) associated with deflecting device. Lasers for the TLF method need to operate with $\tau \approx 100 ps$ pulse duration. Any point on accelerating structure remains illuminated by ~0.3 *ps* only. TLF method promises up to 30 *TeV/km* with 0.3 *J/m*. With such high gradients, $\mu^+\mu^-$, $\pi^+\pi^-$, $\pi p, \mu p$ and ion-ion collisions become feasible. We conclude that acceleration in a laser-driven linac with TLF method is a present day technology and no physical limitation found on this way.

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