CBN 10-7

FUNDAMENTAL LIMITATIONS IN ADVANCED LC SCHEMES

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ABSTRACT

Fundamental limitations in acceleration gradient, emittance, alignment and polarization in acceleration schemes considered in application for novel schemes of acceleration, including laser-plasma and structure - based schemes. Problems for each method underlined whenever it was possible.

Main attention paid to scheme with tilted laser bunch (1989).

Reminder:

This method uses multi-cell microstructures.

Each cell of microstructure has an opening from one side.

Focused laser radiation excites the cells by special sweeping device through these openings locally, in accordance with instant position of accelerated micro-bunch of particles in the structure.

So the laser density ~0.3 J/cm^2 accelerating rate ~10Gev/m.

Illumination time for every point is <0.3ps while the time duration of laser pulse is ~0.1 nsec.

2 x 1 TeV collider will require a laser flash 2x0.3 J total. Luminosity could reach 10^{35} with wall-plug power of few tens of kW only.

Cost of such installation could be as low as 100M$ (plus the cost of detector).

Quest for high energy

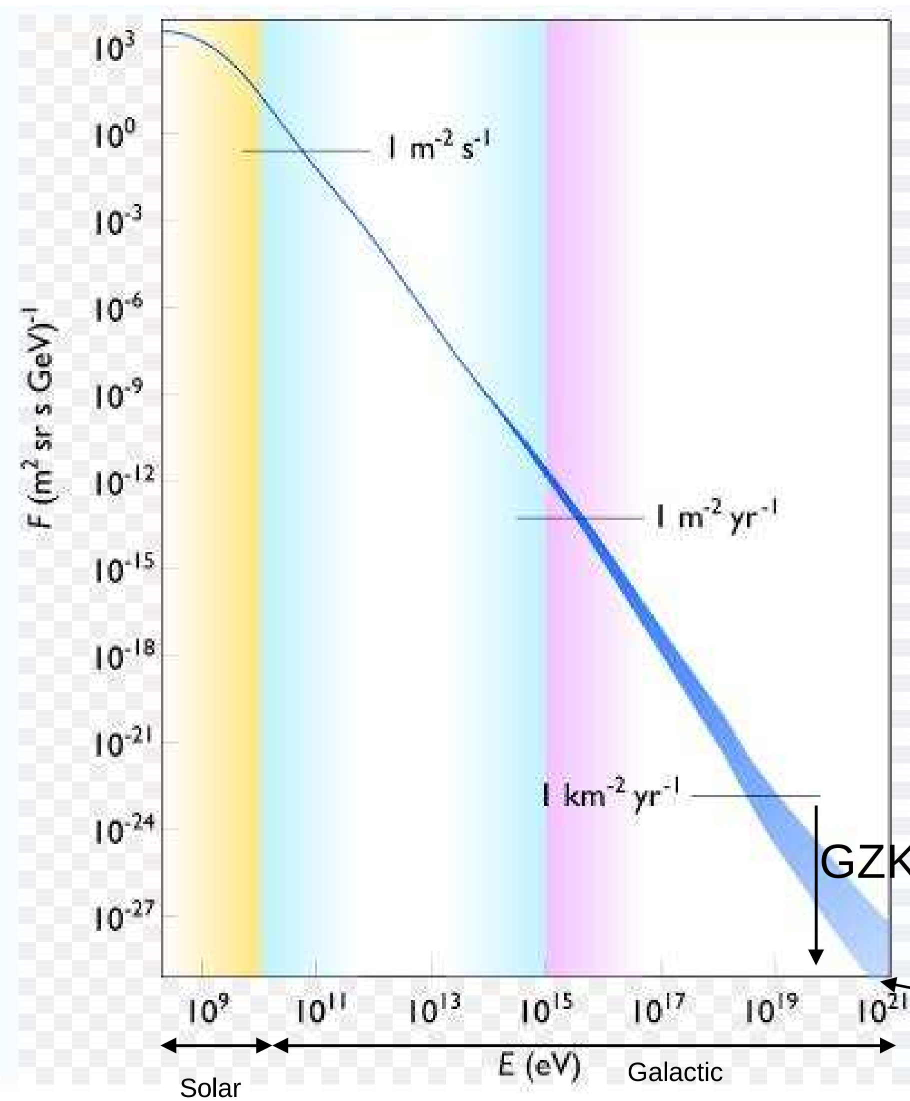
Presence of particles with energy >1000 TeV in cosmic showers, tells us that these high energy particles were somehow involved in process of formation of our Universe.

This inspires the quest for high energy achieved in accelerators

How big is "High energy"

Spectrum flux of Cosmic radiation

From Wikipedia



Radiation is pretty isotropic Energy density ~0.6eV/cm^3

Greisen-Zatsepin-Kuz'min predicted in 1966 that cosmic rays with energies *over* 5×10^{10} GeV would interact with cosmic microwave background photons producing pions via Δ resonance . This process continues until the cosmic ray energy falls below the pion production threshold (GZK limit) . With known density of cosmic background radiation the characteristic length of interaction runs to be ~ 163 Mly and particles with energies greater than this threshold should never be observed on Earth. Meanwhile some groups report about registration of particles with energy higher, than this limit.

GZK limit

Microwave photons

$$p + \gamma \rightarrow \Delta \rightarrow p + \pi$$

Single particle carries 1kJ

Approach to understand…

H.Volek, P.Biermann, “ *Maximum energy of Cosmic –ray particles Accelerated by Supernova remnant Shocks in Stellar Wind Cavities*”, Astrophysical Journal, Part 2-Letters, vol.333, Oct 15, 1988,p.L65-L68

Authors suggest that supernova shock freely expanding into stellar wind cavity may produce particles up to 10^{19} eV of a supernova explosion in a compact star.

Our conclusion: approaches like this are problematic – no radiation included in theirs consideration, even for such huge energy - 10^{19} eV

The way to model such process in Lab –
Create appropriate accelerators

Livingstone diagram

Fixed target : $E_{cm} \approx c(Em)^{1/2}$

Collider : $E_{cm} \approx 2E$

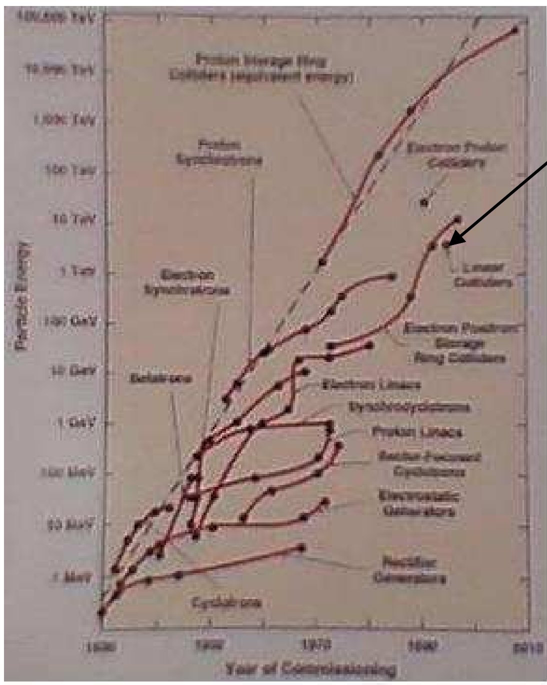
1TeV cm e^+e^- collider will be equivalent $1TeV x 2 \cdot 10^6 \approx 2 \cdot 10^{18}$

Our goal

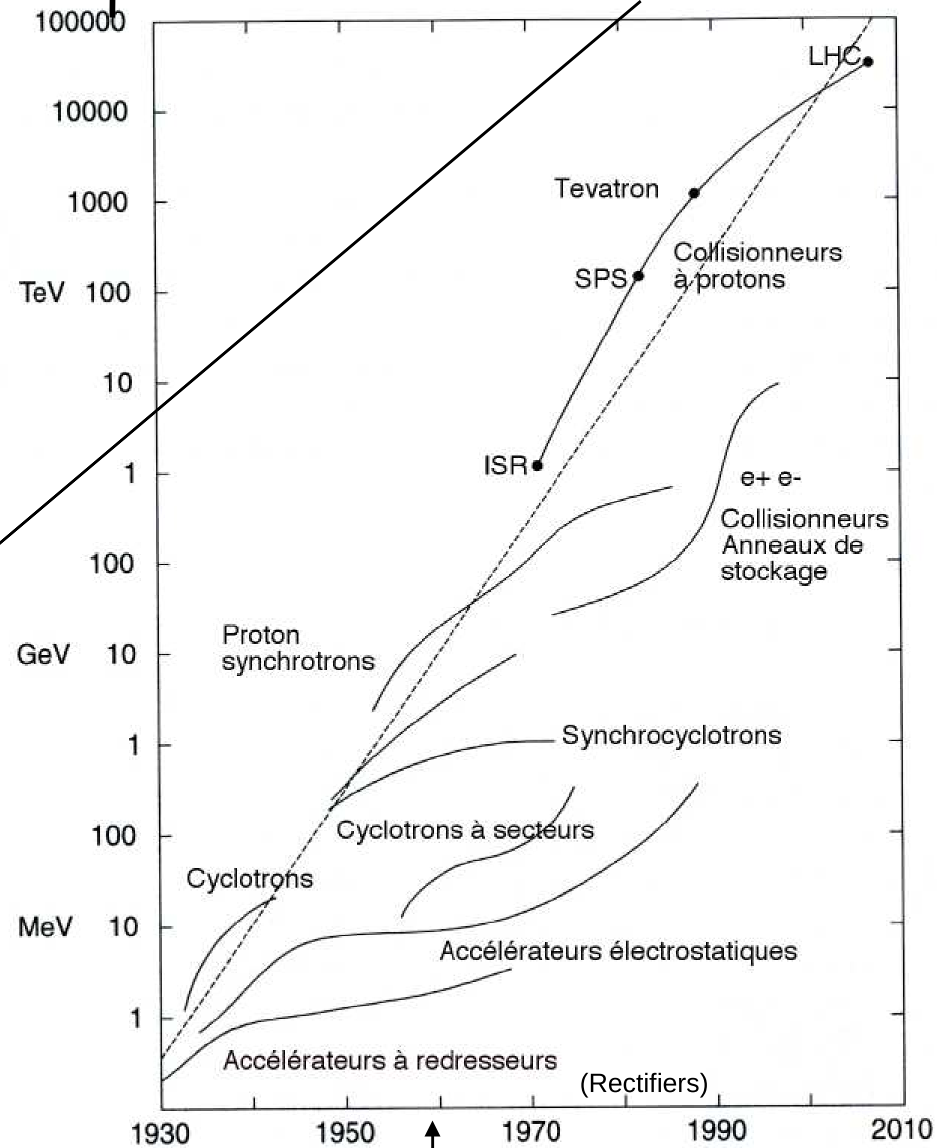
ILC

GZK limit.

Point must be here



From A.Chao, W.Chou poster



First published in 1954

Scheme for acceleration of charged particles should be realized with technologies available on the market today.

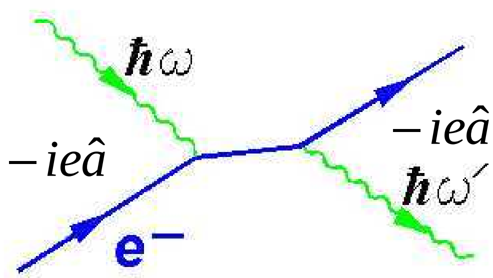
As a rule, technology is much ahead of its request. There is no restriction on this matter, I mentioned that phonograph could be fabricated at ancient times with technology available at that times.

Schemes with **laser** as a souse of radiation are interesting for us.

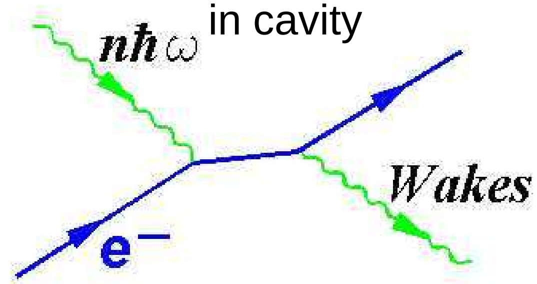
No intermediate *media* between laser radiation and particle (so we excluding all plasma methods from candidates)

But some **agent** between laser and particle required by fundamental physics…

Interaction between EM wave and particle is a two photon process



Coherent photons stored in cavity



(spontaneous radiation)

Particle acquires *many* RF photons during the acceleration process.

This second photon is crucial in all business.

Presence of this (radiated) photon allows, for example, particle acceleration by the plane wave; the process is going while particle re-radiates.

Energy balance in classical language

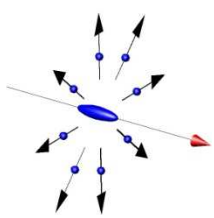
$$(E_{sp}+E_0)^2 = \sum(E_{sp,i}+E_0)^2 \rightarrow E_{sp,i}{}^2+2E_{sp,i}E_0+E_0{}^2$$

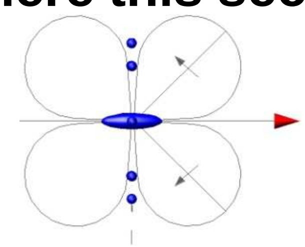
Change of angular momentum defined by

Angle of deflection

$$\Delta L = \frac{1}{c^2}\int \vec{r}\times((\vec{E}_0+\vec{E}_{sp})\times(\vec{H}_0+\vec{H}_{sp}))dV - \frac{1}{c^2}\int \vec{r}\times(\vec{E}_0\times\vec{H}_0)dV = mc\gamma\vartheta$$

It is not shown where this second photon hidden in plasma methods.





So, the structure serves for delivery of second photon(s) in Feynman's diagram – ***spontaneous radiation*** (wakes).

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.
So the structure can not be much larger, than the wavelength of laser radiation, otherwise the fluctuations in a process of the field establishment will generate long living (in terms of period) perturbations with undesirable spatial structure.
(That is why so called photonic structures are useless for particle acceleration in short RF pulses)
One good property of small structure is that it can not accommodate thermal photons, especially if the structure is cooled down–this positive property of compact structure goes in its advantage (analog of GKZ effect with thermal photons).

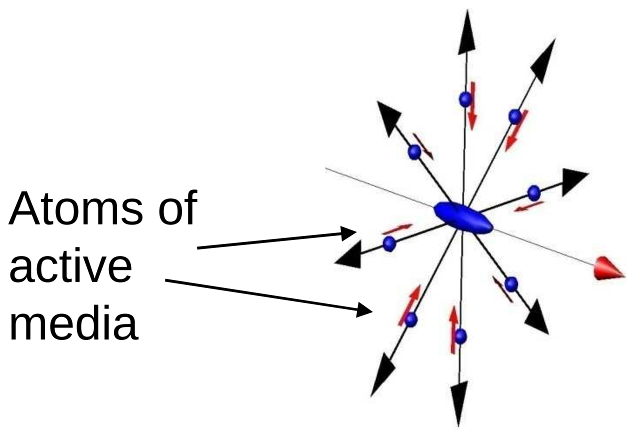
So fundamental requirements for energy change are:
Cross interference of accelerating and spontaneous (wake) fields.
Spatial orientation of accelerating field must be directed ***along*** particle’s trajectory.

One example: *PASER*

PASER is a system which uses an active (in a sense of Laser activity) medium. Active media, (CO_2 gas at ~0.25 *atm*), excited by discharge of electrical pulse, so the atoms of this media transferred to excited state. When the electron beam is passing through, its electric field triggering transition of excited atoms into ground state, while radiated photon absorbed by electrons.

Electric field of relativistic bunch is *transversely* polarized, however. So induced radiation will "pump" transverse field, which increases the transverse momentum, not the longitudinal one. At any moment resulting force due to induced radiation defined by averaging of momentum transferred to the field by many atoms. **So this system is not able to accelerate relativistic beam**.

In original experiments done by Leypunksy and Latyshev, the electrons were nonrelativistic, so the active media could increase the *temperature* of electron beam. In some sense this is acceleration, but not in a sense required for high energy physics application.



Induced radiation "pumps" transverse momentum

Positioning of center of accelerating field

Electrons are running in thin layer which wraps the surface of cavity (skin layer)

Accuracy due to electron plasma in a metal is ~ r_D/λ , where Debye radius r_D defined as

$$r_D = \frac{v_p}{\omega_p} \cong \frac{\sqrt{k_B T/m}}{\omega_p} = \sqrt{\frac{k_B T}{4\pi n e^2}}$$

$k_B \cong 1.38 \cdot 10^{-23}$ J/°K –is Boltzmann's constant, T –is electron temperature, n –is an electron density in a metal,

r_0 –is a classical electron radius.

As $\omega_p \cong 10^{16} 1/s$ $v_p \cong 10^8 cm/s$ $r_D \cong 10^{-8} cm$ ← No problem for cm-wavelength RF

and the ratio for 1 μm wavelength comes to $r_D/\lambda \cong 10^{-4}$ ← also OK

In diluted plasma with electron density ~10^{-6} of density in metal, the last ratio becomes

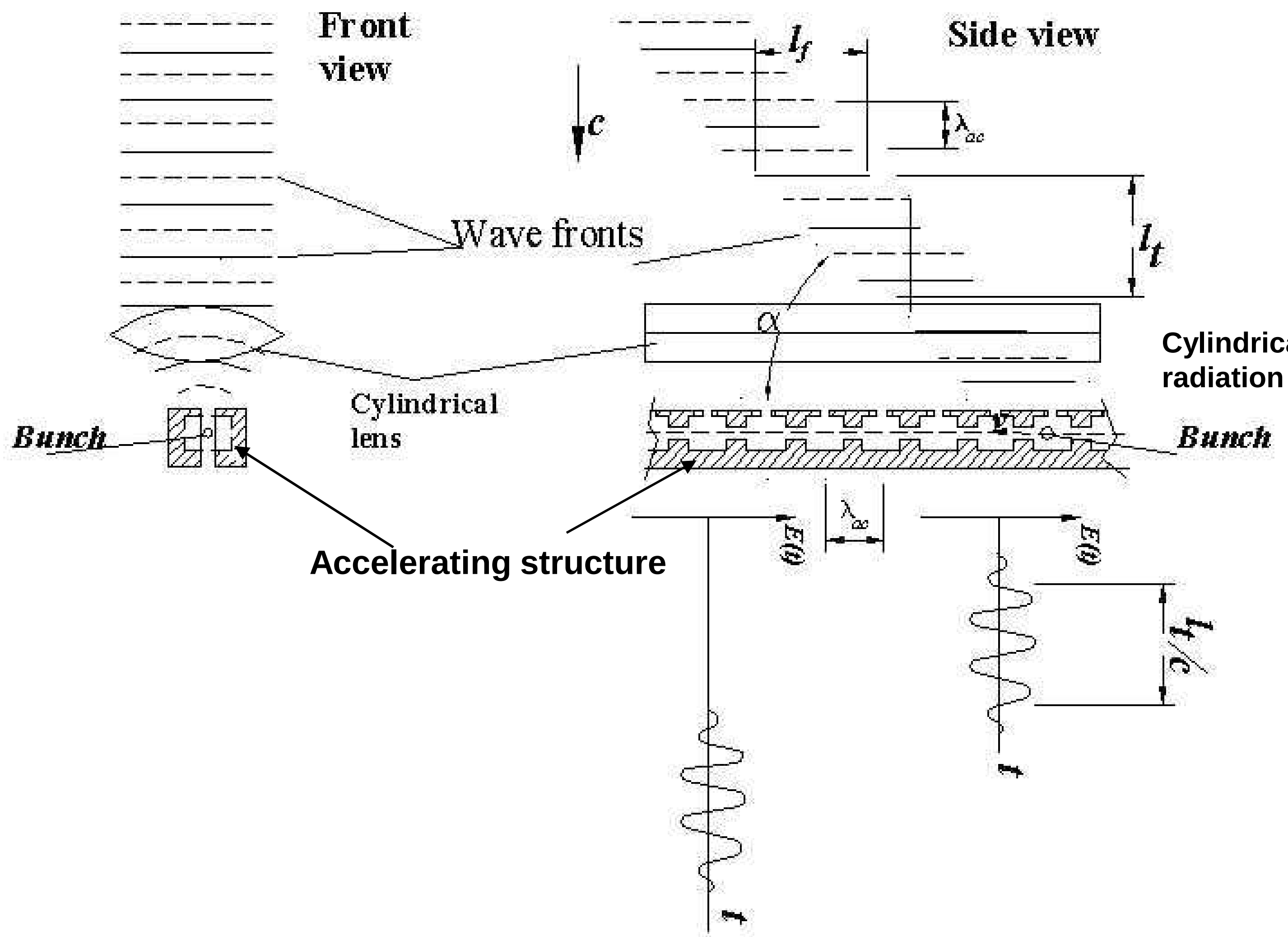
$r_D/\lambda \cong 10^{-1}$, only.

In general, the plasma methods must experience problems with fluctuations of the number of electrons in Debye sphere.

This makes stable acceleration in plasma problematic.

What is emittance of beam *at exit* in plasma methods?

TRAWELING LASER FOCUS (TLF,1989)



Cylindrical lens focuses laser radiation in transverse direction.

This method eliminates restrictions associated with Raleigh length

$$Z_R = \pi\, w^2(0) / \lambda$$

Tilted (sloped) laser bunch can be prepared by two methods :

By sweeping

With grating

REALIZATION OF TRAVELING LASER FOCUS WITH SWEEPING DEVICE (1989)

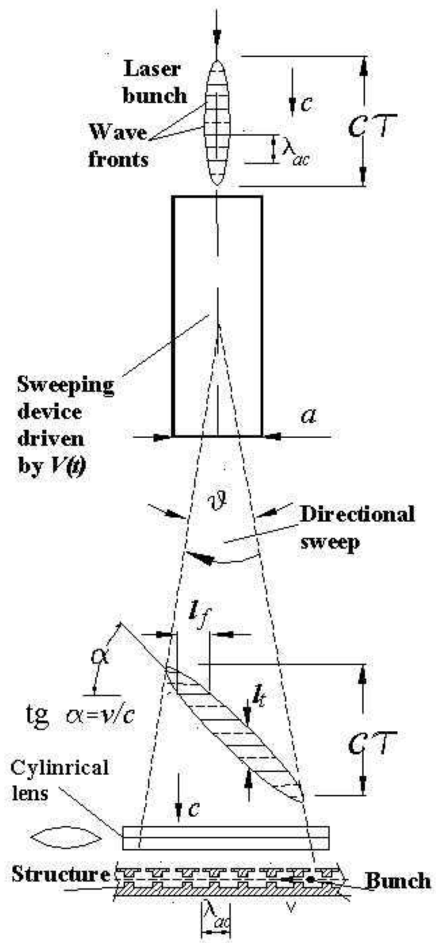
Laser radiation applied to every point of structure during $\tau = l_t \,/\, \lambda_{ac}$,

The number of accelerating cells excited simultaneously is ~ $l_f\,/c$

The focal point is following the beam *in average*.

Phase of the laser radiation is synchronized once with the particle's bunch motion.

Accelerating cells in a structure separated in longitudinal direction with distance λ_{ac}, so an electromagnetic field is in phase inside each cell.



СОЮЗ СОВЕТСКИХ СОЦИАЛИСТИЧЕСКИХ РЕСПУБЛИК
ГОСУДАРСТВЕННЫЙ КОМИТЕТ ПО ИЗОБРЕТЕНИЯМ И ОТКРЫТИЯМ
ПРИ ГОСУДАРСТВЕННОМ КОМИТЕТЕ СССР ПО НАУКЕ И ТЕХНИКЕ
(ГОСКОМИЗОБРЕТЕНИЙ)

АВТОРСКОЕ СВИДЕТЕЛЬСТВО

№ 1609423

На основании полномочий, предоставленных Правительством СССР, Госкомизобретений выдал настоящее авторское свидетельство на изобретение:

"Способ ускорения заряженных частиц"

Автор (авторы): Михайличенко Александр Алексеевич

Заявитель: он же

Заявка № 4704750 Приоритет изобретения 10 мая 1989г.

Зарегистрировано в Государственном реестре изобретений СССР

22 июля 1990г.

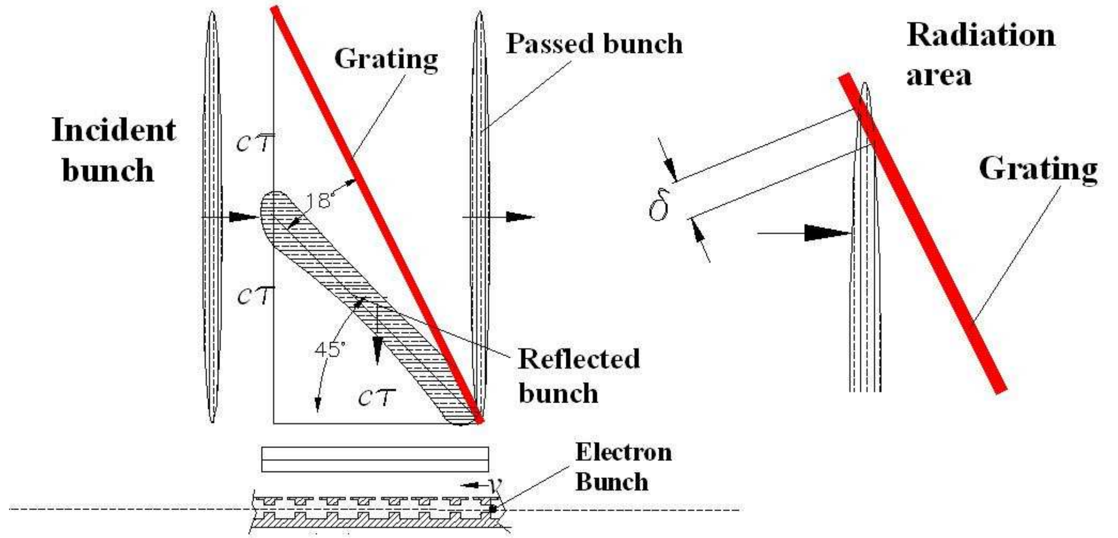
Действие авторского свидетельства распространяется на всю территорию Союза ССР.

Председатель Комитета

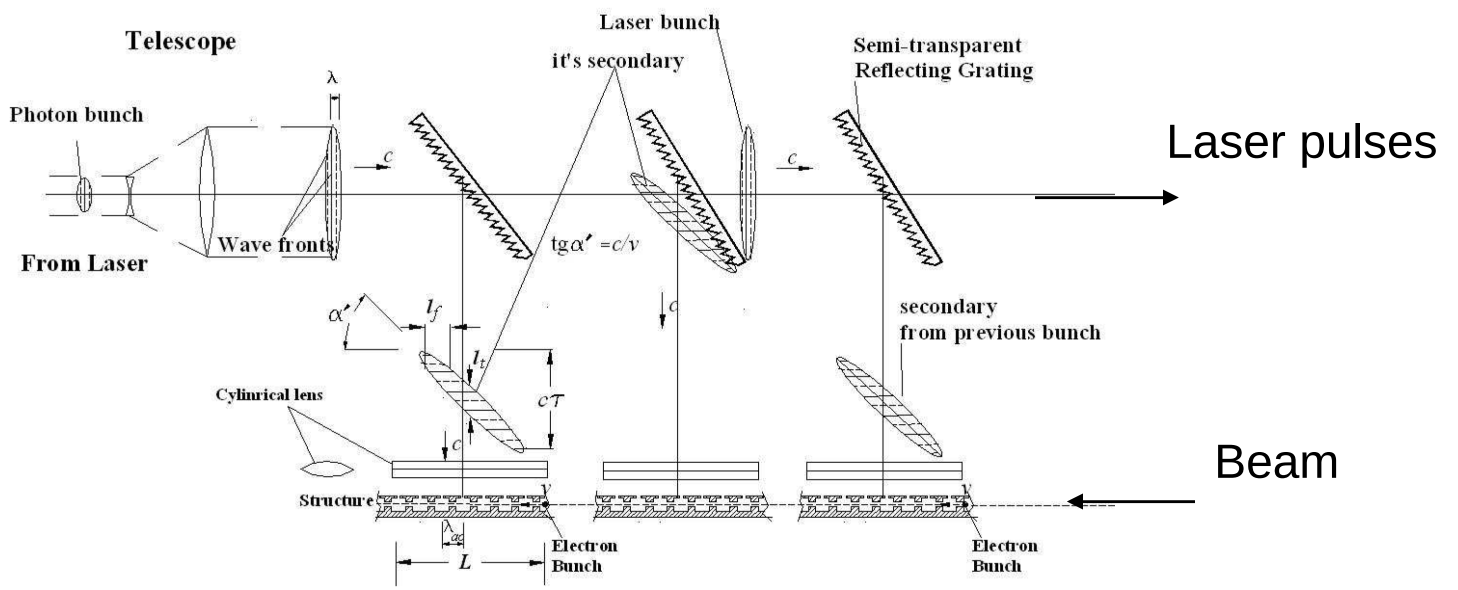
Начальник отдела

Illumination time τ=0.3ps . Laser density = 0.3 J/cm^2 for E=10GeV/m

REALIZATION OF TILTED LASER BUNCH WITH GRATING (1996)



B.Ya.Zel'dovich, N.D. Kudnikova, F.V.Podgornov, L.F.Rogacheva, Quantum Electronics **26**(12) 1097-1099 (1996).
I.V. Pogorelsky *et al.*, Advanced Accelerator Concepts Workshop, 12-18 October 1996, Granlibakken, Lake Tahoe, CA, AIP 398 Proceedings, p.930.



Possible set up with semi-transparent gratings

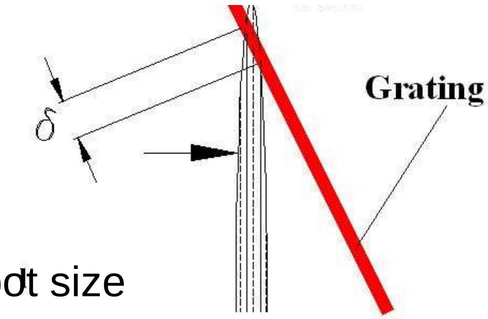
Comparison between sweeping and grating methods

Diffraction angle in case of grating $\vartheta_d^g \cong \sqrt{\lambda / \delta}$

Diffraction angle in case of sweeping $\vartheta_d^s \cong \lambda / a$

a stands for aperture of sweeping device

For comparison with sweeping device $\delta \approx l_f \cong l_t$ -spot size



For the sweeping device we have $l_t \cong L / N_R \cong a / N_R$ N_R - number of resolved spots

So for comparison of these two schemes, we represent the diffraction angle as

$$\vartheta_d^g \cong \sqrt{\lambda N_R / a}$$

The ratio of diffraction angles in these two methods goes to be

$$\vartheta_d^g / \vartheta_d^s \cong \sqrt{\lambda_{ac} N_R / a} / (\lambda_{ac} / a) \cong \sqrt{N_R a / \lambda_{ac}}$$

With some optimization of grating profile this could be improved, probably, to

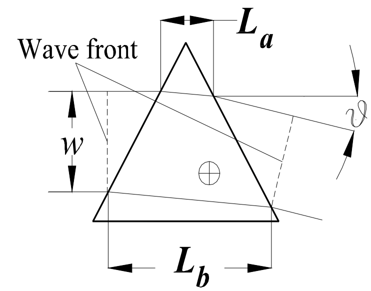
$$\vartheta_d^g / \vartheta_d^s \cong N_R$$

at the best. So the advantage of using the sweeping device is obvious-it gives much smaller laser spot size in longitudinal direction.

The difference is ~100 times minimum in favor of **sweeping** device.

So the sweeping method is preferred one

SWEEPING DEVICE WITH ELECRO-OPTICAL PRISMS

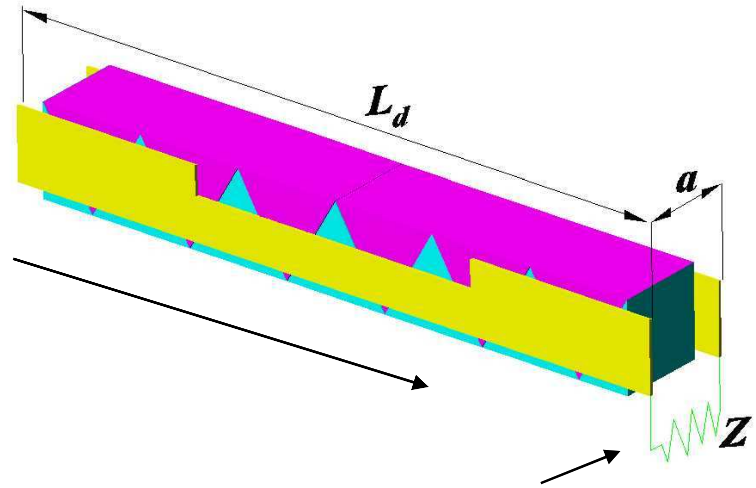


For a prism-based device, change in refraction index yields the change in deflection angle. To arrange such a change, the basements of the prism must be covered by metallic foils and a high voltage applied to them.

The deflecting angle is defined by the phase delay across the laser beam front arising from differences in the path lengths in material of the prism having a refractive index *n* ,

$$\Delta\vartheta \cong n\frac{(L_a - L_b)}{a}$$

At the right- prisms with *oppositely directed optical axes* installed in series between two parallel strip–line electrodes, Electromagnetic pulse propagates with laser bunch to the right as traveling wave.



In this case the *full length* of this device is working for deflection.

Sweeping device could be characterized by deflection angle ϑ and by the angle of natural diffraction –

$$\vartheta_d = \lambda / a,$$

where *a* –is the aperture of the sweeping device which is o the order of the transverse laser beam size.

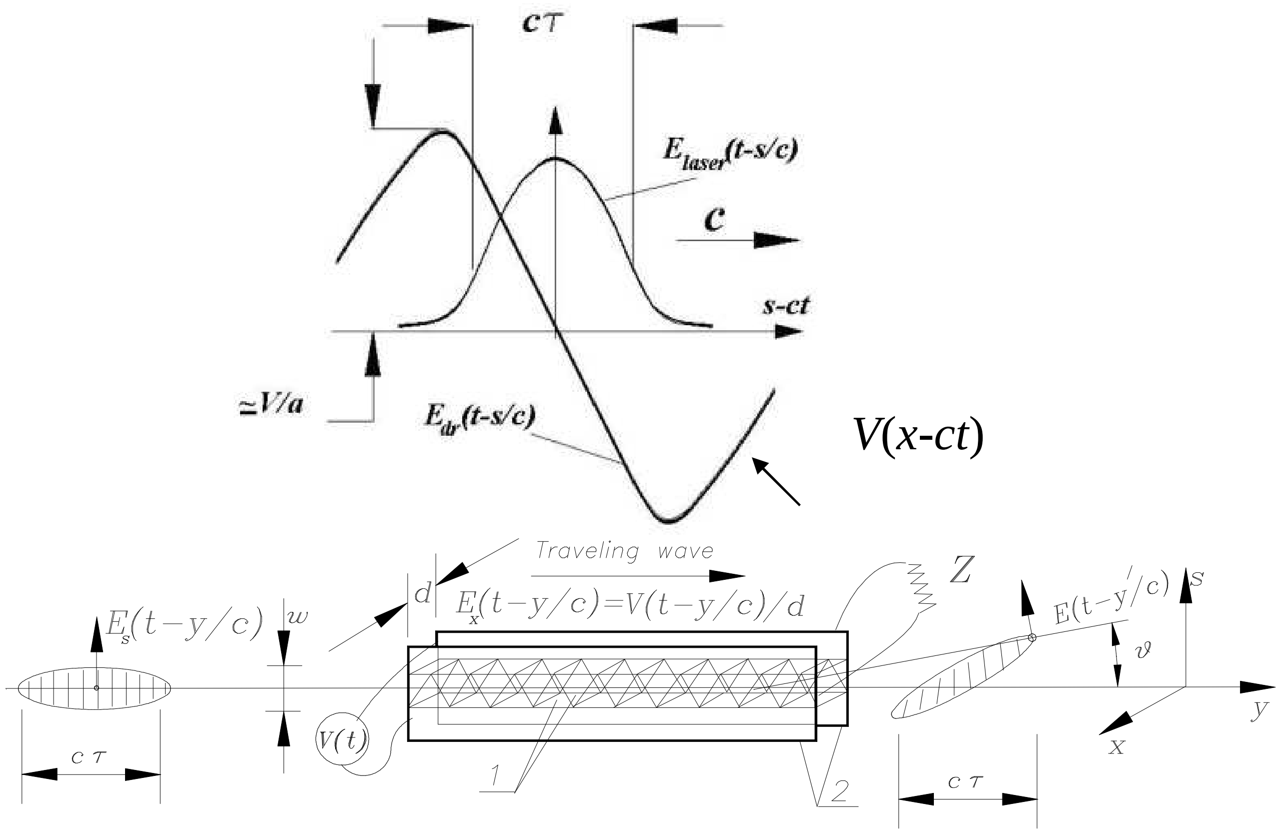
The ratio of deflection angle to diffraction angle is fundamental measure of the quality for any deflecting device. This ratio defines the *number of resolved spots (pixels)* placed along the structure. The last number is an invariant under optical transformations.

$$N_R = \vartheta / \vartheta_d$$

The deflection angle and the number of resolved spots for such device become

$$\Delta\vartheta \cong \Delta n(t)\frac{L_d}{a} \qquad N_R \cong \frac{|\Delta\vartheta|_{\max}}{\lambda / a}$$

Different voltage should be applied to head and tail of laser bunch



1-crystalls with oppositely oriented optical axes, 2-strip-line electrodes feed by fast pulser

CHANGE OF REFRACTION INDEX IN ELECTRO-OPTICAL CRYSTALLS

$$1/n_i^2 = 1/n_{0i}^2 + \sum_j r_{ij} \cdot E^j$$

$$\begin{pmatrix} \Delta(1/n_1^2) \\ \Delta(1/n_2^2) \\ \Delta(1/n_3^2) \\ \Delta(1/n_4^2) \\ \Delta(1/n_5^2) \\ \Delta(1/n_6^2) \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{pmatrix} \times \begin{pmatrix} E_x \\ E_y \\ E_s \end{pmatrix}$$

Tensor r_{ij} links refraction index change and applied electrical field

$$\Delta n_i \cong (\partial n_i / \partial E_j) E^j(t)$$

$$\partial n_i / \partial E_j = -n_{0i}^3 r_{ij} / 2$$

GaAs

$$(r)_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1.5 & 0 & 0 \\ 0 & 1.5 & 0 \\ 0 & 0 & 1.5 \end{pmatrix} \times 10^{-12} [m/V]$$

KDP

$$(r)_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 8.8 & 0 & 0 \\ 0 & 8.8 & 0 \\ 0 & 0 & 10.5 \end{pmatrix} \times 10^{-12} [m/V]$$

$$\Delta\vartheta \cong \Delta n(t) \frac{L_d}{w} \cong \frac{L_d}{a^2} n_0^3 \cdot r_{ij} \cdot V(t)$$

V(t) from previous slide

$$N_R \cong \frac{|\Delta\vartheta|_{\max}}{\lambda / w} = |\Delta n|_{\max} \frac{2L_d}{\lambda} = \frac{L_d}{\lambda} n_0^3 r_{ij} |\Delta V|_{\max}$$

Materials for 1μm: KDP,DKDP,ADP,KDA,$LiNbO_3$

Materials for 5μm: $LiNbO_3$, $LiTaO_3$, CuCl

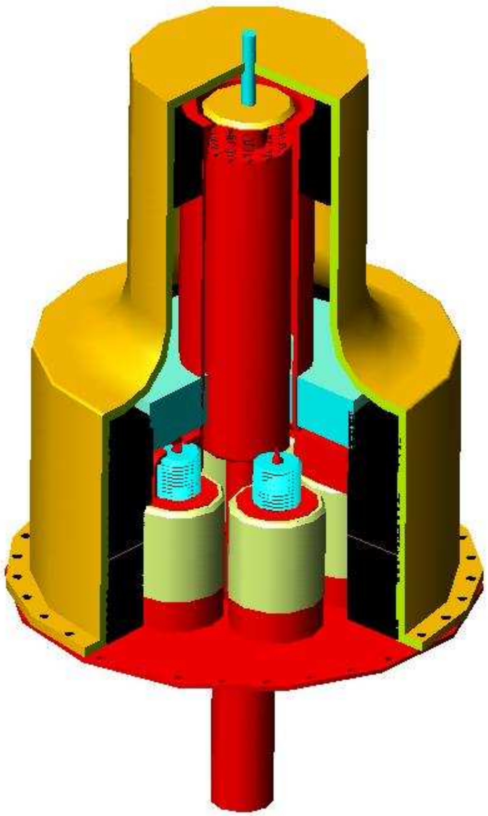
Materials for 10μm: GaAs, ZnTe, ZnS,CdS, CuCl

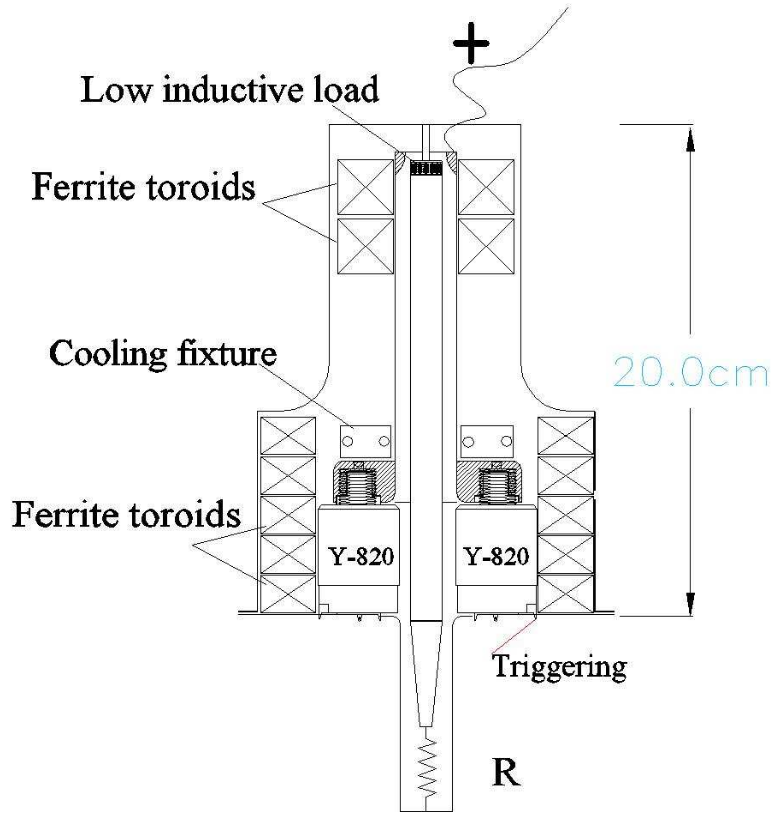
For L_d =25*cm*, a=0.5 *cm*, deflection angle is $\Delta\vartheta \cong 10^{-2}$
N_R= *200* for $\lambda \cong 1\mu m$

Such devices can be manufactured routinely

FAST PULSER

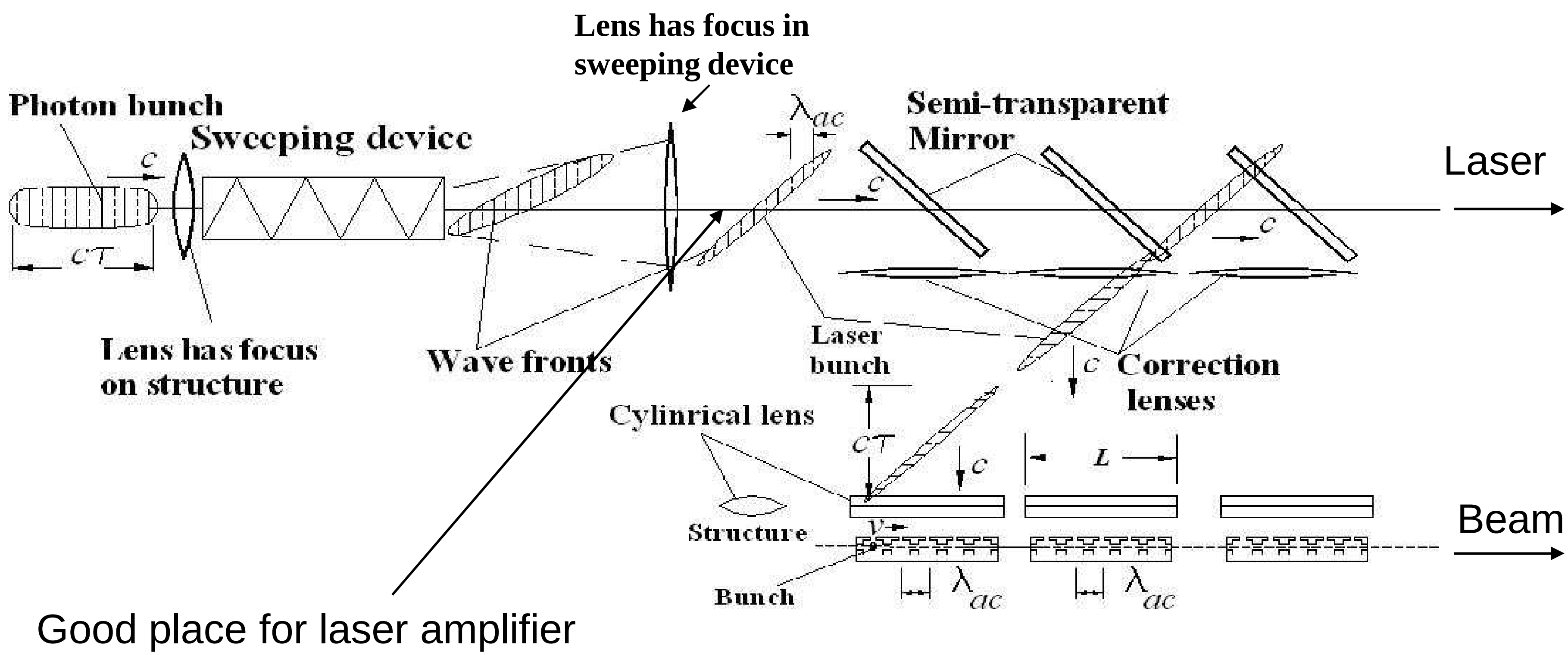
The pulser we developed and suggesting for usage at ERL and ILC



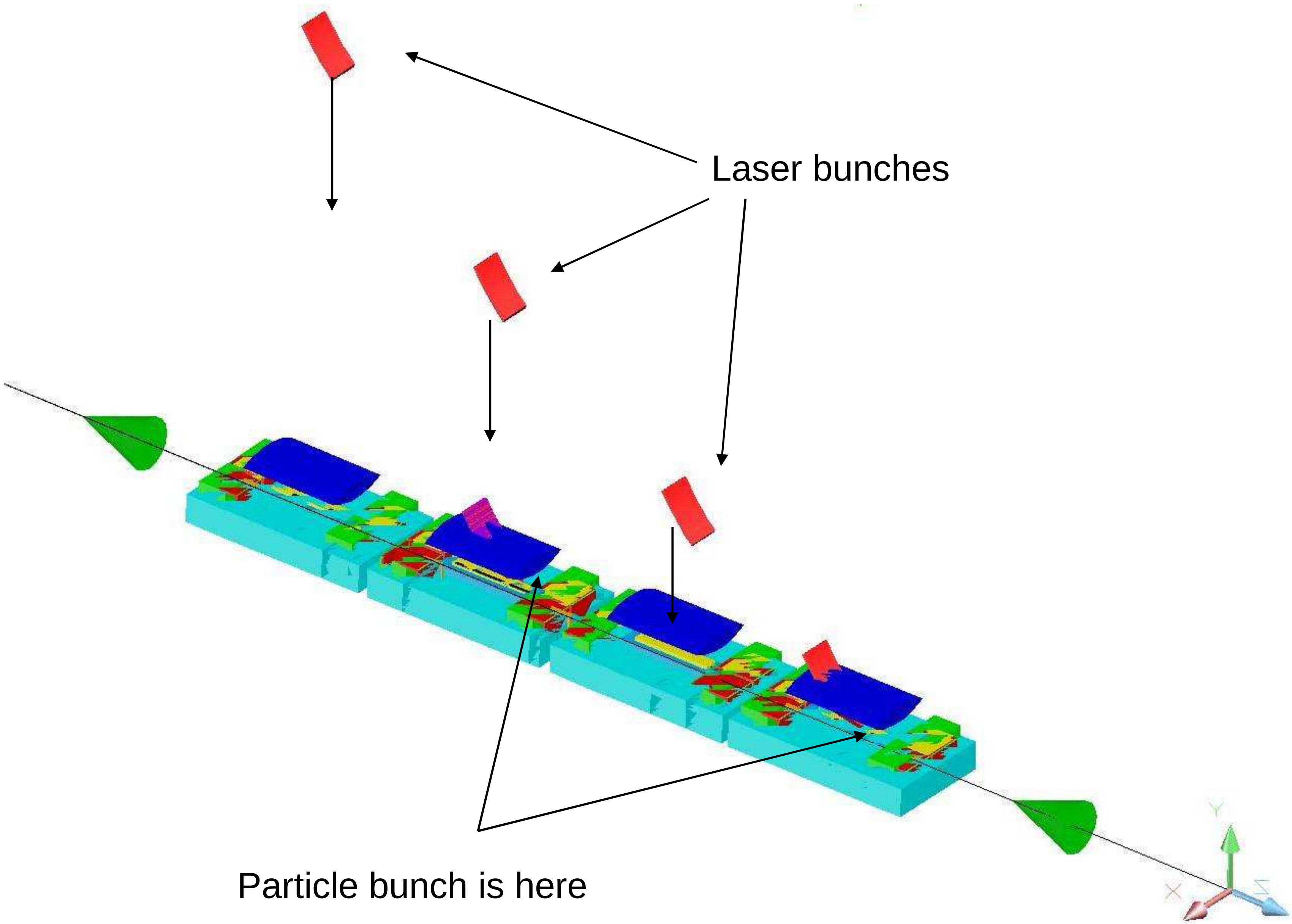


Pulser provides ~30kV, ~100A in ~1ns pulse up to 3 MHz.

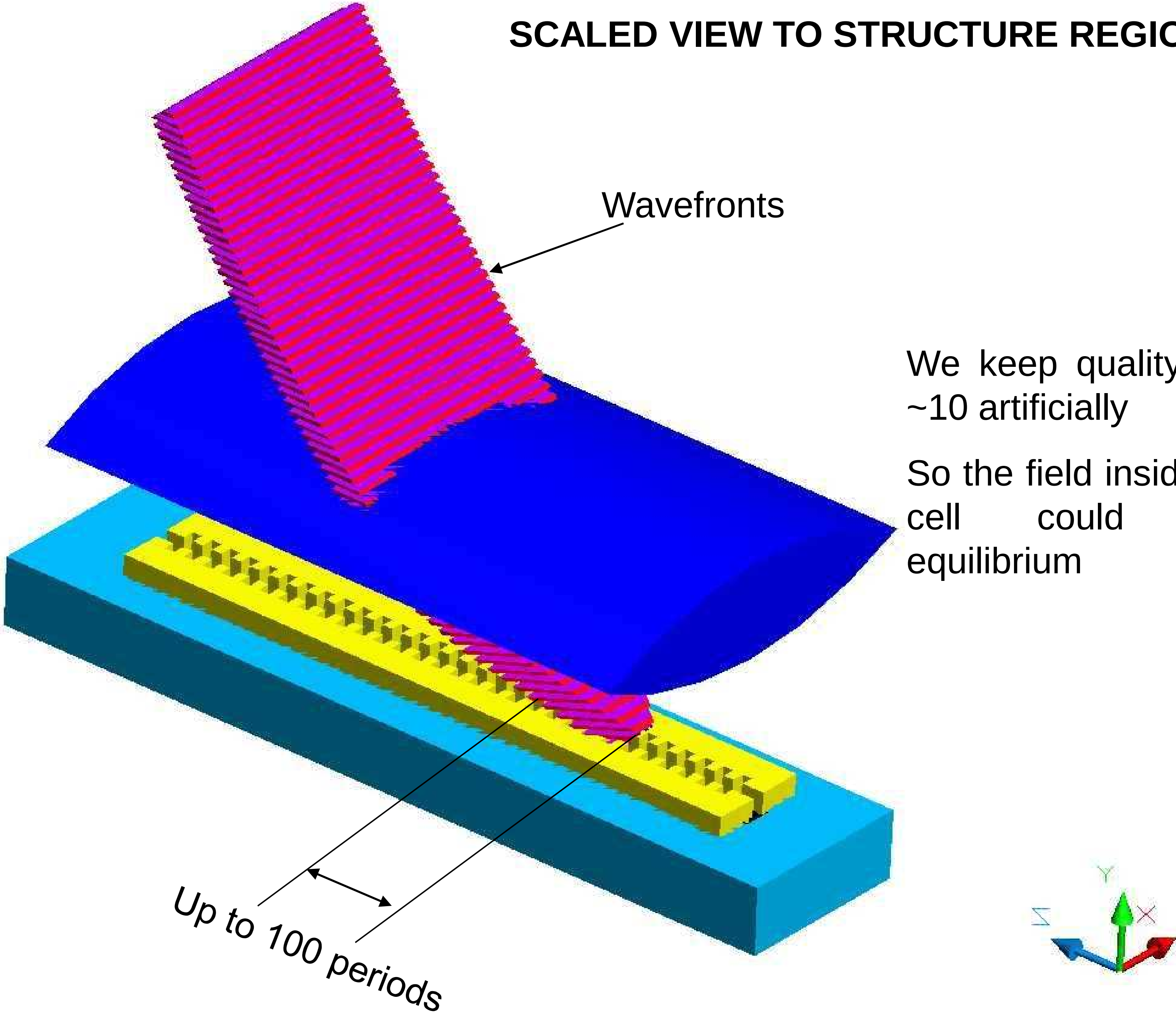
ARRANGEMENT OF LONG TERM ACCELERATION



3D VIEW OF PROCESS

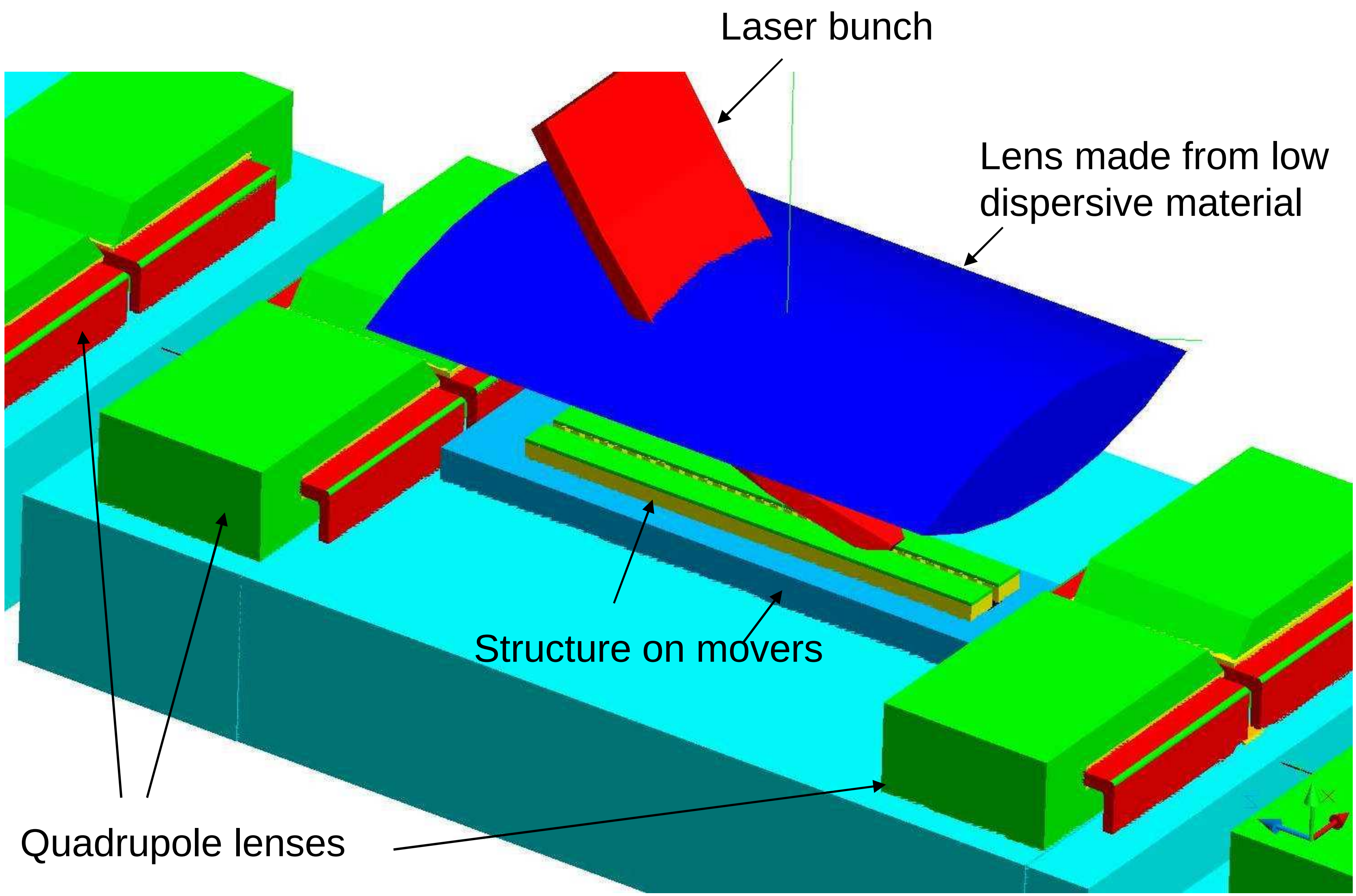


SCALED VIEW TO STRUCTURE REGION



We keep quality factor ~10 artificially

So the field inside each cell could reach equilibrium


Laser bunch
Lens made from low dispersive material
Structure on movers
Quadrupole lenses

ACCELERATING STRUCTURE

The mostly important role of the structure is in proper *positioning* of accelerating field in space.

Structure generates wakes, necessary for acceleration process

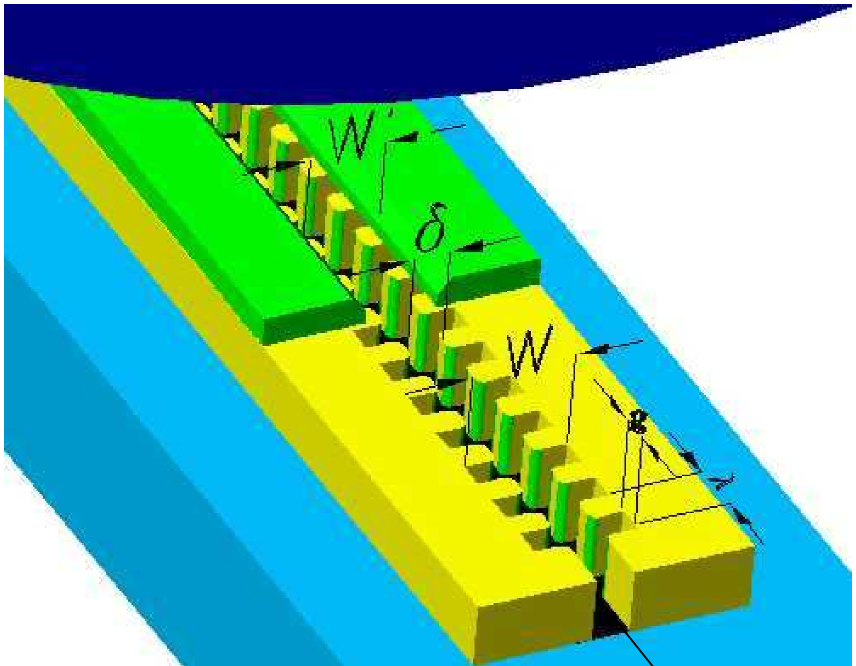
Many projects on laser acceleration suffer from sensitivity to fluctuations in laser homogeneity.

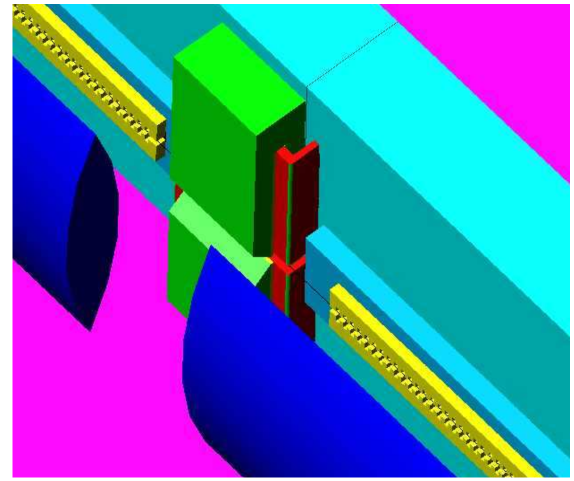
This is especially so in some schemes used split lasers beam and combined further to obtain symmetrically crossed wave fronts. In its turn precise location defined by accuracy of fabrication, accuracy of positioning, how far from equilibrium the fields are and by physical limitations.

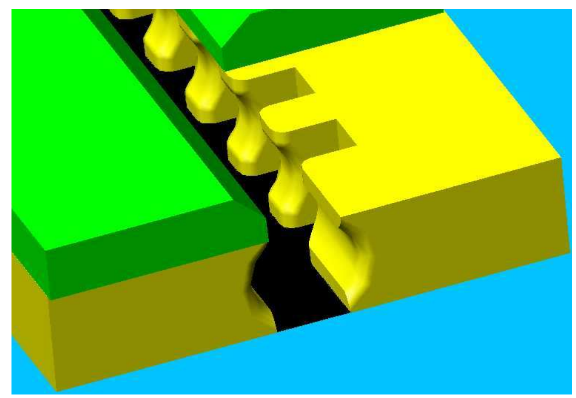
The coupled electrons having frequencies much higher, than the laser one, define the effective boundaries of the structure for nonconductive materials.

Any type of structure could be used with TLF method, we suggested modified foxhole structure

R.C.Fernow, J.Claus, *The Foxhole Accelerating Structure*, BNL 52336, UC-414 1992.
J. Kirchgessner et al., *Superconducting RF Activities at Cornell University*, SRF 950908-13, Cornell, 1995, see also SRF 950714-05.
H.Henke, *mm Wave Linac and Wiggler structure*, EPAC 94, London.





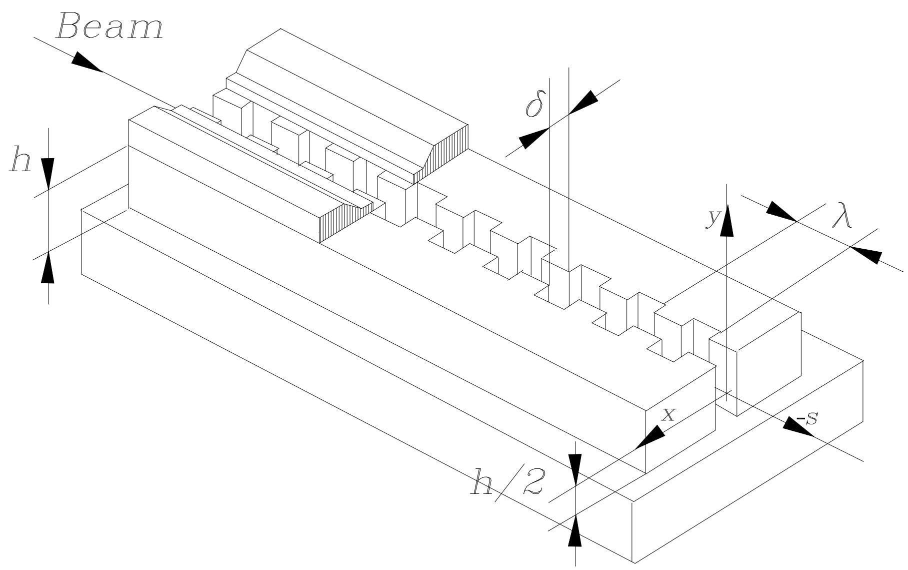


Beam is going *inside the structure at half of the height*.

Each cell has inductive coupling with outer space as its height ~$\lambda_w/2$

Modified Foxhole type structure

Better pumping



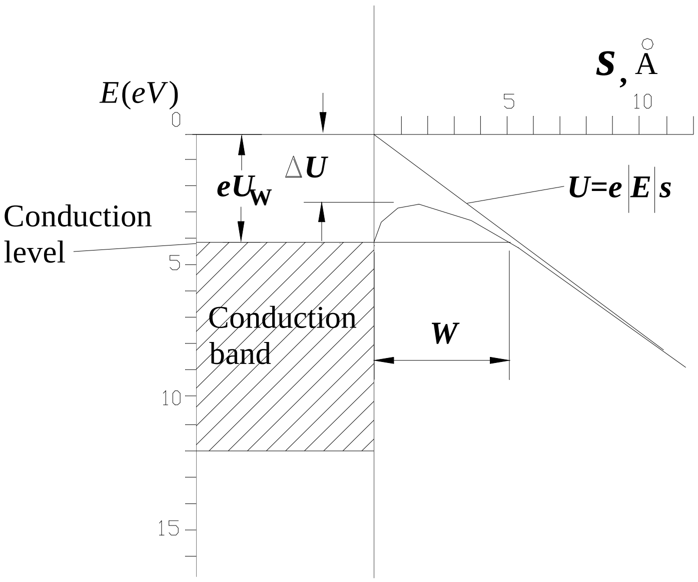
Our structure has height h~λ/2;

Inductive coupling

$$E_s \cong E_m Cos\frac{\pi x}{W} Cos\frac{\pi y}{h} Cos\omega t \qquad H_x \cong \frac{E_m \lambda}{2hc} Cos\frac{\pi x}{W} Sin\frac{\pi y}{h} Sin\omega t \qquad H_y \cong \frac{-E_m \lambda}{2Wc} Sin\frac{\pi x}{W} Cos\frac{\pi y}{h} Sin\omega t$$

$$k_x = -\frac{1}{pc}\frac{\partial\langle F_x\rangle}{\partial x} \cong -\frac{e\lambda_{ac}E_m}{mc^2\gamma W^2} Sin\varphi \qquad \approx 4\cdot 10^5 \cdot Sin\varphi [m^{-2}]$$

ELECTRON SOURCE –MAXIMAL GRADIENT



Quantum diffusion

$$D \approx \exp\left[-\frac{4\sqrt{2m}}{3\hbar eE}\left(eU_W - e\sqrt{eE}\right)^{3/2}\right]$$

$$U_F \approx 5V \qquad E \approx \frac{4\pi\varepsilon_0 U_w^2}{e} \cong 17GeV/m$$

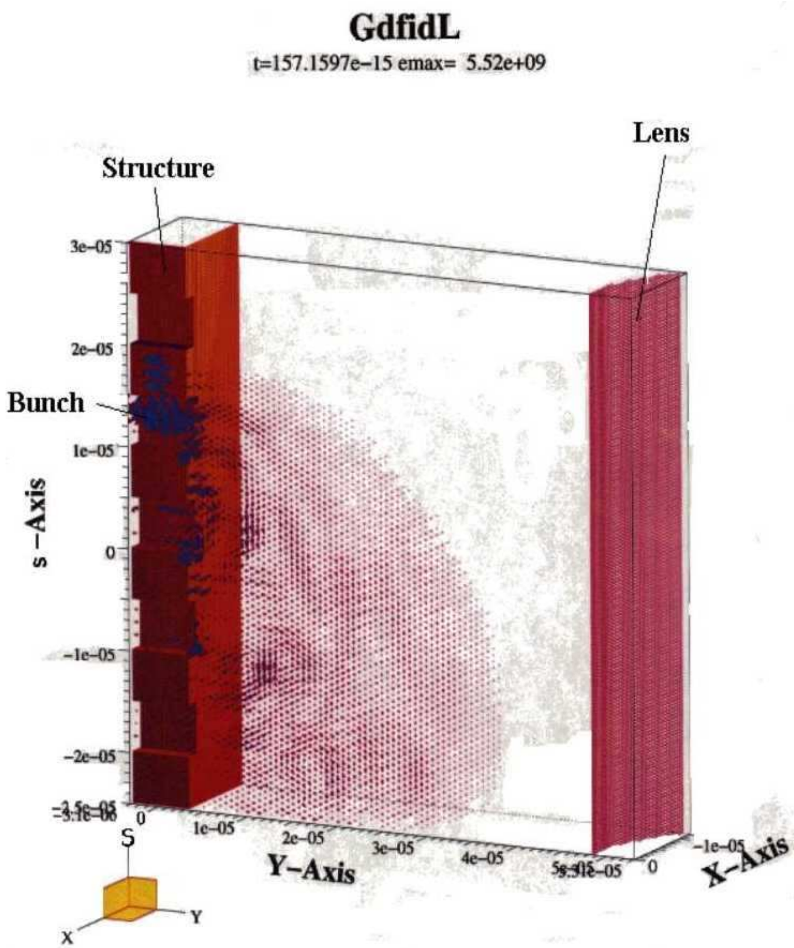
With taking into account, image potential $-e^2/4s$ the diffusion coefficient becomes

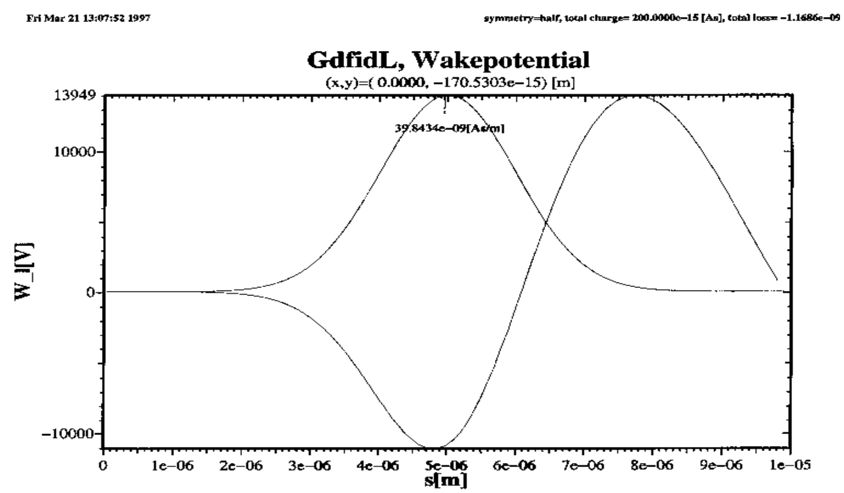
$eE, V/cm$ →	10^6	$5\cdot10^6$	10^7	$2\cdot10^7$	$2\cdot10^7$	$2\cdot10^7$	10^8 ← 10*GeV/m*
eU_W=-2V	10^{-80}	$8\cdot10^{-15}$	$1.3\cdot10^{-6}$	0.013	1	1	1
eU_W=-3V	10^{-150}	$8\cdot10^{-28}$	$7\cdot10^{-14}$	$2.3\cdot10^{-6}$	$7\cdot10^{-4}$	0.07	1
eU_W=-5V	10^{-328}	$8\cdot10^{-65}$	10^{-31}	$2\cdot10^{-15}$	$6\cdot10^{-10}$	10^{-5}	0.01

Gol'dman, V.D.Krivchenkov," Problems in Quantum Mechanics", Dover Publications, INC, ed by B.T.Gelikman.

WAKES

Wakes calculated with MAFIA and GdfidL, FlexPDE still under preparation





$W_{\parallel} \cong -7kV/pC$ $W_{\perp} \cong 2.2 \cdot 10^2 V/pC/\mu m$

$N \cong 310^5$ $eN \cong 4.8 \cdot 10^{-14} C = 0.048 pC$

Wakes/Acceleration $\sim 4\%,$

SCALING OF IMPEDANCES

Transverse wake scales *linearly*, as it follows from its dimension: Volt/Coulombs/meter. Impedances are

$$Z_{\|} \cong -i\frac{Z_0}{R\sigma_b}\cdot(ah-...)\rightarrow[Z_0] \qquad Z_{\perp} \cong -i\frac{Z_0}{R^3}\cdot(ah-...)\rightarrow\left[Z_0\frac{1}{meter}\right]$$

Where *a* radius of cavity counted from drift tube, *h* its height (along the beam trajectory), *R* is radius of drift tube of iris, $Z_0 \cong 377Ohm$. One can see that if the bunch length together with other dimensions just scaled down as wavelength, so the amplitude of longitudinal current remains the same (as the charge density remains the same), then the voltage applied to the beam induced along the cavity will be the same, . Voltage applied to the beam across the cavity will be the same also, as despite transverse impedance increased reversely proportional to the wavelength, the charge reduced in the same proportion, .

So basically the structure is scaled down from 10 *cm* to 1 *μm* i.e. 10^5 times. If we accept that the bunch population for 10-cm cavity is ~10^{10}, then for laser-scale cavity the bunch population should be ~10^5. The structure of our interest (the foxhole type one) has transverse gap, which makes transverse wakes in direction of slit negligible. In rectangular direction slit focuses particles, making focusing wavelength proportionally stronger. Focusing in direction along the slit is arranged by small quadrupoles.

High gradient requires for keeping reasonable ratio of $\frac{Energy\ carried\ out\ by\ beam}{Energy\ stored\ in\ field}$

This is in line with desire to have accelerator as compact as possible.

Minimal emittance

Fundamental restriction to the minimal emittance is

$$(\gamma\varepsilon_x)(\gamma\varepsilon_y)(\gamma\varepsilon_s) = (\gamma\varepsilon_x)(\gamma\varepsilon_y)(\gamma l_b(\Delta p / p_0)) \geq \tfrac{1}{2}(2\pi\bar{\lambda}_C)^3 N$$

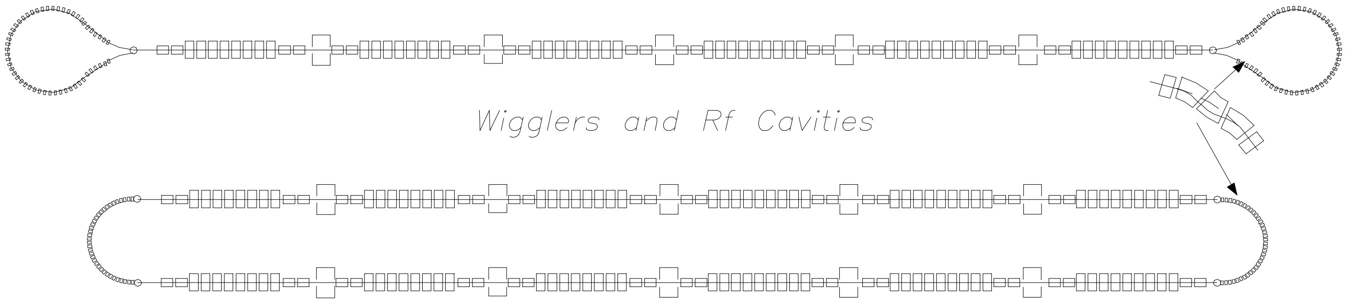
A.A. Mikhailichenko, *On the physical limitations to the Lowest Emittance (Toward Colliding Electron-Positron Crystalline Beams)*, 7th–Advanced Accelerator Concepts Workshop, 12-18 October 1996, Lake Tahoe, CA, AIP 398 Proceedings, p.294. See also CLNS 96/1436, Cornell, 1996, and in *To the Quantum Limitations in Beam Physics*, CLNS 99/1608**,** PAC99, New York, March 29- April 2 1999, Proceedings, p.2814.

This formula can be obtained from counting the number of states in Fermi gas phase space:

$$dn \cong 2\frac{dp_x dp_y dp_s \cdot V}{(2\pi\hbar)^3} \quad \longrightarrow \quad N = \int dn \cong 2\frac{p_x p_y \Delta p_\parallel \, S_\perp l_b \gamma}{(2\pi\hbar)^3} \cong 2\frac{\gamma\varepsilon_x \gamma\varepsilon_y \gamma l_b (\Delta p / p_0)}{(2\pi\bar{\lambda}_C)^3} = 2\frac{\gamma\varepsilon_x \gamma\varepsilon_y \gamma\varepsilon_z}{(2\pi\bar{\lambda}_C)^3}$$

The problem is that in fully degenerated state polarization of beam is zero

INJECTION SOURCE



For wiggler dominated cooler equilibrium emittance

$$(\gamma\varepsilon_x) \cong \tfrac{1}{2}\cdot ƛ_C \overline{\beta}_x (1+K_x^2/2)\gamma/\rho_x \cong \tfrac{1}{2}\cdot ƛ_C \overline{\beta}_x (1+K_x^2/2) K_x / ƛ \qquad (\gamma\varepsilon_y) \cong \frac{1}{2}\cdot ƛ_C \overline{\beta}_y \gamma/\rho_x \cong \frac{1}{2}\cdot ƛ_C \overline{\beta}_y K_x / ƛ$$

Cooling time $\tau_{cool} \cong (3/2)\cdot(ƛ^2 / r_0 c K^2 \gamma)$~ 8.6 *ms*. $K = eH_\perp ƛ / mc^2$ Number of particles~10^5 makes IBS acceptable

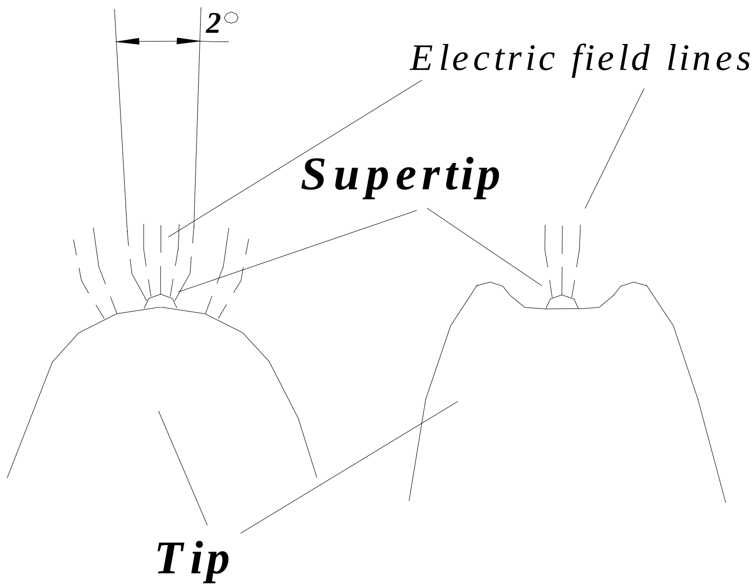
TEMPERATURE

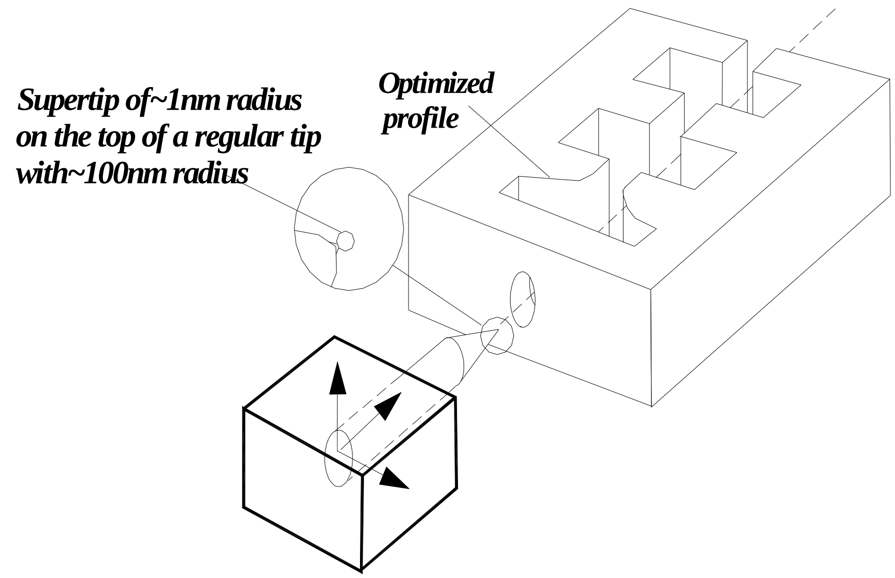
$$\tfrac{3}{2} N k_B T \cong N\cdot mc^2\gamma\left[\frac{\gamma\varepsilon_x}{\beta_x}+\frac{\gamma\varepsilon_y}{\beta_y}+\gamma\frac{1}{\gamma^2}\left(\frac{\Delta p_\parallel}{p_0}\right)^2\right] \to N\cdot mc^2\gamma\left[\frac{\gamma\varepsilon_x}{\beta_x}+\frac{\gamma\varepsilon_y}{\beta_y}+\gamma\left(\frac{1}{\gamma^2}-\left\langle\frac{D}{\beta_x}\right\rangle\right)\left(\frac{\Delta p_\parallel}{p_0}\right)^2\right]$$

Emittance possible

$$(\gamma\varepsilon_y) \cong 9.5\cdot 10^{-10} cm\cdot rad \qquad (\gamma\varepsilon_x) \cong 2.5\cdot 10^{-8} cm\cdot rad$$

ELECTRON SOURCE WITH SUPERTIP





$$\gamma\varepsilon \cong 10^{-7}\,cm \cdot 10^{-2}\,rad = 10^{-9}\,cm \cdot rad$$

BEAM PARAMETERS

If laser flash lasts τ ***sec*** **and caries energy *Q Joules* then maximal field** $E_m \cong 2\sqrt{\dfrac{Q}{\varepsilon_0 c\tau\lambda l_f}}$

Q=10^{-4} J $\tau \cong$ 0.1 *ns* $\lambda \cong 1\mu m$ Q_{RF}=9 $E_m \cong$ 10*GeV/m*

Bunch population $N \cong \dfrac{\eta}{2eI(g)}\sqrt{\dfrac{\varepsilon_0 \lambda_{ac}^3 Q}{c\tau l_f}} \cong 3\cdot 10^5$ For 5% load

Luminosity $L = \dfrac{N^2 f H_B}{4\pi\sigma_x\sigma_y}$ $\gamma\varepsilon_x \cong 2.5\cdot 10^{-8} cm\cdot rad$ $\beta_x \approx \beta_y \approx 0.3\lambda_{ac}$ $f \cong$ 1 kHz, H_B=1

$\gamma\varepsilon_x \cong 9.5\cdot 10^{-10} cm\cdot rad$

$$L \approx 1.7\cdot 10^{35} cm^{-2} s^{-1}$$

$Y_0 \equiv 2\hbar\omega_c / 3E = \gamma H / H_c$ ~10^3

$H_c = m^2c^3 / e\hbar \cong 4.4\cdot 10^{13}$

Aspect ratio at IP $\sigma_x / \sigma_y \cong$ **5**

Critical energy $\hbar\omega_c \cong mc^2\gamma / Y_0$

Formation length $l_F \cong \lambda\!\!\!^{-}_C \gamma / Y_0^{2/3}$

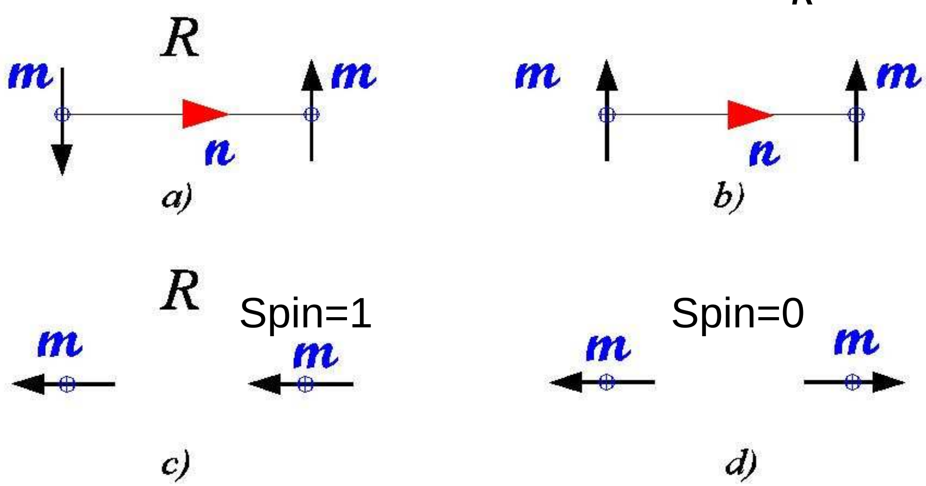
Transverse size of coherence $\sigma_\perp^{coh} \cong \sqrt{\lambda\!\!\!^{-}_{cr} l_F \sigma_b} \cong Y_0^{1/6} \lambda\!\!\!^{-}_C$

$\sim 3\lambda\!\!\!^{-}_C \cong 1.15\cdot 10^{-10} cm$

SUPERCONDENSATION of ELECTRON GAS

Magnetic dipole $\vec{m}$ defines magnetic field around as

$$\vec{H} = \frac{3\vec{n}\cdot(\vec{m}\cdot\vec{n}) - \vec{m}}{R^3}$$



In case *a)* and *c)* there is attraction

by magnetic force.

In case *b)* and *d)* there is additional repulsion

Balancing attraction by magnetic force and repulsion by the same sign of charge, one can obtain

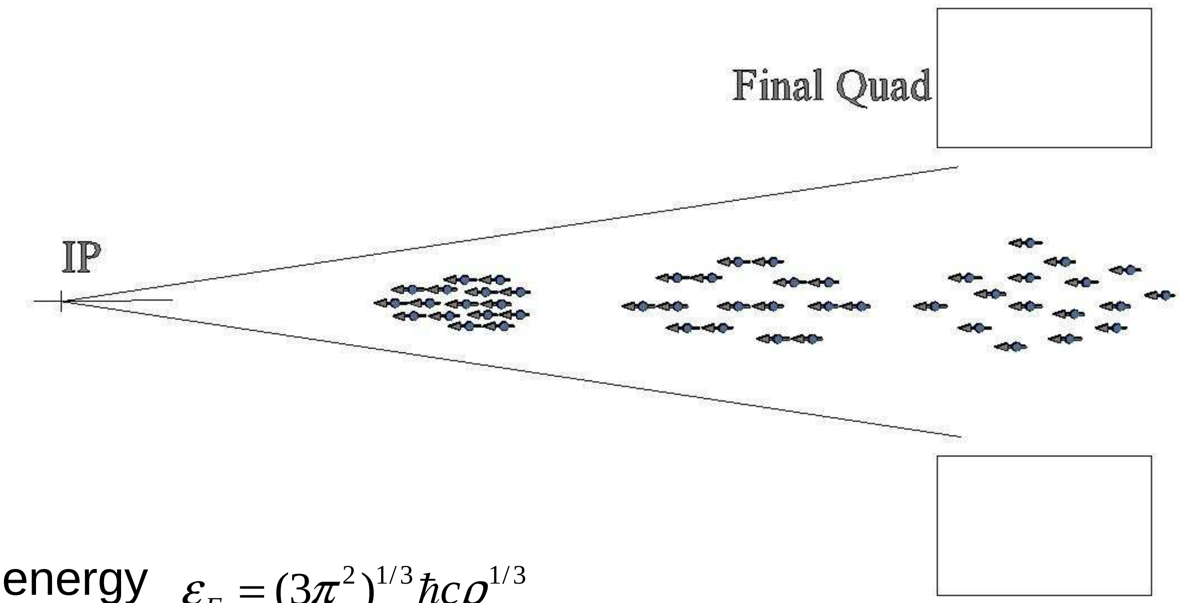
$$\frac{3(\vec{m}\cdot\vec{n})^2 - \vec{m}^2}{4R^4} \cong \frac{e^2}{R^2} \quad \longrightarrow \quad R \cong \frac{(2)\hbar}{4mc} = \frac{(2)}{4}\cdot\bar{\lambda}_C$$

Energy required bringing two electrons to the distance of Compton wavelength is $\frac{e^2}{\bar{\lambda}_C} \cong \frac{e^2}{r_0}\cdot\alpha \cong \alpha\cdot mc^2$

i.e. pretty small compared with energy of transverse motion at IP especially

SUPERCONDENSATION AT IP

While beam in running to IP its density increases



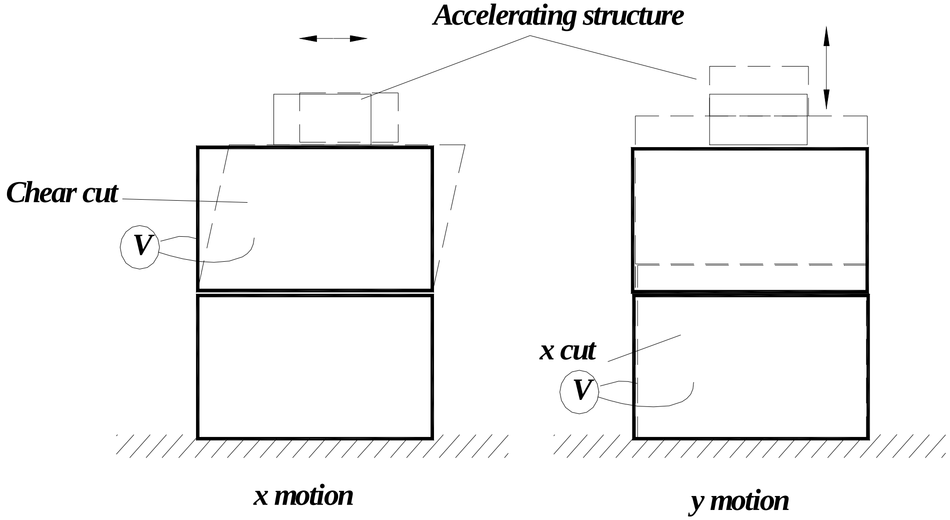
Fermi energy $\varepsilon_F = (3\pi^2)^{1/3}\hbar c\rho^{1/3}$

The condition for degeneration $k_B T \leq \left(3\pi^2\right)^{1/3}\hbar c\rho^{1/3}$

Fermi gas becomes more degenerative while its density increased.
These conditions realizing better and better while beam traveling to IP.
Taking into account interaction through magnetic momentum, it will possible to condense beam below Fermi-limit (couple of fermions behaves as a boson).

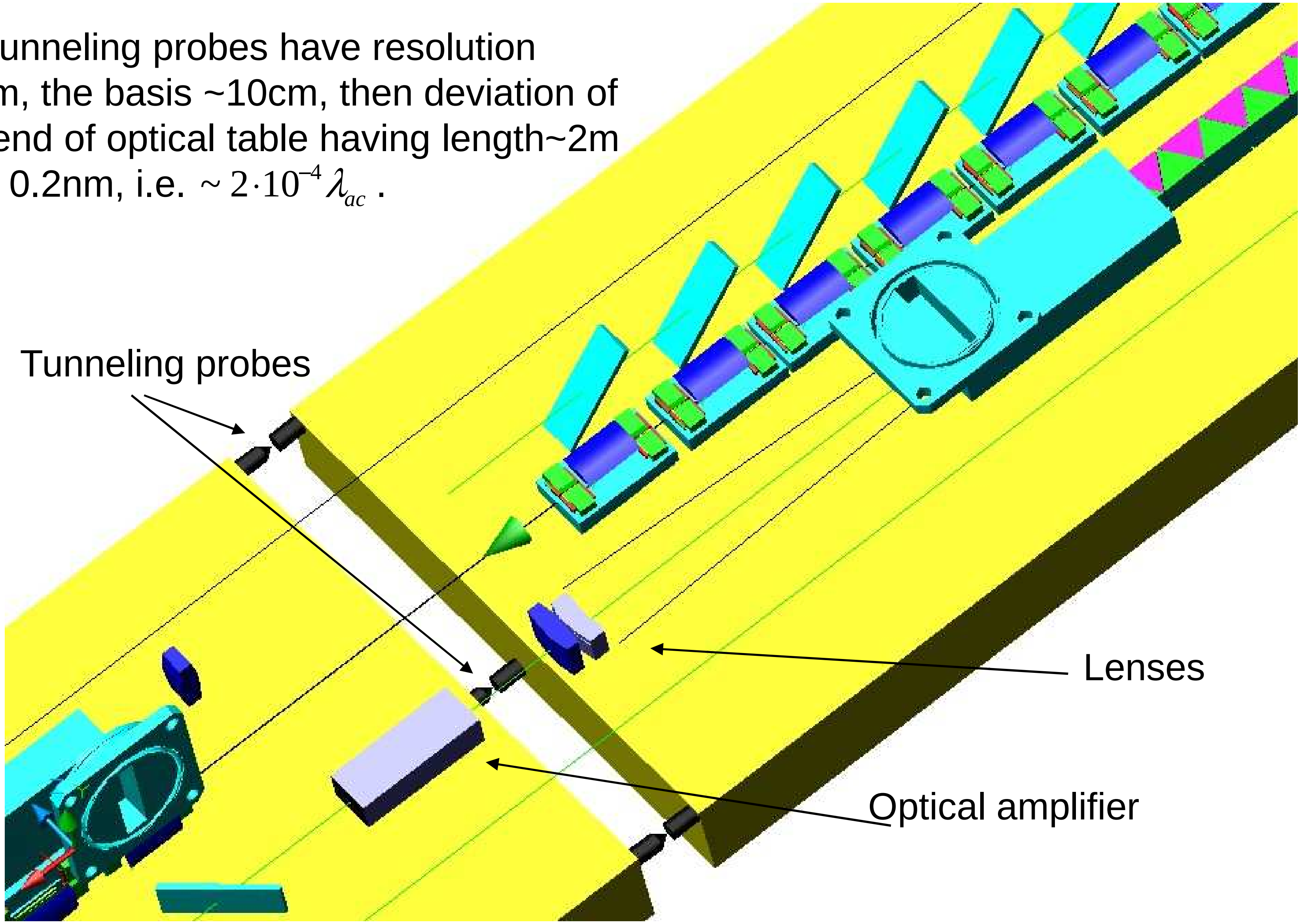
SOME TECHICAL DETAILS

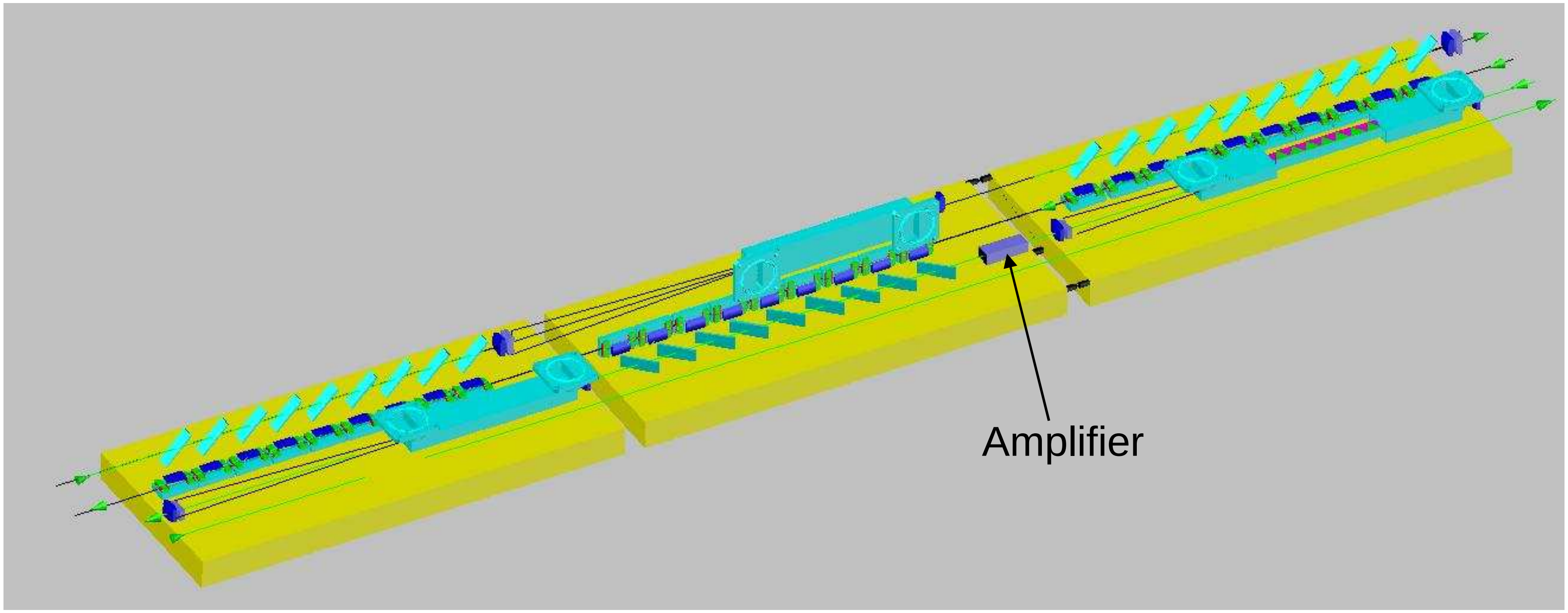
ALIGNMENT



Movement of structure arranged with help of piezoelectric

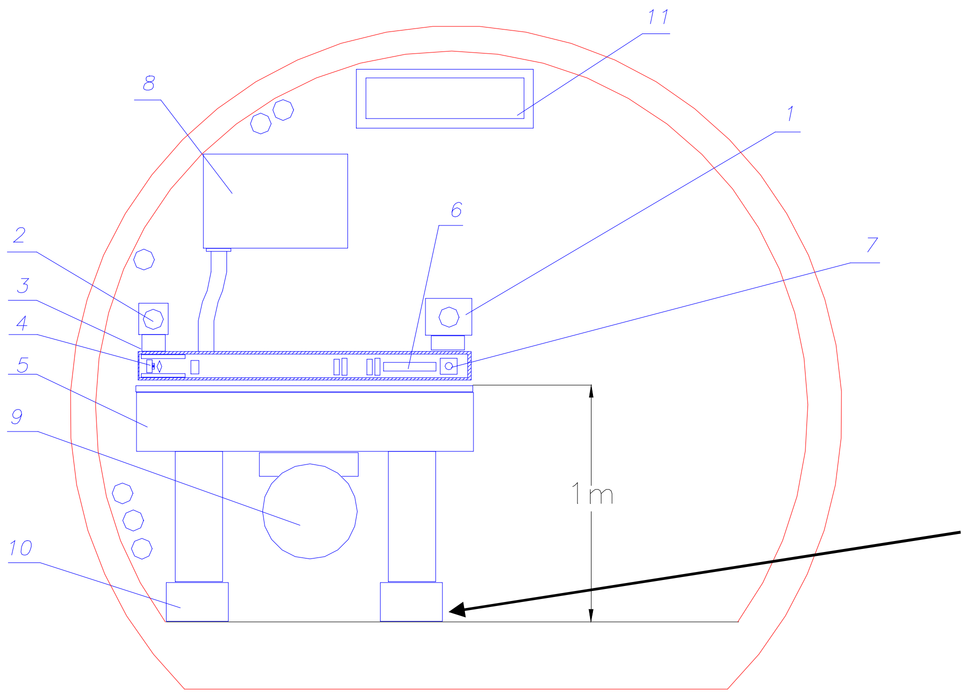
If the tunneling probes have resolution 0.01nm, the basis ~10cm, then deviation of other end of optical table having length~2m will be 0.2nm, i.e. $\sim 2 \cdot 10^{-4} \lambda_{ac}$.





Another 3D view of accelerating modules

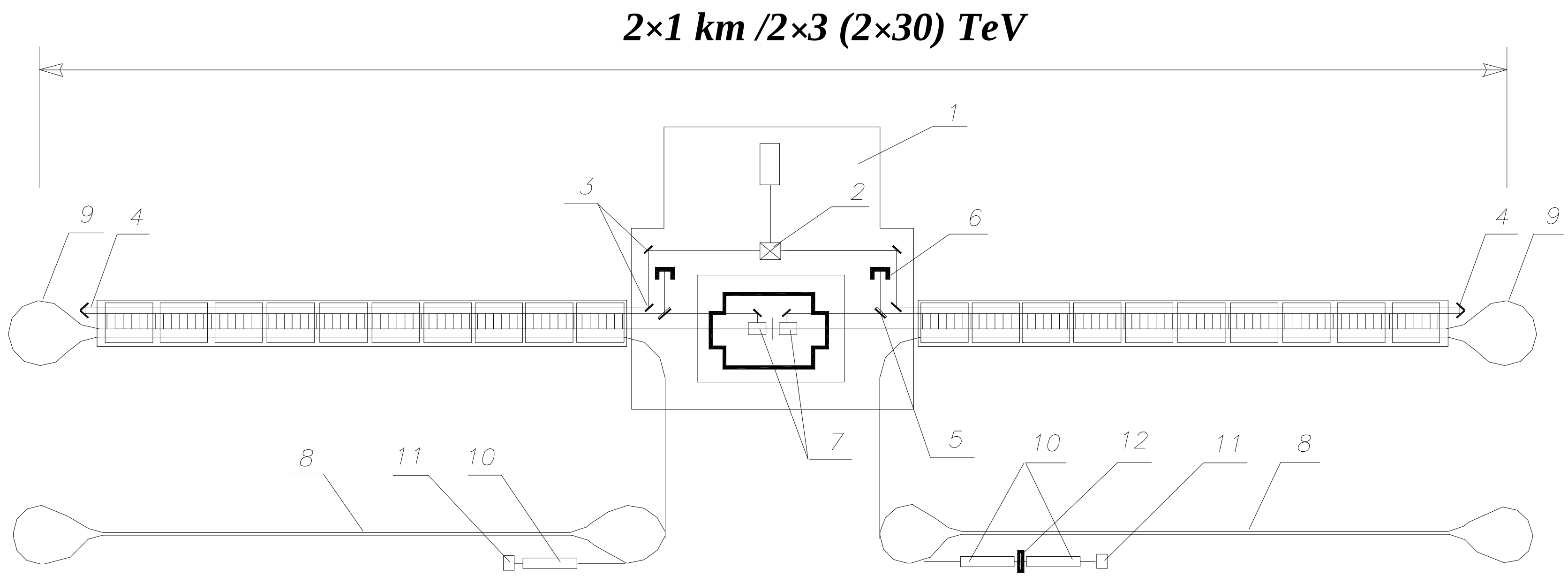
Cross section of a tunnel with accelerating system for underground location.



STACIS commercial system

1– is a primary optical beam line. 2–is a primary particle's beam line. 3–is a vacuumed container with all equipment. 4–is an accelerating structure with sub systems. 5–is an optical table. 6–is the deflecting device, 7 –is the line for driving optical beam, 8–is a box with equipment for deflecting device and control. 9–is a tube with optical elements for active alignment of all optical tables. 10–is an anti-vibration active system. 11–is a duct for air-conditioning.

Laser Linear Collider (LLC) complex



1–is a laser master oscillator platform, 2 –is an optical splitter, 3,4–are the mirrors, 5–is a semi-transparent mirror, 6–is an absorber of laser radiation. 7–are the Final Focus Systems. 8–are the damping systems for preparing particle's beams with small emittances, 9–are the bends for particle's beam. 10–are the accelerating X-band structures, 11–is an electron gun, 12–is a positron converter. The scheme with the damping rings as sources are shown here.

PARAMETER LIST

Wavelength	$\lambda_{ac} \cong 1\mu m$
Energy of $e^{\pm}$ beam	$2 \times 10\ TeV$
Luminosity	$10^{35} cm^{-2} s^{-1}$
Total two-linac length	$2 \times 1\ km$
Main linac gradient	$10\ GeV/m$
Bunch population	$3\ 10^5$
Bunch length	$0.1\ \mu m$
No. of bunches/train	30
$\gamma\ \varepsilon_x\ /\ \gamma\ \varepsilon_y$	$5 \cdot 10^{-9} / 1 \cdot 10^{-9} cm \cdot rad$
Laser flash energy	$2 \times 3J$
Laser density	$0.3\ J/cm^2$
Illumination time	0.1 ps
Length of section	$3cm$
Laser flash energy/section	100μJ
Repetition rate	$1\ kHz$
Laser beam power	$2 \times 3kW$
Damping ring energy	$2\ GeV$
Damping time	10ms
Wall plug power**	$2 \times 30\ kW$

** Without supplementary electronics.

Cost of this installation 200M$/2000m=100k$/m looks reasonable

From Snowmass 2001; conservative ~1.5 *GeV/m*

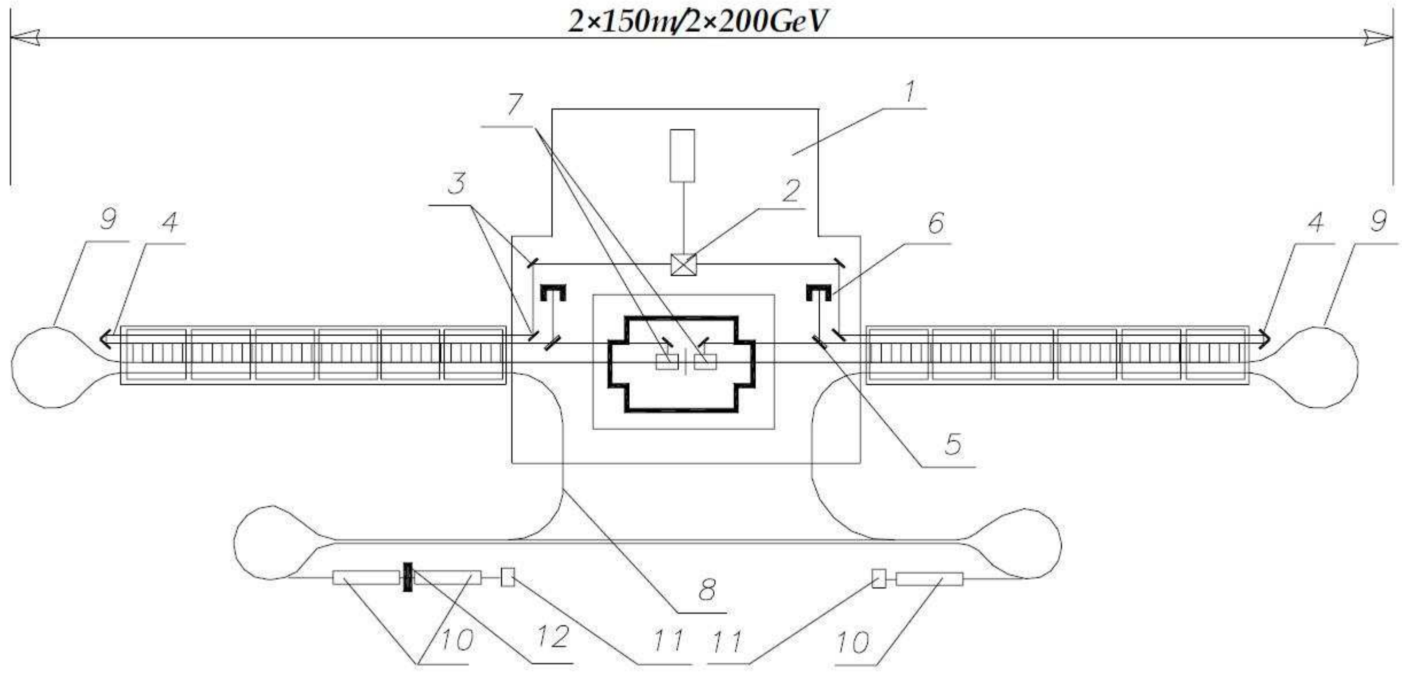


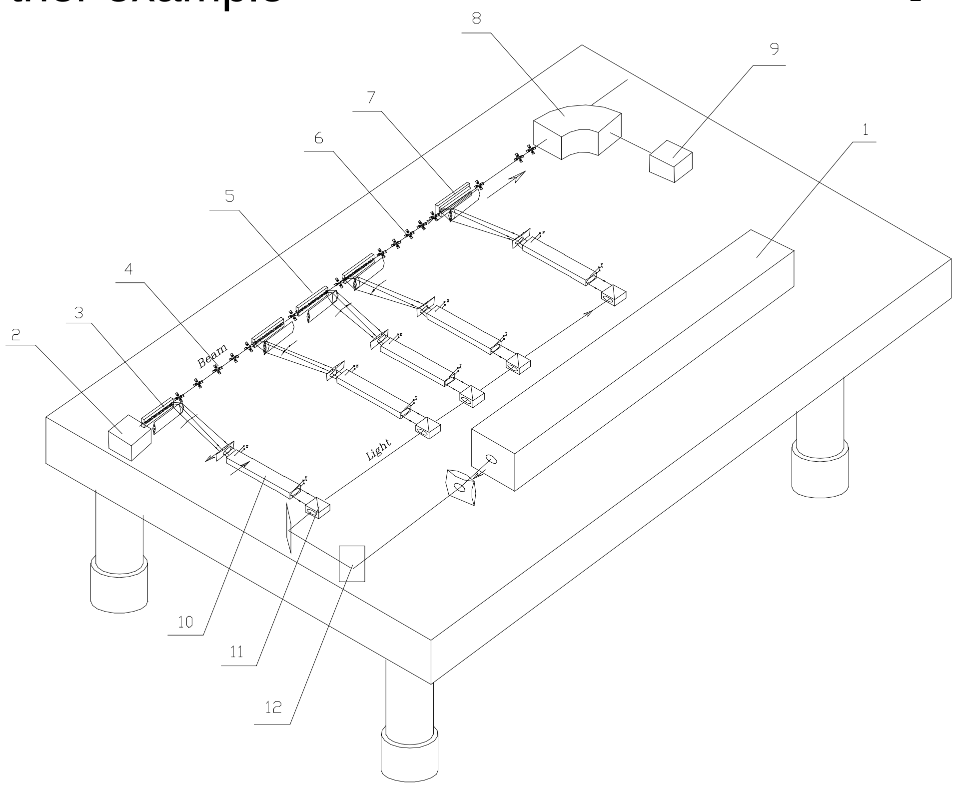
FIGURE 37: Laser Linear Collider (LLC) complex. 1–is a laser master oscillator platform, 2 –is an optical splitter, 3,4–are the mirrors, 5–is a semi-transparent mirror, 6–is an absorber of laser radiation. 7–are the Final Focus Systems. 8–are the damping systems for preparing particle's beams with small emittances, 9–are the bends for particle's beam. 10–are the accelerating X-band structures, 11–is an electron gun, 12–is a positron converter. The scheme with the damping rings as sources are shown here.

Even for cost 1M$/m this 2x200GeV collider will cost 300M$ only

(compare with 15B$ for ILC)

Other example

Table top device



All elements installed on a platform. Vacuumed cover for the beam part is not shown. 1 –is a laser, 2–source of particles, including micro-tip and movers, 3–RF pre-buncher, 4–space for buncher (if necessary), 5–main acceleration modules, 6–focusing elements, 7–a region for laser wiggler, 8–bending magnet, 9–beams dump, 10–a sweeping device, 11–a splitting device, 12–a mirror.

Wavelength	$\lambda_{ac} \cong 1\mu m$
Energy of the $e^{\pm}$ beam	100 *MeV*
Active linac length	10 *cm*
Main linac gradient	1.0 *GeV/m*
Bunch population	10^6
No. of bunches/pulse	10(<100)
Laser flash duty	100 *ps*
Laser flash energy	*5mJ*
Repetition rate	160 *Hz*
Average laser power	~0.8*W*
Average beam power	26 *mW*
Bunch length	0.1 μm
$\gamma\,\varepsilon_x$ / $\gamma\,\varepsilon_y$	$\approx 10^{-8}/10^{-8}\,cm\cdot rad$
Length of section/Module	3*cm*
Wall plug power	3.5*kW*

SUMMARY

•Limitations arising from fundamental physical phenomena and processes need to be taken into account while projecting installations with plasma and structure based ones.

•One class of limitations associated with the nature of electron/positron bunch as a Fermi-Gas. The only occupancy by single particle in each state immediately yields a limitation of minimal emittance and maximal polarization which could be achieved in colliding beams. Considered sources for generation of electrons with minimal emittance.

• Suggested new mechanism for compaction of beam.

• Limitations in density of carriers may restrict precise alignment of accelerating gradient due to fluctuations of geometrical center of accelerating field (in plasma). Different capabilities of plasma methods for focusing electron and positron during acceleration might be important as well.

• For structure based schemes we considered limitations in accelerating gradient arising from quantum tunneling of electrons through potential barrier, limiting achievable gradient to ~10 *GeV/m* depending on material of structure. For acceleration scheme with sloped laser beam, considered fundamental limitations in preparation of such beam by laser sweeping device and by grating.

Summary for TLF method

- Any point on accelerating structure remains illuminated by ~0.3 *ps* only. Laser density <0.3 J/cm^2
- Lasers for the TLF method need to operate with pulse duration ~100ps.
- Nano–technology available creates solid base for accelerator with Travelling Laser Focus.
- TLF method promises up to 10 *TeV/km* with 3 *mJ/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 and technical limitations found on this way.
- Method is self consistent for arrangement of collisions for High Energy Physics
- **Testing this method might be highest priority task for accelerator physics.**

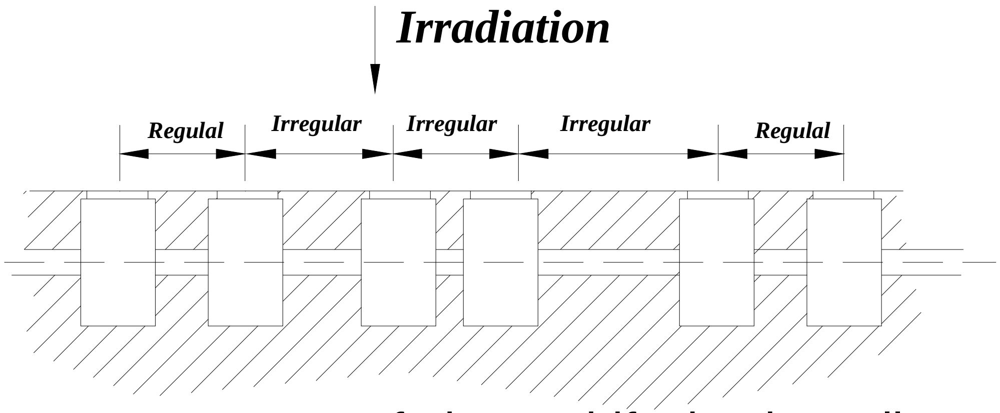
Backup slides

STAGING FOR PROF OF PRINCIPLE EXPERIMENT

1) Assemble a sweeping device
2) Assemble a pulser
3) DemonstratIon sweeping (line on the screen)
4) Demonstrate higher level of damage while the laser beam is swept
5) Fabricate accelerating structure at Nano-Factory
6) Investigate reflection with tunable low power laser
7) Fabricate a nano-mover
8) Fabricate a source of electrons with small emittance based on micro-tip
9) Complete setup
10) Demonstrate acceleration
11) Cost estimation could be done at this stage

Parallel jobs are possible

Focusing with RF lenses

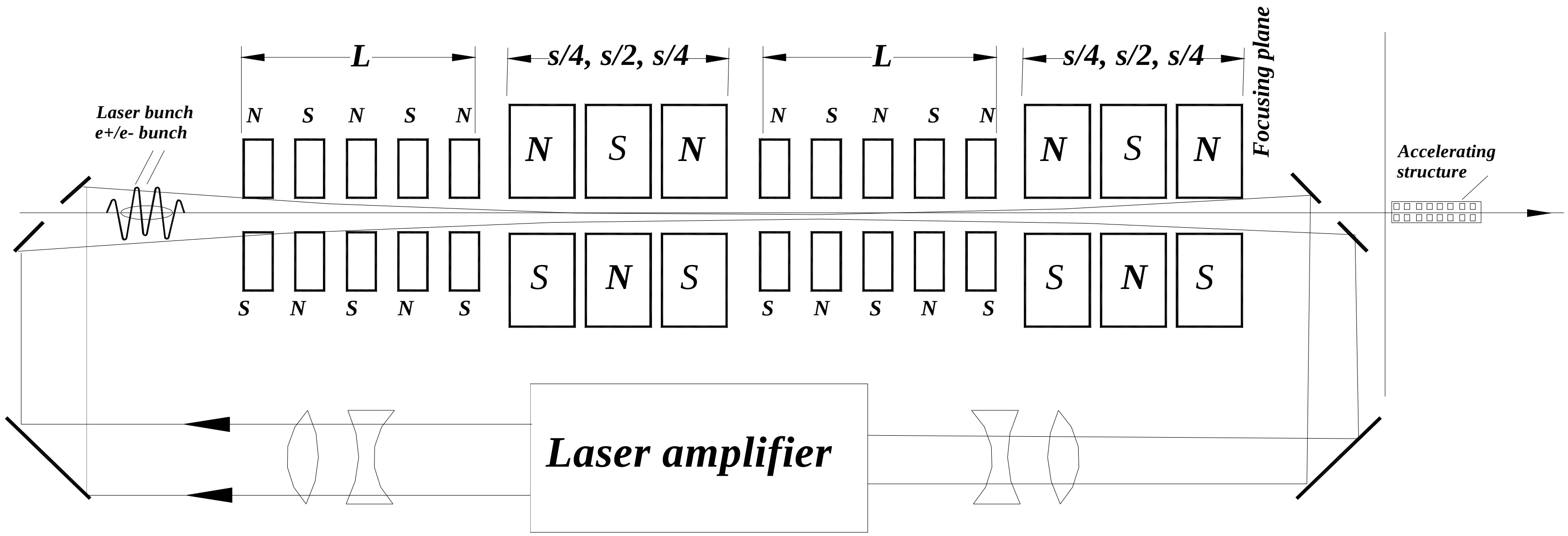


Arrangement of phase shifts in the cells

$$k_x = -\frac{1}{pc}\frac{\partial\langle F_x\rangle}{\partial x} \cong -\frac{e\lambda_{ac}E_m}{mc^2\gamma W^2} Sin\varphi$$

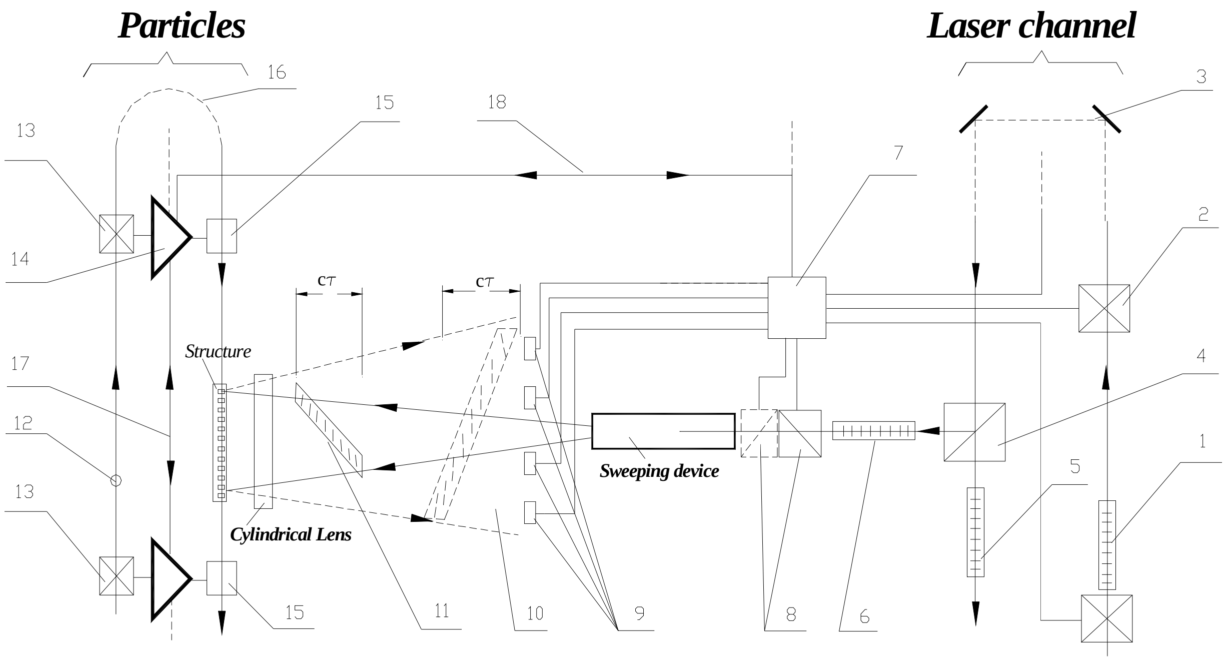
$$k_y = -\frac{1}{pc}\frac{\partial\langle F_y\rangle}{\partial y} \cong -\frac{e\lambda_{ac}E_m}{mc^2\gamma h^2} Sin\varphi$$

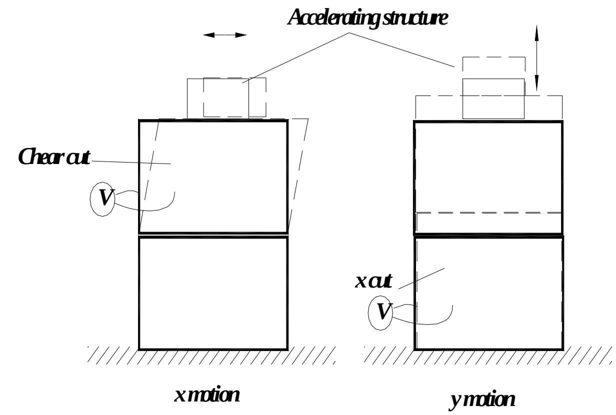
BUNCHING (1999)



A cascade bunching scheme. *K* factor in second wiggler is other, than in the first one. This scheme is an analog of a Klystron with two cavities and two drifts

FEEDBACK AND ALIGNMENT





Movement of structure

$$(\Delta\vartheta)^2 \equiv \left(\frac{\Delta p_\perp}{\Delta p_\parallel}\right)^2 << \frac{\varepsilon}{\beta}\left(\frac{p_\parallel}{\Delta p_\parallel}\right)^2 = (\Delta\vartheta)^2_{beam}\left(\frac{\gamma}{\Delta\gamma}\right)^2$$

1–is a driving laser bunch, 2–is transverse position sensor for a laser bunch, 3–is a laser back reflector loop, 4 –is a power splitter, 5–is a driving bunch on the way to next module, 6–is a splitted part of driving laser bunch, 7–is a processor, 8–are the beam deflectors for two transverse directions, 9–is an array of optical sensors, 10–is a reflected laser bunch, 11–is a sweeped laser bunch. 12–is an electron/positron bunch on the way to the beginning of accelerator. 13–are the pick up electrodes, 14–is a functional amplifier, 15–is a transverse kickers, 16–is a beam back returning loop, 17,18 –are the lines of the signal processed. Lines across the laser bunch indicate the wavefronts. The back loop 3 located at the beginning of accelerator (acceleration process).

$$\Delta\vartheta_y \cong 2\cdot 10^{-5}$$

$$\Delta\vartheta_x \cong 7\cdot 10^{-4}$$

EFFICIENCY OF DIOD PUMPING SYSTEM IS MORE THAN 50% (approaching to 75%)

Datasheet	Product Drawing	Application Notes	
		P10	P16
Optical			
Wavelength	nm	80x / 88x / 9xx	
Wavelength tolerance	nm	± 3	
CW output power	W	50 / 60 / 70	100 / 110 / 120
Fiber core diameter	µm	400, 600 @ 0.16NA 800 @ 0.13NA	400, 600 @ 0.16NA
Fiber length	m	2.0, 3.0, 5.0	
Slope efficiency	W / A	10.5	17
Electrical			
Power conversion efficiency	%	50 / 54 / 58	
Threshold current	A	1.0 / 1.0 / 0.6	
Operating current	A	5.8	7.0
Operating voltage	V	17	28
Series resistance	Ω	0.3	0.4

nLIGHT PHOTONICS Preliminary Data Sheet | **NL-SAG**

300W (cw), η_e=50%, λ=780-1000 nm

High Power Stacks

nLight Photonics' high power stacked bar module provides state-of-the-art power levels in a compact package. Starting with high power diode 1 cm bars, multiple modules are stacked to provide extremely high output power. These modules are water cooled to maximize output power without sacrificing the lifetime of the diode.

Optical	
Center Wavelength (Range)	780-1000nm
CW Output Power	300W (6 plates)
Center Wavelength Tolerance	±3.0nm
Array Length	1cm
Electrical	
Total Conversion Efficiency	50%
Threshold Current	10A
Operationg Current	60A
Operating Voltage	< 12V
Series Resistance	0.04Ω
Thermal	
Thermal Resistance	0.35°C/W
Operating Temperature	10°C to 40°C
Fluid Flow Rate	300 ml/min/plate
Inlet to Outlet presure drop	30 psi
Deionized Water Resistivity	.5 – 2Mohm-cm
Filter	< 20µm