**Dielectric acceleration and photonic »on-chip » module**

Jean-Luc Babigeon

Dielectric Acceleration, some insights

Past and prospective

Profile of our project : developpement of a missing stage of on-chip Linear Collider

Performance objectives of the integrated source

FEAs and DLAs : State of the art

Feas

DLAs

# *Dielectric acceleration and photonic »on-chip » module*

Jean-Luc Babigeon

CNRS-IJC-In2P3

Laboratoire Irene Joliot Curie

# Why Dielectric laser Acceleration ?



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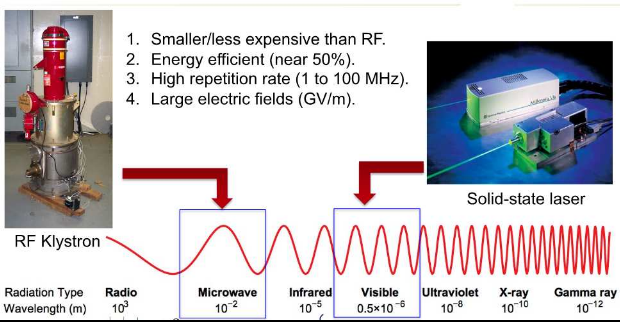

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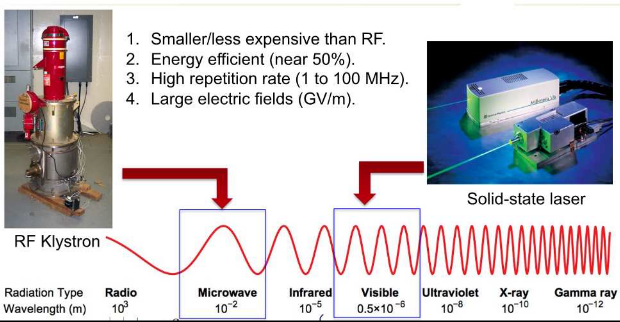

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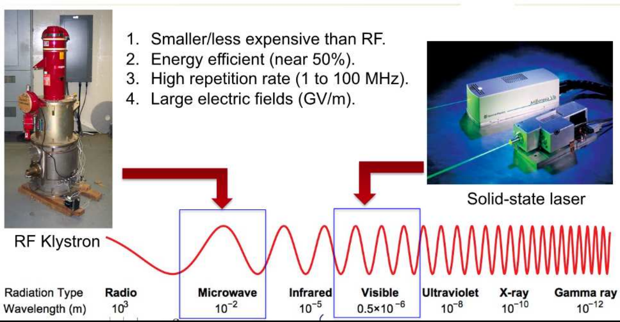


- Metal structure reach their strength limit E fields $\sim 150 MV/m$

# Laser Acceleration in vacuum, escaping Lawson-Woodward



Remind : W-W applies specifically to . . . *There is no net energy gain for an electron when interacting with a laser field Laser field in vacuum . . .*

## Examples of exceptions are :

1. boundaries (laser interaction not in free space/3D vacuum)
2. particle velocity not constant (ex sub relativistic) and/or trajectory not in straight line
3. non linearities (ex : plasmas)
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   (dielectric laser acceleration, laser beam forming, vortex...)

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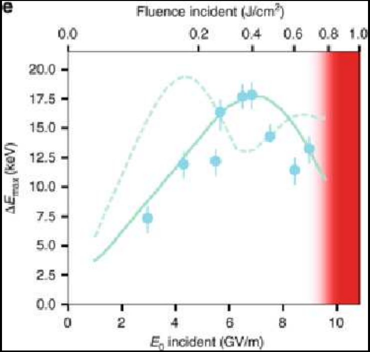
- 


FIGURE – Limits of non linear effects in Si dielectric, at e- 8MeV [D. Cesar, 2018]

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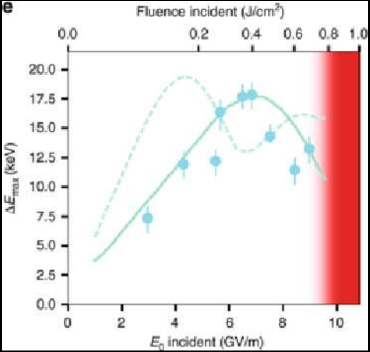
- 


FIGURE – Limits of non linear effects in Si dielectric, at e- 8MeV [D. Cesar, 2018]

- Laser intense fields + breakdown strength of dielectric = DLAs outperform standard acceleration some more

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# From 1968 to 2019

## Dielectric acceleration : recent but not new idea . . .

**LASER LINAC WITH GRATING**

Y. TAKEDA and I. MATSUI

*Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo, Japan*

Received 13 February 1968

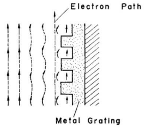


Fig. 2. Configuration of electric-field near grating surface.

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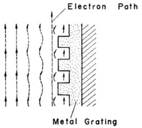


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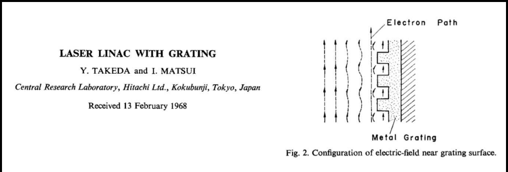

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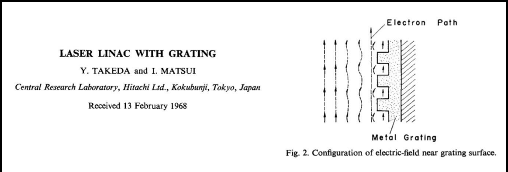

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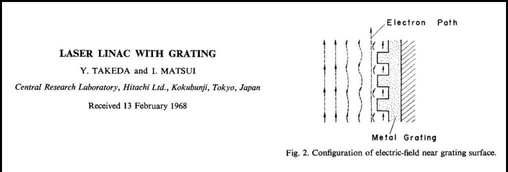

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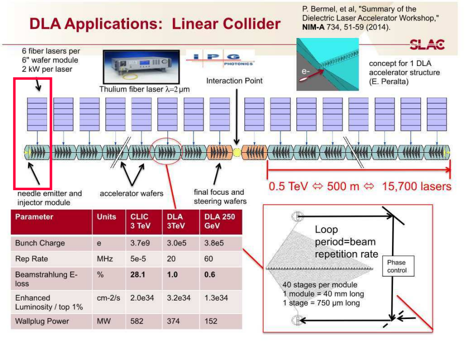
Then several major improvements : **High fields**, **tremendous** compacity associated to **low cost** structures

# To an integrated on chip e-source

- A **first stage** of a future photonic collider : a »photonic » e- source




| Parameter | Units | CLIC 3 TeV | DLA 3TeV | DLA 250 GeV |
|---|---|---|---|---|
| Bunch Charge | e | 3.7e9 | 3.0e5 | 3.8e5 |
| Rep Rate | MHz | 5e-5 | 20 | 60 |
| Beamstrahlung E-loss | % | **28.1** | **1.0** | **0.6** |
| Enhanced Luminosity / top 1% | cm-2/s | 2.0e34 | 3.2e34 | 1.3e34 |
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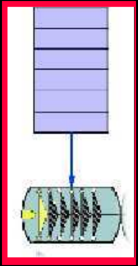

Figure – Needle emitter and injector module

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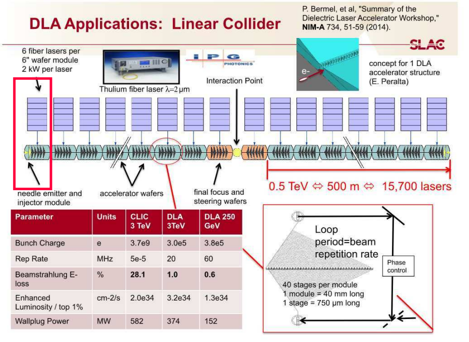


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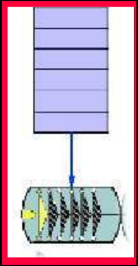

Figure – Needle emitter and injector module

- Inside the same chip, nanoemitters and first accelerating stage. Because e- like to repell each other... further ?

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DLAs

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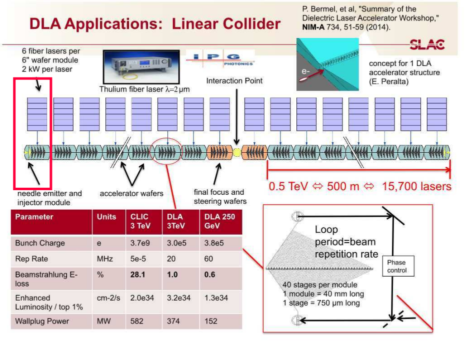


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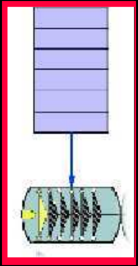

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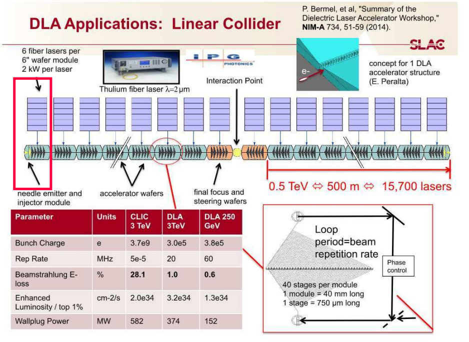


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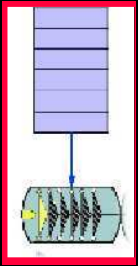

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# Performance objectives of the integrated source

Table of typical and significant parameters

| Parameter | Value | Comment |
|---|---|---|
| | **CHIP** | |
| Overall length | 1mm | |
| Dielectric | Si(fused), Al2O3,CaF2 | |
| DLA Grating pitch | from 250$nm$ to 2.5$\mu m$, more... | $\lambda_{pitch} = m_{harmonic}\beta\lambda$ |
| FEA population | 1000 | |
| Beam entrance | $< 1\mu m$ | |
| Graphene sheet | single layer | equivalent 1000 emit |

# Performance objectives of the integrated source



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Table of typical and significant parameters

| | ELECTRON BUNCH | |
|---|---|---|
| Charge/bunch | $30e- < Q < 0.1fC$ | |
| PrF of the Burst | $50MHz < PrF < 3GHz$ | |
| Macro Pulses | 1kHz | |
| Initial $E_0$ at first stage | $30 < E_0 < 50keV$ | |
| Energy dispersion $\Delta E_0$ | | |
| Emittance (flat beam) | $\sigma_x = 500nRad, \sigma_y = 5nRad$ | |
| $Coherencelength_{1MeV}$ | | |
| Polarisation | | |
| Output Energy | $<= 1MeV$ | |
| Dephasing length | $6\mu m$ | Laser $2\mu m$, $10GV/$ |
| Vacuum | $10^{-9} < P < 10^{-6}$ | High P with carbon |

# Performance objectives of the integrated source



Table of typical and significant parameters

| Parameter | Value | Comment |
|---|---|---|
| | **LASER** | |
| Wavelength | $800nm < \lambda < 10\mu m$ | visible LEDs, $1.5\mu m$ an |
| Spot size | $10mum$ | |
| Duration FWHM | $3 < FWHM < 100fs$ | |
| PrF | $0.1Hz - 80MHz$ | might increase |
| Pulse Energy | $160nJ$[Breuer, 2013] $- 200\mu J$ | might decrease |

# FEAs



## First studied FE (Field Emitter)

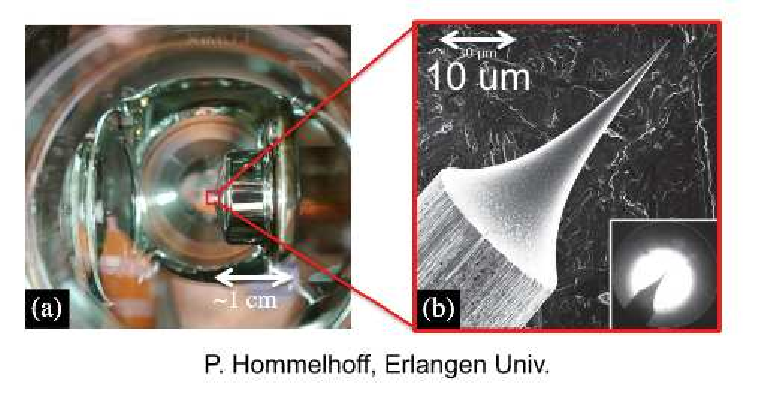


FIGURE – First FE

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## Field Emitter Arrays (FEAs)

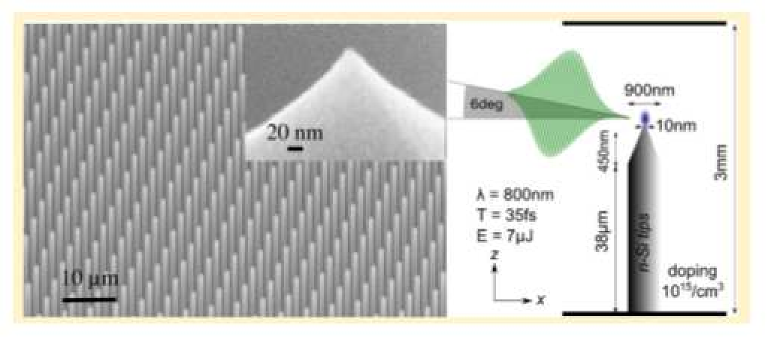


FIGURE – Silicon FEA

# FEAs

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## Coming to new avenues ? . . .

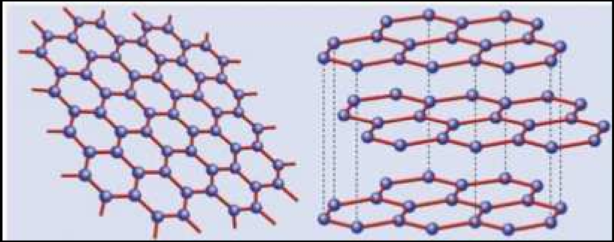

FIGURE – Graphene N-layers, [Novoselov, 2009]

Some + ?

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## The most studied DLA

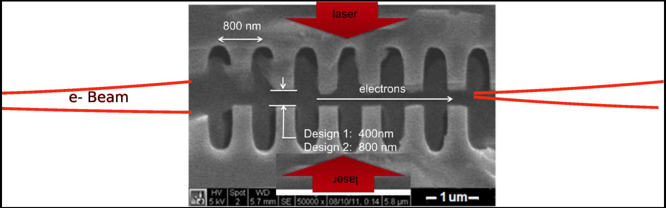


Figure – grating

# DLAs

Other examples

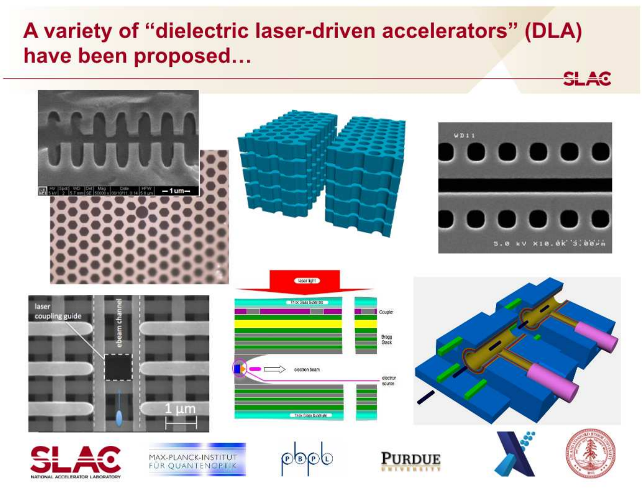


FIGURE – other examples

# DESIGN 1.0 (2/3D)



## A first principle

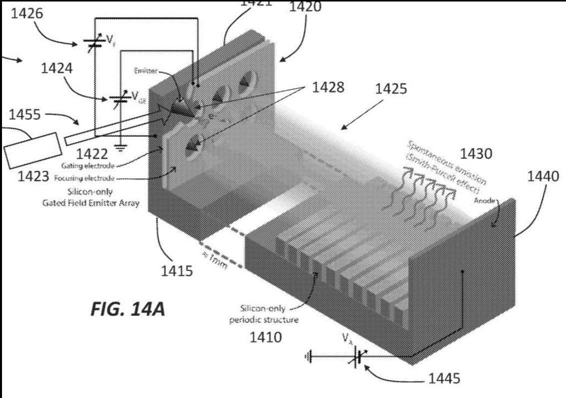


FIGURE – Patent from MIT/Keithley, mars 2019...

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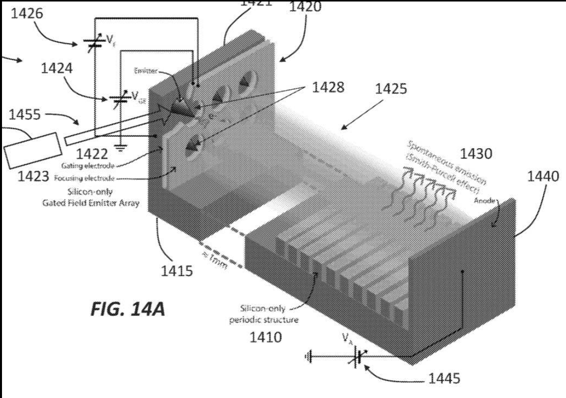
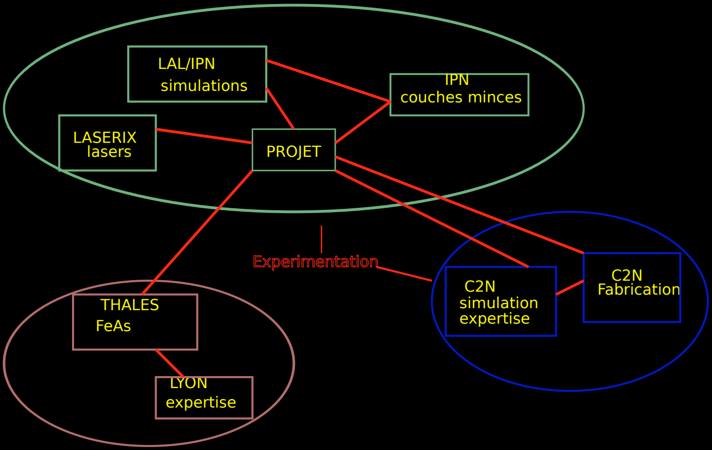



Figure – Patent from MIT/Keithley, mars 2019...

# ORSAY LABS : RESOURCES



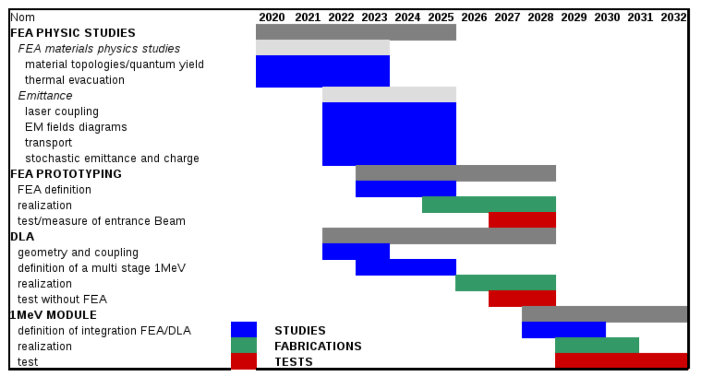
Functional Proposition



# ORSAY LABS : RESOURCES



## Scientific collaborations / Exercise of planning



# Validations



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Designs and simulations

# Validations



Designs and simulations

Emission characteristics, *abinitio*, Electromagnetic fields, PIC simulations

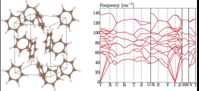


Figure – *abinitio*, Work function, $\beta$ ...

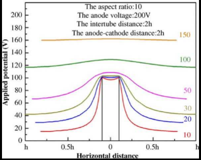


Figure – EM fields

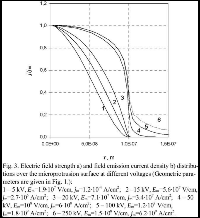


Figure – EM fields

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Designs and simulations

Design, diagnostics identified

1. SEM, EDS, STEM, Raman Spectroscopy, 2D spectroscopy (seam space)
2. Fowler

# Validations



Designs and simulations

Mesure of the output beam, Test of the module

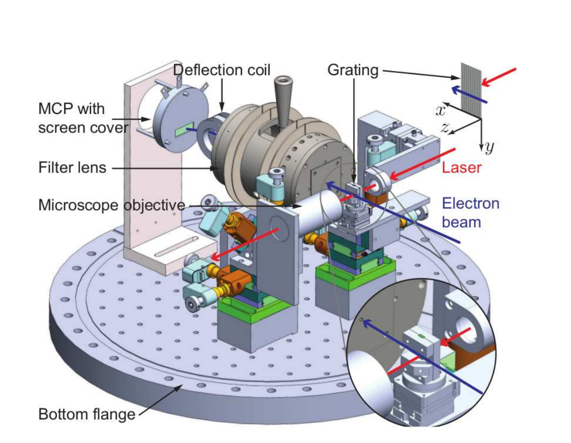


FIGURE – low volume - low **equipement** investment

The end for further reading

# For Further Reading



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*High-field nonlinear optical response and phase control in a dielectric laser accelerator.*
Communications Physics number 46, 2018
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square note

square one

## Field equations lead to attenuation factor

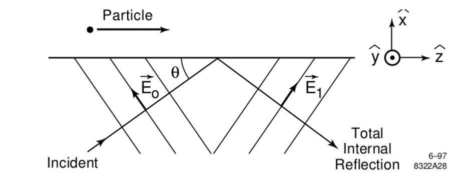


FIGURE – Available field for a particle near an illuminated dielectric

square one

## Field equations lead to attenuation factor

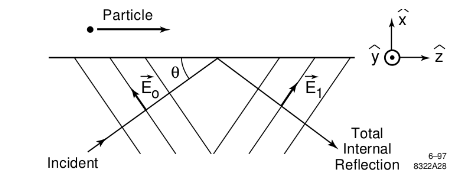


FIGURE – Available field for a particle near an illuminated dielectric

square one

- Field equations lead to attenuation factor

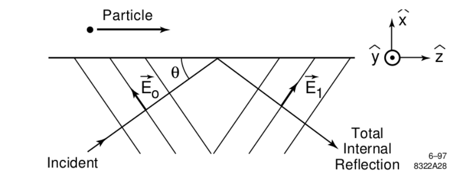


Figure – Available field for a particle near an illuminated dielectric

- Available energy gain and fields with field reduction [?]

$$\frac{dE}{ds} = \frac{-2ieE_0\frac{n}{\beta}}{\gamma + \frac{in^2}{\sqrt{(n^2\beta^2-1)}}} e^{\frac{-\omega x_0}{\gamma\beta c}} e^{i\frac{\omega}{c}nz_0 cos\theta} \quad (1)$$

So with 8MeV incident e- beam, $\gamma \sim 16$ and a laser field of 10GV/m gives 625MV/m available. With a chip of 1mm, we can expect a kick of 625MeV.(In fact, for [?], $L_{eff} = 21\mu m$)

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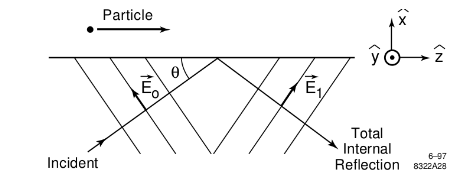


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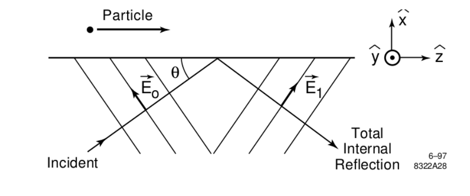


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- note : extreme Efield strength limits for Si, 30GV/m

# What happens with a field effect emitter in free space ?

square one

- Geometry of the equivalent antenna simulation

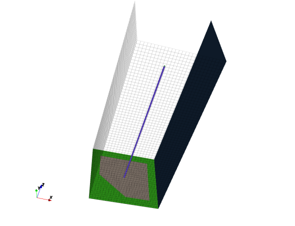

Figure – figure gauche

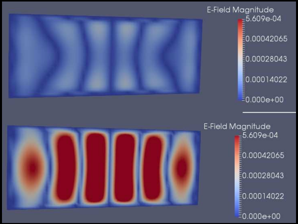


Figure – figure de droite

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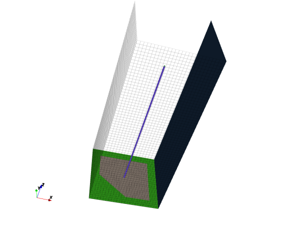

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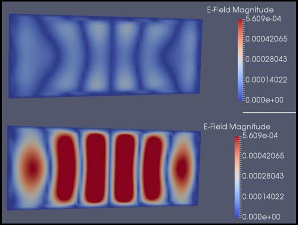


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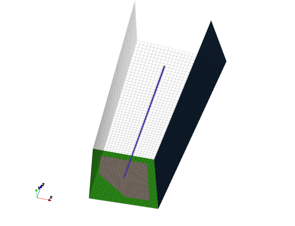

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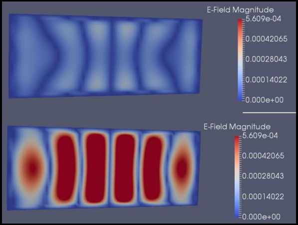


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# Electrons like to repell each other...



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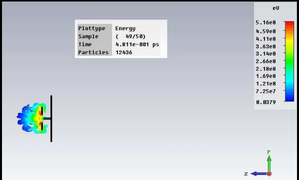


FIGURE – A naive picture (but some 1st order physics)

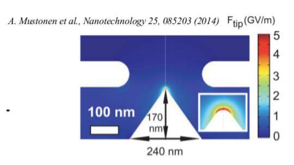


FIGURE – A more real -and less pessimistic description

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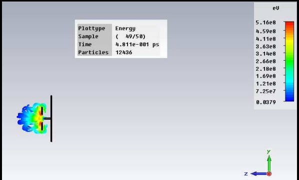


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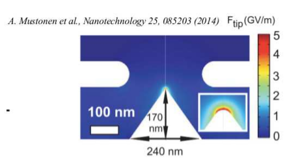


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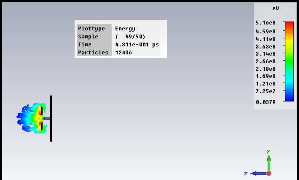


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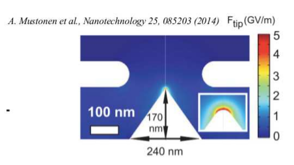


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# Some insight about graphen physics...Mono and few layers



Graphene is made from the mono(or few properly assembled) atomic layer extracted from graphite. It represents a pure 2D form of an interesting class : »materials with topological charges » ie one can produce artificial graphene with many other tricks. But graphene is a beautiful object for Physics !
Its hexagonal structure reveals 2 sub networks A and B, with basis vectors $a_1$ and $b_1$. Computation gives a band structure of energy levels (pseudo-spin), generated by

$$f(k) = \sum_{ij} e^{k_{ij} R_{ij}} \tag{2}$$

where $k_{ij}$, $R_{ij}$ are reciprocal vectors ($kR = 2n\pi$) and network vectors. In a quantum description, The band structure is then given by :

$$E = \pm t\sqrt{3 + f(k)} - t^{'} f(k) \text{ solutions of the Hamiltonian}$$
$$H = -t(\sum_{ij}(a^{+}_{\sigma,i} b_{\sigma,i} + cc) + t^{'}\sum(a^{+}a \ldots + cc \ldots) \text{ where concretely}$$
$$f(k) = 2cos(\sqrt(3)k_y a) + 4cos(\frac{\sqrt(3)}{2}k_y a)cos(\frac{3}{2}k_x a)$$

a,b are creation and annihilation operators for hoping inside from A to B (t), and inside A ($t^{'}$). We don't take real spin $\sigma$ in account. Plotting 2D energy surfaces-fig 12 thanks to f(k), enlight several contact points, **K** and **K'**, localized on edges of BZ. They are solutions of $E_{+} = E_{-}$ Around these points, the first order energy writes as : $E \sim v_F q$ where $k_{Kpts} = K + q$ and $v_F = 10^6 m/s$ . **It is a signature of a relativistic massless fermion**, indeed, compared with the classical electron form $E = \frac{k^2}{2m*}$

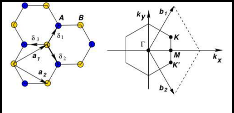


Figure 2 (Color online) Left: Lattice structure of graphene, made out of two interpenetrating triangular lattices ($a_1$ and $a_2$ are the lattice unit vectors, and $\delta_i$, $i = 1, 2, 3$ are the nearest neighbor vectors); Right: corresponding Brillouin zone. The Dirac cones are located at the K and K' points.

Figure – from[Novoselov, 2009]

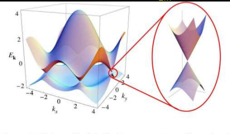


Figure 3 (Color online) Left: Energy spectrum (in units of $t$) for finite values of $t$ and $t'$, with $t$ =2.7 eV and $t' = 0.2t$. Right: zoom-in of the energy bands close to one of the Dirac points.

Figure – citation id

# Some insight about graphen physics...Mono and few layers



Fourier developpement of operators a,b near K,K' lead to hamiltonian formulation :

$$H = -iv_F \sigma \nabla \tag{2}$$

, and 2 spinorial solutions,

$$\psi_{\pm,K} = \frac{1}{sqrt(2)} \begin{pmatrix} 1 \\ \pm e^{i\theta_k} \end{pmatrix}$$

and a reverse sign of $\theta_k$ for $\psi_{\pm,K'}$.
Dirac 2D particles are subject to **klein paradox**, ie they could tunnel across a square potential **without loss**. It can be verified with the continuity relations of spinors across potential barrier As f(k) is not developped along z, the tunnelling occurs only into xOy, so particularly at the edges.
We can meet 2 types of edges, zigzag and armchair (fig **??**) :

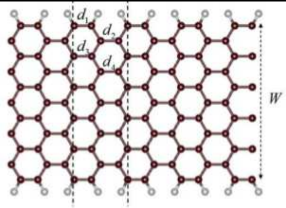


Figure – zigzag and armchair edges

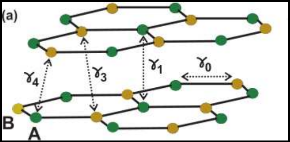


Figure – configurations of multi layers of graphene

Field Emission and Laser Photofield capacity at edge depends also on Density of States (DOS), which has an intricate expression. To say it simpler, zigzag edge presents some surface states - armchair should not have it, in present knowledge - and the armchair emission could be much more important than zigzag one. Graphene sheets are also used in 2 configuration, Bernal and orthorombique (fig **??**). Depending on the configurations, behaviour of electrons may be -or not- quasi-particle like.

# Some insight about graphen physics...Mono and few layers



Some remarks :

1. Field Emission and Photofield will be sensible to DOS and geometrical configuration (edge/armchair,. . . )
2. Emissions will be sensible to the choice of single or multi-layers
3. Many variants are possible with that young physics

square one

# ACHIP collaboration CERN/ALEGRO initiative



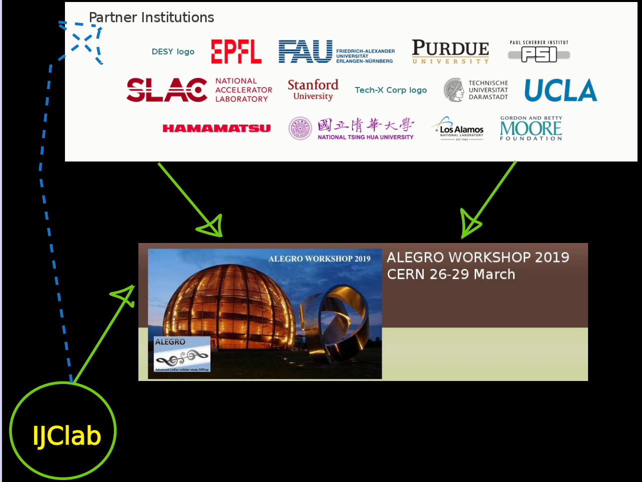


FIGURE – Interest to engage collaboration to ACHIP