FEMTOSECONDE ELECTRON BUNCHES BETWEEN FEA [1] PHOTO-CATHODE AND FIRST STAGE OF A DLA [2]

QUALITATIVE DESCRIPTION

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Introduction

The principle of DLA based electron sources for next generations of high energy light sources and lepton colliders has already been explained [5]. A first recent study precised more deeply the faisability of multistage acceleration at low energy [4], so despite numerous remaining technical issues, the "accelerator in-chip" concept starts to acquire more strength. Among difficulties, stays the design of a bright electron source adapted to the first acceleration stage. We have precedently described the principle of such association FEA/DLA [1], [2]. That presentation points out :

1. a more detailed scheme of an electron source, designed for a first stage injection in DLA,
2. a numerical evaluations of electron bunch parameters,
3. a qualitative description of bunch transport, from FEA to DLA

Two concepts could be examined :
The figures 1, **coaxial geometry**, and 4, **2D layout**, illustrate these two differents approaches :

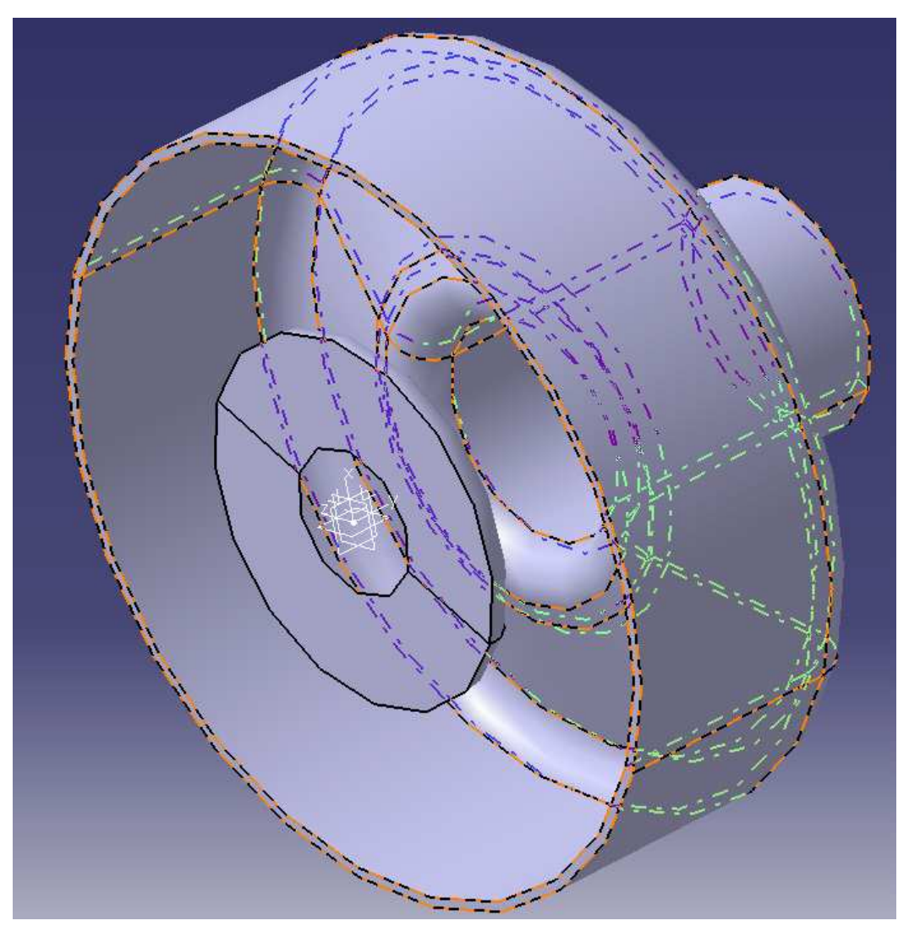

Figure 1 – project for electron coaxial pulsed gun

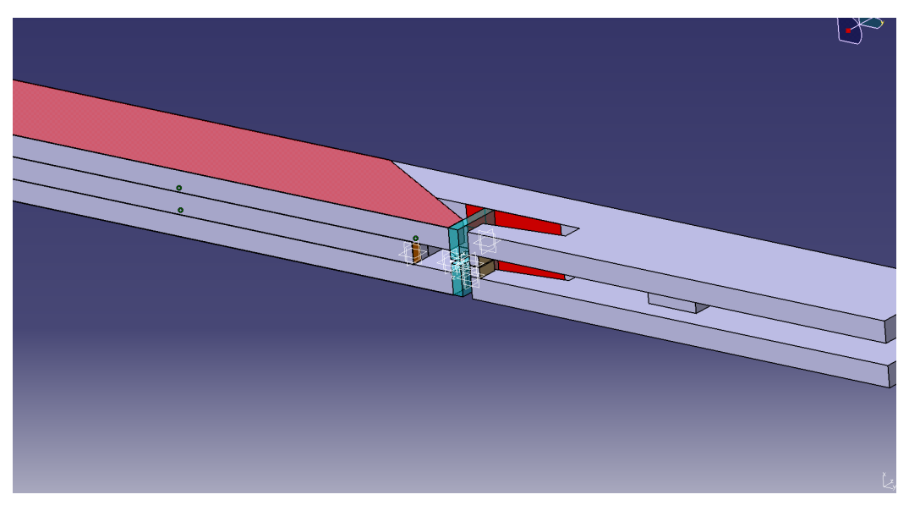

Figure 2 – 2D layout idea for in-chip source

We have opted for the coaxial design of figure 1[a]. The DLA first stage is put immediately after the anode iris, so we plan to avoid any electron optic between the two devices.[b]. The DLA is of standard design, a corrugated symetrical lattice, and will be positionned by precision actuator.[c][d]
That presentation is based on analysis of FEA/DLA compatibility. To our point, it implies :

1. a numerical evaluation of emission phenomenon, near from the cathode,
2. a qualitative description of electron bunch behaviour between cathode and the entrance of DLA

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[a] however the FEA is intended to be a flat beam, in order to improve emittance in the DLA entrance section

[b] Placing intermediate optic keeps the spatial extension low, but introduces other chromatic or non paraxial defects. It is then to be verified that inside the short propagation distance, less than 1 cm, without supplementary optic, the bunch will not expand too much

[c] The specification of that future demonstrator of electron source will be available very nextly

[d] I have recently analysed the design elaborated by [10], so I shall not compare it, but -in short- the floating electrode acts as a guard in a DC gun, and we face again with drawbacks high continuous voltages. Nevertheless, it is shown that in 10keV range, **no supplementary optic device** is required to drive correctly e- to the DLA entrance. Comparing with our pulsed proposal, our anode play that role during electric nanosecond pulse, and we have determined distances roughly equal to those of that publication. Regarding relaxation breakdown on pulse mode, we could probably reduce these distances and improve the performances.

I Numerical evaluations

1. Schottky emission and electromagnetic fields

The two FEA structures have been precedently defined. The simulation geometry is given by figure 3 ; first field results with openEMS software [9] are given by figure 4

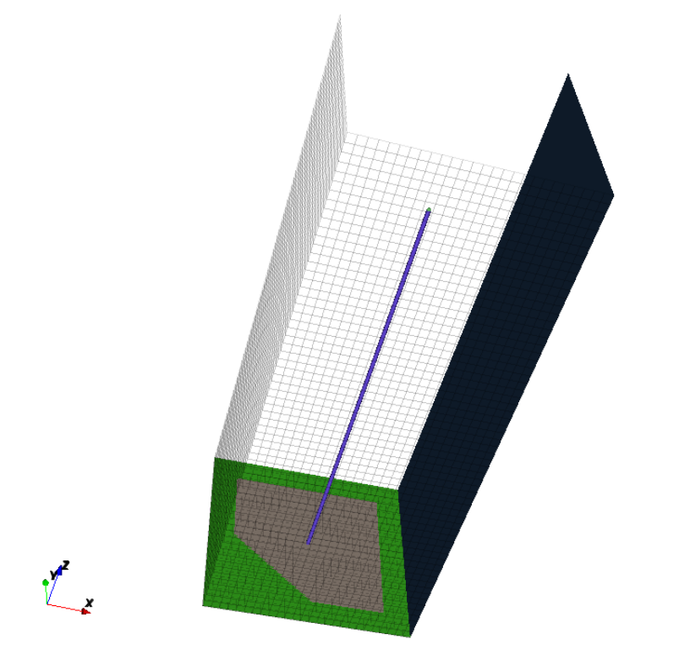

Figure 3 – tip geometry : $h = 2\mu m$, $apex = 10nm$

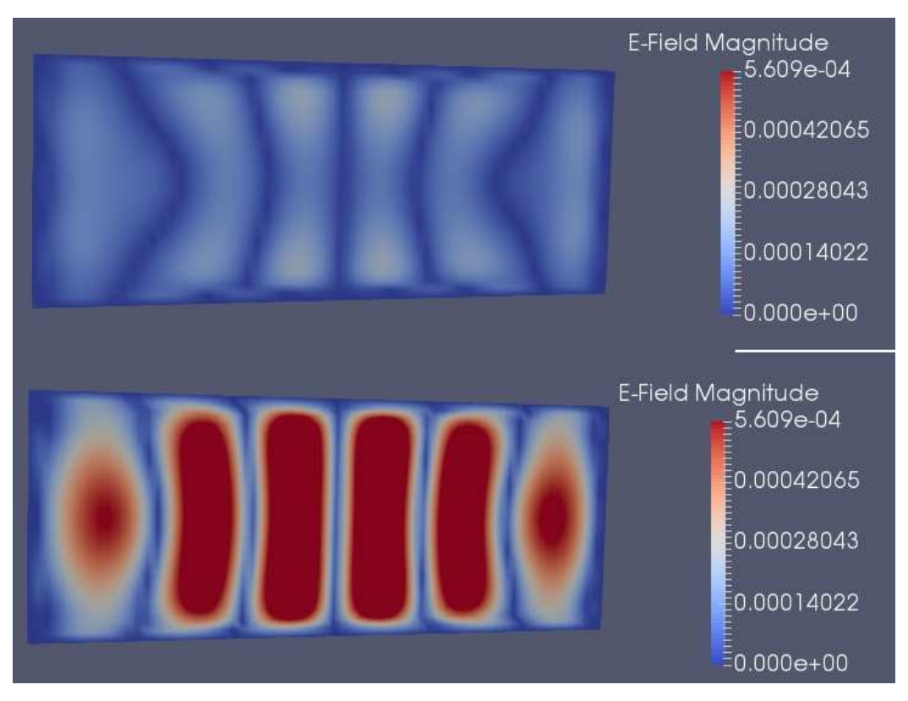

Figure 4 – Efield transient tip Response to laser gaussian 100fs pulse, opposite plane, times 95 (up) and 139fs

Intertip distance is taken to $2\mu m$. The cathode is to be pulsed by nanosecond 10kV voltage, at less 1MHz rate. We evaluate the field amplification $\beta \sim 11$.[12][a]. The gap cathode-anode is 3mm. The peak macroscopic electric field is -without tip- $E_{gap}^{electric} = 3.3MV/m$, and with tip, $E_{Schottky}^{electric} = 36MV/m$. The laser field is evaluated to $1.28GV/m$ without tip amplification, and to $14.1GV/m$ with tip. We took for the work function of Carbon Nano Tube, $\phi = 5eV$ [11]. Computation from FN theory [6] shows for current density, $J^{electric} = 0$ and $J^{laser} = 4.3710^{11}A/m^2$. The apex surface is $10x10nm^2$, then the effective peak current by pulse will be $i = J \times S = 43\mu A$. For such β, the -notable- Schottky current threshold is 1mA for $1GV/m$ across the gap, so the applied voltage should be 10MV across 3mm[b] to generate a comparable Schottky emission.

In the proximity of cathode, space charge limited current

$$J_{SCL} = \epsilon_0 \sqrt{(\frac{2e}{m})} \frac{V^{\frac{3}{2}}}{l_{beam} d_{cathode-anode}} \quad (1)$$

was computed in these conditions, with 100fs bunch, to $1.810^8 A/m^2$. Nevertheless, in the space charge formula the distance cathode-anode must be replaced by the real laser acceleration distance. For example if $l_{laser} = 100nm$ the space charge limit is certainly higher by 6 orders of magnitude. After that first zone, the current density decreases well below the Space Charge limit.

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[a] β seems to be under evaluated here

[b] which is to my knowledge not feasible in practice with such a distance, even inside ultra low vacuum

2. Maximum entrance current in DLA

In other side, we computed the maximum current that could accept the first stage of a DLA module, starting at 10keV [4]. If we consider a sub laser cycle micro bunch and admit a beam equilibrium, the maximum entrance current is given by :

$$I_b = I_0 \frac{G\beta\gamma r_m}{2m_e c^2} \quad (2)$$

where :

1. I_0, Alfven current, 17kA,
2. β, γ, relativistic electron factors, m_e electronic mass, c, light speed,
3. G, acceleration gain

G was computed with laser field. The laser source is specified for 70kW, for a beam size of $\sigma_x = \sigma_y = 2\mu m$ so is the figure above, of $E_{laser} = \frac{\sqrt{(P_{laser} Z_0)}}{\sigma_x \sigma_y} = 1.28GV/m$. The acceleration G was computed by a heuristic-like expression [4], extracted from simulations : $G = 0.027$, so we find at last : $I_{max}^{DLA} = 34mA$
We can conclude :

1. with a 10kV pulsed cathode, Schottky effect will not contribute to dark current, for the laser induced emitted bunches,
2. the photo-emitted current, evaluated in our project with a CNT structure, will be better $43\mu A$ for only one tip,
3. given a maximum peak current of 34mA for DLA max current, for a matched design if we want that source current equal entrance current, we can multiply the number of tips,
4. these two figures show that for example an array of 1000 tips should be sufficient to correctly match the DLA.

Finally, the real current inside an optical cycle, ie an attosecond bunch, will not be 34mA. If we take in account the optical cycle duration and estimate to 10% the useful accelerating phase range, the charge by optical cycle will be $Q_{bunch} = 9.1510^{-18}C = 57 electrons$. In practical first experiment, the timing sequence has been estimated with 30 useful micro pulses inside a 100fs pulse. With present version of HV pulsed source, $f_{rep} = 10Hz$, so the total charge is estimated to $Q_{10Hz} = 30 * 57 * 10 = 17100e- = 2.73fC$. With a 1MHz future version, $Q_{1MHz} = 273pC$, which is an interesting result, knowing that the maximum charge is lower in sub relativistic stages than in others. The FEA cathode is to be designed for a flat beam, so we consider a linear array. This has some consequences about laser excitation and propagation.

II Emittance evolution

1. Description

It is customary to argue that the Schottky reduction of intrinsic emittance should be balanced by the quenching of quantum yield [14]. But if density of State (DOS) is of non standard nature, like CNT on a Bernal plane of graphene, the quantum yield may stay significant at very low emittances.
Now, let's take current density evaluated before. Then, for $i = 43\mu A$ for one tip, in his immediate vicinity, there will be $N_{e-} = 43\mu A * 100fs = 4.310^{-18}C$. it corresponds to 26 électrons. In quasi-static dipole approximation, where tip radius is far lower than wave length, [7], the field component decreases as $\frac{1}{r^2}$ in the beam axis, so at the axial distance R_0, the field amplitude is roughly $E_{R_0} = E_{1nm}\frac{1^2}{R_0^2}$, [a]. So at 100nm, $E_{100nm} = 1.4MV/m$, which is lower than the mean field of the 3mm gap under 10kV voltage. We can deduce that there are 2 principal zones, ($z < 100nm$ and $z > 100nm$) inside which electron dynamics, even physiognomy, is strongly different. Are the Coulomb interactions $e - e-$ screened or not in first zone ? We estimate the density inside 100nm, supposing that 27 électrons are effectively located uniformly inside a 100nmx20nm tube. So electronic density is about $\frac{27}{100*20*10^{-18}} = 1410^9 e - /cm^3$. I found a Debye length of $628\mu m$, far above typical size of the beam. So particles are strongly correlated in the first zone.

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[a] if we consider that electric field is strongly localized inside a reference distance of 1nm

1. Some theoretical approach

Few descriptions are applicable to an electronic gaz, because the environnement is generally inside solid or multi species plasmas. As Broglie wavelength of electron is 123pm at 100eV, we may consider it as a particle inside first zone. An intuitive model is to evaluate the N-body interaction as a recurrence process [3]. The N-particle Green operator is constructed on the already knew N-1 one by a cluster concept. The figure 5 illustrate the decomposition.

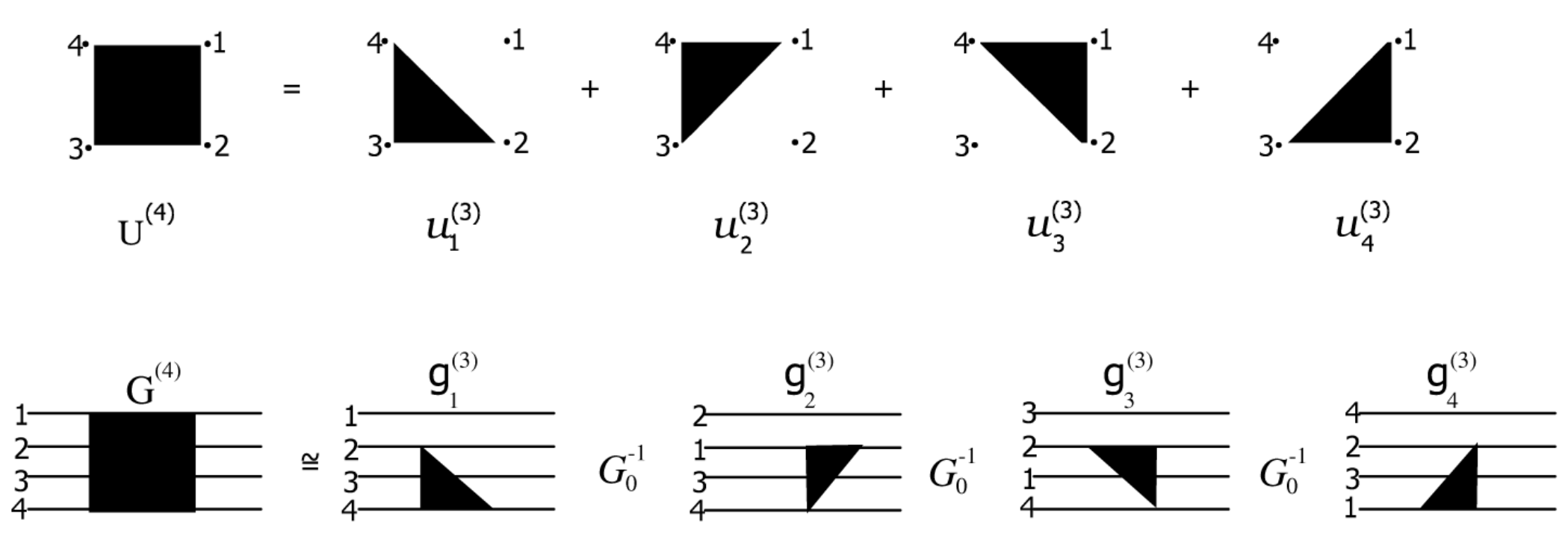

Figure 5 – decomposition of Green operator on 4 particle cluster - from [3]

More precisely we have :

$$G^{(n)} = \prod_{j=1}^{n-1} (\tilde{G}_j^{(n-1)} G_0^{-1} \tilde{G}_{j+1}^{(n-1)})$$
$$\tilde{G}_j^{(n+1)} = G_0 + G_0 u_j^{(n-1)} G_j^{(n-1)}$$

Where G_j^k is the Green operator of particle j in a k-interaction potential $u_j^{(k)}$. Then, we can « propagate » the numerical solution at order n if we now the solution at $n-1$ order. It is closely related to GW method, but with the original idea of recurrence.

Discussion :

1. the 2-body elementary potential is arbitrary rending that method very powerful,
2. in his references, the author consider singularities only as collisions, we could imagine long range interactions, where low influence is present,
3. the numerical results are not validated for a great number of particles like 27 ; results were given for 4 particles,

There is an other approach which makes analogy with gravitational potential [8]. But in that case, N-body interaction is analysed in periodic systems (synchrotron)In the restricted problem, [13], the singularities are treated by local regularization, consisting of scaling space and time by functions in complex plane.

III Experimental project

A first specification draft of an experimental setup has been recently written. Its scope is to demonstrate the integration in a first non relativistic DLA stage, of a FEA source.
In spite of serious contributions [4], we face to many -now well known- challenges :

1. precision positioning of the beam at the DLA entrance,
2. coupling of laser to FEA, and proper focusing between FEA and DLA,
3. synchronisation of electric HV pulsed generator to laser. picosecond range or less if possible, regarding jitter, is the objective,
4. thermal issues,
5. measurements of ultra fast bunches...

In other side, we need microelectronic components, like FEA, DLA...So we have defined fabrication procedure and presented a fabrication project to IEF Orsay

IV SUMMARY

1 We have analysed two new designs of FEA sources interfacing them with a first DLA stage and showed the practical deasibility. The total charge, in the case of 1MHz pulsed cathode with 10kV peak voltage, is reaching 273pC with a 1000 tips FEA.

2 The main chalenge is now to verify that a passive focusing, ie good perveance of the gun, will allow us to transport the bunch without any supplementary optics. The behaviour of electronic gas in the first zone seems predominant. Coulomb explosion must be constrained by focusing forces.

3 It is intuitive that we must not also deal with simple transport optic software in the first zone. In fact, electronic distribution will not behaves as frequently assumed Gaussian distribution. It is the scope of next work to study that question.

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