Contribution aux exercices de prospective nationale 2020-2030

Accélérateurs et instrumentation associée

Innovating Photonic MeV Module (PMM), for dielectric acceleration
Application to photonics and THz acceleration

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consultations have been done, but too late for any scientific and administrative caution to be collected. Instance representants informed/consulted : C2N, Desy/Ares/Sinbad, FLUO/Accl Dpt, Thales

Contribution à rédiger en français ou en anglais et à envoyer à PROSP2020-GT07-COPIL-L@IN2P3.FR avant le ***1***

1. Informations générales

Titre : Innovating electron source (Field effect emitters, FEA) for dielectric accélération Application to Dielectric Laser Acceleration, (DLA) by photonic or TeraHerz techniques

Acronyme : ***PMM***

Résumé *(max. 600 caractères espaces compris)*

High Energy physics (HEP) quest leads to concepts like 30TeV e+ e- collider. Required compacity and costs are not compatible with conventional CERN like technology. Among new proposed alternative, is Dielectric Laser Acceleration (DLA).

DLA demonstrators have to be compelling in MeV, GeV and TeV ranges. The MeV one will be a critical step. For that we anticipated the need of innovating electron sources based on Field Emitter Arrays (FEAs), integrated with the MeV acceleration stages, in the frame of accelerator on-chip.

Préciser le domaine de recherche *(plusieurs choix possibles)*

- ***Sources de particules*** *(**électrons,** positrons, muons, protons, ions lourds stables, ions radioactifs…) et cibles associées*
- *Accélération plasma (électrons, ions…) et* ***interaction lasers/faisceaux***
- ***Technologies*** *RF* ***innovantes*** *(structures haut gradients, alimentations RF…)*

Préciser la motivation principale visée par la contribution:

- ***Accélérateurs pour la physique des particules***
- ***Accélérateurs pour les sources de lumière*** *ou de neutrons*
- *Accélérateurs pour les applications sociétales (**santé**, énergie, **industrie**…)*

2. Description des objectifs scientifiques et techniques

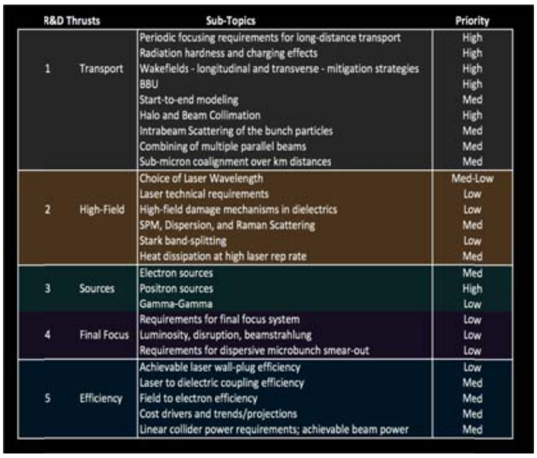
(2 pages max incl. figures)

Décrire les objectifs scientifiques et/ou techniques de la contribution proposée en en précisant les motivations.
Préciser comment ces objectifs se situent par rapport à l'état de l'art et au contexte international (ex : est-ce une contribution visant un développement théorique ou expérimental ? Est-elle dans la continuité de concepts ou technologies actuelles, ou bien est-ce une nouvelle approche conceptuelle ?)
Préciser les liens éventuels avec d'autres projets nationaux ou internationaux existants ou envisagés.

The 2020-2050 emergent HEP requests 1 2may imply the exploration of 0.1 to 30 TeV range by a precise tool like an electron-positron e+e- collider. Such a machine based on conventional techniques, with 50-100 MV/m gradients in metric sized cavities, should have a 100 km footprint, an excessive cost of multi milliards of Eu, and environnemental construction consequences. Only change of paradigm -very high gradients and drastic size of component reduction – brings us a reasonnable alternative. This is analogue to the replacement of 60's super computers by today portable PC.

Such e+e- new collider definition has been initiated inside ANA workshop3. Among promising technologies -most of them theoretically predicted in 90s decade4 but not today implemented[1]- Dielectric Laser Acceleration, DLA, presents anticipated performances such a grow of 10 ratio at least in accelerating gradients, 1 to 40 GV/m, an outstanding compacity – accelerator on chip concept4 – leading to estimated 1,5km footprint against 100km precedently, an anticipated tremending cost reduction due to suppression of all magnetic and electric cumbersome electron optics, natural staging ability and linear mode functionning, generalization of low cost solid state lasers, and serial production of nanometric (or millimetric precision devices if THz) DLA stages, the ability to accelerate identically e+ as e- by a simple phase change [2], and a strong reduction of Bremsstrahlung losses due to low bunch charges.

ANA workshop decomposed the TeV objective in three strategic steps, MeV, GeV and TeV to Interaction Point, IP, stages. In next decade, MeV and GeV demonstrators are logically waited. The following table from [3] explicits the main research stepping stones for DLA technology.



R&D Thrusts		Sub-Topics	Priority
1	Transport	Periodic focusing requirements for long-distance transport	High
		Radiation hardness and charging effects	High
		Wakefields - longitudinal and transverse - mitigation strategies	High
		BBU	High
		Start-to-end modeling	Med
		Halo and Beam Collimation	High
		Intrabeam Scattering of the bunch particles	Med
		Combining of multiple parallel beams	Med
		Sub-micron coalignment over km distances	Med
2	High-Field	Choice of Laser Wavelength	Med-Low
		Laser technical requirements	Low
		High-field damage mechanisms in dielectrics	Low
		SPM, Dispersion, and Raman Scattering	Med
		Stark band-splitting	Low
		Heat dissipation at high laser rep rate	Med
3	Sources	Electron sources	Med
		Positron sources	High
		Gamma-Gamma	Low
4	Final Focus	Requirements for final focus system	Low
		Luminosity, disruption, beamstrahlung	Low
		Requirements for dispersive microbunch smear-out	Low
5	Efficiency	Achievable laser wall-plug efficiency	Low
		Laser to dielectric coupling efficiency	Med
		Field to electron efficiency	Med
		Cost drivers and trends/projections	Med
		Linear collider power requirements; achievable beam power	Med

Our proposed contribution deals with the developpement of DLA MeV energy stage with direct on chip integration of innovating Field Effect Emitters electron source (FEA). Such a composite device should generate femtosecond (fs) polarized electron bunches with very high Pulse Repetition Frequency (PrF) 50MHz and with very low charge, from 1 to 10^4 e-/pulse. Let's recall that this device may be staged/compatible with any friend technology other than pure photonics, for instance THz accelerator modules. Such on-chip collider permits to reach Luminosity performance of 10^{36} $cm^{-2}sec^{-1}$ but should also drastically improve the detection diagnosis, rendering the IP tremendously more defined, in size (emittance and low number of e-) and spin (beam polarization) with a much less unwanted background.

Field Effect, more precisely laser assisted field emission belongs to standard mechanisms of electron cathodic emission5. e- are braught to vacuum energy state by electric field enhancement due to tip arrays, in a Spindt like design6. The electric field applied to the tips is generated by high frequency HV pulse generator, pulsed or CW RF7, and then electrons are emitted in proper phase thanks to the supplementary energy of a short laser pulse hitting the tips. In adequacy with cost/compacity and on chip requirements, the e- source doesn't use high power klystrons/modulators, so output is a low energy bunch3.

In order to constrain emittance, the best trick is to directly integrate the FEA inside a DLA stage, and reach as soon as possible relativistic range. It was evaluated 8 that starting from 0 keV to 1MeV could be done with as less as 3 DLA stages of total length approx 1mm, fabricated on the same wafer. FEA, typically far from 1µm to 1st stage, will deliver a beam section compatible with the thin 1µm acceptance of DLA relatively to emitted bunches. Still now, the experimental Field Effect was obtained by the HV column of a microscope8, losses at the entrance reducing significantly the useful bunch charge inside the first stage[4]. A schematic view of the future couple FEA/DLA is represented hereafter :

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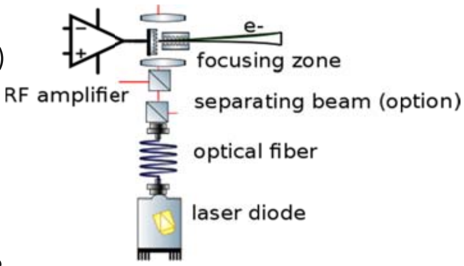
1 So although not a new concept, it may generate many innovating devices, and perhaps enlighten some remarquable phenomenas in accelerator physics, interaction laser-bosons and quantum phenomena associated with emission in recent cathode materials (graphene and CNT)

2 Positrons generation is not studied in that document. The R&D on the high intensity positron sources will be addressed within the corresponding task in the Next Particle Colliders (NPC) proposal.

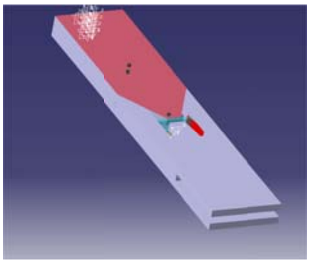
3 In one experiment was succesfully introduced a Q coefficient for DLAs, enhancing the field and I suggest also to do it in the space between cathode and 1st stage. Such weakly resonnating mode is intended to homogeneize the mean field in that entire space between FEA and 1st DLA

4 It is why I should requalify as «High» the priority of RD&Thrusts n°3 / electron sources, instead of «Medium»



This ambitious R&D program is probably in phase advance at present time : indeed, experiments involve a single DLA chip receiving Linac relativistic bunches (GeV) for characterization of THz or photonic acceleration [5]. Valuable work is done on FEAs topic 9 10but only associated with a conventional RF gun. Even the -closely related to our scope- research laboratories leaders SLAC11, Planck group12 for photonic, Sinbad/Ares for THz have not yet integrated FEAs with DLA stage.

DLA design are studied in planar 13or cylindrical geometries14. Cylindrical one promotes an optimized coupling, but planar chips are better candidates for serial production and could however reveal high performance depending of laser injection and accelerating mode profile. For instance, a principle schematic of a planar geometry is represented hereafter, «easily» made on PCB techniques and RF microstrips. The FEA could then be arranged linearly to generate a flat beam.



Such integration is sometime viewed as an engineering process. However there are yet many fundamental and hard technology problems to solve, among them the FEA quantum emission with experimental and simulation tools151617, the laser coupling to FEA, the bunch transport to first DLA, the acceleration yield by FEA/DLA interaction, the photonic optics18, fabrication8 … One recurring issue-to be solved either by proper specification or technology trick- is the balance between contradictory parameters, ie between ultra low emittance, say 0,1nm rad, reached with a single tip19, and the minimum requested charge/pulse, reached by an array of tips20.

An important item is cathode research: The discovery of graphene, and Carbone Nano Tubes permits us to design high performance cathodes, with unprecedented Field Effect densities associated with better thermal conductivity than metals, strong resistance to ion bombardment and secondary emission, and predicted high reliability. However, their physics in photoemission and High fields effects is yet badly known[6] Moreover it is essential to focus on bunch coherence 21 and on the spin yield (ratio of polarized/emitted electrons), a few studies being for now available22 .[7]

Inside CNRS, some «pre FEA» studies started at Lyon and Toulouse with one tip emitter. An international collaboration between DLA/FEA researchers, A(ccelerator on a)CHIP, ACHIP23, is established since some years. 8 . Contributions on FEAs/DLAs come from SLAC, Technion, PSI, Erlangen Planck Institute…showing that many dynamic researches are paving the way without us. A window is however opened with Desy/Lal/Laserix exchanges on THz dielectric acceleration inside ARES/SINBAD.

Regarding FEAs and photonics, it is possible to initiate concrete actions at Orsay. In2p3 and CNRS/UPS Orsay dispose of equipement and platform for prototyping : white rooms (C2N), simulation tools for quantum effects, electromagnetic fields and particle tracking softwares, laser platform (LaseriX), diagnosis equipements inside FLUO (PANAMA). The white room expertise/realizations may also be found with Thales9. As we deal with nano objects, the experimental costs are of an order lower than those of «great instruments», but it induces a deep human investment and white room expertise. An association inside Orsay, for instance Lal/LaseriX/C2N/Thales appears an adequate group and is presently investigated.

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[5] With a starting informal collaboration of Lal/Desy, and some ideas to implement nextly a THz acceleration setup at FLUO

[6] An intriguing feature and worth while study, is for instance the Dirac cone in graphene, well known in solid physics, but not exploited yet in cathode works for accelerators.

[7] We do not describe here the necessary instrumentation, it is at itself a topic, just to note that photonic devices may solve the needs assumed still now by energy spectrometer, BPM, current measurement, etc... They are also to be adressed by our correspondant group.

[8] Regrettably for now, in2p3 labs have no participation in it.

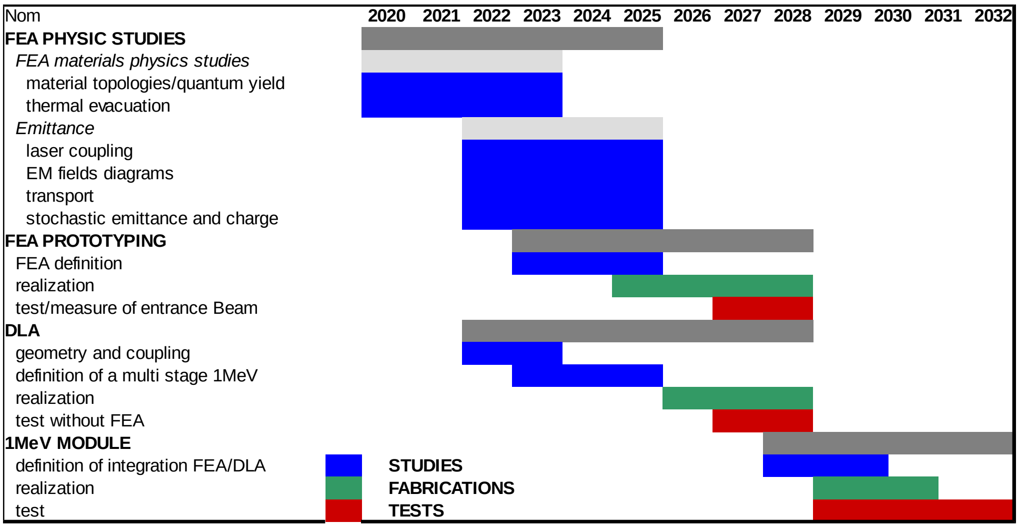
[9] Thales has also a recognized expertise/publications on FEAs not cited here, and has significant realizations to its credit

3. Développements associés, calendrier et budget indicatifs
(1 page max. incl. figures)

Préciser les travaux envisagés pour mener à bien les objectifs décrits (étude conceptuelle, expérience, prototypage, construction…) ainsi que les résultats espérés et leur échéance, en précisant si possible les partenaires potentiels.
Si possible, évaluer grossièrement l'ordre de grandeur du financement nécessaire pour mener le développement envisagé (coût complet, en distinguant équipements, consommables et ressources humaines).

Task calendar [10]

The project paths are built on relative independance of FEA and DLA studies. Then there are 2 quasi parallel actions, each one respectively resulting in single FEA and DLA prototypes; There output must converge to the definition of a final integrated module FEA/DLA. Studies implies theory and simulations in first on a single tip, and then on an array, but could be supported by experimental work, either done in IN2P3, CNRS labs or with Thales. Regarding fabrication, Lal has an entry to C2N machine (physics group), so costs are in order of 5kEu/year. Thales possibilities, or inside CNRS is to investigate. FLUO/ Acc Dpt has also PANAMA diagnosis platform for Surface Physics.



Nom	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
FEA PHYSIC STUDIES	▓	▓	▓	▓	▓	▓							
FEA materials physics studies	░	░	░	░									
material topologies/quantum yield	🟦	🟦	🟦	🟦									
thermal evacuation	🟦	🟦	🟦	🟦									
Emittance			░	░	░	░							
laser coupling			🟦	🟦	🟦	🟦							
EM fields diagrams			🟦	🟦	🟦	🟦							
transport			🟦	🟦	🟦	🟦							
stochastic emittance and charge			🟦	🟦	🟦	🟦							
FEA PROTOTYPING				▓	▓	▓	▓	▓	▓				
FEA definition				🟦	🟦	🟦							
realization						🟩	🟩	🟩	🟩				
test/measure of entrance Beam								🟥	🟥				
DLA			▓	▓	▓	▓	▓	▓	▓				
geometry and coupling			🟦	🟦									
definition of a multi stage 1MeV				🟦	🟦	🟦							
realization							🟩	🟩	🟩				
test without FEA								🟥	🟥				
1MeV MODULE									▓	▓	▓	▓	▓
definition of integration FEA/DLA									🟦	🟦	🟦		
realization										🟩	🟩	🟩	
test										🟥	🟥	🟥	🟥

🟦 **STUDIES**
🟩 **FABRICATIONS**
🟥 **TESTS**

Resources evaluations is presented hereafter

Item	**START**	**END**	**Duration**	**Human resources**	**Mat resources**
FEA physic studies	02/01/20	31/12/25	1532		
FEA materials physics studies	02/01/20	29/12/23	1023	1 year*Tech	provisions
material topologies/quantum yield	02/01/20	29/12/23	1023	4 years*eng	250kEu
thermal evacuation	02/01/20	29/12/23	1023	Thesis1	progressive
emittance	03/01/22	31/12/25	1019		equipment
laser coupling	03/01/22	31/12/25	1019	1 year*Tech	
EM fields diagrams	03/01/22	31/12/25	1019	2 year*eng	provisions
transport	03/01/22	31/12/25	1019	Thesis2	250kEu
stochastic emittance and charge	03/01/22	31/12/25	1019		progressive
FEA prototyping	02/01/23	29/12/28	1529		equipment
FEA definition	02/01/23	31/12/25	763	1 year*eng	
realization	02/01/25	29/12/28	1020	2 year*eng mat	
test/measure of entrance Beam	04/01/27	29/12/28	511	Thesis3	
DLA	03/01/22	29/12/28	1785		
geometry and coupling	03/01/22	29/12/23	510	1 year*eng	
definition of a multi stage 1MeV	02/01/23	31/12/25	763	2 year*eng	
realization	02/01/26	29/12/28	766	2 year*eng mat	
test without FEA	04/01/27	29/12/28	511	Thesis4	
1MeV module	03/01/28	31/12/32	1275		
definition of integration FEA/DLA	03/01/28	31/12/29	509	2 year*eng,1year*Tech	
realization	02/01/29	02/01/31	510	2 year*eng mat	
test	02/01/29	31/12/32	1021	1 year*eng	
test...				Thesis5	

Material costs : to refine, given the present achievement/time. A precise basis is found in 8

experimental costs 10 years

	licence C2N	wafers
prototypes chips	80kEu	tbd
laser sources	tbd	
RF amplifier	20kEu	
oscilloscopes	tbd	
vacuum (small volume, approx 10^{-} 7 Torr)	tbd	
energy spectrum analysers	tbd	

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[10] Schedule overcome 2030 due to explicit character of mid term research. Delays are estimated in a optimistic scenario (no feed back), well known aleas are studies difficulties and prototype rebuilding following upsets. It may have consequences on necessary human resources, but much less on materials one. Cathode studies should be considered as a permanent/long term activity rather than a isolated one shot project. Fabrication periods superimpose to definition one for multi version optimizations. Much time is devoted to FEA alone and DLA alone, because we have to gain expertise by ourselves, and also because of logical and technical reasons, relating to cartesian cutting, ie one must consider the great intrication of FEA and DLA inside such 1MeV module.

4. Impact

(0.5 page max.)

Décrire les retombées espérées pour le développement de futures installations de recherche basées sur des accélérateurs ou pour d'autres applications sociétales.
Le cas échéant, préciser les partenariats industriels envisageables.

We already described the HEP context but ANA group distinguishes also many applications of dielectric acceleration for light FEL. A significative signal is the interest of Desy Xfel center for DLA and PSI for FEAs. We shall not detail the natural application of an experimental platform based at Lal. Note that a Mev DLA Platform will certainly take a volume lower than a MeV photoinjector, without -power sources- for exemple.

As we preoccupe with compacity/costs, the virtual appliances in society are extremely numerous. Simply using a scanning machine in hospital shows that a costly modulator may be replaced by a shoes box with DLAs. Anyway, the DLA techniques are not universal. They can't supply needs of high current accelerators, like induction one for instance. They are rather oriented to High Energy probes (fs and as spectroscopy) security devices, art diagnosis … briefly all the already listed applications of accelerators with low current by pulse.

The main partner recensed today is Thales, which already has a starting activity with some type of FEAs. But optic and laser industry are also concerned.

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