Contribution aux exercices de prospective nationale 2020-2030

Accélérateurs et instrumentation associée

NEXT PARTICLE COLLIDERS (NPC)

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1. Informations générales

Titre : Next Particle Colliders

Acronyme : *(optionnel)* ***NPC***

Résumé *(max. 600 caractères espaces compris)*

New accelerator facilities and in particular colliders are being considered for the future scientific advances in particle physics. A rich R&D programme is driving the developing and building of these new facilities. A strong cooperation between national institutes, CERN and others global laboratories or collaborations is vital for the progress of the field and also for preserving the expertise. In this context the main goal of the NPC project is to ensure an appropriate contribution to this vibrant and diverse R&D programme focusing in: nanobeams, high-intensity positron sources, vacuum science, luminosity monitoring and MDI backgrounds, stabilization and its monitoring as well as the application of Machine Learning in advance control and optimization techniques; where we have already demonstrated our know-how and expertise.

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

- ***Physique des accélérateurs (nouveaux concepts machines, optique et dynamique des faisceaux…) X***
- ***Sources de particules (électrons, positrons, muons, protons, ions lourds stables, ions radioactifs…) et cibles associées X***
- ○ *Supraconductivité accélérateur (aimants fort champ, cavités SRF…)*
- ○ *Accélération plasma (électrons, ions…) et interaction lasers/faisceaux*
- ○ *Technologies RF innovantes (structures haut gradients, alimentations RF…)*
- ○ *Diagnostics faisceau, instrumentation et contrôle intelligent*
- ○ *Développement durable de la discipline (infrastructures technologiques, efficacité énergétique, fiabilité…)*
- ***Autre R&D spécifique : Vacuum technology, Artificial Intelligence /Machine Learning X***

Préciser la motivation principale visée par la contribution :

- ○ *Accélérateurs pour la physique nucléaire*
- ***Accélérateurs pour la physique des particules X***
- ○ *Accélérateurs pour les sources de lumière ou de neutrons*
- ○ *Accélérateurs pour les applications sociétales (santé, énergie, industrie…)*
- ○ *Autre : (préciser)*

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.

Accelerators and in particular Colliders are an essential tools for the future of Particle Physics. The recent discovery of the Higgs boson at the LHC was the result of an enormous effort of many different scientific and technical expertise coming together with a common goal. This amazing achievement could not have been possible without the success of each of these contributions, and any future particle-physics accelerator must rely on the synergy between all of these different components.

New accelerator facilities are being considered for the future scientific advances in particle physics (HEP). Their development is driving the progress in accelerator science and will impact in the development of the accelerators for societal applications such as in medicine, industry, energy and environment, security, photonics and neutronics, between others.

In this sense future pp colliders drive the development of **high field magnets**, with the goal of achieving fields of 16T with the Nb3Sn superconductor. For the e^+e^- collider options the main challenges for both linear and circular colliders are the **RF cavities** (energy) and **nanobeam** (luminosity) performances. In the design of $\mu^+\mu^-$ colliders, one of the most critical issues in the traditional approach of producing muons by means of protons is the **muon cooling** after the production in the target. Others approaches are using the annihilation of e^+e^- above the threshold using 45 GeV e+ impinging on targets. Even the **novel plasma-based particle accelerators**, where accelerating fields are created by the collective motion of plasma electrons driven by lasers or particle beams, have shown capability of reaching an order of magnitude higher gradients than presently achieved, although the possibility to reach the **beam quality** needed for HEP applications remains to be demonstrated [1].

There is a rich R&D programme (Figure 1) for improving the existing facilities, building and developing new facilities. A strong cooperation between national institutes, CERN and others global laboratories or collaborations is vital for the progress of the field and also for preserving the expertise. *In this context the main goal of the NPC project is to ensure an appropriate contribution to this vibrant and diverse R&D programme focusing in: nanobeams, high-intensity positron sources, vacuum science, luminosity monitoring and MDI backgrounds, stabilization and its monitoring as well as the application of Machine Learning in advance control and optimization techniques; where we have already demonstrated our know-how and expertise*.

More in detail:

Nanobeam size handling

One of the main challenges of future e^+e^- linear colliders (ILC/CLIC) [15, 17, 25] is to achieve a **nanometer vertical beam size** at the Interaction Point (IP) in order to reach high-luminosity. During the last years an important effort has been conducted at the Accelerator Test facility 2 (ATF2) in KEK, with an active participation of the LAL, in order to handle the nanobeam sizes. After several years of operations and commissioning, a vertical beam size at the IP of around 40 nm has been achieved (Figure 2). A **complex tuning process** to **mitigate** all the effects impacting and degrading the IP beam size is being tested and ameliorated. The **understanding** of these **mechanisms** is crucial to assure the nanobeam sizes routine operation, and will be the main objective of **Task1,** [21].

High-Intensity positron sources

Positron sources are critical components of the future e^+e^- / $\mu^+\mu^-$ collider projects (ILC, CLIC, FCCee, CepC, LEMMA [16, 26, 11]) due to the very high-beam intensity required to achieve high-luminosity (Table 2). In a conventional positron source, positrons are produced by high-energy electrons hitting a target, where the low-momentum population is captured and accelerated in the positron capture section until the energy needed. This scheme has been used in all the e^+e^- colliders (ADA, ACO, KEKB, ADONE, LEP, SLC [2], Table 1). A possible way to increase the positron intensity is to increase the incident electron intensity and energy. However, the allowable heat load as well as the thermo-mechanical stresses in the target severely limit the beam power of the incident electrons. The complete optimization of the positron production requires not only the maximization of the total positron yield, but also innovative studies of thermal effects in the targets, especially the dynamical behaviour limiting the performance. Therefore, further investigations concerning the heat dissipation and thermo-mechanical stresses in the targets are mandatory to ensure a performant reliability of the different positron source types. Furthermore the positron production are rather complex process [5], requiring the optimization of every stage including the previous injection and the posterior, capture and acceleration.

Besides polarization is also an essential feature of positron sources, especially at smaller energies typical of Hadron Physics (MAMI, MESA, JLab, EIC etc.), and in the much smaller energy range of Atomic Physics and Material Science [3]. In these domains, a conventional positron source design using initially polarized electrons and capturing high-energy positrons has been demonstrated to be particularly efficient [4].

In this framework, the main objective of **Task 2** will be the further study of the different methods of **positron production**, both classical and **novel/exotic** ones (micro/nano-undulators, plasma undulators, crystal undulators, crystal–assisted pair production, pair production in vacuum using high-power lasers and/or extremely short electron bunches, Gamma factory concept [8,9]). We will focus mainly on future HEP applications requiring orders of magnitude higher intensities than what was demonstrated up to now (Table 2) [6], but also hadronic physics applications requiring both polarization and intensity [7] will also be considered.

Vacuum Science and related techniques

The performance of the different devices constituting an accelerator is directly related to the chemical composition of the material itself in one hand and in the other hand to the manufacturing process as welding qualities, thin films or coatings, between others. When the beam enter in contact with these devices, trigger some **phenomena** as: (i) **stimulated desorption** leading to the degradation of the vacuum; (ii) **collective effects** (multipacting, electron clouds) leading to beams instabilities. The **mastering of the materials** is of paramount importance to mitigate the impact of these effects.

The main objective of the Task 3 will be the **study of these phenomena** in order to propose solutions to improve the overall performance of accelerator components. These studies will involve the **characterization of materials** of interest (and more particularly their surface), and their behavior under bombardment (energy and nature of the incident particle, conditioning effects, evolution of stimulated desorption yields, reduction of secondary particle emission yields). We will focus more particularly on the determination of ion stimulated molecular desorption yields (ISD). This action will study reference (Cu, Stainless steel) and new materials (carbon coated, laser treated, 3D printed) samples. Besides we will continue the collaboration in the development of the simulations to calculate the dynamic pressure under these conditions.

Luminosity monitoring and Machine Detector Interface Issues

High-luminosity is one of the main issues in the future generation of particle colliders, for instance FCCee expects a luminosity of $2x10^{36}cm^{-2}s^{-1}$ at the Z pole. A common feature in all of them is the **high frequency bunch collision rate** in combination with nanobeam transverse sizes. These collisions may produce large electromagnetic backgrounds, such as low energy e^+e^- pairs or **radiative Bhabha**, which can reach the detectors, **producing backgrounds** for the physics and degrade the quality of the beam, and thus its life time as well as the luminosity. Armed with the experience developed in the design of FLC (ILC/CLIC) and SuperKEKB the main objective of **Task 4** will be first the calculation of **the pair background** and second **the luminosity monitoring** based on the measurement of the radiative Bhabha at zero angle process. Incoherent pair background arises from three processes which involve both real photons (from beamstrahlung) and virtual photons. Due to beam-beam deflection effect, it cans reach inner detector (e.g. vertex detector) and it is important to evaluate the generated occupancy rate. For this purpose, precise estimation can be performed using dedicated simulation software, such as GuineaPig. Luminosity monitoring is required during tuning phases to adjust beam alignment, as well as during run phases in presence of dynamical instabilities. Radiative Bhabha scattering at zero photon angle offers a large cross section and can be in principle detected outside the beam pipe after bending sections. Our contribution will consists of studying the Bhabha losses along the beam pipe close to the IP region in order to determine the best location for its measurement [12-14].

Stabilization and its Monitoring

Nanobeam stabilization is one of the critical issues in order to reach high-luminosity in the next particle collider generation. The evaluation of vibration patterns and ground motion and their impact in the luminosity as well as the possible mitigation strategies are essential. Taking into account the acquired know-how in the design of the stabilisation system of the CLIC MDI, ATF2 final focusing solutions, and the current participation in monitoring the ground motion in the SuperKEKB MDI area [17-20], the main objective of **Task 5** will be the **evaluation of the vibrations** and their **impact on the luminosity**, focused in FCCee. The developments will be tested as much as possible on the SuperKEKB, which has similarities to FCC-ee in terms of MDI setup and beam parameters.

State of art simulation tools and their eventual development, integrating various worldwide ground motion models and the associated coherences will be performed. The outcome of the previous studies will be completed by taking into account the beam feedbacks and, possibly, the beam-beam effect. A mitigation strategy will be selected to achieve the tolerance requirements. Depending on the defined vibrations tolerances, the vibration control strategy at the IP will be defined. Finally taking into account all the elements of the final focusing magnets, their supports and the models of the chosen active-passive control solutions in the MDI area we will carry out a whole simulation to verify if the vibration requirements are respected. This procedure will also give a more complete view of the interplay among all these effects and their influence on the luminosity.

Advance control and optimization techniques
Machine Learning (ML) techniques has been successfully applied to a variety of real-world tasks to solve scientific and engineering problems, recently they have also been applied to **optimize t**he **beam parameters** and to **assess the control systems** of various accelerators [22-24]. In the frame of a rising activity at LAL in this aspect the main objective of **Task 6** will be the investigation and demonstration of applicability and efficient use of ML techniques for advanced optimization and control focusing in the next generation of colliders which have an extensive complex parameter dependence.

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).

The project will be organized in 7 Tasks:

Task 0: Performance, Parameters and Design studies for Future Colliders
This task leaded by A. Faus-Golfe, where all the tasks leaders participate will survey the boundaries of the next colliders proposed and asses all the others tasks, in order to develop a long term strategy for consolidating in some cases, boosting in others and opening new ones in each of the R&D subjects aforementioned before.
A kick-off meeting will be organized to agree on scopes of work and responsibilities, having an annual meeting to review the work being done and to discuss the future perspectives.

This task is related with the Inno Pilot submitted to ARIES: Pushing Accelerator Frontiers (PAF).

Task 1: Nanobeam sizes handling
In this task we will continue the participation in the understanding of reaching nanobeam sizes through the collaborations ATF2, ILC and CLIC. This task will be leaded by A. Faus-Golfe.

Task 2: High Intensity positron sources
In this task leaded by I. Chaivkoska we will address the further study of different source types including novel/exotic ones, target designs and capture and first stage acceleration, focused in HEP but also the polarized ones for hadronic applications.
The studies will be performed in the collaborations FCC and CLIC and with the labs: CERN, LNF, JLab, BINP, PSI and KEK. In this last laboratory where the world's highest intensity positron source currently is in operation: SuperKEKB we will able to test experimentally some of the new designs. Moreover, the possible construction of a new test-bench for positron source R&D in one of the beam lines of the Swiss FEL in PSI open the possibility to start a new collaboration. Finally the

development of a polarized positron source at 12 GeV in JLab will also open a new opportunity that has to be considered carefully.

This task is related with the Inno Pilots submitted to ARIES: Pushing Accelerator Frontiers (PAF) and MUon colliders STrategy network (MUST).

Task 3: Vacuum Science and related techniques

This task leaded by G. Sattonnay will produce a very useful data base of both ISD yields and SEY for references and new materials available for research centres and industries.

Part of these studies will be performed in the FCC collaboration.

This task is closely related to the Inno Pilots: Demands in vacuum science and technology for future particle accelerators, Ion Stimulated molecular Desorption of future materials for accelerator and Thermal Outgassing Database. Furthermore a contribution related to this task: Matériaux pour Accélérateurs, Vide dynamiquE et Recherche Innovante sur les Cavités Supraconductrices (MAVERICS) has also been submitted in this call.

Task 4: **Luminosity monitoring and Machine Detector Interface Issues**

This task leaded by C. Rimbault will consist of the study of the Bhabha losses along the beam pipe close to the IP in order to determine the best location for its measurement and the subsequent implementation of the luminosity monitoring.

This task is closely related with the activity developed in superKEKB and will be framed in the FCC collaboration.

Task 5: Stabilization and its Monitoring

This task leaded by L. Brunetti and M. Serluca will continue the stabilization studies and its monitoring being developed in ATF2, CLIC and SuperKEKB and start new studies for the FCCee. Furthermore a particular contribution related to FCCee MDI, will be the collaboration in the development of the mechanical design of the final focus quadrupole system cryostat in cantilever mode which is strongly affected by the vibrations in the MDI area. A possible follow-up of the construction of prototypes of the main elements is envisaged.

This task is closely related to the “Frontier Circular Collider Innovation Study” (EU H2020 INFRADEV) proposal being submitted recently.

Task 6: Advance control and optimization techniques

This task leaded by V. Kubytskyi will explore the possibility of applicability of ML in order to optimize the beam parameter space of next colliders.

This activity is in a very preliminary stage and collaboration with others partner are envisaged.

Per year	*Task 1*	*Task 2*	*Task 3*	*Task 4*	*Task 5*	*Task 6*	**TOTALS (kEu)**
Personnel*	1 PhD	1 Postdoc 1 PhD 0.3 Engineer	1 Engineer 1 PhD	1 Postdoc	1 Postdoc	1 PhD	4 PhD 3 Postdoc 1.3 Engineers
Travelling	10	15	10	15	5	8	**63**
Material and other costs		30	30			4	**64**
							127

*indicate the number and degree (PhD, postdoc, engineer, technical…) of the non-permanent staff needed to carry out these activities

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.

The activities and assessments developed by this project will help in one hand to ensure our contribution to the R&D programs in the areas and projects already mentioned and in the other hand will identify the approaches with greatest potential for the next generation or colliders or possible applications of accelerators.

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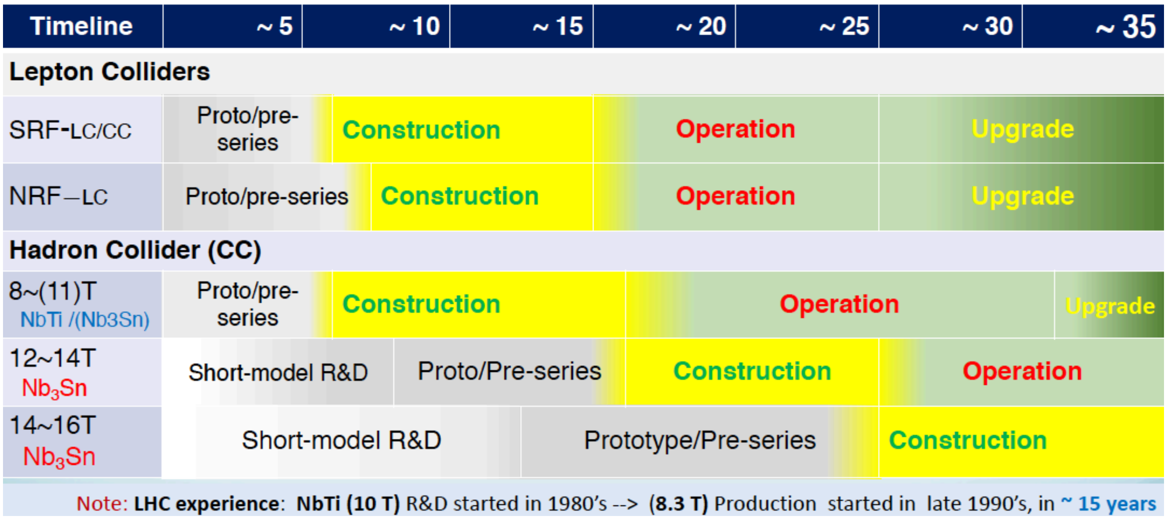
Appendix



Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF–LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

Note: **LHC experience**: **NbTi (10 T)** R&D started in 1980's --> **(8.3 T)** Production started in late 1990's, in **~ 15 years**

Figure 1 : Personal (A. Yamamoto) Technology View on Relative Timelines.

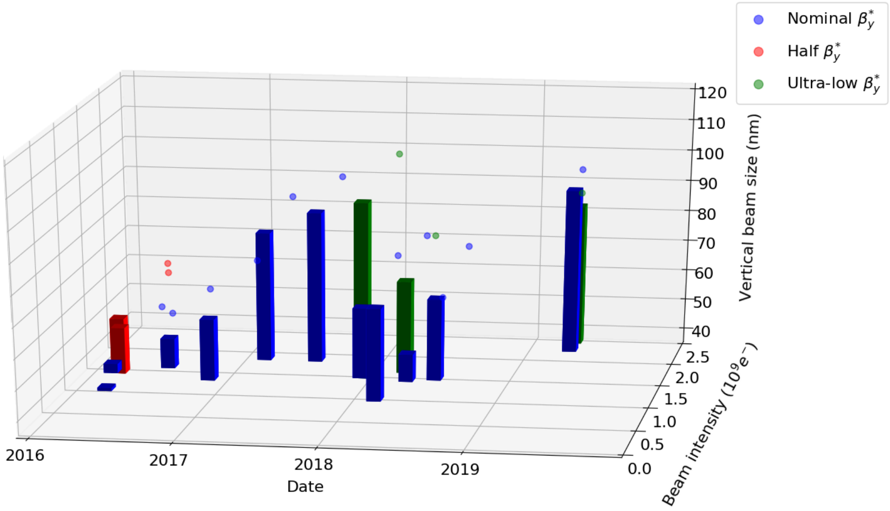


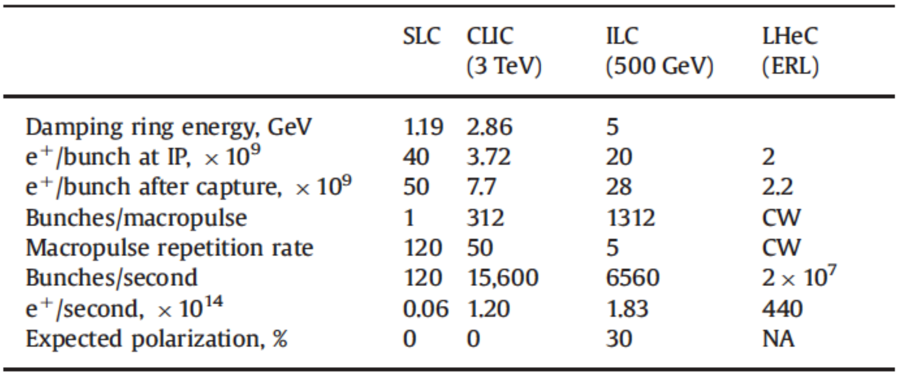
Figure 2: History of the observed vertical beam size at the IP in function of the intensity.

Table 1
Positron sources parameters.

Facility	PEP-II	KEKB	DAFNE	BEPC	LIL	CESR	VEPP-5
Research center	SLAC	KEK	LNF	IHEP	CERN	Cornell	BINP
Repetition frequency, Hz	120	50	50	12.5	100	60	50
Primary beam energy, GeV	33	3.7	0.19	0.14	0.2	0.15	0.27
Number of electrons per bunch	5×10^{10}	6×10^{10}	1.2×10^{10}	5.4×10^{9}	3×10^{9}	3×10^{10}	2×10^{10}
Target	W-25Re	W	W-25Re	W	W	W	Ta
Matching device	AMD	QWT	AMD	AMD	QWT	QWT	AMD
Matching device field, T	6	2	5	2.6	0.83	0.9	10
Field in solenoid, T	0.5	0.4	0.5	0.35	0.36	0.24	0.5
Capture section RF frequency	S-band	S-band	S-band	S-band	S-band	S-band	S-band
Positron yield, 1/GeV	0.054	0.023	0.053	0.014	0.0295	0.013	0.1
Positron output, 1/s	8×10^{12}	2×10^{11}	2×10^{10}	2.5×10^{8}	2.2×10^{10}	6.6×10^{10}	10^{11}

Table 2

Linear colliders positron source parameters.



	SLC	CLIC (3 TeV)	ILC (500 GeV)	LHeC (ERL)
Damping ring energy, GeV	1.19	2.86	5	
e^+/bunch at IP, $\times 10^9$	40	3.72	20	2
e^+/bunch after capture, $\times 10^9$	50	7.7	28	2.2
Bunches/macropulse	1	312	1312	CW
Macropulse repetition rate	120	50	5	CW
Bunches/second	120	15,600	6560	2×10^7
e^+/second, $\times 10^{14}$	0.06	1.20	1.83	440
Expected polarization, %	0	0	30	NA