

Machines en Développement et Défis Futurs

*F. Bouly (LPSC), A. Chance (CEA), N. Pichoff (CEA),
C. Thaury (LOA), D. Uriot (CEA)*



Sources de lumière (voir [les sources de lumière](#) de L. Nadolski).

- Haute brillance → Haut courant et très basses émittances.
- Consommation énergétique (rayonnement synchrotron).

Sources de neutrons (voir [Accélérateurs de production de neutrons](#) de F. Ott)

- Faisceaux intenses
- Cibles permettant de gérer des puissances incidentes de plusieurs mégawatts.

Machines pour la médecine et l'industrie.

- [Accélérateurs d'ions](#) de B. Jacquot
- [Accélérateurs d'électrons](#) de J-P. Larbre
- Accélérateurs modulaires et compacts.

Physique des hautes énergies.

- Gradients accélérateurs élevés et hauts champs magnétiques.
- Protection de la machines.

Développement de cavités supraconductrices.

- Facteur de qualité.
- Gradient maximum.

Développement de cavités chaudes

- Plus haut gradient en allant vers les hautes fréquences (> 10 GHz).

Nouvelles techniques d'accélération

- Accélération plasma.

Hautes intensités:

- Sources d'ions.
- Charge d'espace et halo.
- Pertes dans la machine.

Cibles permettant de gérer des flux intenses.

- Chocs thermiques.

Aimants de haut champ

Diagnostics

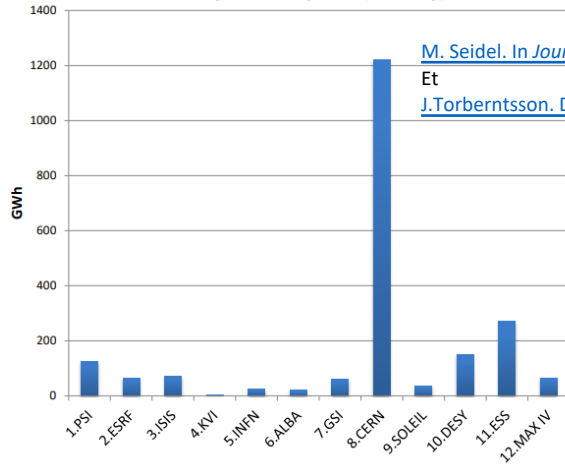
Réduction du coût de construction:

- Accélérateurs plus compacts: Maximiser gradients accélérateurs *mais maintenir la qualité du faisceau*
→ voir l'exemple de l'**accélération plasma**.
→ Exemple d'une **source compacte de neutrons: ICONÉ**.

Réduction du coût d'opération (coût énergétique)

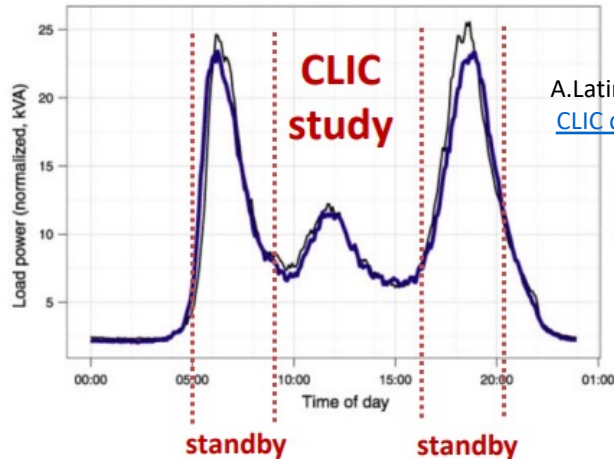
- Meilleure efficacité énergétique (sources RF plus efficaces, meilleur facteur de qualité, ...).
- Récupération de l'énergie après utilisation pour accélérer les faisceaux suivants.
 - Principe du linac à récupération d'énergie (ERL).
→ Exemple d'un **ERL multi-tours: PERLE**.

Electricity consumption (GWh/y)



M. Seidel. In *Journée accélérateurs de la SFP, 2019*
 Et
 J. Torberntsson. *Deliverable D3.1 EuCARD2-Del-D3-1-Final*.

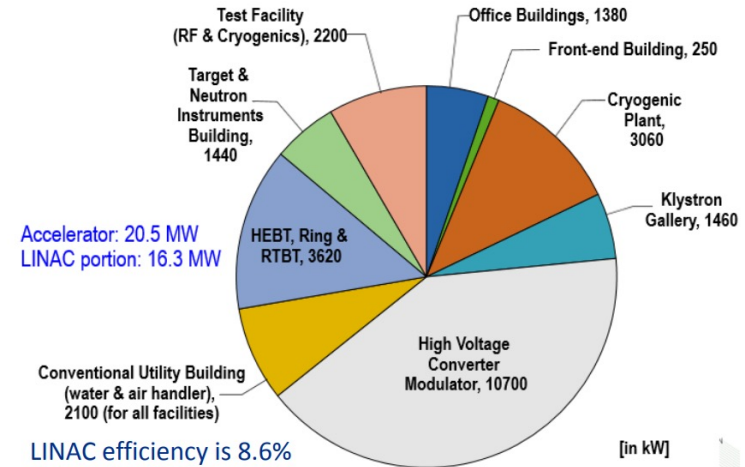
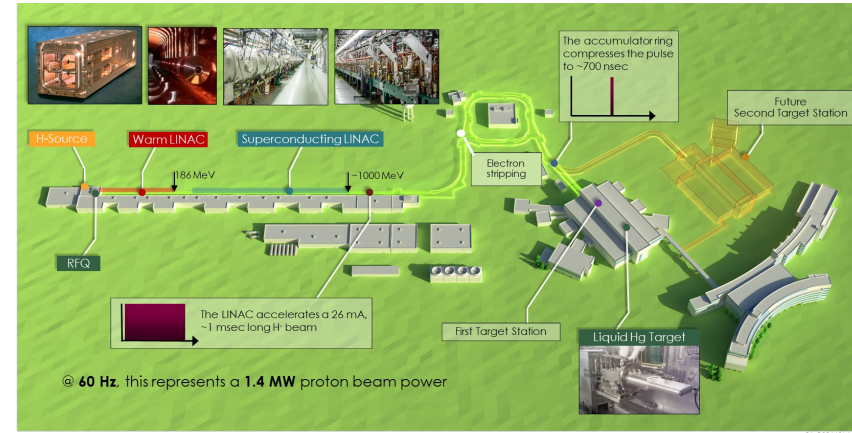
Conso. Energ. / jour en France



A. Latina et al.,
[CLIC dynamic operation Study @ 3TeV](#)

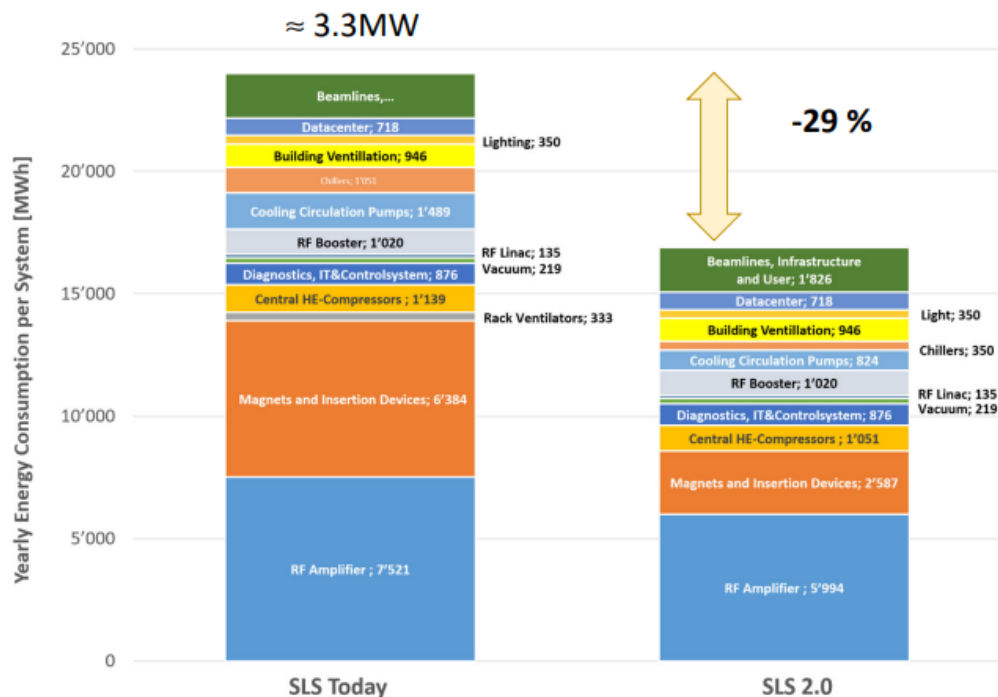
Energy consumed is reduced by 18% (-2.826 GWh)
 Luminosity delivered is reduced by 37% (-0.648 fb⁻¹)

Exemple de SNS



V. P. Yakovlev et al., The Energy Efficiency of High Intensity Proton Driver Concepts. In *Proc. IPAC'17*, [doi:10.18429/JACoW-IPAC2017-FRXC1](https://doi.org/10.18429/JACoW-IPAC2017-FRXC1).

Example Swiss Light Source SLS and its Upgrade



**More radiated X-ray power for users
Less electricity consumption**

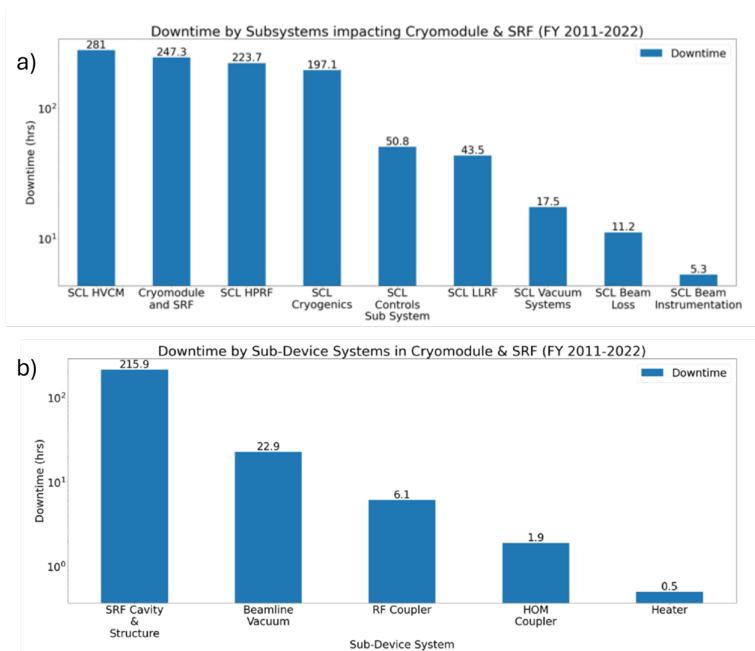
Key savings:

- Electromagnets → Permanent magnets
- Klystrons → Solid state amplifiers (63%)
- standard pumps → modern pumps for cooling

SLS2.0	
P_{tot}	= 2.4MW
P_{RF}	= 0.82MW
P_{γ} (undulators)	= 91kW

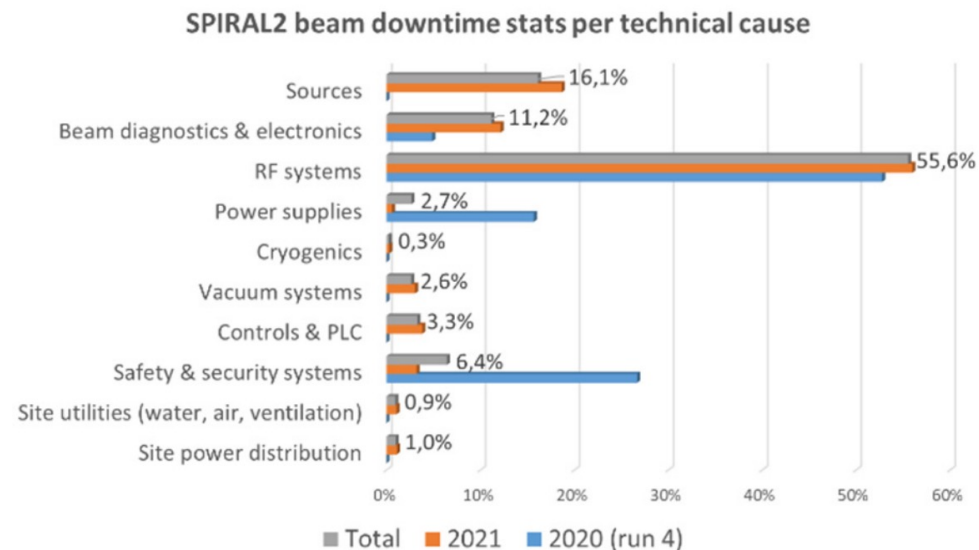
M. Seidel. Towards Efficient Particle Accelerators - A Review. In *Proc. IPAC'22*, number 13 in International Particle Accelerator Conference, URL : <https://jacow.org/ipac2022/papers/frplygd1.pdf>

SNS



R. Geng et al., Reliability analysis of sns srf linac and perspective for future high-power proton srf linacs. In Proc. 14th International Particle Accelerator Conference - IPAC'23, <https://doi.org/10.18429/JACoW-IPAC2023-TUPM066>

SPIRAL2

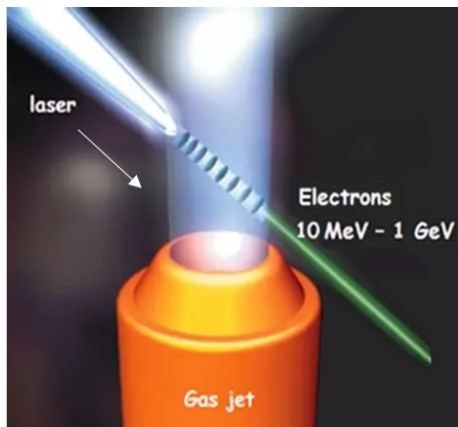


P.-E. Bernaudin, et al., Three Years of Operation of the SPIRAL2 LINAC : Cryogenics and Superconducting RF Feedback. In Proc. 31st International Linear Accelerator Conference (LINAC'22), <https://jacow.org/linac2022/papers/tupage02.pdf>

Systèmes RF + cavités sensibles aux pannes

- Améliorer la robustesse / Stratégie de compensation / limiter le nombre d'éléments

Accélération Laser Plasma Haut gradient et compacité

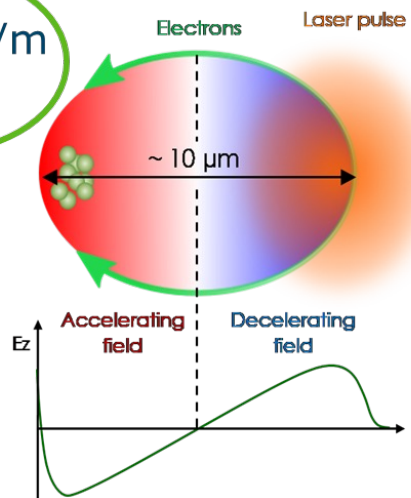


An intense laser pulse focused in a gas jet drives an accelerating cavity with electric fields exceeding 100 GV/m

Key features

- Compact: mm to cm long gas targets
- Energies in the range 30 MeV – 10 GeV
- Rep. Rate : up to 1 kHz, put typically ~ 1 Hz
- Energy spread possibly $< 0.1\%$, but typically few %
- Charge: up to ~ 1 nC / shot
- Normalized emittance ~ 1 mm.mrad,
- femtosecond bunch length, $\sim \mu\text{m}$ source size fs
- Laser to electrons conversion efficiency $\sim 1-5\%$

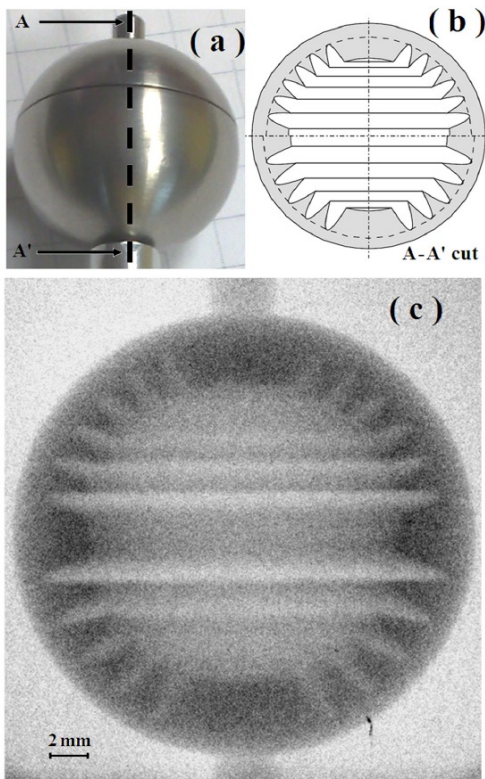
100 GV/m fields!



Key Applications

- **Radiobiology**: leverages ultra-high peak dose rates and the source compactness
- **Hard X-ray sources**: fs duration, spatial coherence and broad spectra
- **FEL**: compactness, fs pulse length, high peak currents
- **Non-Destructive-Testing**: leverages compactness and μm source size
- **QED**: high electron energies and ultra-intense laser fields on the same platform

The μm -scale source size enables radiography with a resolution of $< 30 \mu\text{m}$, with $\sim 100 \text{ MeV}$ electron beams



A. Ben-Ismaïl et al. *APL* 98, 264101 (2011)

Non-Destructive Testing

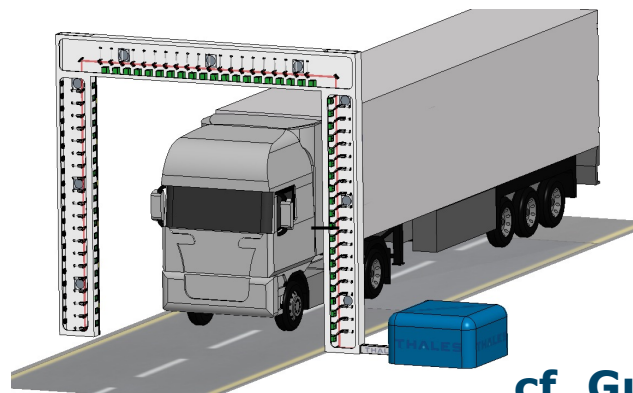


Horizon 2020
European Union Funding
for Research & Innovation

Multiscan 3D project

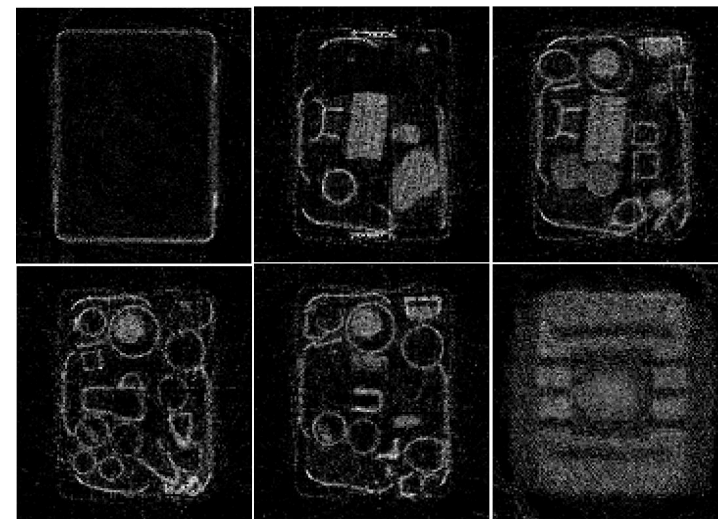
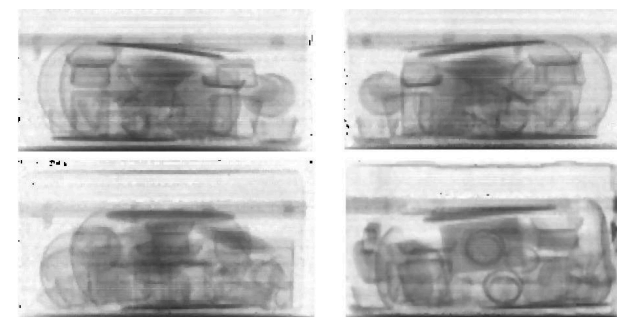
The compactness enables multi-view imaging, which is key for tomography of cargo:

- Gantry with tens of sources
- mm source size
- $< 10 \text{ MeV}$ electron energy
- 1 shot per image

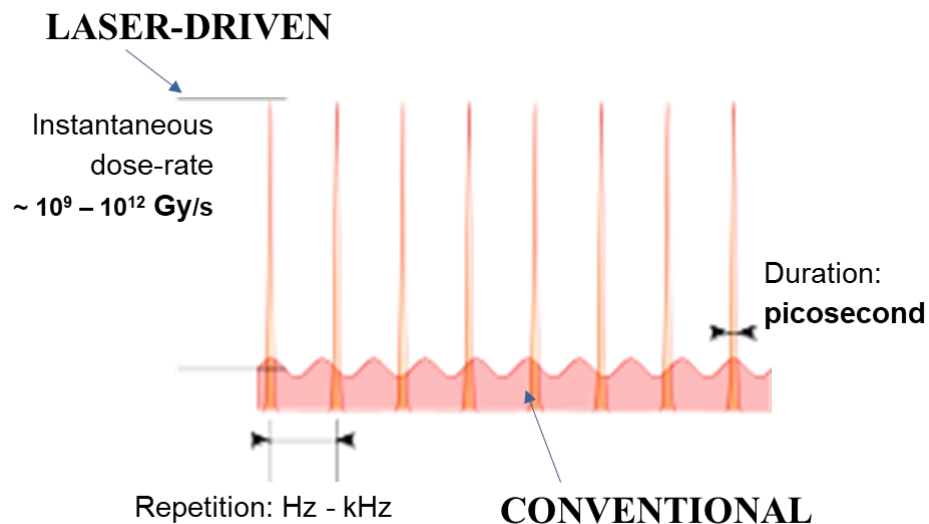


cf. Guillaume Chapelant's poster

Detection of a drug simulant in a 1 m^3 case filled with ceramics.



Laser plasma accelerators can deliver extreme dose rates

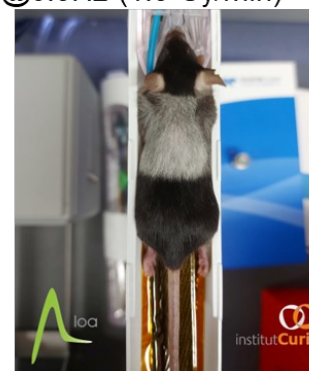


- **Ultra-high instantaneous dose rate** with an average dose rate comparable to conventional radiotherapy.
- Low repetition rate (~1 Hz) necessitates total irradiation times largely exceeding 100 ms.

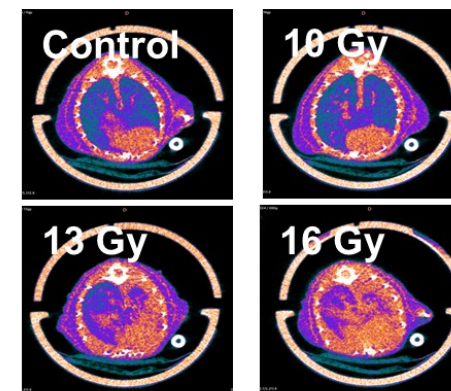
$$\frac{\dot{D}_{inst}}{\dot{D}_{avg}} \geq 10^9$$

Irradiated mouse

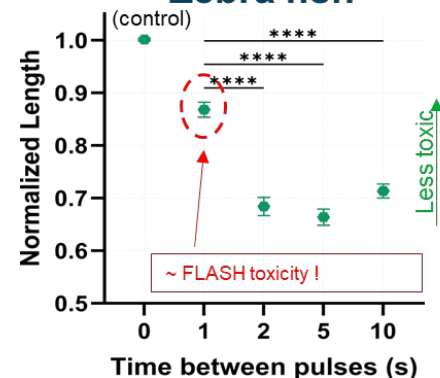
16Gy full thorax, 4months Post
Dose per pulse: 50 mGy/shot
@0.5Hz (1.5 Gy/min)



Corona,
7months Post



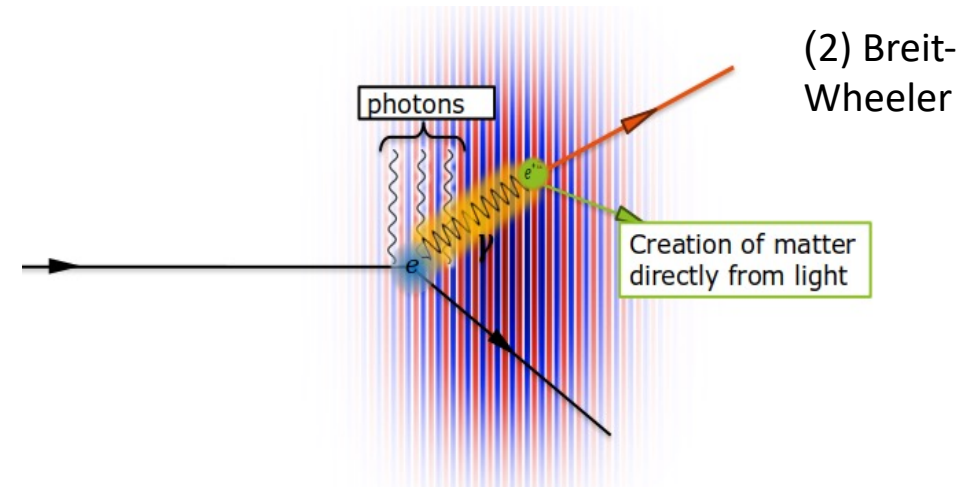
Zebra fish



FLASH effect driven by the ultra-high instantaneous dose rate, even if the total irradiation time exceeds 100ms

- The Mission: Validate QED in the "Strong-Field" regime**, where the vacuum becomes unstable.

The χ Parameter: Measures the field strength relative to the "Schwinger limit. At $\chi \sim 1$, the vacuum becomes unstable, allowing the conversion of light into matter.
- Current Status:**
 - Legacy Benchmarks (SLAC E144):** Reached $\chi \sim 0.3$ with a normalized laser amplitude $a_0 \sim 0.4$. This was the "multiphoton" regime, limited to interactions involving only a few photons.
 - The LPA Advantage:** LPA has already broken the conventional record, reaching $\chi \sim 0.5$ at far higher beam densities.
- Short-Term Objective: The $\chi \geq 1$ Milestone** where QED effects dominate the plasma dynamics (Apollon, ELI lasers).
- Medium-Term Motivation: The Non-Perturbative Frontier**
 - Validate Non-linear Breit-Wheeler:** Directly measure positron production from the vacuum ($\gamma + n \gamma_L \rightarrow e^+ e^-$).
 - Beyond "Counting Photons":** Transition to the truly non-perturbative regime ($a_0 \gg 1$), where the laser field acts as a continuous, ultra-intense background rather than individual particles.



- **Boost facility repetition rate (LAPLACE-HC at LOA):**
- From 1–10 Hz to 100 Hz–1 kHz, achieving a 1–2 order-of-magnitude gain in the short to medium term.
- **Enhance reliability and stability of LPA (LAPLACE-HC at LOA, PALLAS at IJC-LAB):**
Currently at a few percent level.
- **Approaches:**
 - Bayesian optimization feedback loop.
 - Advanced injection techniques
- **Increase energy output:**
Current record: ~10 GeV.
- **Pathways:**
 - New acceleration schemes → 10x energy increase (LAPLACE-HE at LOA et APOLLON at CEA Saclay) .
 - Multi-stage acceleration → scalable energy gain + improved control of electron properties (IJCLAB, LOA, LLR, LPGP).

Implementation of a national project leveraging all domestic investments in ALP (LAPLACE + PALLAS) to address a primary field challenge

- **Objective: Construction of a two-stage accelerator demonstrator:**

- **State of the Art:** Only one demonstration in the literature for staged ALP: 100 MeV gain with low charge coupling (Steinke et al., Nature 2016).

- **Existing Concepts:** Several schemes proposed for 2-stage coupling (C. Lindstrom, PRAB, 24, (2021)).

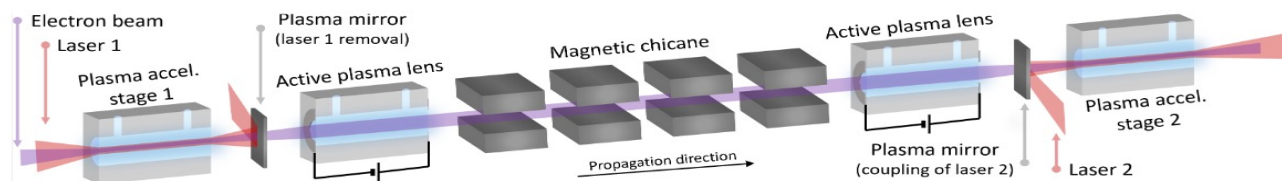
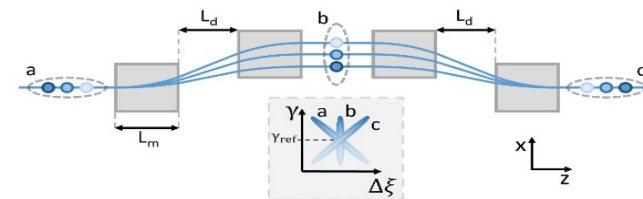


Image source: A. Ferran Pousa et al., arXiv:1811.07757 (2018) [4]



Injector (150–200 MeV) + Transport + Booster (2 GeV) – 30 pC @ 1 Hz.

- Utilizing PALLAS for injector and transport development.

- Utilizing the LAPLACE HE upgrade as the laser driver and host facility for the demonstrator by 2030.

Projet ICONE Source de Neutrons



Neutrons ?

Peu d'interaction

Interaction nucléaire

Diffusion élastique

Diffusion inélastique

Spin

Diffusion inélastique

STUDY **DYNAMICS**

Neutron energies are comparable to the time scales of molecular diffusion, vibrations and rotations.

Diffusion élastique

STUDY **STRUCTURE**

Neutron wavelengths are comparable to the spacings of atoms and molecules.

Peu d'interaction

PENETRATION POWER

Neutrons can penetrate deep into matter (including many different metals) enabling the study of large samples - even within complex sample environments.

Spin

STUDY **MAGNETISM**

The neutron's magnetic moment can be used to study the microscopic magnetic properties of materials.

Peu d'interaction

NON-DESTRUCTIVE

Neutrons are suitable for the characterisation of delicate and precious samples.

Peu d'interaction

VERSATILE SAMPLE ENVIRONMENTS

Sophisticated sample environments enable studies under operating conditions, including extreme temperatures and pressures.

Interaction nucléaire

SENSITIVITY TO LIGHT ELEMENTS

The neutron scattering power of nuclei varies in a quasi-random manner such that lighter atoms (e.g. H, Li) can be studied in the presence of heavier ones.

Interaction nucléaire

COMPLEMENTARITY

Neutron scattering is highly complementary to other techniques, such as X-ray scattering, electron microscopy, magnetic resonance and computational methods.

Interaction nucléaire

ISOTOPIC CONTRAST

Neutrons are sensitive to different isotopes of the same element, so isotopic substitution (e.g. H/D) can be used to highlight specific features.

https://lens-initiative.org/wp-content/uploads/2022/08/LENS-Report-fin_doublepages.pdf

→ 12 Instruments répondant aux exigences de la communauté : 300 expériences/an

Diffraction

PRESTO IIIII
(with polarisation)



PRECIS IIIII
High resolution

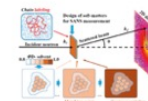


Large Scale Structures

PREMS ■
Reflectometer



LAMBDA ■
SANS

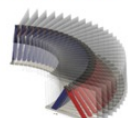


NANOSANS ■
Nanostructure

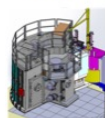


Spectroscopy

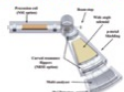
FANTASTIC IIIII
Inelastic



INEDIT IIIII
ToF

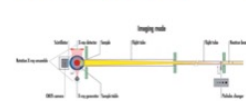


PULSE
Spin-echo ■
or back-scattering? IIIII

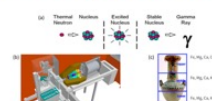


Material and engineering

IMAGING ■
Radiography



GOLF ■
PGAA - Analyse élémentaire



LITE HF + HR
■ IIIII



Instr. Phase 1

■ Long pulse (HF x6)

● Soft matter

⊖ Magnetism

🧪 Material sciences

🏭 Industry

Instr. Phase 2

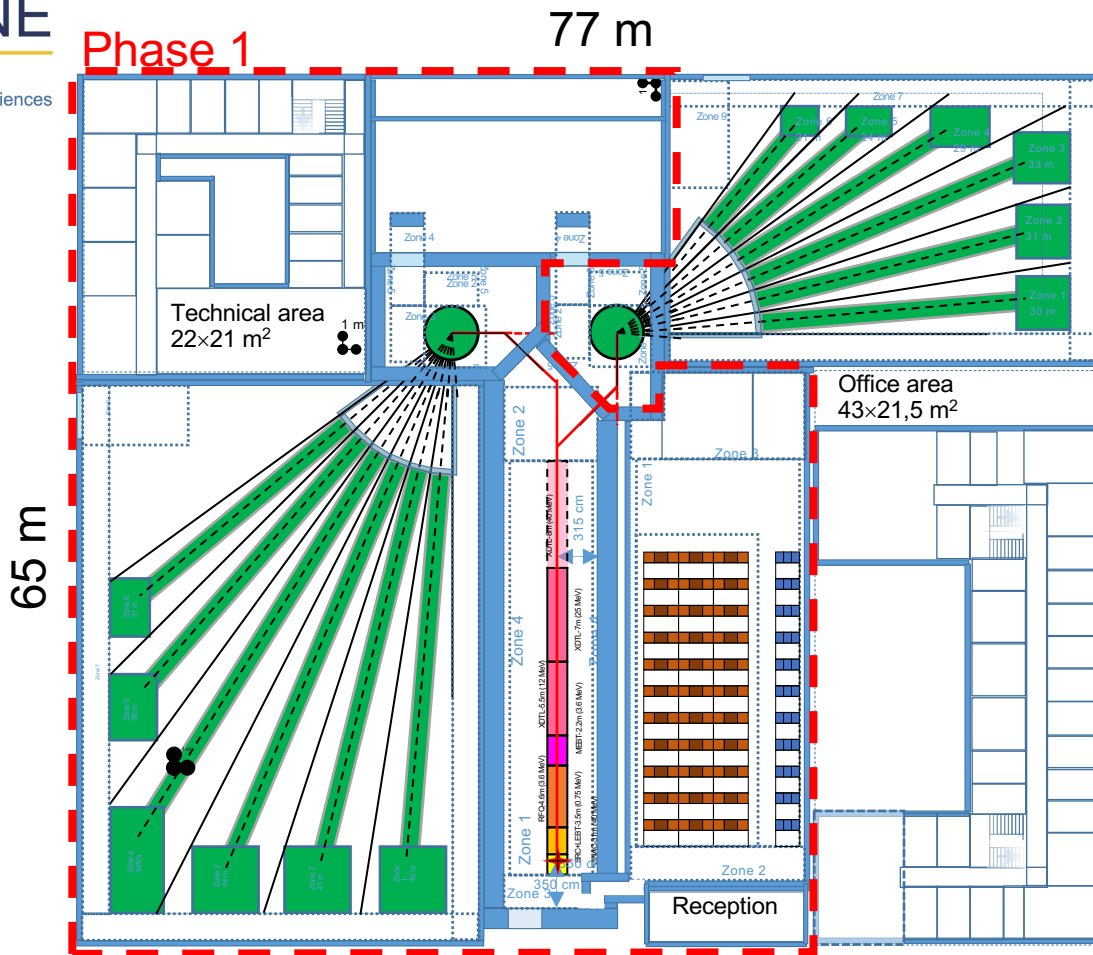
IIII Short pulse (HR x6)

🌿 Biology

🔧 Engineering and geoscience

🦖 Archeo and culture heritage

4



→ Construction sur le centre CEA de Saclay

- Accélérateur p⁺, 80 mA, 25 MeV @ 8%CU

- Neutron Brillance crête:

- ~ 5 10¹¹ /s/cm²/sr/Å @ 1 Å et 2.5 Å

- ~ 10¹¹ /s/cm²/sr/Å @ 5 Å

- Cible 1 : 0,4 ms@50 Hz (2%CU)

- 6 instruments HReso (<44 m)

- Cible 2 : 2,0 ms@20 Hz (4%CU)

- 6 instruments HFlux (<33 m)

- Tertiaire :

- Zone technique (~1000 m²)

- Zone bureau (~1500 m²)

Cf. Poster Nicolas Pichoff

Hypothèse : T0 le 01/01/2026

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
Phase 1	Construction						Installation		Operation				
Instruments	Studies		Construction				Installation	Comm	Operation				
TMR	Studies	Construction					Installation	Commission	Operation				
Linac	Construction						Installation	Commissioning	Operation				
Infrastructure	Studies		Construction			Install	Commissioning		Operation				
Phase 2					Studies				Construction		Install	Comm	Operation
Instruments					Studies				Construction		Install	Comm	Operation
TMR								Studies	Construction		Install	Comm	Operation
Linac								Studies	Construction		Install	Comm	Operation
Infrastructure					Studies				Construction	Install	Commission	Operation	

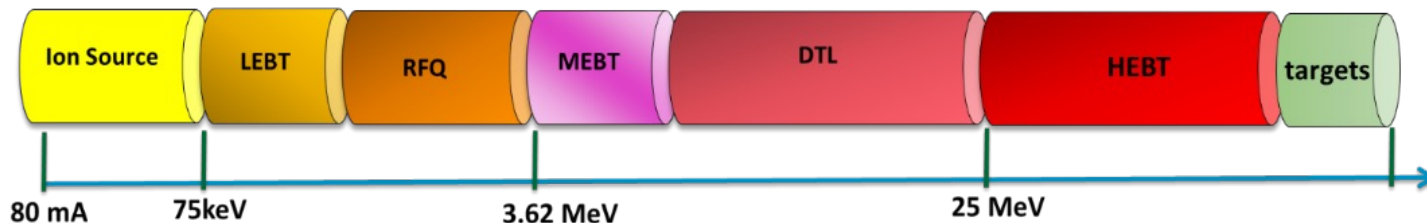
Cost Consolidation
Schedule Consolidation
Performance Consolidation

Maximiser la quantité d'information utile accessible

- Flux de neutrons (temps de manip),
- Disponibilité (fiabilité),
- Pertinence (taux d'occupation),
- Complémentarité avec d'autres installations

En minimiser le coût

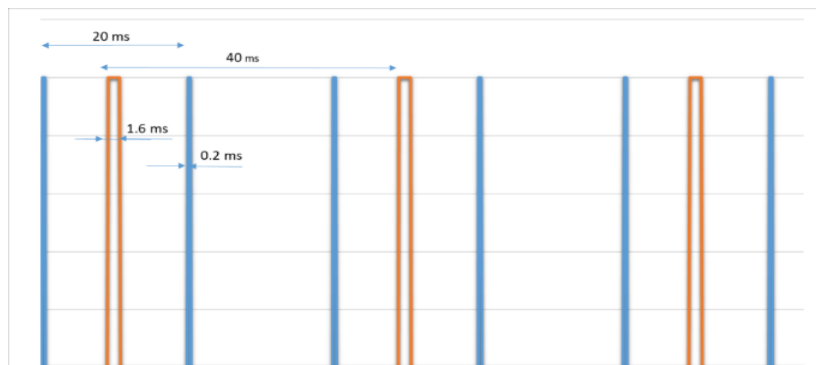
- construction,
- opération.



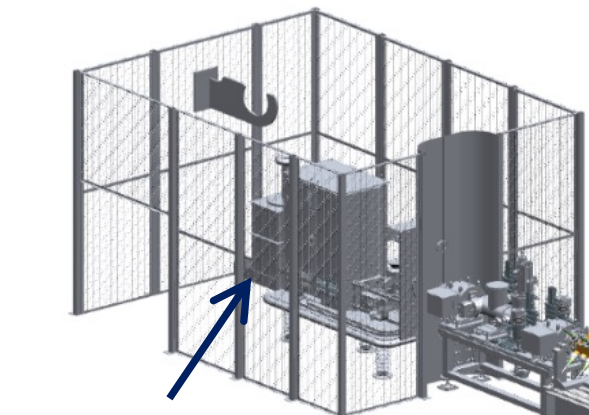
Top level performance requirements

- Main technical choices:**
- Linac
 - Reuse of existing developer bricks
 - Minimize risks and R&D
 - Warm solution

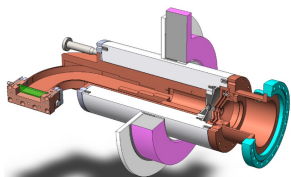
Required	Unit		Specifications
Particle			Proton
Final Peak Current	mA	≥	80
Final Energy	MeV	≥	25
Final Energy upgrade	MeV	≥	40
Beam Duty-Cycle Max	%	≥	6%
Construction time	y	≤	5
Linac operation time	h/y	≥	3600



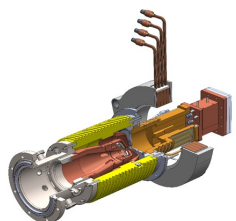
Structure temporelle	2 ms – 20 Hz
	0.4 ms – 50 Hz



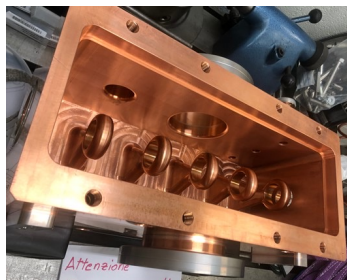
Source ECR



ALISE3 ion Source



SILHI3 ion Source



IH-DTL

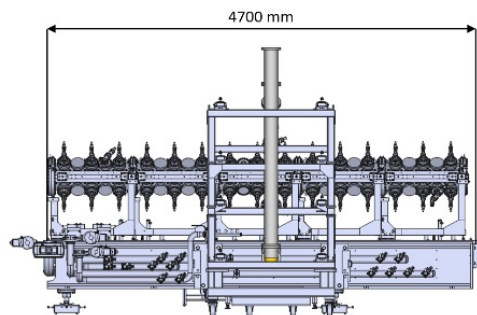
Advantages:
 Small pieces, easy fabrication, easy to replace if necessary.
 Low RF power in each cavity.
 Greater robustness of pieces.
 Independent adjustment of each cavity (phase/amplitude).
 Very little sensitivity to misalignment and tolerances.

Advantages:
 Allows you to benefit from the experience acquired by the INFN for the ESS project.
 ESS DTL is qualified. Little additional development required to adapt it to ICONE.
 One piece, with one very large RF amplifier.

Alvarez DTL



RFQ design ESS



Parameter	Requirement
Frequency	352.21 MHz
Nominal beam current	80 mA ←
Output beam energy	≥ 3.6 MeV
Local peak electric field	< 2 kilp
Inter-vane Voltage	≤ 120 kV
Transmission	> 90 %
Beam duty cycle	6 %
RF duty cycle	10 % ←
Total length	< 5 m
Max beam losses 99% of error cases	< 1W/m

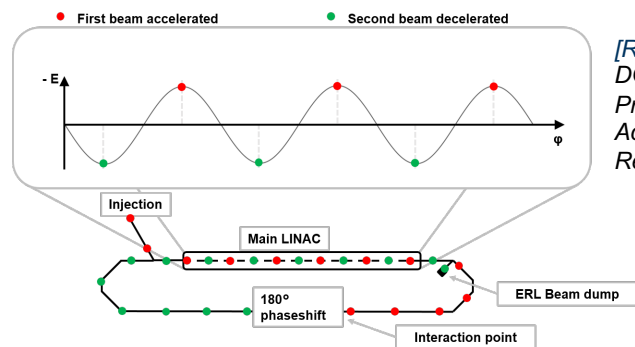
Projet PERLE Energy Recovery Linac



Maury Tigner, 1965 : Première idée de la récupération d'énergie (i. e. puissance faisceau)

[Ref] Tigner, M. A possible apparatus for electron clashing-beam experiments. *Nuovo Cim* 37, 1228–1231 (1965).
<https://doi.org/10.1007/BF02773204>

Evolution du concept vers un système de recirculation du faisceau



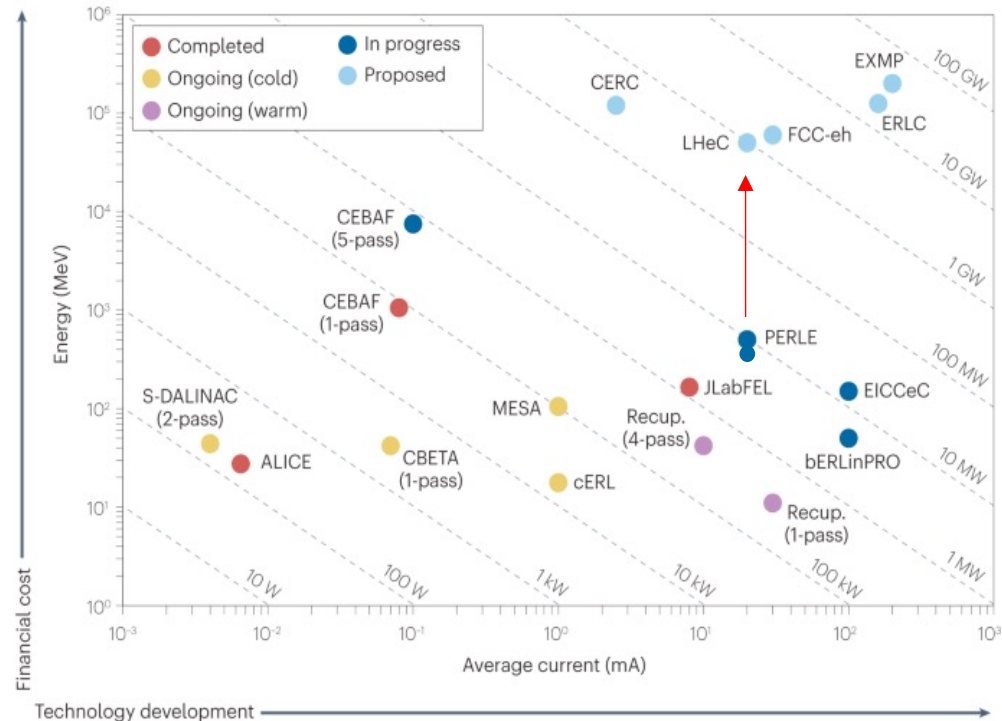
[Ref] Energy recovery linacs, M. Arnold, DOI: 10.23730/CYRSP-2024-003. 2073, in: *Proceedings of the Joint Universities Accelerator School (JUAS): CERN Yellow Reports: School Proceedings.*

Démonstration expérimentale effectuée à :

- ◇ Courant faible / intermédiaire (8 mA), 1 tour et FEL
 [Ref] R. Alarcon et al, *Phys. Rev. Lett.* 111, 164801 (2013)
- ◇ Courant faible (μA), plusieurs tours
 [Ref] F. Schliessmann et al, *Nature Physics* volume 19, pages 597–602 (2023)

Jamais démontré à forte puissance (multi MW)

[Ref.] Hutton, A. Energy-recovery linacs for energy-efficient particle acceleration. *Nat Rev Phys* 5, 708–716 (2023). <https://doi.org/10.1038/s42254-023-00644-6>



European Strategy for Particle Physics 2020

“The energy efficiency of present and future accelerators [...] is and should remain an area requiring constant attention.”

“A detailed plan for the [...] saving and re-use of energy should be part of the approval process for any major project.”



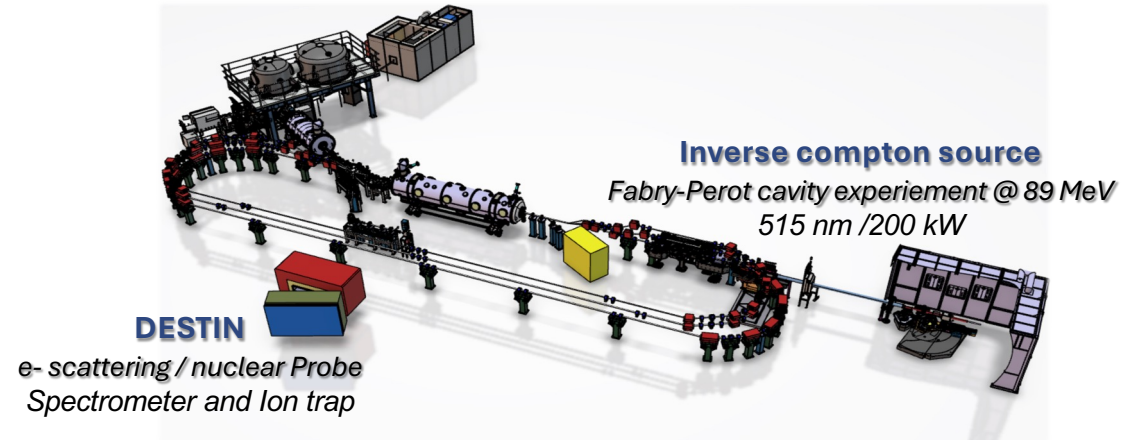
Objectifs principaux

- ◆ Démontrer la récupération de puissance multi-tour, fort courant → Régime multi-Mégawatts
- ◆ “Test Facility” pour les cryomodule 800 MHz FCCee
- ◆ Héberger des expériences d’intérêt pour le laboratoire et les instituts : Cavité Fabry-Perot, DESTIN.

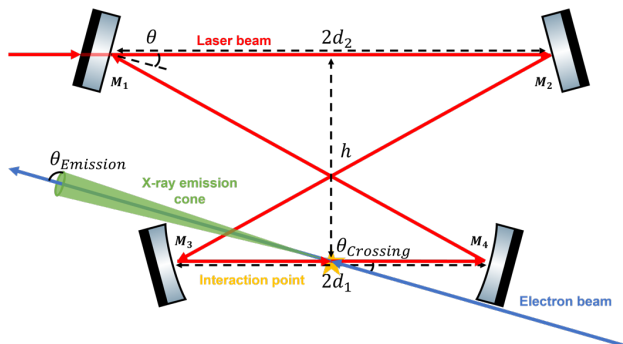
Challenges

- ◆ e- gun à haute charge, faible émittance : 125pC → 500pC à 40 MHz, CW
- ◆ Arc d’accélération décélération commun, gestion du ‘beam path’ pour le synchronisme
- ◆ Instabilités faisceau : BBU, (SCR), Impédance (zone de recombinaison)
- ◆ Cavités SRF haute performance : $Q_0 \sim 3 \cdot 10^{10}$, limiter les effets parasites : multipacting et émission de champs + amortissement des HOM
- ◆ Control RF (bande-passante ~ 100 Hz), Gestion des transitoires RF (source RF limitée en puissance)
- ◆ Diagnostics non invasifs et méthode pour mesurer le chemin faisceau (nécessaire pour la synchro accel/deccel)
- ◆ Design des aimants avec champs haute qualité (minimiser les erreurs de déphasage faisceau)

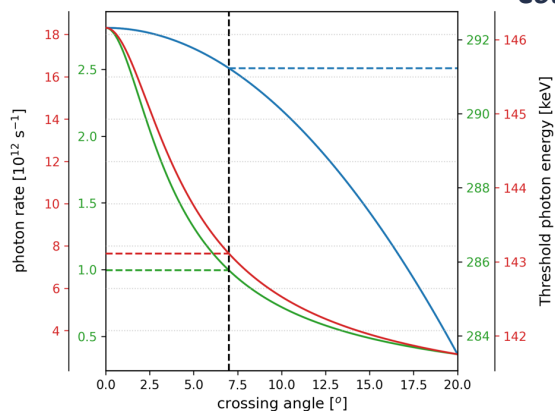
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	89/250/500
Normalised Emittance $\gamma\epsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW



Source Compton innovante

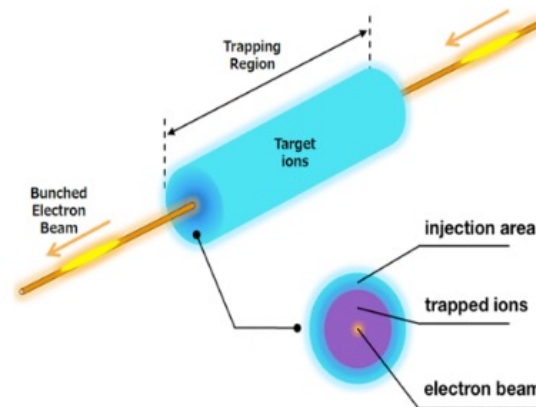


Courtesy A. Renaux (IJCLab)

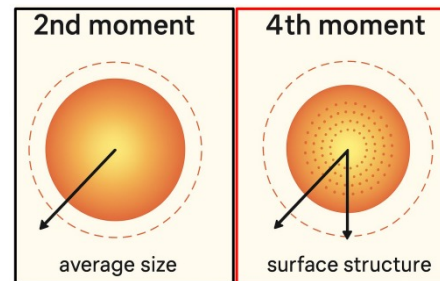


Production d'X : 100 - 300 keV
Laser : $\lambda = 515 \text{ nm}$
PERLE 1 tour : 89 MeV

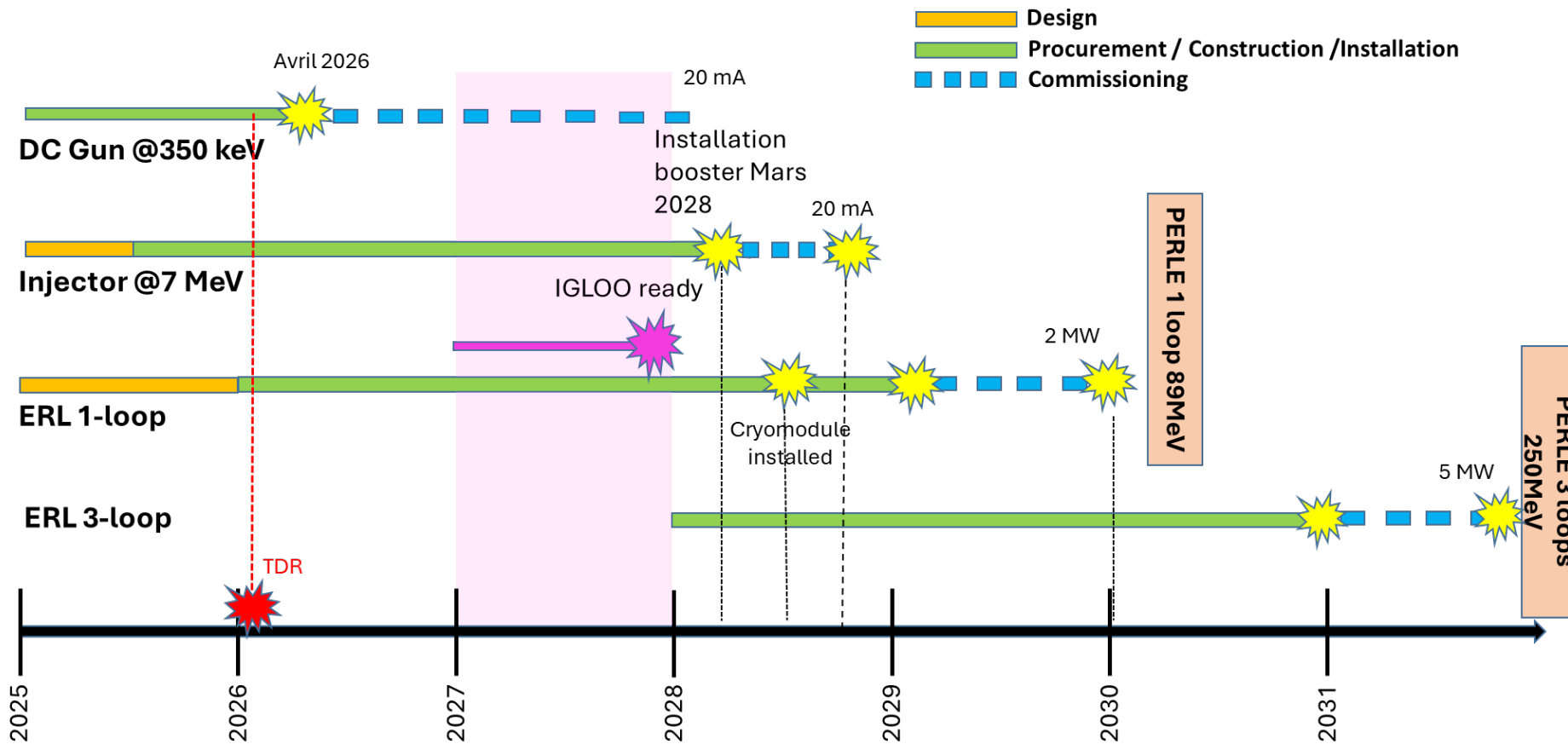
DESTIN Mesure de structure nucléaire



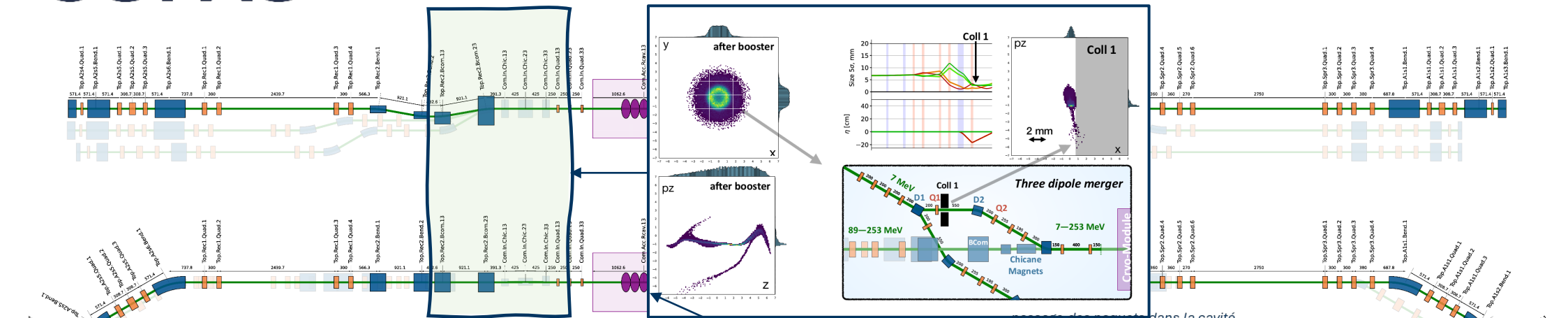
4th moment of the charge distribution of a nucleus & RMS radius of neutrons distribution



Electron scattering at low q
 → PERLE will be the only facility to provide electrons for low- q scattering on the rare isotopes nuclei

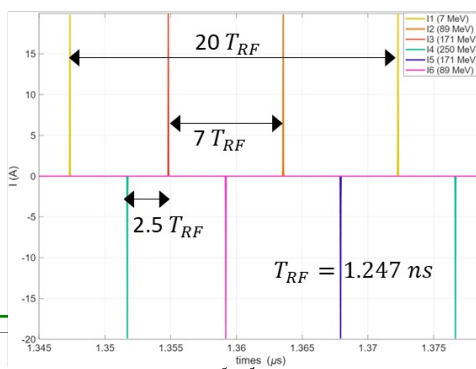


ERL : opération



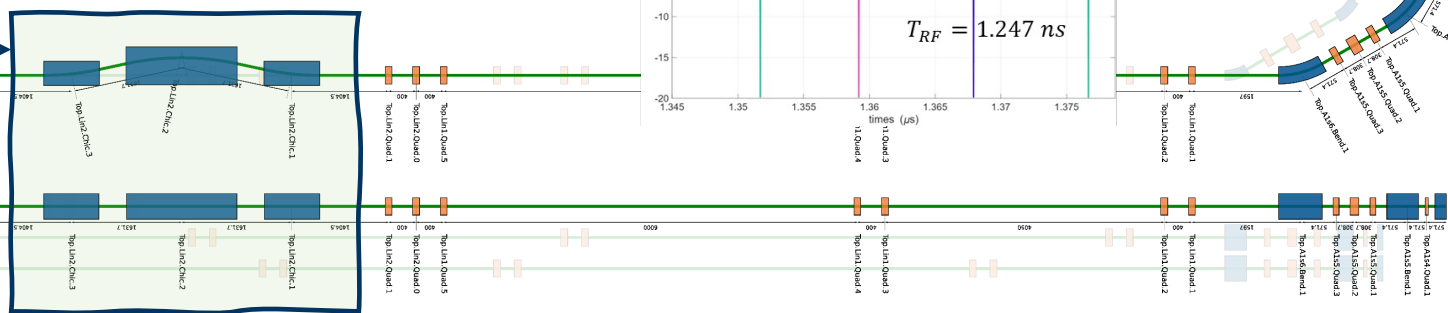
Optimisation des schémas de Collimation – Cf. Poster Arnaud Cieplak

Gestion du synchronisme et dynamique longitudinale cf. Poster Janine Issa



$$\Delta\phi = \frac{\omega_{RF}}{c} [S(B) - S(B_0)]$$

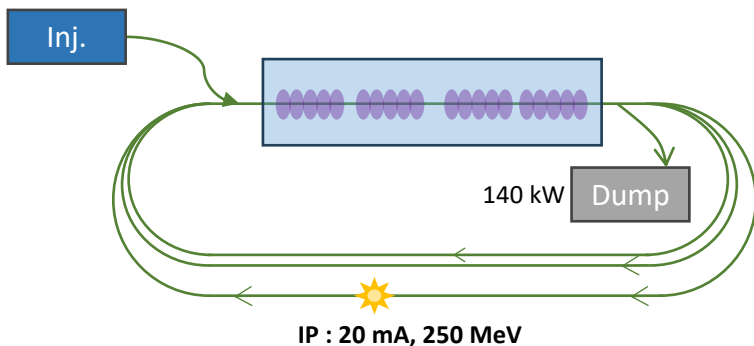
$$S(B) = 4 \frac{L_1}{\sin \theta(B)} \theta(B) + 2 \frac{L_2}{\cos \theta(B)}$$

$$\theta(B) = \frac{qBL_1}{p}$$


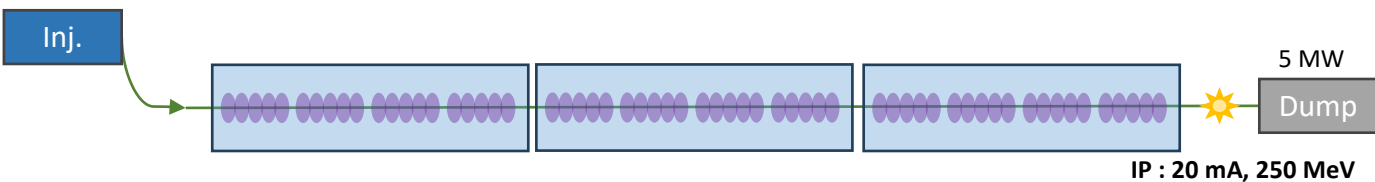
Etude préliminaire Consommation « électrique à la prise »

- Faisceau de 5 MW à l'IP (250 MeV, 20 mA, CW)
- Hypothèse optimiste :
 - Machine parfaitement réglée
 - rendement alim et amplificateurs

ERL 3 tours



Linac (3 Cryomodules)



Type	Elec. Power (kW)							
	PERLE 3 Turns (250 MeV, 20 mA)			SC Linac (250 MeV, 20 mA)				
Magnets (Power supply eff. ~85%)	219.7 kW			15.2 kW				
Injector	0.3			0.3				
Merger	0.4			0.4				
ERL or SC linac	219.1			14.6				
RF Power (ampli eff. ~55% + att. & errors)	475.5 kW			9 626.6 kW				
Injector (Booster + Buncher)	275.8			275.8				
ERL (4 cavities) or Linac (3*4 cavities)	199.7			9350.9				
Cryogenic Systems	190.5 kW			424.3 kW				
Cryomodule Booster	Stat.	Dyna.	Lhe (FPC)	Stat.	Dyna.	Lhe (FPC)		
	21.75	9.9	~8	21.75	9.9	~8		
Cryomodule ERL ou 3 Cryomodules Linac	Stat	Dyna	HOM (St & Dy)	Lhe (FPC)	Stat	Dyna	HOM (St. & Dy.)	Lhe (FPC)
	17.9	84.3	16.7	~8	53.75	253.0	3	~24
Cryolines & Valves box	23.9			50.5				
Diagnostics	~2.2 kW			~2.0 kW				
Gun (HV, laser, laser room)	7.9 kW			7.9 kW				
Total	≈ 895.8 kW ≈ 0.9 MW			≈ 10 076.0 kW ≈ 10 MW				
Cooling systems (water, air, ...) (+ Vacuum) + ..	++			-				
Power to dissipate @ dump	140 kW			5000 kW				

Réduction du coût de construction:

- Compacités: Maximiser gradients accélérateurs *mais maintenir la qualité du faisceau*
→ **Laser-Plasma : enjeu de la répétabilité**
- *Optimiser le mode de fonctionnement et utiliser des technologies éprouvées / « faciles » à fabriquer*
- *Minimiser la puissance RF utilisée*

Exemple d'une **source compacte de neutrons: ICONÉ**.

Réduction du coût d'opération = Gagner en efficacité et garantir en disponibilité faisceau

- Concept de récupération de la puissance faisceau après utilisation pour accélérer les faisceaux suivants.
→ Exemple d'un **ERL multi-tours: PERLE**, mais valable que si le faisceau est « récupérable »
 - Sources RF de nouvelle génération, haut rendement
 - Améliorer les rendements des cavités accélératrices (supra) et systèmes associés
- Smart LLRF , Fast reactive ferro-electric tuner, Supra haute température (ref : iSAS european project)

Accélérer Fiable et Efficace ou Efficace et Fiable