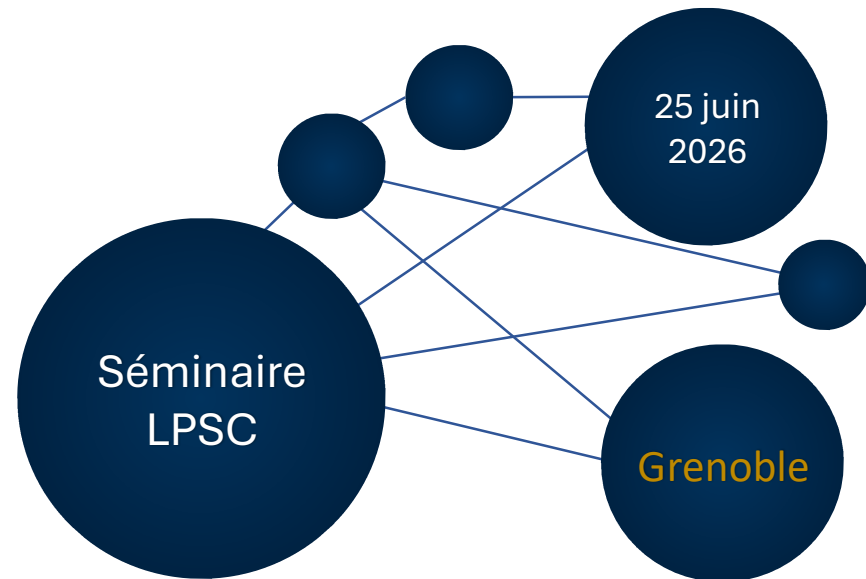
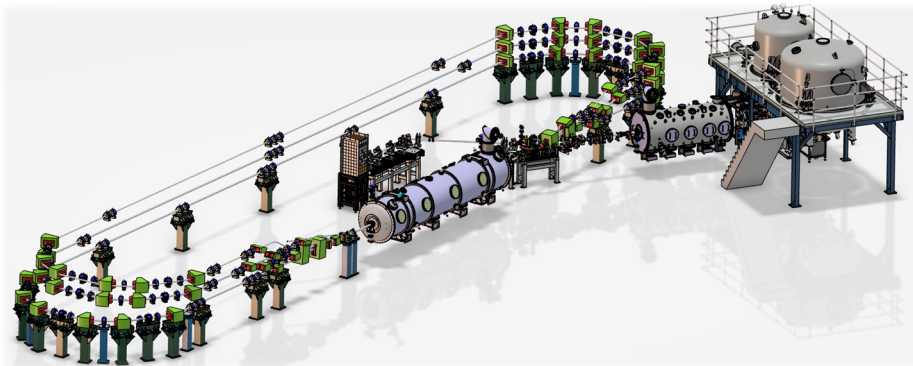




Energy Recovery Linac & Projet PERLE

Accélération et Récupération de Puissance

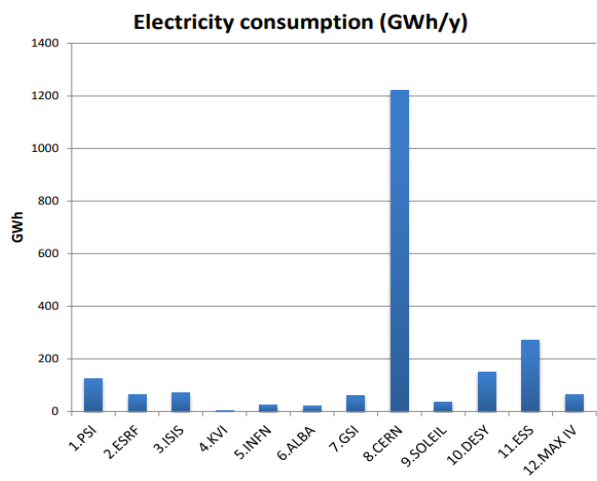
F. Bouly (LPSC) pour la collaboration PERLE



1. Introduction : Contexte & Principe ERL
2. Principe de fonctionnement des cavités accélératrices
3. Modélisation : interaction cavité/faisceau + systèmes RF
4. Opération d'un ERL et récupération de puissance
5. Projet PERLE avancement et enjeux
6. Bilan de puissance et conclusions

Installations européenne

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

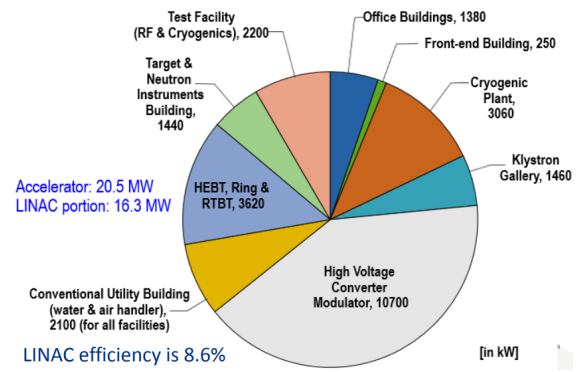
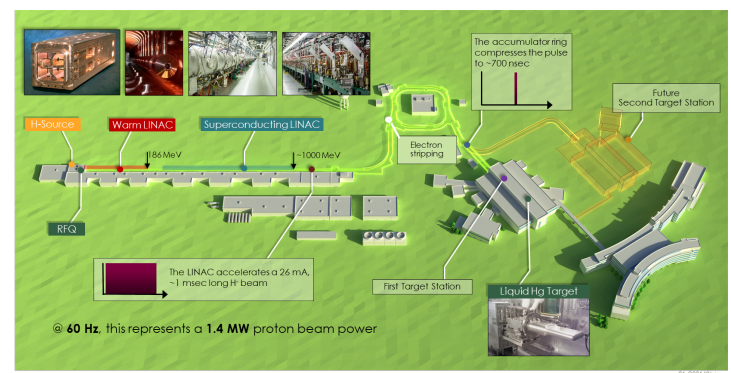


Conso elec. Grenoble Alpes Métropoles
 ~3 TWh /an (2023, ~450 000 hab)
Observatoire regional climat air eau AURA

Ordres de Grandeurs / Production

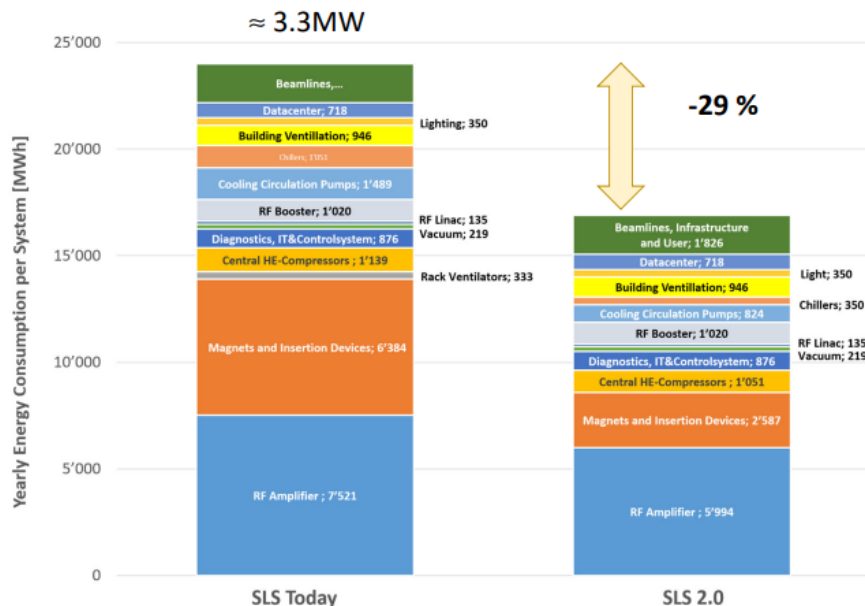
Type	Production	
	1 jour	Total /an en France
Nucléaire	~ 30 GWh (une centrale)	~362 TWh
Eolien	~12 MWh	~47 TWh
1 cycliste (pro)	~1.12 kWh (4h*280 W)	~62 kWh (55 jrs de course)

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).

Exemple de Swiss Light Source (SLS) à PSI



**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

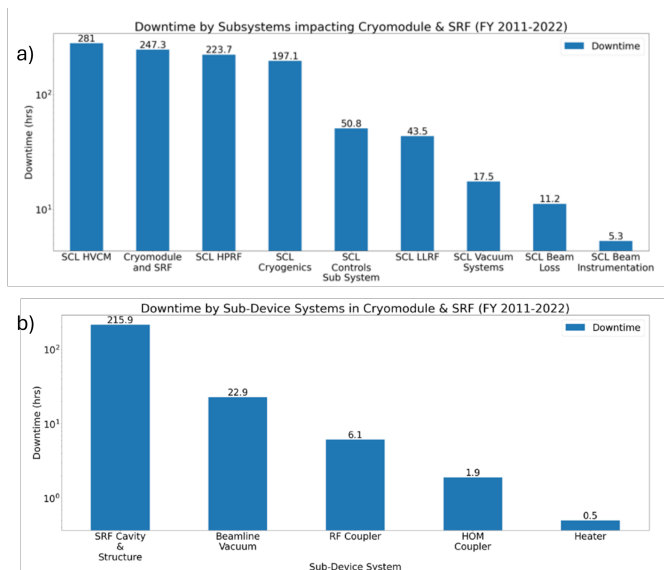
P_{tot}	= 2.4MW
P_{RF}	= 0.82MW
$P_{\gamma}(\text{undulators})$	= 91kW

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>

◇ Réduction de la consommation par « jouvence » et choix technologiques

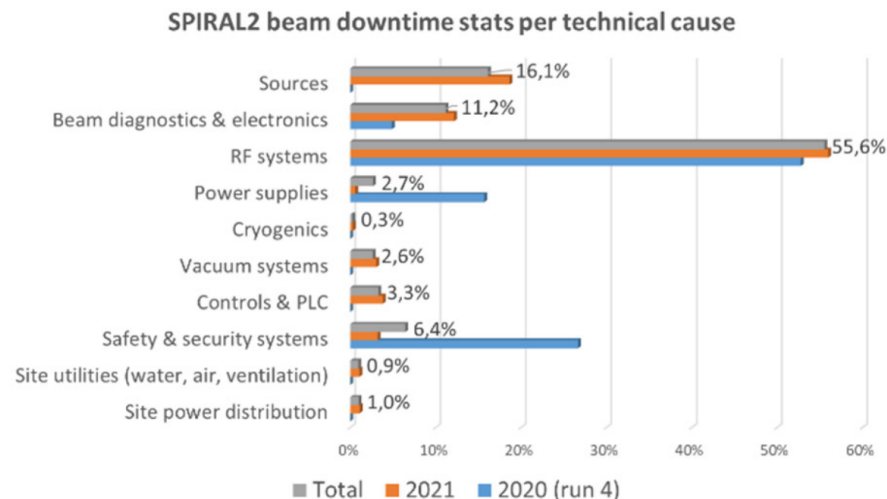
◇ Accroître la disponibilité du faisceau → Fiabilité

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. Bernardin, 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/tupoge02.pdf>

◇ Systèmes RF + cavités sensibles aux pannes et éléments les plus consommateurs et coûteux

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

- ◇ Maury Tigner, 1965 : Première idée de la récupération d'énergie (i. e. puissance faisceau)
 - ◇ But : minimiser la consommation RF d'un collisionneur linéaire et réduire la puissance au dump
 - ◇ Recycler l'énergie cinétique d'un faisceau décéléré pour accélérer un nouveau faisceau injecté à faible énergie.

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

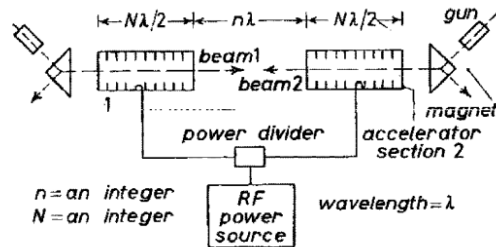


Fig. 2.

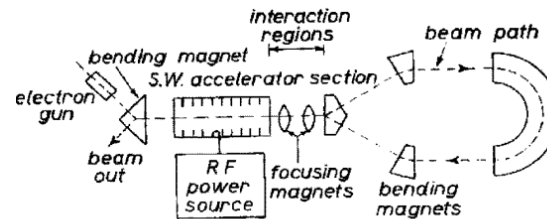
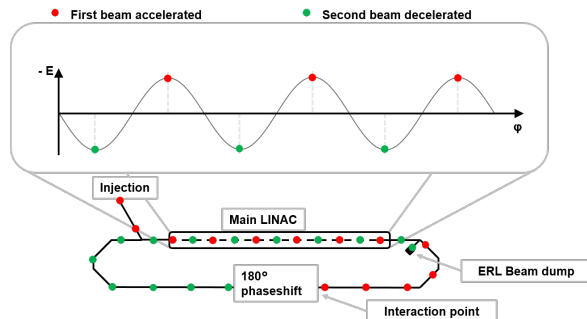


Fig. 3.

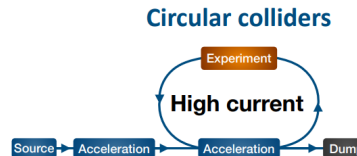
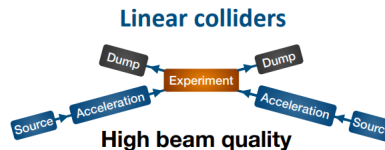
◇ Evolution du concept vers un système de recirculation du faisceau

- ◇ Accélération/décélération « on-crest » - déphasage ajusté par le temps de vol faisceau pour recirculer



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

Combiner les avantages de différentes machines



Applications

- Collisionneurs
- Light Source : FELs, Compton, ...
- Physique nucléaire: Ions/e⁻

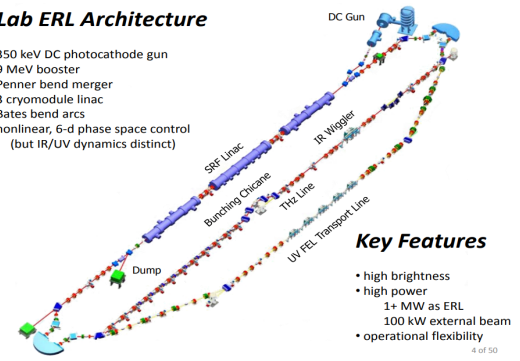
◇ **Démonstration expérimentale effectuée à :**

- ◇ Courant intermédiaire (8 mA), 1 tour et FEL (JLab)

[Ref] R. Alarcon et al. Phvs. Rev. Lett. 111. 164801 (2013)

JLab ERL Architecture

- 350 keV DC photocathode gun
- 9 MeV booster
- Penner bend merger
- 3 cryomodule linac
- Bates bend arcs
- nonlinear, 6-d phase space control (but IR/UV dynamics distinct)



- ◇ Courant faible (μA), plusieurs tours (exemple, S-DALINAC, Darmstadt)

[Ref] F. Schliessmann et al, Nature Physics volume 19, pages 597–602 (2023)

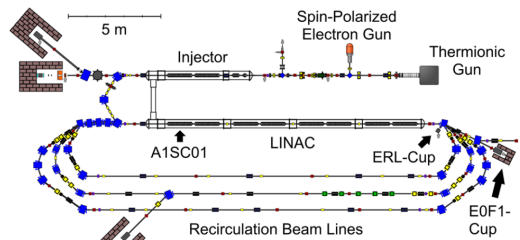
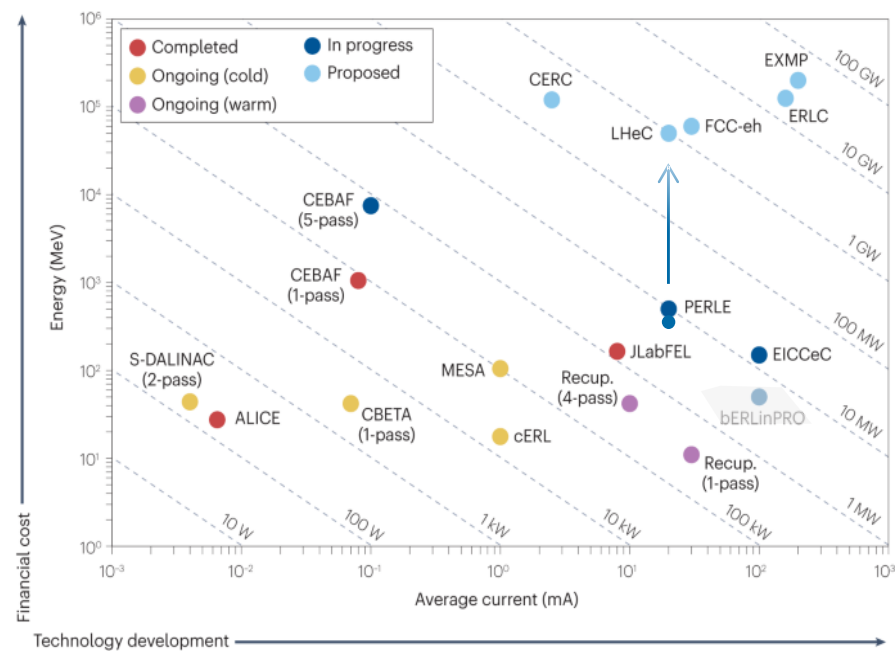


FIG. 2. Schematic floorplan of the S-DALINAC.

[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>



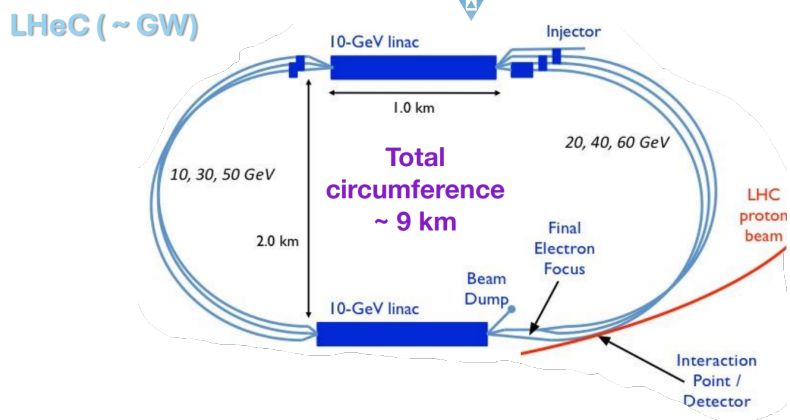
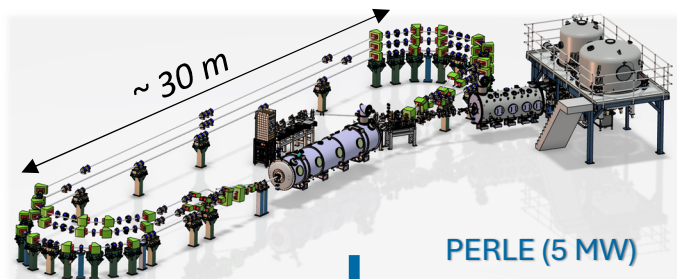
European Strategy for Particle Physics 2020

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

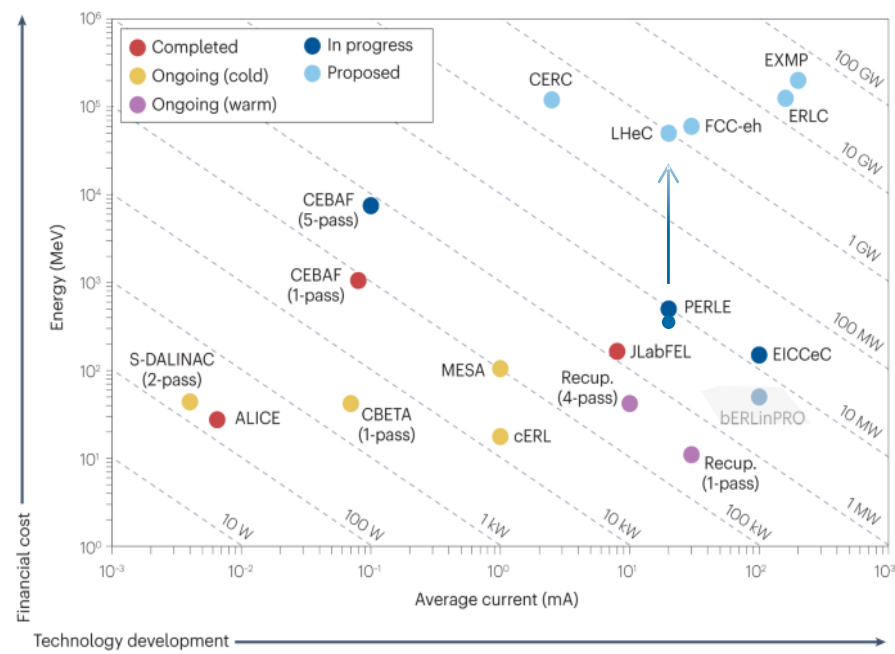
“A detailed plan for the [...] saving and re-use of energy should be part of the approval process for any major project.”

❖ Démonstration haute puissance multi -MégaWatt

- ❖ Démontrer opération multi-tour et fort courant
- ❖ Valider les choix technologiques : SRF 800 MHz, electron source, etc.



[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.”



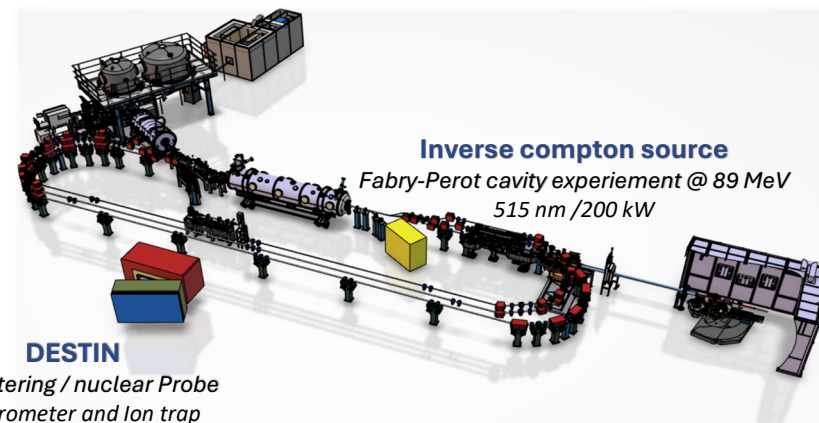
◆ Objectifs principaux

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

◆ Etudier les problématiques spécifiques à l’opération ERL multi-tour MW

- ◆ 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 : Beam Break Up, (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, contrôle de la dispersion)
- ◆ ...

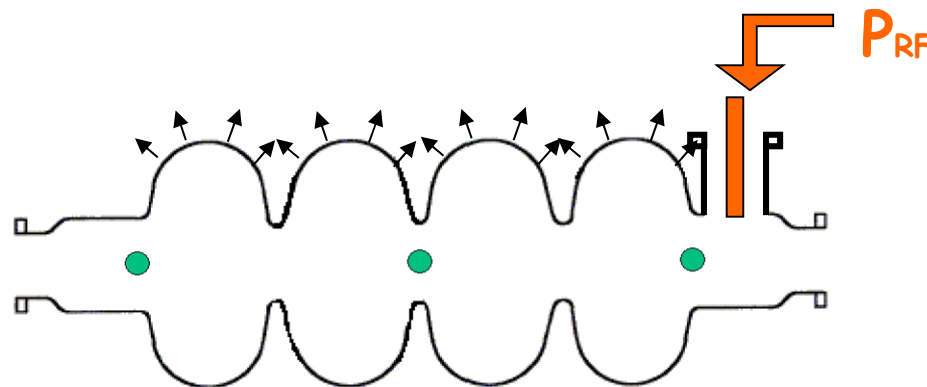
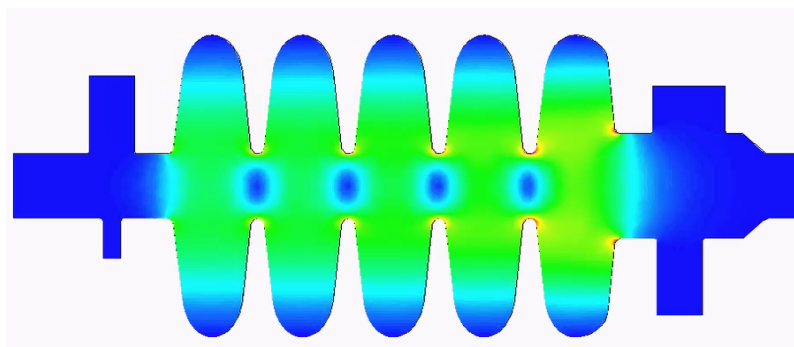
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	89/250
Normalised Emittance $\gamma\epsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor	CW	



Cavité Accélératrice

Principe de fonctionnement

- ◇ Electromagnetic wave resonating inside the cavity.
- ◇ TM_{01} mode with E_{acc} along beam axis.
- ◇ Resonance Freq. synchronised with the bunch



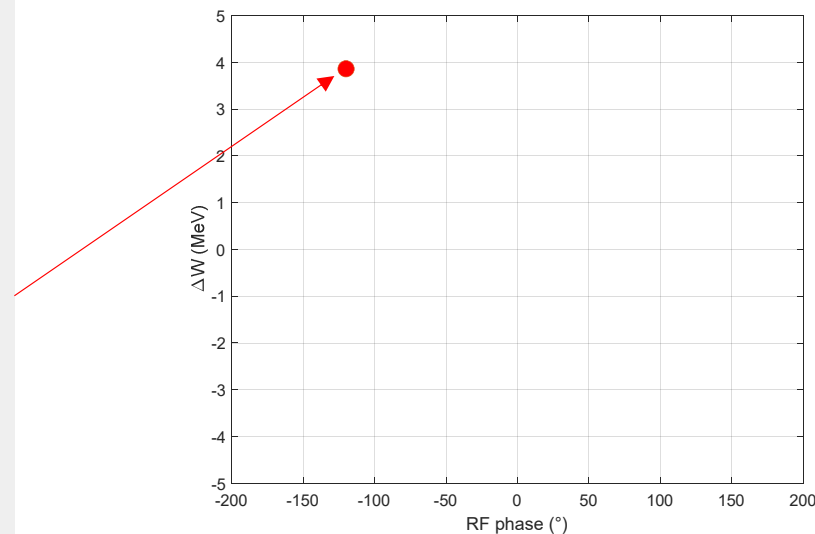
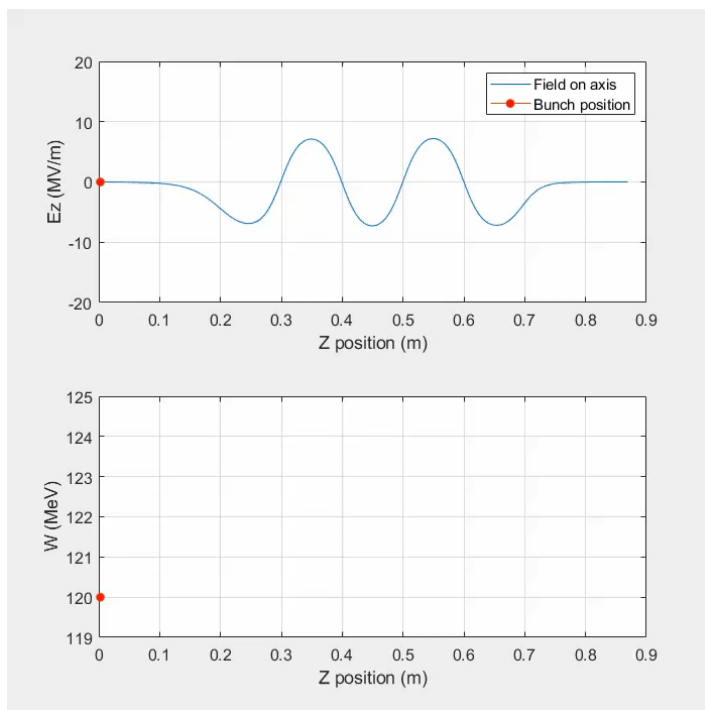
- ◇ Acceleration : Work of the electromagnetic Force

$$\delta W = \overrightarrow{F}_{elec} \cdot \vec{v} dt = q \vec{E} \cdot \vec{v} dt$$

$$\Rightarrow \Delta \overline{W} = q \int_{t_{in}}^{t_{out}} E_z(z, r = 0) e^{j(\omega_0 t + \varphi)} \beta(t) c dt$$

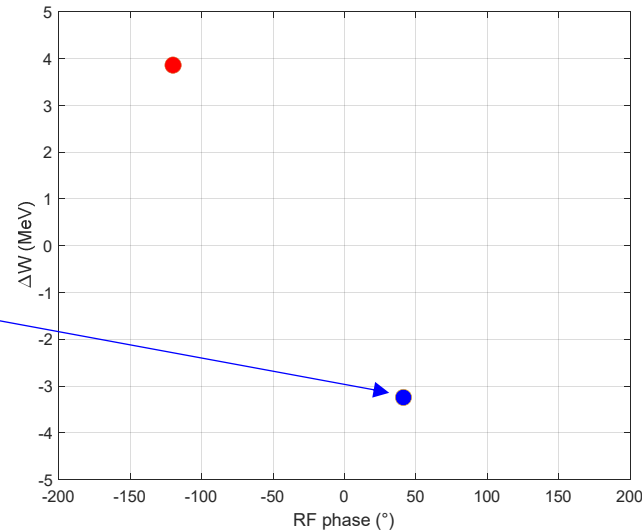
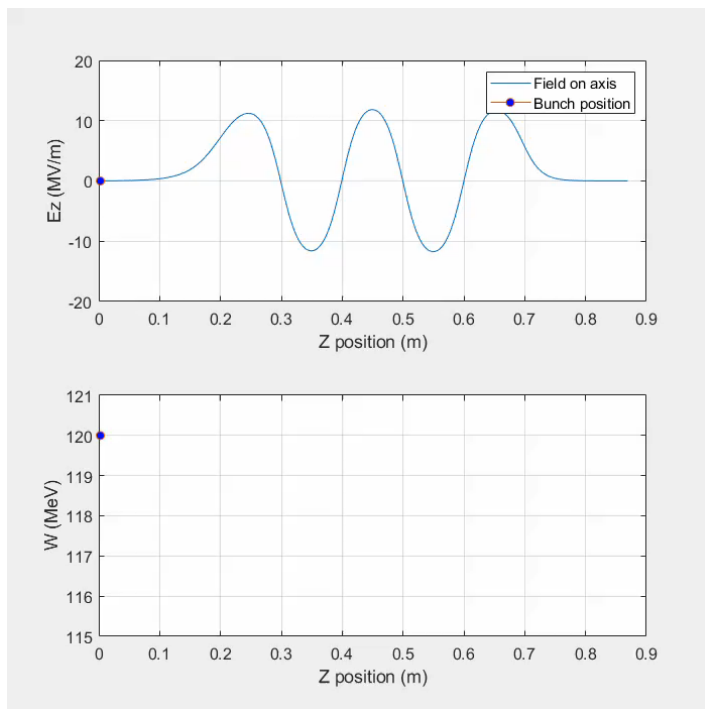
- ◇ Ex : 5-cell elliptical cavity ($\beta_{opt} = 0.5$) accelerating a proton beam
- ◇ $W_{in} = 120$ MeV

$$\varphi_{RF} = -120^\circ$$



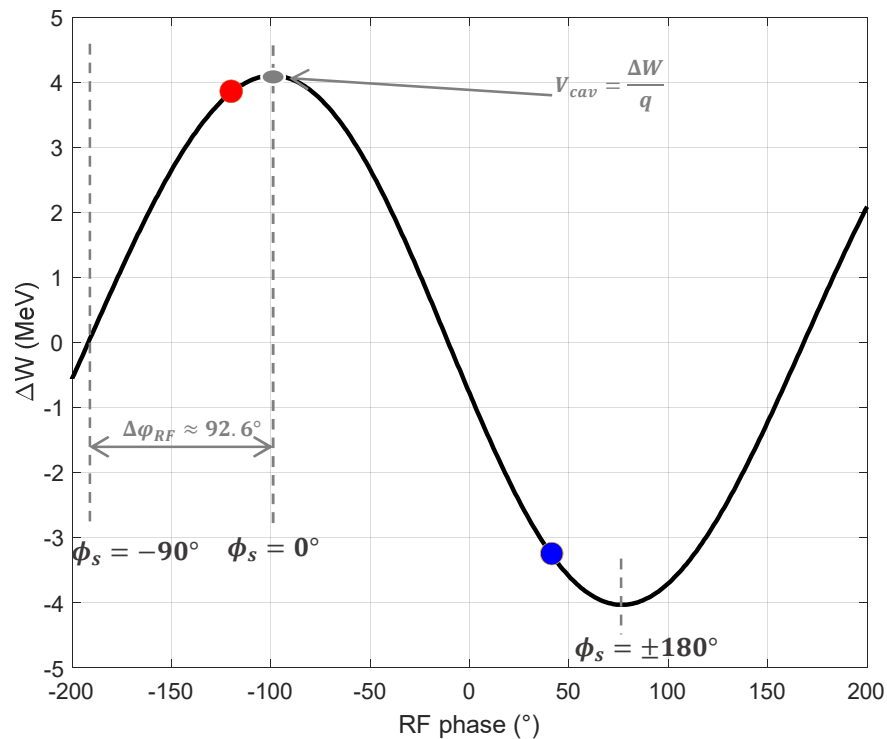
- ◇ Ex : 5-cell elliptical cavity ($\beta_{opt} = 0.5$) accelerating a proton beam
- ◇ $W_{in} = 120$ MeV

$$\varphi_{RF} = 41.3^\circ$$



- ◇ Ex : 5-cell elliptical cavity ($\beta_{opt} = 0.5$) accelerating a proton beam
- ◇ $W_{in} = 120$ MeV

Scan φ_{RF}

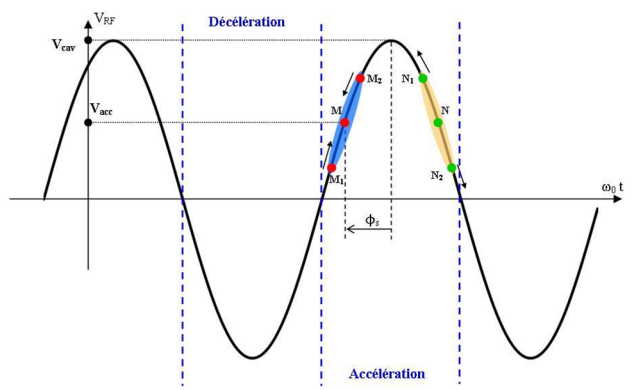
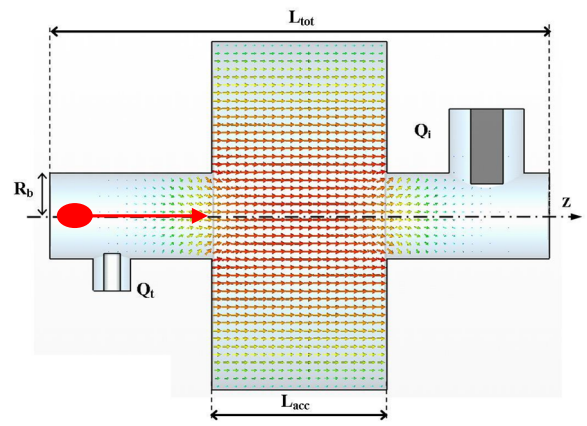


$$\Delta W = q V_{cav} \cos(\phi_s)$$

with

$$V_{cav} = \frac{|\Delta \tilde{W}|}{q}$$

$$\phi_s = \arg(\Delta \tilde{W})$$



◇ Energy gain

$$\Delta W = q V_{cav} \cos(\phi_s)$$

◇ Accelerating voltage

$$V_{cav} = \left| \int_{t_{in}}^{t_{out}} E_z(z, r = 0) e^{j(\omega_0 t + \phi)} \beta(t) c dt \right|$$

◇ Accelerating field and accelerating length

$$E_{acc} = \frac{V_{cav}}{L_{acc}} \quad L_{acc} = \frac{N\beta\lambda}{2} = \frac{N\beta c}{2f}$$

PERLE : $L_{acc} = 0.9179 \text{ m}$ & $E_{acc} = 22.33 \text{ MV/m}$

◇ Synchronous phase*

$$\phi_s = \arctan \left(\frac{\int_{t_{in}}^{t_{out}} E_z(z, r = 0) \sin(\omega_0 t + \phi) \beta(t) c dt}{\int_{t_{in}}^{t_{out}} E_z(z, r = 0) \cos(\omega_0 t + \phi) \beta(t) c dt} \right)$$

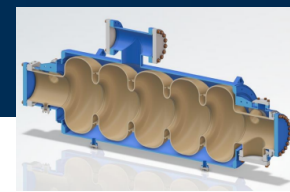
◇ Quality factor

$$Q_0 = 2\pi \frac{\text{Stored energy}}{\text{dissipated energy per RF cycle}} = \omega_0 \frac{W}{P_{cav}}$$

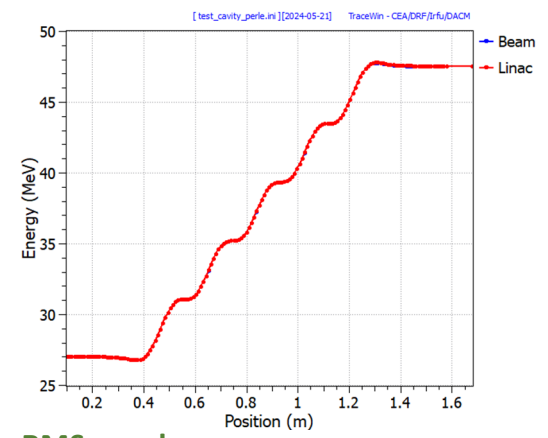
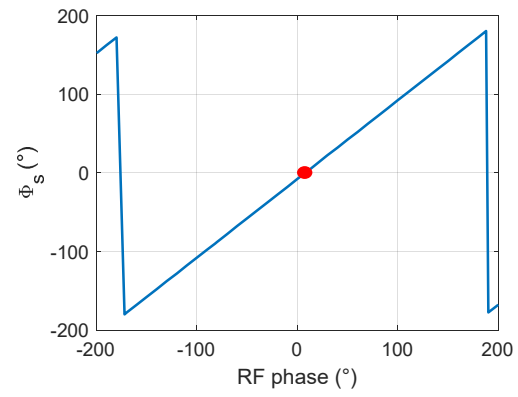
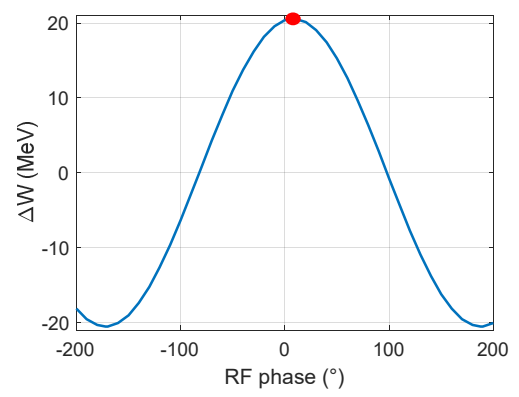
◇ (r/Q)

$$(r/Q) = \frac{V_{cav}^2}{\omega_0 W}$$

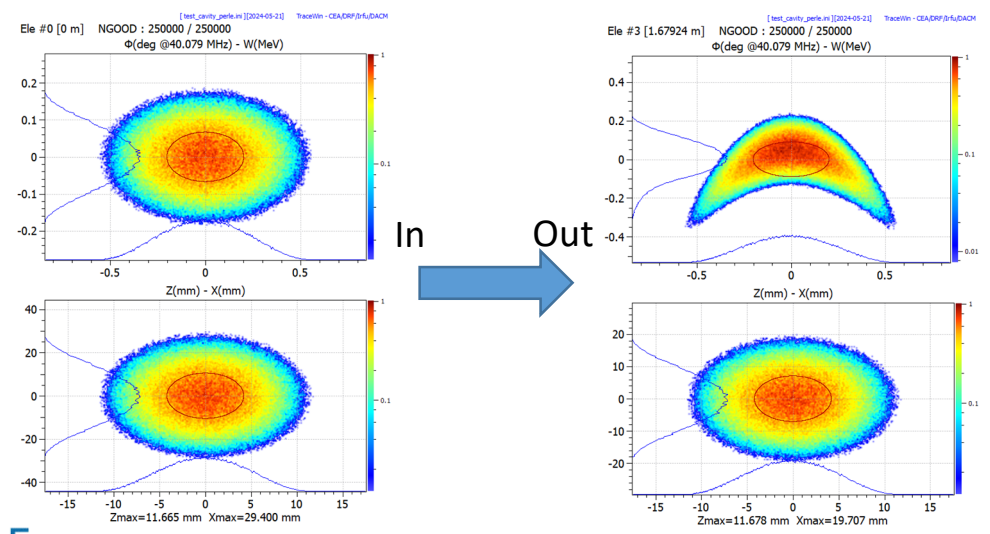
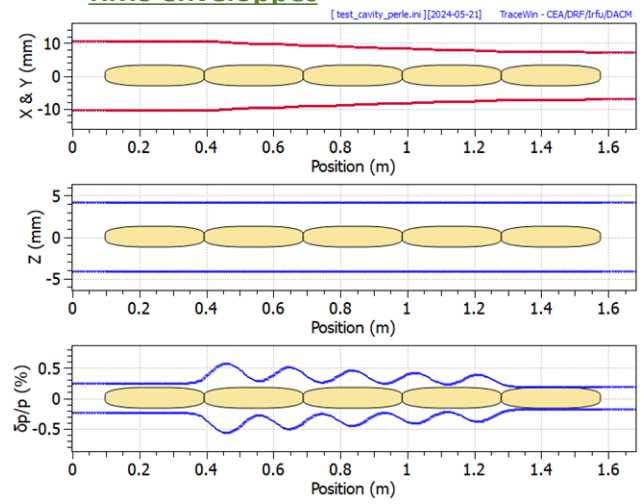
* Subtlety at high $\Delta\beta$: New definition, JM Lagniel, Roscoff, 2021



◇ electron beam (20 mA) entering the cavity with a kinetic energy of 27 MeV

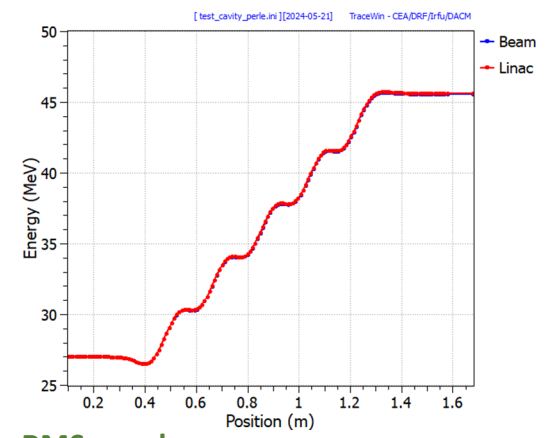
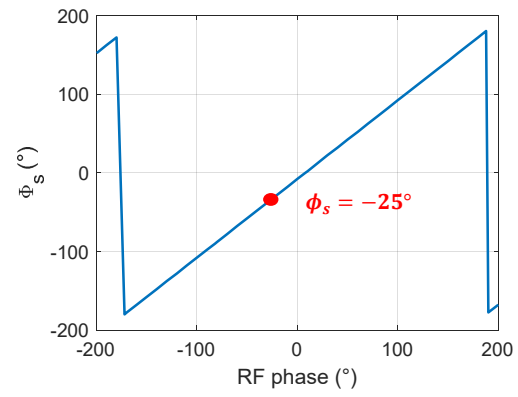
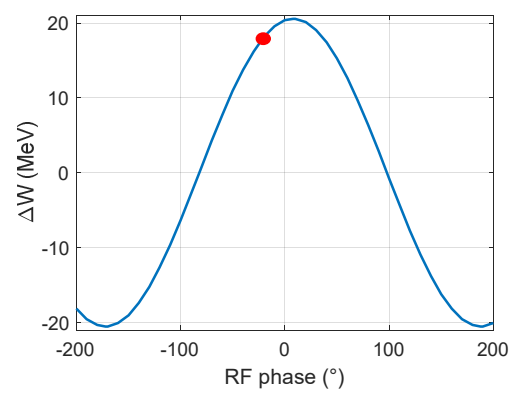


RMS envelopes

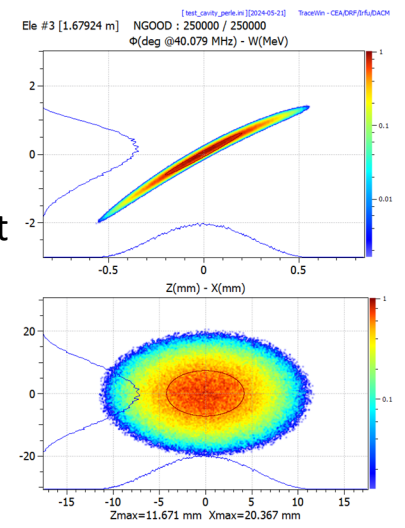
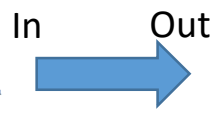
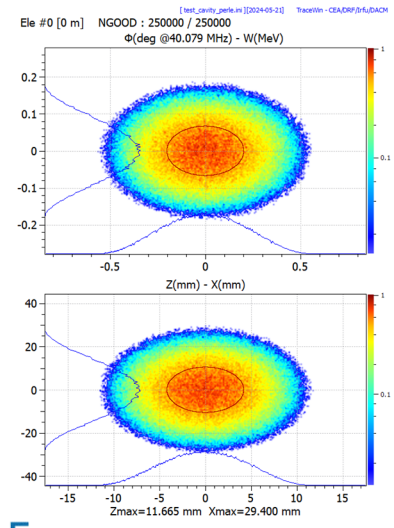
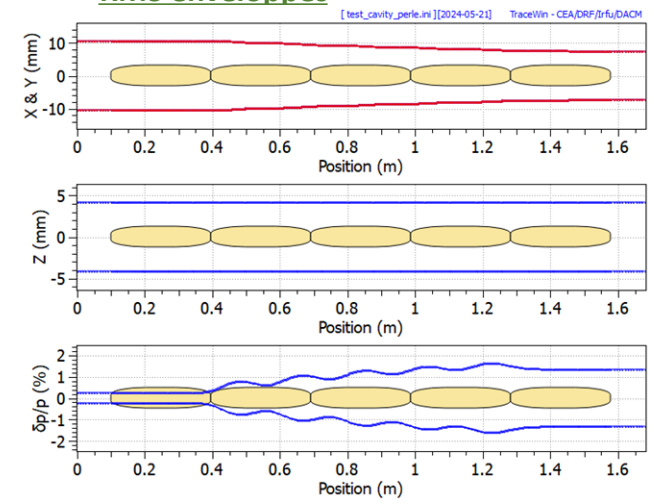




◇ electron beam (20 mA) entering the cavity with a kinetic energy of 27 MeV

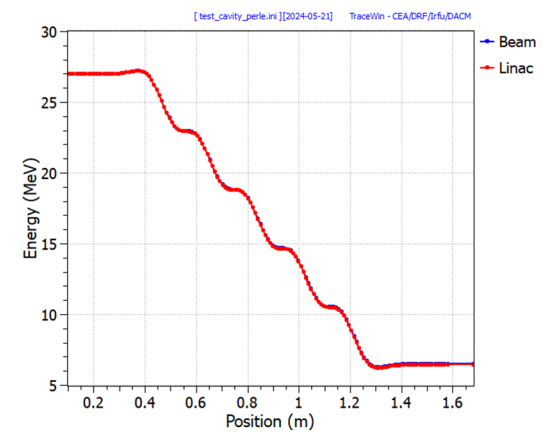
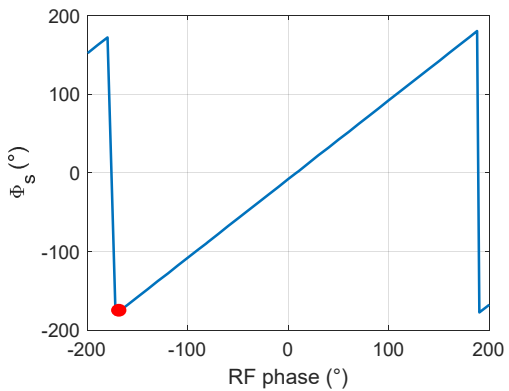
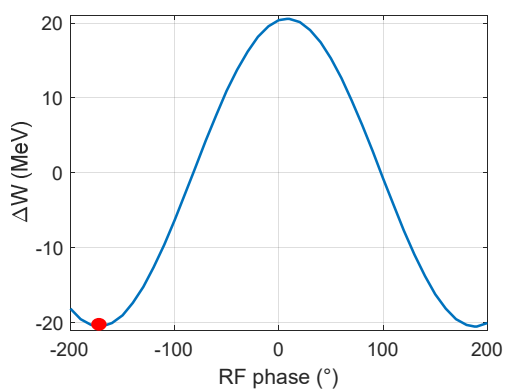


RMS envelopes

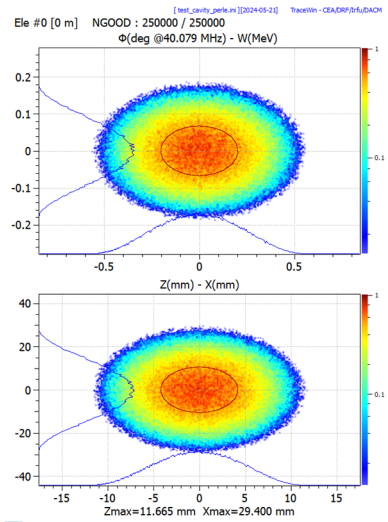




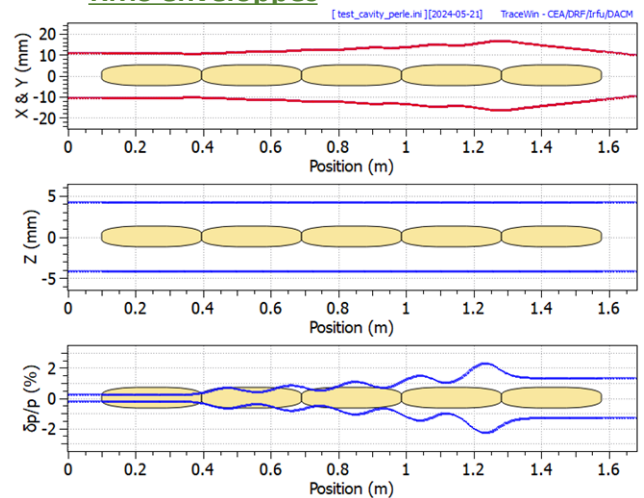
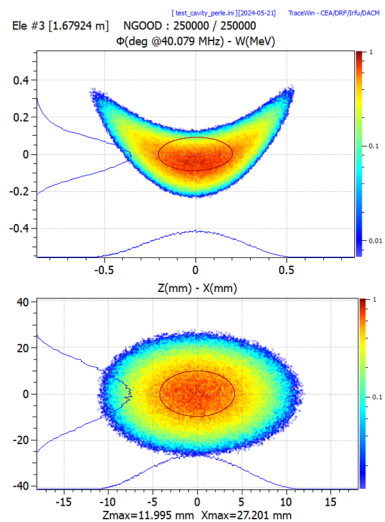
◇ electron beam (20 mA) entering the cavity with a kinetic energy of 27 MeV



RMS envelopes



In → Out

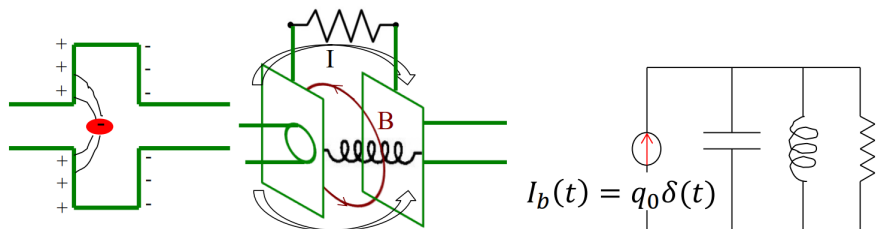
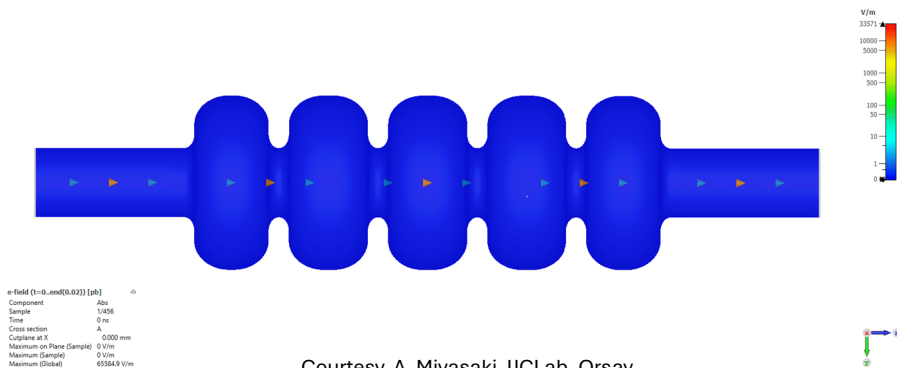


Modélisation

Interaction cavité / Faisceau

Système RF

Mode ERL



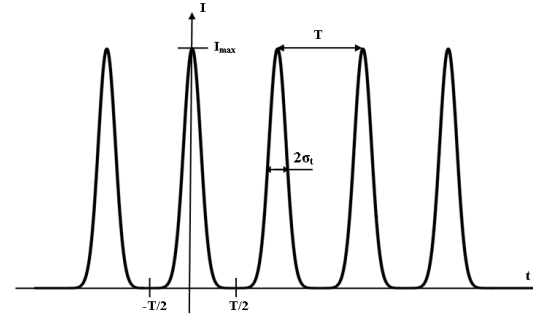
Collective effects, M. Migliorati, DOI: [10.23730/CYRSP-2024-003.539](https://doi.org/10.23730/CYRSP-2024-003.539), in: Proceedings of JUAS

- ◇ Lorsqu'une charge traverse une structure résonante, telle qu'une cavité RF, elle excite des modes résonants (mode fondamental et HOMs — modes d'ordre supérieur).
- ◇ Chaque mode peut être traité comme un circuit électrique **RLC** alimenté par un courant impulsionnel. Après le passage de la charge, le condensateur est chargé à une tension $V_0 = q_0/C$
- ◇ Le passage du courant impulsionnel ne charge que le condensateur, ce qui modifie son potentiel d'une valeur V_0 .
- ◇ Ce potentiel oscillera ensuite et décroît progressivement, produisant un courant dans la résistance et l'inductance.

◆ Bunch : Assuming gaussian distribution in the longitudinal direction

◆ Period $[-T/2; T/2]$

$$I(t) = \frac{Q}{\sqrt{2\pi}\sigma_t} e^{-\frac{t^2}{2\sigma_t^2}} = I_{max} e^{-\frac{t^2}{2\sigma_t^2}} \quad I_{b0} = \frac{Q}{T}$$



◆ Fourier series decomposition

$$I(t) = \frac{a_0}{2} + \sum_{n=1}^{+\infty} a_n \cos(n\Omega t) + b_n \sin(n\Omega t)$$

$$\begin{cases} \Omega = (2\pi/T) \\ a_0 = (2Q/T) \\ a_n = (2Q/T) e^{-\frac{(n\Omega\sigma_t)^2}{2}} \\ b_n = 0 \end{cases}$$

$$a_n = 2 I_{b0} e^{-\frac{(n\Omega\sigma_t)^2}{2}} = 2 I_{b0} e^{-2\left(\frac{n\pi\sigma_t}{T}\right)^2}$$

◆ Cavity is a bandpass filter so :

◆ only the n^{th} harmonic of the beam corresponding to its resonance pulsation is seen : $\omega_0 = n \Omega$

◆ One should also considered the ration T/σ_t :

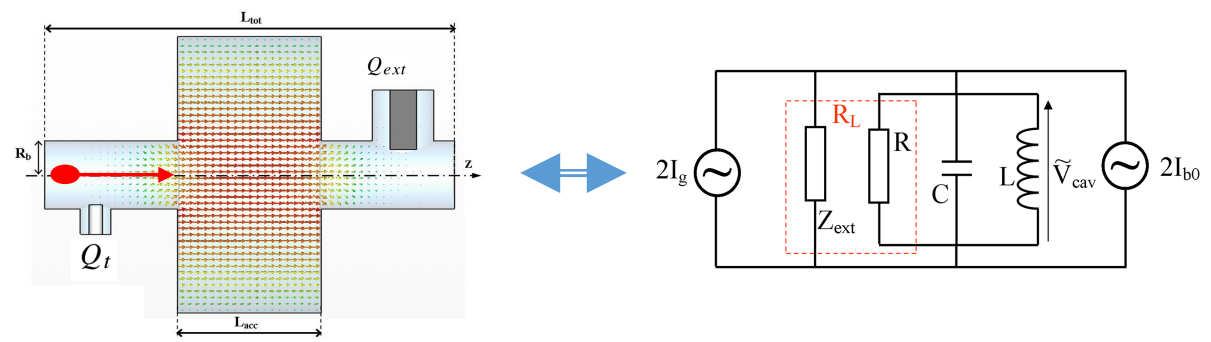
◆ Ex of PERLE ($n = 20$) :

$$\begin{aligned} n &<< \frac{T}{\sigma_t} \\ \sigma_t &\sim 8.4ps \\ T &= 25 ns (40MHz) \end{aligned}$$

$$a_n(\Omega) = 2 I_{b0}$$

$$I_b(t) = 2 I_{b0} \cos(\omega_0 t)$$

◆ Band pass resonator ↔ RLC parallel circuit.



◆ Cavity parameters (r/Q , Q_0 , Q_L) can be related to equivalent circuit parameters to R_L (or R), L et C .

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad Q_0 = \omega_0 R C = \frac{R}{L\omega_0}$$

$$\frac{R}{Q_0} = \frac{R_L}{Q_L} = \sqrt{\frac{L}{C}} \quad \left(\frac{r}{Q}\right) = \frac{2}{\omega_0 C}$$

◆ Coupling :

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} + \frac{1}{Q_t} \quad Q_L = \omega_0 \frac{W}{P_{cav} + P_{ext}}$$

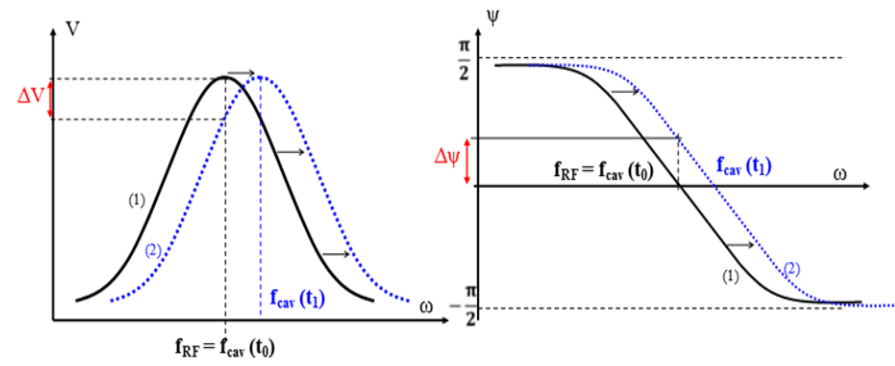
← Cavity
← **Power coupler**
← Pick-up antenna

Band-pass resonator

$$BP_\omega \approx \frac{\omega_0}{Q_L} \iff BP_f \approx \frac{f_0}{Q_L} \quad \tan(\psi) \approx 2Q_L \frac{\Delta\omega}{\omega} = 2Q_L \frac{\Delta f}{f}$$

Steady state

$$V_{cav}(\omega) = \frac{(r/Q)Q_L}{\sqrt{1 + (\tan(\psi))^2}} (I_g + I_{b0})$$



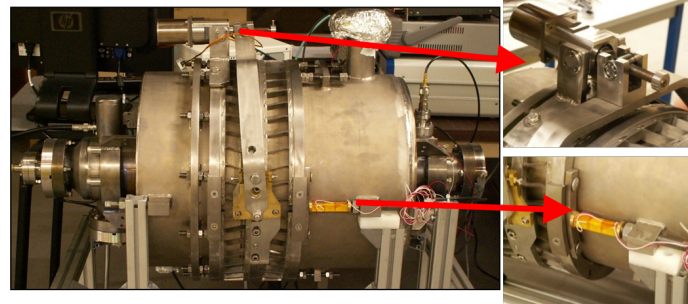
[Ref] : T. Wangler, "RF linear accelerators", Wiley, 1998

- ◇ Power delivered to the beam :

$$P_b = V_{cav} I_{b0} \cos(\phi_s)$$

- ◇ Optimal frequency detuning :

$$\Delta f_{opt} = -\frac{I_{b0}(r/Q) \sin(\phi_s)}{2V_{cav}} \cdot f_0$$



■ Moteur : action «lente» (~1s) – grande dynamique de réglage (~ 250 kHz).

■ Piézoélectriques : action «rapide» (~ 1 ms) – dynamique de réglage plus fine (~ 2 kHz).

- ◇ RF power required from the generator when cavity is at optimal frequency tuning :

$$P_{fwd}(\Delta f_{opt}) = \frac{V_c^2 Q_{ext}}{4(r/Q)Q_L^2} \left(1 + \frac{I_{b0}(r/Q)Q_L \cos(\phi_s)}{V_c} \right)^2$$

- ◇ Optimum for coupling : Ideally, each cavity should have its own power coupler with an optimised Q_{ext} (in function of its (r/Q) , ϕ_s , V_c & I_{b0})

$$Q_{ext\ opti} = \frac{V_c}{V_c \left(\frac{1}{Q_0} + \frac{1}{Q_t} \right) + I_{b0} (r/Q) \cos(\phi_s)}$$

- ◇ To find out the most adapted couplings : we look for the value of Q_{ext} which minimise P_{fwd} / P_b

- ◇ Vue synoptique de PERLE
- ◇ $T = t_0$, injection premier paquet

1. **7 MeV** (→ 89 MeV or to dump)
2. **89 MeV** (→ 171 MeV)
3. **171 MeV** (→ 250 MeV)
4. **250 MeV** (→ 171 MeV)
5. **171 MeV** (→ 89 MeV)
6. **89 MeV** (→ 7 MeV)

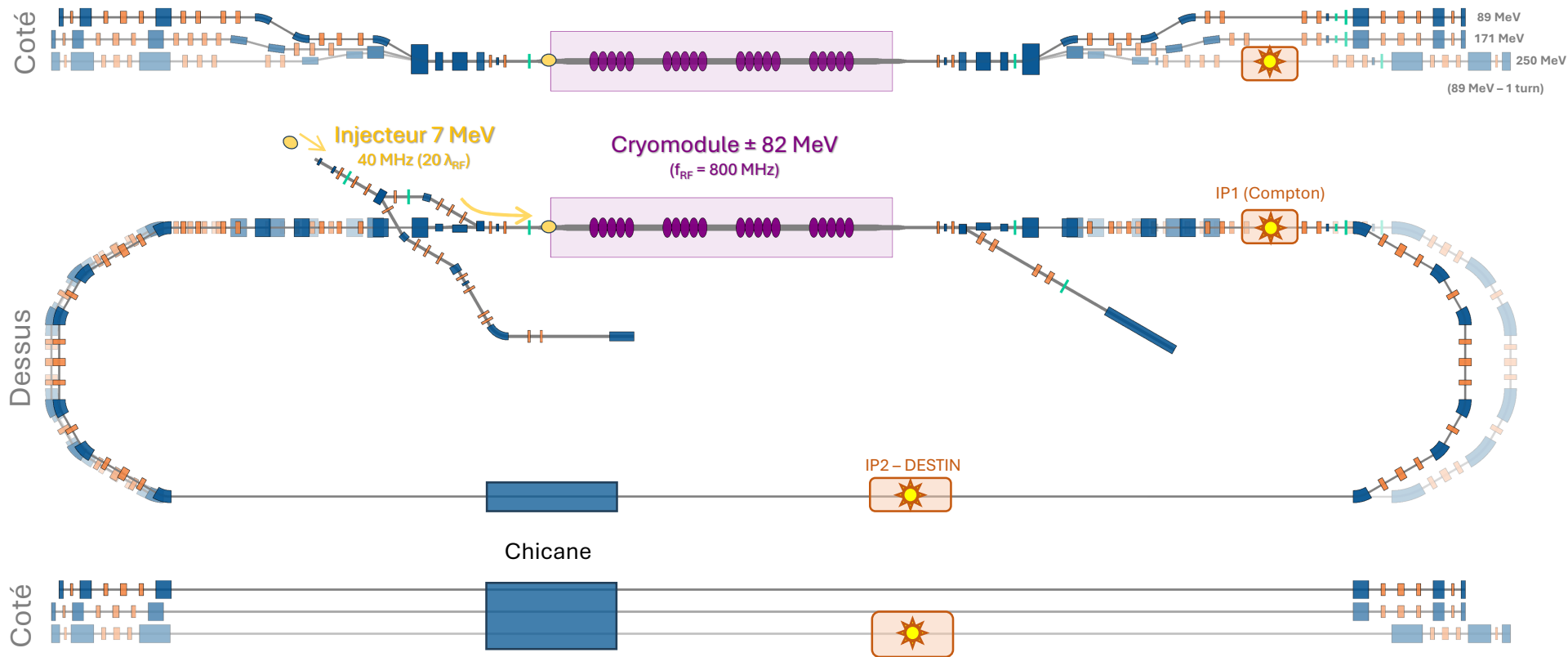


Schéma de PERLE Courtesy A. Fomin, IJCLab, Orsay



- ◇ Vue synoptique de PERLE
- ◇ $T = t_0 + \sim 207 \text{ ns}$

1. **7 MeV** (\rightarrow 89 MeV or to dump)
2. **89 MeV** (\rightarrow 171 MeV)
3. **171 MeV** (\rightarrow 250 MeV)
4. **250 MeV** (\rightarrow 171 MeV)
5. **171 MeV** (\rightarrow 89 MeV)
6. **89 MeV** (\rightarrow 7 MeV)

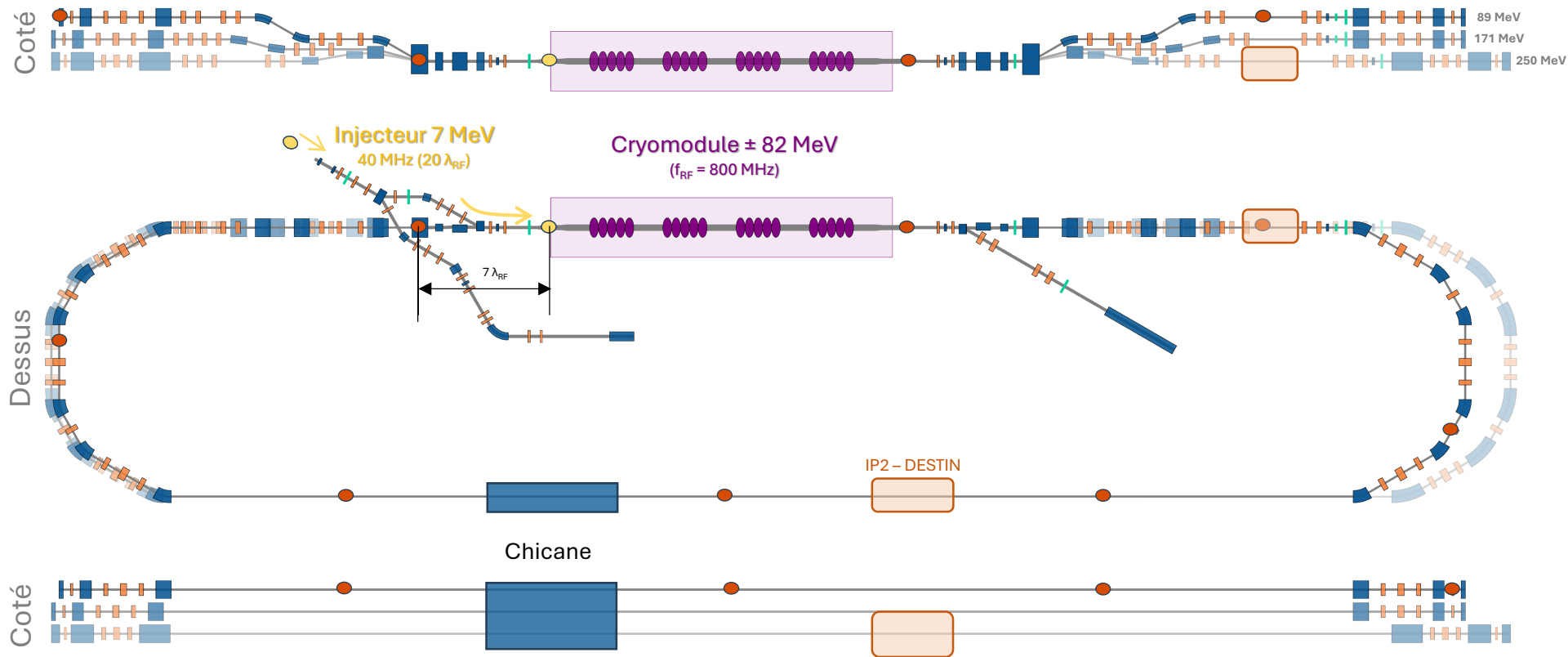


Schéma de PERLE Courtesy A. Fomin, IJCLab, Orsay

- ◇ Vue synoptique de PERLE
- ◇ $T = t_0 + \sim 405 \text{ ns}$

1. **7 MeV** (\rightarrow 89 MeV or to dump)
2. **89 MeV** (\rightarrow 171 MeV)
3. **171 MeV** (\rightarrow 250 MeV)
4. **250 MeV** (\rightarrow 171 MeV)
5. **171 MeV** (\rightarrow 89 MeV)
6. **89 MeV** (\rightarrow 7 MeV)

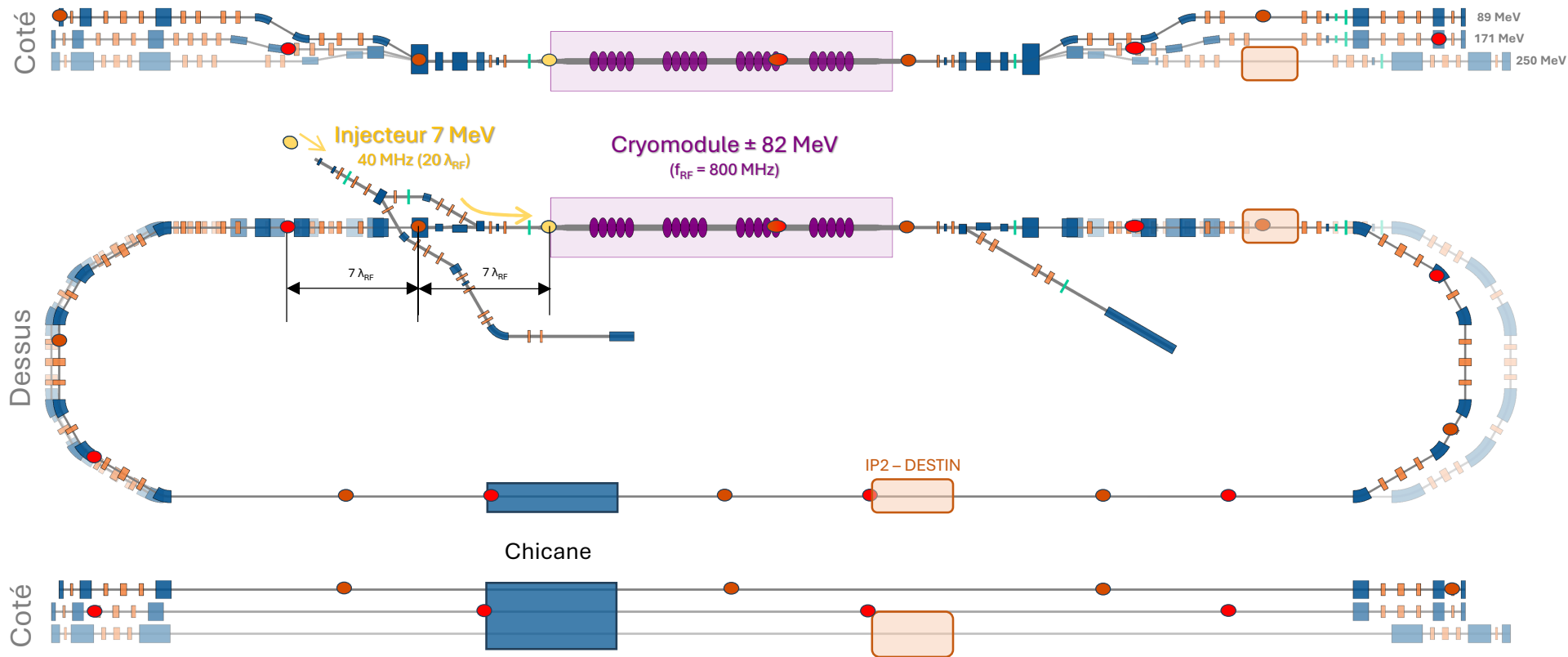


Schéma de PERLE Courtesy A. Fomin, IJCLab, Orsay



- ◇ Vue synoptique de PERLE
- ◇ $T = t_0 + \sim 1.1 \mu s \rightarrow$ Régime ERL établi

1. 7 MeV (\rightarrow 89 MeV or to dump)
2. 89 MeV (\rightarrow 171 MeV)
3. 171 MeV (\rightarrow 250 MeV)
4. 250 MeV (\rightarrow 171 MeV)
5. 171 MeV (\rightarrow 89 MeV)
6. 89 MeV (\rightarrow 7 MeV)

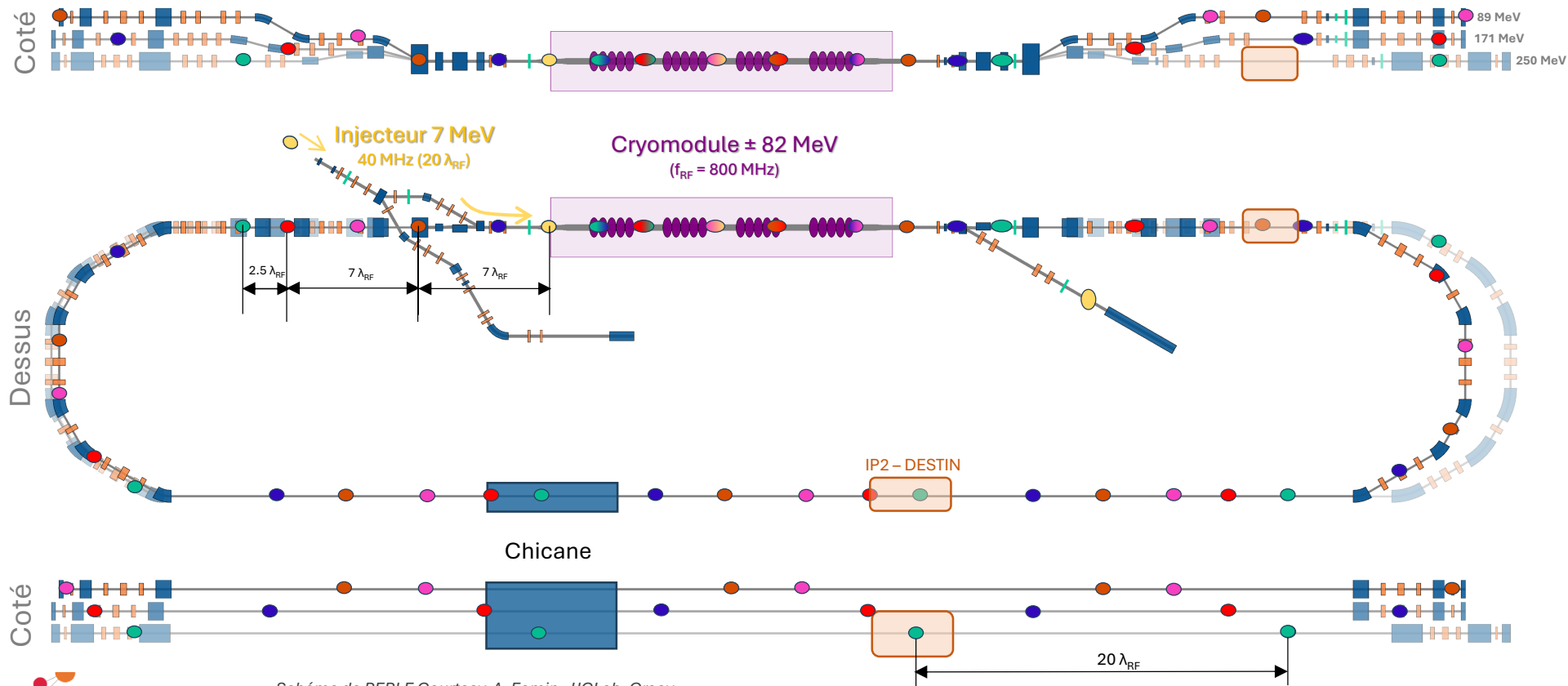


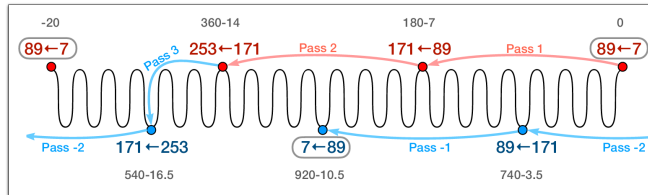
Schéma de PERLE Courtesy A. Fomin, IJCLab, Orsay



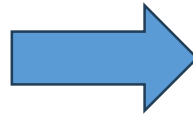
Beam Loading perçue par les cavités

Exemple de la cavité 1

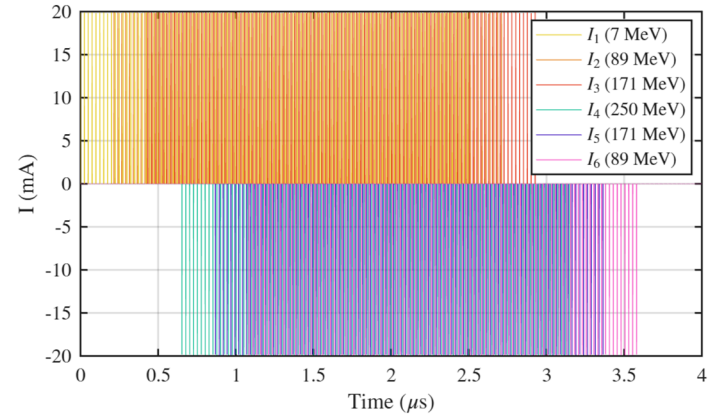
Filling Pattern of PERLE 250 MeV



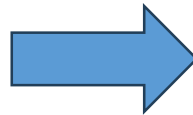
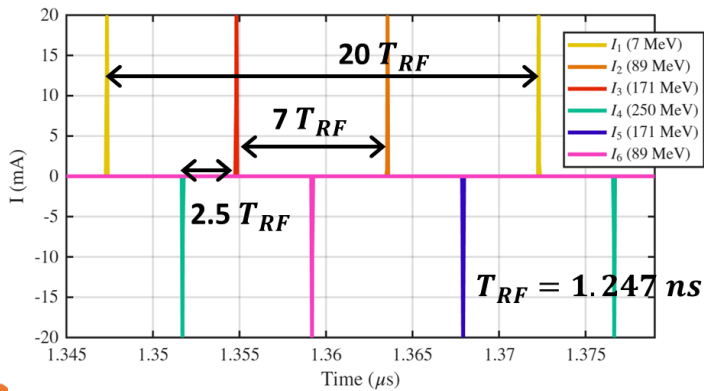
Full length of one turn: $(180 - \Delta) \lambda_{RF}$ *Courtesy of A. Fomin, ICLab*
 optimal shift: $\Delta = 7, 7, 2.5, 7, 7$



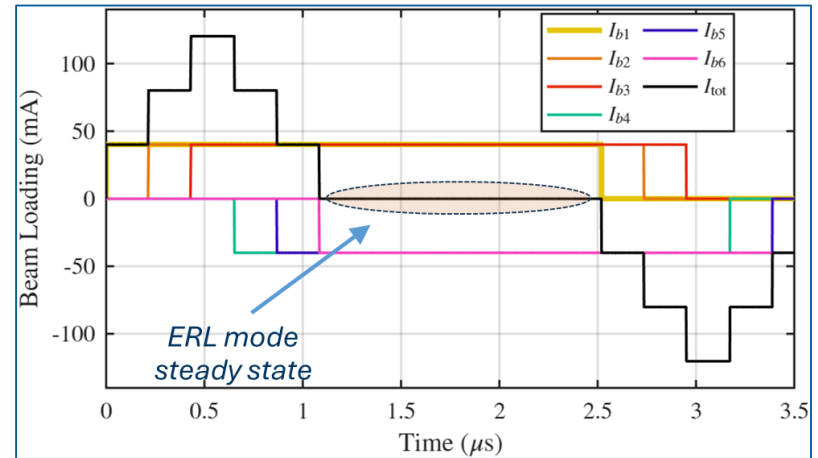
Ex.: Macropulse of 100 bunches



Zoom : Bunches through a cavity

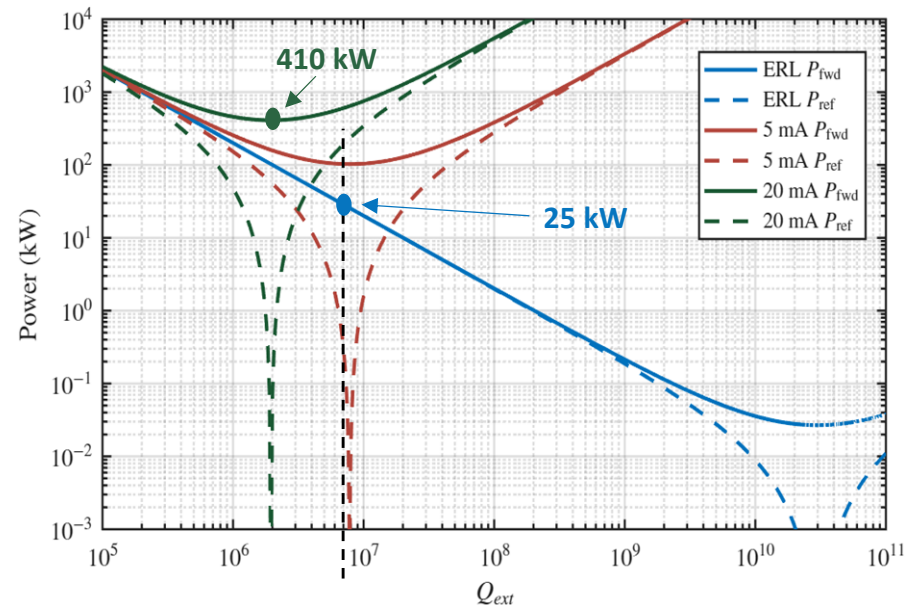


Cavity beam loading



RF Power and Q_{ext} (ERL vs. Linac)

$$P_{fwd}(\Delta f_{opt}) = \frac{V_c^2 Q_{ext}}{4(r/Q)Q_L^2} \left(1 + \frac{I_{b0}(r/Q)Q_L \cos(\phi_s)}{V_c} \right)^2$$

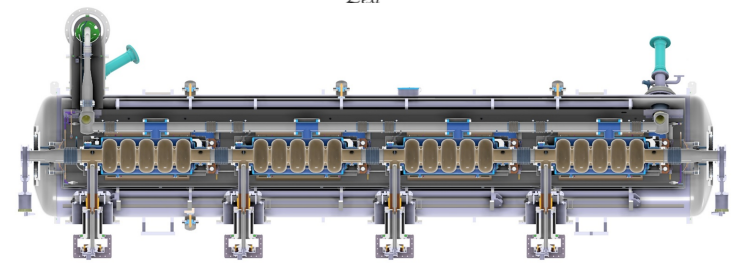
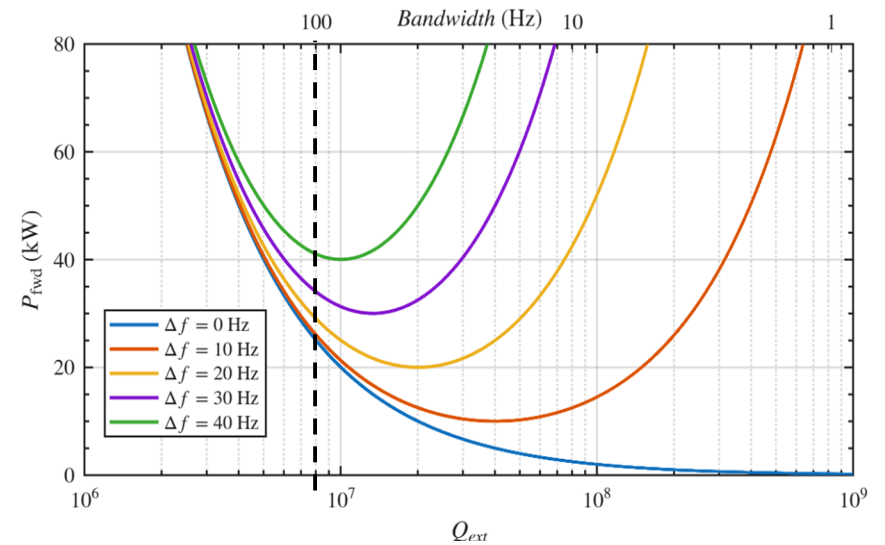


$Q_{ext, ERL} = 8.0 \cdot 10^6$
 Bandwidth ≈ 100 Hz

Effect of frequency detuning

$$BP_\omega \approx \frac{\omega_0}{Q_L} \iff BP_f \approx \frac{f_0}{Q_L}$$

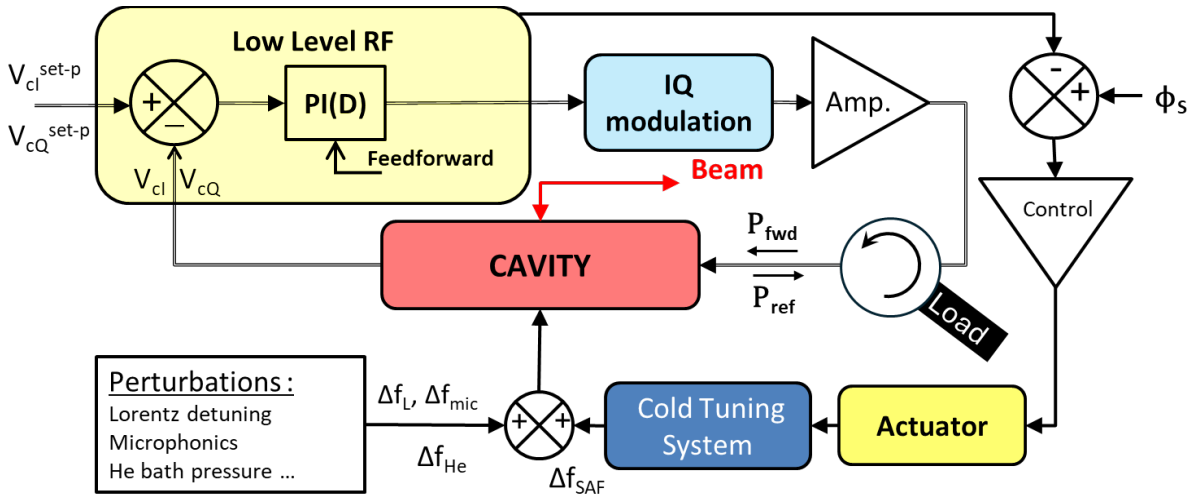
$$P_{fwd} = \frac{V_c^2 Q_{ext}}{4(r/Q)Q_L^2} \left[\left(1 + \frac{I_{b0}(r/Q)Q_L \cos(\phi_s)}{V_c} \right)^2 + \left(2Q_L \frac{\Delta f}{f} + \frac{I_{b0}(r/Q)Q_L \sin(\phi_s)}{V_c} \right)^2 \right]$$



Opération d'un ERL

Réduction de la puissance RF consommée
Effets transitoires

◆ Vue schématique



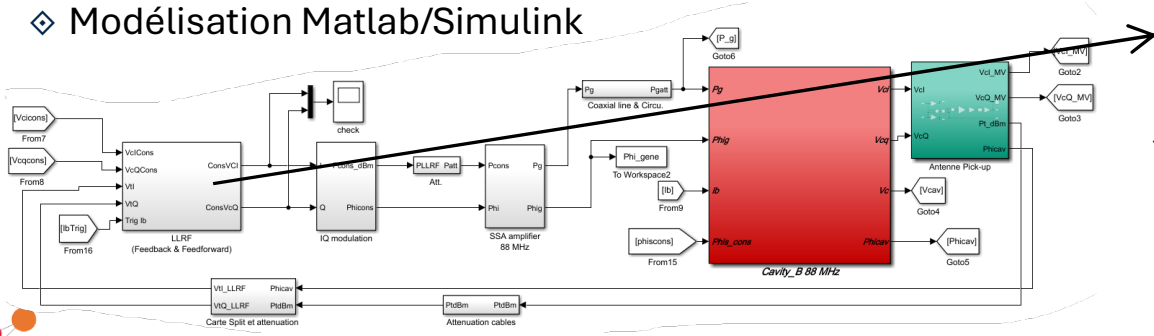
◆ Lorentz detuning model

$$\tau_m \dot{\Delta f_L}(t) + \Delta f_L(t) = -k_L E_{acc}^2$$

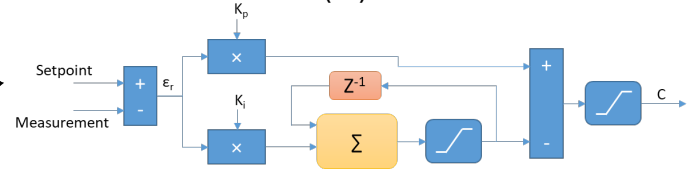
◆ With,

- ◆ k_L : Lorentz detuning factor (Hz/(MV/m)²)
- ◆ τ_m : mechanical constant (msec.)

◆ Modélisation Matlab/Simulink



◆ Correction de boucle (PI)



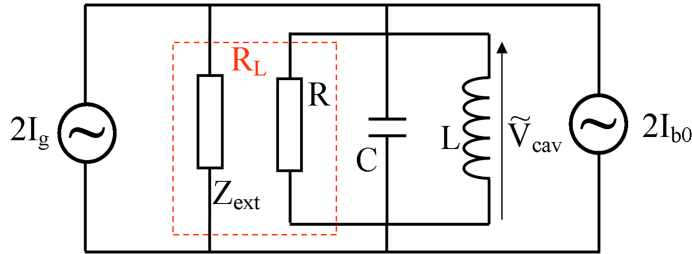
◆ Discrete PI, with T_e the PI sampling period

$$C(n) = K_p \cdot \epsilon_r(n) + K_i \cdot T_e \cdot \sum_{k=1}^n \epsilon_r(k)$$

◆ Backward Euler integrator

$$H(z) = \frac{C(z)}{\mathcal{E}_r(z)} = K_p + K_i \cdot T_e \cdot \frac{z}{z-1}$$

◇ Band pass resonator ↔ RLC parallel circuit.



$$I_{RF} + I_b = 2I_g + I_b = I = I_C + I_{R_L} + I_L$$

$$\frac{dI(t)}{dt} = C \frac{d^2 V_{cav}(t)}{dt^2} + \frac{1}{R_L} \frac{dV_{cav}(t)}{dt} + \frac{1}{L} V_{cav}(t)$$

◇ Solving the equation in the complex plane

Transient

$$\begin{cases} \dot{V}_{cI} &= \frac{\omega_0(r/Q)}{4} (2I_{gI} + I_{bI}) - \frac{\omega_0}{2Q_L} [V_{cI} + V_{cQ} \tan(\psi)] \\ \dot{V}_{cQ} &= \frac{\omega_0(r/Q)}{4} (2I_{gQ} + I_{bQ}) - \frac{\omega_0}{2Q_L} [V_{cQ} - V_{cI} \tan(\psi)] \end{cases}$$

$$\tilde{Z} = Z_I + j Z_Q$$

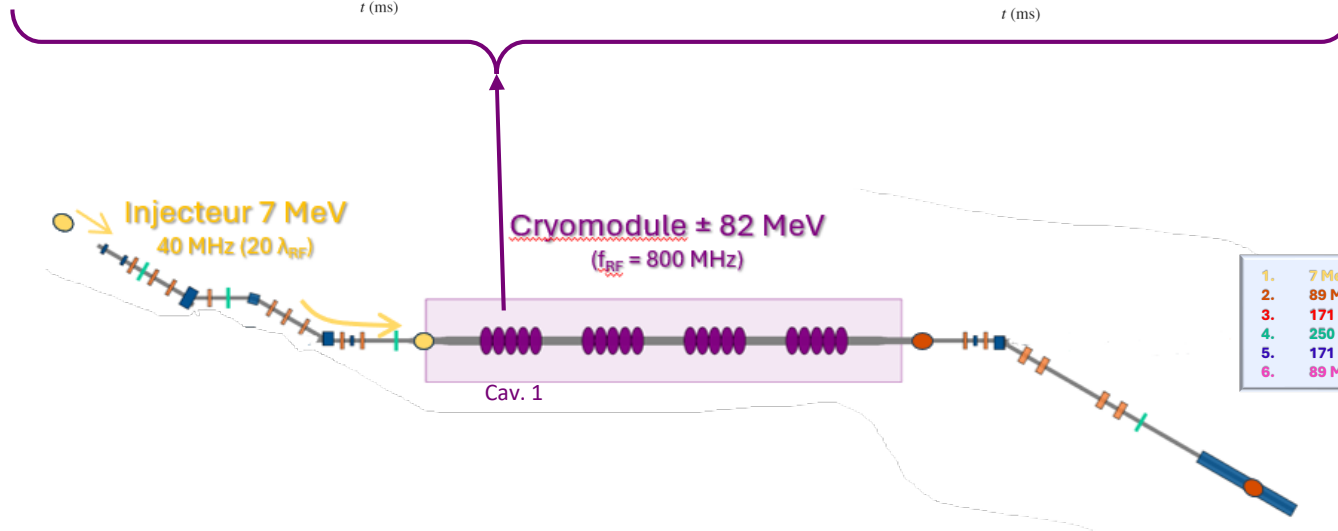
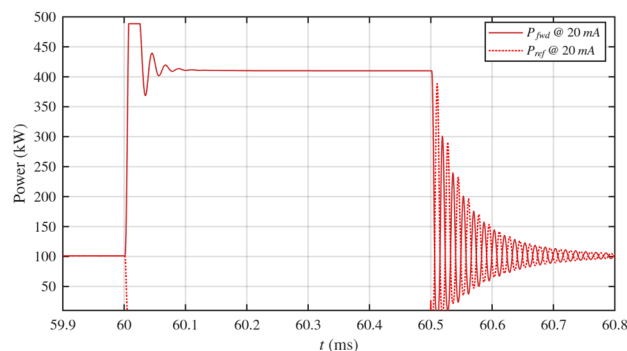
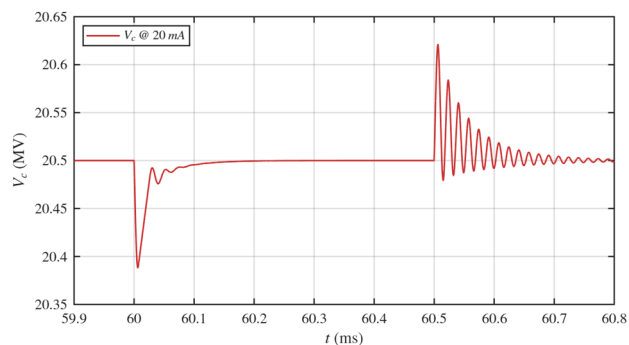
$I = In\ phase = \Re\ part$

$Q = Quadrature = \Im\ part$

$$\begin{aligned} I_{bI} &= I_b \cos(\varphi_b) = -2I_{b0} & et & I_{bQ} = I_b \sin(\varphi_b) = 0 \\ I_{gI} &= I_g \cos(\varphi_g) & et & I_{gQ} = I_g \sin(\varphi_g) \\ V_{cI} &= V_{cav} \cos(\phi_s) & et & V_{cQ} = V_{cav} \sin(\phi_s) \end{aligned}$$

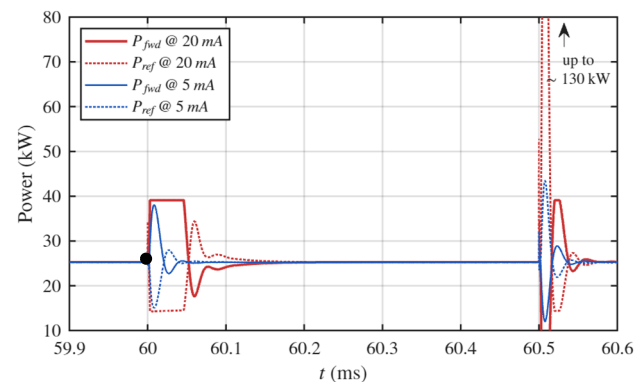
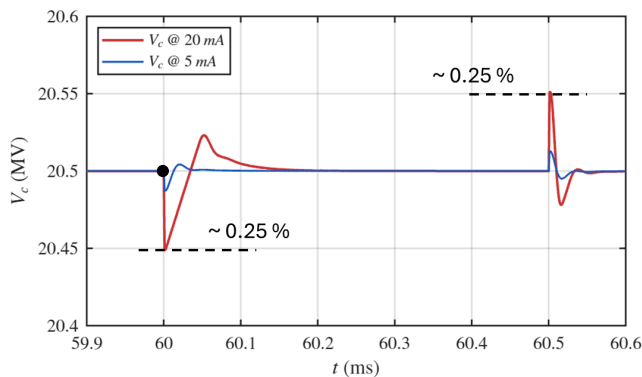
[Ref] : T. Schilcher, "Vector sum control of pulsed accelerating fields in Lorentz force detuned superconducting cavities", Ph.D., DESY, 1998

◇ Exemple. Accélération d'un faisceau de 20 mA - Macro-pulse de 1 ms

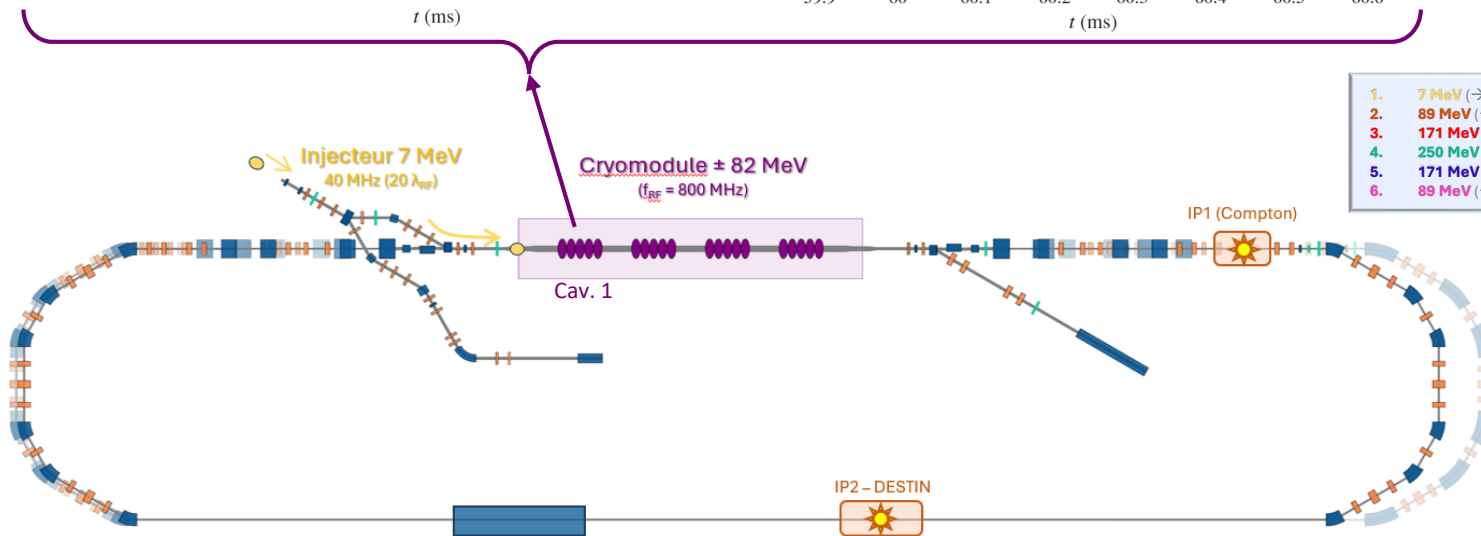


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6. **89 MeV** (\rightarrow 7 MeV)

◆ Accélération d'un faisceau de 20 mA - Macro-pulse de 1 ms (40 000 Bunchs)

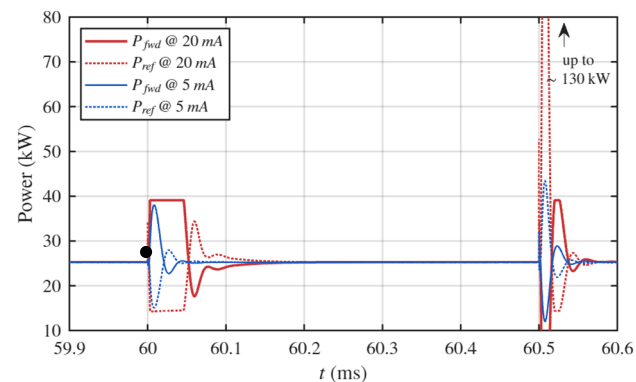
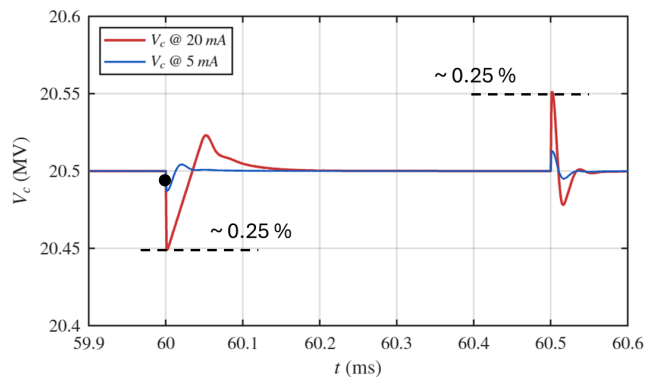


$T = t_0$

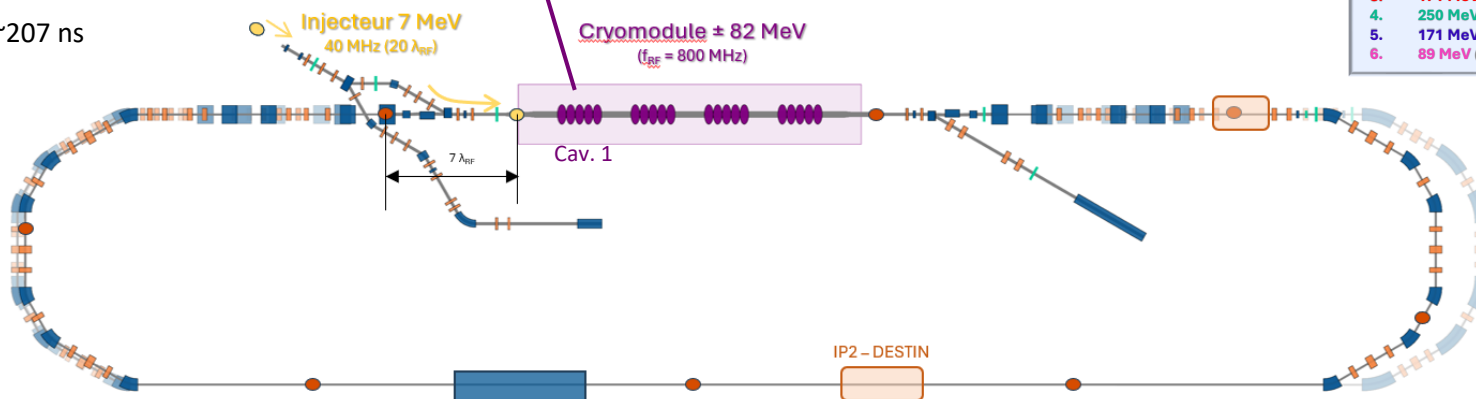


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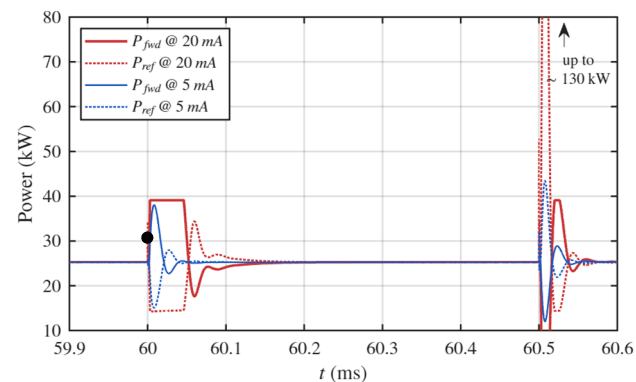
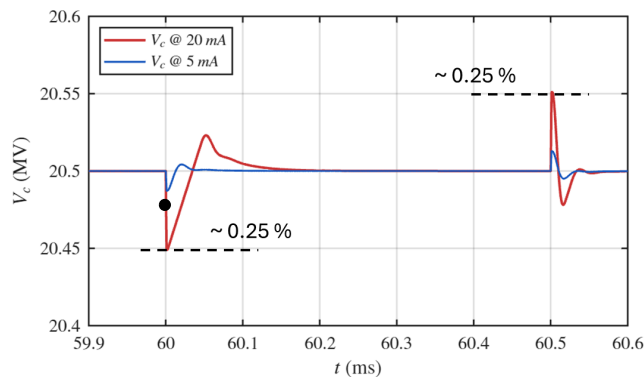


$T = t_0 + \sim 207 \text{ ns}$

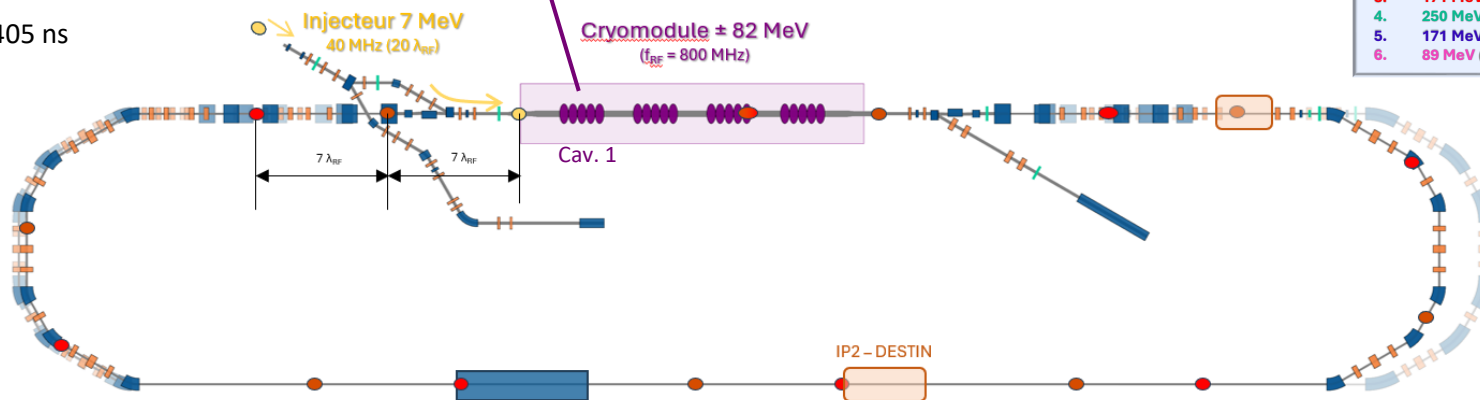


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◆ Accélération d'un faisceau de 20 mA - Macro-pulse de 1 ms (40 000 Bunchs)

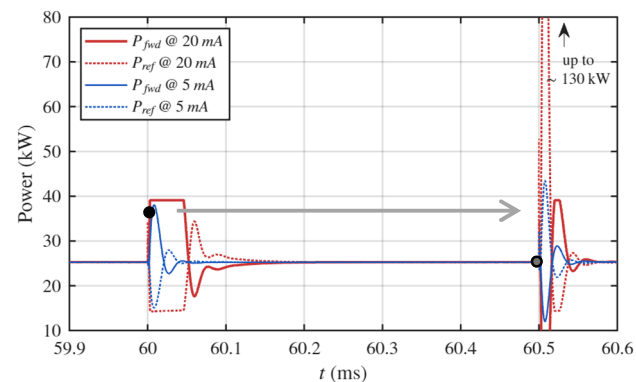
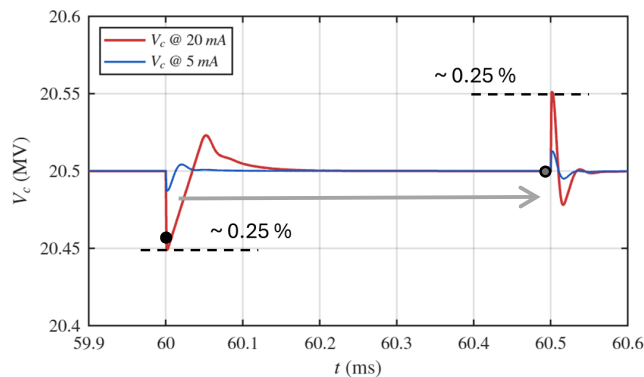


$T = t_0 + \sim 405 \text{ ns}$

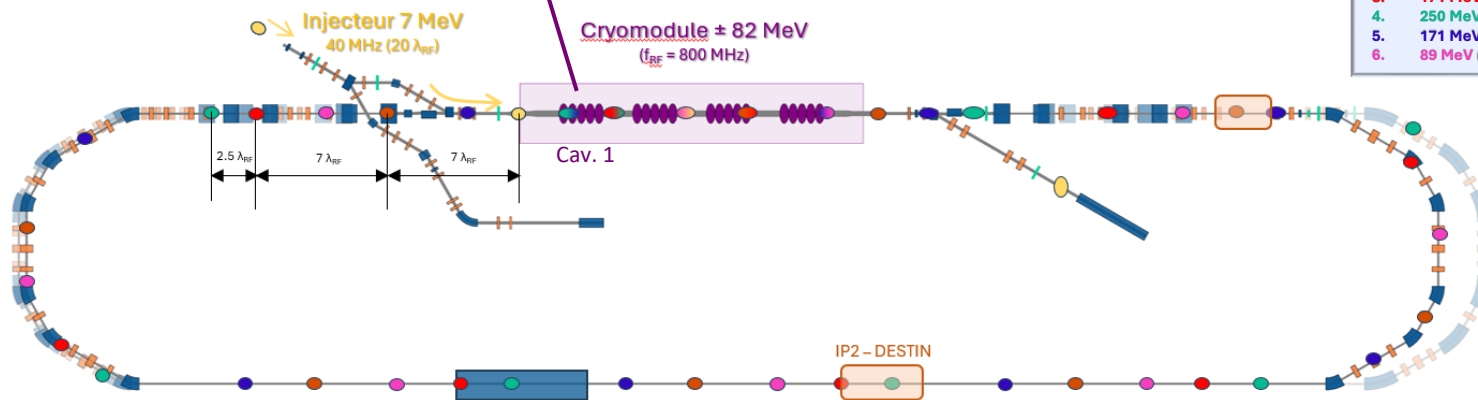


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◆ Accélération d'un faisceau de 20 mA - Macro-pulse de 1 ms (40 000 Bunchs)

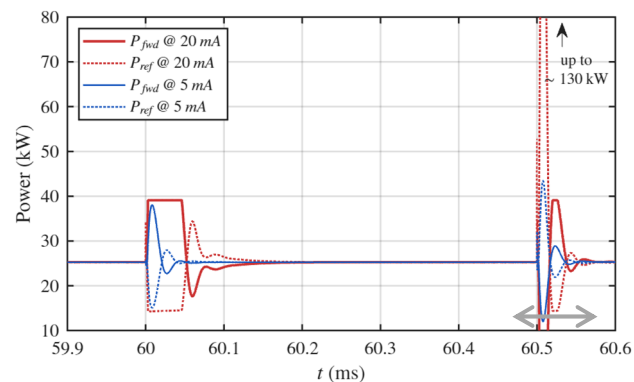
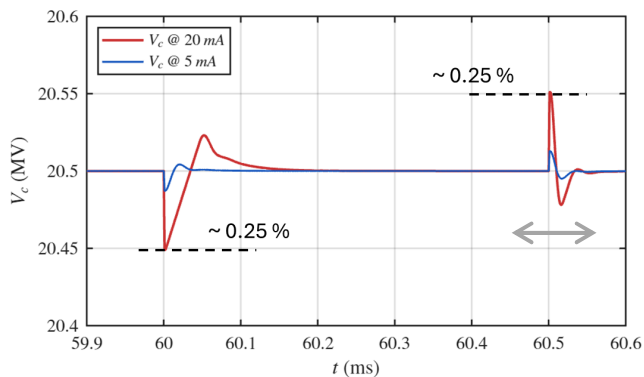


$T = t_0 + \sim 1.1 \mu s \rightarrow$ Régime ERL établi

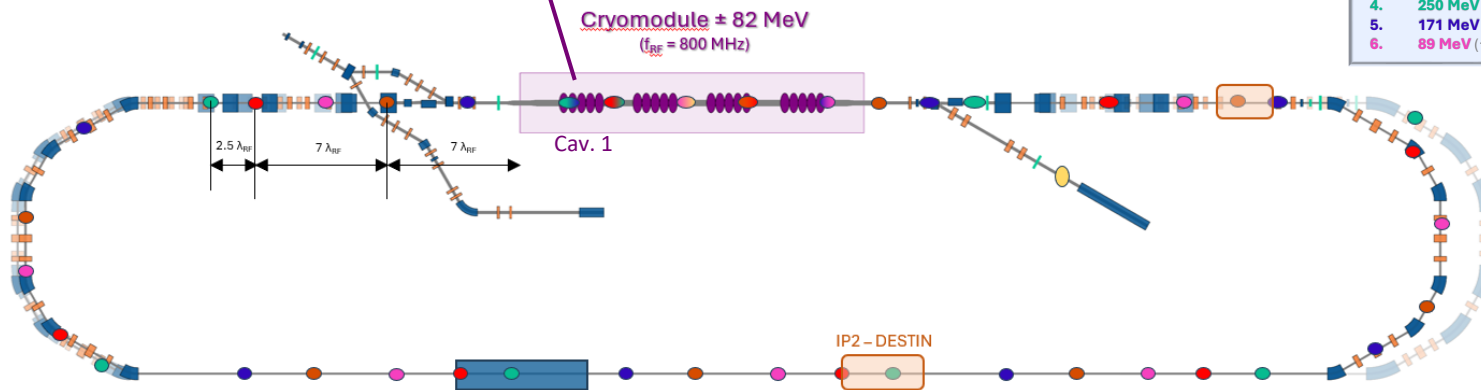


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4. **250 MeV** (\rightarrow 171 MeV)
5. **171 MeV** (\rightarrow 89 MeV)
6. **89 MeV** (\rightarrow 7 MeV)

◆ Accélération d'un faisceau de 20 mA - Macro-pulse de 1 ms (40 000 Bunchs)



$T = t_0 + 1 \text{ ms} \rightarrow$ « décharge » de la machine



- | | |
|----|--|
| 1. | 7 MeV (\rightarrow 89 MeV or to dump) |
| 2. | 89 MeV (\rightarrow 171 MeV) |
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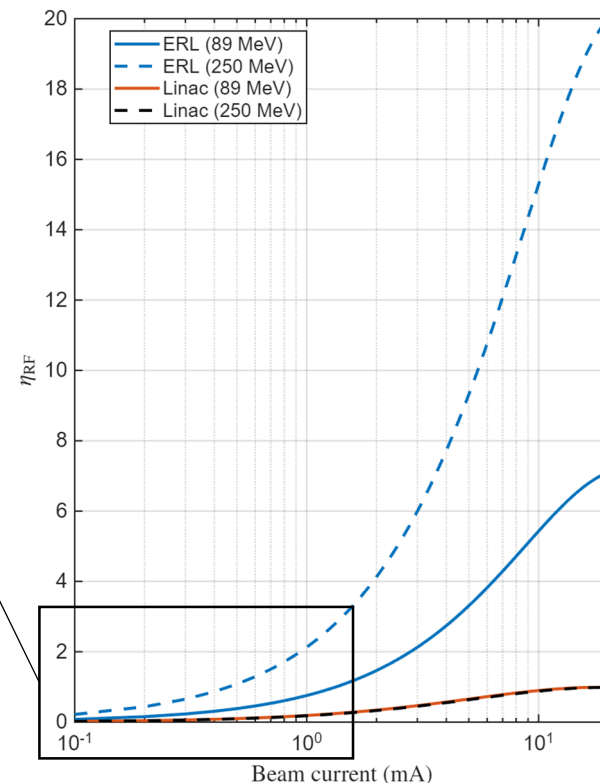
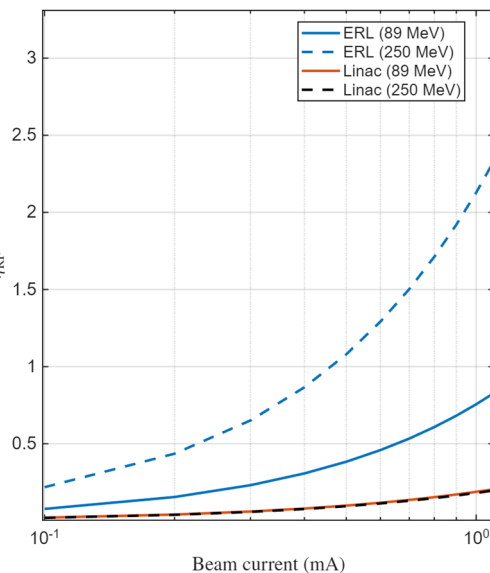
Cavities parameters & Coupling

Parameters	1-cell	5- cell ERL	5-Cell linac
Frequency [MHz]	801.58		
Bandwidth [Hz]	471.5	100	411
(r/Q) [Ω]	109	523	
Q ₀	1 10 ¹⁰	3 10 ¹⁰	
Q _{ext}	1.7 10 ⁶	8.0 10 ⁶	1.95 10⁶
V _c [MV]	1.53	20.5	

RF to beam efficiency

$$\eta_{RF} = \frac{\Delta P_{beam}}{P_{RF\ injector} + P_{RF\ ERL\ or\ linac}}$$

$$P_{fwd}(\Delta f_{opt}) = \frac{V_c^2 Q_{ext}}{4(r/Q)Q_L^2} \left(1 + \frac{I_{b0}(r/Q)Q_L \cos(\phi_s)}{V_c} \right)^2 \eta_{RF}$$

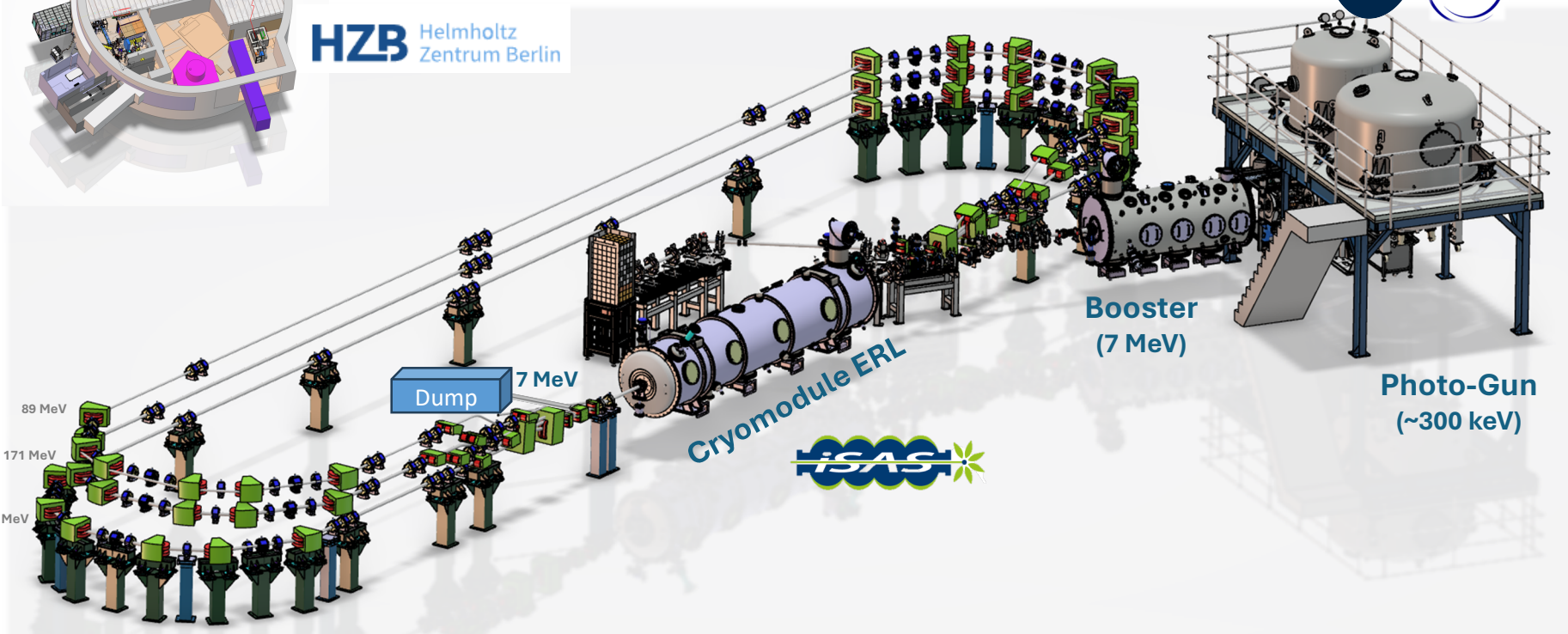
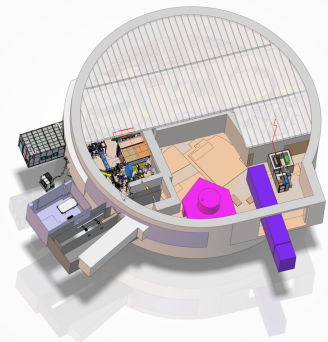


Projet PERLE

Cryoplant (In-Kind)

HZB Helmholtz Zentrum Berlin

Projet ERL4ALL (RI²)



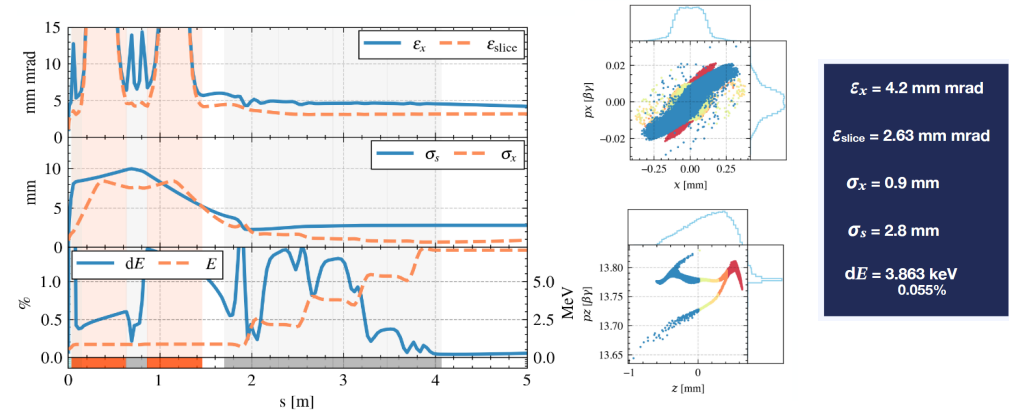
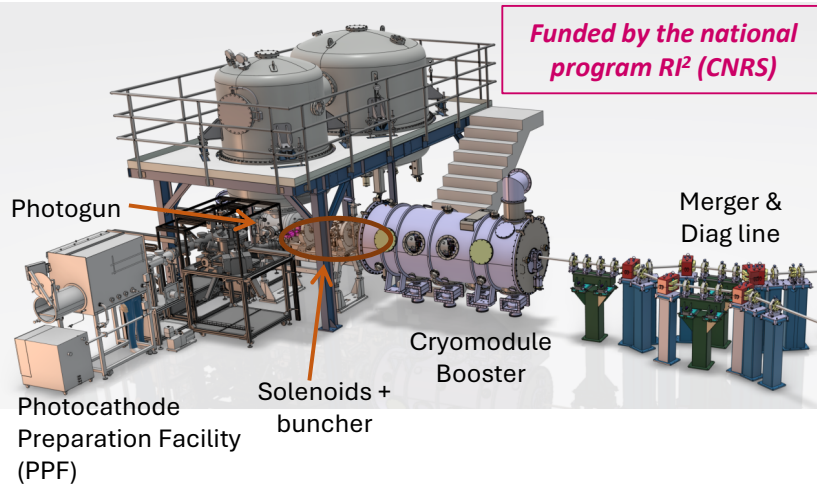
Cryomodule ERL

Booster (7 MeV)

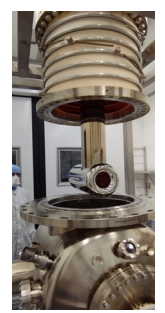
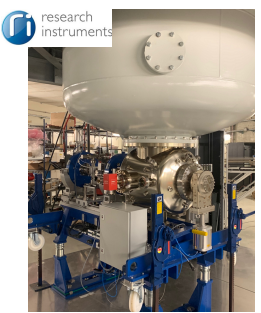
Photo-Gun (~300 keV)

Dump 7 MeV





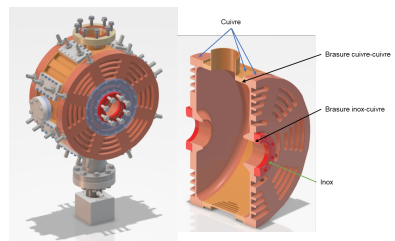
C. Monaghan, Phd thesis, Univ. Liverpool/ ICLab, Space Charge Dominated Low Energy Beam Dynamics in High Current Energy Recovery Linac - Soutenance prévue fin 2026



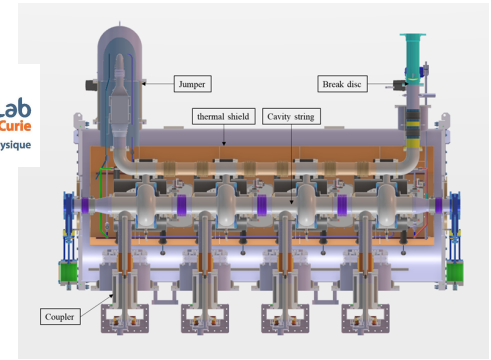
Photogun

- ◇ Commissioning en cours
- ◇ Gun installé
- ◇ Première photocathode : 30.Sept. 2025!
- ◇ Premier tests fin 2025
- ◇ Premier faisceau mai 2026

M. Baylac, G. Sattonnay et al., High current photogun and photocathode preparation for the PERLE project, Journées Accélérateurs Roscoff 2025



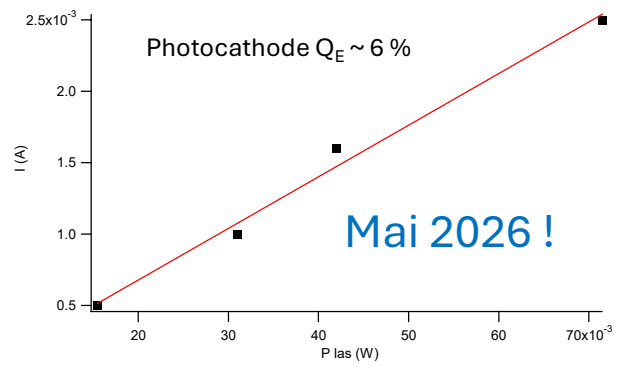
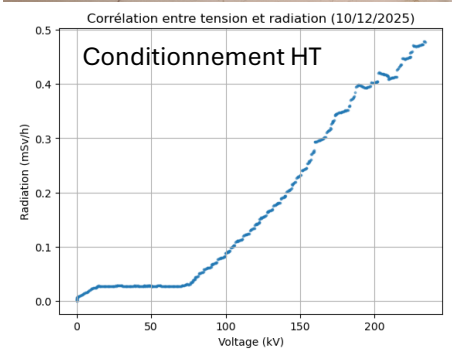
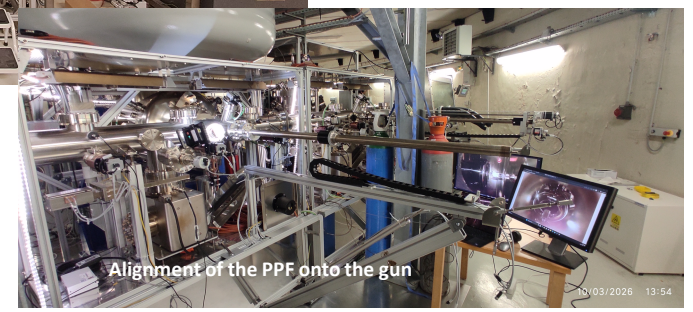
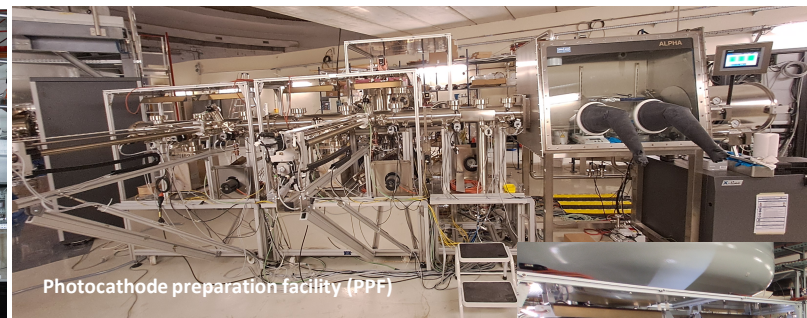
Buncher 800 MHz
Prêt pour fabrication



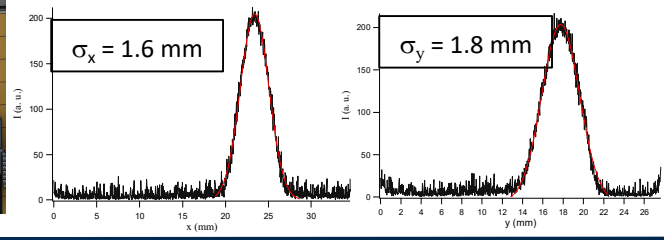
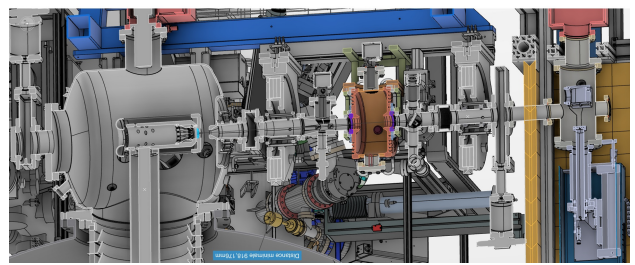
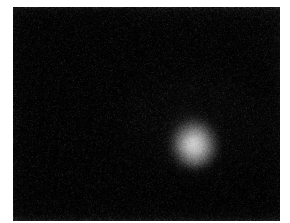
Cryomodule Booster

4 cavités monocell. (Q_0 (@2K)= 1.10^{10} , $E_{acc-max} \sim 10$ MV/m)

R. Roux et al., "Status of the PERLE's injector", presented at the IPAC'26, Deauville, France, May 2026, paper WEP5090

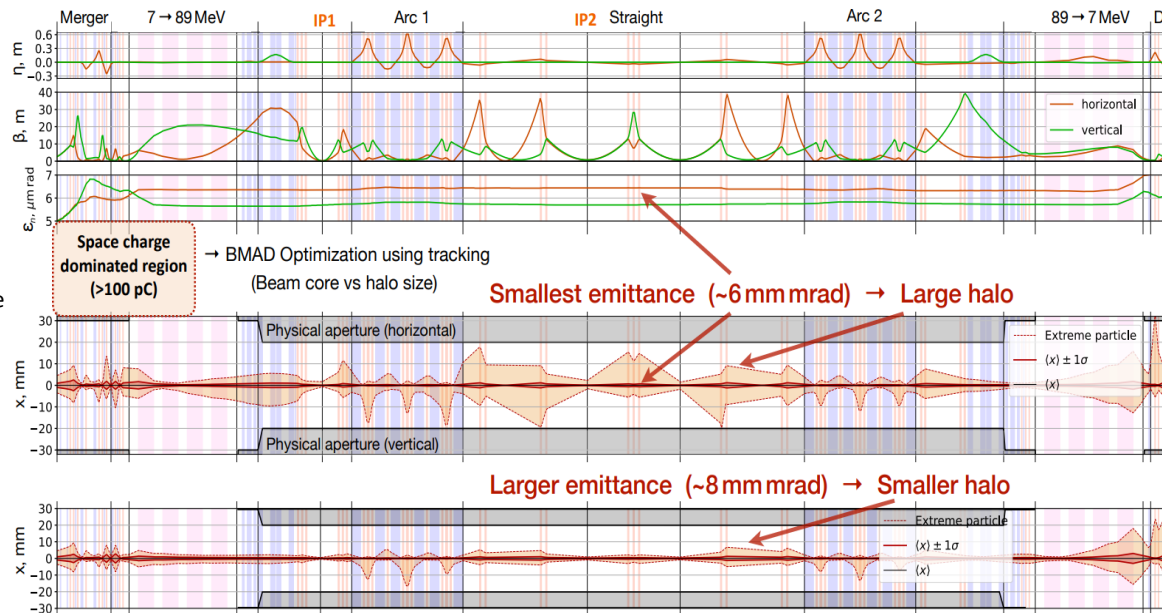


M. Baylac et al., "High current photogun for the energy recovery linac PERLE", presented at the IPAC'26, Deauville, France, May 2026, paper THP2104

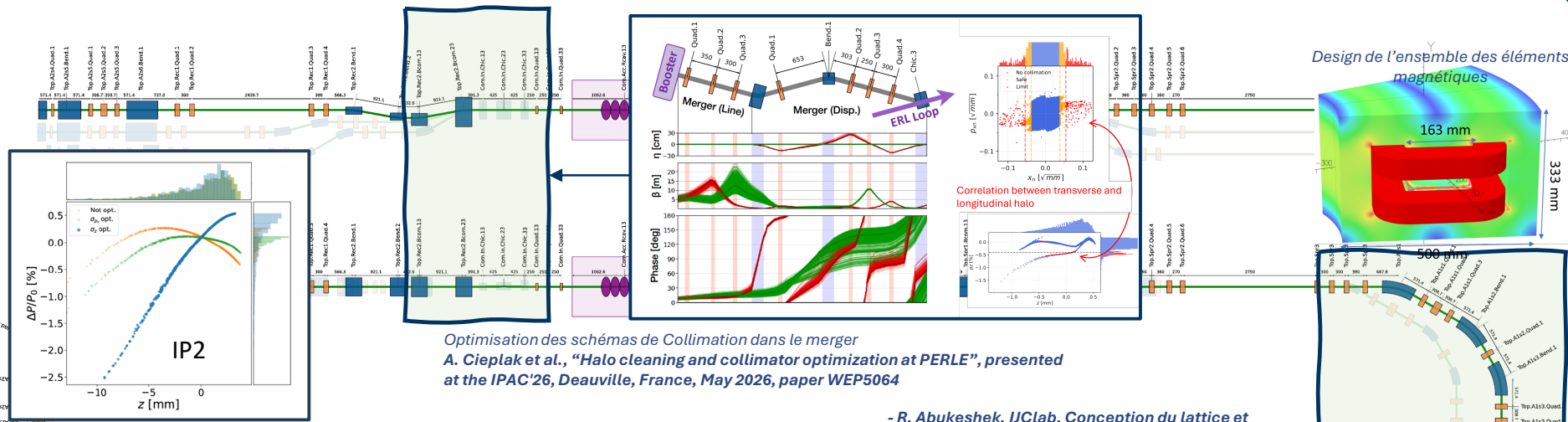


◆ Designs PERLE 3 Tours et 1Tour finalisés

- ◆ Merger u-bend → 3 dipoles
 - ◆ Injection optimisée
 - ◆ Permet insertion ligne symétrique pour mesure de propriété faisceau (Energie, Profils et Dispersion)
- ◆ Modèle start-to-end pour études systématiques : Bmad
- ◆ Halo contrôlé (« tracking »)
 - ◆ < 10 mm (except @ 7 MeV phase décélération)
- ◆ Régions « bas-β »/« bas-α » pour les expériences
 - ◆ IP1 : Fabry- Perot : section spreader après cryomodule
 - ◆ IP2 dans la section droite (sans cavité)
- ◆ Gradient Max des quad : 24 T/m
- ◆ Optique des Arcs réglable pour control de M56
 - ◆ Dispersion longitudinale (1^{er} ordre)
 - ◆ Contrôle de la (dé)compression longitudinale



A. Fomin et al., “Beam Dynamics Challenges and Optics Development for the PERLE Multi-Turn ERL”, presented at the IPAC’26, Deauville, France, May 2026, paper WEO5M01



Optimisation des schémas de Collimation dans le merger
A. Cieplak et al., "Halo cleaning and collimator optimization at PERLE", presented at the IPAC'26, Deauville, France, May 2026, paper WEP5064

- **R. Abukeshek, ICLab, Conception du lattice et optimisation de l'optique faisceau de la machine PERLE, PhD, déc. 2025**

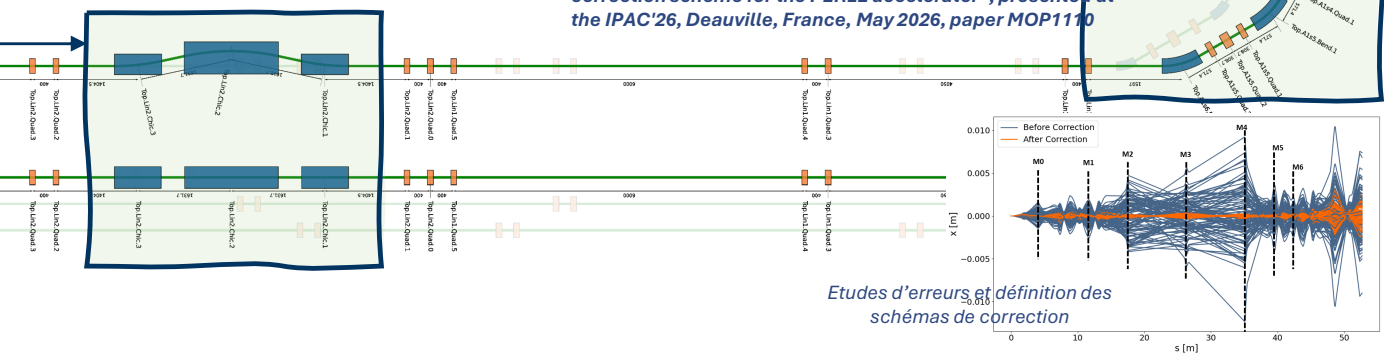
- **R. Abukeshek et al., "Linear imperfection and orbit correction scheme for the PERLE accelerator", presented at the IPAC'26, Deauville, France, May 2026, paper MOP1110**

Chicane pour maîtriser le synchronisme + étude du matching longitudinal
J. Issa, et al., "Longitudinal Matching and Timing Control Studies for the PERLE Energy Recovery Linac", presented at the IPAC'26, Deauville, France, May 2026, paper WEP5006

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

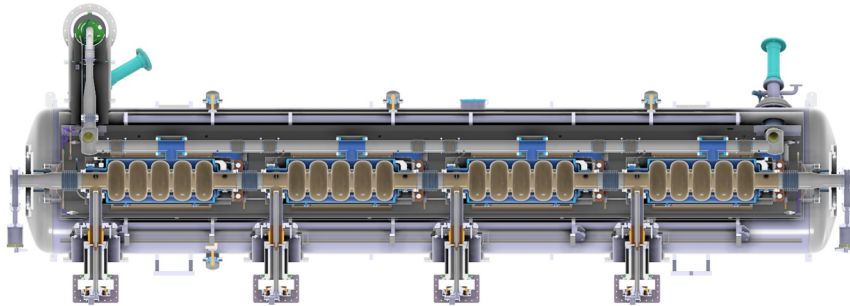
$$S(B) = 4 \frac{L_1}{\sin \theta(B)} \theta(B) + 2 \frac{L_2}{\cos \theta(B)}$$

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



Etudes d'erreurs et définition des schémas de correction

- ◇ Cryomodule (ERL) design d'ESS optimisé pour une operation ERL fort courant.
 - ◇ Systèmes RF ré-optimisés (Cavités SRF, coupleurs et absorbeurs HOM, coupleurs de puissance)
 - ◇ Développé au sein du **projet européen iSAS**.

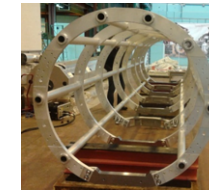
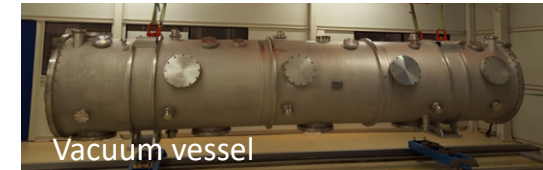


G. Olivier et al. , ESS cryomodule adaptation , ISAS design report, WP 6.3, 2025



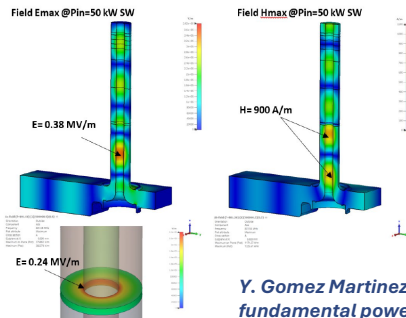
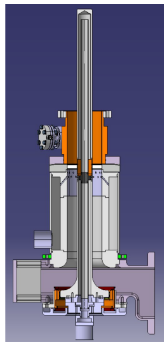
Collaboration
CNRS, CERN, ESS,
CEA, INFN-LASA

ESS In-kind contribution ESS to iSAS
Reuse medium beta prototype components



- ◇ Nouveaux composants
 - ◇ Cavity string
 - ◇ Bouclier magnétique et circuits cryo. adaptés

◇ Design coupler adapté de SPL

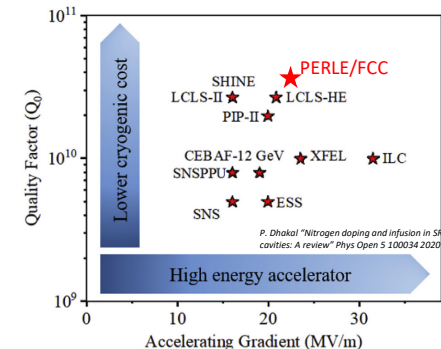


Y. Gomez Martinez et al. , Design of fundamental power coupler , ISAS design report, WP 4 , milestone 4.1, 2025

◇ R&D spécifique pour la preparation des cavité

- ◇ Cavité haut gradient et haut Q_0
- ◇ Traitement de surface et préparation
- ◇ "Mid-T baking", cooling with thermal gradient

A. Miyazaki et al. , Progress and challenges on SRF technology development for PERLE, SRF'25, Tokyo, Japan



◆ Beam Breakup Unstability (BBU) studies: Q_{ext} requirements for HOM

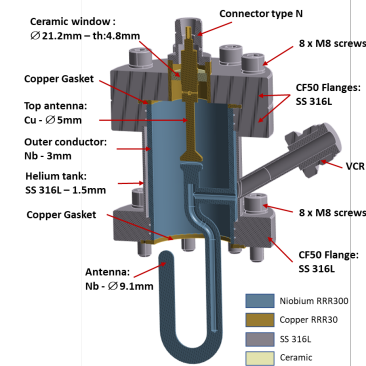
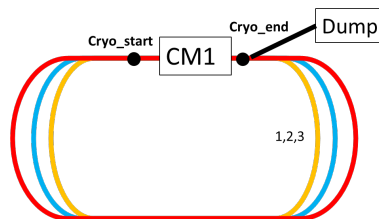
➤ Threshold current for a multi-pass machine:
$$I_{th} = - \frac{2E_b}{e(R/Q)_n Q_{L,n} k_n \sum_{m>l=1}^{N_c} (E_b/E_b^m) M_{ij}^{lm} \sin(\omega_n t_r^{lm})}$$

◆ Longitudinal impedance threshold of a monopole mode n:

$$Z_{||,n}^{th} = (R/Q)_{||,n} Q_{L,n} = - \frac{2E_b}{e I_{b,op} k_n \sum_{m>l=1}^{N_c} [(E_b/E_b^m) M_{ij}^{lm} \sin(\omega_n t_r^{lm})]}$$

◆ Transversal impedance threshold of a dipole mode n :

$$Z_{\perp,n}^{th} = (R/Q)_{\perp,n} Q_{L,n} k_n = - \frac{2E_b}{e I_{b,op} \sum_{m>l=1}^{N_c} [(E_b/E_b^m) M_{ij}^{lm} \sin(\omega_n t_r^{lm})]}$$



P. Duchesne (IJCLab) et al. , Design of 800 MHz HOM couplers, ISAS report, WP4, Milestone 4.2, 2025

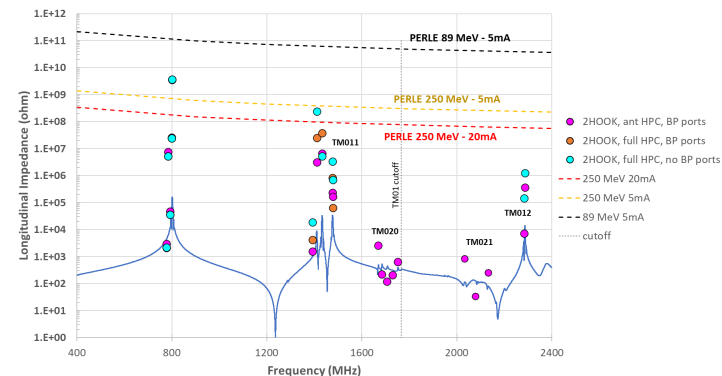
◆ Average HOM Power

$$P_{HOM} = k_{||,HOM} Q_b I_{b,op} = (k_{||} - k_{||,0}) Q_b I_{b,op}$$

	Ptot [W]	2 x BPs [W]	FPC [W]	2 x Hook [W]	2 x Probe [W]	4 x DQW [W]
2H2P	130	113	13	1	2,5	-

- ◆ Most of the HOM power propagates through the beam pipes → **Absorbers**
- ◆ **Extracted power** by the HOM coupler is **a few watts**.

Modes monopolaires : TM010, TM011, TM020, TM021, TM012



Longitudinal impedance of the 5-cell cavity

[Ref.] Carmelo Barbagallo. Design and optimization of higher order mode couplers for the superconducting cavities of the PERLE energy recovery linac. Phd Thesis, Université Paris-Saclay, 2024.

**IJCLab and IN2P3 Directions
(COFIL, EAP, CODEC, CS, CSI...)**



Project Directorate / Local French Management Board

Achille Stocchi (Spokeperson) **SP, Scientific Coordinator**
 Walid Kaabi (Technical Project Leader) **TPL**
 Denis Reynet (Systems Engineer) **Associate to TPL** in charge of the installation
 Guillaume Oly **Associate to TPL** in charge of RH, budget
 Sophie Chance (Project Manager/PBS, WBS, planning) **PM**
 Virginie Quipourt (Financial Manager) **FM**
 Aurore Lermilage (Quality Manager) **QM**
 Maud Baylac (External Relations / In-Kind Management)
 Frédéric Bouly Associate to SP → Experimental Programs **Associate to EP**

**International Collaboration Board
(ICB)**

Oliver Bruning (**CERN**) (Chair)
 Rongli Geng (**Jlab**)
 Carsten Welsh (**Liverpool University**)
 Stewart Boogert (**Cockcroft Institute**)
 Deepa Angal-Kalinin (Daresbury-**STFC**)
 Georg Hoffstaetter (**Cornell University**)
 Ibon Bustinduy (**ESS-Bilbao**)
 Hadil Abualrob (**An-Najah University**)
 Maud Baylac (**LPSC**)

Ex-officio :

Achille Stocchi (Spokeperson) (IJCLab)
 Walid Kaabi (Technical Project Leader) (IJCLab)

Invité :

Jorgen D'Hondt (**Nikhef**) for iSAS

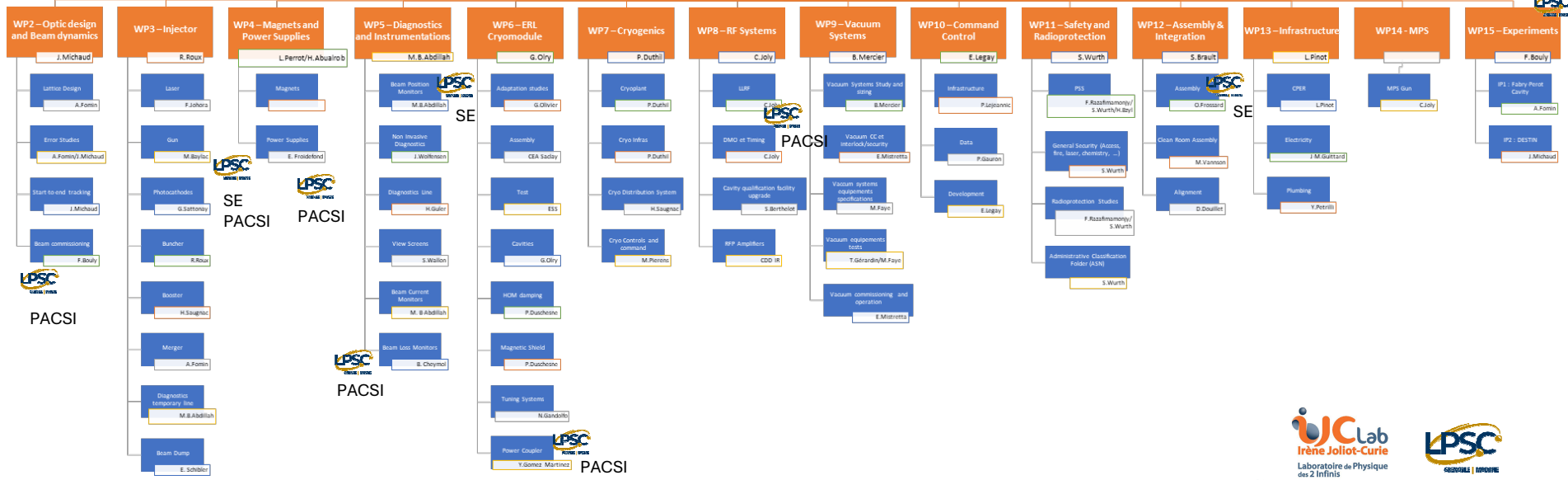


Directoire
 Spokeperson SP - A. Stocchi
 Technical Project Leader (TPL) - W. Kaabi
 Associate to TPL : D. Reynet (System engineer)
 Associate to TPL : G. Oly (Budget and RH)
 PM/PBS, WBS, Planning : S. Chance
 Financial Manager : V. Quipourt
 Quality Manager : A. Lermitage
 External relations : M. Baylac
 Associate to SP : F. Bouly



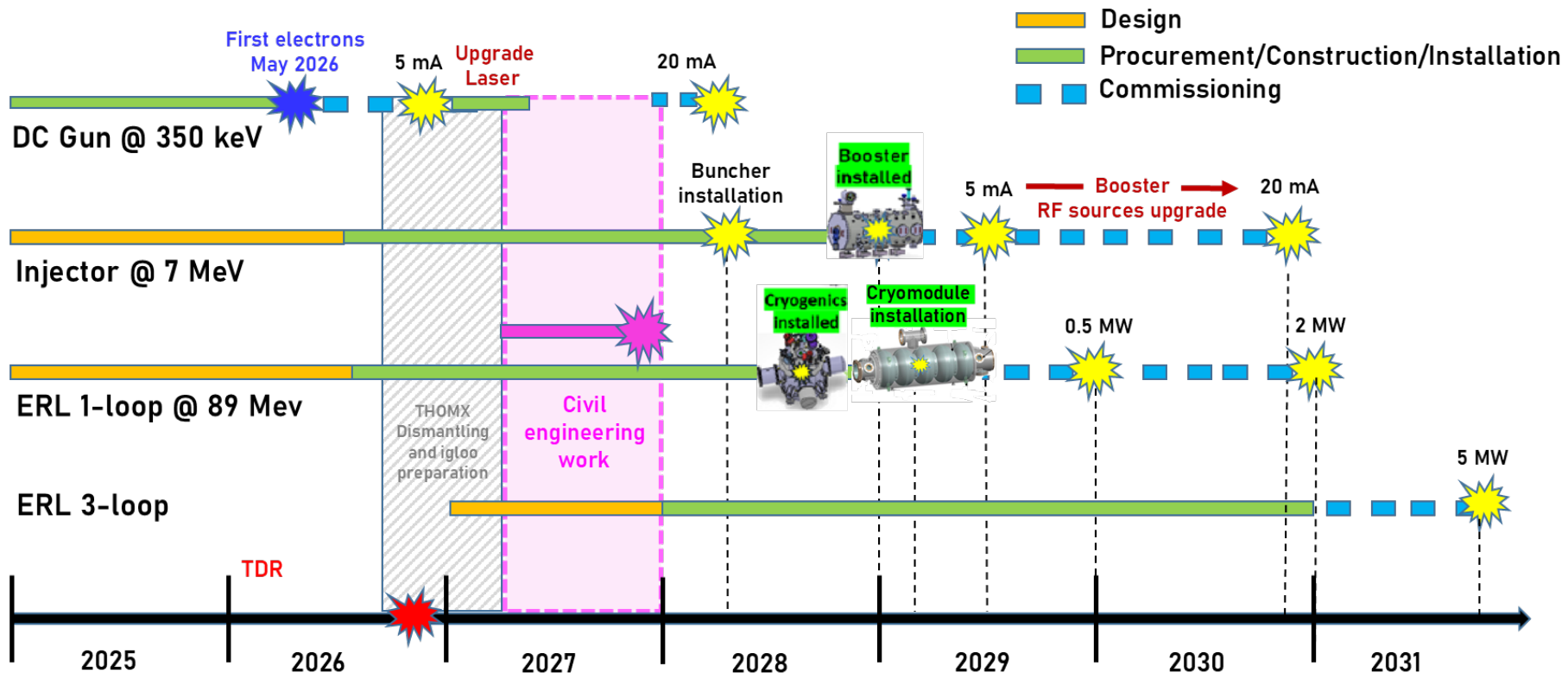
Sustainability
 F. Bouly / Michaud

PACSI



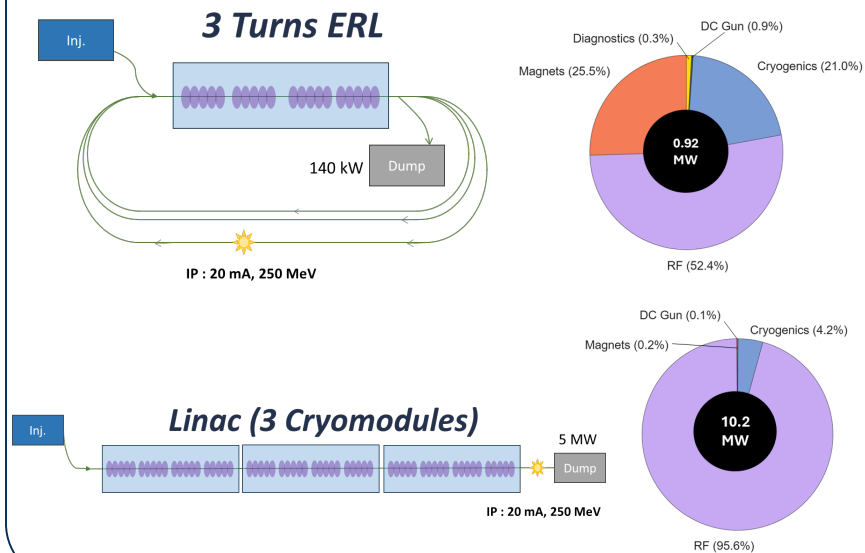
Service électronique (SE) LPSC : BPM et câblage





Bilan de Puissance Conclusion

Comparison ERL vs Linac



“Wall-Plug “ Power Consumption

Preliminary study : 5 MW beam (250 MeV, 20 mA, CW) @ IP

Type	Electrical Power (kW)							
	PERLE 3 Turns (250 MeV, 20 mA)				SC Linac (250 MeV, 20 mA)			
Magnets	233.6 kW				16.3 kW			
> Considered : Solenoids, Quads, Dipoles > Power supply eff. ~80%								
Injector	0.3				0.3			
Merger	0.5				0.5			
ERL or SC linac	232.8				15.5			
RF Power	481.3 kW				9 741.0 kW			
> Assumed attenuations & errors : • +5 % booster and linac config. Cavities • +10 % for ERL cavities > Amplifier eff. ~55%								
Injector : Booster + Buncher	278.8				278.8			
ERL (4 cavities) or Linac (3*4 cavities)	202.5				9462.2			
Cryogenic Systems	192.4 kW				427.2 kW			
Cryomodule Booster	Static losses	Dynamic losses		Lhe line (FPC)	Static losses	Dynamic losses		Lhe line (FPC)
	21.75	9.9		8.3	21.75	9.9		8.3
1 ERL Cryomodule ERL or 3 linac Cryomodules	Static losses	Dynamic losses	HOM contribution (Static & Dyna.)	Lhe (FPC)	Static losses	Dynamic losses	HOM contribution (Static & Dyna.)	Lhe (FPC)
	17.9	84.3	16.7	8.3	53.75	253.0	< 3	24
Cryolines & Valves box	24.7				50.5			
Diagnostics	~2.5 kW				~1.5 kW			
DC Gun (HV, laser, laser room)	7.9 kW				7.9 kW			
Total	918.7 kW (~ 1 MW)				10 194.0 kW (~ 10 MW)			
Cooling systems (water, air, ...) (+ Vacuum) + ...	+++				-			
Power to dissipate @ dump	140 kW				5000 kW			

ERL Efficiency

$$\eta_{elec} = \frac{P_{beam}}{P_{grid}} \approx 5.4$$

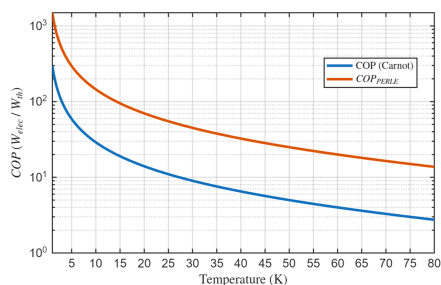
Linac Efficiency

$$\eta_{elec} = \frac{P_{beam}}{P_{grid}} \approx 0.49$$

Cryogenic System Coefficient of performance

$$COP = \frac{T_{300K} - T_{Cold}}{T_{Cold}} / \eta_{capacity}$$

$\eta_{capacity} = 20\%$, Based on Strobridge Diagram



- ◇ Avantages des ERL :
 - ◇ Fort courant, haute qualité faisceau à l'IP (avantages combinés des linacs supra et anneaux)
 - ◇ Haute efficacité énergétique (potentiellement 10 fois plus efficace / linac)
 - ◇ Radioprotection : Arrêt faisceau à basse Energie (celle d'injection)
- ◇ Application :
 - ◇ Collisionneurs
 - ◇ Source de Lumière (complémentaire aux synchrotrons): Compton (cavité Fabry-Perot), FEL
 - ◇ Machine compactes (50/100 MeV) mais fort courant et CW : physique nucléaire, source Compton
 - ◇ Application « dérivée » : accélérateur/injecteur à recirculation

- ◇ PERLE vise à démontrer la faisabilité technologique des ERL supraconducteur en régime MW
- ◇ PERLE servira de banc d'essai stratégique pour les futurs grands projets d'accélérateurs
 - ◇ FCC, LHeC
- ◇ Approche : construction par phases permettant de respecter les financements et les contributions in-kind.
- ◇ Phase de design se termine (TDR à venir) début de la construction et du prototypage
 - ◇ **Premier faisceau Mai 2026 !**

PERLE status

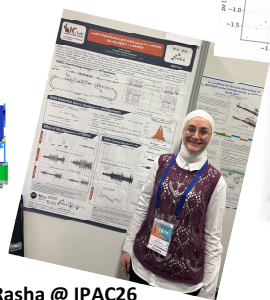
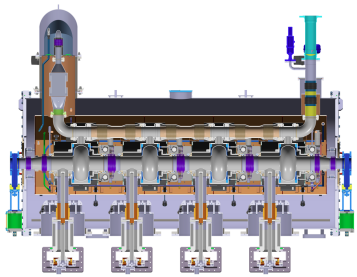
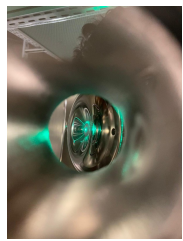
- 06.2017 — First Site in Annecy and Borex Campus Test Facility — CEA member of IAC/ERL
- 08.2017 — First Lattice Design (Alex Bogacz)
- 08.2017 — Powerful ERL for Experiments
- 10.2016 — PERLE at Orsay (Achille Stocchi) and Max Planck
- 05.2017 — Conceptual Design Report
- 03.2024 — Start of building phase
- 04.2024 — HV conditioning up to 350 kV (ongoing)
 - MEP5000 (R. Fross)
- 04.2024 — LBL job synthesizers, US 4.5%
 - TRP2102 (M. De Wit)
 - TRP2104 (M. Bayard)

11.05.2026 First Electrons !!!

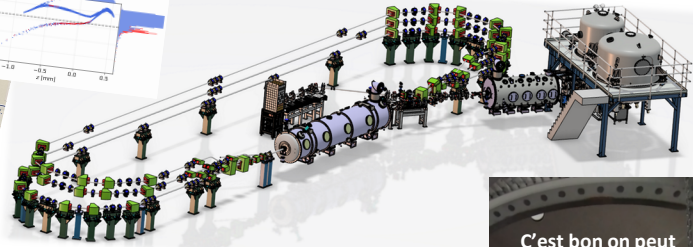
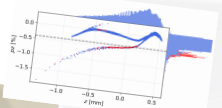
Next day — 23 hA in the Tunnel Hall

10 May 2008 Alex Fortin PERLE Beam Dynamics and Optics PAC79, Daville, France

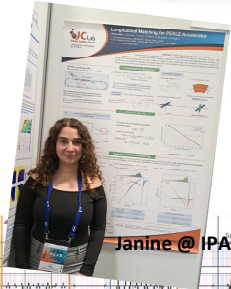
PERLE Talk @ IPAC26 (Alex)



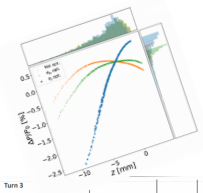
Rasha @ IPAC26



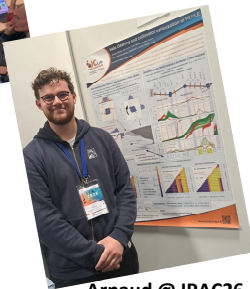
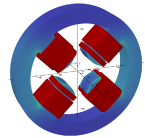
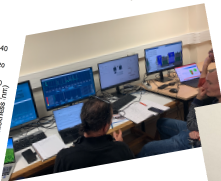
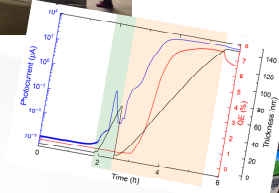
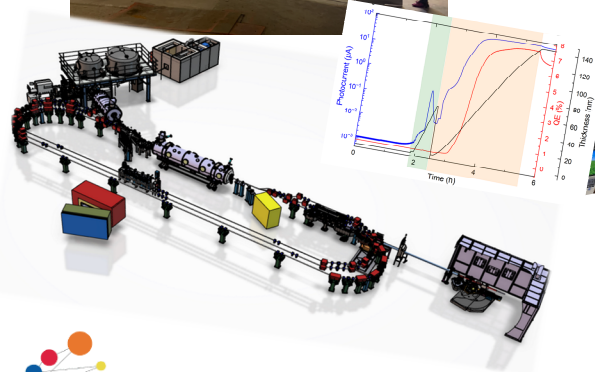
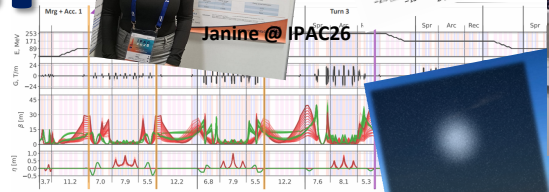
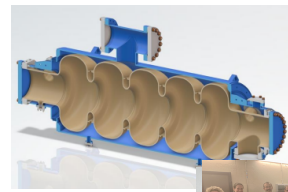
Merci



Janine @ IPAC26



DC break & Sylvain



Arnaud @ IPAC26



Y'a que le Gun et c'est déjà le bordel

