IN2P3 Scientific Council

PERLE: A powerful Energy Recovery Linac at Orsay

TDR phase

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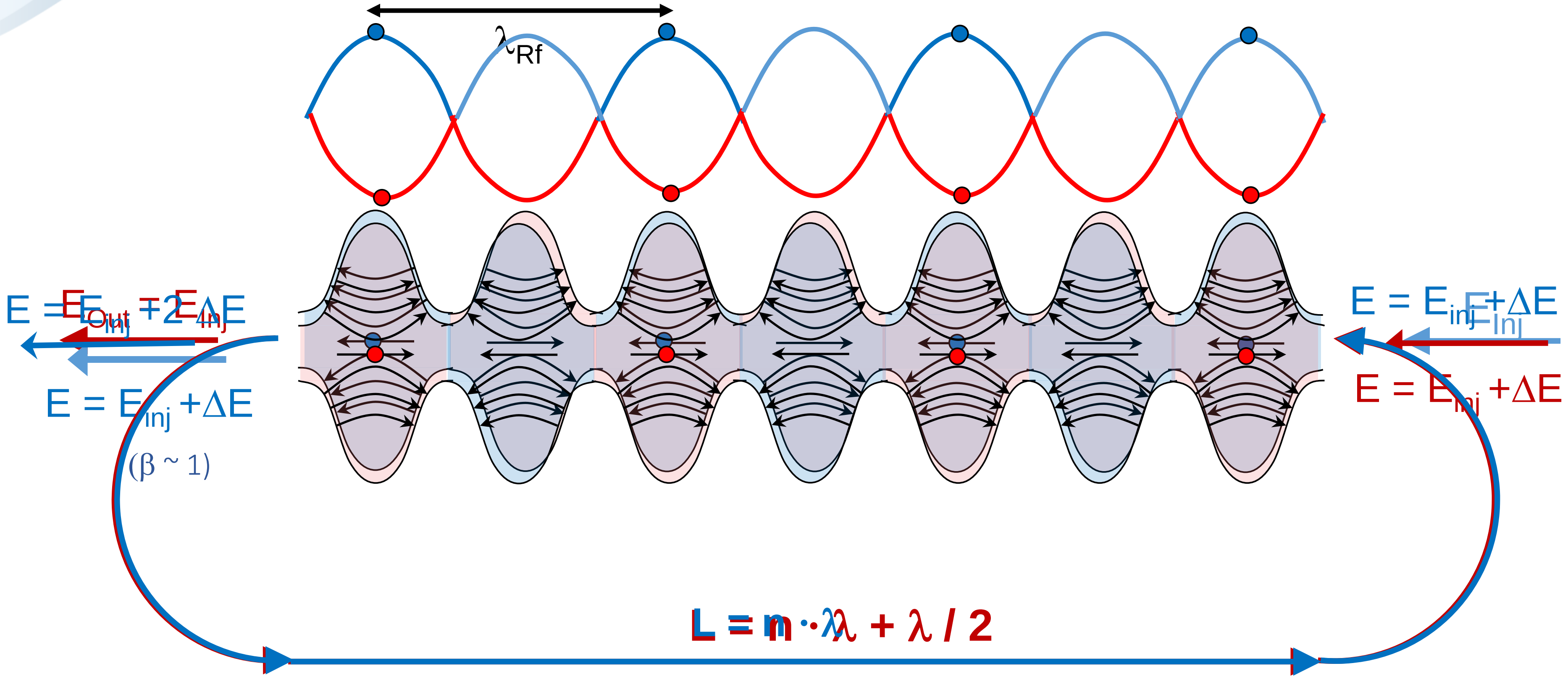
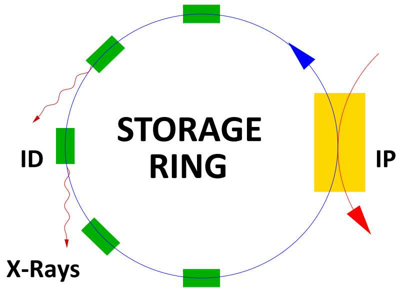
09 February 2021

Introduction- Energy Recovery in RF Fields



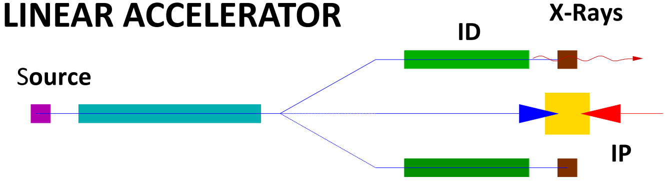
- Energy supply → acceleration
- Deceleration = "loss free" energy storage (in the beam) → Energy recovery

Introduction- ERLs: The Best of Two Worlds



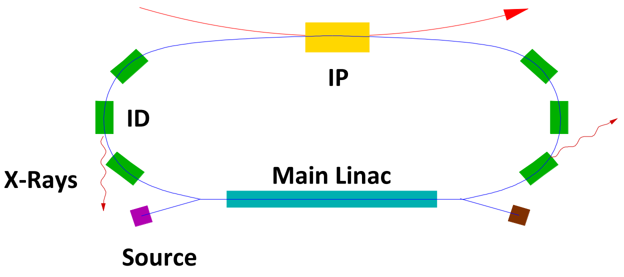
- Beam parameters defined by equilibrium
- Limited flexibility – multi-pass
- High average beam power (A, multi GeV)
- Typically long bunches (20 ps – 200 ps)
- Many user stations

LINEAR ACCELERATOR



- Beam parameters defined by the source
- High flexibility – single pass
- Limited average beam power (<< mA)
- Possible short bunches (sub psec)
- Low number of user stations

ENERGY RECOVERY LINAC



- Linac-like beam quality
- Easy to upgrade (add linac section or recirculation passes)
- Tolerate more “damage” to the beam from collisions with another beam (the beam is dumped soon after)

- High beam current possible (RF power limit removed)
- Reduced power bill (RF power recovered)
- Reduced cost of RF amplifiers (smaller RF power amplifiers)
- Reduced beam power and energy in beam dump (less shielding / activation issues)

High average beam power in compact machine, excellent beam parameters with high flexibility

Scientific International Context

2020 Strategy Statements

European Strategy Update

3. High-priority future initiatives

Accelerator R&D is crucial to prepare the future collider programme

- The European particle physics community should develop an accelerator R&D roadmap focused on the critical technologies needed for future colliders, maintaining a beneficial link with other communities such as photon or neutron sources and fusion energy
- The roadmap should be established as soon as possible in close coordination between the National Laboratories and CERN
- A focused, mission-style approach should be launched for R&D on high-field magnets (16 T and beyond) including high-temperature superconductor (HTS) option to reach 20 T. CERN's engagement in this process would have a catalysing effect on related work being performed in the National Laboratories and research institutions
- The roadmap should also consider: R&D for an effective breakthrough in plasma acceleration schemes, an international design study for a muon collider and R&D on high-intensity, multi-turn energy-recovery linac (ERL) machines

b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

19/06/2020 CERN Council Open Session 18

H. Abramowicz, secretary of the European strategy update- June 2020

Scientific International Context

- CERN Council mandated the Laboratory Directors Group (LDG) to define and maintain a prioritised accelerator R&D roadmap towards future large-scale facilities for particle physics.

- The LDG suggested to invite expert panels to each of the areas and has very recently endorsed their tentative composition. Among the selected few key areas is the development of ERLs.

- We (IJCLab) will be represented in this ERL world wide expert panel (including US and Asia), to support this joint attempt for advancing the coordinated development of the ERL technology. The initial task of this panel is to develop a roadmap for presentation to CERN Council, in December 2021.

- The chair (M. Klein- UoL) and co-chair (A. Hutton- JLab) of the panel are members of the PERLE collaboration.

Scientific National Context

Spiro Committee: Contribution to the future of GANIL:

Proposal of an electron-Radioactive Ions collision facility (e-RI) at GANIL:

- Option of a high current ERL as electron source is strongly supported.
- Preliminary investigations and analysis oriented the choice for a single tour, 100 mA (up to 200 mA), 500 MeV ERL.
- A key point in this facility is the ion capture efficiency: ***The more efficient the capture is, the less electron intensity is needed.***

→ Need of an intermediated step for an original ion trap R&D and test with a high performance electron machine: Initiative DESTIN (DEep STructure Investigation of exotic Nuclei) @ Orsay coupler to PERLE facility.

Scientific National Context

French Strategic Plan Report 2020-2030- Particle accelerators & associated instrumentation WG:

Extract of the executive summary:

“ERL is a very promising technology for future electron accelerators. The ambitious PERLE@Orsay initiative should be strongly supported, provided that an adequate international participation to the project can be settled”.

Common Scientific Council LAL & IPNo- June 2019:

Extracts of the SC report on PERLE:

“… Some expertise will not be available in Orsay and the participation of collaborators external to LAL and IPN will be necessary. The organisation of the project is a key issue. The scientific council recommends setting up an international organisation with official collaborations to drive the project. Project management should be strengthened. In the same spirit, a (new) attempt to extend the collaboration to CEA should be tried”.

“A TDR would give a clear picture on the project. Hence, the scientific council recommends to achieve the phase 1.1 as described in this document. The TDR should already be elaborated with international collaborators”.

The PERLE Collaboration

PERLE international collaboration leaded by IJCLab involves today:

CNRS IN2P3 Les deux infinis — CERN — Jefferson Lab, Thomas Jefferson National Accelerator Facility — Science & Technology Facilities Council — Budker Institute of Nuclear Physics — Cornell University — University of Liverpool

- A Collaboration Agreement (CA) under final approval by CNRS legal service.
- All the partners received preliminary draft of the CA and are ready to sign it.
- The collaboration aims at performing a technical detailed study of the PERLE facility and at preparing the ground at its construction and operation phase.
- The effort of the collaboration is currently focused on the organization and work sharing toward the publication of the PERLE Technical Design Report (TDR) by fall 2022.

PERLE Beam Parameters

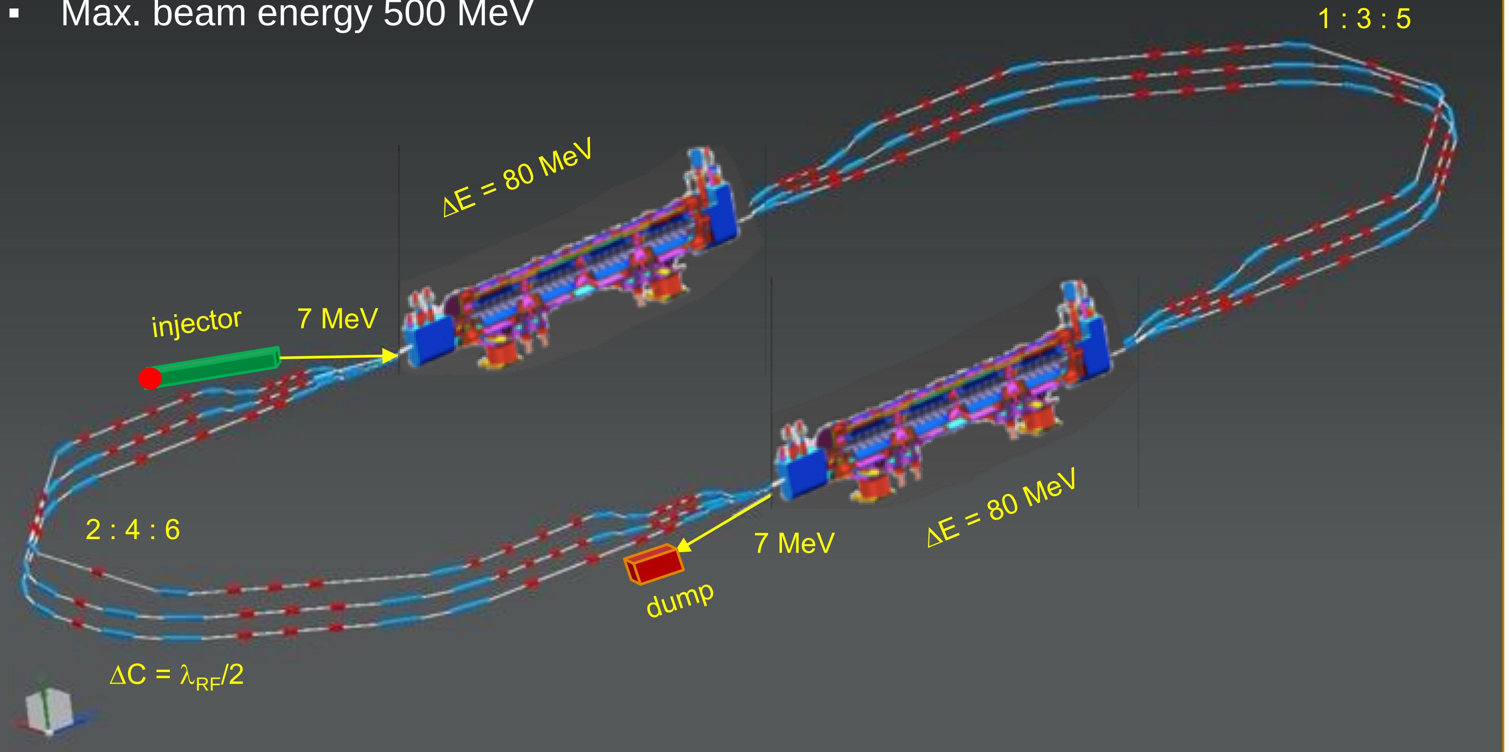
PERLE: A proposed 3 turns ERL, based on SRF technology, to serve as testbed for studying, testing and validating a broad range of accelerator phenomena & technical choices for future projects.

Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	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

[2] J.L. Abelleira Fernandez et al, “ A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector “, J.Phys. G39 (2012) 075001, arXiv:1206.2913

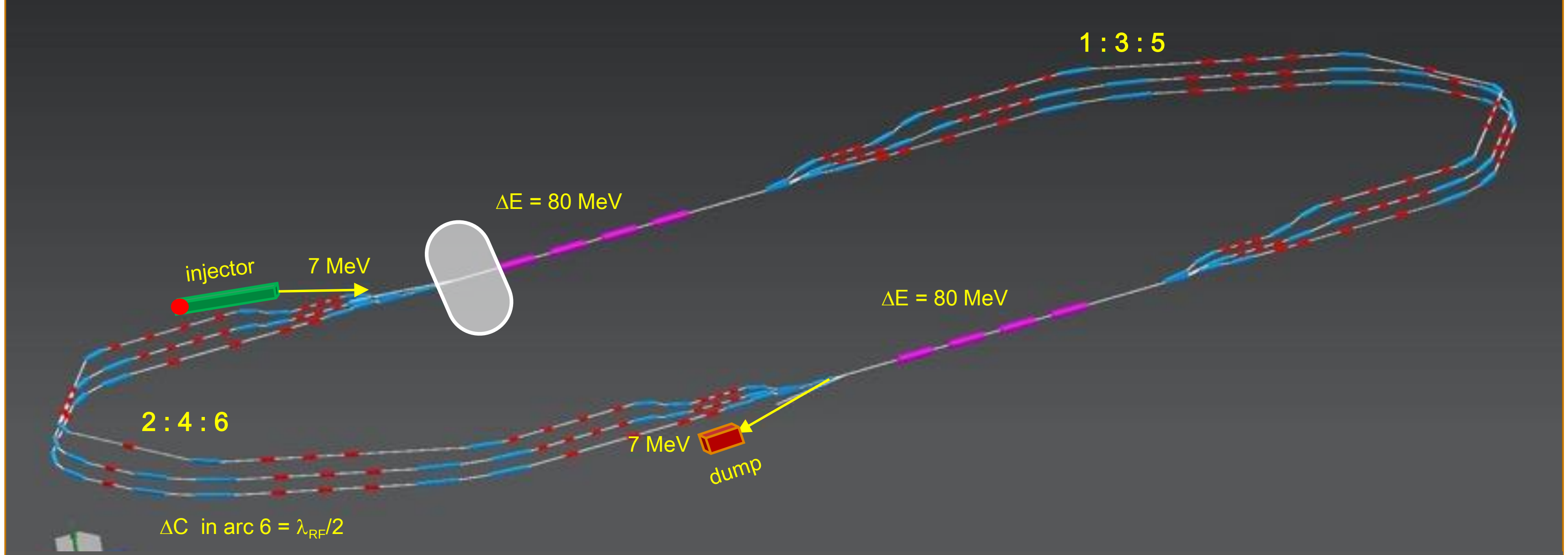
PERLE Configuration

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV



PERLE Configuration

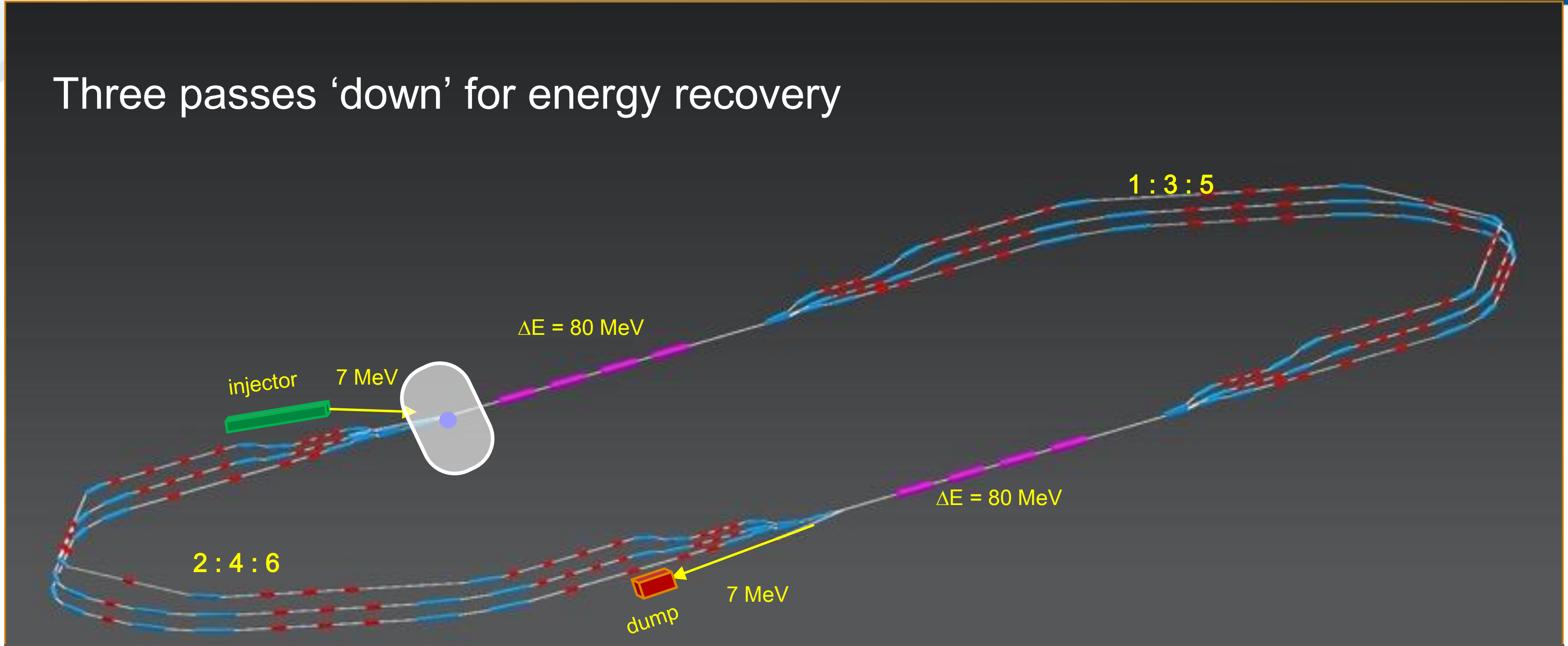
Three passes 'up' to reach the maximum energy



Electron beam at maximum energy could be used for:

- Elastic electron-proton scattering with polarised beam (Particle physics)
- Exploration of proton densities in exotic nuclei by electron scattering (Nuclear physics)
- Gamma ray production between 0.2 and 5 MeV (wide applications in Photo-nuclear physics),

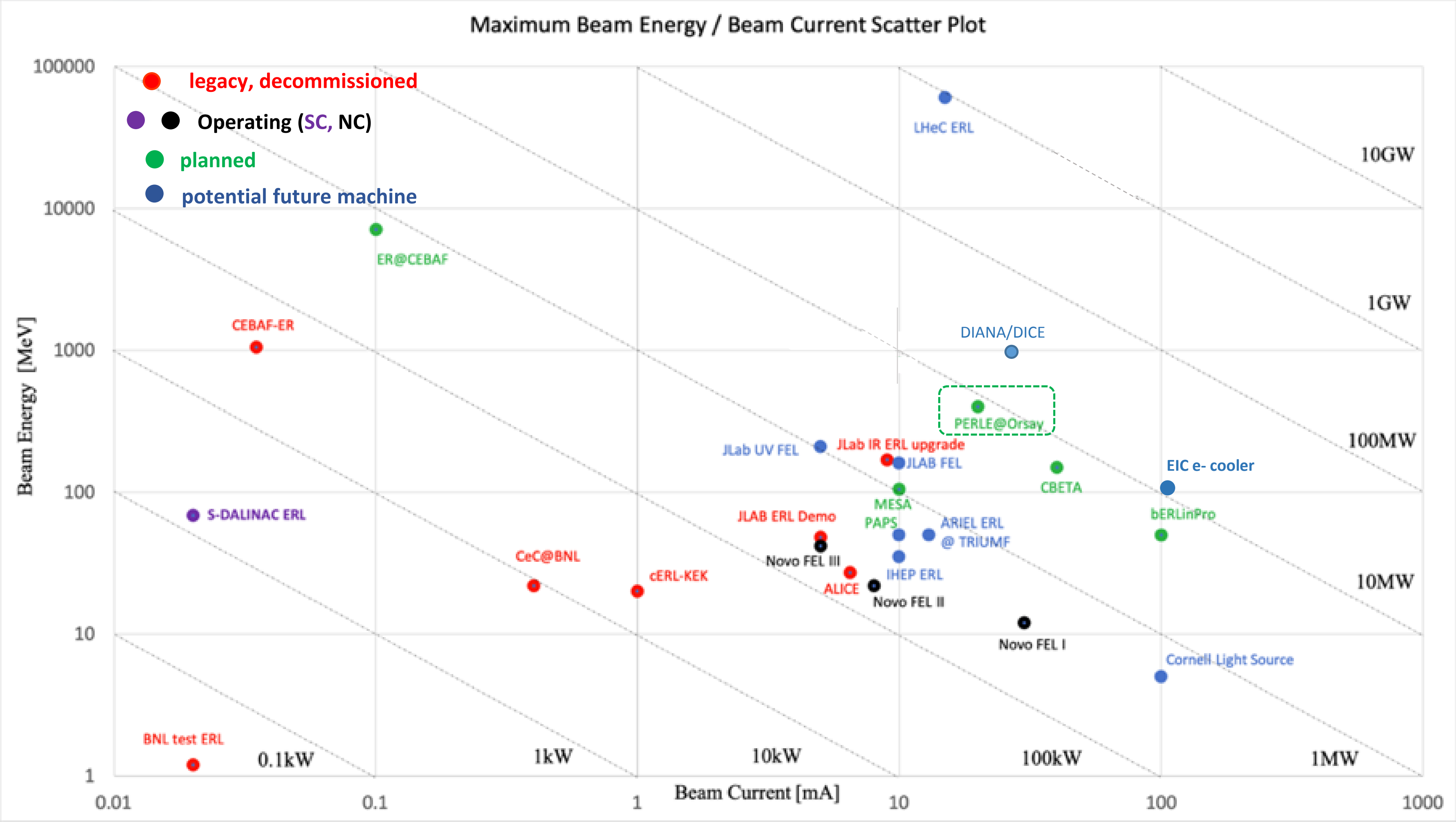
PERLE Configuration



Several benefits from this manipulation:

- The required RF power (and its capital cost and required electricity) is significantly reduced to that required to establish the cavity field and make up minor losses.
- The beam is constantly renewed: never reach equilibrium state --> provides flexibility to adapt beam properties for specific applications.
- The beam power that must be dissipated in the dump is reduced by a large factor.

PERLE in the Global ERL Landscape



Toward PERLE Realisation

Given the challenges imposed by PERLE design and technical choices, we plan to go through two main phases toward PERLE realisation :

- A design and prototyping phase that ends with the PERLE TDR:
  - Study the main phenomena imposed by the challenging design choices
  - Prototyping and test of the critical components (full dressed cavity, power coupler, dipoles…)
  - Design completion of the main sub-systems (booster, main cryomodule, DC gun upgrade…)
- Three staged construction, commissioning and exploitation phase, sketched in the following.

Project Organisation

We have established the PERLE Management Board (MB):

Composition:

- Alex Bogacz (JLAB)
- Patxi Duthil (IJCLab)
- Frank Gerick (CERN)
- Eugène Levitchev (BINP-Novosibirsk)
- Frank Marhauser (JLAB)- tbc
- Boris Militsyn (STFC-Daresbury)

And

- Max Klein (University of Liverpool)- spokesperson
- Walid Kaabi (IJCLab)- Project Leader

Role:

Assists the project leader in defining the project tasks (at IJCLab and/or other collaboration sites), and to ensure the execution and monitoring of the project tasks in their respective labs.

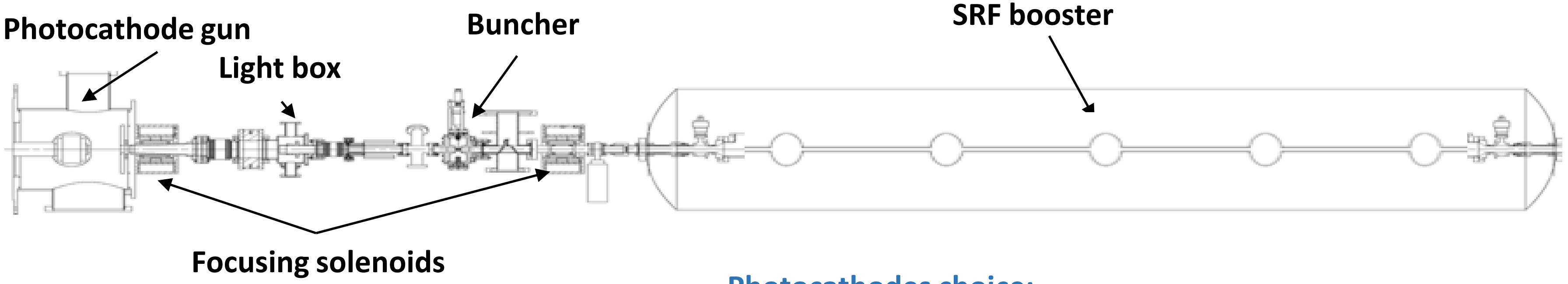
→ MB first task: setting up the Work Breakdown Structure (WBS) of the project (Still in progress).

PERLE Injection Line

Courtesy to B. Hounsell and B. Militsyn

It consist of:

- A DC photoemission electron gun (The ALICE DC gun to be upgraded).
- A bunching and focusing section: 401 MHz normal conducting buncher cavity placed between two solenoid.
- A superconducting booster with five 802 MHz cavities individually supplied and controlled on amplitudes and phases.
- Merger to transport the beam into the main LINAC,
- Beam diagnostics to be placed between components.



Photocathode laser choice:
Nd: YAG laser (532 nm) or Ti: Sapphire laser (400 nm).

Photocathodes choice:

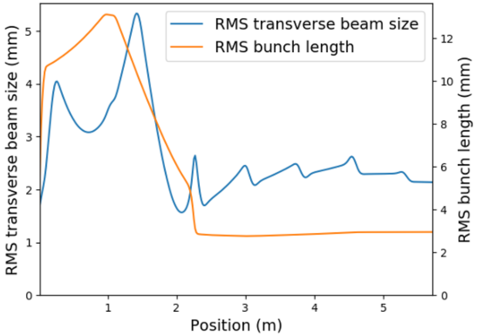
- **Sb-based photocathodes (unpolarized electrons) operated at 350 kV**
- **GaAs photocathodes (polarized electrons) operated at 220 kV**

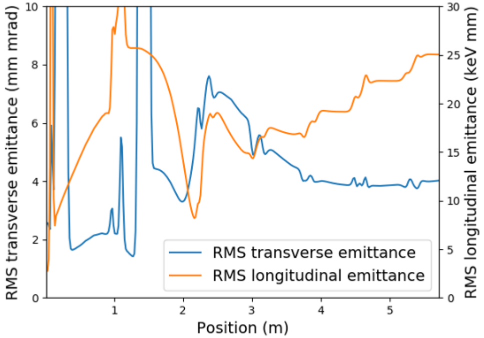
PERLE Injection Line

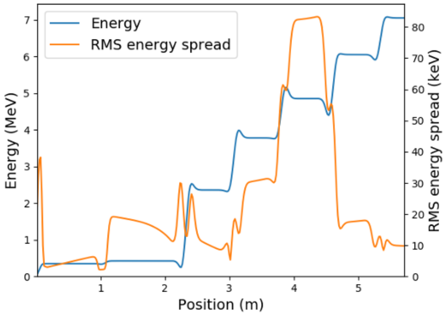
Electron source to booster exit optimisation:

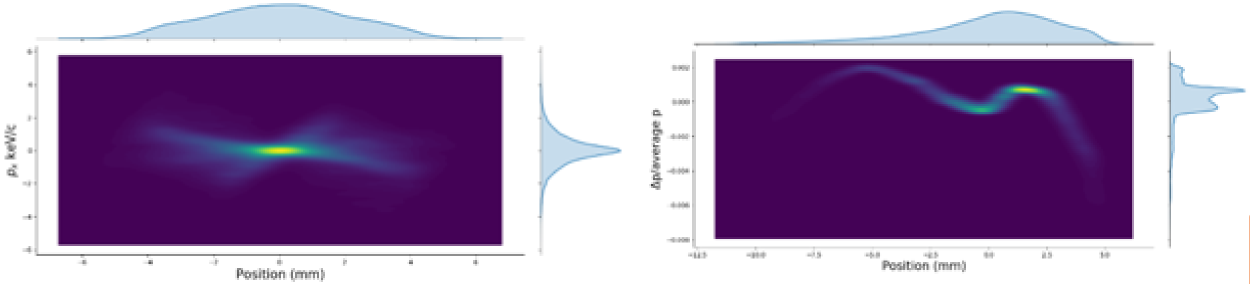
- The ALICE electron gun electrode geometry has been re-optimised for PERLE's new requirements.
- An optimisation with a 5 cavity booster linac, from the cathode to the booster exit, was done and meets the specification.
- If booster will be switched to a 4 cavity design, The tools for performing the re-optimisation are in place.

Achieved bunch parameters	
Transverse emittance/ mm mrad	4.0
Longitudinal emittance/ keV mm	25.1
Bunch length/ mm	3.0
Energy/ MeV	7.0



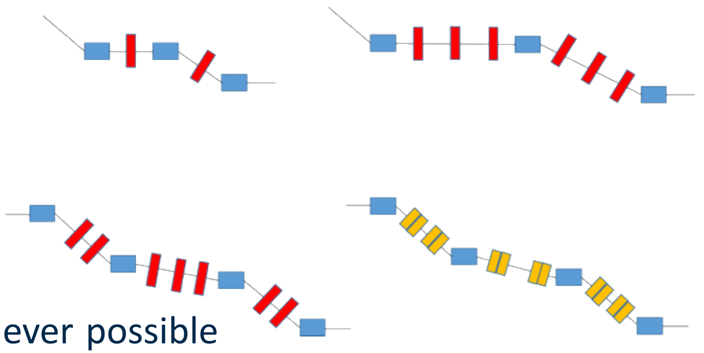


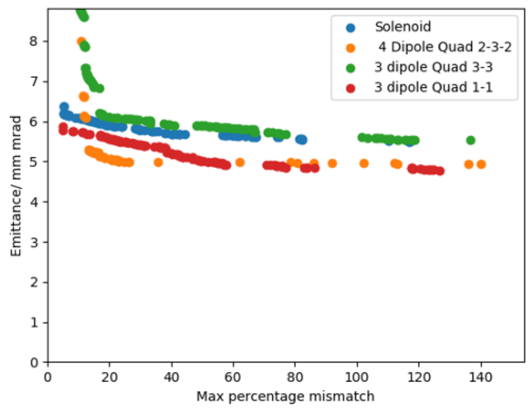




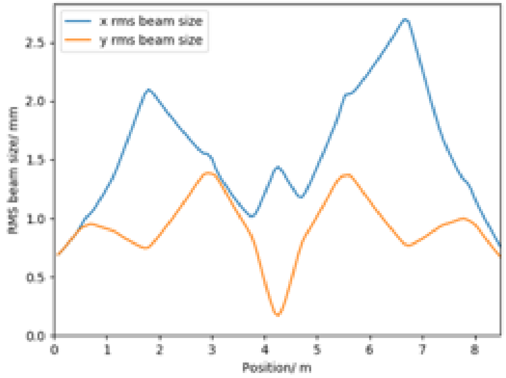
PERLE Injection Line

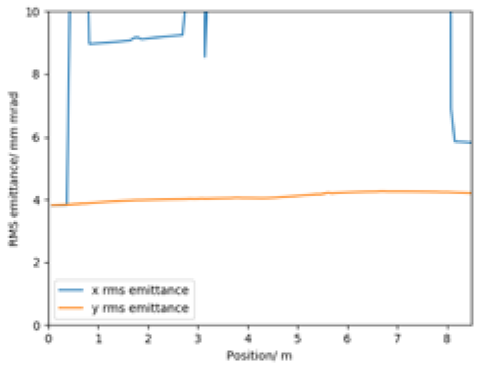
Merger tentative design:





- Several merger schemes are investigated.
- Design philosophy: use adjustable elements where ever possible to keep as much flexibility in operation as possible and to avoid building an assumption about the amount of space charge force present into the physical system. possibility to operated with different bunch charges, bunch sizes, injection momentums
- Space charge is still significant and will need to be managed to prevent significant degradation to the emittance.
- 4 dipole schemes are currently being investigated as they have the potential to mitigate the effects of space charge on the dispersion and the consequent emittance growth.
- Implications of the current optimisation on the beam dynamics in the main lattice should be investigated or possibly modifying some of the requirements on the merger which might open up alternative schemes.





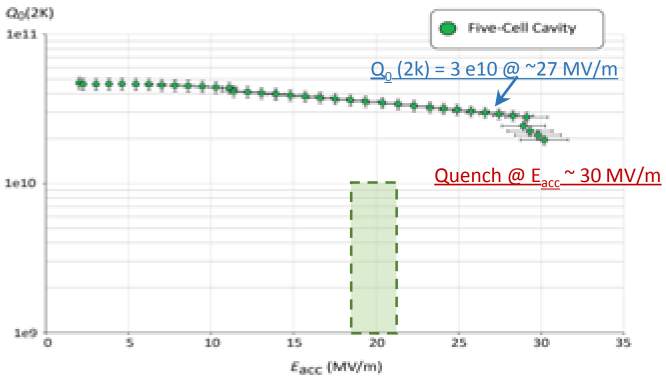
PERLE Injection Line

Task	involved parties	Task Manager	Contributer
Electron source and injection	IJCLab, STFC and UoL		
DC Gun upgrade for operation with interchangable photocathodes		IJCLab and STFC	
Review of the gun upgrade design			IJCLab and STFC
Identification of missing and additional gun upgrade components			IJCLab and STFC
Desing of transport vessel fo alkali photocathodes			IJCLab and STFC
Photocathode fabrication and load lock system design		STFC	
Buncher study and design		IJCLab	
RF design			IJCLab
Mechanical design			IJCLab
Booster studies and design		–	
Booster cavities design			–
Cryostating need and design			–
Merger		IJCLab	
Physical design			IJCLab + UoL + STFC
Mechanical design			IJCLab
Photo-injector Laser system for unpolarised regime		IJCLab	
Diagnostics need		IJCLab	

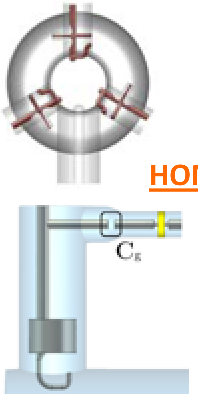
PERLE SRF System Development

Courtesy to F. Marhauser, N. Hu & G. Olivier

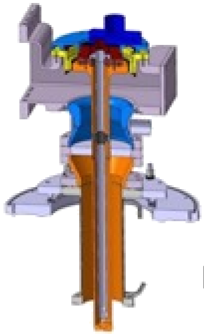
Design and prototyping of a **full dressed SRF cavity**: demonstration of level of SRF performance required in CW operation, high-average current environment, adequate damping of **HOM**.

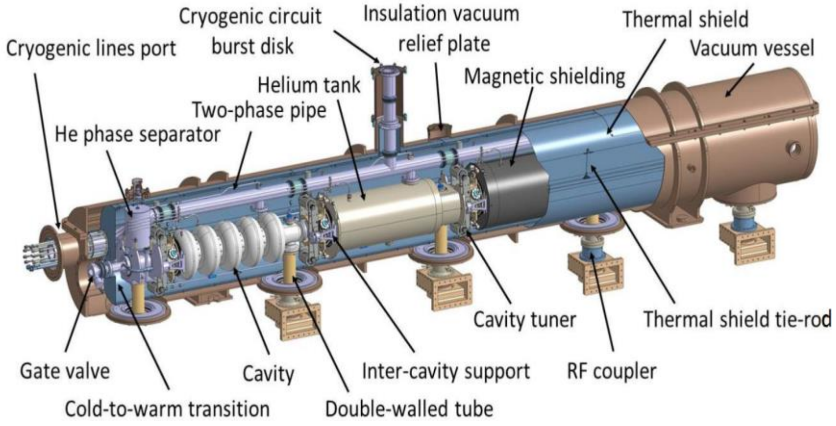


HOM coupler study



DQW HOM Coupler





Linac cryomodule design: **SPL cryomodule adaptation** to PERLE need, **complete design of a cryomodule** for PERLE later.

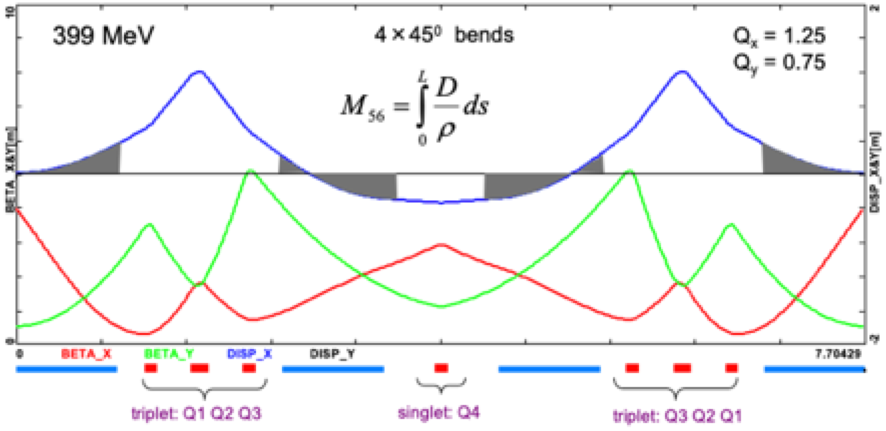
Design and prototyping of an **input power coupler**

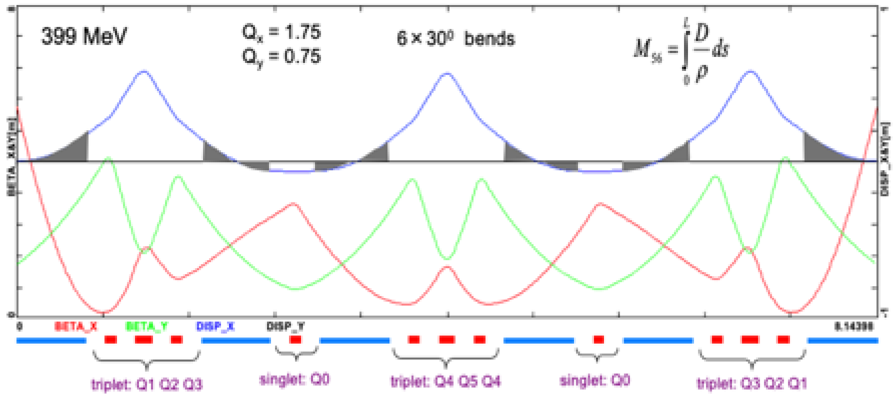
PERLE SRF System Development

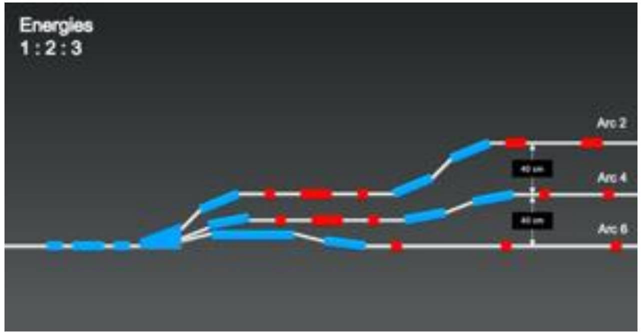
Task	involved parties	Task Manager	Contributer
SRF Cavity	JLAB and IJCLab	Frank Marhauser	
RF cavity and HOMs design			JLAB and IJCLab
HOM damping needs			JLAB and IJCLab
HOM EM design			JLAB and IJCLab
HOM mechanical design			CERN
End-group design			JLAB and IJCLab
Fabrication & tests of first HOM couplers for first cavity			IJCLab
Fabrication & tests of first dressed cavity			JLAB
Power coupler	IJCLab and CERN		
Definition of characteristics: Qex, Pav, Pmax,			IJCLab
Adaptation of SPL coupler to 800 MHz			CERN
Design and fabrication of 800 MHz test box			IJCLab and CERN
Procurement & set-up of amplifier, LLRF, controls			IJCLab and CERN
Test and conditioning			CERN
Fast Reactive Tuner (FRT)	CERN		
Feasibility study (& integration on cavity)			CERN
Electrical & mechanical design			CERN
Pocurement & prototyping			CERN
Cold test on cavity			CERN, JLAB

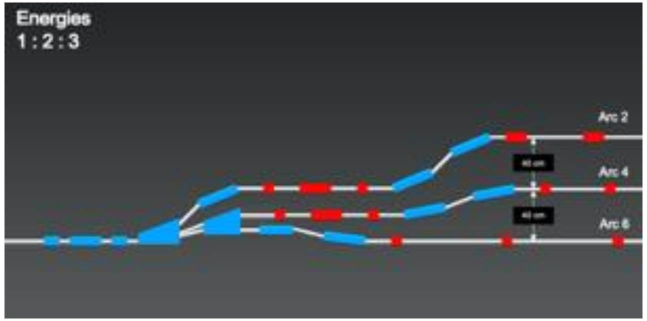
Lattice Design Optimisation

Courtesy to A. Bogacz and C. Vallerand

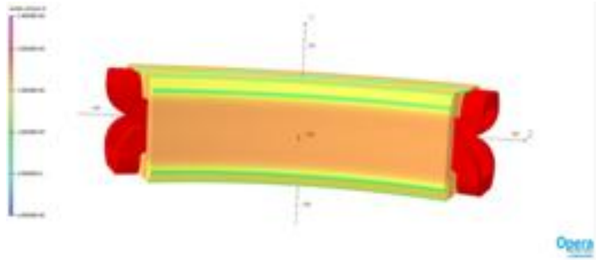


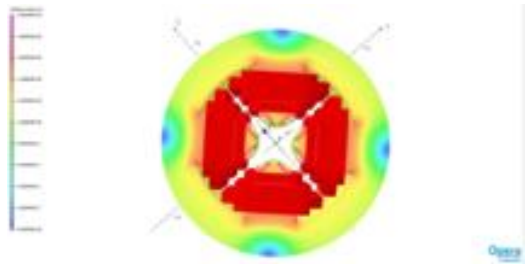






Design and prototyping of main **magnets for arcs and switchyards**





Lattice Design Optimisation

Task	involved parties	Task Manager	Contributer
Lattice and Optics	JLAB-IJCLab	Alex Bogacz	
Linear lattice optimization			JLAB
Arcs 1-6 (6-bend architecture)			JLAB
Spr/Rec 1-6 (two b-com switchyard)			JLAB
Matching sections 1-6 including two experimental inserts (Rec 6 and Spr 2)			JLAB
Linacs 1-2 with new cryo configuration			JLAB
Repository and data base with version control			**IJCLab**
Linear lattice optimization Initial magnet specs			JLAB
Momentum acceptance and longitudinal match			JLAB
Correction of nonlinear aberrations with multipole magnets			JLAB
Final magnet specs			**IJCLab**
Lattice design - External review			JLAB
Final Lattice			**IJCLab**

Task	involved parties	Task Manager	Contributer
Beam Dynamics	JLAB-IJCLab	Alex Bogacz	
Start-to-End simulation with CSR & micro-bunching			JLAB
BBU studies			JLAB
Space-charge studies at injection			**IJCLab**
Multi-particle tracking studies, error effects and halo formation			**IJCLab**
Impedance analysis and wakefield effect mitigation			JLAB
Beam dynamics issues - External review			JLAB

T-COM magnets prototyping WBS part will be settled up between IJCLab, BINP and CERN (Magnetic design, mechanical design…)

Involved Manpower

Evolution of IJCLab manpower implication during TDR phase

Year	2019	2020	2021	2022
FTE	1.5	1.9	5	7

Rise of the permanent staff implication is foreseen from 2021 in several tasks (SRF, mechanics, beam dynamics, electron source, cryogenics…)

Non-Permanent positions by task in 2021 and beyond

		Task		
		Electron source and injection line	Optics and beam dynamics	SRF activities
Fund origins	IN2P3			12 M post-Doc (Sept 21- Sept 22)
	EU (CREMLINplus)		24 M Post-Doc (2021-2022)	
	IJCLab (own fund)	PhD (2017-2021)		50% Post-doc (Sept 2019- Aug 2021) PhD (2022-2025)

Financial Resources

During the TDR phase, the financial support is mainly needed for:

- Manpower: hiring post-dc and PhD.
- Critical component prototyping and test: HOM coupler (s), b-COM dipoles in the switchyards, bare cavity completion…
- Adaptation of existing components for PERLE needs: SPL cryomodule, Alice DC gun upgrade, SPL power coupler.
- Travel cost, workshop organisation

Received funds, origins, distribution of expenses over the years and estimation of the needs for 2022 and beyond.

	Year							
	2019		2020		2021		2022-2023	
Fund origin	Manpower	Materials, prototypes, travel cost, WS organisation	Manpower	Materials, prototypes, travel cost, WS organisation	Manpower	Materials, prototypes, travel cost, WS organisation	Manpower	Materials, prototypes, travel cost, WS organisation
IN2P3	_	20 k€	_	_	57 k€	5 k€		
EU (CREMLINplus)	_	_	_	_	26 k€	_	52 + 26 k€	105 k€
IJCLab (own fund)	9 k€	6 k€	18 k€	_	9 k€ + 40 k€		2 x 40 k€	
Total	35 k€		18 k€		137 k€		263 k€ + Additional 80 to 100 k€ needed	

Toward PERLE Realisation

PERLE configuration entails the possibility to built it in stages, we propose three main phases to attend the final configuration:

Phase 0: Installation of the injection line with a beam dump at its end

- Injection line includes: DC gun, load lock photocathode system, solenoids, buncher, booster, merger and required beam instrumentations to qualify the generated beam.
- Commissioning of the injection line will require the installation of cryogenics, Rf power source, power supplies for optics, photocathode laser, beam dump, control-command system, vacuum systems, site shielding, safety control system, fluids, etc.
- Many of these installations must be already sized according to the final configuration of PERLE.

Toward PERLE Realisation

Phase 1: 250 MeV version of PERLE

Installation of a single cryomodule in the first straight + beam pipes and complete return arcs. Both, the spreader and re-combiner with energy acceptance ratio 1:2:3. This version of the race track will be connected to the injection line built in phase 0, via the merger.

This particular staging is determined by the existence of SPL cryomodule. It will allow:

- Test the various SRF components with beam .
- Prove the multi-turn ERL operation.
- Gain essential operation experience.

PERLE Phase 1 layout

Phase 2: PERLE at its design parameters as a 10MW machine

→ Upgrade of the e- gun to obtain the required nominal current.

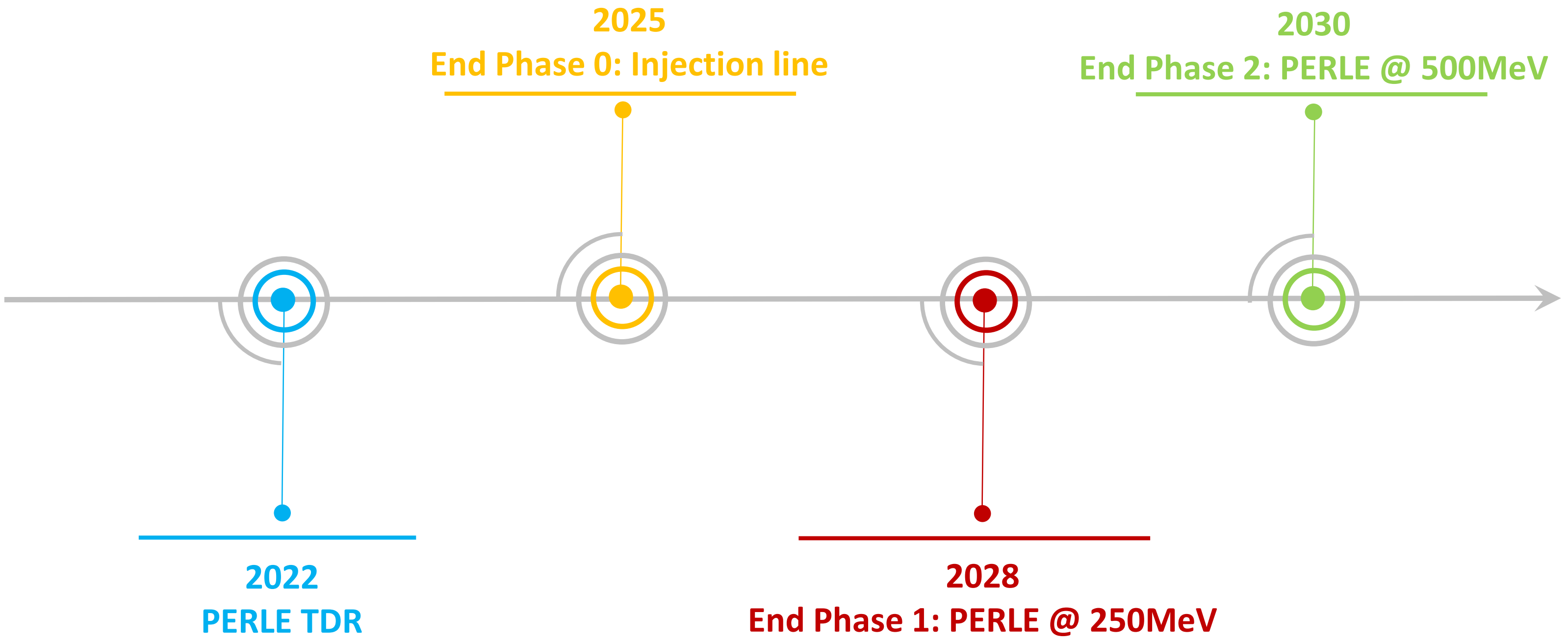
→ Installation of the 2nd Spreader and re-combiner at the required energy acceptance ratio.

→ Installation of the second cryomodule in the second straight.

PERLE Phase 2 layout

PERLE Timeline

The collaboration will develop later a detailed time schedule for the different upcoming phases. Currently it is foreseen to complete the TDR by 2022, Phase 0 by 2025, Phase 1 by 2028 and Phase 2 by 2030. A scheme of milestones will be worked out and agreed upon with emphasis on the accelerator but including a timeline for future experiments.

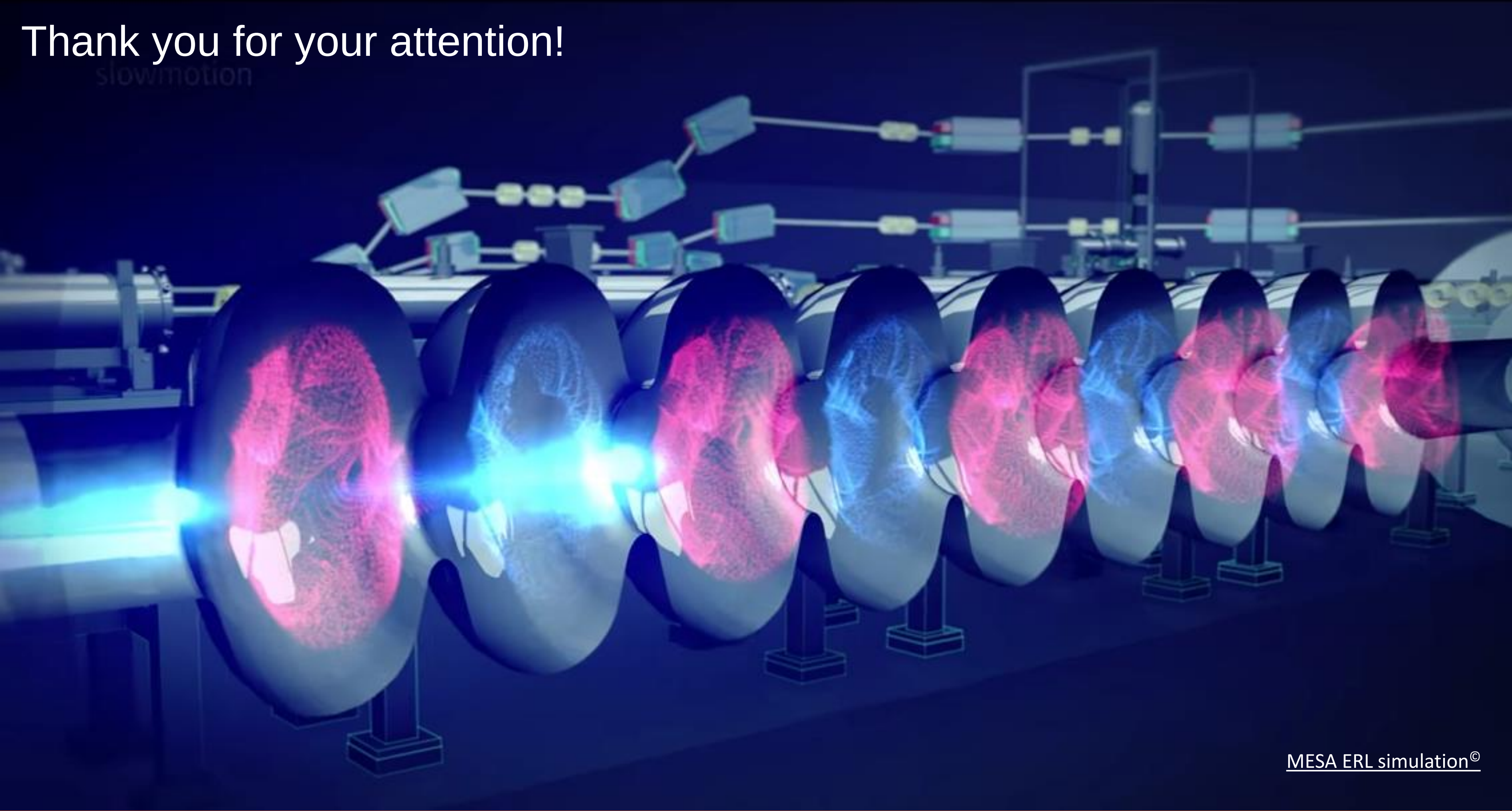


Summary

PERLE is **now founded** and has made **major progress in consolidating its configuration** (injection line and main loop designs) as high brightness, high energy (multiturn) new generation ERL. Its **partners** comprise main **leading labs in the field**, a unique advantage. Delivery of **in-kind essential components** (gun, booster and main linac cryomodules) may **boost the realisation** of PERLE significantly forward. To meet this unique opportunity it needs now **increased support**- because:

- ERLs are considered nowadays among the innovative accelerator technologies that deserve a vigorous R&D effort in the upcoming years.
- PERLE will be in the front line of the R&D roadmap on high-intensity, multi-turn ERLs to be developed by an international expert panel: high visibility, international attention, but also high pressure…
- The project need more resource involvement to overcome the challenges imposed by machine design and beam parameters. PERLE success could have a considerable impact on future ERLs (also on HEP).
- PERLE is a compact but powerful machine, attractive for number of applications that require high intensity beam: electron cooler, trapped ions interaction with electrons, FEL, gamma ray sources…

Thank you for your attention!



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