PERLE : Status and Plans

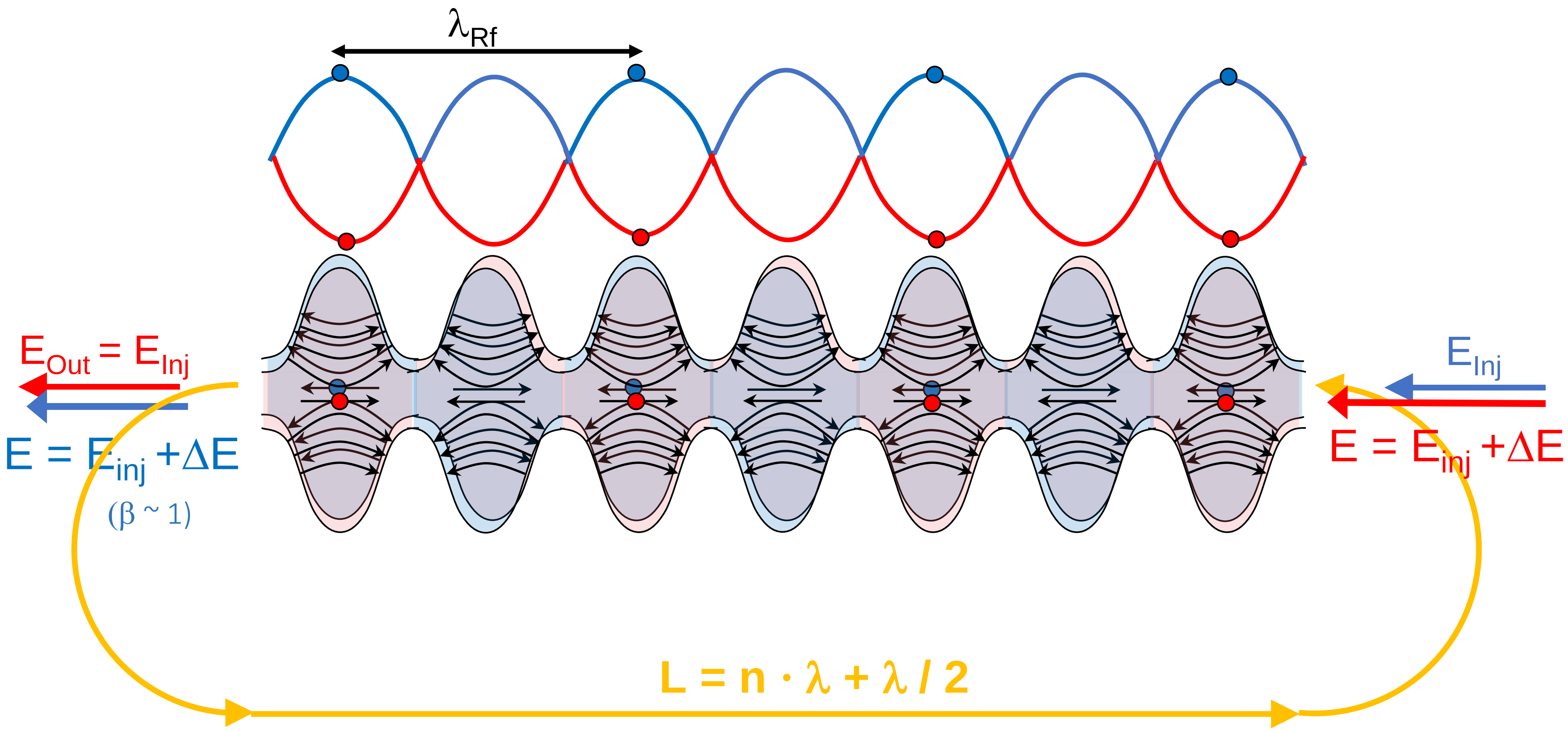
Future Circular Collider Conference - FCC Week 2019

Brussels, 24-28 June 2019

On behalf of the PERLE Collaboration

Walid KAABI-LAL/CNRS

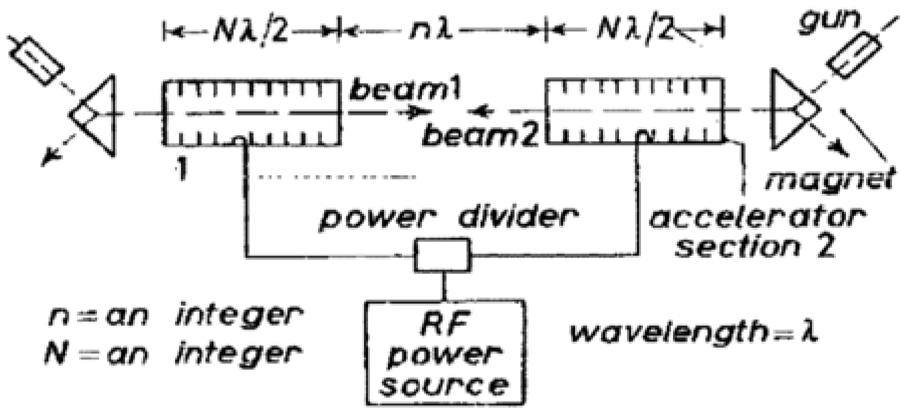
Introduction- Energy recovery in RF fields

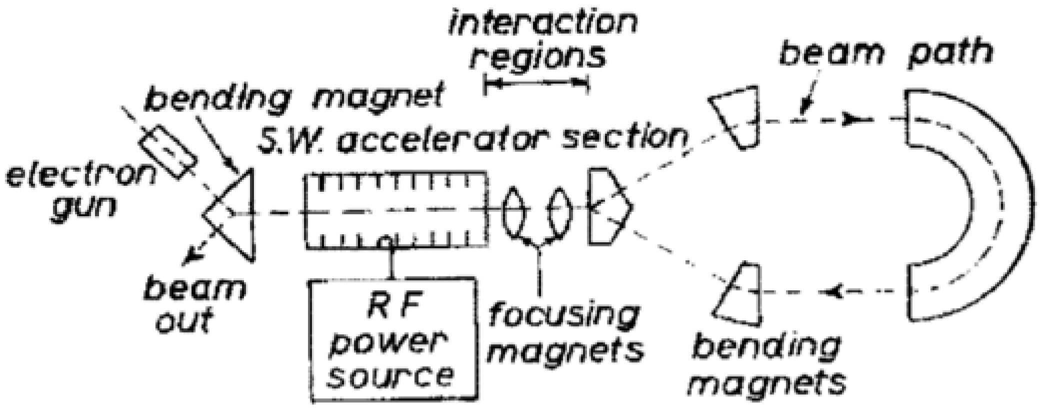


- Energy supply → acceleration
- Deceleration = "loss free" energy storage (in the beam) → Energy recovery

Introduction- ERL concept

- ERL concept was proposed first in 1965 by Maury Tigner [1]





[1] M. Tigner: "A Possible Apparatus for Electron Clashing-Beam Experiments", Il Nuovo Cimento Series 10, Vol. 37, issue 3, pp 1228-1231,1 Giugno 1965

- First test was done at SCA@ Stanford in 1986 (interesting concept for FELs, Compton light sources and high current electron cooler)

- Concept become only viable with recent advances in SRF technology.

Introduction to PERLE:

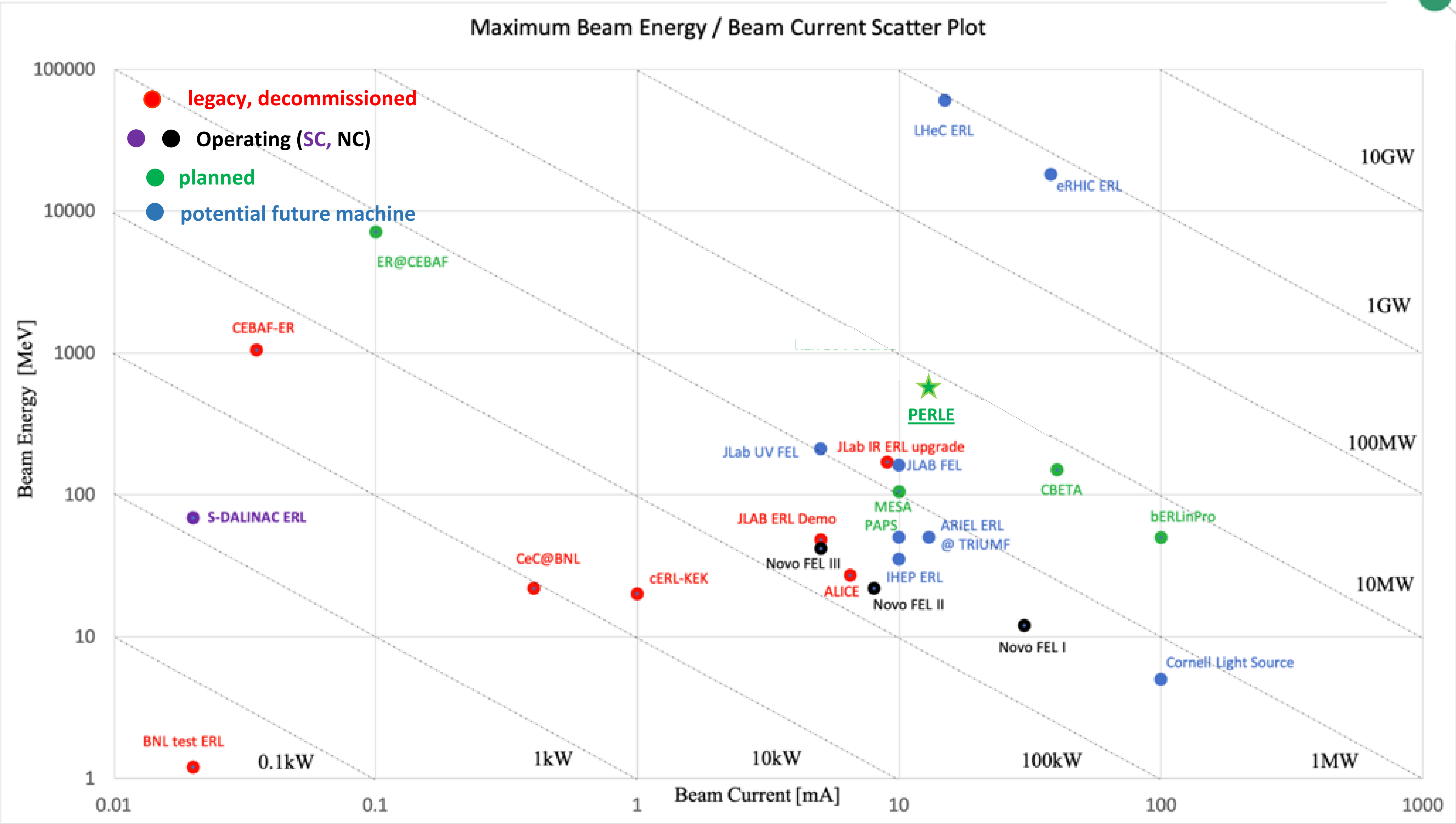
PERLE: A proposed three pass ERL based on SRF technology, to serve as testbed for validating and testing a broad range of accelerator phenomena & technical choices for future projects.

Particularly, design challenges and beam parameters are chosen to enable PERLE as the hub for technology development (especially on SRF) for the Large Hadron Electron Collider (LHeC) [1]:

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

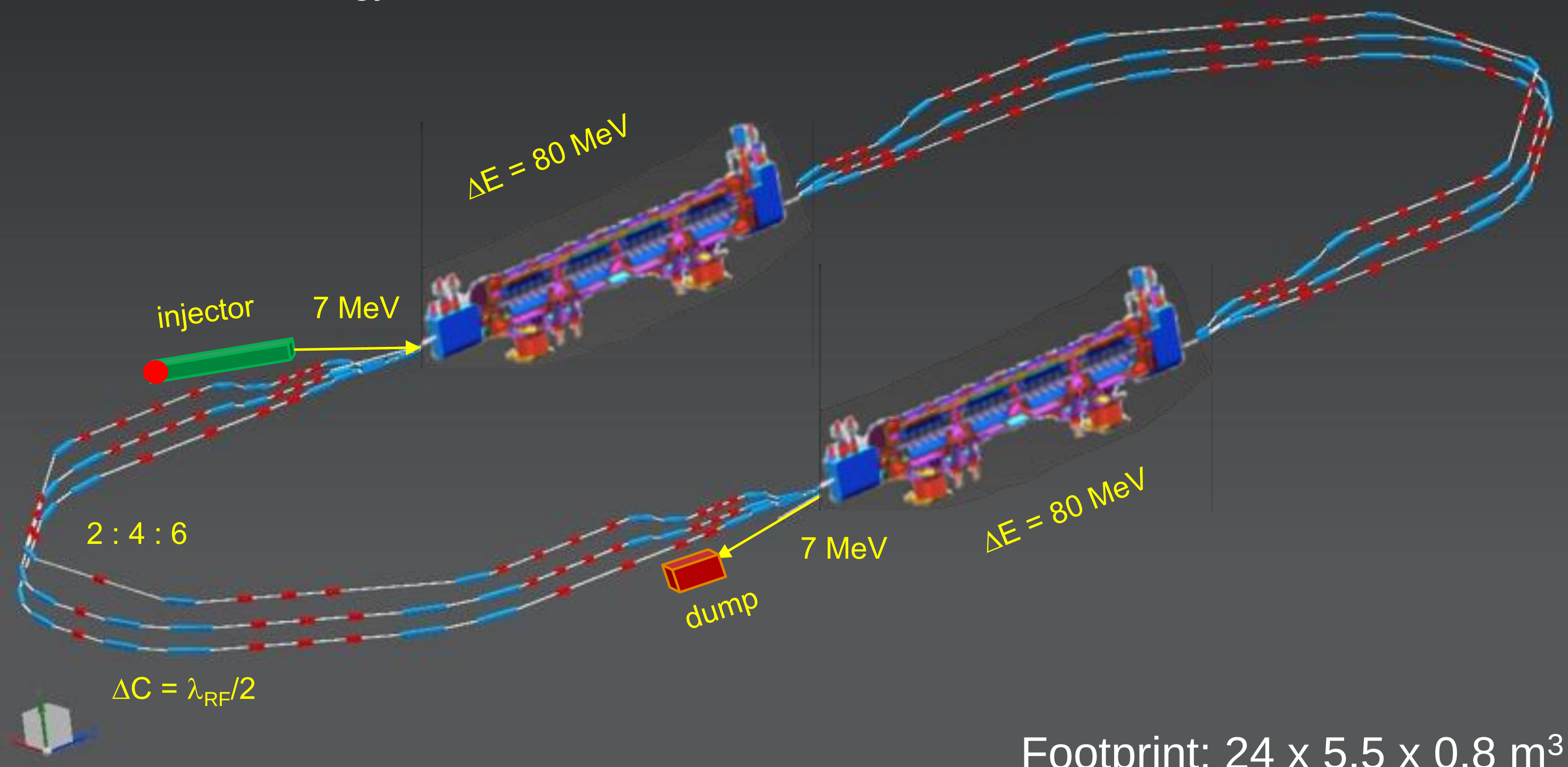
[1] J.L. Abelleira Fernandez et al, " A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector ", J.Phys. G39 (2012) 075001, arXiv:1206.2913

PERLE in the global landscape:



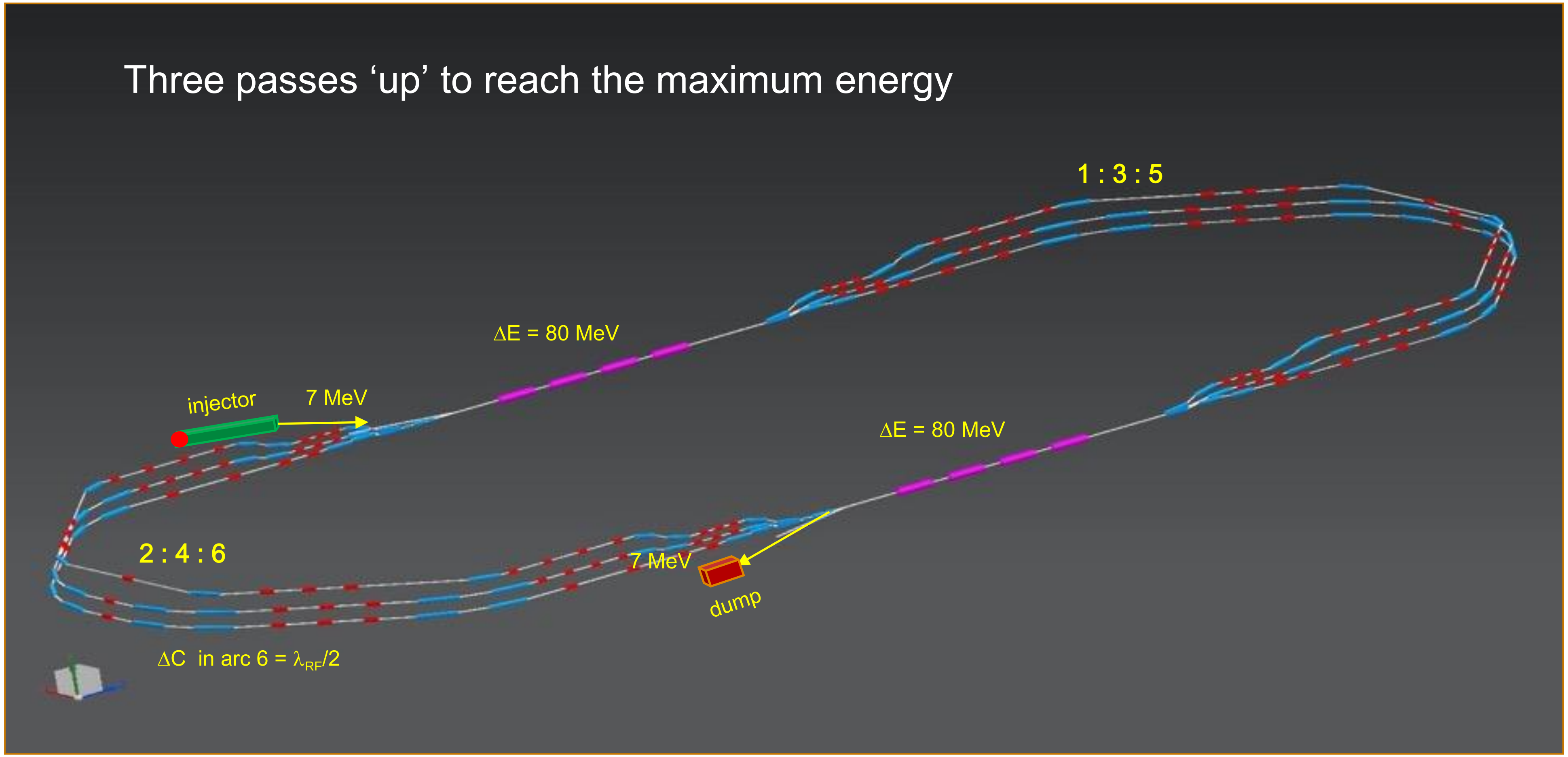
PERLE configuration:

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

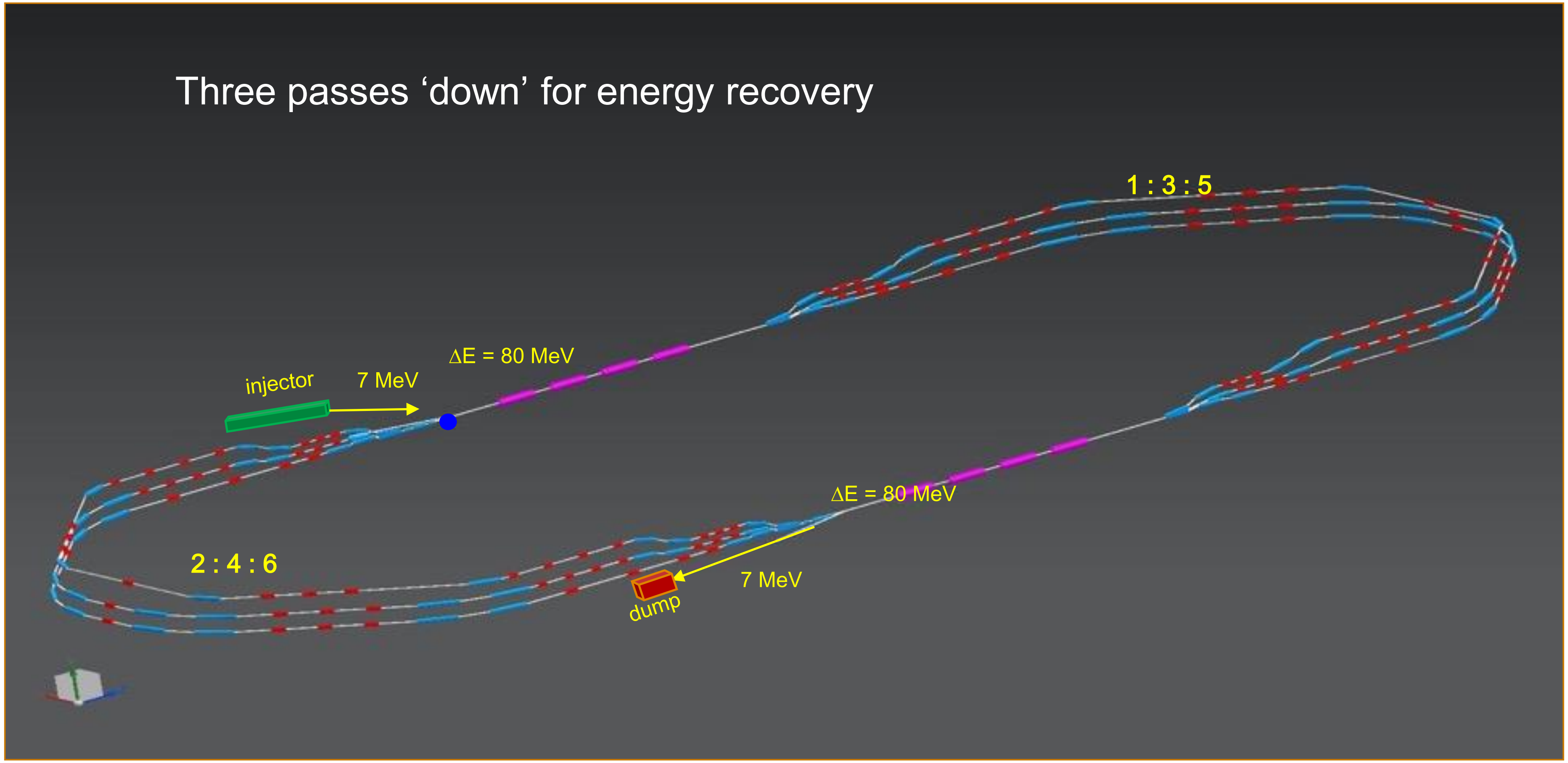


Footprint: 24 x 5.5 x 0.8 m^3

PERLE configuration:



PERLE configuration:



Project staging strategy:

The PERLE configuration entails the possibility to construct PERLE in stages. We propose in the following two main phases to attend the final configuration.

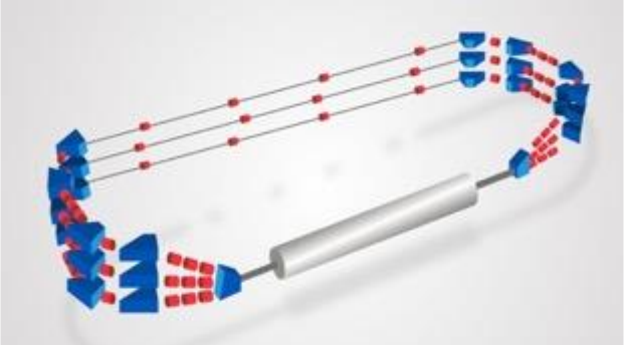
Phase 1: Installation of a single cryomodule in the first straight and three beam lines in the second (consideration motivated by the SPL cryomodule availability)

→ To allow a rather rapid realisation of a 250 MeV machine.

→ To test with beam the various SRF components.

→ To prove the multi-turn ERL operation.

→ to gain essential operation experience.



PERLE Phase 1 layout

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

→ Upgrade of the e- gun

→ Installation of the 2nd Spreader and recombinar

→ Installation of the second cryomodule in the second straight.

PERLE Phase 2 layout

Project staging strategy:

Phase 1 is divided in two sub-stages:

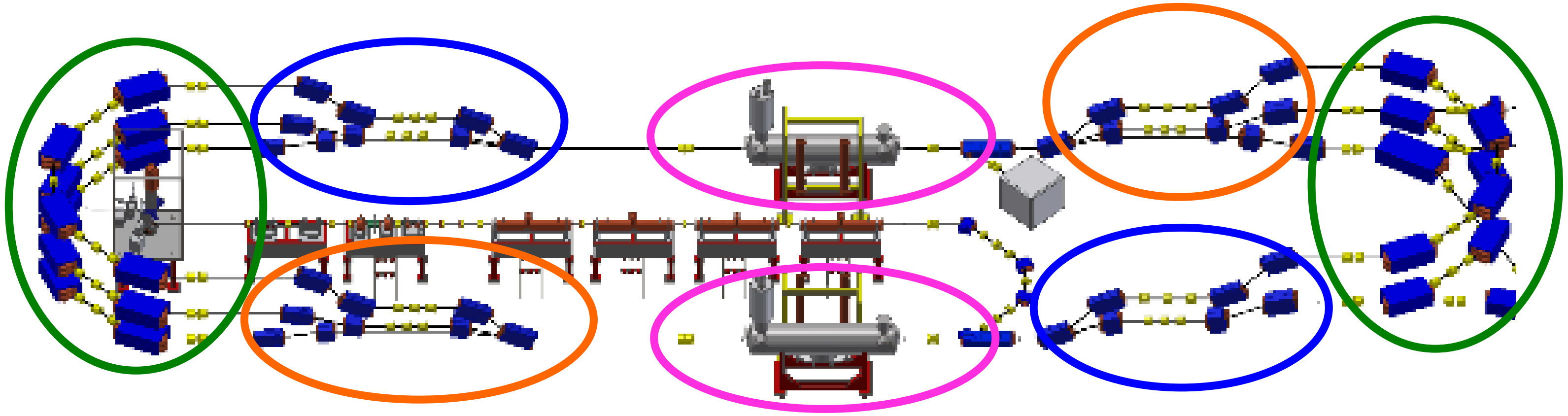
- **Studies and prototyping stage**: Mainly for design completion of the main sub-systems (DC gun, booster, cryomodule, arcs and switchyards optics), the beam dynamics studies and the prototyping of the main components (cavity, power coupler, HOM, dipoles…). All the outcomes will be included in the **PERLE Technical Design Report**.
- **Assembly, test and installation stage**: of all the subsystems according to their final design (injection line most likely without the upgrade of the DC gun, the SPL cryomodule, the 6 arcs, a spreader & a recombiner), leading to PERLE-Phase 1 configuration.

It is foreseen that phase 1 includes also the realisation of infrastructure work and the installation of equipment sized as for their final use (beam dump, cryogenics, cooling circuit, shielding, electrical power, etc.).

PERLE transport optics:

Appropriate recirculation optics are of fundamental concern in a multi-pass machine to preserve beam quality. The design comprises different regions:

- **The Linac optics:** The focusing strength of the quadrupoles along the linac needs to be set to transport co-propagating beams of different energy and to support a large number of passes.
- **The Spreader optics:** The beams need to be directed into the appropriate energy dependent arc. Spreaders separate vertically beams and match optics functions to arcs.
- **The Arc optics:** Disturbing effects on beam space charge such us cumulative emittance and momentum growth have to be counteracted through a pertinent choice of the basic optics cell
- **The Re-combiner optics:** Re-combiners and spreader are mirror symmetric.



Switchyard- Vertical Separation of Arcs (1, 3, 5):

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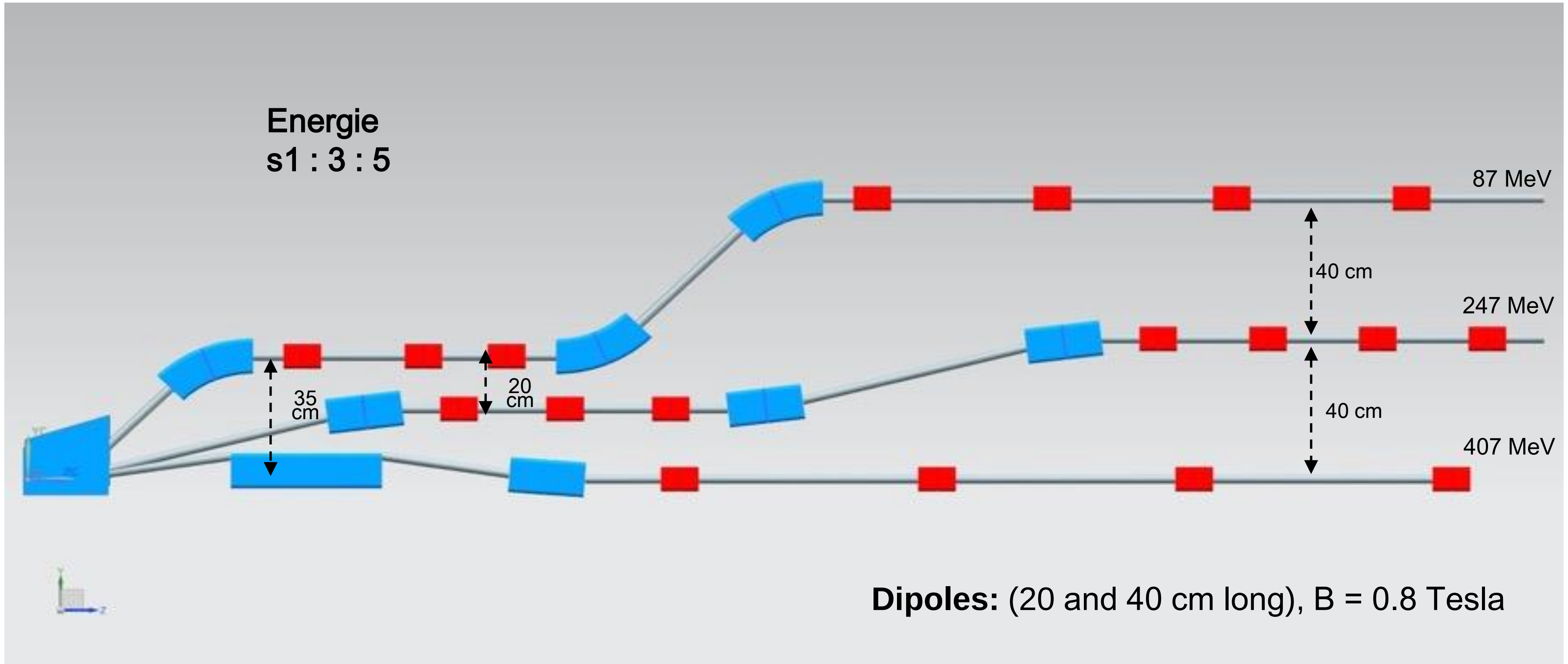

Arc optics, Arc 1 (71 MeV) as example:

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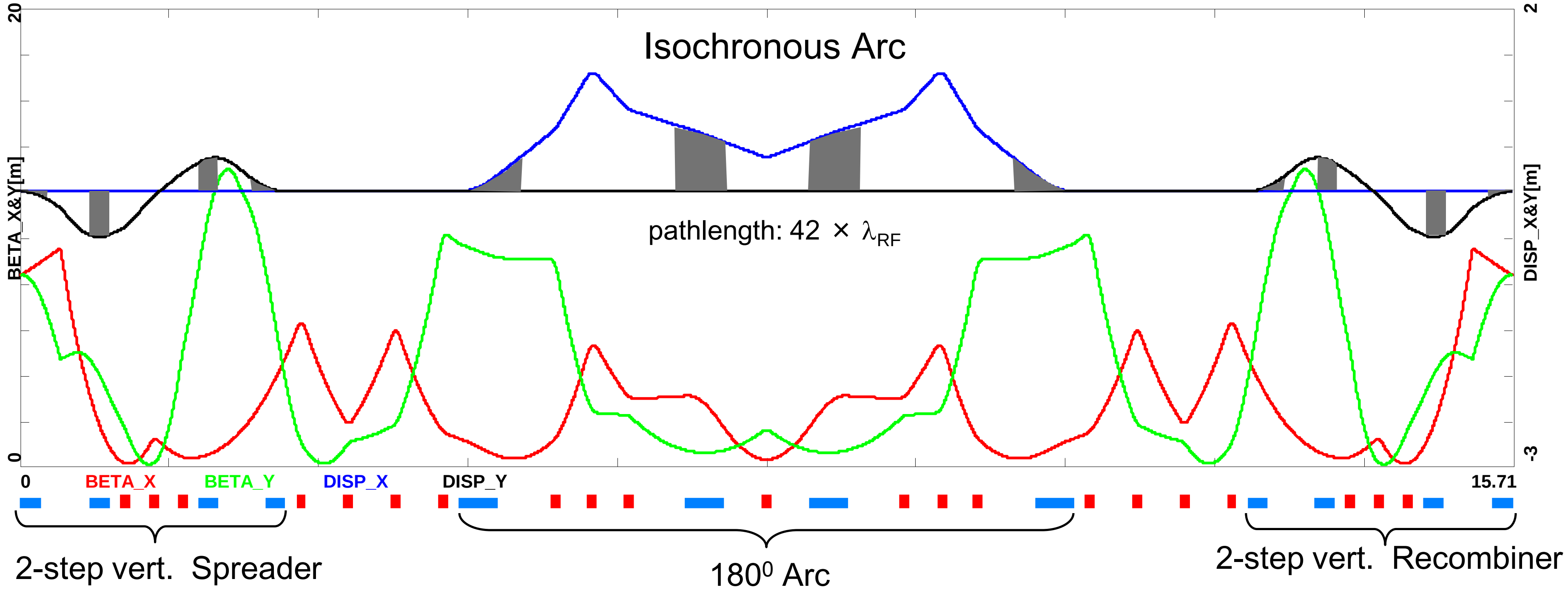

Spr. dipoles:

4× 45⁰ bends

L = 20 cm

B = 9.5 kGauss

Arc dipoles :

4×45⁰ bends

L = 45.6 cm

B = 4.5 kGauss

Rec. dipoles:

4× 45⁰ bends

L = 20 cm

B = 9.5 kGauss

quads: L = 10 cm G ≤ 1 kGauss/cm

1 pass up + 1 pass down optics:

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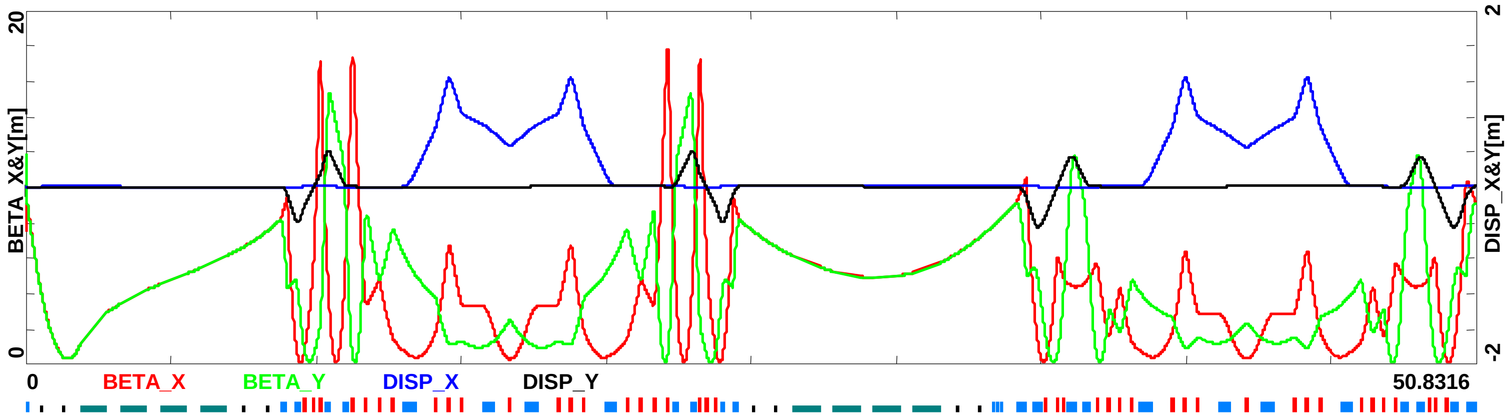
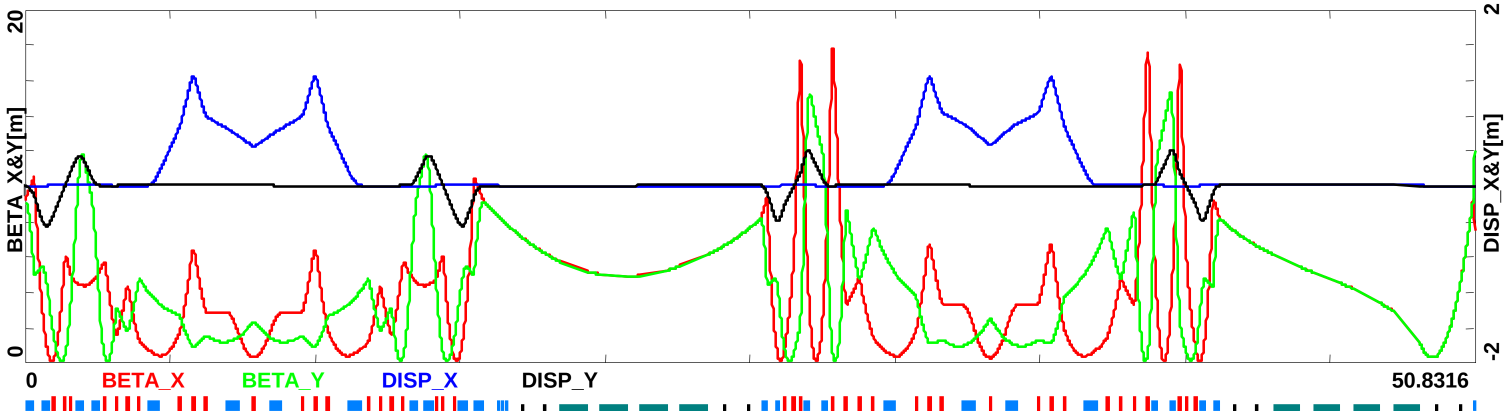
Pass-1 'up'



7 MeV 87 MeV 167 MeV

Pass-1 'down'



167 MeV 87 MeV 7 MeV

Bunch recombination pattern:

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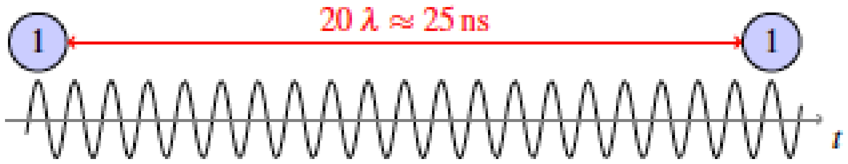
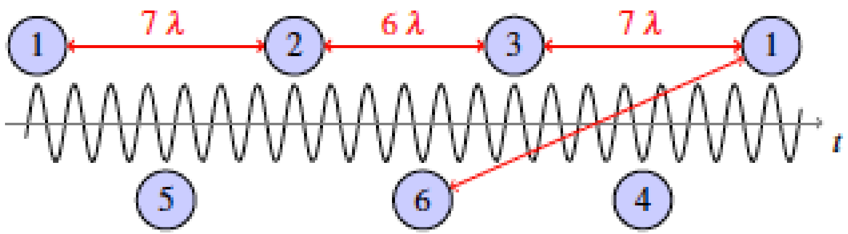
- Basic RF structure, without recirculation: Bunches are injected every 25 ns



- When recirculation occurs → bunches at different turns in the linacs:
  - Ovoid bunches in the same bucket
  - Recombination pattern adjusted by tuning returned arcs length of the required integer of λ

Turn number	Total pathlength
1	$n \times 20\lambda + 7\lambda$
2	$n \times 20\lambda + 6\lambda$
3	$n \times 20\lambda + 3.5\lambda$



- Maximize the distance between the lowest energy bunches (1 & 6): ovoid reducing the BBU threshold current due to the influence of HOMs kicks
- Achieve a nearly constant bunch spacing: minimize collective effects

Cost-effective magnet solution:

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PERLE

- Iron-dominated resistive magnets preferred for improving tunability
- Magnet aperture of +/- 20 mm
- Current density of 7-8 A/mm2
- H design to reduce the magnet height for stacking
- Homogeneous field as low as possible due to the use of one power supply by arc
- Cost minimization with a design of the arc magnets coupled to studies of the power converters, the vacuum system and cooling as well as only one magnet per bend with a 45° deflection

Arc	Energy [MeV]	Count	angle [deg]	B [T]	L [mm]	Curv. radius [mm]	Pole gap [mm]	GFR width [mm]	
#1	80	4	45	0.45	456	596	±20	±20	MBA
#2	155	4	45	0.87	456	596	±20	±20	
#3	230	4	45	1.29	456	596	±20	±20	
#4	305	4	45	0.85	912	1191	±20	±20	MBB
#5	380	4	45	1.06	912	1191	±20	±20	
#6	455	4	45	1.27	912	1191	±20	±20	

PERLE magnet design (dipoles and quadrupoles):

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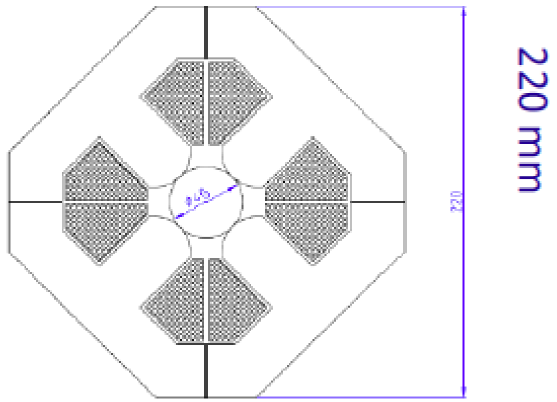
70 dipoles 0.45-1.29 T

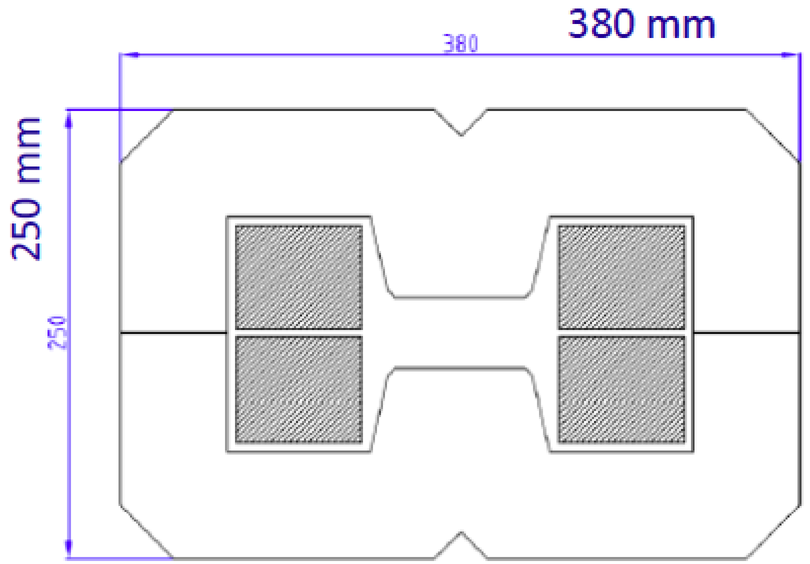
+- 20 mm aperture, l=200,300,400 mm

May be identical for hor+vert bend

7A/mm2 (in grey area) water cooled

DC operated





114 quadrupoles max 28T/m

Common aperture of 40mm all arcs

Two lengths: 100 and 150mm

DC operated

P Thonet, A Milanese (CERN), C Vallerand (LAL), Y Pupkov (BINP)

PERLE magnet design:

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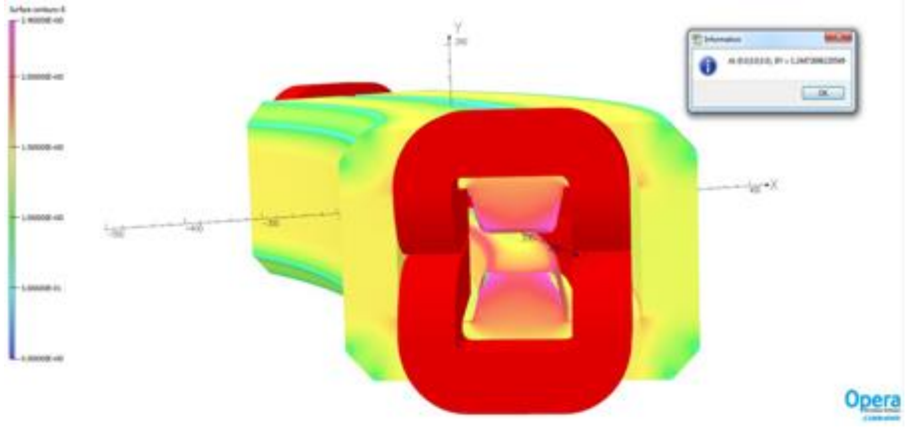
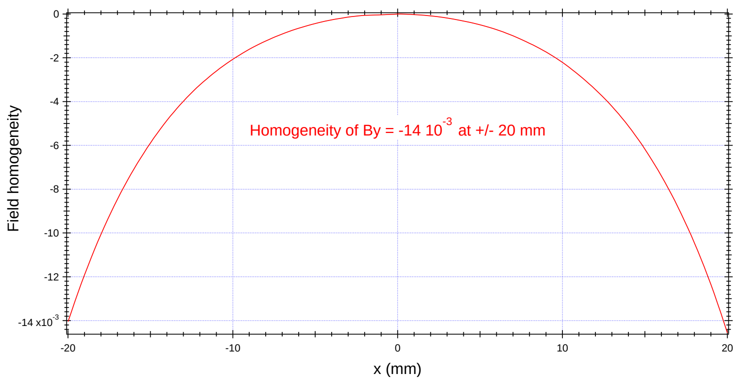
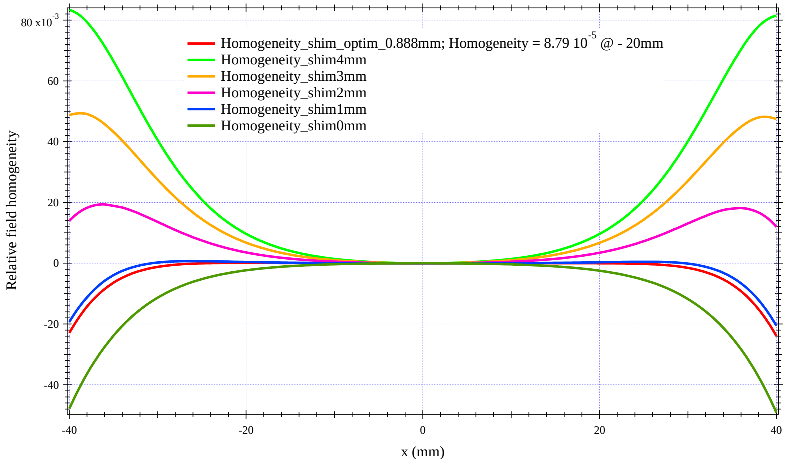
Simulations for magnet design optimization.

→ Main concern: magnet compactness configuration in spreaders and combiners: magnet saturation risk, cross-talk between magnets.





3D Simulation results from 2D design with bedstead coils



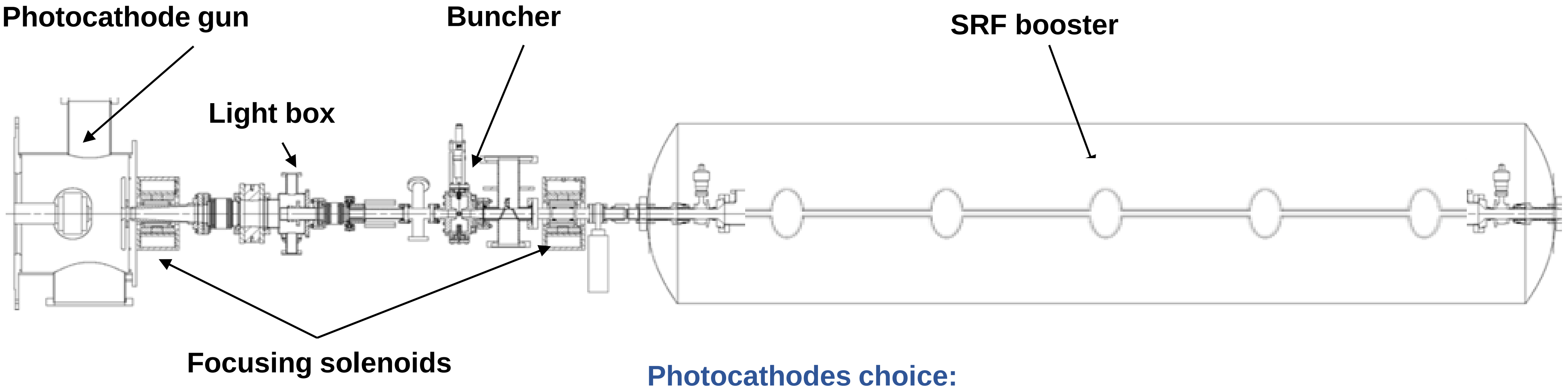
Bending magnets: field homogeneity with optimized shim of 8.8 10^{-5} at ± 20 mm (GFR), better than expected (5 10^{-4}).

Electron source and injector:

LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

The PERLE injector consists of:

- A DC photoemission electron gun (The ALICE DC gun to be upgrated).
- A bunching and focusing section: 401 MHz or 802 MHz normal conducting buncher cavity placed between two solenoid.
- A superconducting booster with five 802 MHz cavities individually feeded 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:

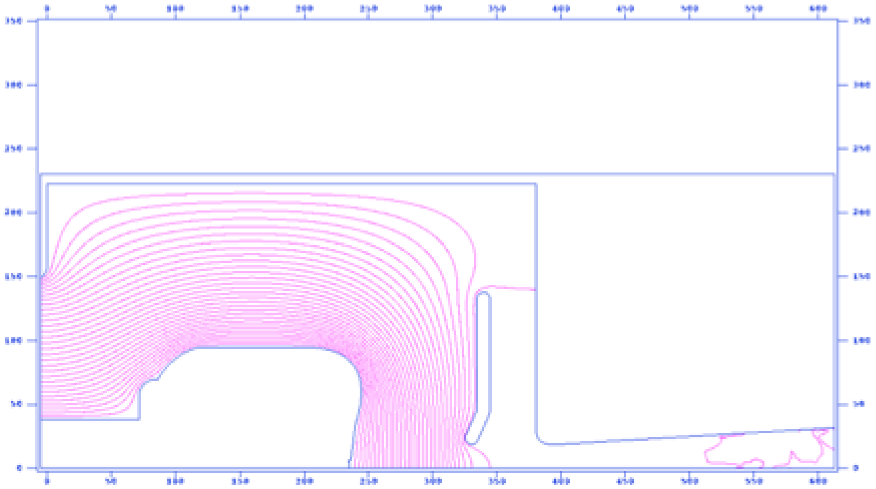
- **Sb-based photocathodes (unpolarized electrons) operated at 350 kV**
- **GaAs photocathodes (polarized electrons) operated at 220 kV**

Electron source and injector:

LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

Studies on ALICE gun upgrade to operate at up to 500 pc (B. Hounsell PhD thesis):

- ✓ Optimisation of the electrode geometry, the laser pulse spatial and temporal profile and the field in the first solenoid to preserve the emittance in the gun and first solenoid section and to reduce transverse beam size in the focusing and bunching section. The electrode geometry optimisation was also performed so that the same electrode shape must be used for both voltages (350 and 220 kV) → Use of a mlti-objective optimisation algorithm NSGAIII.



- ✓ Optimise the buncher frequency (**401 MHz** or 802 MHz) in order to minimise emittance growth.
- ✓ Optimise beam transport from the gun to the main Linac to minimise transverse beam size and compensate emittance.

Electron source and injector:

LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

- **Once the beam's parameters coming from the injector optimized (emittance, momentum spread, halo), we will be able to perform:**
  - A beta matching to the rest of PERLE starting with the first linac.
  - A 'first ' end-to-end simulation: Tracking initial particle distribution, as defined by the injector and using magnet error tolerances would validate beam transport through the entire ERL complex.

- Relatively short lifetimes of the photocathode impose their frequent replacement (on a daily basis for GaAs and weekly for Alkali antimonides) → Need of preparation and transfer chambers for each photocathode material. For GaAs photocathodes an existing design of photocathode preparation facility produced for ALICE could be easily implemented.

Electron source and injector:

LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration



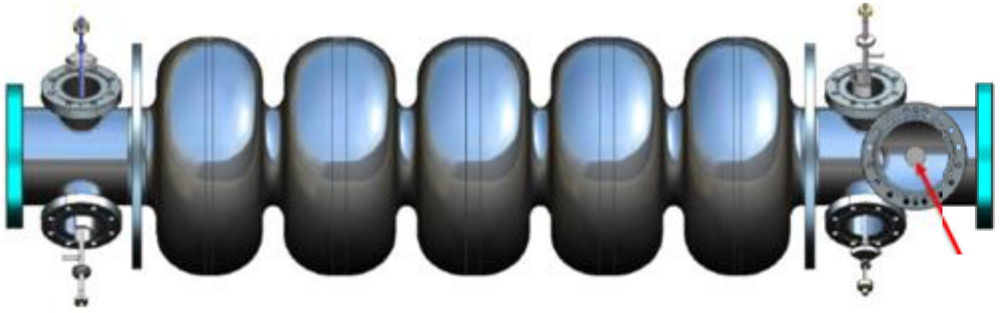
ALICE DC-Gun and equipment transferred from Daresbury to LAL on May 9 & 10, 2019



Main cavity parameters:

LAL/IPNo – CERN - JLAB Collaboration

Parameter	Unit	Value
Frequency	MHz	801.58
Number of cells		5
Iris/tube ID	mm	130
L_{act}	mm	917.9
$R/Q = V_{eff}^2/(\omega \cdot W)$	Ohm	524
G	Ohm	274.7
R/Q·G/cell		143940
$\kappa_{\|\|}$ (2mm rms bunch length)	V/pC	2.74
E_{pk}/E_{acc}		2.26
B_{pk}/E_{acc}	mT/(MV/m)	4.20
k_{cc}	%	3.21



Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration

The first Nb 802 MHz 5-Cell cavity fabricated October 2017 at JLAB

Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration

5-cell cavity successfully electropolished with new flange adapters

Cavity fabrication and test:

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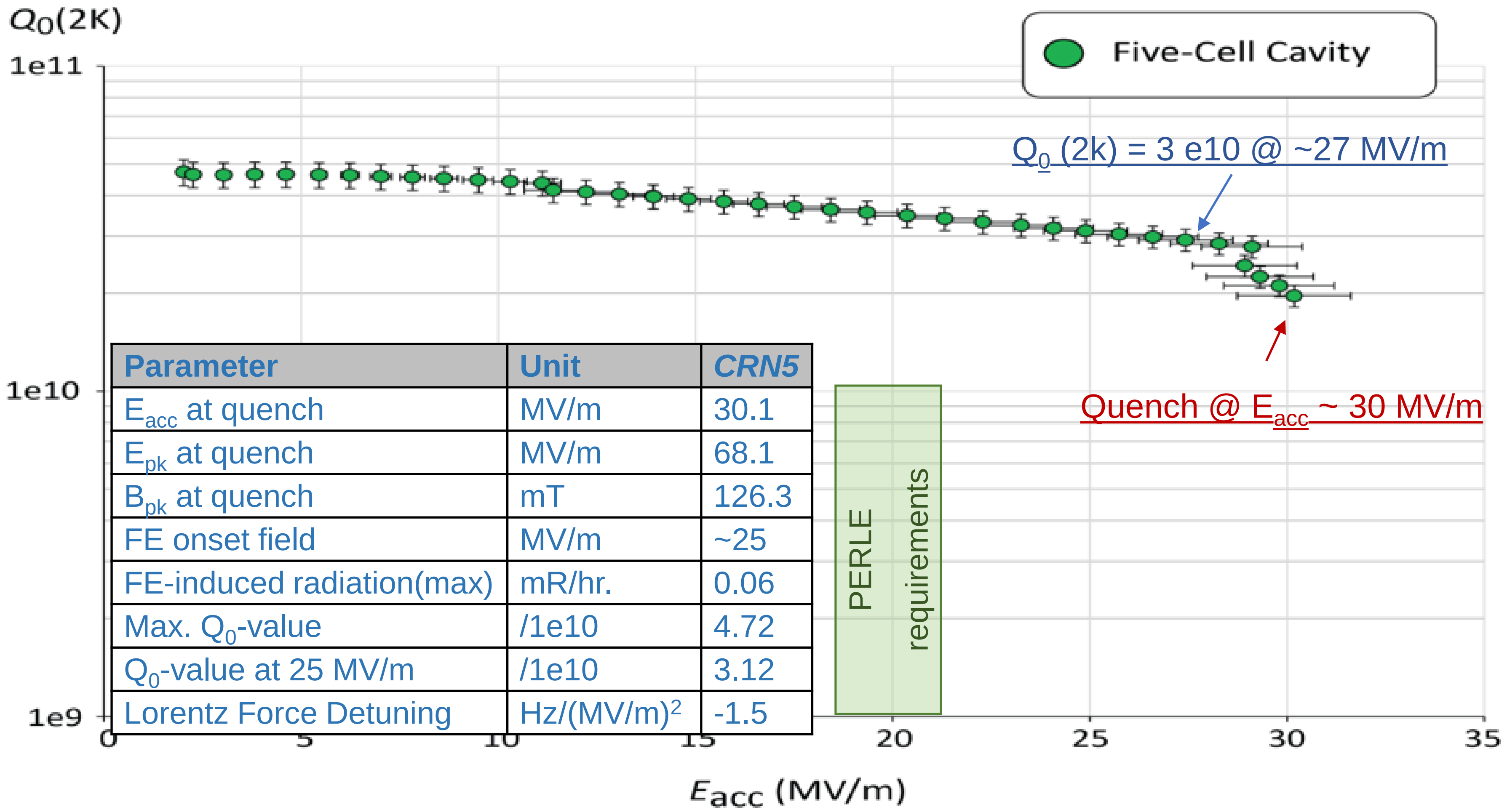


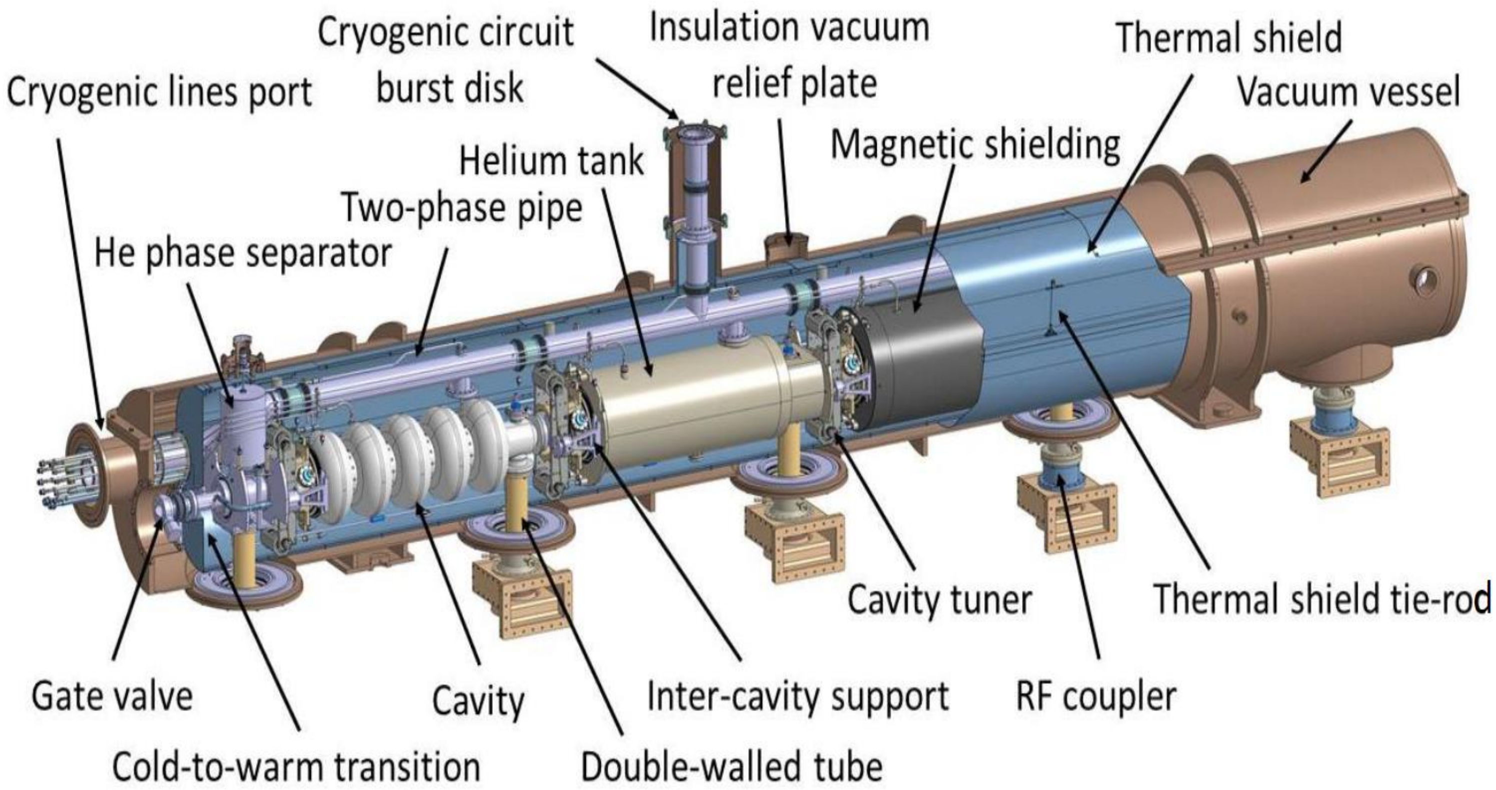
Parameter	**Unit**	***CRN5***
E_{acc} at quench	MV/m	30.1
E_{pk} at quench	MV/m	68.1
B_{pk} at quench	mT	126.3
FE onset field	MV/m	~25
FE-induced radiation(max)	mR/hr.	0.06
Max. Q_0-value	/1e10	4.72
Q_0-value at 25 MV/m	/1e10	3.12
Lorentz Force Detuning	$Hz/(MV/m)^2$	-1.5

For more details: F. Marhauser's talk in the FCC Week, April 2018, Amsterdam, Netherland

Cryomodule design study:

LAL/IPNo – CERN Collaboration

IPN-Orsay & CERN are studying the SPL cryomodule adaptation for PERLE.



SPL cryomodule: designed to integrate 4 elliptical 5-cells 704 MHz cavities

Cryomodule design study:

LAL/IPNo – CERN Collaboration

First results:

- ✓ Thermal and magnetic shielding are well sized for PERLE operation parameters.
- ✓ Input coupler designed for SPL cavity could be easily adapted to meet PERLE requirement
- ✓ Space liberated due to cavity frequency difference give a margin for auxiliaries integration.

Pending issues:

- HOM study to define the design and the number of HOM couplers to be used for PERLE cavities.

→ A review meeting dedicated to HOM couplers will be organized early in September at CERN.

→ Big impact on the decision to adapt the SPL cryomodule for PERLE or not.

A Post-doc is hired to address HOM issue and other related to cavity final design

R&D effort to be done

Important R&D effort still to be done in several fields:

- Linear lattice optimization and Initial magnet specifications
- Correction of nonlinear aberrations (geometric & chromatic) with multipole magnets
- Beam Dynamics (start to end simulation with synchrotron radiation, CSR and micro-bunching, Multi-particle tracking studies of halo formation
- Beam dumps optimization
- RF power source specification
- Cryogenics optimization
- Beam instrumentations
- LLRF
- Control software system
- Shielding and safety system

Thank you for your attention

La jeune fille à la perle- J. Vermeer (1665)