PERLE : A High Power Energy Recovery Facility at Orsay

On behalf of the PERLE Collaboration

Walid KAABI-LAL/CNRS

Introduction to PERLE:

PERLE: A proposed 3 pass 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.

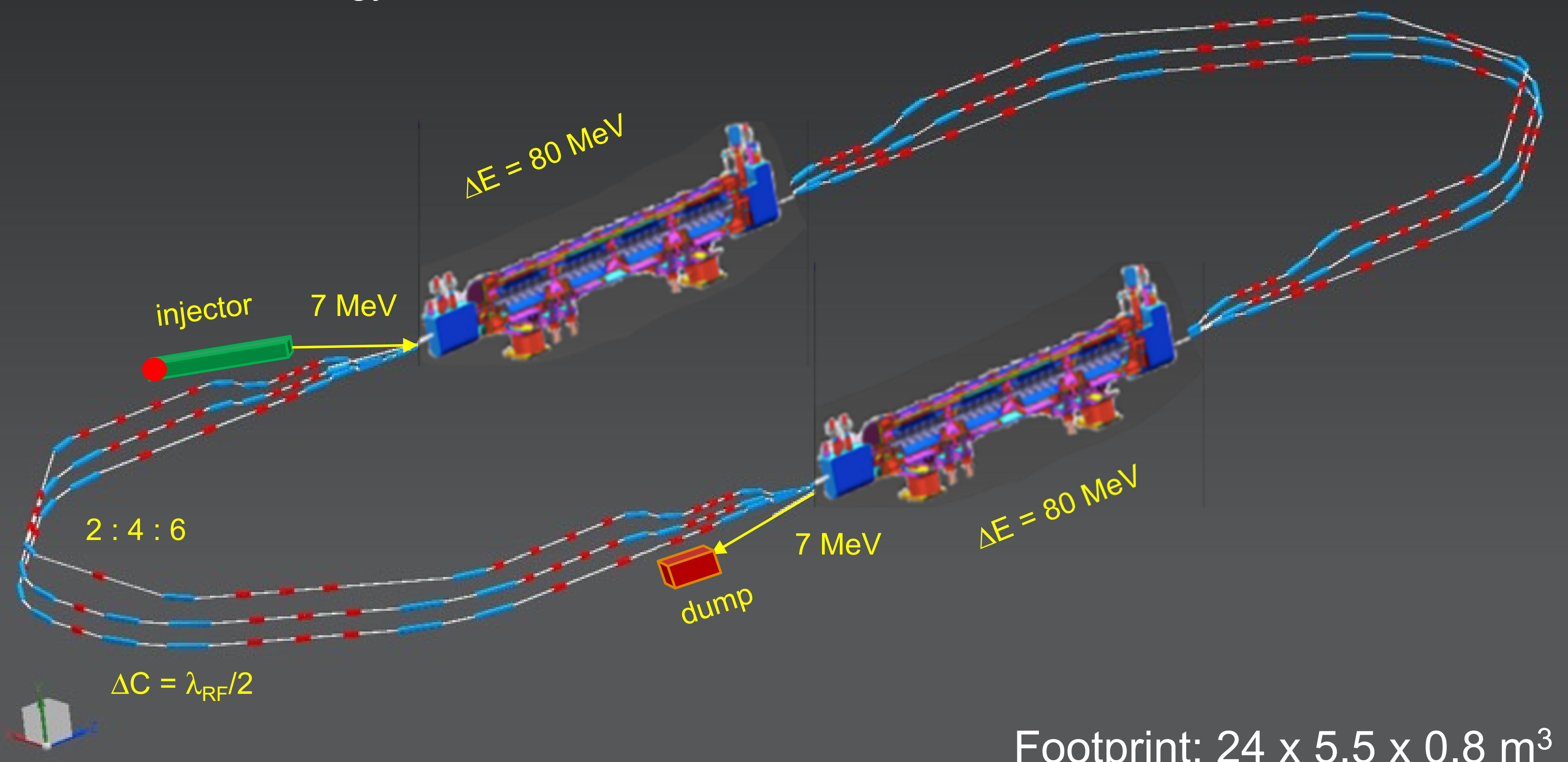
Particularly, design challenges and beam parameters are chosen to enable PERLE as the hub for technology development (especially on SRF) for the Large Hadron Electron Collider (LHeC) [1]:

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

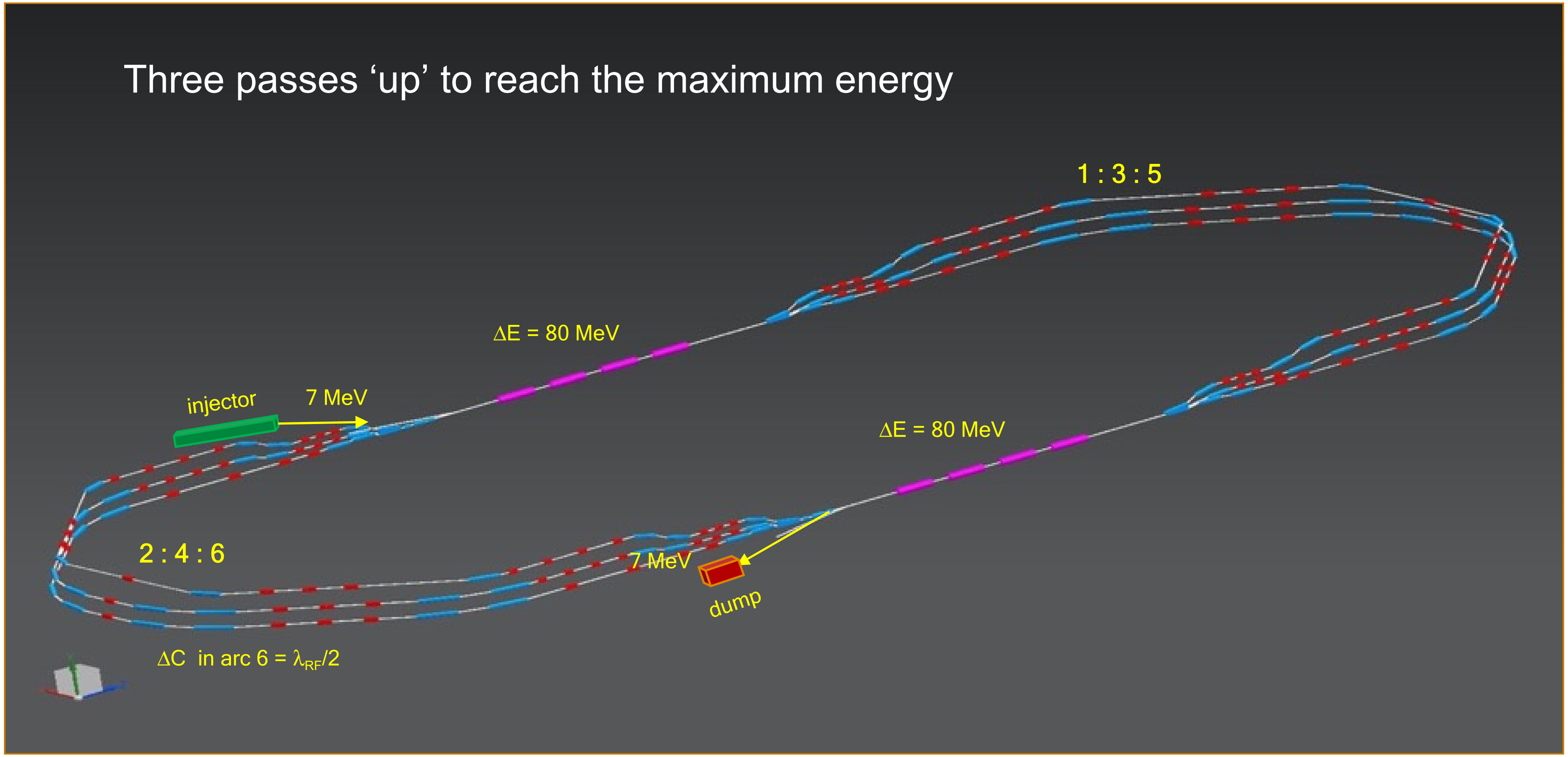
PERLE configuration:

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



Footprint: $24 \times 5.5 \times 0.8\ m^3$

PERLE configuration:



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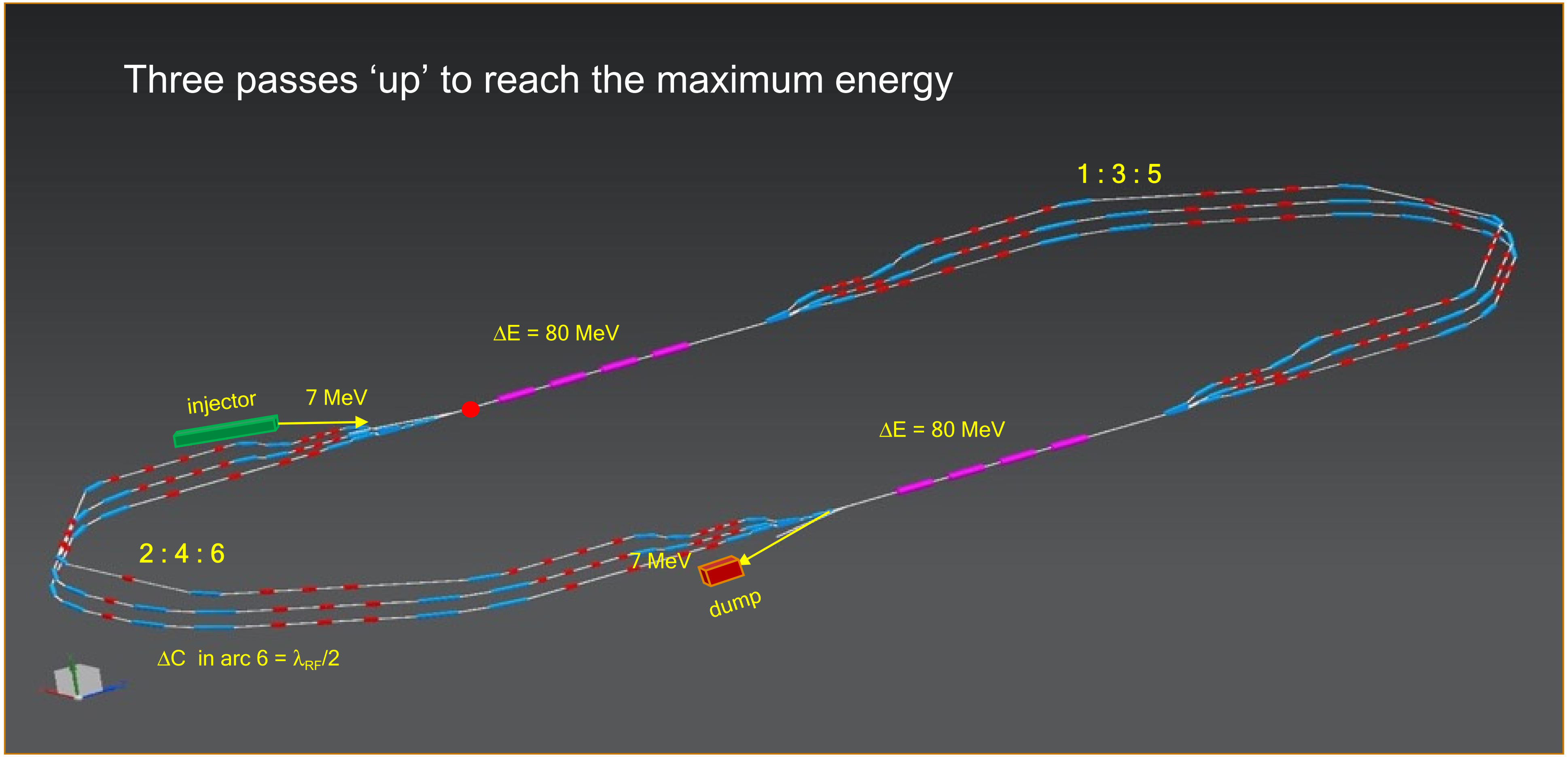

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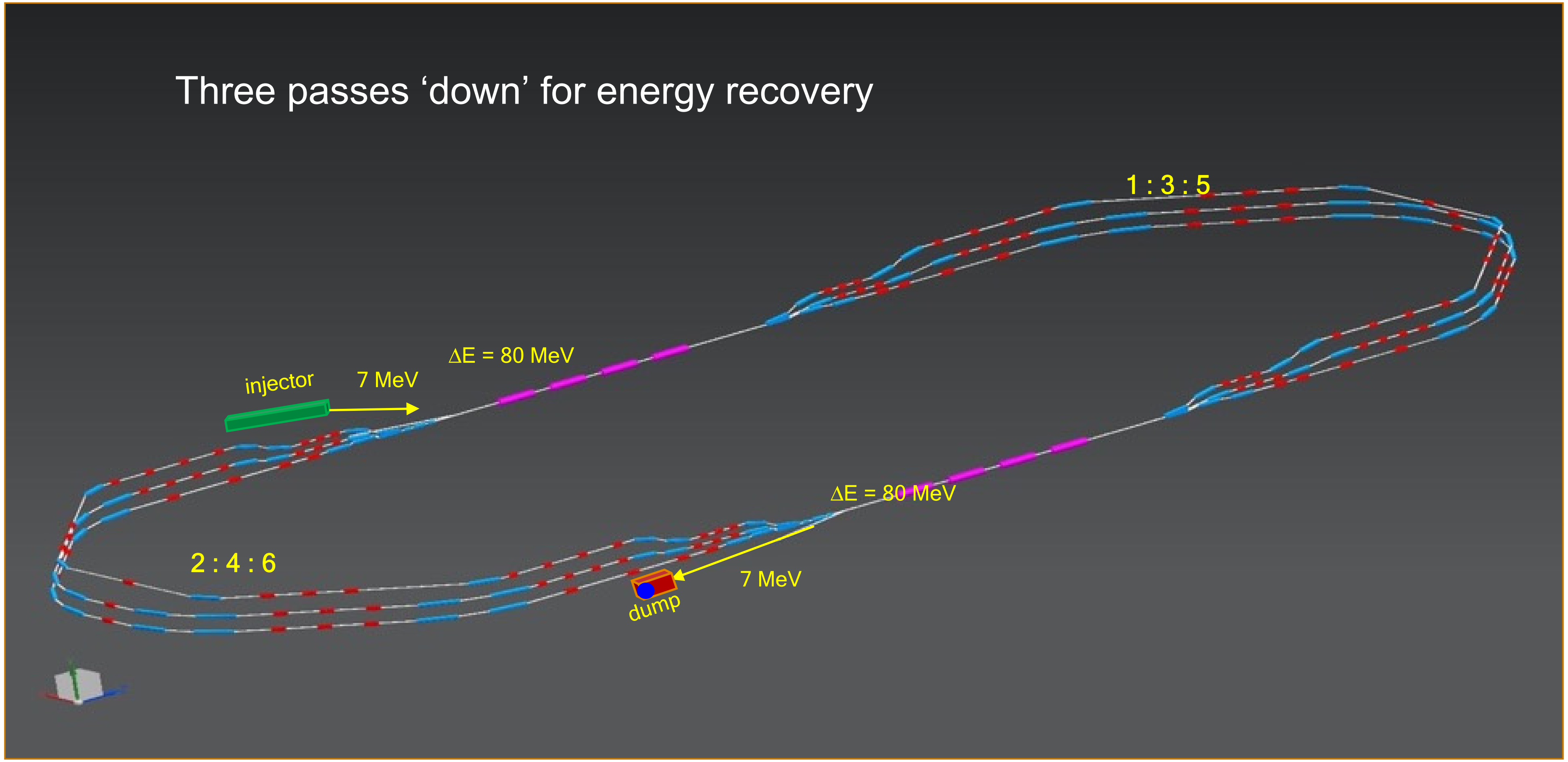
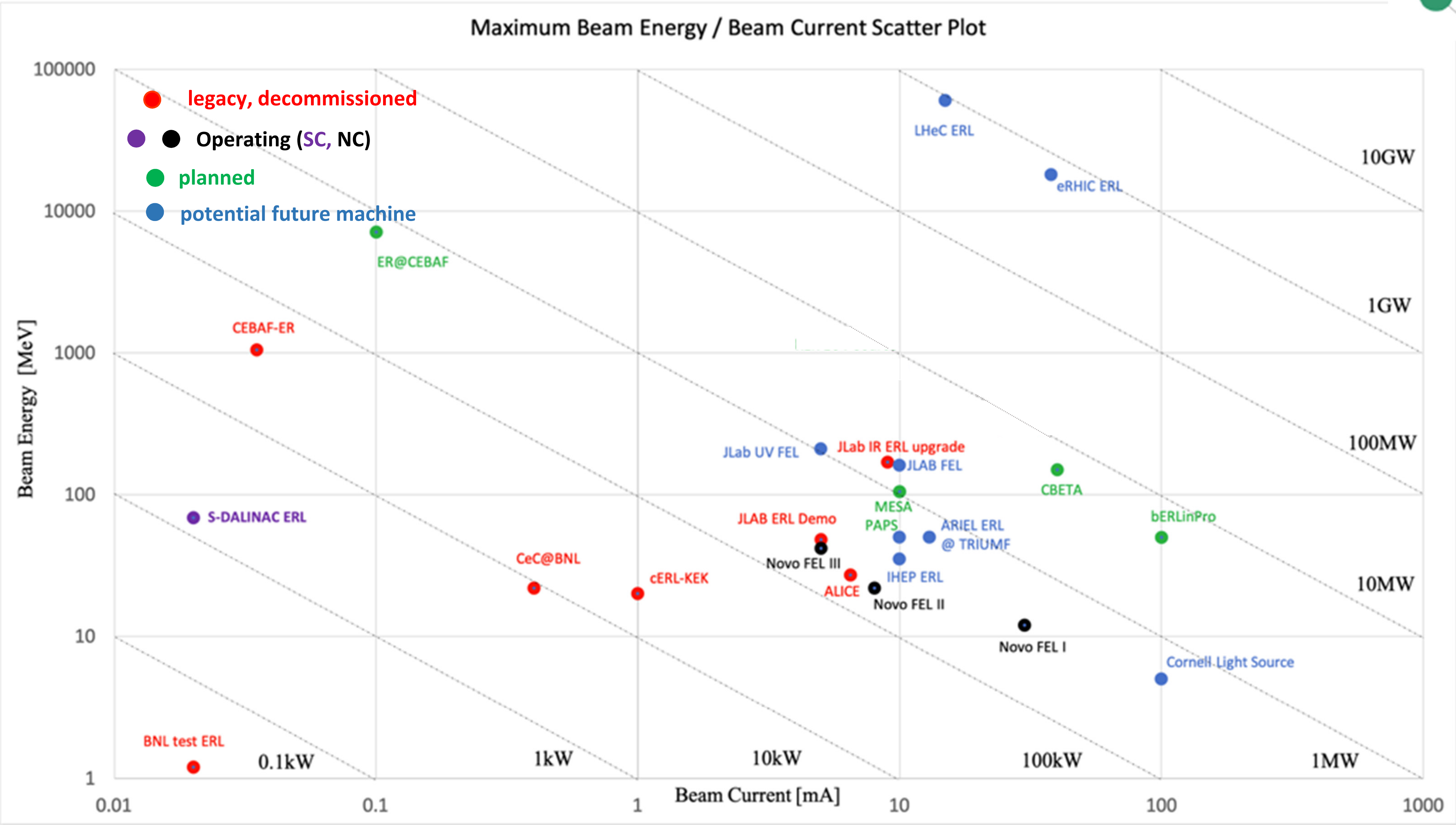


PERLE in the global landscape:



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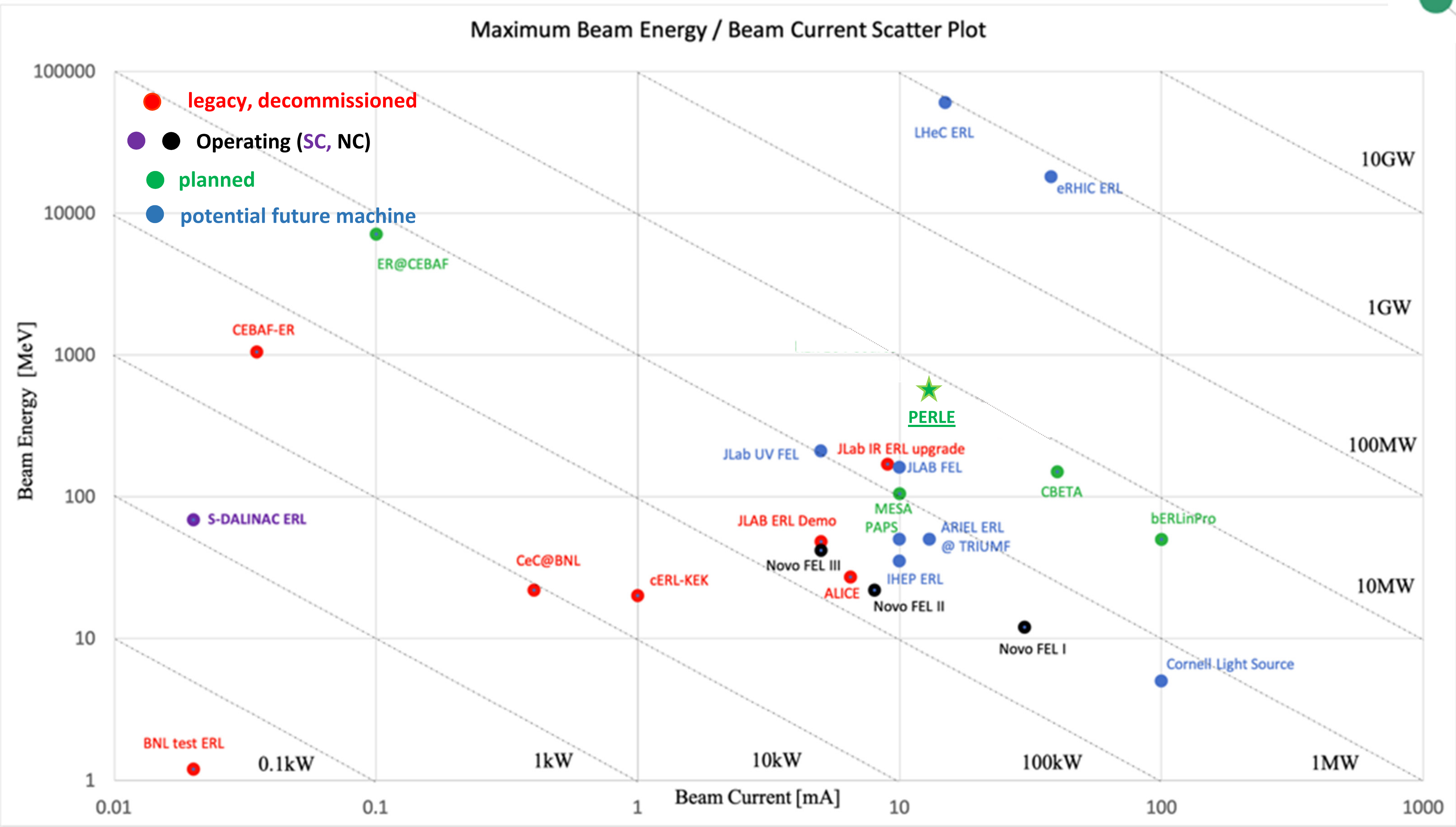
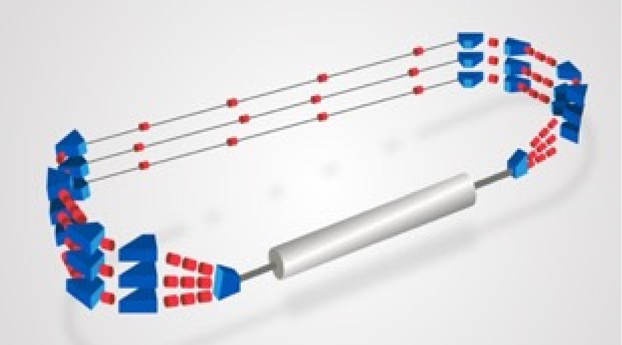


Project staging strategy:

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


PERLE Phase 1 layout

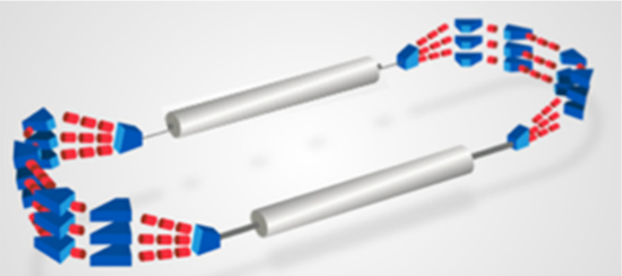
Phase 1: Installation of a single cryomodule in the first straight and three beam lines in the second (consideration motivated by the SPL cryomodule availability)

→ 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 2 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.

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.).

Project staging strategy:

PERLE

Milestones, Timeline & Collaborator Involvement

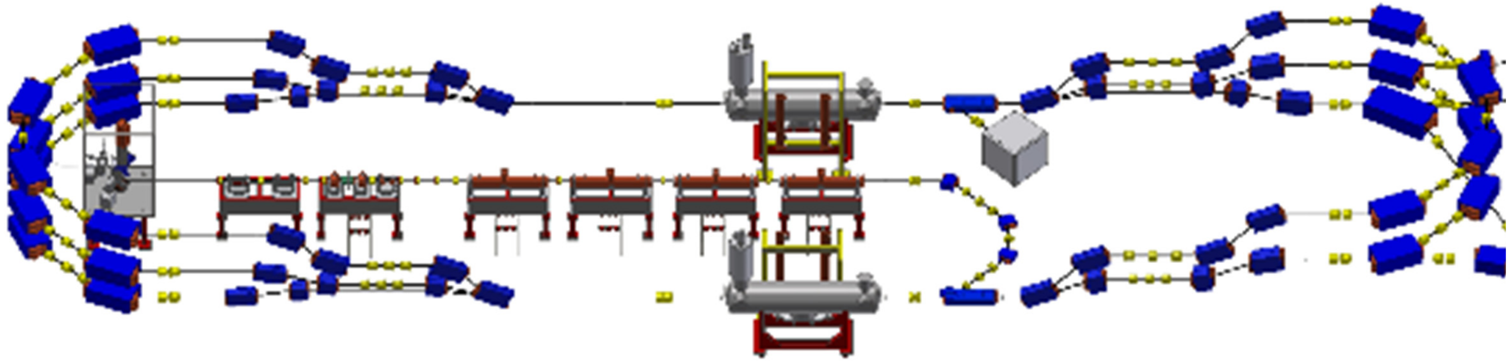
Phase	Stage	Milestone	Targeted date	Collaborator(s) Involvement
Phase 1	Studies & prototyping	Dressed cavity design completion	Oct 2019	CERN-JLAB
		SPL cryomodule design completion	May 2020	CERN
		Injection line design completion	Mid 2020	STFC-Univ. Liverpool
		Final design cavity fabrication and V. test	Mid 2020	JLAB-CERN
		Arc and switchyard dipole prototypes	End 2020	BINP Novosibirsk
		Booster cryomodule design completion	End 2021	-
		Technical Design Report	End 2021	All
	Ass., test & installation	DC gun installation (1)	Early 2021	STFC
		Booster assembly & RF test (2)	Mid 2023	STFC
		Injector installation & commisionning (3)	End 2023	STFC
		SPL cryomodule assembly and RF test (2)	Early 2024	CERN
		Sequential installation at Orsay (4)	End 2024	-
		Phase 1 operation	2025	Open to all

Phase 2

Milestone	Targeted date	Collaborator(s) Involvement
DC gun upgrade	2026	STFC
Second cryomodule completion	2027	CERN
PERLE phase 2 operation	2028	Open to all

PERLE transport optics:

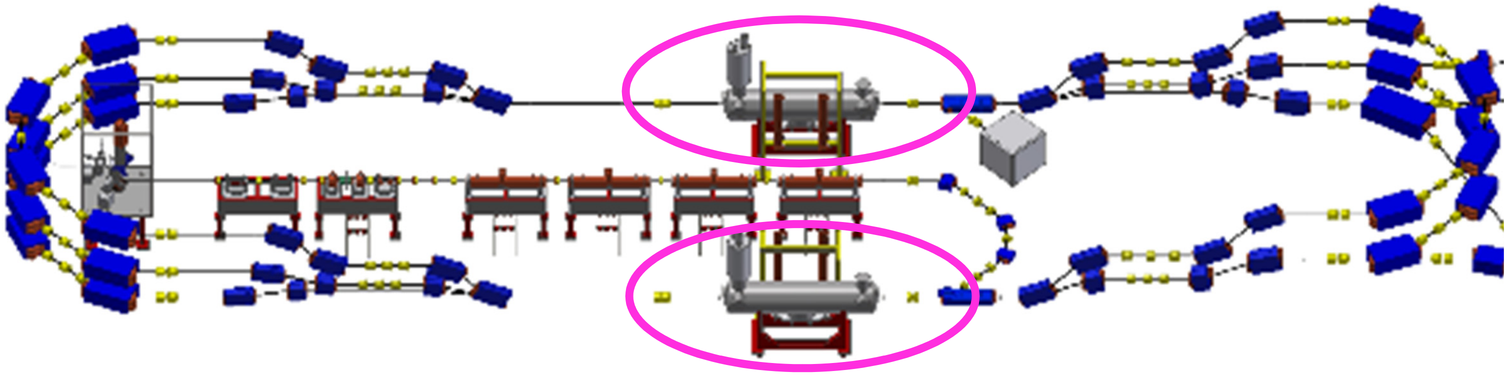
Appropriate recirculation optics are of fundamental concern in a multi-pass machine to preserve beam quality.
The design comprises different regions:



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.



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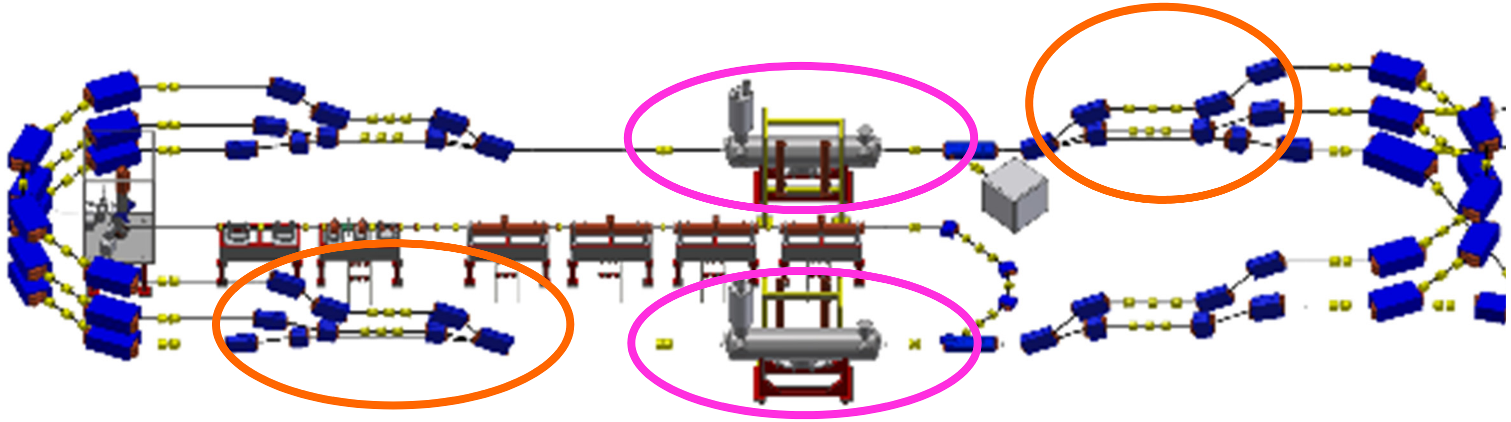

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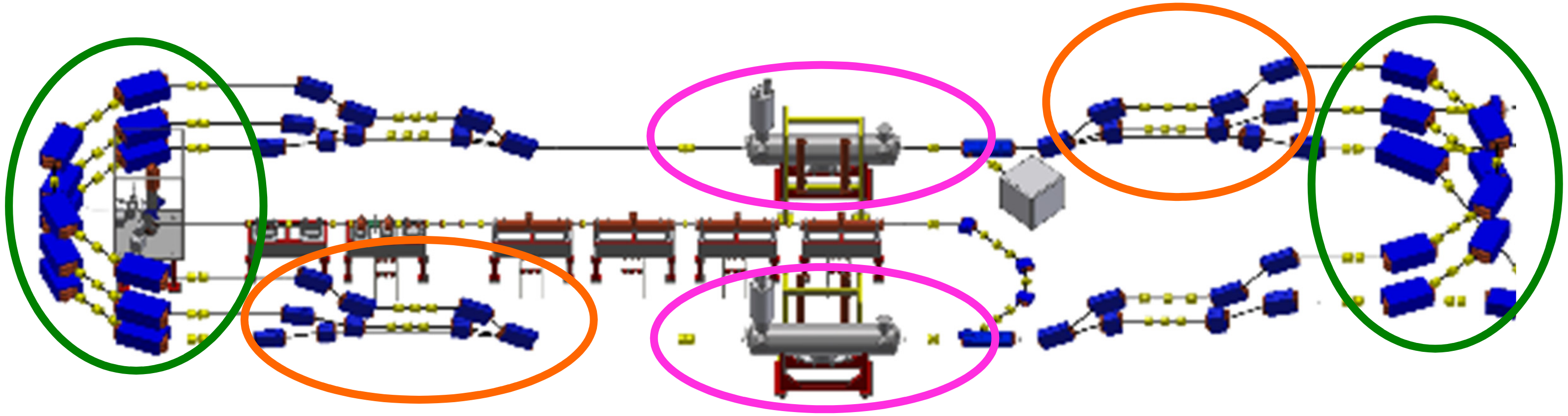

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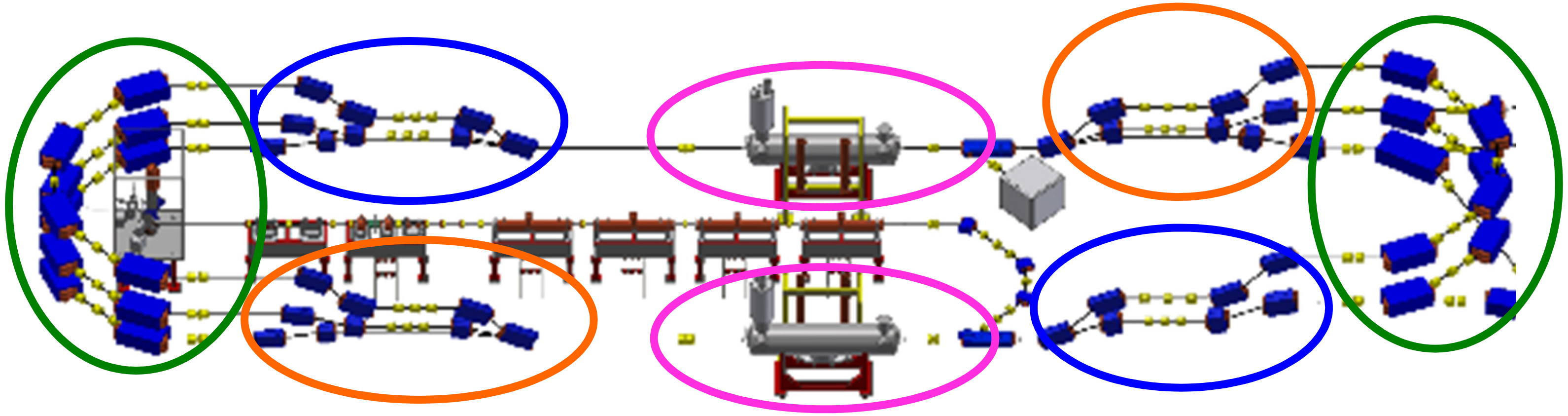
- **The Re-combiner optics:** Re-combiners and spreader are mirror symmetric.

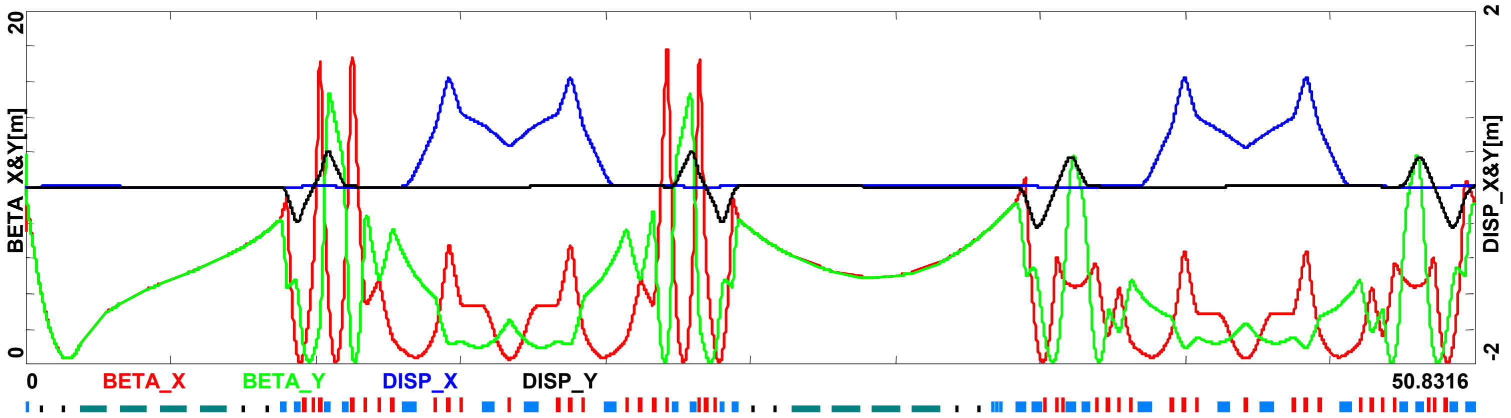


1 pass up + 1 pass down optics:

LAL/IPNo – JLAB Collaboration

Courtesy to Alex Bogacz

Pass-1 ‘up’



7 MeV 87 MeV 167 MeV

1 pass up + 1 pass down optics:

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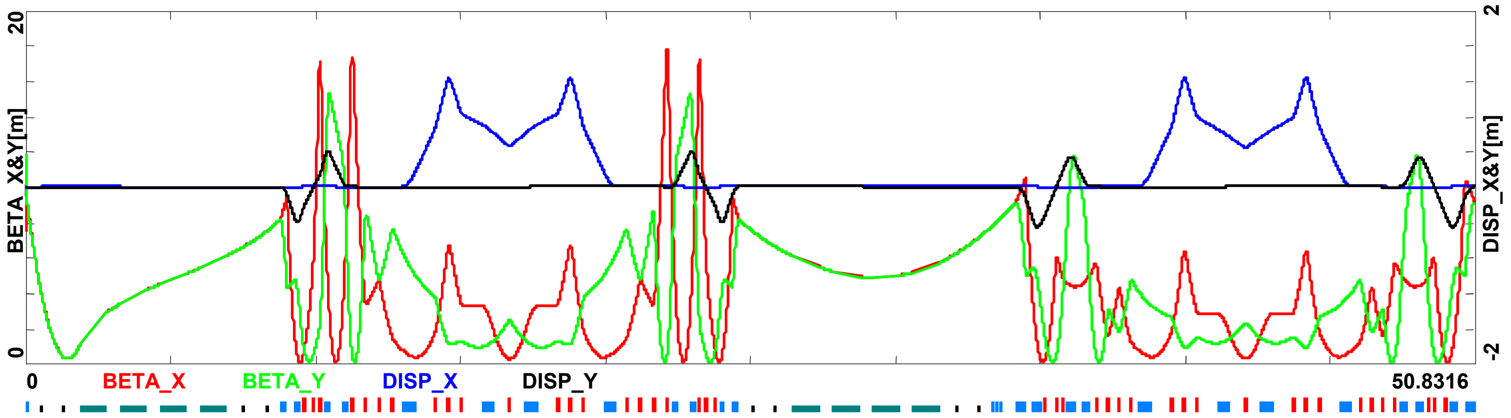
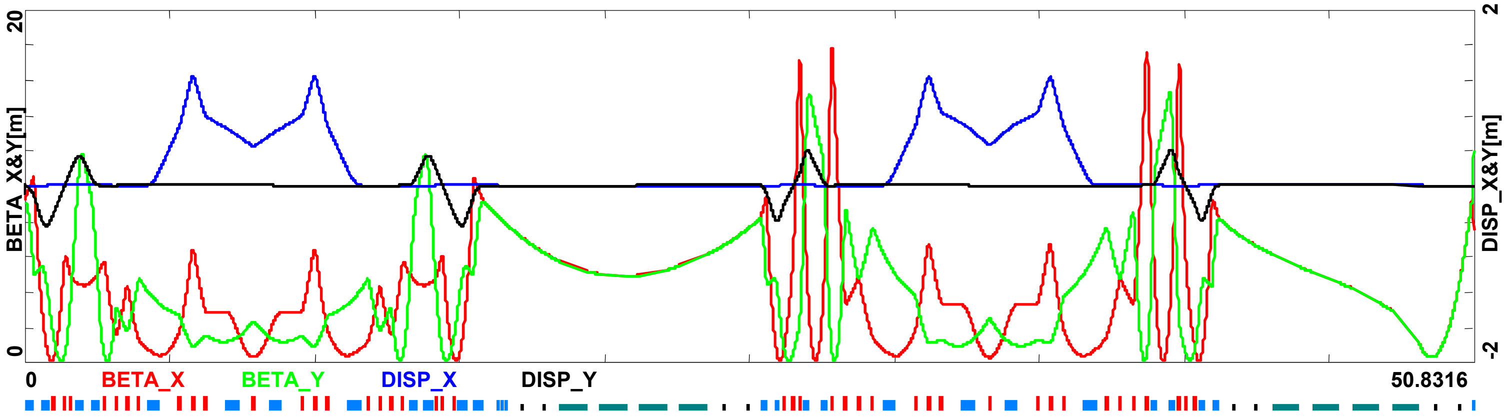
Pass-1 'up'



7 MeV 87 MeV 167 MeV

Pass-1 'down'

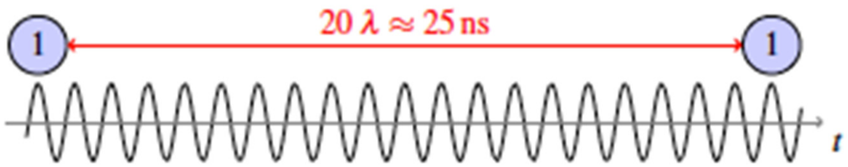


167 MeV 87 MeV 7 MeV

Bunch recombination pattern:

LAL/IPNo – JLAB Collaboration

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



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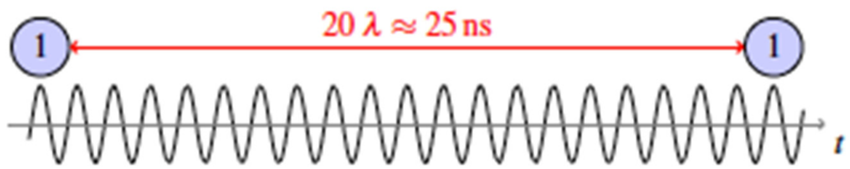

- When recirculation occurs → bunches at different turns in the linacs:
  - Ovoid bunches in the same bucket
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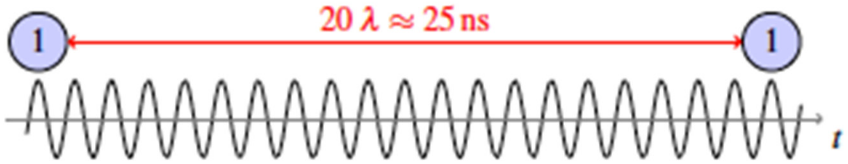

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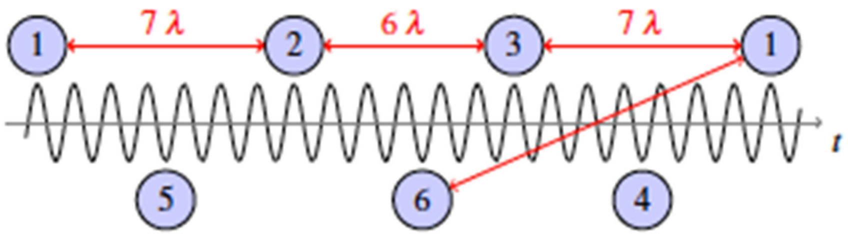
Turn number	Total pathlength
1	$n \times 20\lambda + 7\lambda$
2	$n \times 20\lambda + 6\lambda$
3	$n \times 20\lambda + 3.5\lambda$



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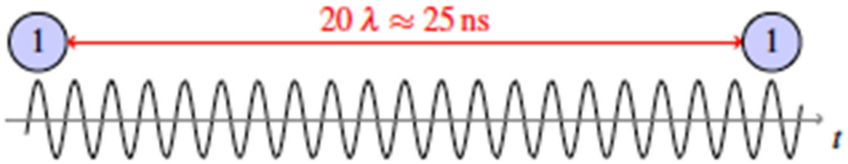

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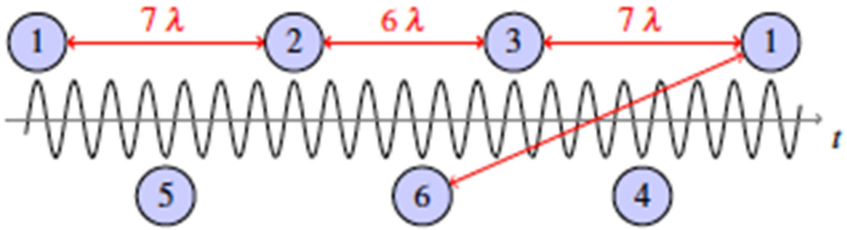


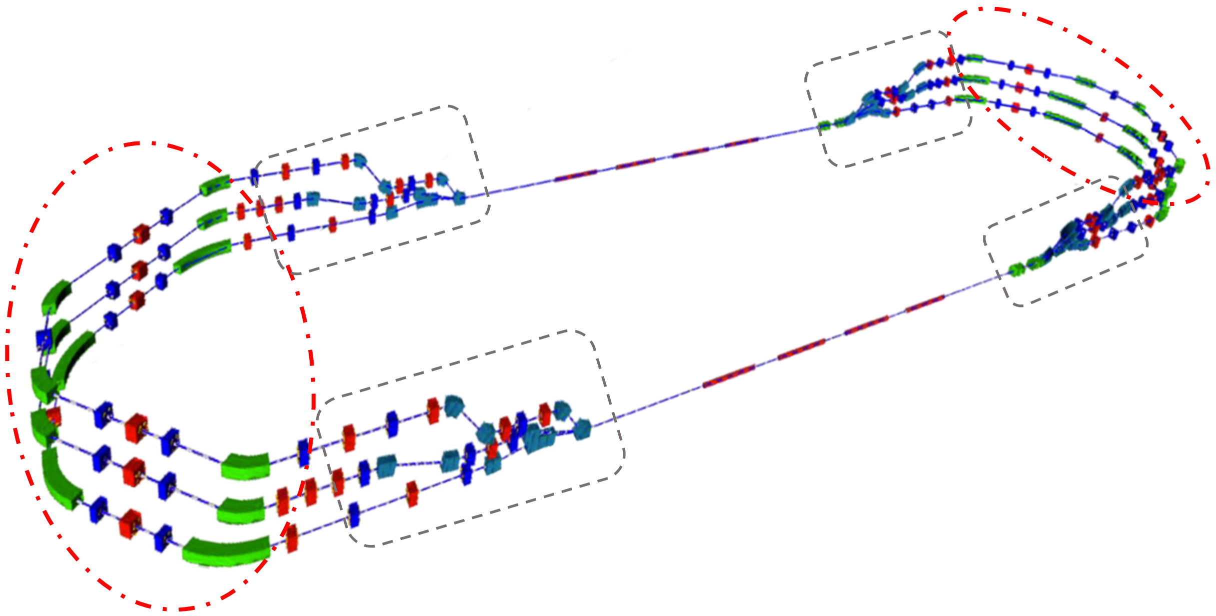
- ➢ Maximize the distance between the lowest energy bunches (1 & 6): ovoid reducing the BBU threshold current due to the influence of HOMs kicks
- ➢ Achieve a nearly constant bunch spacing: minimize collective effects

PERLE magnets design: Magnet inventory

LAL/IPNo – CERN - BINP Collaboration

Courtesy to Cynthia Vallerand

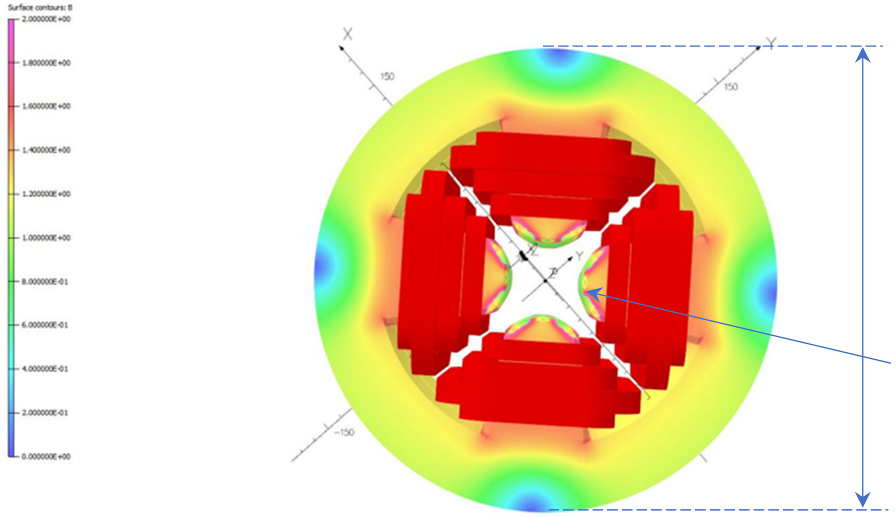
- 6 recirculation arcs, for different beam energies: 87, 167, 247, 327, 407 and 487 MeV.
- Each arc contains 4 dipoles, powered in series within the arc .
- 114 quadrupoles, powered individually
- Number of sextupoles, correctors included and octupoles to be defined
- 46 spreader/combiner dipoles, powered individually



PERLE magnets design: Quadrupoles

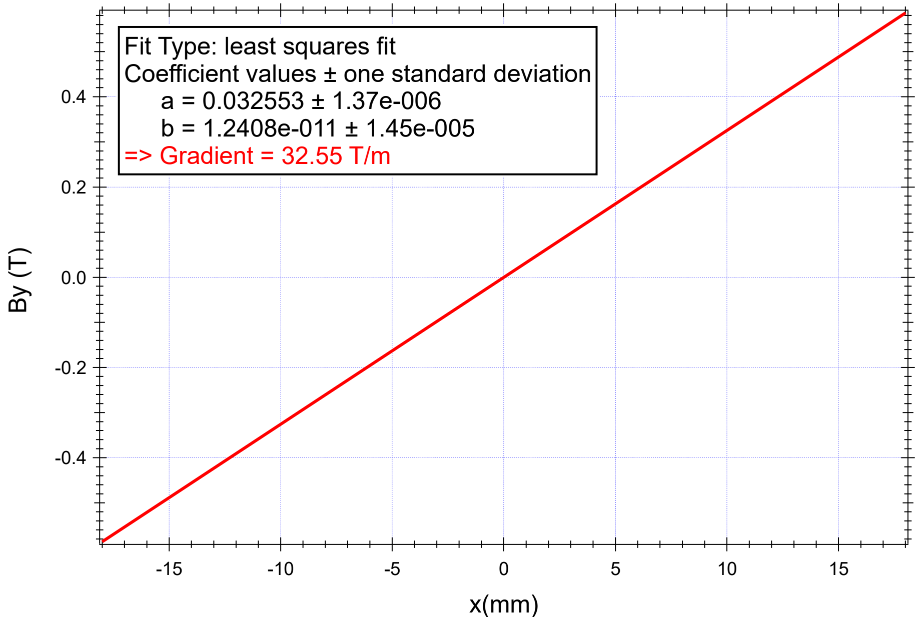
LAL/IPNo – CERN - BINP Collaboration

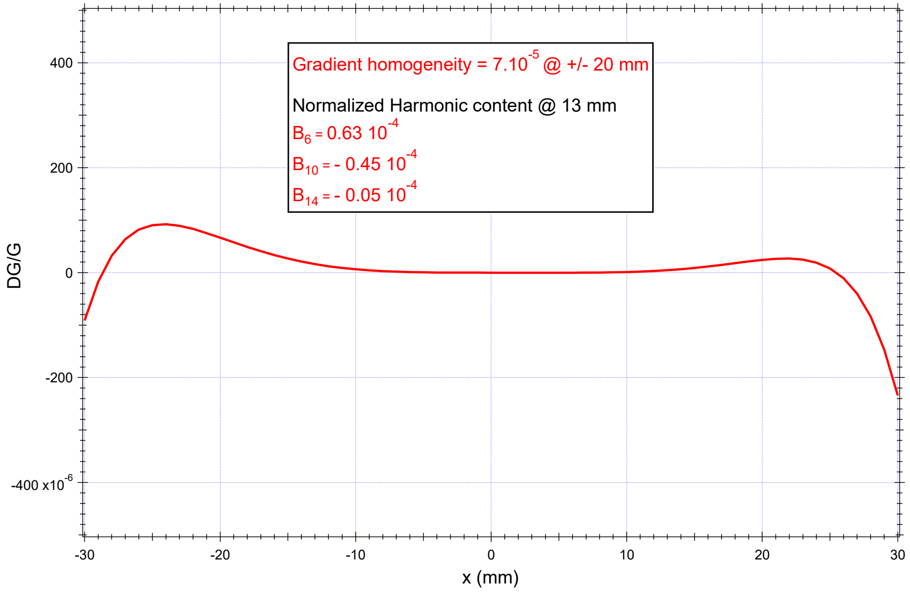
Features of quadrupoles magnets	
Quantity	114 + 1 (pre-serie)
Magnetic length	100 - 200 mm
Main gradient G_0	30T/m
Gap	40 mm
Good field region	+/- 20mm
Beam energy	From 50 to 400 MeV



Diameter increase to 250 mm (220 mm initially)

Chamfer optimization: 2.46 mm depth





	Harmonic @ 13 mm
B6/b2	$0.63\ 10^{-4}$
B10/b2	$-0.45\ 10^{-4}$
B14/b2	$-0.05\ 10^{-4}$
B18/b2	$-0.003\ 10^{-4}$

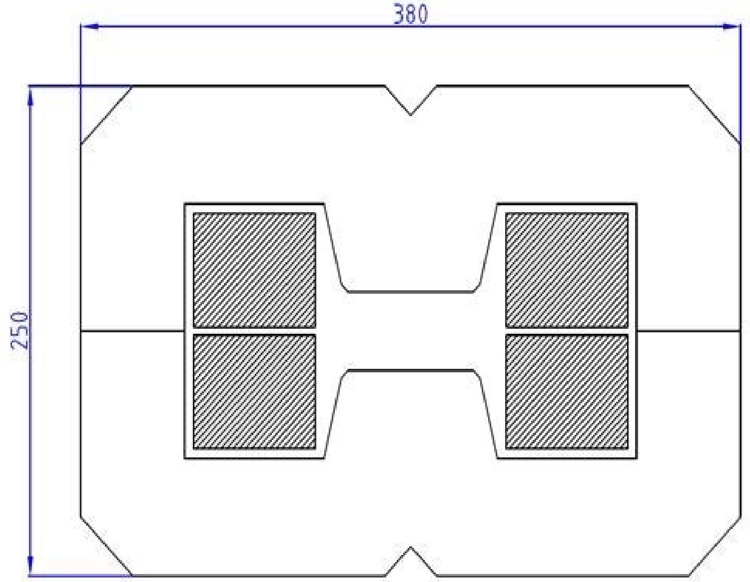
PERLE magnets design: Arc bending magnets

LAL/IPNo – CERN - BINP Collaboration

- Iron-dominated resistive magnets preferred for improving tunability
- Engineering current density of 7-8 A/mm^2
- H design to reduce the height of magnet for stacking
- Homogeneous field as low as possible due to the use of one power supply by arc
- Cost optimization by coupling the design of arc magnets to studies of power converters, vacuum system and cooling as well as using one magnet per bend with a 45° deflection

Features of arc bending magnets

Quantity	12 + 1 (pre-serie)	12 + 1 (pre-serie)
Rotation angle	45°	45°
Radius of curvature	1192 mm	596 mm
Main field B_0	1.25 - 1.3 T	1.25 - 1.3 T
Gap	40 mm	40 mm
Good field region	+/- 20mm	+/- 20mm
Mechanical length	936 mm	468 mm
Current max.	Not defined	Not defined
Beam energy	305 to 455 MeV	80 MeV to 230 MeV

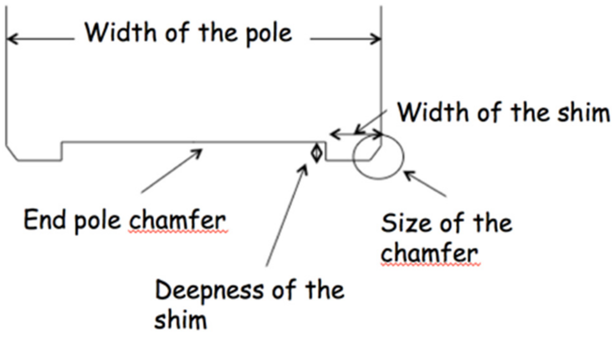


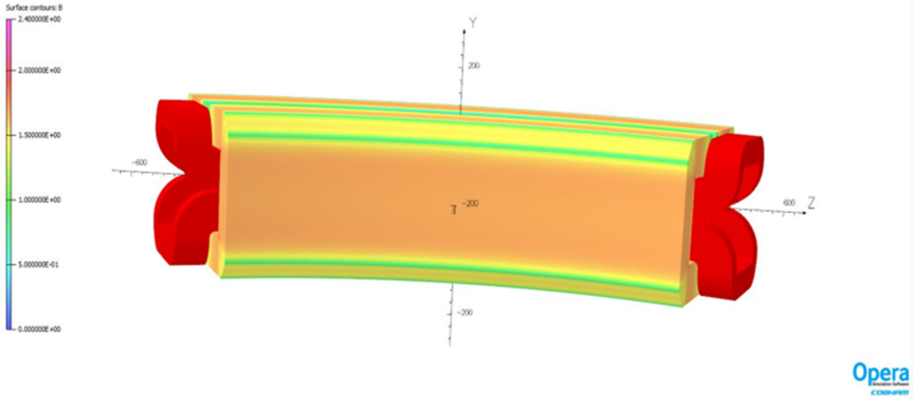
Challenge to highlight : Very compact bending magnet while keeping a reasonable current density for 6 arcs and using the same structure for Arc 1 up to 3 and for Arc 4 up to 6.

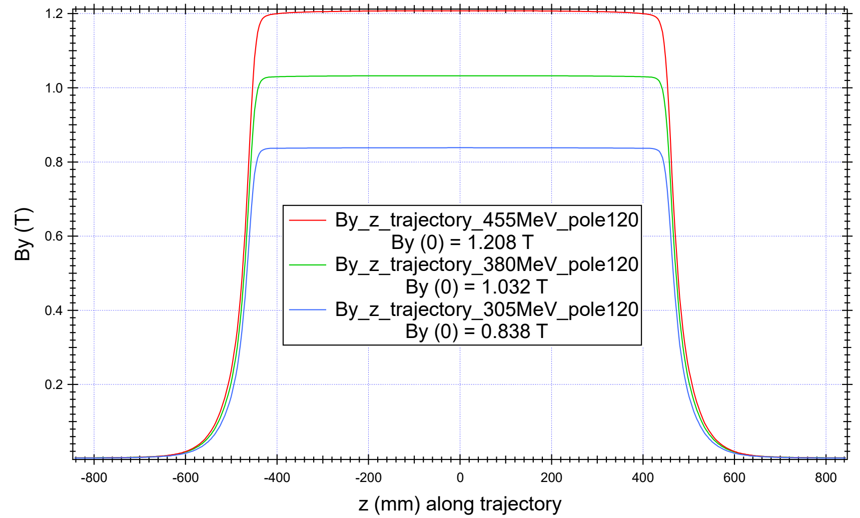
PERLE magnets design: Arc bending magnets

LAL/IPNo – CERN - BINP Collaboration

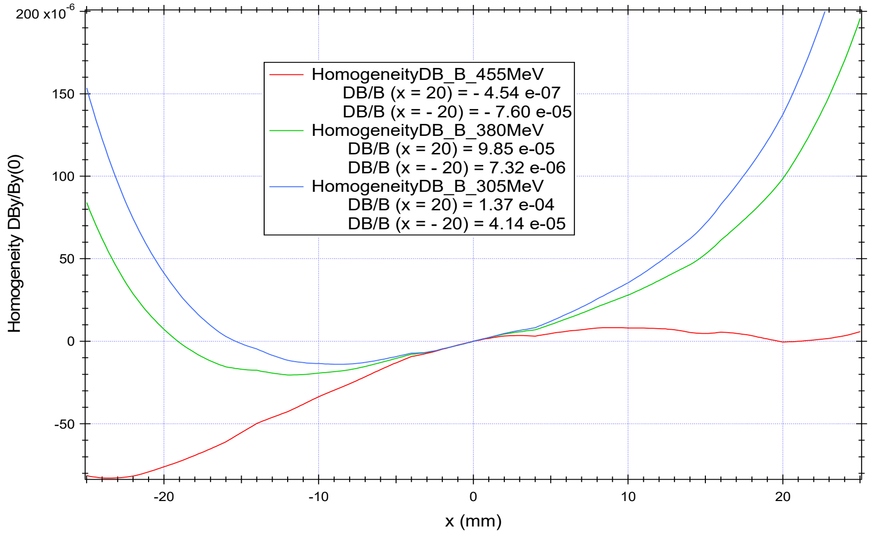
- Parameters for dipole design optimization:







Depth shim (mm)	Homogeneity ($*10^{-4}$) with a pole width 90 mm			Homogeneity ($*10^{-4}$) with a Pole width 105 mm			Homogeneity($*10^{-4}$) with a pole width 120 mm		
	305 MeV	380 MeV	455 Mev	305 MeV	380 MeV	455 Mev	305 MeV	380 MeV	455 Mev
1	9.2	6.5	-2.5	3.5	2.5	-8	1.4	1	0
2	45	40.5	26	15	13	9	5	4.4	3
3	86	78	53	28	26	18	9	8	6



Shim is optimized for 3 energies to get a field homogeneity lower than $5. 10^{-4}$
Magnetic design is finished for the arc bending magnet R1192 mm

PERLE magnets design : Spreader/Recombiner dipoles

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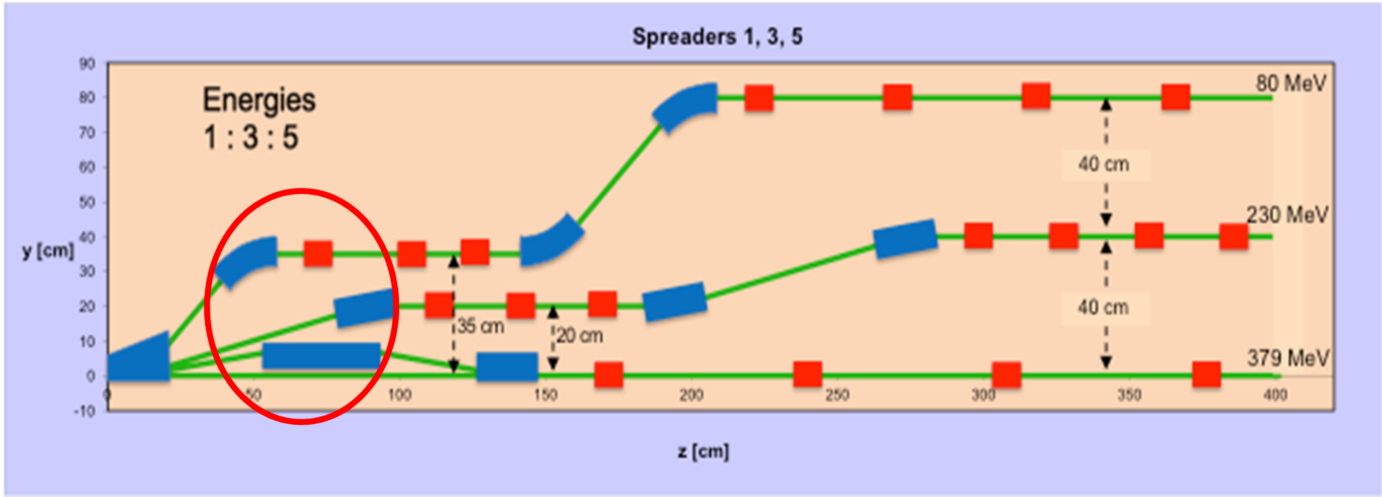
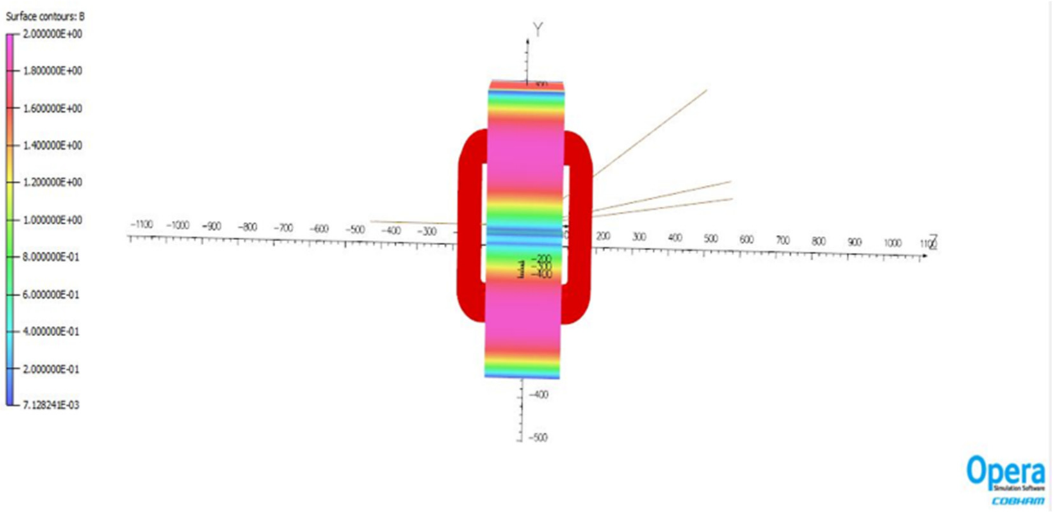


Preliminary results for Spreader dipole:



- H-magnet design was chosen for the dipoles in order to minimize stray fields given the close proximity of the beamlines.
- Maximum field restricted to 6 kG, to limit flux leakage out of central pole iron.

	Energy (MeV)	Brho (T.m)	Angle (deg)	Bl (T.m)	Vertical coordinate of beam axis (mm) at z=400 (mm)/spreader	Distance between beams z=400 (mm)	Vertical coordinate of beam axis (mm) at z=500 (mm)/spreader	Distance between beams z=500	Vertical coordinate of beam axis (mm) at z=800 (mm)/spreader	Distance between beams z=800
Arc 1	80	0,269	41	0,19217	347,71		434,64		695,43	
Arc 3	230	0,769	14,32	0,19217	102,11	151,54	127,63	307,01	204,21	491,22
Arc 5	380	1,269	8,67	0,19217	61,03	43,90	76,29	51,35	122,06	82,15

- Trajectories at 80 MeV, 230 MeV and 380 MeV are correct.
- Feasibility is done but iron saturated.

⇒ Need to check if mechanical length can be increased.

=> Need to adjust magnetic length with mechanical length.

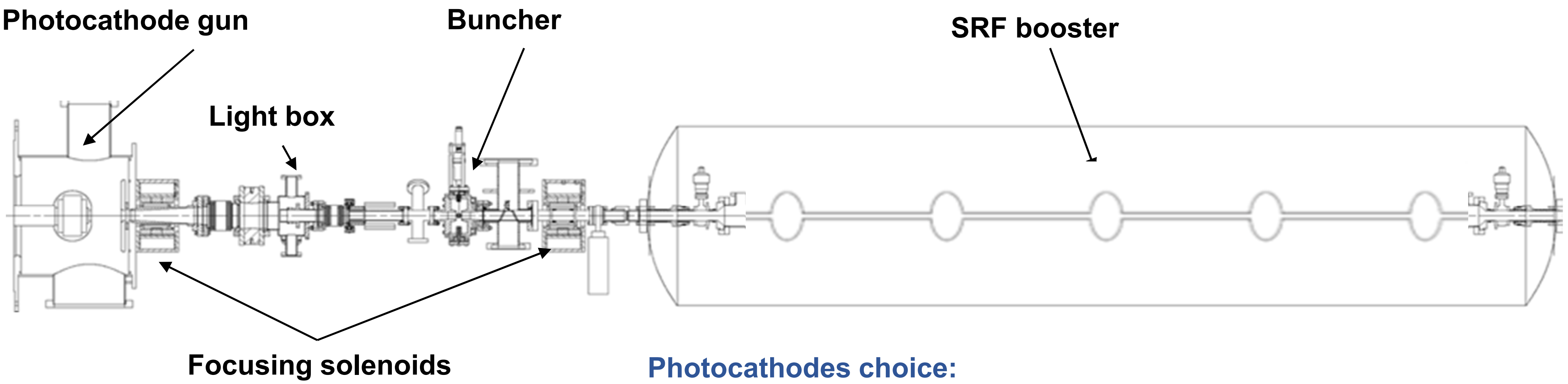
Electron source and injector:

LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

Courtesy to Ben Hounsell

The PERLE injector consists 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 feeded and controlled on amplitudes and phases.
- Merger to transport the beam into the main LINAC,
- Beam diagnostics to be placed between components.
- Spin manipulator for the polarised electrons option.



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:

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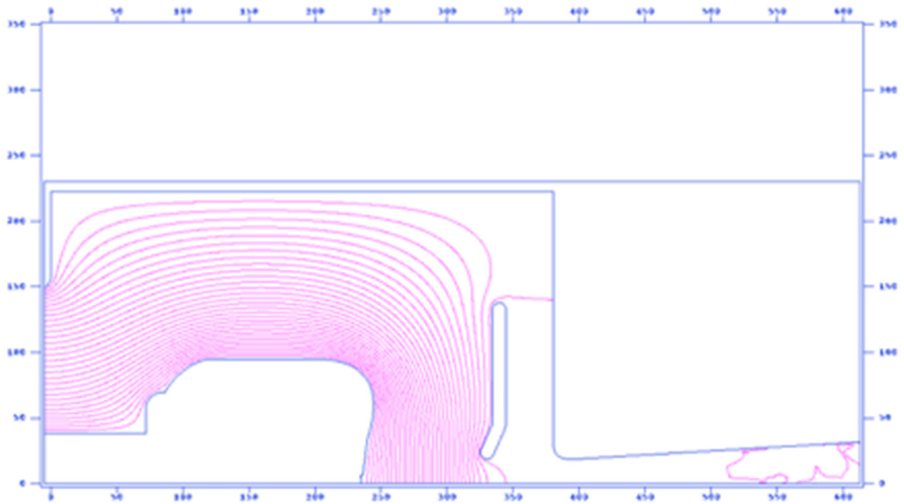
Studies on ALICE gun upgrade to operate at up to 500 pc (B. Hounsell PhD thesis):

- ✓ 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.



- ✓ Optimisation of the buncher frequency (**401 MHz** or 802 MHz) in order to minimise emittance growth.

Hounsell et al. «Re-optimisation of the ALICE gun upgrade design for the 500 pC bunch charge requirements of PERLE», IPAC 19, Melbourne-Australia

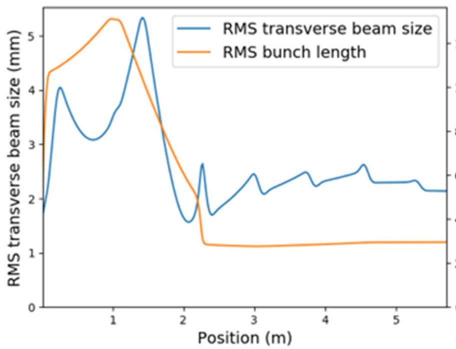
Electron source and injector:

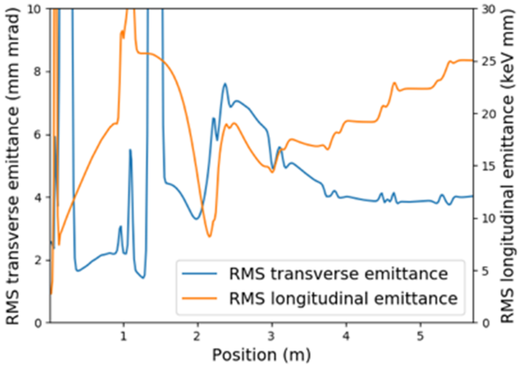
LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

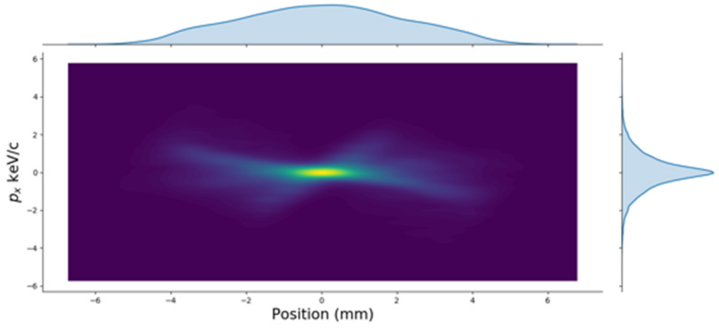
PERLE injector (up to the booster exit) was optimised using **NSGAIII**: a many objective optimisation algorithm

- **Variables**: laser parameters, solenoid settings, buncher amplitude and phase, distances between elements and the booster cavity amplitudes and phases.
- **Constrains**: injection energy of 7 MeV & final bunch length of 3 mm

⇒ The objectives were all minimised at the point of the booster exit. They were rms transverse emittance, rms longitudinal emittance, rms energy spread, x halo parameter and z halo parameter.







The solution was not only selected for its transverse emittance but also the shape of the bunch distributions:

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

=> The PERLE injector is capable of achieving the specification at the booster exit. The possibility of improving the bunch distributions and longitudinal phase space will be investigated (linearizing the longitudinal phase space)

For more: See the poster B. Hounsell « Status of the PERLE injector optimisation » @ERL 2019

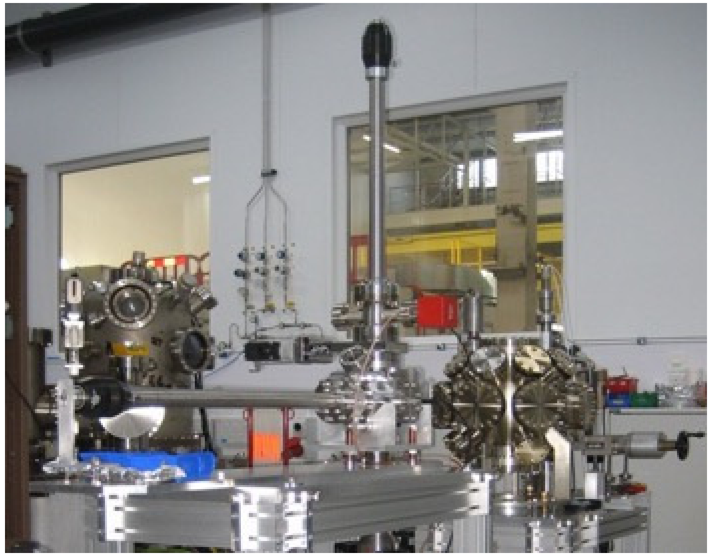
Electron source and injector:

LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

PERLE

- **Still to be done:**

- The final step towards a complete injector design is **the merger**=> Work is ongoing.
- 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.
- Studies on the tolerances required for the injector.
- The possible options for a polarised injector will be considered.
- 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

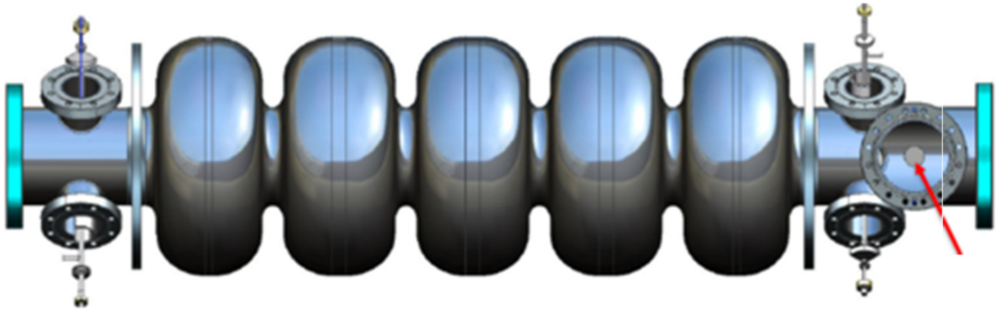
ALICE DC-Gun and equipment transferred from Daresbury to LAL on May 9 & 10, 2019

Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration

Courtesy to Frank Marhauser

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



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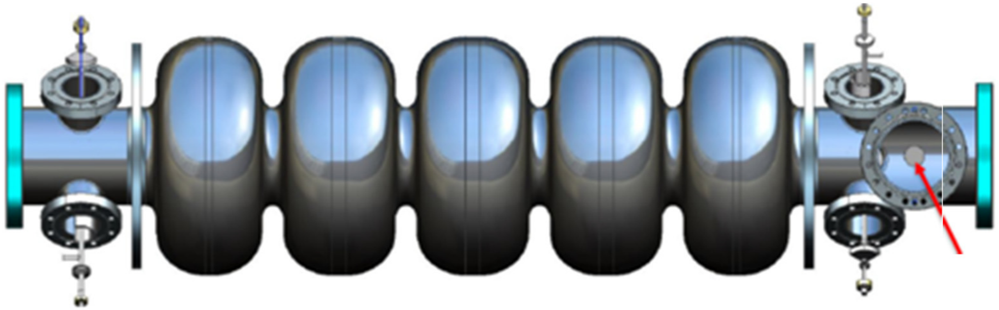
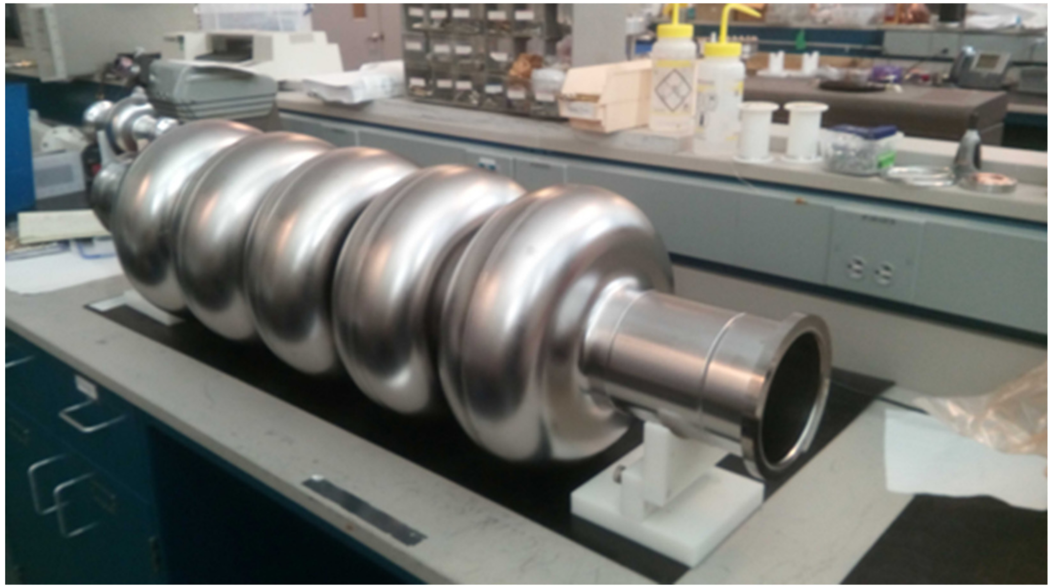
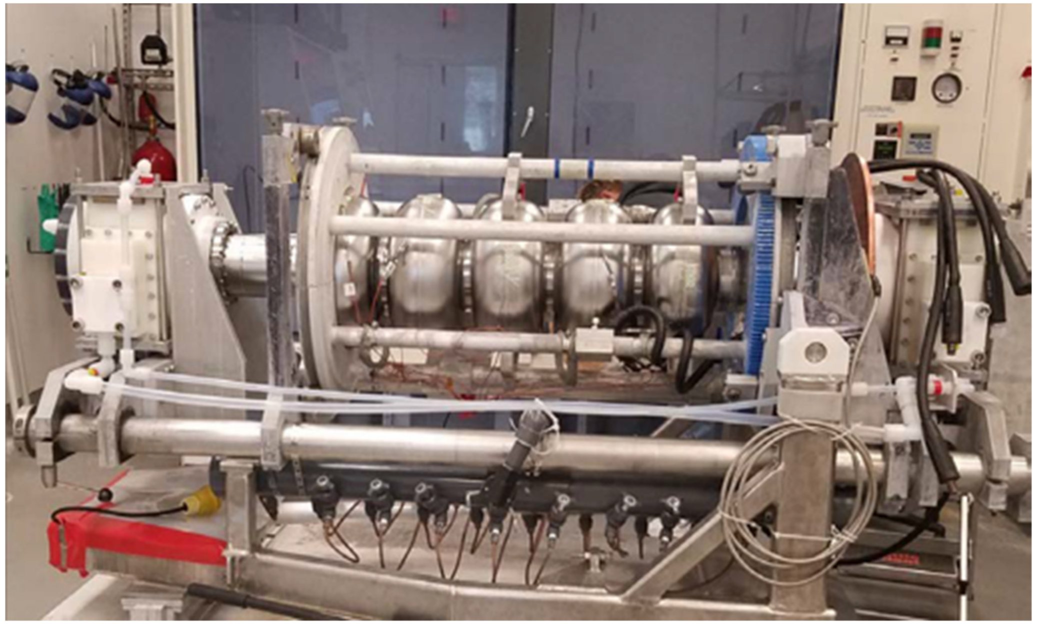




The first Nb 802 MHz 5-Cell cavity fabricated October 2017 at JLAB

Cavity fabrication and test:

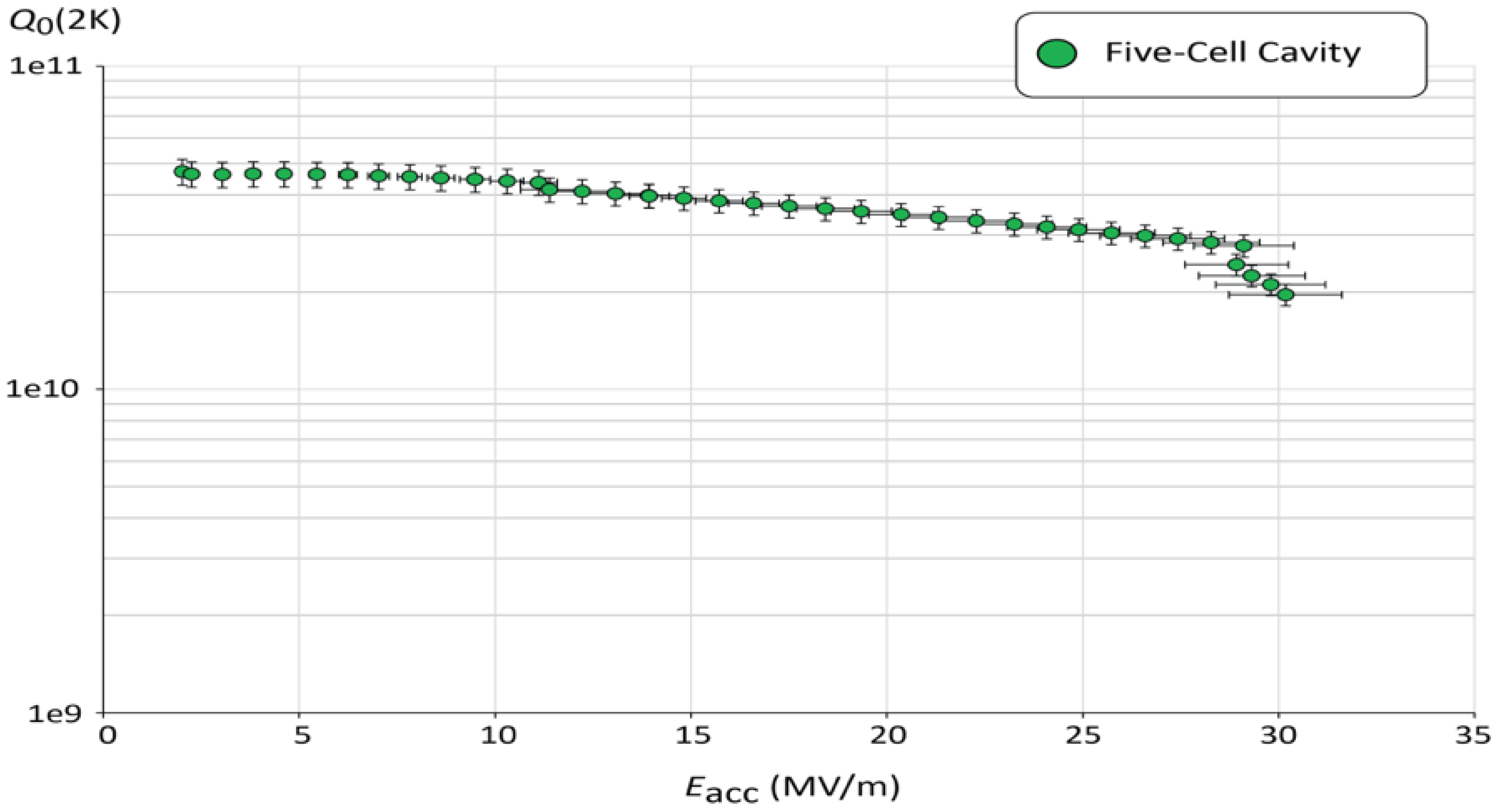
LAL/IPNo – CERN - JLAB Collaboration



5-cell cavity successfully electropolished with new flange adapters

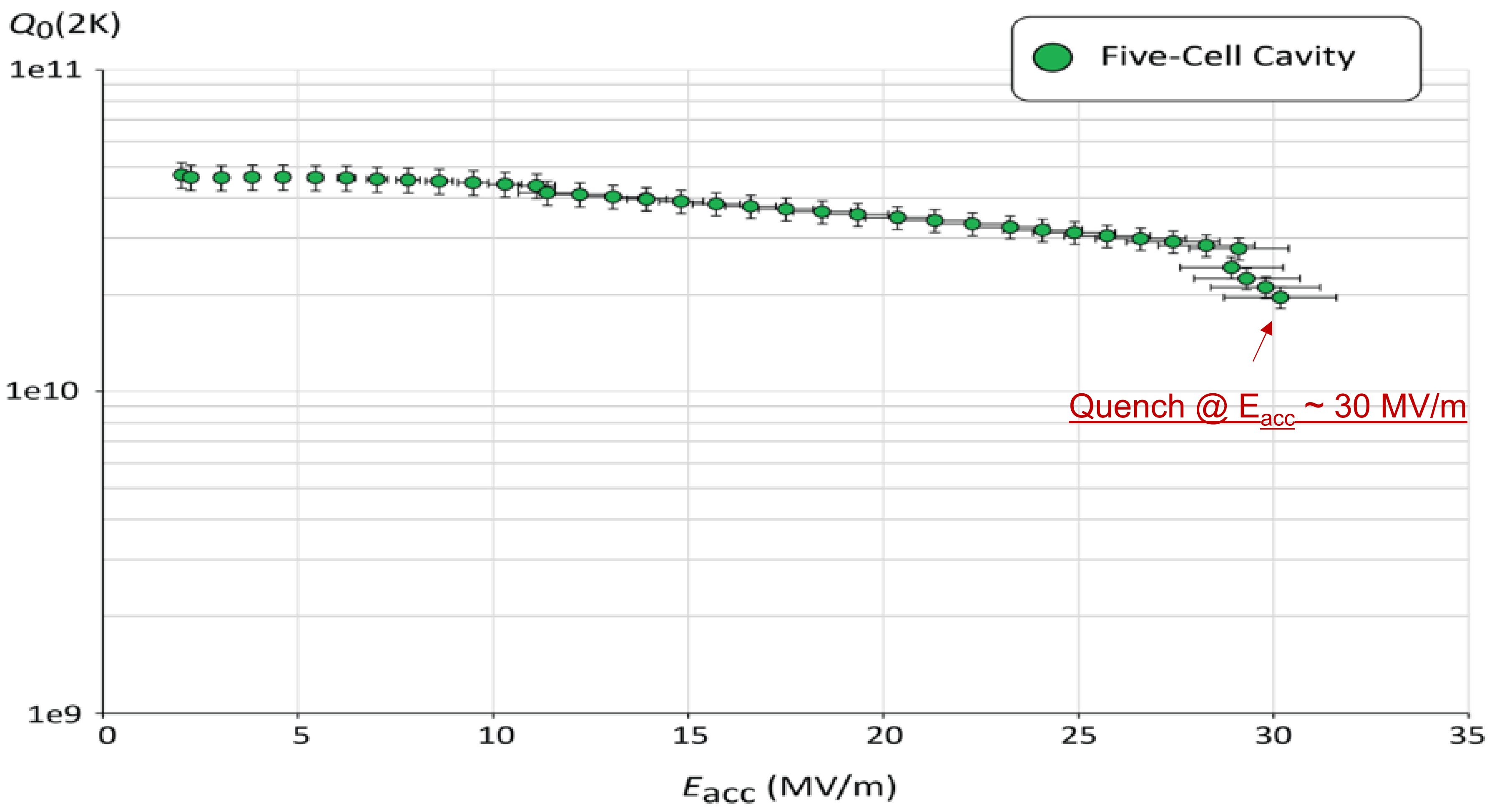
Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration



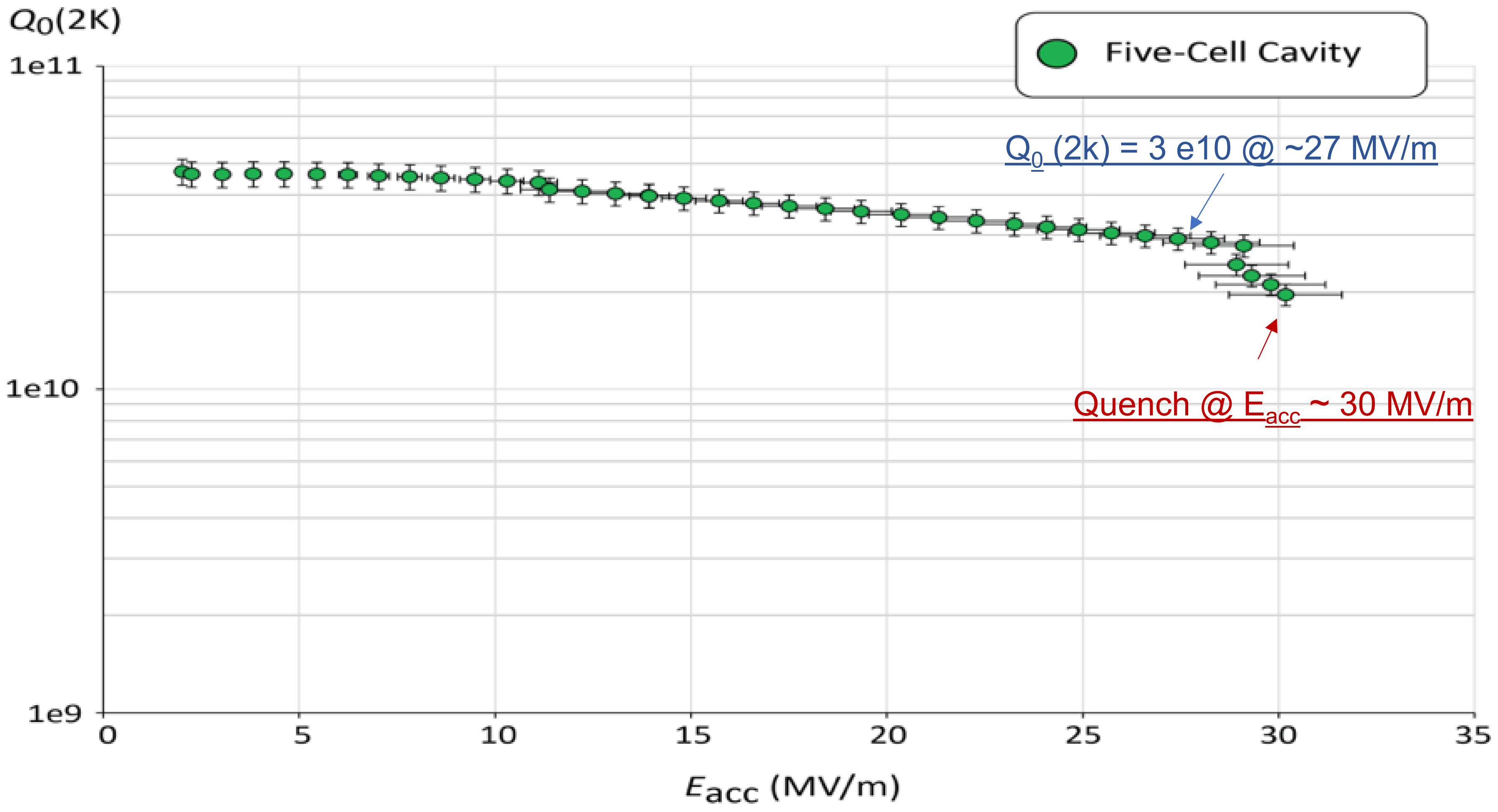
Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration



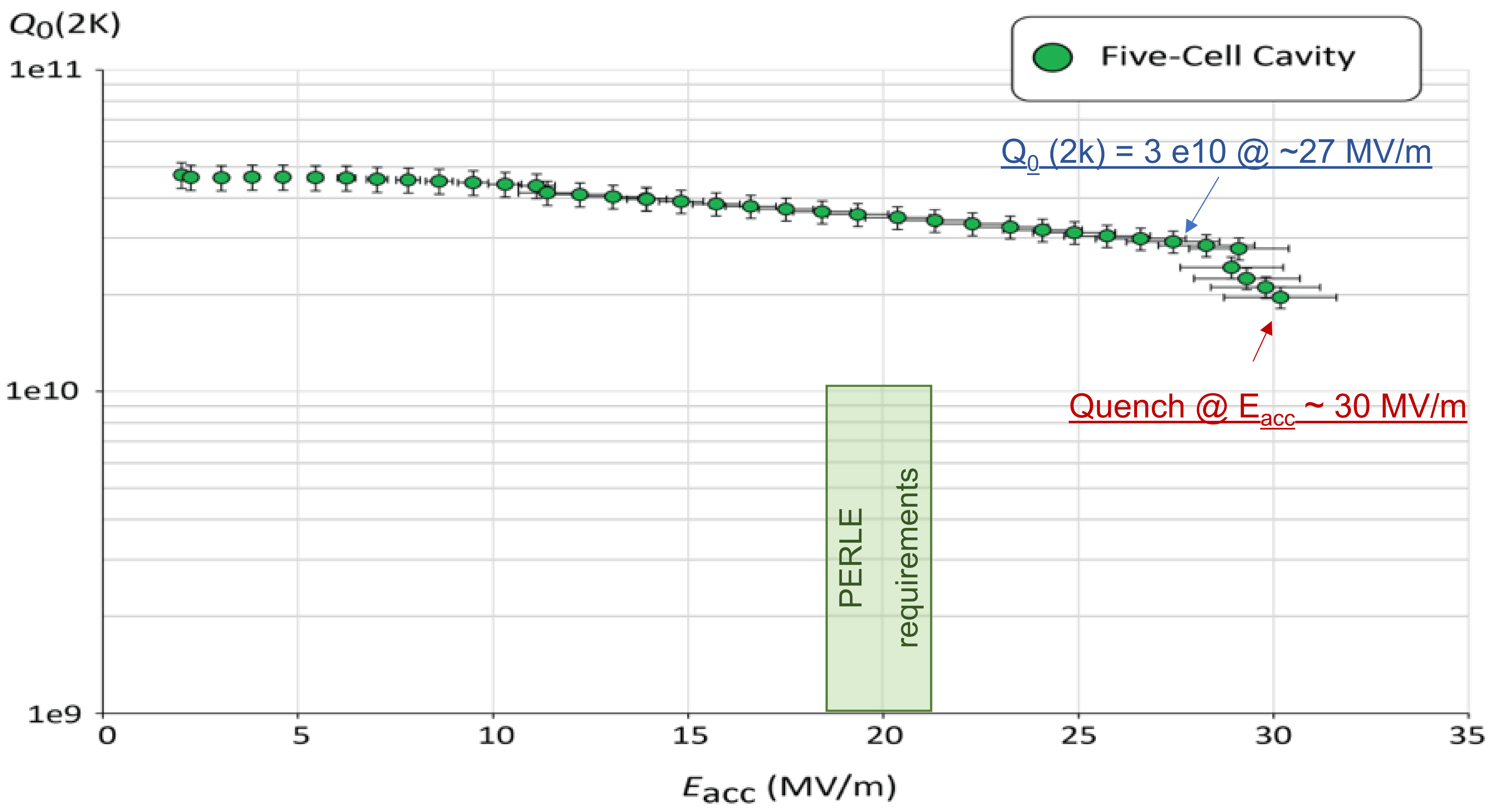
Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration



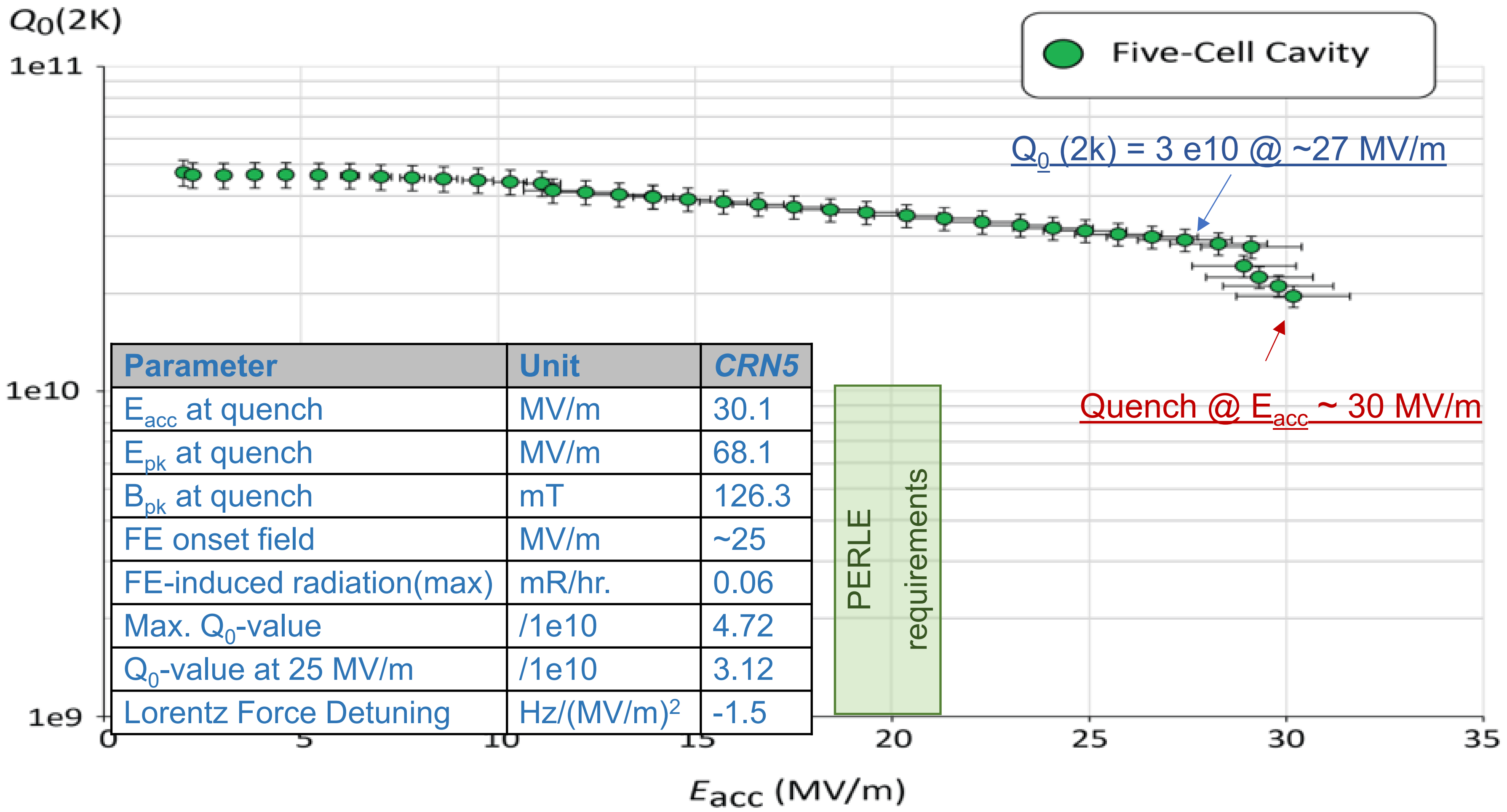
Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration



Cavity fabrication and test:

LAL/IPNo – CERN - JLAB Collaboration



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

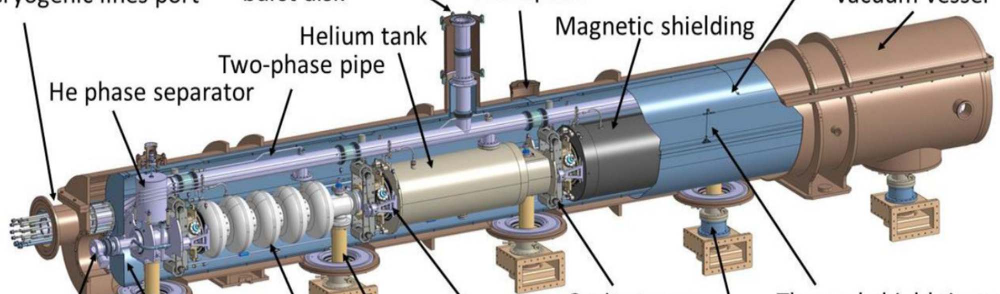
For more details: F. Marhauser's talk in the FCC Week, April 2018, Amsterdam, Netherland

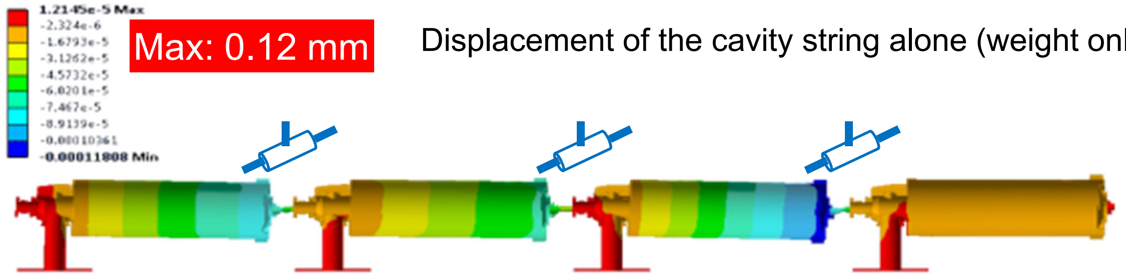
Cryomodule design study:

LAL/IPNo – CERN Collaboration

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

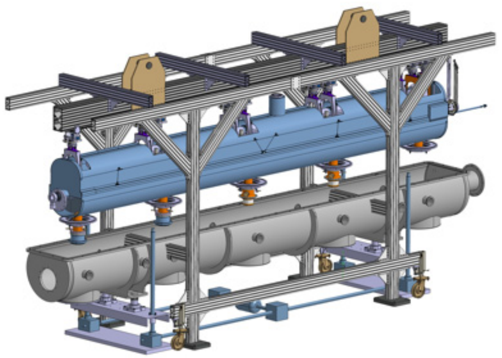
Courtesy to Gilles Olivier



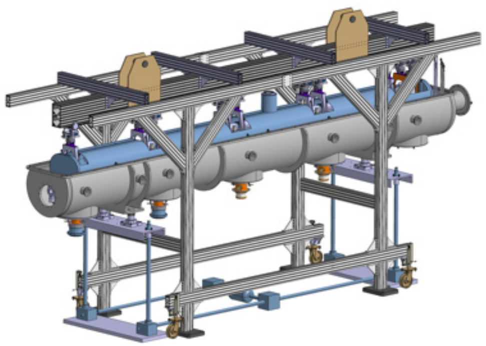


Displacement of the cavity string alone (weight only)

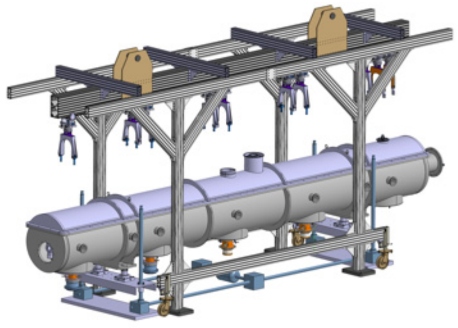
SPL cryomodule: designed to integrate 4 elliptical 5-cells 704 MHz cavities



Cavity string equipped with magnetic shield, CTS, cryogenic lines and thermal shield



Insertion of the complete assembly inside the vacuum vessel



Closing of the top lid and of the beam ports

Cryomodule design study:

LAL/IPNo – CERN Collaboration

CHARACTERISTICS	SPL (704MHz)	PERLE / JLAB (802MHz)
Coupler to coupler length (mm)	1490,5	-
Length flange to flange (mm)	1397,3	1292,5
Coupler to flange dimension (mm)	116,4	96,7
Cells external diameter (mm)	386,5	335
Beam port internal diameter (mm)	129,8 / 139,8 (coupler side)	130
Flanges internal diameter (mm)	79,7 (CF100)	130 (CF160)
Vacuum valve diameter	CF63	tbd
Coupler internal diameter (mm)	100	100
Coupler flange	CF100	CF100
Beam axis to ext. coupler flange	403	tbd

=> The two cavities present similar features

Main Issue: the HOM extraction

- How many extraction ports (interferences with CTS)?
- Which power (W, tens of W, more)?
- What kind of damper (waveguide, loop coupling)?
- Active helium cooling or thermalization by copper braids.
- What kind of RF line to the external load (cable sufficient, which kind of connector)?
- Intermediate thermalization of the cables
- External cooled RF loads

Cryomodule design study:

LAL/IPNo – CERN Collaboration

First results:

- ✓ Thermal and magnetic shielding are well sized for PERLE operation parameters. Their design could be modified if needed.
- ✓ Vacuum vessel could be reused without refurbishing
- ✓ Input coupler designed for SPL cavity could be easily adapted to meet PERLE requirement
- ✓ Further studies will define if Cryogenic lines have to be adapted
- ✓ Space liberated due to cavity frequency difference give a little margin for auxiliaries integration.

Pending issues:

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

  → Risk of interference between CTS and HOM dampers

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

Thank you for your attention!