Electrons for the LHC: LHeC, FCC-eh and PERLE Workshop

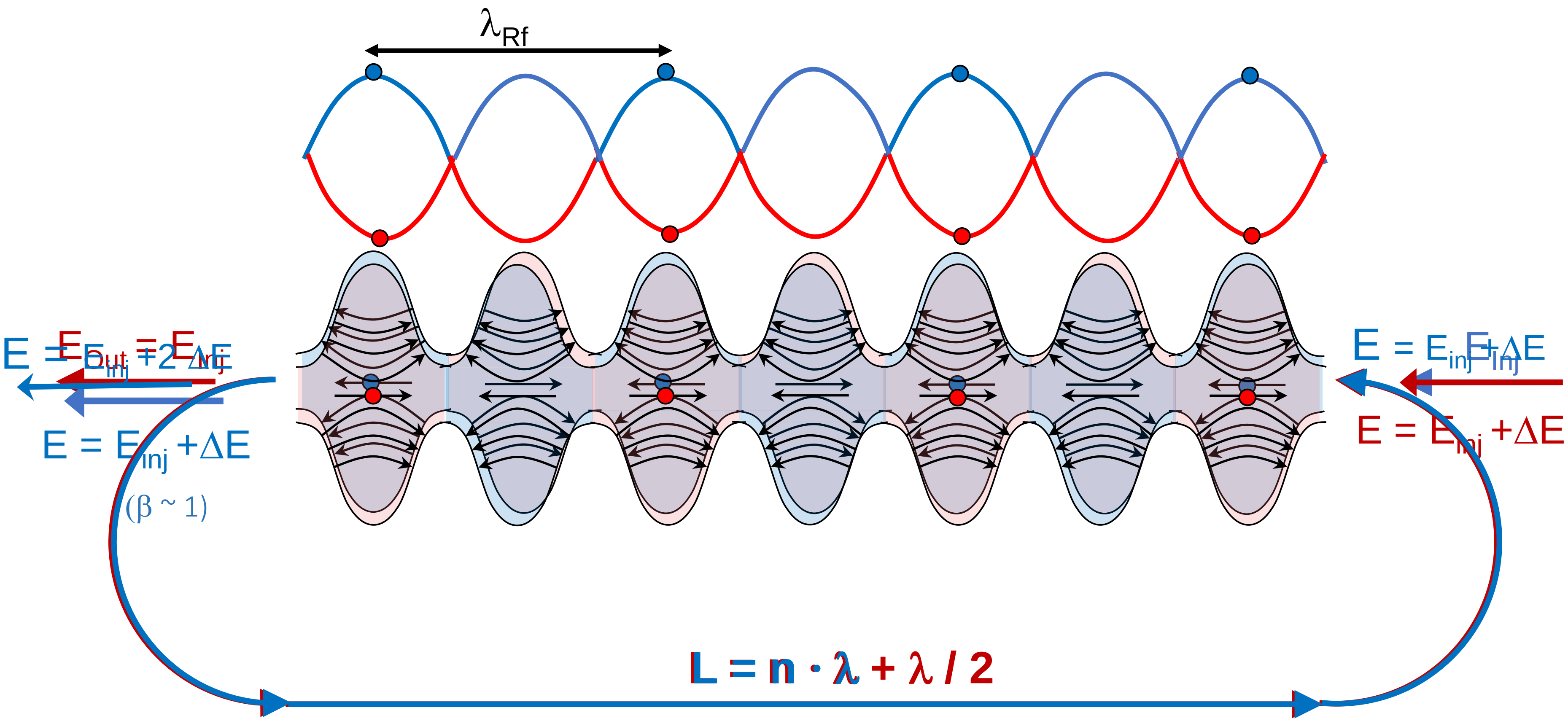
Chavannes de Bogis, 24-25 October 2019

PERLE : Status and Prospects

On behalf of 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 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.

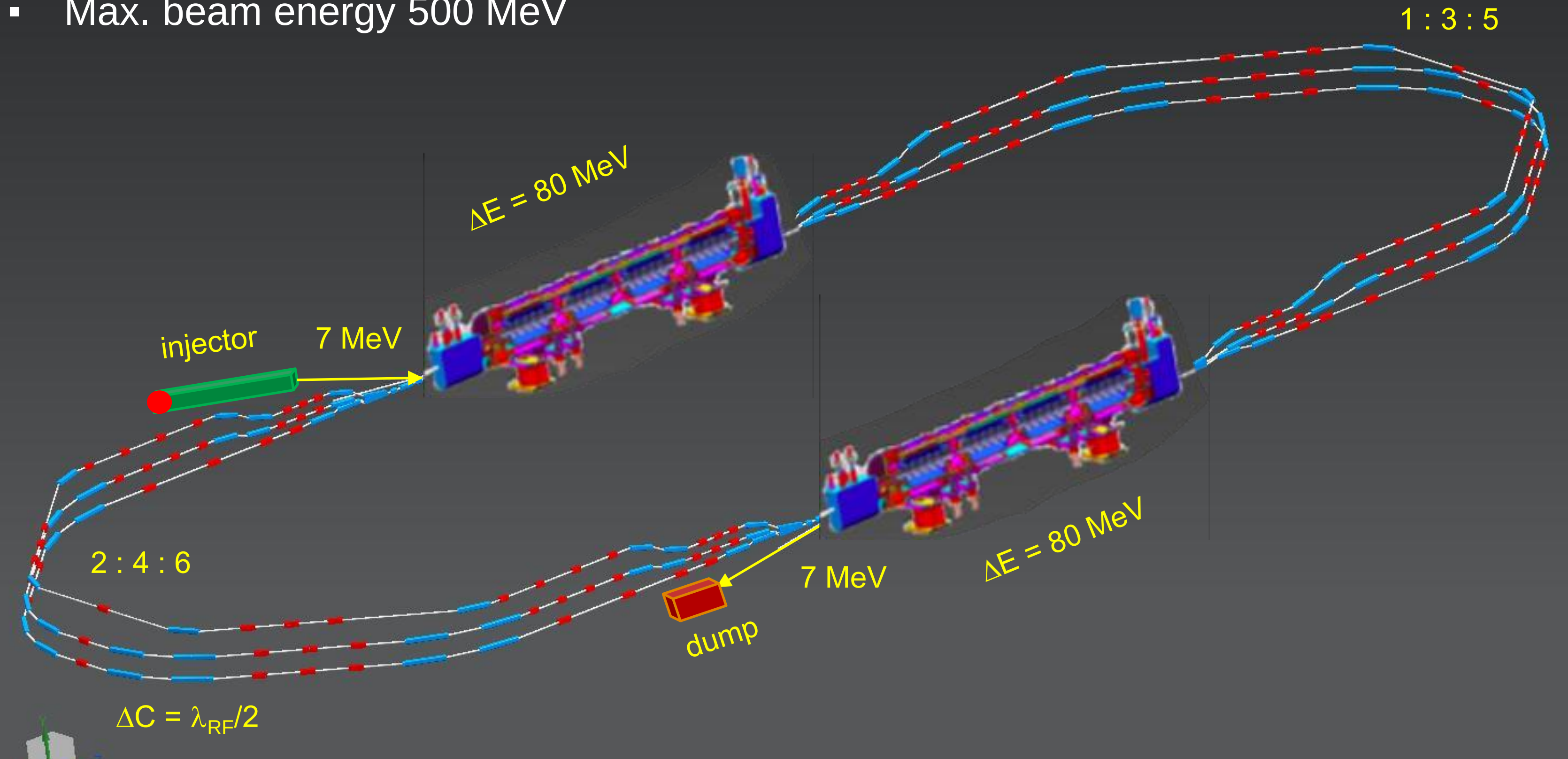
Particularly, design challenges and beam parameters are chosen to enable PERLE as the hub for technology development (especially on SRF) for the Large Hadron Electron Collider (LHeC)[2]:

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

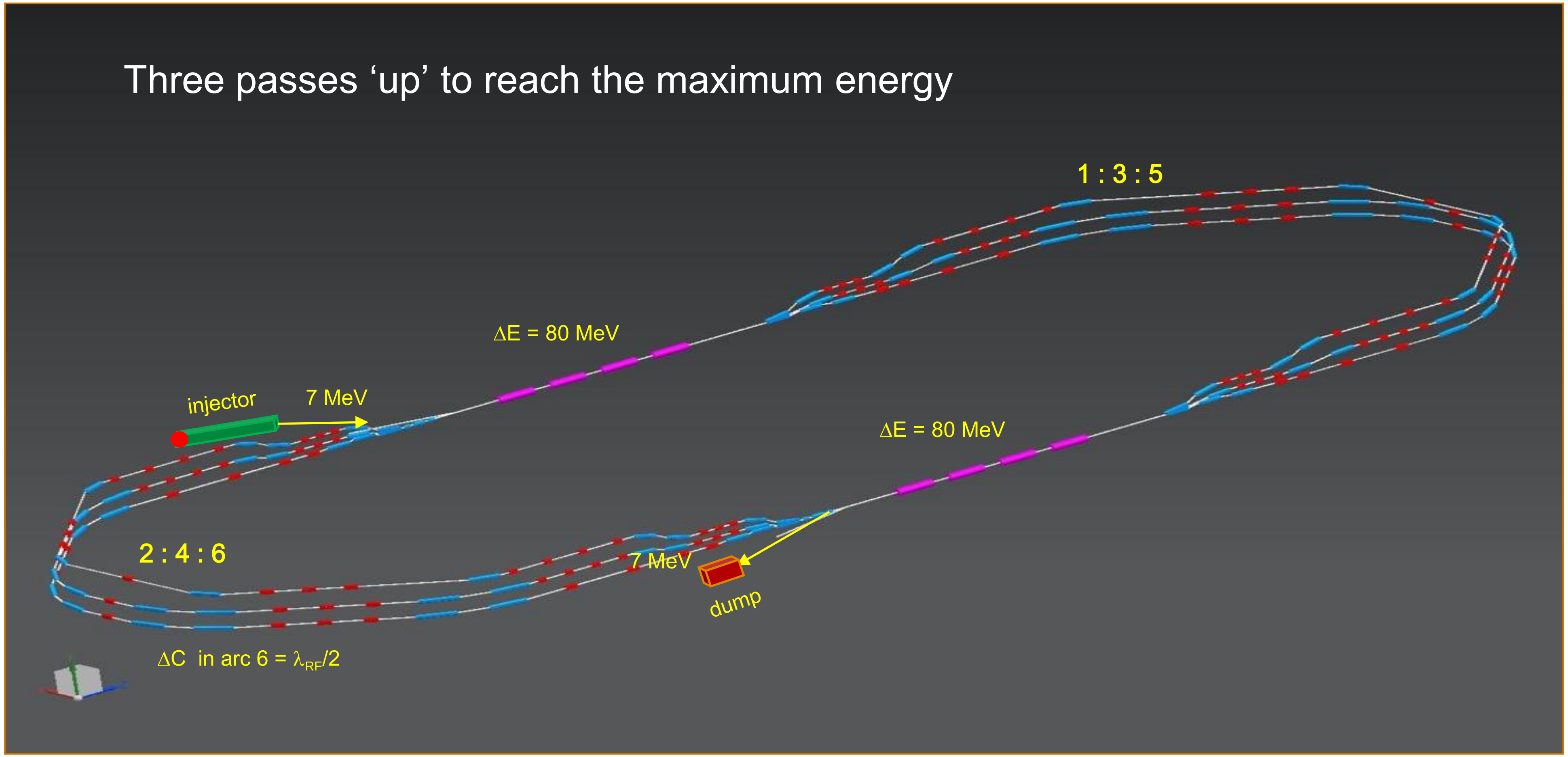
PERLE configuration:

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

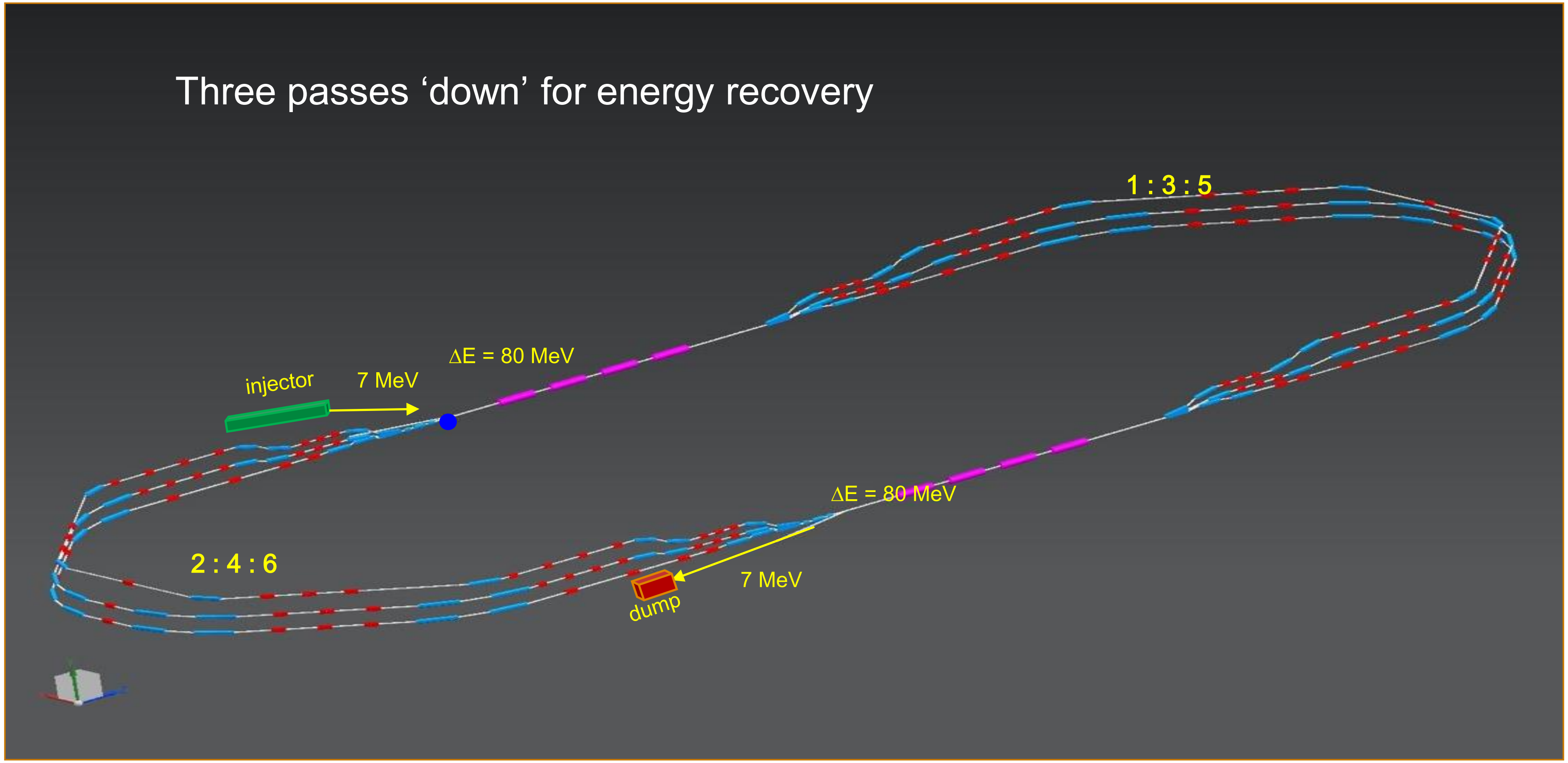


Footprint: 24 x 5.5 x 0.8 m^3

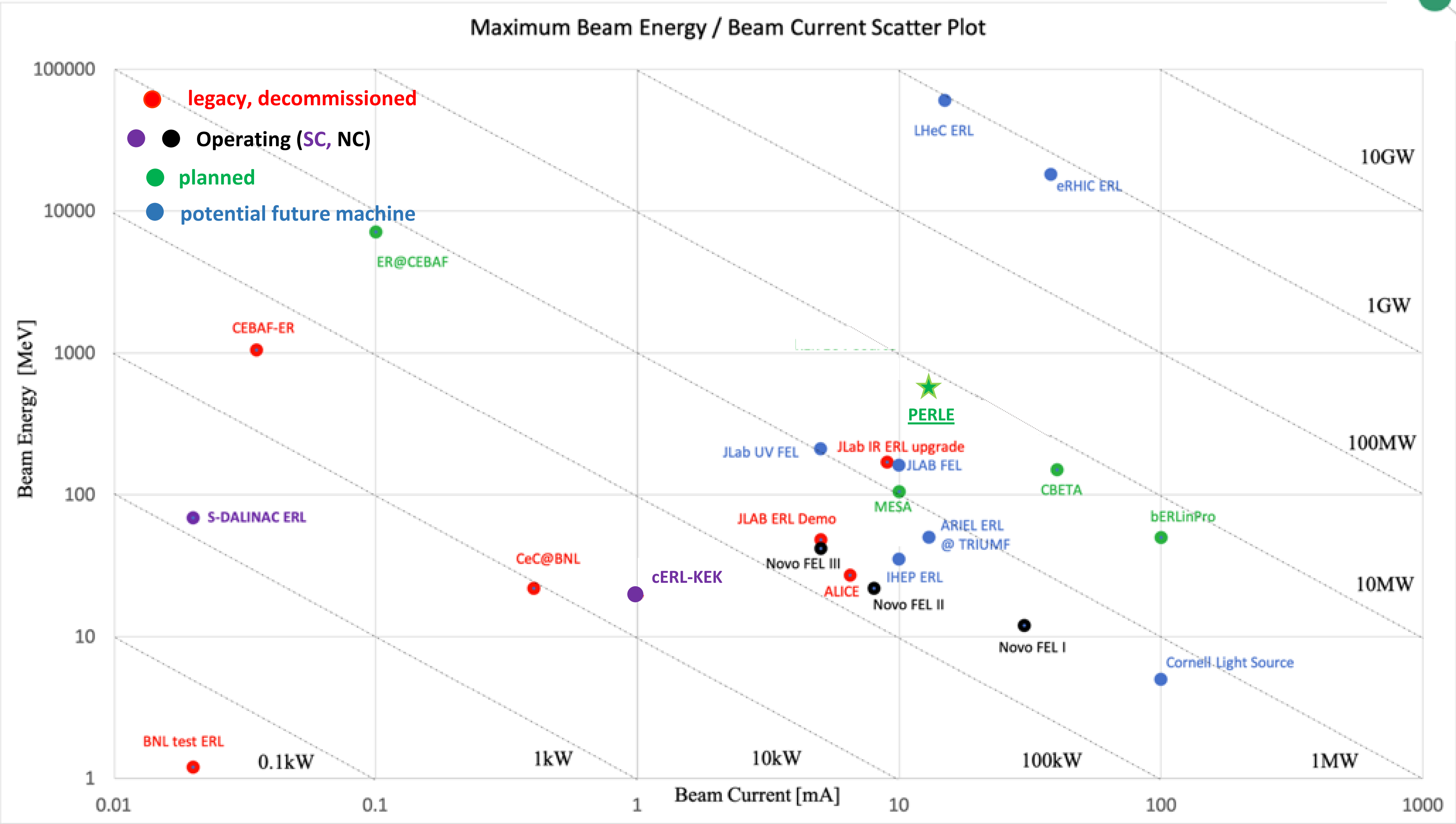
PERLE configuration:



PERLE configuration:



PERLE in the global landscape:



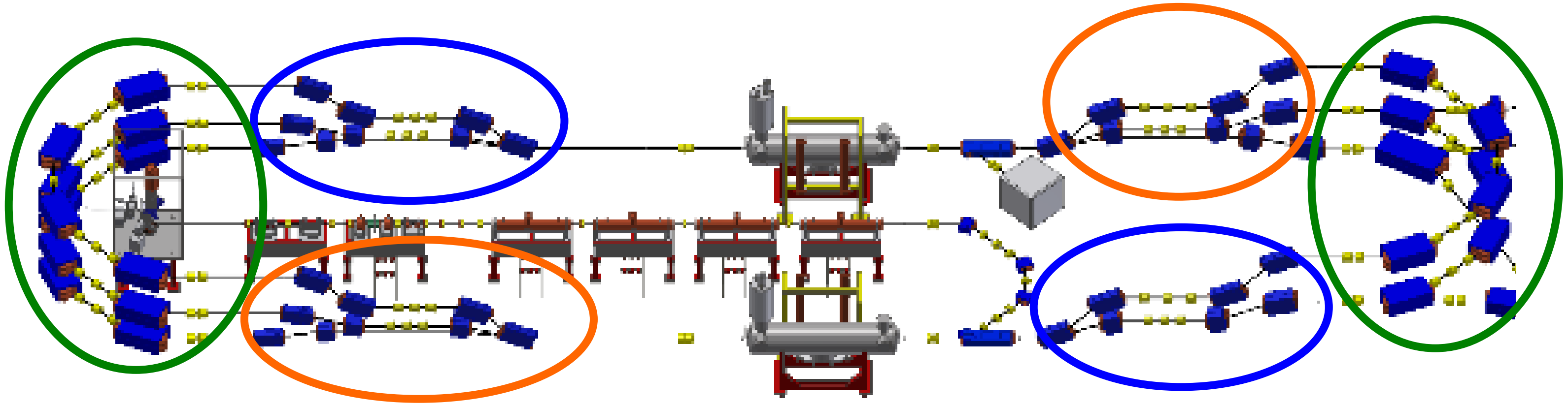
PERLE transport optics:

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

- **The 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 as **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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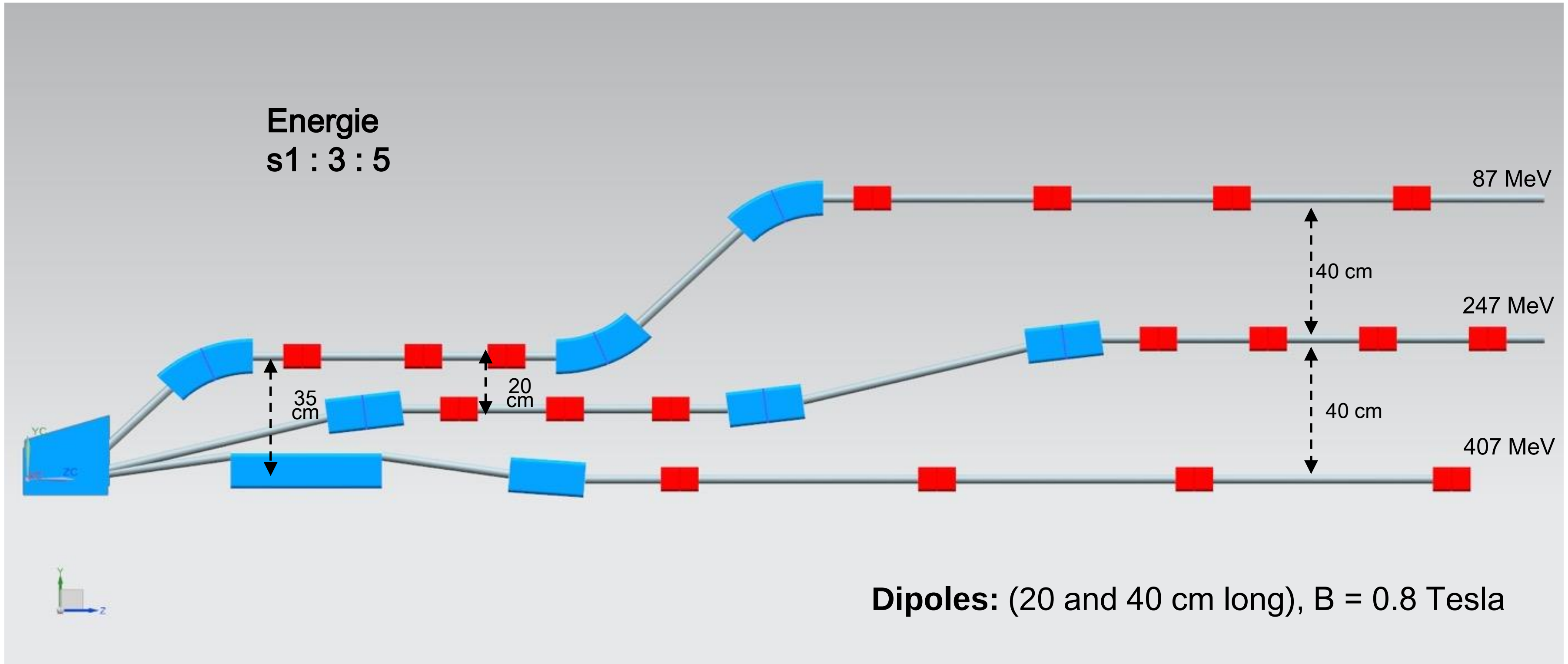

Arc optics, Arc 1 (87 MeV) as example:

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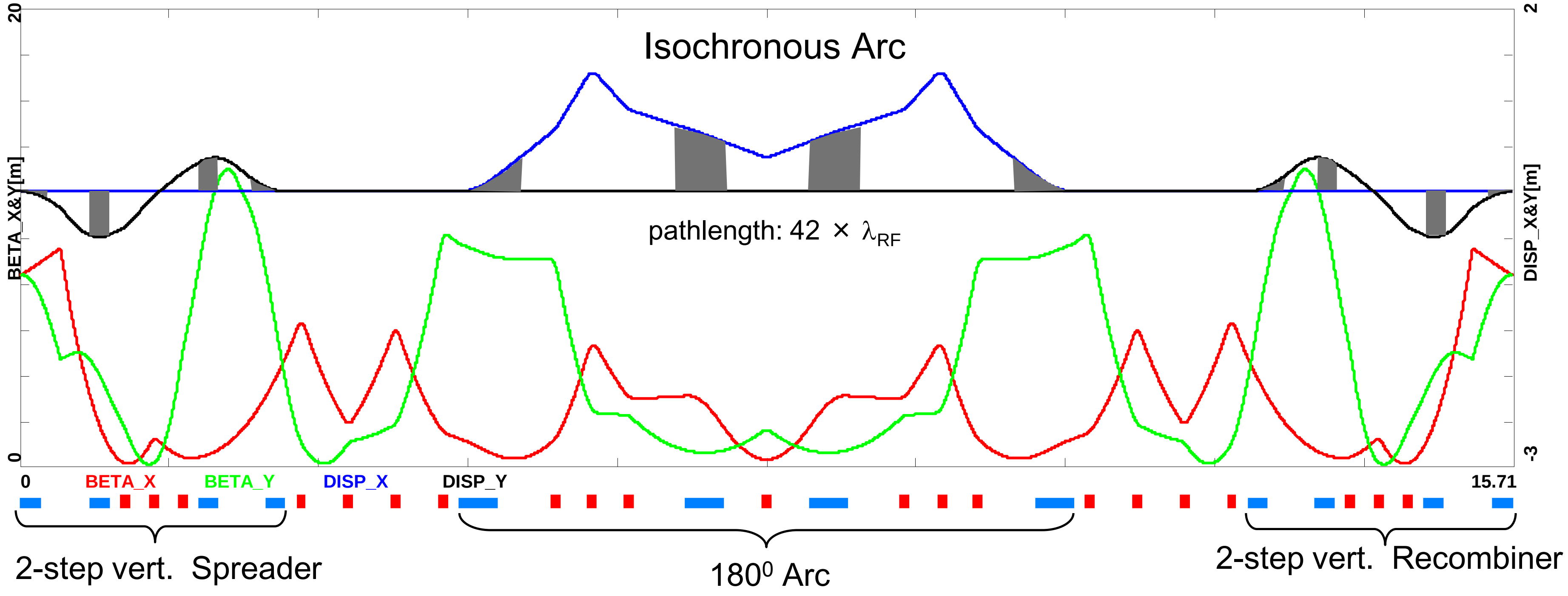

Spr. dipoles:
4× 45⁰ bends
L = 20 cm
B = 9.5 kGauss

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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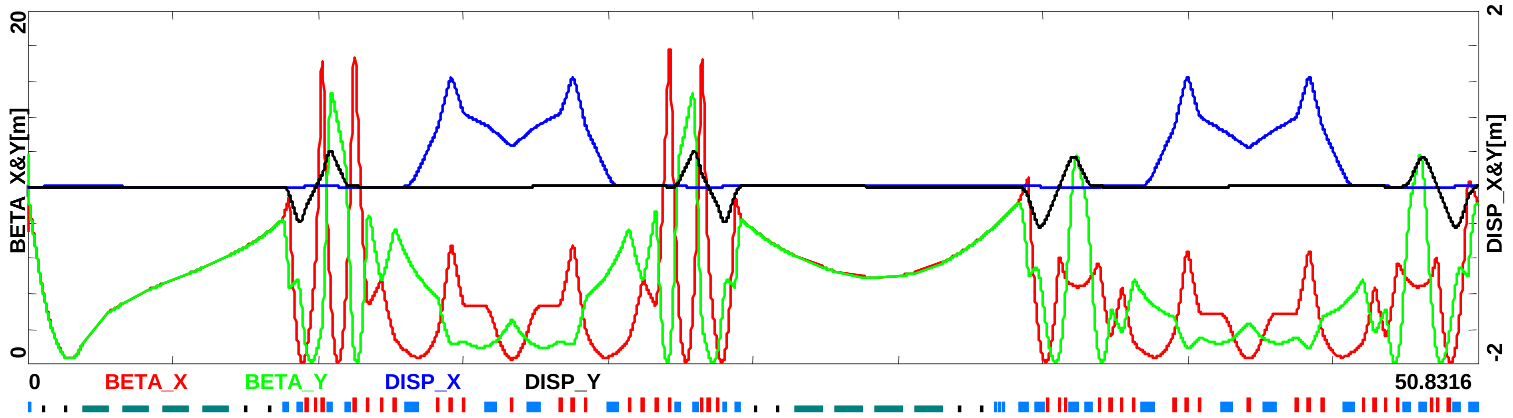
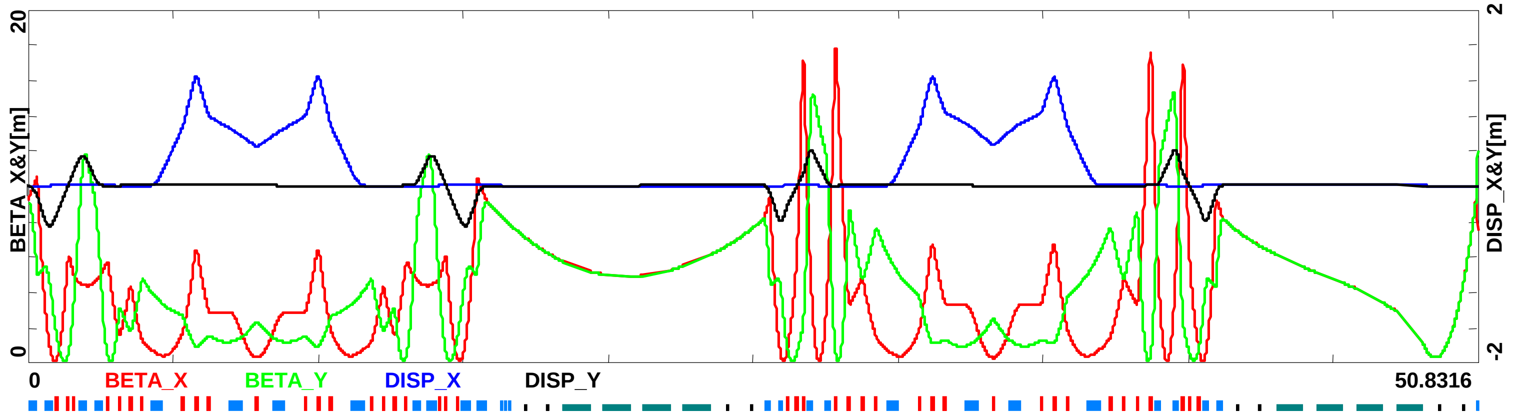
Pass-1 ‘up’



7 MeV 87 MeV 167 MeV

Pass-1 ‘down’



167 MeV 87 MeV 7 MeV

Bunch recombination pattern:

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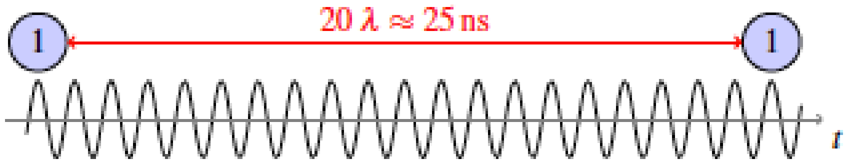
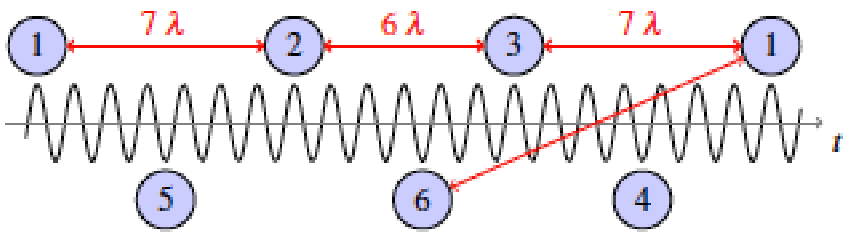
- Basic RF structure, without recirculation: Bunches are injected every 25 ns



- 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

PERLE magnets design: Magnet inventory

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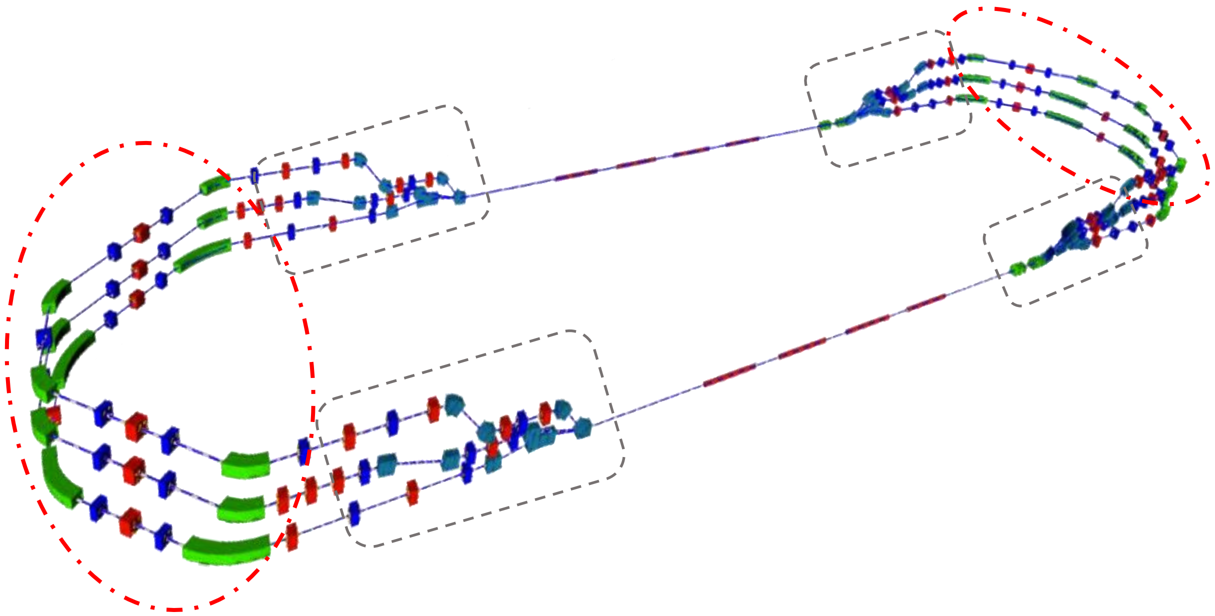
Courtesy to Cynthia Vallerand

- 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 dipoles** in the spreader/combiner, powered individually



PERLE magnets design: Quadrupoles

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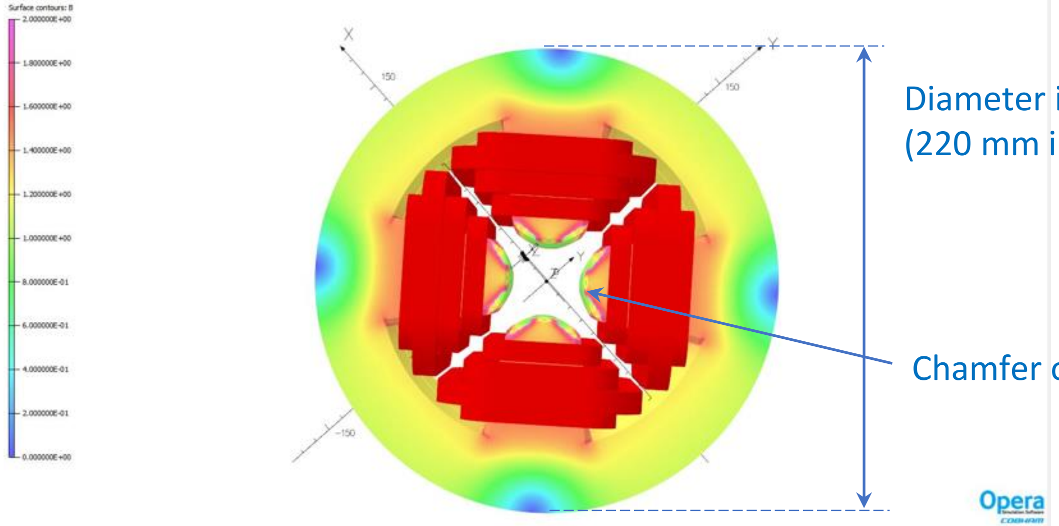
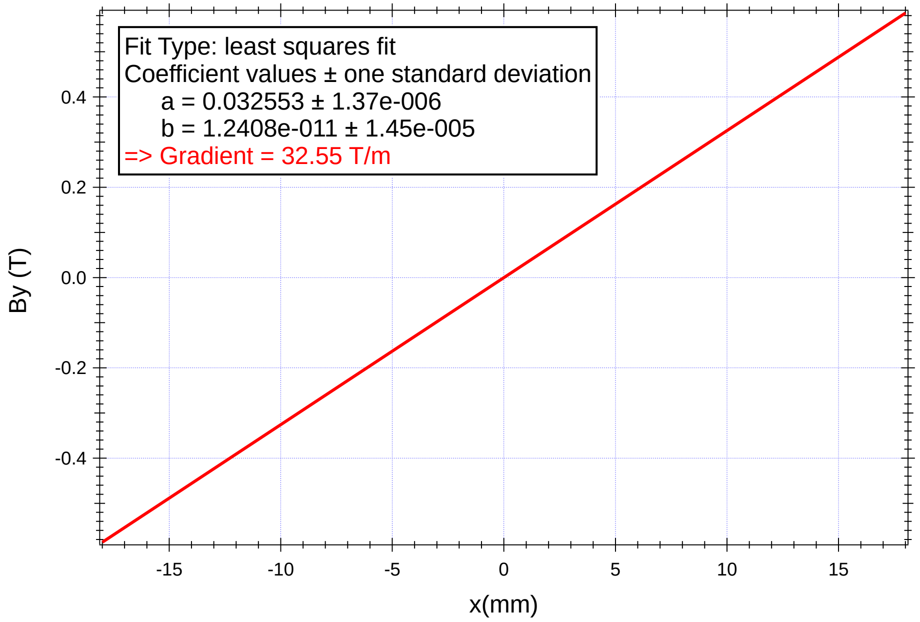
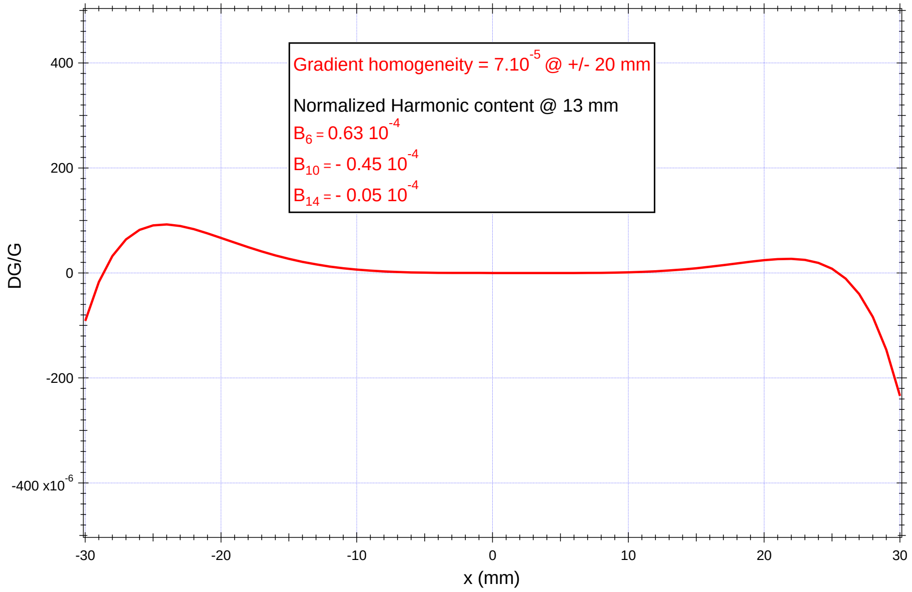
Features of quadrupoles magnets	
Quantity	114 + 1 (pre-serie)
Magnetic length	100 - 200 mm
Main gradient G_0	30T/m
Gap	40 mm
Good field region	+/- 20mm
Beam energy	From 50 to 400 MeV







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

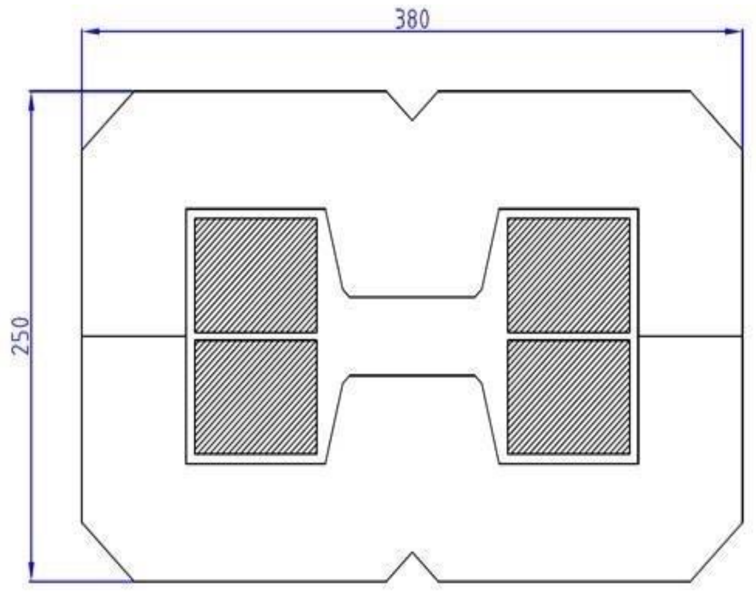
PERLE magnets design: Arc bending magnets

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

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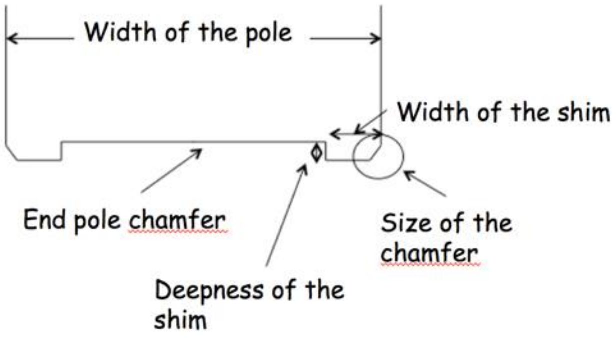
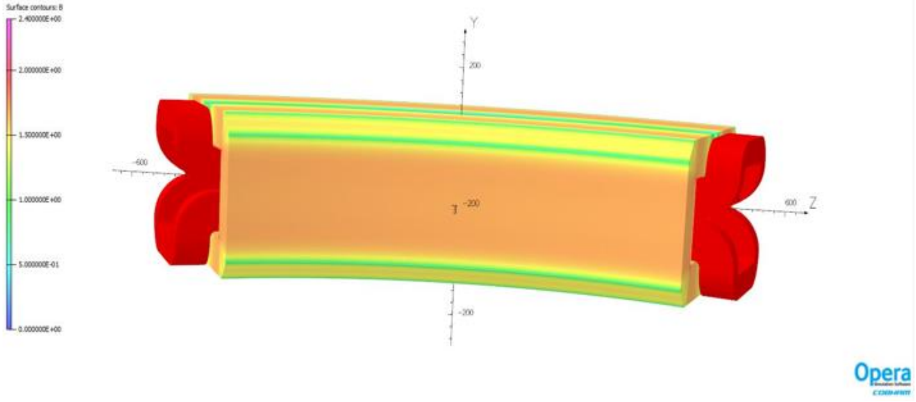
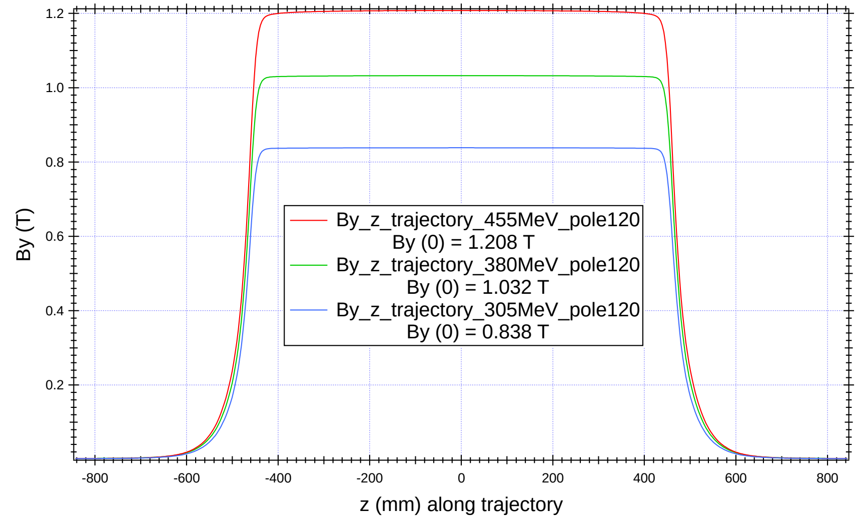
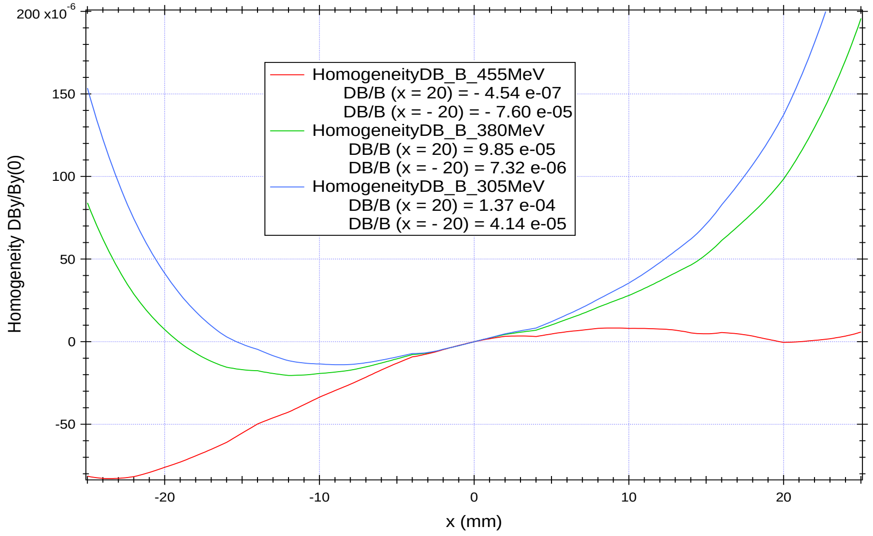
- Parameters for dipole design optimization:







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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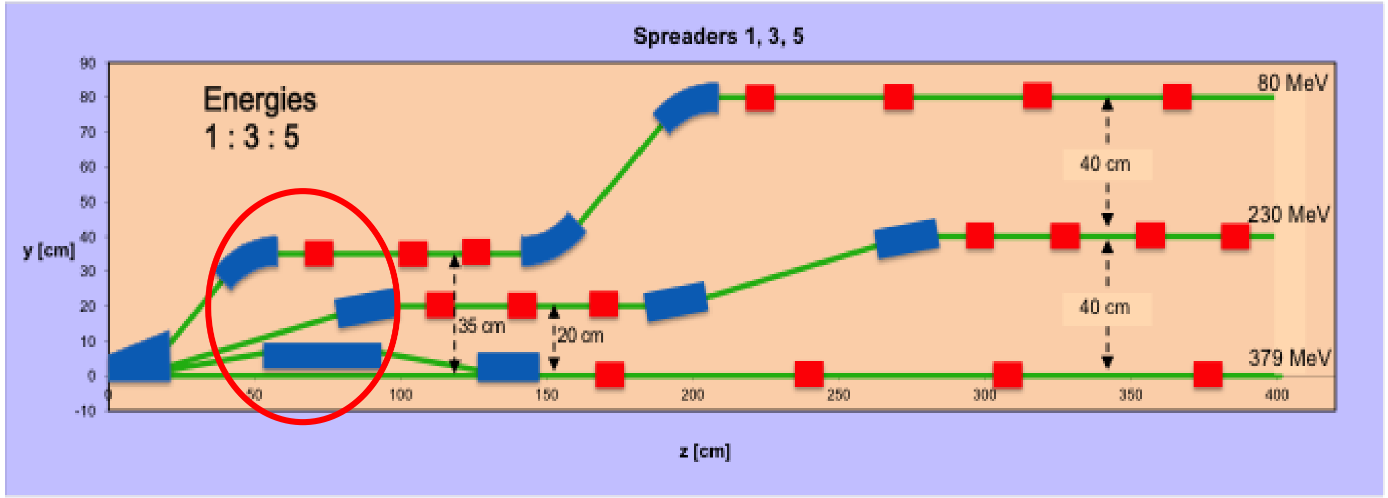
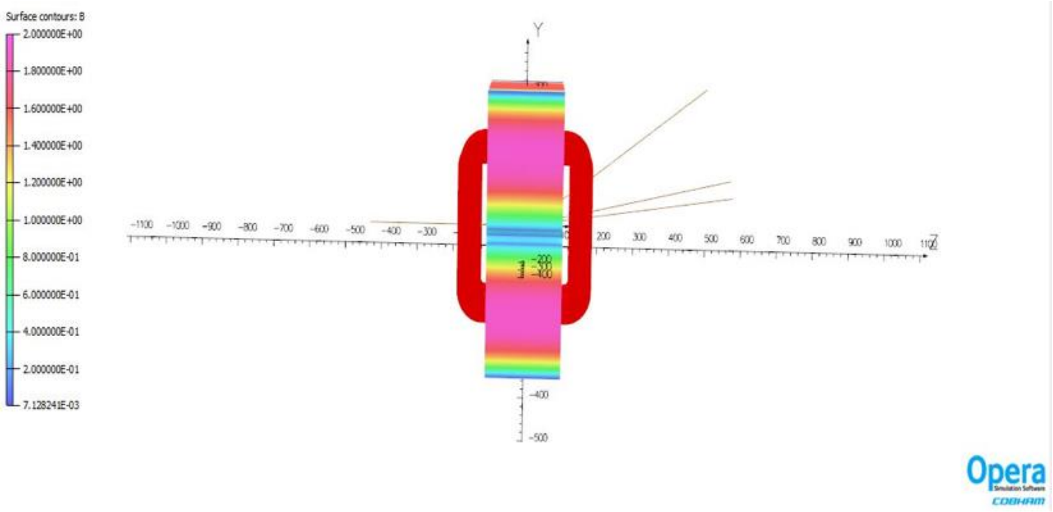


Preliminary results for Spreader dipole:



- 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:

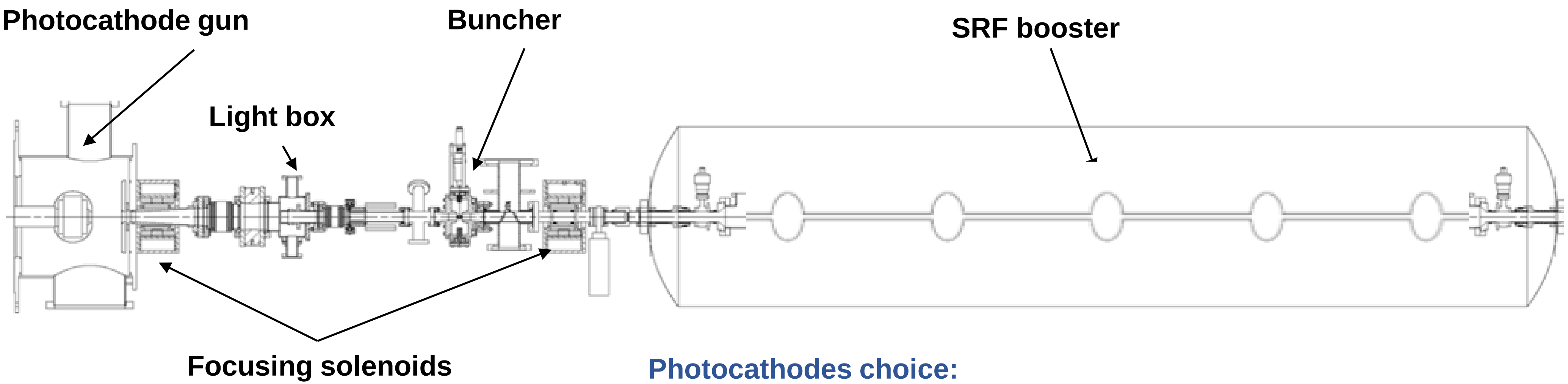
LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

PERLE

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**

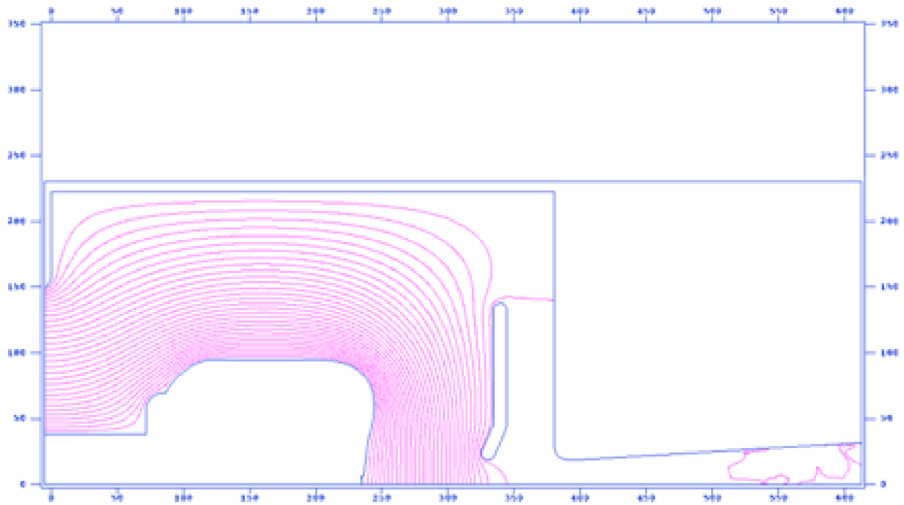
Electron source and injector:

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.



- ✓ 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

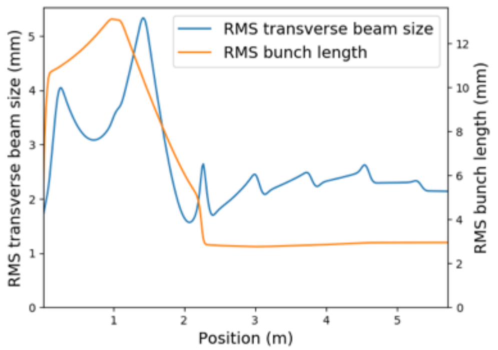
Electron source and injector:

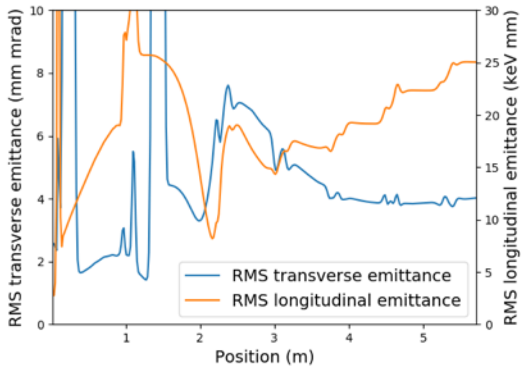
LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

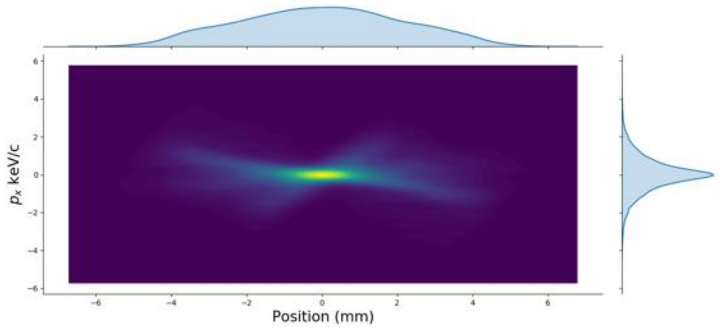
PERLE injector (up to the booster exit) was optimised using **NSGAIII**: a many objective optimisation algorithm

- **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**:

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

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)

Electron source and injector:

LAL/IPNo – STFC Daresbury- Univ. Liverpool Collaboration

- **Still to be done:**

- The final step towards a complete injector design is **the merger**=> Work is ongoing.
- A **'first ' start-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 beam injection** 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



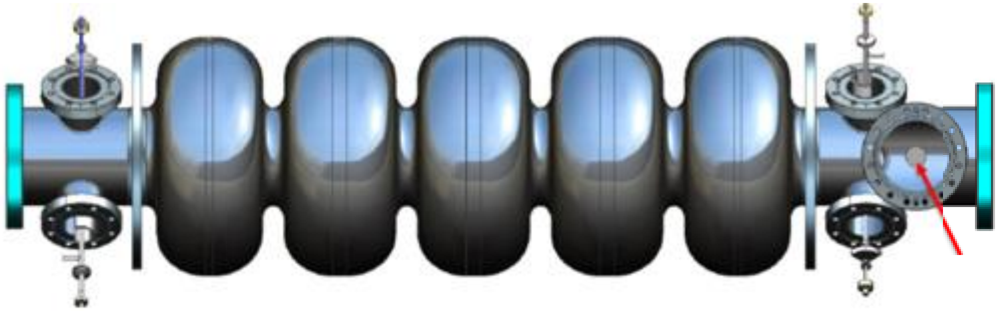
ALICE DC-Gun and equipment transferred from Daresbury to LAL on May 9 & 10, 2019

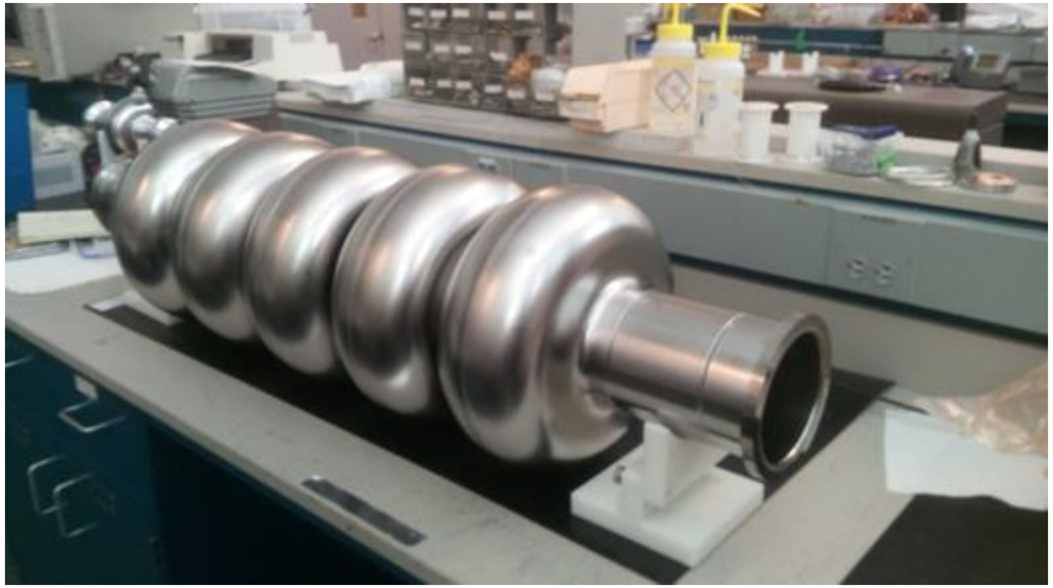

Cavity fabrication and test:

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

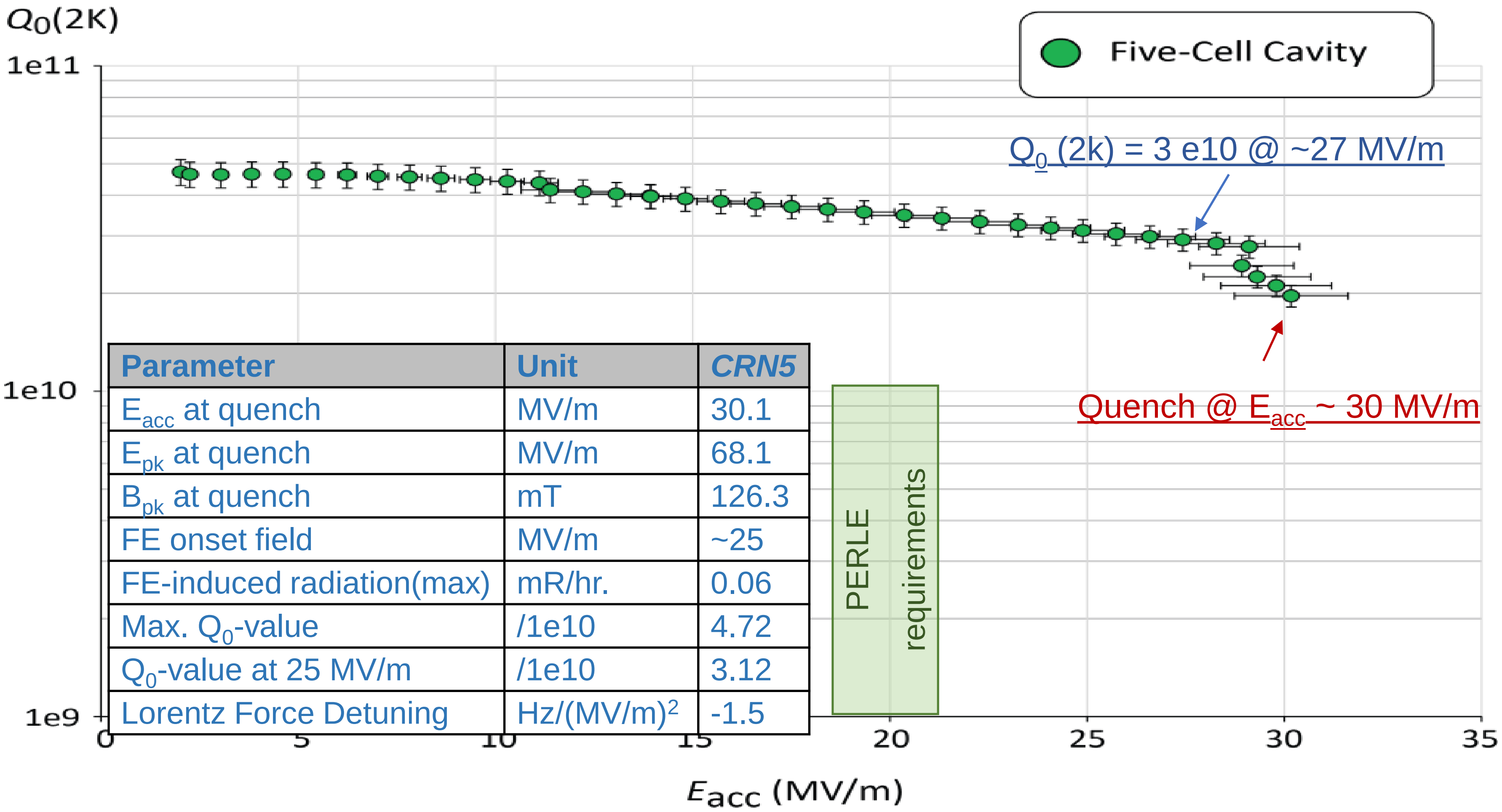




The first Nb 802 MHz 5-Cell cavity fabricated October 2017 at JLAB

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

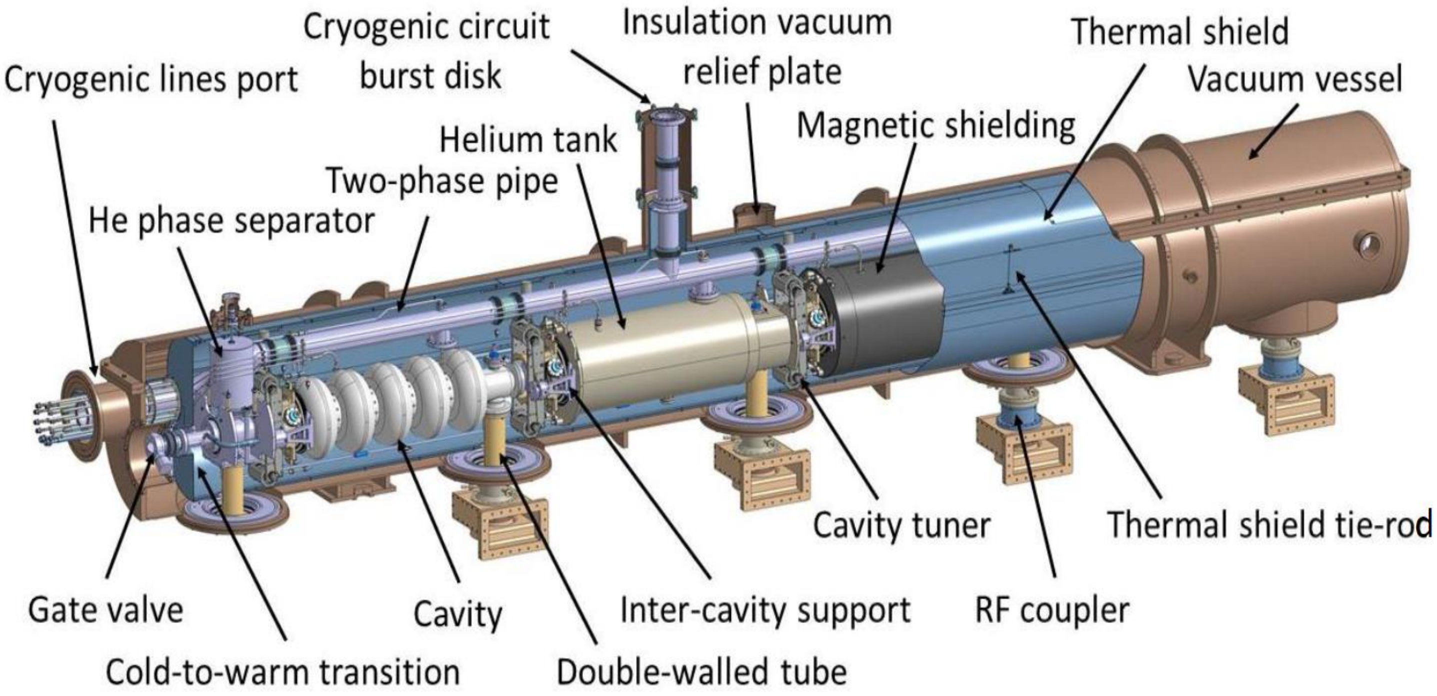
For more details: F. Marhauser's talk in the FCC Week, April 2018, Amsterdam, Netherland

Cryomodule design study:

LAL/IPNo – CERN Collaboration

Courtesy to Gilles Olivier

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

PERLE

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.

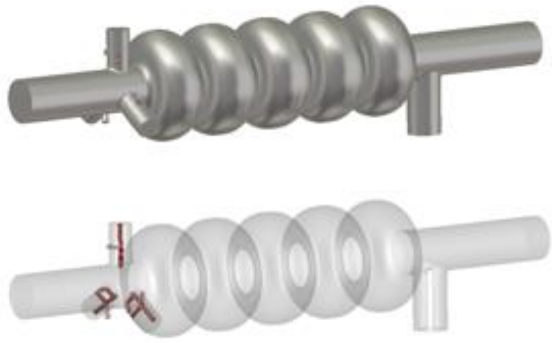
Ongoing studies:

- HOM coupler study to address the following questions:
  - → How many extraction ports: Risk of interference between CTS and HOM dampers
  - → What kind of damper (waveguide, loop coupling)?
  - → Power to extract: W, tens of W, more?
  - → Active helium cooling needed? or only thermalization by copper braids.

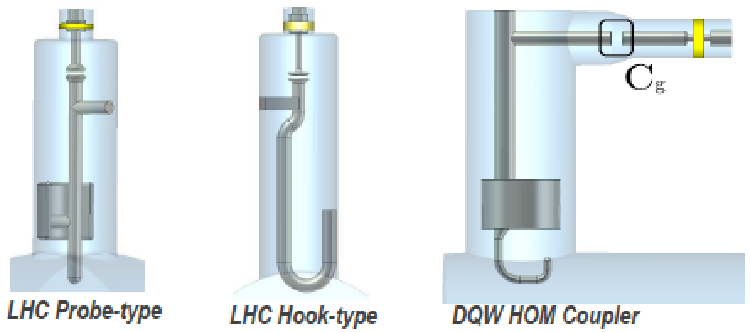
HOM coupler studies

LAL/IPNo – CERN and JLAB Collaboration

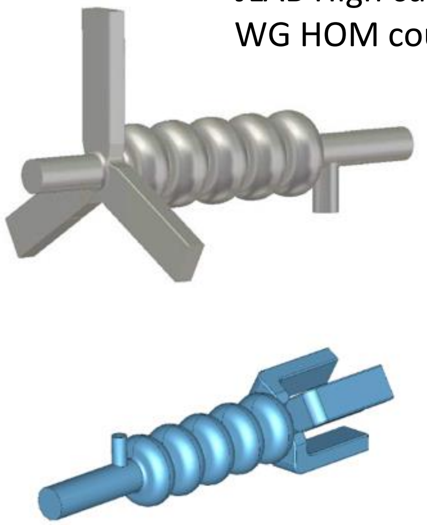
Several HOM coupler types were investigated for adaptation to the new cavity :



HOM 'Y' end-group with 3 coaxial couplers (here with scaled TESLA-type couplers)



JLAB High current (HC) WG HOM coupler type



- Waveguide couplers could be 'overkill' for PERLE since 3-pass peak beam current is comparably small (< 100 mA)
- Yet, trapped *TE*111 and *TM*110 dipole modes with high impedances could be better captured with coaxial couplers (cf. *Supercond. Sci. Technol. 30 (2017) 063002*)

HOM coupler studies

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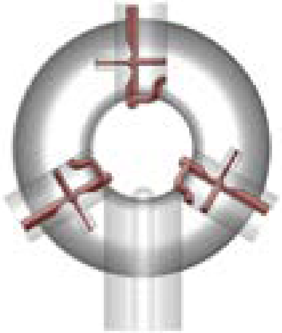
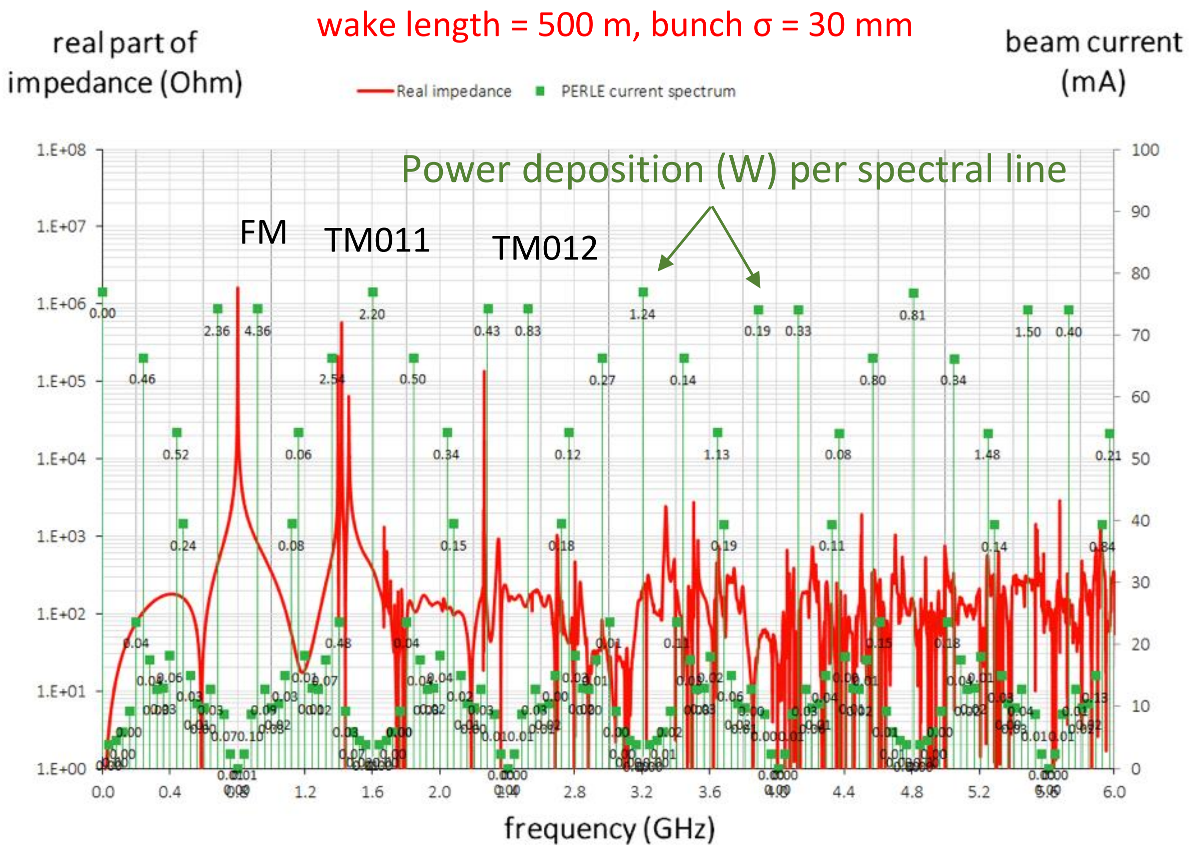


Scaled DESY/TESLA-type HOM couplers with Y configuration



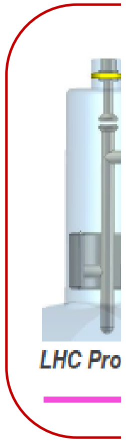
Benefit of 'Y' end-group:

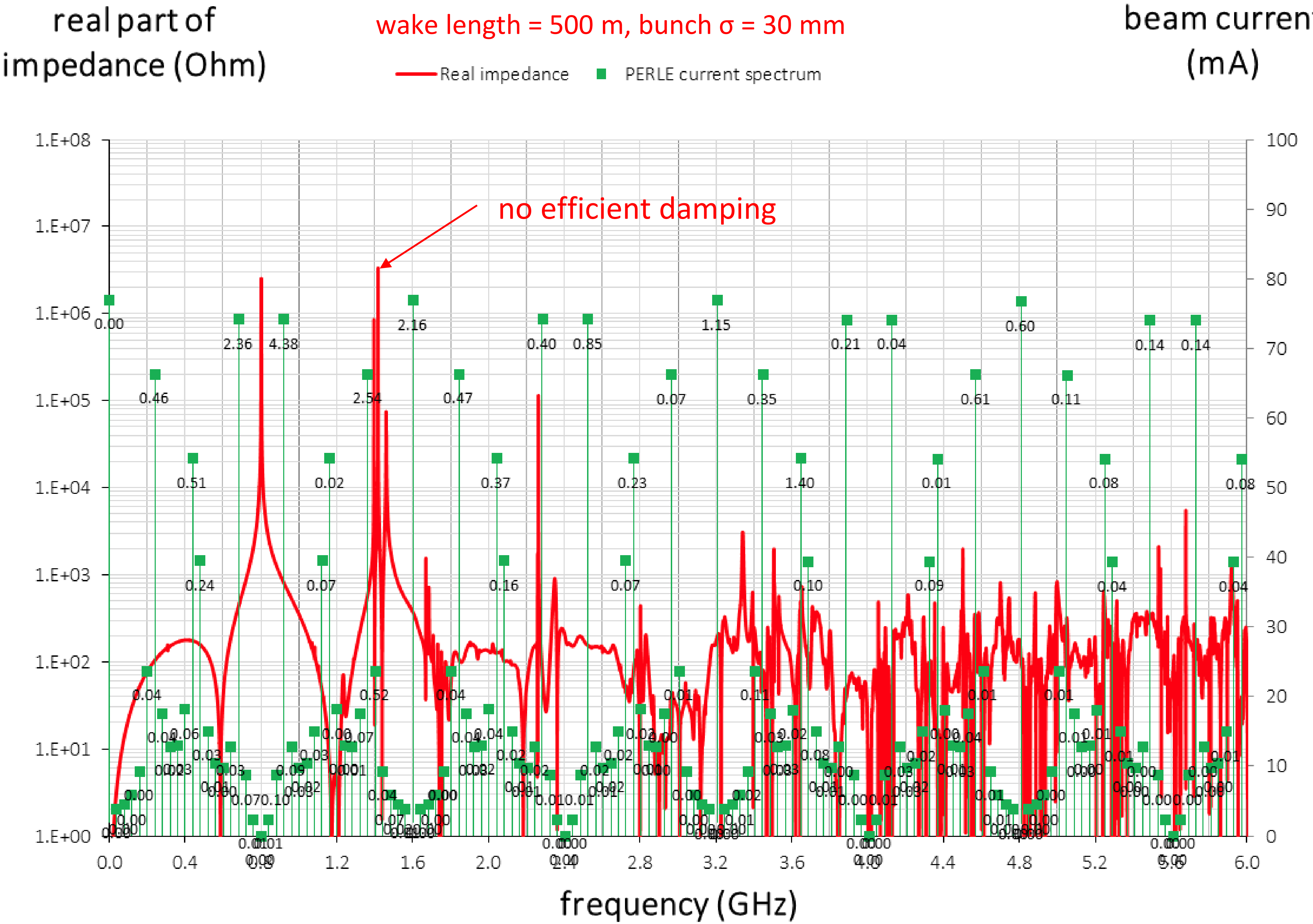
- Minimizes/eliminates dependency on transverse mode polarization
- Monopole power deposition to each coupler quasi identical

Disadvantage:

Space occupied in the Cryomodule and risk of interference with cavity tuning system

HOM co





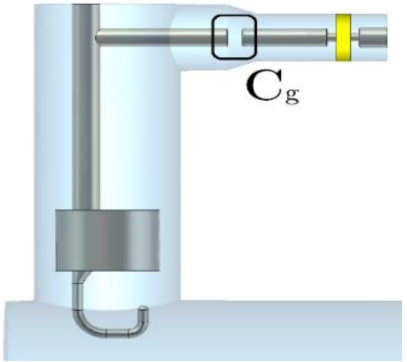
Broadband LHC type

solved.

HOM coupler studies

LAL/IPNo – CERN and JLAB Collaboration

The DQW HOM coupler can deliver a high value of transmission at both first higher order dipole and monopole band.

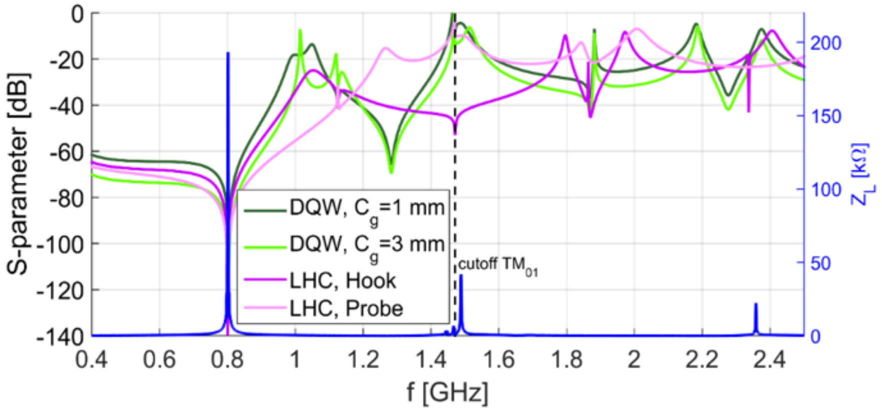


DQW HOM Coupler

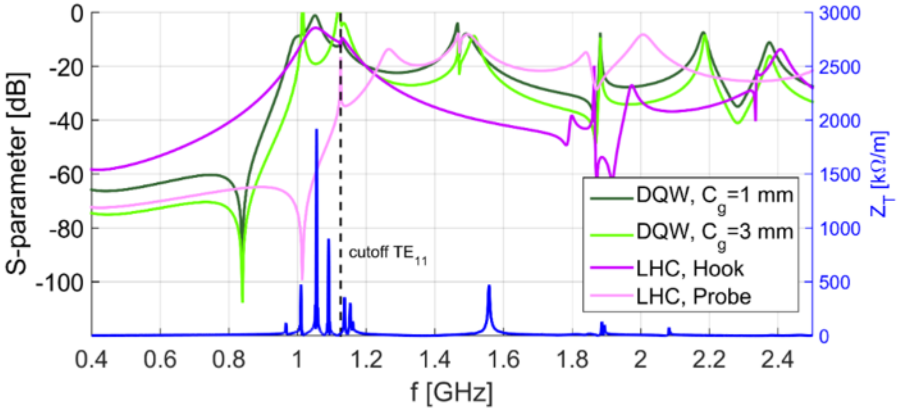
C_g = 3 mm

C_g = 1 mm

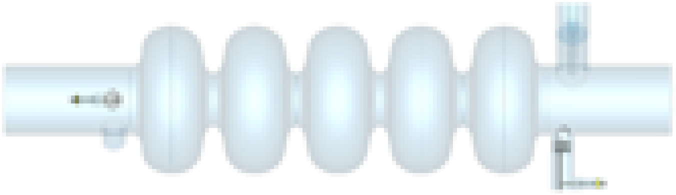
TM01-TEM *transmission (Monopole coupling)*

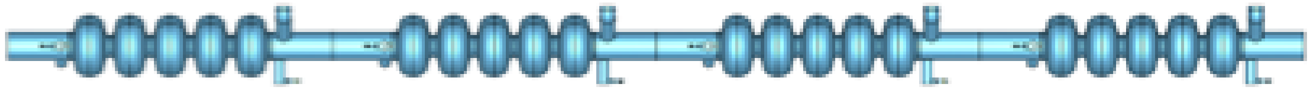


TE11-TEM *transmission (Dipole coupling)*



2 DQW

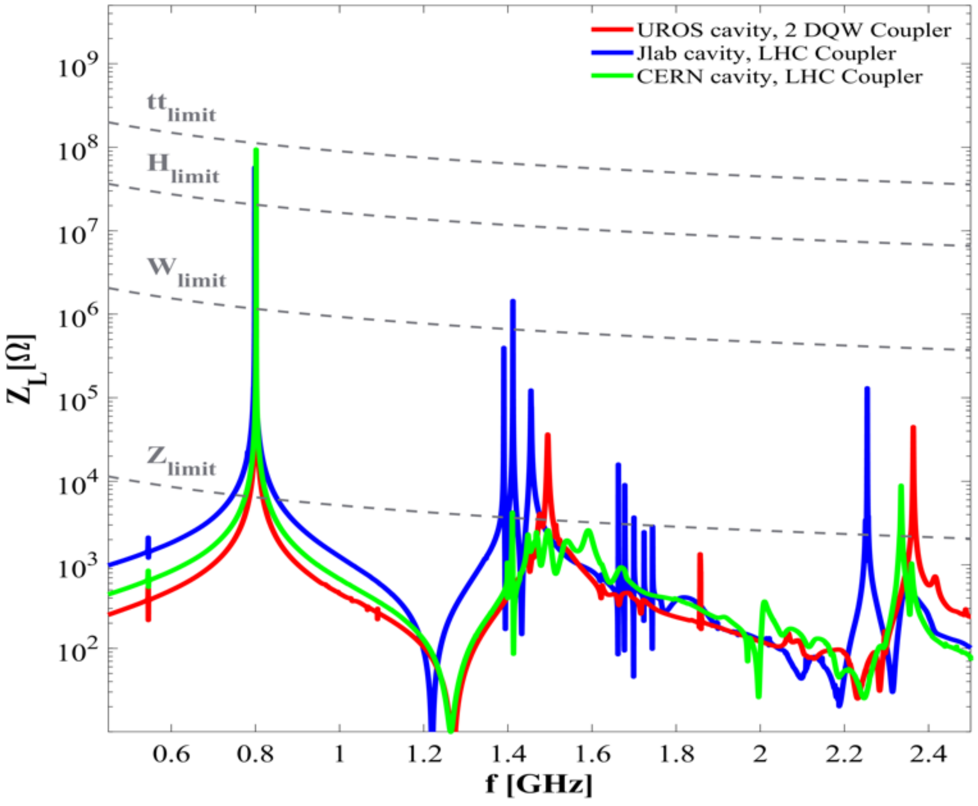


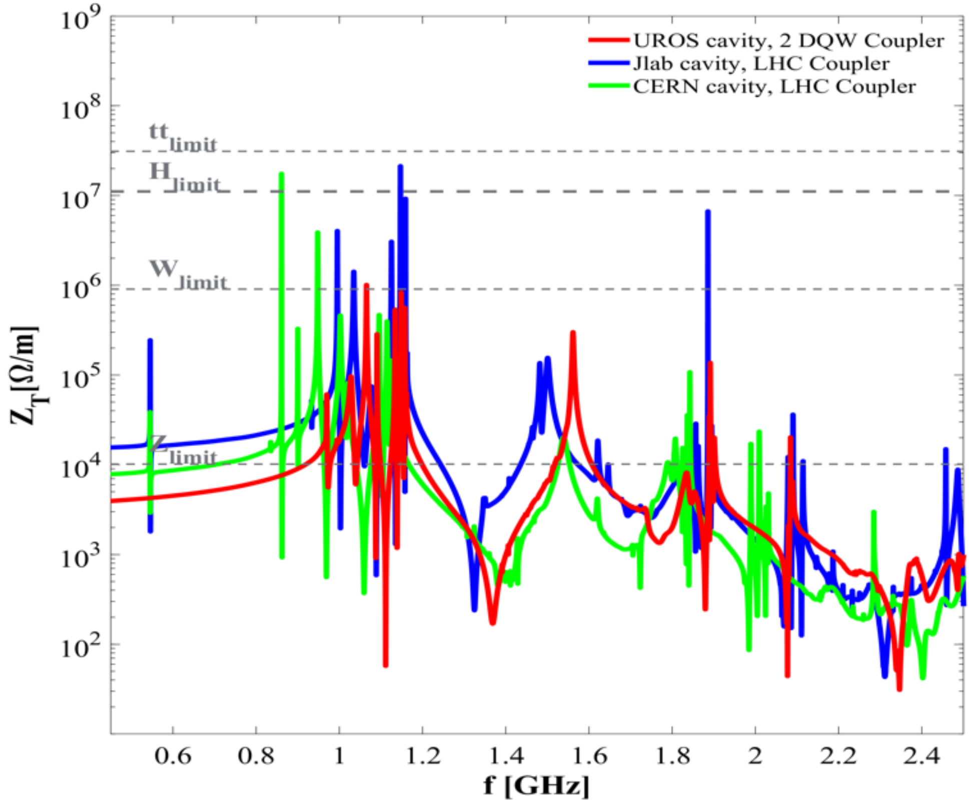


*** Impedances are for bare cavity and the peaks are not fully resolved.**

HOM coupler studies

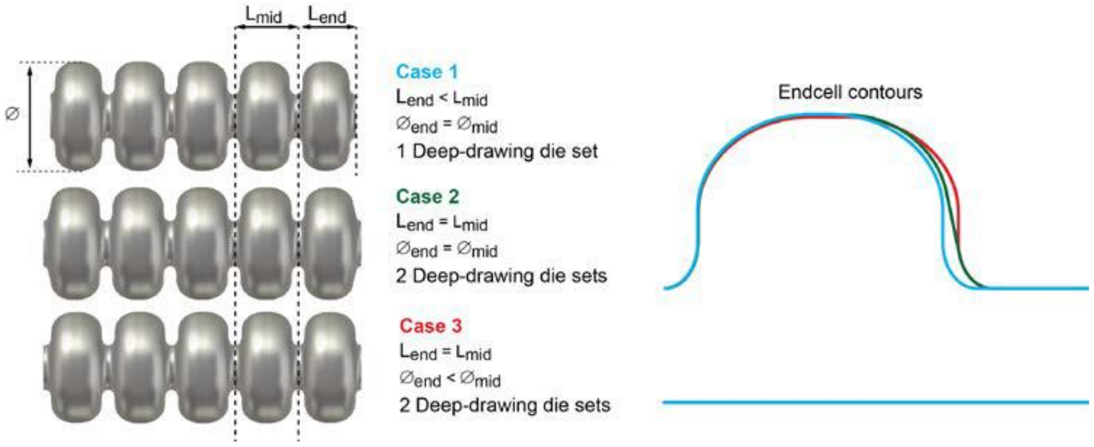
LAL/IPNo – CERN and JLAB Collaboration

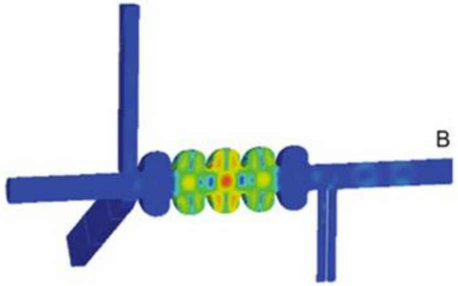


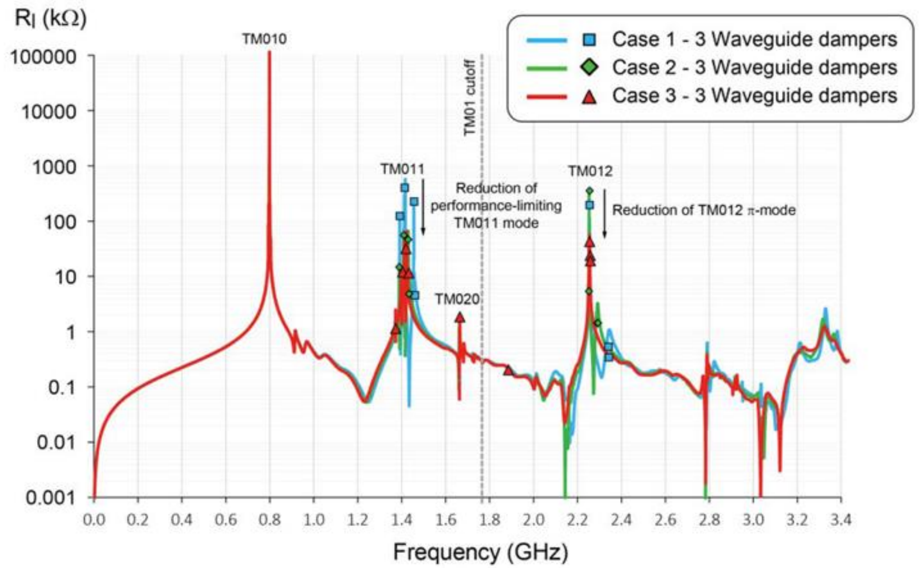


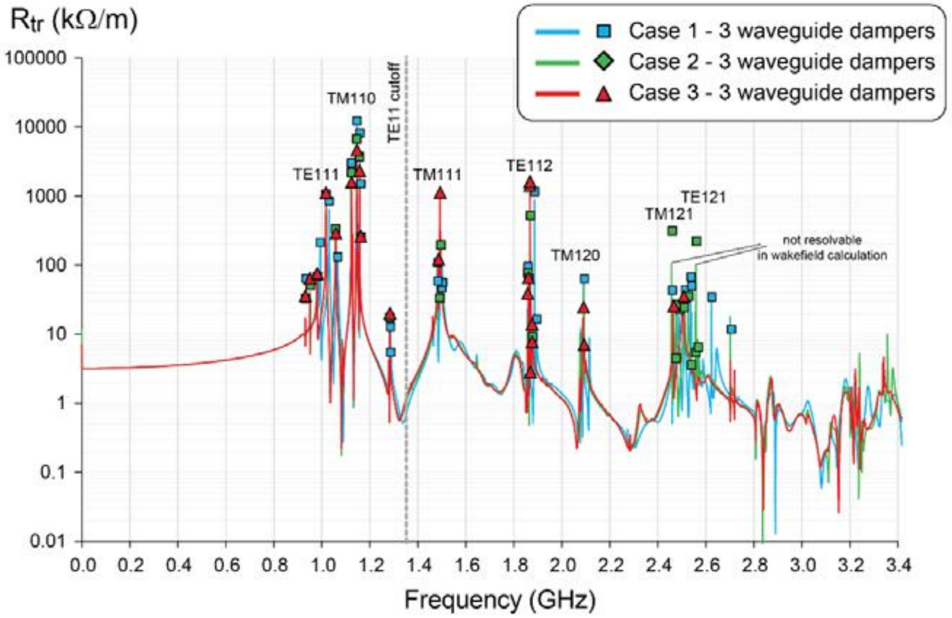
HOM coupler studies

LAL/IPNo – CERN and JLAB Collaboration









LAL/IPNo – CERN and JLAB Collaboration

Main conclusions of the HOM workshop:

- Regarding SPL cryomodule constrain (space available for HOM couplers), using 2 DQW HOM couplers seems to be the most convenient solution. However, more in deep studies are required taking into account the specifications of PERLE cavity, the beam parameters and bunch recombination pattern.
- Any new HOM coupler version should consider 3D multipacting analyses Just scaling from existing design can be dangerous due to potential MP.
- Regarding the power dumped in the HOM couplers, active cooling is necessary and should be integrated during cryomodule design.
- Cavity end cells shape could be optimised for a better efficiency of HOMs extraction.
- PERLE project requires dedicated coupler design studies for given cavity→ this will be done during the 2nd cryomodule design optimisation.

The site:

PERLE footprint: 24 x 5.5 x 0.8 m^3

Administrative classification of PERLE:

According to French safety regulation (Code de l'environnement L593-2, Décret n°2007-830 du 11 mai 2007), an electron accelerator is considered as Basis Nuclear Installation (INB) when these two criteria are reached simultaneously:

- Beam energy > 50 MeV
- Beam power > 1 kW

In case of PERLE:

Parameters	Values
Bunch charge	500 pC
Bunch spacing	25 ns
Average current	20 mA
Beam energy	7 to 500 MeV
Beam power	140 kW to 10 MW

The « INB » administrative regime **would not be applicable** to PERLE if it is proven that beam losses of power > 1 kW could not be maintained for relatively long time (>1s) in all cases (exploitation or accidental beam loss scenario).

Types de pertes	Puissance perdue	Durée du phénomène	Phénomènes physiques limitant le phénomène
Pertes d'exploitation			
Perte continue sur le piège à faisceau d'exploitation	75 kW	Continue	Énergie des électrons de 7 MeV
Perte continue en exploitation normale le long de l'accélérateur	Inférieure à 1 kW	Continue si pas de systèmes de protection machine (MPS) Avec MPS, dur[illegible] inférieure [illegible] second[illegible]	Échauffement des é[illegible]ments par interaction [illegible]c le faisceau primaire d'électrons
Perte instantanée sur un piège à faisceau d'urgence	Puissance crête : 16 MW - 30 MW Puissance moyenne : 5 W	175 [illegible]	
Pertes acciden[illegible]lles			
Pertes de faisceau sur les cavités supraconductrices	Inférieure à 1kW	0,[illegible] µs	Quench dû à l'échauffement local des parois des cavités supraconductrices
Pertes de faisceau sur les arcs de recirculation ou un collimateur	Inférieure à 1 kW	C[illegible]ambre à [illegible]ide : 2,4 ms - 1[illegible] ms Mâc[illegible] collimat[illegible] [illegible]8 ms - [illegible]9 ms	Fusion locale du matériau entraînant la dégradation de la qualité du vide
P[illegible]tes virtuell[illegible]			
Perte sur cible épaisse - cavité supraconductrices et chambre à vide amont/aval	Puissance [illegible]e : Inférieure à 1 kW	1[illegible] - 24 ms	Fusion locale du matériau entraînant la dégradation de la qualité du vide
Perte sur cible épaisse - Arc de recirculation 1-5	Pu[illegible]ance crête - moyen[illegible] avant arr[illegible]t r[illegible]upération P[illegible]ance crête après [illegible]rte du phé[illegible]ne de récupéra[illegible] : 17 MW - [illegible] MW Inférieure à 1 kW	875 ns 11 ms - 24 ms	Fusion locale de la cible entraînant la dégradation de la qualité du vide
Perte sur cible é[illegible]sse - Arc de recirculati[illegible]5	Inf[illegible]e à 1 kW	10 ms	Fusion locale de la cible entraînant la dégradation de la qualité du vide
Perte sur cibl[illegible]nce au niveau d'[illegible] cavité supracond[illegible]tri[illegible] ou une ch[illegible] vide amon[illegible]aval	[illegible]ieure à 1 kW	Variable suivant le matériau : 2 ms -7 ms	Fusion locale de la cible entraînant la dégradation de la qualité du vide
Perte [illegible]le mince au niveau d'un arc d[illegible] recirculation 1 [illegible]	Si perte d'énergie inférieure à 25 keV : inférieure à 1 kW Inférieure à 1 kW	Continue Inférieure à 1 seconde	Fusion locale de la cible entraînant la dégradation de la qualité du vide
Perte sur cible mince au niveau d'un arc de recirculation 6	Si perte d'énergie inférieure à 50 keV : inférieure à 1 kW Inférieure à 1 kW	Continue Inférieure à 1 seconde	Fusion locale de la cible entraînant la dégradation de la qualité du vide

Conclusion: PERLE could not be considered as INB

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.

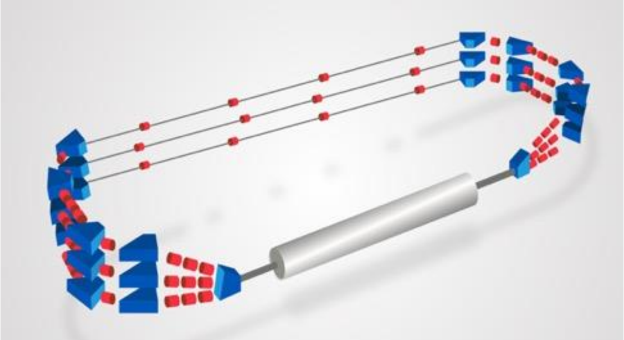
Phase 1: Installation of a single cryomodule in the first straight and three beam lines in the second (consideration motivated by the SPL cryomodule availability)

→ 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.



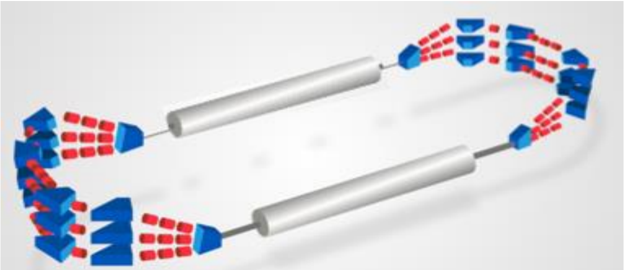
PERLE Phase 1 layout

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, 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:

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

Thank you for your attention