PERLE – a powerful ERL for Experiments

Erk Jensen[1], A. Bogacz[2], O. Brüning[1], R. Calaga[1], V. Chetvertkova[1], E. Cormier[3], W. Kaabi[4], M. Klein[5], F. Marhauser[2], A. Milanese[1], B. Militsyn[6], E. Montesinos[1], D. Pellegrini[1], R. Rimmer[2], A. Stocchi[4], A. Valloni[1], D. Wollmann[1], F. Zomer[4]

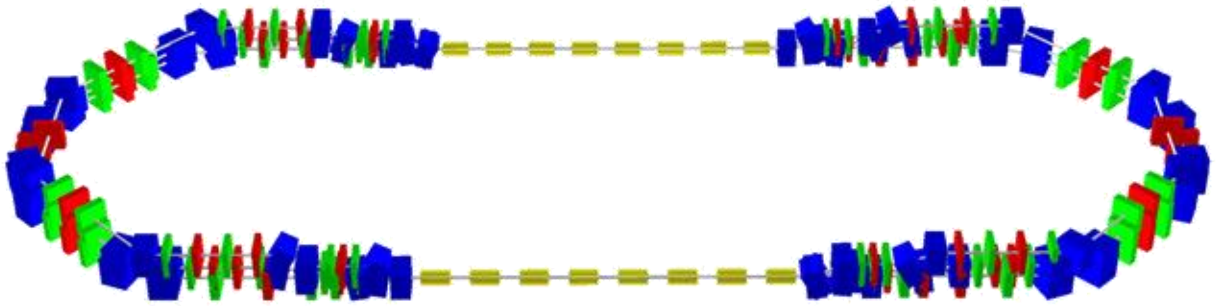
1) CERN
2) Thomas Jefferson National Laboratory (JLAB)
3) Centre Lasers Intenses et Applications (CELIA)
4) Laboratoire de l' Accélérateur Linéaire (LAL)
5) University Liverpool
6) ASTeC

The PERLE proposal was born from the necessity to build a demonstrator to validate design choices of a large, ERL based electron accelerator for LHeC and FCC-he, both proposals for hadron-electron colliders at CERN. The demonstrator features CW operation, large electron current and multi-pass acceleration/deceleration. It soon became apparent that such a small scale demonstrator has huge potential beyond its primary goal, including potential applications in 1) testing of accelerator equipment, 2) elastic ep scattering experiments, 3) a variety of photonics applications including THz radiation, IR and EUV lasing and gamma via laser Compton scattering. The proposal features an 800 MHz superconducting RF system, FMC based, vertically stacked return arcs and a high-current, 5 MeV photo injector. In up to 3 re-circulation passages it could reach up to 900 MeV with currents in excess of 10 mA. A version of PERLE optimized for small footprint is presently considered for implementation at LAL (Orsay).

650. WE-Heraeus-Seminar on "Physics of Energy-Recovery Linacs"

Outline

- Introduction: the context at CERN: LHC, LHeC, FCC
- The basic concept
- Components:
  - Injector, buncher and booster
  - Optics of linacs and arcs, layout and emittance control
- Potential of *PERLE* as γ source by Compton backscattering
- From *PERLE* to *PERLE@Orsay*
  - Cavities, cryomodules and RF power
  - Cost effective magnets



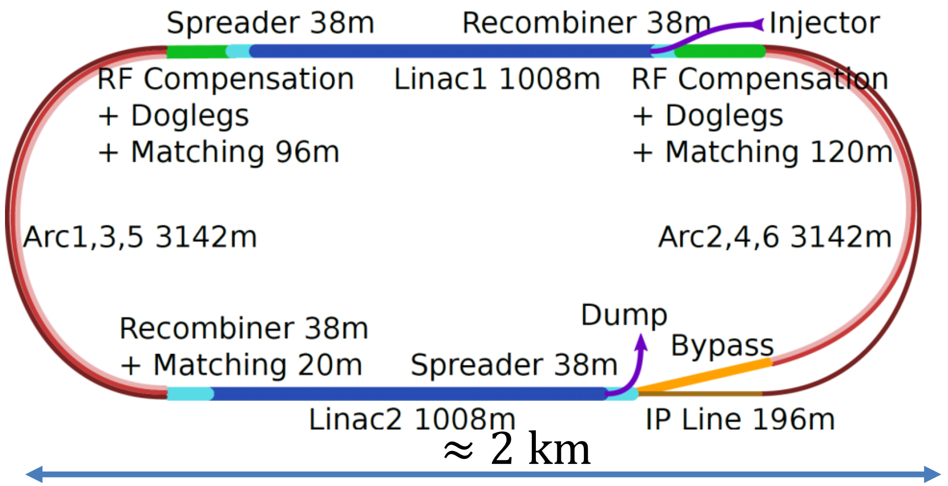
The context at CERN

The present LHC is a proton-proton collider in operation at 13 TeV.

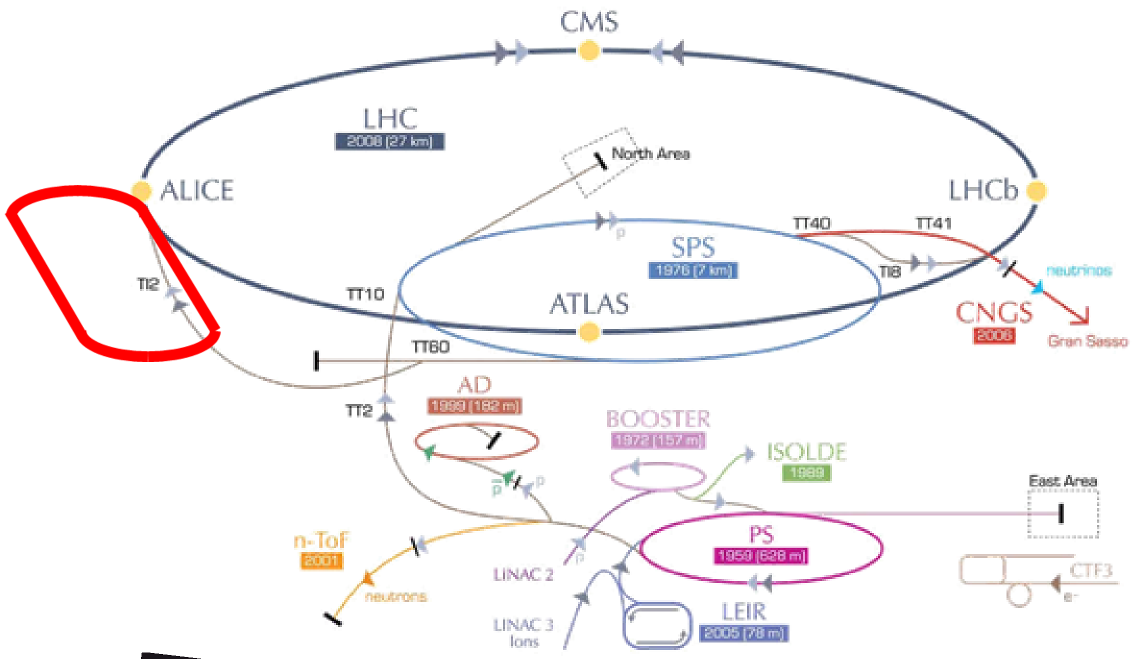
The luminosity upgrade project HL-LHC is in full swing and will be fully implemented 2024-2025 for a physics exploitation until ≈2035.

Adding a 60 GeV electron injector would allow for complementary electron-proton physics simultaneously.

This study is called LHeC. It requires a 60 GeV, 6 mA*) Energy Recovery Linac (ERL).



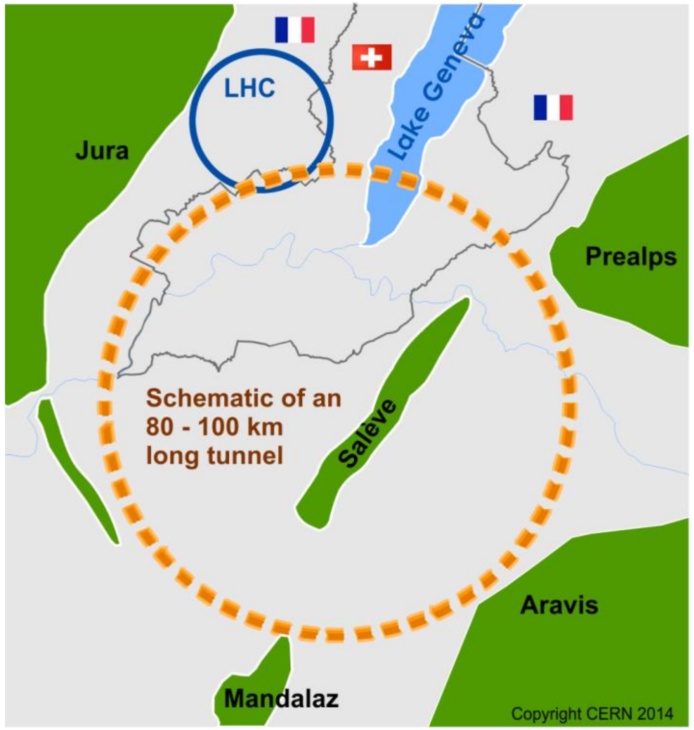
*) Virtual beam power: 360 MW

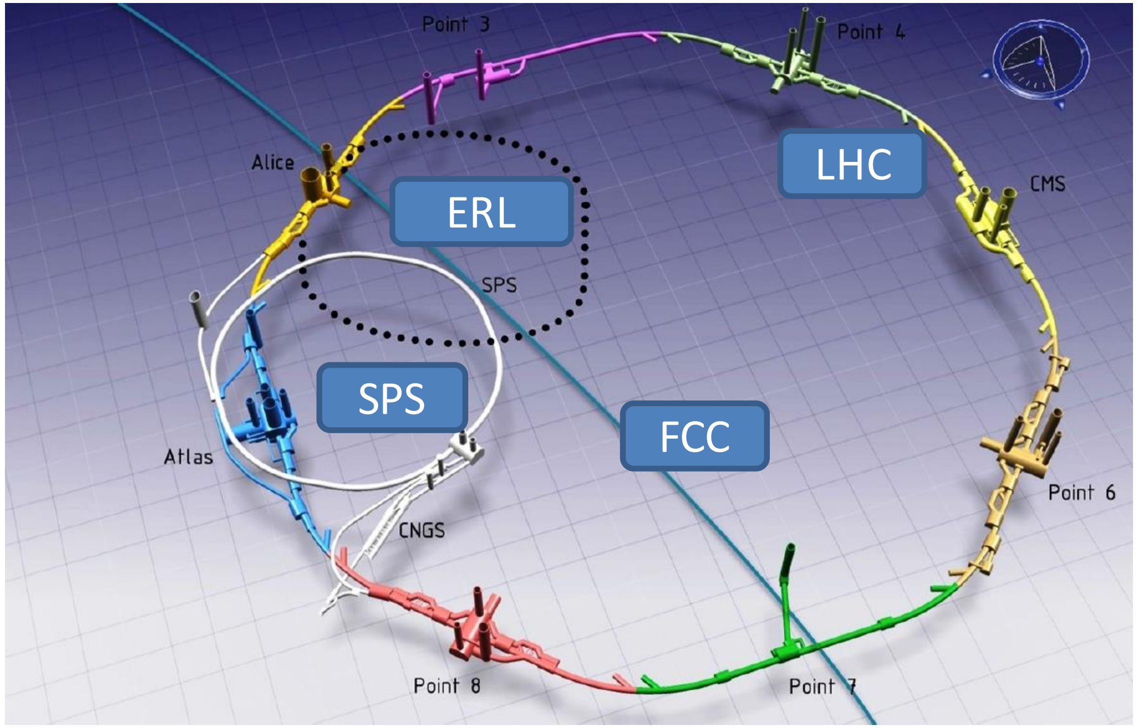


LHeC CDR available.

Compatibility with FCC

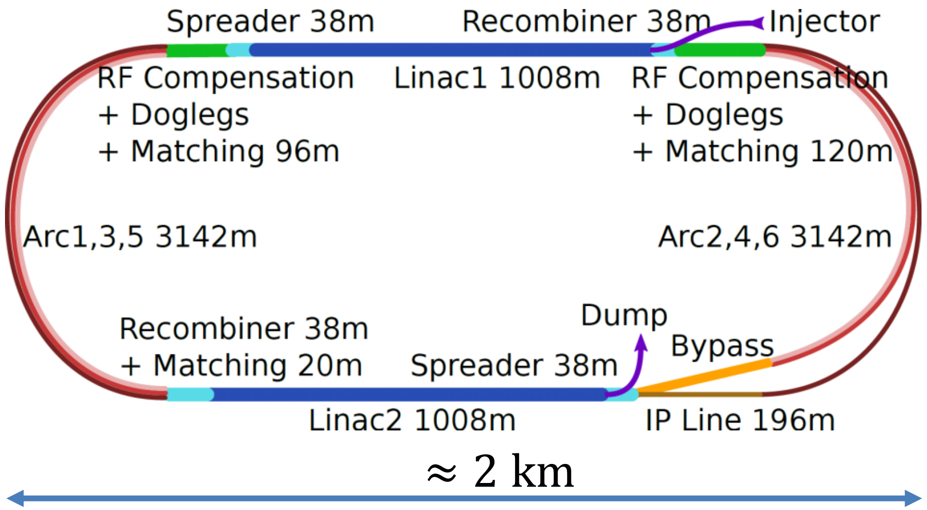
- The FCC (Future Circular Collider) is a study of a 100 km Ø collider, about 3 to 4 times the size of LEP/LHC.
- The 60 GeV ERL is also the baseline injector for a hadron-electron version of the FCC.





The LHeC ERL vs. *PERLE*

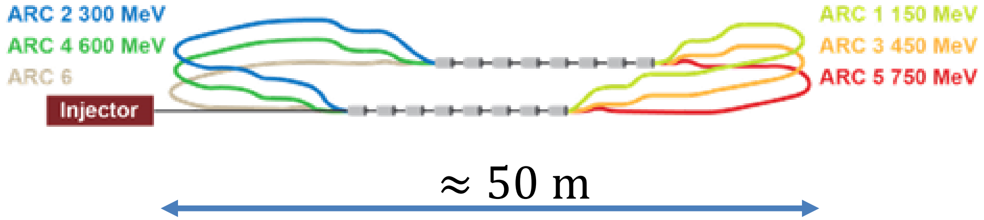
The **LHeC** baseline ERL is a 3-pass ERL to provide a 60 GeV, high-current e- beam. It consists of two parallel 10 GeV SC linacs operating in CW. This is a novel concept



The **ERL Facility *PERLE*** is much smaller: the baseline is a 3-pass ERL to provide up to 900 MeV, to be constructed in stages.

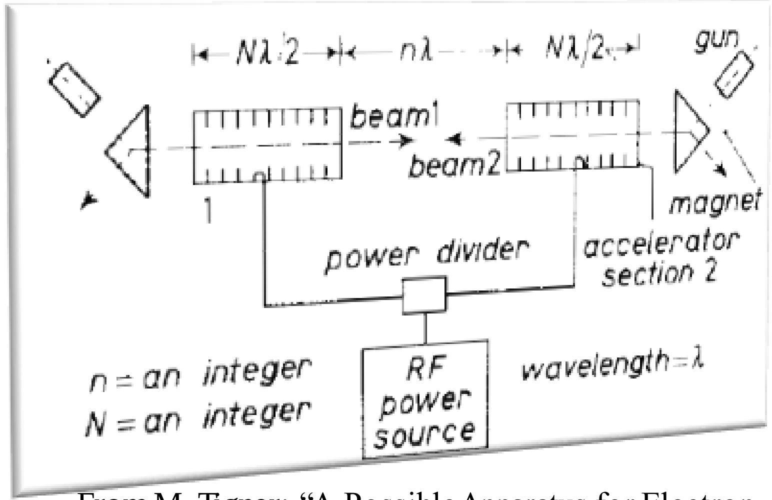
It would allow to

- validate LHeC design choices,
- gain experience with an ERL,
- build up expertise
- … and do interesting physics …



Why study and ERL?

- Because it's a great idea – accelerate, use the beam, then decelerate the beam and recover its energy!
- For all large future accelerators we have an obligation to optimize their energy efficiency!
- Recovering energy or increasing efficiency one gains twice – since needing less energy also means smaller installation, less irradiation and less cooling.
- Look at the 50-year-old concept of Maury Tigner – can you see the TeV-range linear collider with energy recovery?
- To prepare technology for any future accelerator: it's accelerator R&D at its best!



From 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

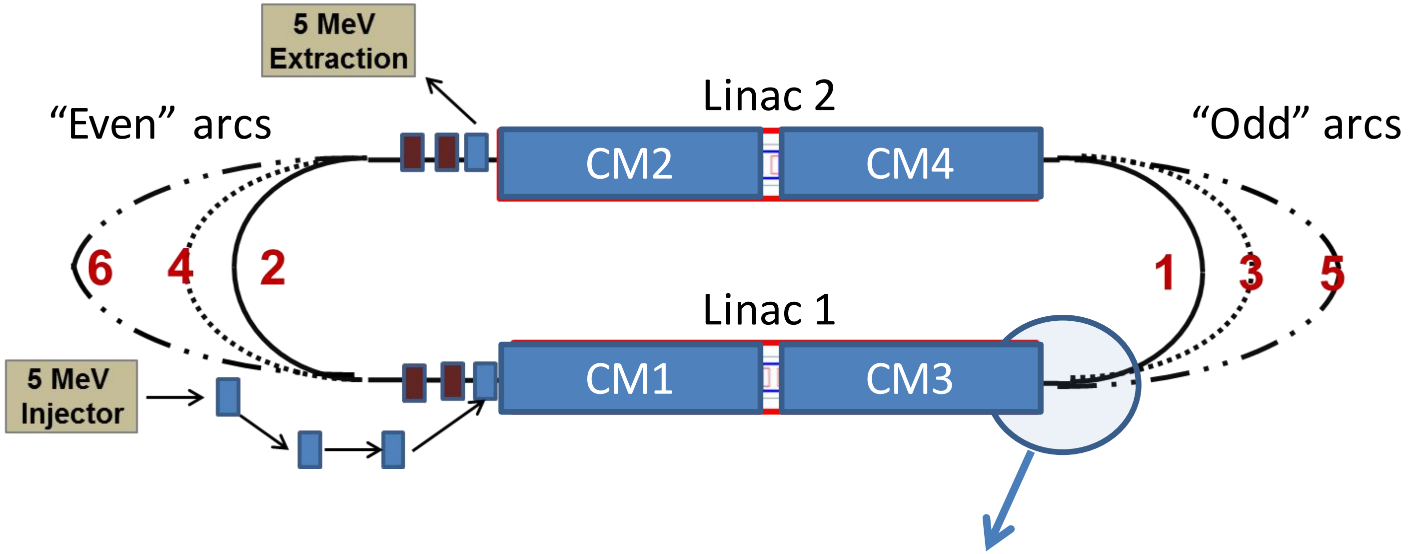
Purpose of *PERLE*

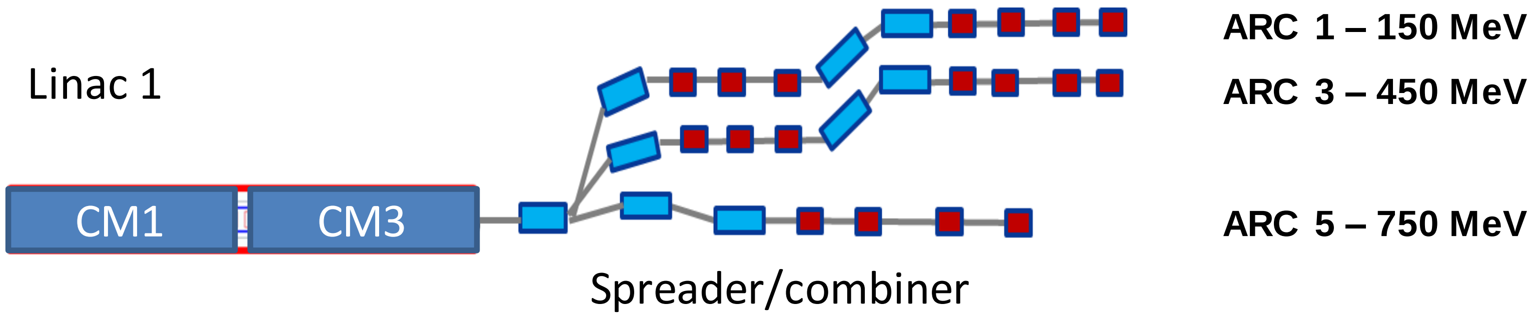
- Study an ERL – to gain expertise and to train staff
  - conceive, design, engineer, construct,
  - build the real thing,
  - test, commission, operate.
- Initially: test SRF cavities/cryomodules
  - Present concept allows to test at 704, 802 and 1300 MHz
  - Complements vertical cryostats and horizontal CM bunkers at CERN for **tests with beam**.
  - Have a real facility – not interfering with HEP – that the next generation of accelerator scientists can work with.
  - Strongly synergetic with other projects – SRF R&D needed in many future accelerators (LHC upgrades, FCC study…)
- But later – it can be used for other applications!
  - possibly it even could become an injector ERL for the LHeC ERL?

The name *PERLE*

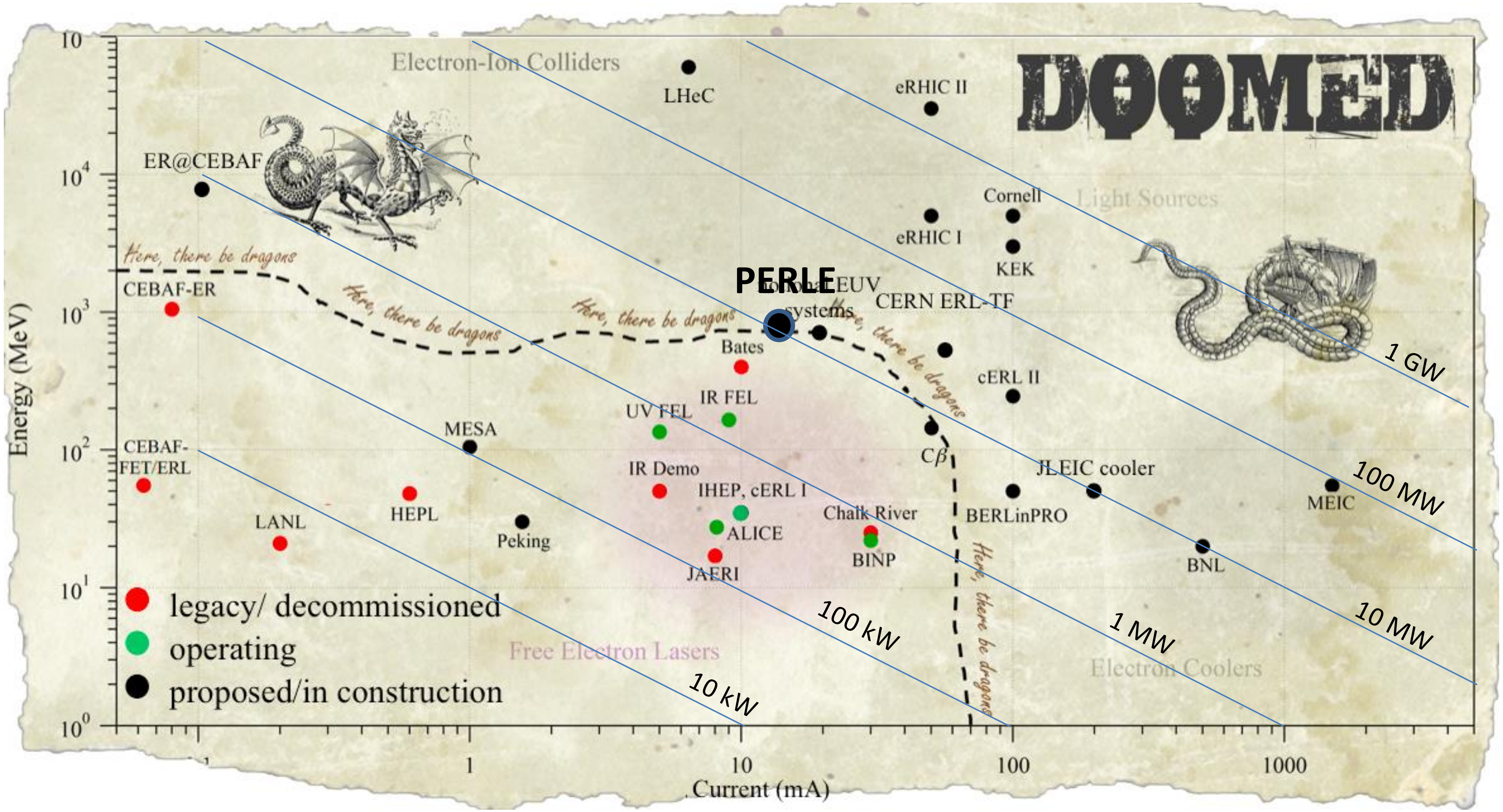
- ***P**owerful **ERL** for **E**xperiments*
- We think the name sounds nice…
- … and in Italian it means "string of pearls"

Conceptual Layout



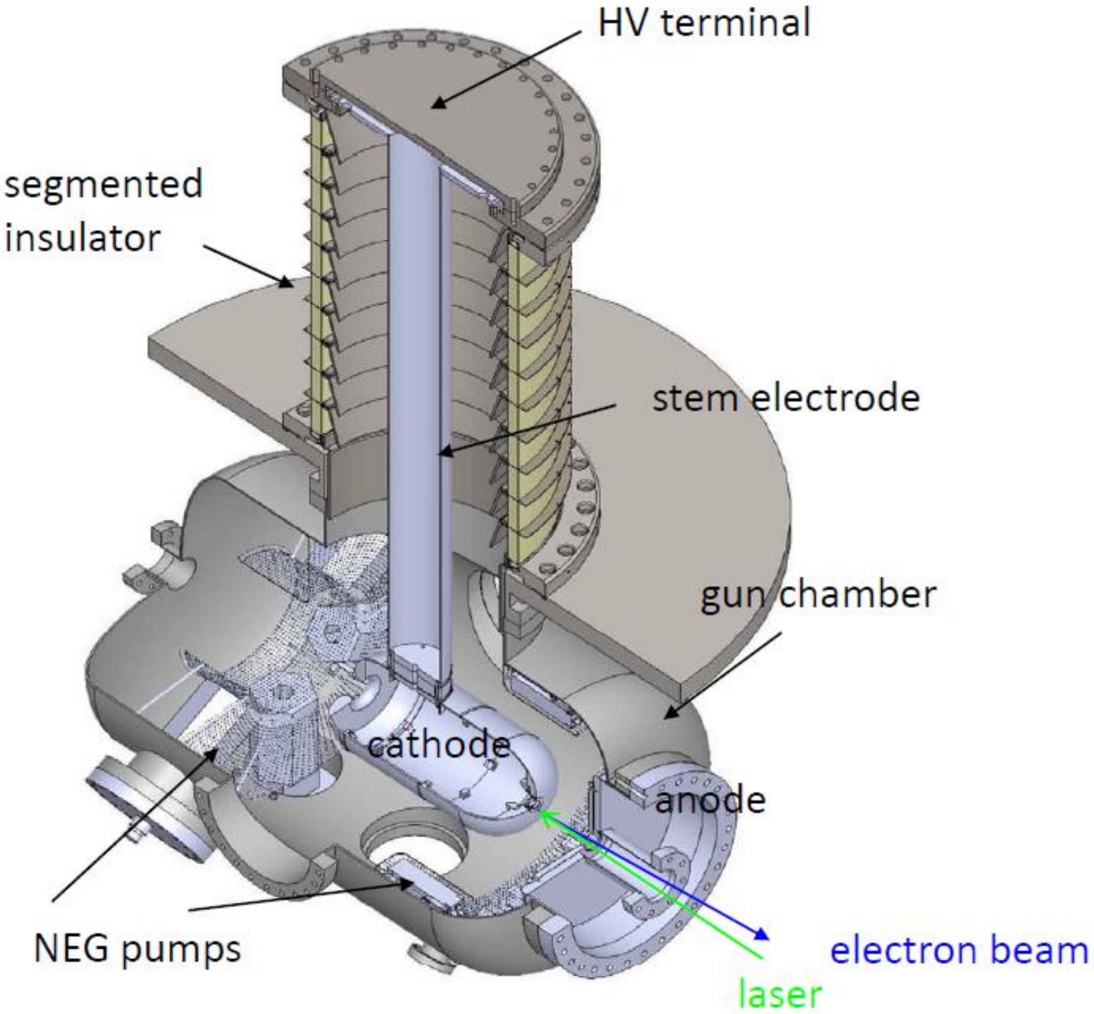


PERLE in parameter space



Courtesy Chris Tennant

Photoinjector – e.g. cERL*) injector

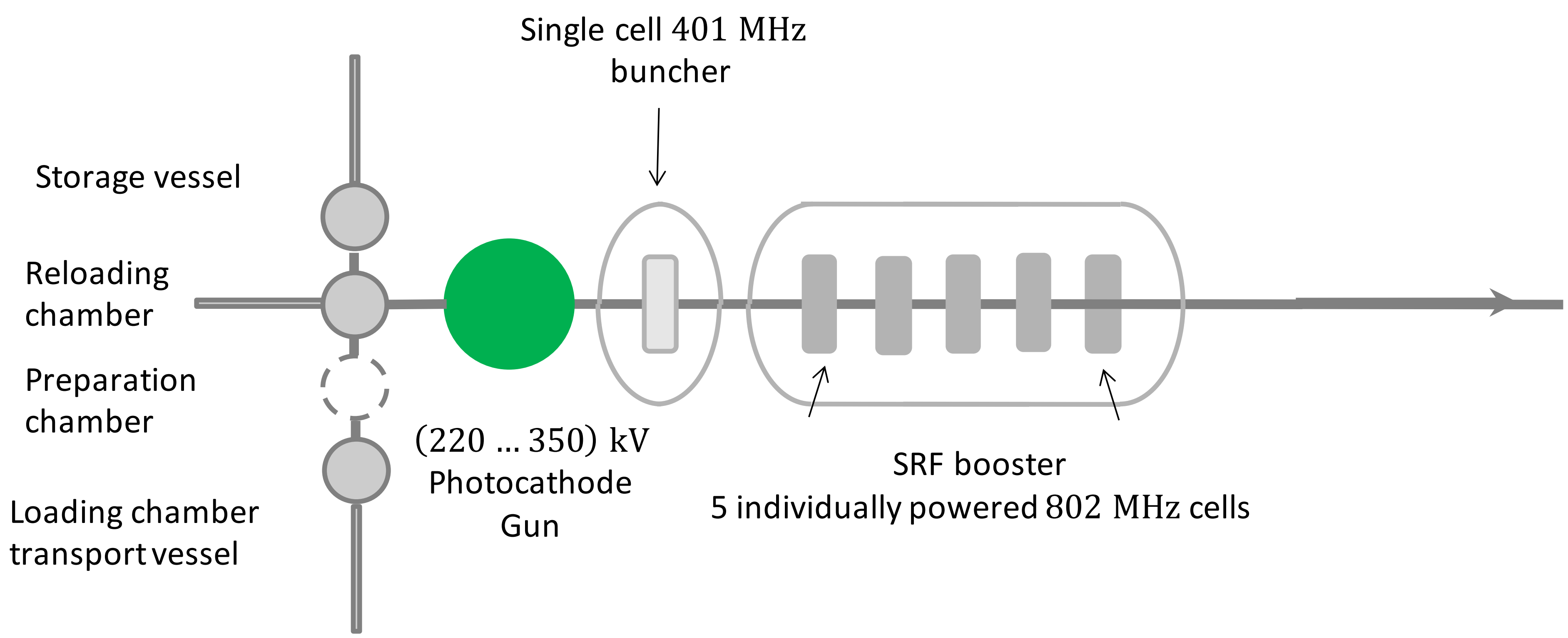


- Maximum voltage achieved – 500 kV
- Maximum design current – 10 mA
- Photocathode – GaAs
- Photocathode preparation system (not shown) integrated with the gun
- For protection of the ceramic insulator from field emission and scattered electrons it is made segmented

*) cERL is the KEK "Compact-ERL"

Boris Militsyn

First ideas for the *PERLE* photoinjector



350 kV for Sb-based photocathodes (unpolarised)
220 kV for GaAs photocathodes (polarized) to reduce dark current
Work in progress…

Boris Militsyn

Choice of photocathode

Material	Typical operational wavelength	Work function	Observed Q.E.	Laser power required for 20 mA	Observed maximum current	Observed operational lifetime
Sb-based family, unpolarised	532 nm	(1.5 … 1.9) eV	(4 … 5)%	3.0 W	65 mA	days
GaAs-based family, polarised	780 nm	1.2 eV	(0.1 … 1.0)%	20.4 W	(5 … 6) mA	hours

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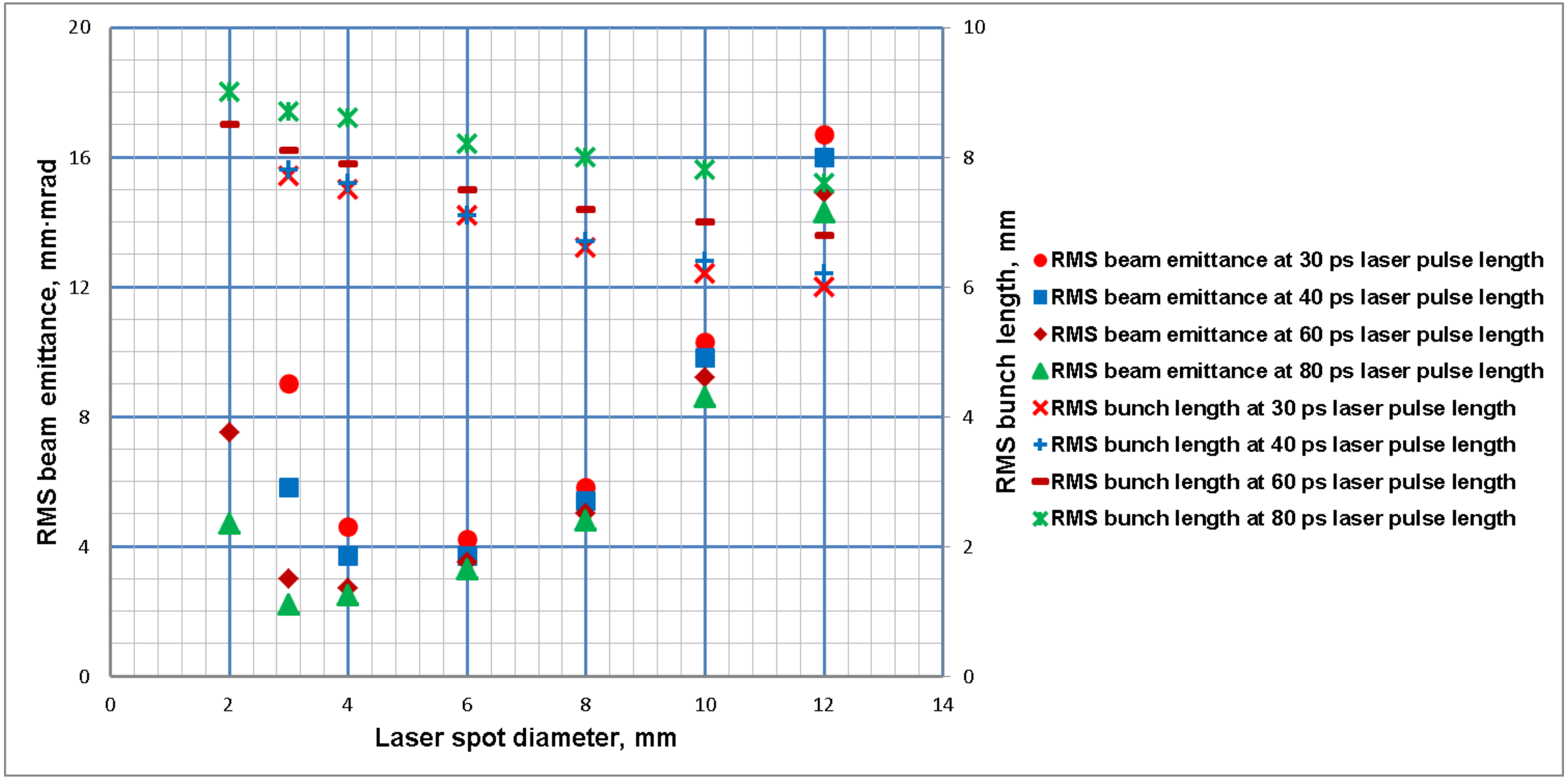
Gun emittance optimization

For 350 kV photocathode and 320 pC bunch charge



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Buncher and booster

- **Buncher:**
  - Velocity modulation of beam requires a voltage of about 1 MV
  - Frequency is defined by the bunch length at the booster and for $8\ \mathrm{mm}$ should be less than $830\ \mathrm{MHz}$. Main harmonic ($401\ \mathrm{MHz}$) is acceptable for $320\ \mathrm{pC}$.
  - Gap should be as short as possible to prevent essential energy sag in the buncher
- **Booster:**
  - Accelerate the beam to $(5 \dots 6)\ \mathrm{MeV}$,
  - It requires RF power (CW) $60\ \mathrm{kW}$ at $802\ \mathrm{MHz}$,
  - Number of cells 4…5, defined by power distribution – operate first two cavities far from crest
  - Individual control and coupling for at least first two cells.

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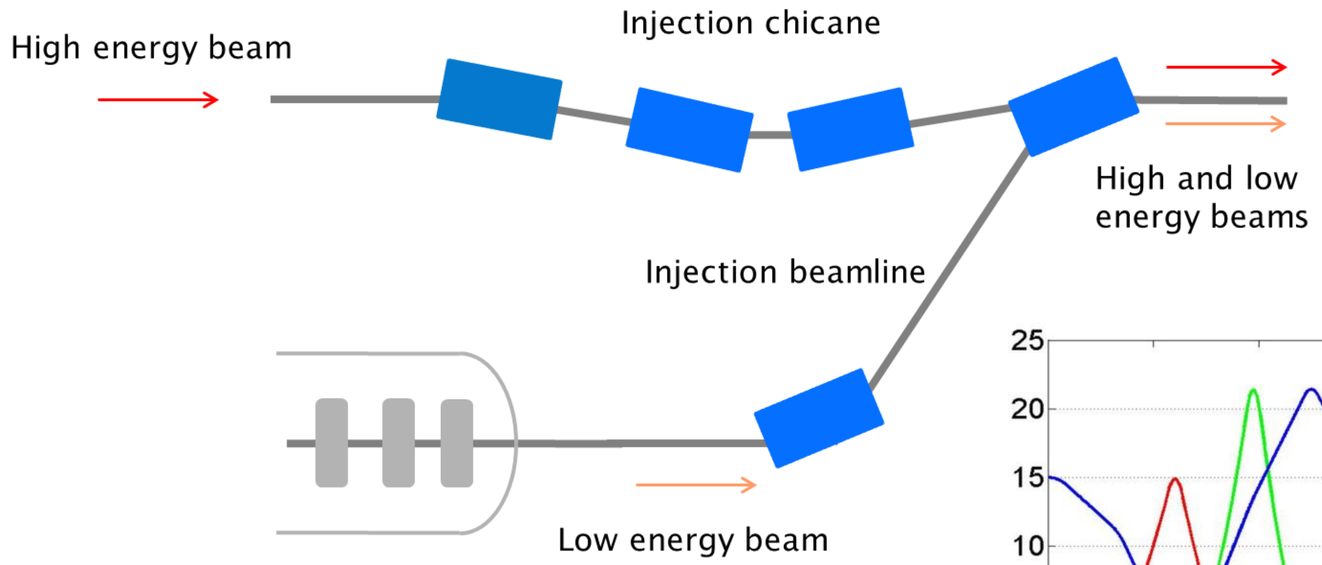
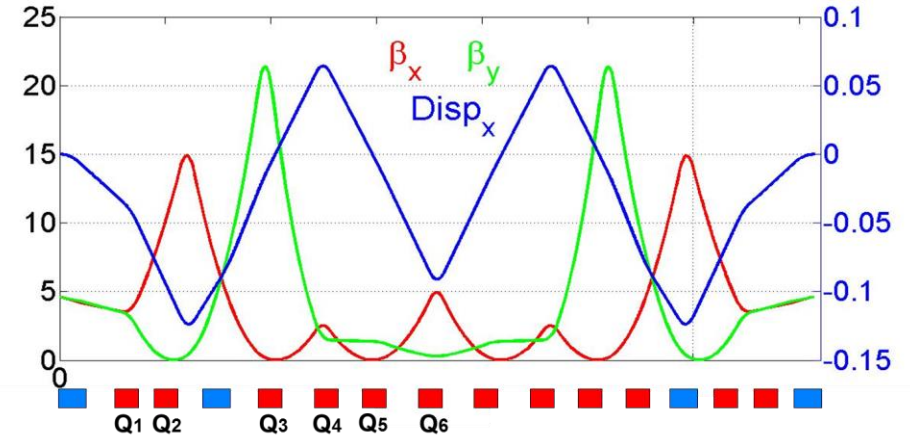
Injection chicane



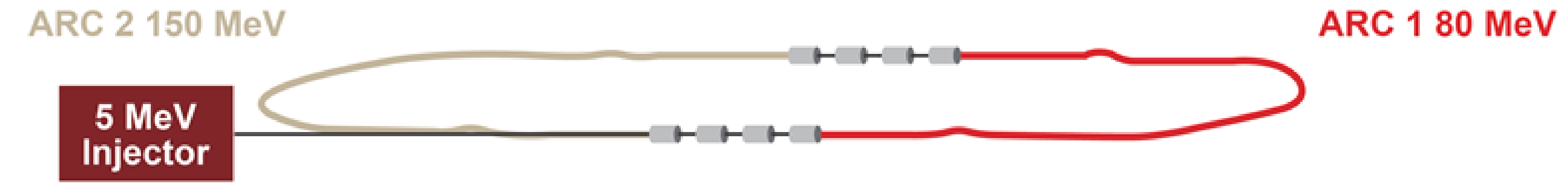


The chicane optics features a horizontal achromat with tunable momentum compaction to facilitate bunch-length control and with Twiss functions matched to the specific values required by the linac.

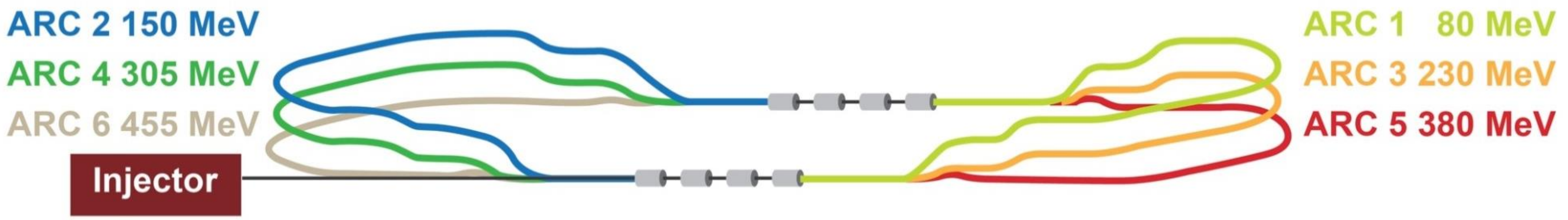
Boris Militsyn, Alesandra Valloni

Possible staged construction

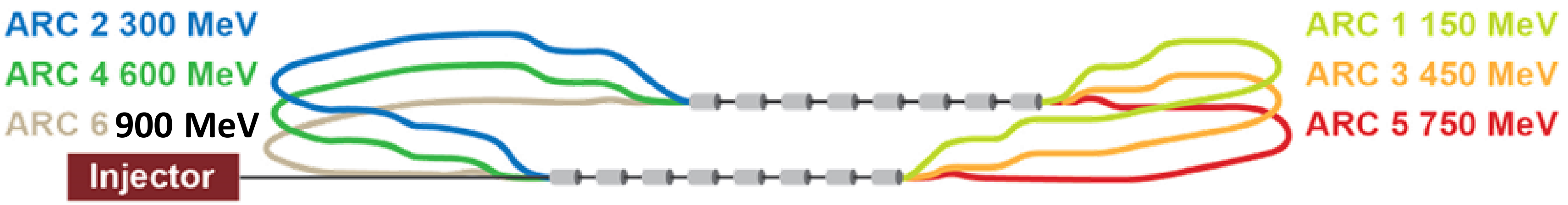
Stage 1 – 2 cryomodules (CMs), test installation – injector, cavities, beam dump.



Stage 2 – 2 CMs, set up for energy recovery, 2…3 passes



Stage 3 – 4 CMs, set up arcs for higher energies – reach up to 900 MeV



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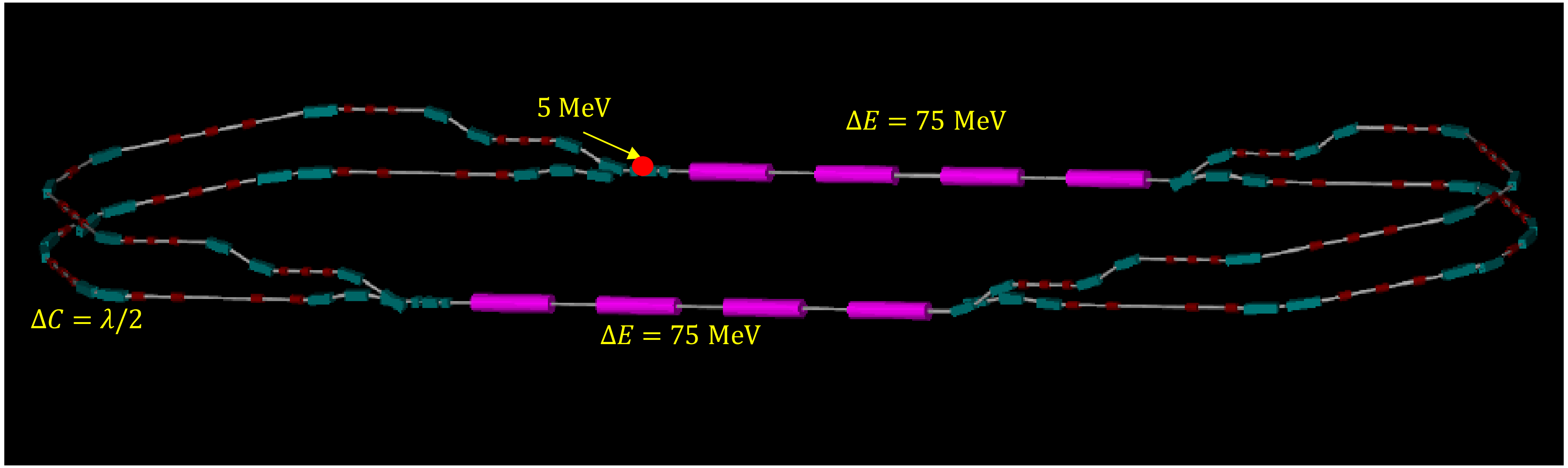
PERLE at 300 MeV – acceleration

2 passes up:



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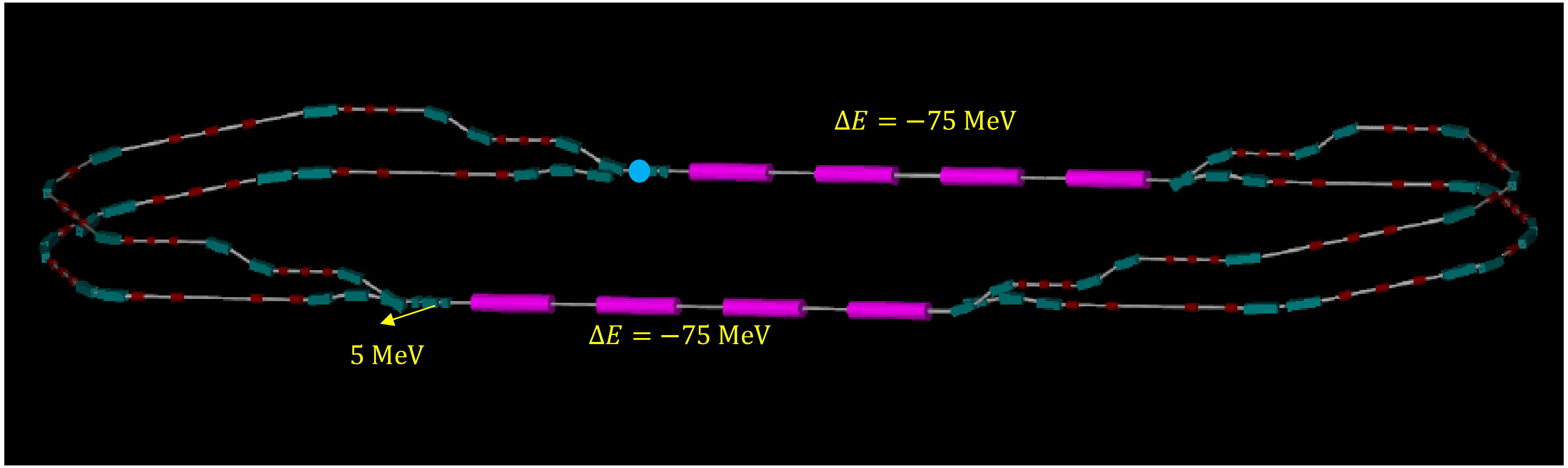
PERLE at 300 MeV – deceleration

2 passes down:



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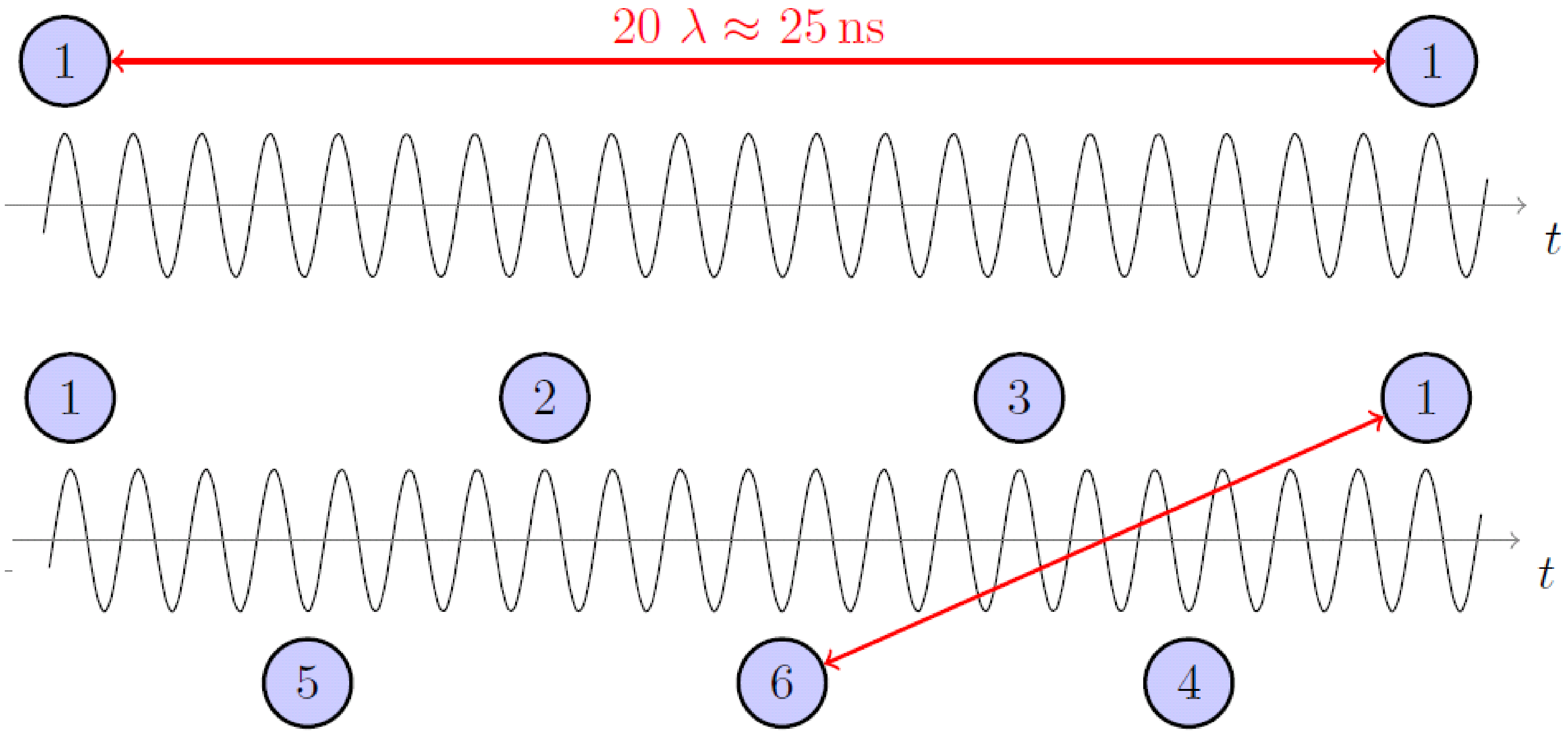
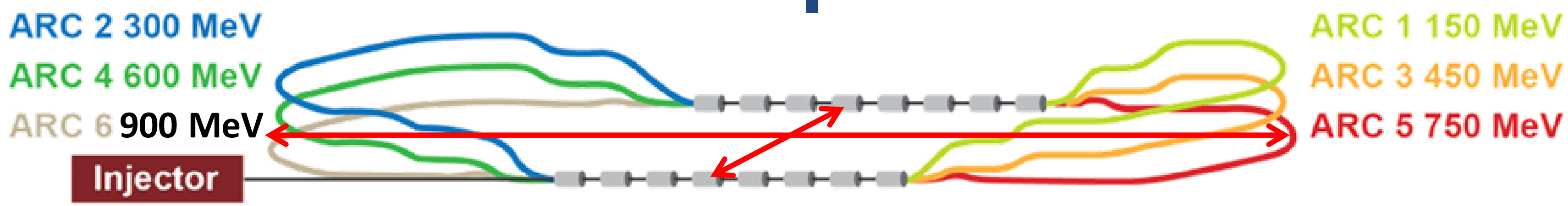
Filling and recombination scheme



Maximum separation between lowest energy passages allows for better damping

Footprint



ARCS

Total length for Pass 1: 99.86 m

$$267 \times \lambda_{RF} = h \cdot n \cdot \lambda_{RF} + 7 \cdot \lambda_{RF}$$

Total length for Pass 2: 99.48 m

$$266 \times \lambda_{RF} = h \cdot n \cdot \lambda_{RF} + 6 \cdot \lambda_{RF}$$

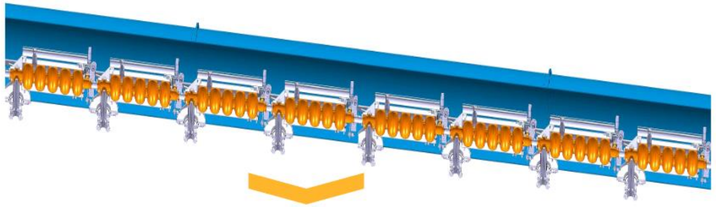
Total length for Pass 3: 98.55 m

$$263.5 \times \lambda_{RF} = h \cdot n \cdot \lambda_{RF} + 3.5 \cdot \lambda_{RF}$$

Total length for 3 passes: 297.9 m

$h = 20$ (bunch distance = $h \cdot \lambda_{RF}$)
$n = 13$ (choice to fit arc length)

LINAC



ONE CRYOMODULE: 8 RF CAVITIES

PARAMETER	VALUE
Frequency	**801.58 MHz**
Wavelength	37.4 cm
Lcavity= 5λ/2	93.5 cm
Grad	20.02 MeV/m
ΔE	18.71 MV per cavity

Linac length: ≈ 12.6 m
Injection/extraction chicane: ≈ 1.42 m

TOTAL DIMENSIONS
42.46 m x 13.66 m

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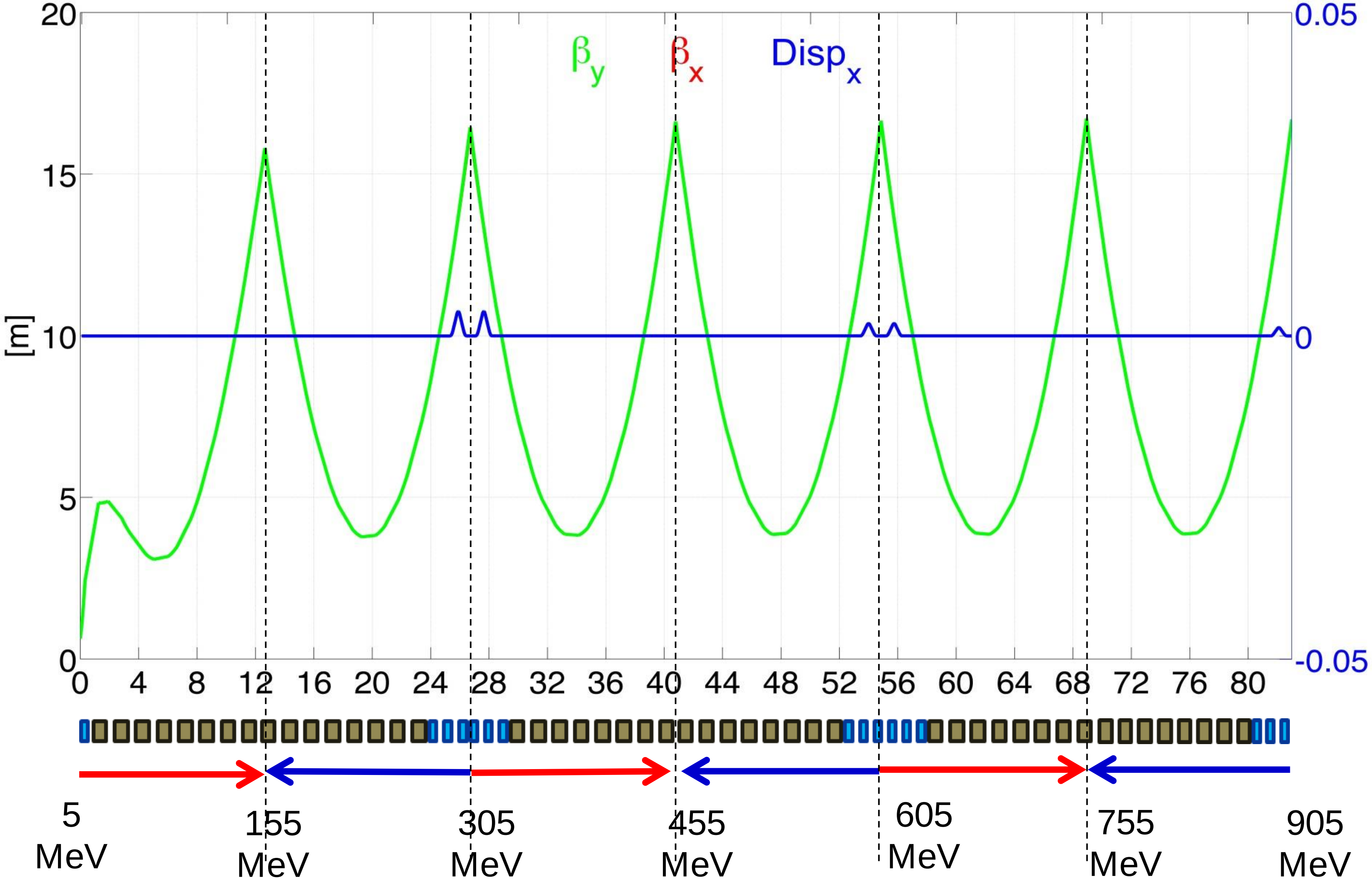
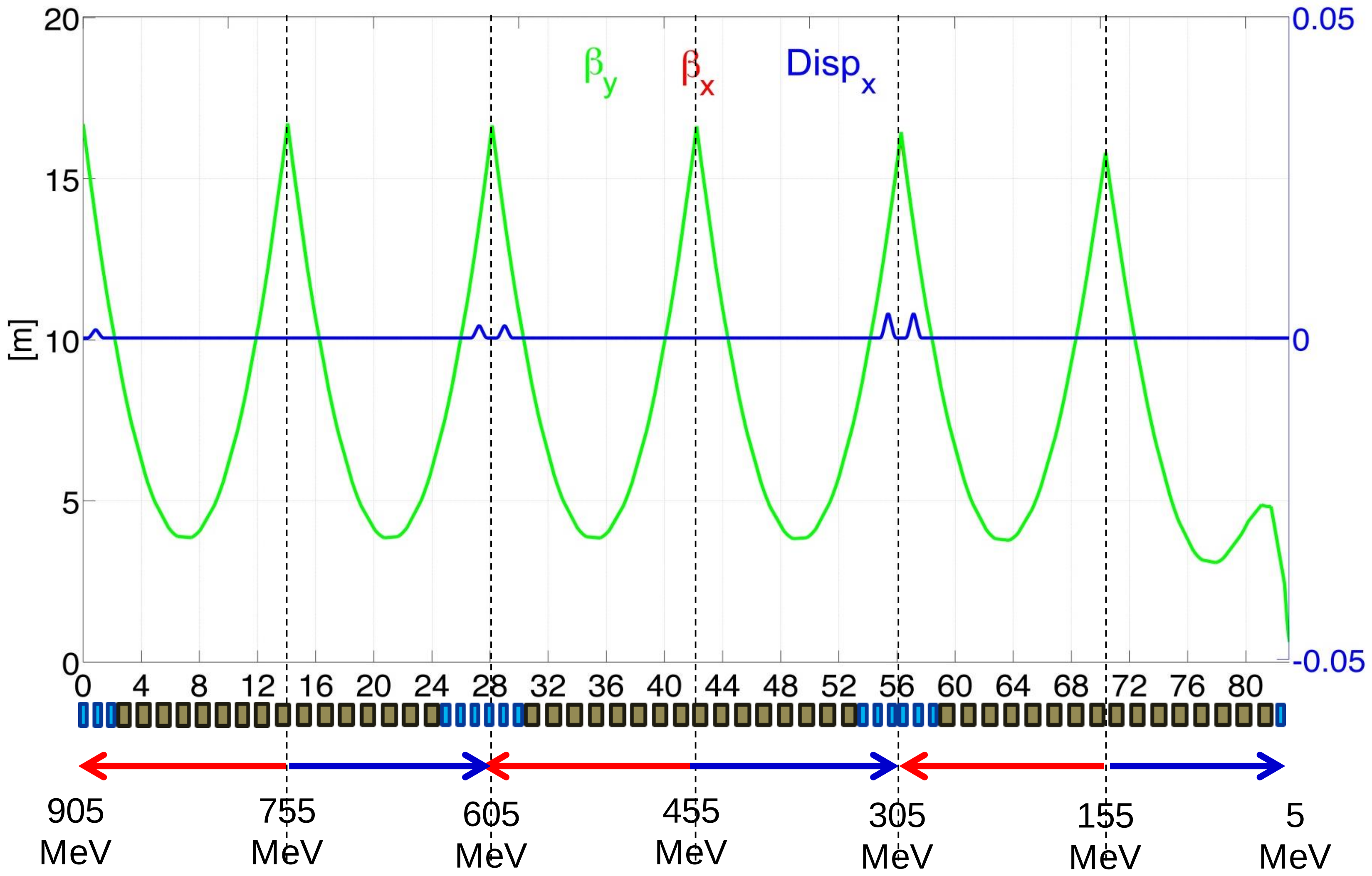
Linac1 multi-pass optics



Linac2 multi-pass optics



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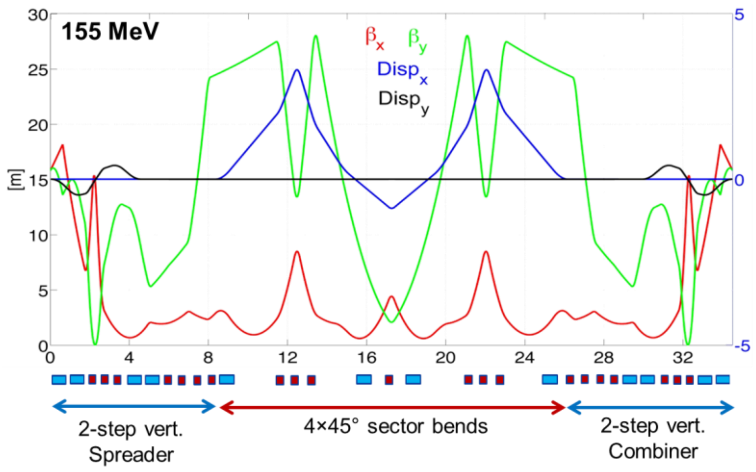
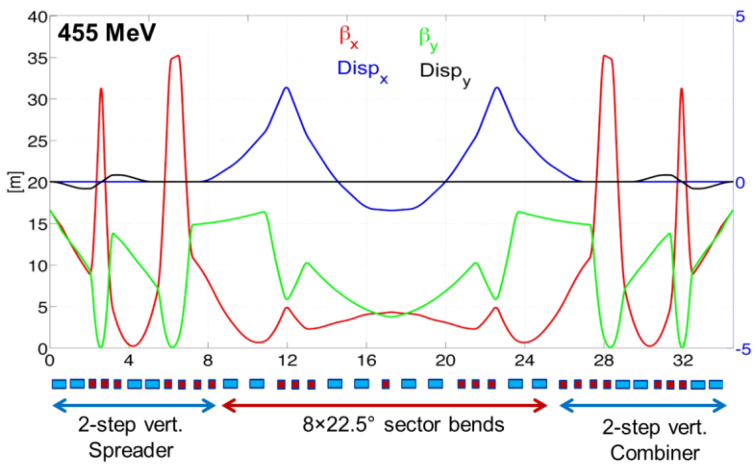
Arc optics (e.g. “odd” arcs)

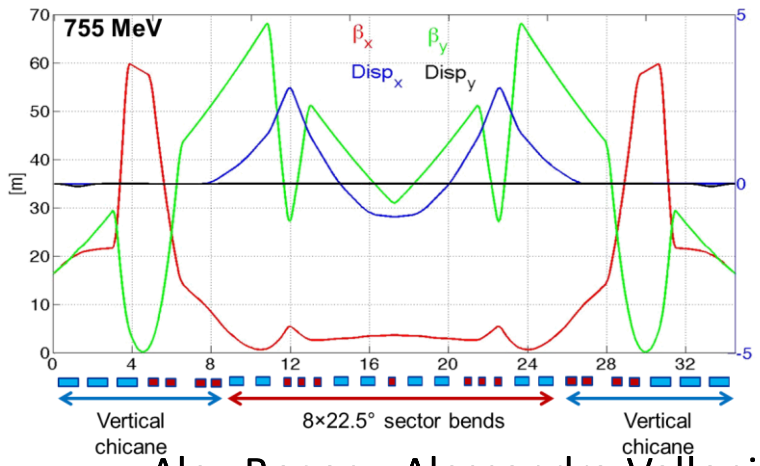
Arc 1



Arc 3



Arc 5



- Isochronous
- Achromatic
- FMC*) optics
- Symmetric

*) Flexible Momentum Compaction

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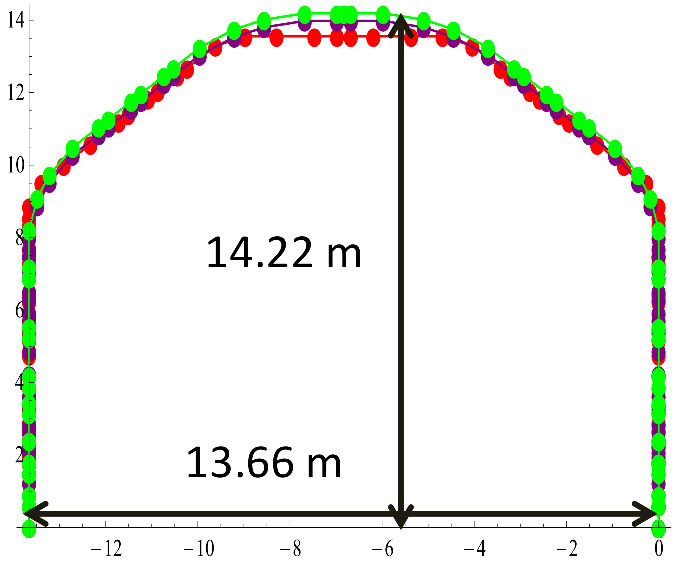
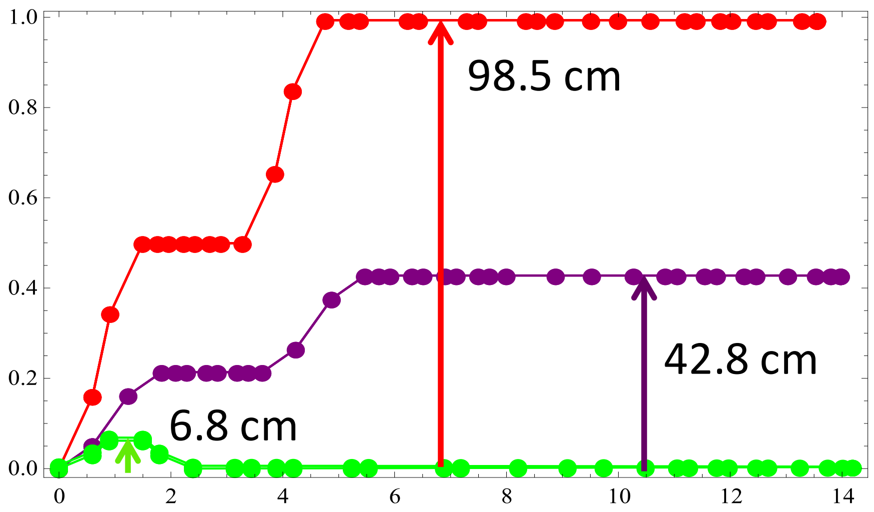
Arc Layout





- Isochronous
- Achromatic
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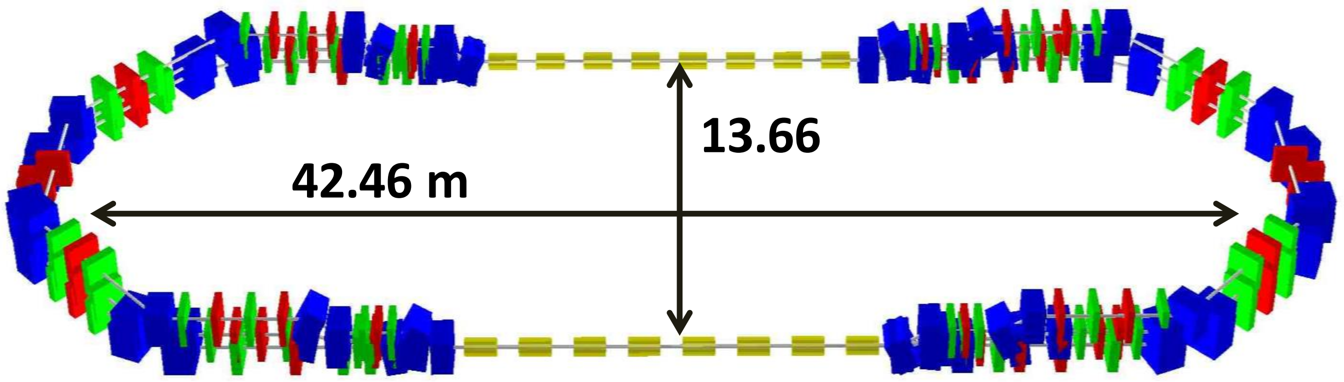

*) Flexible Momentum Compaction

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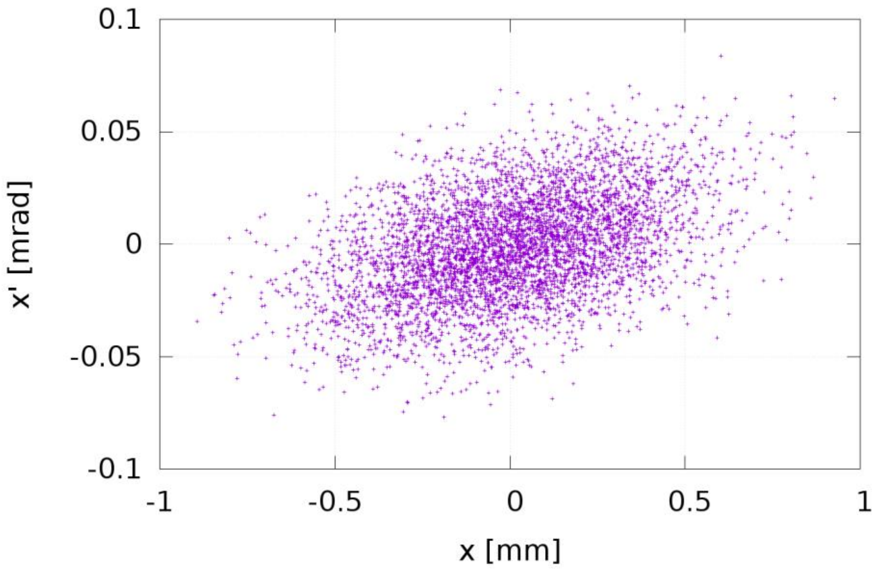
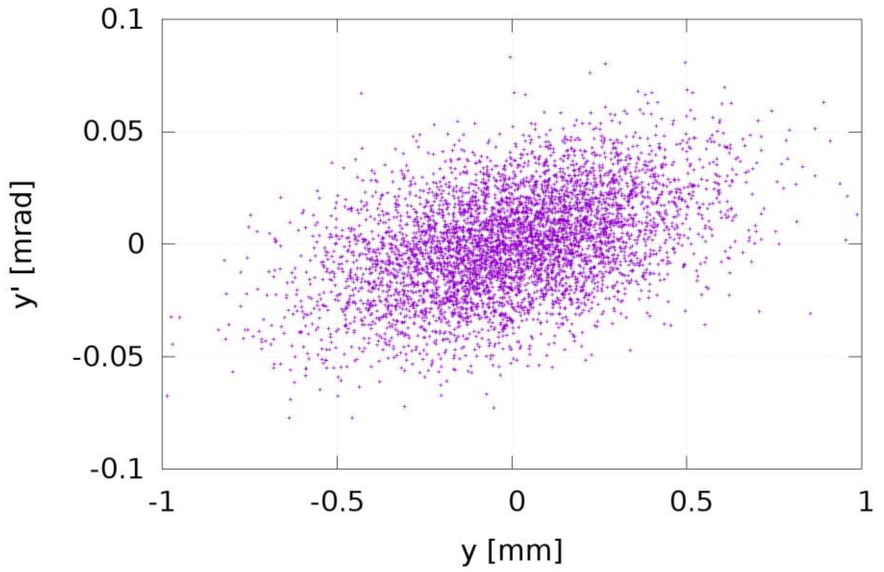
Particle tracking results

Transverse phase space at 900 MeV, *PLACET2*

Horizontal phase space



Vertical phase space

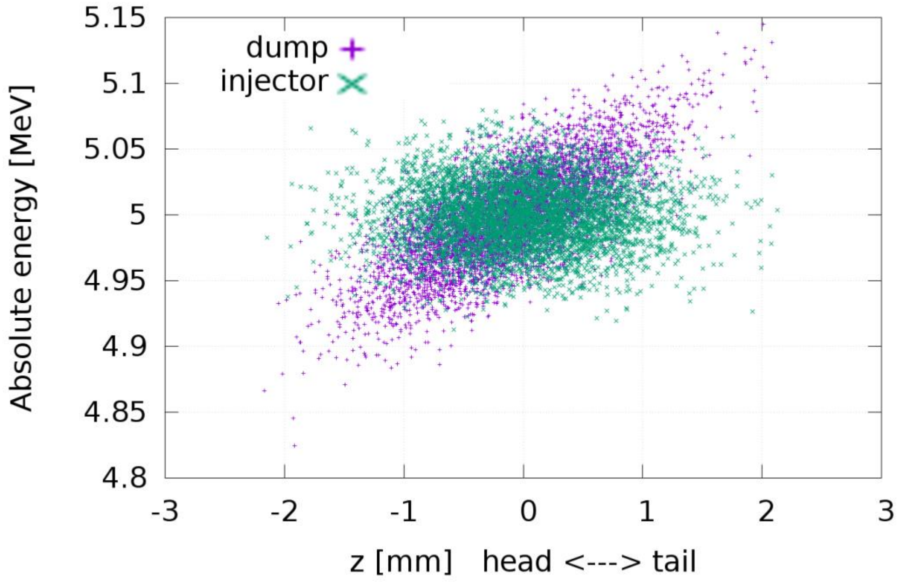


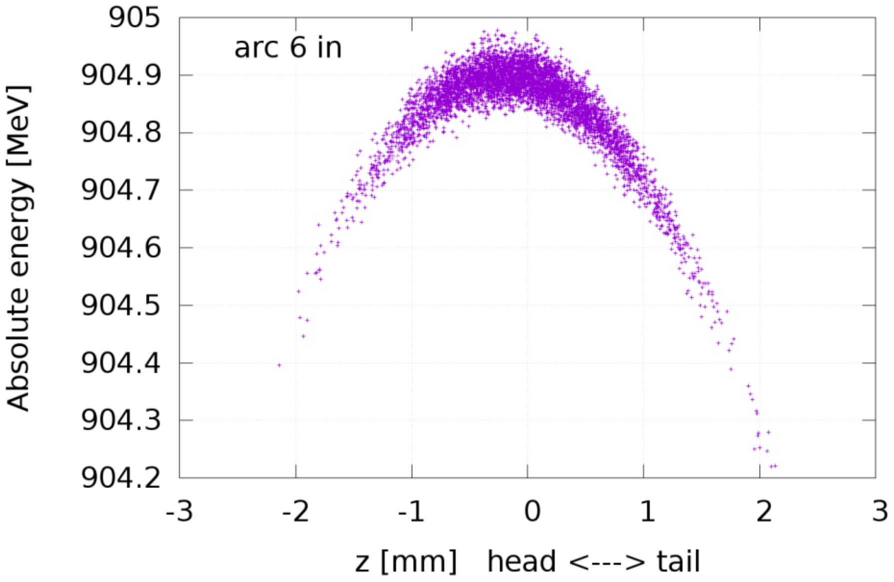
- Very well preserved phase space and transverse emittance at 900 MeV and down to the dump.
- Small impact of (coherent) synchrotron radiation verified with *Elegant*.
- Small impact of short-range wakefields expected (to be further investigated).

Dario Pellegrini

Particle tracking results

Longitudinal phase space, *PLACET2* simulations





- Bunch length preservation down to dump (very good isochronicity).
- Some energy chirp at dump → requires fine tuning of the arc lengths.
- With 6 mm long bunches, the RF curvature can be seen at high energy, still extremely small energy spread: $5 \cdot 10^{-3}$ at injector → 10^{-4} at 900 MeV.
- Possibility to introduce energy chirp and tune the arcs R_{56} to manipulate the phase space.

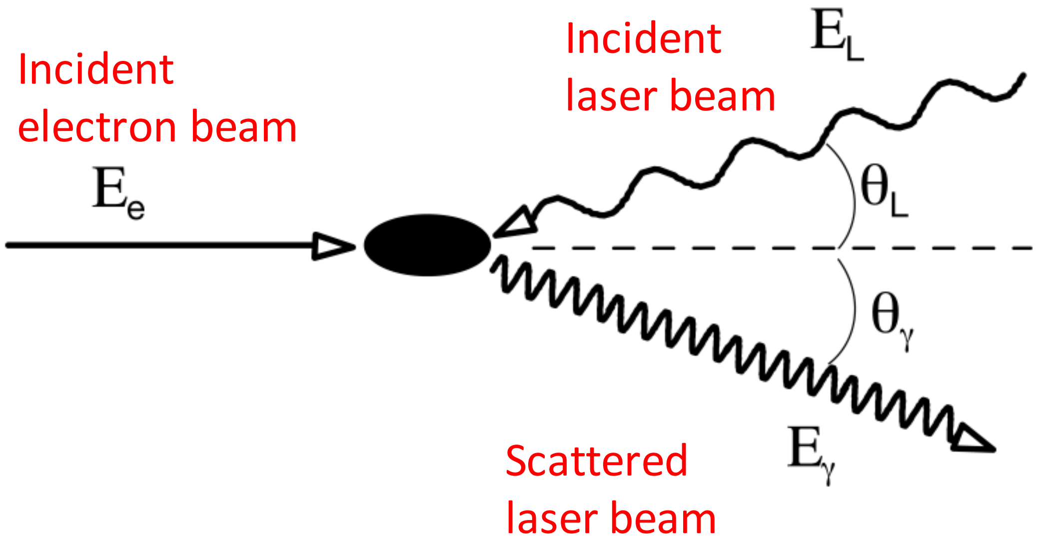
Dario Pellegrini

Possible applications of *PERLE*

- Test of SRF Cavities/Cryomodules
- Test of Beam Instrumentation
- Controlled Quench & Damage Tests of SC wires and magnets
- γ source by Compton Backscattering

γ beams with *PERLE*

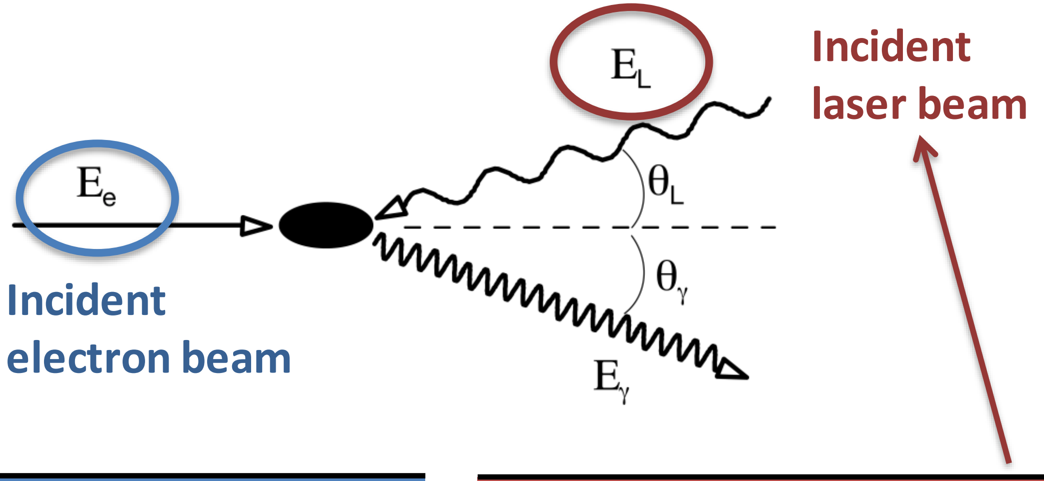
GOAL: Generation of high-energy monochromatic polarized photons via Compton backscattering of laser light from relativistic electrons for nuclear physics research



$$E_\gamma = 2\gamma_e^2 E_L \frac{1+\cos\theta_L}{1+(\gamma_e\theta_\gamma)^2+\left(\frac{eE_0}{m_0c\ \omega_0}\right)^2+\frac{4\gamma_e E_L}{m_0c^2}}$$

Fabian Zomer

γ beams with *PERLE*: input parameters



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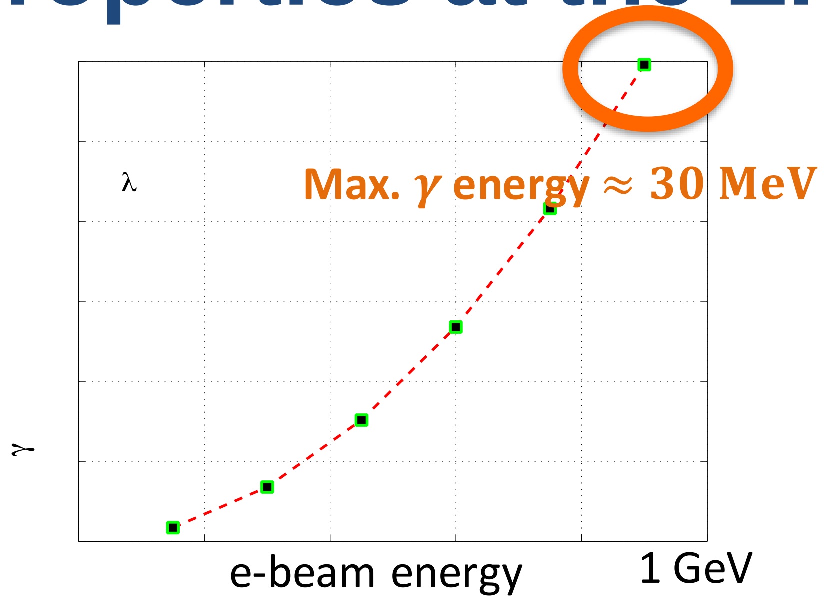
ELECTRON BEAM PARAMETERS	
Energy	900 MeV
Charge	320 pC
Bunch Spacing	25 ns
Spot size	30 μm
Normalized $\varepsilon_\perp$	5 μm
Energy Spread	0.1%

LASER BEAM PARAMETERS	
Wavelength	515 nm … 1030 nm
Average Power	300 kW … 600 kW
Pulse length	3 ps
Pulse energy	7.5 mJ … 15 mJ
Spot size	30 μm
Bandwidth	0.02%
Repetition Rate	40 MHz

A. Valloni

γ beam properties at the ERL facility



Fabian Zomer

GAMMA BEAM PARAMETERS	
Energy	$30\ \mathrm{MeV}$
Spectral density	$9 \cdot 10^4\ \mathrm{s^{-1}eV^{-1}}$ photons
Bandwidth	$<\ 5\%$
Flux within FWHM bandwidth	$7 \cdot 10^{10}\ \mathrm{s^{-1}}$ photons (**total flux** $\mathbf{9 \cdot 10^{12}\ s^{-1}}$)
ph/e$^-$ within FWHM bandwidth	10^{-6}
Peak Brilliance (photons in 0.1% BW)	$3 \cdot 10^{21} (\mathrm{s\ mm^2 mrad^2})^{-1}$

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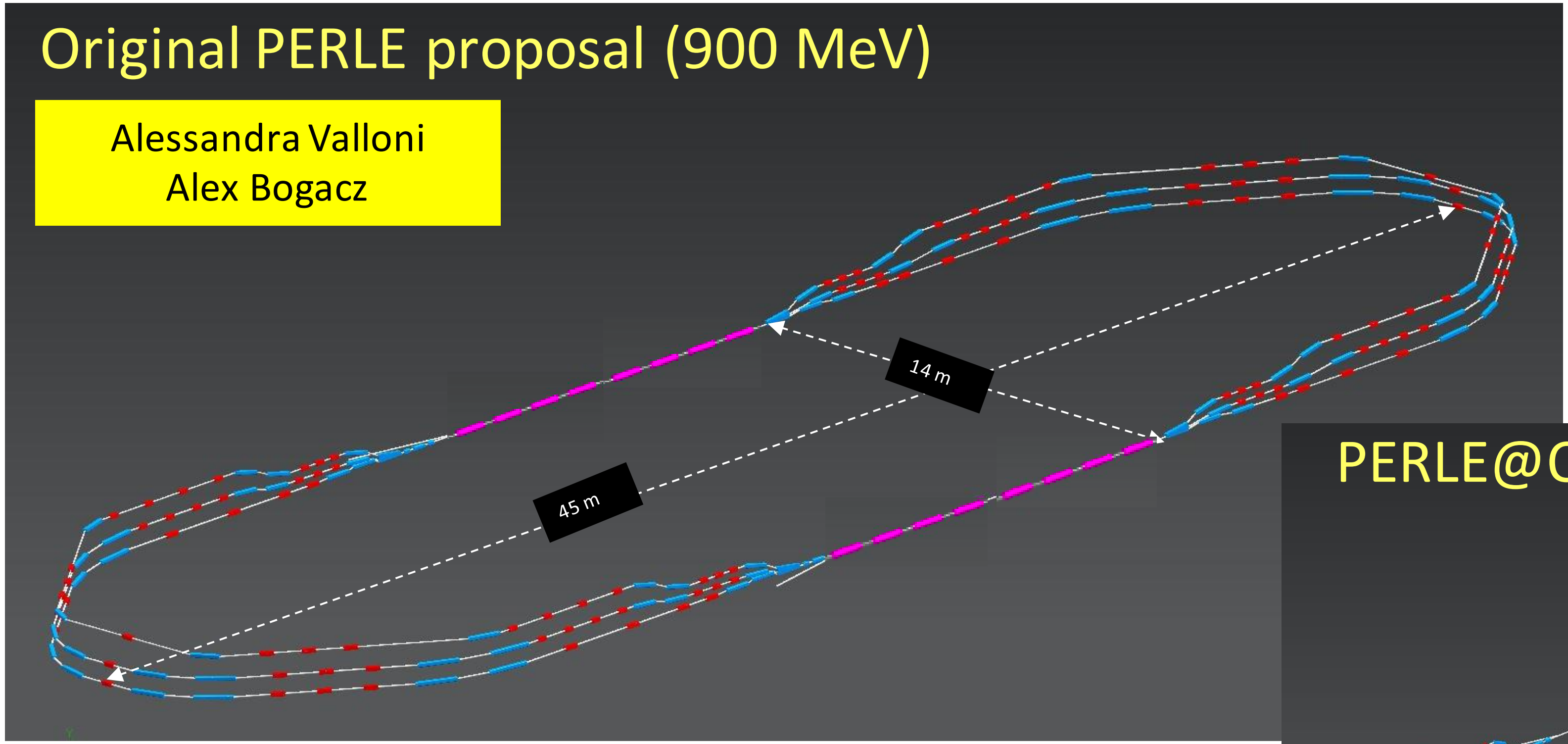
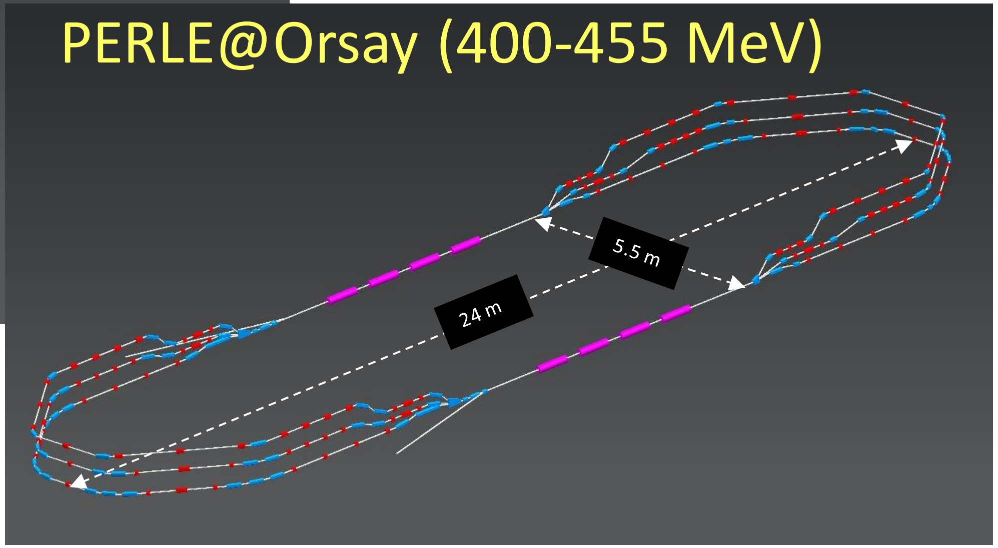
From PERLE to PERLE@Orsay



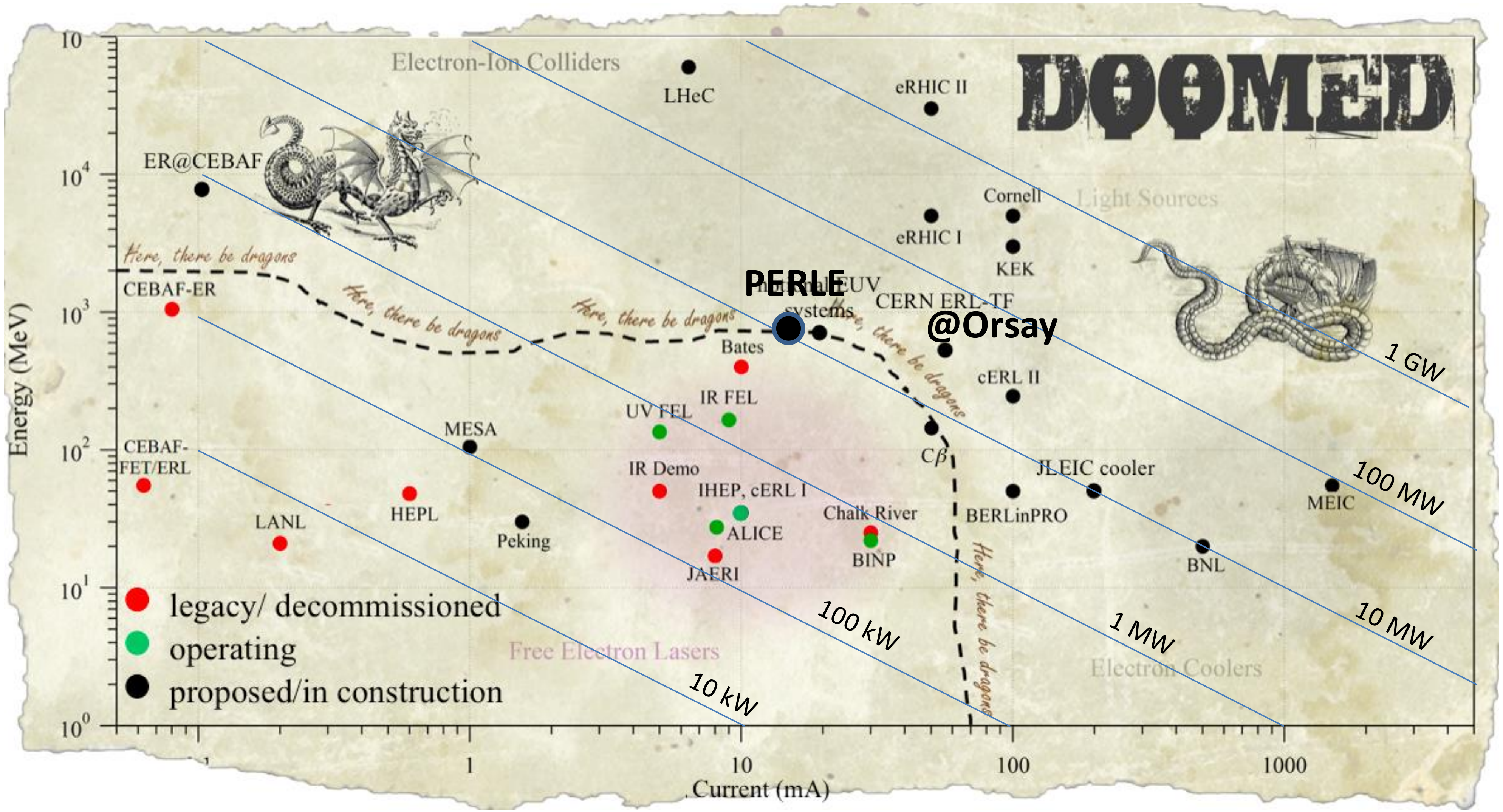


Initiative by LAL/Orsay to make *PERLE* real

PERLE Workshop held in February 2017 at Orsay
https://indico.lal.in2p3.fr/event/3428/

Target parameter	PERLE (CDR)	PERLE@Orsay
Injection energy	(5 … 6) MeV	
Top energy	905 MeV	(400 … 456) MeV
# of passes	1 … 3	
Norm. $\varepsilon_\perp$	6 µm	
Beam current (inj)	12.8 mA	(10 … 40) mA
Bunch spacing	25 ns	25 ns
RF frequency	801.58 MHz	
Duty factor	CW	

PERLE@Orsay in parameter space



Courtesy Chris Tennant

PERLE@Orsay – site

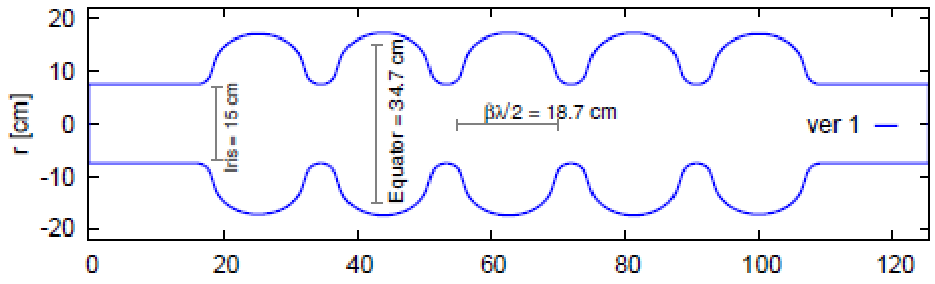
800 MHz Cavity Parameters

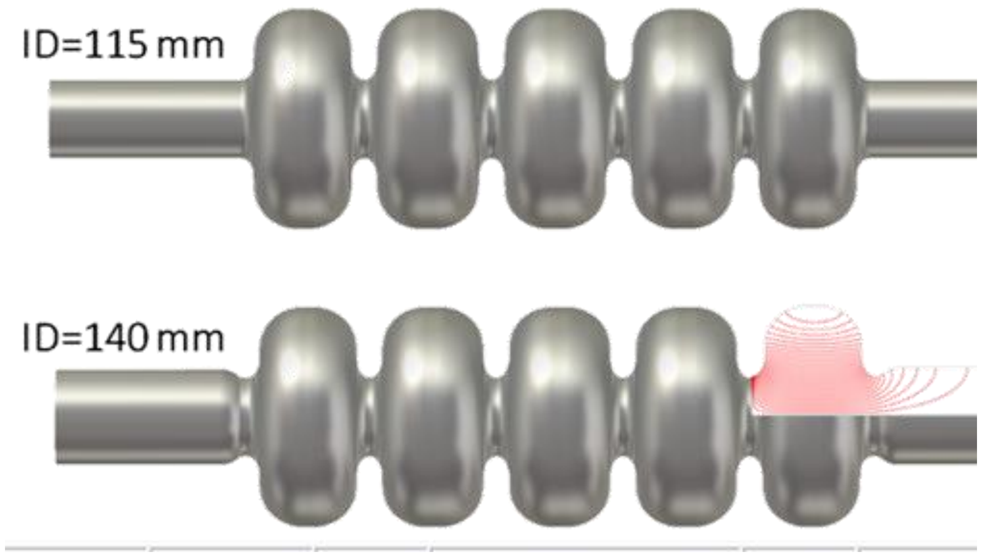
Parameter	Value
Acceleration gradient	$< 20\,\mathrm{MV/m}$
# cells/cavity · cavities/CM · CMs	$5 \cdot 4 \cdot 2$
Accelerating voltage/cavity	$(16.4 \dots 18.75)\ \mathrm{MV}$
$5 \cdot \lambda/2$, total cavity length	$935\ \mathrm{mm},\ 1.2\ \mathrm{m}$
Operation frequency	$801.58\ \mathrm{MHz}$
RF power/CM	$< 50\ \mathrm{kW}$
Bunch charge	$2 \cdot 10^9\ e = 320\ \mathrm{pC}$
Beam current	$\frac{(320 \dots 500)\ \mathrm{pC}}{25\ \mathrm{ns}} \approx (12.8 \dots 20)\ \mathrm{mA}$
Duty factor	CW

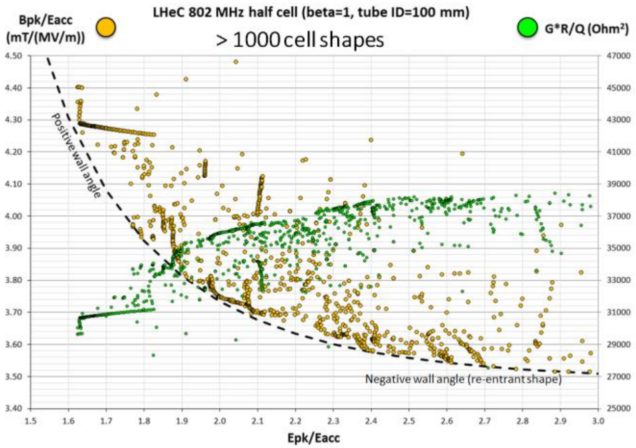
Rama Calaga

Towards an 802 MHz cavity

f	801.58 MHz
W_{stored}	131 J
E_{acc}	18 MV/m
$G\ (Q_0/R_{surf})$	276 Ω
E_{pk}	41 MV/m
B_{pk}	86 mT
R/Q	462 Ω
P_{diss}@2 K	< 28 W
P_{HOM}@40 mA	200 W





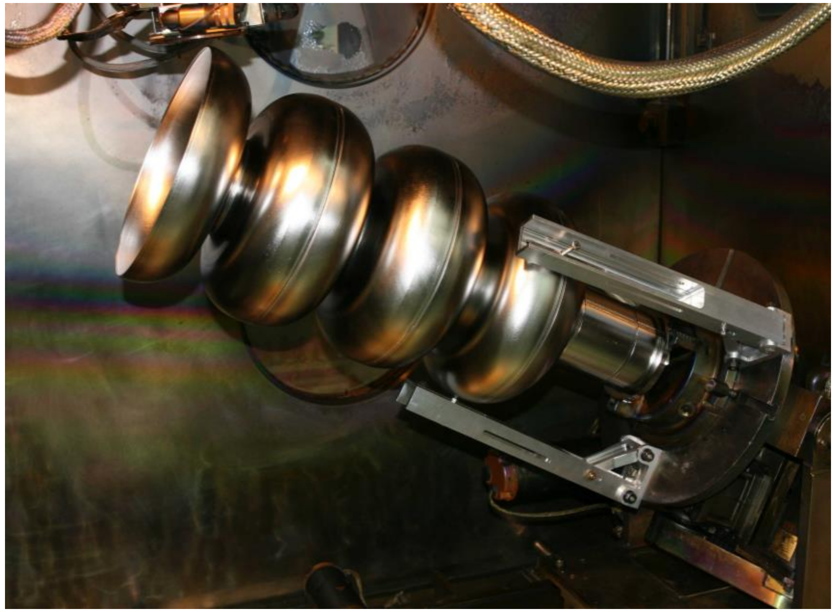


Chosen ID: 130 mm

Rama Calaga, Bob Rimmer, Frank Marhauser

Status of 800-MHz 5-cell cavity (JLAB)

25-April-2017



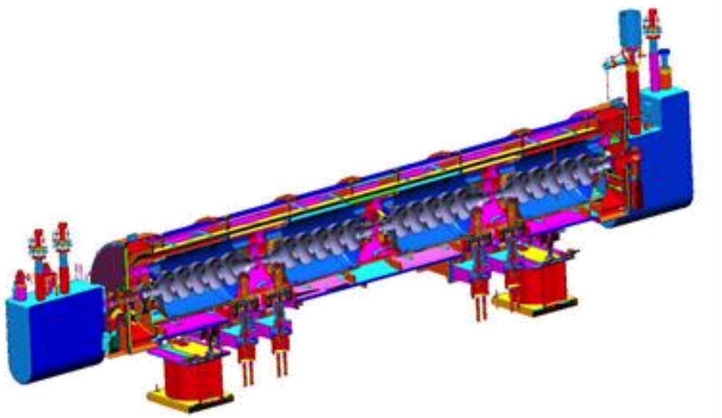
11-Oct-2017

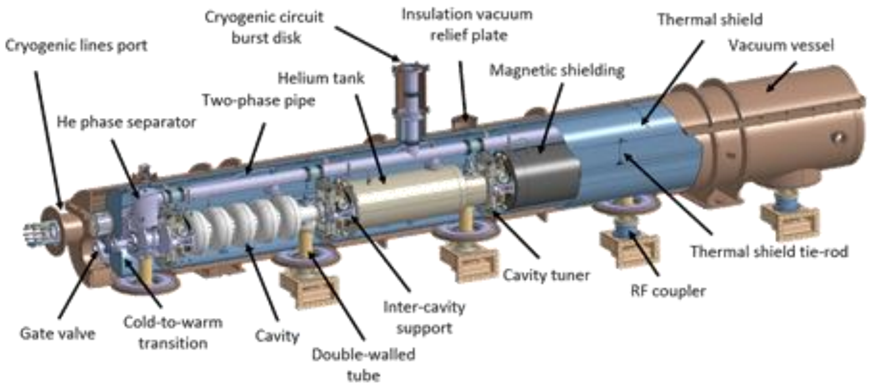
13-Oct-2017 – almost finished

Courtesy Frank Marhauser, JLAB

Cryomodule work

- JLAB has relevant experience with SNS 805 MHz CM (left)
- Alternative design: CERN SPL CM (right)





- Multiple f possible (e.g. with 12.15 MHz rep rate):

$$(802\text{ MHz}, 704\text{ MHz}, 1300\text{ MHz}) = (66, 58, 107) \cdot 12.15\text{ MHz}$$

- Synergy: Tests relevant & interesting for LHC, LHC upgrades and FCC study.

Sebastien Bousson, Rama Calaga, Bob Rimmer, Frank Marhauser

RF Power

CERN is used to 802 MHz RF power (SPS Landau system)

New CERN 801.6 MHz, 60 kW CW IOT TX.
9 units operational at CERN.

Thales trolley with IOT

A total of 5 of these systems would be needed (1 for booster + 1 per CM)

Eric Montesinos

Cost-effective magnet solution

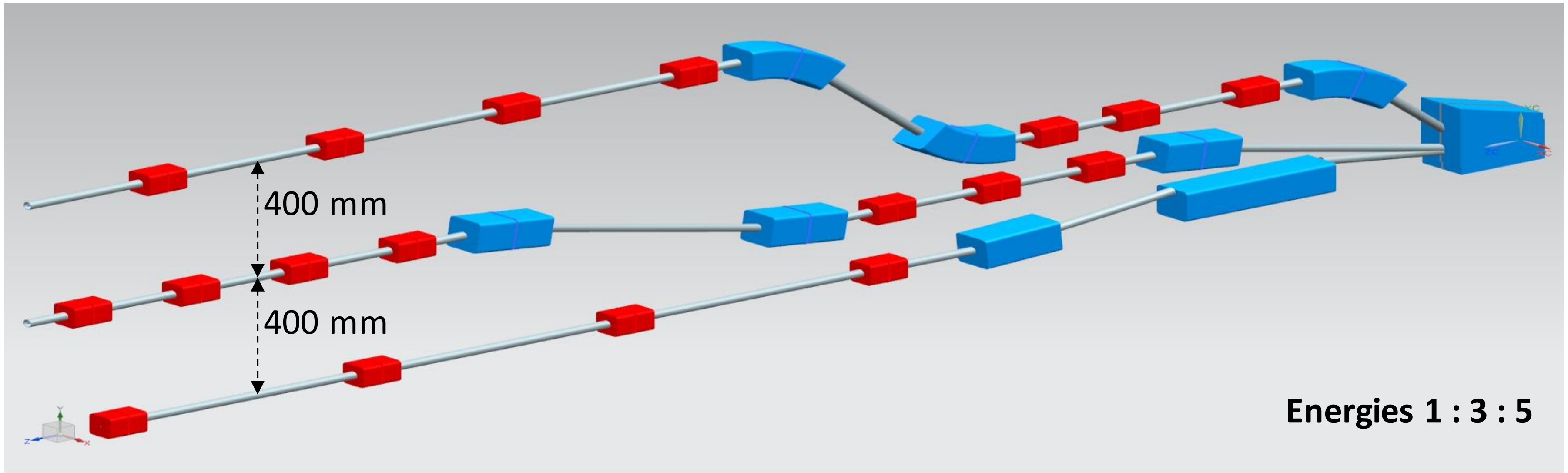
- Longer and curved bending magnets for arcs.
- Two different magnet types with same cross section (only length changes)
- Only 1 magnet per bend with 45° deflection
- Reduction of magnet number could help reduce cost

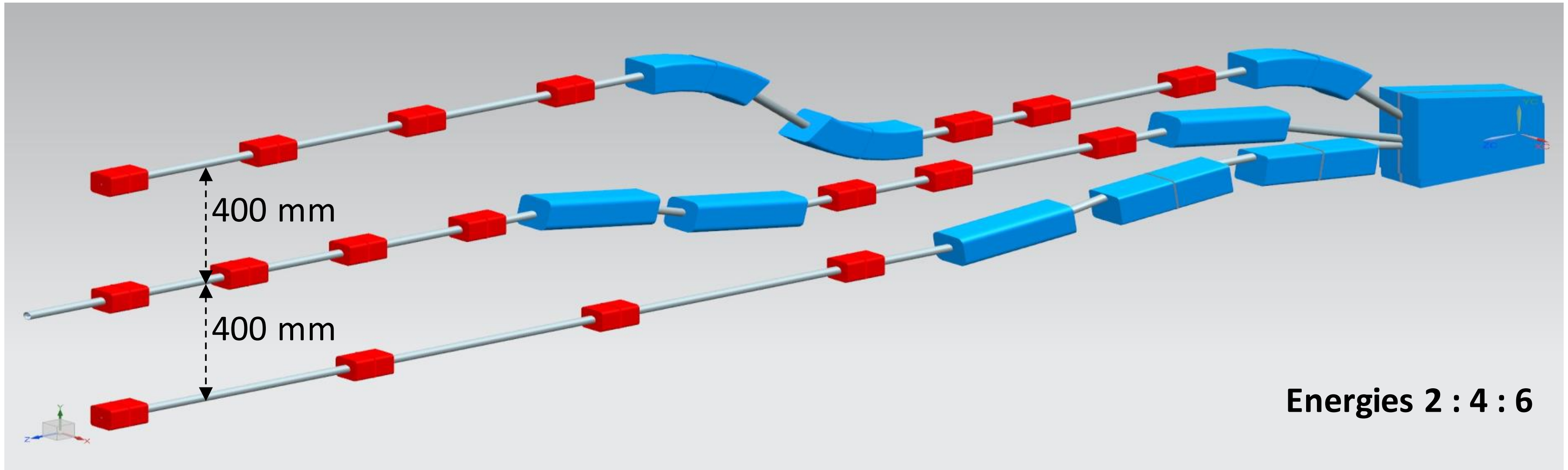
Arc #	Energy [MeV]	Count	Angle [°]	B [T]	L [mm]	ρ [mm]	Pole gap [mm]	GFR width [mm]	Family
1	80	4	45	0.45	456	596	±20	±20	MBA
2	155	4	45	0.87	456	596	±20	±20	
3	230	4	45	1.29	456	596	±20	±20	
4	305	4	45	0.85	912	1191	±20	±20	MBB
5	380	4	45	1.06	912	1191	±20	±20	
6	455	4	45	1.27	912	1191	±20	±20	

Pierre-Alexandre Thonet

650. WE-Heraeus-Seminar on "Physics of Energy-Recovery Linacs"

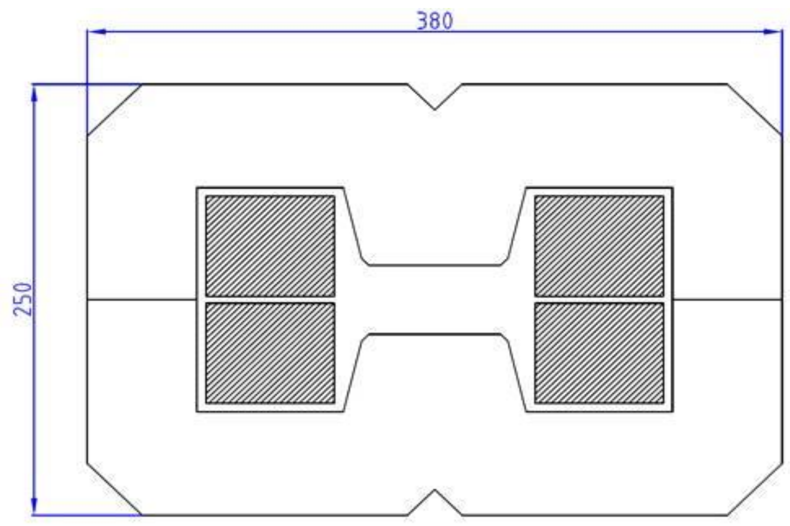
Switchyards' layout



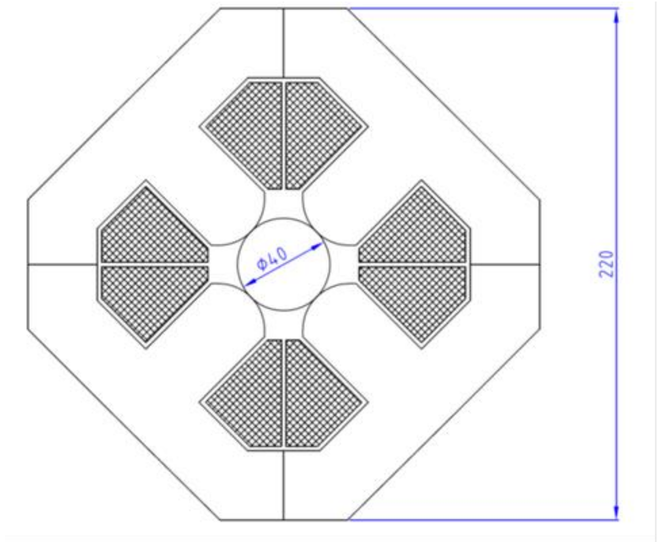


PERLE magnet design (dipoles & quadrupoles)

- 70 dipoles, $(0.45 \ldots 1.29)$ T
  - $\pm$ 20 mm aperture
  - $l = (200,300,400,456,912)$ mm
  - 7 A/mm
  - Water cooled
  - DC operated
  - Curved sector (large l) or straight



- 114 quadrupoles, max. 28 T/m
  - Common aperture Ø 40 mm all arcs,
  - $l = (100,150)$ mm
  - DC operated



Magnets inventory

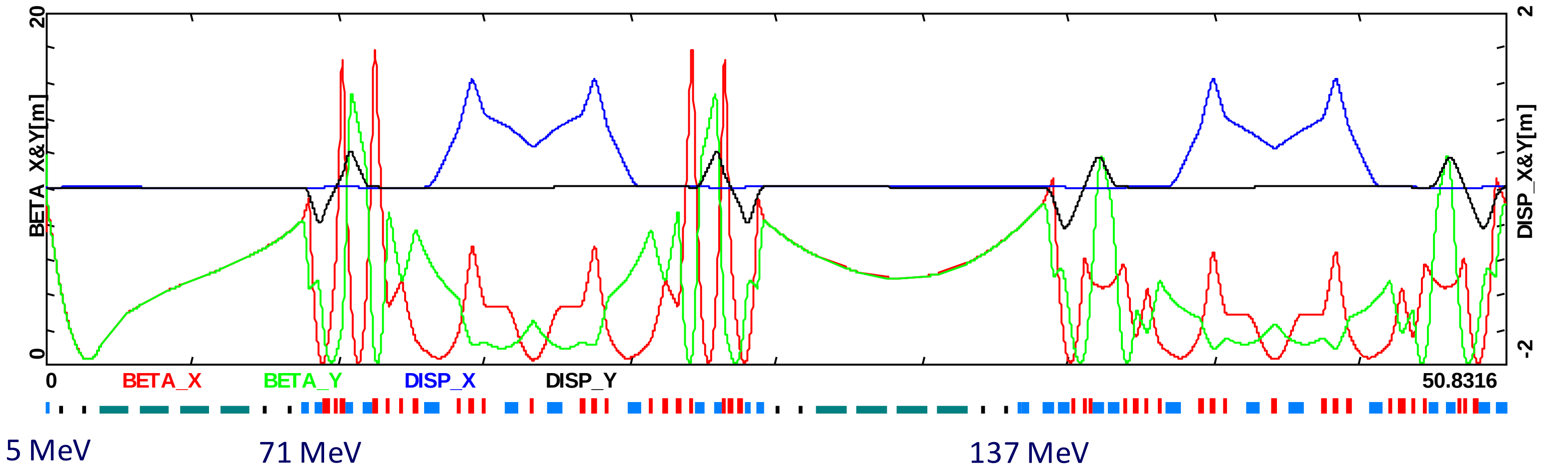
Type	Magnetic length [mm]	count	Yoke profile	Max. field [T]max. gradient [T/m]
MBA	456	12	Curved sector	1.3 T
MBB	912	12	Curved sector	1.3 T
Spreader and combiner dipoles	200	16	Curved sector	0.95 T
	300	20	Curved sector	1.3 T
	400	2	Curved sector	0.95 T
	50	8	Straight	0.18 T
Quadrupoles	100	102	Straight	29 T/m
	150	12	Straight	29 T/m

Totals: 70 bends, 114 quadrupoles

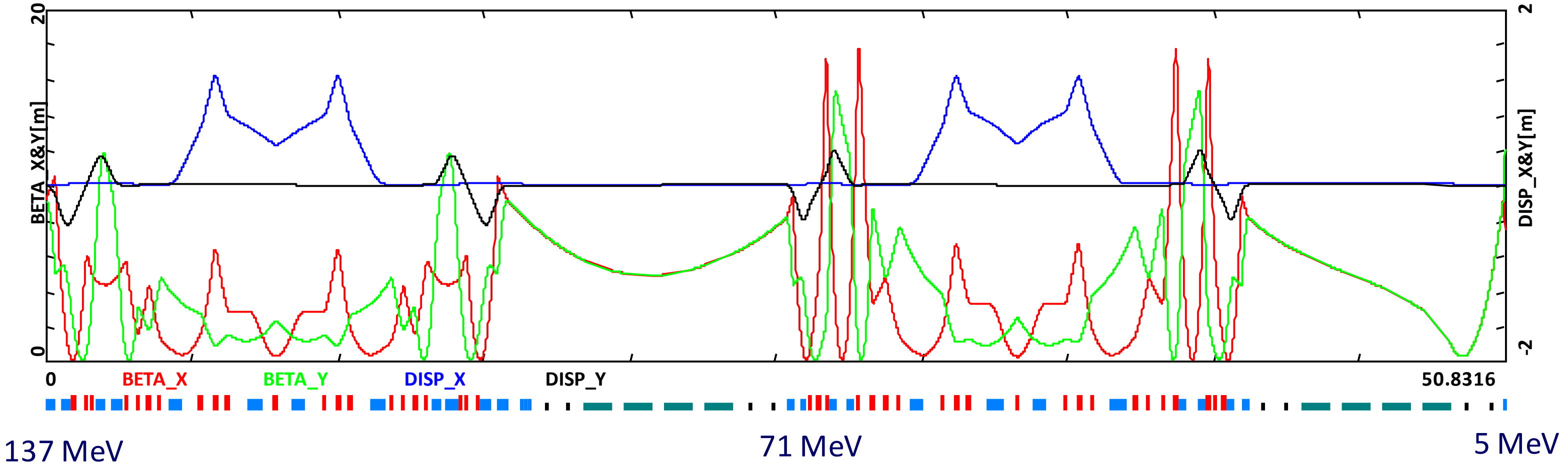
C. Vallerand, P.A. Thonet & A. Milanese

1 pass up + 1 pass down optics

Pass 1 ‘up’



Pass 1 ‘down’



Alex Bogacz

Summary

- *PERLE* is a versatile, small ERL facility, which looks feasible.
- It allows study of a high-energy, multi-pass ERL.
- It can be used for many applications.
- As a γ source, it could reach 30 MeV with a total flux above $10^{12}\ \mathrm{s}^{-1}$ photons (at 900 MeV electron energy).
- The *PERLE* CDR is presently in print with Journal of Physics G, preprint at https://arxiv.org/abs/1705.08783
- LAL (CNRS/IN2P3) is presently investigating the possibility to construct *PERLE*@Orsay (a “lean” version of *PERLE*)

Thank you for your attention!