Concept of *PERLE*, a High Intensity Energy Recovery Linac Facility

Erk Jensen

presenting a team effort of a growing collaboration (so probably I missed some – sorry):

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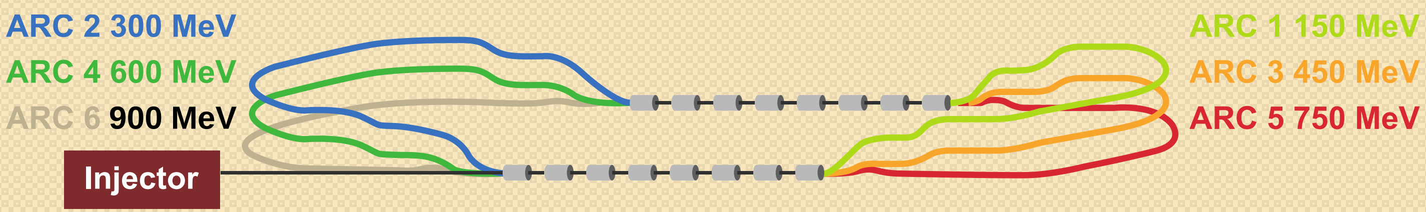
and special thanks to:

Kurt Aulenbacher (U Mainz), Ilan Ben-Zvi (BNL), Ralf Eichhorn, Georg Hoffstaetter (Cornell), Andrew Hutton (JLAB)

What are we talking about?

- Let’s call it *PERLE* for now (***P***owerful ***ERL*** for ***E***xperiments) – please propose a better name!



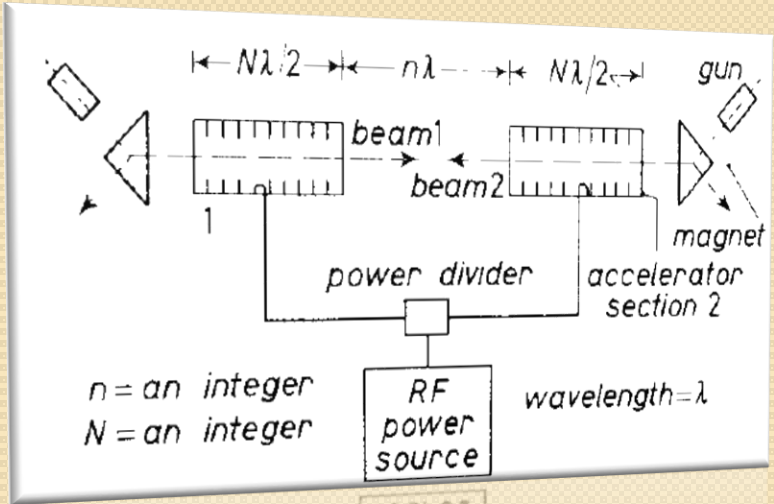
$12.8\ \mathrm{mA}\ (320\ \mathrm{pC} \times 40\ \mathrm{MHz})$, CW

Up to sixteen 5-cell cavities in four cryomodules, 802 MHz, 19 MV/cavity

- Construction in stages:
  - Initially: Injector – Cryomodule – Beam dump,
  - add arcs
  - add CM’s
  - … later use as user facility …

Why study ERL?

- Because it's a great idea – accelerate, use the beam, decelerate and recover beam energy! This saves 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!



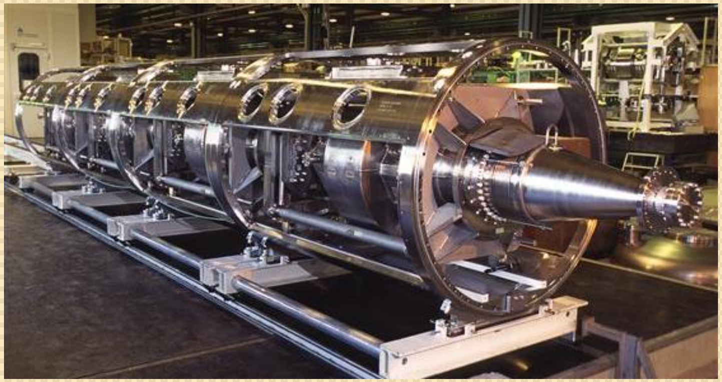
From M. Tigner: "A Possible Apparatus for Electron Clashing-Beam Experiments", Il Nuovo Cimento Series 10, Vol. **37**, issue 3, pp 1228-1231,1 Giugno 1965

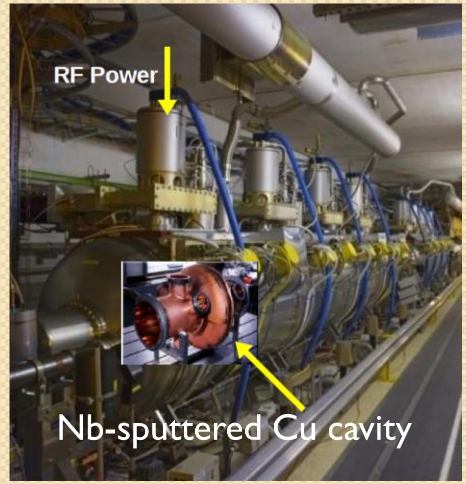
Why at CERN?

- CERN is intensifying R&D on SRF, getting ready for the next generation of HEP accelerators:
  - SRF needed for: ***LHC, HL-LHC***, HIE-ISOLDE, ***SPL, LHeC, FCC*** see next pages.
  - … the highlighted can directly take advantage of this facility
- It is important that the next generation of accelerator physicists, engineers and technicians can ***work and train with a real beam facility*** without risking interruption of LHC Physics!
- *PERLE* is above all a facility for SRF R&D! With it we can complement the SRF testing – typical sequence of tests:
  - Sample tests in quadrupole resonator,
  - low power tests of bare cavity in vertical cryostat,
  - high power tests of dressed cavity in horizontal cryomodule,
  - tests with beam (HOM excitation!)

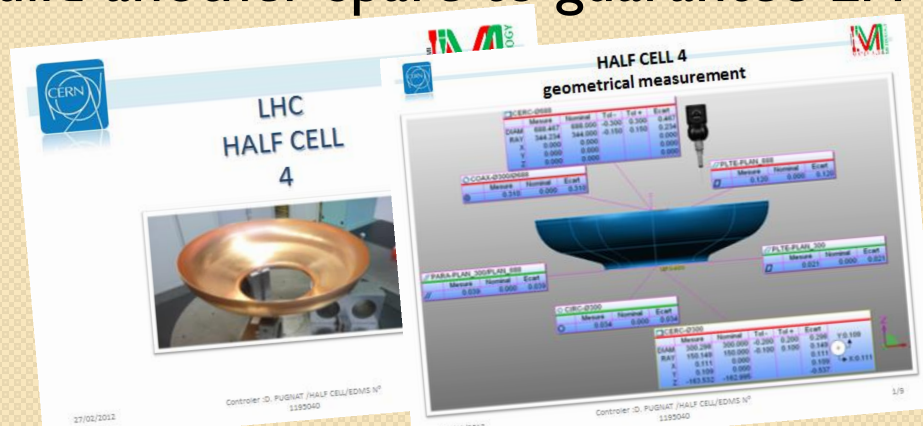
SRF at CERN 1: LHC

- LHC: In operation: 4 cryomodules with 4 single-cell cavities each



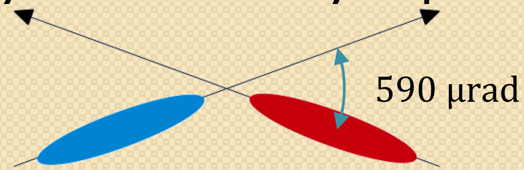


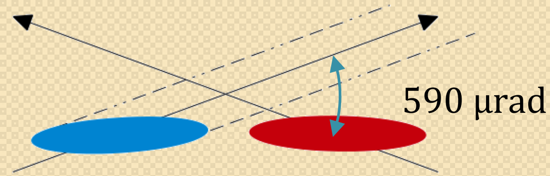
- Recently, one module was swapped with the only spare module
- We are in the process to build another spare to guarantee LHC availability!
- Parameters: 401 MHz,
  2 MV/cavity, 4 cavities/CM
  Nb sputtered on Cu



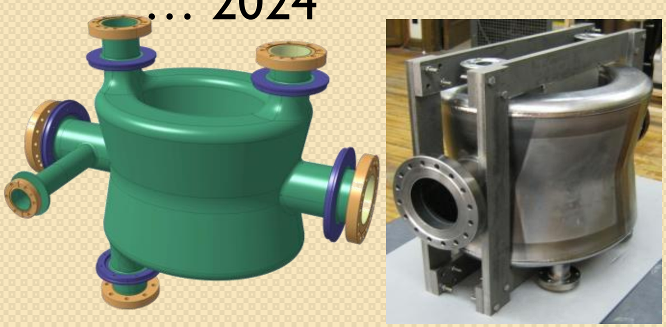
SRF at CERN 2: HL-LHC

- Crab cavities are part of baseline for HL-LHC – w/o crab cavities, the available luminosity cannot be fully exploited.

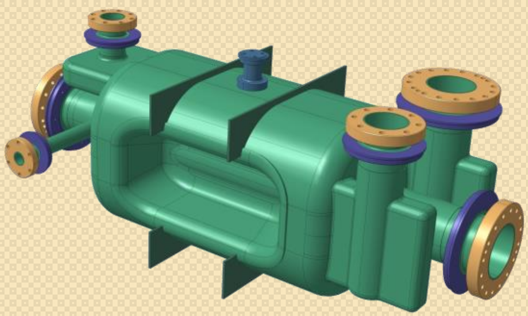




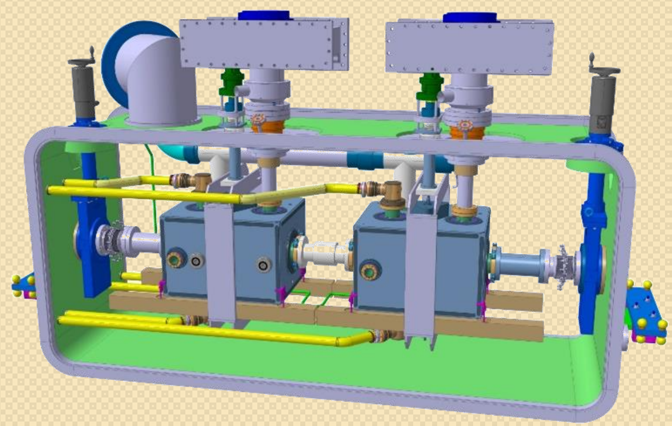
- Prototypes have been built, CM's are in construction, tests with proton beams are foreseen in SPS in 2018, production phase for 32 cavities plus spares: 2019 … 2024



DQW: concept and prototype for vertical x-ing (IP1)



RFD: concept for horizontal x-ing (IP5)



CM concept (common)

- Parameters: 401 MHz, 3.4 MV/cavity, 2 cavities/CM
- Also in HL-LHC: Study of harmonic cavities for LHC : 200 MHz and 802 MHz.

SRF at CERN 3: HIE-ISOLDE

- Upgrade of existing ISOLDE Facility (Isotope Separator OnLine) to initially (3, 5.5, 10) MeV/u in stages. 101 MHz, $\beta = 0.103$, 6 MV/m. Nb sputtered on Cu.

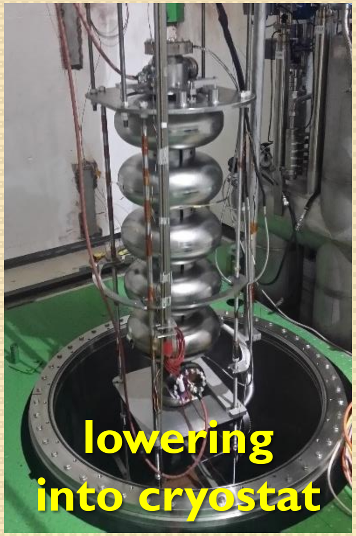

Cavity preparation


before …


… and after sputtering


First completely assembled cryomodule

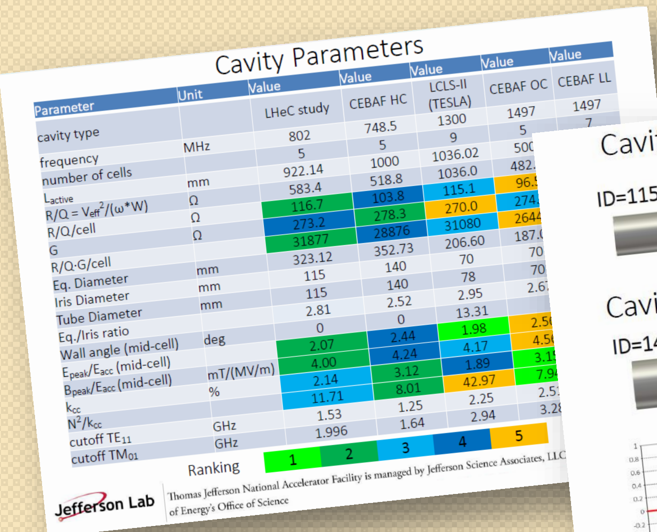
SRF at CERN 4: SPL



- Pure SRF R&D project!
- Presently 704 MHz (ESS), but we're considering change to 802 MHz.
- Bulk Nb, 5-cell
- SS He-vessel, alternative CM design

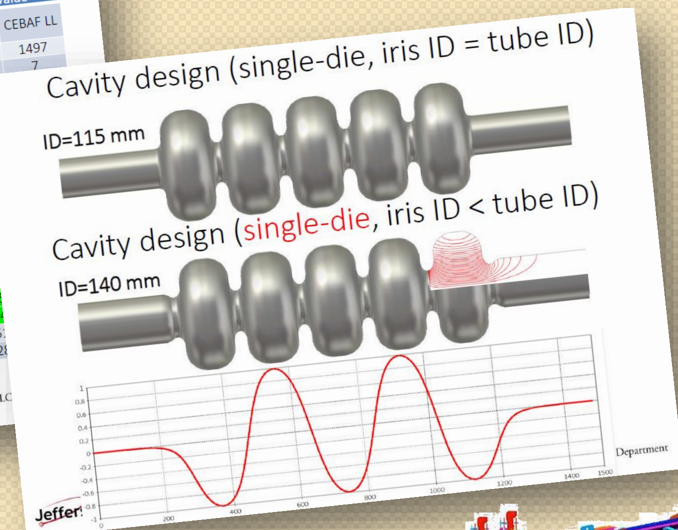
SRF at CERN 5: LHeC

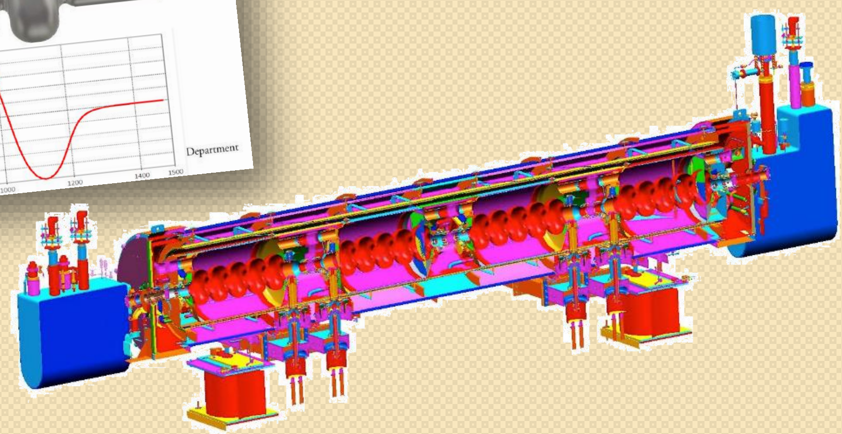
- LHeC is presently not a high priority at CERN – but of course it was the LHeC study (Linac-Ring option) that triggered the study of an ERL and of *PERLE.*
- A cavity/cryomodule design is identical to that of *PERLE.*
- 802 MHz, bulk Nb, 5-cell cavities.


Cavity Parameters

Parameter	Unit	Value	Value	Value	Value	Value
cavity type		LHeC study	CEBAF HC	LCLS-II (TESLA)	CEBAF OC	CEBAF LL
frequency	MHz	802	748.5	1300	1497	1497
number of cells		5	5	9	5	7
L_{active}	mm	922.14	1000	1036.02	500	
$R/Q = V_{eff}^2/(\omega*W)$	Ω	583.4	518.8	1036.0	482.	
R/Q/cell	Ω	116.7	103.8	115.1	96.5	
G	Ω	273.2	278.3	270.0	274.	
R/Q·G/cell		31877	28876	31080	2644	
Eq. Diameter	mm	323.12	352.73	206.60	187.	
Iris Diameter	mm	115	140	70	70	
Tube Diameter	mm	115	140	78	70	
Eq./Iris ratio		2.81	2.52	2.95	2.67	
Wall angle (mid-cell)	deg	0	0	13.31		
E_{peak}/E_{acc} (mid-cell)		2.07	2.44	1.98	2.56	
B_{peak}/E_{acc} (mid-cell)	mT/(MV/m)	4.00	4.24	4.17	4.56	
k_{cc}	%	2.14	3.12	1.89	3.15	
N^2/k_{cc}		11.71	8.01	42.97	7.94	
cutoff TE_{11}	GHz	1.53	1.25	2.25	2.51	
cutoff TM_{01}	GHz	1.996	1.64	2.94	3.28	
Ranking		1	2	3	4	5

Jefferson Lab
Thomas Jefferson National Accelerator Facility is managed by Jefferson Science Associates, LLC of Energy's Office of Science





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SRF at CERN 6: FCC Study

- FCC-hh: RF system approximately LHC system x5,
  401 MHz (plus harmonic system 802 MHz), Nb on Cu

- FCC-ee: Huge RF system, 100 MW RF power in CW!
  - 401 MHz and 802 MHz, maximum efficiency (including cryogenics) – challenging SRF R&D, Nb sputtered and bulk, new materials? More on next slide

- FCC-he: baseline is 60 GeV ERL identical to that of LHeC.

FCC-ee: 4 different machines!

Parameter	Z-peak	W	Higgs	$t\bar{t}$
E_{beam} [GeV]	45	80	120	175
SR energy loss/turn [GeV]	0.03	0.33	1.67	7.55
Beam current for 50 MW [mA]	1450	152	30	6.6
1st stage: 1.9 GV RF @ 401 MHz, RF power 12 MW				
Beam current [mA]	350	36	7.2	
Luminosity $[10^{34}\ \text{cm}^{-2}\text{s}^{-1}]$	5.1	1.7	0.49	
2nd stage: 4.7 GV @ 401 MHz, RF power 30 MW				
Beam current [mA]	850	90	18	
Luminosity $[10^{34}\ \text{cm}^{-2}\text{s}^{-1}]$	15.3	5.9	2.3	
3rd stage Z "Z-peak exploration": 4.7 GV @ 401 MHz, RF power 50 MW				
Beam current [mA]	1450			
Luminosity $[10^{34}\ \text{cm}^{-2}\text{s}^{-1}]$	26.5			
3rd stage top: 4.7 GV @ 401 MHz + 6 GV @ 802 MHz, RF power 50 MW (baseline)				
Beam current [mA]		150	30	0.007
Luminosity $[10^{34}\ \text{cm}^{-2}\text{s}^{-1}]$		11.9	5.1	1.4

Credits: U. Wienands

SRF at CERN: Summary

- The CERN SRF R&D has to cover many areas, accelerators, technologies.
- Where possible, choices were made to **exploit synergies**!

CERN

Programme	Frequency (MHz)
LHC, spare and more	401 MHz
LHC upgrade	200 MHz, 802 MHz
HIE-ISOLDE	101 MHz
HL-LHC crab cavities	401 MHz
Linac4 (NC)	352 MHz
SPL (ESS)	704 MHz
LHeC, FCC-he, *PERLE*	802 MHz
FCC-ee, FCC-hh	401 MHz & 802 MHz

International

Programme	Frequency (MHz)
ILC, X-FEL, LCLS-2, …	1,300 MHz
PIP-II	650 MHz
SNS	805 MHz
ESS	352 MHz, 704 MHz
eRHIC	422 MHz
JLAB MEIC	953 MHz
JAERI	500 MHz

Motivation for *PERLE*:

- Validation of key LHeC design choices
- Build up expertise in the design and operation for a facility with a fundamentally new operation mode:
  - ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no ‘automatic’ longitudinal phase stability, etc.)
  - Gain experience with the operation of such a machine!
- Proof validity of fundamental design choices:
  - Multi-turn recirculation (other existing ERLs have only two passages)
  - Implications of high current operation ($6 \times 11.8\ \mathrm{mA} = 71\ \mathrm{mA}$!)
- Verify and test machine and operation tolerances before designing a larger scale facility
  - Tolerances in terms of field quality and alignment of the arc magnets!
  - Required RF phase stability (RF power) and LLRF requirements!

Parameters of *PERLE*

Parameter	Value	
injection energy	5 MeV	
RF frequency	801.59 MHz	
acc. voltage per cavity	18.7 MV	
# cells per cavity	5	
$5 \cdot \lambda/2$, total cavity length	935 mm, $\approx$ 1.2 m	
# cavities per cryomodule	4	
RF power per cryomodule	$\leq$ 50 kW	
# cryomodules	4	
max. acceleration per pass	300 MeV	
bunch repetition f	40.079 MHz $*$)	
injected beam current	11.8 mA	
nominal bunch charge	320 pC $= 2 \cdot 10^9\ e$	
number of passes	2	3
top energy	604 MeV	903 MeV
duty factor	CW	

With a photo-injector, other frequencies are possible – see next page!

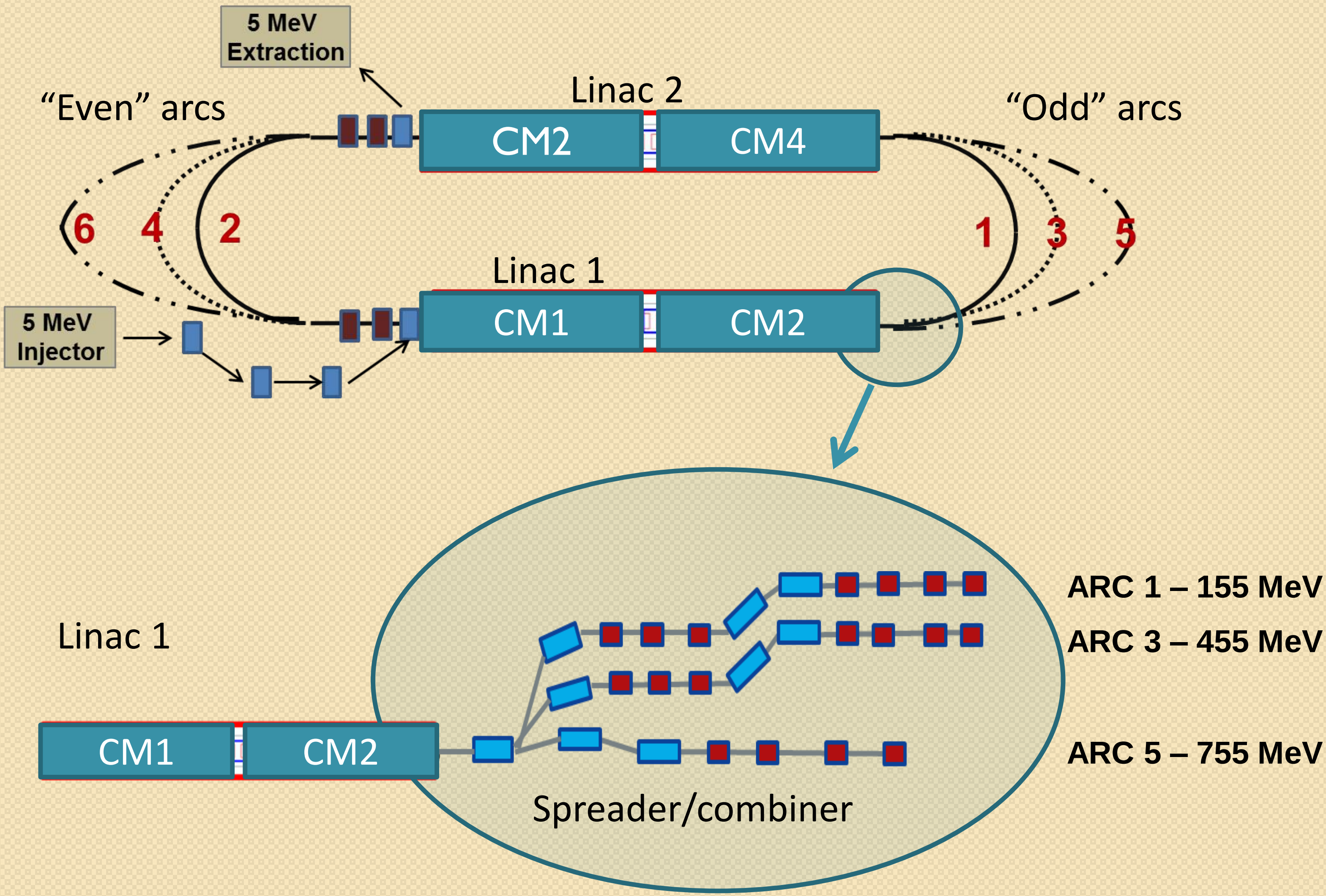
Operation at different frequencies

- With a 40 MHz injector, cavities at $n \times 40$ MHz can be tested (baseline)
- With a 10.835 MHz injector, test frequencies include 325 MHz, 401 MHz, 422 MHz, 500 MHz, 650 MHz, 704 MHz, 802 MHz, 953 MHz, 1,300 MHz.
- With a 12.146 MHz injector, test frequencies include 352 MHz, 401 MHz, 704 MHz, 802 MHz and 1,300 MHz.
- This makes *PERLE* a versatile SRF beam test facility with global synergies!

Reminder:

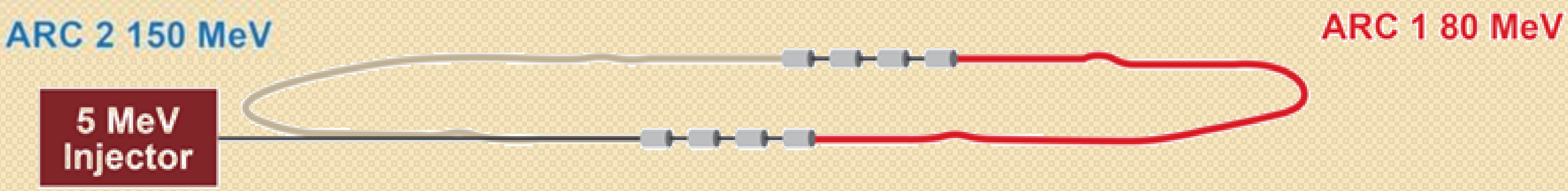
Programme	Frequency (MHz)
CERN frequencies	200 MHz, 401 MHz, 704 MHz, 802 MHz
ILC, X-FEL, LCLS-2, …	1,300 MHz
PIP-II	650 MHz
SNS	805 MHz
CERN Linac4, ESS	352 MHz
ESS	704 MHz
eRHIC	422 MHz
JLAB MEIC	953 MHz
JAERI	500 MHz

Conceptual Layout

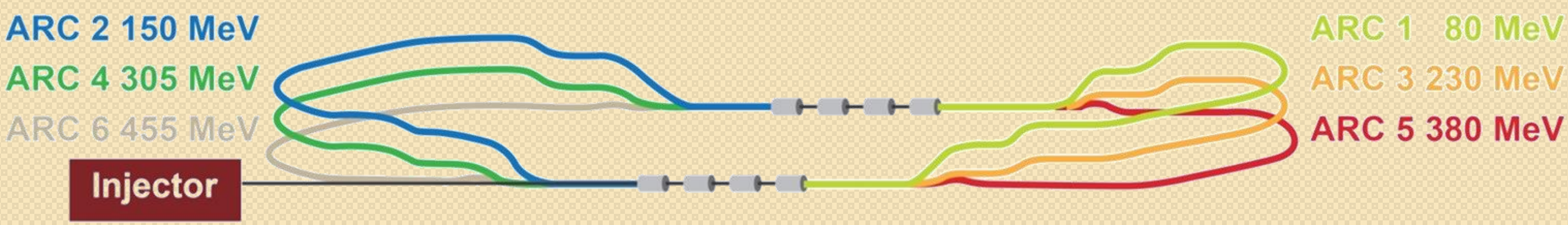


Staged construction

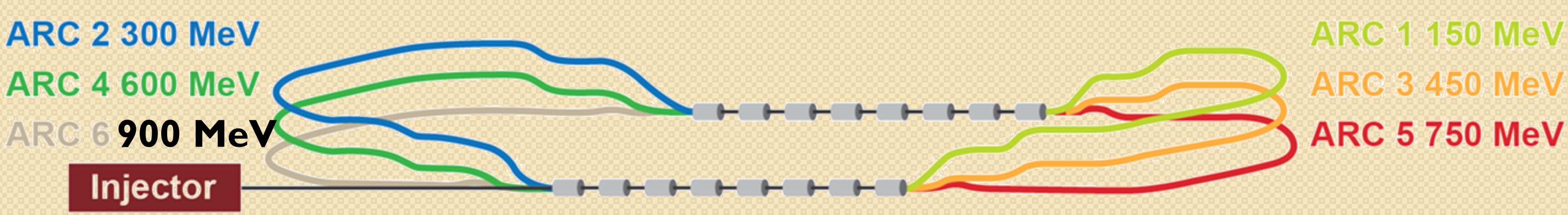
Stage 1 – 2 CMs, test installation – injector, cavities, beam dump.



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

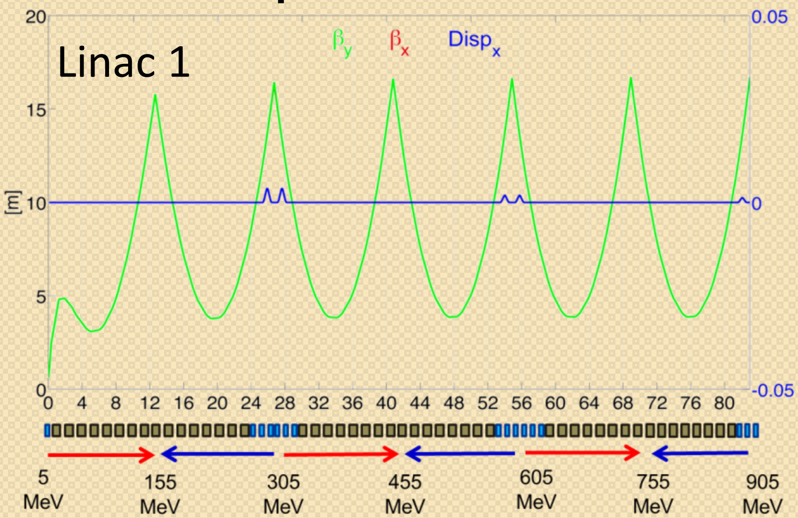


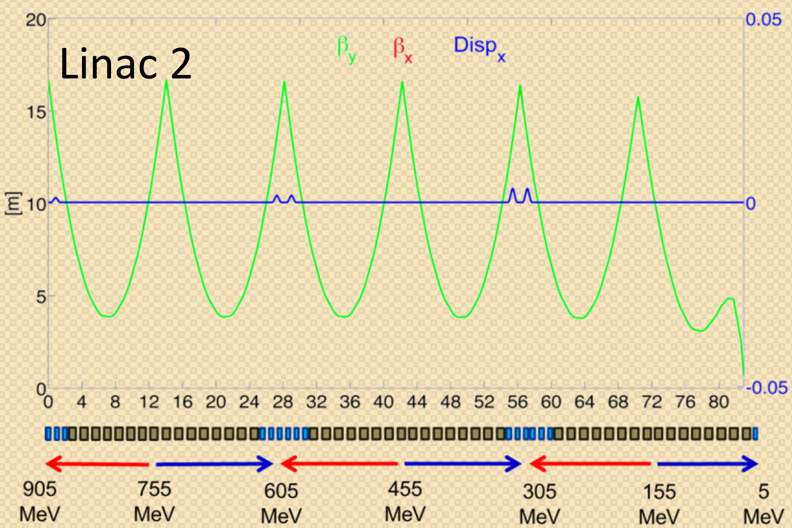
Stage 3 – 4 CMs, set up arcs for higher energies – reach up to 900 MeV



Linac and arc optics

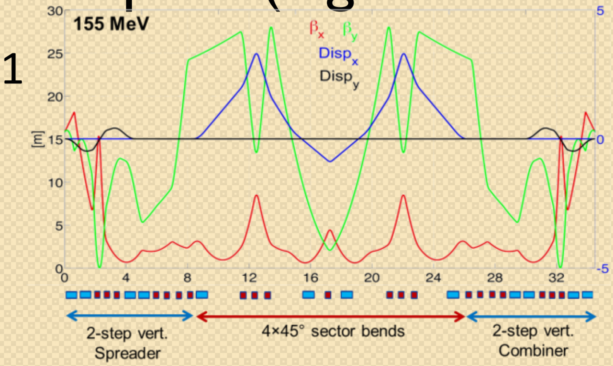
- Linac optics



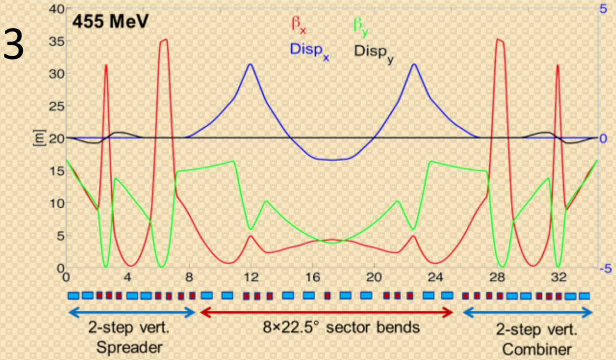


- Arc optics (e.g."odd" arcs)

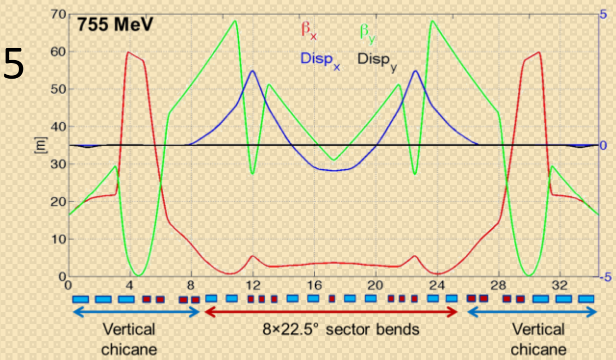
Arc 1



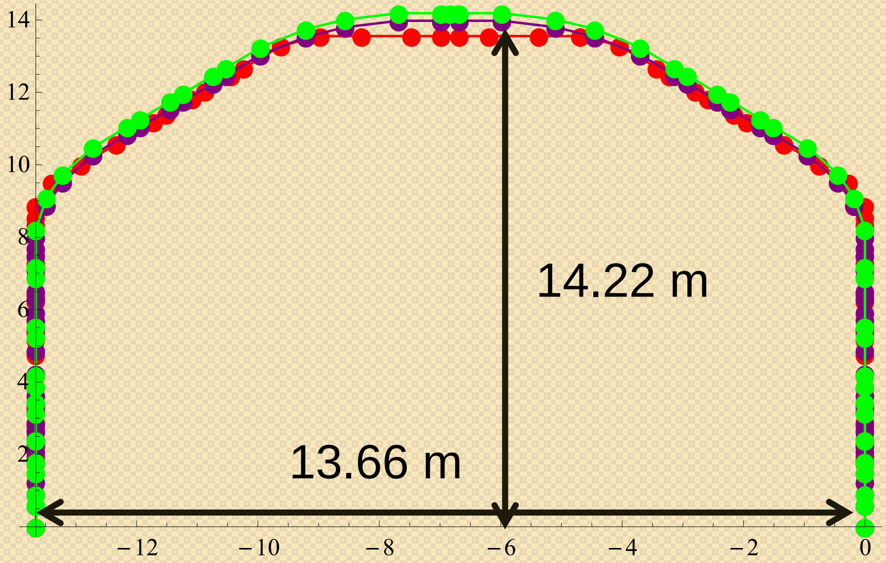
Arc 3

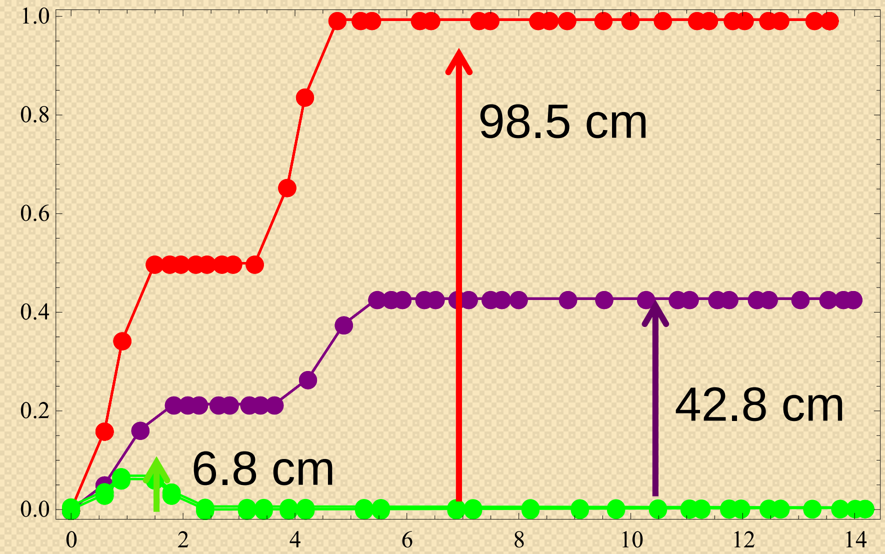


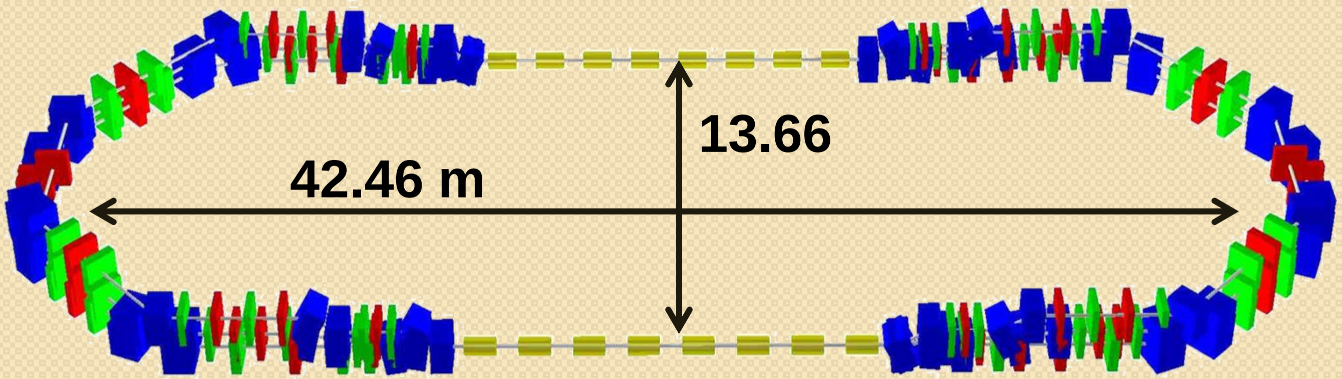
Arc 5



Arc Layout

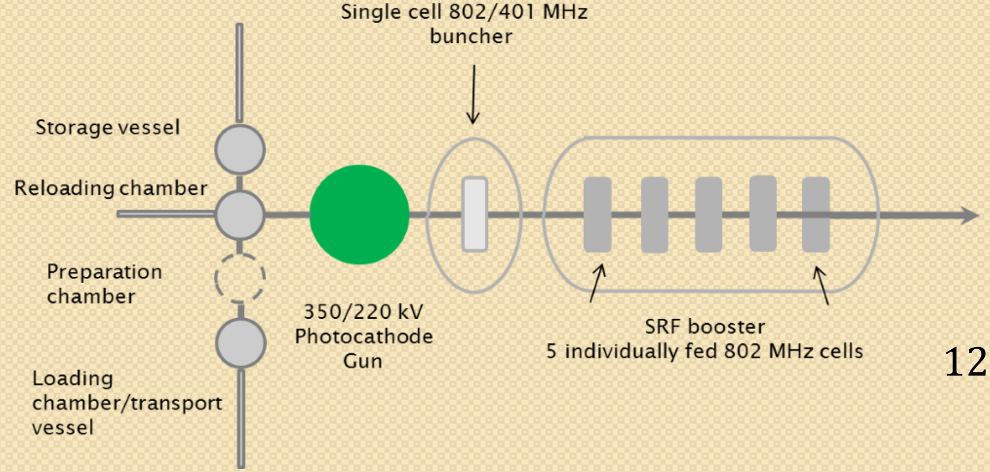






Injector & injector R&D

- Present concept: DC photo-cathode with SCRF acceleration to $5\ MeV$.
- Nominal repetition rate: $40.1\ \mathrm{MHz}$ (20th subharmonic)
- Nominal bunch charge $2 \cdot 10^9 e = 320\ \mathrm{pC}$ ($320\ \mathrm{pC} \cdot 40\ \mathrm{MHz} = 12.8\ \mathrm{mA}$)



$12.8\ \mathrm{mA} \cdot 5\ \mathrm{MV} = 64\ \mathrm{kW}$

- Considered photo-cathode materials:

Material	typical laser λ	work function	observed Q.E.	laser power fo 20 mA	observed maximum current	observed lifetime
Sb-based family, unpolarised	532 nm	1.5-1.9 eV	4-5%	4.7 W**	65 mA [Cornell]	No deterioration reported
GaAs-based family, polarised	780 nm	1.2 eV*	0.1-1.0%	31.8 W***	5-6 mA [JLAB]	to be checked
***- at NEA state, ** - at Q.E.=1%, *** - at Q.E.=0.1%**						

RF Power

- 5 MeV injector: $P_{beam} = 64$ kW (12.8 mA)
- Main linacs (in ERL mode zero beam loading):

$$P = \frac{V^2}{R/Q} \cdot \frac{\Delta f}{f}$$

with $Q_{opt} = \frac{1}{2} \cdot \frac{f}{\Delta f}$ and Δf the peak detuning.

Q_{opt}	RF power
10^6	250 kW
$5 \cdot 10^6$	50 kW
10^7	25 kW

New CERN 802 MHz, 60 kW CW IOT TX
9 units received & tested

Cavity and Cryomodule Design

- Collaboration with JLAB established – work has started. Cavity designs exist with different apertures (115 mm … 160 mm), optimization ongoing
- The cavity prototypes will be fabricated for *PERLE* by JLAB in the framework of our collaboration agreement.
- JLAB equally helps us with the design of the cryomodule (alternative to the SPL design).

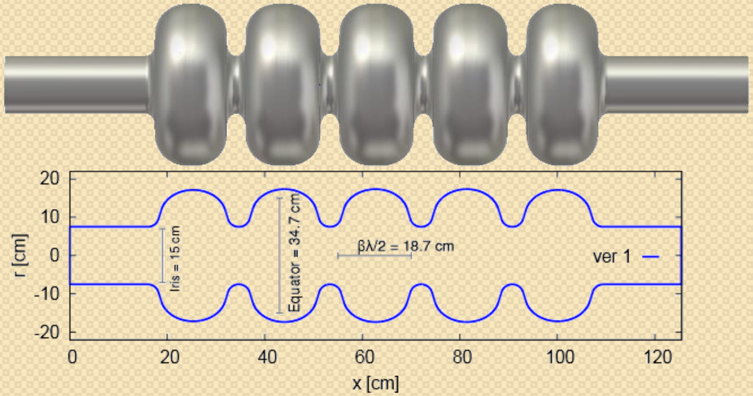
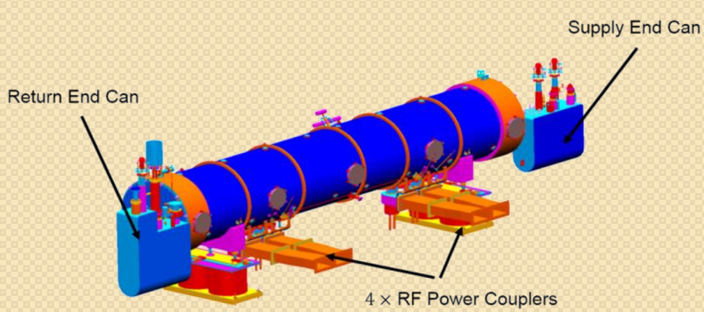
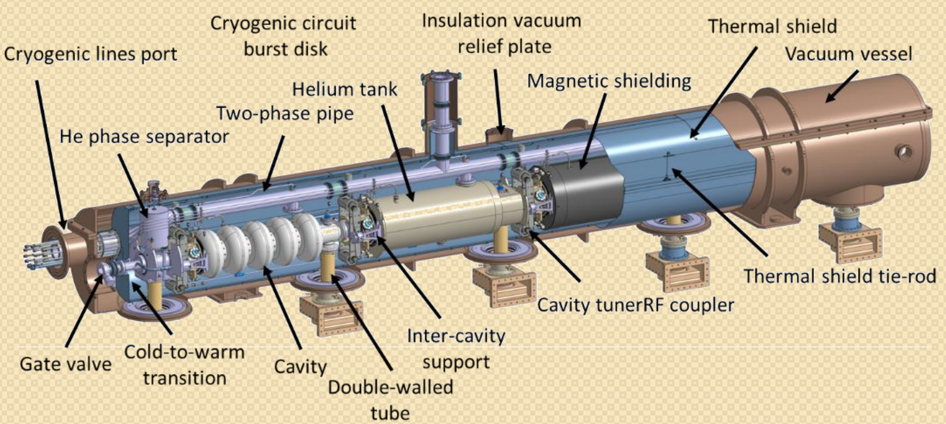


Fig. 2: Envelope of the first proposal for a five-cell ERL cavity at 802 MHz.

R. Calaga, M. Karppinen, K. Schirm, R. Torres-Sanchez (CERN)
F. Marhauser, R. Rimmer (JLAB)



JLAB design (based on SNS 805 MHz)



CERN design (based on SPL 704 MHz)

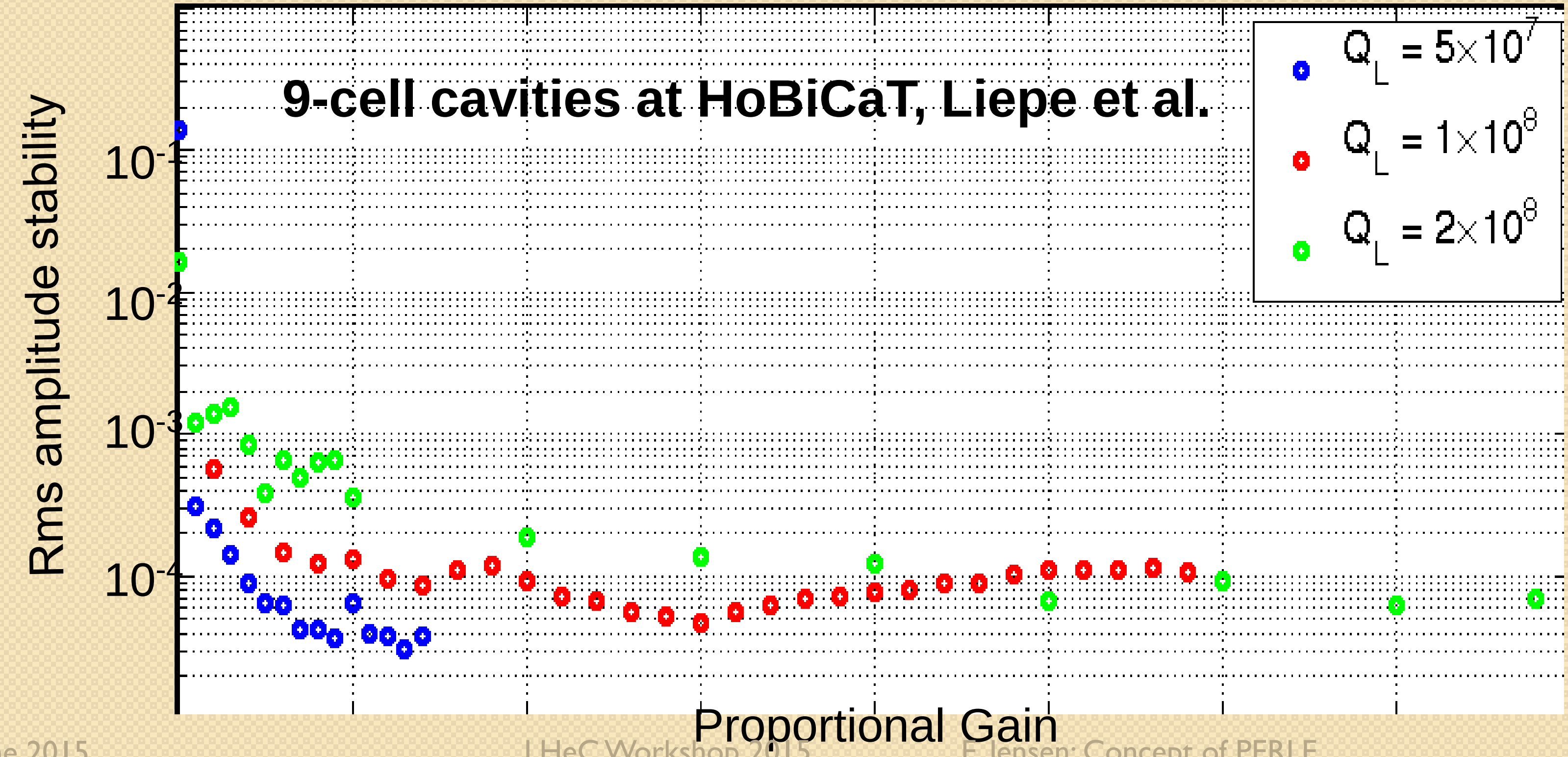
RF Controls

Development of digital LLRF system (Cornell type ?)

Amplitude and phase stability at high $Q_0 \sim 1 \times 10^8$

Reliable operation with high beam currents + piezo tuners

In case of failure scenarios: cavity trips, arcs etc..



Further uses of *PERLE*

- Test facility for SCRF cavities and cryomodules (described above)
- Test facility for multi-pass, multiple-cavity ERL, reliability and operational aspects,
- Injector studies,
- Beam diagnostics developments and testing with beam,
- Possible use for detector development and experiments suggests ~1 GeV as final stage energy,
- Test facility for controlled SC magnet quench tests,
- Facility for gamma-ray generation via Compton backscattering,
- It may become the injector to LHeC ERL and to FCC-he.

Beam diagnostics application

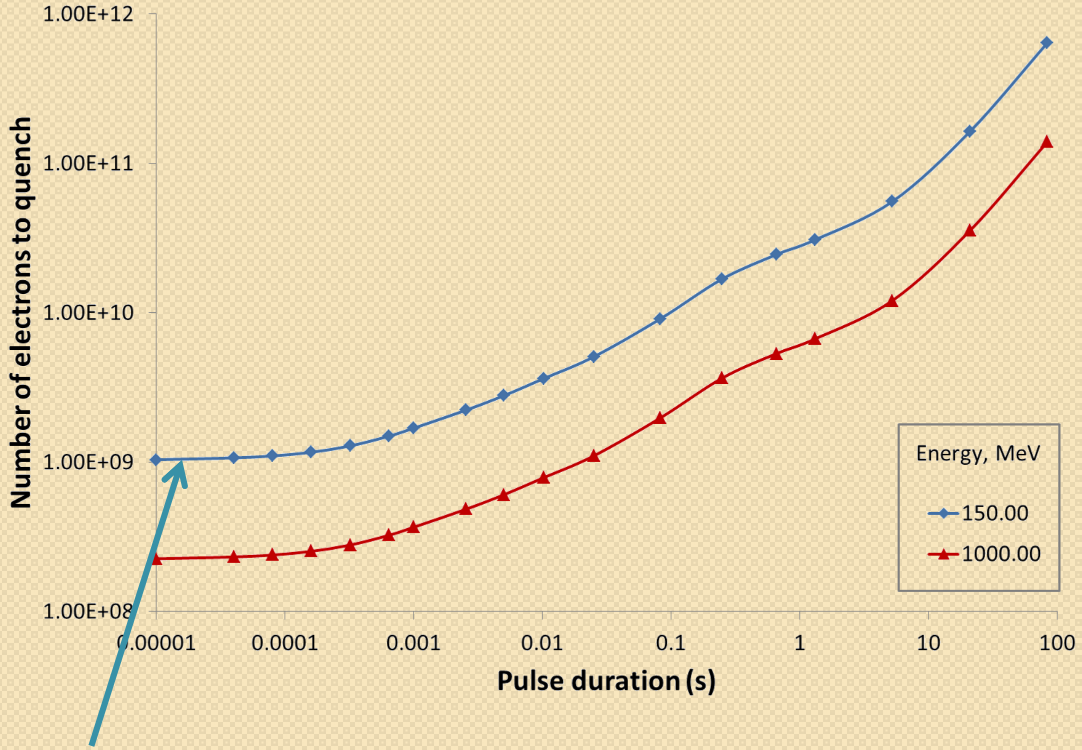
- Desired parameters:
  - Beam energy $> 200\ \mathrm{M}eV$ if possible (γ close to protons in LHC)
  - CW operation
  - bunch length below ps
  - bunch charge $(200 \div 1000)\ \mathrm{pC}$ ideal
- Proposed BI tests:
  - Test of BI based on the measurement of radiation produced by charged particles.
  - Test of electronics for future BI upgrades (all machines, but especially HL-LHC era diagnostics & FCC if rep rate can be made to match)
  - Test of BI for high resolution transverse & longitudinal diagnostics (making use of short bunches)
  - Further interesting tests would be possible in non-ERL mode with a dedicated external test beam line.

Controlled quench & damage tests

- Test of beam induced quenches and tests of SC cables and SC magnets
- Advantages compared to existing CERN facilities:
  - Beam will directly hit a sample (straightforward calculation of loss distribution)
  - SC wires, magnets/prototypes could be tested off line
  - Cryogenic environment in the experimental area
  - Fast losses (μs) and steady-state (s) are well described by our electro-thermal models and the experiments at LHC; intermediate (ms ... s) need to be better understood.
  - With PERLE, the whole time range (ns - several s) would be available to test – e.g. HiRadMat maximum length of losses is $7\ \mu s$ every $\approx 40\ s$.
- Are the intensities appropriate?

Intensity for controlled quench

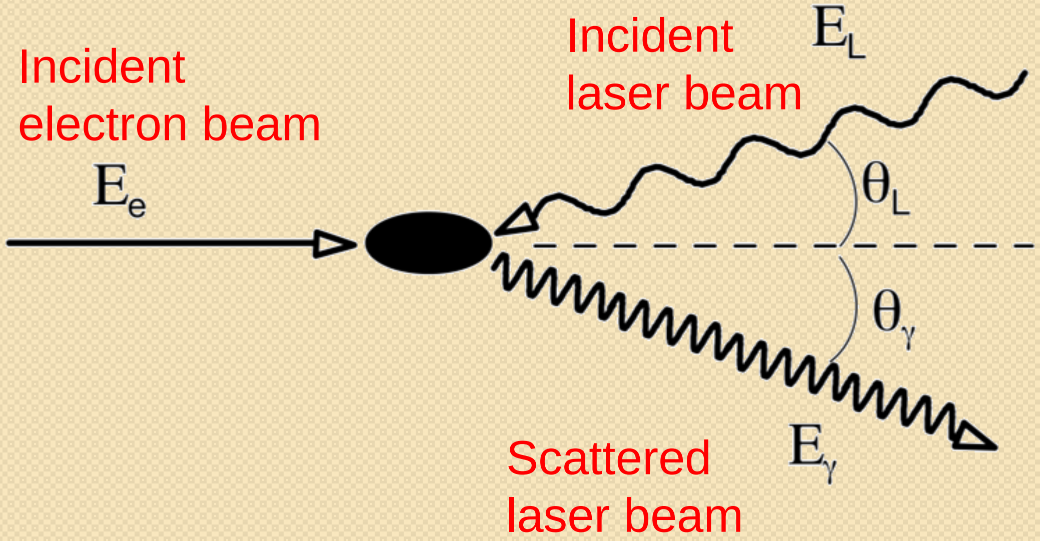
- Fluka simulation results for quenching an LHC Main dipole:



- One can easily quench with a single bunch, even at $150\ \mathrm{M}e\mathrm{V}$.
- *PERLE* nominal bunch charge $2 \cdot 10^9 >$ quench threshold $1 \cdot 10^9$

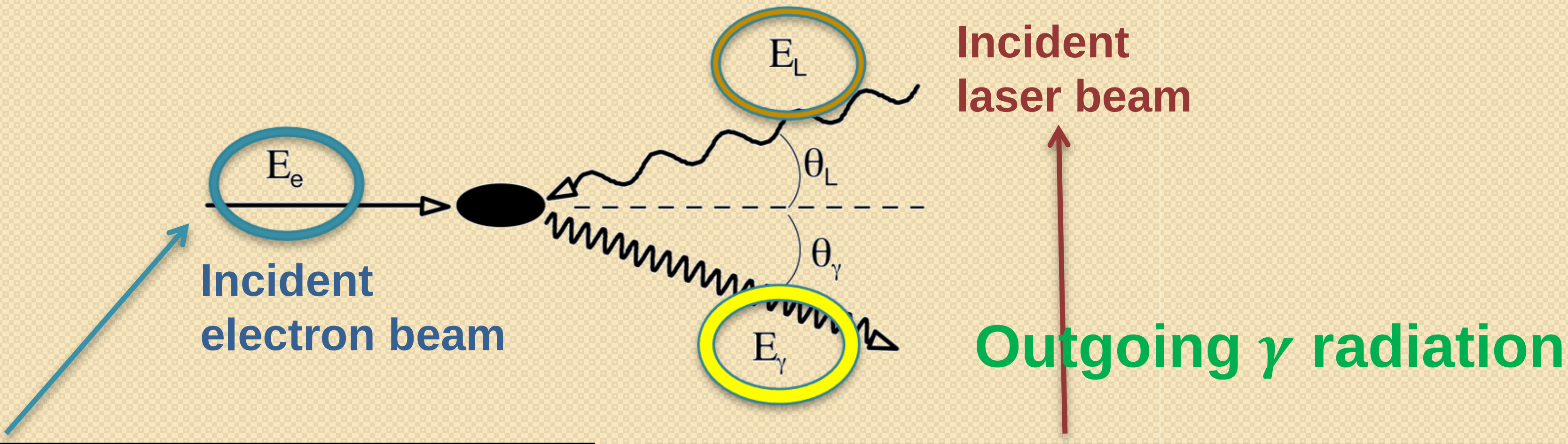
γ beams at *PERLE*: the idea

- Goal: generation of high-energy, monochromatic, polarized photons via Compton scattering (for nuclear physics research)



$$E_\gamma = 2\gamma_e^2 E_L \frac{1+\cos\theta_L}{1+\left(\gamma_e\theta_\gamma\right)^2+\left(\frac{eE_0}{m_0 c\,\omega_0}\right)^2+\frac{4\gamma_e E_L}{m_0 c^2}}$$

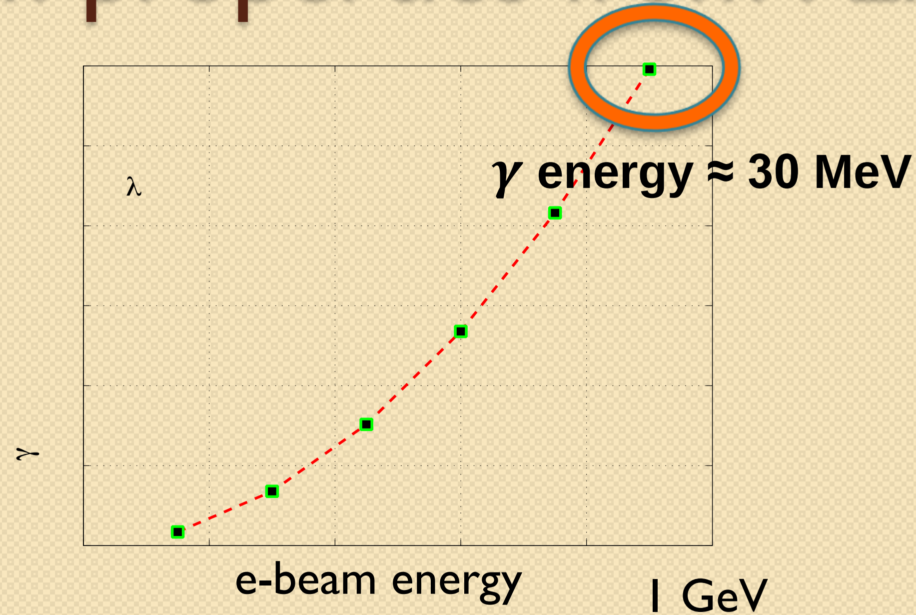
γ beams at *PERLE*: Parameters



ELECTRON BEAM PARAMETERS	
Energy	900 MeV
Charge	320 pC
Bunch Spacing	25 ns
Spot size	30 um
Norm. Trans. Emittance	5 um
Energy Spread	0.1 %

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

γ beam properties from *PERLE*



GAMMA BEAM PARAMETERS	
Energy	30 MeV
Spectral density	$9*10^4$ ph/s/eV
Bandwidth	< 5%
Flux within FWHM bdw	$7*10^{10}$ ph/s
ph/e^- within FWHM bdw	10^{-6}
Peak Brilliance	$3*10^{21}$ ph/s*mm^2*mrad^2 0.1% bdw

Summary

- *PERLE* is a proposed small, but powerful & versatile ERL facility
- It allows to study experimentally the exciting concept of beam energy recovery – an important concept for future accelerators.
- It would be an ideal facility for SRF R&D, compatible and synergetic with most CERN and many international projects.
- It would allow to train new accelerator experts on a real machine.
- Additional uses include:
  - Testing of beam instrumentation
  - Detector test beam
  - Controlled beam induced quench tests of magnets and cables
  - High brilliance, large energy γ source for nuclear physics
  - An injector of LHeC and FCC-he