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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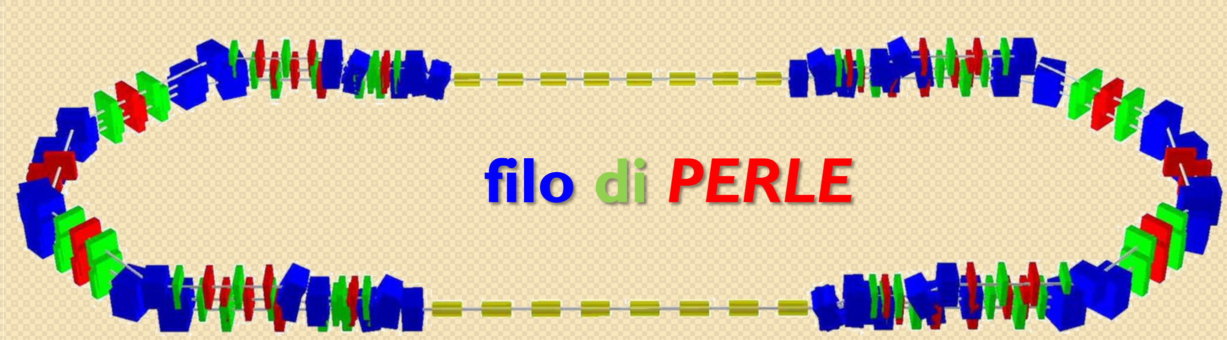
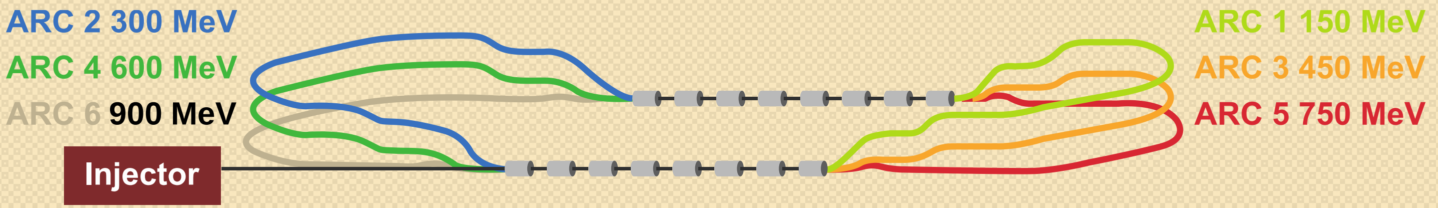
and special thanks to:

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!



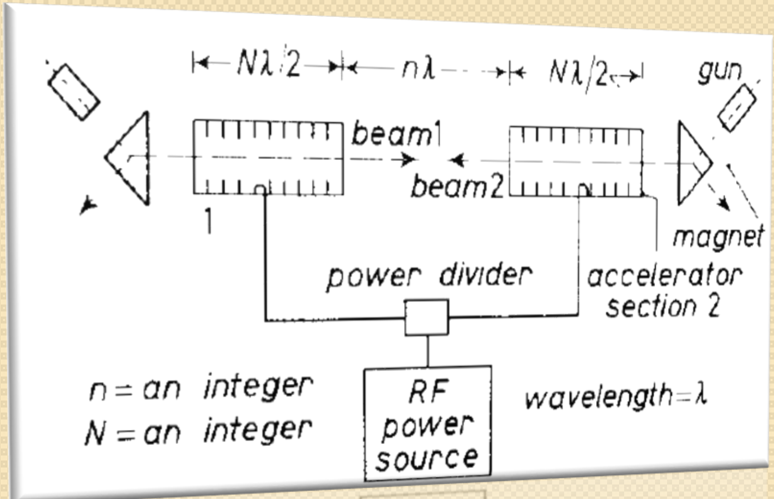
$12.8\ \mathrm{mA}\ (320\ \mathrm{pC} \times 40\ \mathrm{MHz})$, CW   **Up to sixteen 5-cell cavities in four cryomodules, 802 MHz, 19 MV/cavity**

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

PERLE | Powerful energy recovery linac experiments

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?

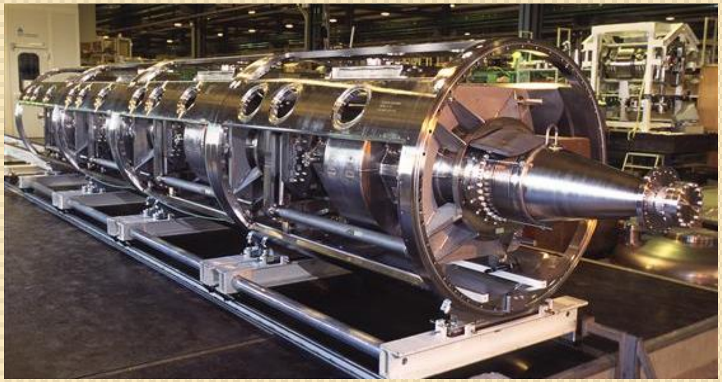
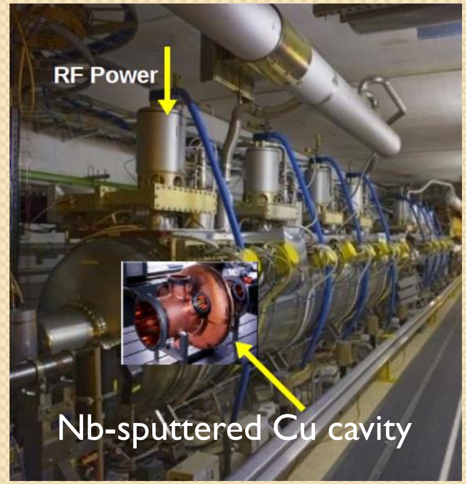
- CERN is intensifying R&D on SRF, getting ready for the next generation of HEP accelerators:
  - SRF needed for: ***LHC, HL-LHC***, HIE-ISOLDE, ***SPL, LHeC, FCC*** see next pages.
  - … the highlighted can directly take advantage of this facility

- 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!

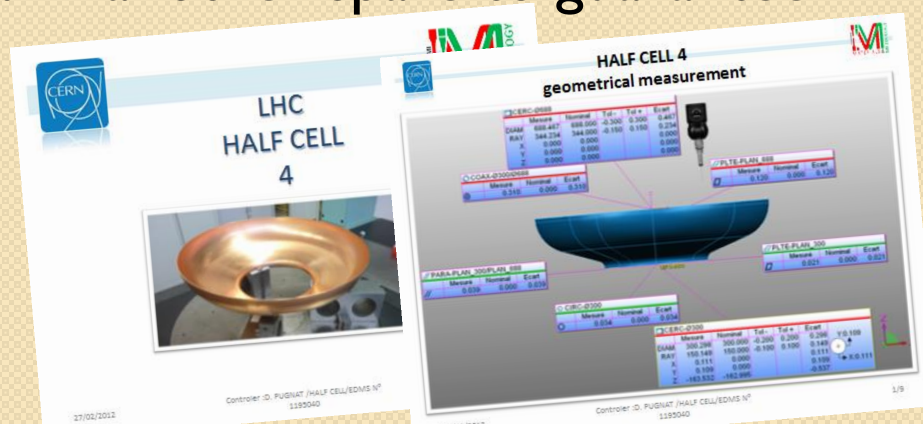
- *PERLE* is above all a facility for SRF R&D! With it we can complement the SRF testing – typical sequence of tests:
  - Sample tests in quadrupole resonator,
  - low power tests of bare cavity in vertical cryostat,
  - high power tests of dressed cavity in horizontal cryomodule,
  - tests with beam (HOM excitation!)

SRF at CERN 1: LHC

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

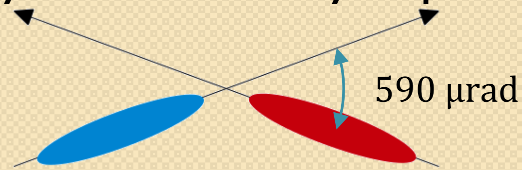



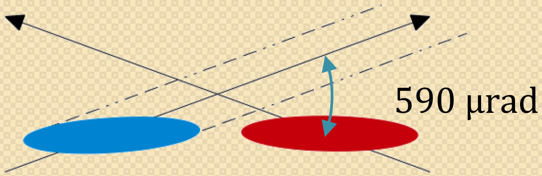
- Recently, one module was swapped with the only spare module
- We are in the process to build another spare to guarantee LHC availability!
- Parameters: 401 MHz,
  2 MV/cavity, 4 cavities/CM
  Nb sputtered on Cu



SRF at CERN 2: HL-LHC

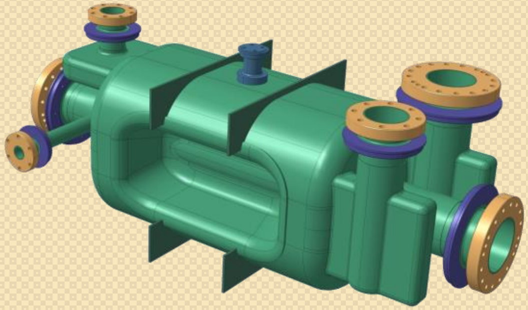
- Crab cavities are part of baseline for HL-LHC – w/o crab cavities, the available luminosity cannot be fully exploited.



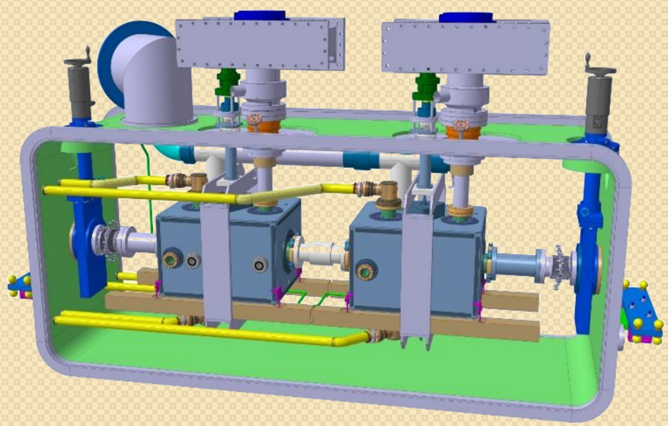


- Prototypes have been built, CM's are in construction, tests with proton beams are foreseen in SPS in 2018, production phase for 32 cavities plus spares: 2019 … 2024

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.

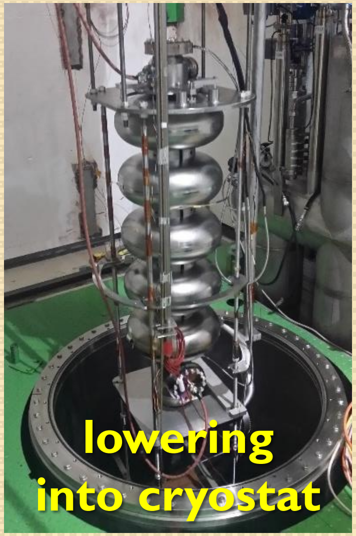

Cavity preparation


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	[illegible]
$R/Q = V_{eff}^2/(\omega * W)$	Ω	583.4	518.8	1036.0	482.	[illegible]
R/Q/cell	Ω	116.7	103.8	115.1	96.5	[illegible]
G	Ω	273.2	278.3	270.0	274.	[illegible]
R/Q·G/cell		31877	28876	31080	2644	[illegible]
Eq. Diameter	mm	323.12	352.73	206.60	187.	[illegible]
Iris Diameter	mm	115	140	70	70	[illegible]
Tube Diameter	mm	115	140	78	70	[illegible]
Eq./Iris ratio		2.81	2.52	2.95	2.6	[illegible]
Wall angle (mid-cell)	deg	0	0	13.31		[illegible]
E_{peak}/E_{acc} (mid-cell)		2.07	2.44	1.98	2.5	[illegible]
B_{peak}/E_{acc} (mid-cell)	mT/(MV/m)	4.00	4.24	4.17	4.5	[illegible]
k_{cc}	%	2.14	3.12	1.89	3.1	[illegible]
N^2/k_{cc}		11.71	8.01	42.97	7.9	[illegible]
cutoff TE_{11}	GHz	1.53	1.25	2.25	2.5	[illegible]
cutoff TM_{01}	GHz	1.996	1.64	2.94	3.2	[illegible]

Ranking: 1, 2, 3, 4, 5

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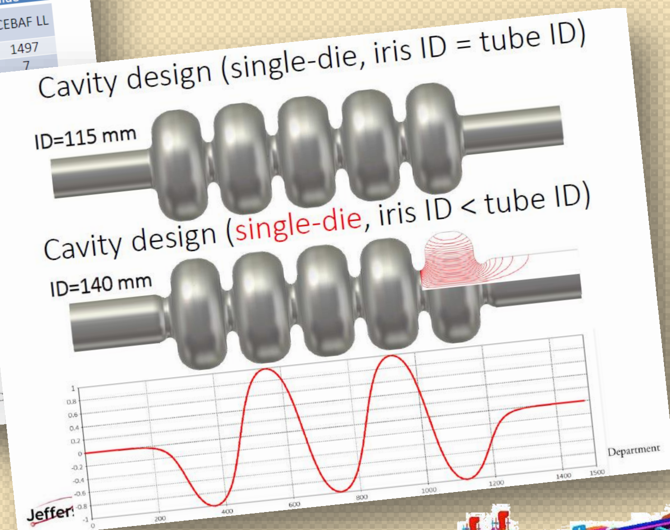

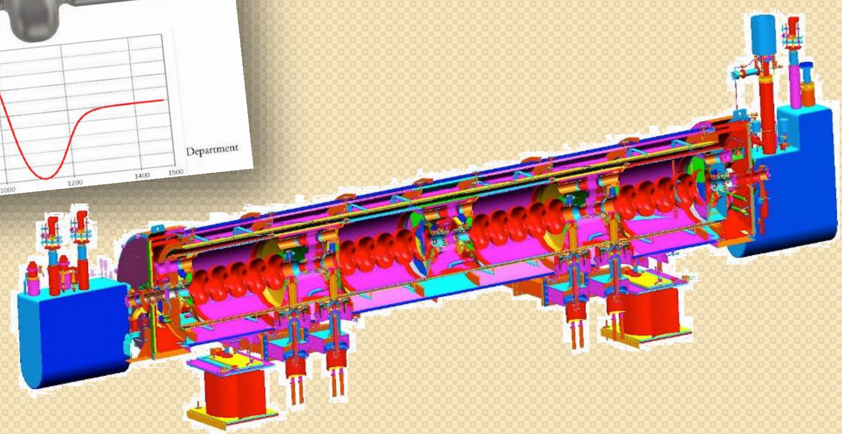

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SRF at CERN 6: FCC Study

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

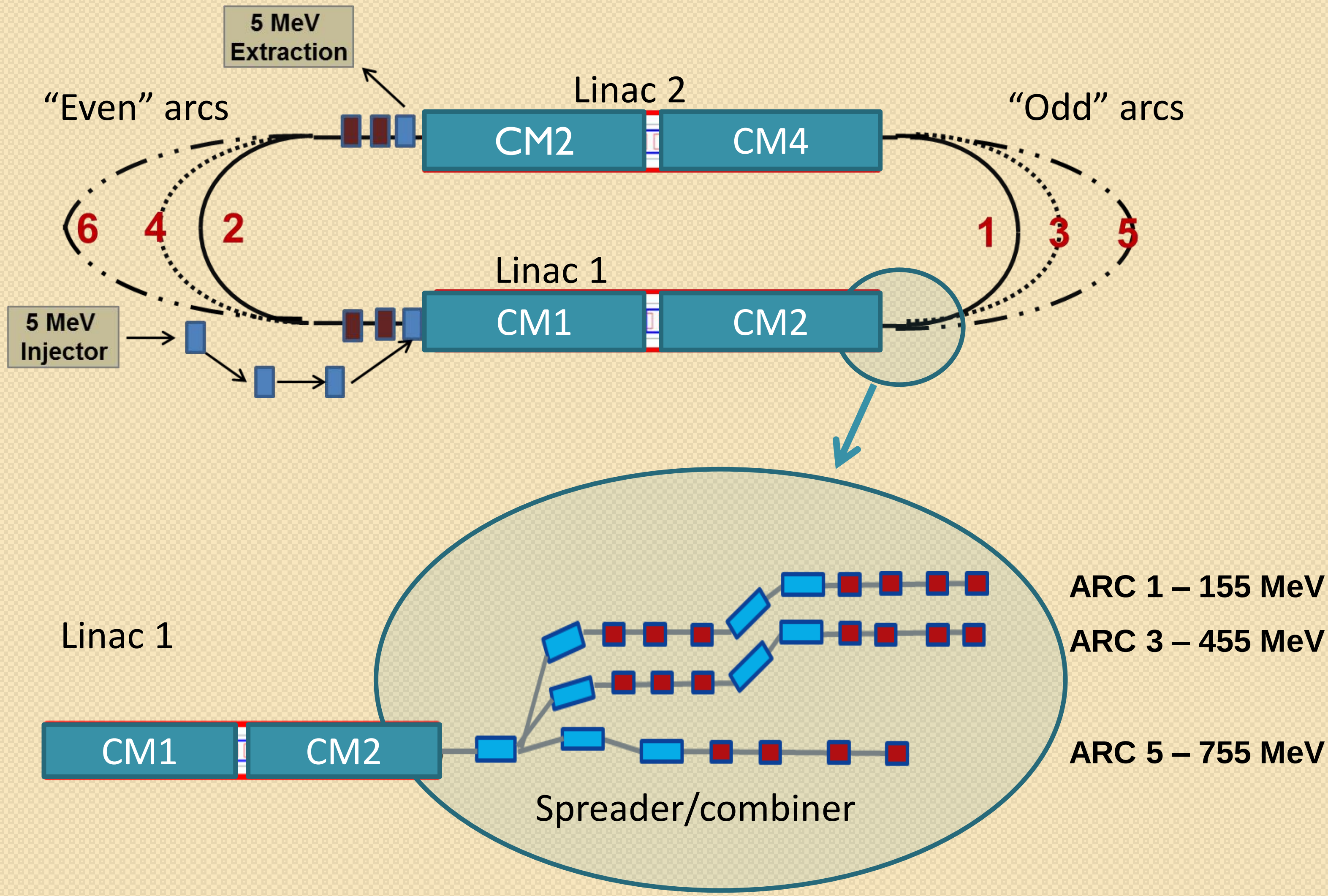
Operation at different frequencies

- 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:

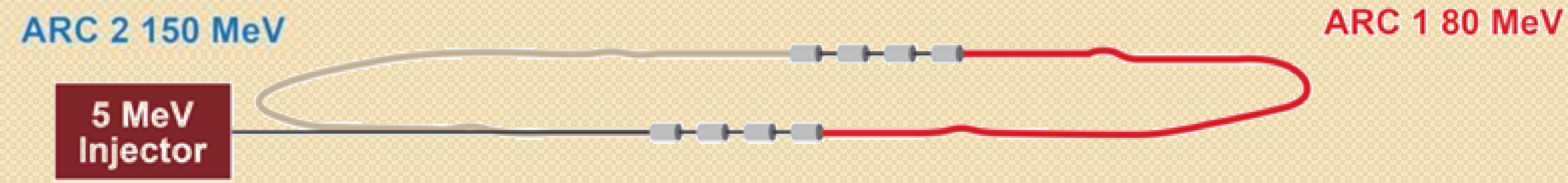
Programme	Frequency (MHz)
CERN frequencies	200 MHz, 401 MHz, 704 MHz, 802 MHz
ILC, X-FEL, LCLS-2, …	1,300 MHz
PIP-II	650 MHz
SNS	805 MHz
CERN Linac4, ESS	352 MHz
ESS	704 MHz
eRHIC	422 MHz
JLAB MEIC	953 MHz
JAERI	500 MHz

Conceptual Layout

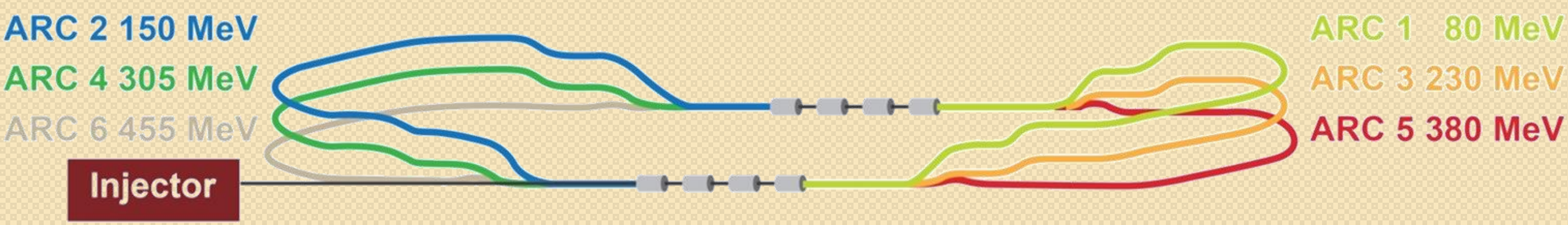


Staged construction

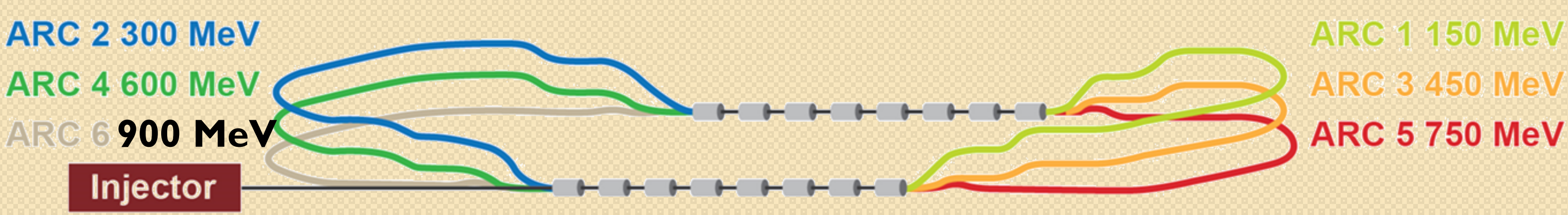
Stage 1 – 2 CMs, test installation – injector, cavities, beam dump.



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

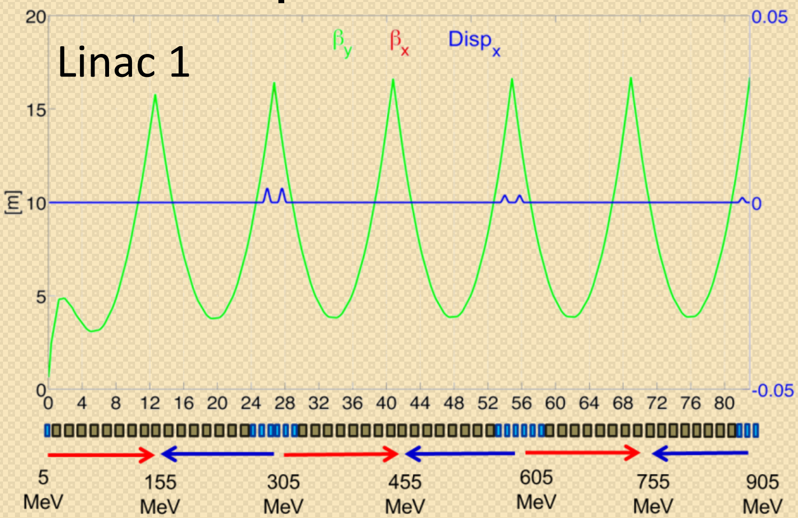


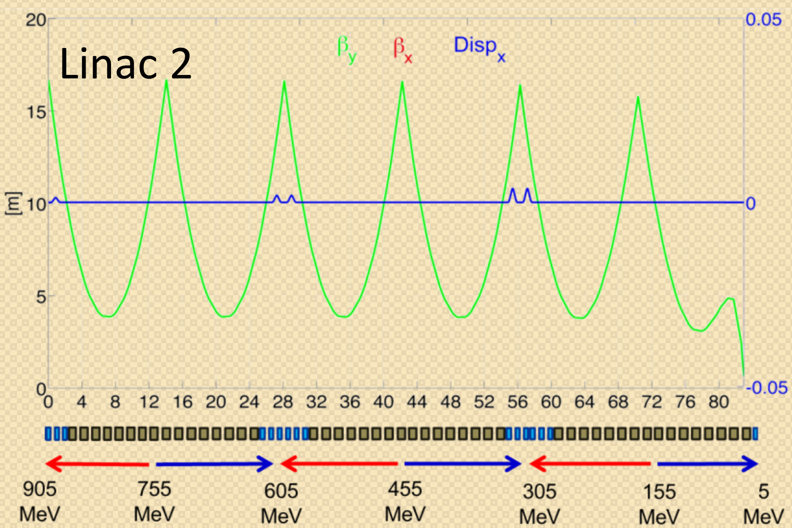
Stage 3 – 4 CMs, set up arcs for higher energies – reach up to 900 MeV



Linac and arc optics

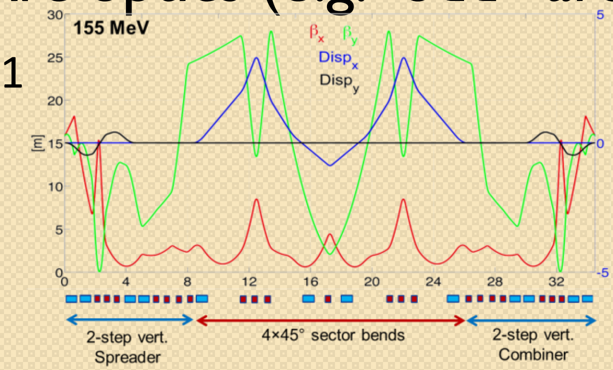
- Linac optics



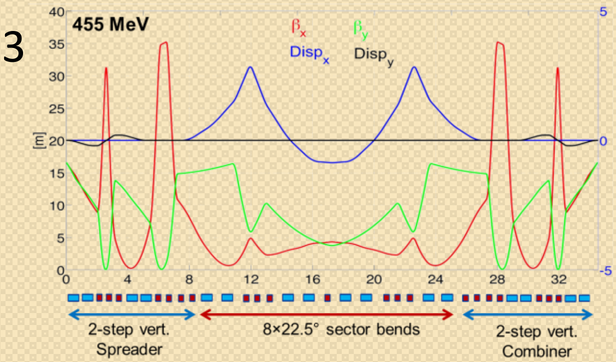


- Arc optics (e.g."odd" arcs)

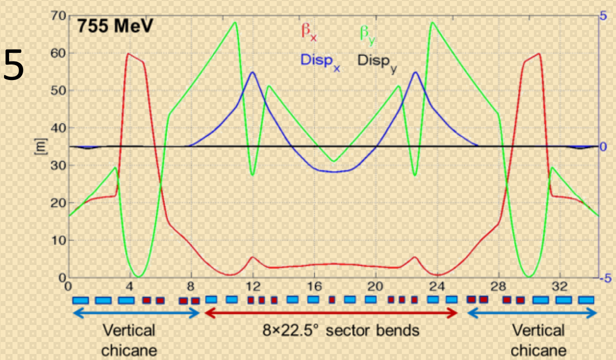
Arc 1



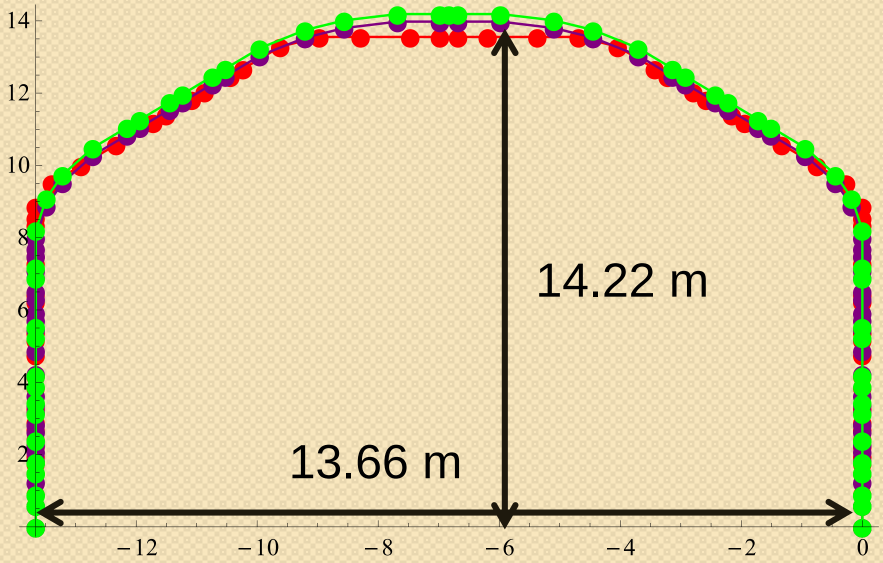
Arc 3

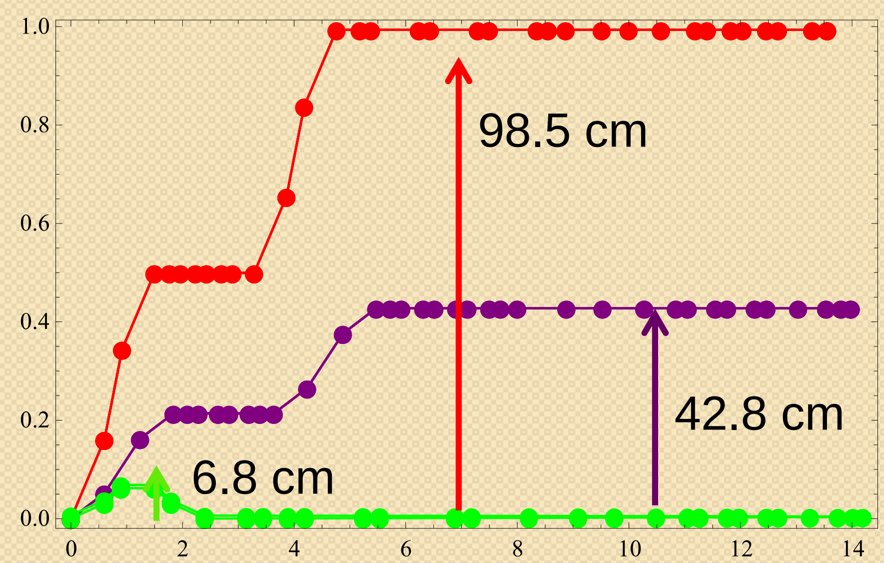


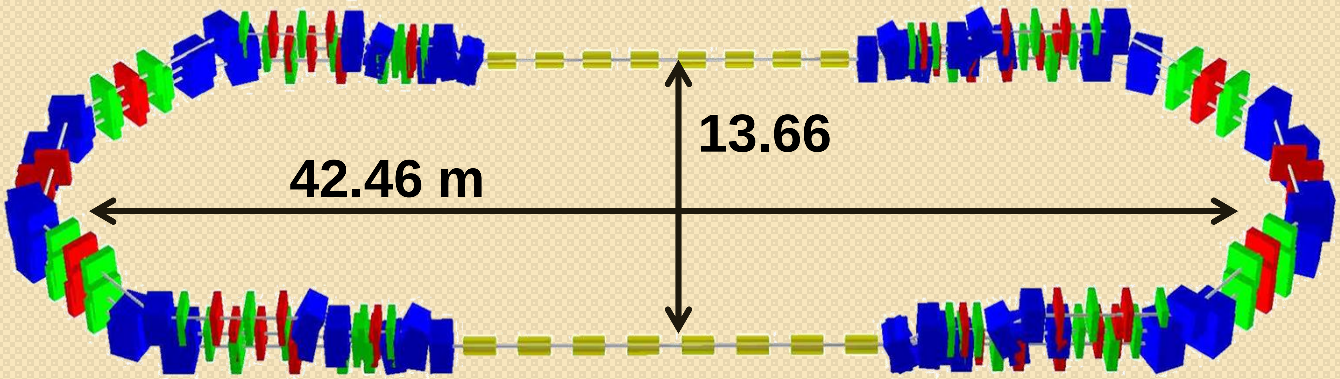
Arc 5



Arc Layout

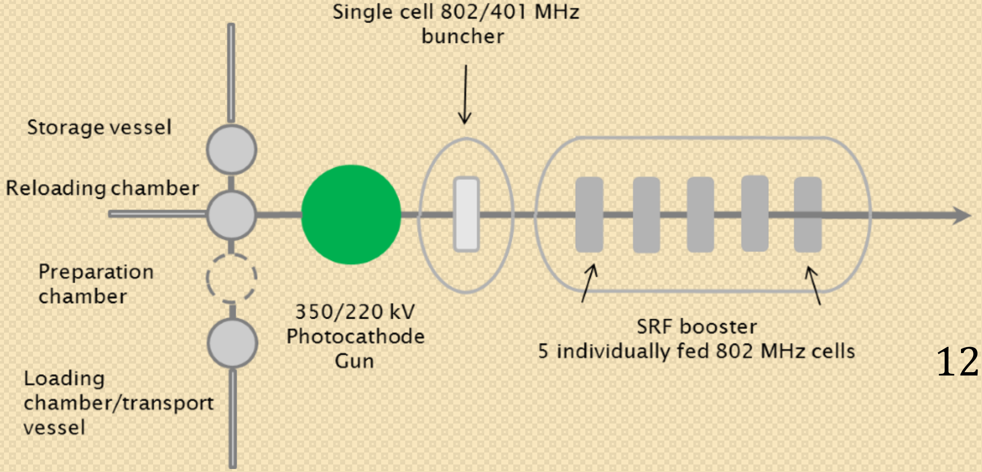






Injector & injector R&D

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



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

- 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 $\mathrm{M}e\mathrm{V}$ injector: $P_{beam} = 64\ \mathrm{kW}\ (12.8\ \mathrm{mA})$
- 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).

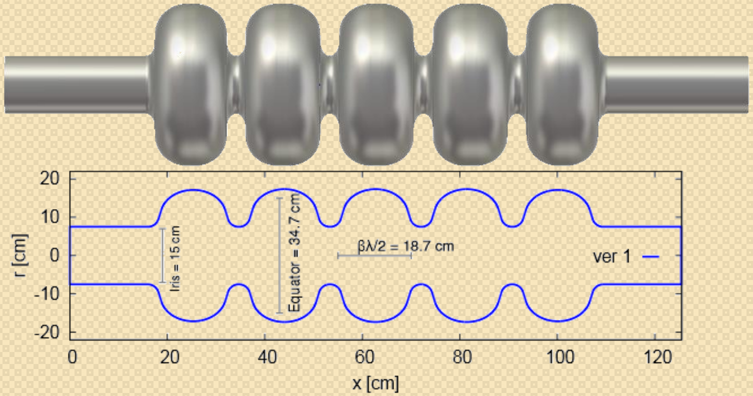


Fig. 2: Envelope of the first proposal for a five-cell ERL cavity at 802 MHz.

R. Calaga, M. Karppinen, K. Schirm, R. Torres-Sanchez (CERN)
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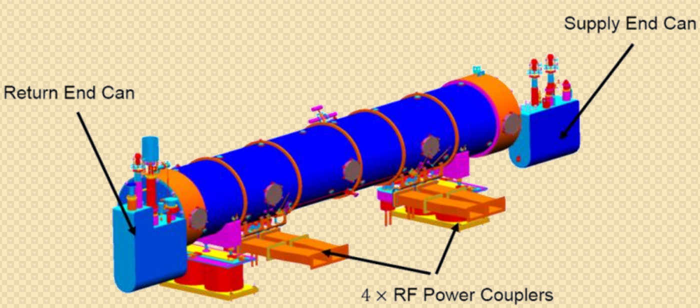
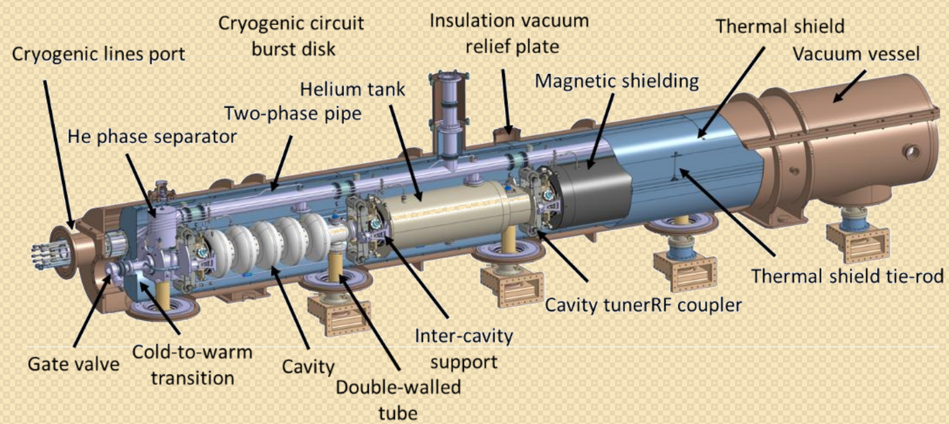


JLAB design (based on SNS 805 MHz)



CERN design (based on SPL 704 MHz)

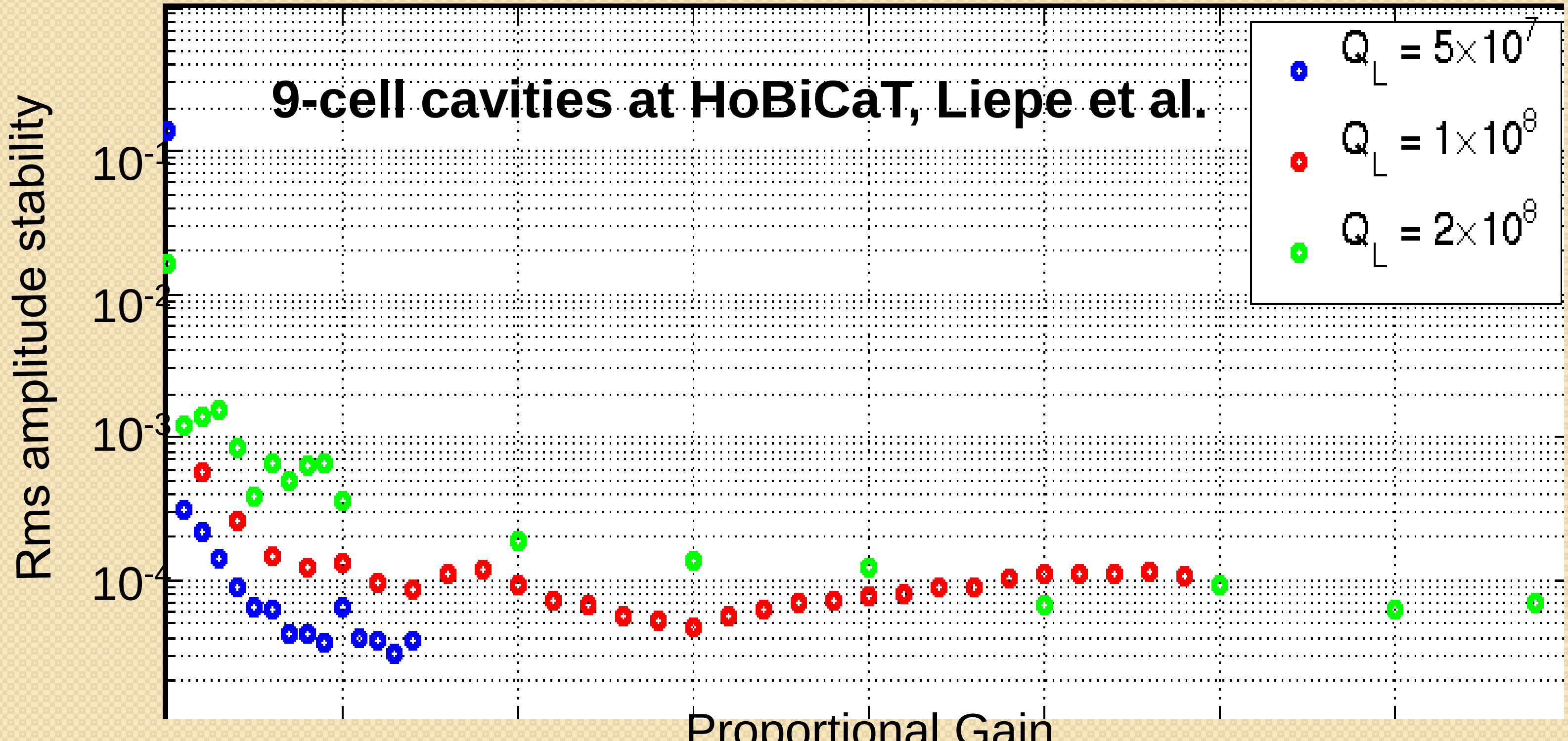
RF Controls

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

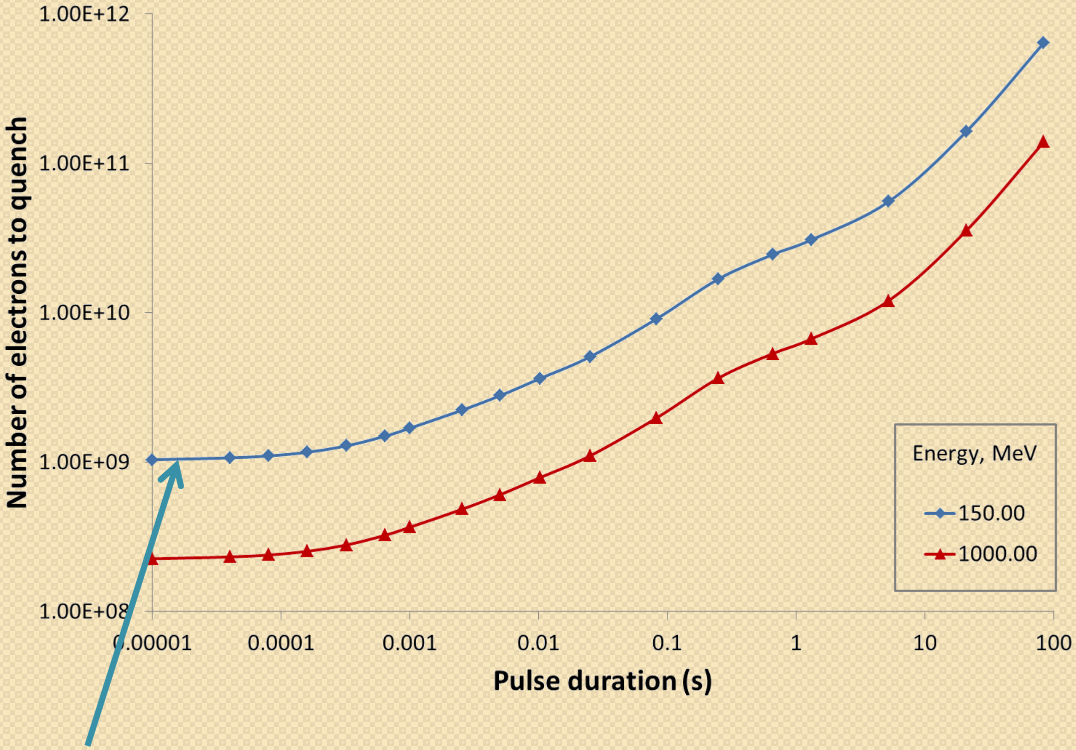
- Desired parameters:
  - Beam energy $> 200\ \mathrm{M}e\mathrm{V}$ if possible (γ close to protons in LHC)
  - CW operation
  - bunch length below ps
  - bunch charge $(200 \div 1000)\ \mathrm{pC}$ ideal
- Proposed BI tests:
  - Test of BI based on the measurement of radiation produced by charged particles.
  - 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

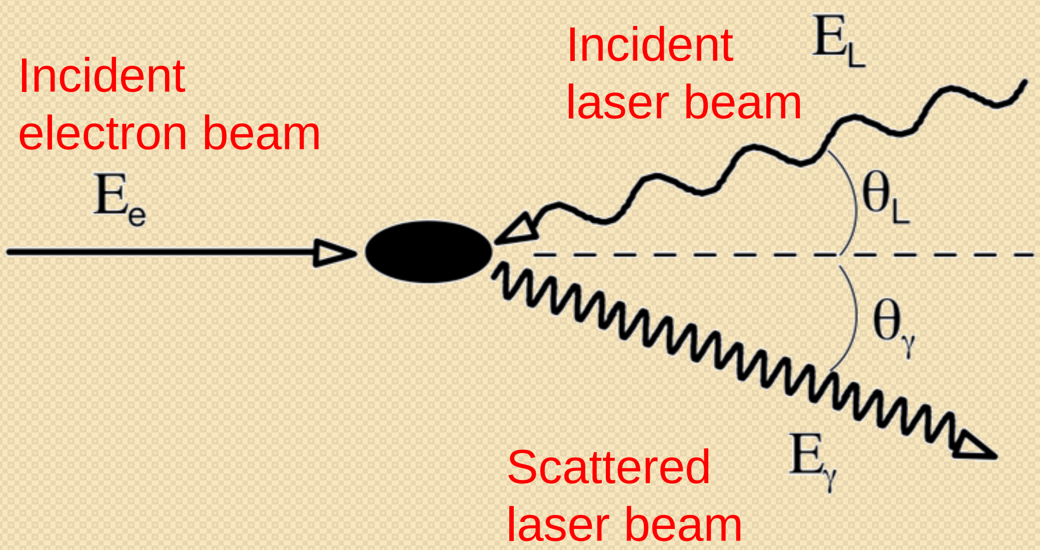
- Fluka simulation results for quenching an LHC Main dipole:



- 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 $1 \cdot 10^9$

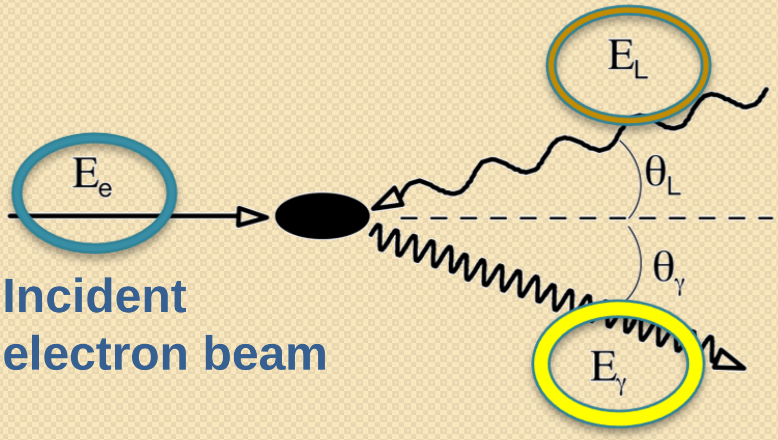
γ beams at *PERLE*: the idea

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



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

γ beams at *PERLE*: Parameters



Incident laser beam

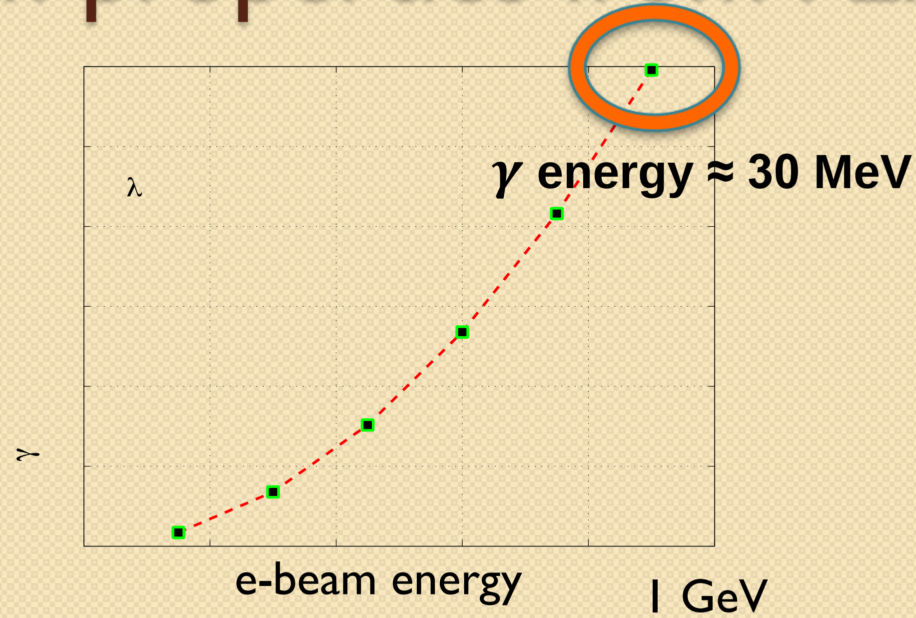
Incident electron beam

Outgoing γ radiation

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