ERL as a versatile SRF test facility

Erk Jensen/CERN

What do you need for an SRF test facility?

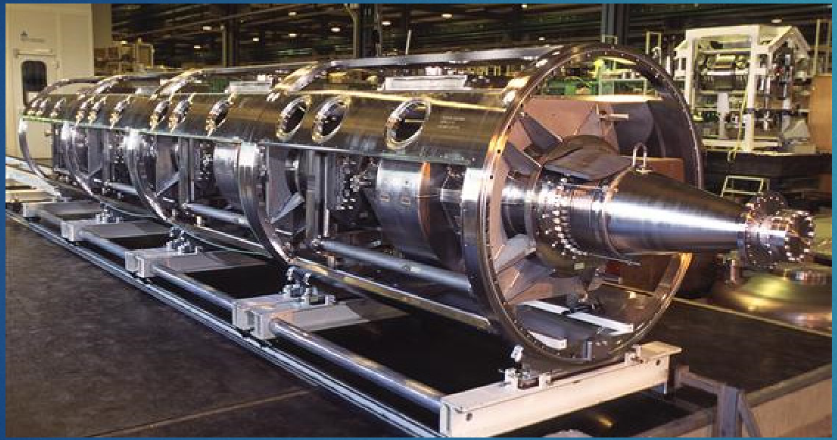
- RF power and controls, at the right frequency,
- Cryogenics,
- Measurement equipment,
- Your "DUT" ("device under test"), i.e. the cavity(-ies) in their cryomodules.
- People (specialized technicians, engineers, scientists)

  At CERN, we have these facilities e.g. in the cryogenic test facility in building SM18.

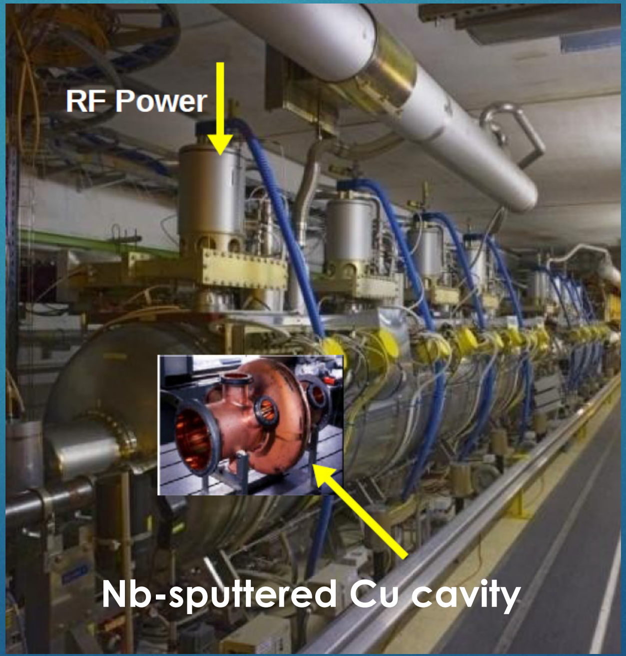
- This allows many relevant and important tests, except the **tests with beam**!

SRF @ CERN (1: LHC)

- LHC: 4 cryomodules with 4 single-cell cavities
- Parameters: 401 MHz, 2 MV per cavity
- Technology: Elliptical single-cell cavities based on spun Cu half-cells, Nb coated by sputtering.



4-cavity CM without MLI and outer vessel

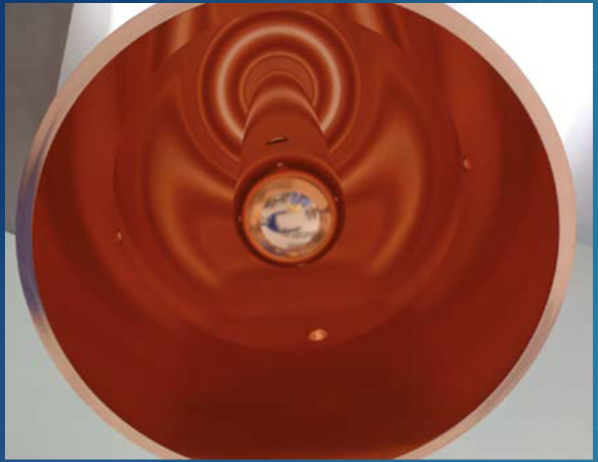


Nb-sputtered Cu cavity

Exchange of an LHC cryomodule

SRF @ CERN (2: HIE-ISOLDE)

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



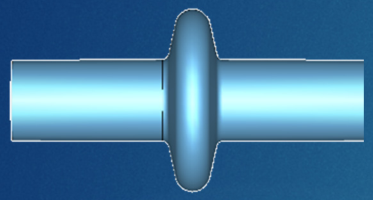
Assembled cryomodule

HIE-ISOLDE with 4 CMs (2018)

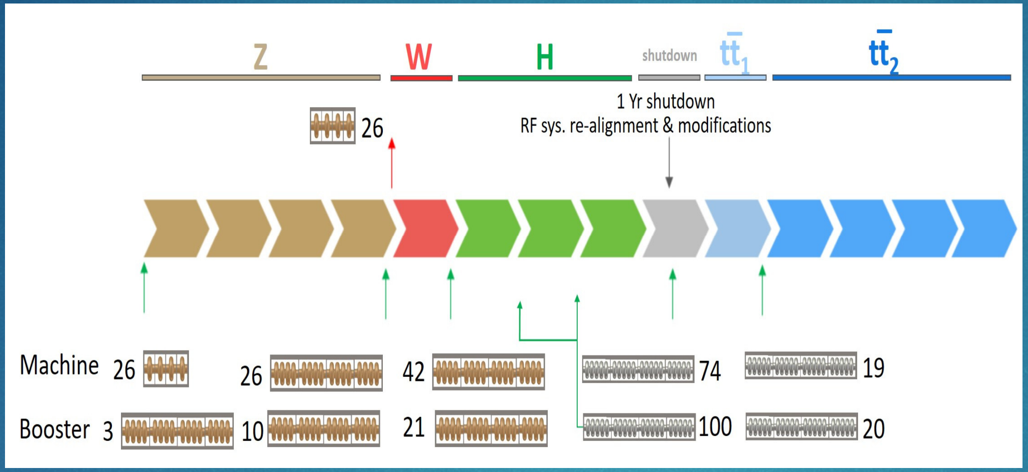
See also: CERN Courier May 2018: https://iopp.fileburst.com/ccr/archive/CERNCourier2018May-digitaledition.pdf

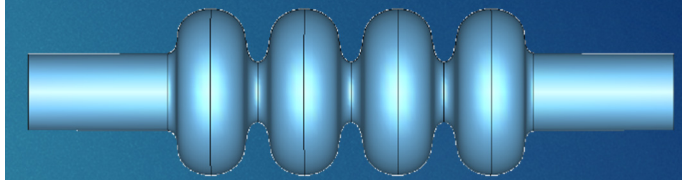
SRF @ CERN (3: FCC study)

- FCC-ee: different cavities for different machine options considered:

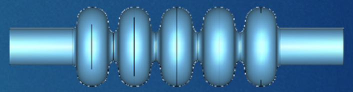


Single-cell at 401 MHz for Z





Four-cell at 401 MHz for W, H, $t\bar{t}$



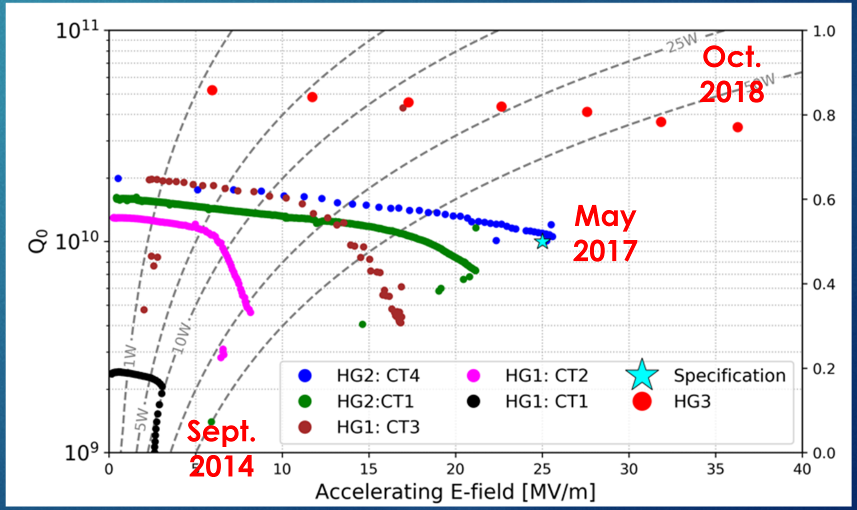
Five-cell at 802 MHz for $t\bar{t}$

- Parameters: 401 MHz single-cell, 401 MHz 4-cell, 802 MHz 5-cell cavities – extension in stages. 802 MHz 5-cell cavities also for the ERL-based FCC-he (and LHeC, and *PERLE*!).
- Technologies chosen:
  - 401 MHz Nb on Cu, based on LHC experience, 802 MHz: bulk Nb with N-doping
  - new fabrication methods studied (Electro-hydro-forming, Electrodeposition, seamless, …),
  - new coating methods studied (HiPIMS, Energetic condensation, …)

SRF @ CERN (4: 704 MHz)

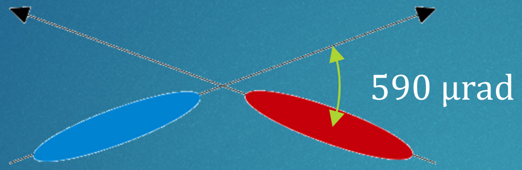
- High-gradient SRF R&D program at CERN, evolved from former "SPL" project.

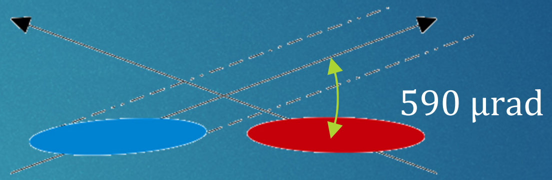
- Important for CERN to validate SRF infrastructure reaches present state of the art.
- Strong synergy with ESS (Lund).



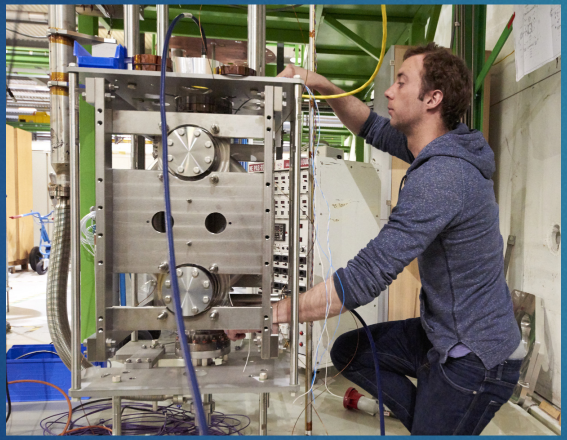
SRF @ CERN (5: HL-LHC, 401 MHz)

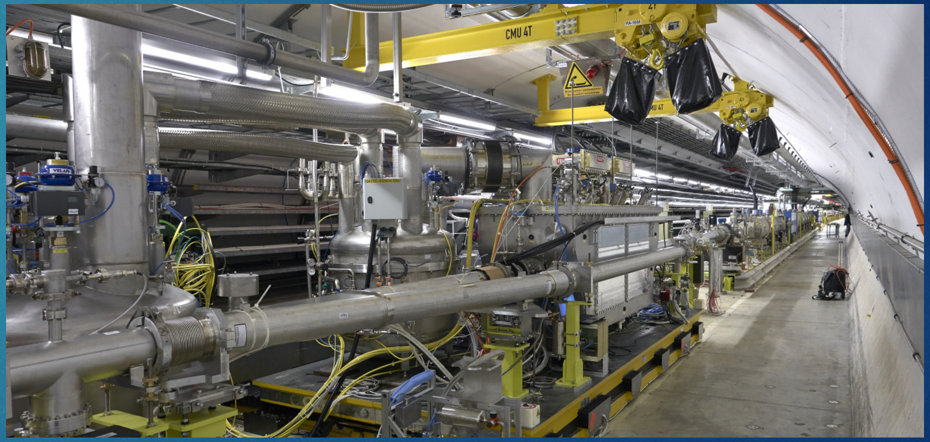
- Crab cavities are part of baseline for HL-LHC – w/o crab cavities, the available luminosity cannot be fully exploited.





- Prototypes cavities and CM's were built and tested with beam in the SPS.





- Parameters: 401 MHz, 3.4 MV/cavity, 2 cavities/CM; total: 16+4 cavities

SRF tests with beam

- Testing cavities/cryomodules without beam is a must, but does not fully validate the system:
  - The beam excites HOMs
  - The beam will influence MP
  - Tests with beam are complementary to lab tests and compulsory to fully validate the system!
- What energy should the beam have?
  - It must be highly relativistic, i.e. for electrons above – say – 5 MeV, or for protons above 10 GeV (in the SPS, we tested crab cavities at up to 450 GeV)
- What beam current should one aim at?
  - Already small beam currents will be useful
  - It should be representative for the desired operation of the cavity – maybe some tens of mA, maybe some Ampere.
- ***You do not necessarily need an ERL.***

The question I address: What characteristics should an ERL have for SRF tests?

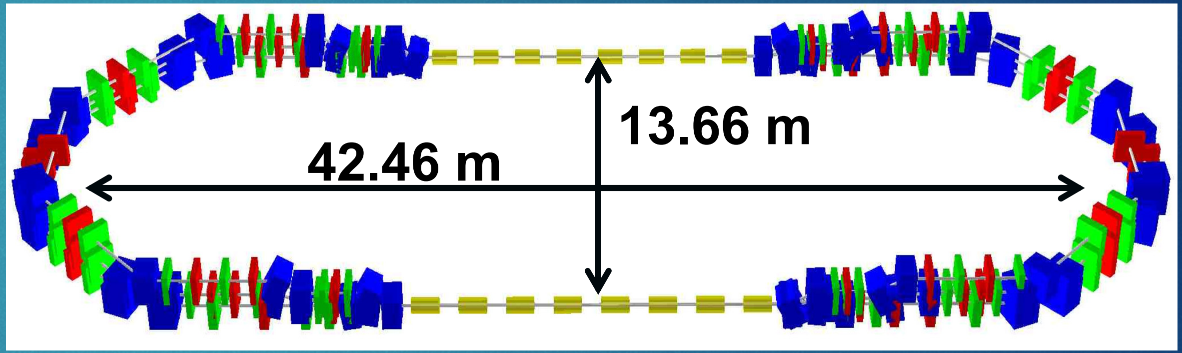
What characteristics should an ERL have as SRF test facility?

- Flexibility to adapt to imperfections,
- Operation at different frequencies,
- Operation at different overall accelerations (different energies)

- In this case, the advantage of the ERL:
  - You can test at larger beam currents ($2 \times n_{\mathrm{pass}}$ times the injected current, for the HOMs)
  - You can realize this large current without substantial beam loading.
  - The electrical installation can be smaller than a non-ERL TF (for similar energy × current)
  - You can perform long-term tests with reduced power consumption.

I will use different flavours of *PERLE* for illustration:

- "Original" PERLE (**P**owerful **ERL** for **E**xperiments) – 2017 :
  - Reference https://doi.org/10.1088/1361-6471/aaa171, "PERLE. Powerful energy recovery linac for experiments. Conceptual design report".
  - 3 pass ERL, up to 900 MeV.
  - Footprint: $45\ \mathrm{m} \times 14\ \mathrm{m} \times 1\ \mathrm{m}$



- PERLE@Orsay (2018) – a smaller version of the above:
  - Reference https://indico.cern.ch/event/765096/contributions/3295979/, "PERLE: A High Power Energy Recovery Facility for Europe".
  - Up to 3 passes, up to 492 MeV, footprint: $24\ \mathrm{m} \times 5.5\ \mathrm{m} \times 0.8\ \mathrm{m}$.

Other example ERLs

	PERLE	S-DALINAC	bERLinPro	CBeta	MESA
# of passes	6	4	2	8	2
Frequency [GHz]	0.8	3	1.3	1.3	1.3
Inj. current [mA]	20	very small	100	40	1 (later 10)
Total current [mA]	120	very small	200	320	2
Max. energy [GeV]	0.45 – 0.9	0.13	0.05	0.15	0.105
Beam power [MW]	~10	$< P_{\mathrm{RF}}$	5	6	0.1
Remarks	Attn.: 2 versions of different size!	path-length adjustment		FFAG lattice!	also operable in external beam mode

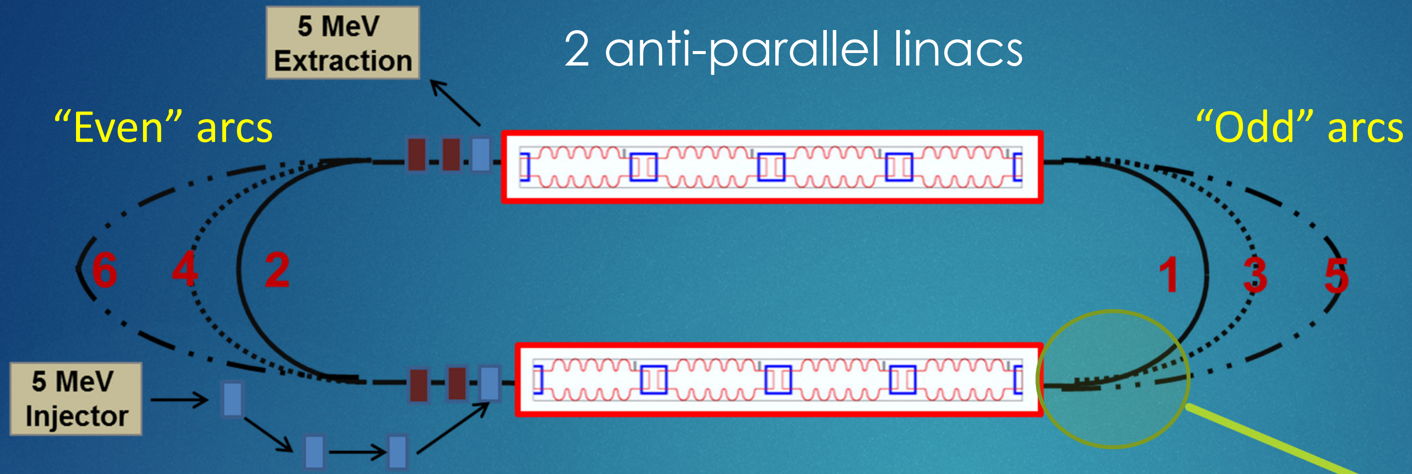
Sorry: non-exhaustive!

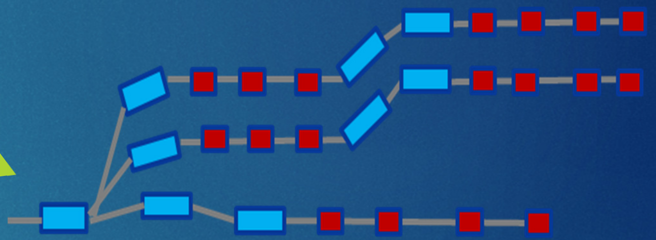
Operation at different acceleration

… considerations also important for staged construction of the ERL

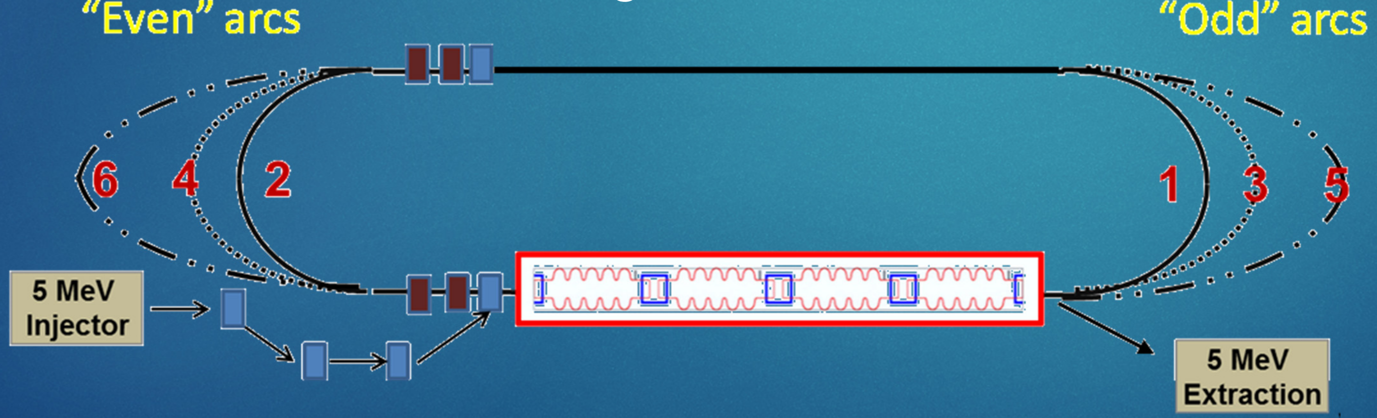
Concept of *PERLE* in phases

2 anti-parallel linacs



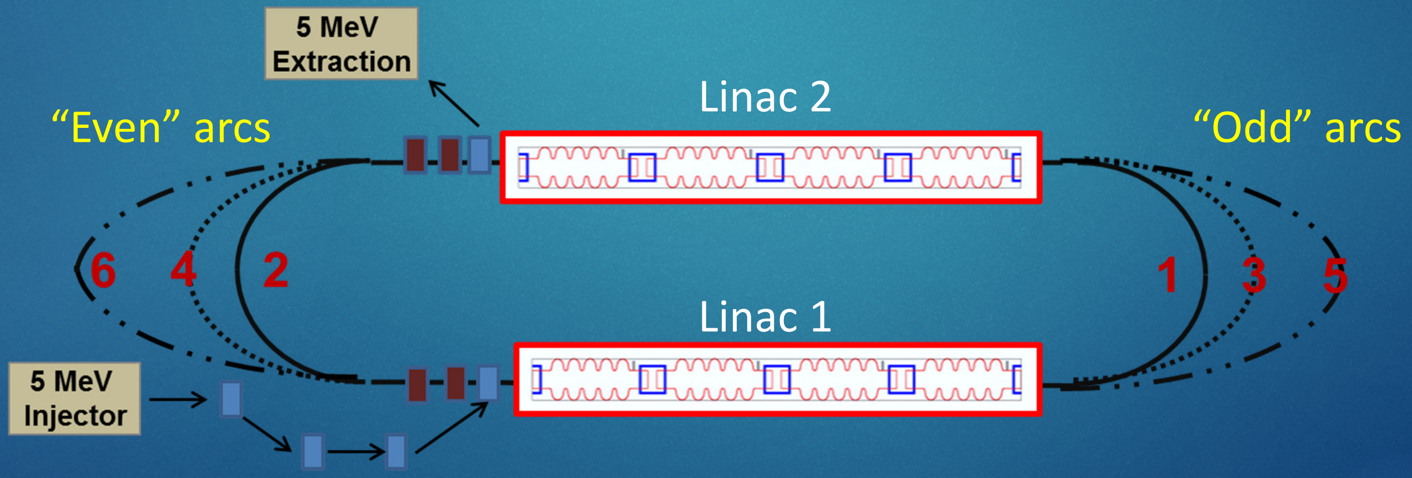


Single linac



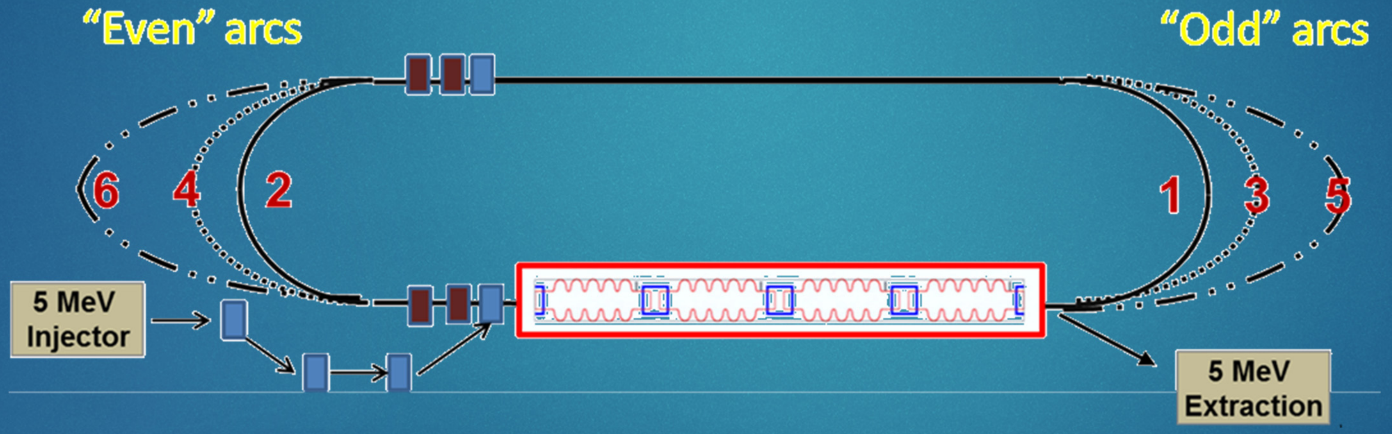
Anti-parallel linacs

- For the anti-parallel linacs configuration, it is important that both linacs provide **the exact same acceleration**: The beam is accelerated to its highest energy in Linac2, but then decelerated in Linac 1, but then must fit in the same "odd" arc again.
- This condition is not necessary for FFAG arcs.



Single linac configuration

- Note that the low-energy extraction/beam dump has to be at different locations for the single-linac configuration.
- The arc magnets and spreaders/combiners are now to be adjusted to arc1=arc2, arc3=arc4, arc5=arc6.



- The single linac configuration is better suited for an SRF test facility.

Requirements of operation at different acceleration

- The return arc magnets, as well as the spreaders/combiners must be individually powered to allow matching the different beam momenta and tuning the lattice functions.
- The low energy injection and extraction optics requires special care since the beam momenta are not strictly proportional! (cf. Figure!)

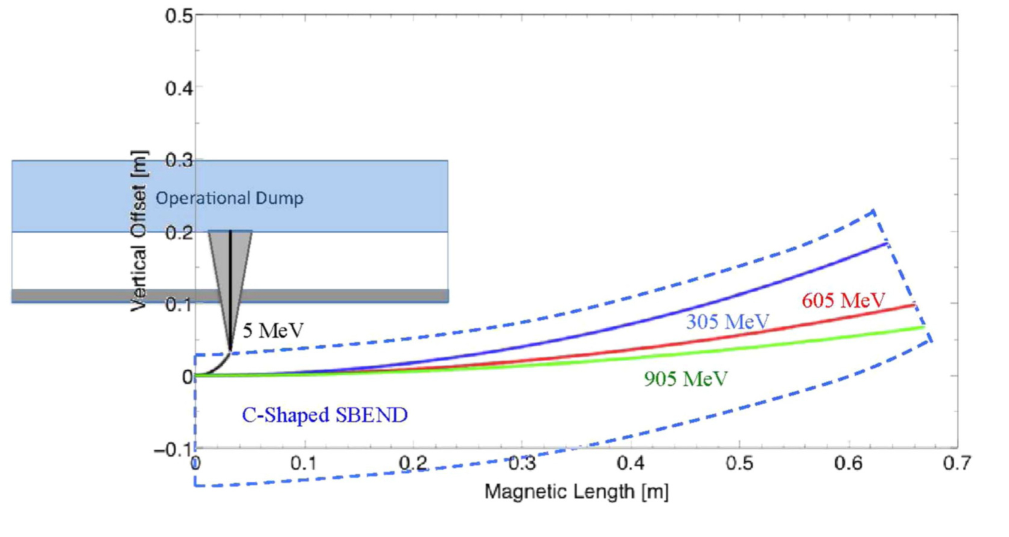


Figure 48. The first dipole of the vertical spreader is a C-Shaped SBEND which allows to extract the 5 MeV beam from the magnetic field region (between the dashed blue lines) towards the vertical dump.

From https://doi.org/10.1088/1361-6471/aaa171

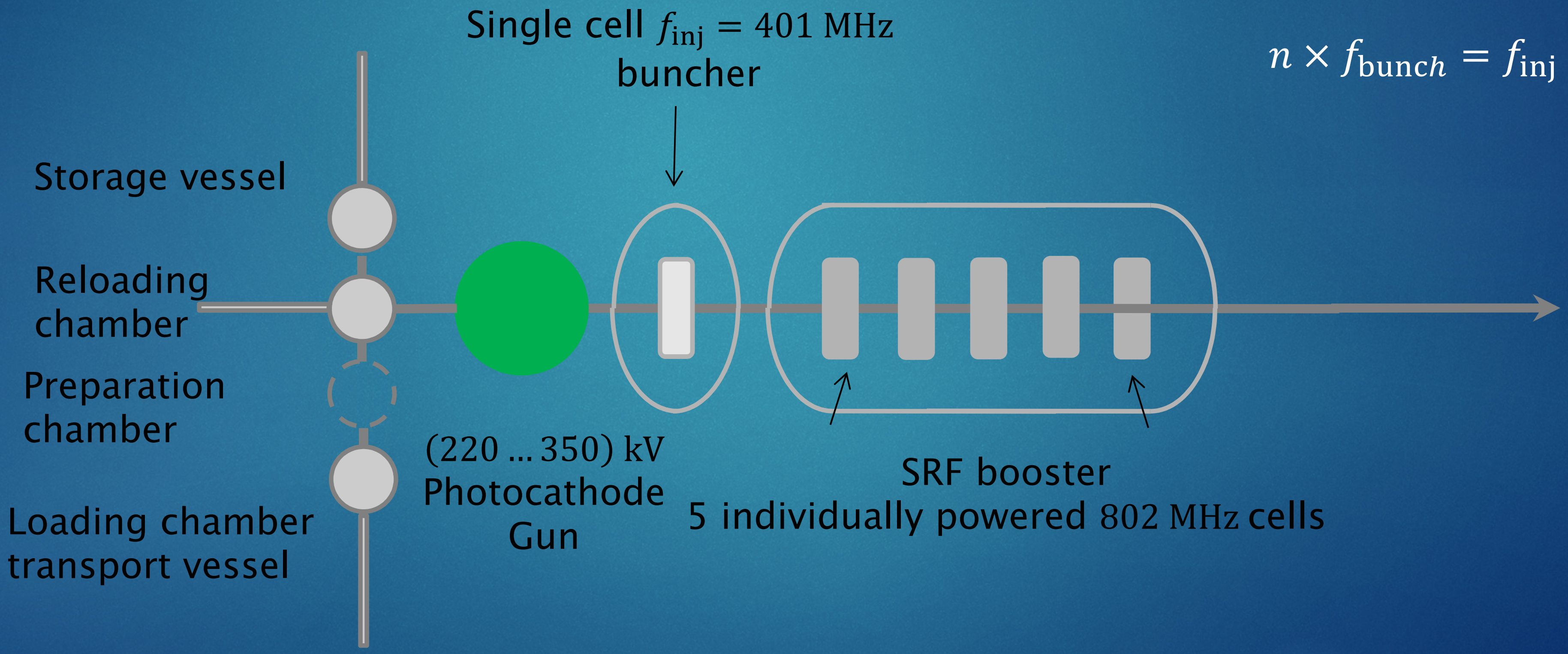
Operation at different frequencies

… for example to test at the commonly used frequencies 352 MHz, 401 MHz, 704 MHz, 802 MHz and 1300 MHz.

Choice of bunch repetition frequency

- In principle, a DC photo-cathode gun can be triggered by the laser at an arbitrary frequency f_{bunch}.
- Operating at a common subharmonic, of the desired test frequencies and the injector linac should be possible.

$$n \times f_{bunch} = f_{inj}$$



Finding a suitable subharmonic

- Assume buncher/booster operating at f_{inj} (e.g. 400.8 MHz)
- With a suitable control system, the laser can be operated at any subharmonic n (e.g. $n = 33$, i.e. $f_{\text{bunch}} = 12.146\text{ MHz}$).
- This principle allows operation at different frequencies f of the main RF system at any harmonic m, $f = \frac{m}{n} f_{\text{inj}}$.
- Subharmonic 33 is particular, since it allows reaching many interesting, frequently used frequencies.
- Examples: : $m = \{29, 33, 58, 66, 107\}$, resulting with $n = 33$ in

$$f = \{352.2, 400.8, 704.5, 801.6, 1299.6\}\text{ MHz}$$

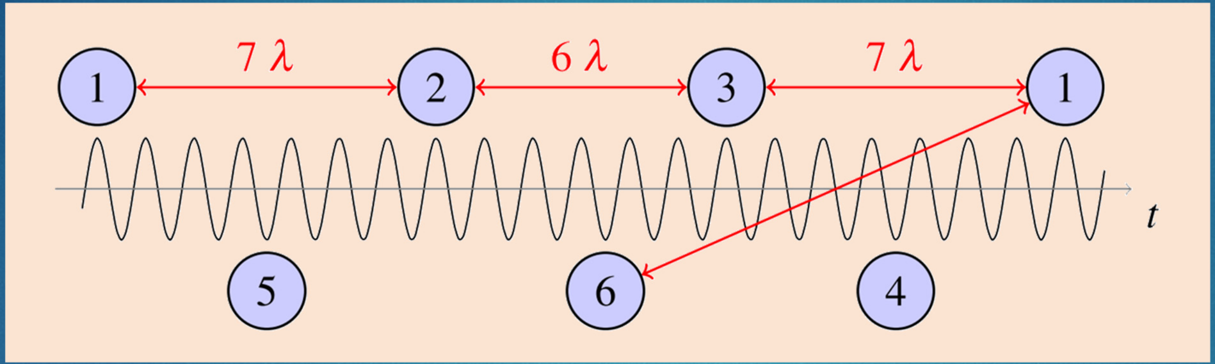
- With a bunch charge of 300 pC, operation at $f_{\text{bunch}} = 12.146\text{ MHz}$ would result in an injected beam current of 3.6 mA.
- Another suitable subharmonic was found at $f_{\text{bunch}} = 10.832\text{ MHz}$ (subharmonic $m = 37$)

Fine tuning the total path length

… the total arc length has to be adjusted to $n \times \lambda$ (or – at top energy – to $\left(n + \frac{1}{2}\right) \times \lambda$) ! … for different λs!

Example original PERLE

- In the original PERLE proposal, it was tried to distribute individual bunches almost equally to minimize collective effects.



- Pass length around $100\ \mathrm{m}$, $n = 10$, $m = 20$. Exact path lengths:
  - Single pass: $269.5\,\lambda$ (where $\lambda = 0.374\ \mathrm{m}$), i.e. 100.793 m
  - 2 passes: pass 1: $270\,\lambda$, pass 2: $265.5\,\lambda$. (100.98 m, 99.297 m)
  - 3 passes: pass 1: $267\,\lambda$, pass 2: $266\,\lambda$, pass 3: $263.5\,\lambda$. (99.856 m, 99.482 m, 98.547 m)
- For the operation at different frequencies, the total path lengths have to be re-adjusted to be exact multiples of their λ, which will require in general adjustment.

Example: $f_{\text{bunch}} = 12.146\ \text{MHz}$

- The following table demonstrates path length for 3 passes adapted to PERLE@Orsay (total path length $\mathcal{O}(51\ \text{m})$)
- This relatively small size does not allow an "almost equal bunch distribution".

f_{bunch} [MHz]	t_{bunch} [ns]	f_{test} [MHz]	λ [m]	Harmonic n	Pass 1 [λ, m]	Pass 1 [λ, m]	Pass 1 [λ, m]
40.08 *)	24.950	801.600	0.3740	20	135, 50.489	135, 50.489	135.5, 50.676
12.1455	82.335	801.600	0.3740	66	135, 50.489	135, 50.489	135.5, 50.676
12.1455	82.335	352.218	0.8512	29	59, 50.218	59, 50.218	59.5, 50.644
12.1455	82.335	1299.564	0.2307	107	218, 50.290	218, 50.290	219.5, 50.636

- To allow testing at $f = \{352.2, 801.6, 1299.6\}\ \text{MHz}$, the possibility to adjust the path length by 40 cm would be sufficient.
- Proposal: mount the return arcs on one side on movable girders with a 20 cm moving range.

*) nominal scheme for comparison

Conclusions

- You don't need an ERL if you need a versatile SRF beam test facility, but if you want to use your ERL as SRF test facility, please note:
  - Build in all the flexibility that you can afford: individually power magnets, adjustable girders, flexible lattice functions that can be retuned.
  - With a photo-cathode in a DC gun, and with a LLRF that can trigger the laser at a sub-harmonic of your injector linac, you can use the facility at different frequencies.
  - We have given the example to operate *PERLE* at 352, 401, 704, 802 and 1300 MHz with the same injector linac – but of course only one frequency at a time.

Thank you very much!