Energy Recovery Linac

Picture: Jan-Christoph Hartung

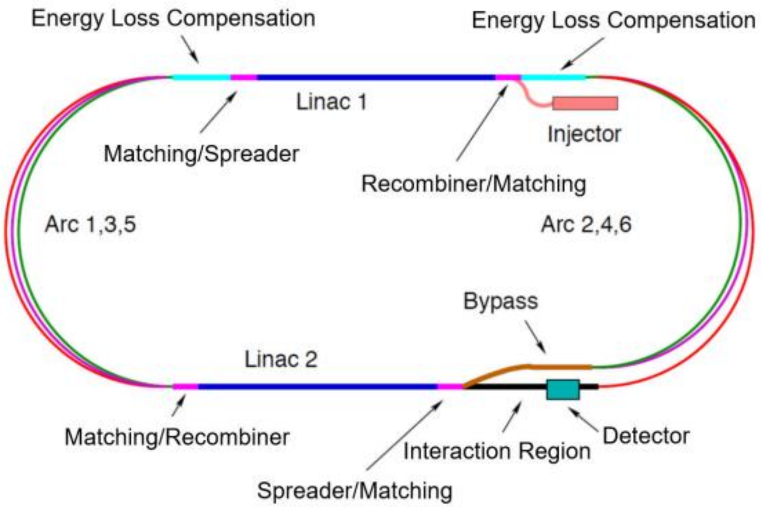
Work supported by DFG [GRK 2128, Project ID 264883531], BMBF (05H21RDRB1), State of Hesse [Cluster Project ELEMENTS (Project ID 500/10.006) and LOEWE Research Cluster Nuclear Photonics]

Motivation

- Electron beam for the LHC needed
- 50 GeV and 20 mA → 1 GW of beam power!
- Typical nuclear power plant: 1 GW

→ Need for sustainable technology

→ Energy recovery Linac



P. Agostini et al., The Large Hadron-Electron Collider at the HL-LHC, subm. to J. Phys. G, arXiv:2007.14491, 2020. https://arxiv.org/abs/2007.14491.

Outline – Part I

- Principle and history
- Basics and reasons to use an ERL
- ERLs around the world
- ERL Mode @ S-DALINAC (Intro)
- Summary

Outline – Part II

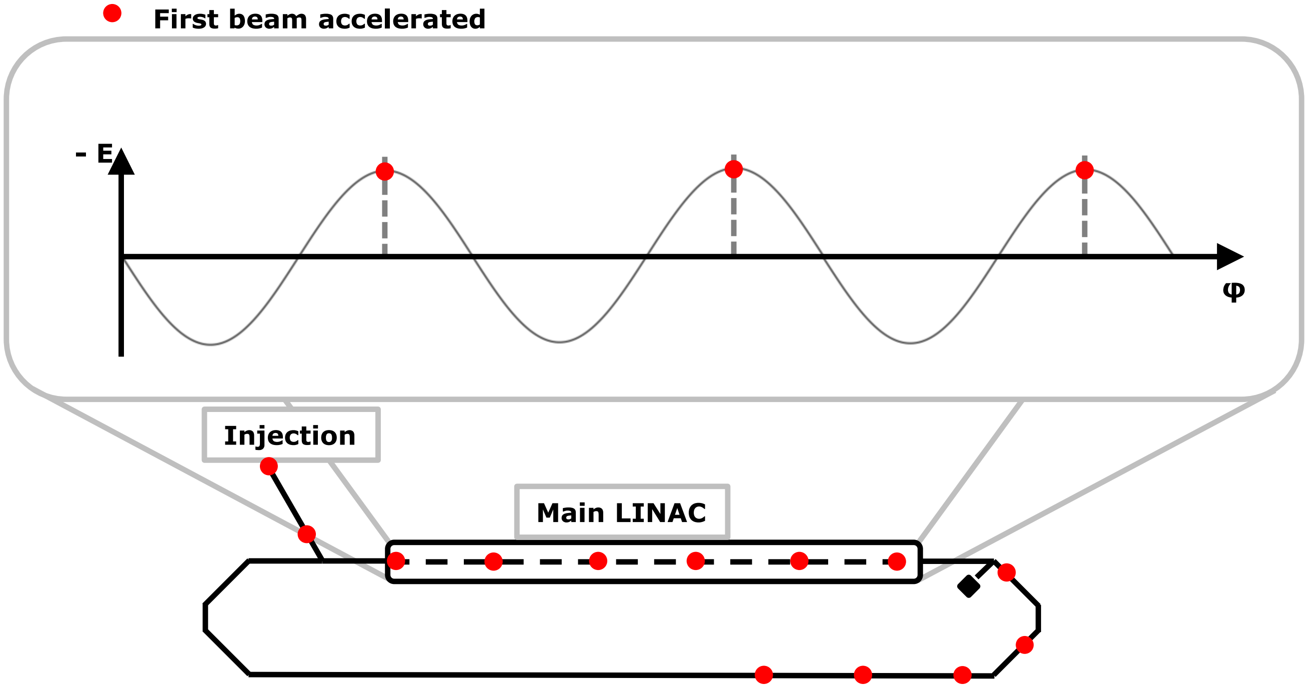
- ERL Mode @ S-DALINAC (1-turn, 2-turn and diagnostics)
- Applications: Laser Compton backscattering
- Future of ERLs
- Summary

Outline – Part I

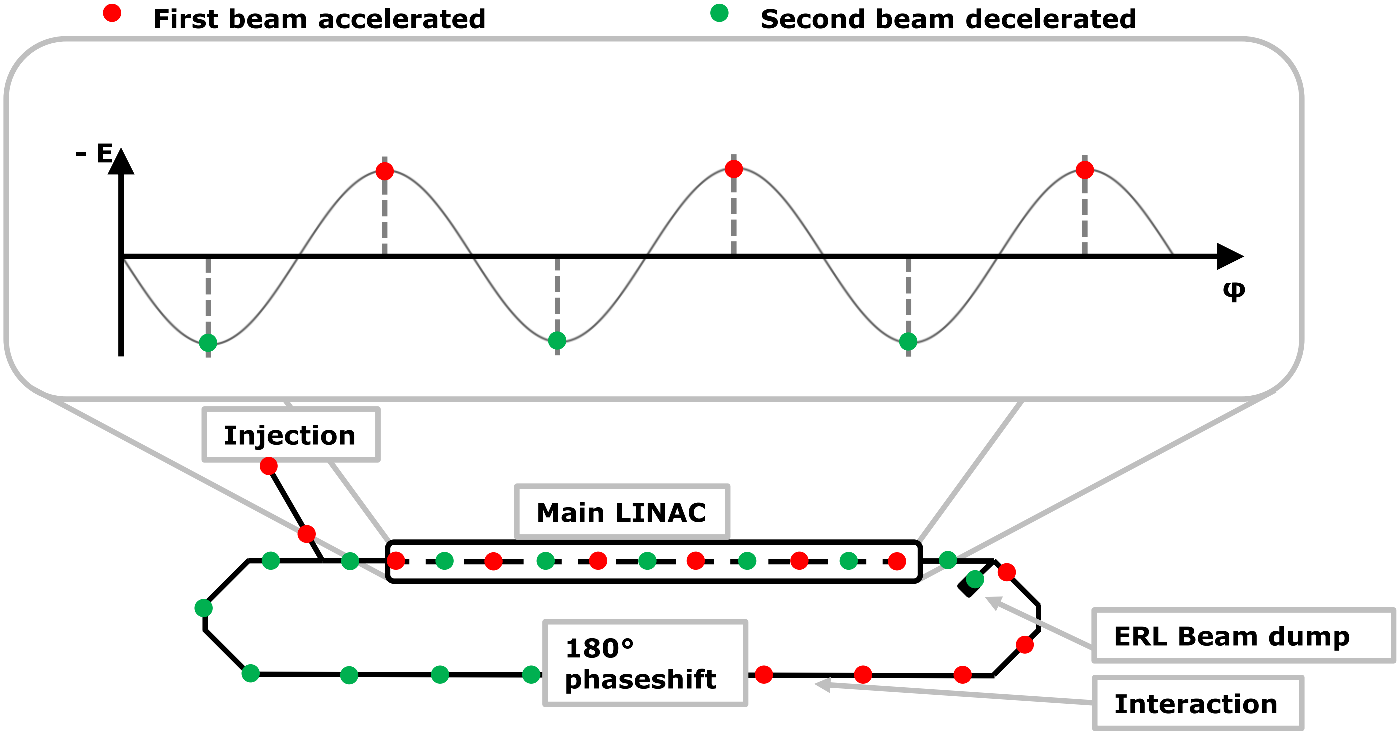
TECHNISCHE UNIVERSITÄT DARMSTADT

- Principle and history
- Basics and reasons to use an ERL
- ERLs around the world
- ERL Mode @ S-DALINAC (Intro)
- Summary

ERL Principle



ERL Principle



ERL History

TECHNISCHE UNIVERSITÄT DARMSTADT

LETTERE ALLA REDAZIONE

(La responsabilità scientifica degli scritti inseriti in questa rubrica è completamente lasciata dalla Direzione del periodico ai singoli autori)

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

ERL History

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

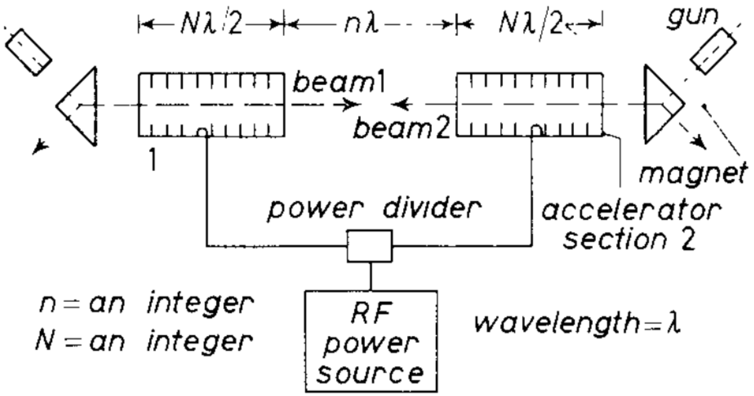


Fig. 2.

- Two systems with same energy gain, same beam current, same frequency and phase
- → Difficult to handle and two accelerator sections needed

ERL History

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner
Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

- Same beam
- Only one accelerator section

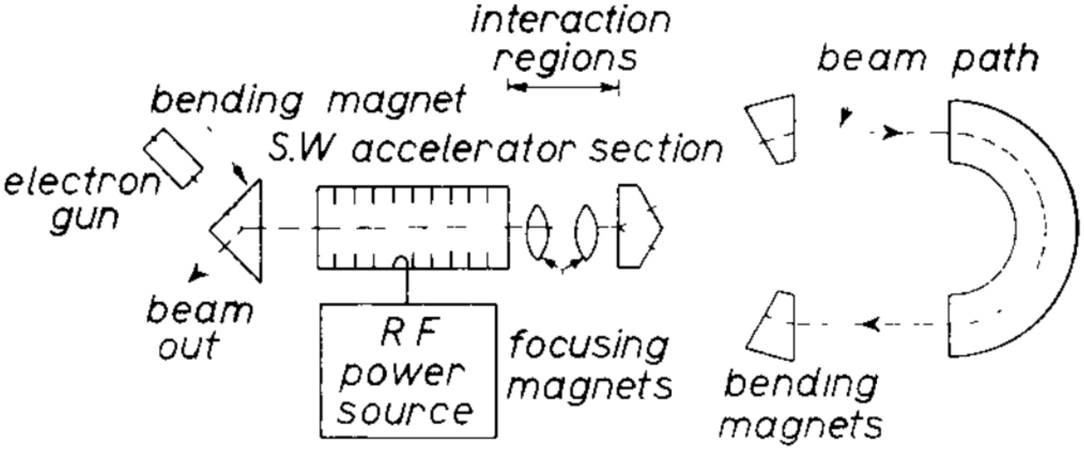


Fig. 3.

ERL – Some Milestones

- Feb. 1965: Principle published (M. Tigner)
- ~ 2000: First successful „same-cell energy recovery“ during FEL operation
- Aug. 2017: S-DALINAC ERL operation
- Dec. 2019: CBETA - first multi-turn SRF ERL operation world-wide (low current and transmission/RF-recovery effect)
- Aug. 2021: S-DALINAC ERL – first multi-turn SRF ERL with medium current and high transmission/RF-recovery effect

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

PHYSICAL REVIEW LETTERS **125,** 044803 (2020)

Editors' Suggestion | Featured in Physics

CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery

A. Bartnik, N. Banerjee, D. Burke, J. Crittenden, K. Deitrick, J. Dobbins, C. Gulliford, G. H. Hoffstaetter, Y. Li, W. Lou, P. Quigley, D. Sagan, and K. Smolenski
Cornell Laboratory for Accelerator Based Sciences and Education, Cornell University, Ithaca, New York 14850, USA

J. S. Berg, S. Brooks, R. Hulsart, G. Mahler, F. Meot, R. Michnoff, S. Peggs, T. Roser, D. Trbojevic, and N. Tsoupas
Brookhaven National Laboratory, Upton, New York 11973-5000, USA

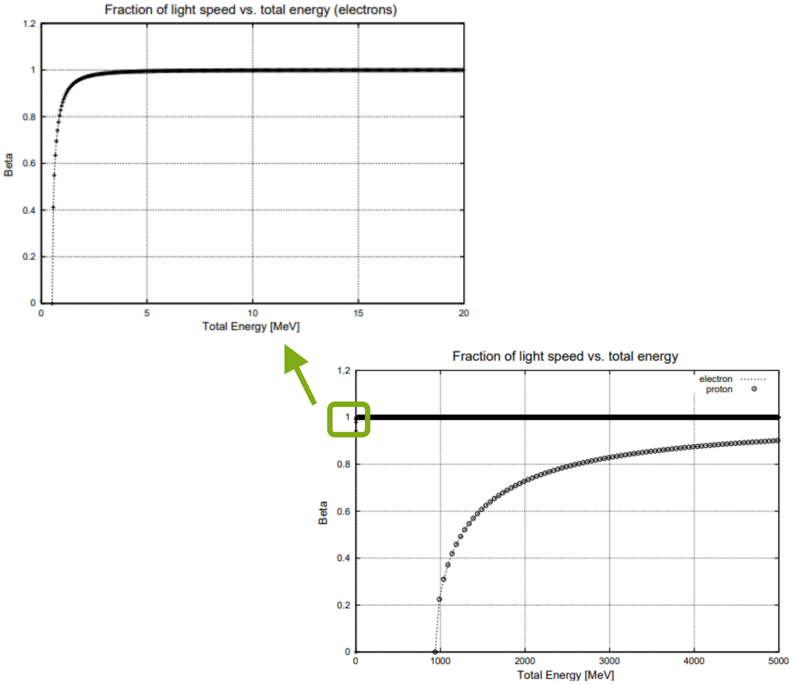
T. Miyajima
High Energy Accelerator Research Organization (KEK), Oho, Tsukuba, Ibaraki 305-0801, Japan

F. Schliessmann et al., submitted to Nature Physics

Outline – Part I

- Principle and history
- Basics and reasons to use an ERL
- ERLs around the world
- ERL Mode @ S-DALINAC (Intro)
- Summary

Electrons



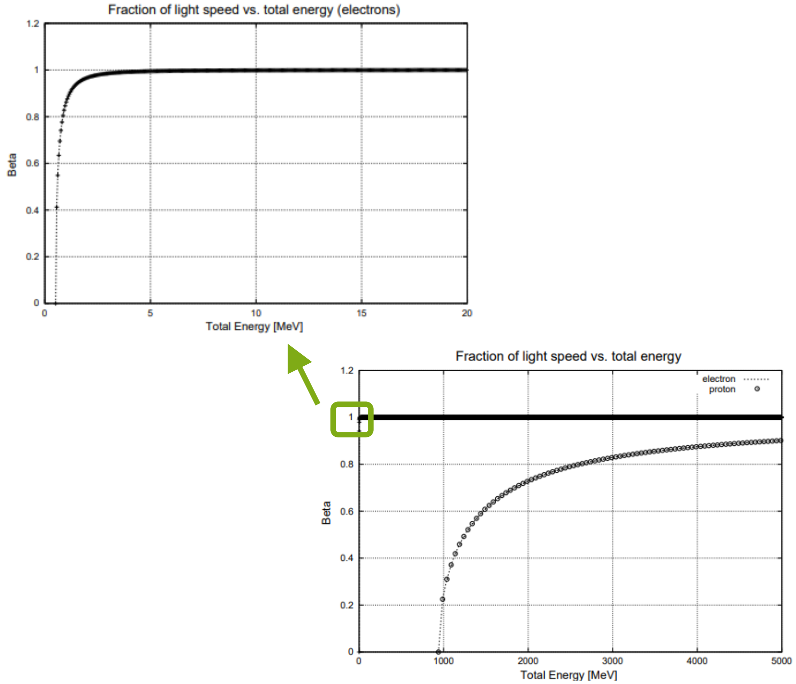
- Full lecture: Particles = electrons

Barletta, Spentzouris, Harms, Lecture notes USPAS
https://uspas.fnal.gov/materials/10MIT/Review_of_Relativity.pdf

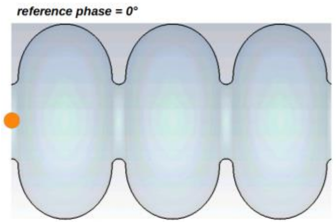
Electrons

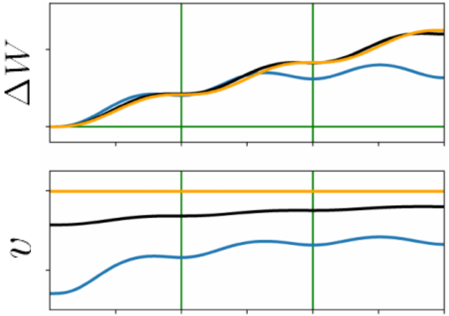
- Full lecture: Particles = electrons

- Although ultra-relativistic at some MeV, phase slippage is an issue
- Speed changes along the cavity
  → Influence of energy gain



Barletta, Spentzouris, Harms, Lecture notes USPAS
https://uspas.fnal.gov/materials/10MIT/Review_of_Relativity.pdf





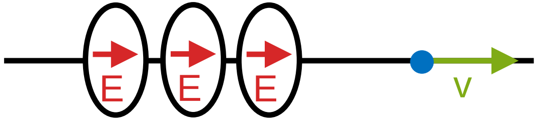
Simulation by Felix Schliessmann, TU Darmstadt

Accelerator Layout

- Comparision only taking into account some differences

Linear Accelerator

- High beam quality („fresh beam“)
- Energy: limited due to length
- Current: limited due to RF power/coupler for high energies



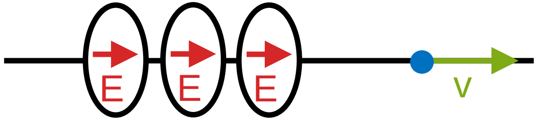
Accelerator Layout

- Comparision only taking into account some differences

[1] F. Hinterberger, Physik der Teilchenbeschleuniger und Ionenoptik, Springer Verlag, Chapter 10.3

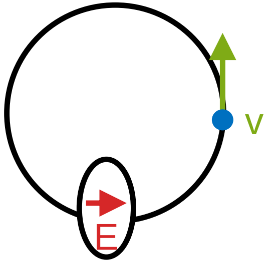
Linear Accelerator

- High beam quality („fresh beam“)
- Energy: limited due to length
- Current: limited due to RF power/coupler for high energies



Circular Accelerator

- Beam quality: equilibrium emittance
  [proportional to E² for electron synchrotrons for high energies][1]
- Energy: limited due to synchrotron radiation
- Current: very high due to injection schemes



Synchrotron radiation: Energy loss per revolution for electrons

$$\Delta E\ [keV] = 88.5 \frac{E^4 [GeV^4]}{R[m]}$$

Accelerator Layout

- Goal for next generation electron machines:
  - Energy ~ 100 GeV
  - Current ~ 100 mA
    → ~ 10 GW beam power [remember: Typical nuclear power plant: 1 GW]

[1] *D. Kostin et al., IPAC 2019, p. 12, MOYPLM22*

Accelerator Layout

- Goal for next generation electron machines:
  - Energy ~ 100 GeV
  - Current ~ 100 mA
    → ~ 10 GW beam power [remember: Typical nuclear power plant: 1 GW]

- Energy
  - Synchrotron: E_{max} ~ some GeV
  - LINAC: take ~ 30 MV/m
    → > 3.3 km „virtual SRF cavity length" (XFEL: ~ 830 m „virtual SRF cavity length")[1]
    → recirculating LINAC with few turns – neglect synchrotron radiation and subsequent effects

[1] *D. Kostin et al., IPAC 2019, p. 12, MOYPLM22*

Accelerator Layout

- Goal for next generation electron machines:
  - Energy ~ 100 GeV
  - Current ~ 100 mA
    → ~ 10 GW beam power [remember: Typical nuclear power plant: 1 GW]

- Energy
  - Synchrotron: E_{max} ~ some GeV
  - LINAC: take ~ 30 MV/m
    → > 3.3 km „virtual SRF cavity length“ (XFEL: ~ 830 m „virtual SRF cavity length“)[1]
    → recirculating LINAC with few turns – neglect synchrotron radiation and subsequent effects

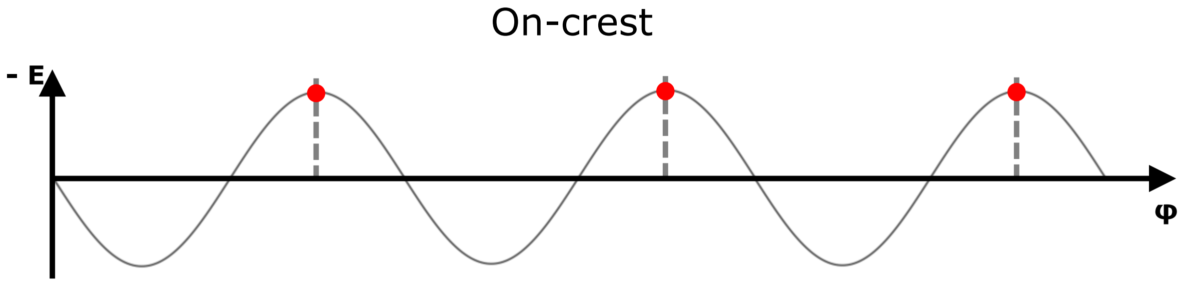
- Current (LINAC)
  - Overcome limitation of RF system/coupler and sustainable operation
    → multi-turn ERL

[1] *D. Kostin et al., IPAC 2019, p. 12, MOYPLM22*

Why should you use an ERL?

- Research in accelerator physics – examples for beam dynamics
  - Multi-turn ERL operation with minimized momentum spread, mitigation of phase-slippage → Non-isochronous ($r_{56} \neq 0$) + off-crest acceleration

On-Crest vs. Off-Crest ERL

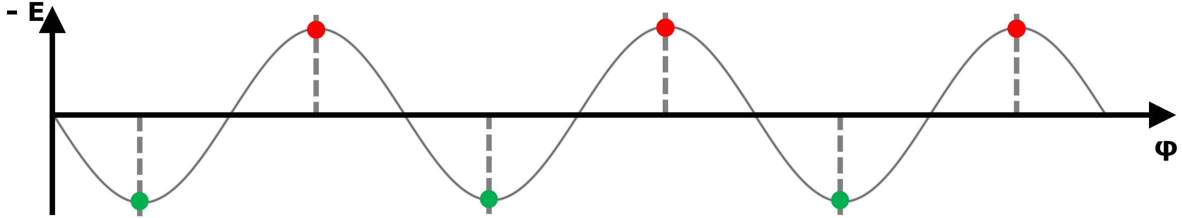


Typically: $R_{56}=0$

● **Accelerated particle** ● **Decelerated particle**

On-Crest vs. Off-Crest ERL

On-crest

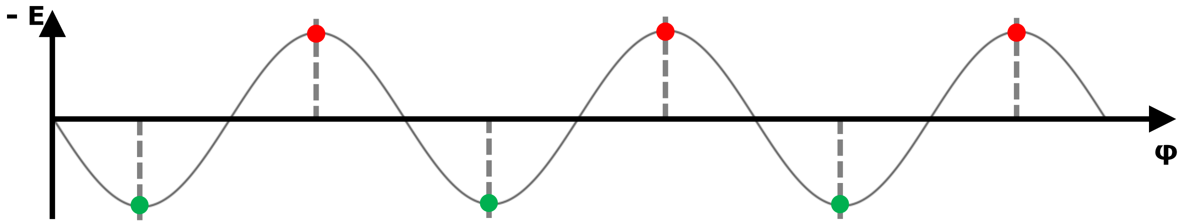


Typically: $R_{56}=0$

● **Accelerated particle** ● **Decelerated particle**

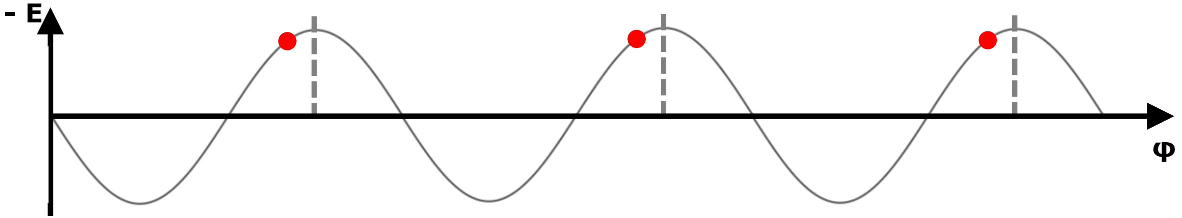
On-Crest vs. Off-Crest ERL

On-crest



Typically: $R_{56}=0$

Off-crest

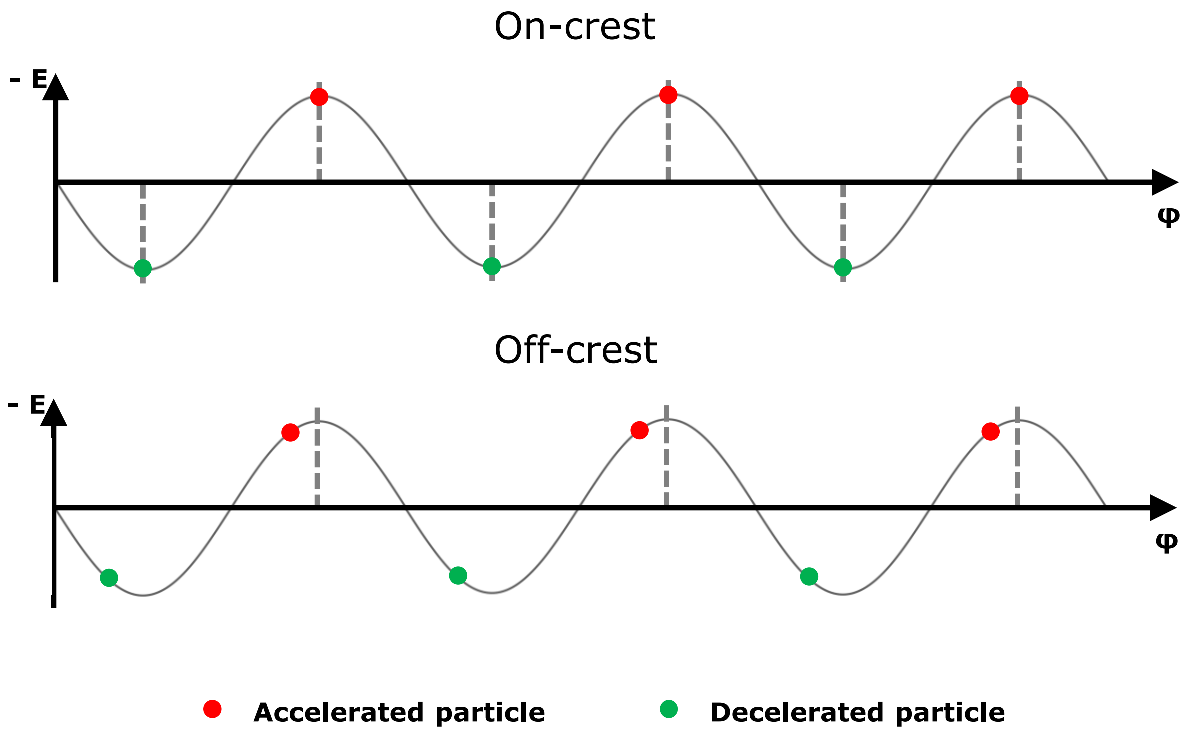


Typically: $R_{56}\neq0$

→ Needed for multi-turn operation

Accelerated particle **Decelerated particle**

On-Crest vs. Off-Crest ERL

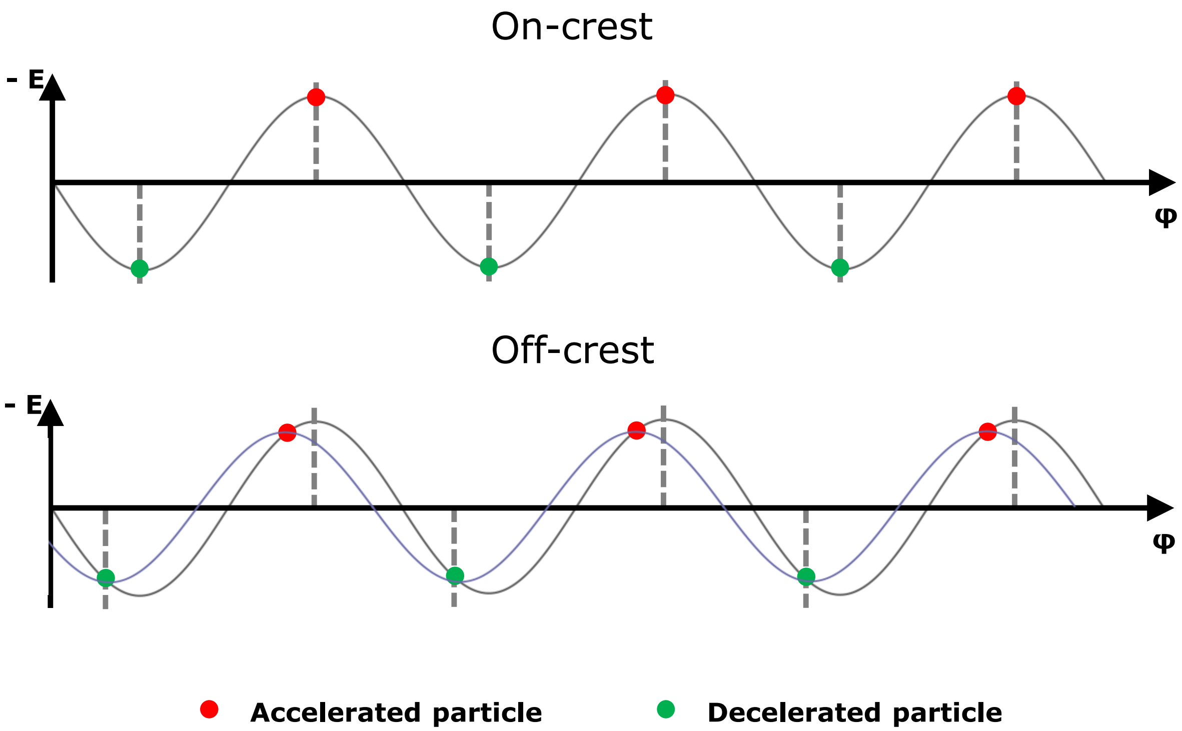


Typically: $R_{56}=0$

Typically: $R_{56}\neq0$

→ Needed for multi-turn operation

On-Crest vs. Off-Crest ERL



Typically: $R_{56}=0$

Typically: $R_{56}\neq0$

→ Needed for multi-turn operation

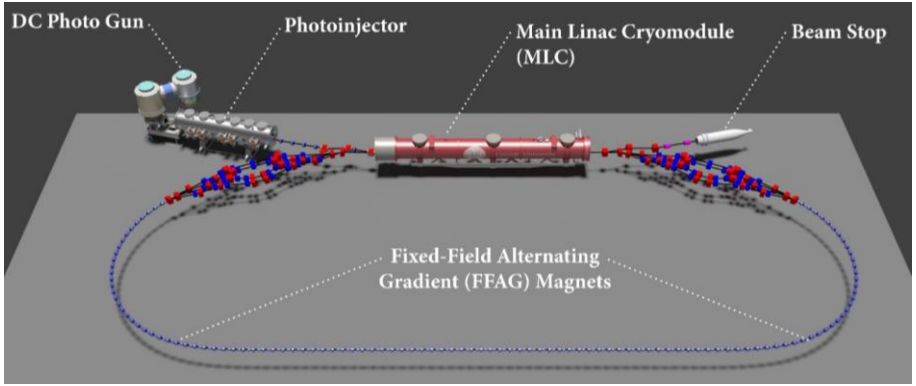
Why should you use an ERL?

TECHNISCHE UNIVERSITÄT DARMSTADT

- Research in accelerator physics – examples for beam dynamics
  - Multi-turn ERL operation with minimized momentum spread, mitigation of phase-slippage → Non-isochronous (r_{56}≠0) + off-crest acceleration
  - FFAG ERL → smaller footprint, permanent magnets (thus cost effective)

FFAG ERL (fixed-field alternating gradient)

- Usage of permanent magnets → no power supplies, no cooling, …
- Cornell-BNL FFAG-ERL Test Accelerator (CBETA) → first ERL based on FFAG lattice
- 4 spreaders, 4 combiners, FFAG return loop (simultaneous transportation of energies that differ by up to a factor of 4)



"The FFAG-ERL moves the cost optimized linac and recirculation lattice to a dramatically better optimum."

White Paper: The Cornell-BNL FFAG-ERL Test Accelerator, 2015

Why should you use an ERL?

TECHNISCHE UNIVERSITÄT DARMSTADT

- Research in accelerator physics – examples for beam dynamics
  - Multi-turn ERL operation with minimized momentum spread, mitigation of phase-slippage → Non-isochronous ($r_{56} \neq 0$) + off-crest acceleration
  - FFAG ERL → smaller footprint, permanent magnets (thus cost effective)

- Enhancement of experiments
  - Facilitates future high-power electron-colliders (e.g. LHeC)
  - Higher intensities with the same RF power (not injector !)
  - High brilliance (low transversal emittance and short pulse length)

Why should you use an ERL?

- Research in accelerator physics – examples for beam dynamics
  - Multi-turn ERL operation with minimized momentum spread, mitigation of phase-slippage → Non-isochronous ($r_{56} \neq 0$) + off-crest acceleration
  - FFAG ERL → smaller footprint, permanent magnets (thus cost effective)
- Enhancement of experiments
  - Facilitates future high-power electron-colliders (e.g. LHeC)
  - Higher intensities with the same RF power (not injector !)
  - High brilliance (low transversal emittance and short pulse length)
- Additional benefit
  - Less power necessary to cool the dumped beam
  - Less activation of beam dump

Outline – Part I

- Principle and history
- Basics and reasons to use an ERL
- ERLs around the world
- ERL Mode @ S-DALINAC (Intro)
- Summary

Prepared for submission to JINST

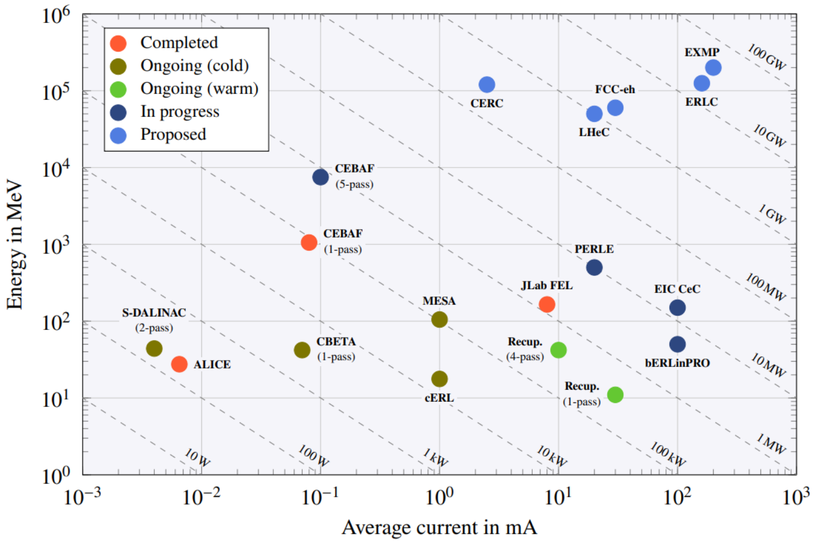
The Development of Energy-Recovery Linacs

Chris Adolphsen,[t] Kevin Andre,[d,i] Deepa Angal-Kalinin,[f] Michaela Arnold,[g] Kurt Aulenbacher,[j] Steve Benson,[o] Jan Bernauer,[m] Alex Bogacz,[o] Maarten Boonekamp,[l] Reinhard Brinkmann, Max Bruker,[o] Oliver Brüning,[d] Camilla Curatolo,[p] Patxi Duthill,[k] Oliver Fischer,[i] Georg Hoffstaetter,[e,c] Bernhard Holzer,[d] Ben Hounsell,[k,i] Andrew Hutton,[o,1] Erk Jensen,[d] Walid Kaabi,[k] Dmitry Kayran,[c] Max Klein,[i] Jens Knobloch,[a,s] Geoff Krafft,[o] Julius Kühn,[a] Bettina Kuske,[a] Vladimir Litvinenko,[m] Frank Marhauser,[o] Boris Militsyn,[f] Sergei Nagaitsev,[v] George Neil,[o] Axel Neumann,[a] Norbert Pietralla,[g] Bob Rimmer,[o] Luca Serafini,[p] Oleg A. Shevchenko,[b] Nick Shipman,[d,q] Hubert Spiesberger,[j] Olga Tanaka,[n] Valery Telnov,[b,r] Chris Tennant,[o] Cristina Vaccarezza,[h] David Verney,[k] Nikolay Vinokurov,[b] Peter Williams,[f] Akira Yamamoto,[n] Kaoru Yokoya,[n] Frank Zimmermann[d]

[a] *Helmholtz-Zentrum Berlin, Berlin, Germany*
[b] *Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
[c] *Brookhaven National Laboratory, Upton, NY, USA*
[d] *CERN, Geneva, Switzerland*
[e] *Cornell University, Ithaca, NY, USA*
[f] *Daresbury Laboratory (STFC), Daresbury, UK*
[g] *Technische Universität Darmstadt, Institute for Nuclear Physics, Darmstadt, Germany*
[h] *INFN, Frascati, Italy*
[i] *University of Liverpool, Liverpool, UK*
[j] *University of Mainz, Mainz, Germany*
[k] *IJCLab, Orsay, France*
[l] *CEA Saclay, Saclay, France*
[m] *Center for Frontiers in Nuclear Science, Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA, and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY, USA*
[n] *KEK, Tsukuba, Japan*
[o] *Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*
[p] *INFN, Milano, Italy, and LASA*
[q] *Lancaster University, Lancaster, UK*
[r] *Novosibirsk State University, 630090, Novosibirsk, Russia*
[s] *University of Siegen, Siegen, Germany*
[t] *SLAC, Menlo Park, CA, USA*
[v] *Fermilab, Batavia, IL, USA*

E-mail: andrew@jlab.org

[1] Corresponding author.



- CBETA: first multi-turn SRF ERL
- S-DALINAC: multi-turn SRF ERL with record in efficiency

arXiv:2207.02095 [physics.acc-ph]; accepted for publication in JINST

Operating ERLs

TECHNISCHE UNIVERSITÄT DARMSTADT

Example is:

CBETA

CORNELL-BNL ERL TEST ACCELERATOR

CBETA

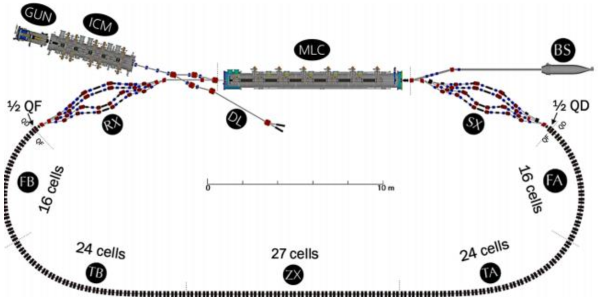


TABLE I. CBETA machine parameters.

Parameter	Value	Units
Bunch charge, design limit	125	pC
Bunch charge, commissioning	5	pC
Bunch rate, design limit	325	MHz
Bunch rate, commissioning	< 1	kHz
Beam current, design limit	40	mA
Beam current, commissioning	1	nA
Beam energy, injector	6	MeV
Beam energy, peak	150	MeV

<u>June 2019:</u>
Successful 1-turn ERL operation

<u>December 2019:</u>
Semi-successful 4-turn ERL operation

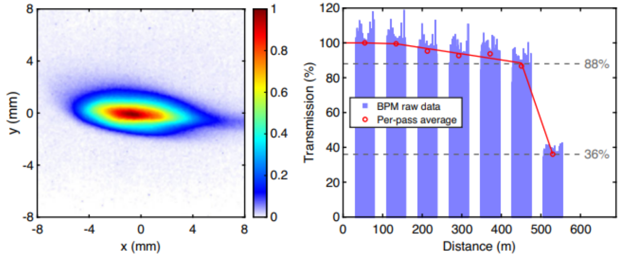


FIG. 4. Left: Image of the beam on the view screen before beam stop. Right: Transmission for each of the seven passes through the FFA arc. Blue bars are a scaled reading of charge from individual BPMs, red circles are an average of that data over each pass. Red lines are included as a guide to the eyes.

A. Bartnik et al., CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery, PRL ***125****, 044803 (2020).*

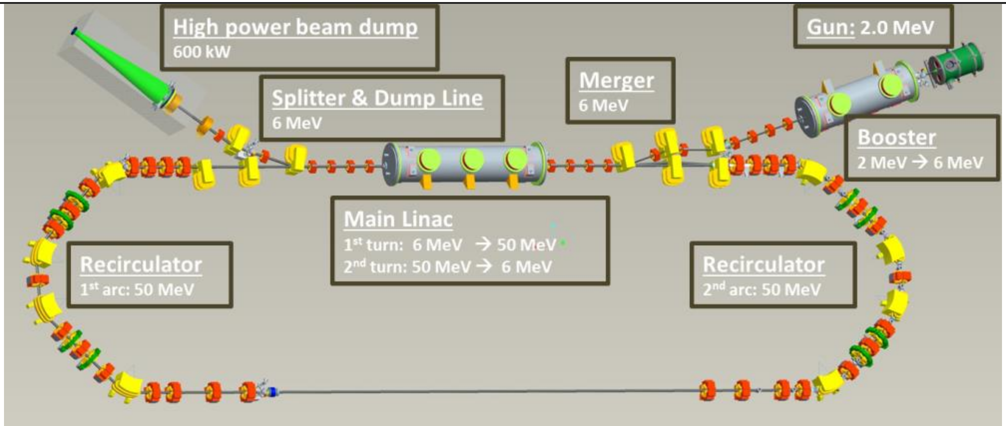
ERLs under Construction

Examples are:

bERLinPro

MESA
Mainz Energy-recovering Superconducting Accelerator

bERLinPro



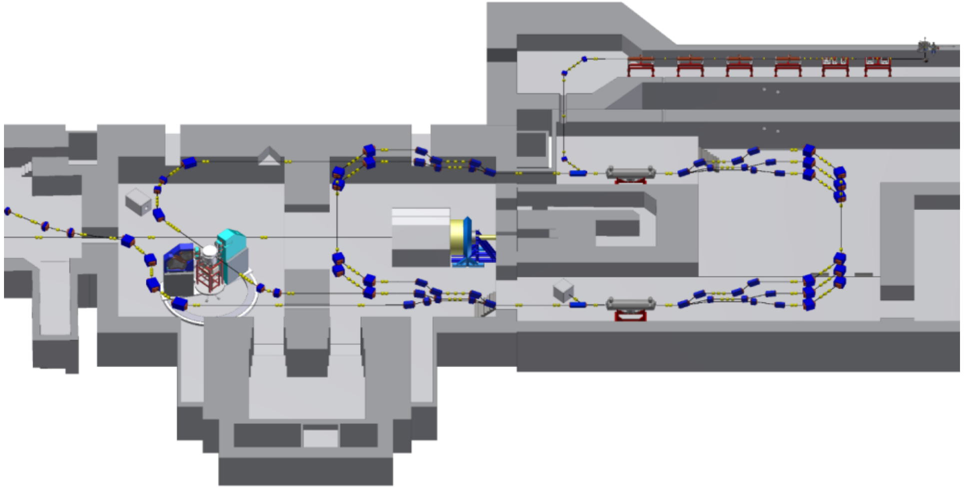
https://www.helmholtz-berlin.de/projects/berlinpro/bpro-overview_en.html

- Demonstrator facility for accelerator R&D
- Flexible parameters → standard mode shown

BERLinPro: Main Project Parameters	
Total beam energy, MeV	50
Maximum average current, mA	100
Bunch charge, pC	77
Bunch repetition rate, GHz	1.3
Emittance (normalized), π mm mrad	≤ 1.0
Bunch length (rms), ps	2.0 or smaller
Maximum Losses (relative)	$< 10^{-5}$

MESA

Picture Courtesy: D. Simon (Mainz)



- External beam mode: polarized, 150µA 155 MeV
- Energy recovery mode: non-polarized, 1mA to 10mA, 105 MeV

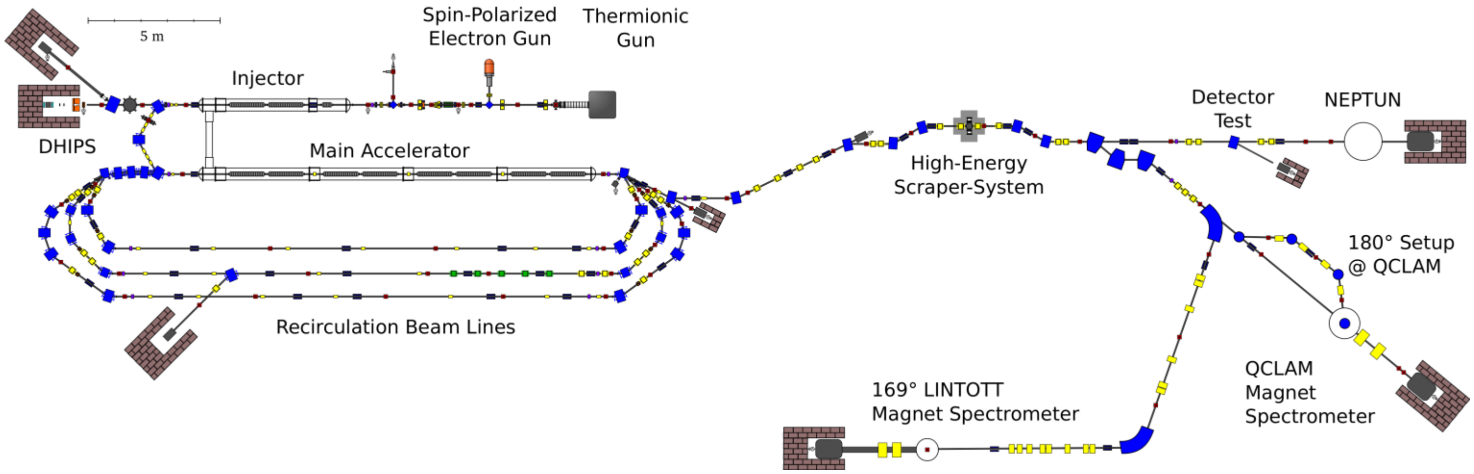
T. Stengler et al., *Status of the Superconducting Cryomodules and Cryogenic System for the Mainz Energy-Recovering Superconducting Accelerator MESA*, Proceedings of IPAC 2016

Outline – Part I

- Principle and history
- Basics and reasons to use an ERL
- ERLs around the world
- ERL Mode @ S-DALINAC (Intro)
- Summary

S-DALINAC

Superconducting **DA**rmstadt **LIN**ear **AC**celerator



[Virtual tour](#)
(click here)

Thrice recirculating operation

Energy gain injector:	7.6 MeV
Energy gain LINAC:	30.4 MeV
Beam current:	20 µA

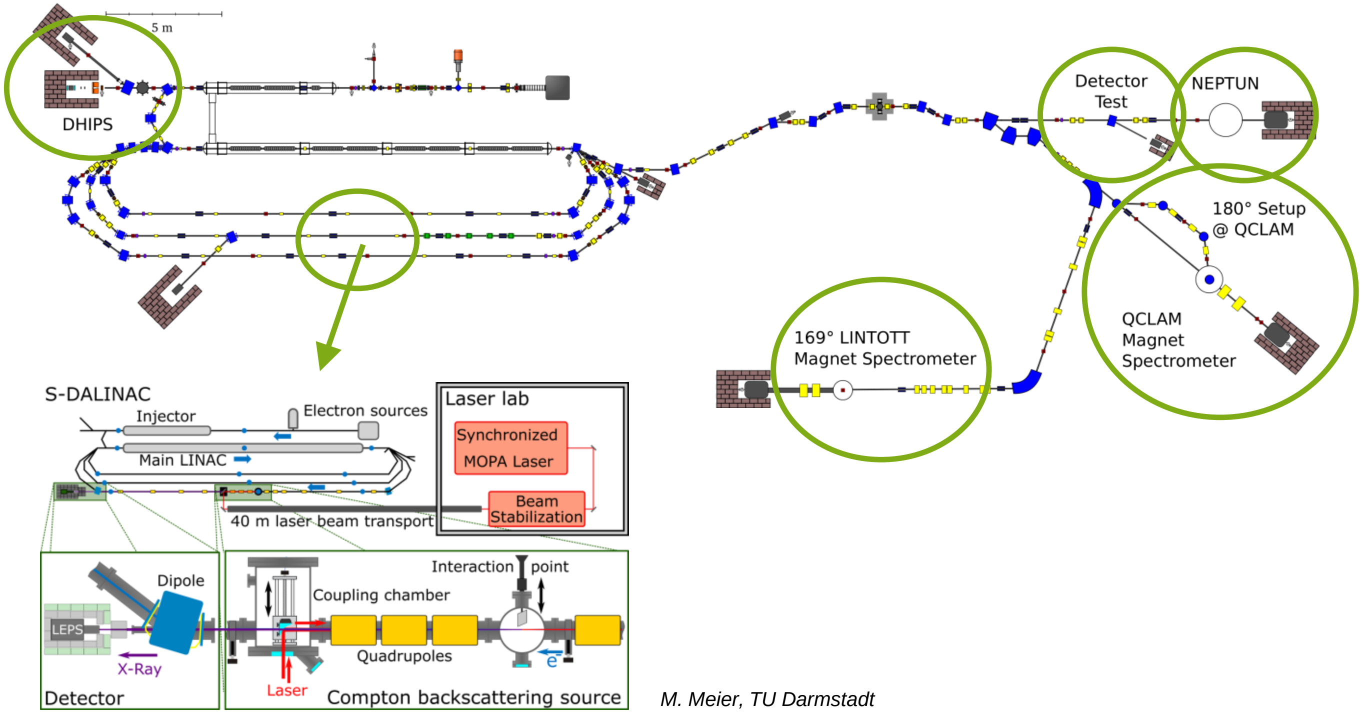
Design (extracted beam): 130 MeV, 20 µA

Design (NRF): 10 MeV, 60 µA

Particles: electrons

Rep. rate: 2.9973 GHz, cw

Experimental Sites



M. Meier, TU Darmstadt

QCLAM special setups

- 180°
- (e,e'γ)
- LHe-target

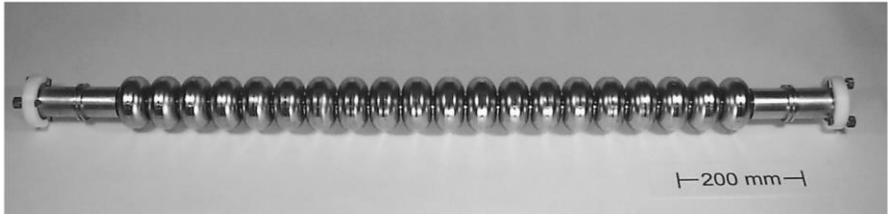
Parameters SRF and ERL

SRF injector

- 1x 6-cell (β=0.86) as capture
- 2x 20-cell (β=1)

SRF main linac

- 8x 20-cell (β=1)



f = 2.9973 GHz

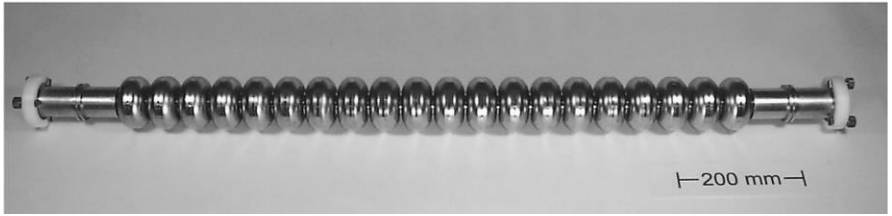
Parameters SRF and ERL

SRF injector

- 1x 6-cell (β=0.86) as capture
- 2x 20-cell (β=1)

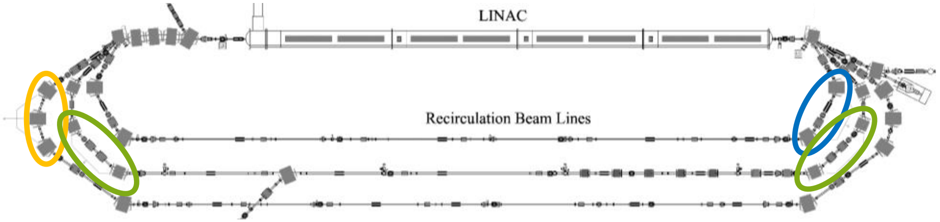
SRF main linac

- 8x 20-cell (β=1)

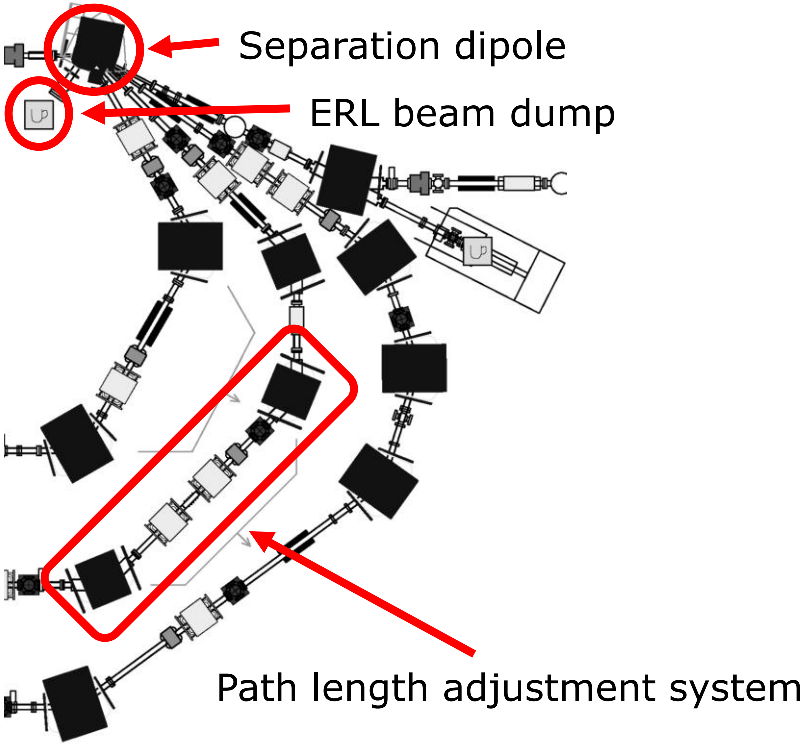


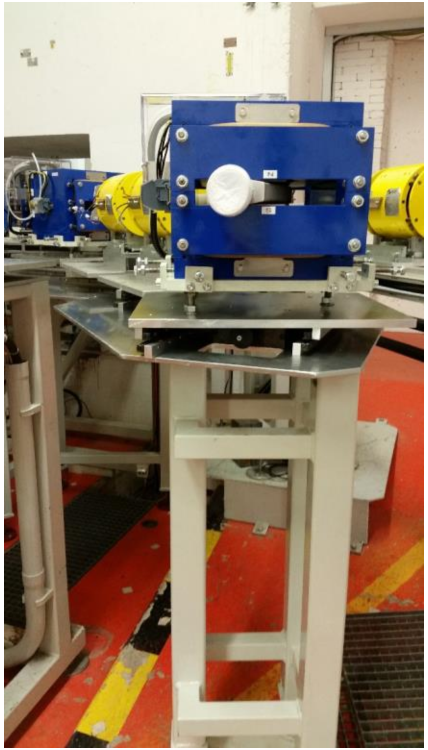
f = 2.9973 GHz

- ERL mode possible since upgrade in 2015/2016
- 360° path length adjustment system in second recirculation → ERL mode
- 265° for first recirculation
- 205° for third recirculation
- Bunch length important for every setting



S-DALINAC as ERL





Efficiency of an ERL

Beam-recovery efficiency

$$\varepsilon_b = \frac{E_{b,max} I_{b,dump} - E_{b,dump} I_{b,dump}}{E_{b,max} I_{b,max}}$$

→ Limited by design of accelerator: $\varepsilon_{b,max} = 1 - \frac{E_{b,dump}}{E_{b,max}}$ for perfect transmission

Efficiency of an ERL

TECHNISCHE UNIVERSITÄT DARMSTADT

Beam-recovery efficiency

$$\varepsilon_b = \frac{E_{b,max} I_{b,dump} - E_{b,dump} I_{b,dump}}{E_{b,max} I_{b,max}}$$

→ Limited by design of accelerator: $\varepsilon_{b,max} = 1 - \frac{E_{b,dump}}{E_{b,max}}$ for perfect transmission

RF-recovery effect

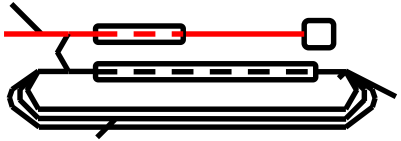
- Reduction of external RF power as compared to single-end operation

$$\varepsilon_{RF} = \frac{P_{RF,acc.} - P_{RF,ERL}}{P_{RF,acc.}}$$

Overview Operation Modes/Commissioning

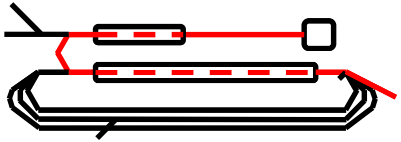
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



December
2016

Single
pass

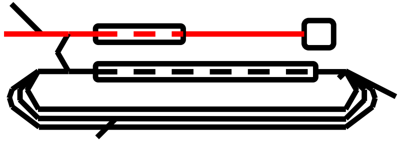


December
2016

Overview Operation Modes/Commissioning

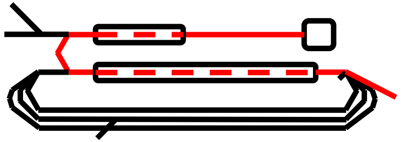
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



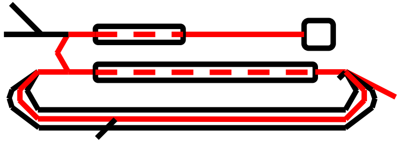
December 2016

Single pass



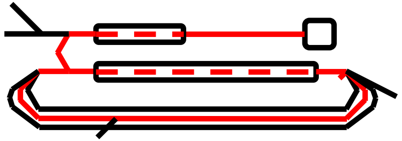
December 2016

1x rec.



May 2017

1x ERL

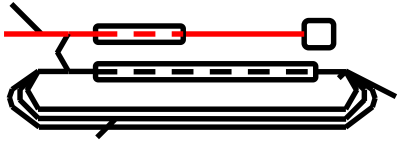


August 2017

Overview Operation Modes/Commissioning

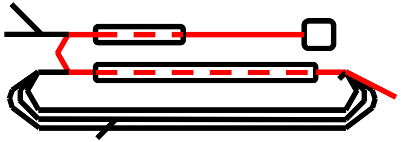
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



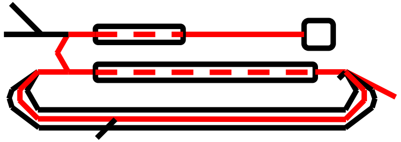
December 2016

Single pass



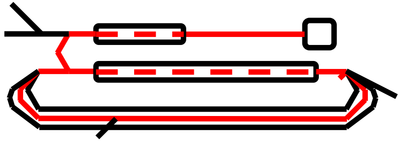
December 2016

1x rec.



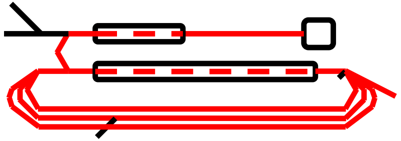
May 2017

1x ERL



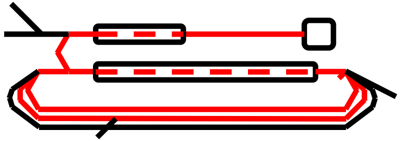
August 2017

3x rec.



November 2018

2x ERL



August 2021

Outline – Part I

TECHNISCHE UNIVERSITÄT DARMSTADT

- Principle and history
- Basics and reasons to use an ERL
- ERLs around the world
- ERL Mode @ S-DALINAC (Intro)
- Summary

Take Home Message

Principle, history, reasons

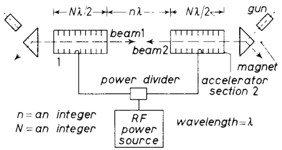
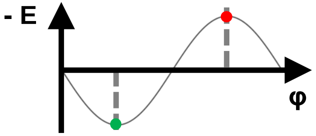


Fig. 2.



Take Home Message

Principle, history, reasons

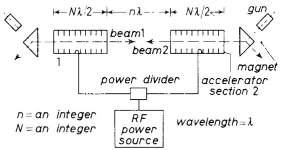
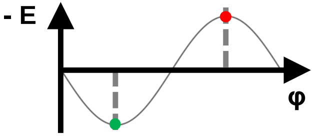
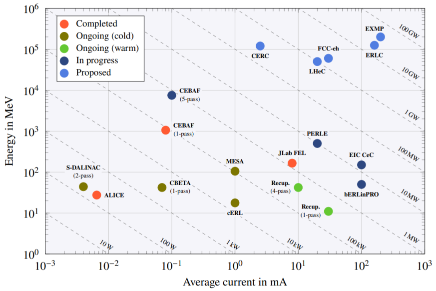


Fig. 2.



World-wide



CBETA
CORNELL-BNL ERL TEST ACCELERATOR

bERLinPro

MESA
Mainz Energy-recovering Superconducting Accelerator

Take Home Message

Principle, history, reasons

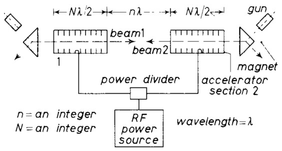
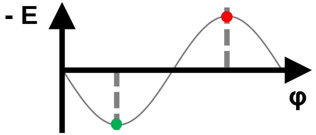
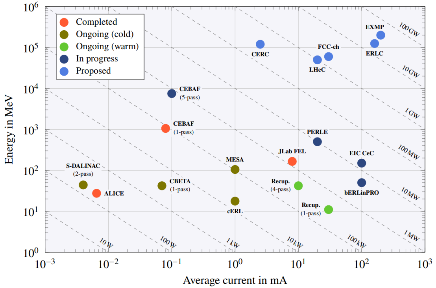


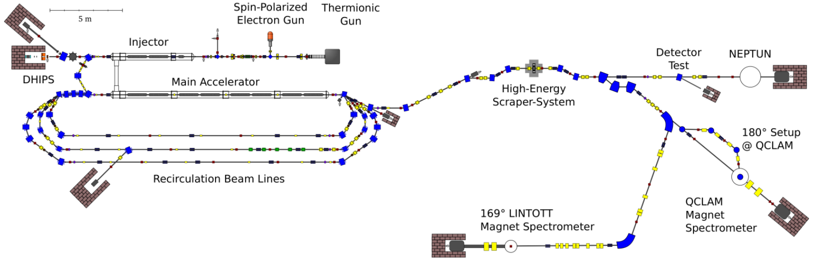
Fig. 2.



World-wide



S-DALINAC



Take Home Message

Principle, history, reasons

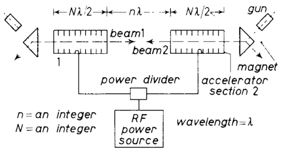
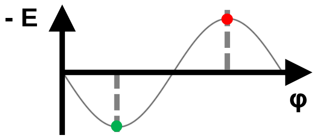
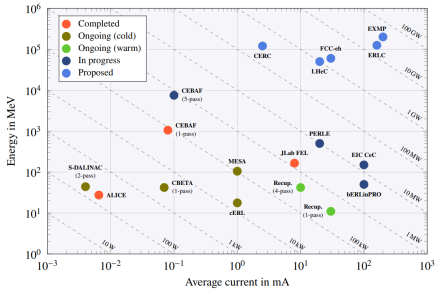


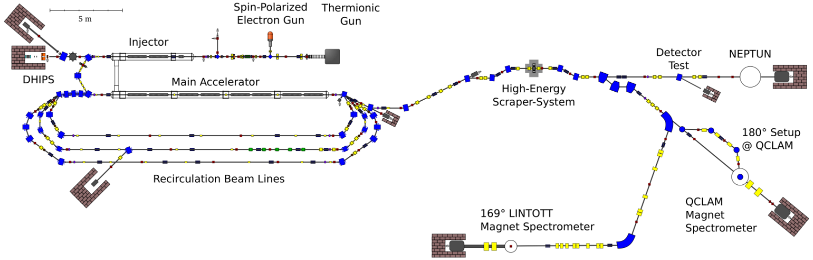
Fig. 2.



World-wide



S-DALINAC



Part II:

- ERL Mode @ S-DALINAC
- Applications: Laser Compton backscattering
- Future of ERLs

Thank you for your Attention!

Picture: Jan-Christoph Hartung