Energy Recovery Linac

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Picture: Jan-Christoph Hartung

ACCELENCE

Work supported by DFG through GRK 2128

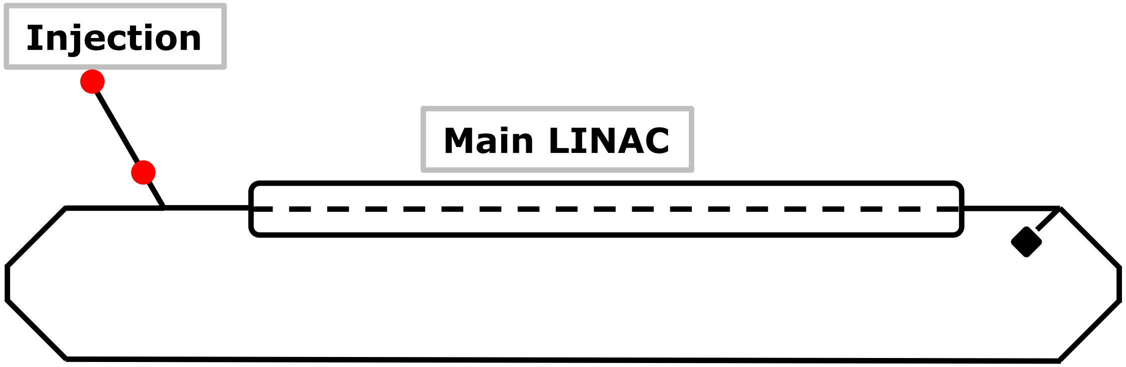
Outline

- Introduction to Energy Recovery Linacs (ERLs)
- Examples
- Commissioning of ERL Mode @ S-DALINAC
- Summary and Outlook
- Research Training Group on ERLs

Outline

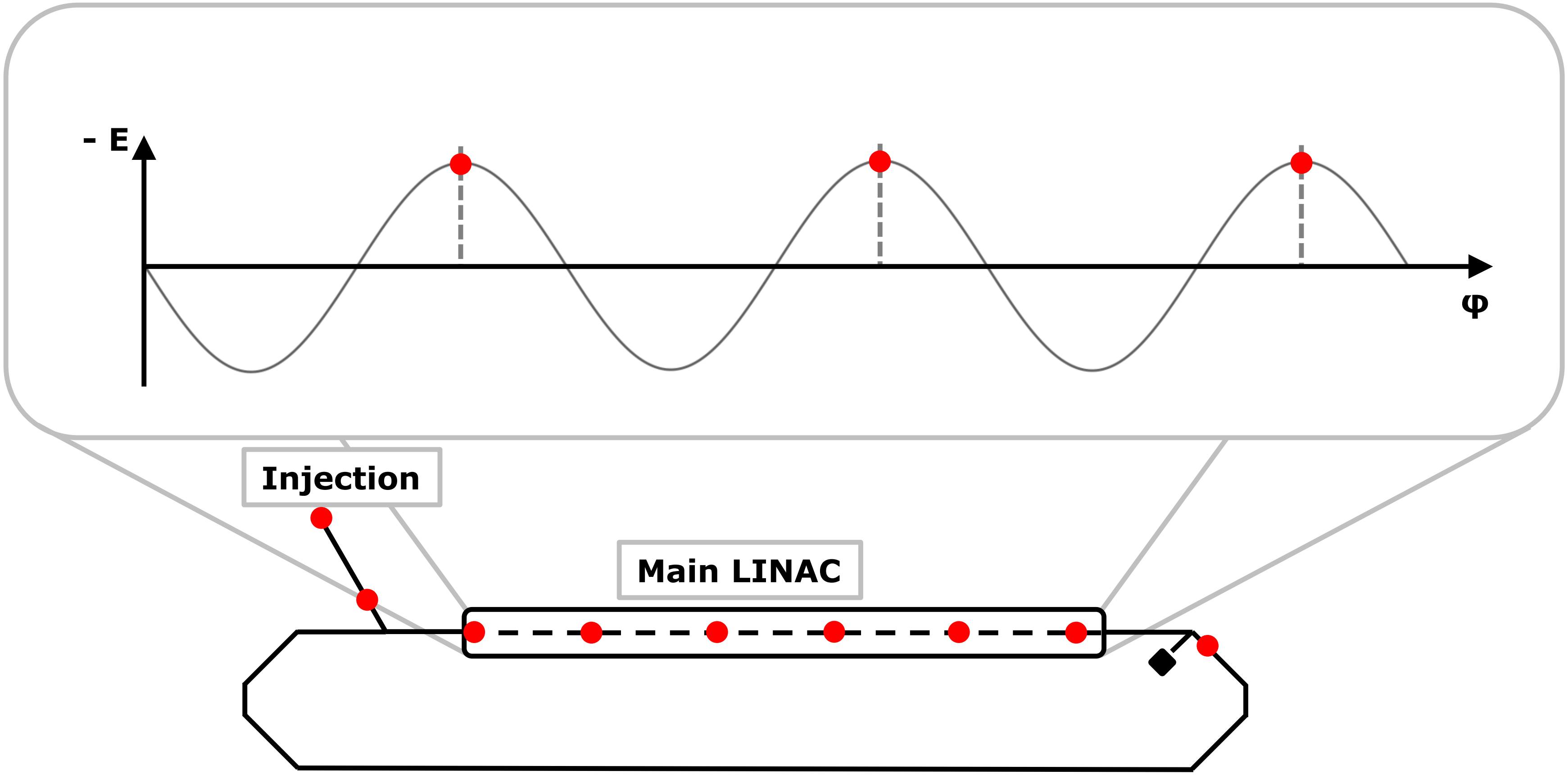
- Introduction to Energy Recovery Linacs (ERLs)
  - How does an ERL work?
  - History
  - Reasons to use an ERL
  - Possible applications
- Examples
- Commissioning of ERL Mode @ S-DALINAC
- Summary and Outlook
- Research Training Group on ERLs

ERL Principle



ERL Principle

- First beam accelerated



ERL Principle

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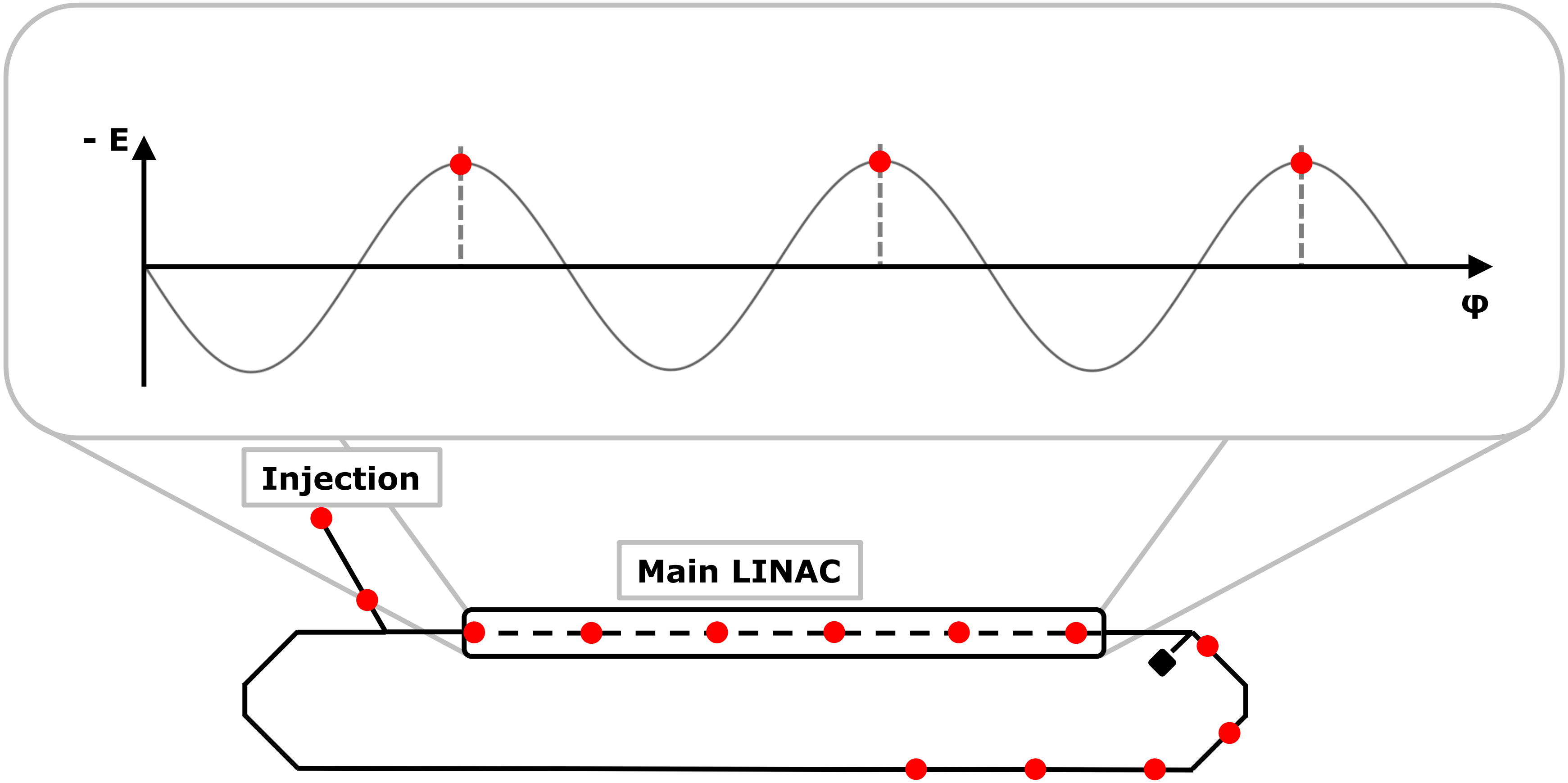
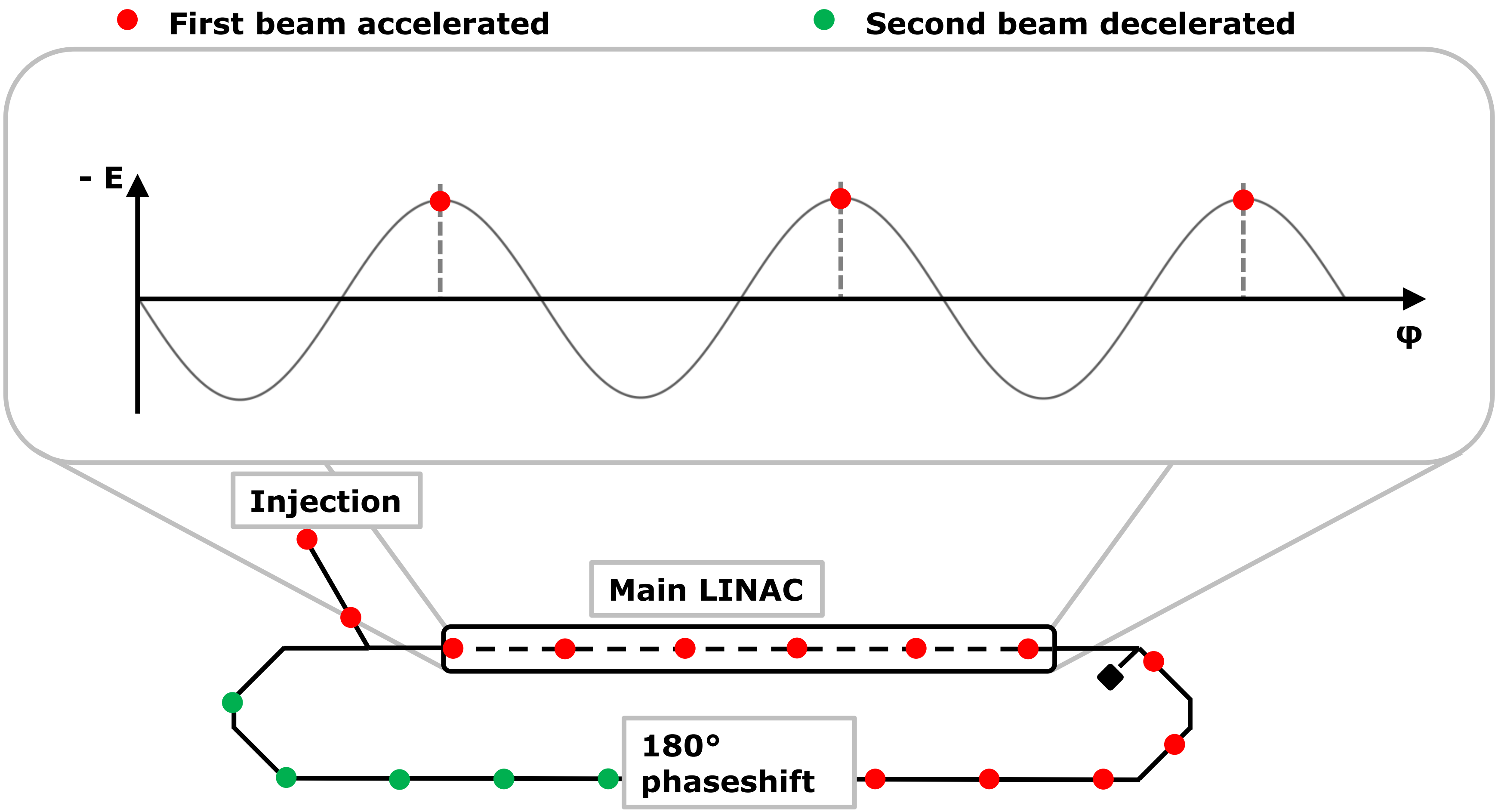
- First beam accelerated



ERL Principle



ERL Principle

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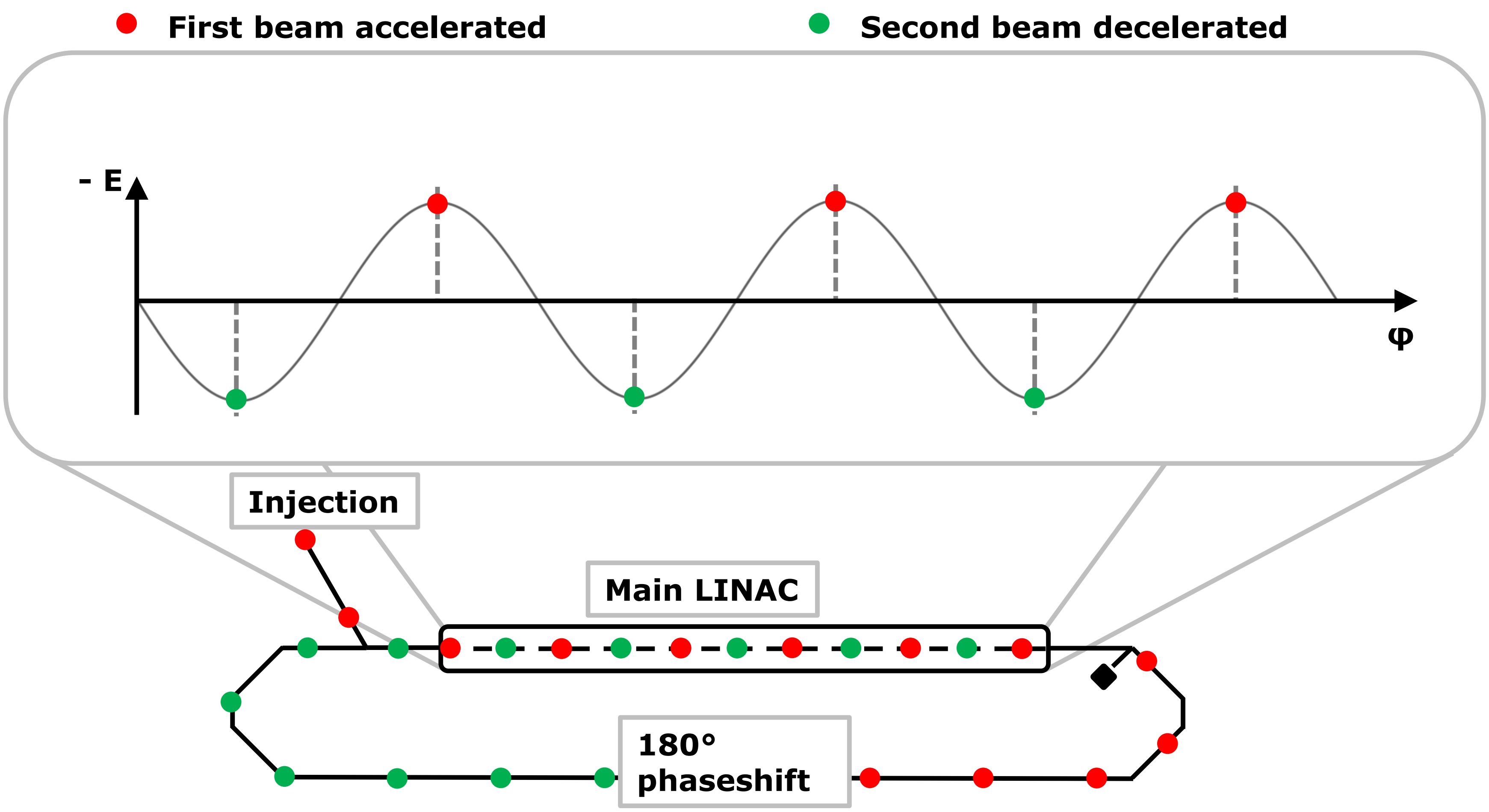

ERL Principle

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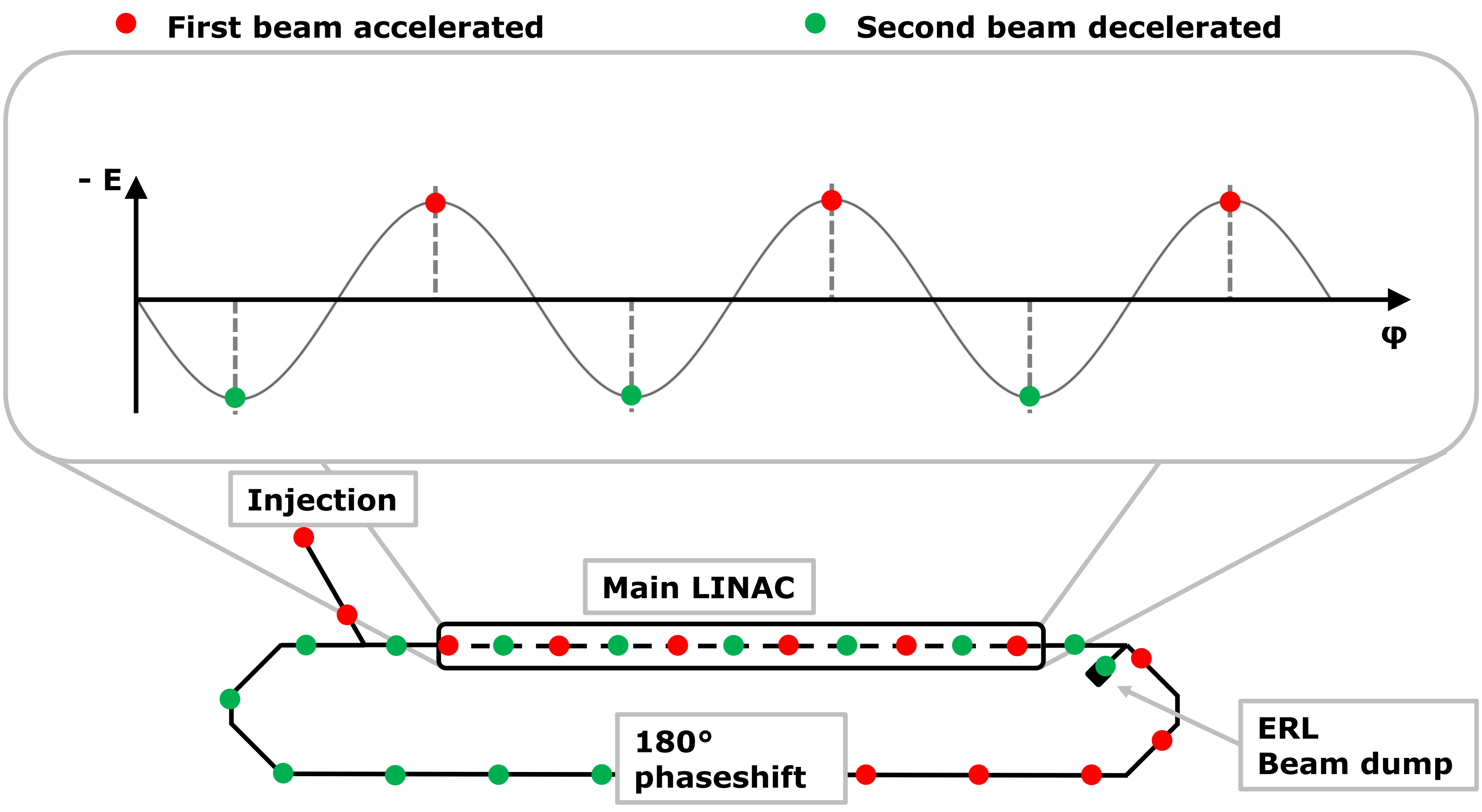

Principle

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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)

Principle

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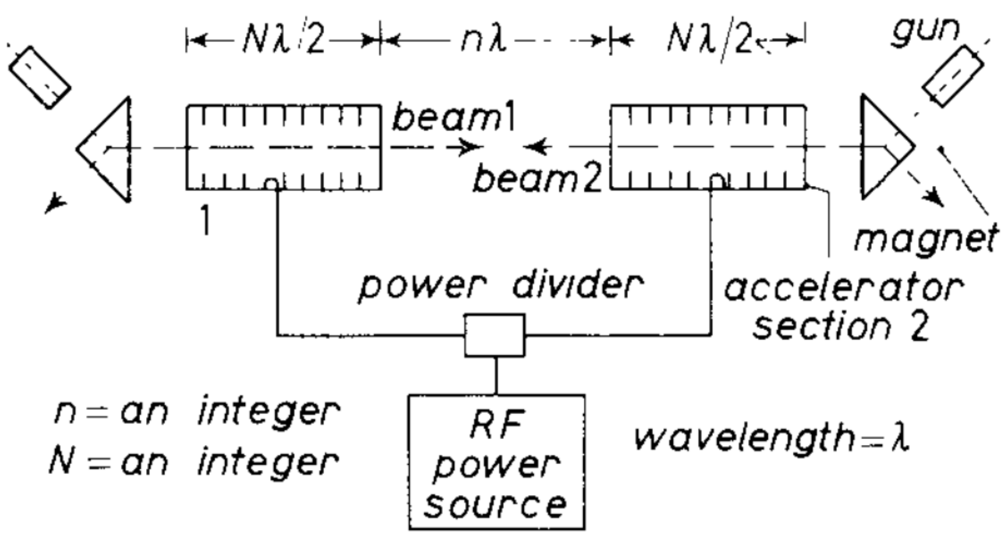

Fig. 2.

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

Principle

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(ricevuto il 2 Febbraio 1965)

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- Same beam
- Only one accelerator section

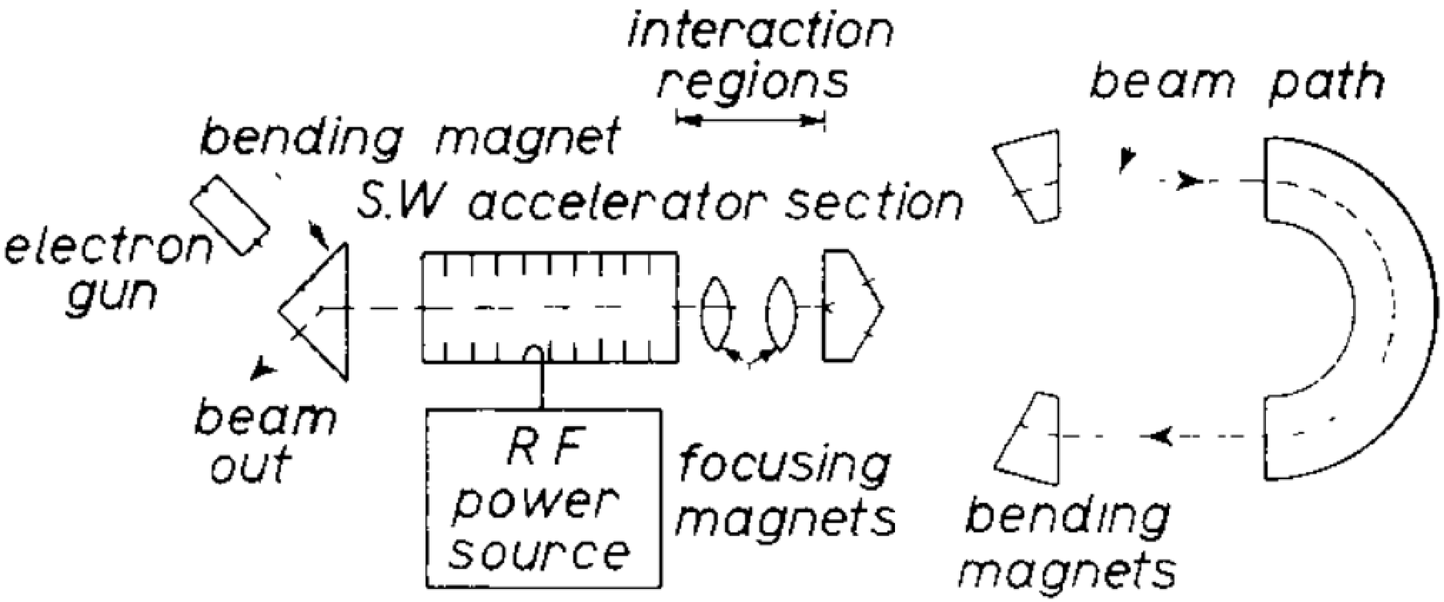

Fig. 3.

First Energy Recovery

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- 1979: First suggested „same-cell energy recovery" – FEL context

  (C.A. Brau et al., High Efficiency Free-Electron Laser System, Proc. Int. Conf. on Lasers 1979)

- July 1986: First successful test of „same-cell energy recovery" – no further user operation

Nuclear Instruments and Methods in Physics Research A259 (1987) 1–7
North-Holland, Amsterdam

Section I. Low gain experiments

DEVELOPMENT OF THE SCA / FEL FOR USE IN BIOMEDICAL AND MATERIALS SCIENCE EXPERIMENTS *

T.I. SMITH, H.A. SCHWETTMAN, R. ROHATGI, Y. LAPIERRE ** and J. EDIGHOFFER

High Energy Physics Laboratory, Stanford University, Stanford, California 94305, USA

ACCELENCE

First Energy Recovery

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2 *T.I. Smith et al. / SCA/FEL for biomedical and materials science experiments*

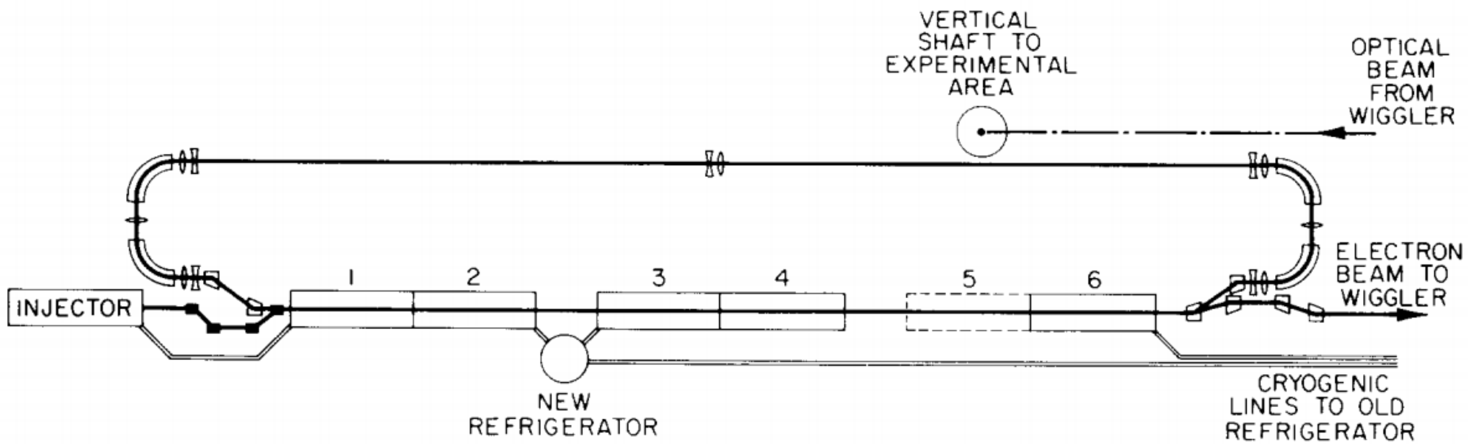

Fig. 1. SCA/FEL plan. Schematic layout of the superconducting linear accelerator, showing the locations of the injector, the linac, the recirculation system and the refrigerators.

- $E_{max} \approx 93$ MeV (N=2)
- $I_{avg} \approx 150$ μA; $I_{peak} \approx 2.5$ A
- $Q_{bunch} \approx 12.5$ pC
- 360° path length adjustment possible

DEVELOPMENT OF THE SCA/FEL FOR USE IN BIOMEDICAL AND MATERIALS SCIENCE EXPERIMENTS *

T.I. SMITH, H.A. SCHWETTMAN, R. ROHATGI, Y. LAPIERRE ** and J. EDIGHOFFER
High Energy Physics Laboratory, Stanford University, Stanford, California 94305, USA

Energy Recovery and FEL

- ~ 2000: First successful „same-cell energy recovery“ during FEL operation

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 445 (2000) 192–196

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.nl/locate/nima

First operation of an FEL in same-cell energy recovery mode

G.R. Neil*, S. Benson, G. Biallas, C.L. Bohn, D. Douglas, H.F. Dylla, R. Evans, J. Fugitt, J. Gubeli, R. Hill, K. Jordan, G. Krafft, R. Li, L. Merminga, D. Oepts, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, B. Yunn

Thomas Jefferson National Accelerator Facility, MS 6A, 12000 Jefferson Avenue, Newport News, VA 23606, USA

Energy Recovery and FEL

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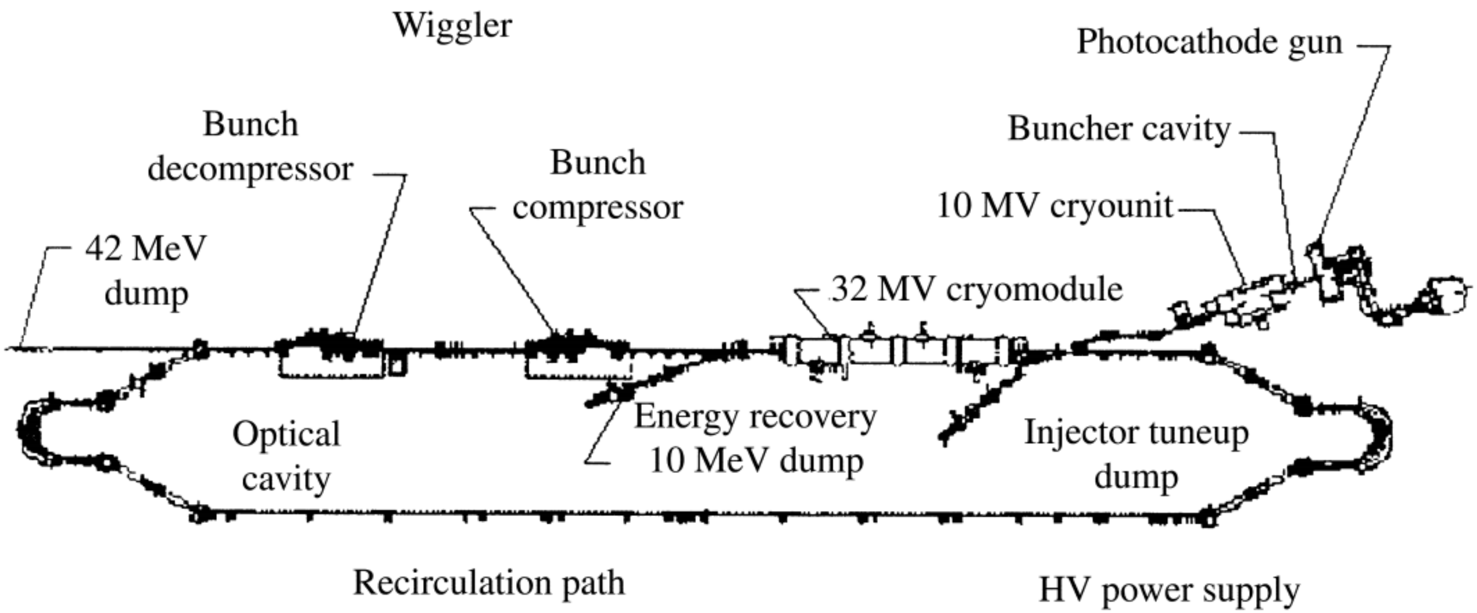

Fig. 1. Schematic view of IR Demo; dimensions of the recirculation loop are roughly 49 m × 6 m.

- E_{max} = 48 MeV
- I_{avg} = 5 mA; I_{peak} = 22 A
- Q_{bunch} = 60 pC

First operation of an FEL in same-cell energy recovery mode

G.R. Neil*, S. Benson, G. Biallas, C.L. Bohn, D. Douglas, H.F. Dylla, R. Evans, J. Fugitt, J. Gubeli, R. Hill, K. Jordan, G. Krafft, R. Li, L. Merminga, D. Oepts, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, B. Yunn

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Why should you use an ERL?

- Research in accelerator physics – examples for beam dynamics
  - Multi-turn ERL operation
  - Non-isochronous operation for reduction of energy spread
  - FFAG ERL

    → smaller footprint, permanent magnets (thus cost effective)

Why should you use an ERL?

TECHNISCHE UNIVERSITÄT DARMSTADT

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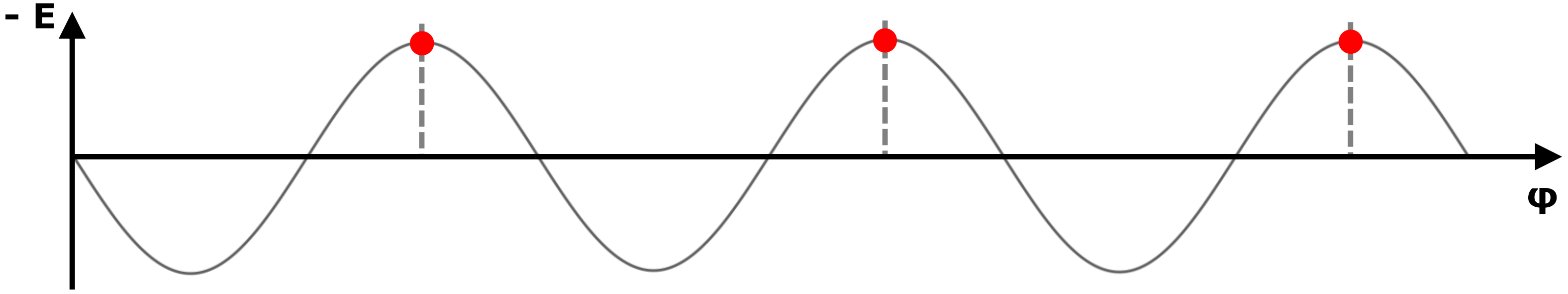
Isochronous / non-isochronous ERL

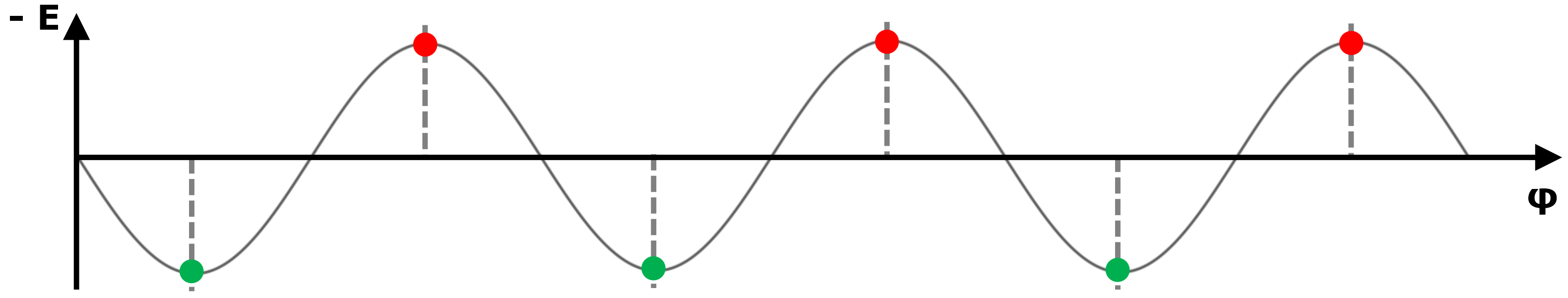
Isochronous



- Accelerated particle
- Decelerated particle

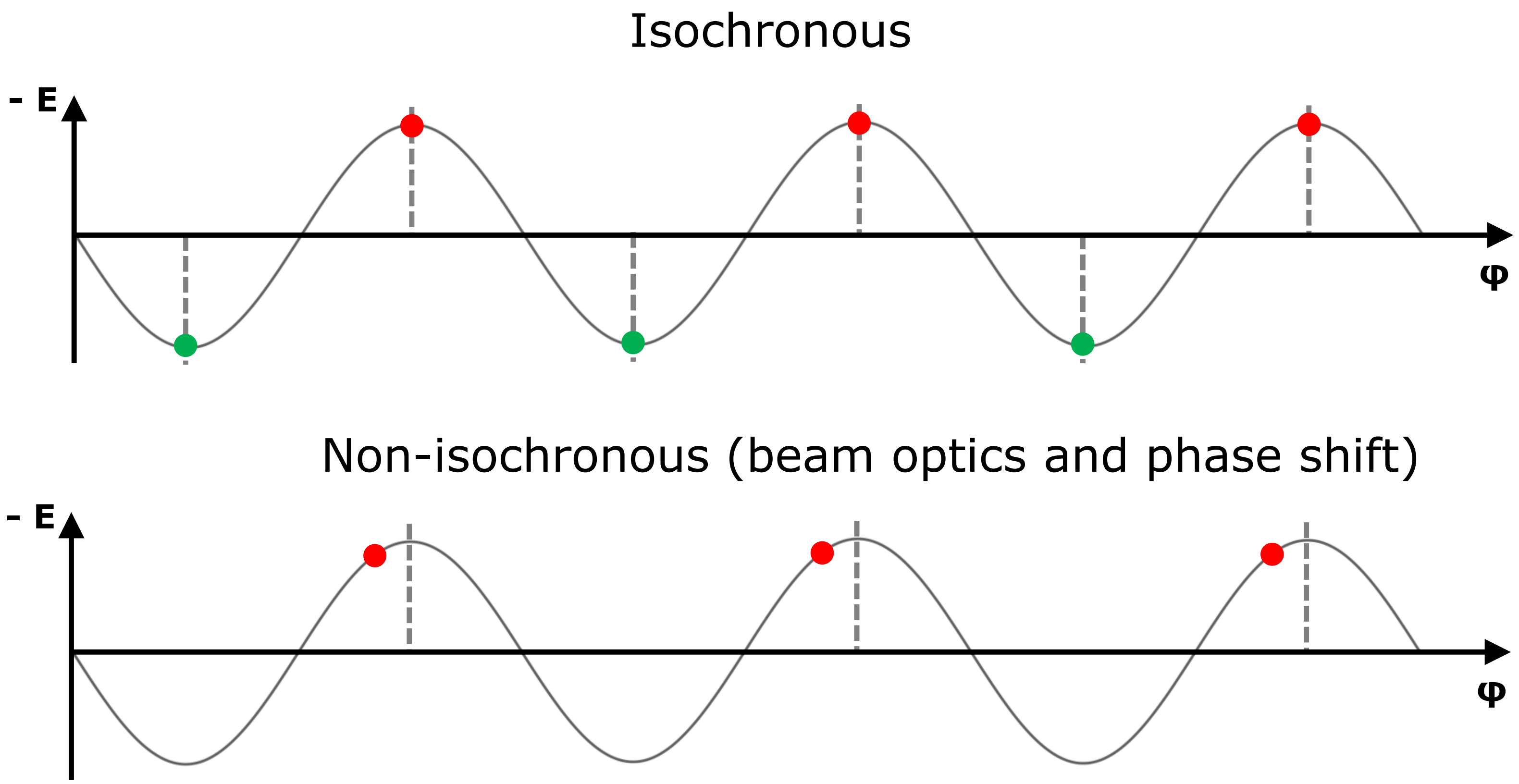
Isochronous / non-isochronous ERL

Isochronous



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

Isochronous / non-isochronous ERL



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

Isochronous / non-isochronous ERL

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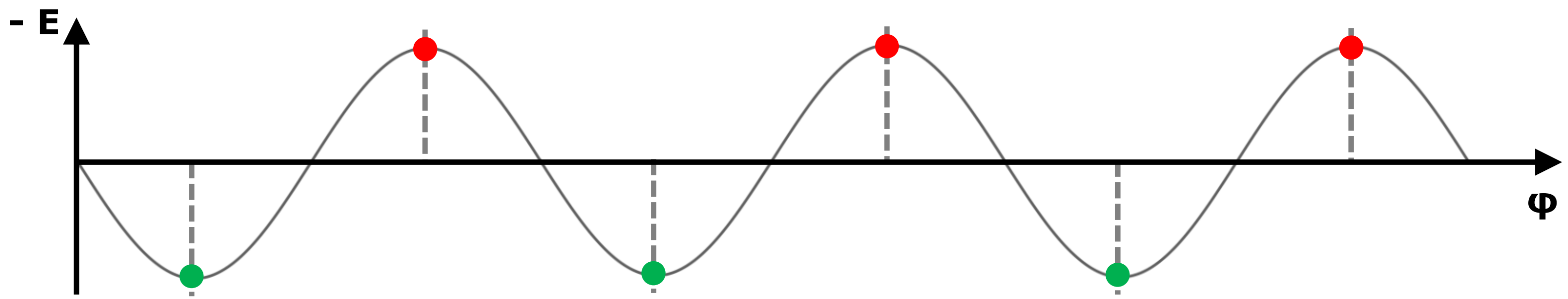
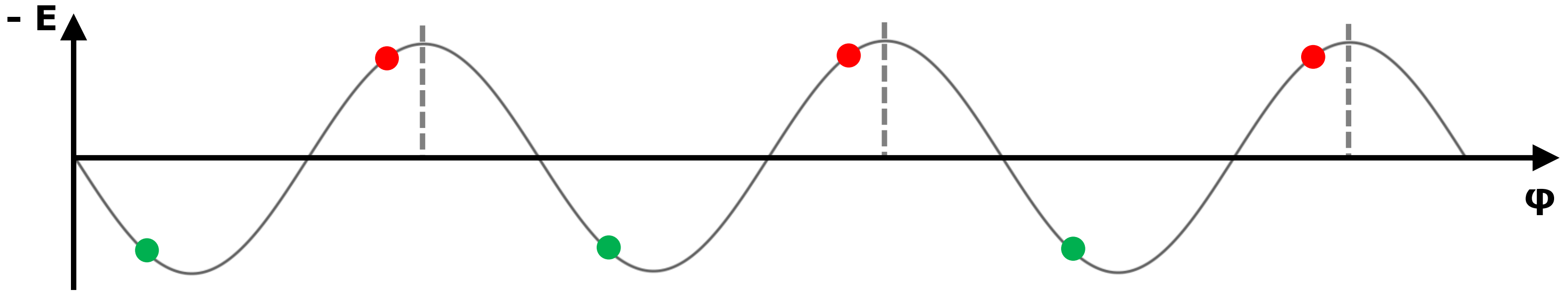
Isochronous

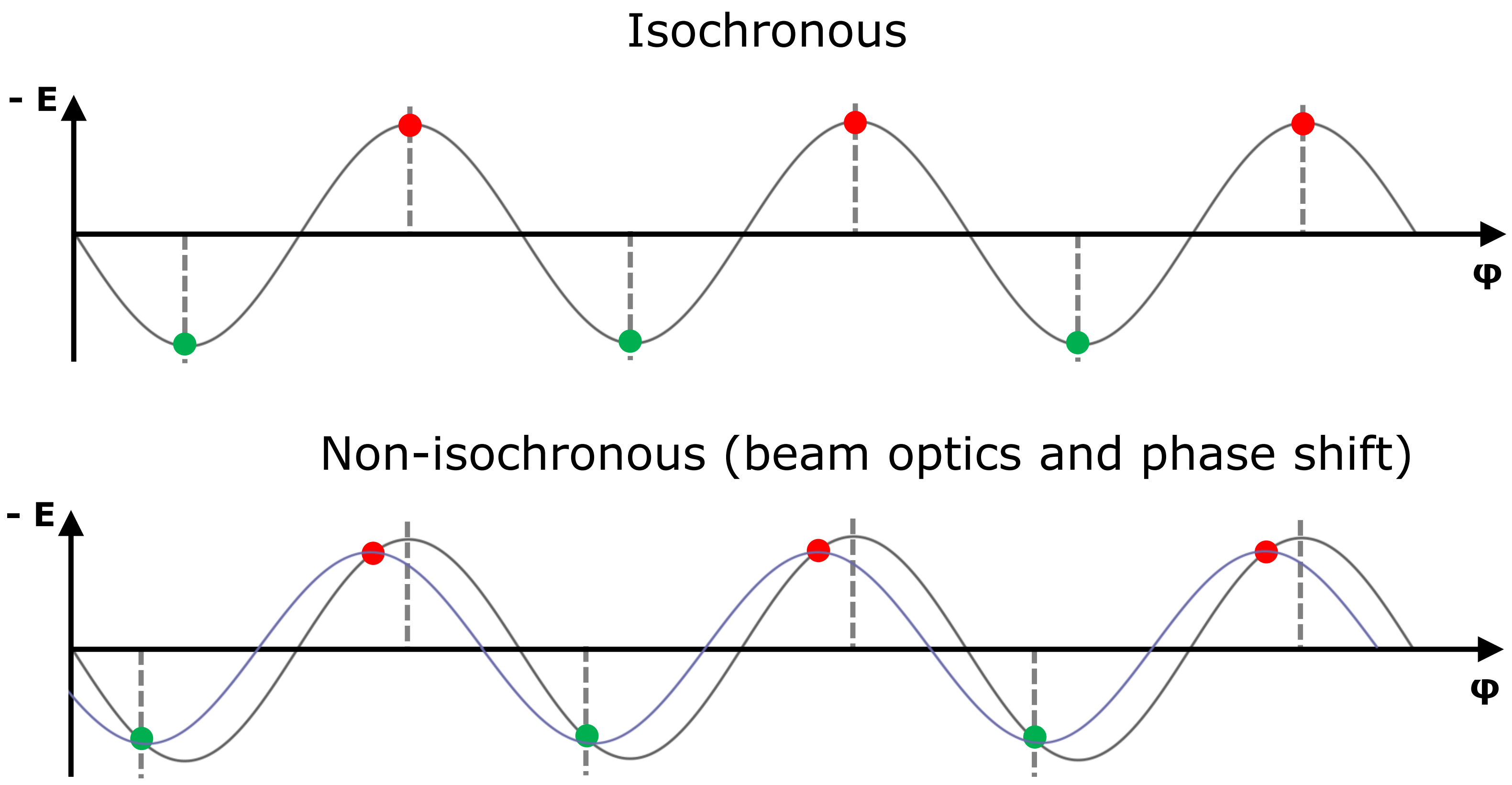


Non-isochronous (beam optics and phase shift)



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

Isochronous / non-isochronous ERL



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

Why should you use an ERL?

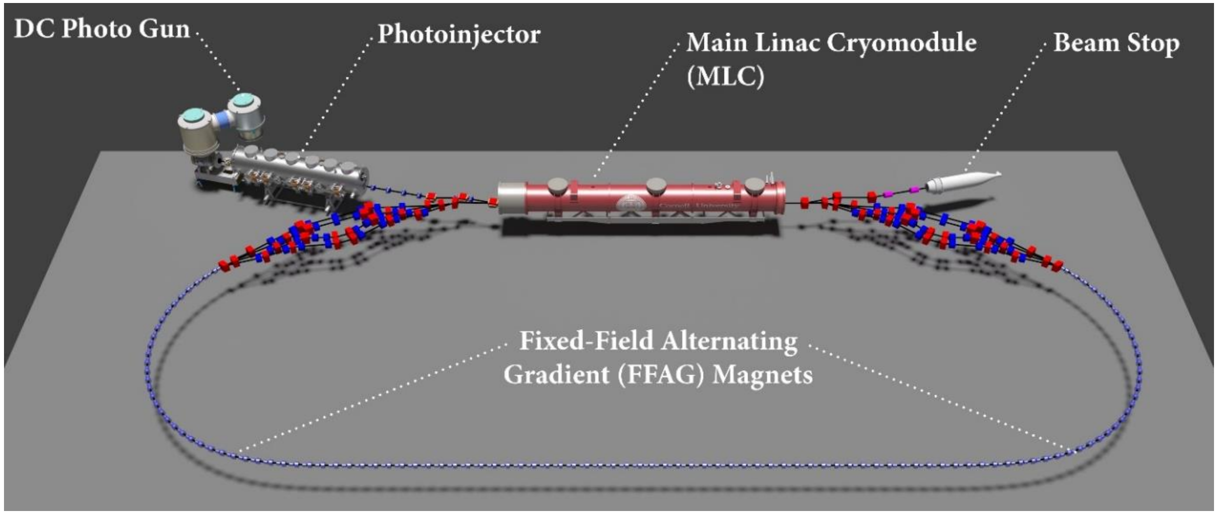
TECHNISCHE UNIVERSITÄT DARMSTADT

- Research in accelerator physics – examples for beam dynamics
  - Multi-turn ERL operation
  - Non-isochronous operation for reduction of energy spread
  - **FFAG ERL**

    → smaller footprint, permanent magnets (thus cost effective)

FFAG (fixed-field alternating gradient) ERL

- Usage of permanent magnets → no power supplies, no cooling, …
- Cornell-BNL FFAG-ERL Test Accelerator (Cβ) → 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

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- Enhancement of experiments
  - Higher intensities with the same RF power (not injector !)
  - High brilliance (lowest transversal emittance and short pulse length)

Why should you use an ERL?

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- Research in accelerator physics – examples for beam dynamics
  - Multi-turn ERL operation
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- Enhancement of experiments
  - Higher intensities with the same RF power (not injector !)
  - High brilliance (lowest transversal emittance and short pulse length)

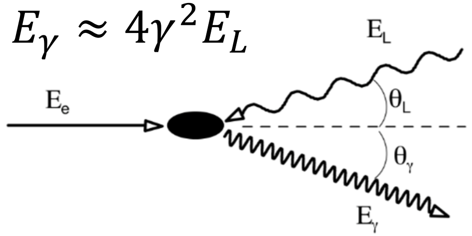
- Additional benefit
  - Less power necessary to cool the dumped beam
  - Less activation of beam dump

Possible Applications

Small impact on the beam, otherwise no further transport possible

- Internal target experiment
- Free Electron Laser (FEL)
- Coherent electron cooling
- Electron-ion-collider
- Compton back-scattering

$$E_\gamma \approx 4\gamma^2 E_L$$



Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Introduction to Energy Recovery Linacs (ERLs)
- Examples
  - Overview
  - Operating ERLs (external)
  - ERLs under design / construction (external)
- Commissioning of ERL Mode @ S-DALINAC
- Summary and Outlook
- Research Training Group on ERLs

ERLs Worldwide

- First collection of all ERLs including parameters (will be updated every ERL workshop)

	Name	JLabFEL	CEBAF-ER	ERL DEMO	IR ERL Upgrade	UV FEL	ER@CEBAF	eIC cooler	cERL	EUV Source	ALICE	bERLinPro	CBETA	Cornell Light Source
2	Institute	JLab	JLab	JLab	JLab	JLab	JLab	JLab	KEK	KEK	STFC	HZB	Cornell	Cornell
3	Main application: Test Facility [TF], Light Source [LS], User Facility [UF], Physics Application [PA]	LS	TF	TF	LS	LS	TF		TF	LS	TF, UF	TF	TF	LS
4	Commissioning Start		2003	1997	2001		2018		2013	In planning 2017	2005	2021	2017	Study
5	Operation End		2003	2001			2018		2016		2016	2022	tbd	tbd
6	# Re-Circulations	1	1	1	1	1	5		1	1	1	1	4	1
7	RF type	SC	SC	SC	SC	SC	SC		SC	SC	SC	SC	SC	SC
8	RF Frequency [GHz]	1,5	1,5	1,5	1,5	1,5	1,50		1,3	1,3	1,3	1,3	1,3	1,3
9	Bunch Frequency [MHz]										81,25	1,3	325	
10	Accelerating Voltage ML [MeV / m]		5, 12				5, 12, 20		8,2	12.5 to 15	10 (14)	12,5	7	16
11	Accelerating structure ML		2 linacs in racetrack, 20 CM / linac, 5-cell				2 linacs, racetrack, 25 CM per linac, 5-cell and 7-cell		one cryomodule with 2 9-cell cavities	one cryomojule with 4 9-cell cavities	1 cryomodule with 2 cavities 2	original: one cryomodule with 3 7-cell cavites; now: MESA Module	1 cryomodule with 6 7-cell cavities	64 CM with 6 7-cell cavities
12	Energy gain / linac [MeV]		500	48			700,00		17	50	24	25	36	5000
13	Accelerating Voltage Injector [MeV / m]											20		
14	Accelerating structure Injector													
15	Bunch charge @ inj [pC]	135	0,07	60	135	60	0,20		0.77 to 40	60	80	77	123	77
16	Bunch length [ps]		0,7		0,15		0,70		0.2 to 3	0.05 to 2	1	2	3	2
17	Energy spread (extraction)		0.0001 (%)		0,5	0,5	0.0001 (2-3%)		1.2×10^{-4}	1×10^{-3}	5 keV	0,005	4,00E-04	2,00E-04
18	Transverse emittance [gamma mm mrad]		0,5		15	10	0,50		1-1.6 (7.7pC/bunch)	(60pC/bunch)	5 to 10	0.5 - 1.0	0,5	0,3
19	Av. Current @ inj [mA]	10	0,035	5	9	5	0,10		1	10	0,013	5	40	100
20	Av. Current @ inj [mA] macro pulse										6,5			
21	Injector Energy [MeV]		56		9	9	79,00		2,9	10,5	8,35	6,5	6	5
22	Max beam energy @ end of accel [MeV]	160	1050	48	170	210	7079,00		20	800	35	32	150	5
23	Max beam power @ end of accel [MW]	1,6	0,03675	0,24	1,53	1,05	0,7079	0	0,02	8	0,000455	0,16	6	0,5
24	Max total current in cavity [mA]	20	0,07	10	18	10	1	0	2	20	0,026	10	320	200
25	Power on dump [MW]	0	0,00196	0	0,081	0,045	0,0079	0	0,0029	0,105	0,0001086	0,0325	0,24	0,5
26	Power consumption of injector [MW]											0,0325	0,75	1,5
27	Power consumption of Facility [MW]								1	10		4,2	0,8	20
28	FEL section		no				no		yes	yes	yes	not planned	no	no
29	FEL light type		n.a.				n.a.		Infrared	EUV	IR	n.a.	n.a	n.a.
30	Source type			DC Photo Injector	DC Photo Injector	DC Photo Injector			DC gun 450 kV	DC gun 500kV	DC Photo gun with 500kV and GaAs cathode	SRF Photo Injector	DC Photo Cathode, 350kV	DC Photo Cathode, 350kV
31	Cathode lifetime				n.a.				few month	one week	1 week	n.a.	2.6 days	2.6 days
32	Polarization		80%	no	no	no	80%		No	No	No	No	No	No

	Name	S-DALINAC ERL	MESA	test ERL	eRHIC ERL	CeC @ RHIC	LHeC	PERLE	ARIEL ERL	APS ERL	IHEP ERL	Peking ERL-FEL		PAPS	ERL	FEL
2	Institute	U Darmstadt	U Mainz	BNL	BNL	BNL	CERN	LAL Orsay	TRIUMF	Argonne	IHEP	IHEP	SINUP	IHEP	BINP	BINP
3	Main application: Test Facility [TF], Light Source [LS], User Facility [UF], Physics Application [PA]	TF	PA	TF	PA	TF	PA	TF & PA	UF							
4	Commissioning Start	2017 (ERL mode)	2019	2014	Study	2017	Study	In planning	In planning							
5	Operation End	tbd		2015	n.a.	n.a.										
6	# Re-Circulations	2	2	0	6	1	3	3	1						3	
7	RF type	SC	SC	SC	SC	SC	SC	SC	SC			SC	SC	SC	NC	NC
8	RF Frequency [GHz]	3	1,3	0,704	0,647	0,704	0,8	0,8	1,3			1,3		0,65	0,18	
9	Bunch Frequency [MHz]	3000					40	40	650MHz							
10	Accelerating Voltage ML [MeV / m]	5		18	18	22,5	18	17,5	10							
11	Accelerating structure ML	4 CM with 2 20-cell cavities each		5-cell cavity cryomodule	2 5-cell cavities / cryomodule	One 5-cell cavity in one CM	4 5-cell cavities / cryomodule	4 5-cell cavities / cryomodule	2 9-cell cavities					2 2-cell cavities in one cryomodule		
12	Energy gain / linac [MeV]	30,4	25	0	1500 x 2 linacs	22	10000	65,5	20							
13	Accelerating Voltage Injector [MeV / m]	5														
14	Accelerating structure Injector	CM1: 1 2-cell plus 1 5-cell cavity; CM2: 2 20-cell cavity							650MHz							
15	Bunch charge @ inj [pC]	0,007	7,7	500	5300	500 to 5000	400	375	15,4			60	240			
16	Bunch length [ps]	5	4,3	8.5, 22	10	10 to 50			1							
17	Energy spread (extraction)	no data		no data	0,001	0,001			0,10%							
18	Transverse emittance [gamma mm mrad]	no data	1	2.5 / 3.5	20 to 70	0,3	50	6	1							
19	Av. Current @ inj [mA]	0,02	10	0,02	38	0,4	15	20	13		10		20	10	30	
20	Av. Current @ inj [mA] macro pulse															
21	Injector Energy [MeV]	7,6	5	1,2	20	2	500	5	10					0,5		
22	Max beam energy @ end of accel [MeV]	68,4	105	1,2	18000	22	60000	400	50		35	30		50	11	
23	Max beam power @ end of accel [MW]	0,001368	1,05	0,000024	684	0,0088	900	8	0,65	0	0,35	0	0	0,5	0,33	0
24	Max total current in cavity [mA]	0,08	40	0	456	0,8	90	120		0	0	0	0	0	180	0
25	Power on dump [MW]	0,000152	0,05	0,000024	0,76	0,0008	7,5	0,1		0	0	0	0	0,005	0	0
26	Power consumption of injector [MW]				2,5											
27	Power consumption of Facility [MW]				24		100									
28	FEL section	no		no	no		no	No	Yes			yes			Yes	
29	FEL light type	n.a		n.a.	n.a.		n.a.		UV and Infrared, THz and CSR and Compton backscatteri						THz	
30	Source type	Thermionic gun (250keV; tungsten wire) and Photo gun (100keV - 200keV); GaAs		Photocathod SRF gun	Photo Injector	113MHz SRF gun with room temperature CsK2Sb cathode;	n.a.		Thermionic 300kV DC gun					Photocathod DC gun 500kV	DC Gun	
31	Cathode lifetime				> 6h											
32	Polarization	85%		No	Yes		No	No								

By ERL 2019, now on HZB page
https://www.helmholtz-berlin.de/projects/berlinpro/

ERLs Worldwide

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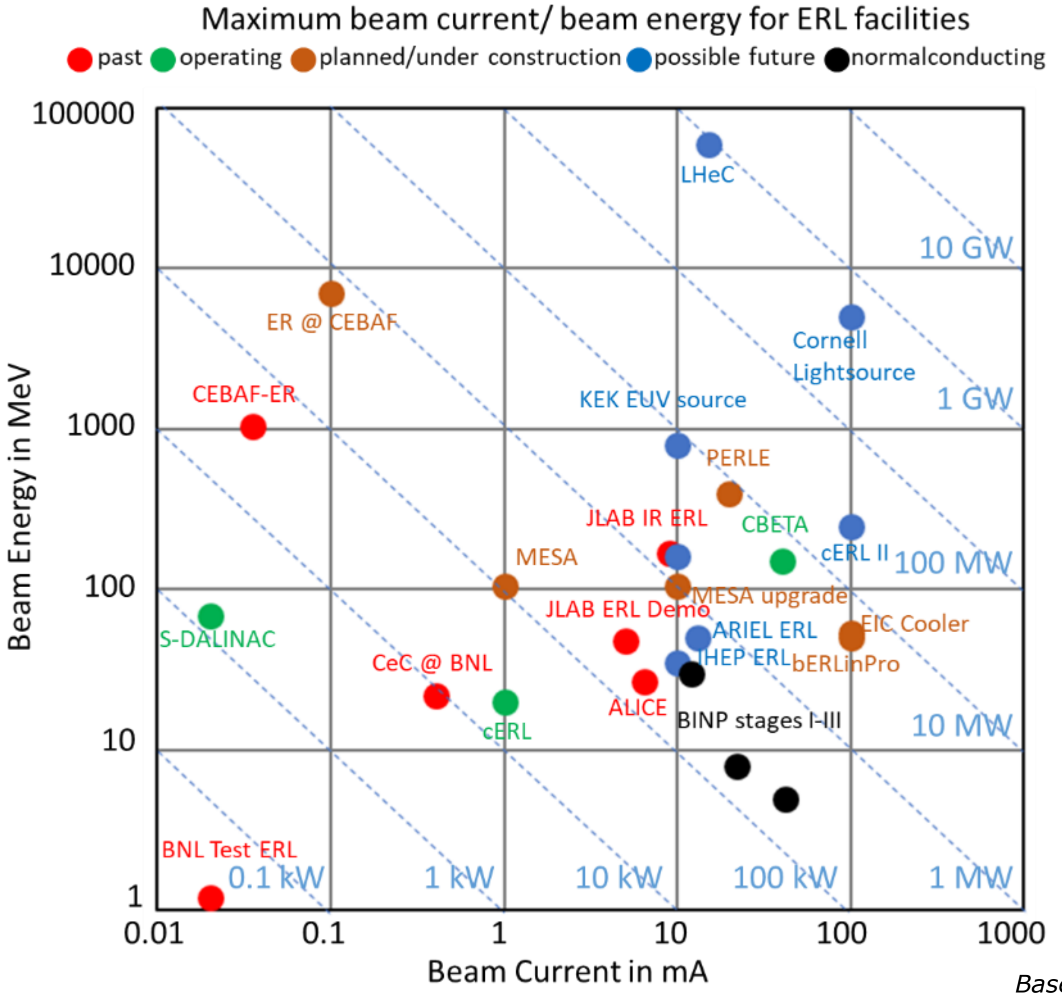


Based on ERL 2019 database, F. Hug

Operating ERLs (external)

Example is:

CBETA

CORNELL-BNL ERL TEST ACCELERATOR

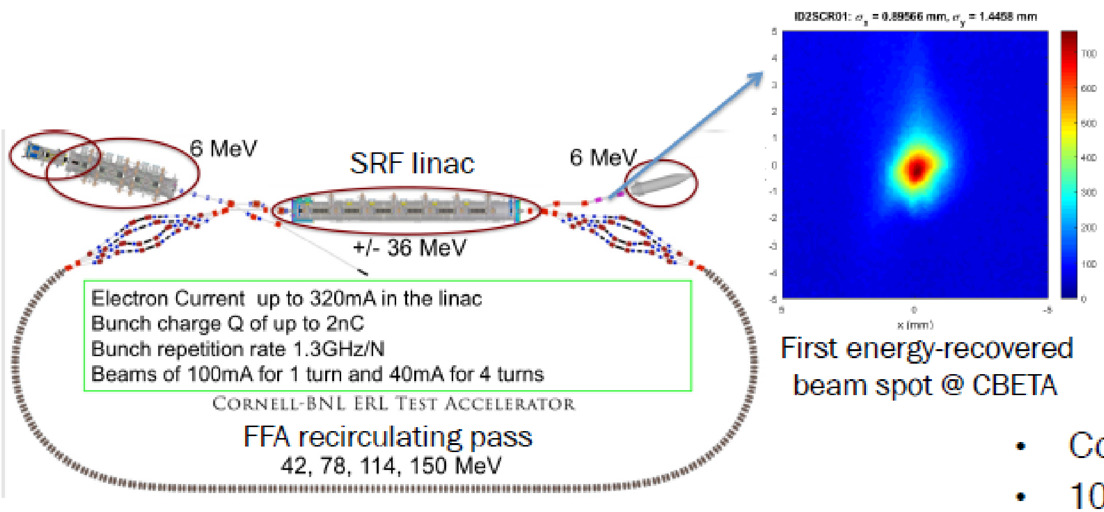
CBETA

TECHNISCHE UNIVERSITÄT DARMSTADT

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Cornell-BNL ERL Test Accelerator CBETA

- At least 100 mA current will be needed for eRHIC hadron cooler (design limit for 1-turn CBETA)
- BNL and collaborators gained and demonstrated expertise in high-power ERLs
- Successful operation, including energy recovery in each cavity (June 24th, 2019).
- Full 4-turn construction is underway.



First energy-recovered beam spot @ CBETA

Georg.Hoffstaetter@cornell.edu - September 16, 2019 – ERL Workshop Berlin

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

<u>December 2019:</u>
Successful 4-turn operation

https://www.bnl.gov/newsroom/news.php?a=116982

- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

ERLs under Design / Construction (external)

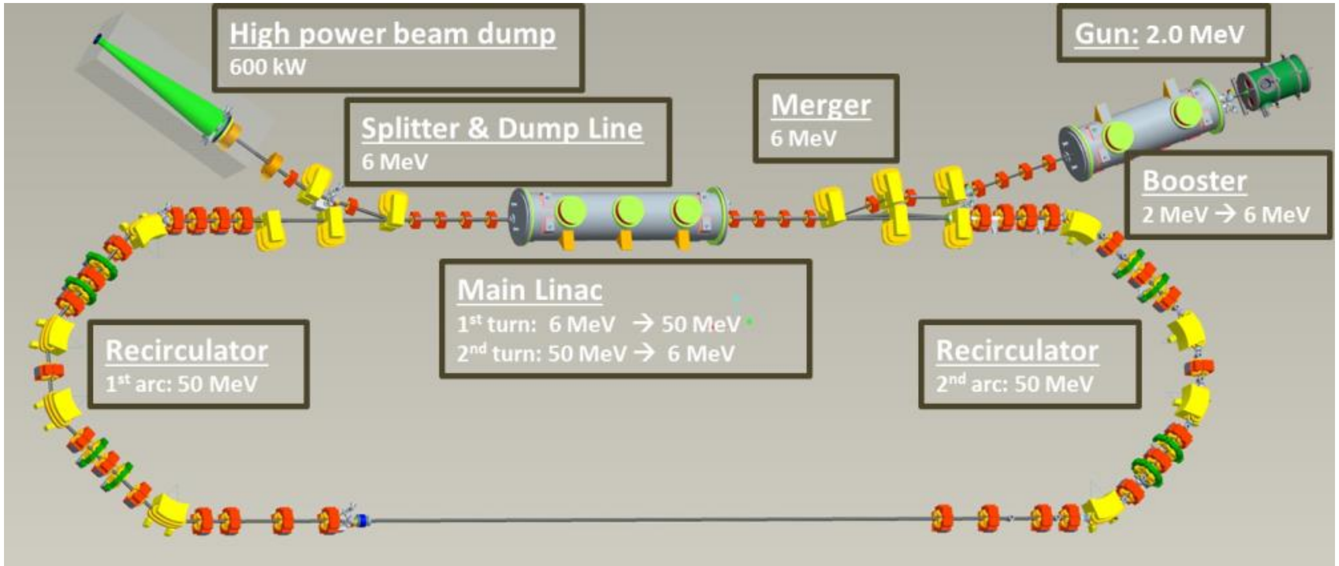
Examples are:

bERLinPro

MESA

Mainz Energy-recovering Superconducting Accelerator

bERLinPro



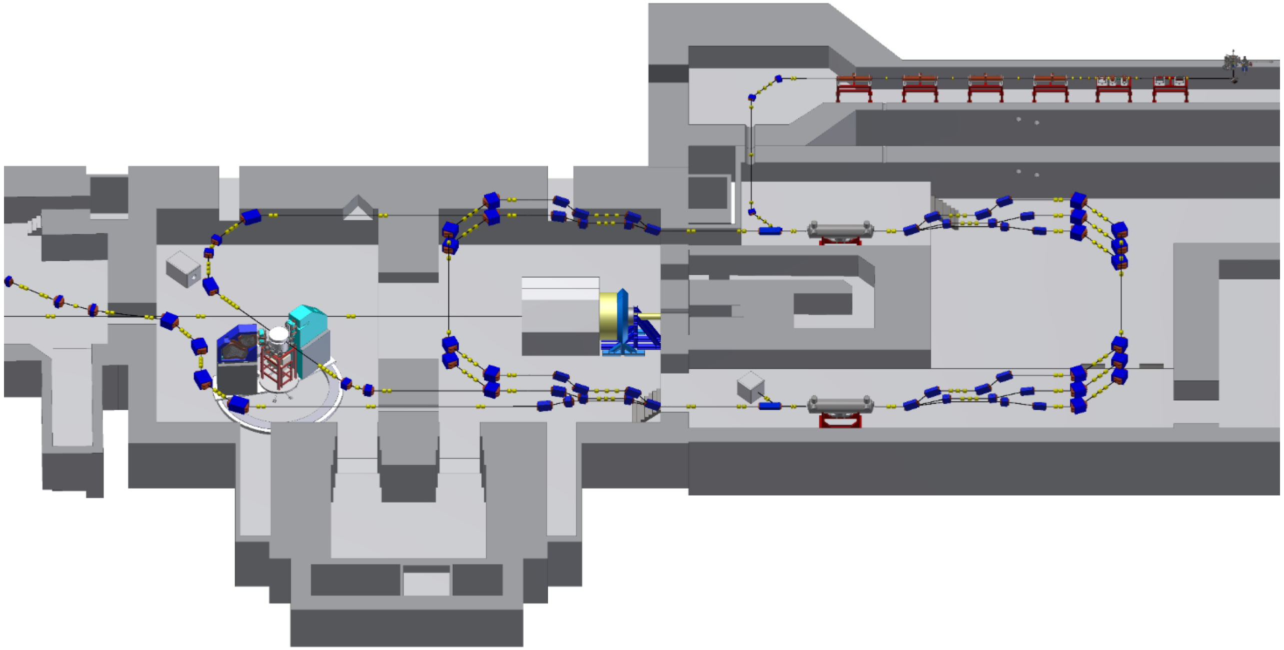
https://www.helmholtz-berlin.de/projects/berlinpro/bpro-overview_en.html

- Demonstrator Facility for accelerator R&D
- Flexible parameters → standard mode shown
- Full energy recovery expected 2021

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

- Introduction to Energy Recovery Linacs (ERLs)
- Examples
- Commissioning of ERL Mode @ S-DALINAC
  - Introduction
  - Once-recirculating ERL operation
  - Test phase twice-recirculating ERL operation
- Summary and Outlook
- Research Training Group on ERLs

S-DALINAC

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

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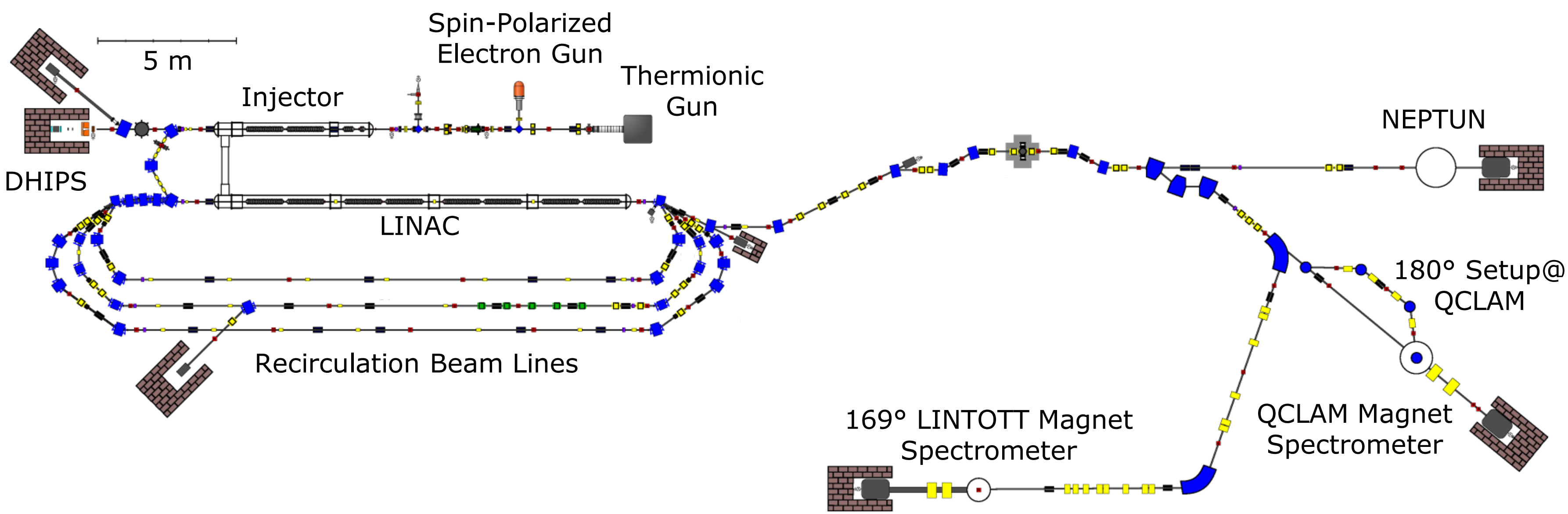


<u>Thrice recirculating operation</u>

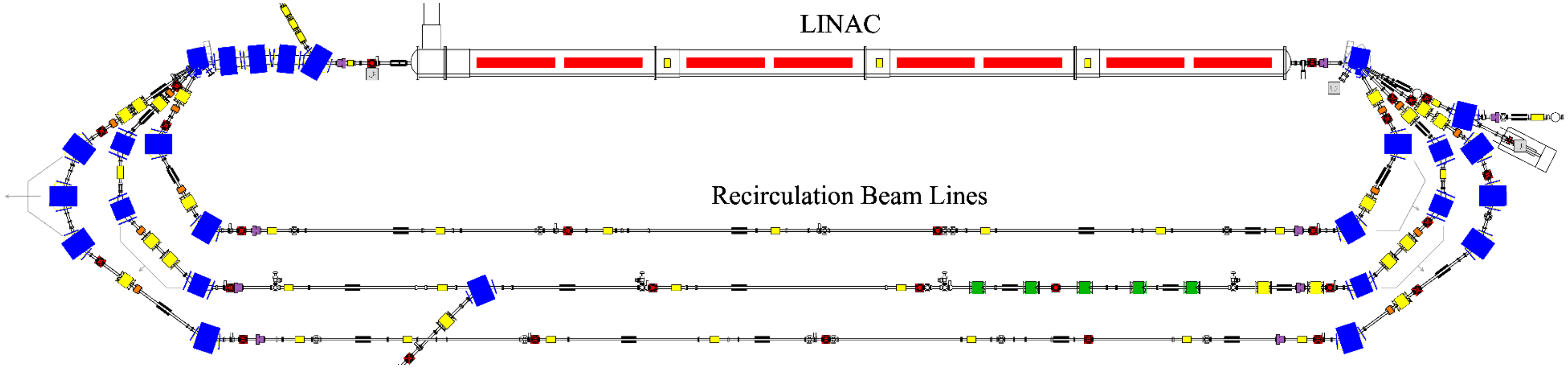
Energy gain injector: 7.6 MeV

Energy gain LINAC: 30.4 MeV

Beam current: 20 μA

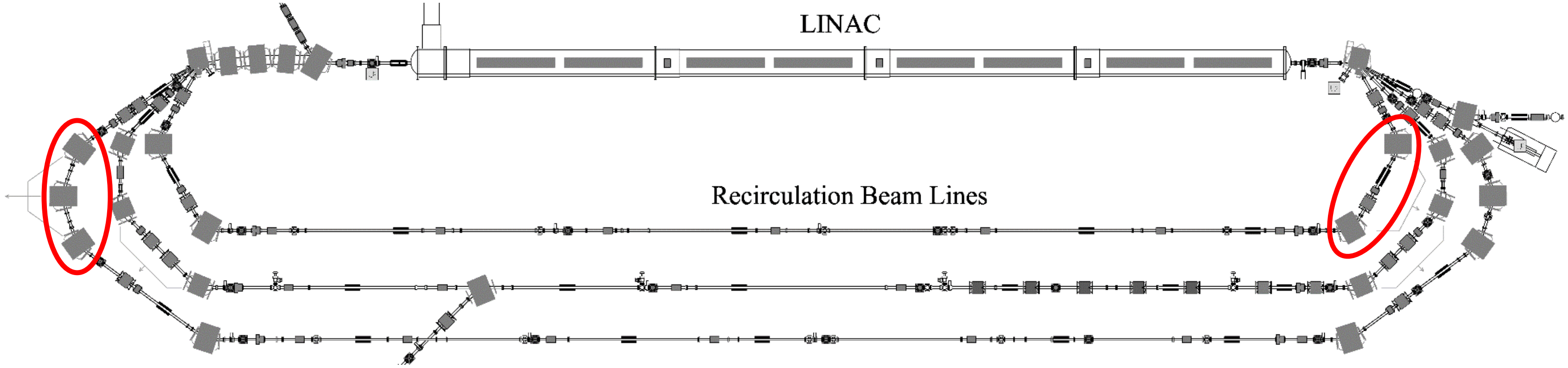
Path Length Adjustment System

TECHNISCHE UNIVERSITÄT DARMSTADT



- Adjusting the phase of the beam re-entering the main LINAC

Path Length Adjustment System

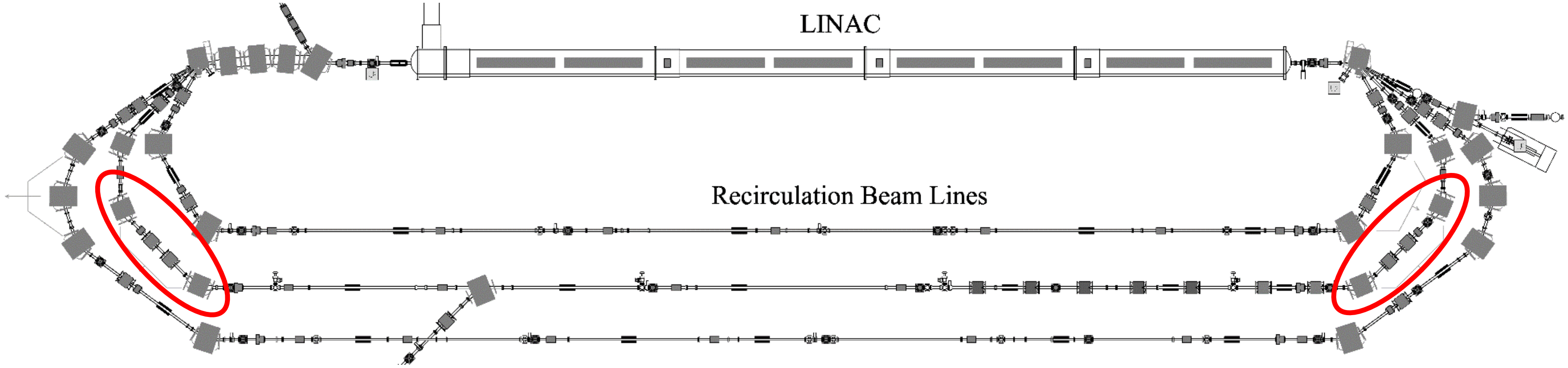


- Adjusting the phase of the beam re-entering the main LINAC
- Existing systems in old recirculation beam lines
  - Stroke F measured: 33.76 mm
  - Stroke T measured: 30.62 mm

Stroke of both systems enlarged

Path Length Adjustment System

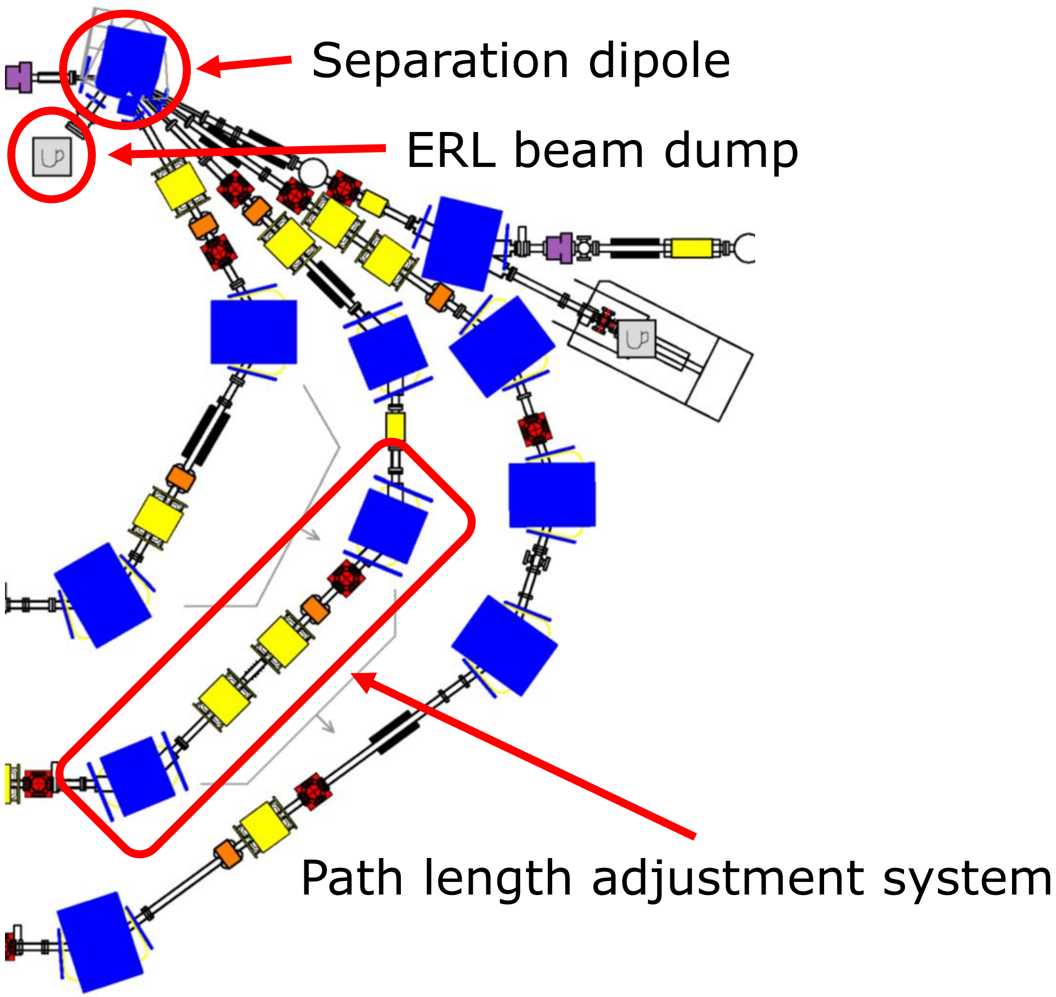
TECHNISCHE UNIVERSITÄT DARMSTADT

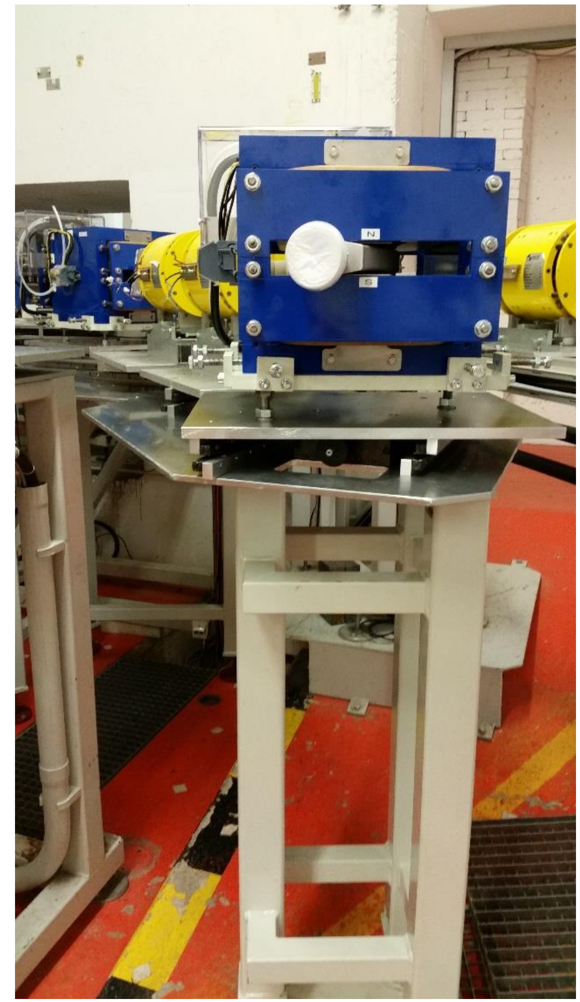


- Adjusting the phase of the beam re-entering the main LINAC
- Existing systems in old recirculation beam lines
  - Stroke F measured: 33.76 mm
  - Stroke T measured: 30.62 mm

  } Stroke of both systems enlarged
- New systems are capable of full RF wavelength adjustment
  - Stroke measured: (50.21 + 50.57) mm = 100.78 mm

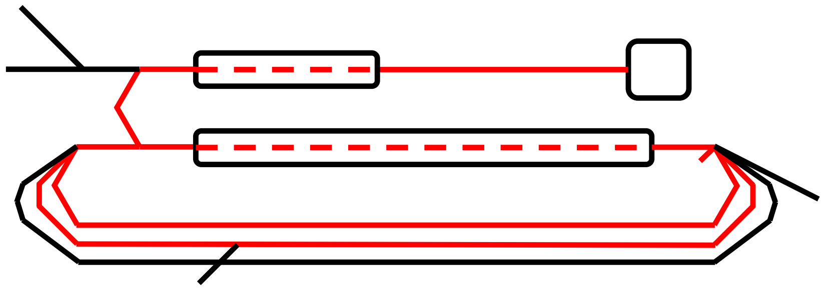
S-DALINAC as ERL





Beam Dynamics ERL

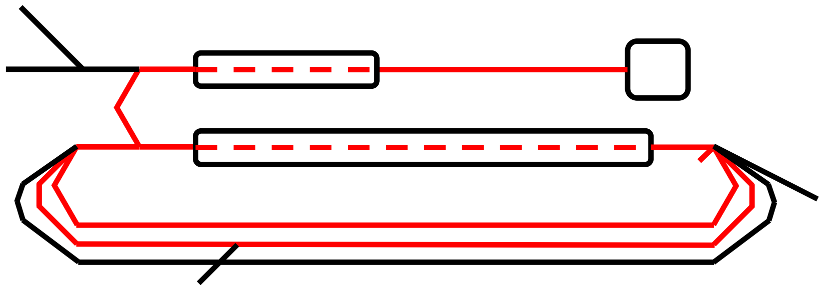
- Thrice-recirculating lattice was not optimized for ERL operation



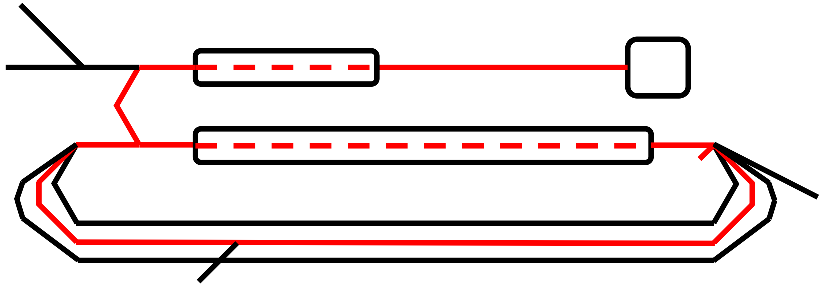
- Under investigation

Beam Dynamics ERL

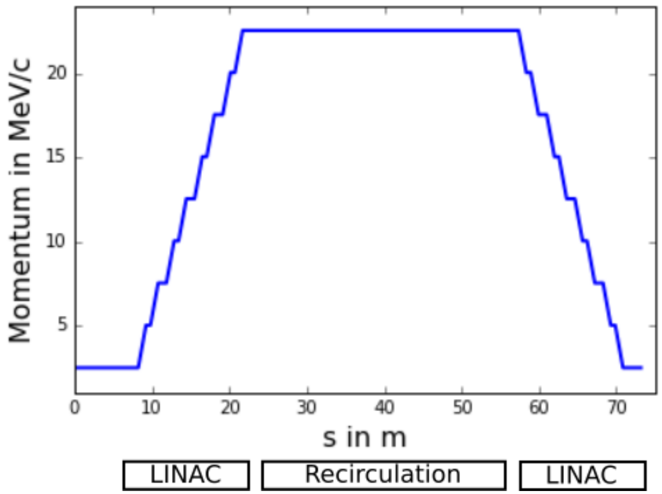
- Thrice-recirculating lattice was not optimized for ERL operation



- Under investigation

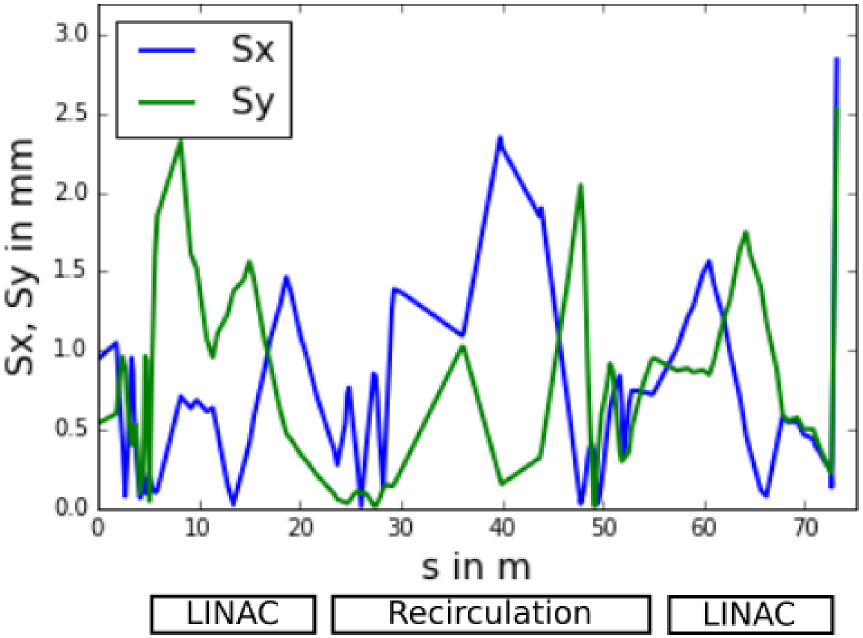


- Simulations finished



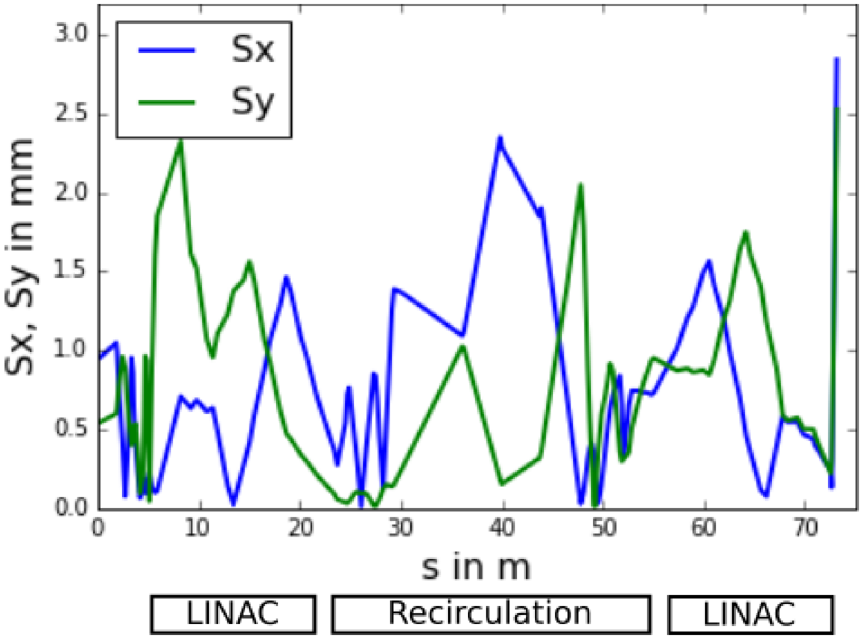
Simulation by Jonas Pforr

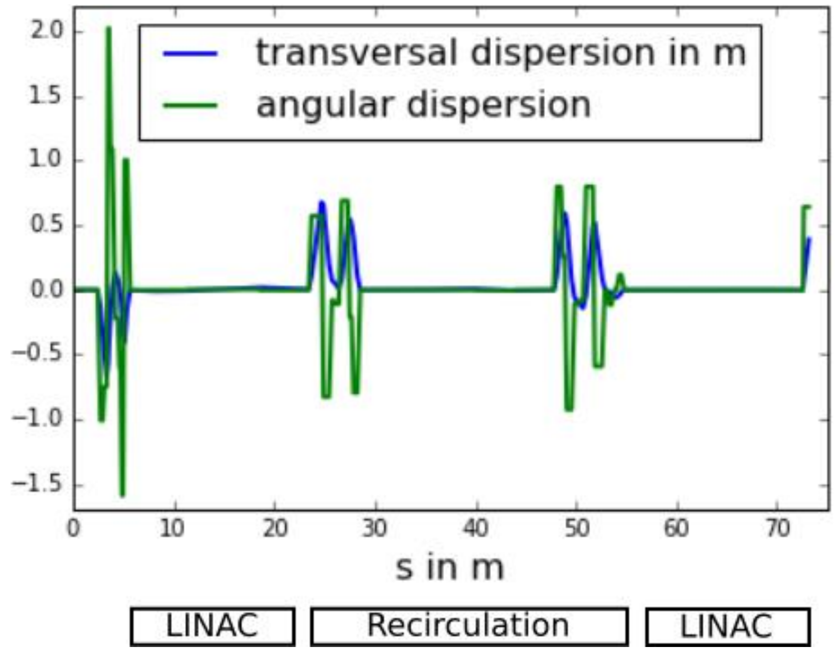
Beam Dynamics ERL



Simulation by Jonas Pforr

Beam Dynamics ERL





Simulation by Jonas Pforr

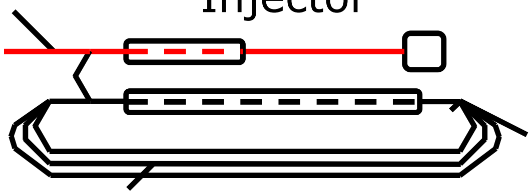
Overview Operation Modes / Commissioning

TECHNISCHE UNIVERSITÄT DARMSTADT

- Modification lattice 2015/2016
- Refurbishment cryoplant 2018

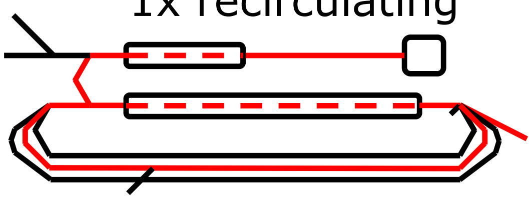
- Commissioning of modes following beam time schedule

Injector



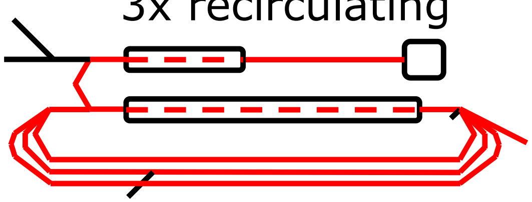
December 2016

1x recirculating



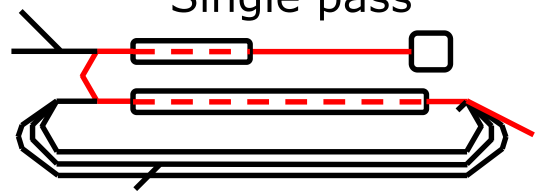
May 2017

3x recirculating



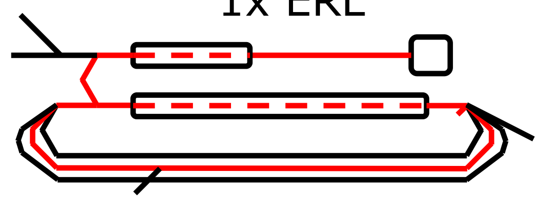
November 2018

Single pass



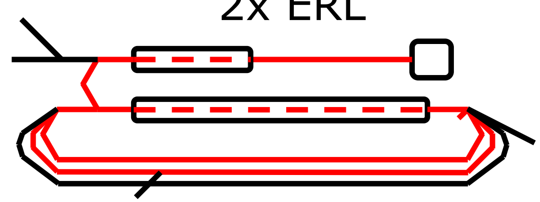
December 2016

1x ERL



August 2017

2x ERL



Test phase

Overview Operation Modes / Commissioning

TECHNISCHE UNIVERSITÄT DARMSTADT

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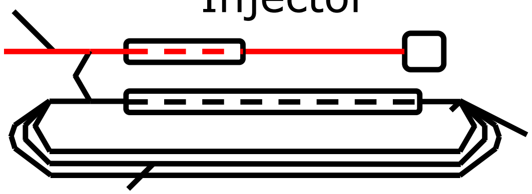
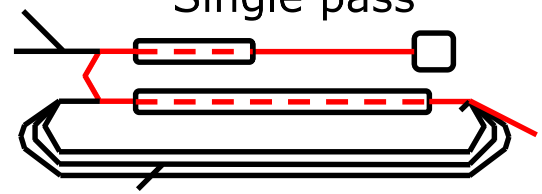
- Commissioning of modes following beam time schedule

Injector



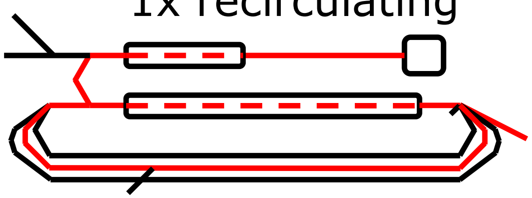
December 2016

Single pass



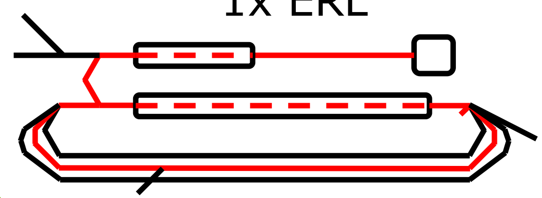
December 2016

1x recirculating



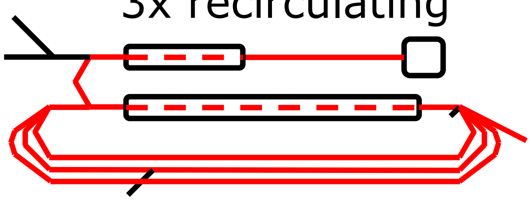
May 2017

1x ERL



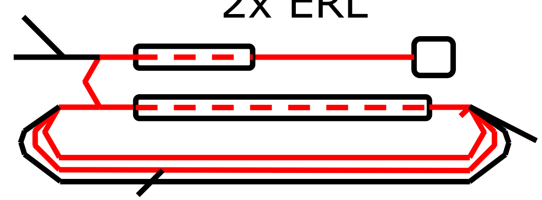
August 2017

3x recirculating



November 2018

2x ERL



Test phase

Efficiency of an ERL

- "*Beam-recovery efficiency*"

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

Perfect transmission

  - Limited by design of accelerator

$$\varepsilon_{b,max} = 1 - \frac{E_{b,dump}}{E_{b,max}}$$

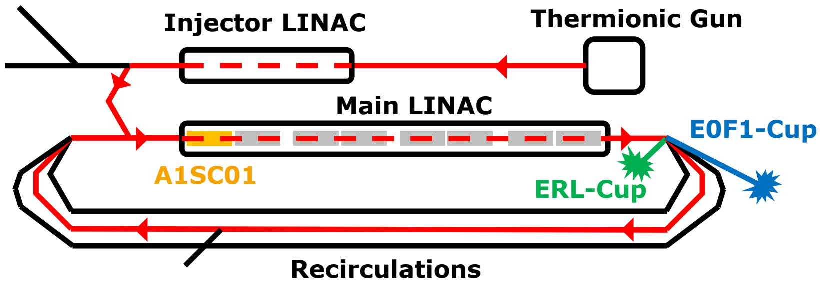
- "*RF recovery effect*"
  - Reduction of external RF power as compared to single-end operation

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

Once-Recirculating ERL Operation

TECHNISCHE UNIVERSITÄT DARMSTADT

- Energy gain injector: 2.5 MeV
- Energy gain LINAC: 20.0 MeV
- Current (I_{in}): 1.2 μA



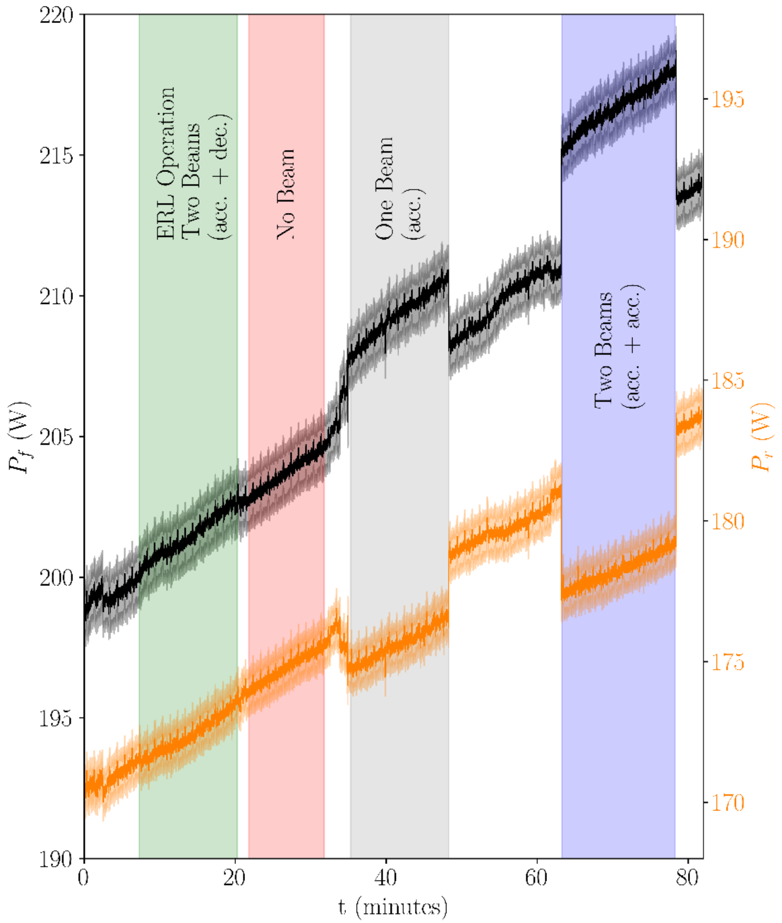
Data taken in four phases:

- Phase 1 (ERL Operation): one accelerated and one decelerated beam
- Phase 2 (no beam): RF operation of cavity without beam
- Phase 3 (1x acc.): one accelerated beam
- Phase 4 (2x acc.): two accelerated beams

- 1st German ERL, August 2017
- 1 of only 3 running SRF ERL worldwide (D, USA, J)

Raw Data

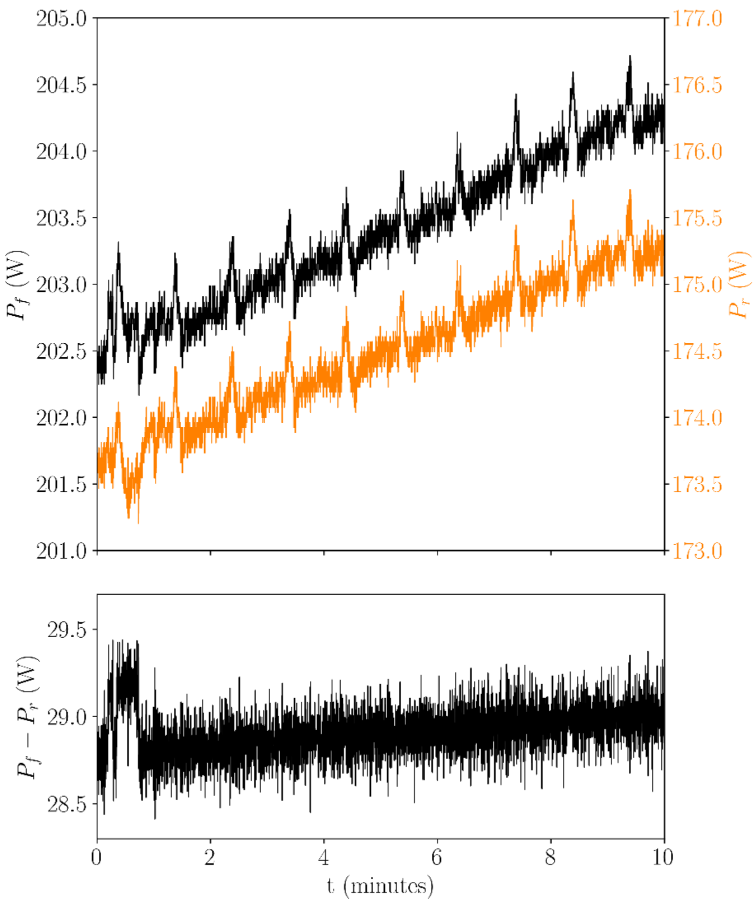
TECHNISCHE UNIVERSITÄT DARMSTADT



- Forward (P_f) and reverse (P_r) powers of first cavity
- Thermal drift over time during beginning of operation due to heating of input coupler
- Only changes due to beamloading relevant

*M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams **23**, 020101 (2020).*

Raw Data (during “no beam”)



- Linear regression
(time period without beam)

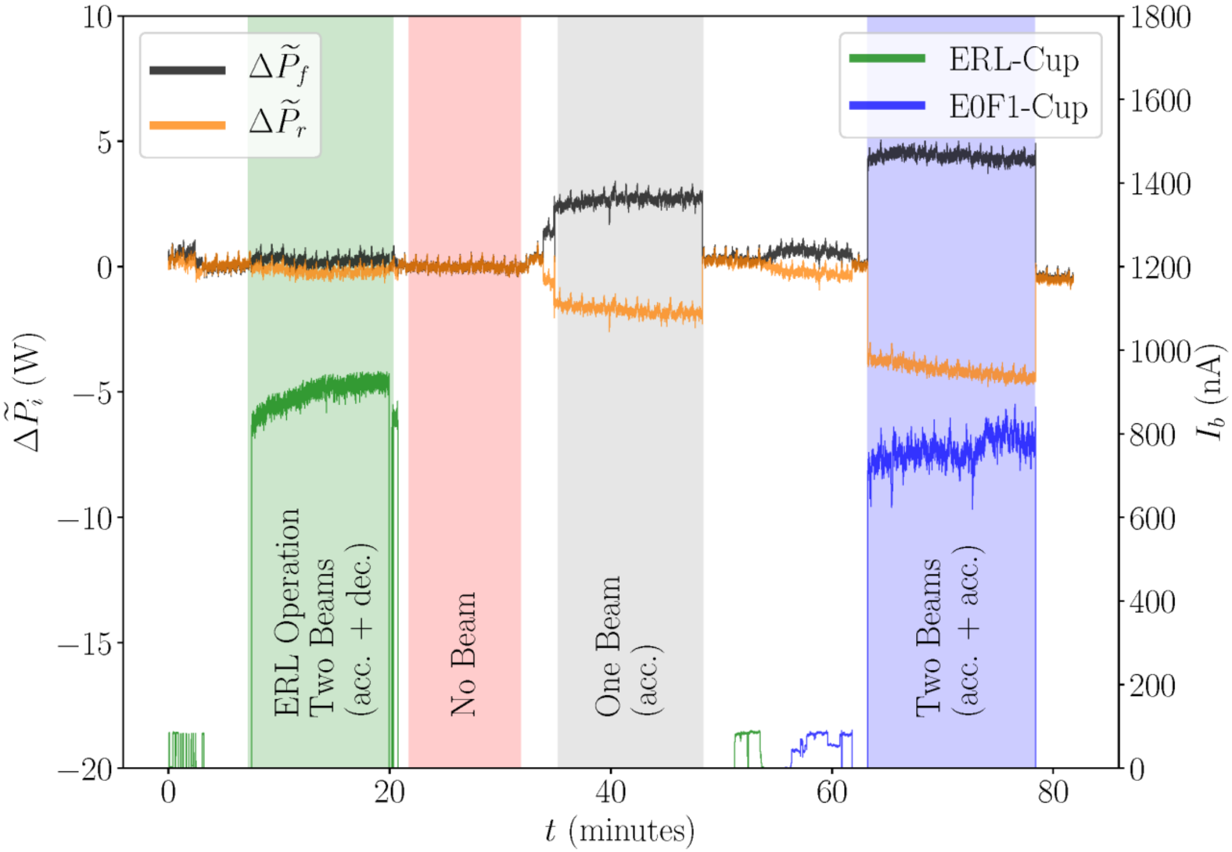
$$\tilde{P}_i = P_i - \left[\left(\frac{\Delta P}{\Delta t} \right)_i t + \tilde{P}_{0,i} \right]$$

- Slope of both powers nearly identical

- Correction of raw data by linear background → trivial warming-up drifts eliminated

M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams ***23****, 020101 (2020).*

Once-Recirculating ERL Operation



M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams ***23****, 020101 (2020).*

RF Measurements - Power

TECHNISCHE UNIVERSITÄT DARMSTADT

Operation	Mean Beam Power in W
No Beam	0.00 ± 0.01
One Beam (acc.)	4.51 ± 0.16
Two Beams (acc. + acc.)	8.59 ± 0.01
ERL (acc. + dec.)	0.45 ± 0.03

RF-recovery effect:

$$\varepsilon_{RF} = (90.1 \pm 0.3)\%$$

Value and uncertainty take correlations between fit parameters into account.

Beam-recovery efficiency:

$$\varepsilon_{b,max} = 88.9\%$$

M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams ***23****, 020101 (2020).*

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Value and uncertainty take correlations between fit parameters into account.

Beam-recovery efficiency:

$$\varepsilon_{b,max} = 88.9\%$$

8.59 about 10% less than 2 x 4.51

Incomplete transmission due to abstaining from beamline optimization

*M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams **23**, 020101 (2020).*

Analytical Model

- Beam as additional external load couples to electric field
- Reflection coefficient changes

$$r = \frac{\beta_{input} - (1 + \beta_{output} + \beta_{beam})}{\beta_{input} + (1 + \beta_{output} + \beta_{beam})} = \sqrt{\frac{P_r}{P_f}}$$

- LLRF system keeps electric field in cavity constant by changes in P_f

$$P_f = P_0 \frac{\left[\beta_{input} + (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}}$$

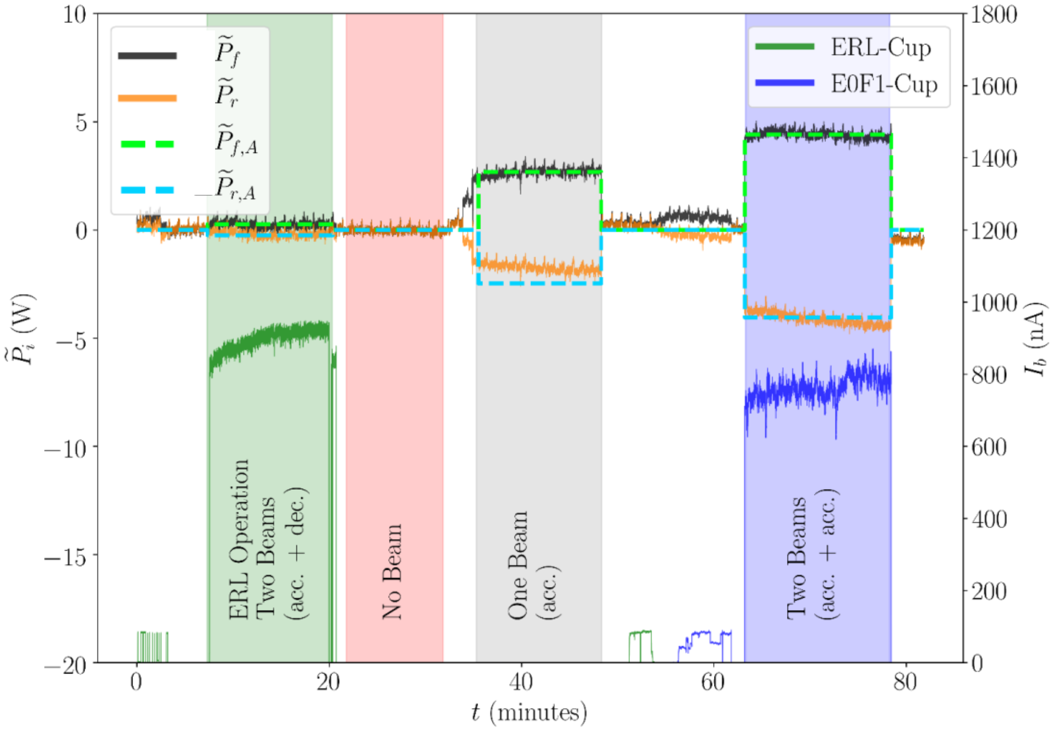
- P_r reacts accordingly (almost symmetrically)

$$P_r = P_0 \frac{\left[\beta_{input} - (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}}$$

*M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams **23**, 020101 (2020).*

Analytical Model

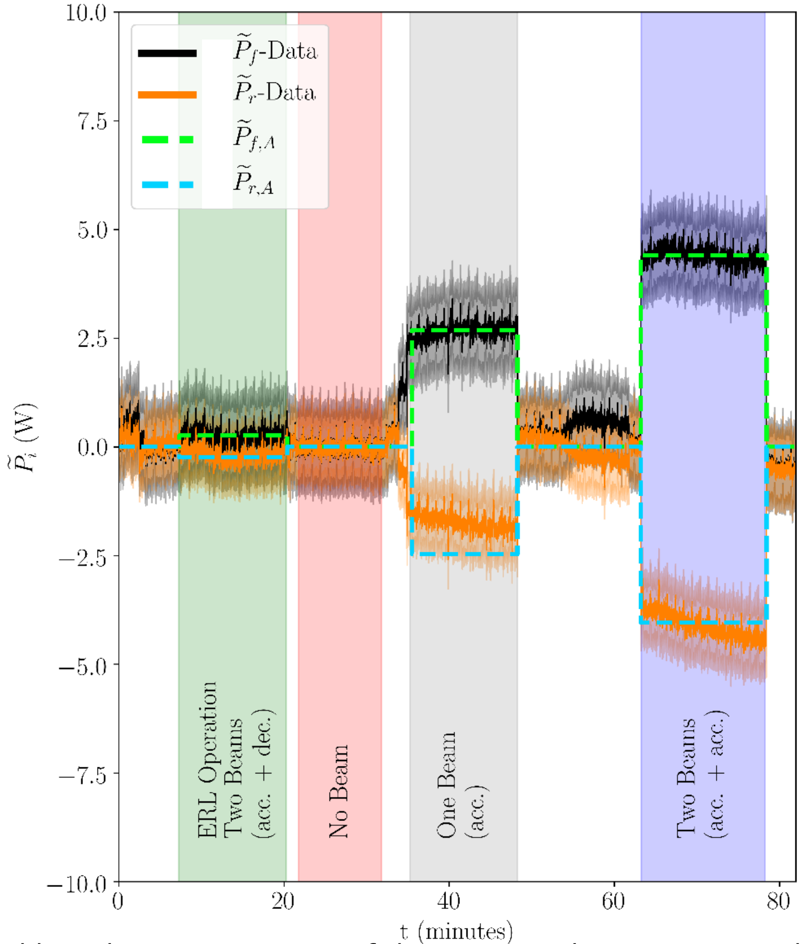
$$P_f = P_0 \frac{\left[\beta_{input} + (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}} \qquad P_r = P_0 \frac{\left[\beta_{in} - (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}}$$



- Curve-fitting to data in P_f
  - $\beta_{beam}=0$: to obtain β_{input}, β_{output} and P_0
  - $\beta_{beam}\neq 0$: to obtain $\beta_{beam,i}$ for each phase i
- Analytical prediction of P_r

M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams ***23****, 020101 (2020).*

Analytical Model
With Uncertainties in Data

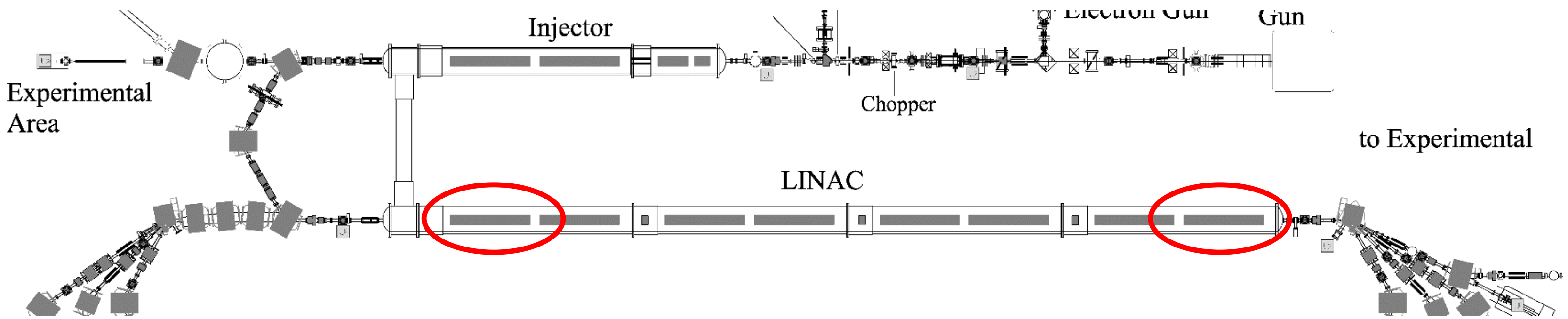


Analytical model describes data within uncertainties satisfactorily

*M. Arnold et al., First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac, Phys. Rev. Accel. Beams **23**, 020101 (2020).*

Phase Slippage

- Total change in setpoint of path length adjustment system: 186°
- Injection energy of 2.5 MeV → $\gamma \approx 4.9$
  - Time-of-flight effects
- Energy after one recirculation to re-enter main linac: 22.5 MeV → $\gamma \approx 44$
- Same effect for deceleration at last cavity
- Need to shift phase of re-entering beam → 6°



Overview Operation Modes / Commissioning

TECHNISCHE UNIVERSITÄT DARMSTADT

- Modification lattice 2015/2016
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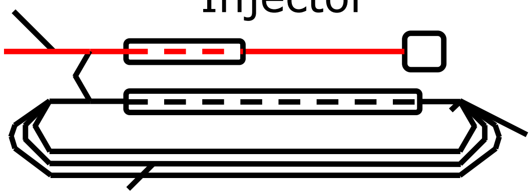
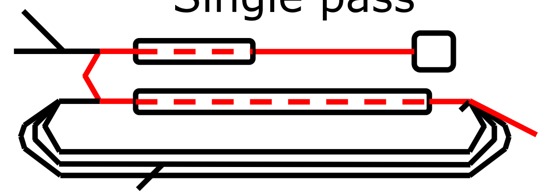
Injector



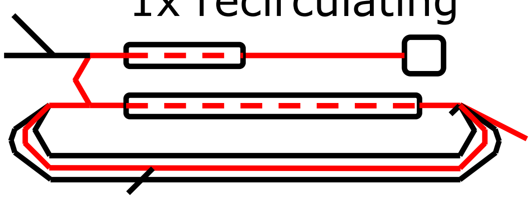
December 2016

Single pass



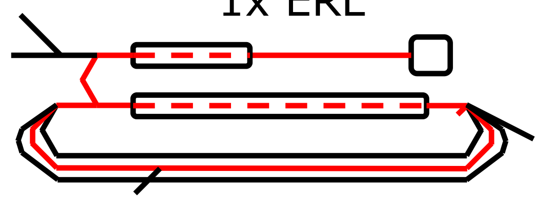
December 2016

1x recirculating



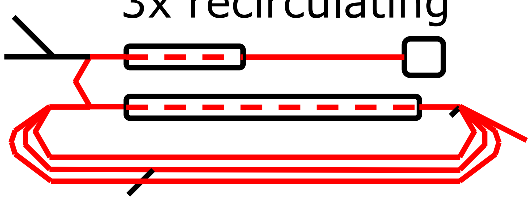
May 2017

1x ERL



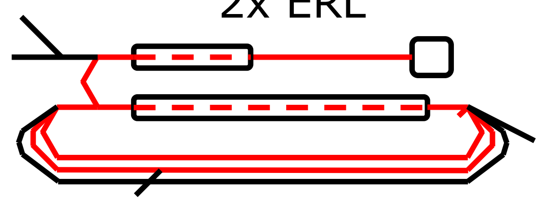
August 2017

3x recirculating



November 2018

2x ERL



Test phase

Trials Twice-Recirculating ERL

Example and Diagnostics

October
2018

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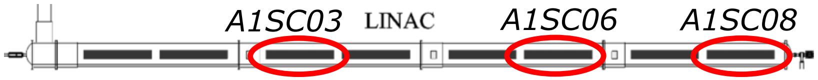
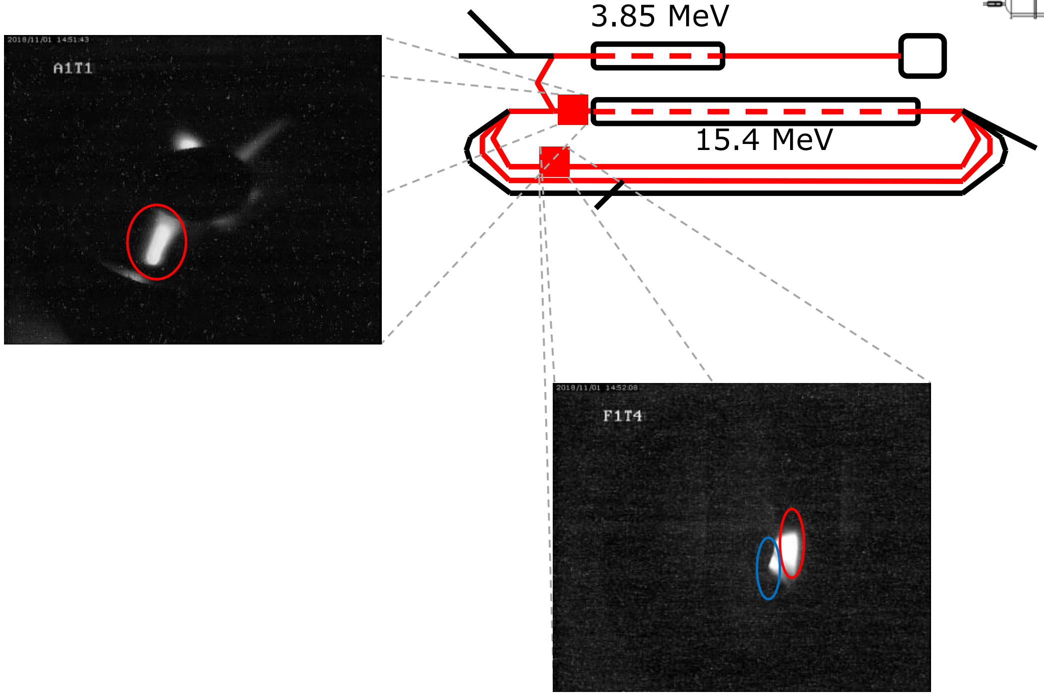
UNIVERSITÄT
DARMSTADT



A1SC03 (detuned), A1SC06 (electronics problem), A1SC08 (damage transfer line) not operable



In F to S

In F to ERL-dump
(once decelerated)

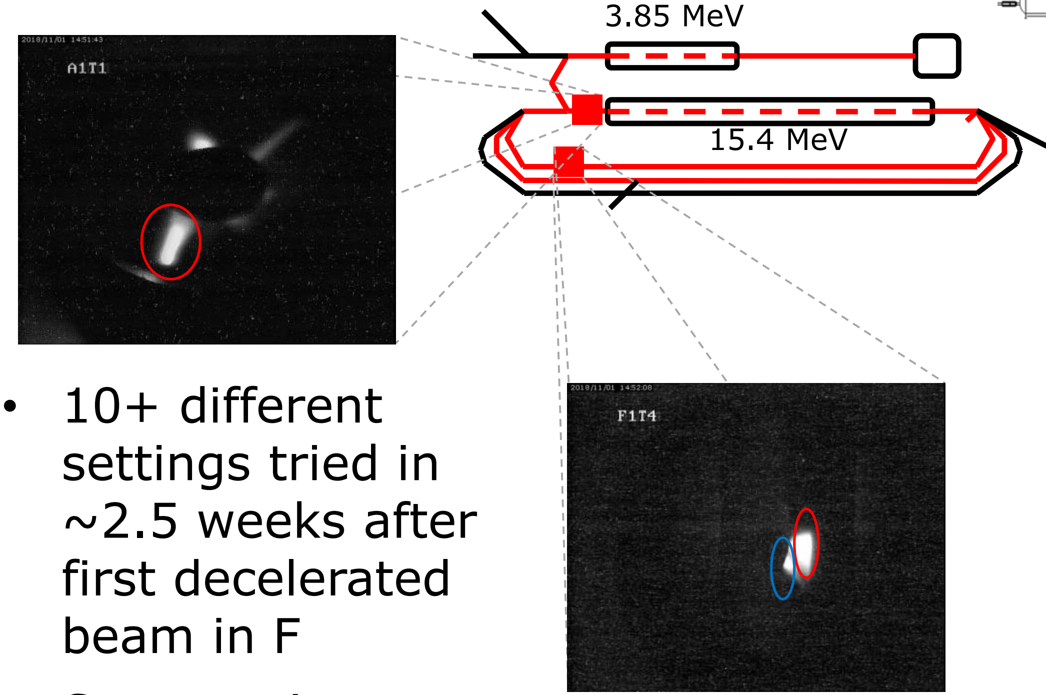
Trials Twice-Recirculating ERL

October 2018

TECHNISCHE UNIVERSITÄT DARMSTADT

Example and Diagnostics

A1SC03 (detuned), A1SC06 (electronics problem), A1SC08 (damage transfer line) not operable



In F to S

In F to ERL-dump (once decelerated)

- 10+ different settings tried in ~2.5 weeks after first decelerated beam in F
- Systematic investigations on settings, phase slippage,…

Diagnostics

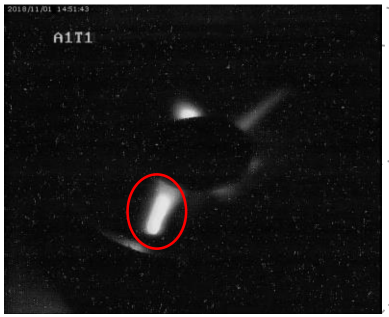
- Beam loading cavities (first decelerated beam in A1SC07 up to ~90% recovered)
- RF monitor system
- Beam loss monitor system
- BeO targets with hole on F1
- Check path-length adjustment system position (→ 180°)

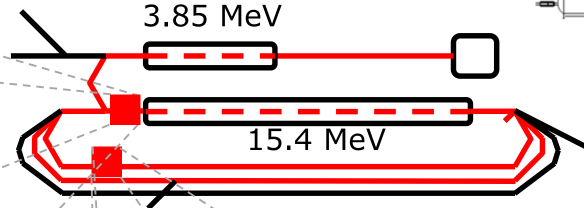
Trials Twice-Recirculating ERL

Example and Diagnostics

October 2018

A1SC03 (detuned), A1SC06 (electronics problem), A1SC08 (damage transfer line) not operable





- 10+ different settings tried in ~2.5 weeks after first decelerated beam in F
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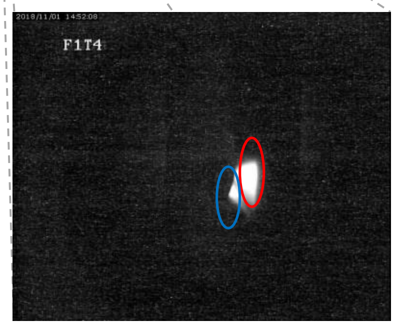


In F to S (blue)

In F to ERL-dump (once decelerated) (red)

2nd setting: March 2020

Diagnostics

- Beam loading cavities (first decelerated beam in A1SC07 up to ~90% recovered)
- RF monitor system
- Beam loss monitor system
- BeO targets with hole on F1
- Check path-length adjustment system position (→ 180°)

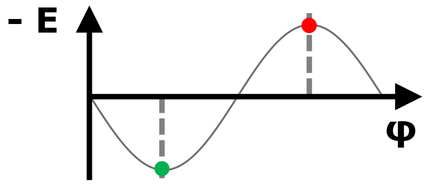
Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Introduction to Energy Recovery Linacs (ERLs)
- Examples
- Commissioning of ERL Mode @ S-DALINAC
- Summary and Outlook
- Research Training Group on ERLs

Take Home Message

Principle,
history,
reasons,
applications



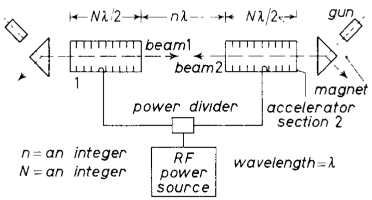
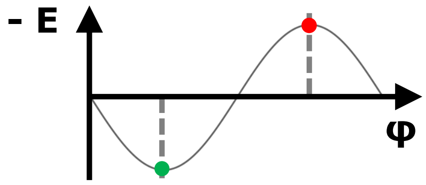


Fig. 2.

Take Home Message

Principle, history, reasons, applications



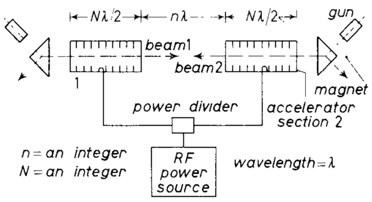
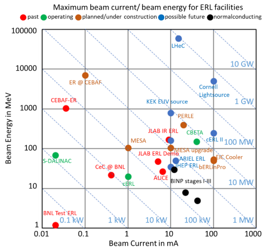


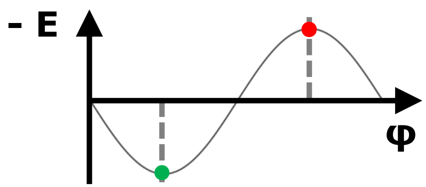
Fig. 2.

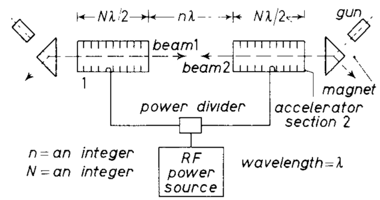
World-wide



Take Home Message

Principle, history, reasons, applications





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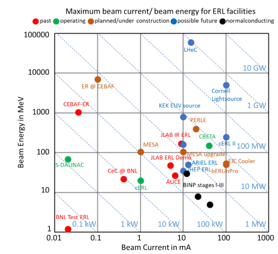
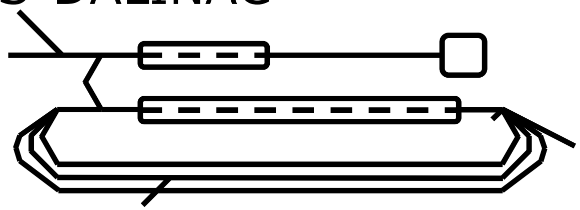
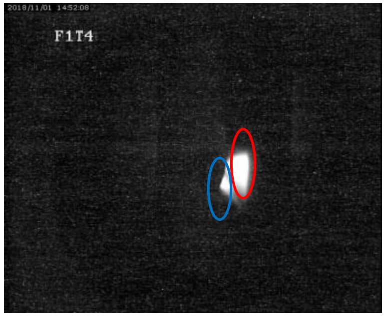
World-wide



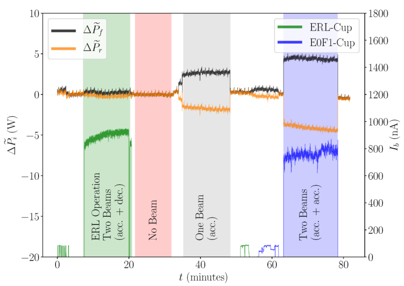
S-DALINAC



Test phase twice-recirculating ERL

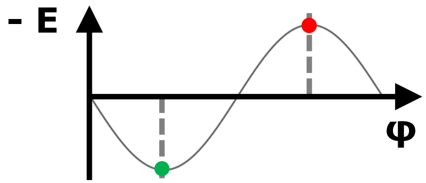


Measurements ERL mode, analytical model



Take Home Message

Principle, history, reasons, applications



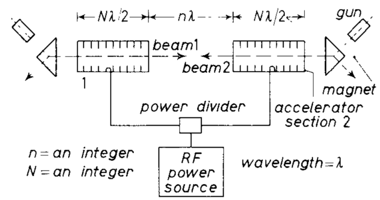
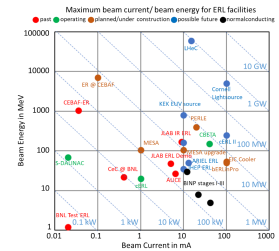
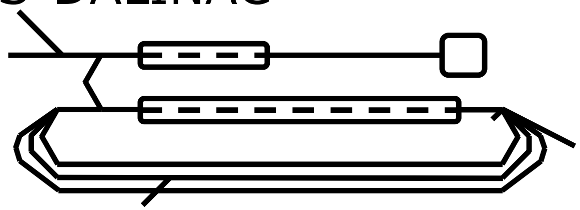


Fig. 2.

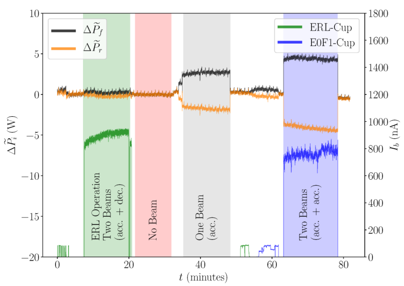
World-wide



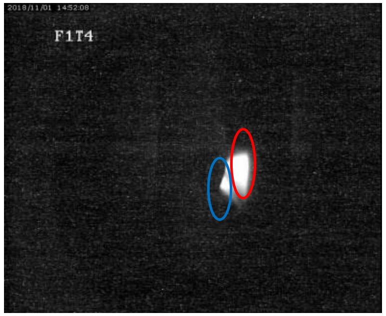
S-DALINAC



Measurements ERL mode, analytical model

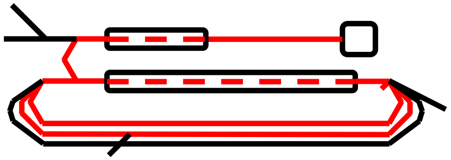


Test phase twice-recirculating ERL



Outlook:

Work on twice-recirculating ERL operation (simulations, diagnostics, tests)



Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Introduction to Energy Recovery Linacs (ERLs)
- Examples
- Commissioning of ERL Mode @ S-DALINAC
- Summary and Outlook
- Research Training Group on ERLs

Research Training Group:
Accelerator Science and Technology for Energy-Recovery Linacs „AccelencE"

TECHNISCHE UNIVERSITÄT DARMSTADT

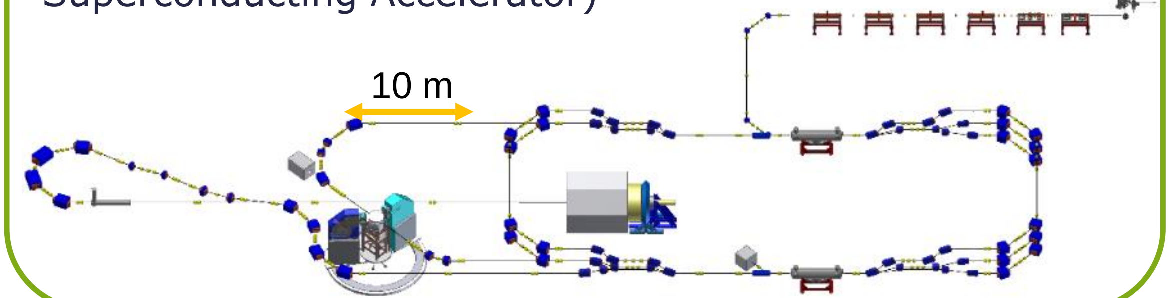
- Sole coordinated DFG support for research training in accelerator science in Germany
- Joint programme by Darmstadt and Mainz
  - ERL in operation
  - ERL under construction

TECHNISCHE UNIVERSITÄT DARMSTADT

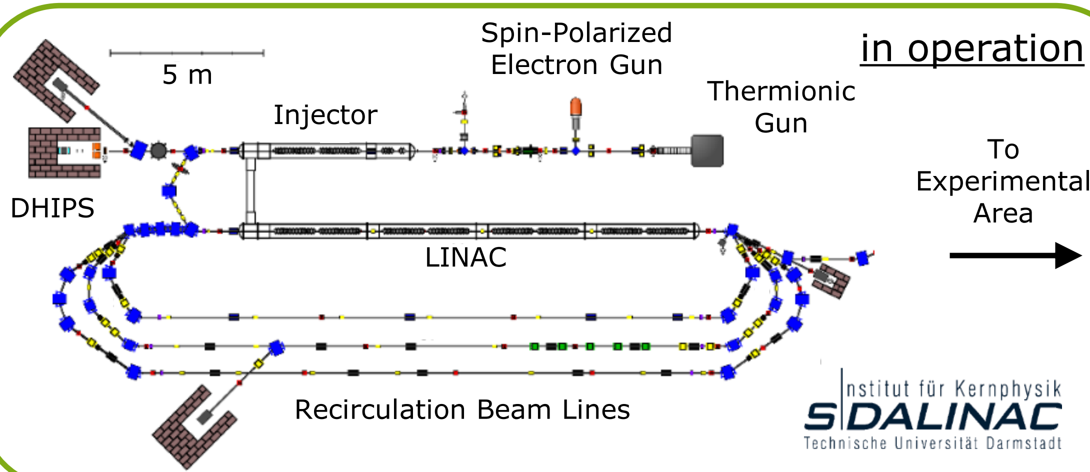
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MESA
(Mainz Energy-Recovering Superconducting Accelerator)

under construction



in operation



ACCELENCE

Research Training Group:

Accelerator Science and Technology for Energy-Recovery Linacs „AccelencE“

Project Areas GRK 2128

- A Sources/Photocathodes
- B Injector Linacs & SRF
- C Control-Systems
- D Beam Dynamics
- E Beam Target Interaction

- Supervising and qualification concept
- Free positions, please apply
- More information after the talk or see https://www.ikp.tu-darmstadt.de/accelence_main/startseite_accelence.en.jsp

TU Darmstadt and JGU Mainz are announcing

12 open Positions for Junior Researchers in Accelerator Science and Instrumentation starting in 2019 or early 2020

Full-time and part-time (75%) positions for doctoral researchers in physics and engineering

within the Research Training Group (GRK 2128):

Accelerator Science and Technology for **Energy Recovery Linacs** funded by the German Research Council, DFG.

The goal of AccelencE is to contribute to the qualification and training of junior researchers in the field of Energy Recovery Linac science and technology.

Research topics comprise:
- Electron Sources/Photocathodes
- Injector Linacs
- Diagnostics and Control Systems
- Beam Dynamics
- Beam Target Interaction

AccelencE offers a thriving research environment for graduates in physics and engineering who aim at specializing in particle accelerator science and technology for their doctoral degree.

If you are interested you can learn more about AccelencE, the research topics, involved scientists, the training programme and open positions on our web page https://www.ikp.tu-darmstadt.de/accelence_main/startseite_accelence.en.jsp.
Contact us by July 15th, 2019, or later!

Interested Junior Researchers are invited to submit electronically their curriculum vitae, copies of transcripts and certificates, a motivation letter, two letters of recommendation and, optionally, a list of publications to accelence@ikp.tu-darmstadt.de
The first round of applications are expected by July 15th, 2019. Further applications will be considered until all positions are filled and throughout the duration of tenure of the GRK 2128 when open positions are available.

Funded by DFG

Thank you for your attention!

TECHNISCHE UNIVERSITÄT DARMSTADT

Picture: Jan-Christoph Hartung