# ERL Operation of S-DALINAC

TECHNISCHE UNIVERSITÄT DARMSTADT

M. Arnold, T. Bahlo, M. Dutine, R. Grewe, J. Hanten, L. Jürgensen, J. Pforr, N. Pietralla, F. Schließmann, M. Steinhorst, S. Weih

*Picture: Jan-Christoph Hartung*

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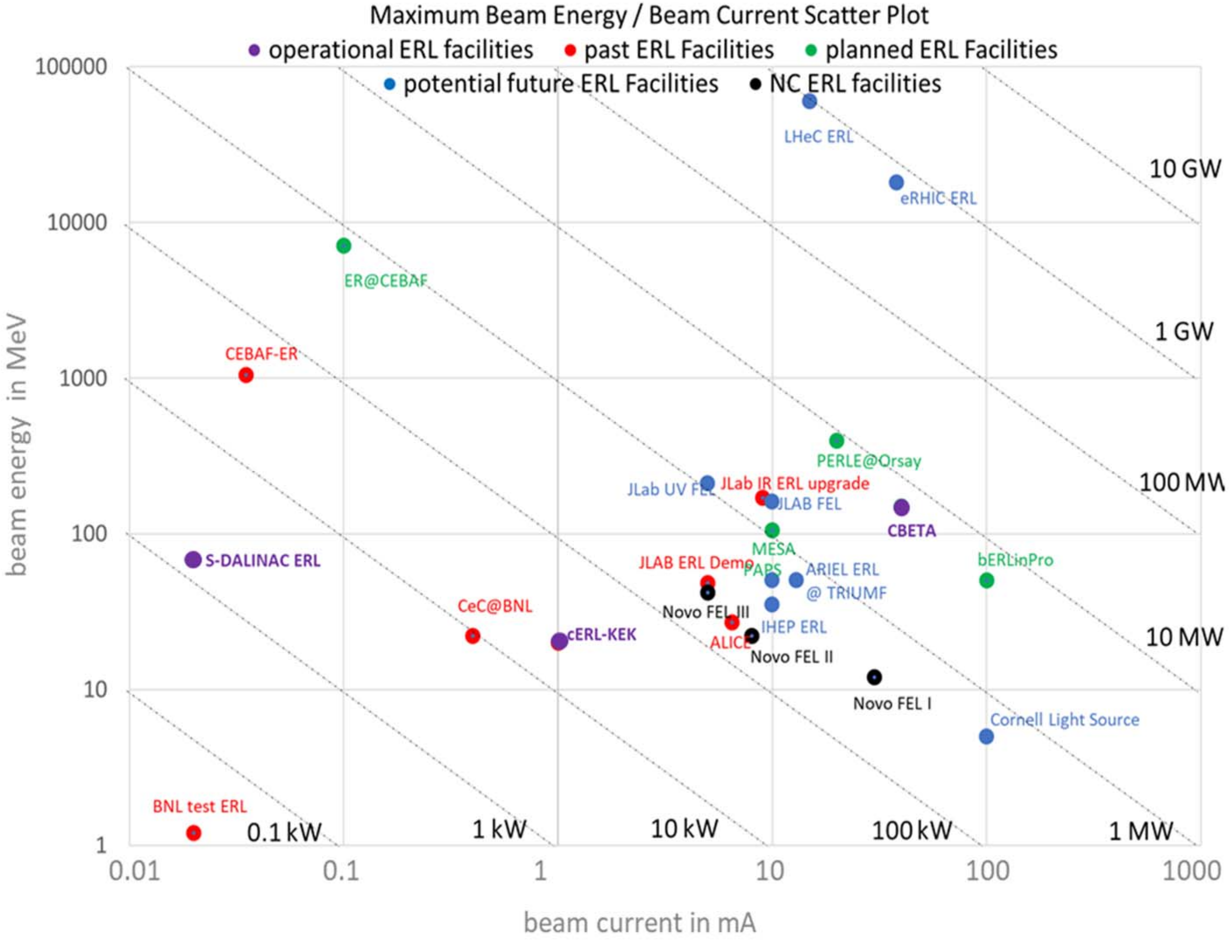
Work supported by DFG through GRK 2128

# ERL Landscape




F. Hug, ARIES Milestone Report MS28 – Parameter Database for Various ERL & Linac Facilities, (2019).


N. Pietralla,
Nuclear Physics News
**28 (2)**, 4 (2018).

# Outline

- S-DALINAC
- Third recirculation beamline
- Once-recirculating ERL operation
- Analytical modeling of observations
- Outlook and Summary

# S-DALINAC

**S**uperconducting-**DA**rmstadt-**LIN**ear-**AC**celerator

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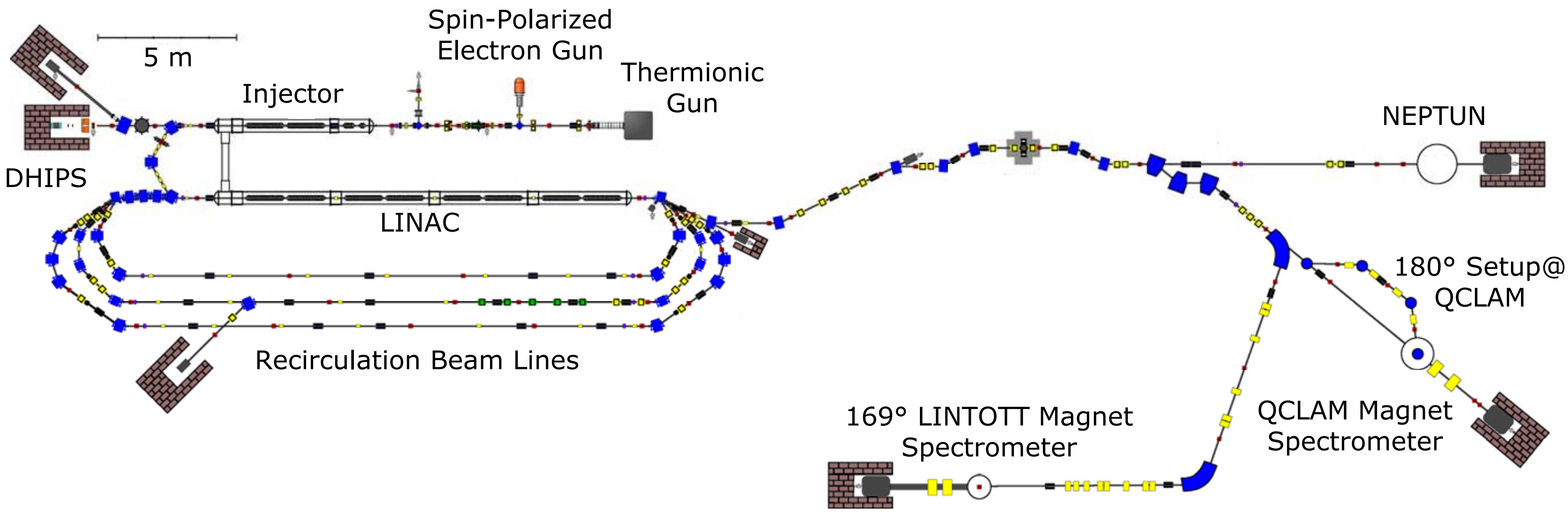


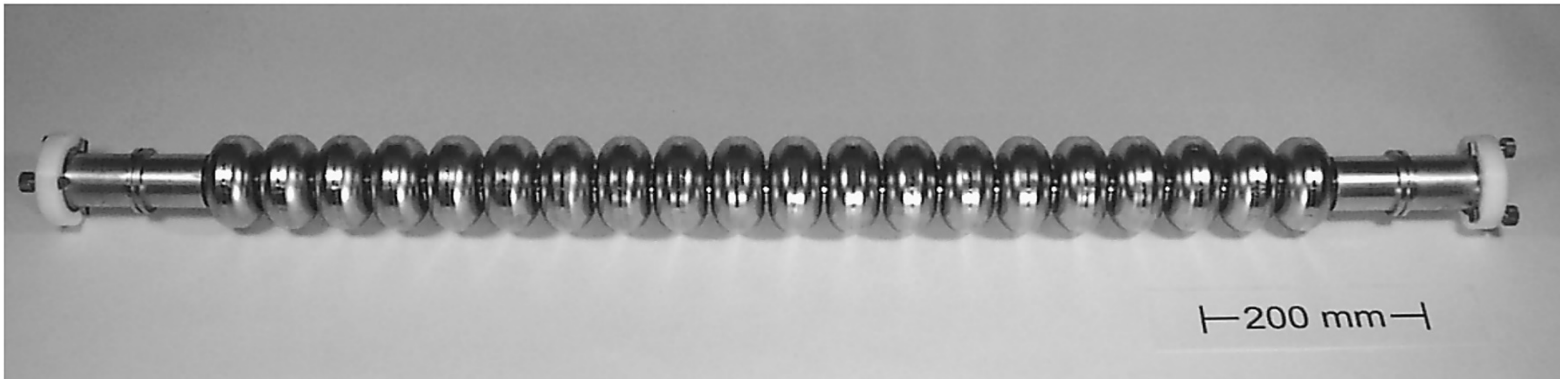

<u>Thrice recirculating operation</u>

Energy gain injector: 7.6 MeV (10 MeV)

Energy gain LINAC: 30.4 MeV

Beam current: 20 μA (@130 MeV)

# SRF Cavities




Material: Niobium (RRR=280)
T: 2 K
f: 2.997 GHz
Mode: $TM_{010}$, $\pi$

| | Design values | |
|---|---|---|
| Number of cells: | 20 | 5 |
| Length: | 1 m | 0.25 m |
| $\beta$: | 1 | 1 |
| $Q_0$: | $3 \cdot 10^9$ | $3 \cdot 10^9$ |
| $E_{acc}$: | 5 MV/m | 5 MV/m |
| Power loss @ $E_{acc}$: | 4.2 W | 1.05 W |

# Motivation for additional recirculation

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- lower Q and higher dissipated power of the sc cavities

  ⇨ Final design energy of 130 MeV (cw) was not reached
- Stable and reliable beam was limited to 85 MeV (cw, 2 recirculations)
- Nuclear cross sections increase with E:

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = 4(Ze^2)^2 \frac{E^2}{(q\hbar c)^4}\left(1 - \frac{(q\hbar c)^2}{4E^2}\right)$$

for given q = const.

⇨ Higher energies lead to higher reaction rates and shorter beam times per nuclear-science experiment

⇨ Goal: 130 MeV final energy (cw): Recirculate once more!



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# New Separation Dipole Magnet

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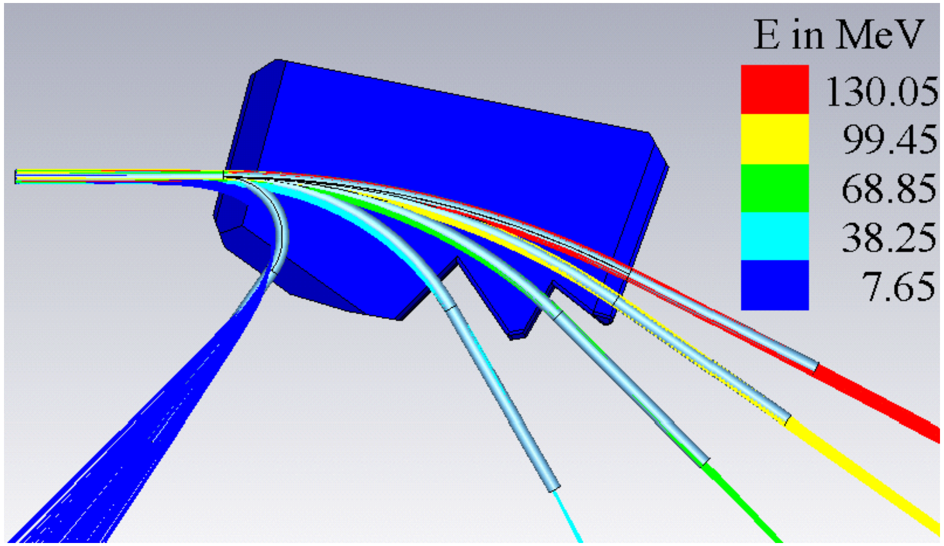
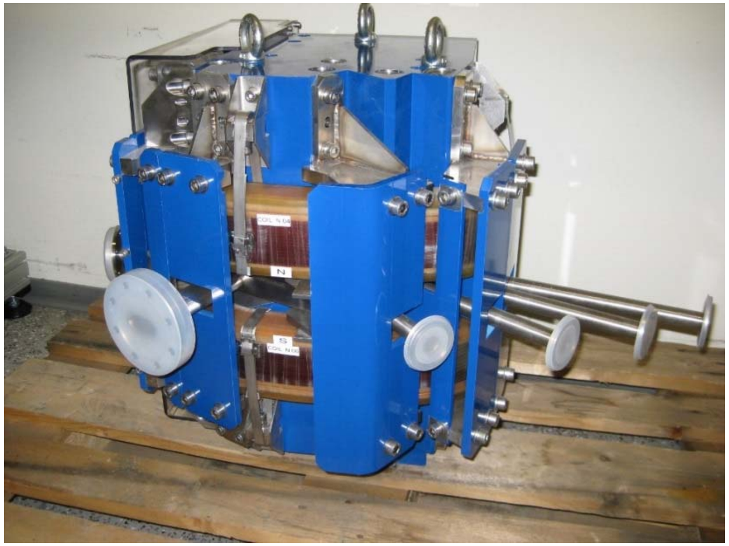
- Particle tracking of all beam energies (CST Particle Studio)
- Conservative starting conditions
  - Max. beam diameter: 10 mm
  - Max. energy spread: $1\cdot10^{-3}$
  - Max. angular spread: 0.1°

M.Arnold
Dissertation
(TU Darmstadt, 2016)



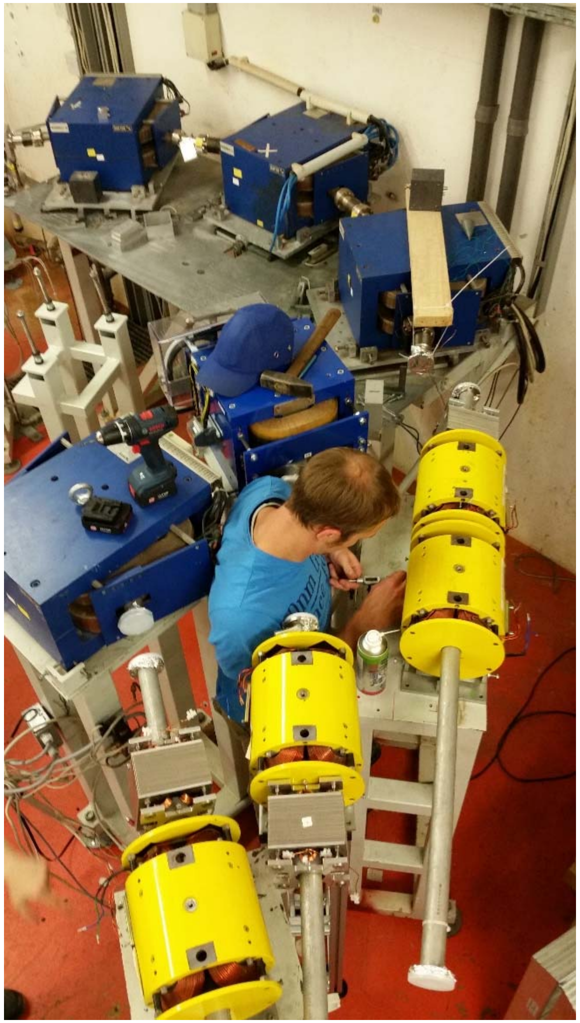
1 : 5 : 9 : 13 : 17

# Director‘s hair turning grey…

# Director‘s hair turning grey…

- 500 cables
- 15 km cables
- 500 m copper-pipes for water
- 250 m flexible tubes
- etc.

# Installation and Adjustment



# Positioning of Beamline Elements to ~200 $\mu$m

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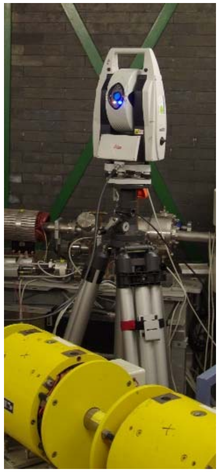
| Position in mm (1D-Residues) | | | |
|---|---|---|---|
| Type | Horizontal (x) | Vertical (y) | Beam Axis (z) |
| Dipole | 0.27 ± 0.12 | 0.20 ± 0.14 | 0.17 ± 0.13 |
| Quadrupole Typ 1 | 0.27 ± 0.11 | 0.19 ± 0.12 | 0.23 ± 0.18 |
| Quadrupole Typ 2 | 0.32 ± 0.16 | 0.21 ± 0.17 | 0.28 ± 0.23 |
| Sextupole | 0.33 ± 0.18 | 0.29 ± 0.22 | (0.15 ± 0.11)[1] |

[1] Precision of measurement-method, no target position used and thus no residues to it

| Type | Tilt in ° around x and z |
|---|---|
| Dipole | 0.020 ± 0.019 |
| Quadrupole Typ 1 und 2 | 0.057 ± 0.051 |
| Sextupole | (0.104 ± 0.084)[2] |

[2] due to adjustment possibilities



Long term observation:

Accelerator hall is „shrinking" by ~ 1mm/3 years → concrete still drying

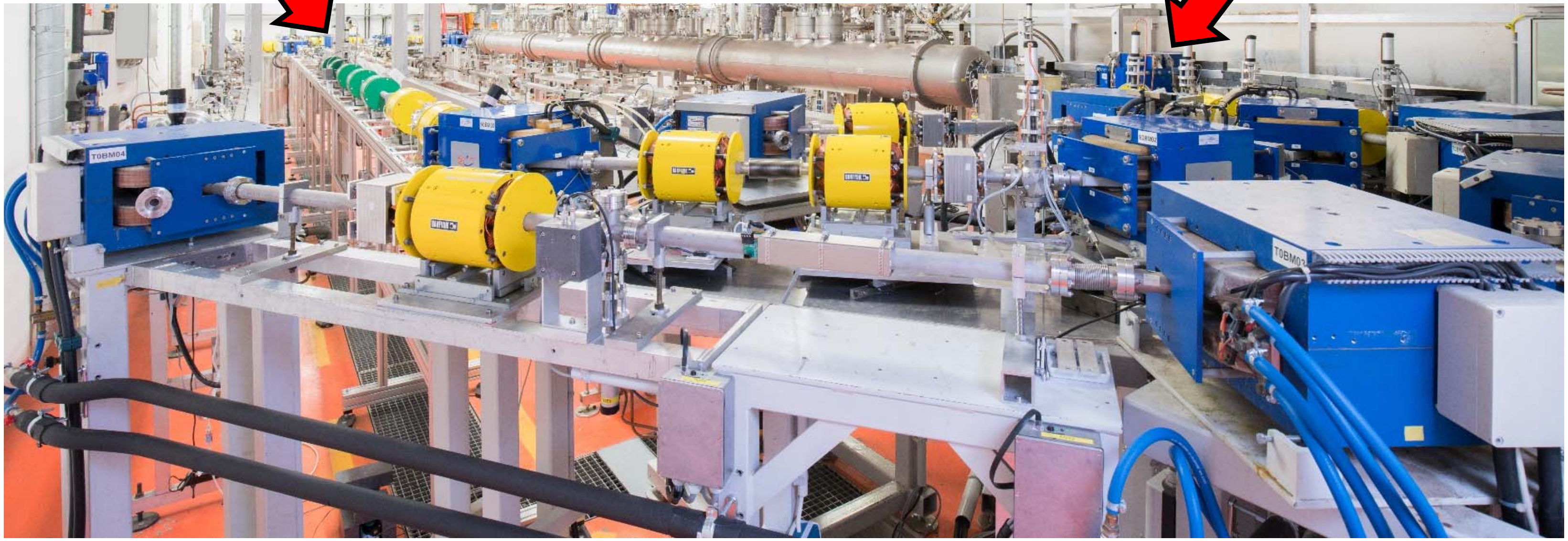
C. Eschelbach, M. Lösler, P. Winkemann, M. Arnold, N. Pietralla, AVN **123(3)**,61-69 (2017).

# Completion and fit for ERL

New beam line
including 360° path length
adjustment system

New separation
dipole

330 mm



# Overview Operation Modes / Commissioning

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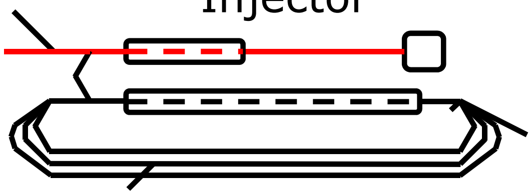
DARMSTADT

- Modification lattice 2015/2016
- Refurbishment cryoplant 2018

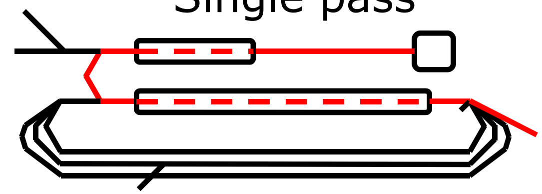
- Commissioning of modes following beam time schedule

Injector



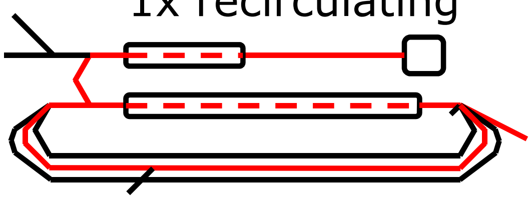
December 2016

Single pass



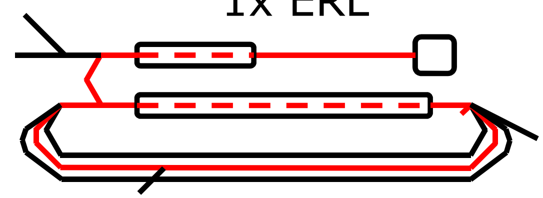
December 2016

1x recirculating



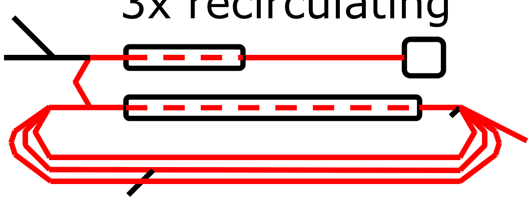
May 2017

1x ERL



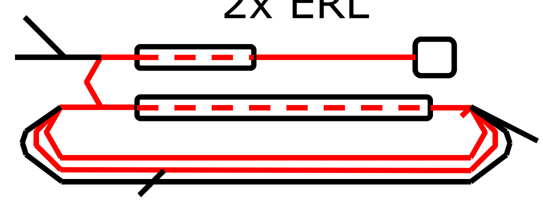
August 2017

3x recirculating



November 2018

2x ERL



in preparation

# Outline

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- S-DALINAC
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- Once-recirculating ERL operation
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# Efficiency of an ERL

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- "*Beam-recovery efficiency*" $\mathcal{E}_b = \frac{\int dP_{\mathrm{decel.}}}{P_{b,\max}}$ $P_{b,\max} = E_{\max} I_{\max}$

$$\frac{(E_{\max} - E_{\mathrm{dump}}) I_{\mathrm{dump}}}{P_{b,\max}} < \mathcal{E}_b < 1 - \frac{E_{\mathrm{dump}}}{E_{\max}} = \mathcal{E}_{b,\max}$$

  - Limited by design of accelerator

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

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

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- Commissioning of modes following beam time schedule

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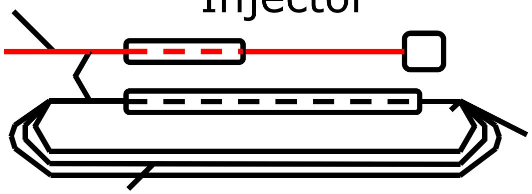
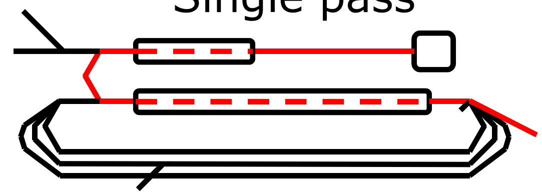


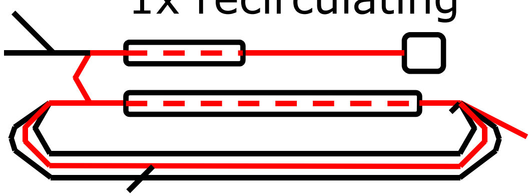
December 2016

Single pass



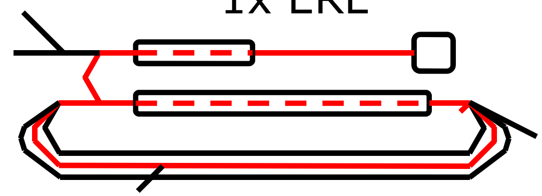
December 2016

1x recirculating



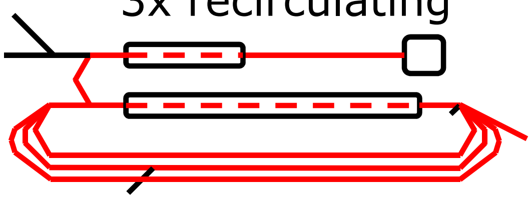
May 2017

1x ERL



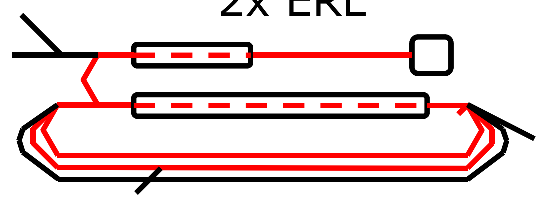
August 2017

3x recirculating



November 2018

2x ERL



Test phase

# Once-Recirculating ERL Operation

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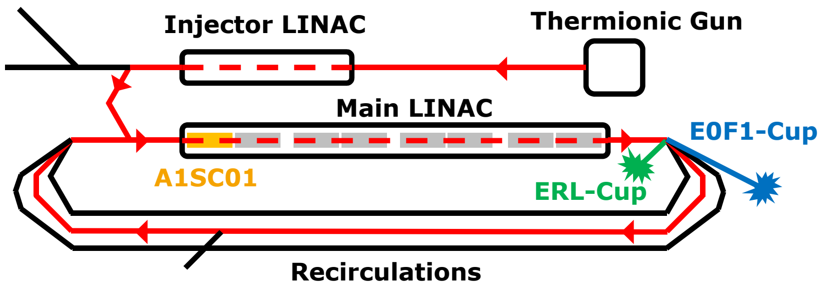
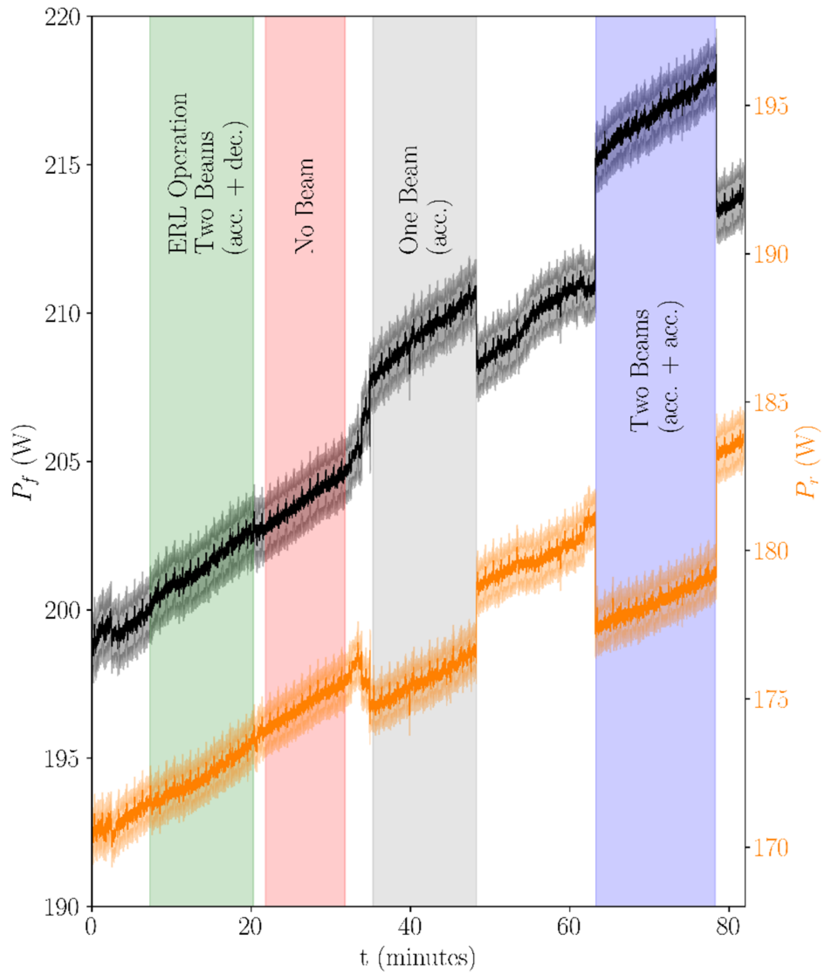
- Energy gain injector: 2.5 MeV
- Energy gain LINAC: 20.0 MeV
- Current ($I_{in}$): 1.2 μA




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

# Raw Data




- 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 S-DALINAC as an Energy Recovery Linac, Phys. Rev. Accel. Beams, submitted (Sept. 2019).*

# Raw Data (during "no beam")

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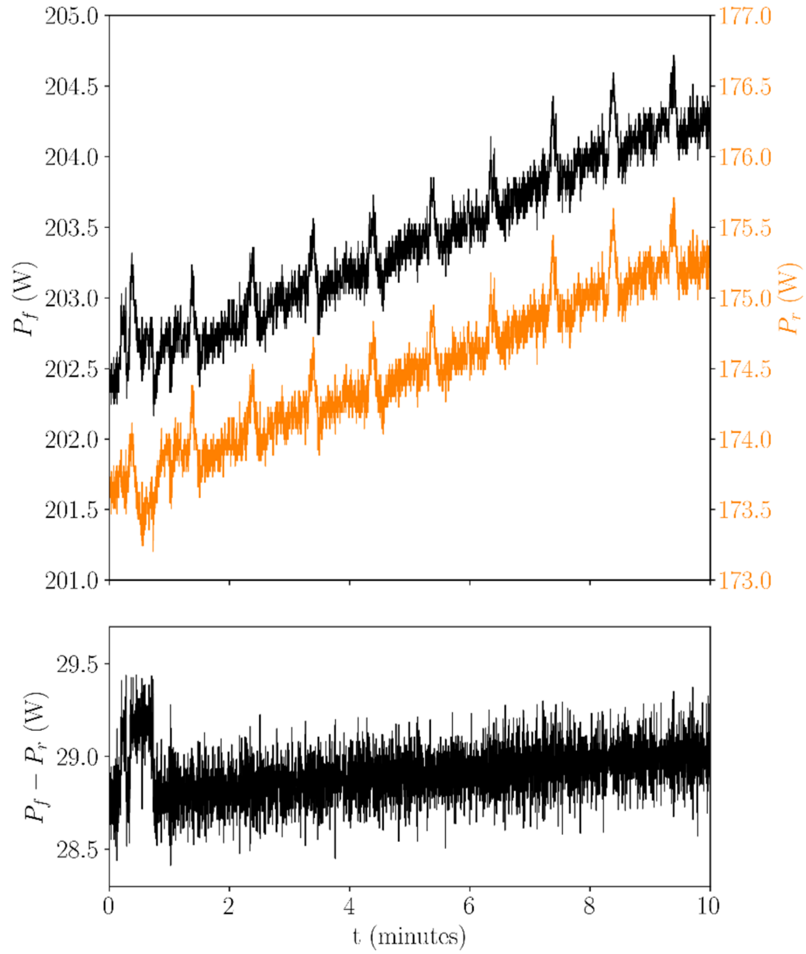


- Linear regression (time period without beam)

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

- Slope of both powers nearly identical

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

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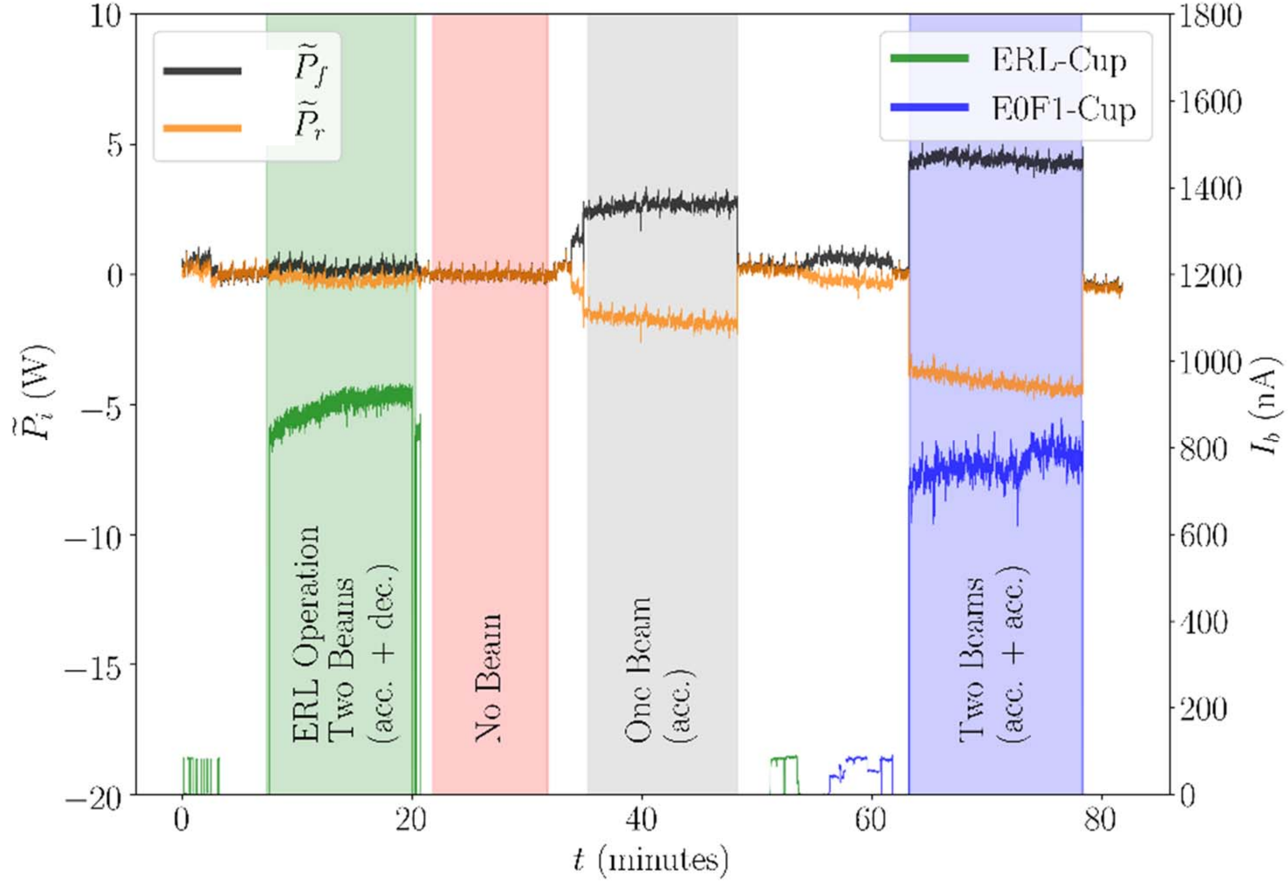
# Once-Recirculating ERL Operation




*K. Sonnabend, Physik Journal 10, 7 (2017).*

*M. Arnold et al., First Operation of the S-DALINAC as an Energy Recovery Linac, Phys. Rev. Accel. Beams, submitted (Sept. 2019).*

# RF Measurements - Power

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

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 S-DALINAC as an Energy Recovery Linac, Phys. Rev. Accel. Beams, submitted (Sept. 2019).*

# 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 $P_f$

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

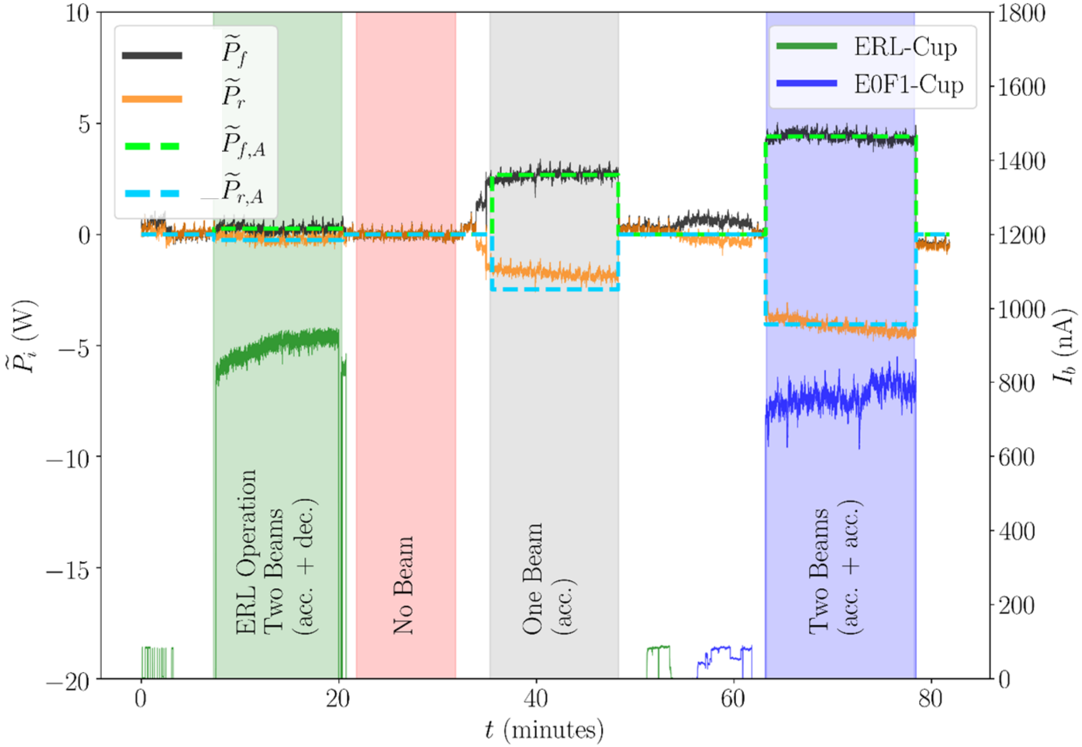
- $P_r$ reacts accordingly (almost symmetrically)

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

*M. Arnold et al., First Operation of the S-DALINAC as an Energy Recovery Linac, Phys. Rev. Accel. Beams, submitted (Sept. 2019).*

# Analytical Model

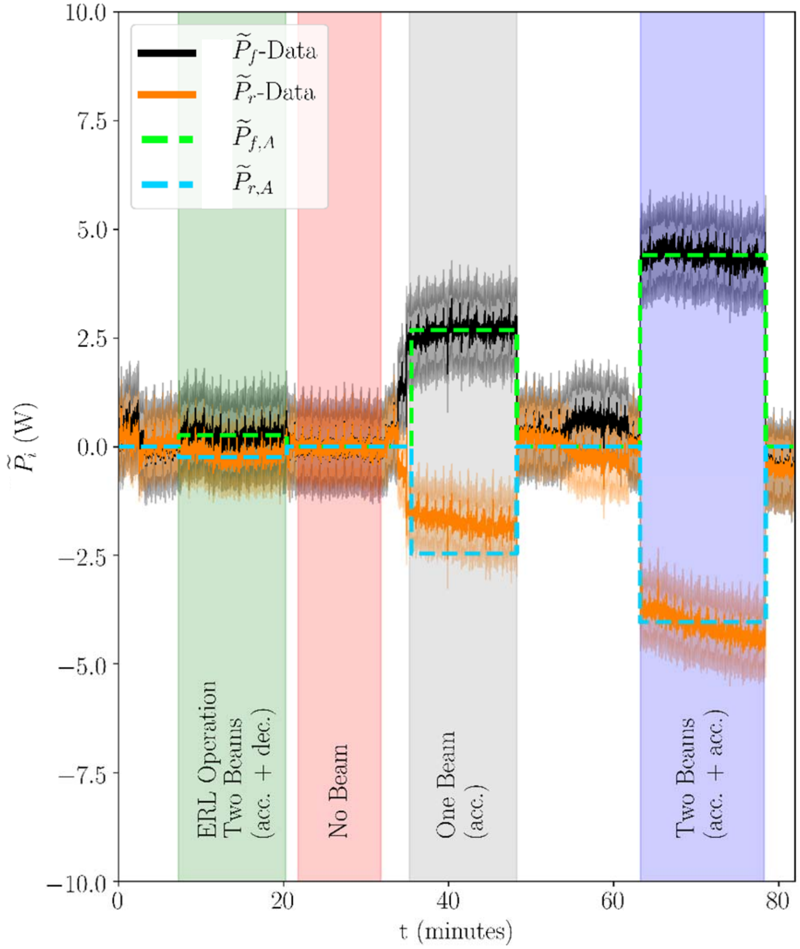
$$P_f = P_0 \frac{\left[\beta_{input} + (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}} \qquad P_r = P_0 \frac{\left[\beta_{in} - (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}}$$




- Curve-fitting to data in $P_f$
  - $\beta_{beam}=0$: to obtain $\beta_{input}$, $\beta_{output}$ 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 S-DALINAC as an Energy Recovery Linac, Phys. Rev. Accel. Beams, submitted (Sept. 2019).*

# Analytical Model
With Uncertainties in Data




Analytical model describes data within uncertainties satisfactorily

*M. Arnold et al., First Operation of the S-DALINAC as an Energy Recovery Linac, Phys. Rev. Accel. Beams, submitted (Sept. 2019).*

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RF-recovery effect:

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

Value and uncertainty take correlations between fit parameters into account.

Beam-recovery efficiency:

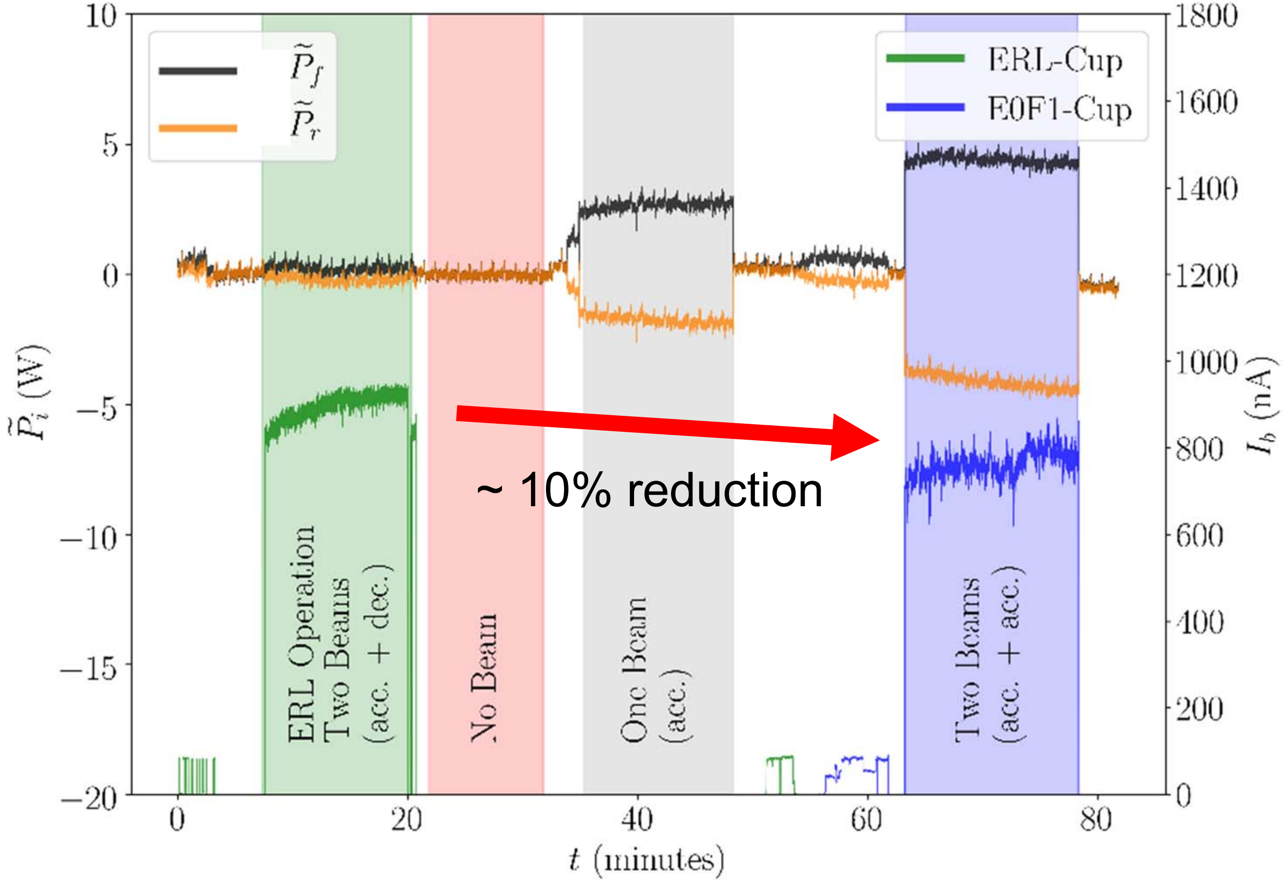
$$\varepsilon_{b,max} = 88.9\%$$

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 S-DALINAC as an Energy Recovery Linac, Phys. Rev. Accel. Beams, submitted (Sept. 2019).*

# Once-Recirculating ERL Operation

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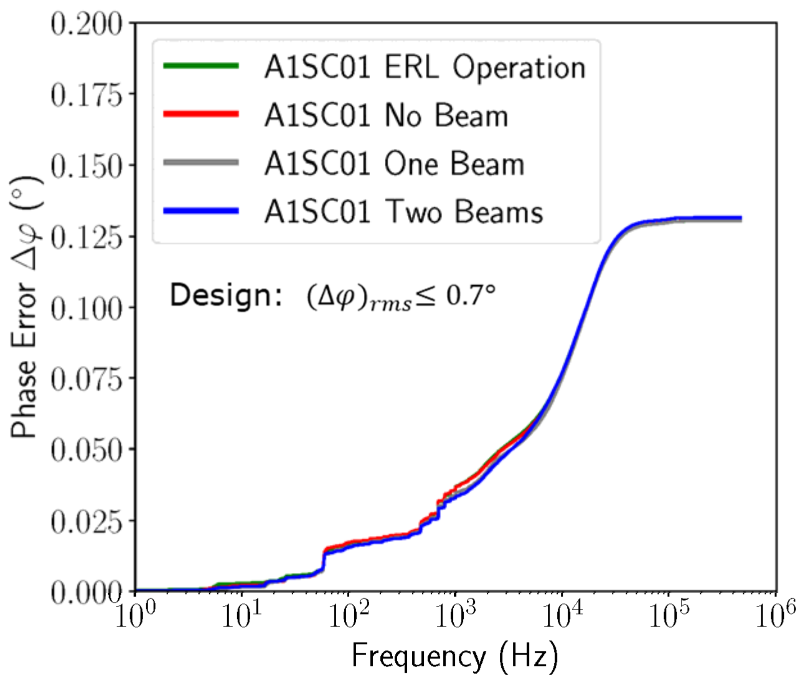
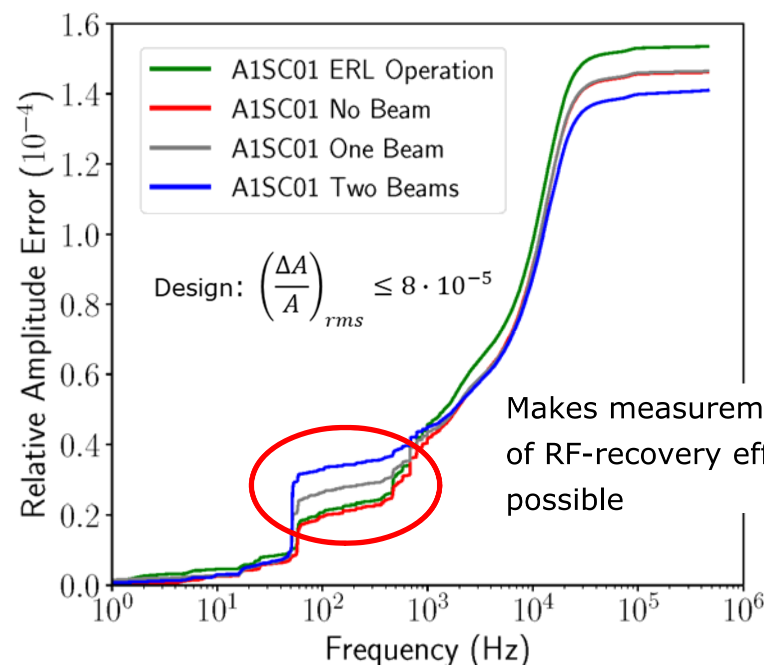
# RF Measurements - Stability

- Amplitude errors sensitive to beam loading

  → “local“ measurement of RF-recovery effect per cavity




Makes measurement of RF-recovery effect possible

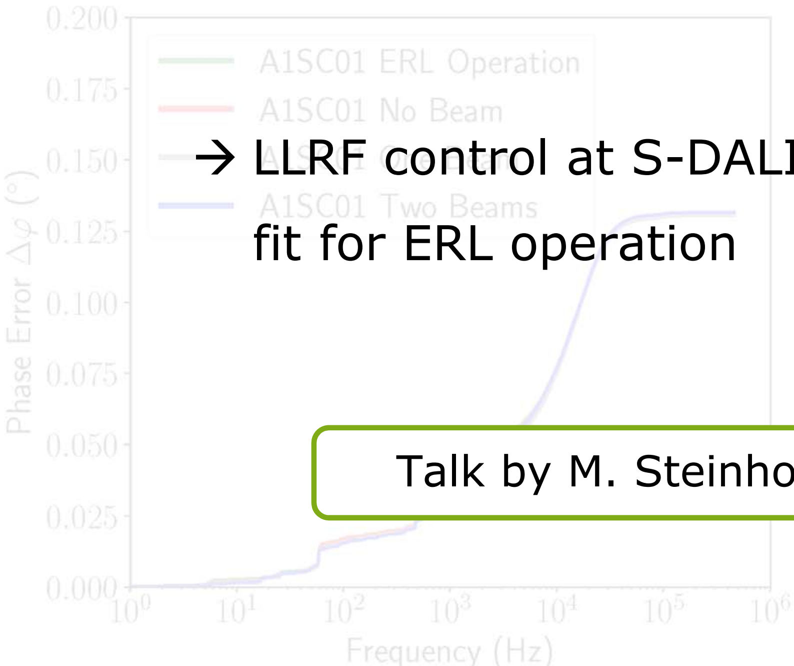
*Results from Manuel Steinhorst*

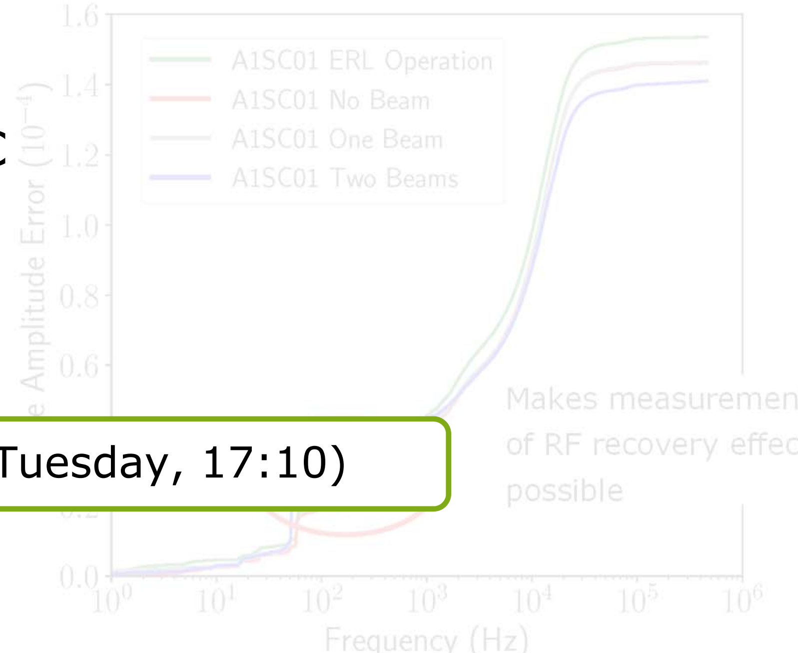
# RF Measurements - Stability

- Amplitude errors sensitive to beam loading

  → “local“ measurement of RF-recovery effect per cavity

→ LLRF control at S-DALINAC
fit for ERL operation




Talk by M. Steinhorst (Tuesday, 17:10)

Makes measurement of RF recovery effect possible

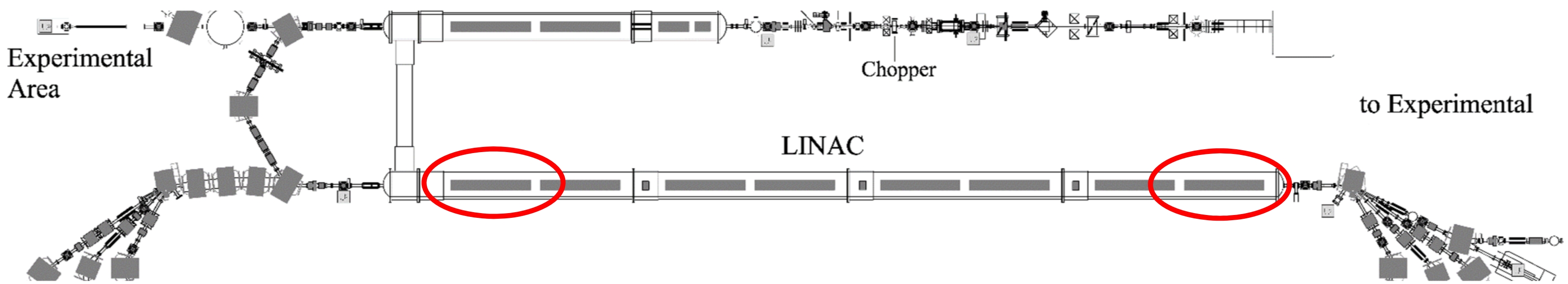
*Results from Manuel Steinhorst*

# 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°
- Constant-gradiant approximation:

$$\beta(z) = 1 - \frac{1}{2}\left(\frac{mc^2}{\Delta E}\right)^2 \frac{1}{\left(\frac{E_{\text{in}}}{\Delta E} + \frac{z}{L}\right)^2}$$

- Expected Half Drift-Time Difference $\delta\Delta T$ = 16°



# Summary and Outlook

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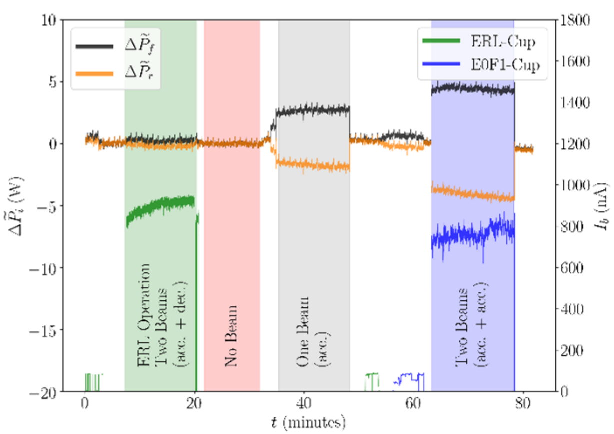
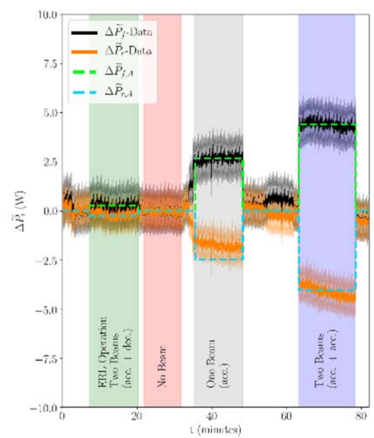
## Once-recirculating ERL operation




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

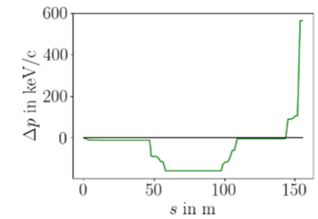
Analytical model

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

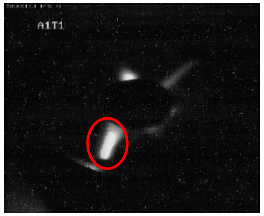
- LLRF system suitable for ERL
- Phase slippage effect (186°)

## Towards twice-recirculating ERL

Simulations on phase slippage

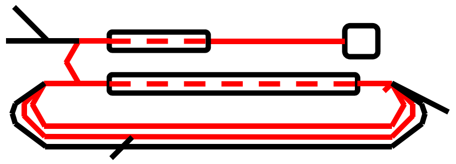



Test phase




## Outlook

- Beam dynamics simulations
- Dedicated ERL beam diagnostics
- Twice-recirculating ERL operation





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# Summary and Outlook

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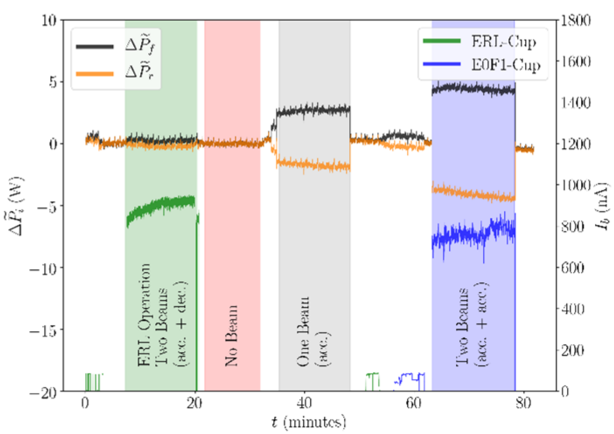
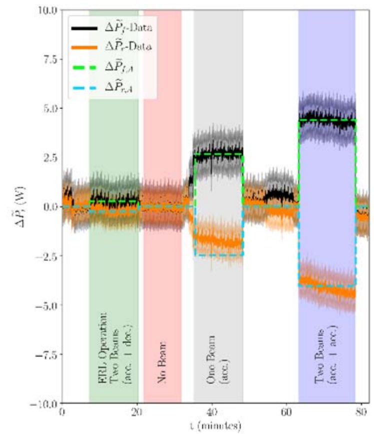
## Once-recirculating ERL operation



Analytical model

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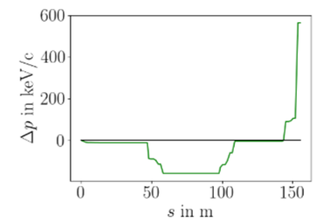
$$\varepsilon_{beam,max} = 88.9\%$$

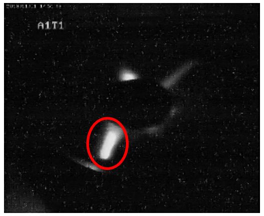
- LLRF system suitable for ERL
- Phase slippage effect (186°)

## S-DALINAC towards twice-recirculating ERL

Simulations on phase slippage



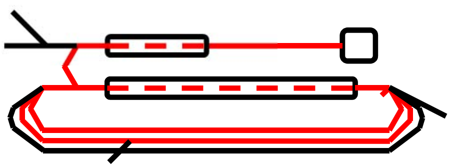

Test phase



**Thank you for your attention**

## Outlook

- Beam dynamics simulations
- Dedicated ERL beam diagnostics
- Twice-recirculating ERL operation



# Thank you for your attention!

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*Picture: Jan-Christoph Hartung*