TECHNISCHE UNIVERSITÄT DARMSTADT

The CERN Accelerator School

Energy Recovery Linac

Picture: Jan-Christoph Hartung

Institut für Kernphysik
S-DALINAC
Technische Universität Darmstadt

ELEMENTS

ACCELENCE

Nuclear Photonics

Bundesministerium für Bildung und Forschung

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]

Outline – Part II

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

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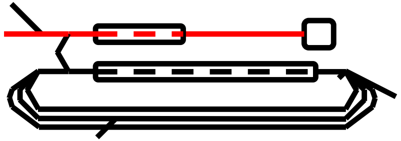
Courtesy of
S-DALINAC group

Overview Operation Modes/Commissioning

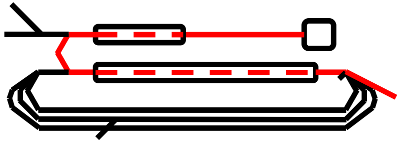
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



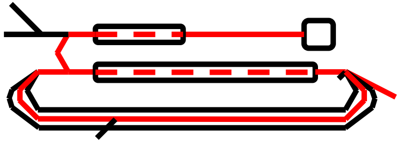
December
2016

Single
pass



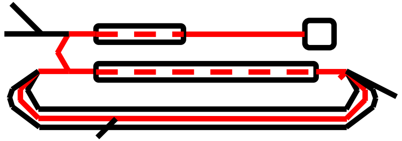
December
2016

1x rec.



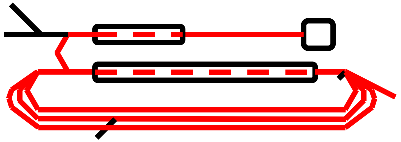
May
2017

1x ERL



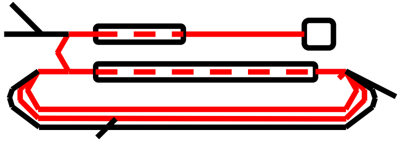
August
2017

3x rec.



November
2018

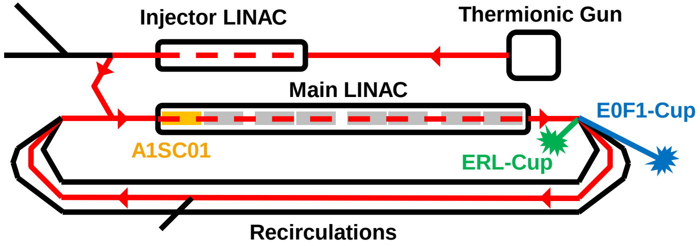
2x ERL



August
2021

Once-Recirculating ERL Operation

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



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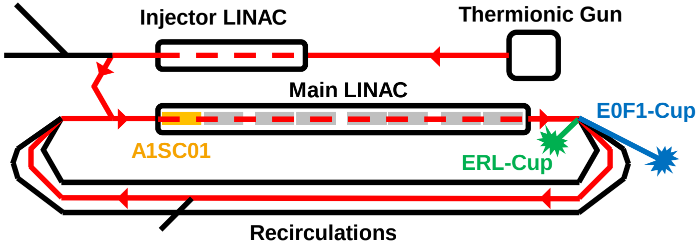
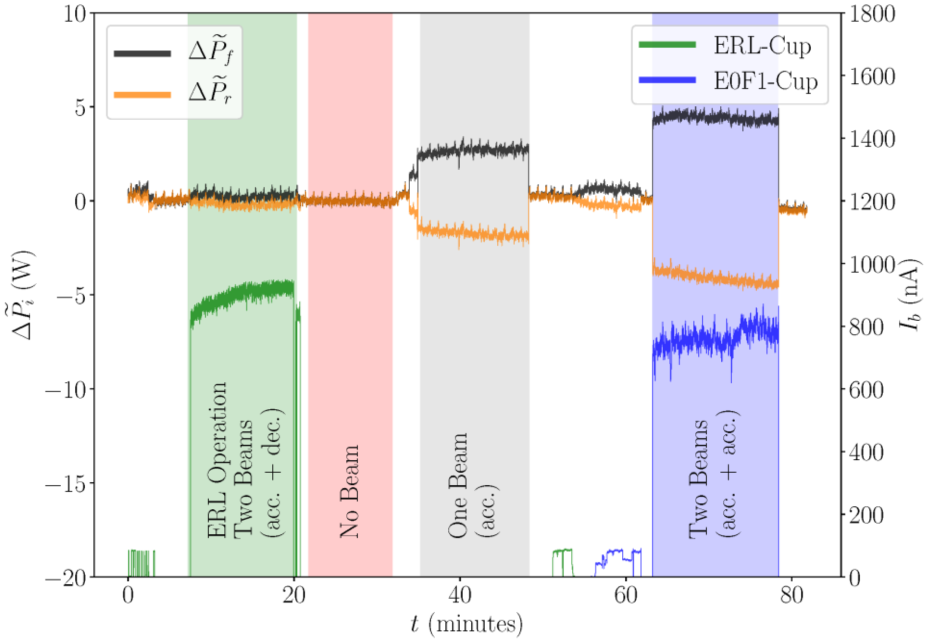
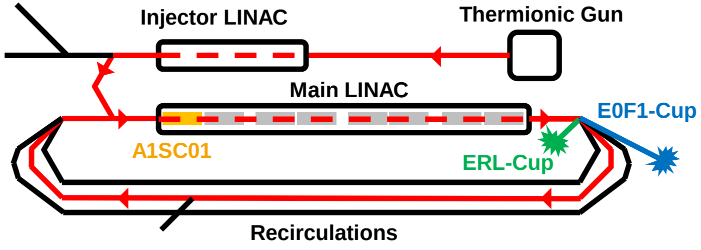


Four phases:

- 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

Once-Recirculating ERL Operation





RF-recovery effect:

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

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

M. Arnold et al., 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)

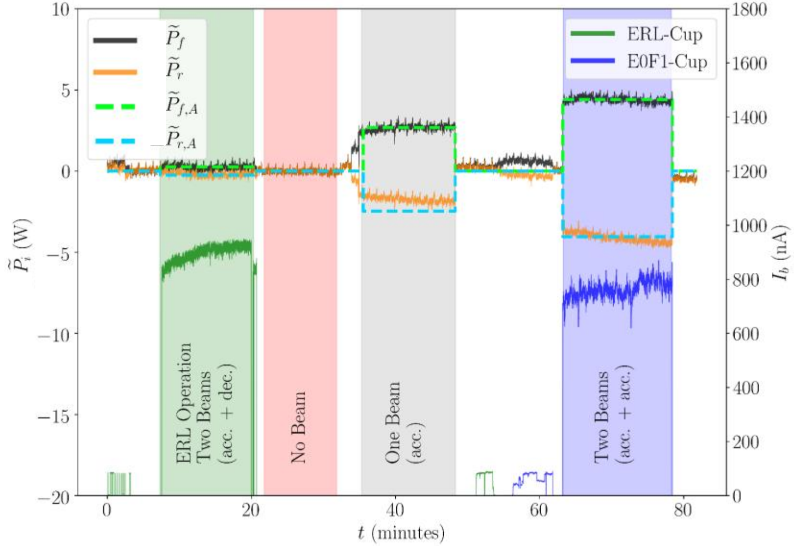
$$P_r = P_0 \frac{\left[\beta_{input} - (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}}$$

M. Arnold et al., Phys. Rev. Accel. Beams ***23****, 020101 (2020).*

Analytical Model

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

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

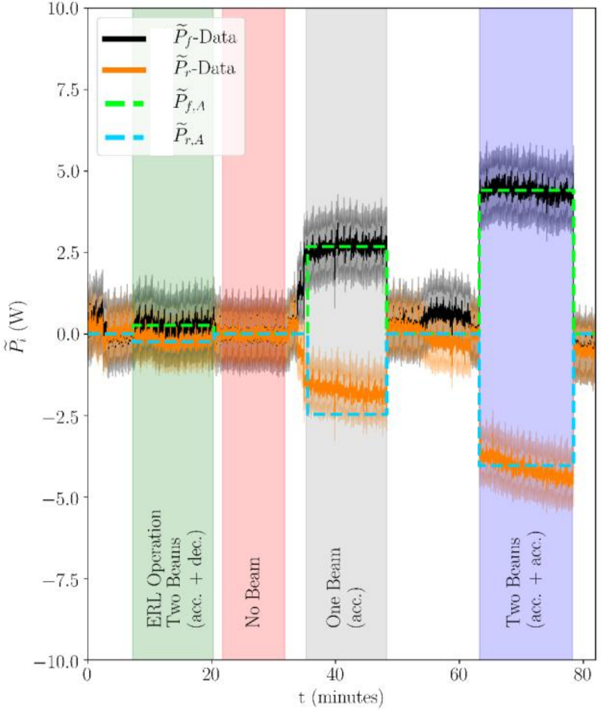


M. Arnold et al., Phys. Rev. Accel. Beams ***23****, 020101 (2020).*

- Curve-fitting to data in P_f
  - β_{beam}=0: to obtain β_{input}, β_{output} and P_0
  - $\beta_{beam}\neq0$: to obtain $\beta_{beam,i}$ for each phase i
- Analytical prediction of P_r

Analytical Model

With Uncertainties in Data



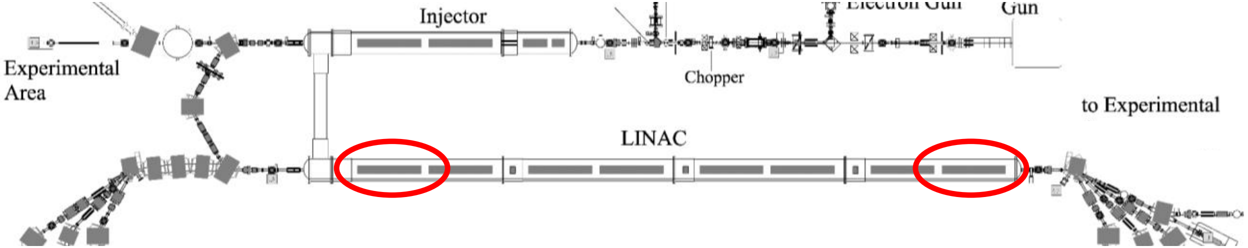
M. Arnold et al., Phys. Rev. Accel. Beams ***23****, 020101 (2020).*

Analytical model describes data within uncertainties satisfactorily

Phase Slippage

- Total change in setpoint of path length adjustment system: 186°
- Injection energy of 2.5 MeV → $\gamma \approx 4.9$ ($\beta \approx 0.97895$)
  - Time-of-flight effects
- Energy after one recirculation to re-enter main linac: 22.5 MeV → $\gamma \approx 44$ ($\beta \approx 0.99974$)
- Same effect for deceleration at last cavity
- Need to shift phase of re-entering beam → 6°

Even more critical for multi-turn ERLs!



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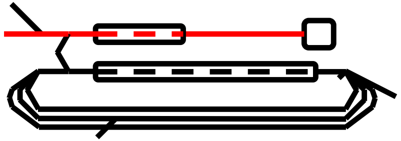

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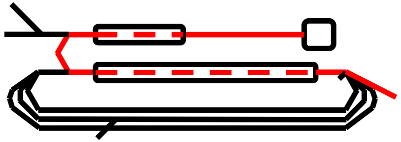
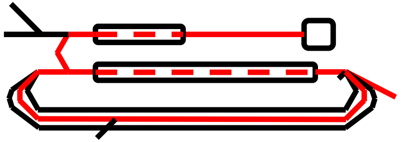
Single pass



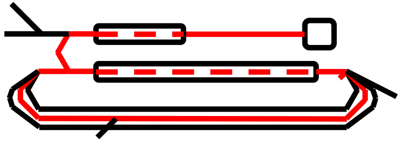
December 2016

1x rec.



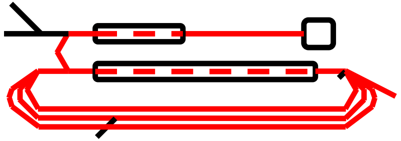
May 2017

1x ERL



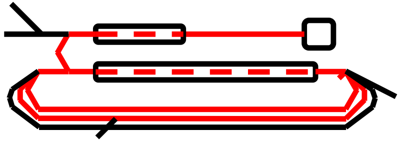
August 2017

3x rec.



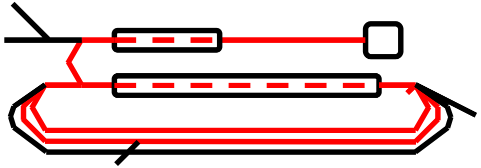
November 2018

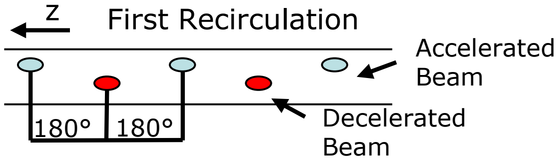
2x ERL



August 2021

2x ERL: Beam Diagnostics System





z

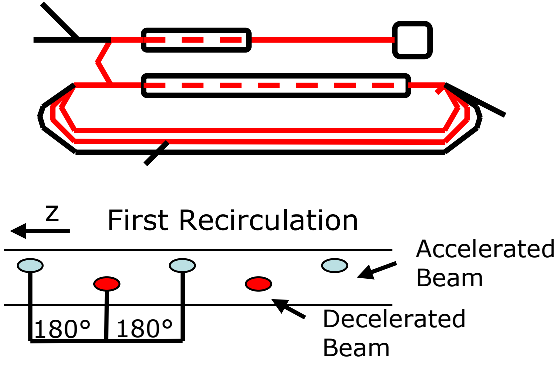
First Recirculation

Accelerated Beam

Decelerated Beam

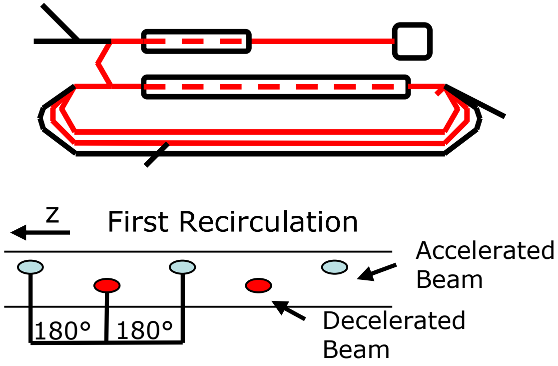
180° 180°

2x ERL: Beam Diagnostics System



- (Non-)destructive position measurement for both beams simultaneously
- Suitable for low bunch charges (S-DALINAC: ~30 aC to ~7 fC in recirculating mode)
- Two options under investigation: Wire scanner and 6 GHz cavity BPM (double of fundamental frequency)

2x ERL: Beam Diagnostics System



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- Suitable for low bunch charges (S-DALINAC: ~30 aC to ~7 fC in recirculating mode)
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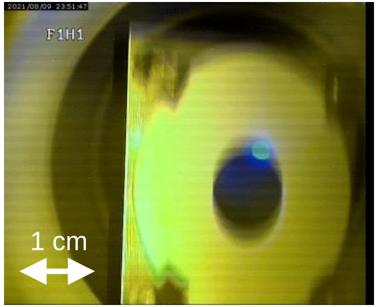
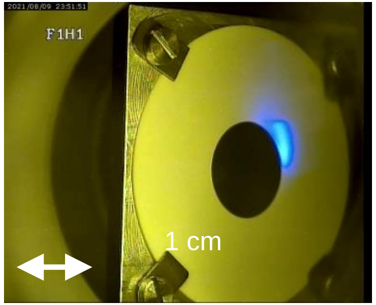
Further diagnostics:

- RF beam loading
- BLMs
- 3 GHz RF monitors
- BeO target with hole



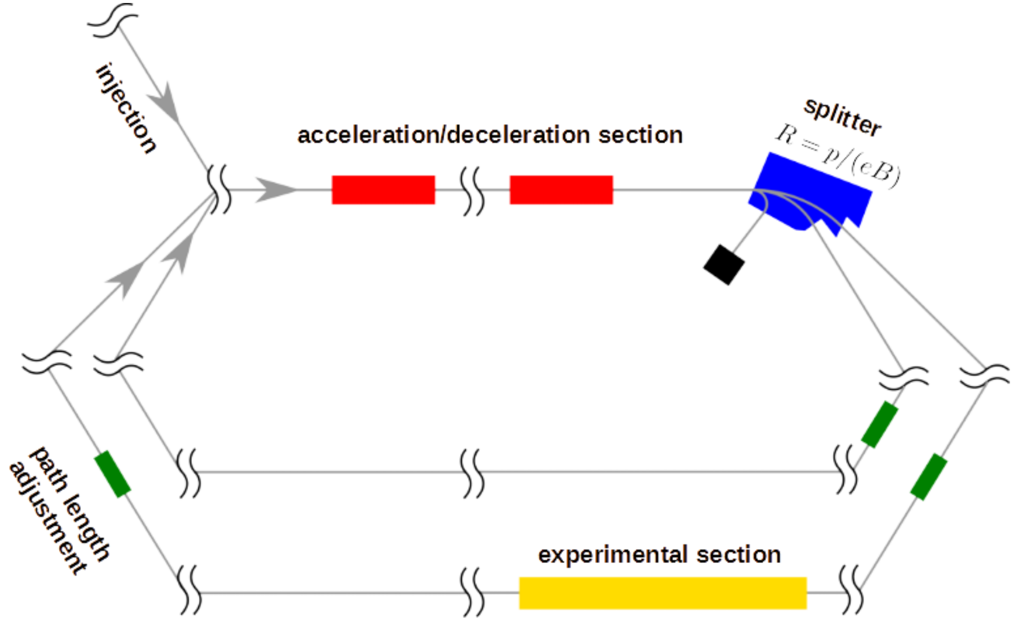
1x acc. beam

1x dec. beam



Twice-Recirculating ERL: Challanges

Concept based on: R. Koscica et al., *Phys. Rev. Accel. Beams* **22**, 091602 (2019)



F. Schliessmann et al., submitted to Nature Physics

Objective functions result from splitter magnet ratio:

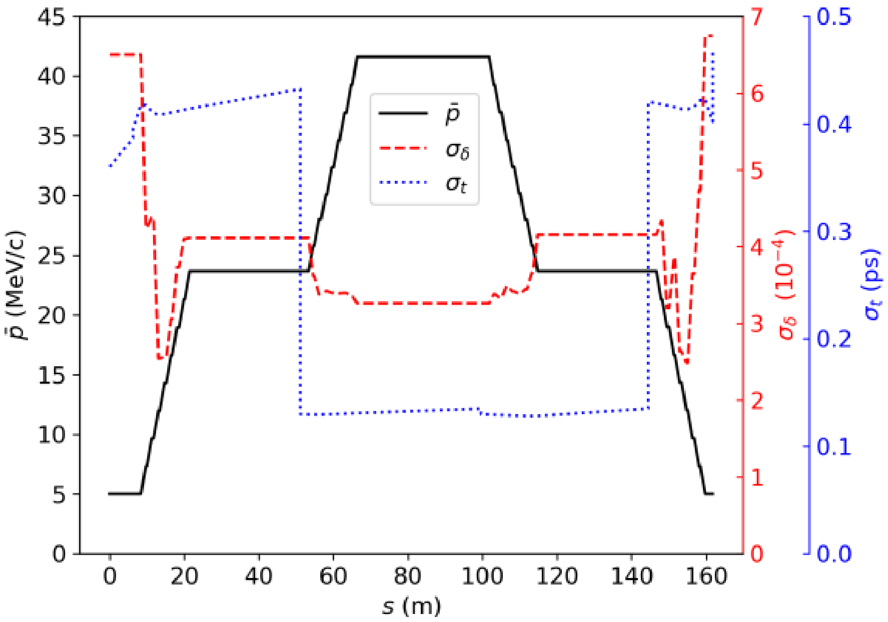
$p_\mathrm{I} : p_\mathrm{F} : p_\mathrm{S} = 1 : 4.73 : 8.32$

Degrees of freedom:

$\vec{A}, \vec{\phi}, \vec{L}, \vec{R}_{56}$

Additional challenge: Phase slippage

Solution for Longitudinal Quantities



Minimizing differences to target momenta while optimizing parameters and adding minimum momentum spread

F. Schliessmann et al., submitted to Nature Physics

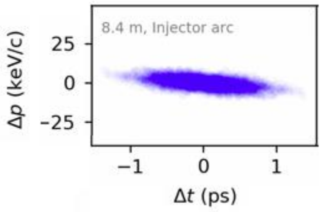
Longitudinal Setup

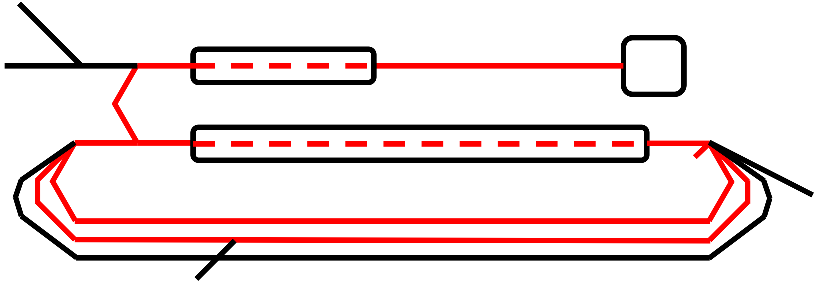
LINAC Cavity	#1	#2	#3	#4	#5	#6	#7	#8
Off-crest phase (°) (during 1st LINAC pass)	-9.7	-5.7	13.2	4.0	6.1	7.2	5.6	3.2
Off-crest momentum gain (MeV/c) (during 1st LINAC pass)	2.34	2.32	2.29	2.34	2.33	2.33	2.35	2.36
On-crest momentum gain (MeV/c) (during 1st LINAC pass)	2.37	2.33	2.35	2.35	2.34	2.34	2.36	2.37

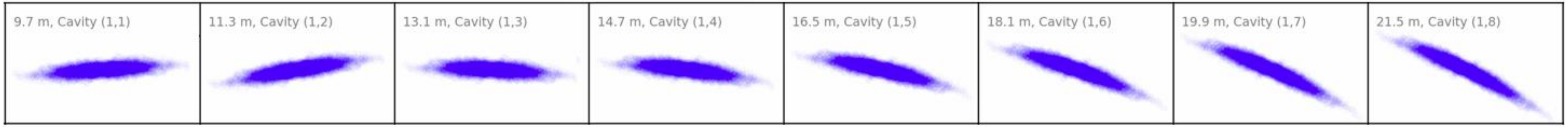
$R_{56,I}$ = -0.01 m
$R_{56,F}$ = +0.33 m
$R_{56,S}$ = +0.18 m

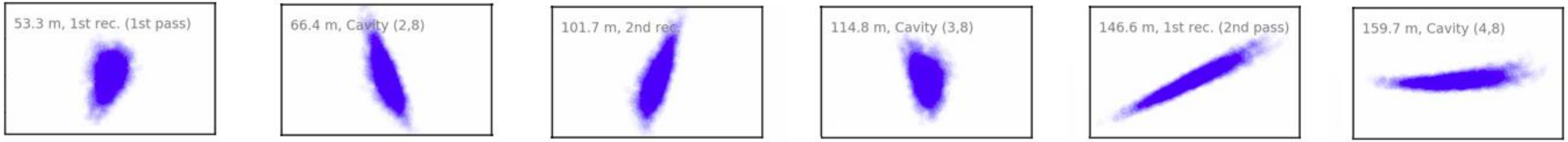
F. Schliessmann et al., submitted to Nature Physics

Longitudinal Phase Space









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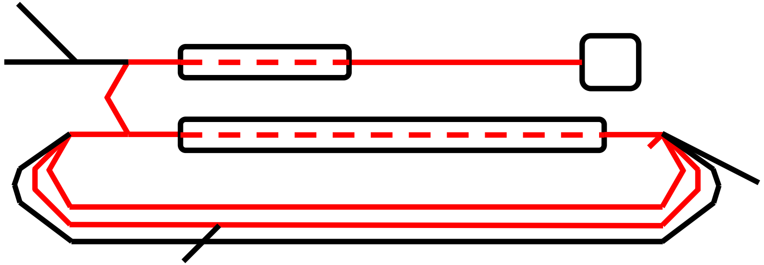
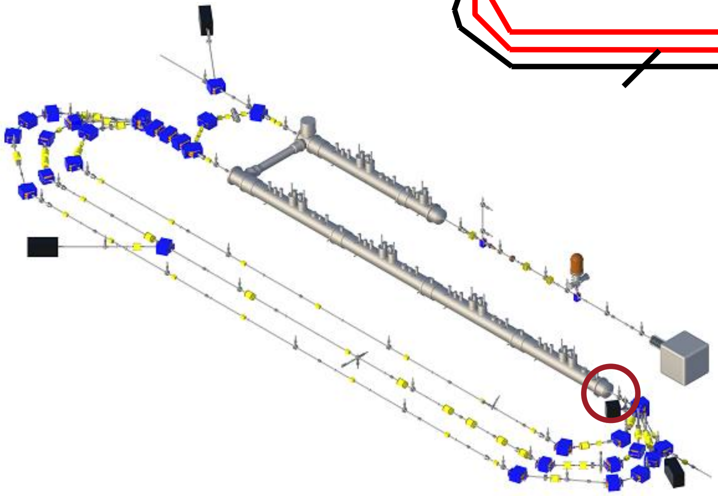
Limits of Transverse Tuning





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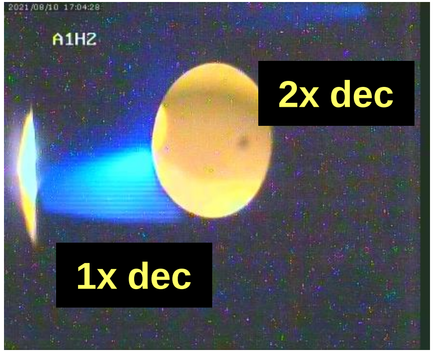
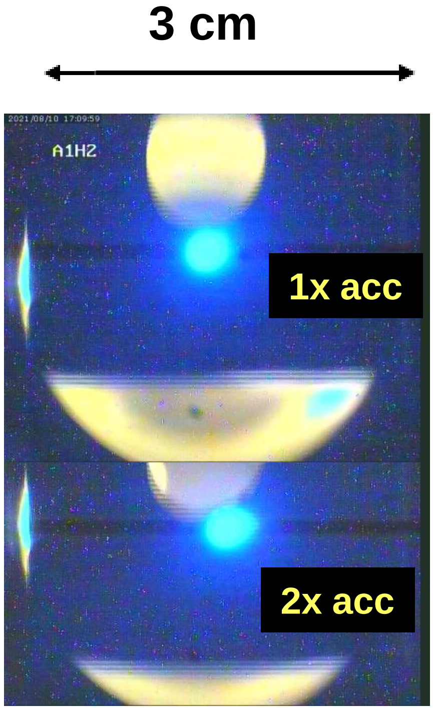
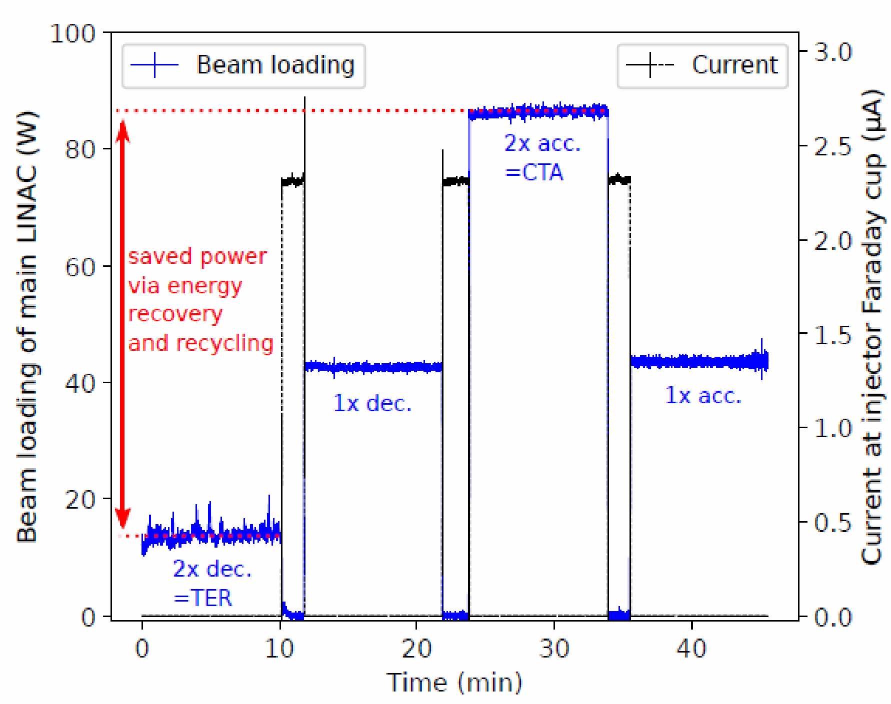




Twice-Recirculating ERL Operation

(August 2021)



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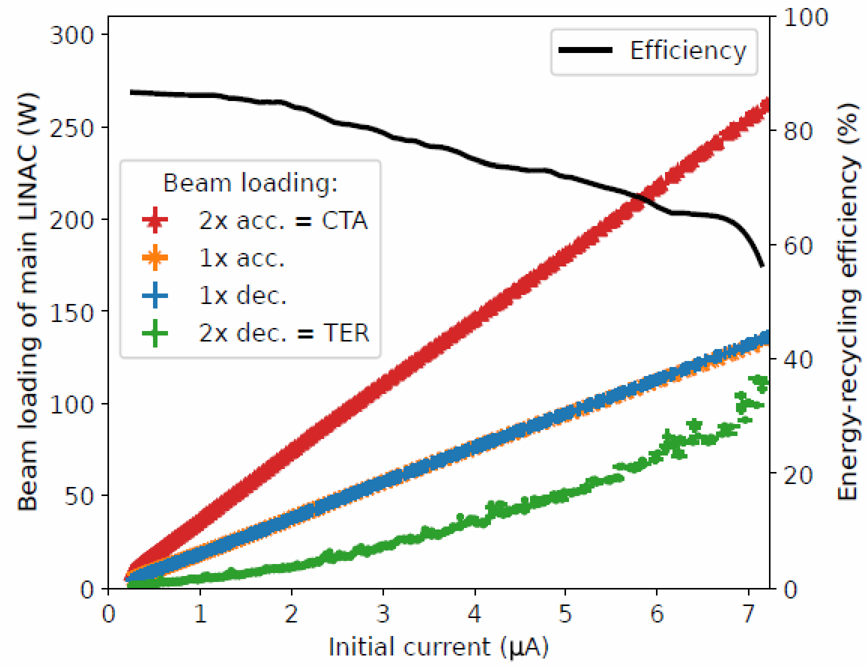

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First multi-turn SRF ERL with medium current and high transmission/RF recycling

Challenges:

- Phase slippage
- Shared beam transport

Outline – Part II

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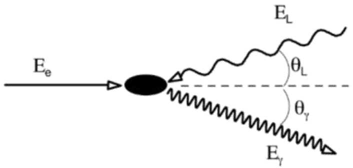
Possible Applications

Small impact on the beam, otherwise no further transport possible

Examples:

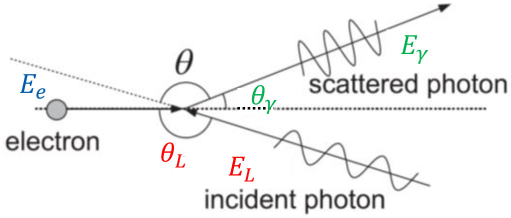
- Internal target experiment
- Free Electron Laser (FEL) → lecture by Wolfgang Hillert
- Coherent electron cooling
- Electron-ion-collider
- Compton backscattering

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



→ E_γ in den MeV-range for Nuclear Photonics

Laser Compton Backscattering



R. Hajima, M. Fujiwara, PRAB **19**, 020702 (2016), modified

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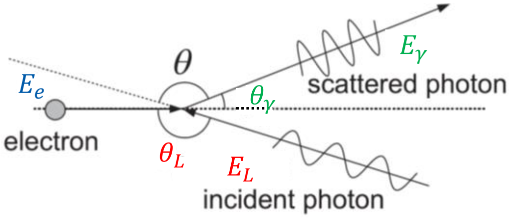

$$\varepsilon_\gamma = \varepsilon_L \frac{1-\beta\cos(\theta_L)}{1-\beta\cos(\theta_\gamma)+(\varepsilon_L/\gamma_e)(1-\cos(\theta))}$$

$$\gamma_e = \frac{E_e}{m_0c^2} \qquad \varepsilon_L = \frac{E_L}{m_0c^2} \qquad \varepsilon_\gamma = \frac{E_\gamma}{m_0c^2}$$

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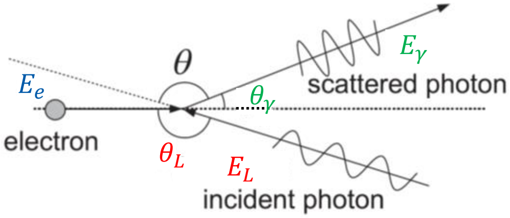

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Head-on collision $(\theta_L = \pi)$

$$\varepsilon_\gamma^{max} = \frac{4\gamma_e^2 \varepsilon_L}{1 + 4\gamma_e \varepsilon_L}$$

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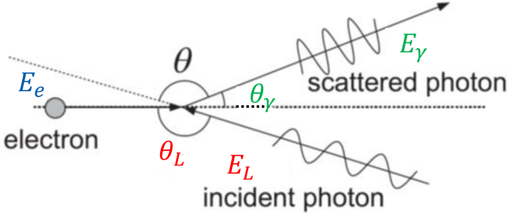
Laser Compton Backscattering



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Head-on collision $(\theta_L = \pi)$

$$\varepsilon_\gamma^{max} = \frac{4\gamma_e^2 \varepsilon_L}{1 + 4\gamma_e \varepsilon_L} \quad \Rightarrow \quad E_\gamma^{max} \approx 4\gamma_e^2 E_L$$

$\varepsilon_L \approx 2 \cdot 10^{-6}$ $(E_L = 1\,eV)$

$\gamma_e \approx 100$ $(E_e = 51\,MeV)$

R. Hajima, M. Fujiwara, PRAB **19**, 020702 (2016), modified

Laser Compton Backscattering

Flux of γ Beam

$$F = \sigma_c L$$

Flux dependent on cross-section of Compton Scattering σ_C (integrated over energy)

R. Hajima, M. Fujiwara, PRAB **19**, 020702 (2016), modified

Laser Compton Backscattering

Flux of γ Beam

$$F = \sigma_c L$$

Flux dependent on cross-section of Compton Scattering σ_C (integrated over energy)

Luminosity at small crossing angles

$$L = \frac{f N_e N_X \cos(\Phi/2)}{2\pi\sqrt{\sigma_{e,y}^2 + \sigma_{L,y}^2}\sqrt{\left(\sigma_{e,x}^2 + \sigma_{L,x}^2\right)\cos(\Phi/2)^2 + \left(\sigma_{e,z}^2 + \sigma_{L,z}^2\right)\sin(\Phi/2)^2}}$$

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Electron beam

- Energy
- N_e: # e^- per bunch
- Emittance ($\sigma_{e,xyz}$)

Laser beam

- Energy
- N_X: # γ per pulse
- Emittance ($\sigma_{L,xyz}$)
- Angles θ_L,Φ

Interaction

- f: collision frequency
- σ_C: cross-section
- Angle θ_γ

R. Hajima, M. Fujiwara, PRAB **19**, 020702 (2016), modified

Laser Compton Backscattering

The „perfect" set-up

Electron beam

- Energy
- N_e: # e^- per bunch
- Emittance ($\sigma_{e,xyz}$)

$$E_\gamma^{max} \approx 4\gamma_e^2 E_L$$

Goal: E_γ in den MeV-range for Nuclear Photonics with high repetition-rate

- High repetition-rate → SRF technology
- High beam current at low emittance + recovery → ERL
- Laser with E_L = 1 eV
  → Electron beam energy in the range of ~ 500 MeV
  → multi-turn ERL

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- Future of ERLs
- Summary

State-of-the-Art and Challenges for Future

arXiv:2207.02095v2 [physics.acc-ph] 27 Sep 2022

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`

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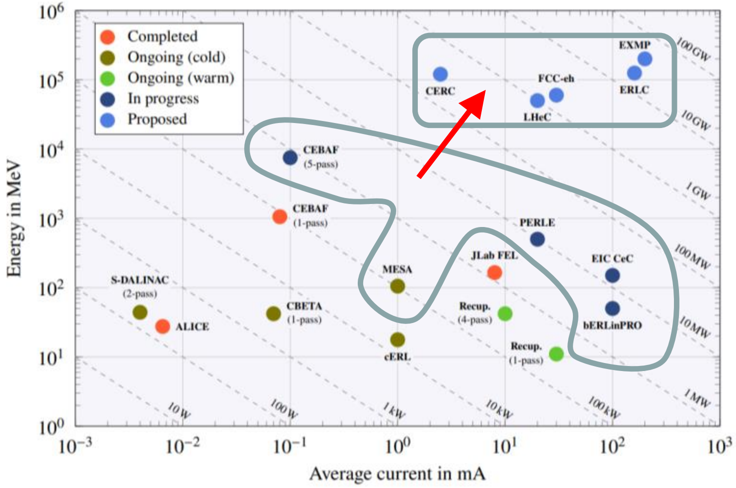
[1] Corresponding author.

"Energy-recovery linacs (ERLs) have been emphasised by the recent (2020) update of the European Strategy for Particle Physics as one of the most promising technologies for the accelerator base of future high-energy physics. They are indeed beginning to assert their potential as game changers in the field of accelerators and their applications."

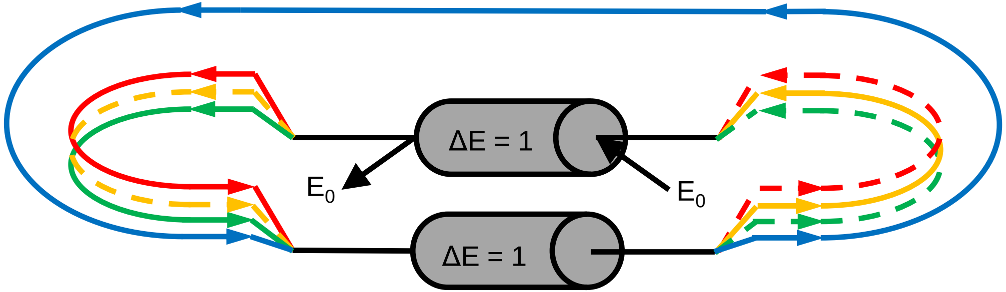


arXiv:2207.02095 [physics.acc-ph]; accepted for publication in JINST

Technology?

Need:

- SRF, multi-turn
- High efficiency, reliability, robustness → separate transport as promising concept (→ Idea of DICE @ TU Darmstadt)



Idea of separate transport: Peter Williams and David Douglas

P. Williams, ERL Design Concepts DIANA and DICE, Electrons for the LHC: Workshop on the LHeC, FCC-eh and PERLE (2019). https://indico.cern.ch/event/835947/contributions/3553736/

Outline – Part II

- ERL Mode @ S-DALINAC (1-turn, 2-turn and diagnostics)
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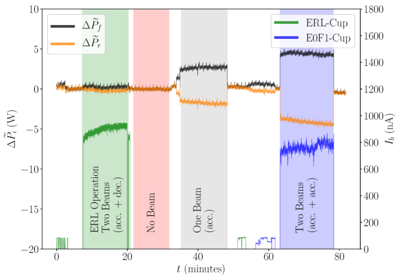
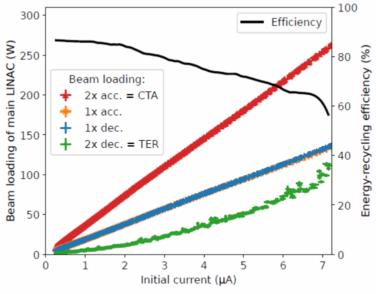
Take Home Message

ERL mode @ S-DALINAC



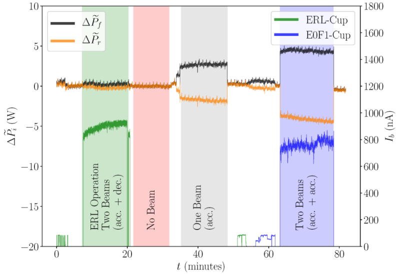
1xERL

2xERL



Take Home Message

ERL mode @ S-DALINAC



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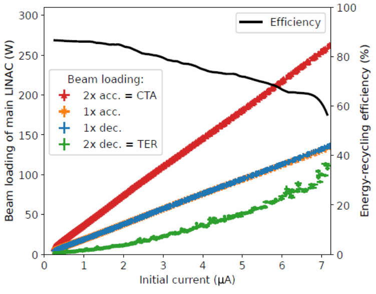
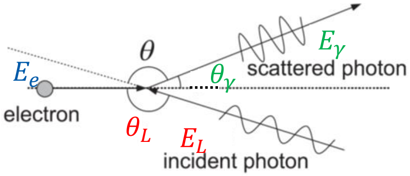
2xERL



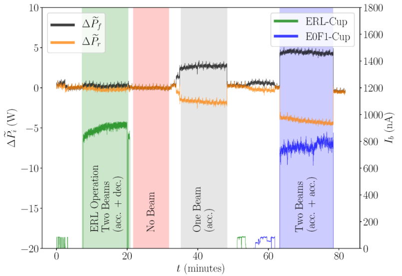
Applications



$$E_\gamma^{max} \approx 4\gamma_e^2 E_L$$

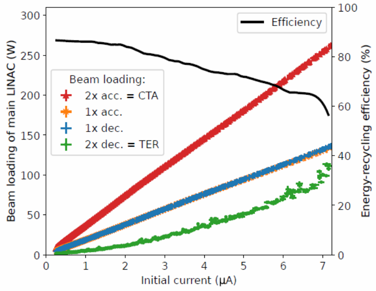
Take Home Message

ERL mode @ S-DALINAC

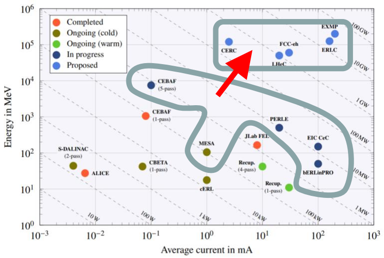


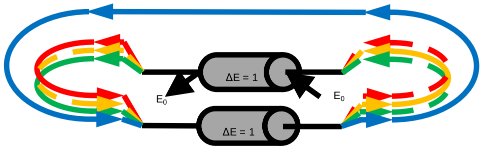
1xERL

2xERL

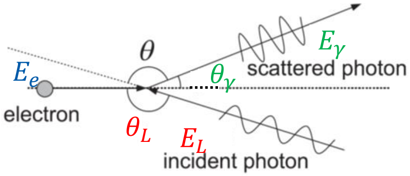


Future of ERLs





Applications



$$E_\gamma^{max} \approx 4\gamma_e^2 E_L$$

Thank you for your Attention!

Picture: Jan-Christoph Hartung