ANGELOTTI – IKP

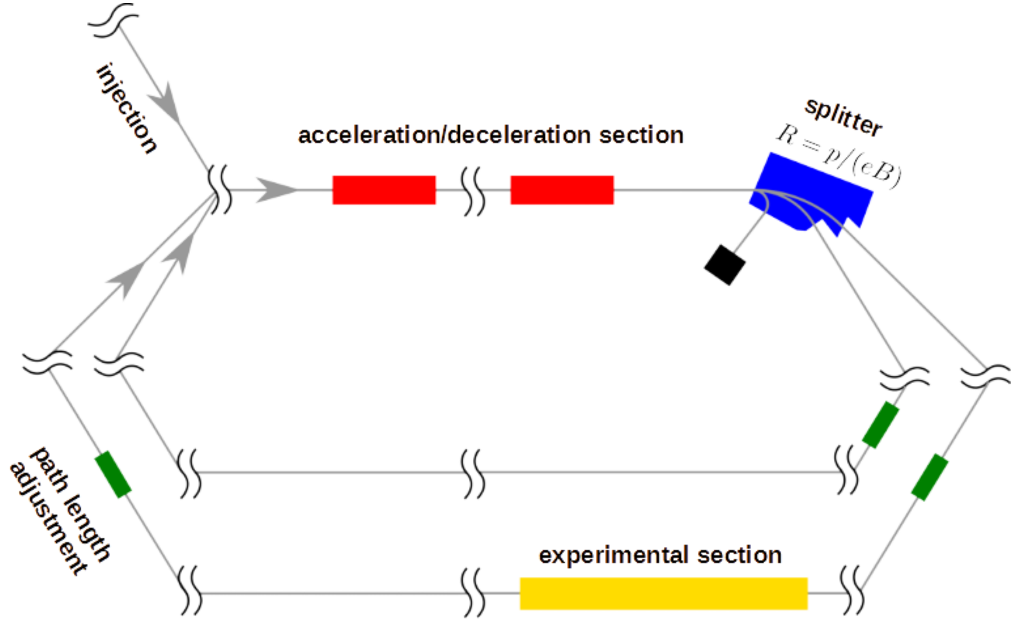
Accelerators: the Next GEneration – materiaLs, cOmponents, sysTems and simulaTIons

Picture: Jan-Christoph Hartung

Work supported by DFG (GRK 2128, SFB 1245), BMBF (05H21RDRB1), State of Hesse (Cluster Project ELEMENTS and LOEWE Research Cluster Nuclear Photonics)

Challenges of Twofold ERL

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



Objective functions result from splitter magnet ratio:

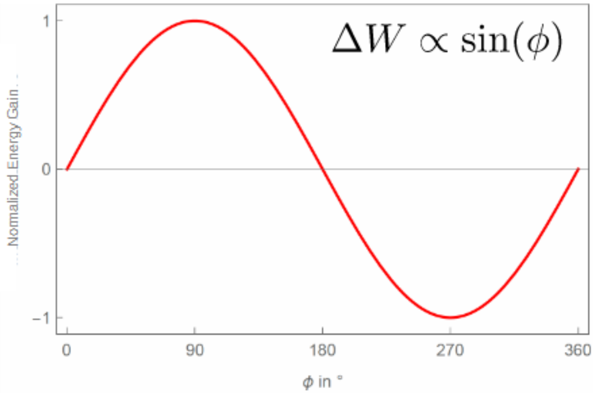
$p_\mathrm{I} : p_\mathrm{F} : p_\mathrm{S} = 1 : 4.73 : 8.32$

Degrees of freedom:

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

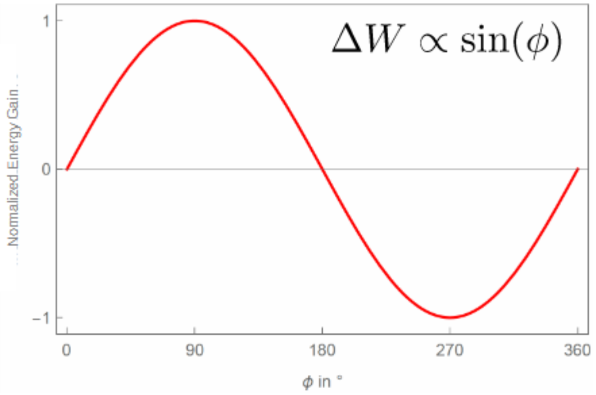
Phase Slippage

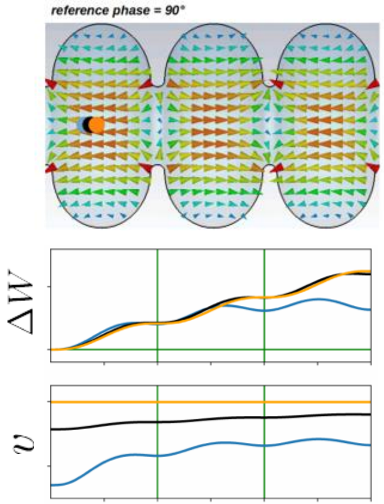
Simplified model of energy gain



Phase Slippage

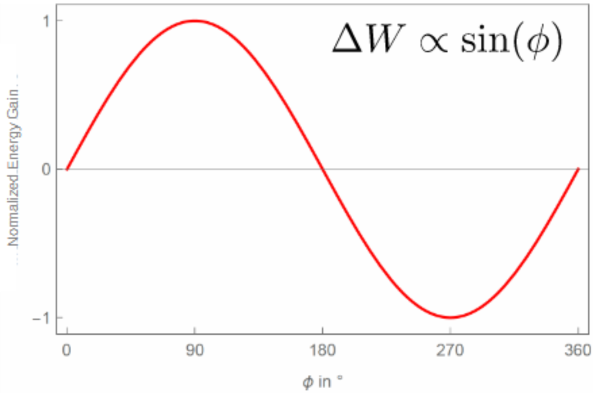
Simplified model of energy gain | **More complex model of energy gain**



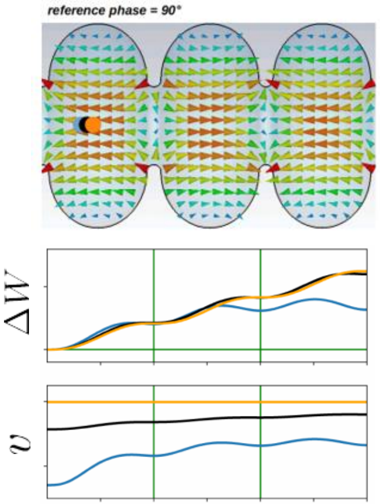


Phase Slippage

Simplified model of energy gain



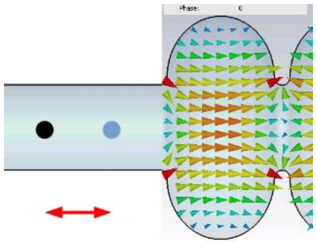
More complex model of energy gain



Speed changes along the cavity

→ Influences interaction with alternating electric field

→ Numerical simulations required



Longitudinal Targets and Degrees of Freedom

$$\begin{pmatrix} \bar{p}_{1\mathrm{x\,acc.}} \\ \bar{p}_{2\mathrm{x\,acc.}} \\ \bar{p}_{1\mathrm{x\,dec.}} \\ \bar{p}_{2\mathrm{x\,dec.}} \end{pmatrix} = \begin{pmatrix} 4.73 \cdot \bar{p}_{\mathrm{inj.}} \\ 8.32 \cdot \bar{p}_{\mathrm{inj.}} \\ 4.73 \cdot \bar{p}_{\mathrm{inj.}} \\ 1.00 \cdot \bar{p}_{\mathrm{inj.}} \end{pmatrix} \quad \bar{p}_{\mathrm{inj.}} = 5\,\mathrm{MeV/c}$$

Longitudinal Targets and Degrees of Freedom

$$\begin{pmatrix} \bar{p}_{1\mathrm{x\,acc.}} \\ \bar{p}_{2\mathrm{x\,acc.}} \\ \bar{p}_{1\mathrm{x\,dec.}} \\ \bar{p}_{2\mathrm{x\,dec.}} \end{pmatrix} = \begin{pmatrix} 4.73 \cdot \bar{p}_{\mathrm{inj.}} \\ 8.32 \cdot \bar{p}_{\mathrm{inj.}} \\ 4.73 \cdot \bar{p}_{\mathrm{inj.}} \\ 1.00 \cdot \bar{p}_{\mathrm{inj.}} \end{pmatrix} \qquad \bar{p}_{\mathrm{inj.}} = 5\,\mathrm{MeV/c}$$

$$\min \left\| \begin{pmatrix} \mathrm{sene}(\bar{p}_{0,1\mathrm{x\,acc.}}, 4.73 \cdot p_{\mathrm{inj.}}, T) \\ \mathrm{sene}(\bar{p}_{0,2\mathrm{x\,acc.}}, 8.32 \cdot p_{\mathrm{inj.}}, T) \\ \mathrm{sene}(\bar{p}_{0,1\mathrm{x\,dec.}}, 4.73 \cdot p_{\mathrm{inj.}}, T) \\ \mathrm{sene}(\bar{p}_{0,2\mathrm{x\,dec.}}, 1.00 \cdot p_{\mathrm{inj.}}, T) \end{pmatrix} \right\|_{1*} \quad \text{s.t.} \begin{cases} A_i \in [0,5]\,\mathrm{MV/m}\ \forall i \in \{1,...,8\} \\ \phi_i \in [0,360)\,^\circ\ \forall i \in \{1,...,8\} \\ L_1 \in [0,74.0]\,\mathrm{mm} \\ L_2 \in [0,101.2]\,\mathrm{mm} \end{cases} \qquad \|\vec{x}\|_{1*} := \sum_i x_i$$

Longitudinal Targets and Degrees of Freedom

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$$\mathrm{sene}(V_1, V_2, T) = \begin{cases} 0, & |V_1 - V_2| \le T \\ ((|V_1 - V_2| - T)/T)^2, & |V_1 - V_2| > T \end{cases} \qquad T = 1\ \mathrm{eV/c}$$

Longitudinal Targets and Degrees of Freedom

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$$\begin{pmatrix} \bar{p}_{1\text{x acc.}} \\ \bar{p}_{2\text{x acc.}} \\ \bar{p}_{1\text{x dec.}} \\ \bar{p}_{2\text{x dec.}} \end{pmatrix} = \begin{pmatrix} 4.73 \cdot \bar{p}_{\text{inj.}} \\ 8.32 \cdot \bar{p}_{\text{inj.}} \\ 4.73 \cdot \bar{p}_{\text{inj.}} \\ 1.00 \cdot \bar{p}_{\text{inj.}} \end{pmatrix} \qquad \bar{p}_{\text{inj.}} = 5\,\text{MeV/c}$$

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$$\min \sigma_\delta(s) \qquad \text{s.t.} \begin{cases} R_{56,\text{I}} \in [-0.7, 0.4]\,\text{m} \\ R_{56,\text{F}} \in [-0.1, 0.8]\,\text{m} \\ R_{56,\text{S}} \in [-0.7, 0.7]\,\text{m} \end{cases}$$

Longitudinal Targets and Degrees of Freedom

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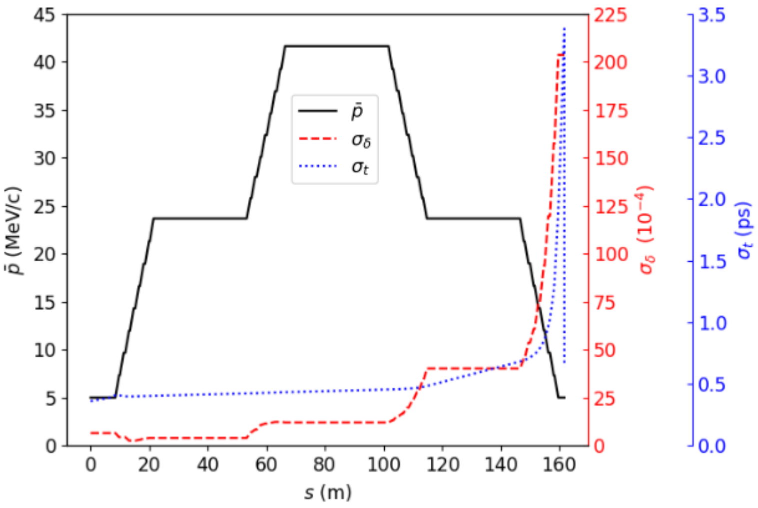
Code Availability:
F. Schliessmann et al., TUdatalib (2022), https://doi.org/10.48328/tudatalib-963

Solution for Longitudinal Quantities

$$\min \|\cdots\|_{1^*}$$



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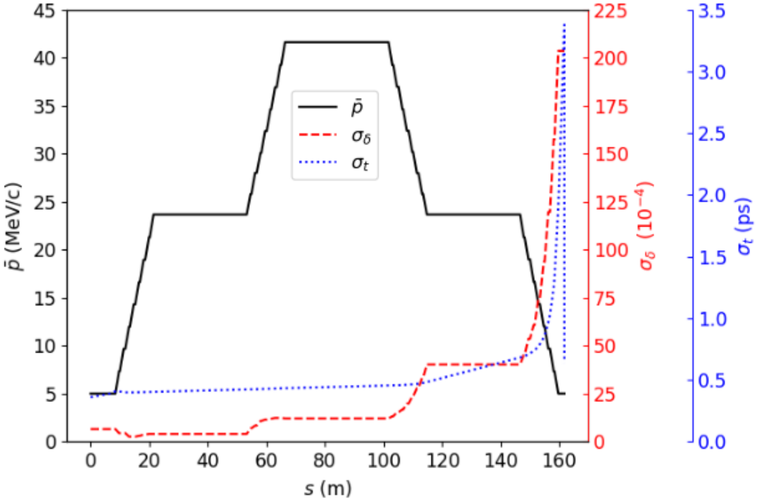
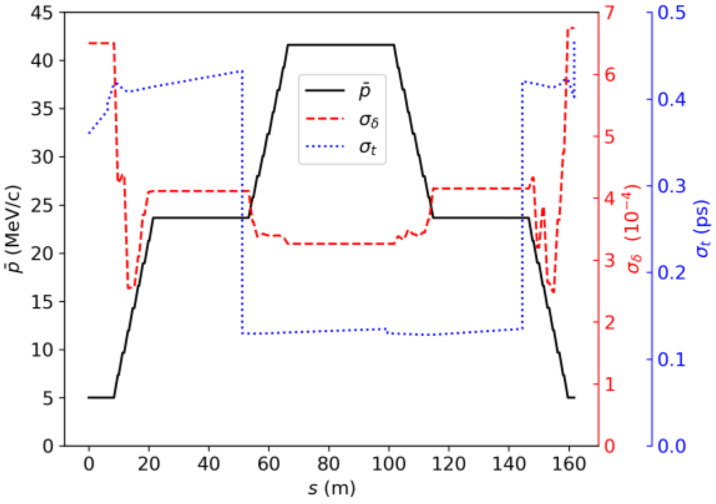


$$\min \|\cdots\|_{1^*} \quad \textbf{and} \quad \min \sigma_\delta(s)$$

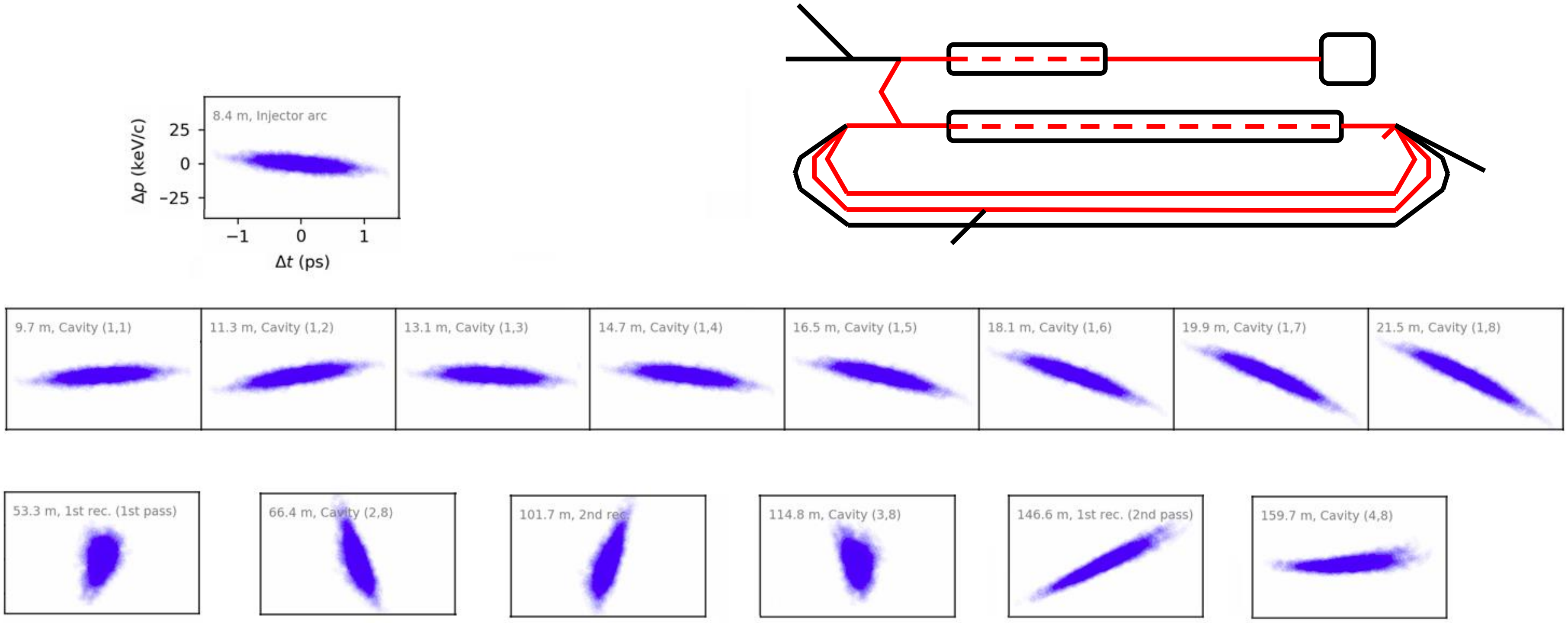


Longitudinal Setup

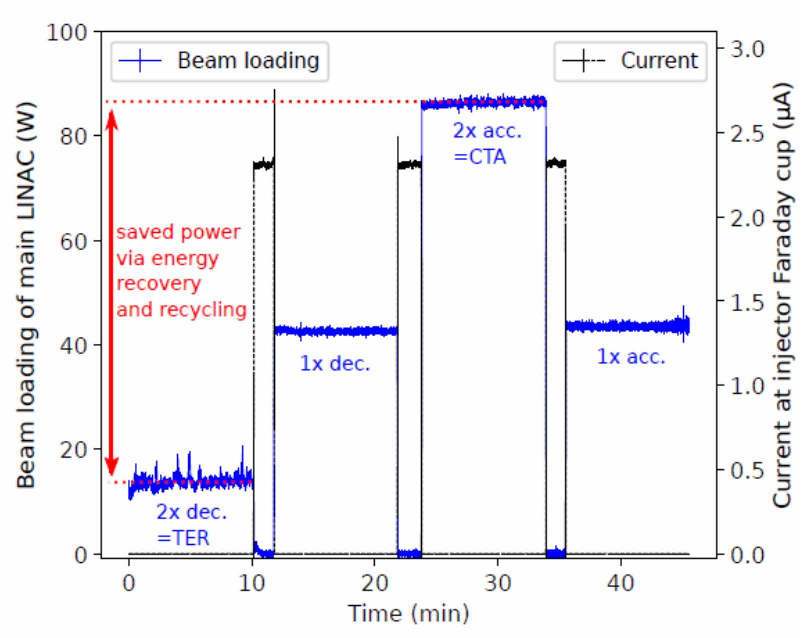
LINAC Cavity	#1	#2	#3	#4	#5	#6	#7	#8
Off-crest phase (°) (during 1st LINAC pass)	-9.7	-5.7	13.2	4.0	6.1	7.2	5.6	3.2
Off-crest momentum gain (MeV/c) (during 1st LINAC pass)	2.34	2.32	2.29	2.34	2.33	2.33	2.35	2.36
On-crest momentum gain (MeV/c) (during 1st LINAC pass)	2.37	2.33	2.35	2.35	2.34	2.34	2.36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

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

Longitudinal Phase Space



Twofold ERL Mode (August 2021)



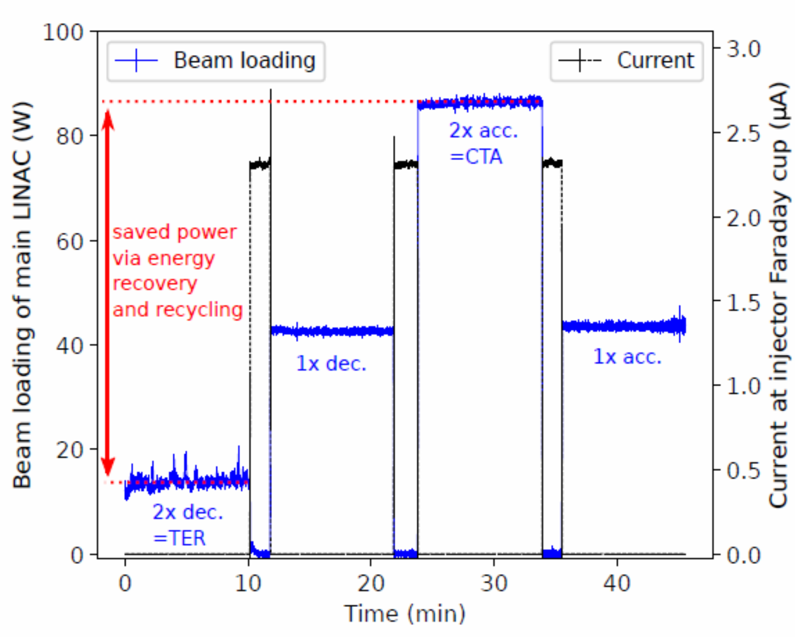
Operation mode	Load at main LINAC (W)
1x acc.	43.5 ± 0.2
2x acc.	86.3 ± 0.3
1x dec.	42.6 ± 0.2
2x dec.	13.8 ± 1.1

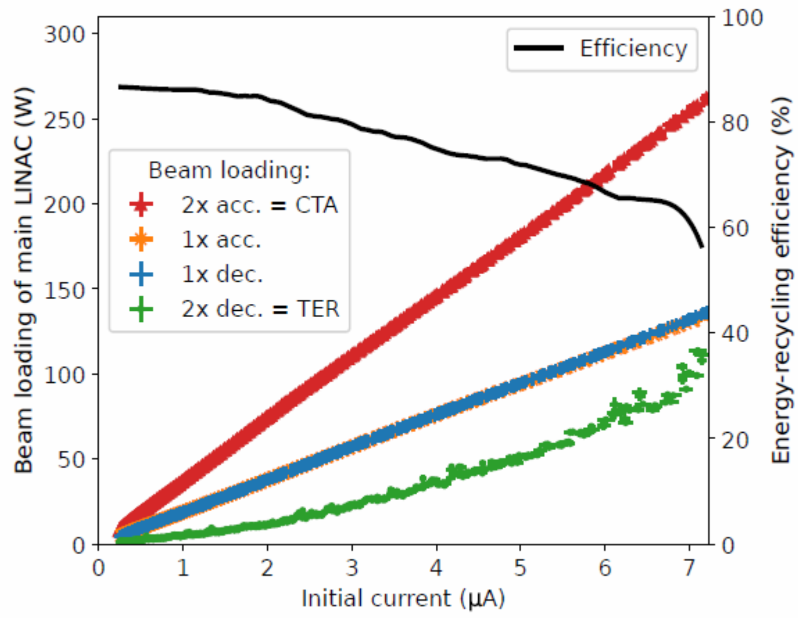
Energy-recycling efficiency:

$$\eta_{\text{main LINAC}} = \frac{P_{\text{b,main LINAC,2x acc.}} - P_{\text{b,main LINAC,2x ERL}}}{P_{\text{b,main LINAC,2x acc.}}}$$

$$= (84.0 \pm 1.2)\ \%$$

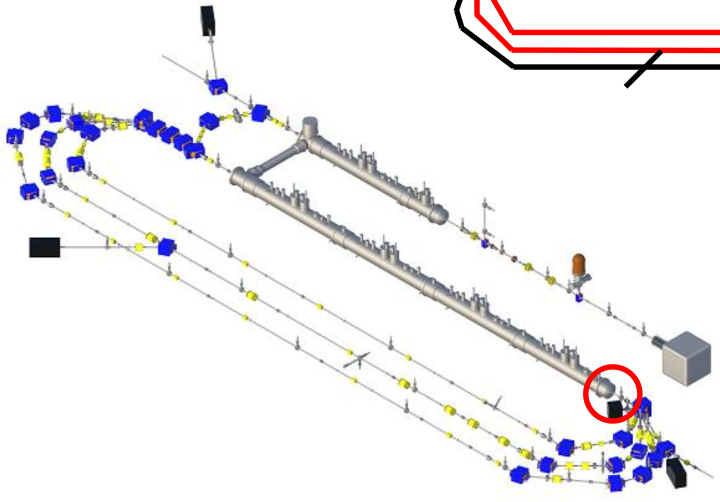
Twofold ERL Mode (August 2021)

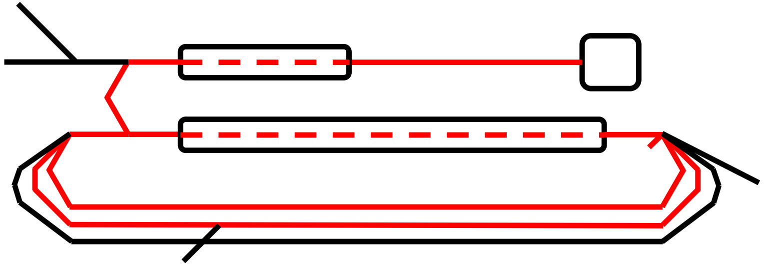


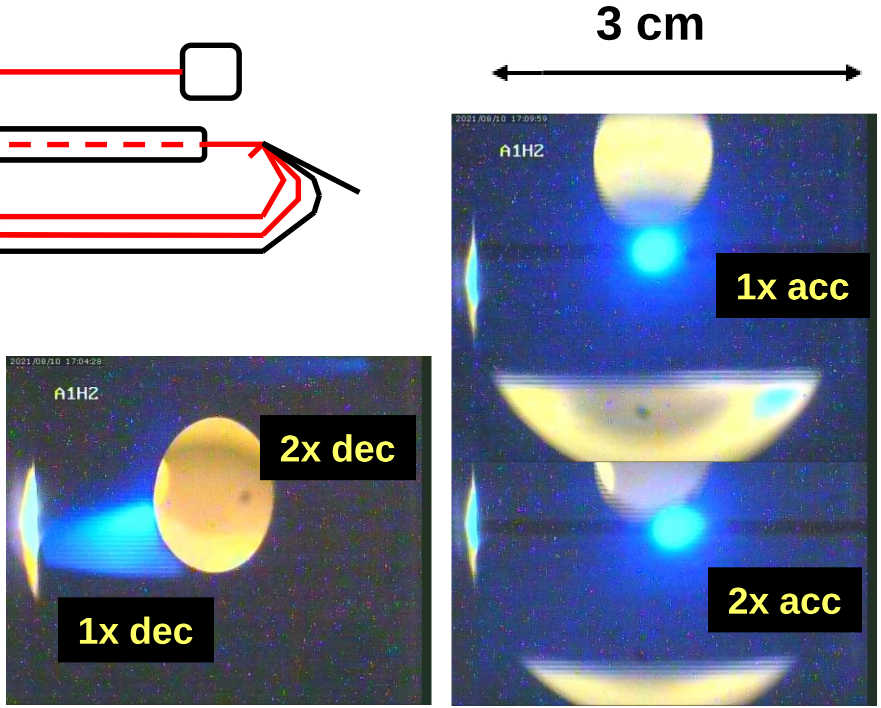


$$\max(\eta_{\text{main LINAC}}) \approx 87\ \%$$

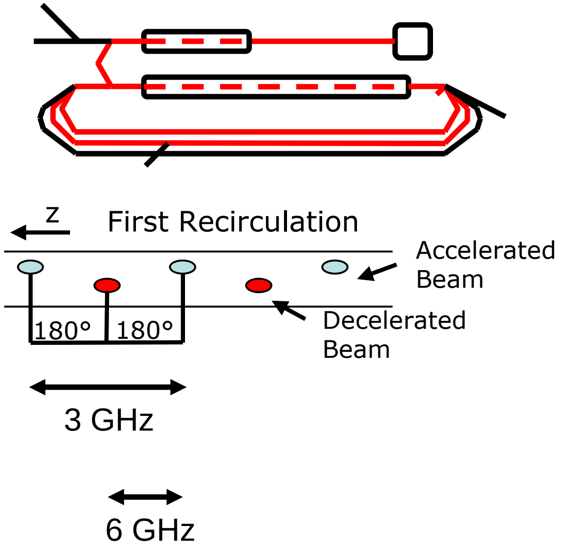
Limits of Transverse Tuning



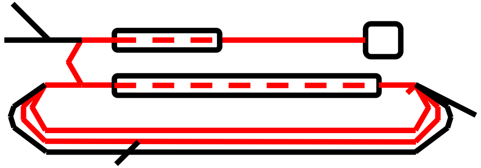


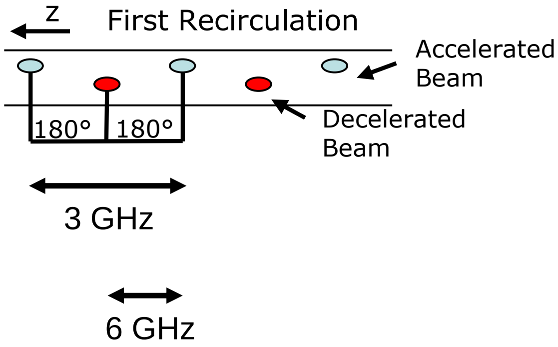


Instrumentation of Superimposing Beams



Instrumentation of Superimposing Beams





- (Non-)destructive position measurement for both beams simultaneously
- Options
  - Screen with hole
  - Beam loss monitors
  - Wire scanner
  - 6 GHz cavity BPM (double of fundamental frequency)
  - 3 GHz cavity BPM in combination with bunch trains

Wire Scanner

Measurement routine:

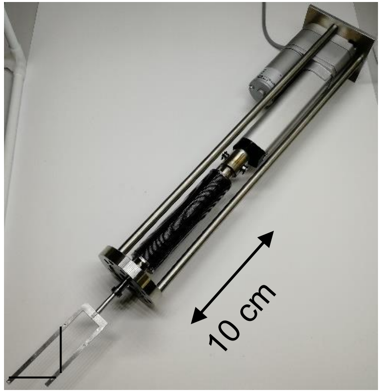
(1) Measure single-accelerated beam alone

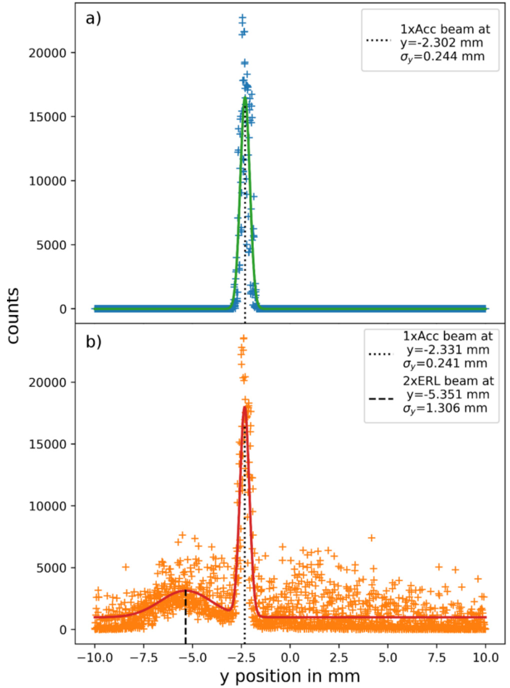
(2) Measure both beams simultaneously

(3) Substract (1) from (2)

→ Gain position of single-decelerated beam

- Tuning of the first beam requires re-calibration of the system
- measurement time: ~ 10 sec.



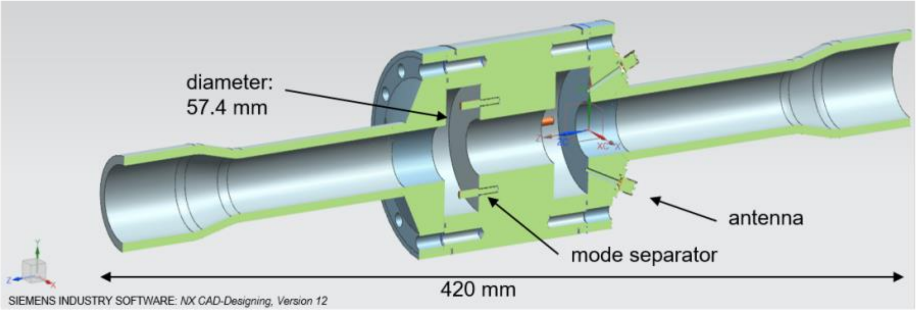


M. Dutine et al., Proc. of IPAC 2022, p. 254-256 (2022)

6 GHz Cavity BPM

Measurement routine:

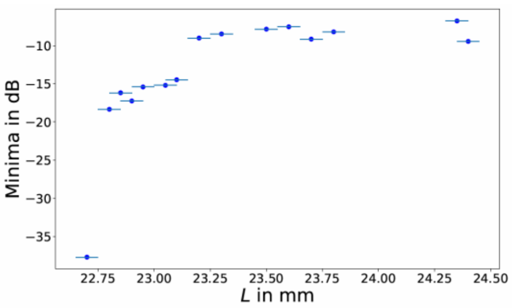
- Identical to wire scanner
- Advantage: online measurement instead of defined measurement points
- Tested at test stand
- Read out electronics under development
- Test with beam planned for 2023
- Comparison to wire scanner

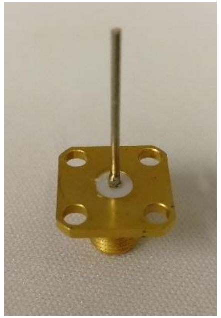


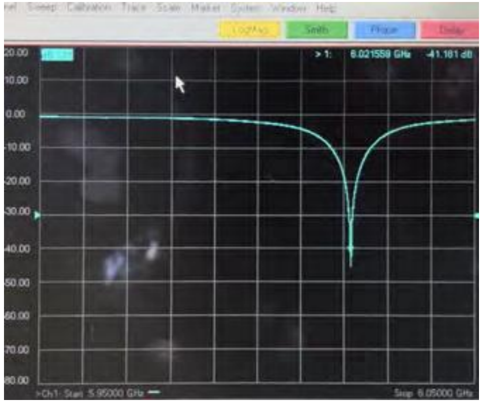
M. Dutine et al., Proc. of IPAC 2022, p. 254-256 (2022)

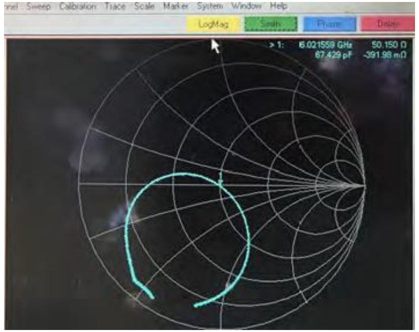
6 GHz Cavity BPM

courtesy of M. Dutine & A. Dimitrov



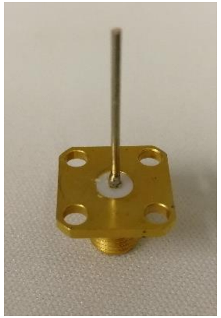


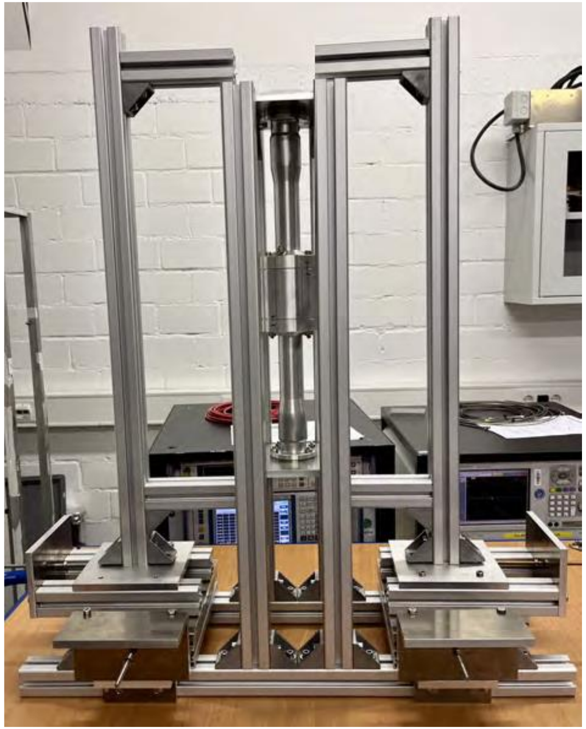


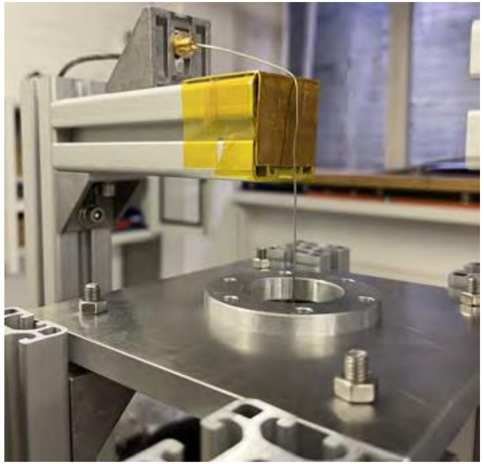


6 GHz Cavity BPM

courtesy of M. Dutine & A. Dimitrov







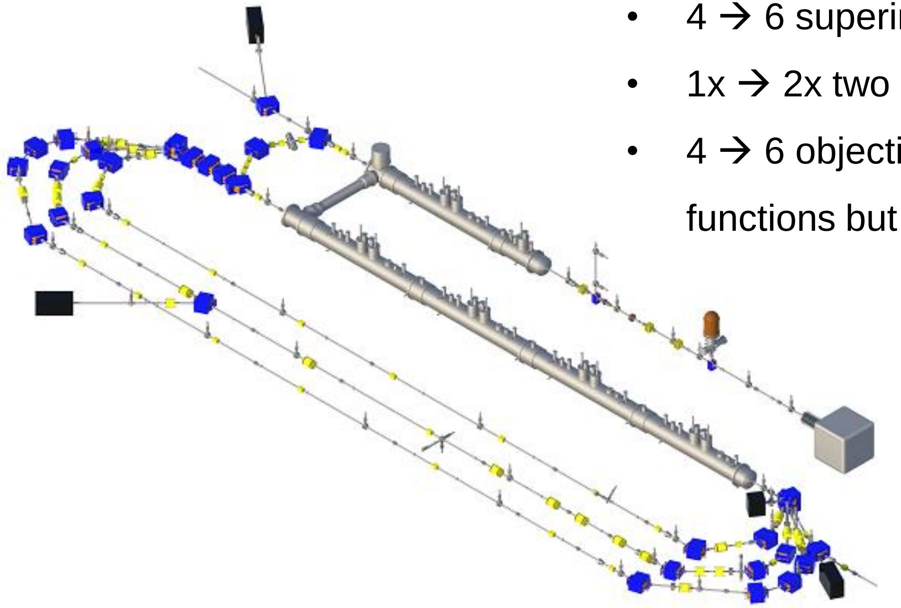
Summary

- Twofold ERL mode at S-DALINAC with up to 87 % efficiency
- Challenges of multi-turn energy-recovery:
  - Low injection energy → Phase slippage
  - Shared beam transport
- Remedies:
  - Numerical simulations
  - Special diagnostic units

Thank you for your Attention.

Backup

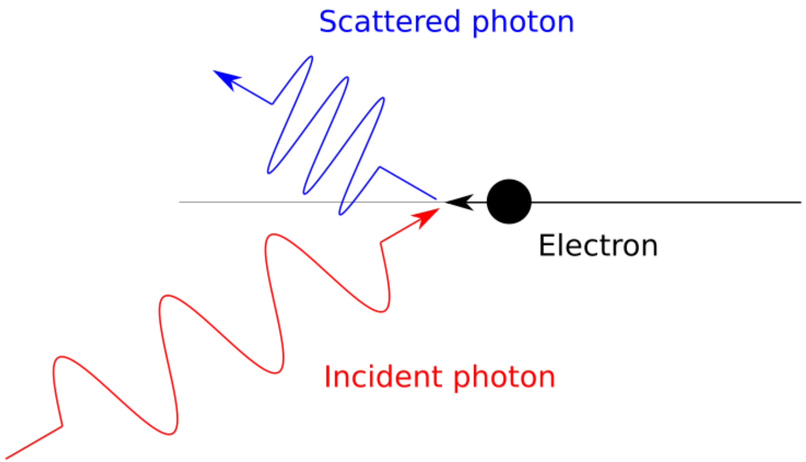
Possible Threefold ERL Mode



Challenges:

- 4 → 6 superimposing beams in main LINAC section
- 1x → 2x two superimposing beams in recirculation beamlines
- 4 → 6 objectives for design momenta (i.e. +2 objective functions but only +1 degree of freedom (PLAS))

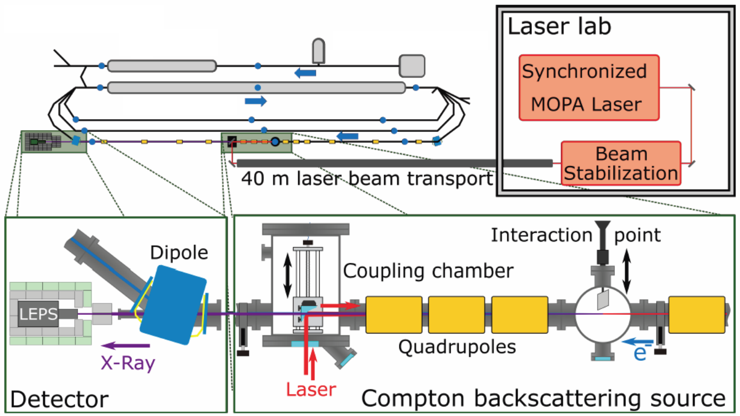
Compton backscattering at the S-DALINAC



- can provide a quasi-monochromatic highly polarized X-ray beam
- weak influence of electron beam due to small recoil and small Compton cross-section

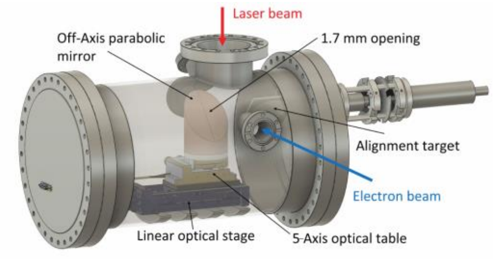
➔ diagnostic tool for energy and energy spread

Compton backscattering at the S-DALINAC



- can provide a quasi-monochromatic highly polarized X-ray beam
- weak influence of electron beam due to small recoil and small Compton cross-section
  ➔ diagnostic tool for energy and energy spread
- Maximum energy in head-on geometry: $E_\gamma \approx 4\gamma^2 E_\mathrm{L}$
  ➔ 180 keV photons from 99 MeV electrons and 1030 nm laser

Coupling Chamber Design:



M. Meier et al., Proc. of IPAC 2022, p. 1121-1124 (2022)