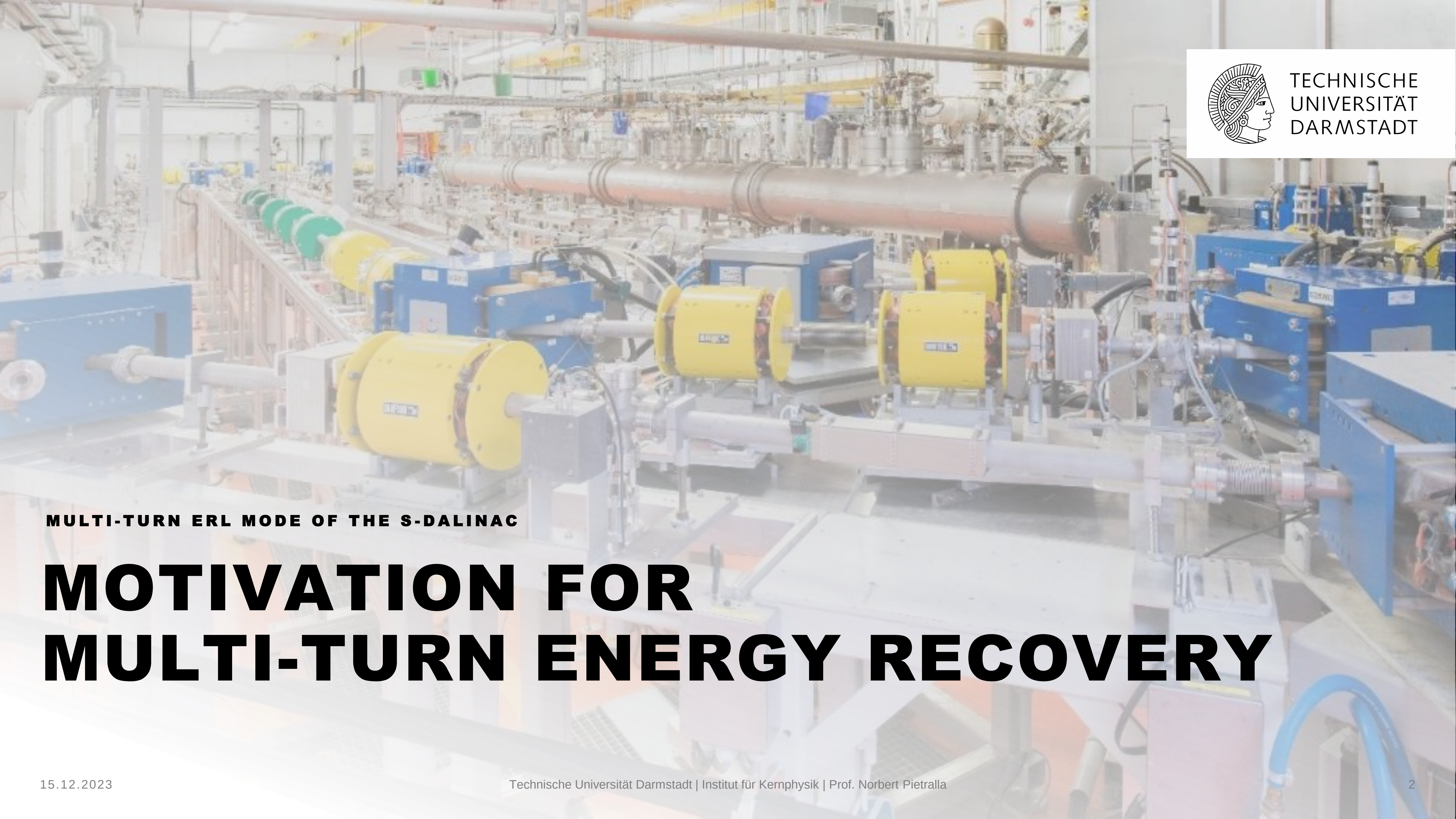
ENERGY-RECYCLING IN A MULTI-TURN ENERGY-RECOVERY LINAC AND PROSPECTS FOR PHOTONUCLEAR REACTIONS

Norbert Pietralla

Michaela Arnold, Jonny Birkhan, Adrian Brauch, Jochim Enders, Ruben Grewe, Johann Isaak, **Lars Jürgensen**, **Jörn Kleemann**, **Maximilian Meier**, **Felix Schliessmann**, Dominic Schneider, Volker Werner + Norbert Pietralla

Work supported by DFG (GRK 2128, GRK 2891), BMBF (05H21RDRB1), and the State of Hesse (Cluster Project ELEMENTS)



MULTI-TURN ERL MODE OF THE S-DALINAC

MOTIVATION FOR MULTI-TURN ENERGY RECOVERY

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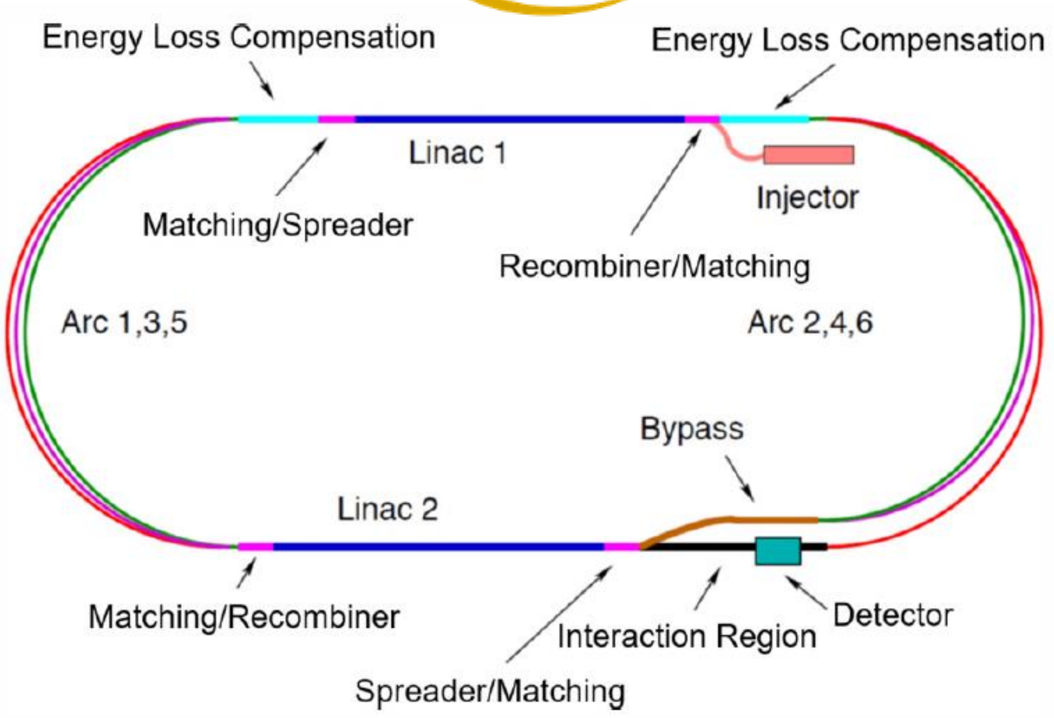
Potential future for CERN beyond 2045

- Collide LHC beam with high power electron beam
- Optimum emittance via use of LINAC
- 50 GeV and 200 mA → 10 GW of (virtual) beam power
- Largest nuclear reactor facility in Europe ca. 8 GW

→ Need for sustainable technology
→ Energy-recovery LINACs



P. Agostini et al,. J. Phys. G: Nucl. Part. Phys. **48,** 110501 (2021)

Nuclear Photonics

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CERN Yellow Reports: Monographs, CERN-2022-001

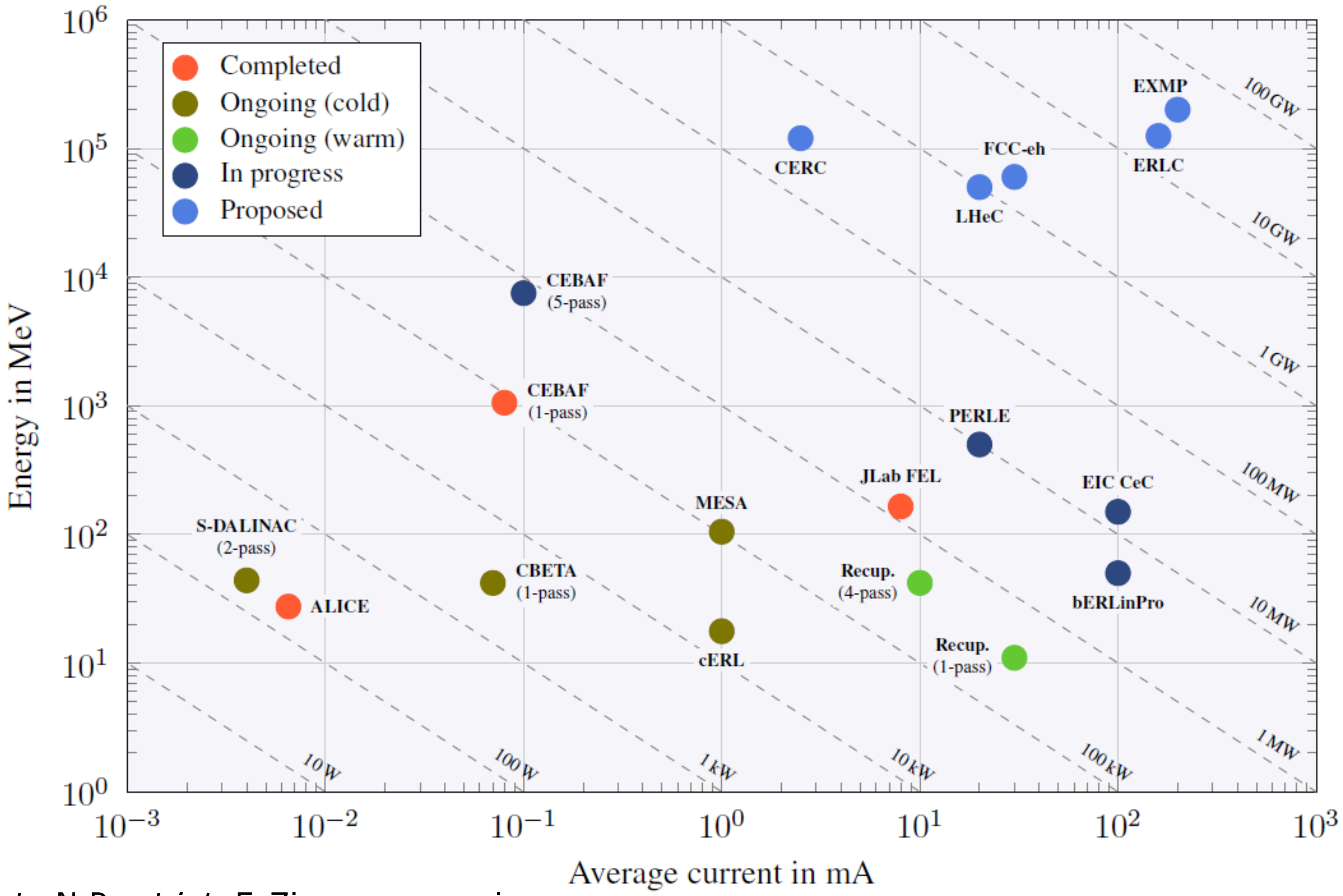
6 Energy-recovery linacs

6.1 Executive summary

Energy Recovery is at the threshold of becoming a key means for the advancement of accelerators. Recycling the kinetic energy of a used beam for accelerating a newly injected beam, i.e. reducing the power consumption, utilising the high injector brightness and dumping at injection energy: these are the key elements of a novel accelerator concept, invented half a century ago [1]. The potential of this

M. Klein, A. Hutton *et int*., N.P., *et int*. F. Zimmermann, in European Strategy for Particle Physics - Accelerator R&D Roadmap,N. Mounet (ed.), CERN-2022-001 (CERN, Geneva, 2022), pp. 185–228.

ENERGY RECOVERY LINACS (ERLS) WORLDWIDE



M. Klein, A. Hutton *et int*., N.P., *et int*. F. Zimmermann, in European Strategy for Particle Physics - Accelerator R&D Roadmap,N. Mounet (ed.), CERN-2022-001 (CERN, Geneva, 2022), pp. 185–228.

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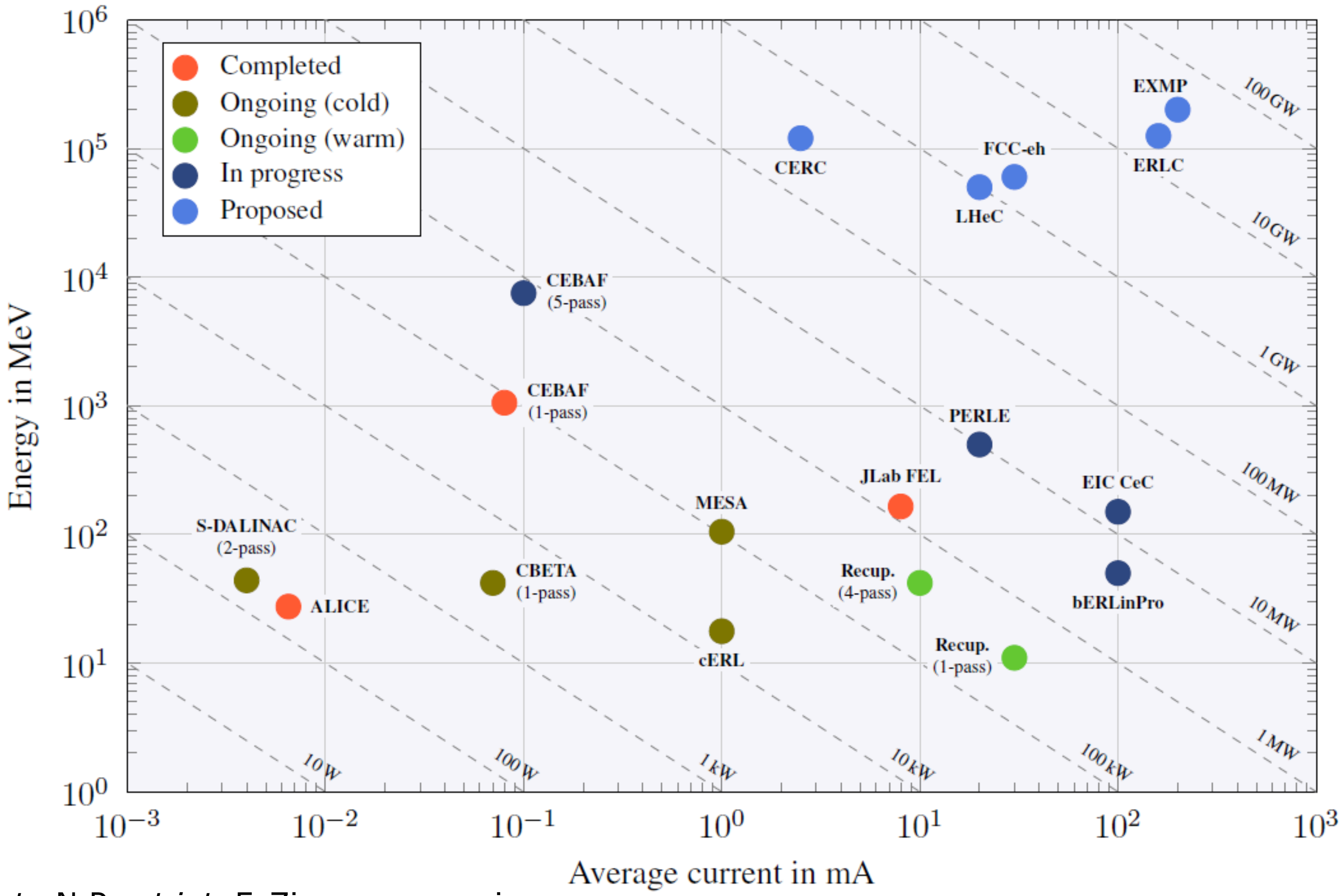

CBETA – first multi-turn SRF-ERL

A. Bartnik et al.,
Phys. Rev. Lett. **125**, 044803 (2020).

M. Klein, A. Hutton *et int.*, N.P., *et int.* F. Zimmermann, in European Strategy for Particle Physics - Accelerator R&D Roadmap,N. Mounet (ed.), CERN-2022-001 (CERN, Geneva, 2022), pp. 185–228.

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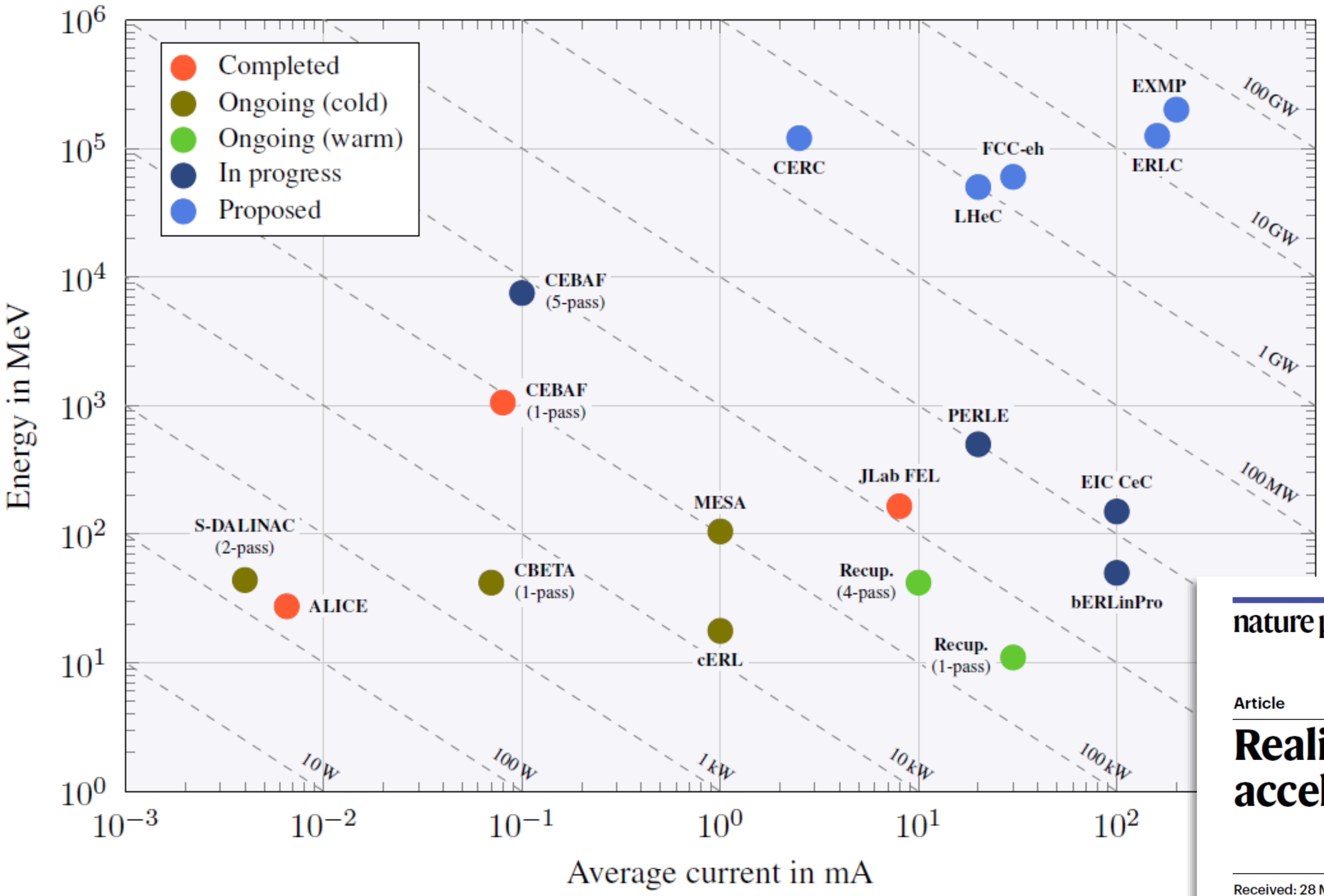

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For the first time, measured energy-recycling directly in multi-turn SRF-ERL.

measured energy-recycling of 87%

nature physics

Article https://doi.org/10.1038/s41567-022-01856-w

Realization of a multi-turn energy recovery accelerator

Received: 28 March 2022
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Published online: 26 January 2023

Felix Schliessmann, Michaela Arnold, Lars Juergensen, Norbert Pietralla, Manuel Dutine, Marco Fischer, Ruben Grewe, Manuel Steinhorst, Lennart Stobbe & Simon Weih

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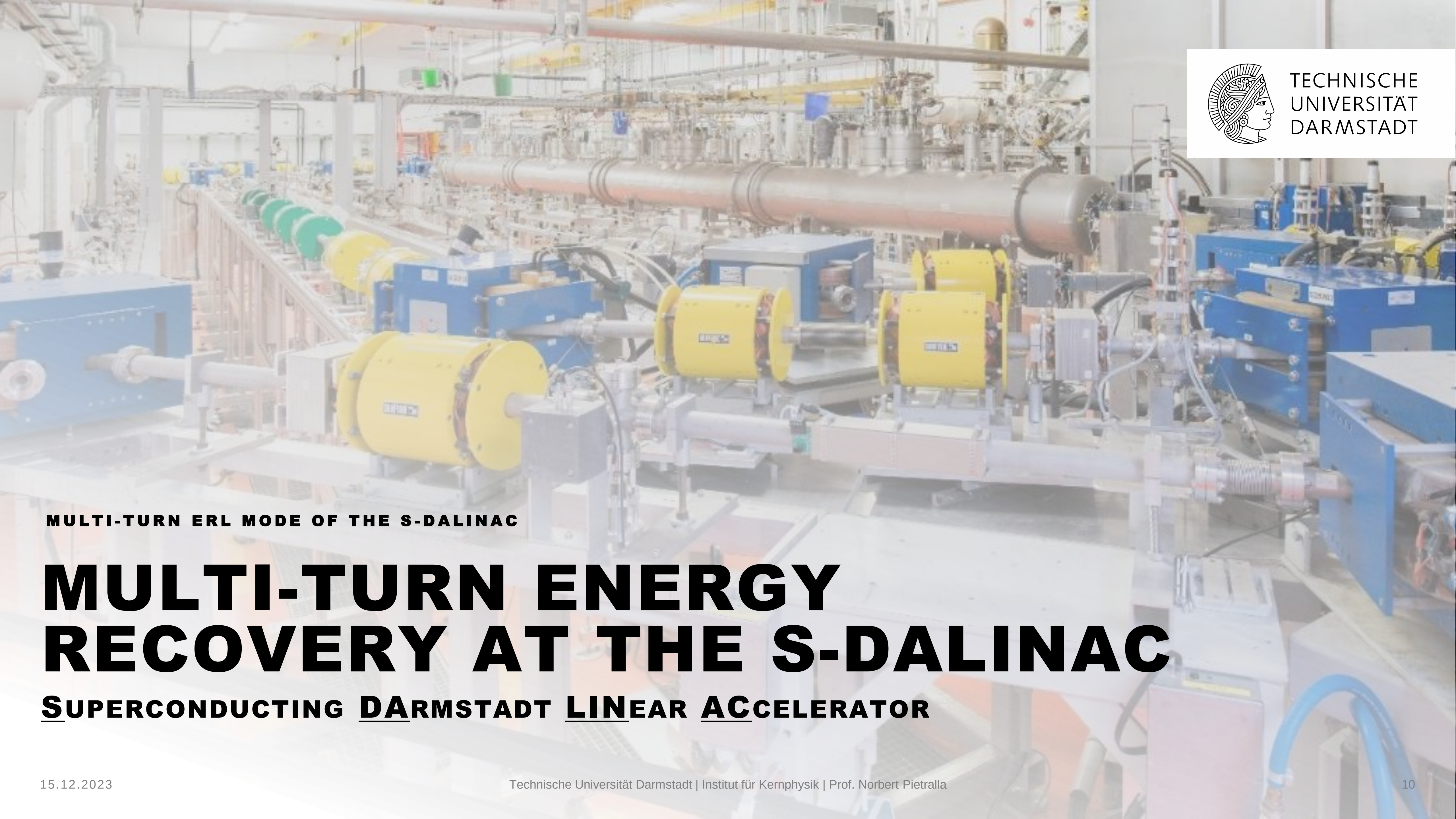
OUTLINE



MULTI-TURN ERL MODE OF THE S-DALINAC

MULTI-TURN ENERGY RECOVERY AT THE S-DALINAC

SUPERCONDUCTING DARMSTADT LINEAR ACCELERATOR

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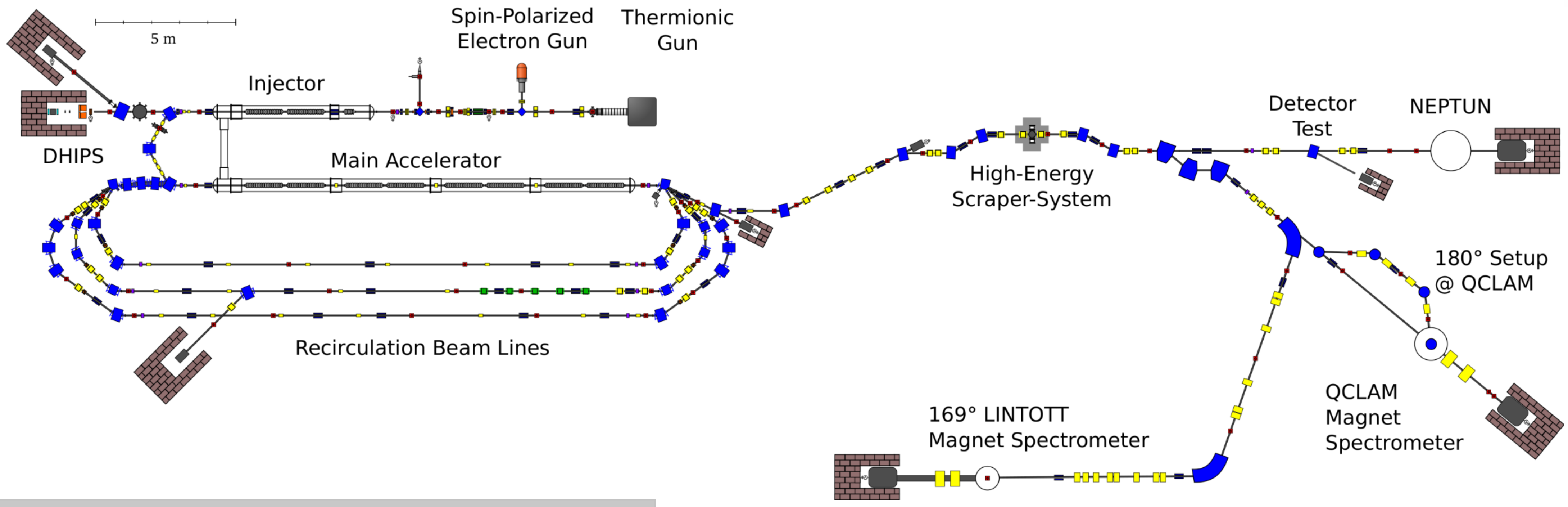

Thrice Recirculating Operation	
Energy Gain Injector	7.6 MeV
Energy Gain Linac	30.4 MeV
Beam Current	20 µA

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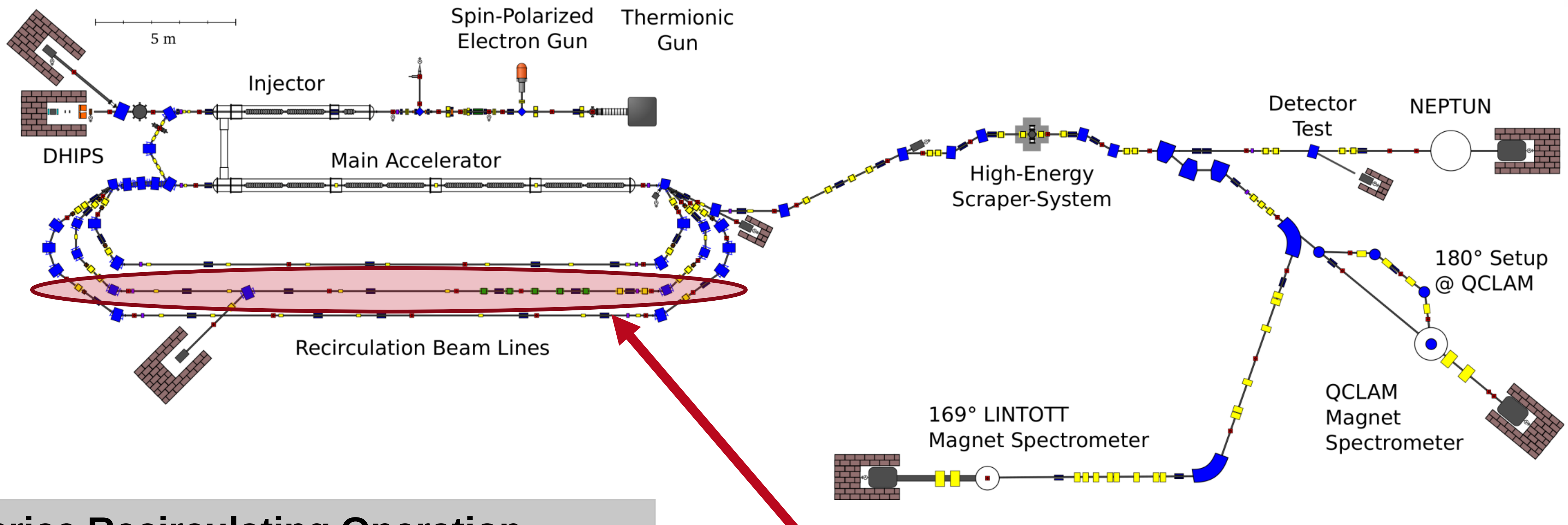

Thrice Recirculating Operation	
Energy Gain Injector	7.6 MeV
Energy Gain Linac	30.4 MeV
Beam Current	20 µA

new beamline in 2015/16

2015/16 NEW BEAM LINE

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ACCELENCE

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

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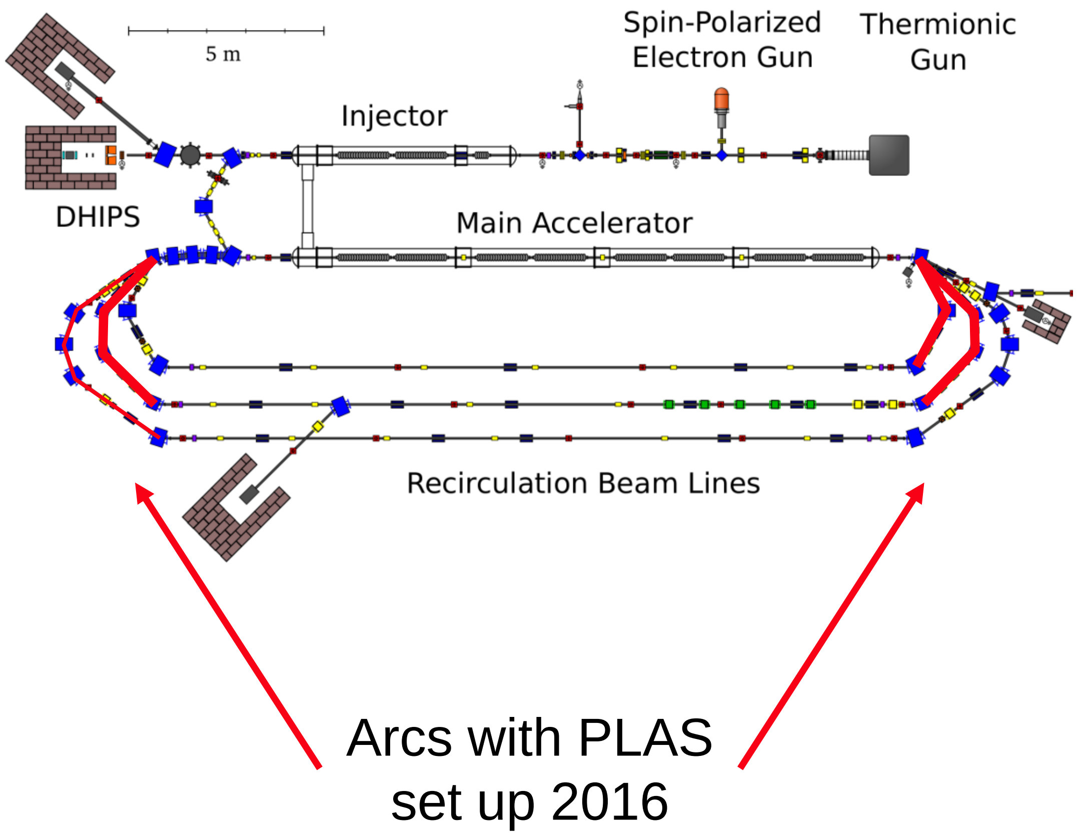


- Path length adjustment system (PLAS) in arcs of the recirculation beam lines

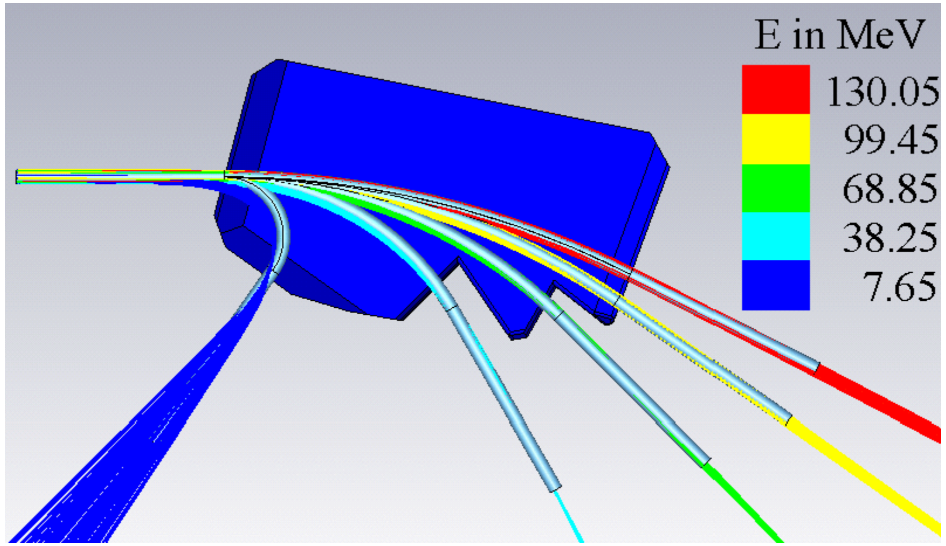
- PLAS in 1st and 2nd recirculation tunable for
  - Beam acceleration
  - Phase change up to 360º
  - ➢ Beam deceleration (Energy Recovery)
- Enables single-fold and two-fold ERL mode

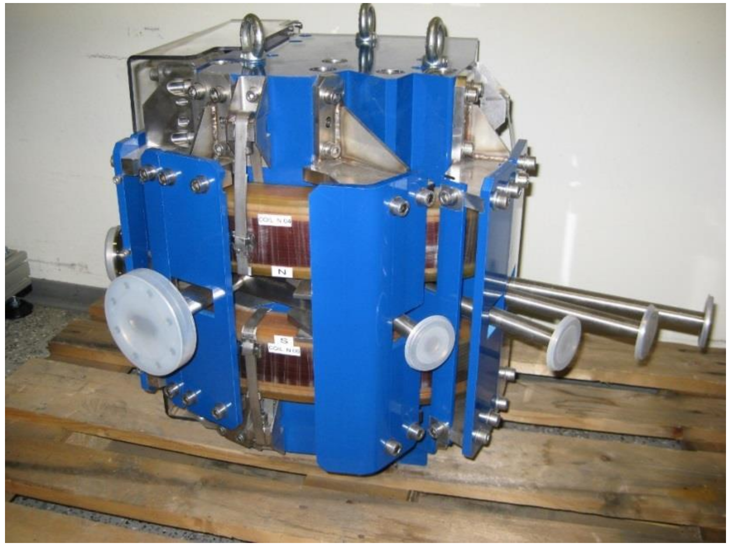
Fall 2015

Summer 2016

Separation Dipole

- Particle tracking of all beam energies (CST Particle Studio)
- Acceptance
  - Beam diameter: up to 10 mm
  - Energy spread: up to $1 \cdot 10^{-3}$
  - Angular spread: up to 0.1°





M. Arnold (PhD thesis, TU Darmstadt, 2016).

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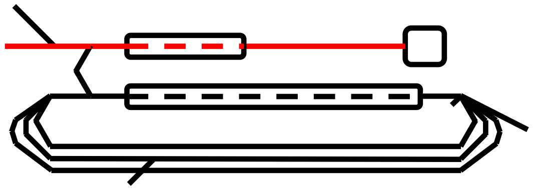
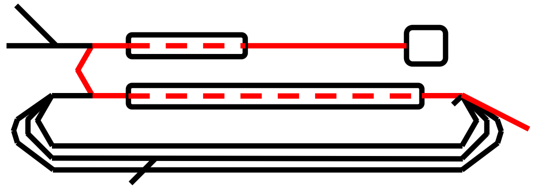
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



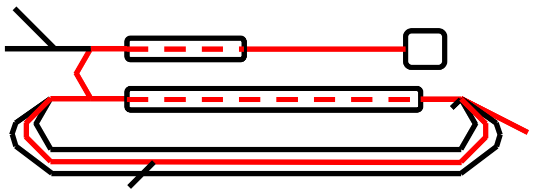
December 2016

Single pass



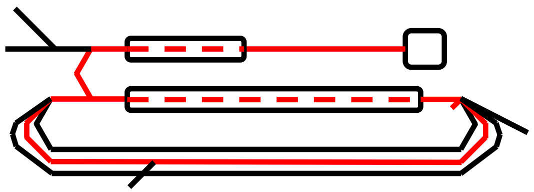
December 2016

1x rec.



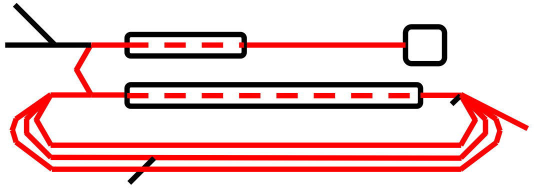
May 2017

1x ERL



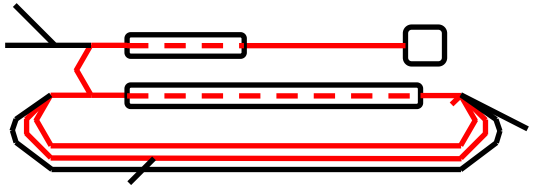
August 2017

3x rec.



November 2018

2x ERL



August 2021

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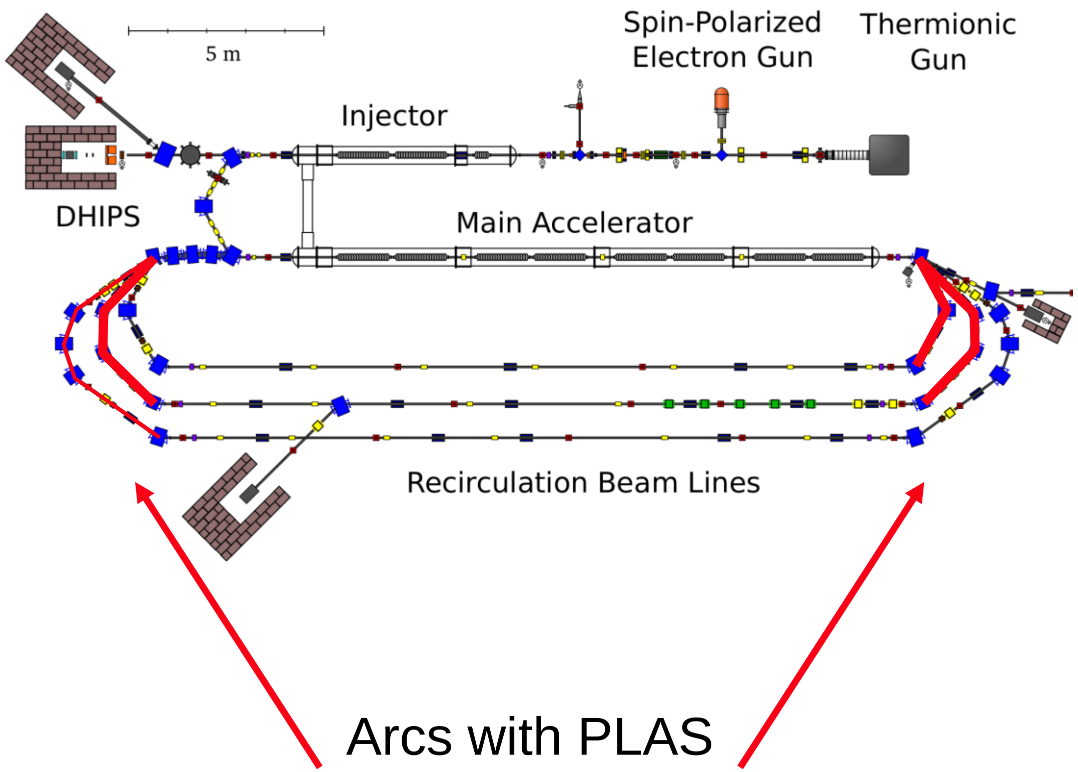


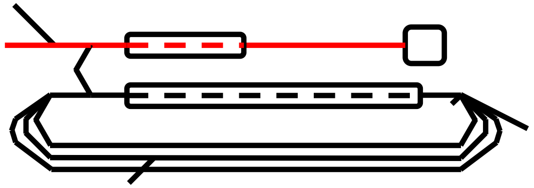
Arcs with PLAS set up 2016

- Path length adjustment system (PLAS) in arcs of the recirculation beam lines
- PLAS in 1st and 2nd recirculation tunable for
  - Beam acceleration
  - Phase change up to 360°
  - ➢ Beam deceleration (Energy Recovery)
- Enables single-fold and two-fold ERL mode
- Research on ERL modes since 2016, e.g.:

1. 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). https://doi.org/10.1103/PhysRevAccelBeams.23.020101
2. F. Schliessmann *et al.* Realization of a multi-turn energy recovery accelerator. *Nat. Phys.* **19**, 597 (2023). https://doi.org/10.1038/s41567-022-01856-w

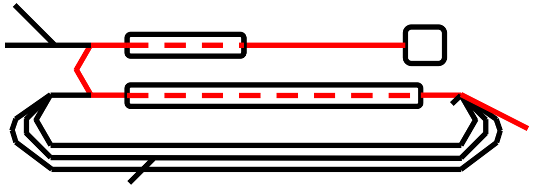
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



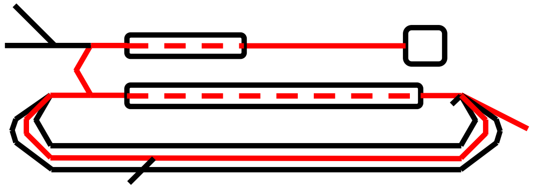
December 2016

Single pass



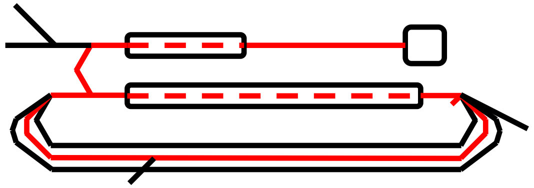
December 2016

1x rec.



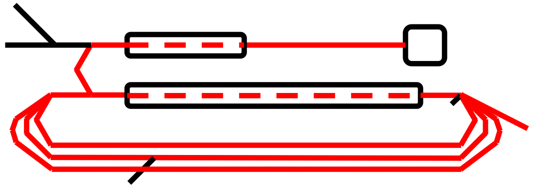
May 2017

1x ERL



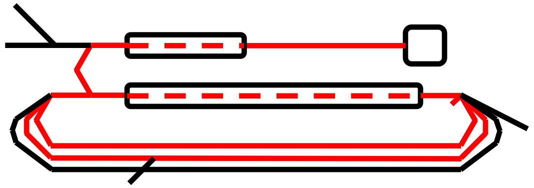
August 2017

3x rec.



November 2018

2x ERL



August 2021

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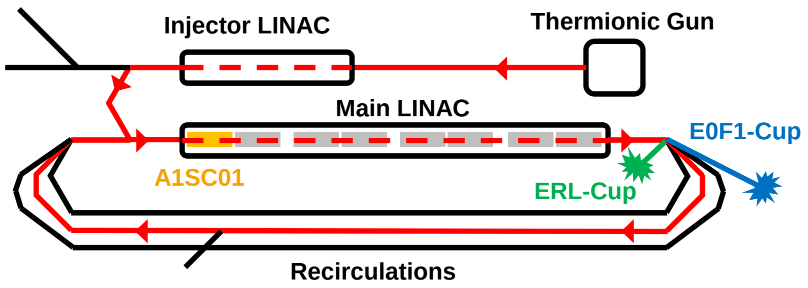
- Energy gain injector: 2.5 MeV
- Energy gain LINAC: 20.0 MeV
- Current (I_{in}): 1.2 µA



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

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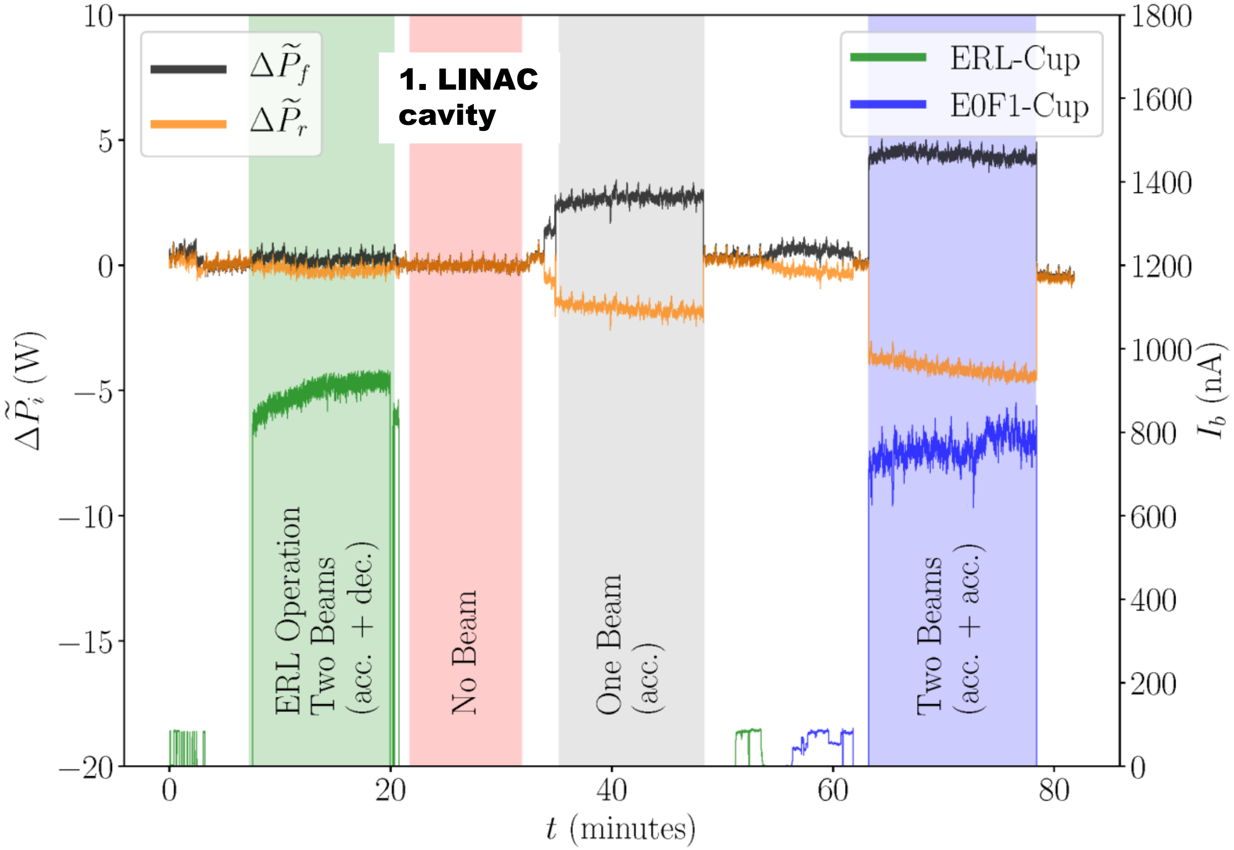
„Cavity beam-load“

difference between forward RF power and reflected power



1^{st} ERL in Germany, August 2017

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).*

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.

8.59 W: about 10% less than 2 x 4.51 W

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).*

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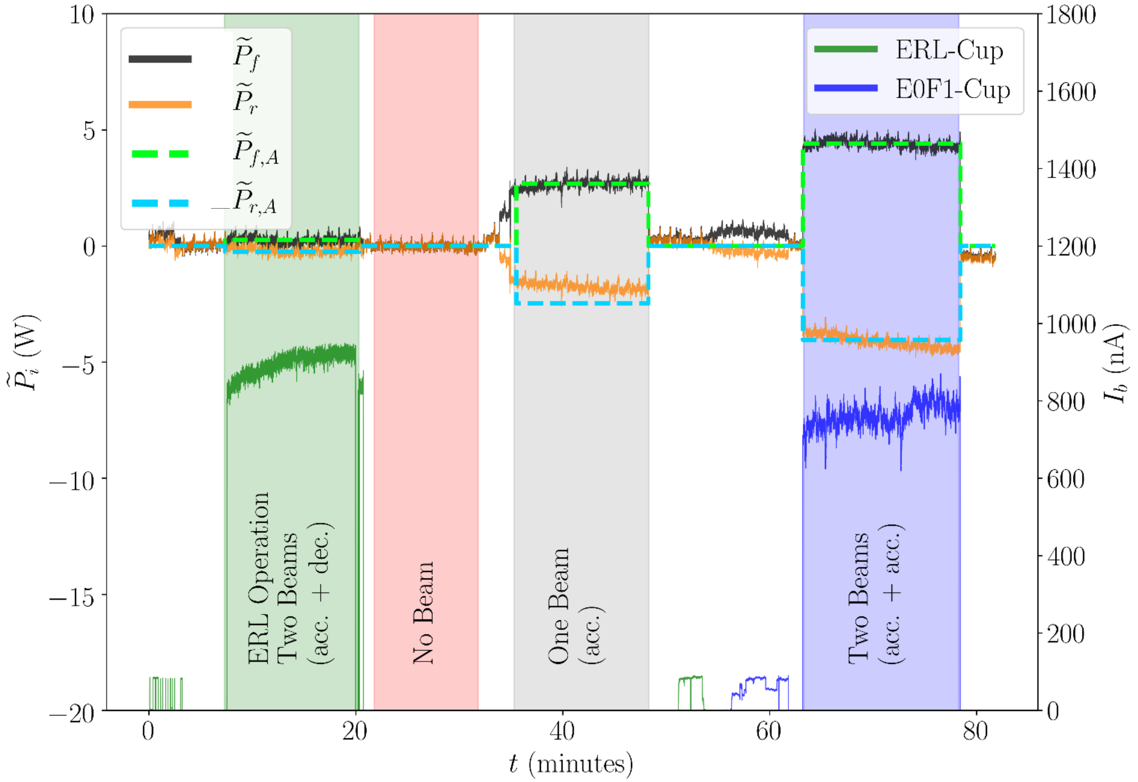
$$P_f = P_0 \frac{\left[\beta_{input} + (1 + \beta_{output} + \beta_{beam})\right]^2}{4\beta_{input}}$$

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



- Curve-fitting to data in P_f
  - β_{beam}=0: to obtain β_{input}, β_{output} and P_0
  - β_{beam}≠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).*

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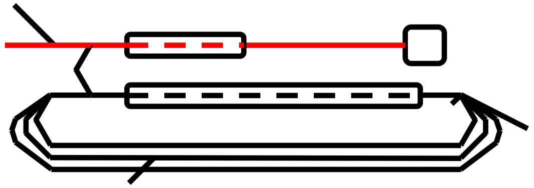
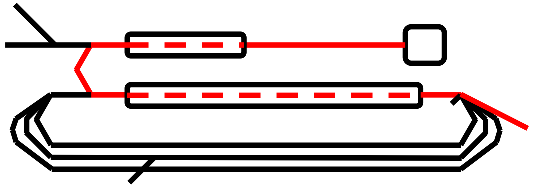
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



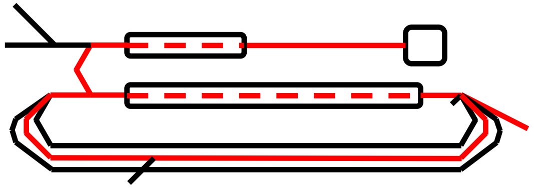
December 2016

Single pass



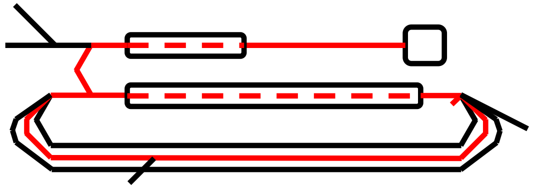
December 2016

1x rec.



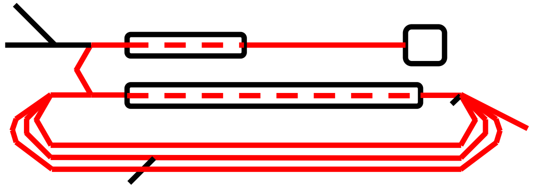
May 2017

1x ERL



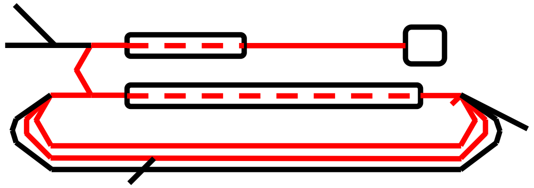
August 2017

3x rec.



November 2018

2x ERL



August 2021

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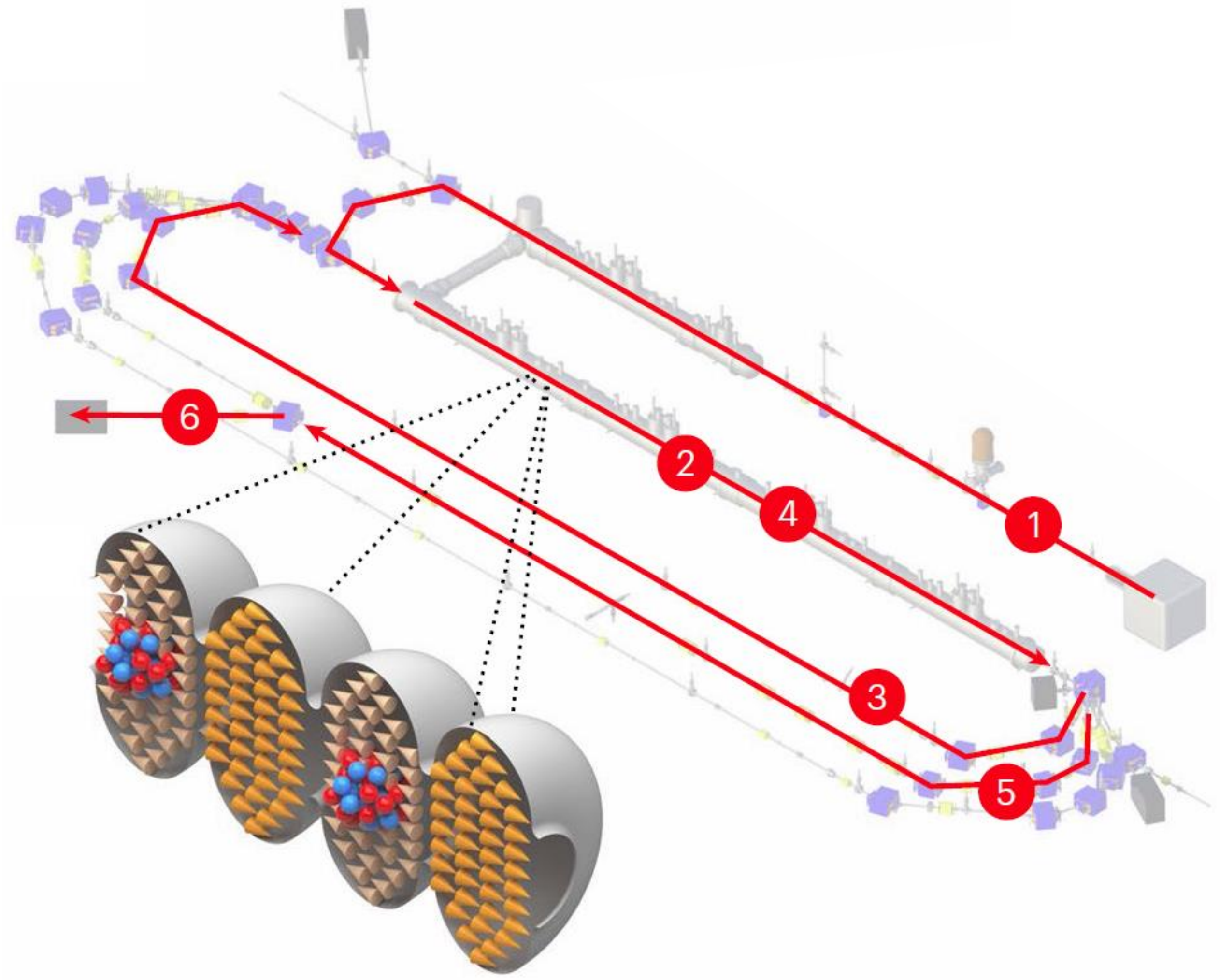

Conventional two-fold Acceleration (CTA)		
(1)	Injection	5.00 MeV/c
(2)	1^{st} acceleration	23.66 MeV/c
(3)	1^{st} recirculation	0° phase shift
(4)	2^{nd} acceleration	41.61 MeV/c
(5)	2^{nd} recirculation	0° phase shift
(6)	Beam dump	

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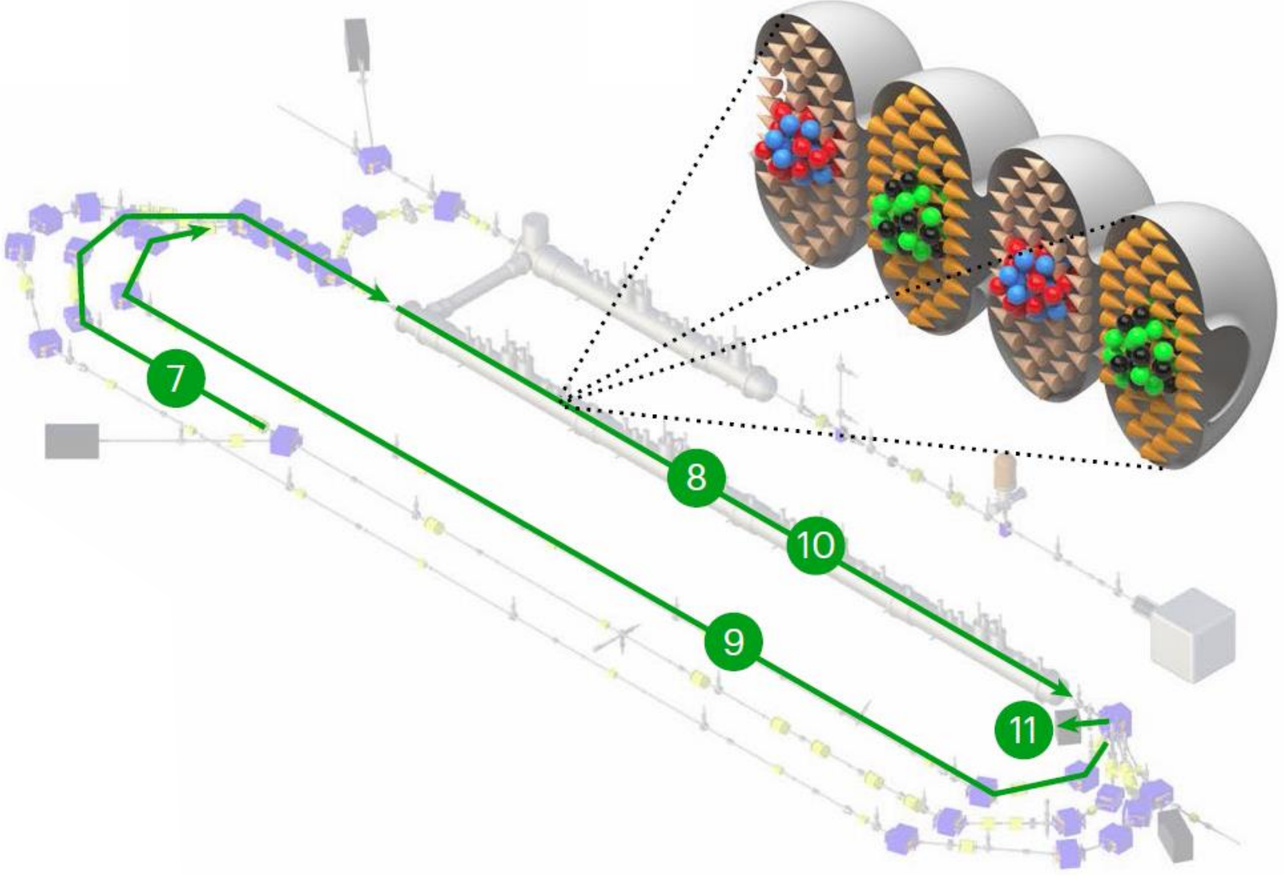
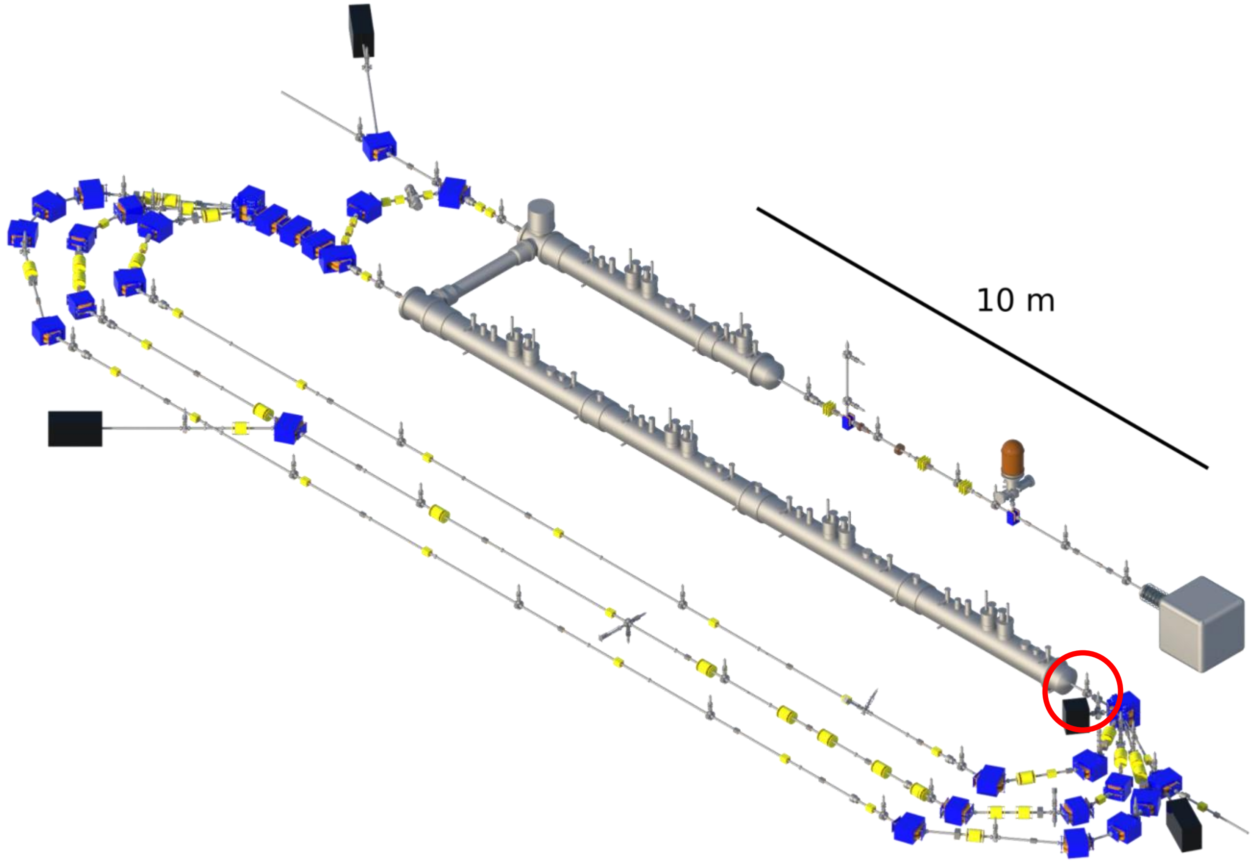
Two-fold Energy Recovery (TER)		
(1) – (6)	As before	41.61 MeV/c
(7)	2nd recirculation	180° phase shift
(8)	1st deceleration	23.66 MeV/c
(9)	3rd recirculation	0° phase shift
(10)	2nd deceleration	5 MeV/c
(11)	Low energy beam dump	





- Eight accelerating cavities
- Two recirculation arcs
- Degrees of freedom:
  - Amplitudes $\vec{A}$
  - Phases $\vec{\phi}$
  - Path lengths $\vec{L}$
  - Longitudinal dispersions $\vec{R}_{56}$

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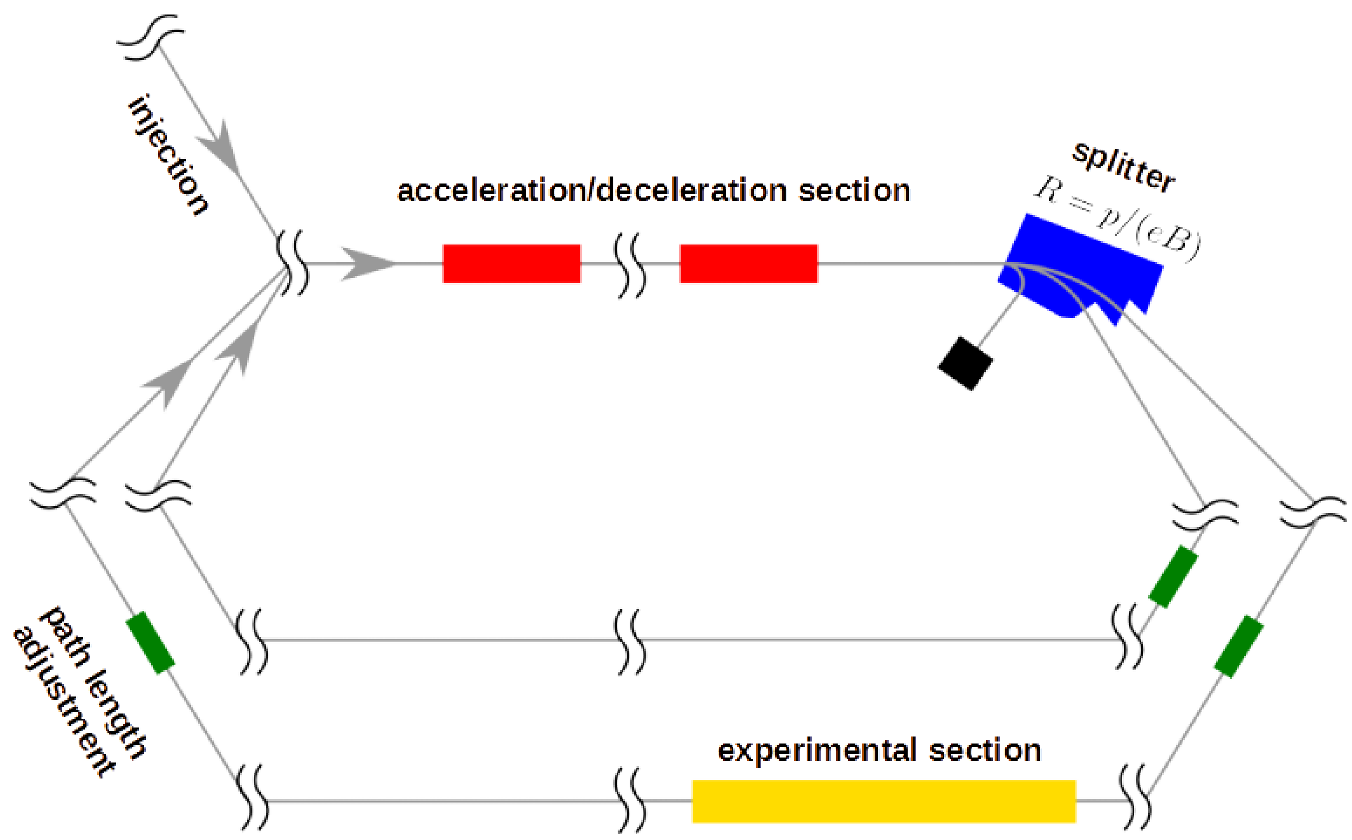
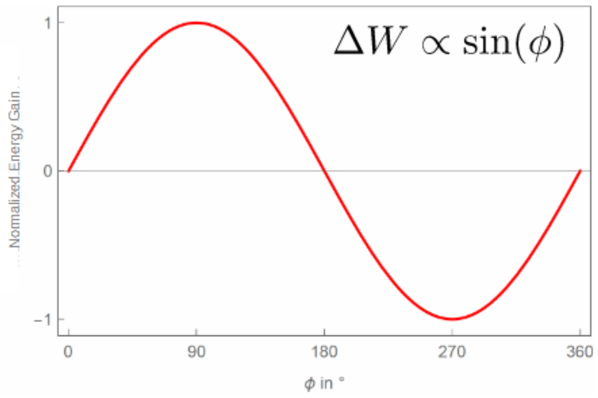


Objective functions result from splitter magnet ratio:
$p_I : p_F : p_S = 1 : 4.7 : 8.3$

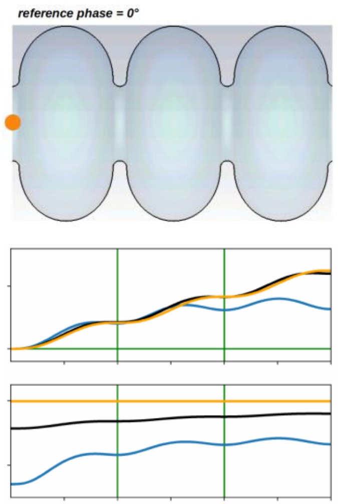
Degrees of freedom:
$\vec{A}, \vec{\phi}, \vec{L}, \vec{R}_{56}$

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

Simplified model of energy gain



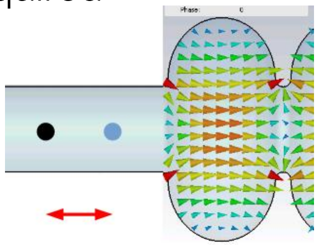
More complex model of energy gain



Speed changes along the cavity

→ Impacts interaction with alternating electric field

→ Numerical simulations required



- Phase slippage not negligible
- Simplified model of energy gain not applicable
- Numerical simulations of interaction between electrons and EM fields required

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

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

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

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

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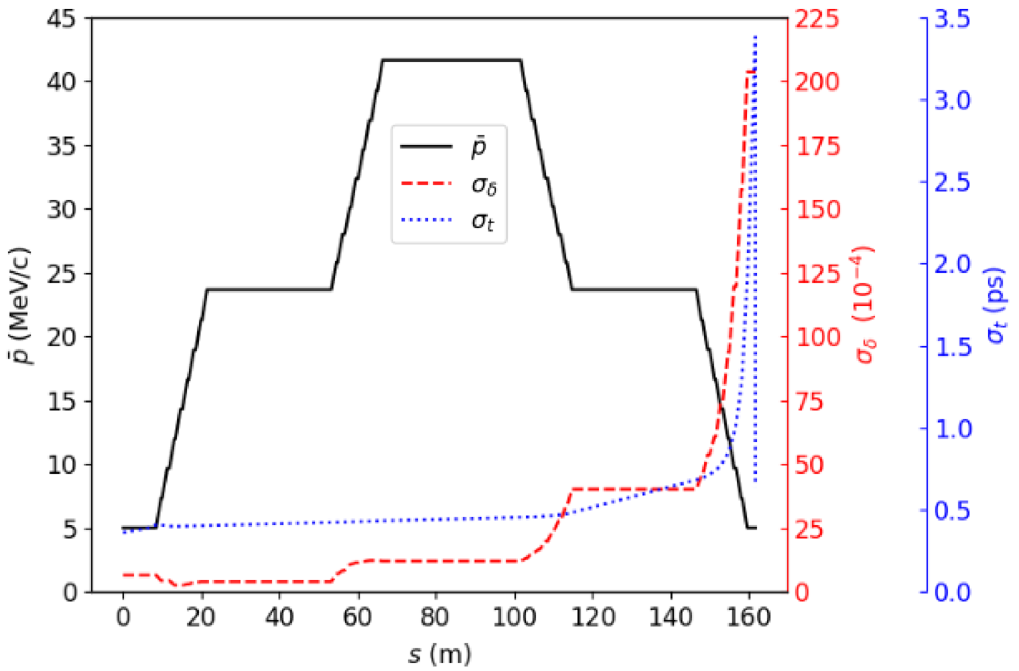
$$\min \|\cdots\|_{1^*}$$



$\bar{p}$
σ_δ
σ_t
$\bar{p}$ (MeV/c)
σ_δ (10^{-4})
σ_t (ps)
s (m)

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

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

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

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

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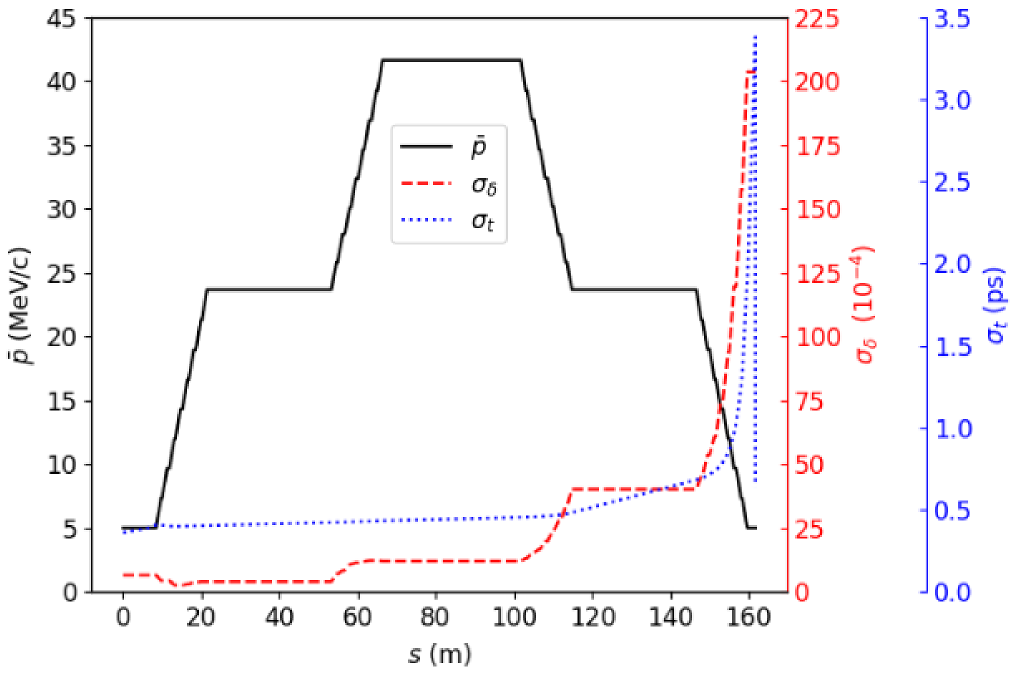
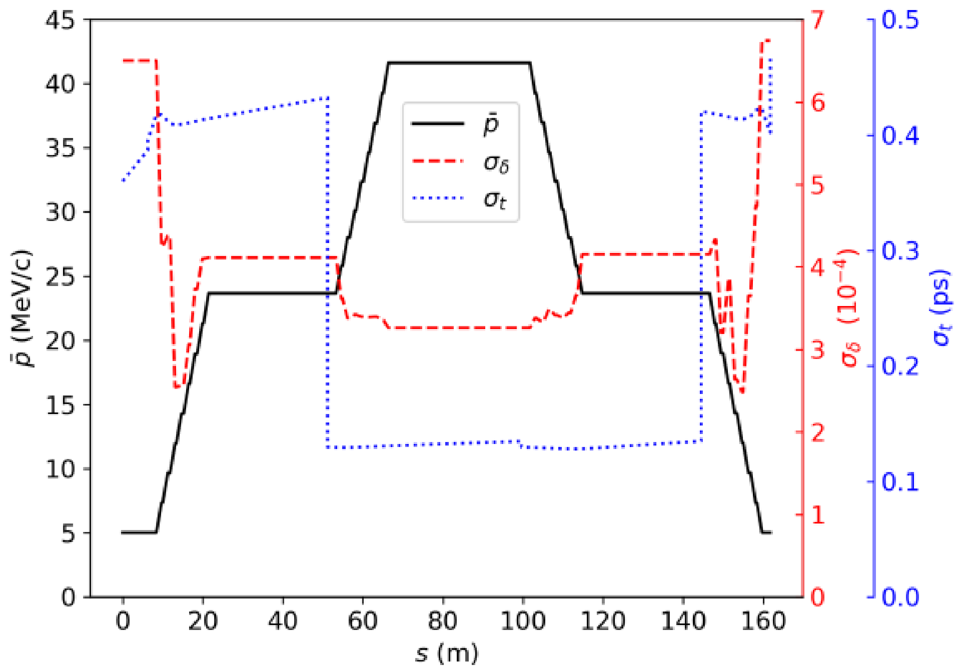
$$\min \|\cdots\|_{1^*}$$



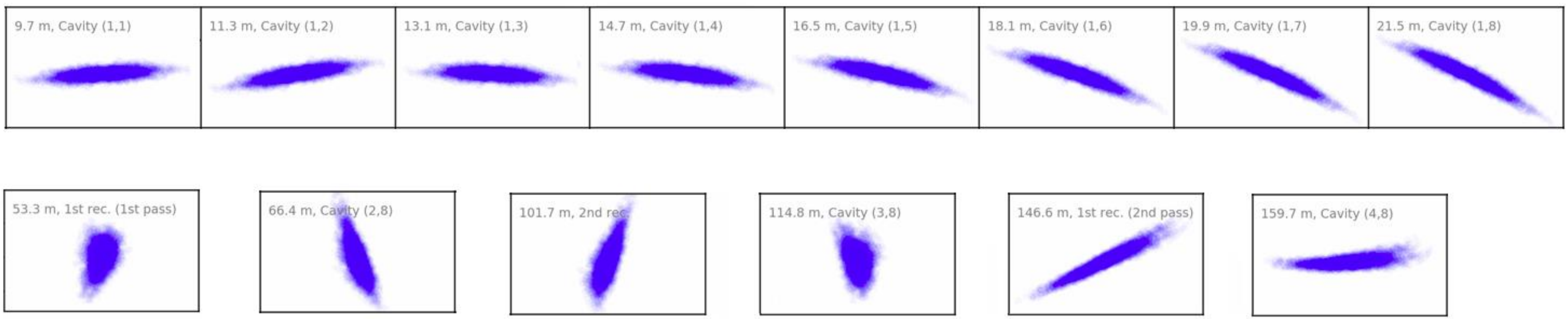
$$\min \|\cdots\|_{1^*} \quad \textbf{and} \quad \min \sigma_\delta(s)$$

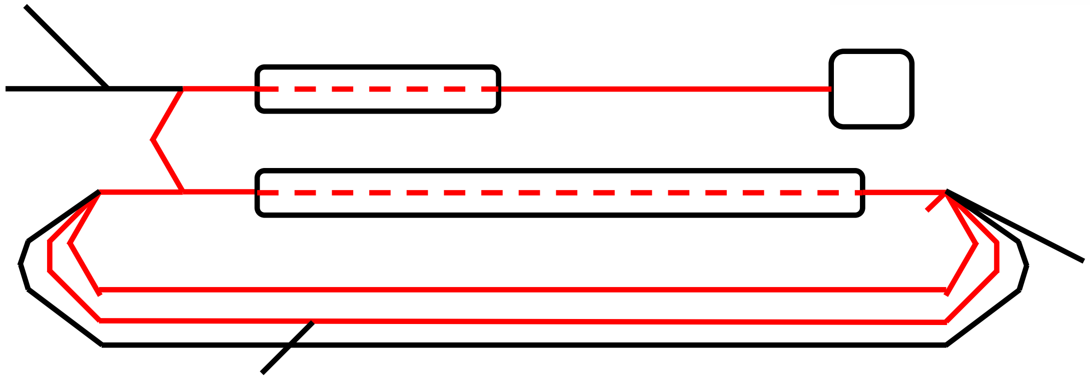


LINAC Cavity	#1	#2	#3	#4	#5	#6	#7	#8
Off-crest phase (°) (during 1st LINAC pass)	-9.7	-5.7	13.2	4.0	6.1	7.2	5.6	3.2
Off-crest momentum gain (MeV/c) (during 1st LINAC pass)	2.34	2.32	2.29	2.34	2.33	2.33	2.35	2.36
On-crest momentum gain (MeV/c) (during 1st LINAC pass)	2.37	2.33	2.35	2.35	2.34	2.34	2.36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

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

LONGITUDINAL PHASE SPACE





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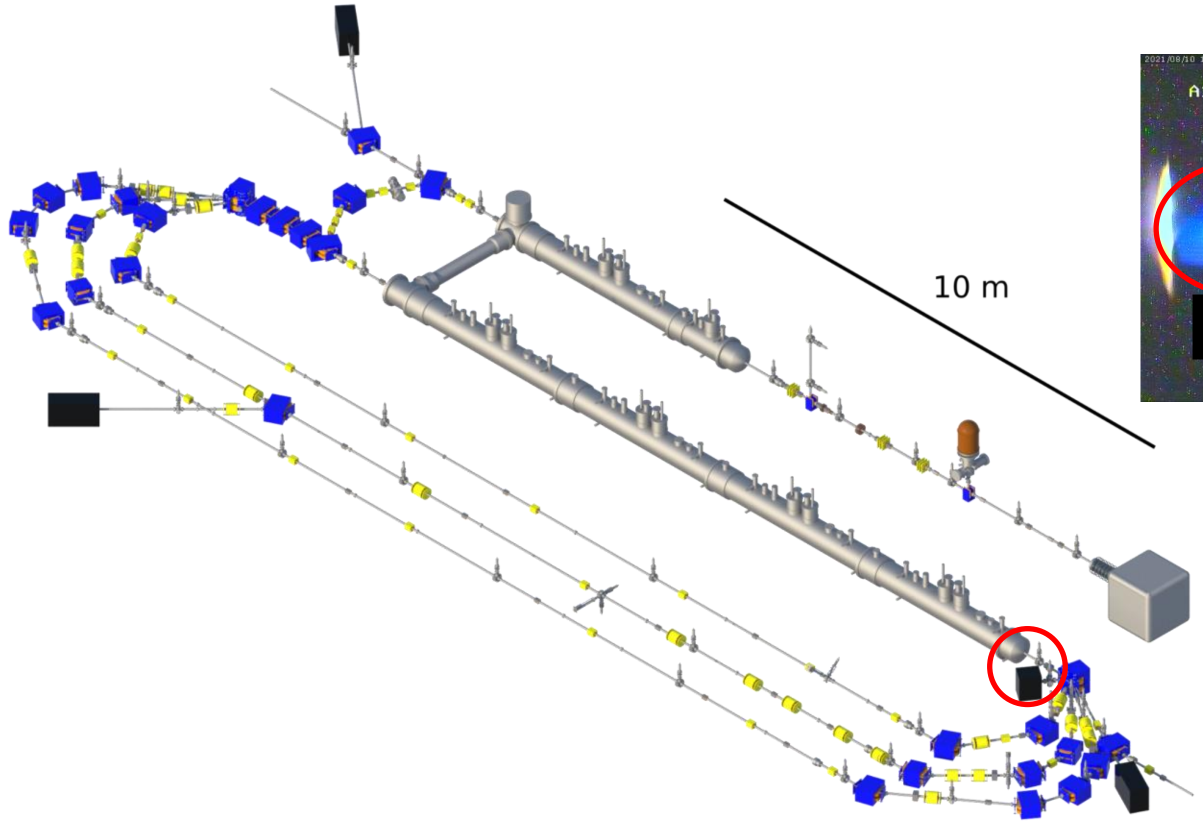

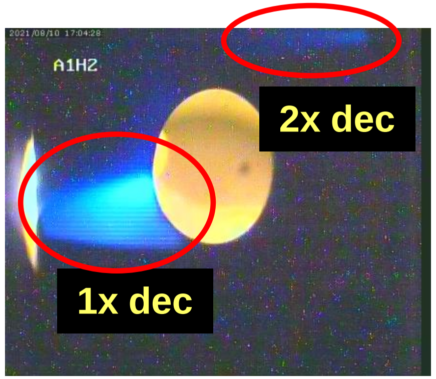

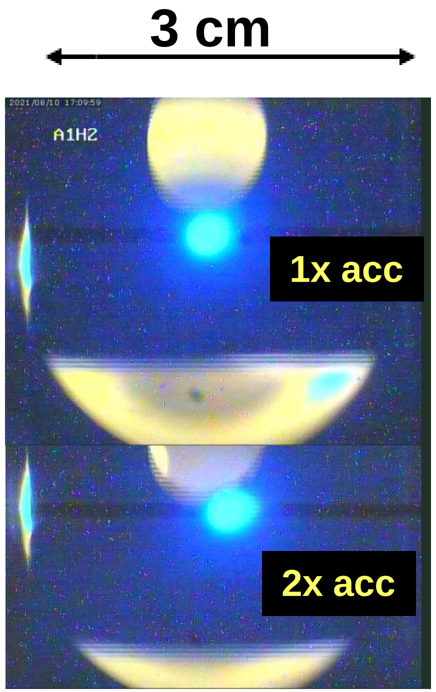

- Limits of transverse beam tuning

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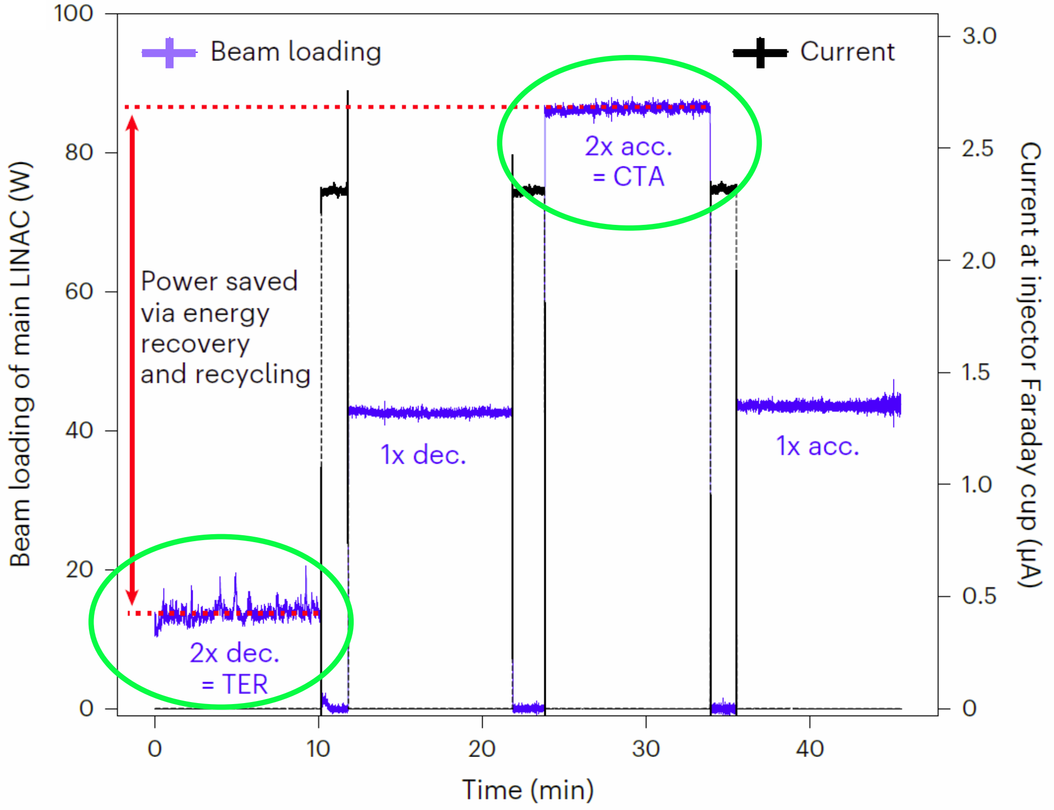
- Measurement of beam loadings of two-fold acceleration $P_{\mathrm{b,CTA}}$ and two-fold ERL $P_{\mathrm{b,TER}}$
- Energy recovery efficency is then given by

$$\eta = \frac{P_{\mathrm{b,CTA}} - P_{\mathrm{b,TER}}}{P_{\mathrm{b,CTA}}}$$

- Stable operation with a beam current of 2.3 μA:

Mode	Beam loading
CTA	86.3 ± 0.3 W
TER	13.8 ± 1.1 W

➢ $\eta = 84.0 \pm 1.2\%$



F. Schliessmann *et al.* Realization of a multi-turn energy recovery accelerator. *Nat. Phys.* **19**, 597 (2023).

https://doi.org/10.1038/s41567-022-01856-w

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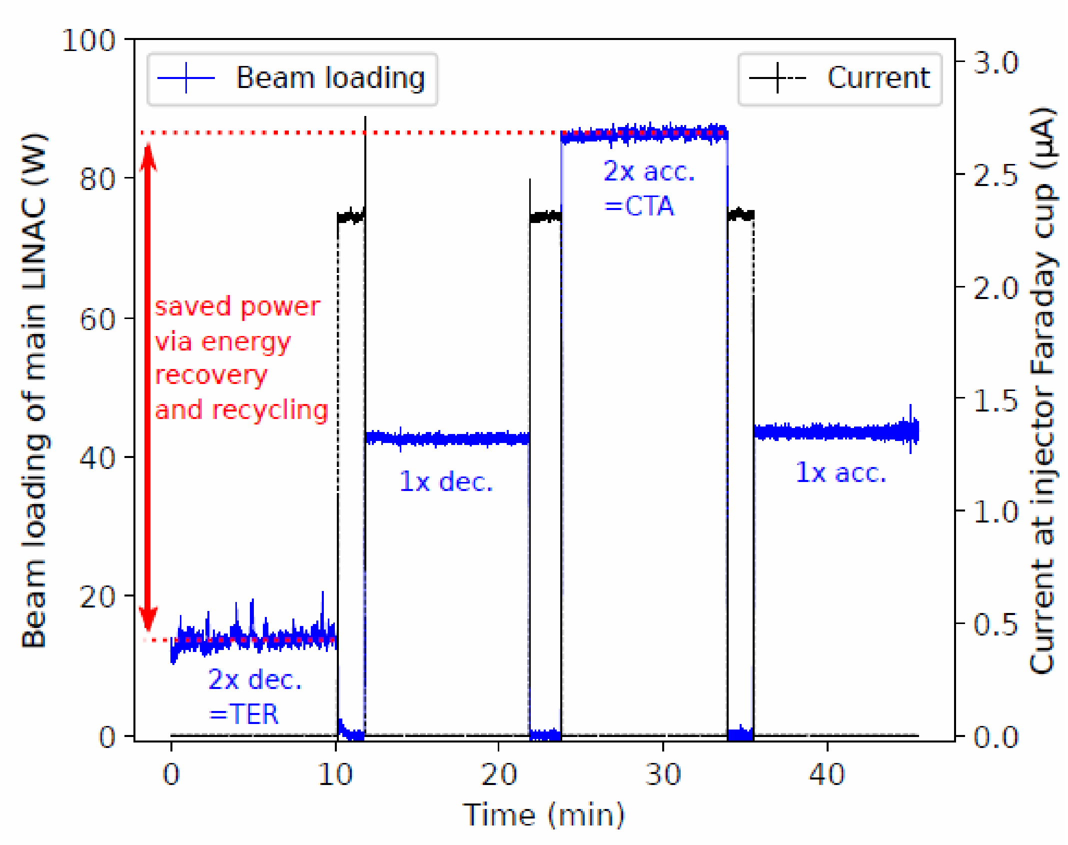

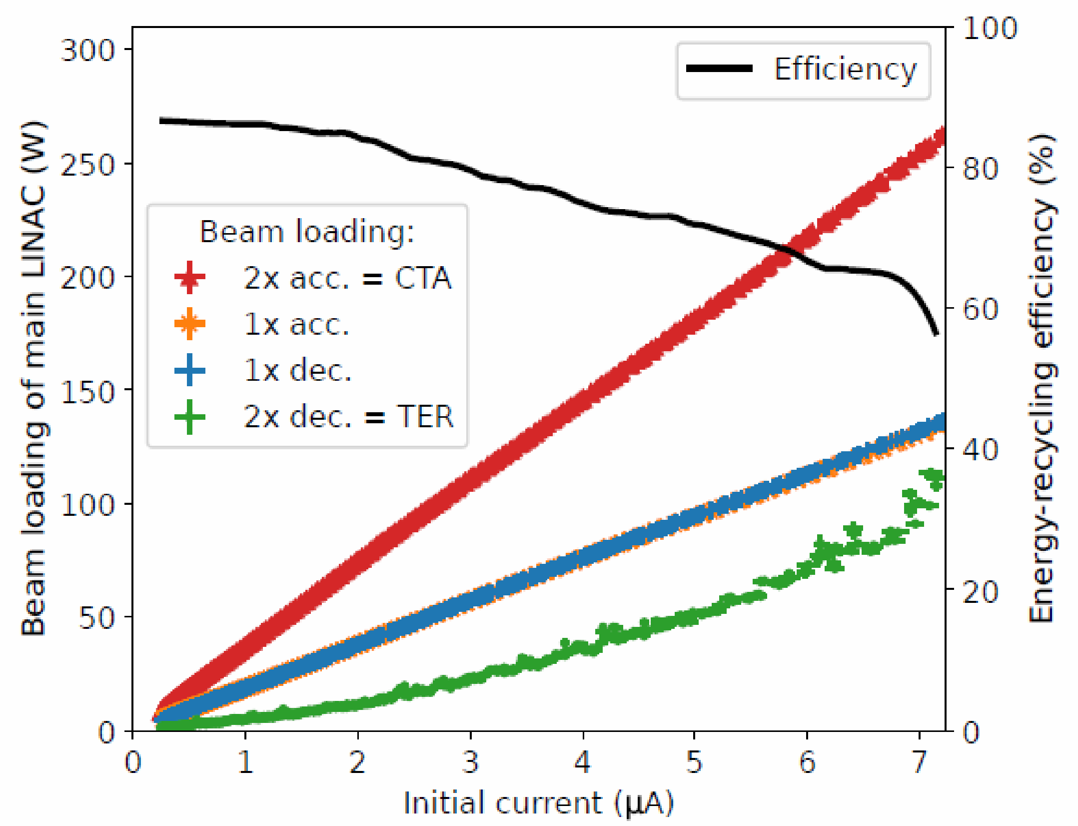

F. Schliessmann *et al.* Realization of a multi-turn energy recovery accelerator. *Nat. Phys.* **19**, 597 (2023).

https://doi.org/10.1038/s41567-022-01856-w

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- Beam loading measured for inital (injection) beam currents from 0.2 to above 7 µA

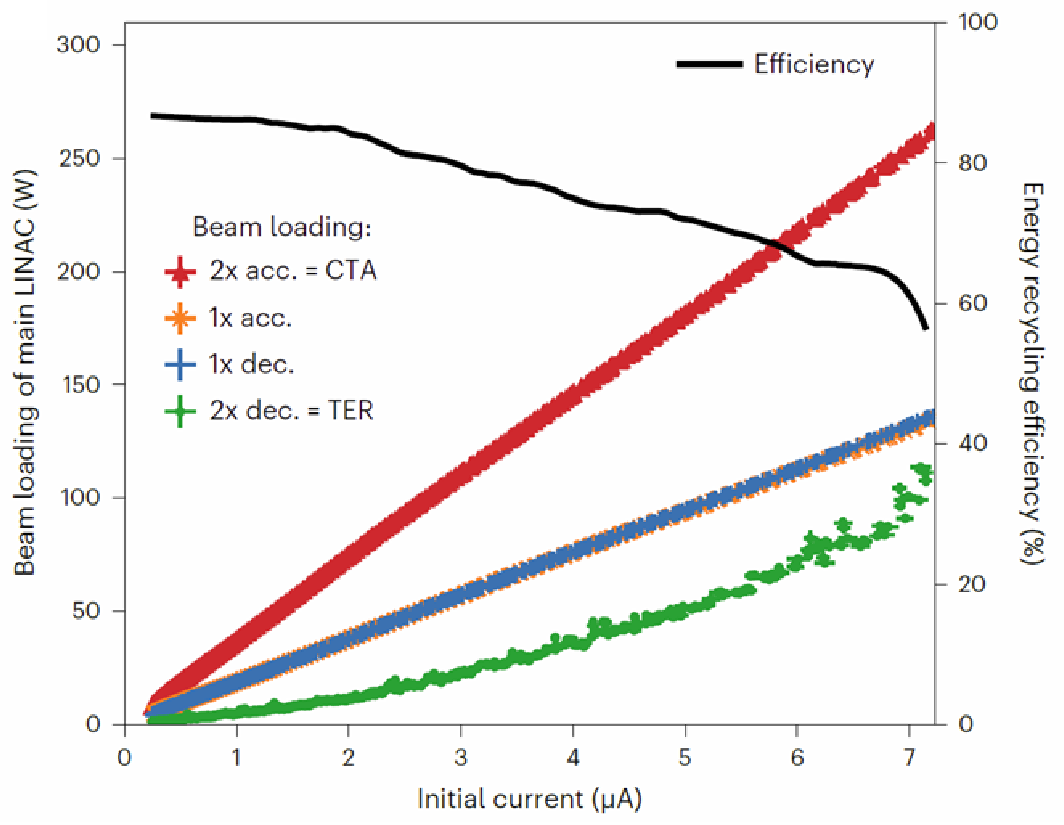
- Recovery efficiency **up to 87** % for low currents

- 1x acc. and TER beam in *shared* beam pipe
- ➢ Increase in transverse emittance
- ➢ TER beam not fully kept in acceptance

- Efficiency decreasing with higher currents

- Extended measurements of beam properties as a function of beam intensity planned

- *individual* beam transport for future ERL accelerators under investigation



F. Schliessmann et al. *Nat. Phys.* (2023)

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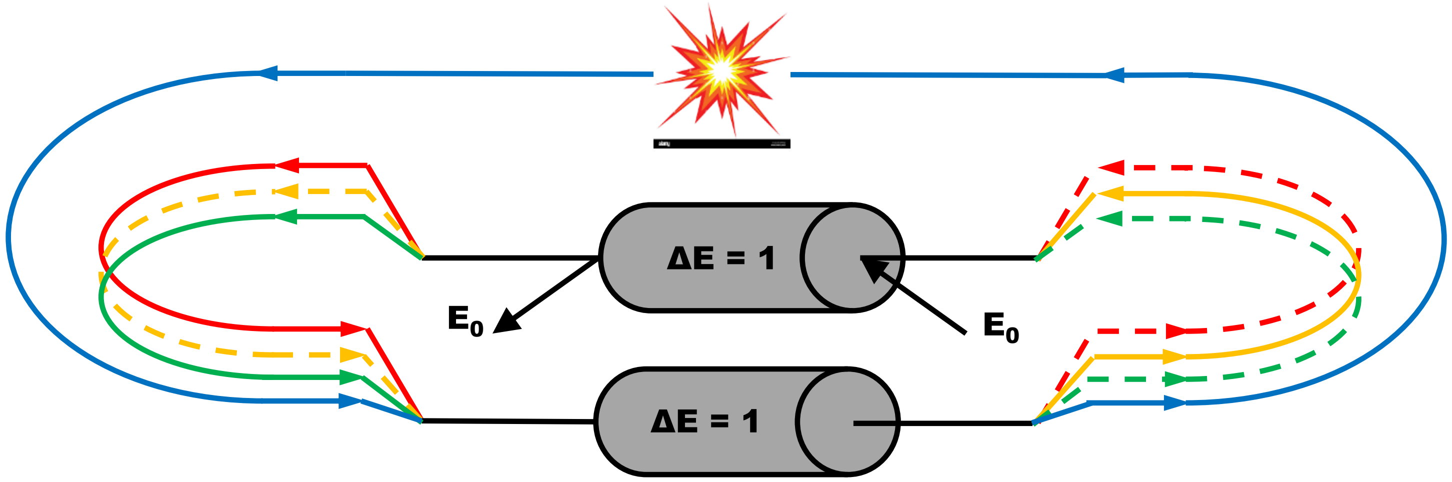
Institut für Kernphysik S-DALINAC Technische Universität Darmstadt

ERL – Applications

An ERL is the optimum collider

- best possible emittance
- high beam current with low beam load
- faint target => high beam current to be recovered

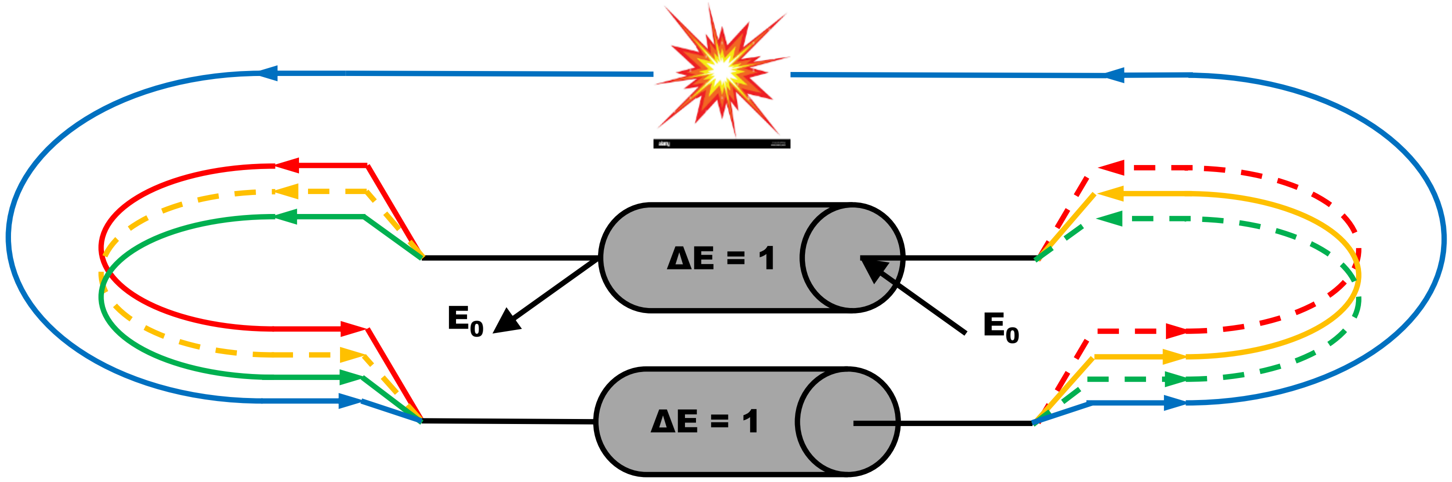


ERL – Applications

An ERL is the optimum collider

- best possible emittance
- high beam current with low beam load
- faint target => high beam current to be recovered

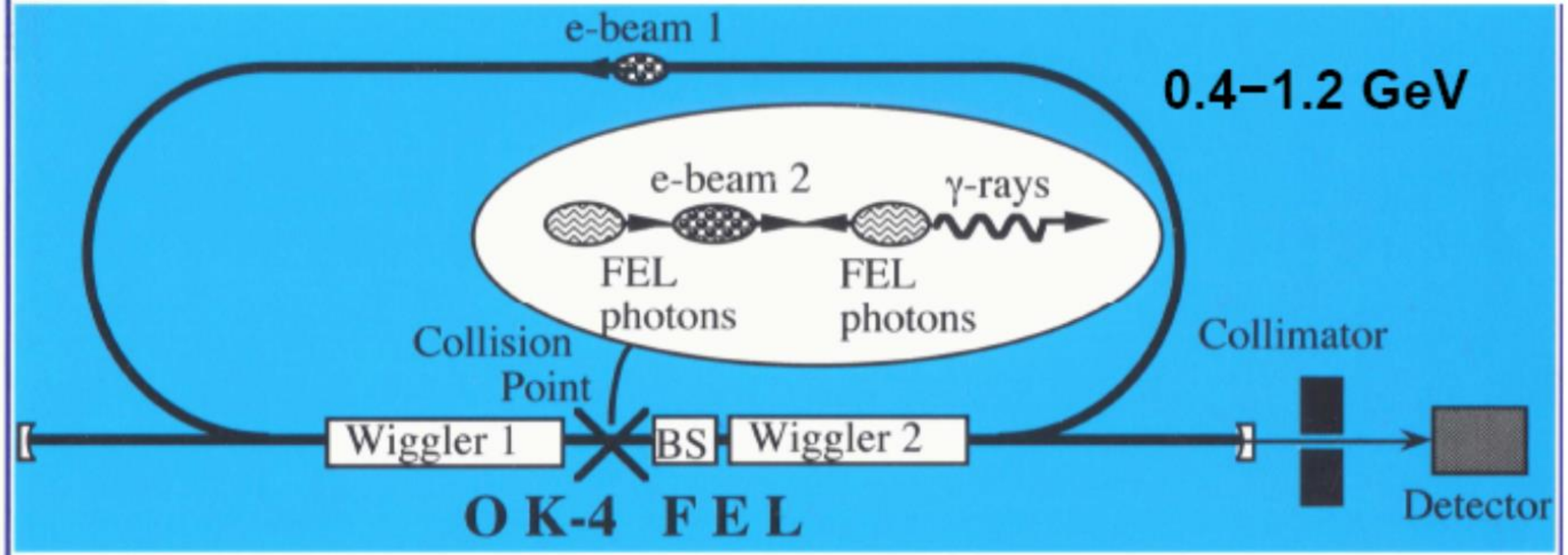
e.g. Laser-Compton backscattering



High Intensity γ–Ray Source (HIgS)

H.R.Weller, V.N.Litvinenko
Duke University, Durham, NC, U.S.A.

Compton Backscattering of Intra–cavity Laser Light



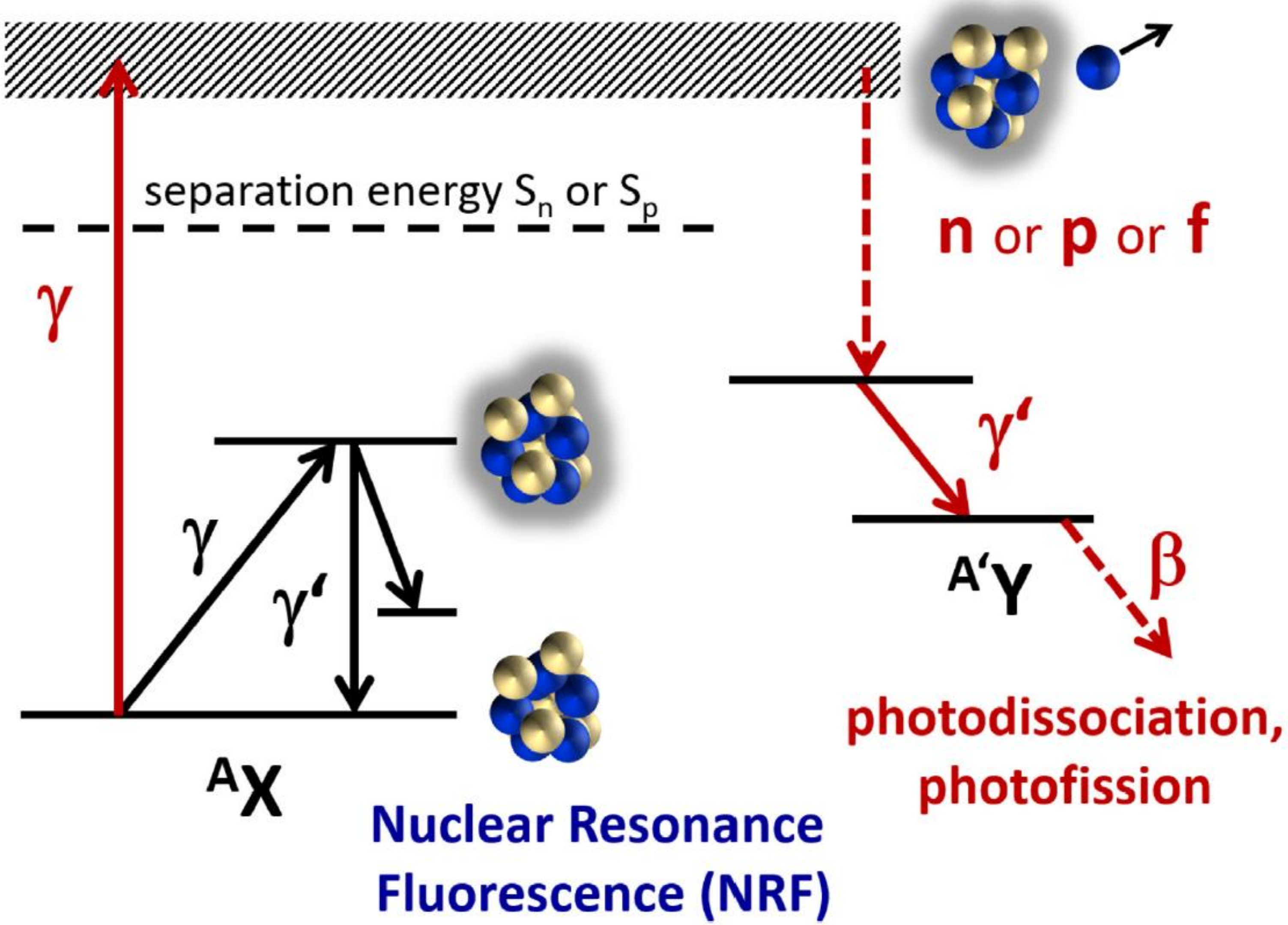
2 – 60 MeV 1.7 – 6.4 eV ~ 1000

$$E_\gamma = \frac{4\gamma^2 E_{ph}}{\left(1 + r + \gamma^2\theta^2\right)}; \quad r = \frac{4\gamma E_{ph}}{mc^2}; \quad E_{ph} = \frac{2\gamma^2 hc}{\lambda_w\left(1 + K_w^2/2\right)}; \quad \gamma = \frac{E_e}{mc^2};$$

nearly monochromatic, tunable, completely polarized

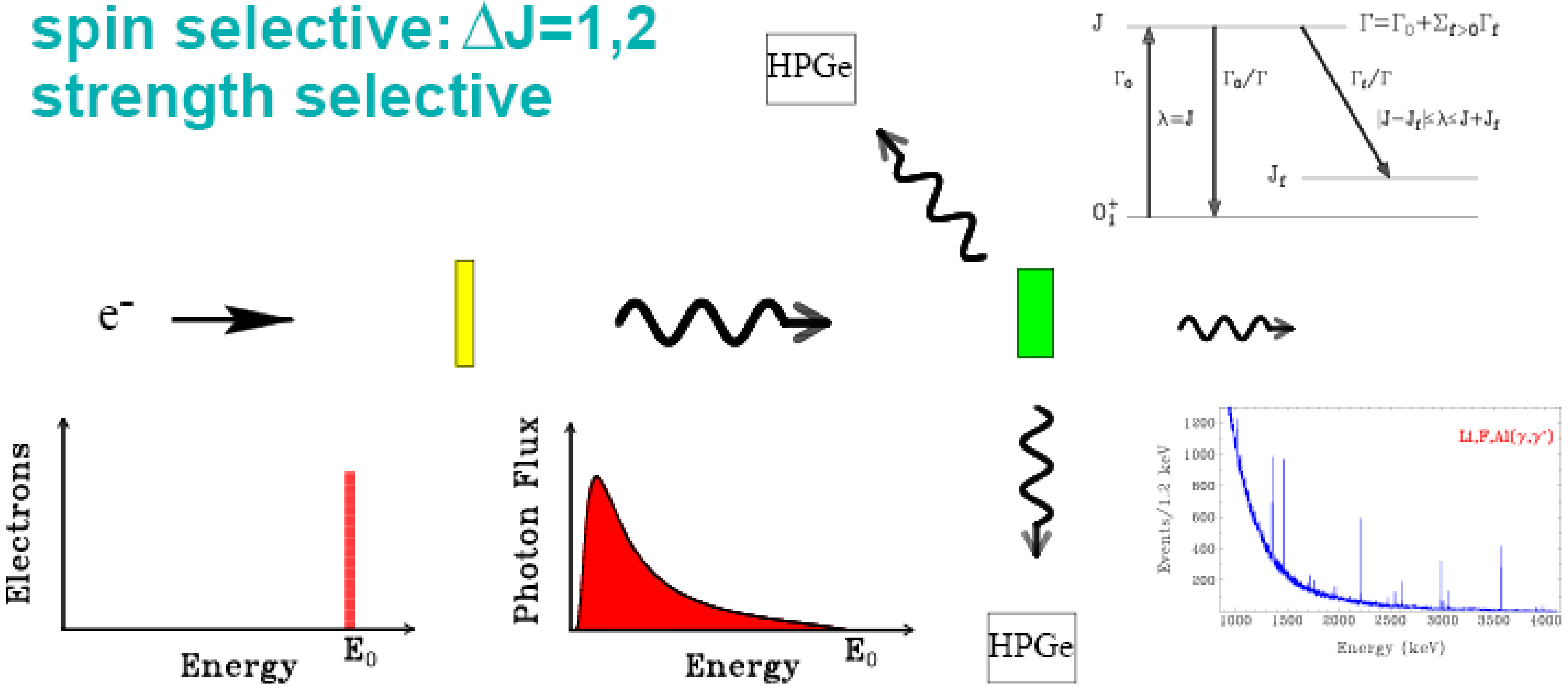
historic transparency
V.Litvinenko, ~ 2000

at the time with
OK-4
from Novosibirsk


separation energy S_n or S_p
γ
γ
γ'
^{A}X
Nuclear Resonance Fluorescence (NRF)
n or p or f
γ'
$^{A'}Y$
β
photodissociation, photofission

Photon Scattering
(Nuclear Resonance Fluorescence)

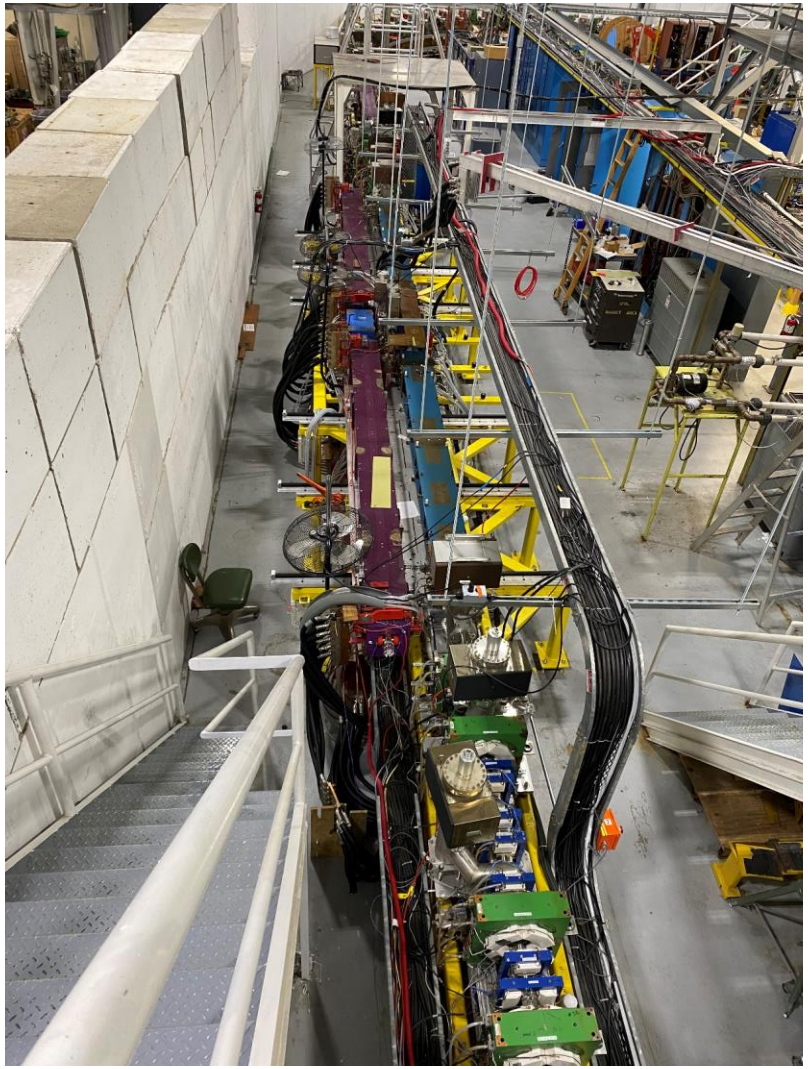
high energy resolution
spin selective: ΔJ=1,2
strength selective

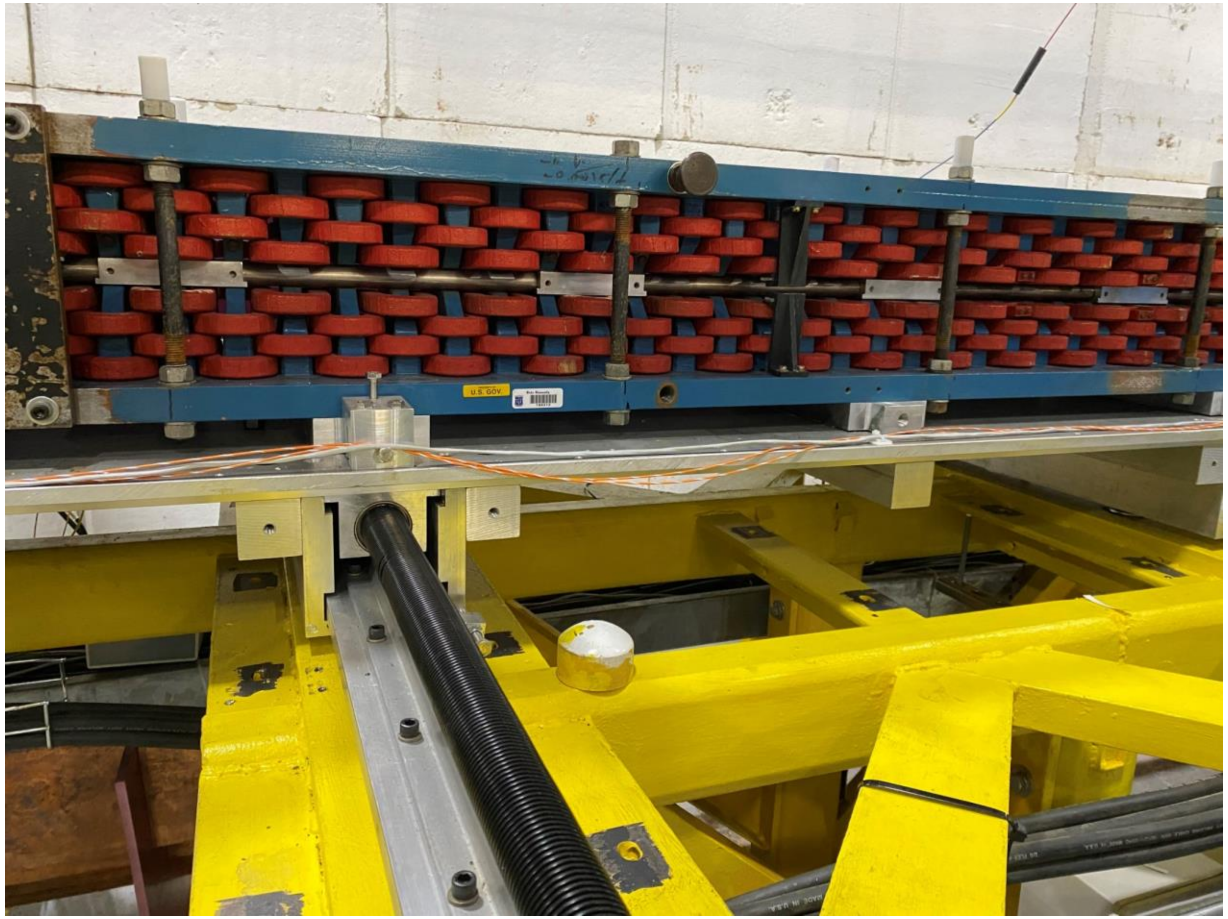


Observables

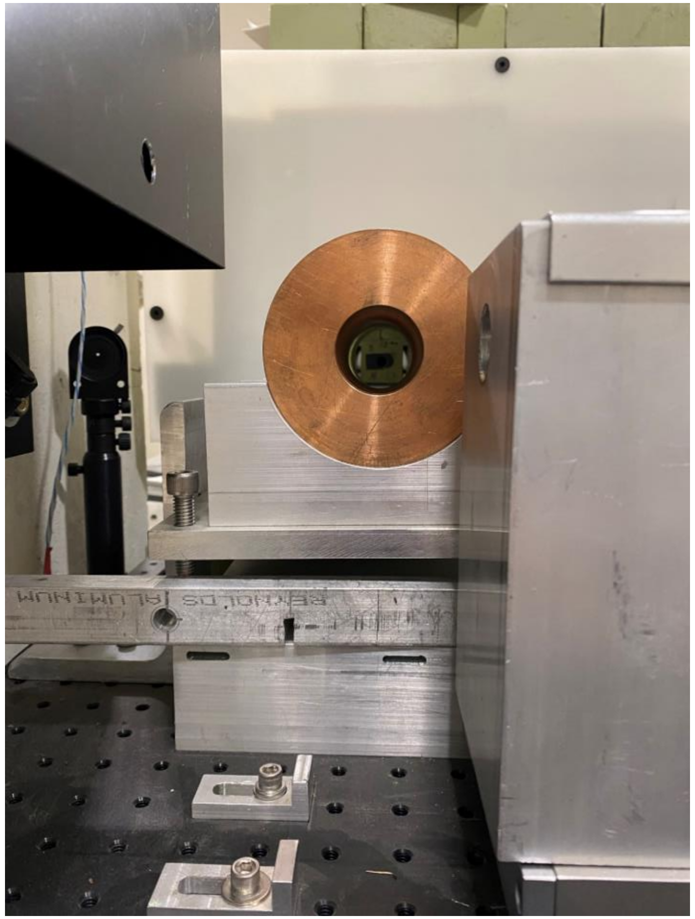
- Excitation Energy E_r
- Spin J
- Parity π
- Decay Energies E_γ
- Partial Widths Γ_i/Γ_0
- K-quantum numbers
- Multipole Mixing δ
- Decay Strengths $B(\pi\lambda)$
- Level Width Γ (eV)
- Lifetime τ (ps – as)

photos from Sept. 2023





OK-5: this is a lamp!



collimators

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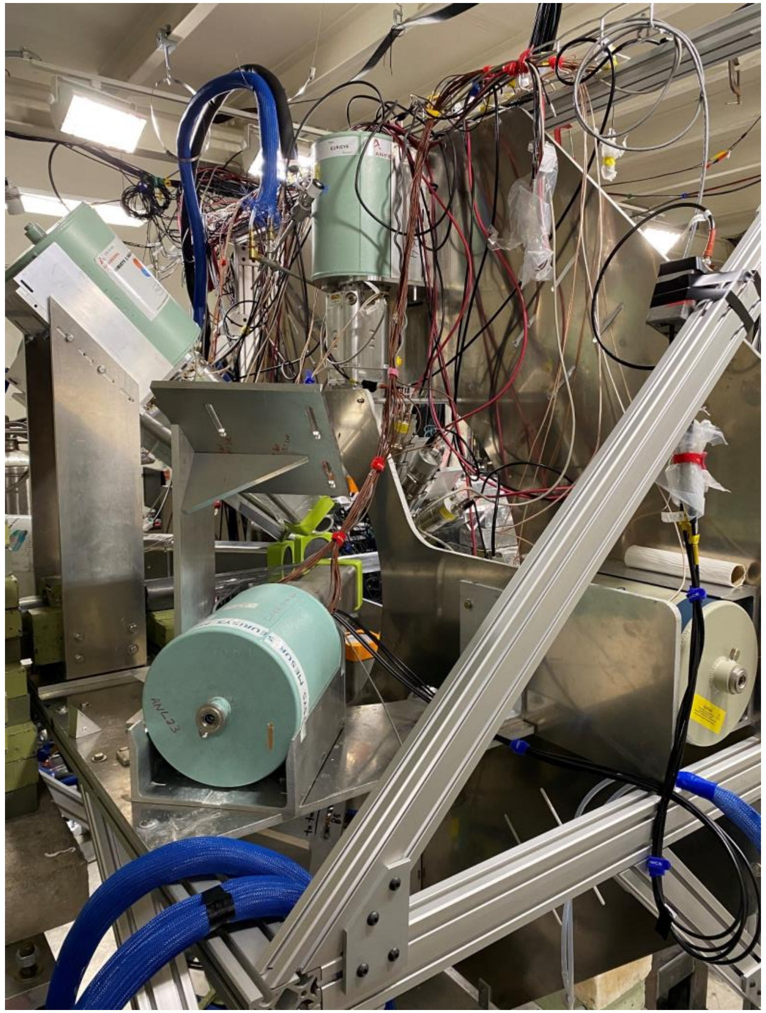

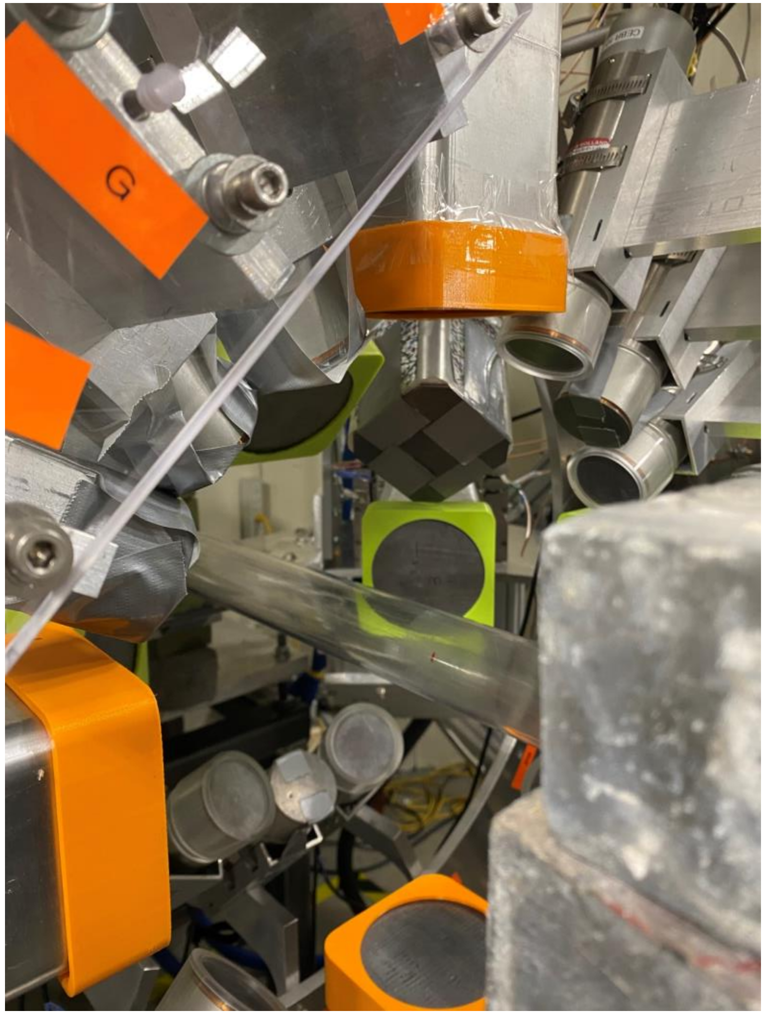

γ-ray detectors in the target room

Looking at the HIGS Gamma-Ray Beam

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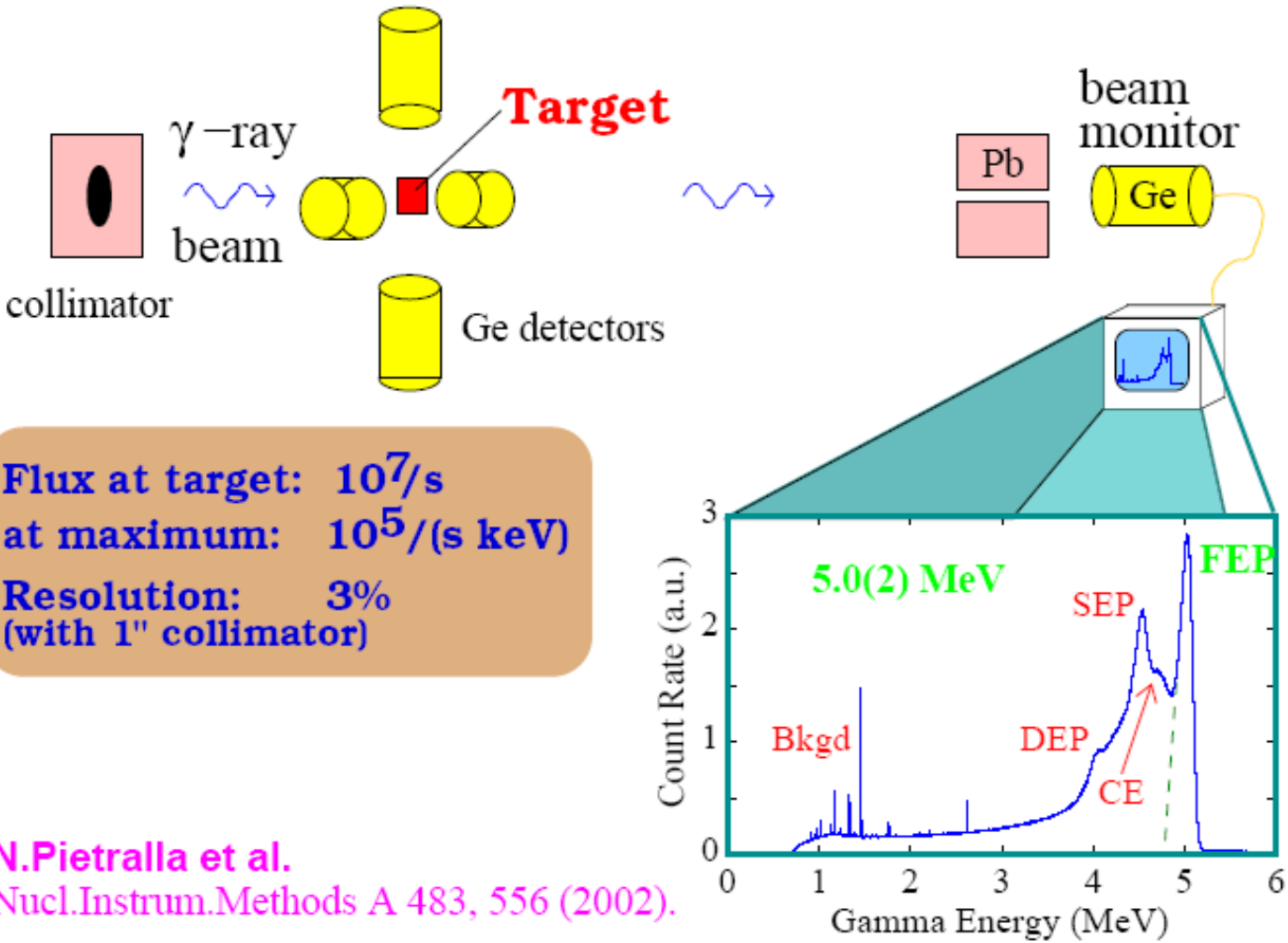
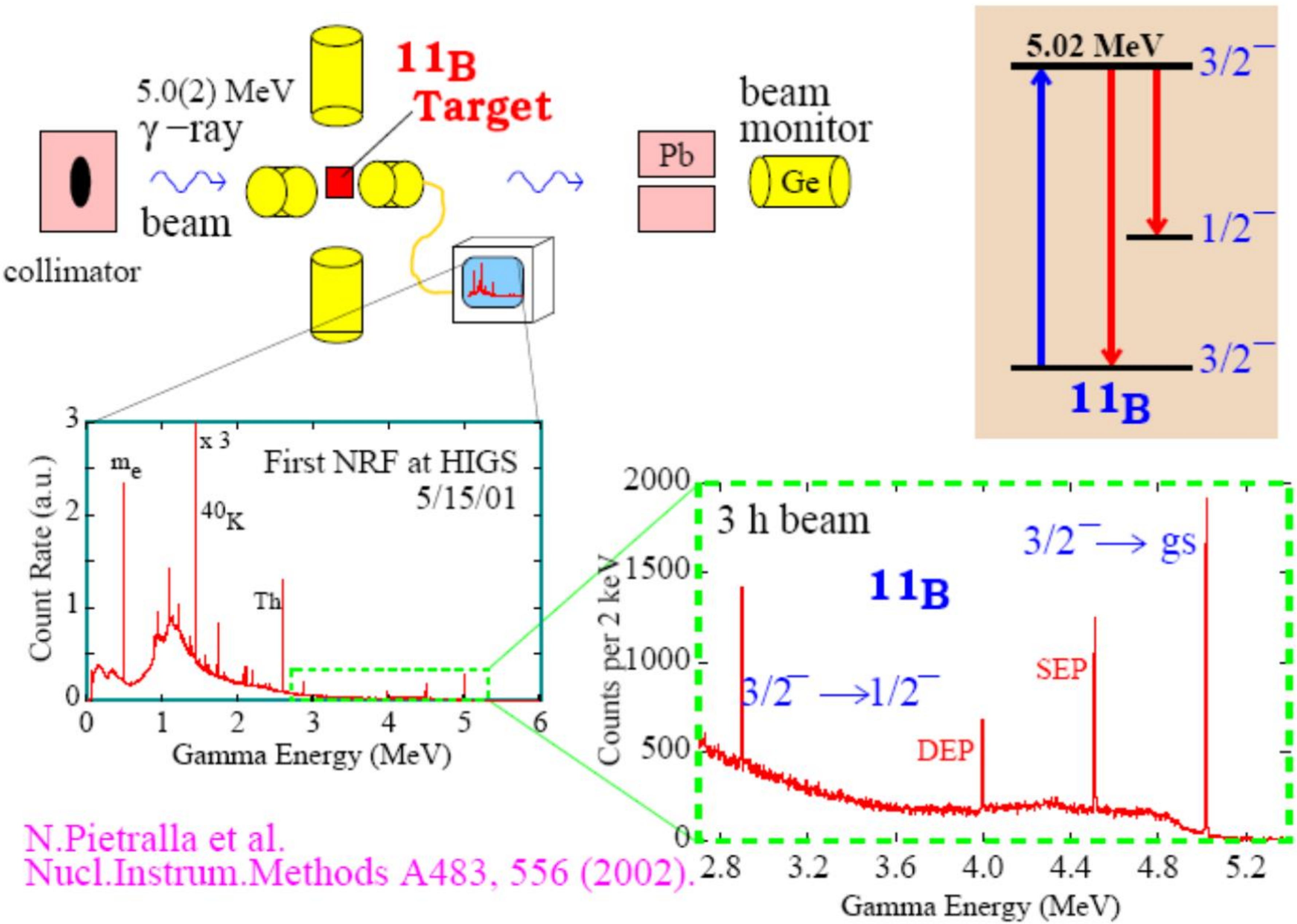


Flux at target: 10^7/s
at maximum: 10^5/(s keV)
Resolution: 3%
(with 1" collimator)

N.Pietralla et al.
Nucl.Instrum.Methods A 483, 556 (2002).

Looking at the Target



N.Pietralla et al.
Nucl.Instrum.Methods A483, 556 (2002).

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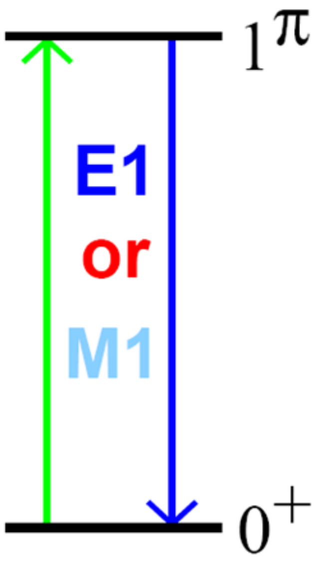
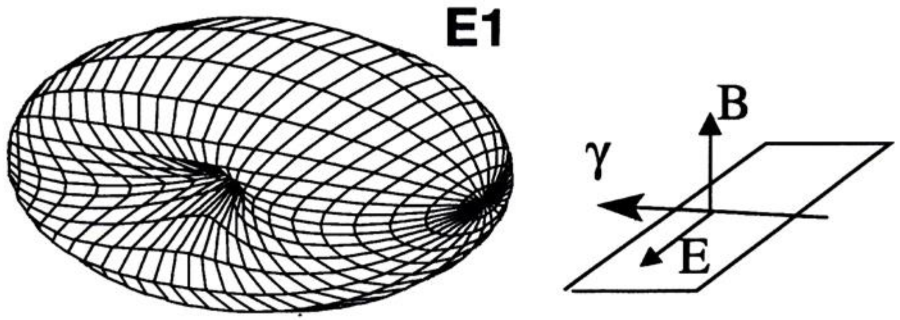
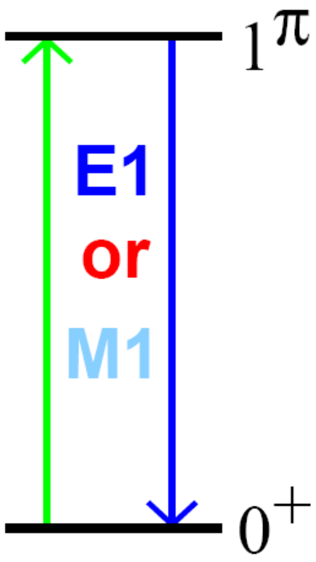
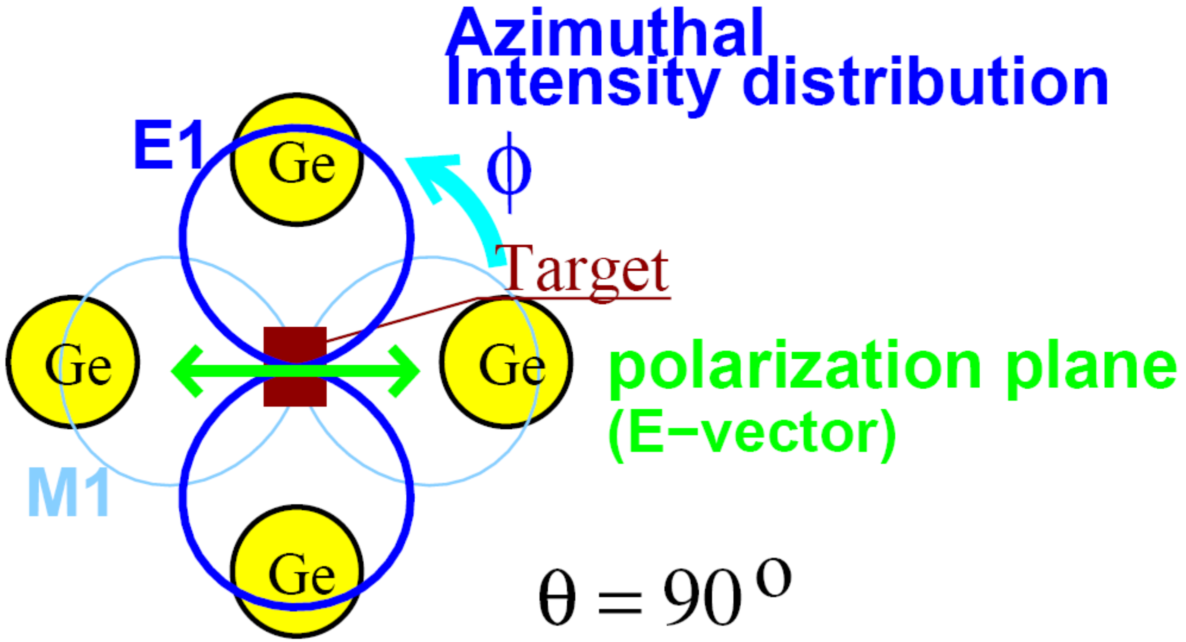
$$\Sigma = \frac{W(90^\circ,0^\circ) - W(90^\circ,90^\circ)}{W(90^\circ,0^\circ) + W(90^\circ,90^\circ)} = \pi_x = \begin{cases} +1 \\ -1 \end{cases} \text{for} \begin{matrix} J^\pi = 1^+ \\ J^\pi = 1^- \end{matrix}$$





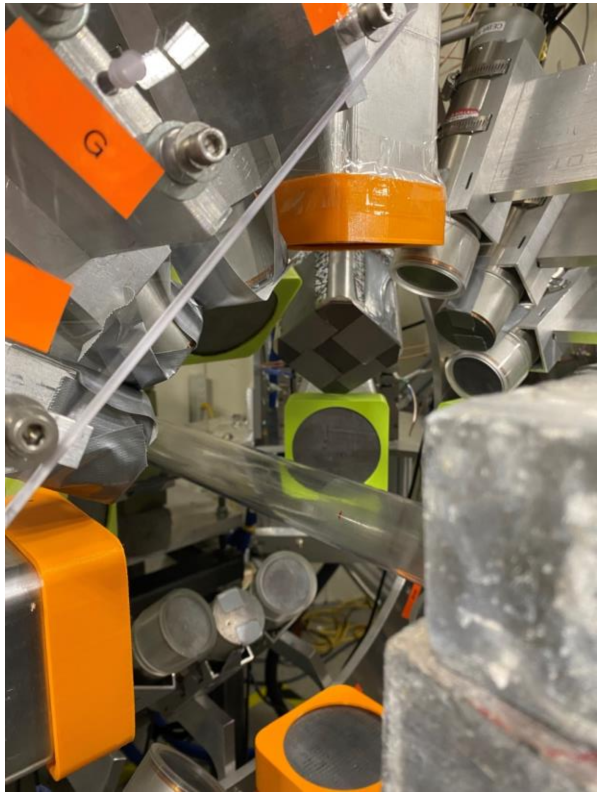
- Elastic scattering distribution not isotropic about incident polarization plane.
- No intensity along oscillating dipole vector
- Azimuthal rotation by 90º for M1 and E1 distributions
- Observable only for linearly polarized beam



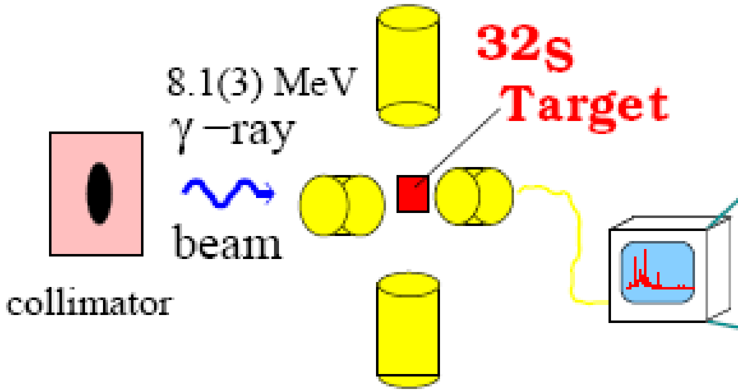


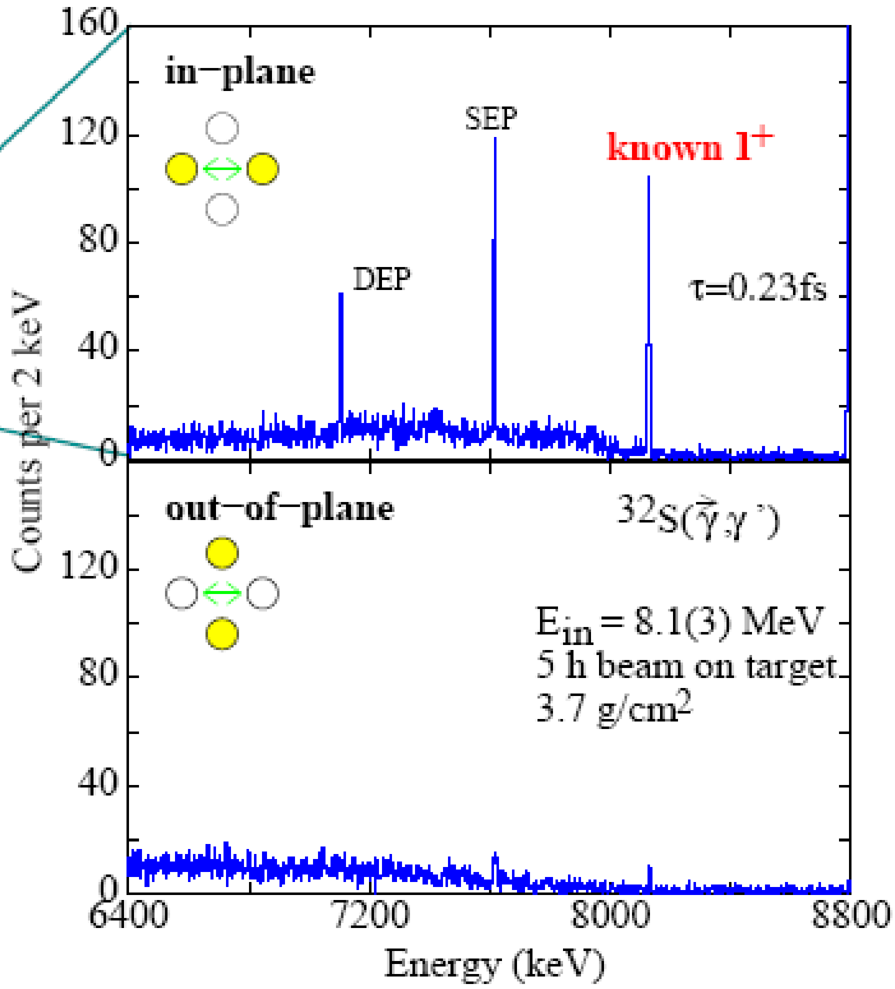
HIγS
2001

HIγS
2023



Proof of Principle

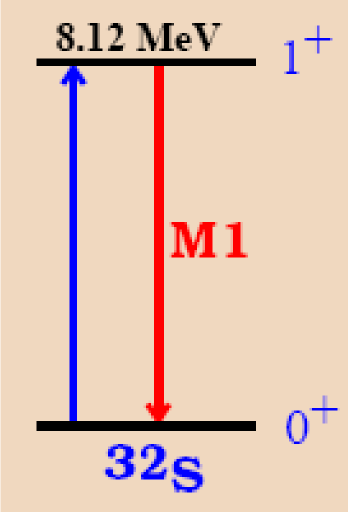




DFELL/TUNL polarimeter

Asymmetry

~ 80%



HIγS 2001

N.Pietralla et al., Nucl.Instrum.Methods A483, 556 (2002).

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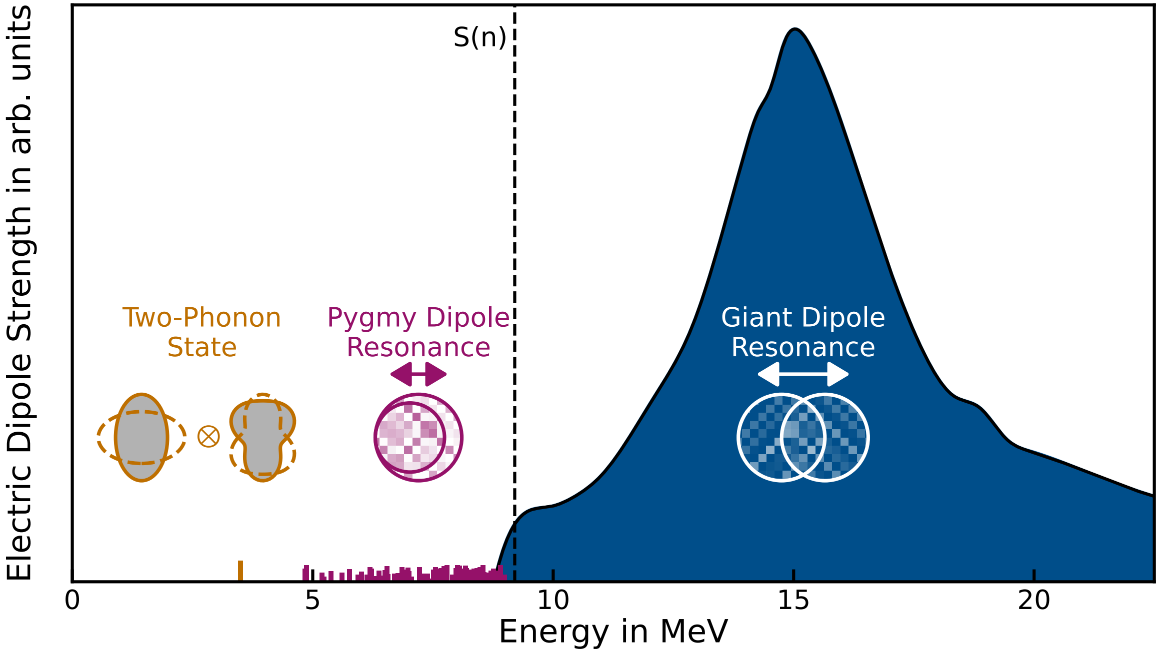
Challenge to my PhD student Jörn Kleemann:

„Study the γ–decay of the GDR in a deformed nucleus as a function of excitation energy!“



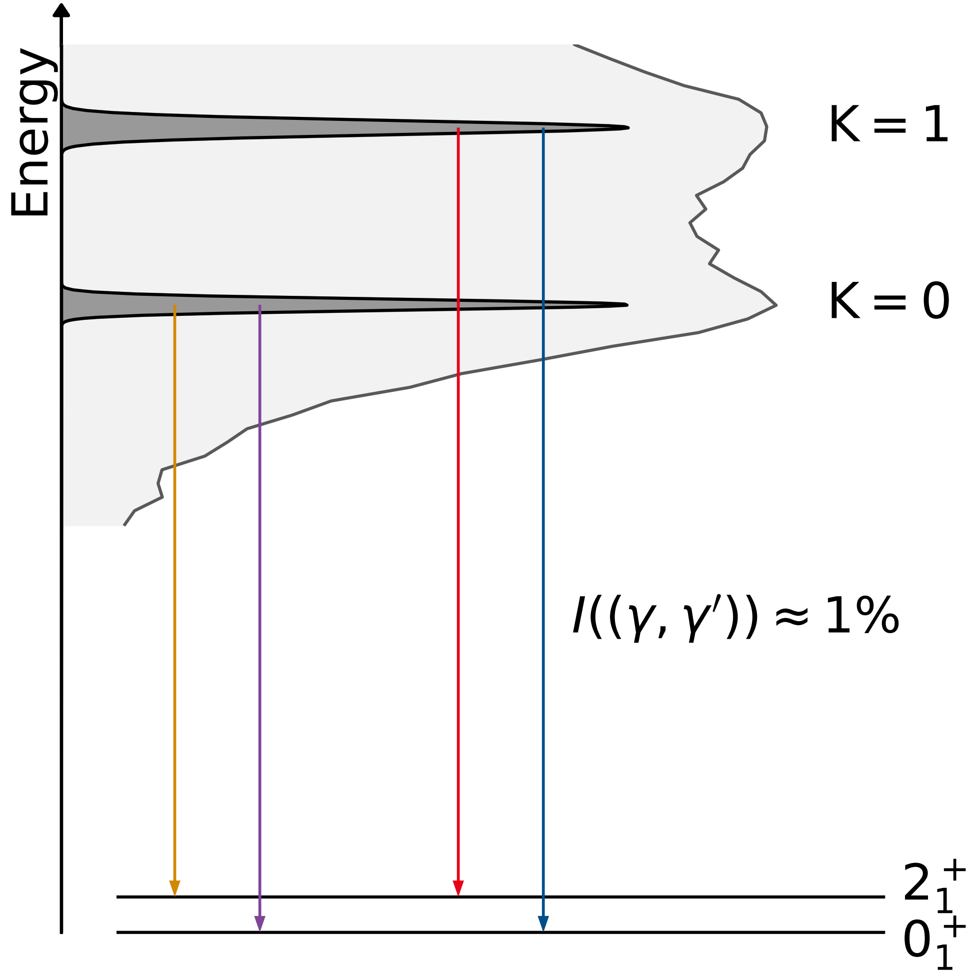
Particle unbound

≈ 99% n-decay

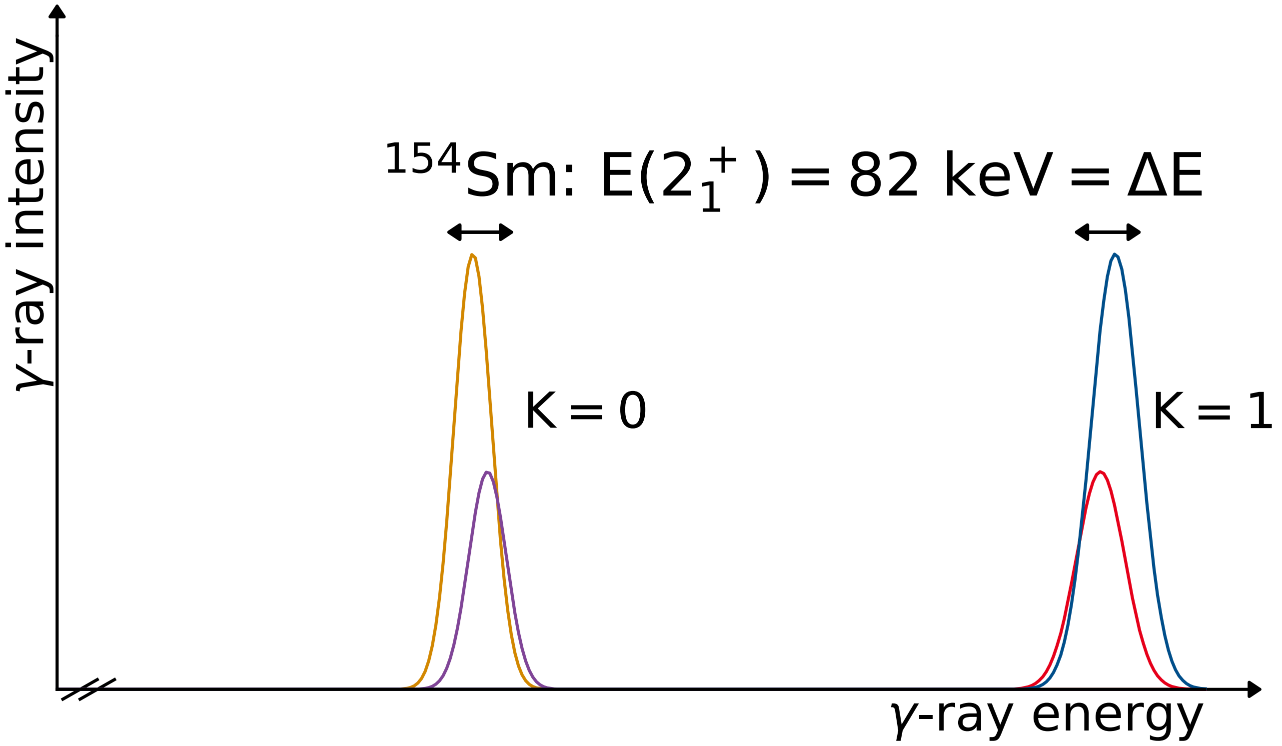
≈ 1% γ-decay

J. R. Beene *et al.*, Phys. Rev. C **41**, 920 (1990)

K. Boretzky *et al.*, Phys. Lett. B **384**, 30 (1996)



Energy
K = 1
K = 0
$I((\gamma,\gamma')) \approx 1\%$
2_1^+
0_1^+



γ-ray intensity
^{154}Sm: $E(2_1^+) = 82$ keV $= \Delta E$
K = 0
K = 1
γ-ray energy

EXCITING THE GDR USING A LINEARLY POLARIZED BEAM

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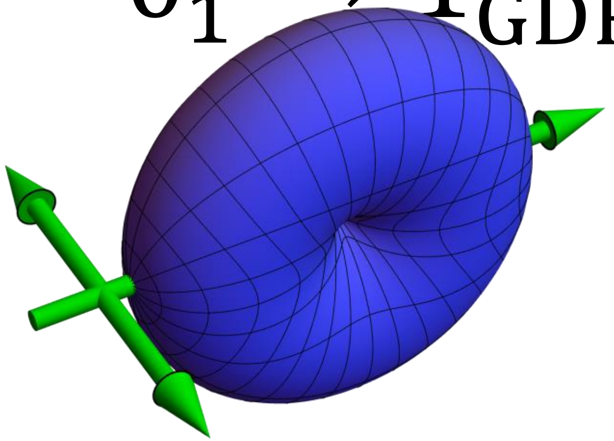
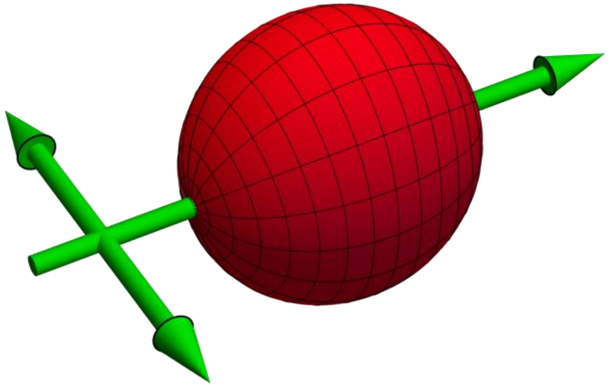
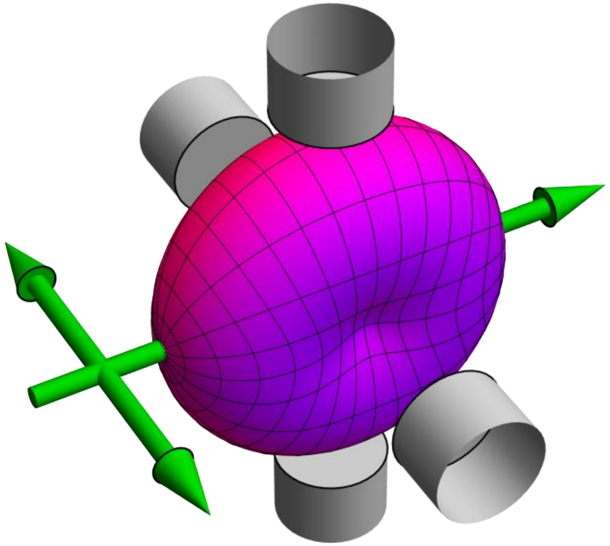
$$0_1^+ \to 1^-_{\mathrm{GDR}} \to 0_1^+ \qquad 0_1^+ \to 1^-_{\mathrm{GDR}} \to 2_1^+$$



$$+\frac{\sigma_{2_1^+}}{\sigma_{0_1^+}} \times$$



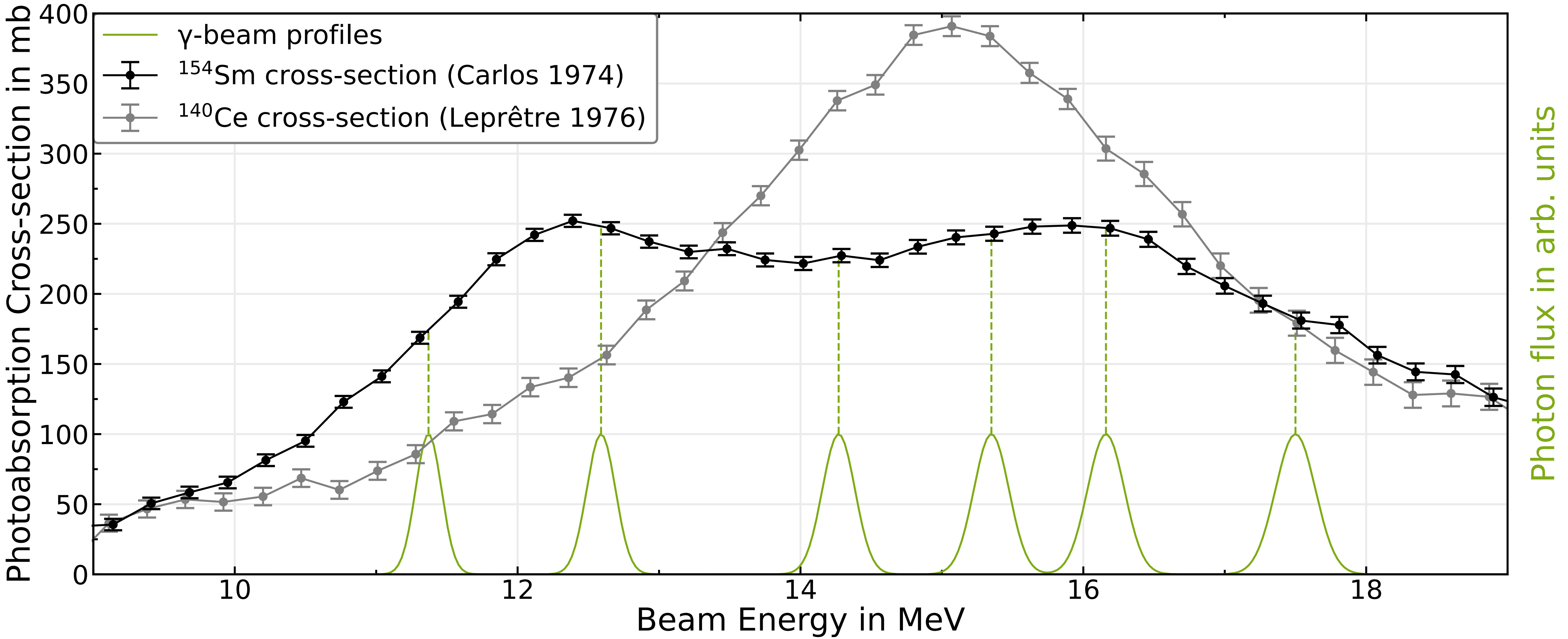
$$=$$



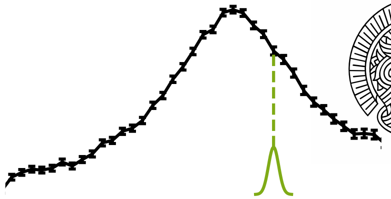
$$\left(\frac{\sigma_{2_1^+}}{\sigma_{0_1^+}}\right)$$

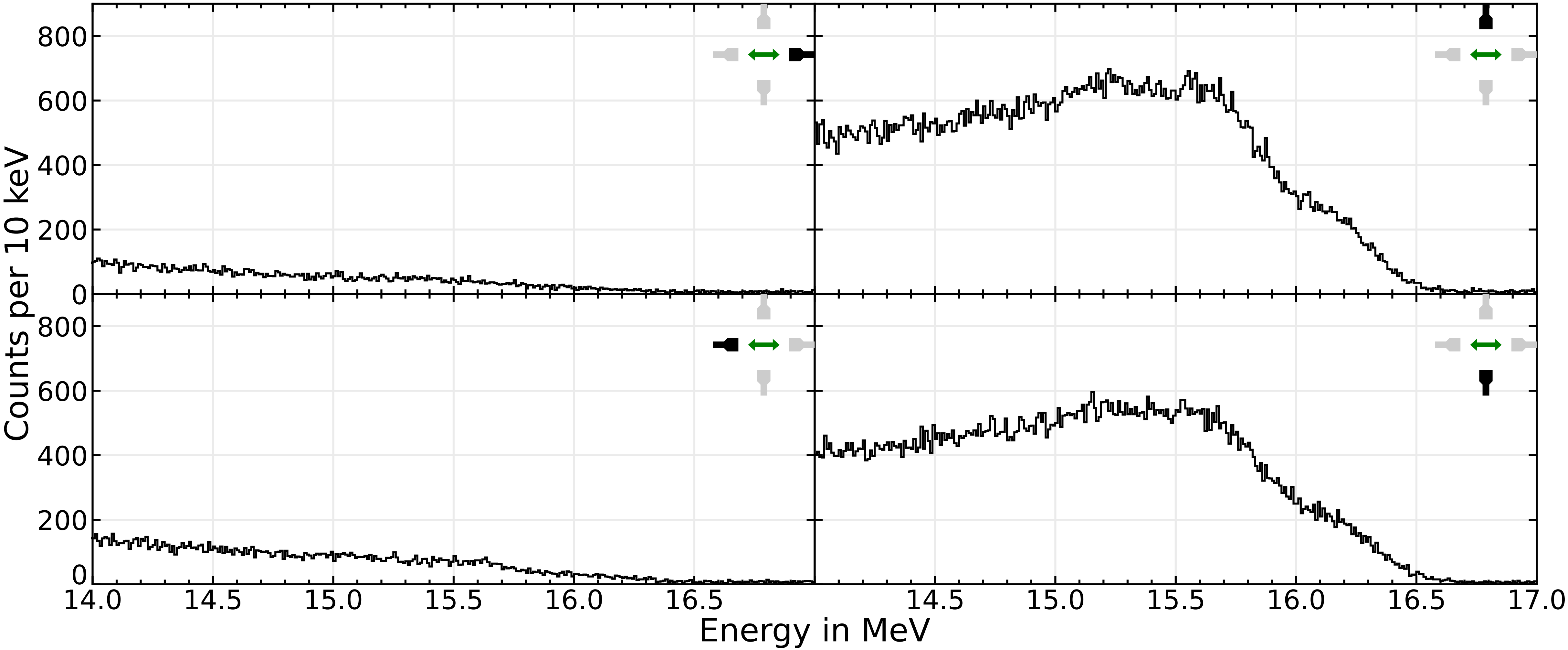
N. Pietralla *et al.*,
Phys. Rev. Lett. **88**, 012502 (2001)

MEASUREMENT POINTS IN THE GDRS OF ^{154}SM AND ^{140}CE



^{140}CE IN 16.2 MEV LINEARLY POLARIZED Γ-BEAM





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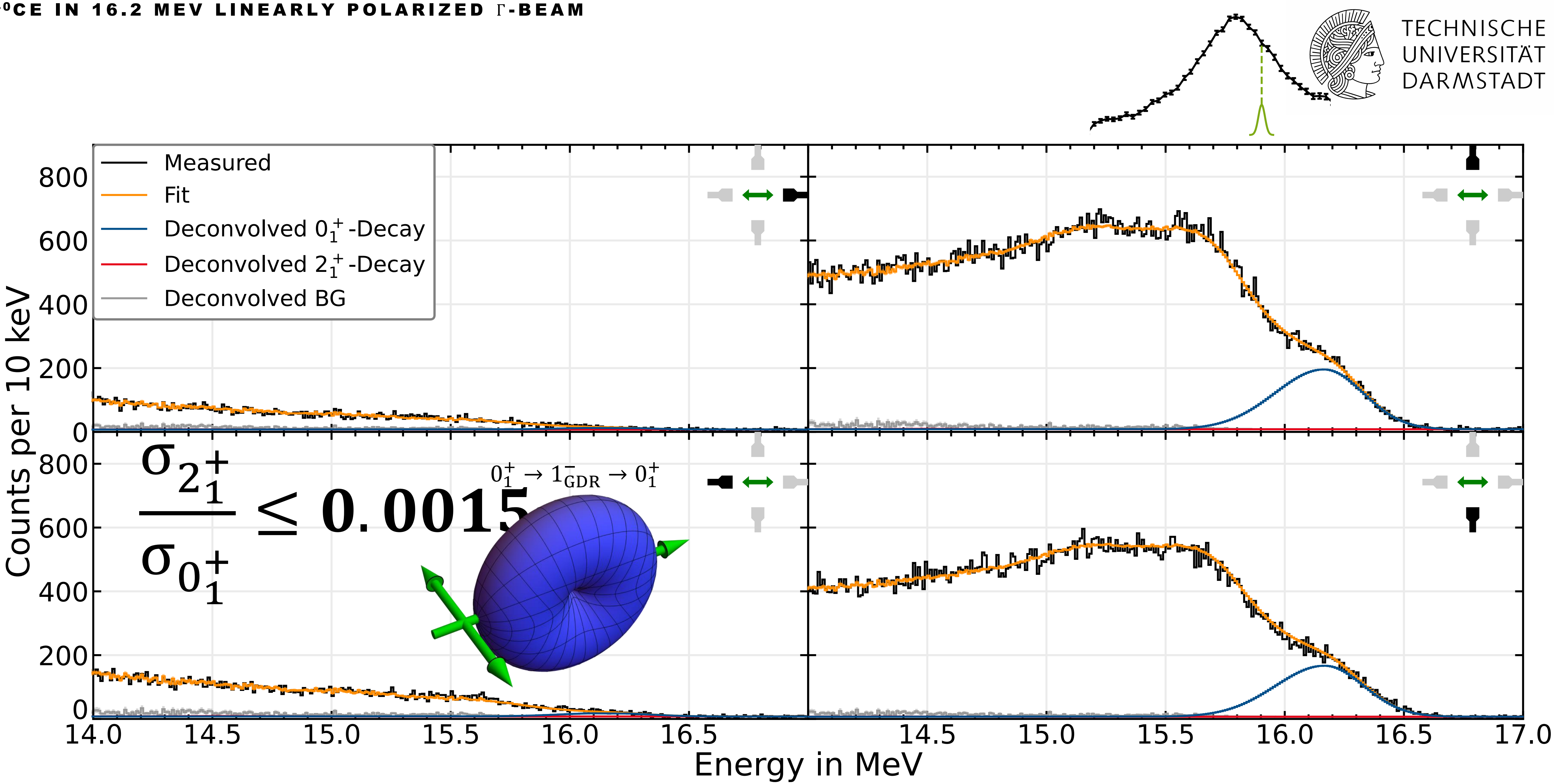

$$\frac{\sigma_{2_1^+}}{\sigma_{0_1^+}} \leq 0.0015$$

^{154}SM IN 16.2 MEV LINEARLY POLARIZED Γ-BEAM

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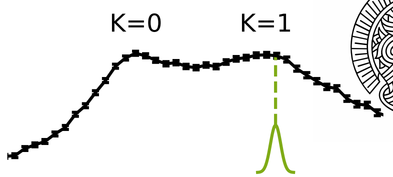

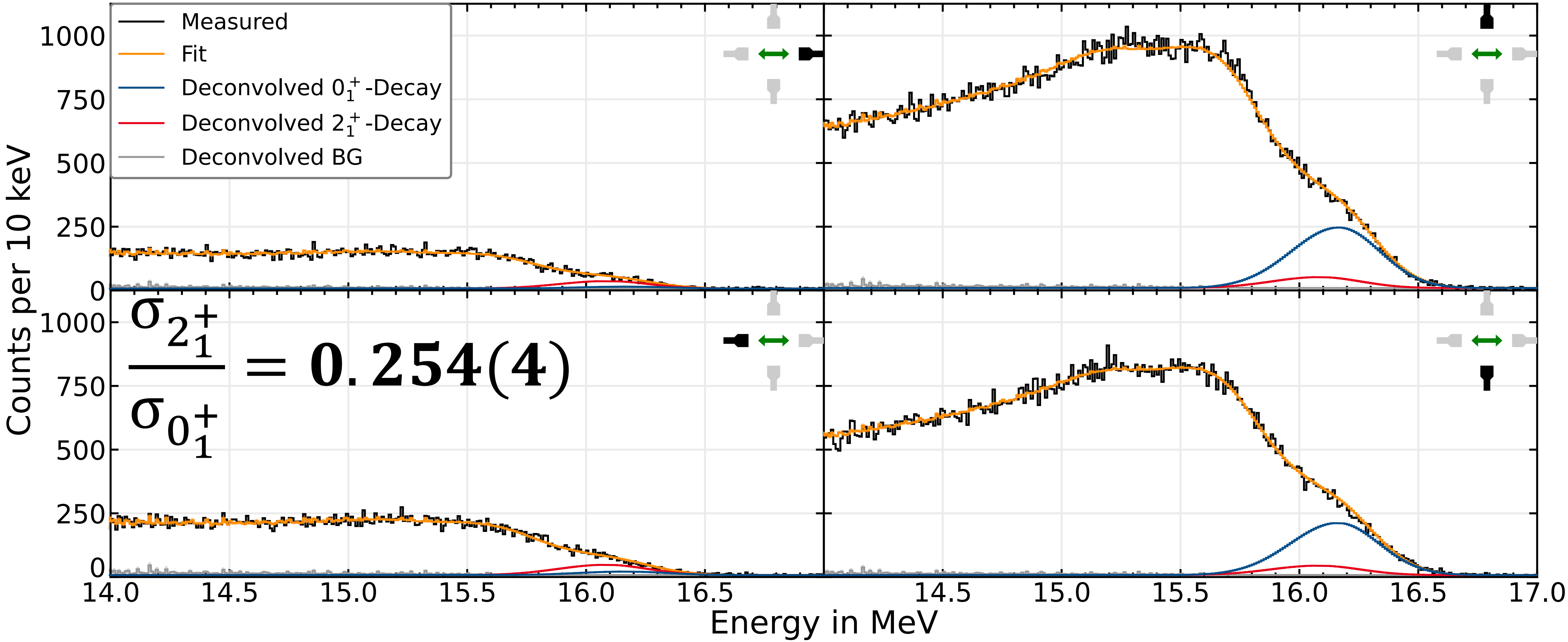

$$\frac{\sigma_{2_1^+}}{\sigma_{0_1^+}} = \mathbf{0.254(4)}$$

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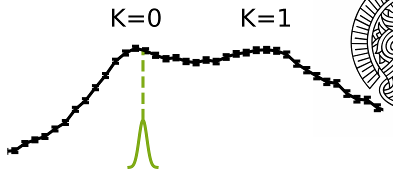
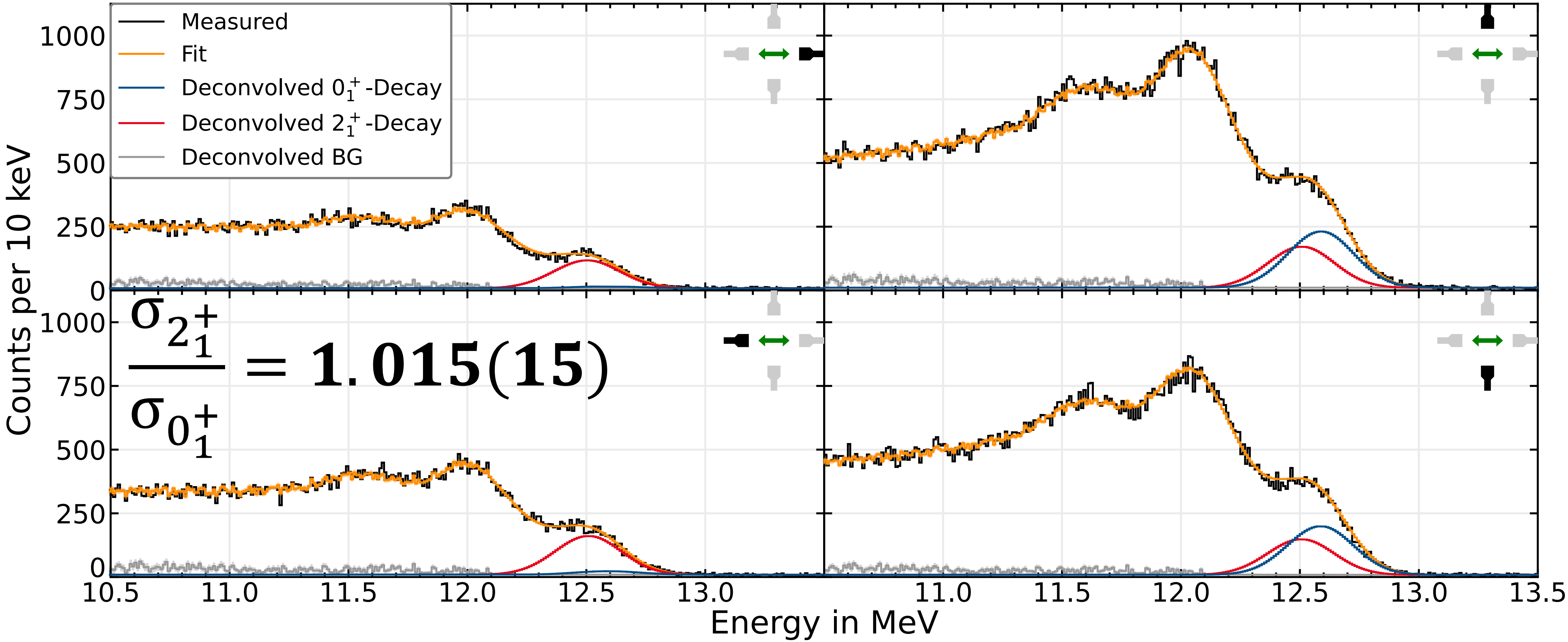
Institut für Kernphysik S-DALINAC Technische Universität Darmstadt

^{154}SM IN 12.6 MEV LINEARLY POLARIZED Γ-BEAM





$$\frac{\sigma_{2_1^+}}{\sigma_{0_1^+}} = 1.015(15)$$

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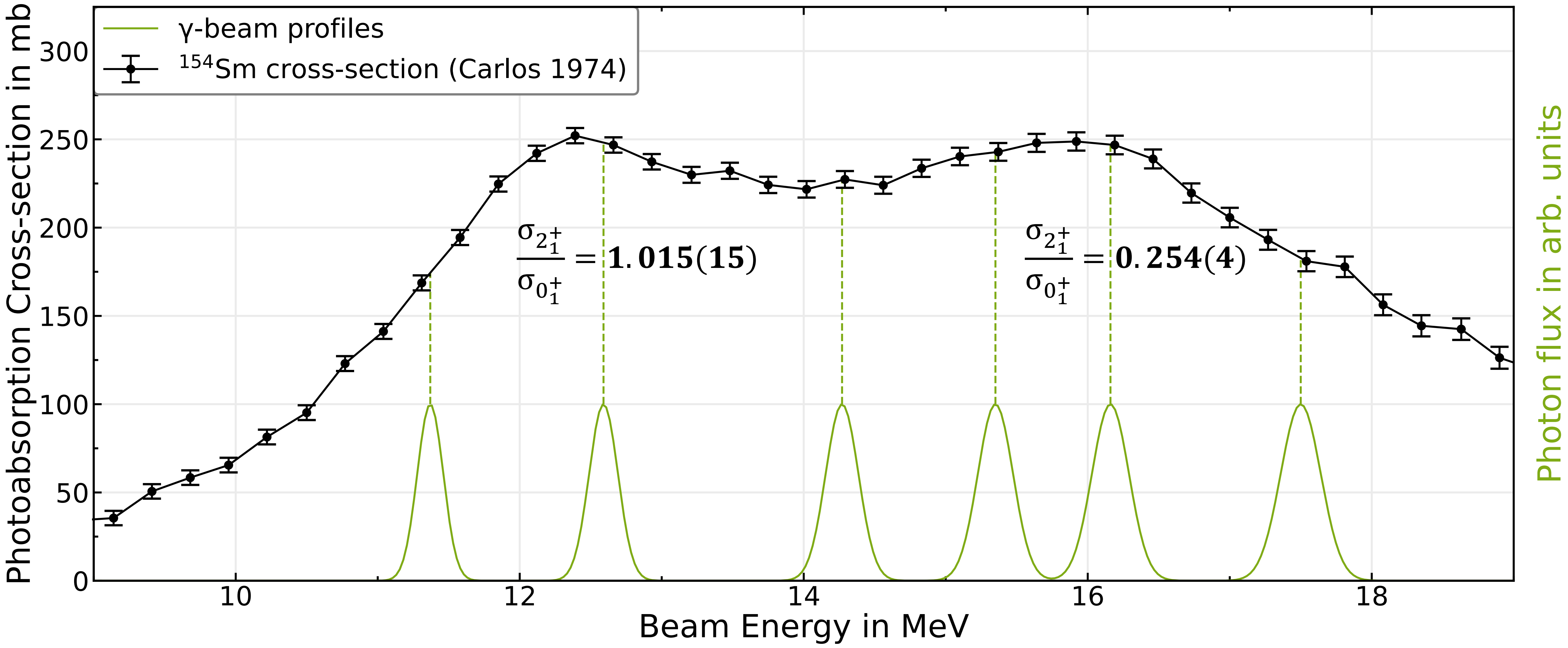

RESULTS ON Γ-DECAY BEHAVIOR OF GDR OF ^{154}SM

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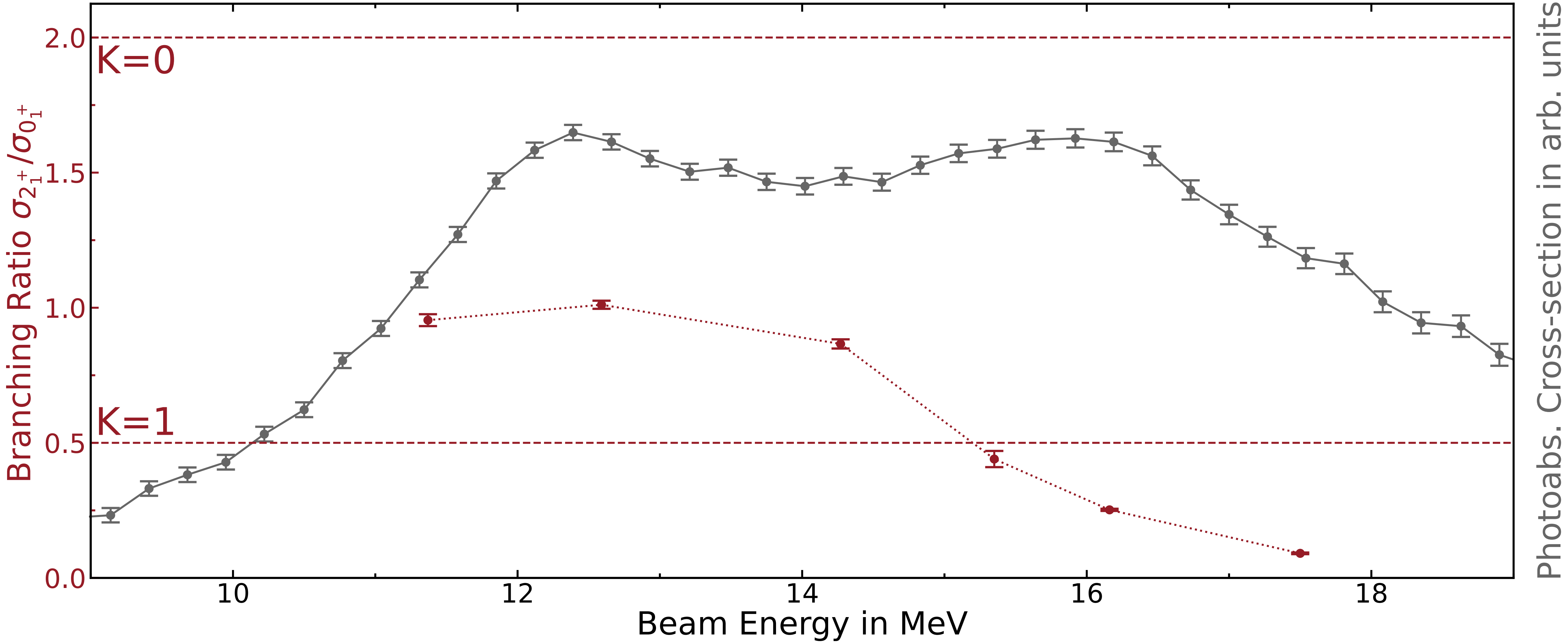


Interference effects in the GDR

E. G. Fuller and E. Hayward, Nucl. Phys. **30**, 613 (1962)

- Thomson scattering interferes with GDR's γ-decay to 0_1^+

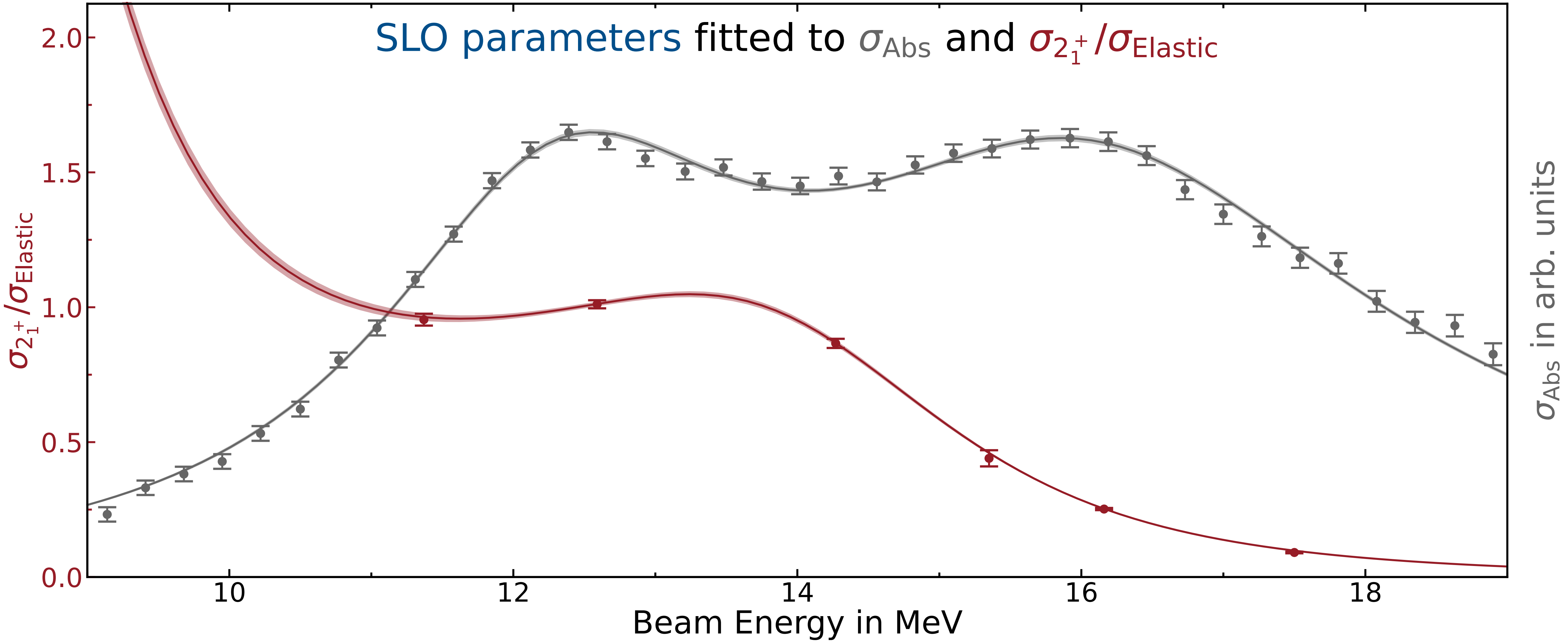
$$\sigma_{\mathrm{Elastic}}(E) = \left| f_{\mathrm{Th}} + f_{0_1^+\,\mathrm{NRF}}(E) \right|^2$$

⇒ Need scattering amplitudes $\mathbf{f(E)} \in \mathbb{C}$ for both processes for correction

⇒ Obtainable from σ_{Abs} through optical theorem and dispersion relations

$$\sigma_{\mathrm{Abs}}(E) = \sum_{k\in\{0,1\}} \sigma_k \frac{E^2\Gamma_k^2}{\left(E_k^2 - E^2\right)^2 + E^2\Gamma_k^2}$$

⇒ Corrections up to 35%


SLO parameters fitted to σ_{Abs} and $\sigma_{2_1^+}/\sigma_{Elastic}$
$\sigma_{2_1^+}/\sigma_{Elastic}$
2.0
1.5
1.0
0.5
0.0
10
12
14
16
18
Beam Energy in MeV
σ_{Abs} in arb. units

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- Measured the γ-decay behavior of the GDRs of ^{154}Sm and ^{140}Ce
  → γ-decay of GDR very sensitive to SLO parameters of GDR

- $E_{K=0}$ = 12.367(21) MeV, Γ = 3.27(6) MeV, $\sigma_{tot,\,K=0}$ = 0.644(15) MeV b for ^{154}Sm
- $E_{K=1}$ = 16.119(20) MeV, Γ = 5.05(5) MeV, $\sigma_{tot,\,K=1}$ = 1.052(17) MeV b for ^{154}Sm

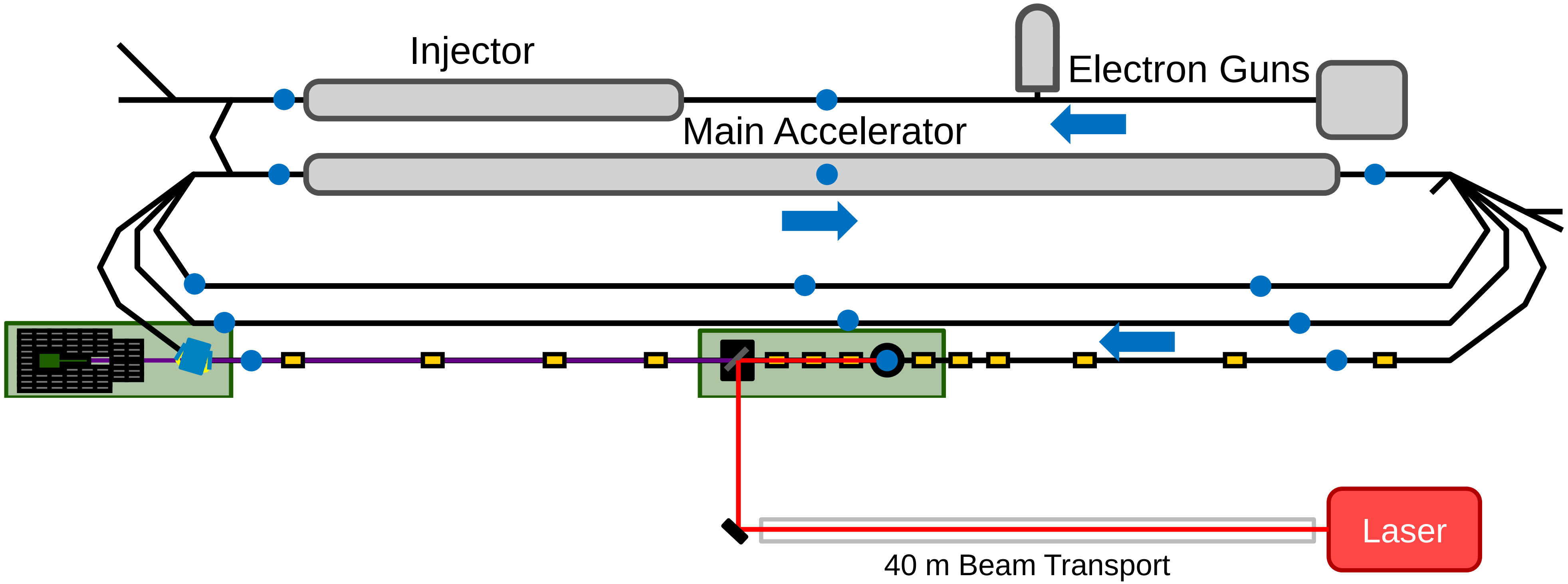
- Simultaneous activation of natural Ce, Sm and Au samples
  → γ/n branching (“≈ 1%”) and absolute cross-sections from activation

- Additional data on GDRs of ^{164}Dy, ^{232}Th & ^{208}Pb measured in April 2023


Jörn Kleemann

M. MEIER, M. ARNOLD, V. BAGNOUD, J. ENDERS & N. PIETRALLA

LASER-COMPTON BACKSCATTERING SOURCE AT THE S-DALINAC



Higher photon energy preferred

Head-On Collision

- ❖For higher Energy
- ❖Easier overlap

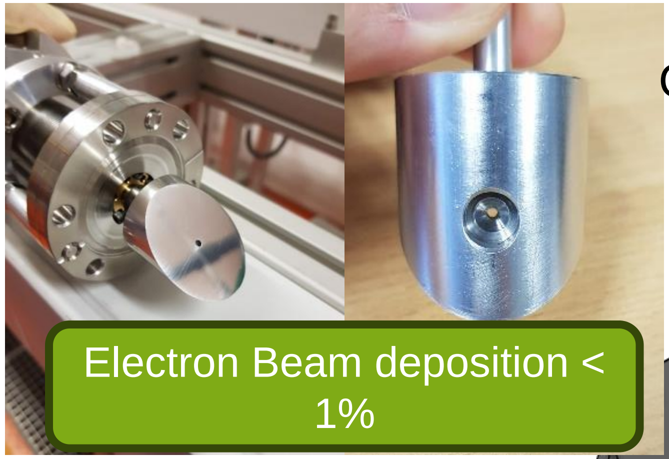
High Laser Pulse Energy (N_L)

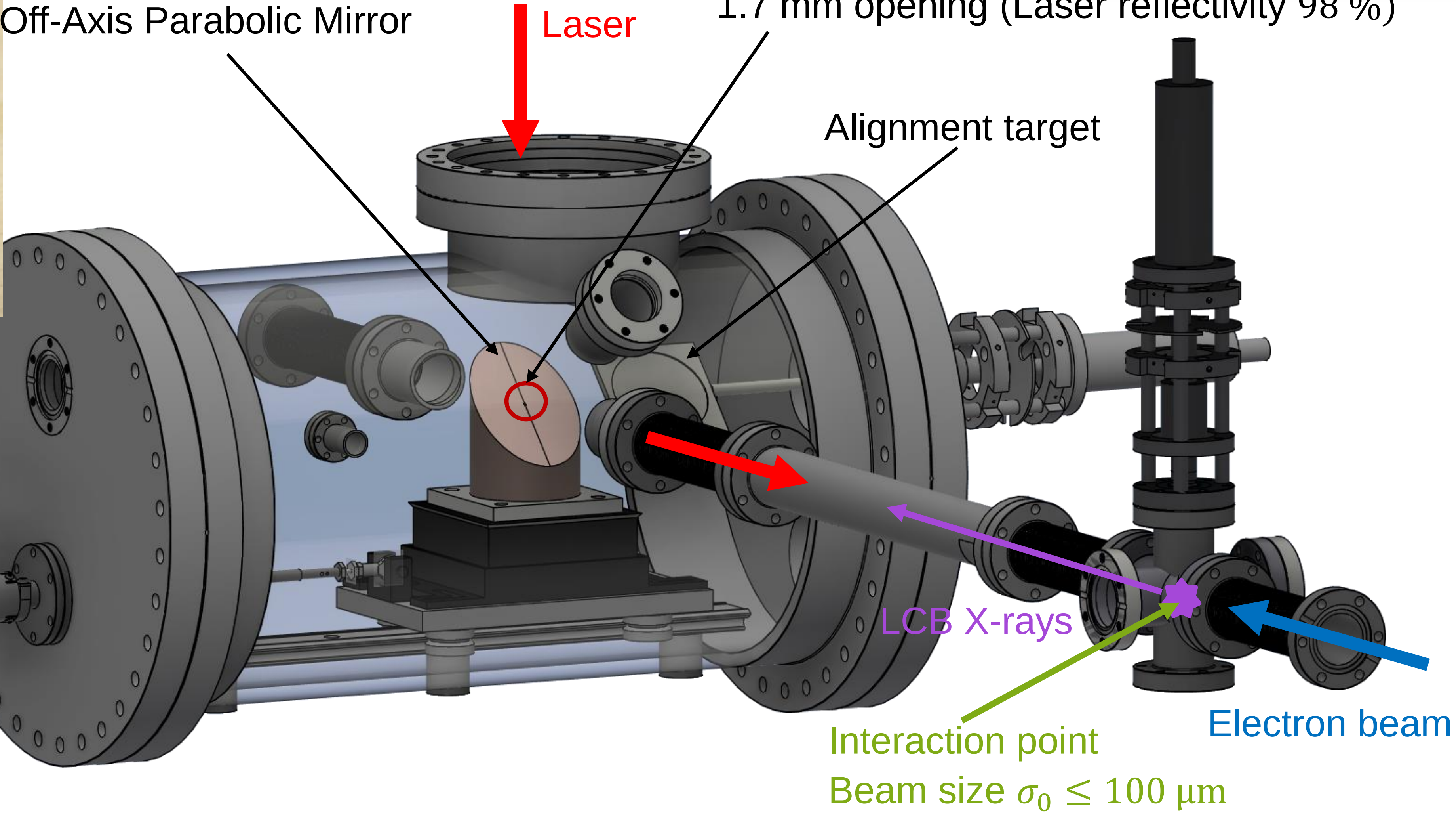
High scattering frequency (f)

Small beam size at IP

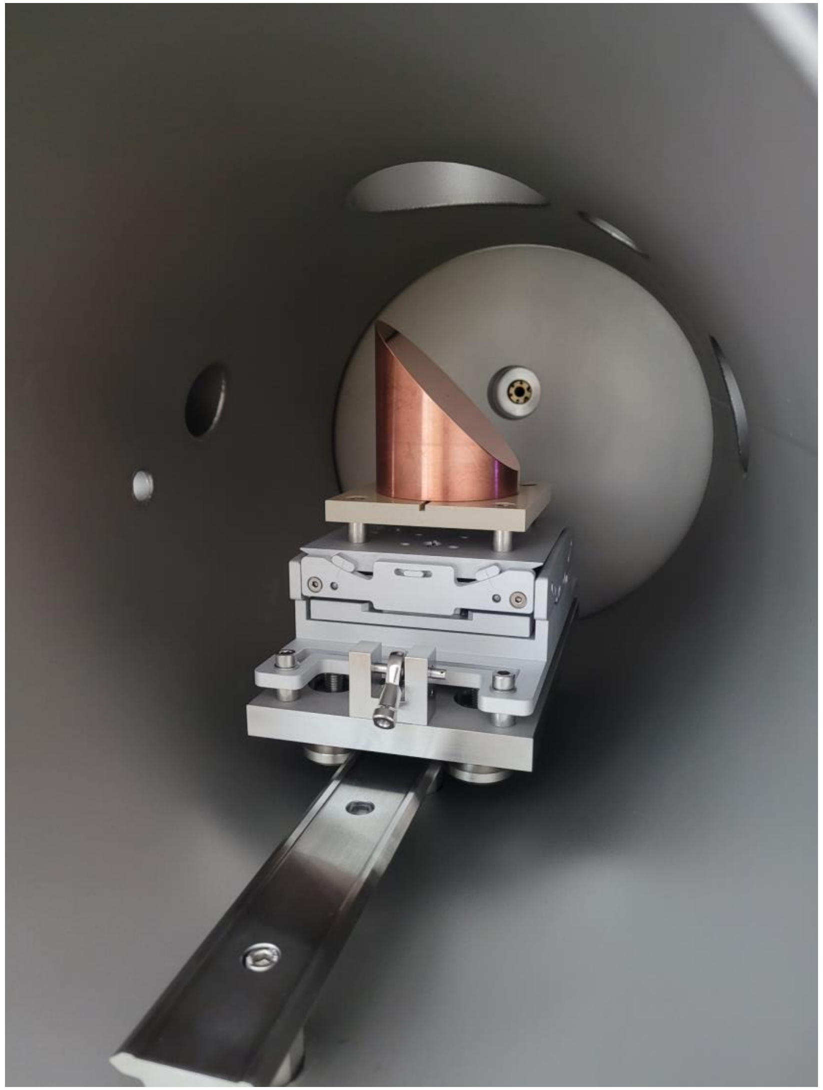
Low M^2

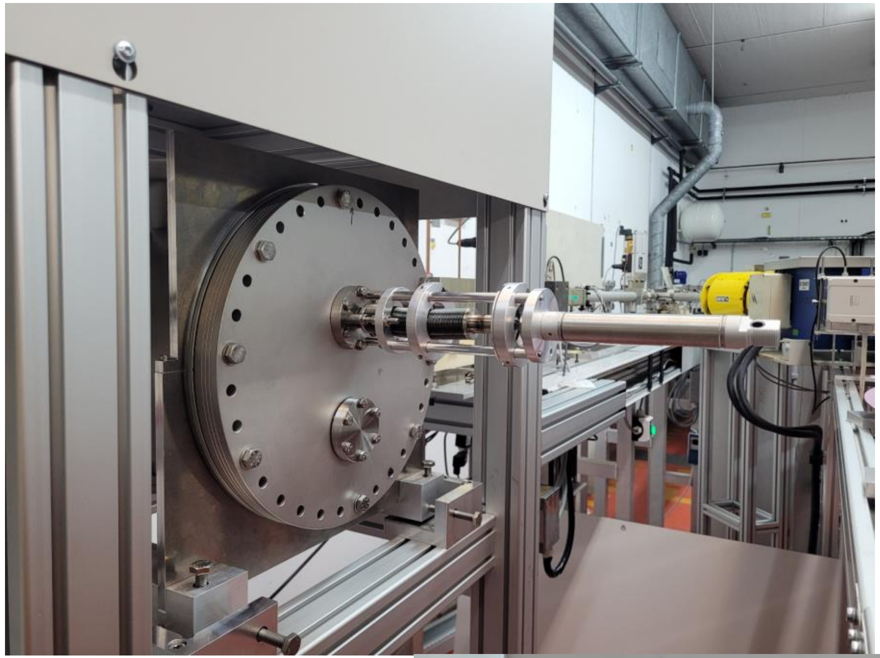
Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$

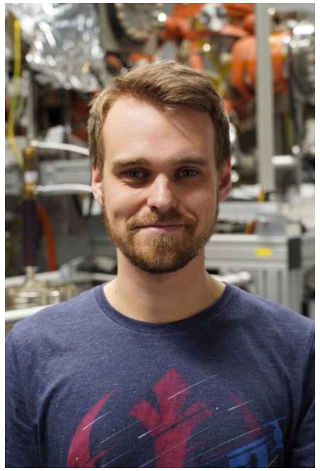

Electron Beam deposition < 1%


Off-Axis Parabolic Mirror
Laser
1.7 mm opening (Laser reflectivity 98 %)
Alignment target
LCB X-rays
Interaction point
Beam size $\sigma_0 \leq 100\ \mu m$
Electron beam

COUPLING CHAMBER OF LCB-SOURCE







Maximilian Meier

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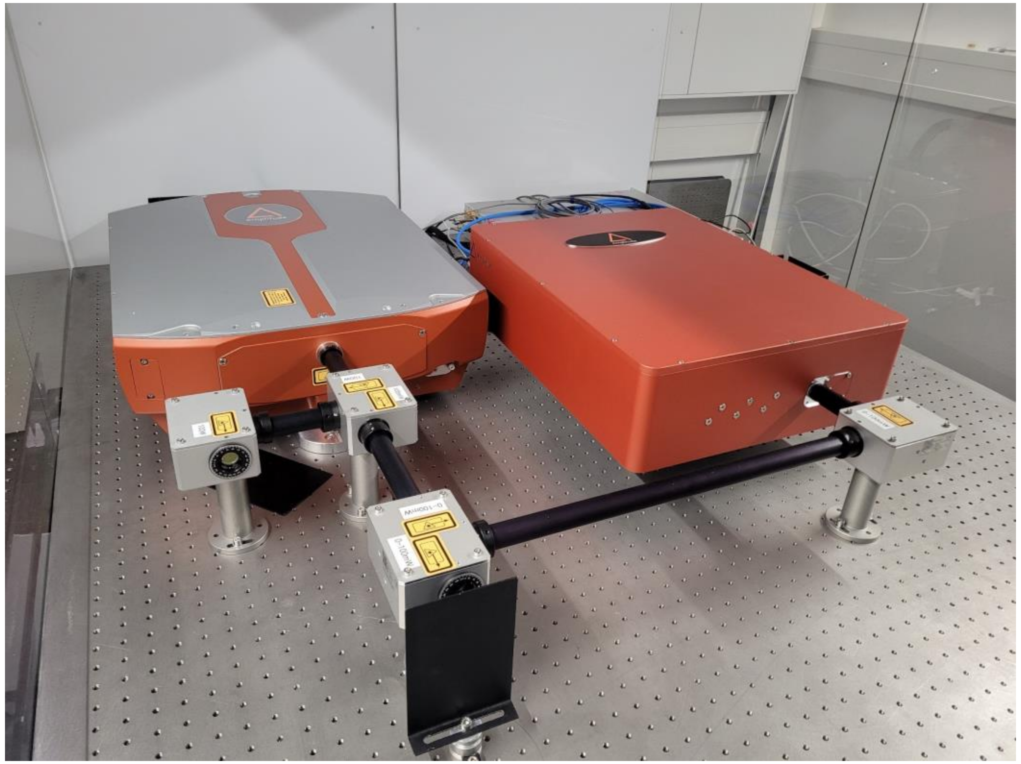


Amplitude – Laser Tangor 100

- λ =1030 nm (Ytterbium)
- $\frac{\Delta\lambda}{\lambda} \sim 2 \cdot 10^{-4}$
- P_{avg} =100 W
- $E_{Pulse} \leq 0.5$ mJ
- f =200 kHz – 40MHz
- $M^2 < 1.3$
- $\sigma_z = 3$ ps

Higher Harmonic Generation

- SHG:
  $\lambda = 515$ nm
  $\eta > 50$ %
- THG:
  $\lambda = 343$ nm
  $\eta > 25$ %

Higher photon energy preferred

Head-On Collision ✓

- For higher Energy
- Easier overlap

High Laser Pulse Energy (N_L) ✓

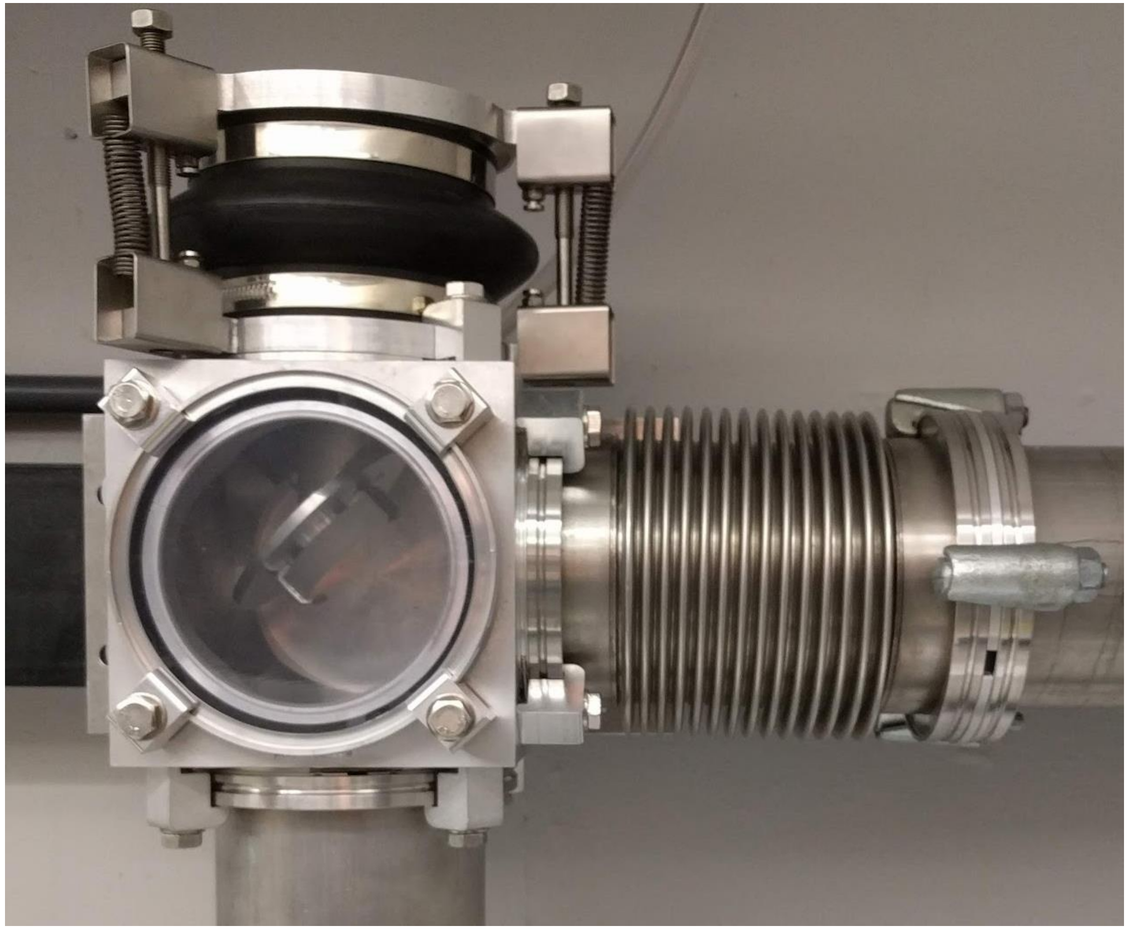
High scattering frequency (f) ✓

Small beam size at IP ✓

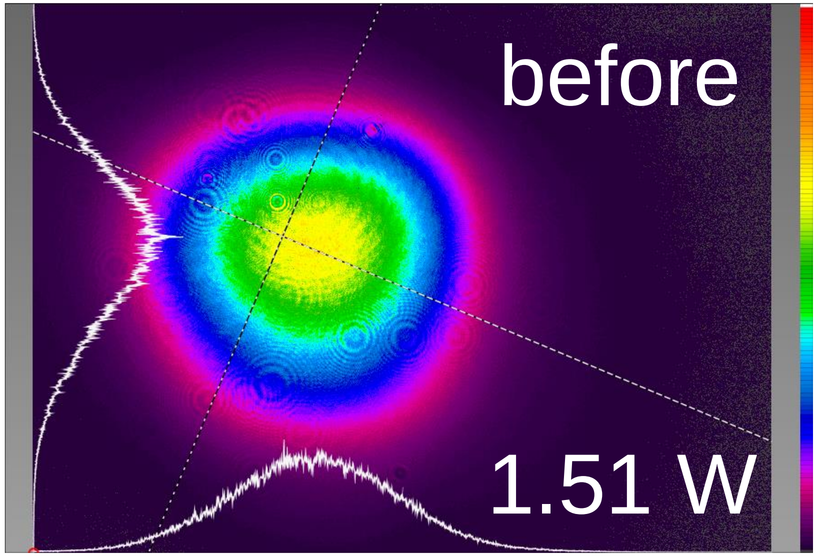
Low M^2 ✓

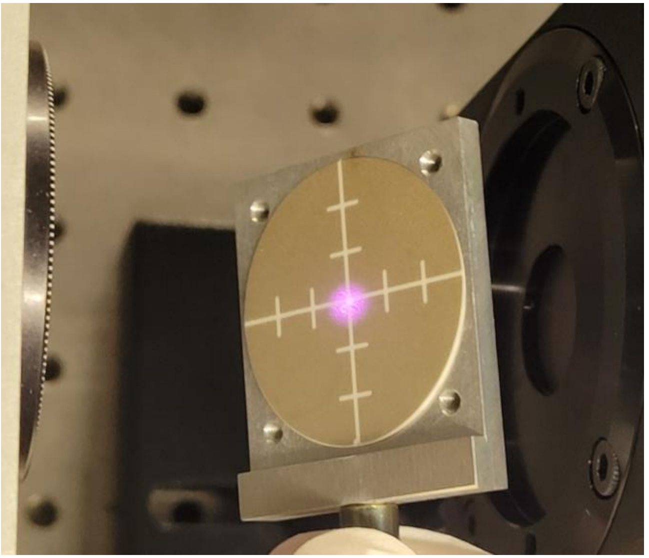
Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$ ✓

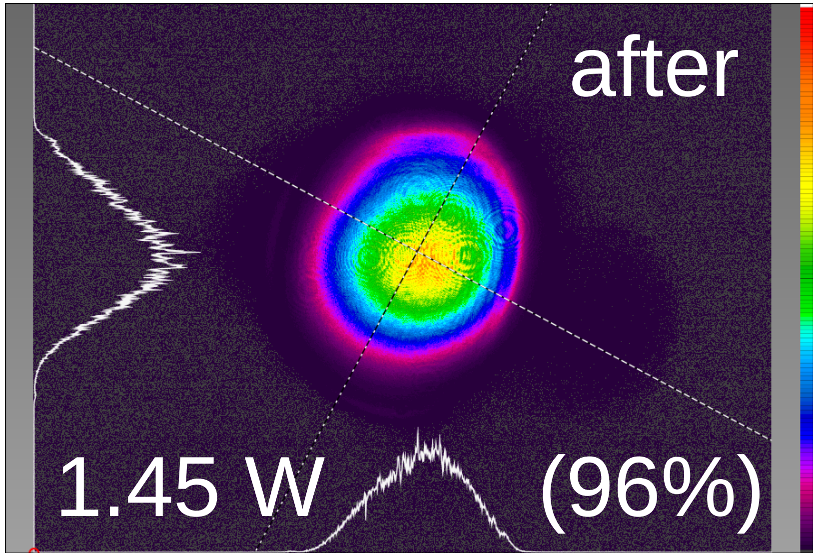
LASER BEAM TRANSPORT

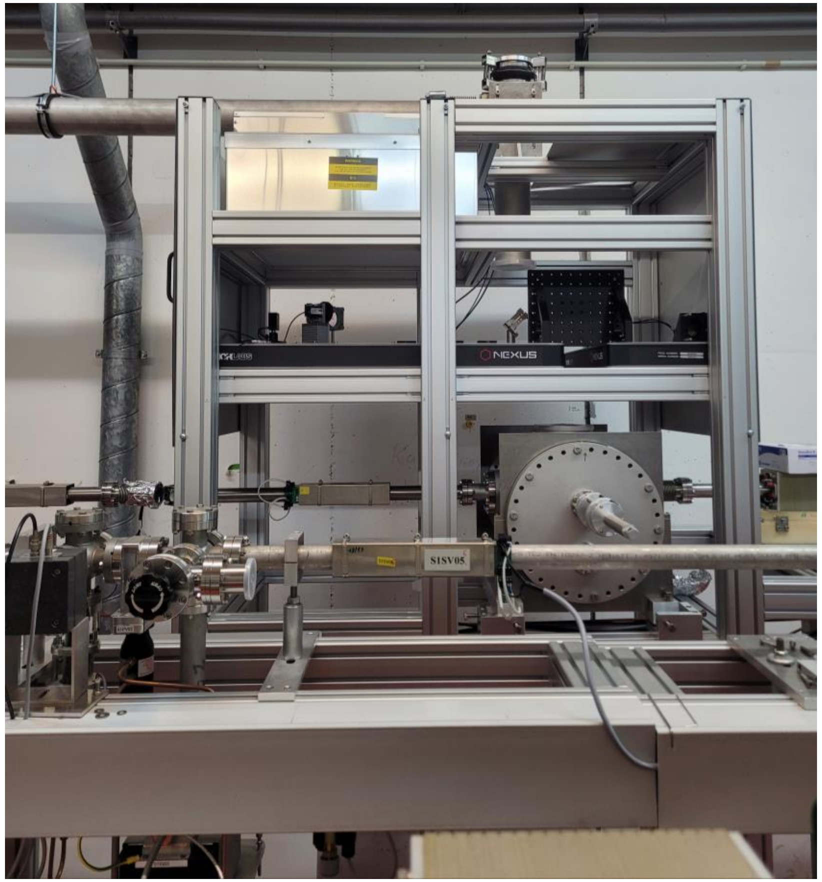


LASER BEAM TRANSPORT









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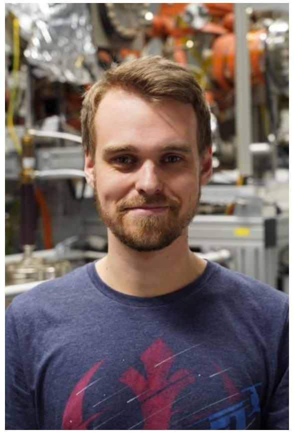
STAY TUNED!

Thank you very much!


Jörn Kleemann


Maximilian Meier

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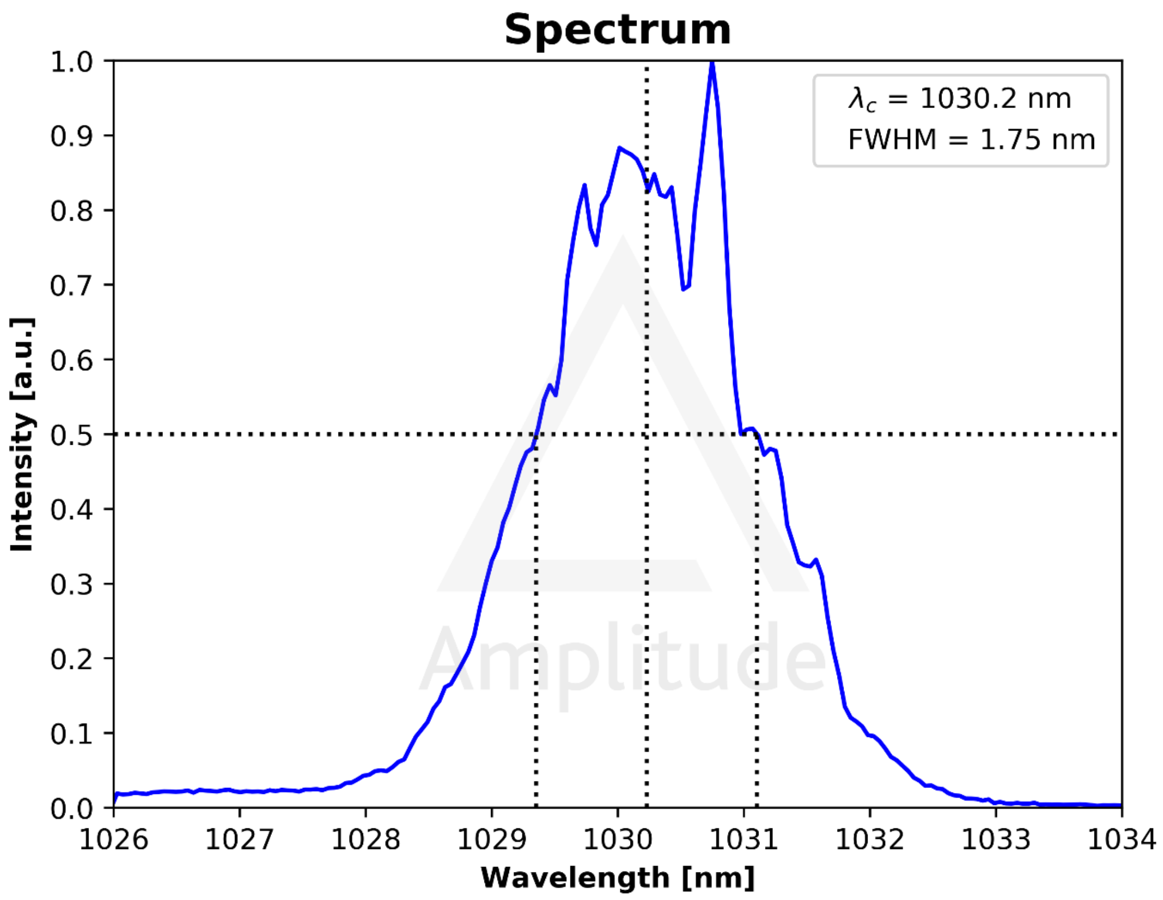
Laser Parameter		Unit	Measurement
Center wavelength		nm	1030.2
Bandwidth FWHM		nm	1.8
Average power		W	103.4
Energy per pulse		µJ	517.0
Short-term energy stability	RMS	%	0.89
Long-term energy stability	RMS	%	0.99
Pulse duration		fs	740
M²	M²x		1.08
	M²y		1.11
Astigmatism		%	11.6
Waist asymmetry		%	0.5
Beam diameter	2Wmax	mm	3.26
	2Wmin	mm	3.11
Beam ellipticity		%	4.6
Short-term pointing stability	Radial	µrad	4.5
Short-term position stability	Radial	µm	1.58
Absolute timing jitter		fs	175.0
Long term jitter on 12h		fs	192.9
Repetition rate adjustibility			Single shot – 40 MHz



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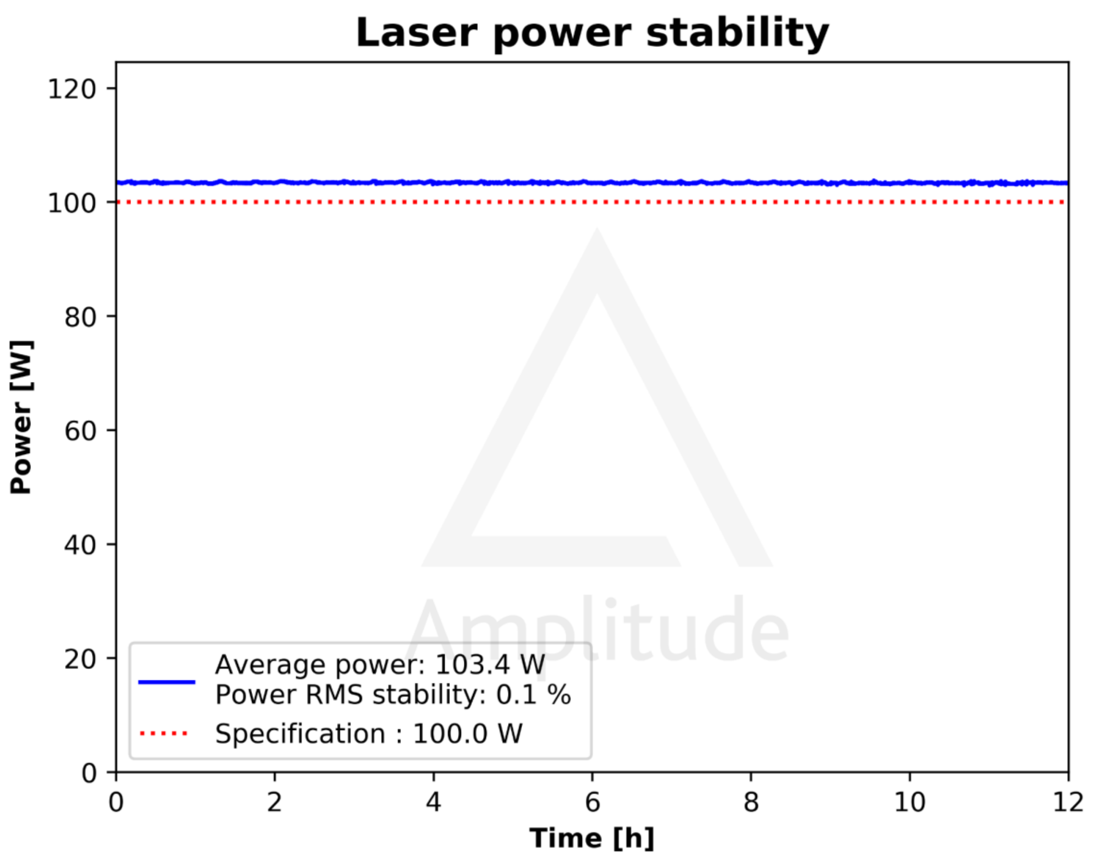

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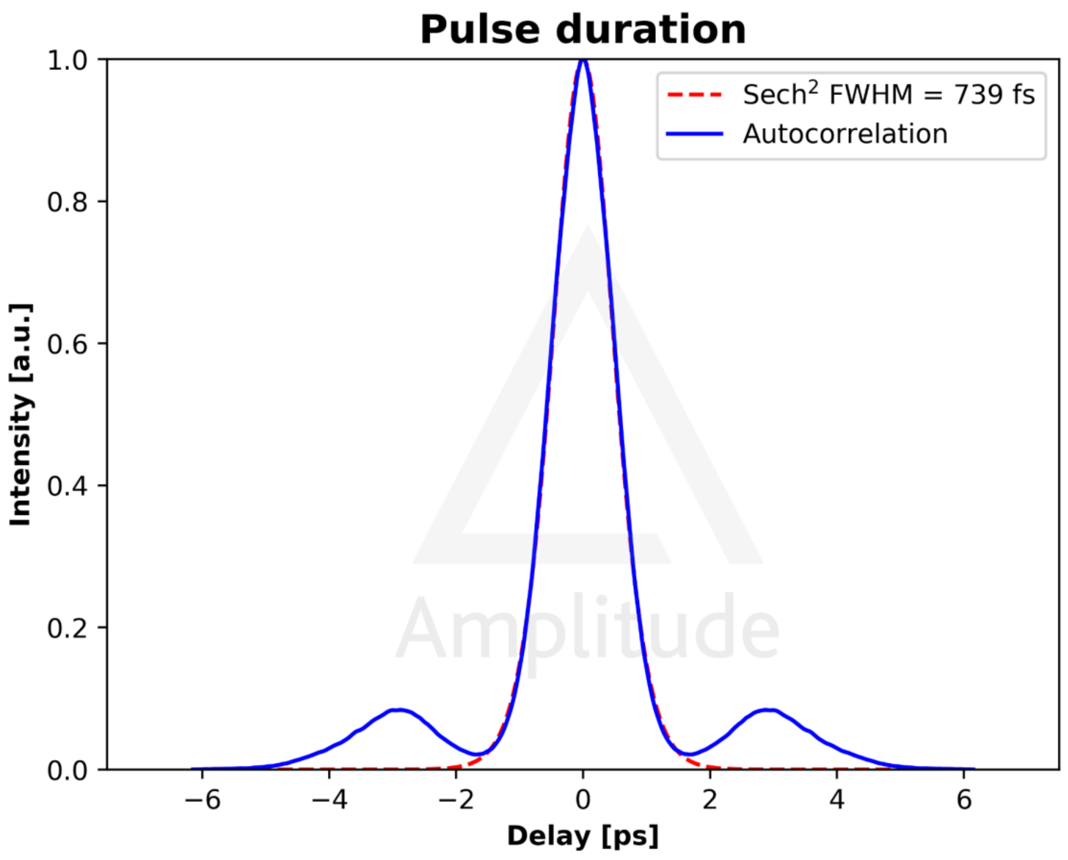

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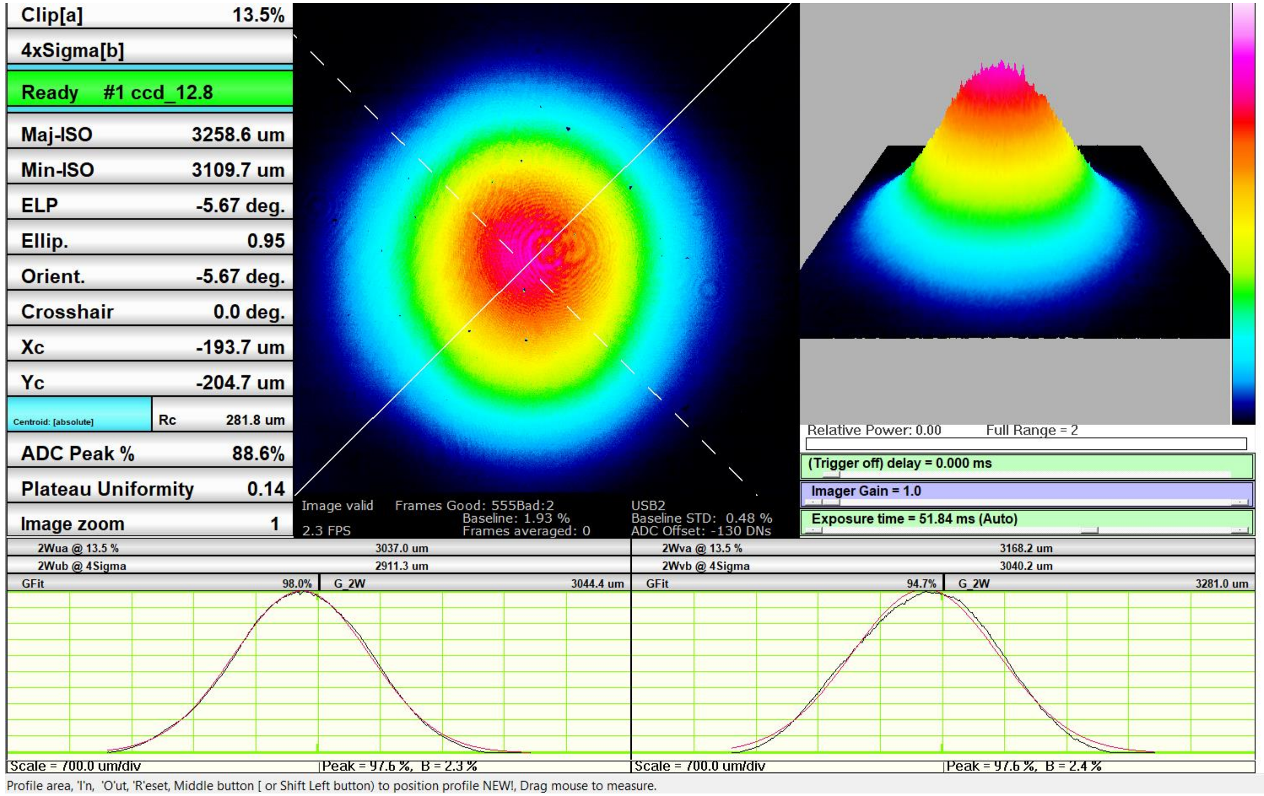

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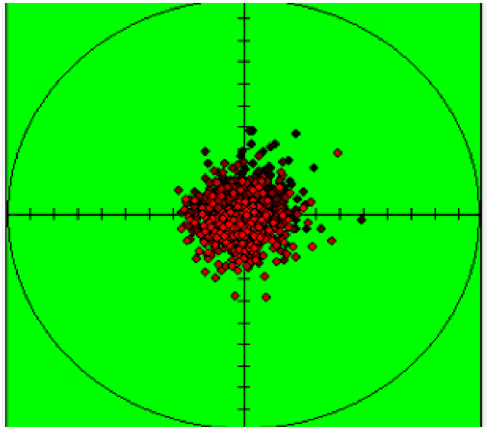

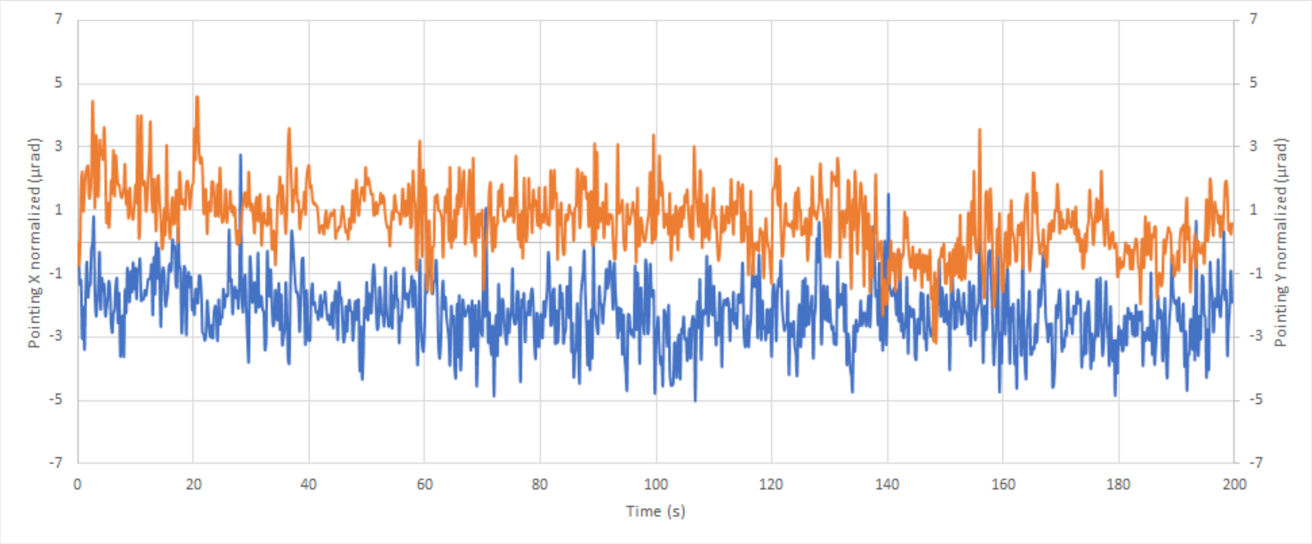

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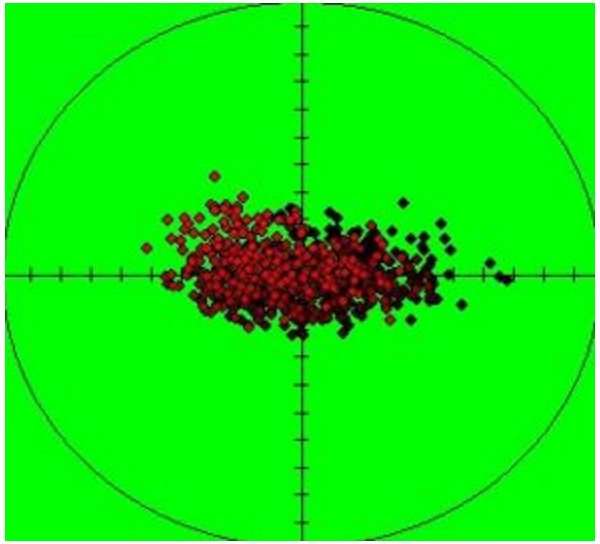

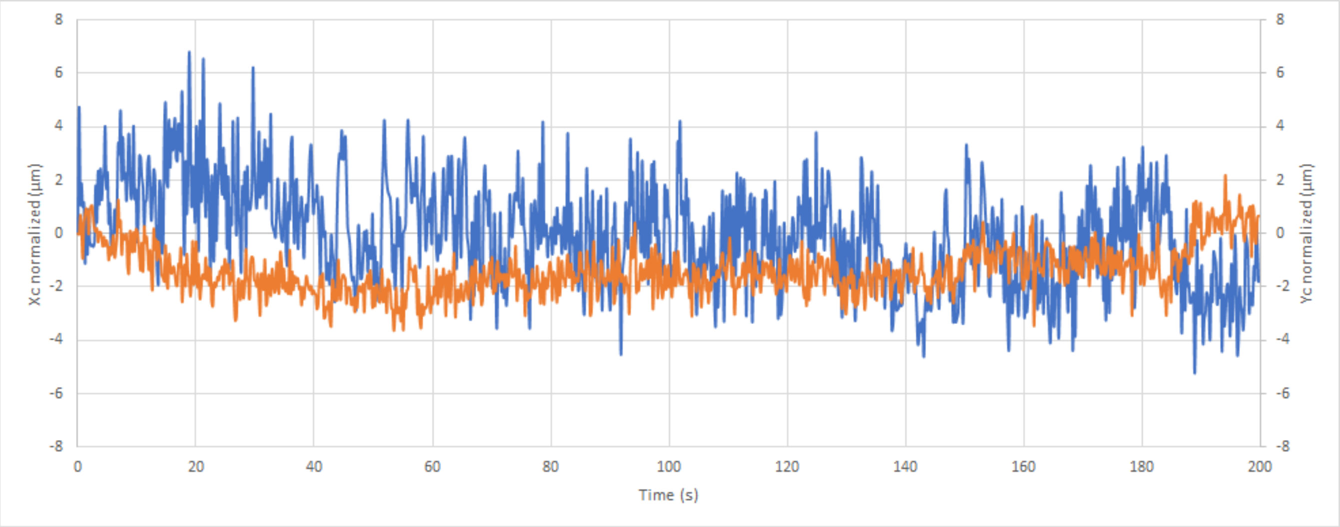

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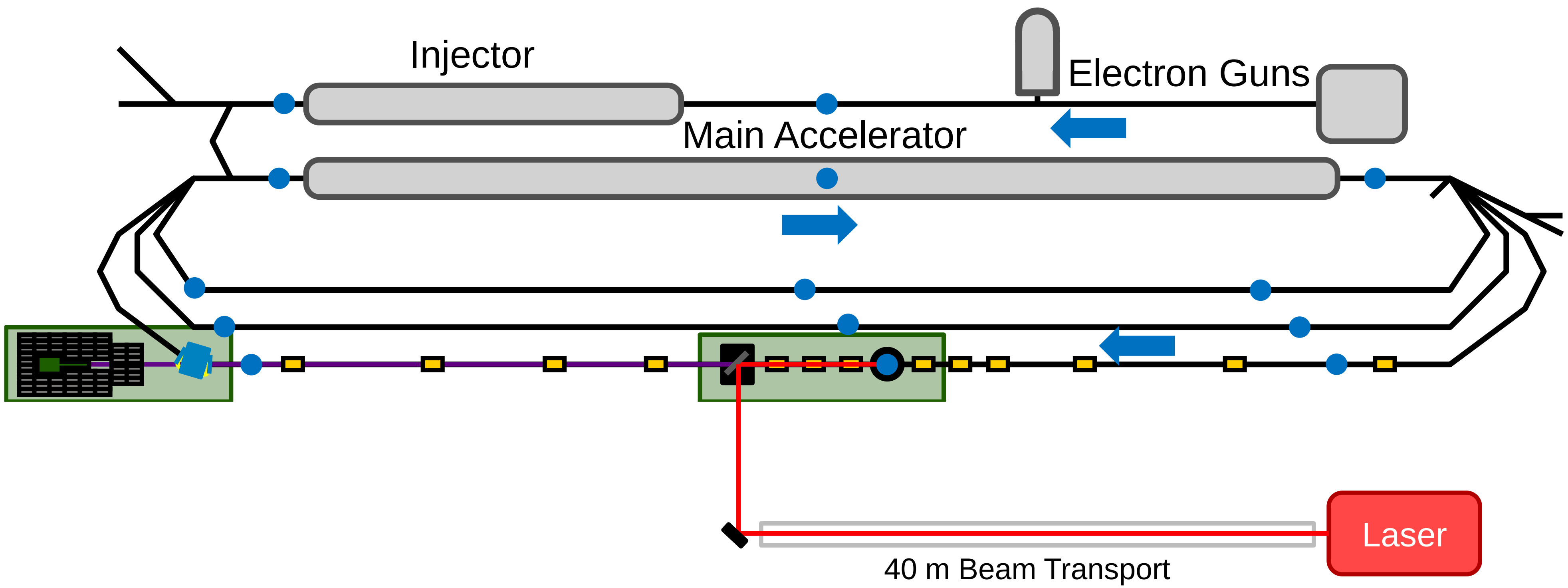


Higher photon energy preferred

Head-On Collision ✓

- For higher Energy
- Easier overlap

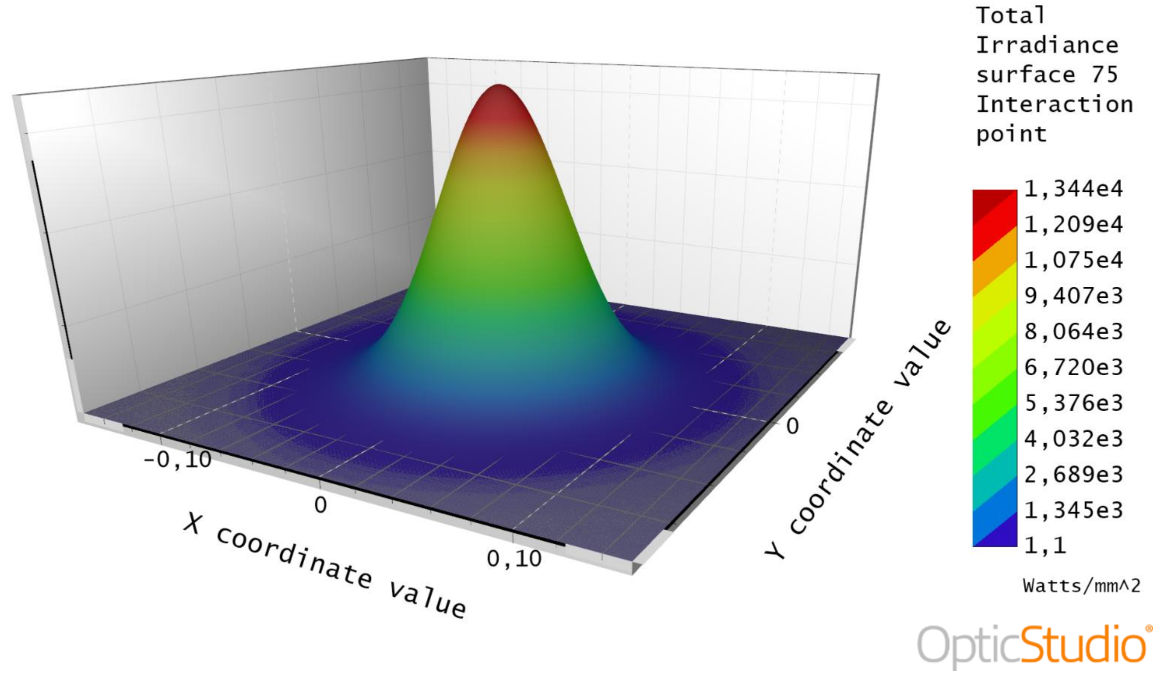
High Laser Pulse Energy (N_L)

High scattering frequency (f)

Small beam size at IP

Low M^2

Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$



Total Irradiance surface 75 Interaction point

Beam wavelength is 1,03000 µm in the media with index 1,00000 at 0,0000 (deg)
Display X Width = 3,0766E-01, Y Height = 3,0767E-01 Millimeters
Peak Irradiance = 1,3439E+04 Watts/Millimeters^2, Total Power = 9,8445E+01 Watts
Pilot: Size= 6,7106E-02, Waist= 5,3623E-02, Pos= 6,5988E+00, Rayleigh= 8,7703E+00

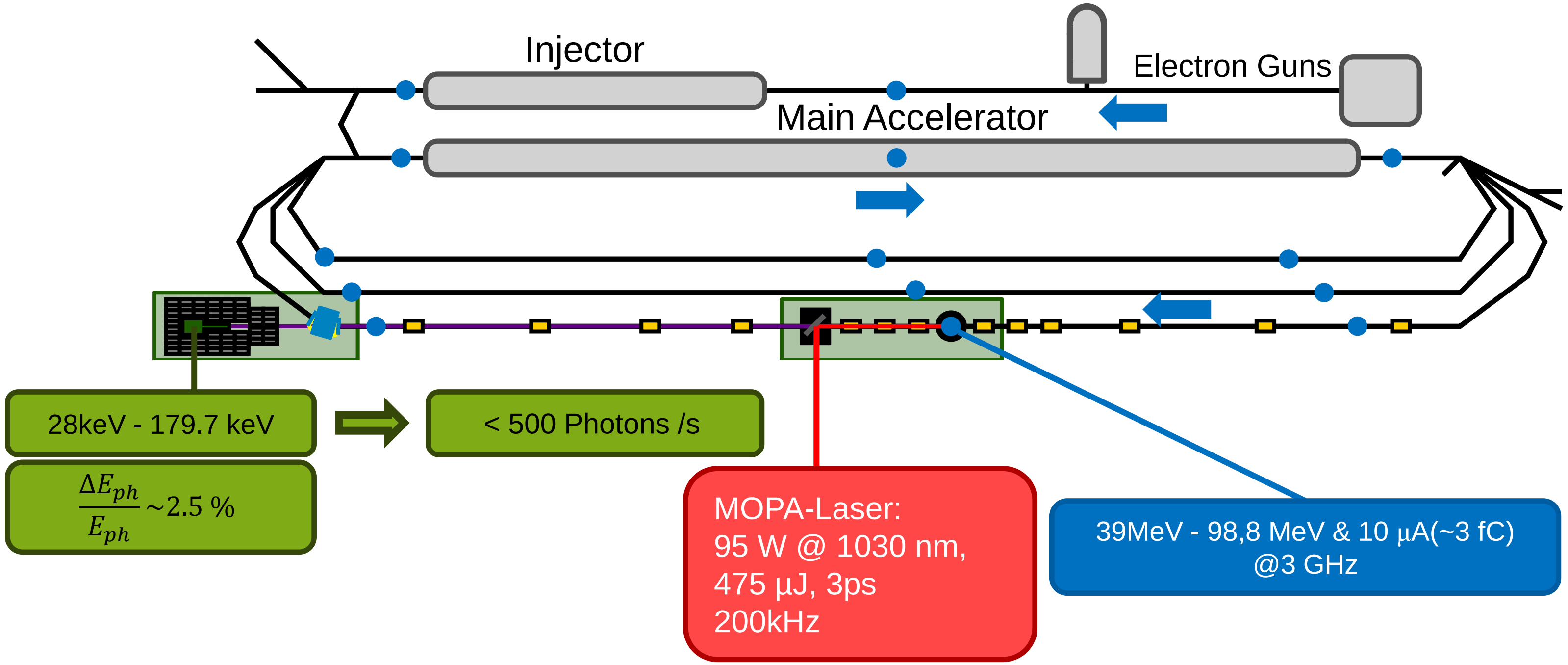
Simulation:

- Zemax OpticStudio
  - Physical optics propagation
- 40 m beam transport
- Telescopes and “relay imaging“
- Off-axis parabolic mirror with hole

Physical optics propagation @ IP:

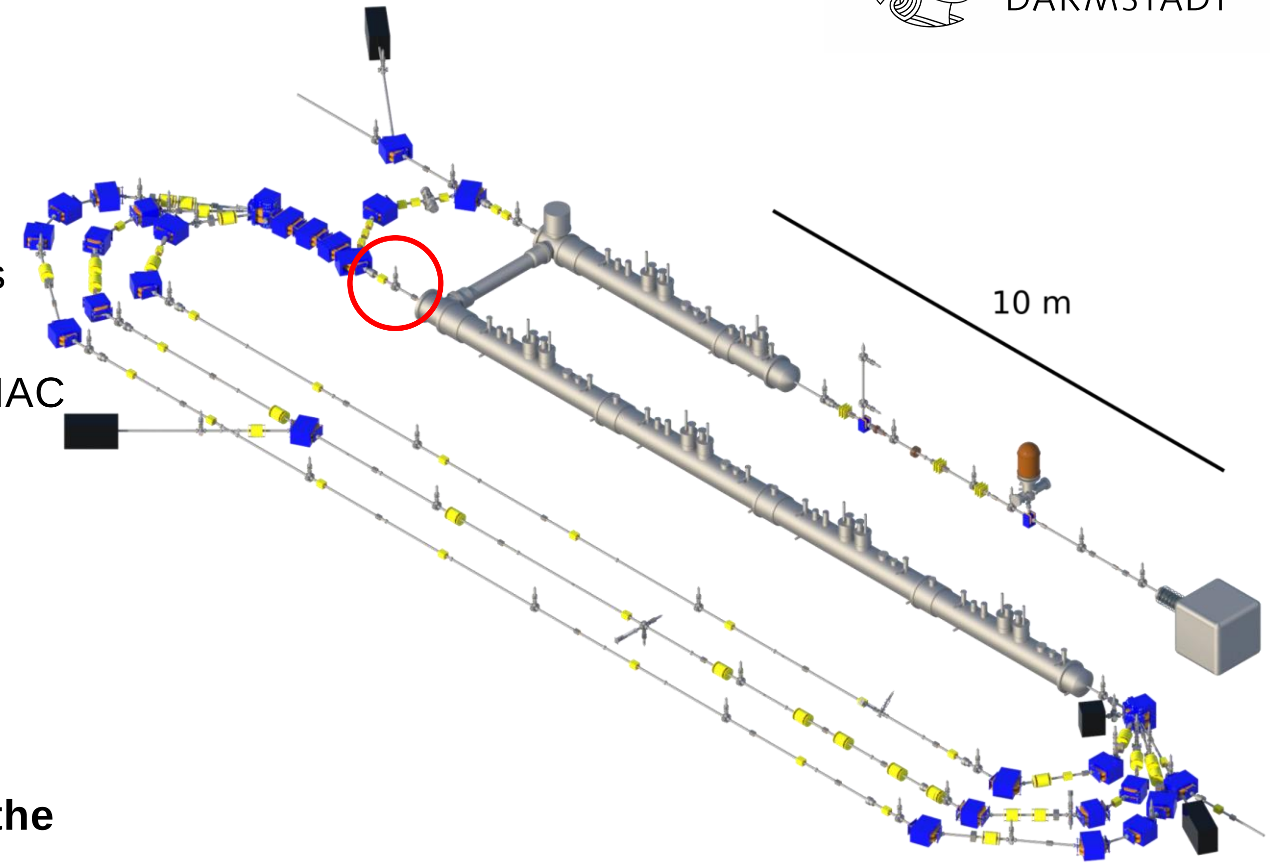
- Total power: 94.5 W (100 W)
- Waist size: 53.6 µm (12 mm)
- Rayleigh length: 8.8 mm

Parameters	Values
Electron Beam	
Electron Energy (E_e)	$39\ \text{MeV} - 98.8\ \text{MeV}$
Rel. Error of Electron Energy (ΔE_e)	$< 10^{-3}$
Beam Current (I)	$10\ \mu\text{A}$
Beam normalized emittance	$5 \cdot 10^{-6}\ \text{m rad}$
Electron Beam Size ($\sigma_{e,rms}$)	$\leq 100\ \mu\text{m}$
Laser Beam	
Wavelength (λ)	1030 nm
Photon Energy (E_L)	1.2 eV
Error Photon Energy (ΔE_L)	$1 \cdot 10^{-3}$ eV
Pulse Energy (E_{pulse})	0.25 mJ
Repetition Rate (f_{rep})	200 kHz
Beam Size ($\sigma_{pulse,rms}$)	$\leq 100\ \mu\text{m}$
Scattered Photon – Results for Head-On Collision	
Energy	$28\ \text{keV} - 179\ \text{keV}$
Min. rel. Energy Bandwidth, FWHM	0.7 %
Total Flux	$6 \cdot 10^3\ \text{Ph}/\text{s}$
Spectral Flux at min. Bandwidth	$38\ \text{Ph}/\text{s}$



AKBP 16.4: Design and Status of the Laser-Compton Backscattering Source at the S-DALINAC

1. AKBP 1.2: Automated Activation Procedure for GaAs Photocathodes
2. AKBP 8.4: Sensitivity Analysis and Online Surrogate Construction at the S-DALINAC Using Polynomial Chaos and Neural Networks
3. AKBP 9.6: Design of a Solenoid Magnet for the S-DALINAC
4. AKBP 14.1: System for Bunch Length Measurements behind the Injector of S-DALINAC
5. AKBP 14.2: Simulationen zur Optimierung von Vakuumsystemen für Beschleunigerstrahlführungen
6. AKBP 16.4: Design and Status of the Laser-Compton Backscattering Source at the S-DALINAC
7. **AKBP 16.5: Development of a 6 GHz Cavity BPM for the Multi-Turn ERL Operation at the S-DALINAC**



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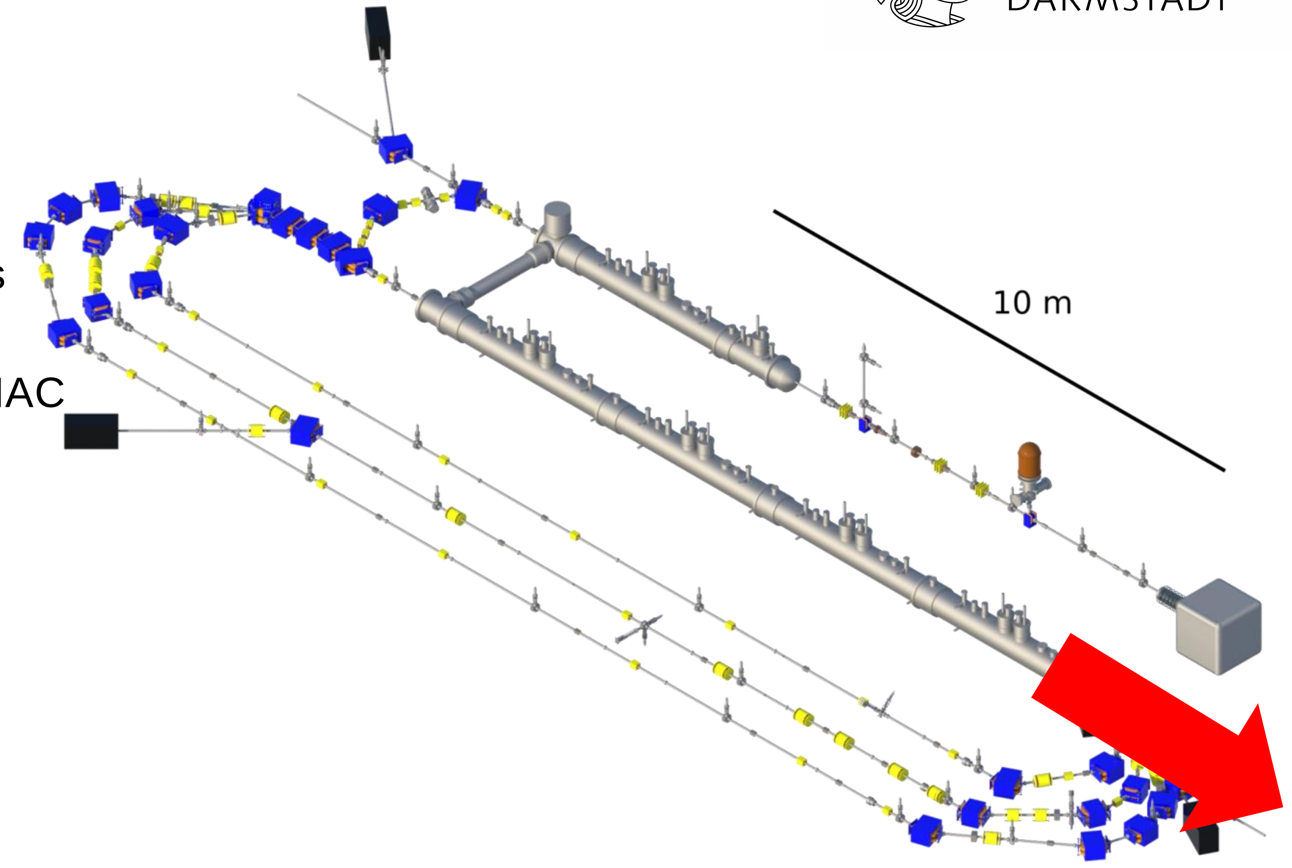
8. **AKBP 16.15: The Scraper System at S-DALINAC and ERL application**



AKBP 16.15: The Scraper System at S-DALINAC and ERL application

- Machine protection
- Improving beam quality
- Background reduction
- Beam cleaning

- Simulation of an ERL interaction point with possible scraper placement

Beamline for ERL experiment

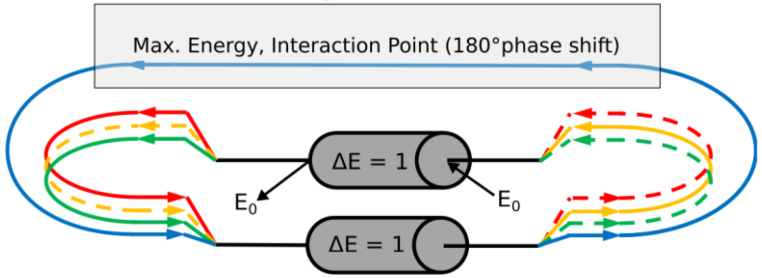


Table 1: Design parameters of S-DALINAC

Design Energy:	130 MeV
Beam current @ 130 MeV:	20 μA
Frequency:	2.997 GHz

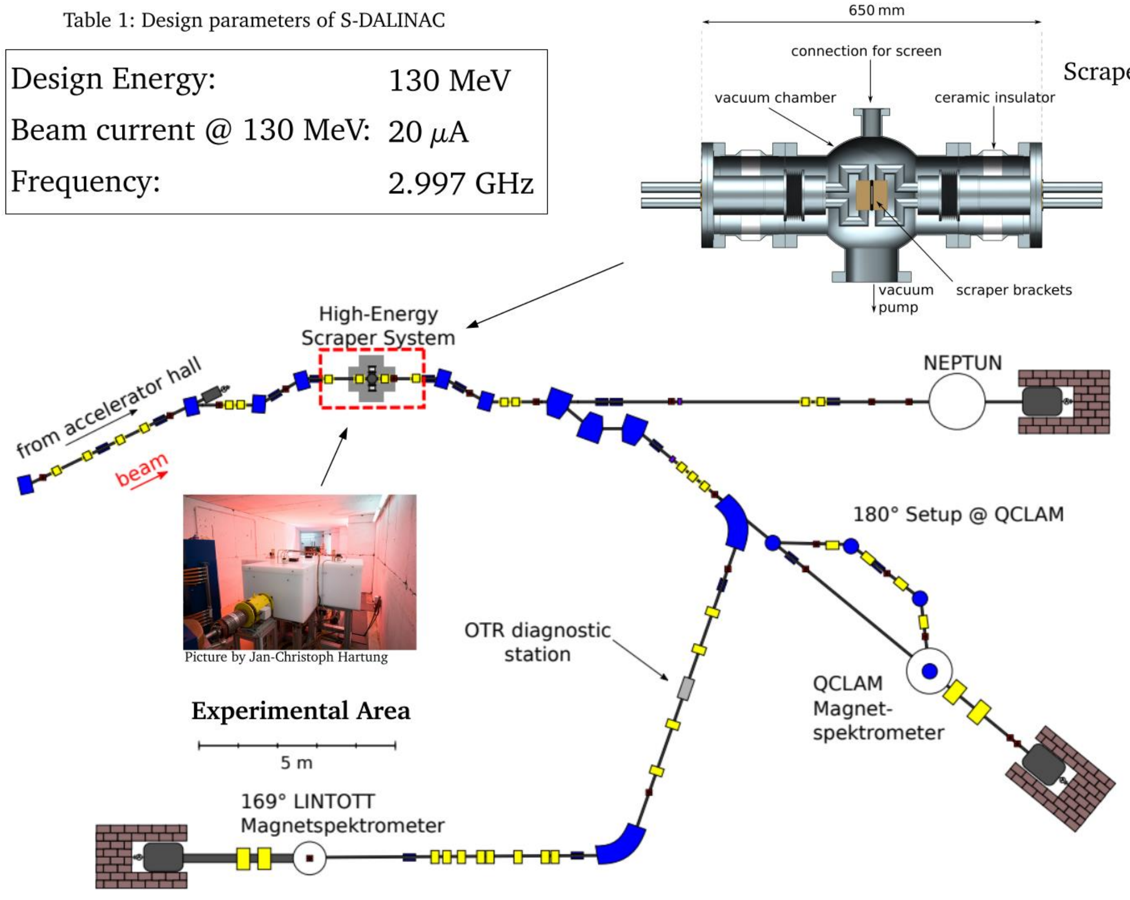


Figure 1: Experimental Area of S-DALINAC

- We successfully implemented a **two-fold energy recovery** (TER) mode at the S-DALINAC with an efficiency of **up to 87 %** (at low currents)
  - ➢ RF power required for a given beam current is substantially reduced

- Methods to increase the efficiency under investigation
- Implementation of a three-fold energy recovery mode in planning

- We have many **projects related to the ERL** operation of the S-DALINAC or future ERL accelerators, some of them **presented at this DPG Spring Meeting**

MULTI-TURN ERL MODE OF THE S-DALINAC

THANK YOU FOR YOUR ATTENTION