DICE: A Proposal for Energy-Efficient Electron Acceleration for Nuclear Photonics Applications

M. Arnold, A. Brauch, L. Dingeldein, M. Dutine, J. Enders, R. Grewe, M. Herbert, L. Jürgensen, M. Meier, N. Pietralla, F. Schliessmann, D. Schneider, V. Werner

THE SCALPEL FOR NUCLEAR PHOTONICS

Quasi-monochromatic, polarized and tunable gamma-ray beam with high flux, E_γ ~ 1 – 20 MeV

THE SCALPEL FOR NUCLEAR PHOTONICS

Quasi-monochromatic, polarized and **tunable** gamma-ray beam with high flux, $E_\gamma \sim 1 - 20$ **MeV**

Laser Compton backscattering (LCB)

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

$E_L \approx 1 - 3$ eV → $E_e \approx 500$ MeV → multi-turn lattice

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Electron accelerator parameters

Flux ~ collision frequency → Superconducting radiofrequency (SRF) technology

Flux ~ 1/emittance of beam → Linear accelerator

Flux ~ number of electrons per bunch → Energy recovery linac technology (ERL) + sustainable

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LCB @ Multi-turn SRF ERL

4^{th} generation γ-source

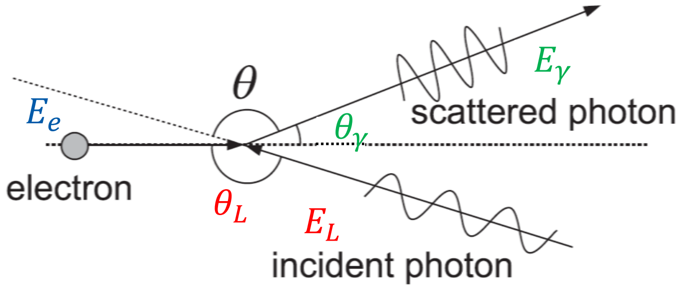
OUTLINE

BASICS

4th GENERATION γ-SOURCE

LCB @ Multi-turn SRF ERL

LCB



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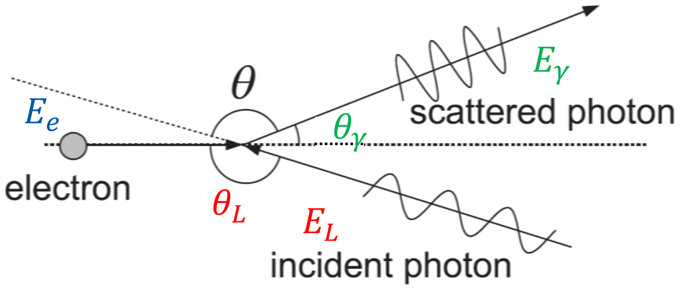
4th GENERATION γ-SOURCE

LCB @ Multi-turn SRF ERL

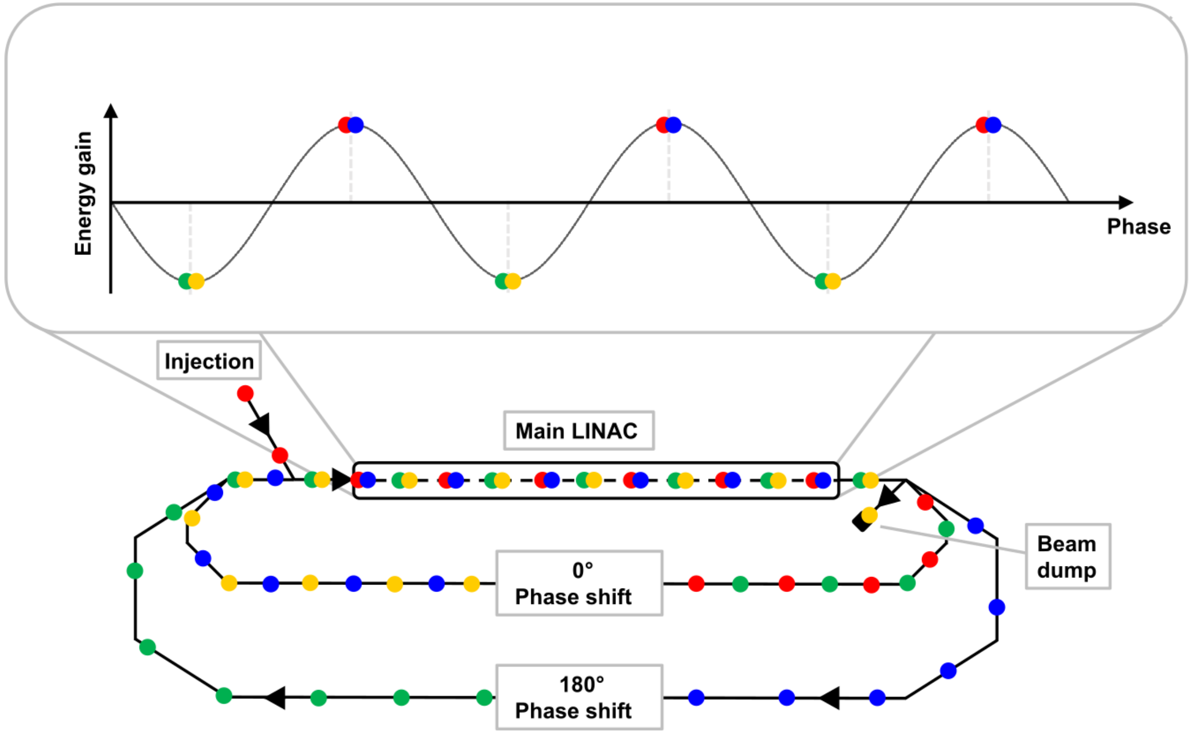
LCB



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

Multi-turn ERL

- First beam (to be) accelerated
- First beam (to be) decelerated
- Second beam (to be) accelerated
- Second beam (to be) decelerated



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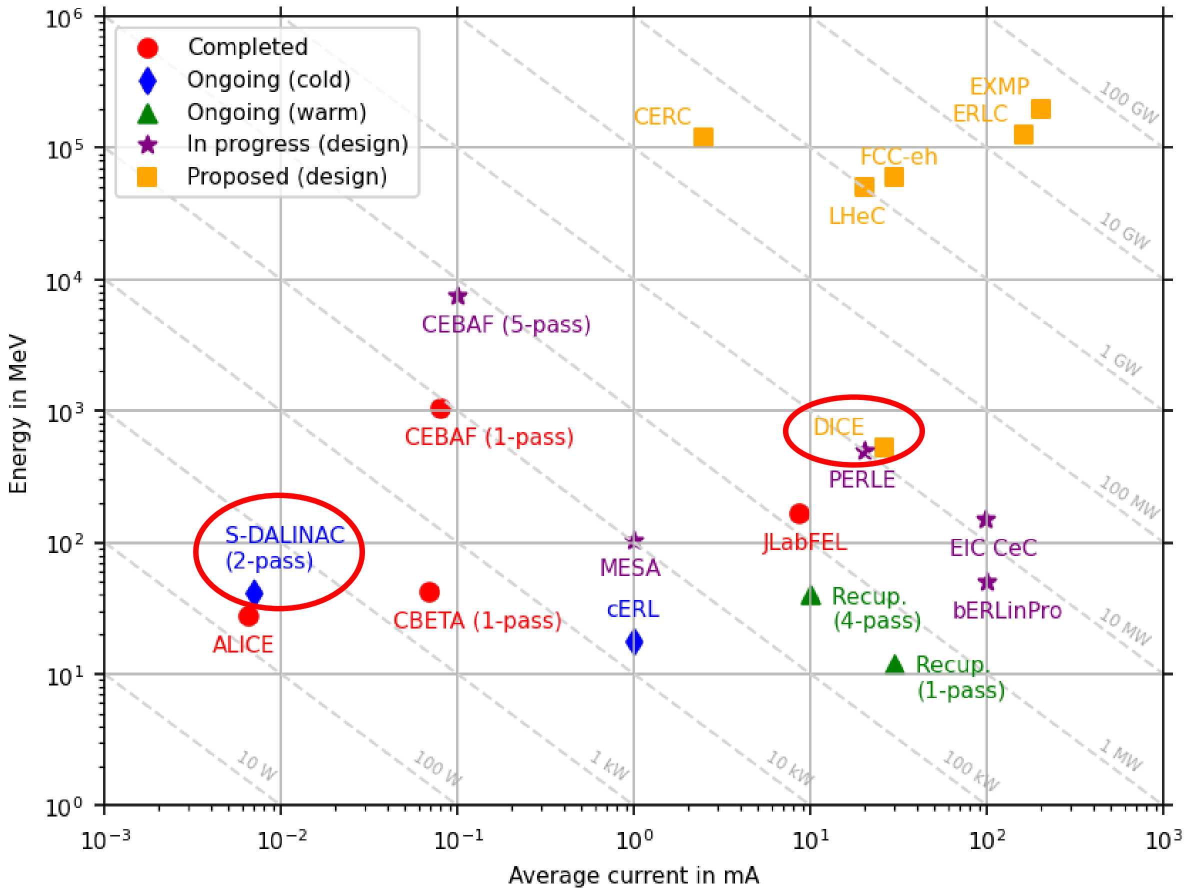
MULTI-TURN ERL OPERATION



Adapted from C. Adolphsen et al., arXiv:2207.02095 [physics.acc-ph] (2022)

Running SRF multi-turn ERLs

- CBETA (USA): 4-turn → 1 nA, beam loss
- S-DALINAC (TUDa): 2-turn → up to 7μA and max. 87% recovery

Near future SRF multi-turn ERLs

- PERLE (France)
- MESA (Mainz)
- CEBAF (5-pass) (USA)

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OUR EXPERTISE

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Talks by J. Isaak, V. Werner, N. Pietralla

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PHOTONUCLEAR REACTIONS

PHYSICAL REVIEW LETTERS 134, 022503 (2025)

Gamma Decay of the ^{154}Sm Isovector Giant Dipole Resonance: Smekal-Raman Scattering as a Novel Probe of Nuclear Ground-State Deformation

J. Kleemann,[1,*] N. Pietralla,[1] U. Friman-Gayer,[2,3,†] J. Isaak,[1] O. Papst,[1] K. Prifti,[1] V. Werner,[1] A. D. Ayangeakaa,[4,3] T. Beck,[1,‡] G. Colò,[5] M. L. Cortés,[1] S. W. Finch,[2,3] M. Fulghieri,[4,3] D. Gribble,[4,3] K. E. Ide,[1] X. K.-H. James,[4,3] R. V. F. Janssens,[4,3] S. R. Johnson,[4,3] P. Koseoglou,[1] Krishichayan,[2,3] D. Savran,[6] and W. Tornow[2,3]

PRL 118, 212502 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017

***E*2 decay strength of the *M*1 scissors mode of ^{156}Gd and its first excited rotational state**

T. Beck,[1,*] J. Beller,[1] N. Pietralla,[1] M. Bhike,[2] J. Birkhan,[1] V. Derya,[3] U. Gayer,[1] A. Hennig,[3] J. Isaak,[4,5,†] B. Löher,[4,5] V. Yu. Ponomarev,[1] A. Richter,[1] C. Romig,[1,‡] D. Savran,[4,5] M. Scheck,[1,6,7] W. Tornow,[2] V. Werner,[1] A. Zilges,[3] and M. Zweidinger[1]
[1]*Institut für Kernphysik, TU Darmstadt, Schlossgartenstr. 9, D-64289 Darmstadt, Germany*
[2]*Department of Physics, Duke University and Triangle Universities Nuclear Laboratory, Durham,*

PHYSICAL REVIEW LETTERS 135, 052501 (2025)

Deviations from the Porter-Thomas Distribution due to Nonstatistical γ Decay below the ^{150}Nd Neutron Separation Threshold

O. Papst,[1,*] J. Isaak,[1,†] V. Werner,[1] D. Savran,[2] N. Pietralla,[1] G. Battaglia,[3] T. Beck,[1,‡] M. Beuschlein,[1] S. W. Finch,[4,5] U. Friman-Gayer,[1,§] K. E. Ide,[1] R. V. F. Janssens,[5,6] M. D. Jones,[5,6] J. Kleemann,[1] B. Löher,[2] M. Scheck,[7,8] M. Spieker,[9,‖] W. Tornow,[4,5] R. Zidarova,[1] and A. Zilges[10]

PHYSICAL REVIEW LETTERS 126, 102501 (2021)

Role of Chiral Two-Body Currents in ^{6}Li Magnetic Properties in Light of a New Precision Measurement with the Relative Self-Absorption Technique

U. Friman-Gayer,[1,2,3,*] C. Romig,[1,†] T. Hüther,[1] K. Albe,[4] S. Bacca,[5,6] T. Beck,[1] M. Berger,[1] J. Birkhan,[1] K. Hebeler,[1,7] O. J. Hernandez,[8,5] J. Isaak,[1] S. König,[1,7,9] N. Pietralla,[1] P. C. Ries,[1] J. Rohrer,[4] R. Roth,[1] D. Savran,[10] M. Scheck,[1,11,12] A. Schwenk,[1,7,13] R. Seutin,[13,1,7] and V. Werner[1]

VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

Parity Measurements of Nuclear Levels Using a Free-Electron-Laser Generated γ-Ray Beam

N. Pietralla[1,2] and Z. Berant[1,3]
[1]*A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520*

Eur. Phys. J. A (2024) 60:108
https://doi.org/10.1140/epja/s10050-024-01285-8
THE EUROPEAN PHYSICAL JOURNAL A
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Review

Photons and nuclear structure

Norbert Pietralla[a]
Physics Department, Institute for Nuclear Physics, TU Darmstadt, Schlossgartenstrasse 9, 64289 Darmstadt, Germany

PRL 111, 172501 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

Constraint on $0\nu\beta\beta$ Matrix Elements from a Novel Decay Channel of the Scissors Mode: The Case of ^{154}Gd

J. Beller,[1,*] N. Pietralla,[1] J. Barea,[2] M. Elvers,[3,†] J. Endres,[3,‡] C. Fransen,[3] J. Kotila,[4] O. Möller,[1] A. Richter,[1] T. R. Rodríguez,[1] C. Romig,[1] D. Savran,[5,6] M. Scheck,[1,7] L. Schnorrenberger,[1] K. Sonnabend,[8] V. Werner,[9] A. Zilges,[3] and M. Zweidinger[1]
[1]*Institut für Kernphysik, TU Darmstadt, Schlossgartenstraße 9, D-64289 Darmstadt, Germany*
[2]*Departamento de Física, Universidad de Concepción, Casilla 160-C, Concepción, Chile*

PHYSICAL REVIEW LETTERS 125, 092501 (2020)

$\Delta K = 0$ *M*1 Excitation Strength of the Well-Deformed Nucleus ^{164}Dy from *K* Mixing

T. Beck,[1,†] V. Werner,[1,2] N. Pietralla,[1] M. Bhike,[3] N. Cooper,[2,*] U. Friman-Gayer,[1,‡] J. Isaak,[1] R. V. Jolos,[4,5] J. Kleemann,[1] Krishichayan,[3] O. Papst,[1] W. Tornow,[3] C. Bernards,[2] B. P. Crider,[6,§] R. S. Ilieva,[2,7] B. Löher,[8] C. Mihai,[9] F. Naqvi,[2,‖] S. Pascu,[9] E. E. Peters,[10] F. M. Prados-Estevez,[6,10] T. J. Ross,[10] D. Savran,[8] J. R. Vanhoy,[11] and A. Zilges[12]

Nuclear Photonics
Institut für Kernphysik S-DALINAC Technische Universität Darmstadt

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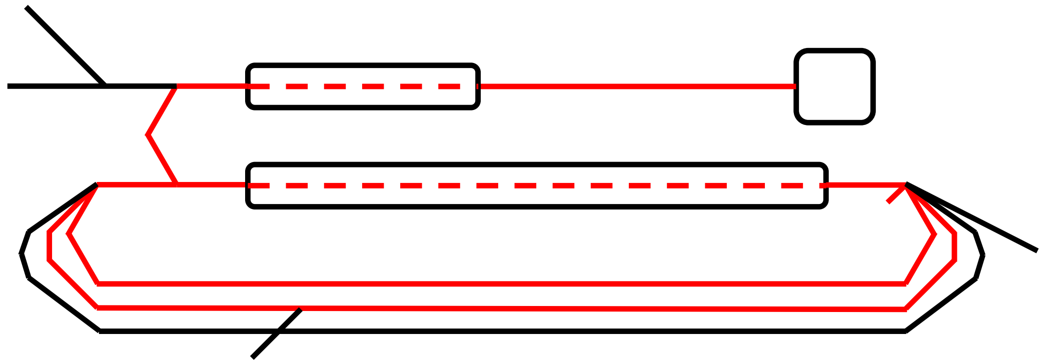
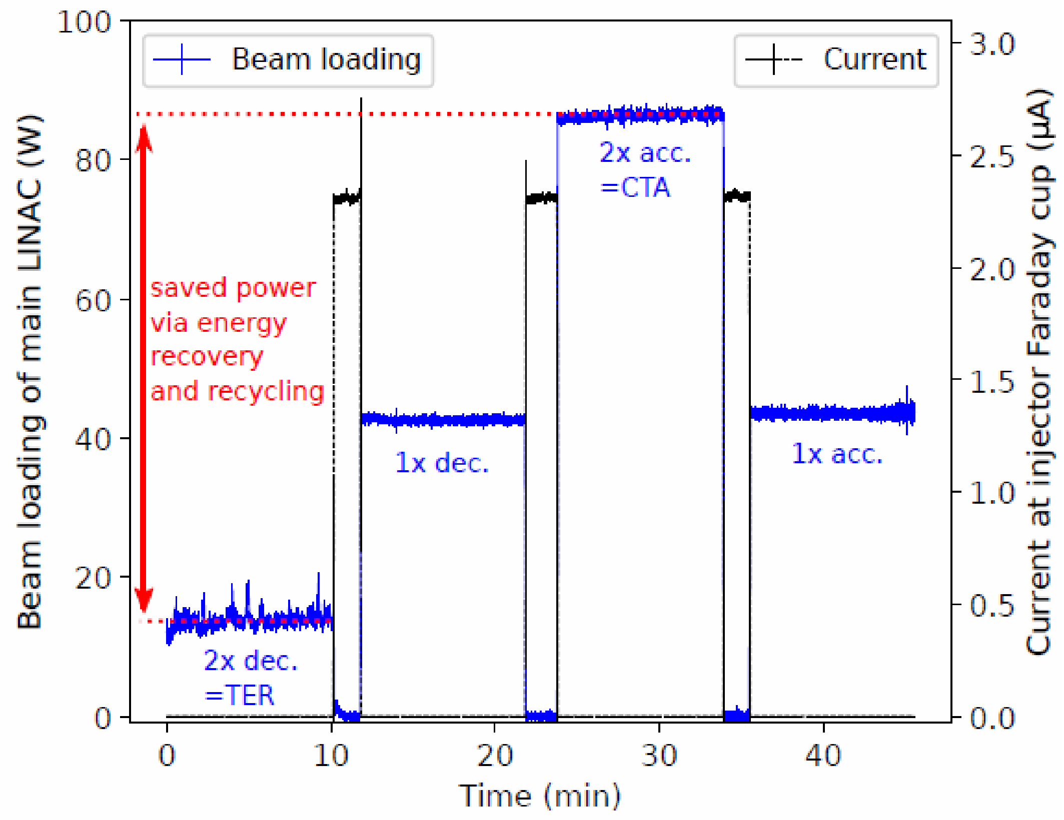
TWO-TURN ERL





F. Schliessmann et al., Nat. Phys. **19**, 597-602 (2023).

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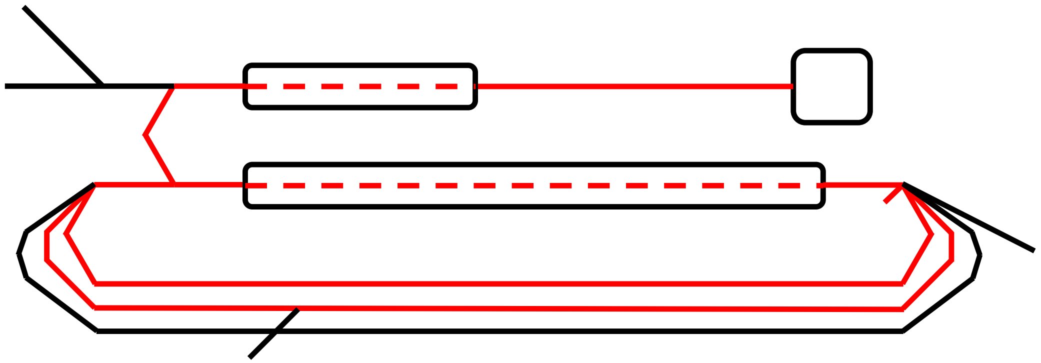

nature physics

Article

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

Realization of a multi-turn energy recovery accelerator

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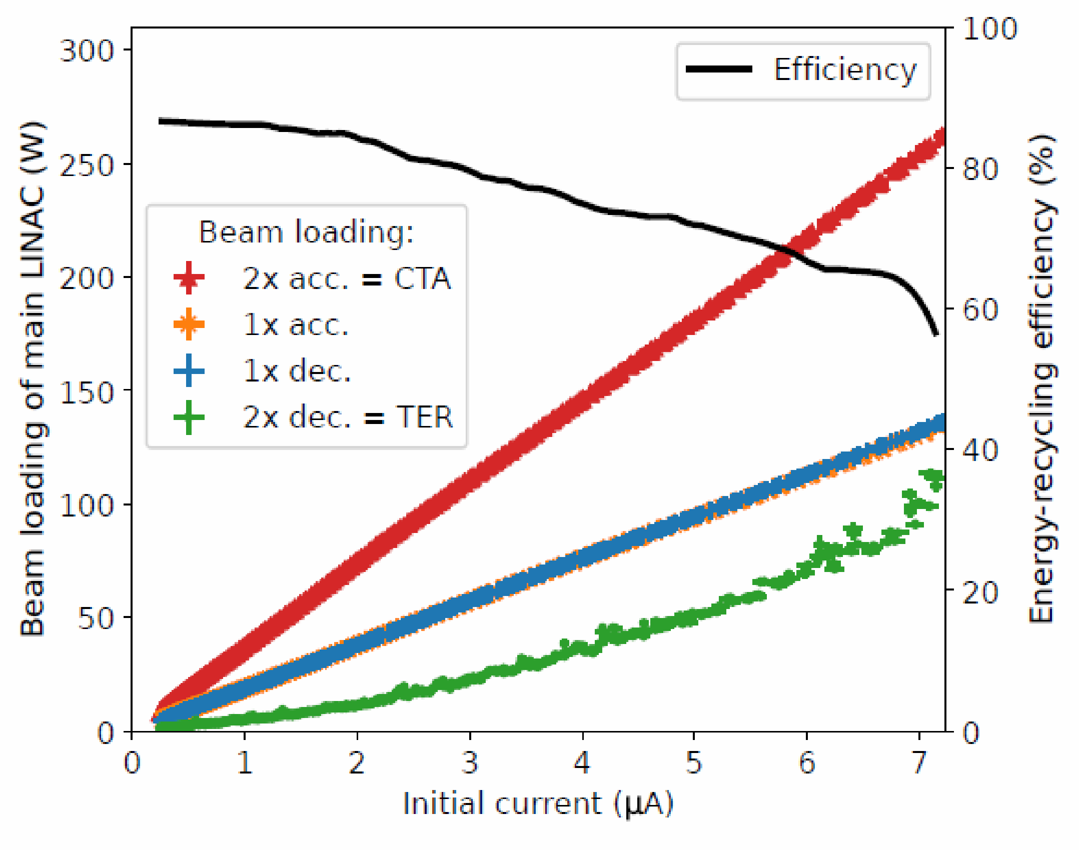
Accepted: 26 October 2022
Published online: 26 January 2023

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

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



F. Schliessmann et al., Nat. Phys. **19**, 597-602 (2023).

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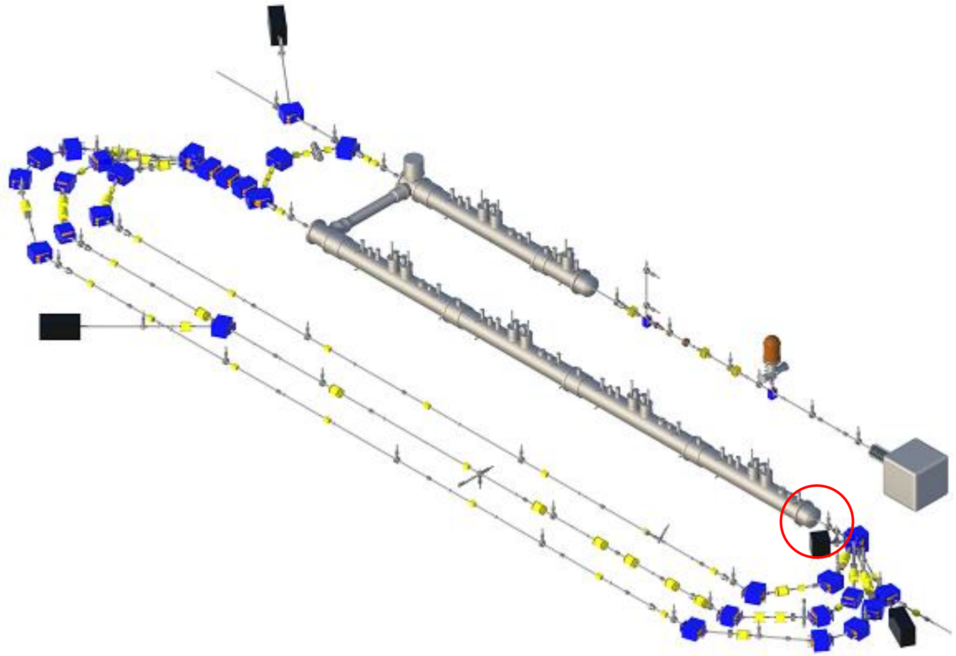
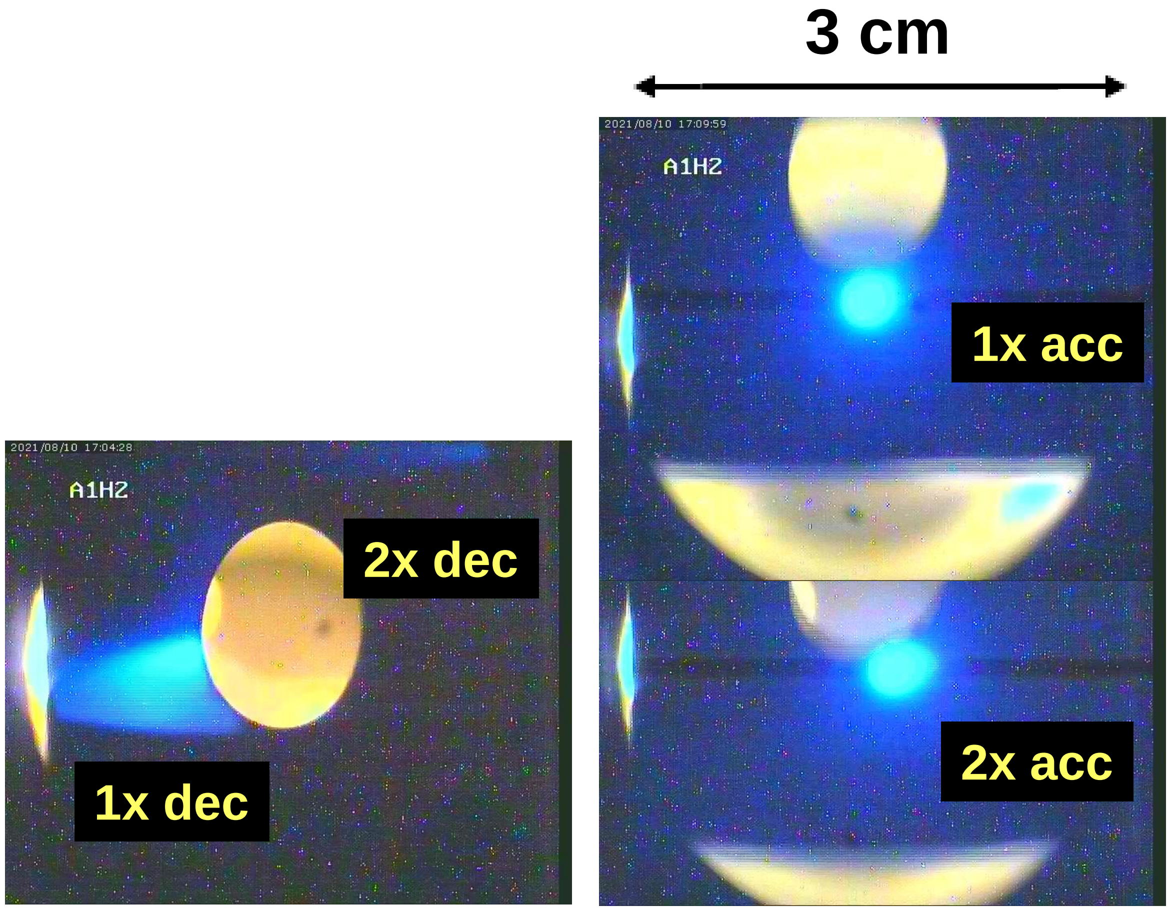
LIMITS OF TRANSVERSE TUNING





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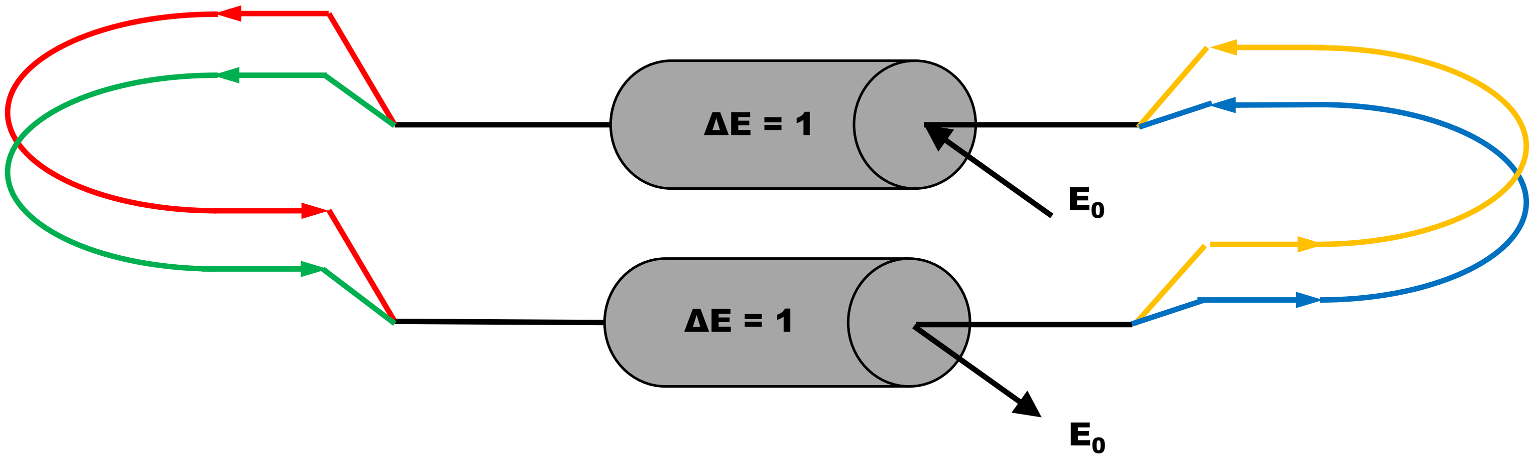
COMMON BEAM TRANSPORT

- Limited in degrees of freedom (e.g. transverse limitations in two-turn ERL operation S-DALINAC)
- Foreseen for multi-turn ERLs close to construction/operation



E_1 – 1. recirculation (accelerate and decelerate)

E_3 – 2. recirculation (accelerate and decelerate)

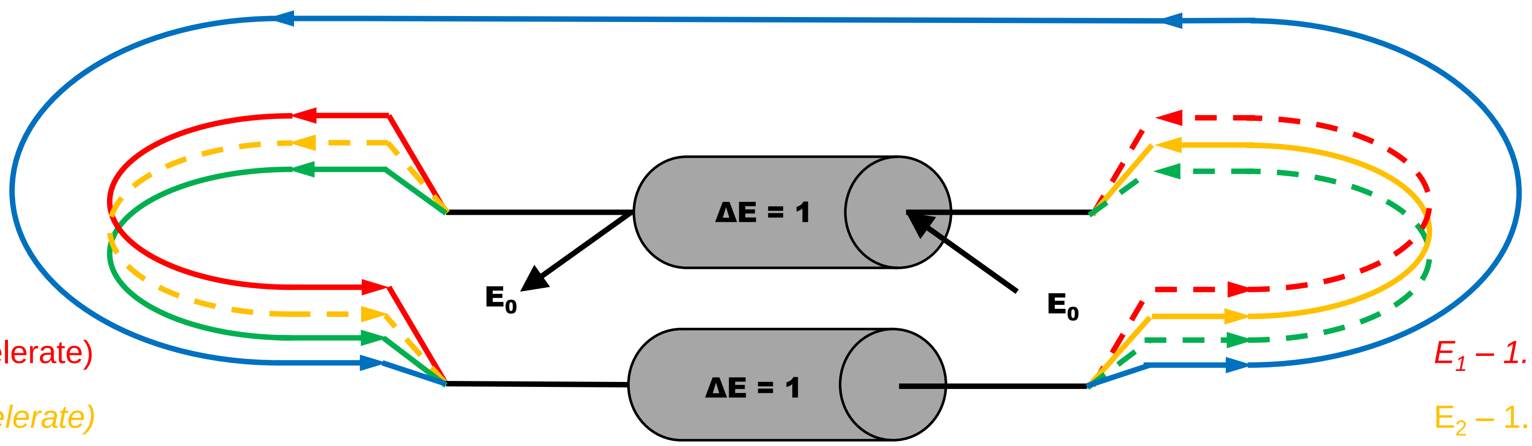
E_2 – 1. recirculation (accelerate and decelerate)

E_4 – max. energy, interaction point (180° phase shift)

SEPARATED BEAM TRANSPORT

- High efficiency, reliability, robustness → separate transport as promising concept
- Proposals of
  - DIANA (Daresbury Industrial Accelerator for Nuclear Applications): ~ 1 GeV, multipass SC-ERL
  - DICE (Darmstadt Individually recirculating Compact ERL): ~ 520 MeV, 26 mA, multipass SC-ERL

E_4 – max. energy, interaction point (180° phase shift)



E_1 – 1. recirculation (accelerate)

E_2 – 1. recirculation (decelerate)

E_3 – 2. recirculation (accelerate)

E_1 – 1. recirculation (decelerate)

E_2 – 1. recirculation (accelerate)

E_3 – 2. recirculation (decelerate)

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/

G. Pérez Segurana et al., Phys. Rev. Accel. Beams 25, 021003 (2022).

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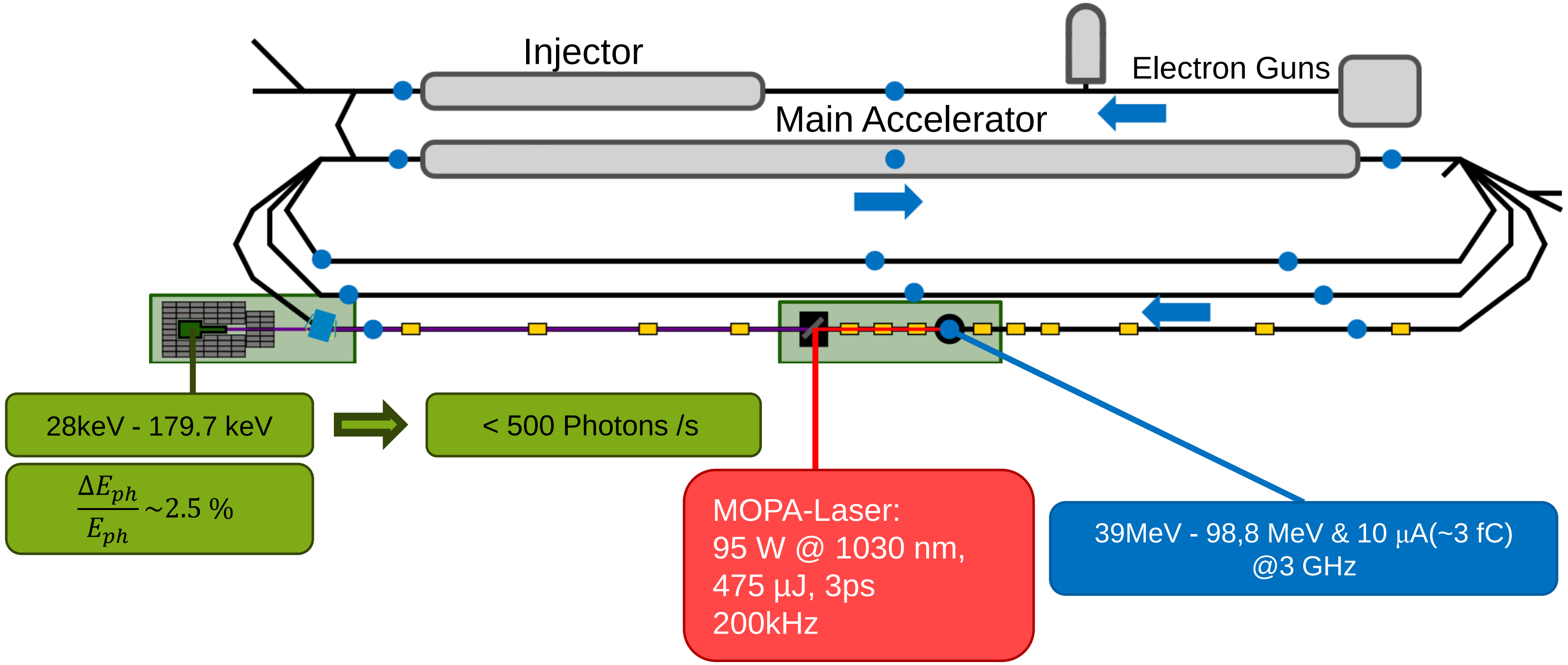
LCB @ COBRA

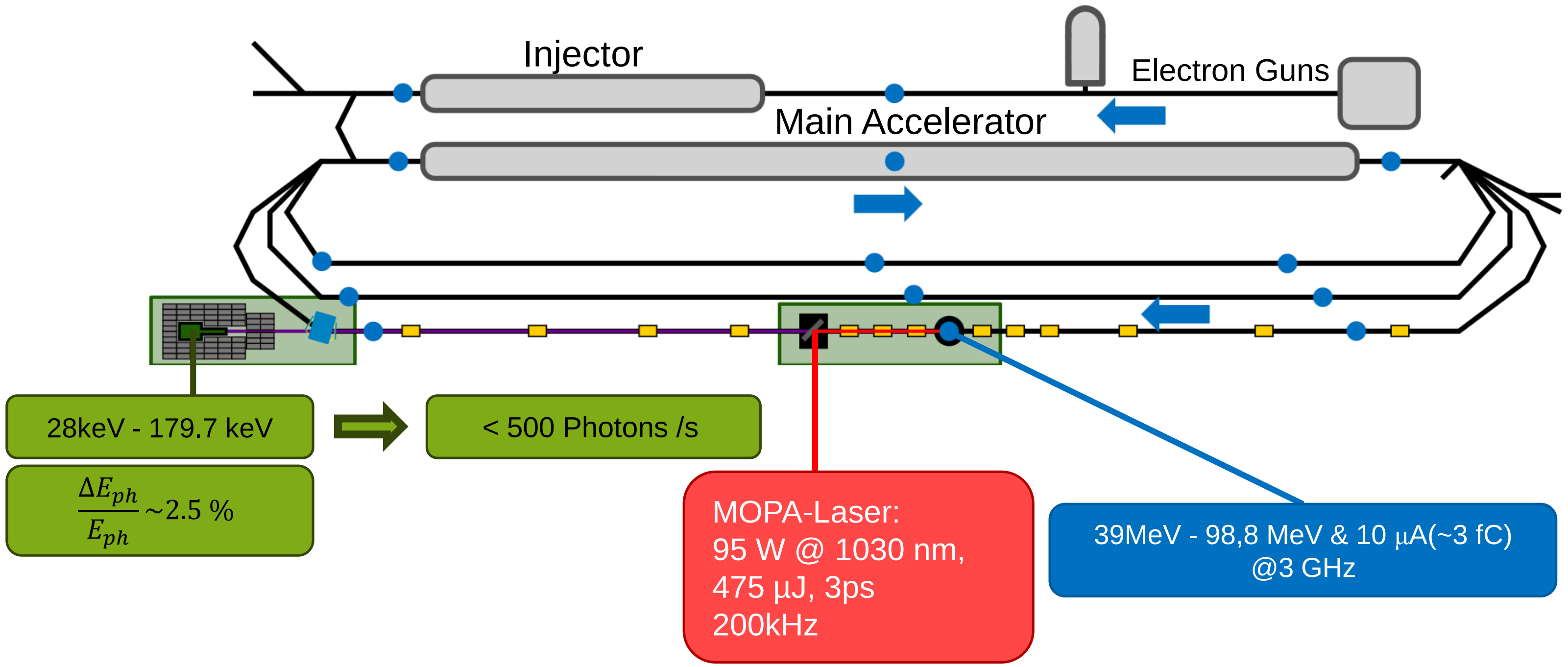
- Example parameters for collision

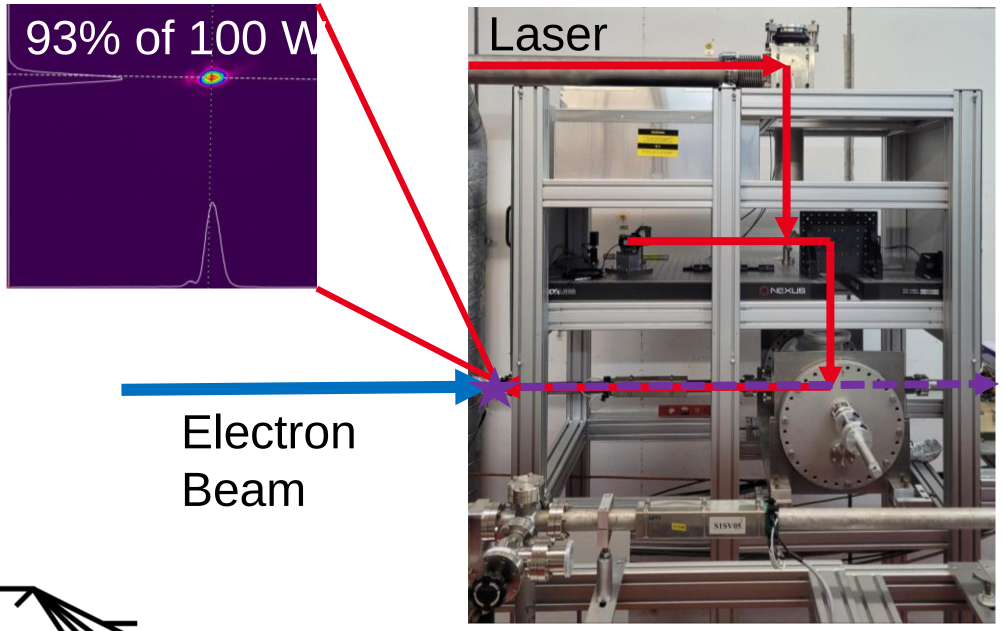


Posters by L. Dingeldein (COBRA) &
D. Schneider (electron beam stabilization)

LCB @ COBRA

- Example parameters for collision

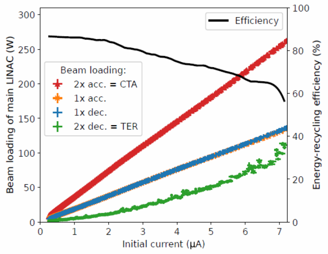


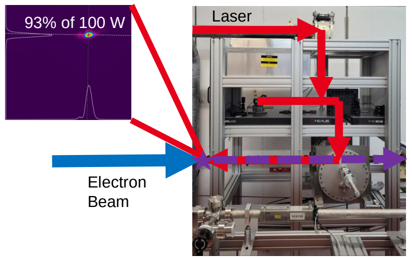


- Laser system commissioned
- Set-up ready
- Commissioning of collision planned for 2026

OUR WAY TO A 4^{th} GENERATION γ-SOURCE

Existing facilities + expertise





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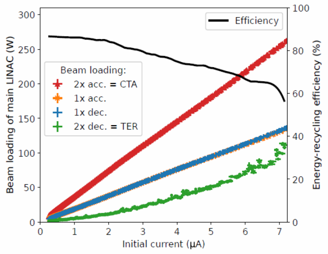
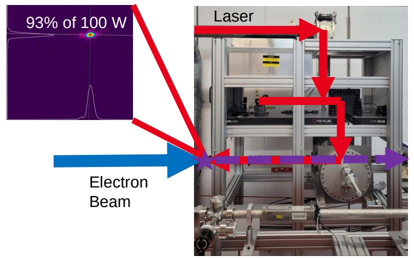
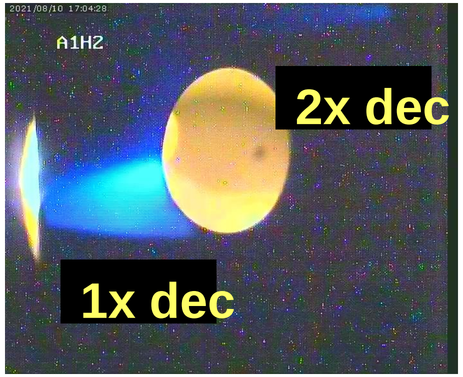
Existing facilities + expertise

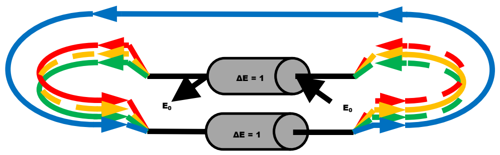




+

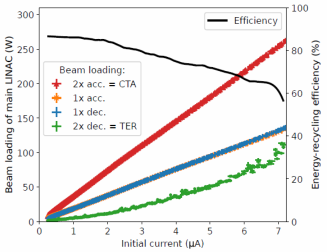
Lessons learned

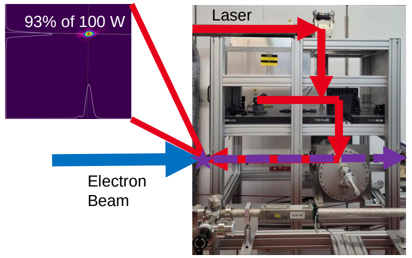




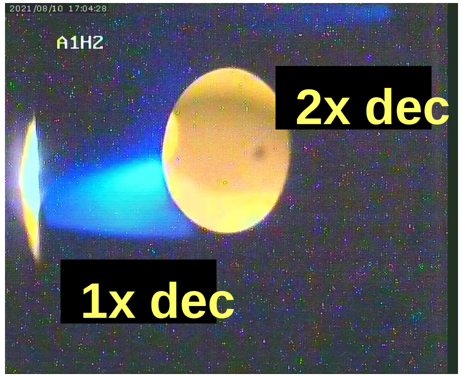
OUR WAY TO A 4th GENERATION γ-SOURCE

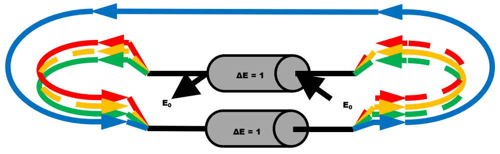
Existing facilities + expertise

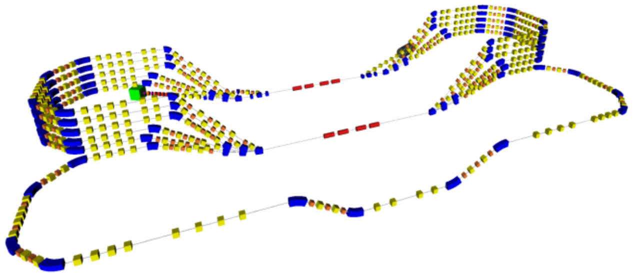




Lessons learned







DICE

Darmstadt **I**ndividual-Recirculating **C**ompact **E**RL

FACILITY CONCEPT DICE

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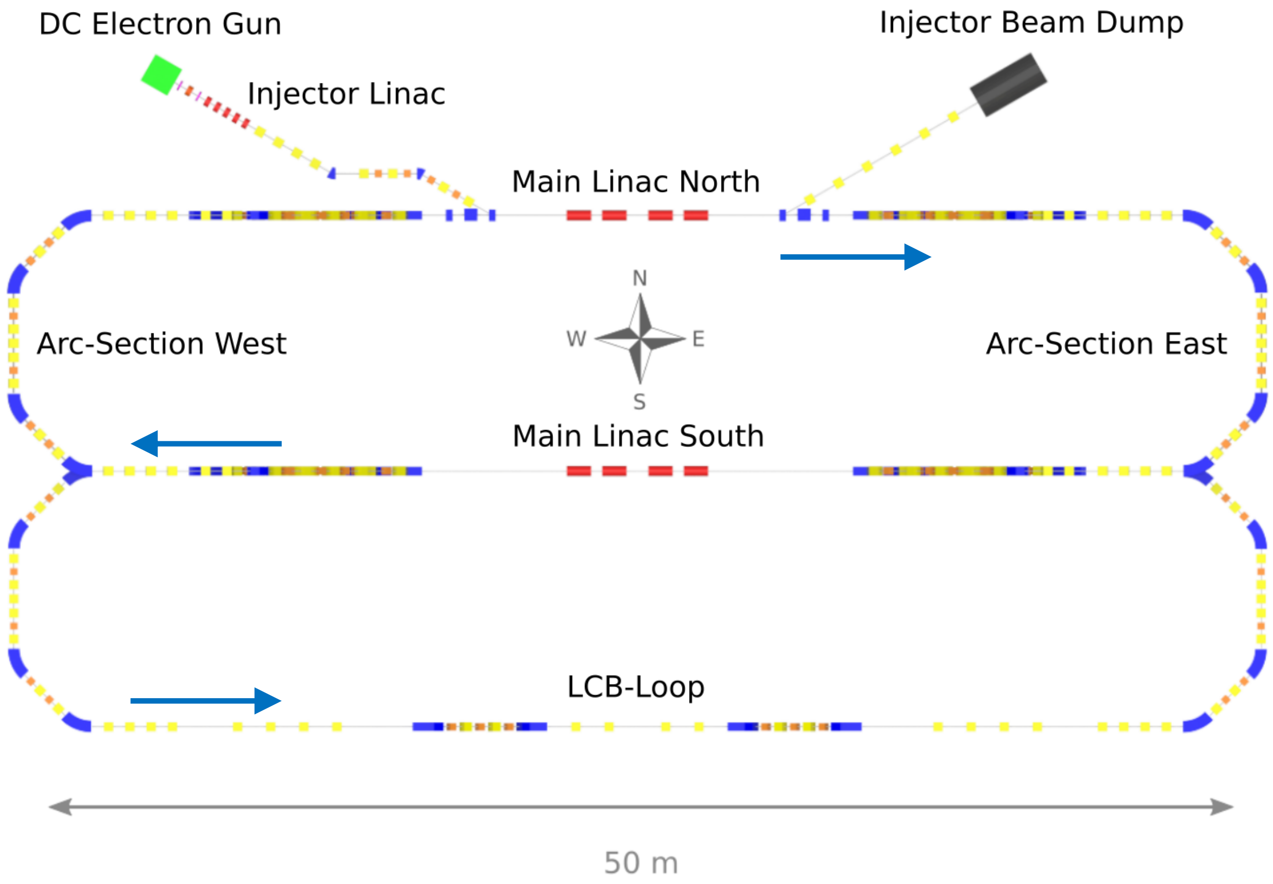
MAIN LAYOUT

- Thrice-recirculating SRF ERL
- Concrete parameters for LCB machine chosen
- Feasibility of concept shown
- Further parameters / experiments / layouts possible

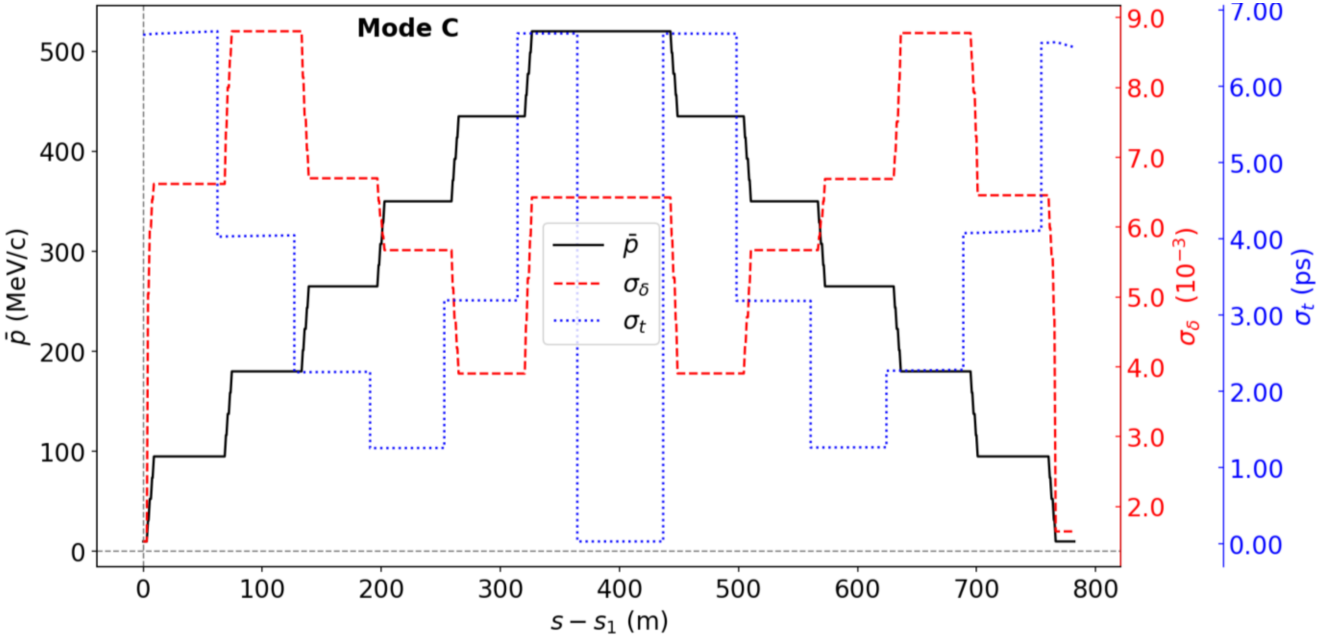
Parameter	Value	Unit
Max. injector energy	10	MeV
Max. energy	520	MeV
Max. average current	26	mA
RF frequency	1300	MHz
Repetition rate	≤1300	MHz



M. Arnold, N. Pietralla et al., *Design Study for an Energy-Sustainable MeV-Ranged Photon-Beam Facility*, EPJ ST, in preparation.

BEAMDYNAMICS

- Longitudinal solution found
- Different operation modes possible, e.g. non-isochronous/off-crest + minimal bunch length at LCB interaction
- Next: 6D tracking, space charge effects, detailed magnet design and optimization of first design



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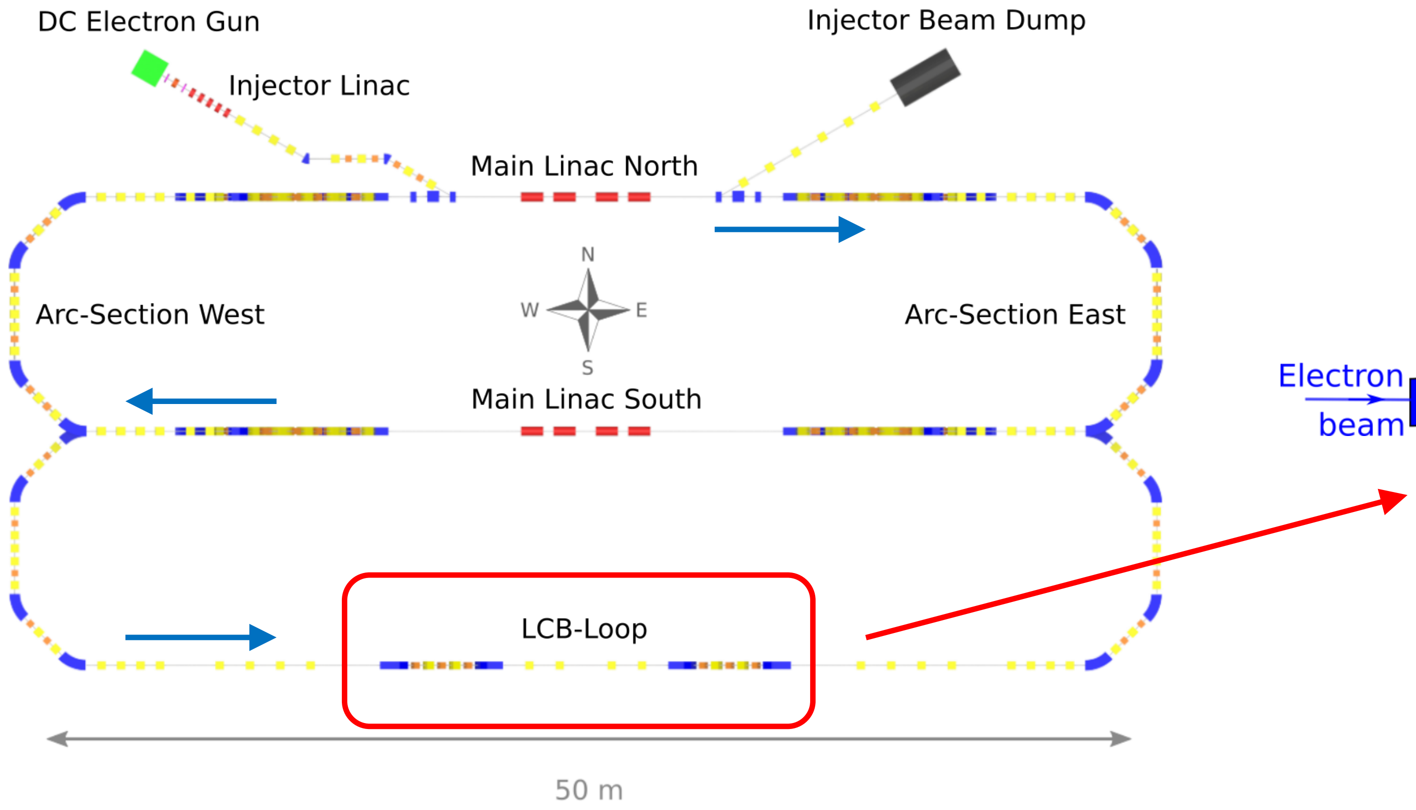
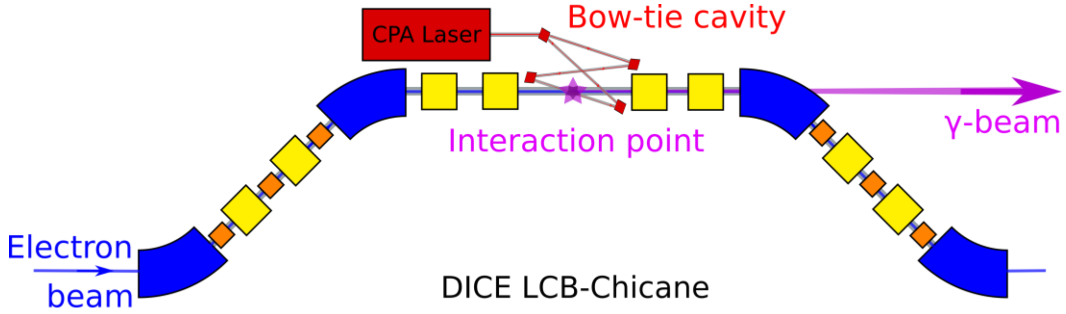
LCB EXPERIMENT





Distance to collimator: ~ 30 m

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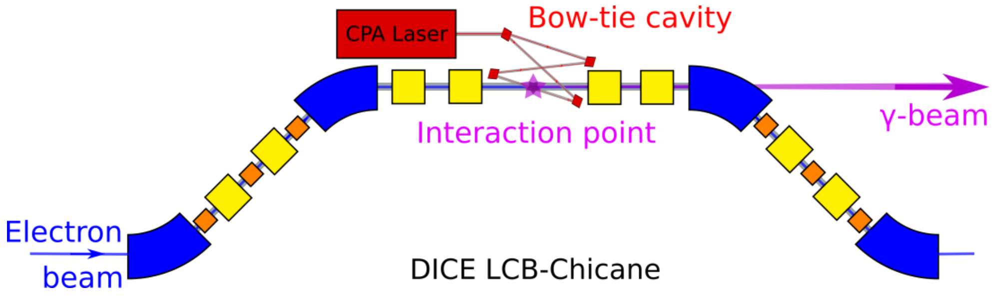
LCB EXPERIMENT: γ-BEAM

Parameter	Unit	DICE IR	DICE green	DICE UV
Min. energy	keV	184	367	550
Max. energy	MeV	4.9	9.8	14.5
Min. bandwidth: 33 μrad coll. (1 mm radius), 520 MeV, 70 μm e^- beam				
Bandwidth	%	0.3	0.6	0.3
Total flux	ph/s	$1.4\cdot10^{12}$	$3.4\cdot10^{11}$	$1.5\cdot10^{11}$
Spectral density	ph/(s·eV)	$5.5\cdot10^{4}$	$3.9\cdot10^{3}$	$2.1\cdot10^{3}$
Max. sp. density: 333 μrad coll. (1 cm radius), 520 MeV, 40 μm e^- beam				
Bandwidth	%	3.4	3.4	3.3
Total flux	ph/s	$2.5\cdot10^{12}$	$6.2\cdot10^{11}$	$2.7\cdot10^{11}$
Spectral density	ph/(s·eV)	$8.2\cdot10^{5}$	$1.0\cdot10^{5}$	$3.1\cdot10^{4}$



M. Arnold, N. Pietralla et al., *Design Study for an Energy-Sustainable MeV-Ranged Photon-Beam Facility*, EPJ ST, in preparation.

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FURTHER POTENTIAL

- Upgrade of LCB source
  - 1 GeV electron energy → higher gamma beam energy
    (~ 18 to 50 MeV for same laser systems)
  - Increase of bunch charge by a factor of four
    → fluxes increased by a factor of four

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FURTHER POTENTIAL

- Upgrade of LCB source
  - 1 GeV electron energy → higher gamma beam energy
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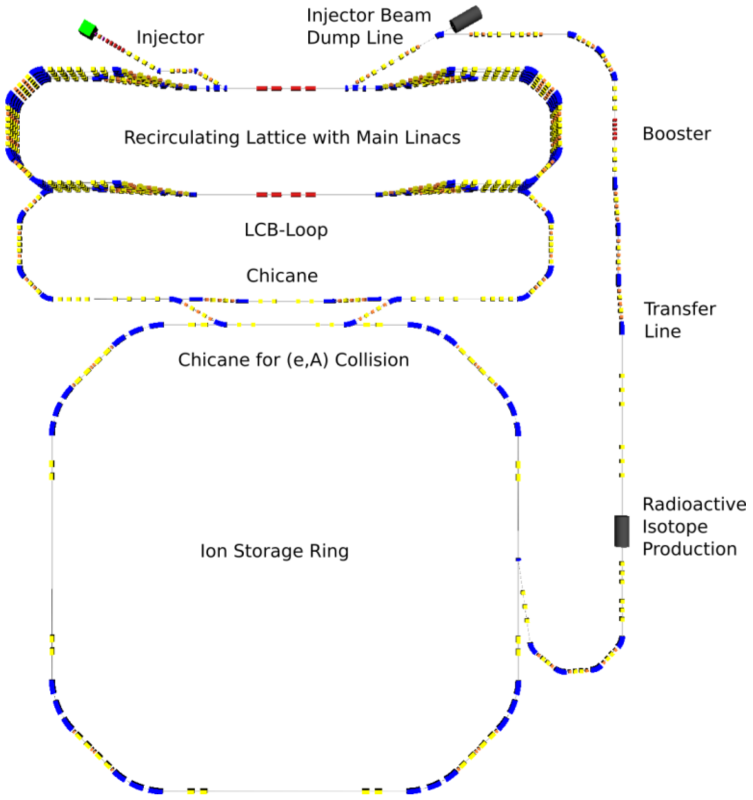
- (e,A) collision in ERL mode



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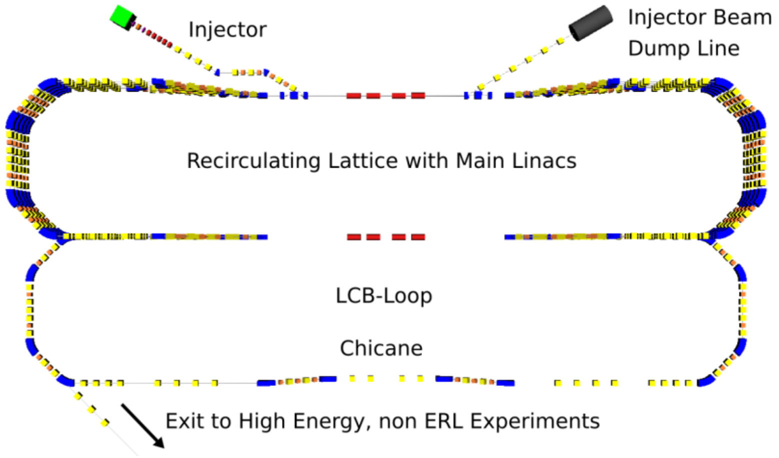
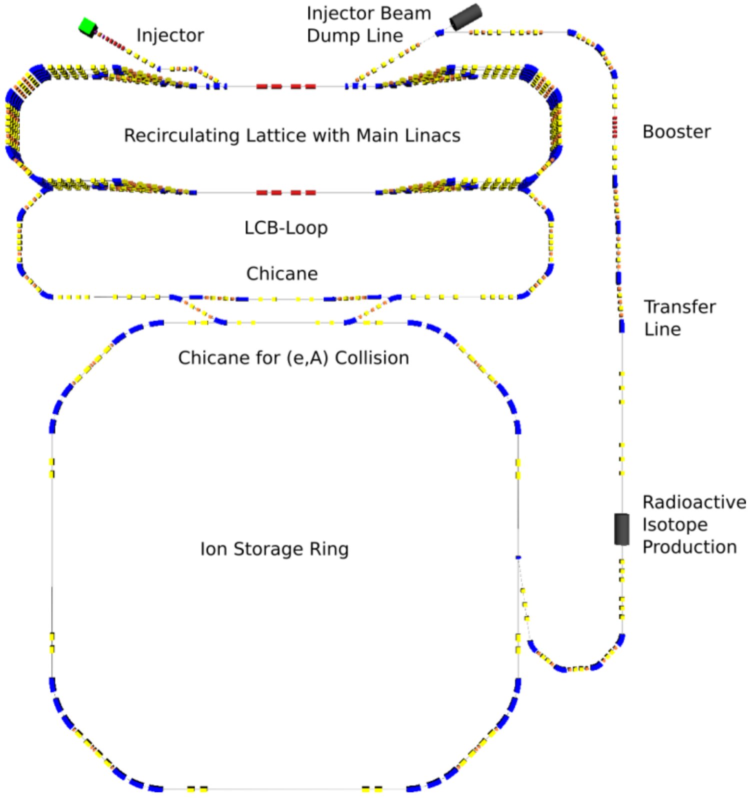
FURTHER POTENTIAL

- Upgrade of LCB source
  - 1 GeV electron energy → higher gamma beam energy (~ 18 to 50 MeV for same laser systems)
  - Increase of bunch charge by a factor of four → fluxes increased by a factor of four
- (e,A) collision in ERL mode
- Fixed-target experiments in conventional mode





M. Arnold, N. Pietralla et al., *Design Study for an Energy-Sustainable MeV-Ranged Photon-Beam Facility*, EPJ ST, in preparation.

SUMMARY

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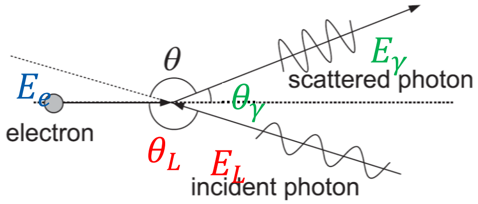
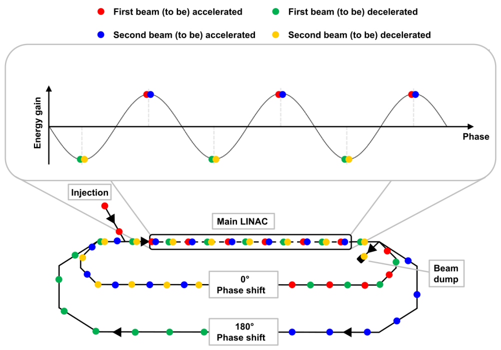


4th generation γ-source



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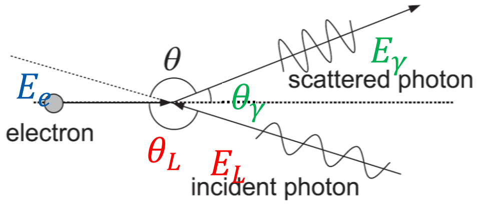

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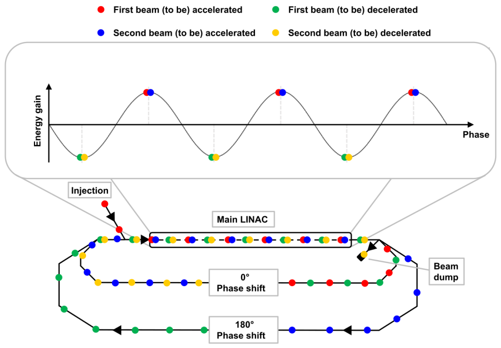

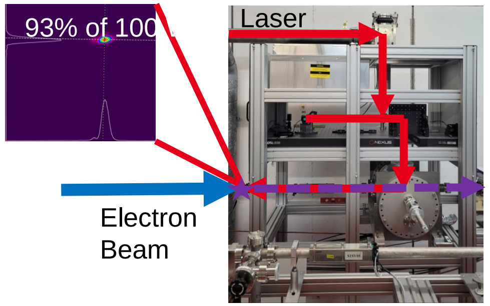

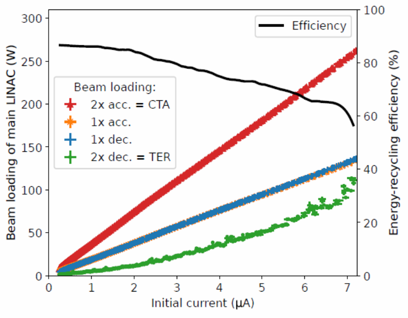

Expertise: Photonuclear reactions, ERL operation, LCB before final commissioning

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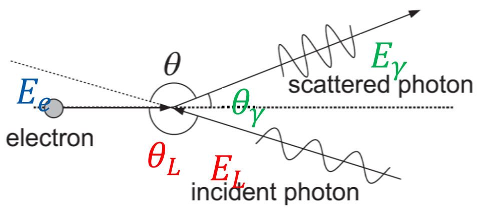
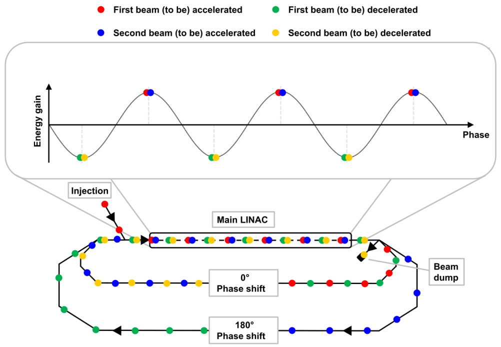
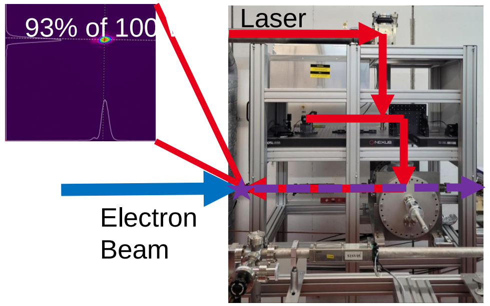
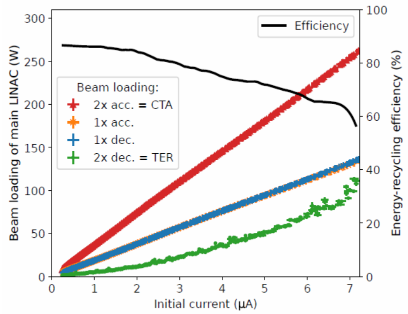


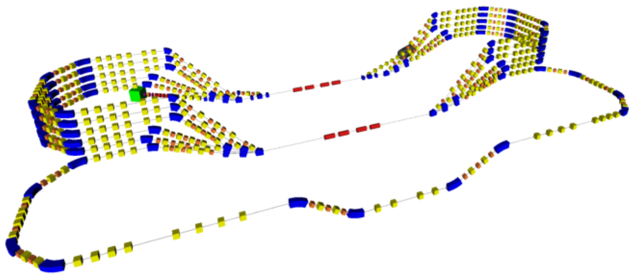


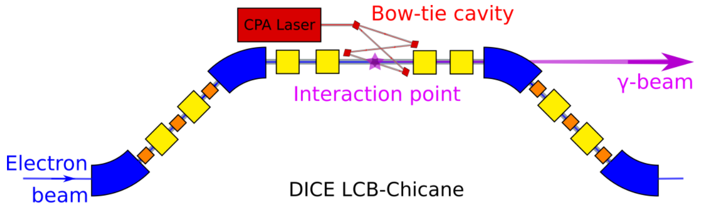
4th generation γ-source





Expertise: Photonuclear reactions, ERL operation, LCB before final commissioning

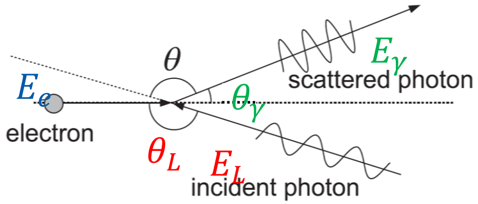




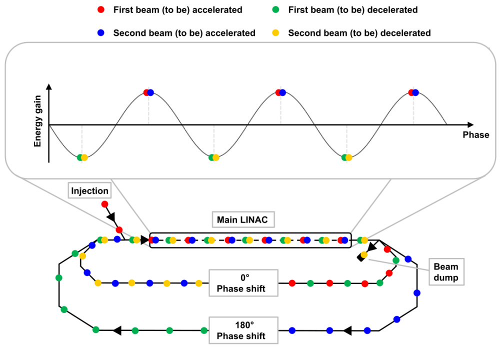
Facility concept DICE – LCB machine

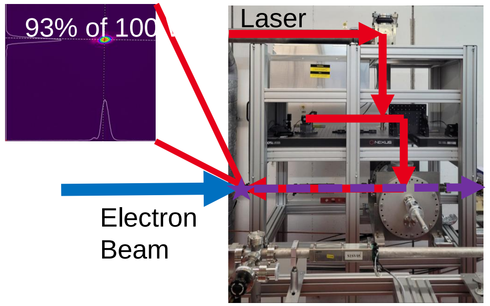
Thank you for your attention!

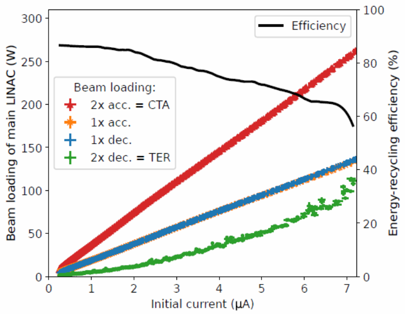
TAKE HOME MESSAGE



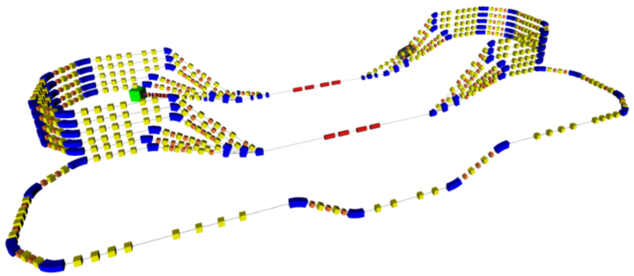
4^{th} generation γ-source

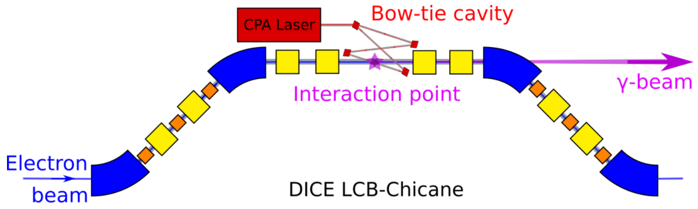






Expertise: Photonuclear reactions, ERL operation, LCB before final commissioning





Facility concept DICE – LCB machine

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BACKUP PARAMETER LIST

Parameter	Value	Unit
Injection energy (max.)	10	MeV
Maximum energy	520	MeV
Max. average current	26	mA
Max. bunch charge	20	pC
RF frequency	1300	MHz
Repetition rate	$\leq$1300	MHz
Norm. Emittance	2	mm mrad
Energy spread	$<$0.7	%
Bunch length	$<$3	mm

Parameter of LCB-source	Unit	DICE infrared	DICE green	DICE ultraviolet
Minimal energy (100 MeV electrons)	keV	184	367	550
Maximum energy (520 MeV electrons)	MeV	4.9	9.8	14.5
Min. bandwidth: 33 μrad collimator (1 mm radius) 520 MeV, 70 μm electron beam				
Bandwidth	%	0.3	0.6	0.3
Total flux	ph/s	$1.4 \cdot 10^{12}$	$3.4 \cdot 10^{11}$	$1.5 \cdot 10^{11}$
Flux in bandwidth	ph/s	$2.4 \cdot 10^{9}$	$5.8 \cdot 10^{8}$	$2.6 \cdot 10^{8}$
Spectral density	ph/(s·eV)	$5.5 \cdot 10^{4}$	$3.9 \cdot 10^{3}$	$2.1 \cdot 10^{3}$
Max. spectral density: 333 μrad collimator (1 cm radius) 520 MeV, 40 μm electron beam				
Bandwidth	%	3.4	3.4	3.3
Total flux	ph/s	$2.5 \cdot 10^{12}$	$6.2 \cdot 10^{11}$	$2.7 \cdot 10^{11}$
Flux in bandwidth	ph/s	$3.4 \cdot 10^{11}$	$8.5 \cdot 10^{10}$	$3.8 \cdot 10^{10}$
Spectral density	ph/(s·eV)	$8.2 \cdot 10^{5}$	$1.0 \cdot 10^{5}$	$3.1 \cdot 10^{4}$

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BACKUP

Input parameter	Unit	DICE infrared	DICE green	DICE ultraviolet
Laser				
Wavelength	nm	1030	515	343
Output power	W	300	150	100
Spectral bandwidth	nm	< 3	< 3	< 1
Pulse length	ps	< 1	< 1	< 1
Pulse energy (40 MHz)	µJ	7.5	3.75	2.5
Repetition rate	MHz	40	40	40
M^2		< 1.35	< 1.35	< 1.35
Optical cavity				
Focal spot size	µm	50	50	50
Finesse		5000	5000	5000
Pulse energy in cavity (40 MHz)	mJ	37.5	18.75	12.5
Effective optical power at IP	kW	1500	750	500
Electron beam				
Energy	MeV	520	520	520
Energy spread	%	0.01	0.01	0.01
Normalized emittance	mm mrad	2	2	2
RMS spot size (min. bandwidth)	µm	70	70	70
RMS spot size (max. sp. density)	µm	40	40	40
Bunch charge	pC	20	20	20
Operating frequency LCB mode	MHz	40	40	40
Beam current LCB mode	mA	0.8	0.8	0.8
Bunch length	ps	0.5	0.5	0.5
Setup geometry				
Laser e-beam scattering angle	mrad	70	70	70
Gamma collimation angle 1	µrad	33	33	33
Gamma collimation angle 2	µrad	333	333	333

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