Novel Approaches and Innovative Modalities in Ultrafast Electron Scattering Applications with Accelerators

Beñat Alberdi Esuain, Thorsten Kamps

June 21st, 2023 | Physics and Applications of High Brightness Beams – San Sebastian

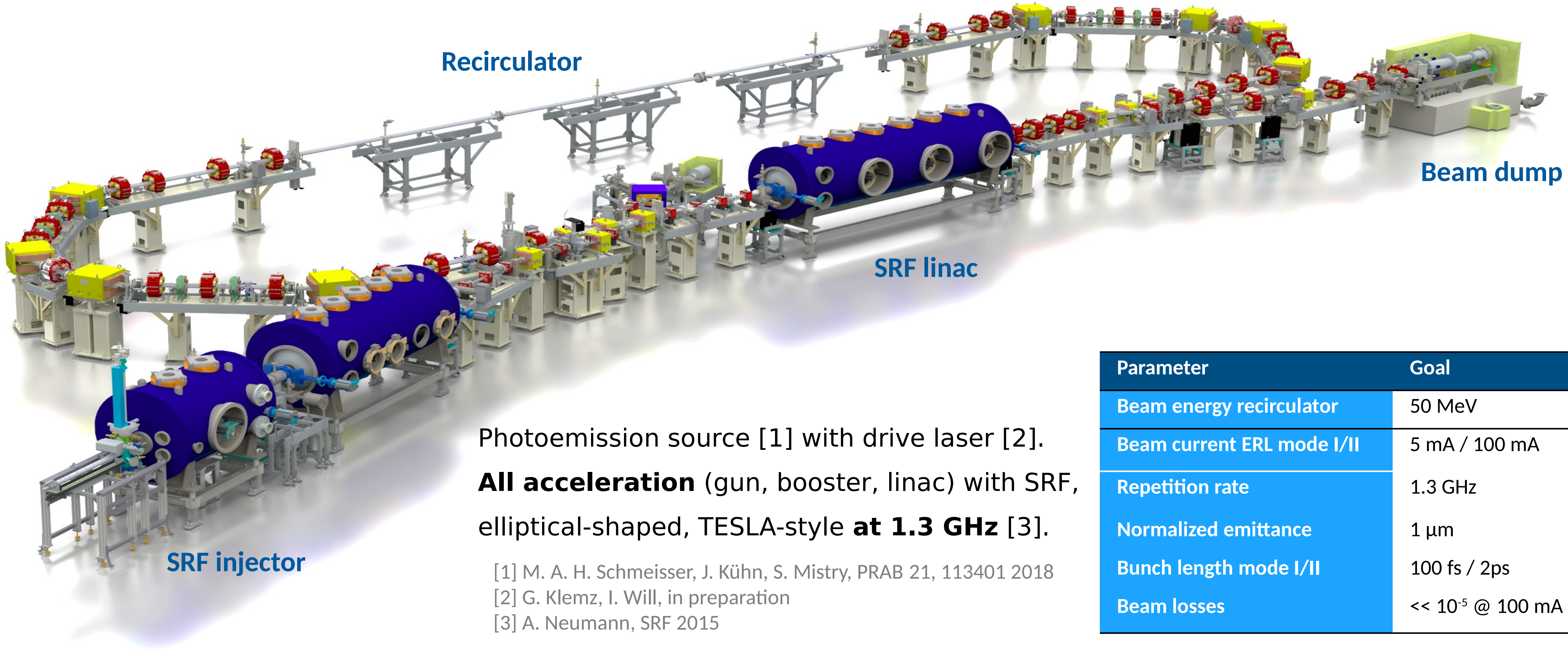
HZB Helmholtz Zentrum Berlin


Helmholtz-Zentrum Berlin, Adlershof campus
MLS
Bessy II
SEALab/bERLinPro

SEALab

Superconducting Electron Accelerator Lab.

ENERGY RECOVERY LINAC AT SEALAB



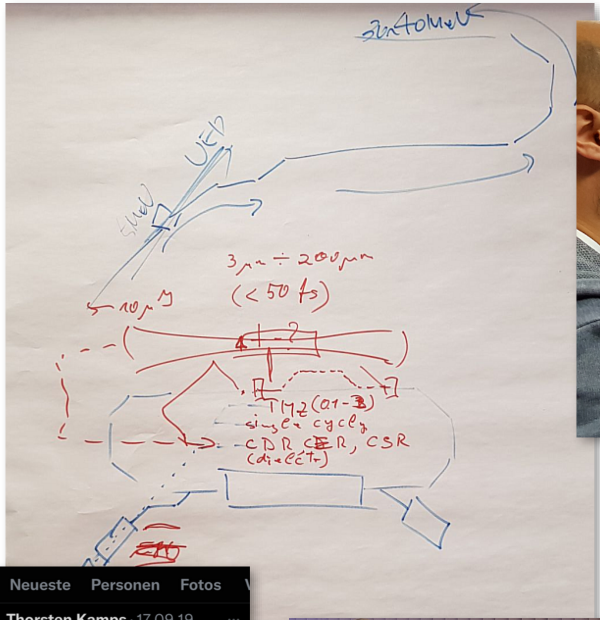
Photoemission source [1] with drive laser [2].

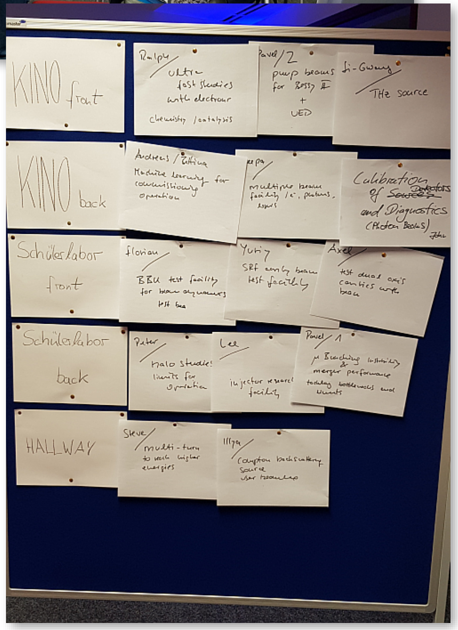
All acceleration (gun, booster, linac) with SRF, elliptical-shaped, TESLA-style **at 1.3 GHz** [3].

[1] M. A. H. Schmeisser, J. Kühn, S. Mistry, PRAB 21, 113401 2018
[2] G. Klemz, I. Will, in preparation
[3] A. Neumann, SRF 2015

Parameter	Goal
Beam energy recirculator	50 MeV
Beam current ERL mode I/II	5 mA / 100 mA
Repetition rate	1.3 GHz
Normalized emittance	1 µm
Bunch length mode I/II	100 fs / 2ps
Beam losses	<< 10^{-5} @ 100 mA

WORKSHOP AT 2019: SCIENTIFIC OPORTUNITIES AT SEALAB





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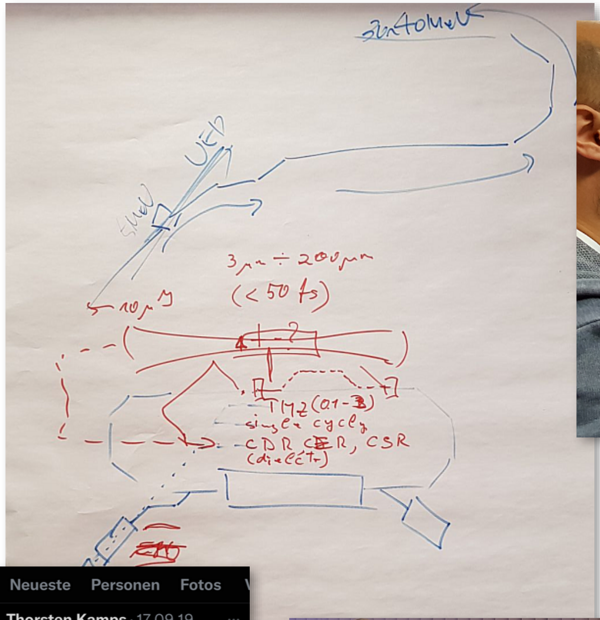

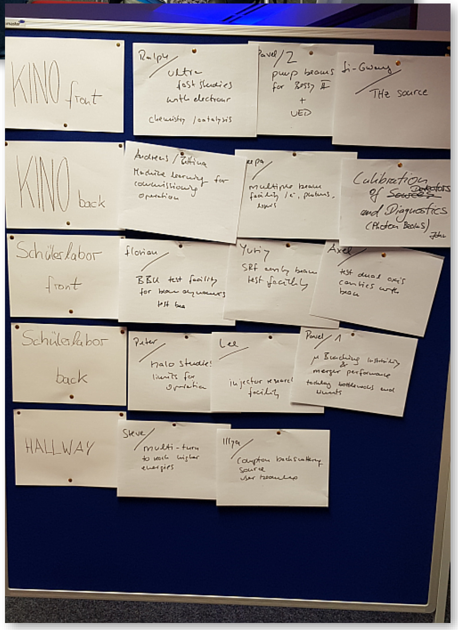

arXiv:1910.00881v1 [physics.acc-ph] 2 Oct 2019

Scientific Opportunies for bERLinPro 2020+,
Report with Ideas and Conclusions from bERLinProCamp 2019

Thorsten Kamps,[1,2] Michael Abo-Bakr,[1] Andreas Adelmann,[3] Kevin Andre,[4] Deepa Angal-Kahn,[5] Felix Armborst,[1] Andre Arnold,[6] Michaela Arnold,[7] Raymond Amador,[2] Stephen Benson,[8] Yulia Choporova,[9] Illya Drebot,[10] Ralph Ernstdorfer,[11] Pavel Evtushenko,[6] Kathrin Goldammer,[12] Andreas Jankowiak,[1,2] Georg Hoffstätter,[13] Florian Hug,[14] Ji-Gwang Hwang,[1] Lee Jones,[5] Julius Kühn,[1] Jens Knobloch,[1] Bettina Kuske,[1] Andre Lampe,[15] Sonal Mistry,[1] Tsukasa Miyajima,[16] Axel Neumann,[1] Nora Norvell,[17] Yuriy Petenev,[1] Gisela Pöplau,[18] Houjon Qian,[19] Hiroshi Sakai,[16] Olaf Schwarzkopf,[1] John Smedley,[20] Yegor Tamachevich,[1] Sebastian Thomas,[14] Jens Völker,[1] Paul Volz,[1] Erdong Wang,[21] Peter Williams,[5] and Daniela Zahn[22]

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2) *Humboldt-Universität zu Berlin, Berlin, Germany*
3) *Paul Scherrer Institut, Villingen, Switzerland*
4) *CERN, Geneva, Switzerland*
5) *ASTEC Daresbury Lab, Warrington, UK*
6) *Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*
7) *Technische Universität Darmstadt, Darmstadt, Germany*
8) *Jefferson Laboratory, Newport News, Virginia, USA*
9) *Budker Institut for Nuclear Physics, Novosibirsk, Russia*
10) *INFN LASA, Milano, Italy*
11) *Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany*
12) *Reiner Lemoine Institut, Berlin, Germany*
13) *Cornell University, Ithaca, New York, USA*
14) *Johannes-Gutenberg Universität Mainz, Mainz, Germany*
15) *@andrelampe, Berlin, Germany*
16) *High Energy Accelerator Research Organization, KEK, Tsukuba, Japan*
17) *SLAC National Accelerator Laboratory, Menlo Park, California, USA*
18) *Universität zu Lübeck, Lübeck, Germany*
19) *Deutsches Elektronen-Synchrotron, DESY, Zeuthen Site, Zeuthen, Germany*
20) *Los Alamos National Laboratrory, Los Alamos, New Mexico, USA*
21) *Brookhaven National Laboratory, Brookhaven, Long Island, USA*
22) *Fritz-Haber Institut, FHI-MPG, Berlin, Germany*

(Dated: 3 October 2019)

The Energy Recovery Linac (ERL) paradigm offers the promise to generate intense electron beams of superior quality with extremely small six-dimensional phase space for many applications in the physical sciences, materials science, chemistry, health, information technology and security. Helmholtz-Zentrum Berlin started in 2010 an intensive R&D programme to address the challenges related to the ERL as driver for future light sources by setting up the bERLinPro (Berlin ERL Project) ERL with 50 MeV beam energy and high average current. The project is close to reach its major milestone in 2020, acceleration and recovery of a high brightness electron beam.

The goal of bERLinProCamp 2019 was to discuss scientific opportunities for bERLinPro 2020+. bERLinProCamp 2019 was held on Tue, 17.09.2019 at Helmholtz-Zentrum Berlin, Berlin, Germany. This paper summarizes the main themes and output of the workshop.

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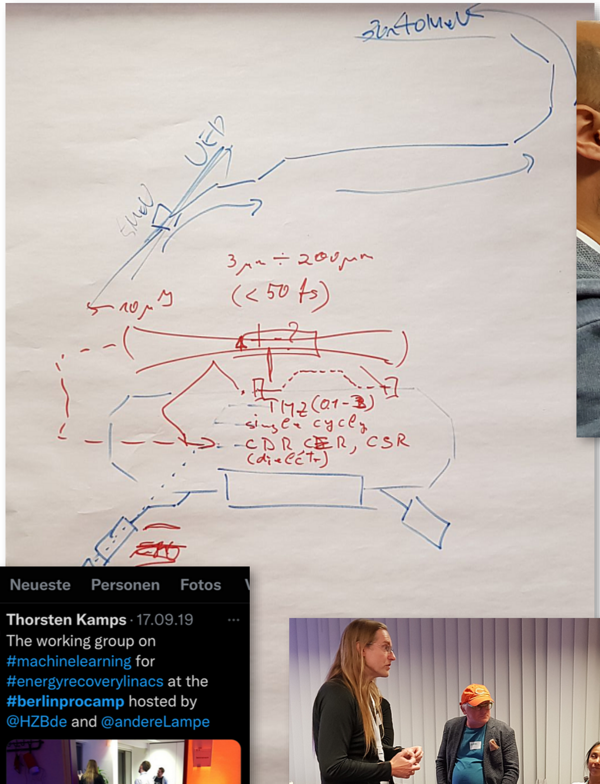

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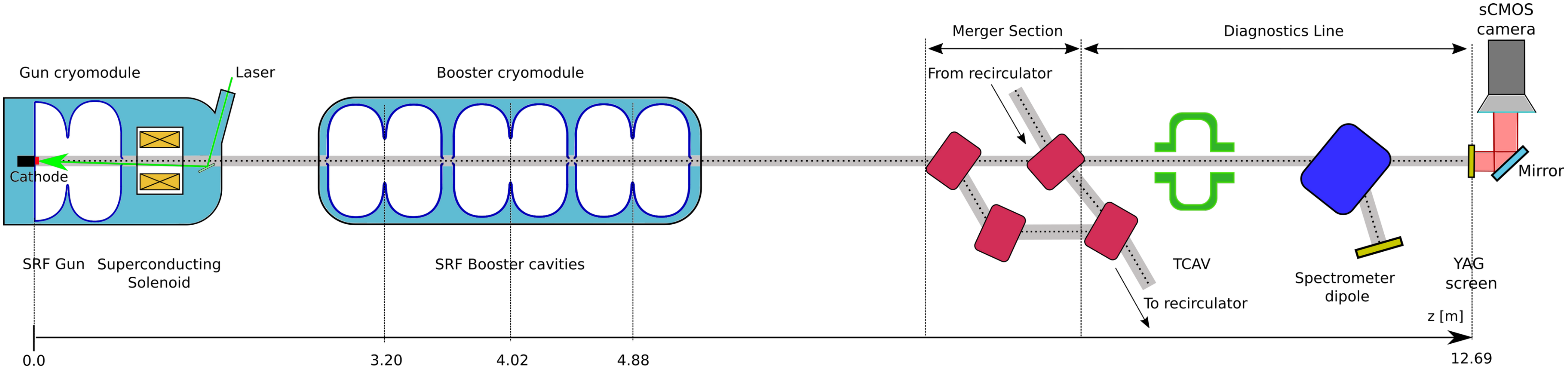
B. Compton (or Thomson) backscattering

backscattering

A. Energy doubling

MAIN CONCLUSION:
MEV ULTRAFAST ELECTRON SCATTERING AT THE INJECTOR

SRF PHOTOINJECTOR – ENABLING SCATTERING EXPERIMENTS



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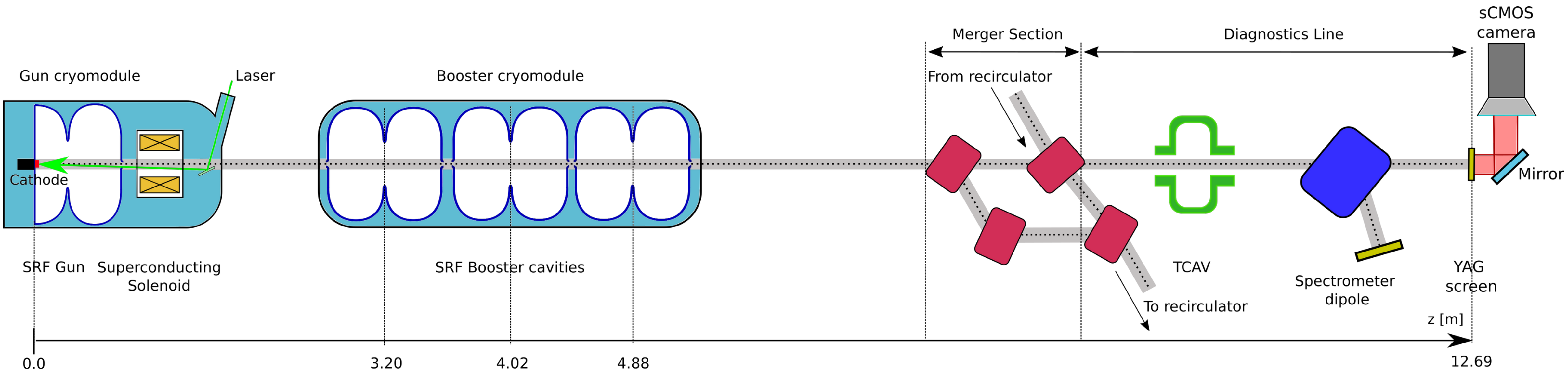

What do we need to enable MeV scattering experiments in the SRF Photoinjector?

- Emittance reduction from 1µm to below 100nm to make sure we have enough spatial resolution.
- Target station for samples and diagnostics.
- Focusing element to control transverse beam size at target.

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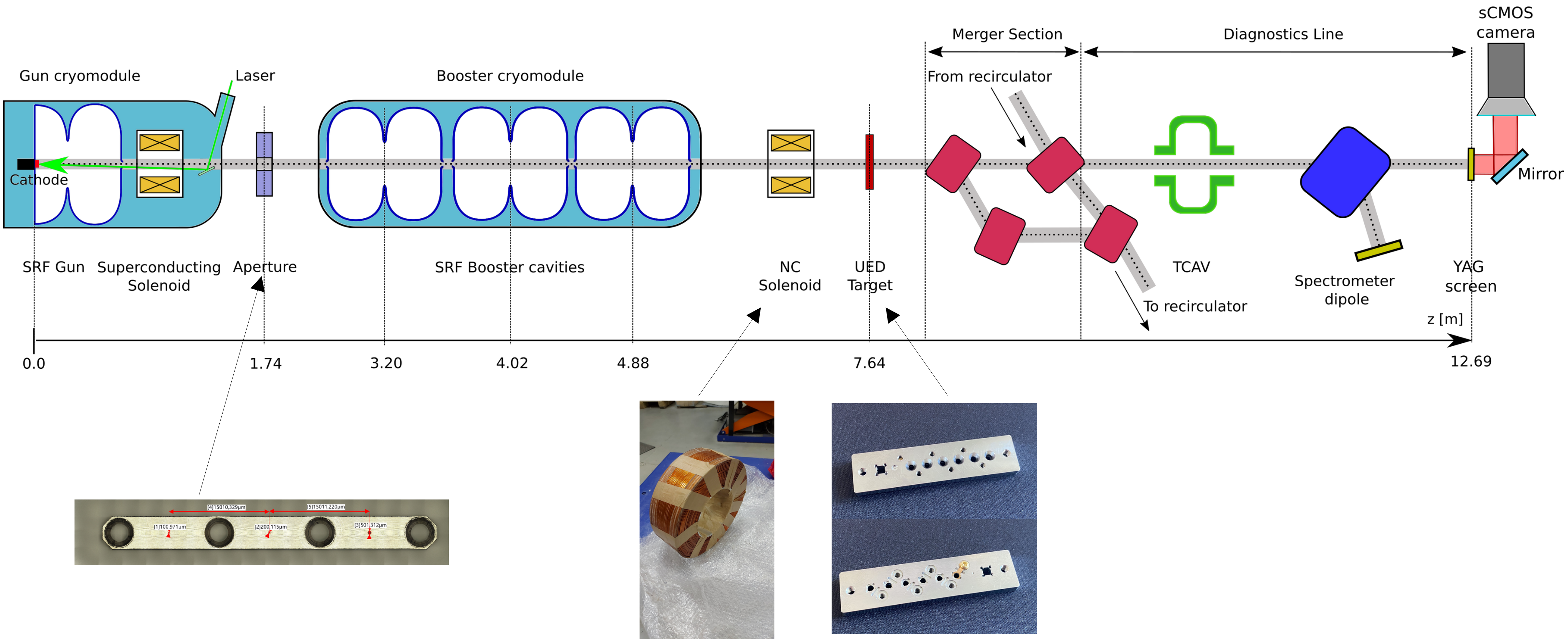

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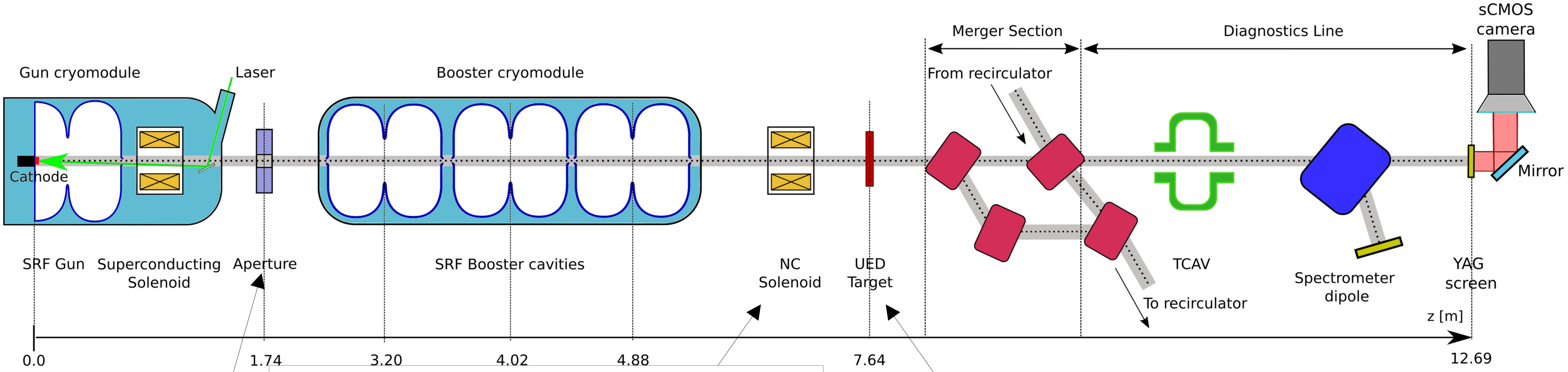

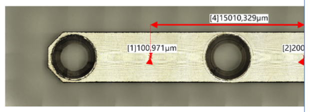

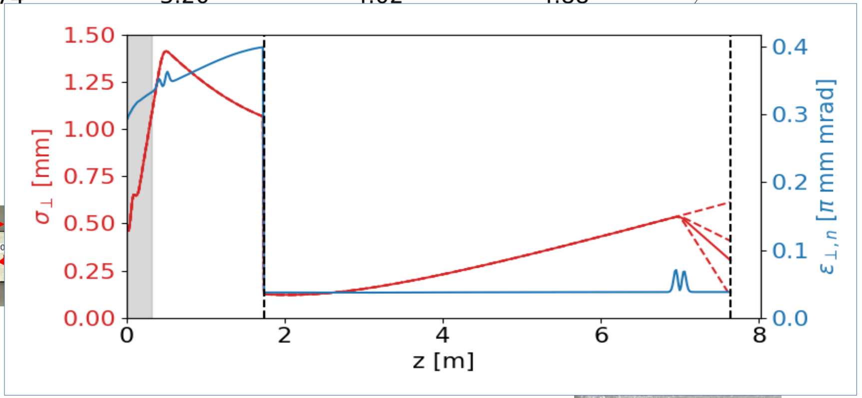

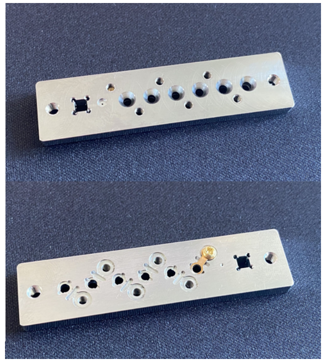

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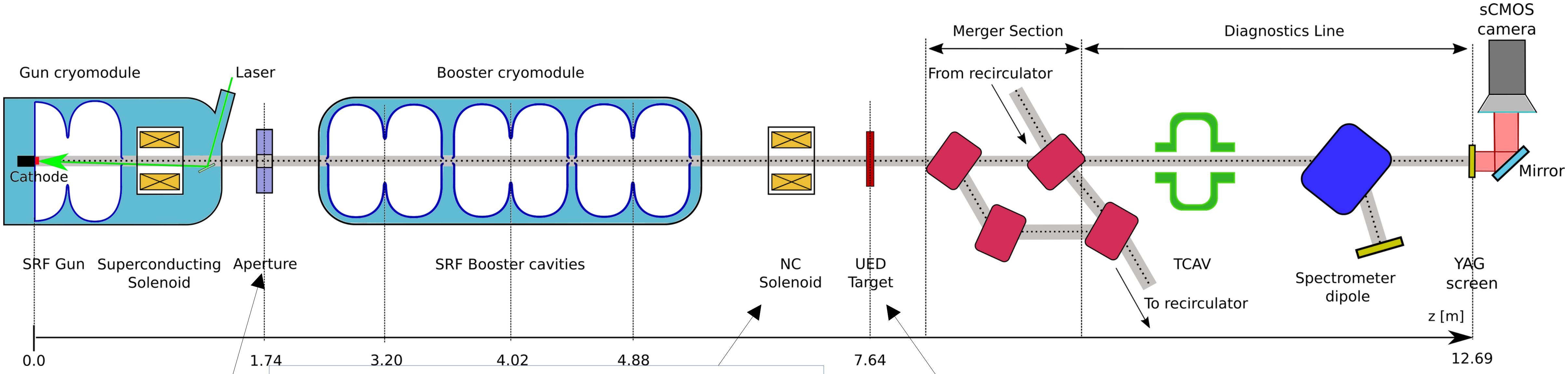
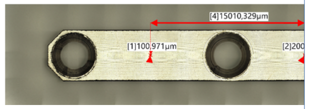
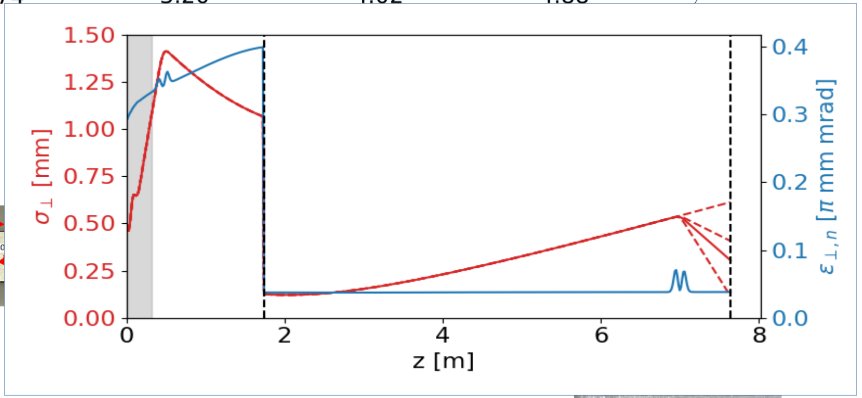
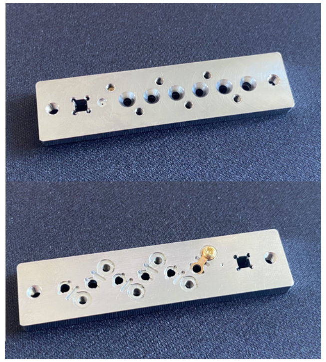


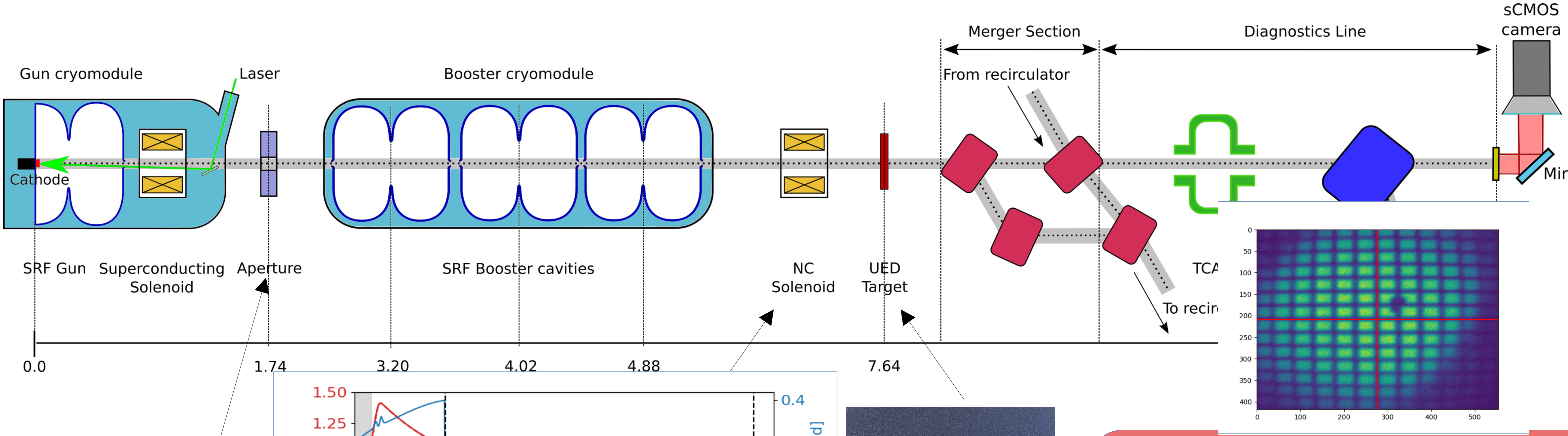


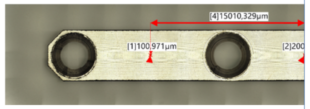


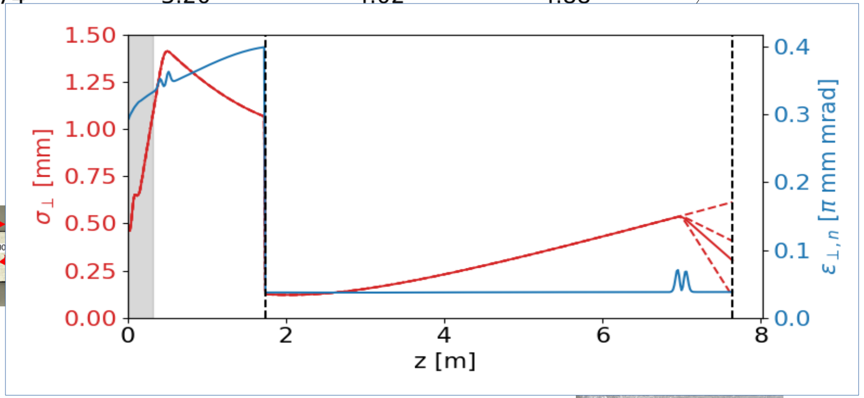


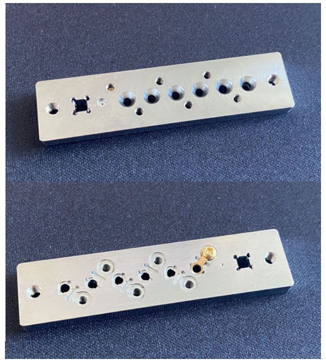
- First scattering exeperiments at the end of 2023 / beginning of 2024
- Beamtime rehearsal done in KAERI, Korea, at the end of 2022.

SRF PHOTOINJECTOR – ENABLING SCATTERING EXPERIMENTS

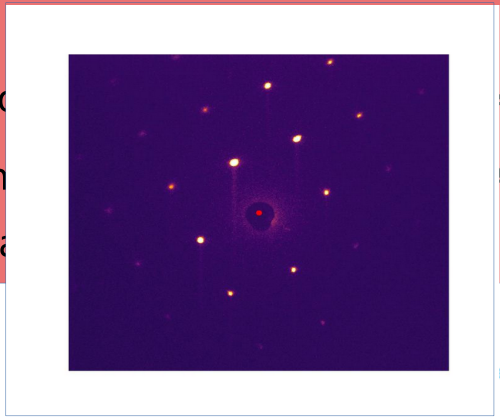




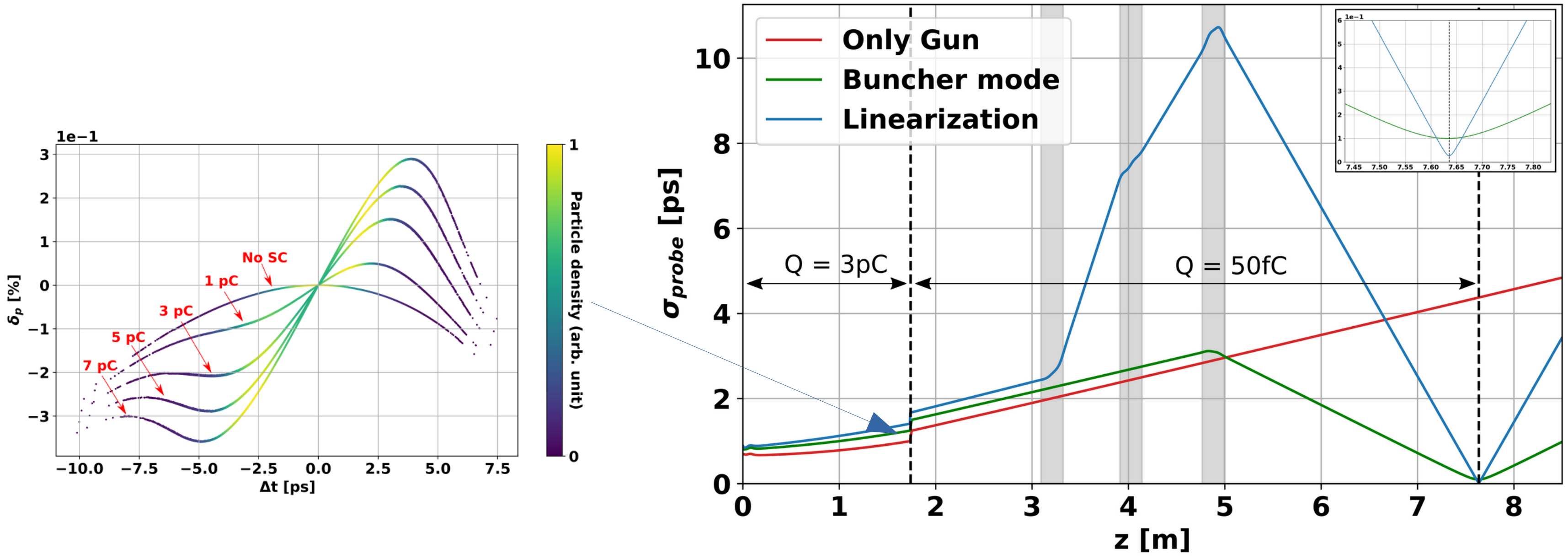




- First … the
  end … 4
- Bean… AERI,
  Korea…



BUNCH COMPRESSION – LINEARIZATION



B. Alberdi, J.-G. Hwang et al., Sci. Rep. 12, 13365 (2022).

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Linearization using the stretcher mode [1] provides the shortest bunch at target.

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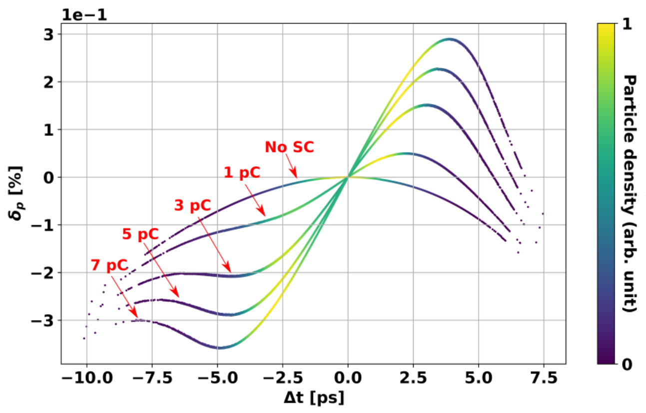

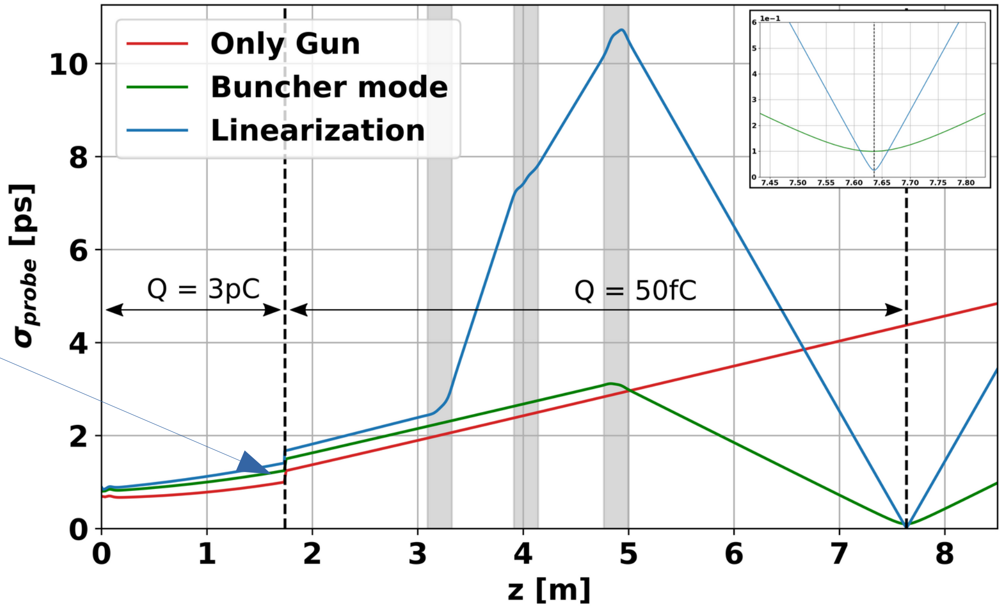

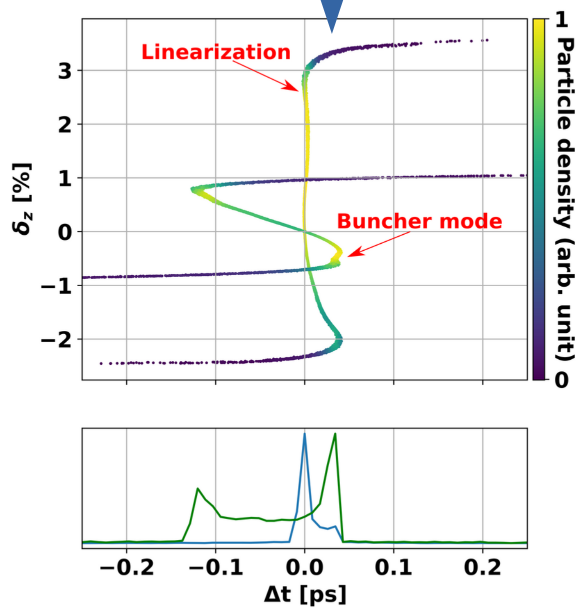

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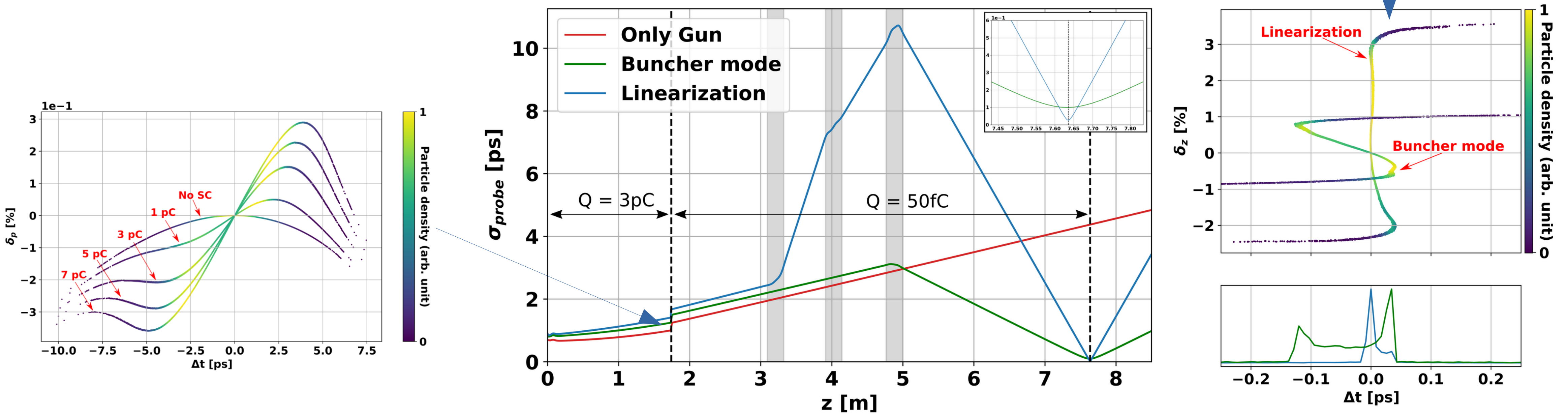

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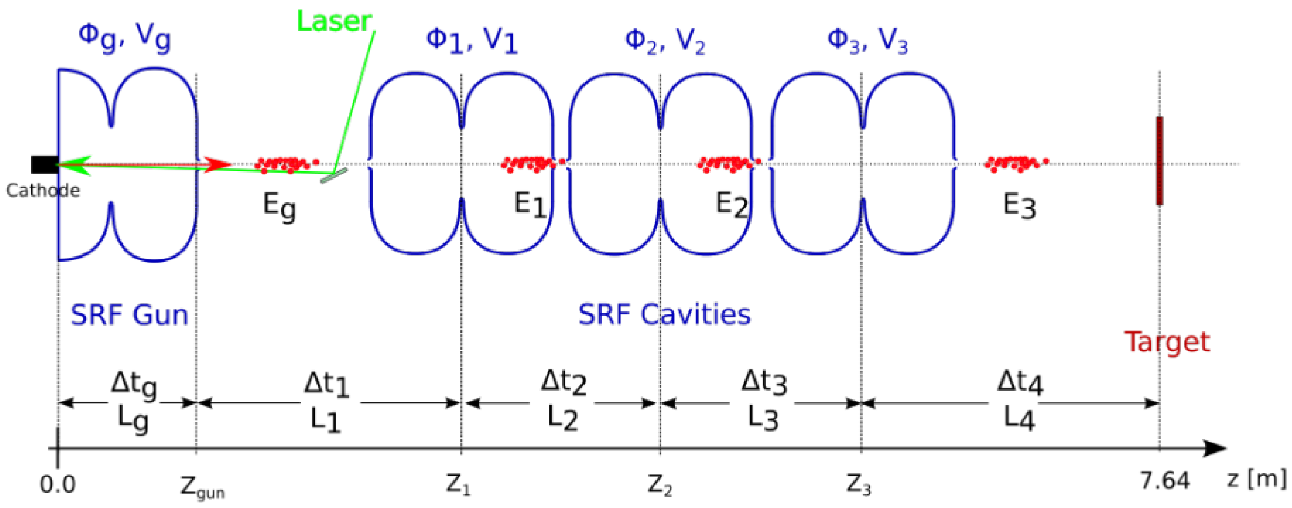
- The use of the three cavities allows us to linearize the bunch at the target, from 1ps → 21fs.
- The minimum achievable bunch length with the buncher mode, on the other hand, is limited to 96fs.

TIME OF FLIGHT JITTER STUDIES

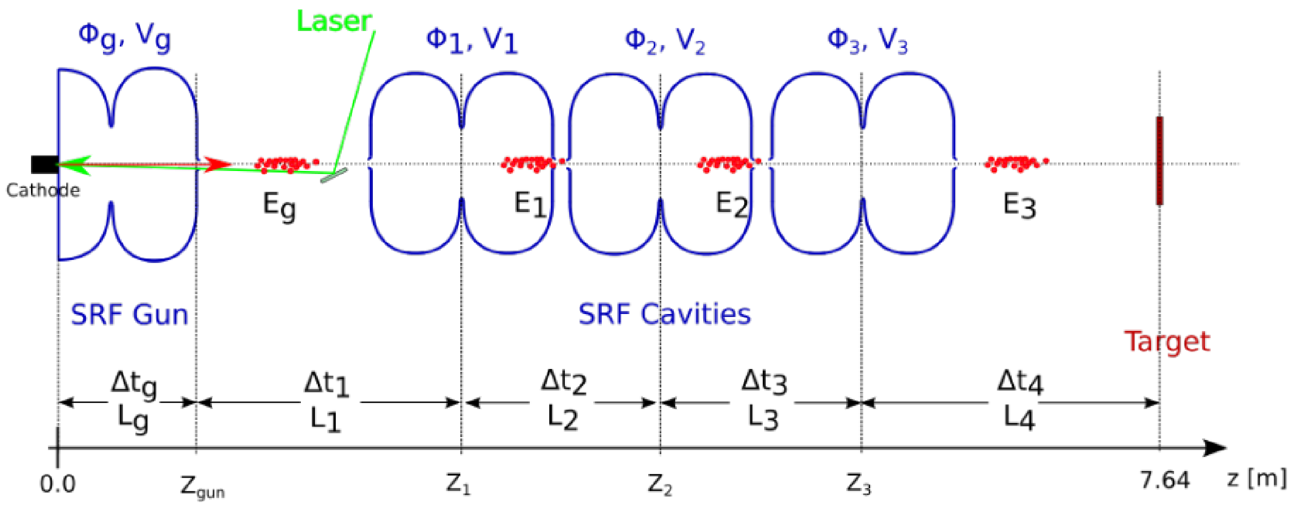


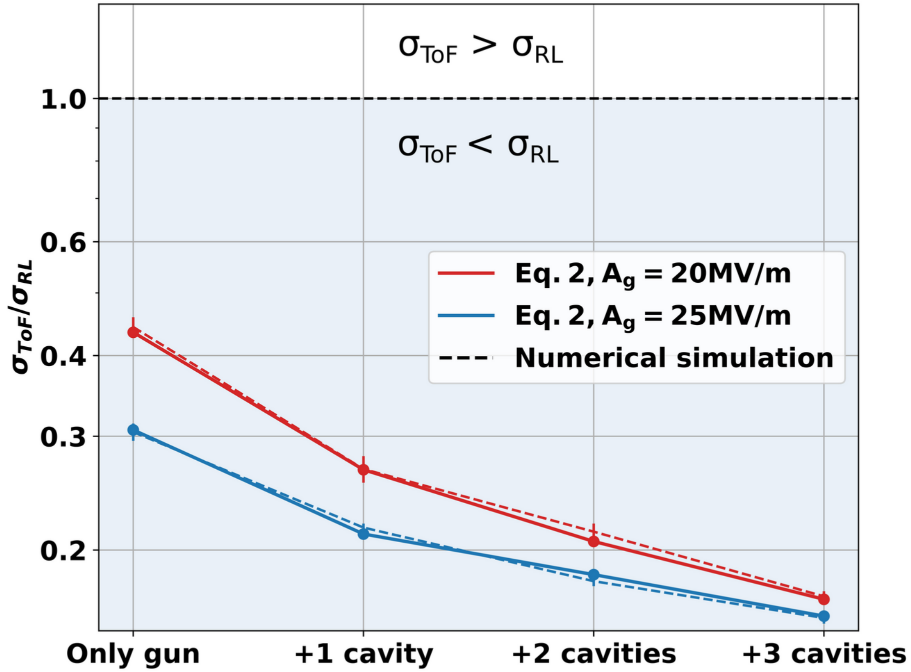
The jitter sources in the SRF Photoinjector are:

- The laser pulse arrival jitter at the cathode.
- The phase jitter in the RF cavities.
- The amplitude jitter in the RF cavities.

Parameter	Fluctuation
Laser arrival [fs]	300
RF Phase [°]	0.05
RF Amplitude	$1 \times 10^{-4} \cdot V$

TIME OF FLIGHT JITTER STUDIES





B. Alberdi, J.-G. Hwang et al., Sci. Rep. 12, 13365 (2022).

- **The use of multiple cavities allows to compensate the effect in time of flight jitter of the timing mismatch between RF fields and laser arrival at the cathode.**
- Minimum ToF jitter achieved with 3 cavities is of 54fs for an initial timing mismatch of 320fs between RF fields at the gun and laser arrival time at the cathode.

MOGA OPTIMIZATION OF TIME RESOLUTION

So we have achieved:

- **Emittance reduction**
- **Bunch compression**
- **Laser to RF jitter effect minimization**

However… the linearization requires to use certain working point of the additional cavities which are not benefitial for the ToF jitter. Hence:

- Find trade-off: compression ↔ ToF jitter
- Find the compromise that reduces the overall time resolution.

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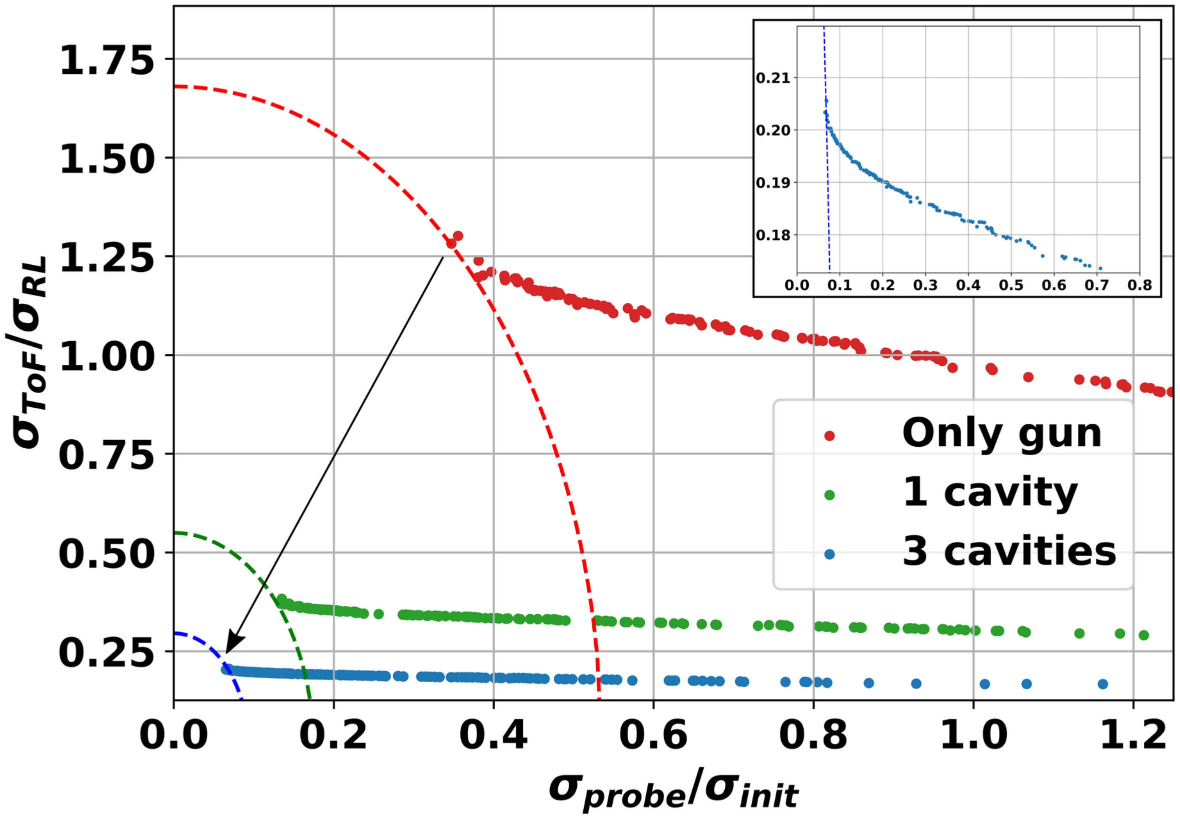
For this we use MOGA algorithms (with constrains for charge, emittance)**:**

$$\sqrt{\sigma_t^2 + \sigma_{ToF}^2} \leq 100\text{fs}$$



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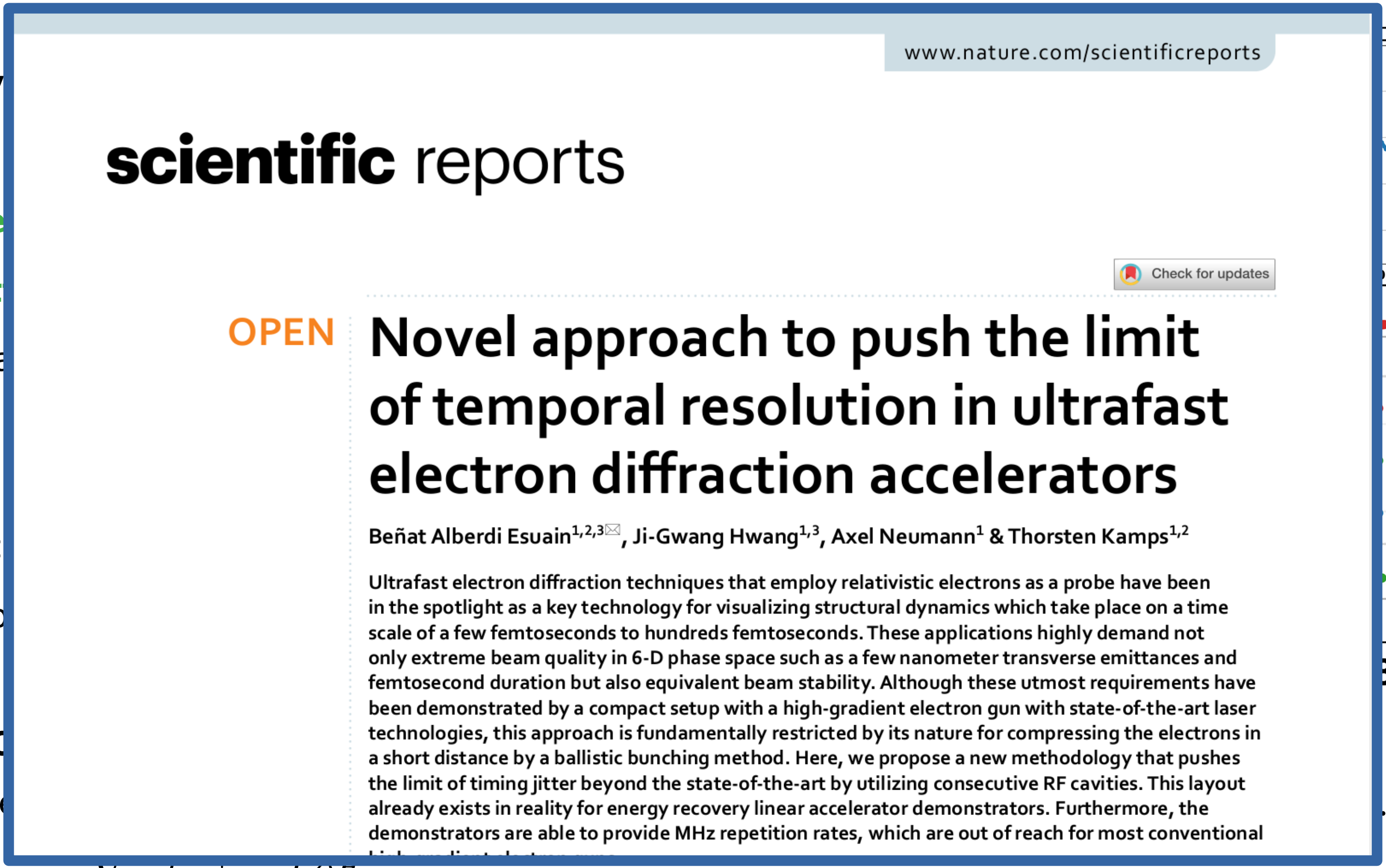

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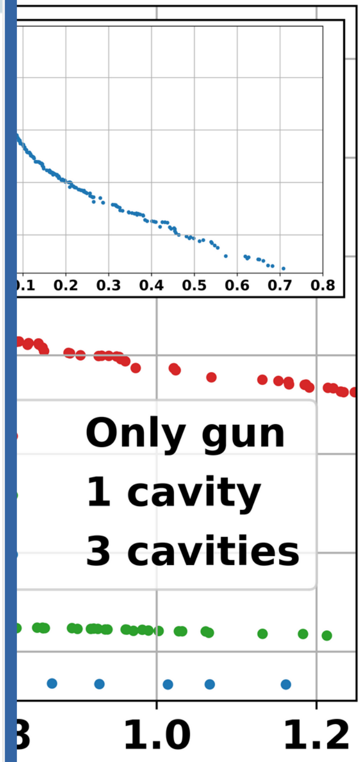
Novel approach to push the limit of temporal resolution in ultrafast electron diffraction accelerators

Beñat Alberdi Esuain[1,2,3], Ji-Gwang Hwang[1,3], Axel Neumann[1] & Thorsten Kamps[1,2]

Ultrafast electron diffraction techniques that employ relativistic electrons as a probe have been in the spotlight as a key technology for visualizing structural dynamics which take place on a time scale of a few femtoseconds to hundreds femtoseconds. These applications highly demand not only extreme beam quality in 6-D phase space such as a few nanometer transverse emittances and femtosecond duration but also equivalent beam stability. Although these utmost requirements have been demonstrated by a compact setup with a high-gradient electron gun with state-of-the-art laser technologies, this approach is fundamentally restricted by its nature for compressing the electrons in a short distance by a ballistic bunching method. Here, we propose a new methodology that pushes the limit of timing jitter beyond the state-of-the-art by utilizing consecutive RF cavities. This layout already exists in reality for energy recovery linear accelerator demonstrators. Furthermore, the demonstrators are able to provide MHz repetition rates, which are out of reach for most conventional



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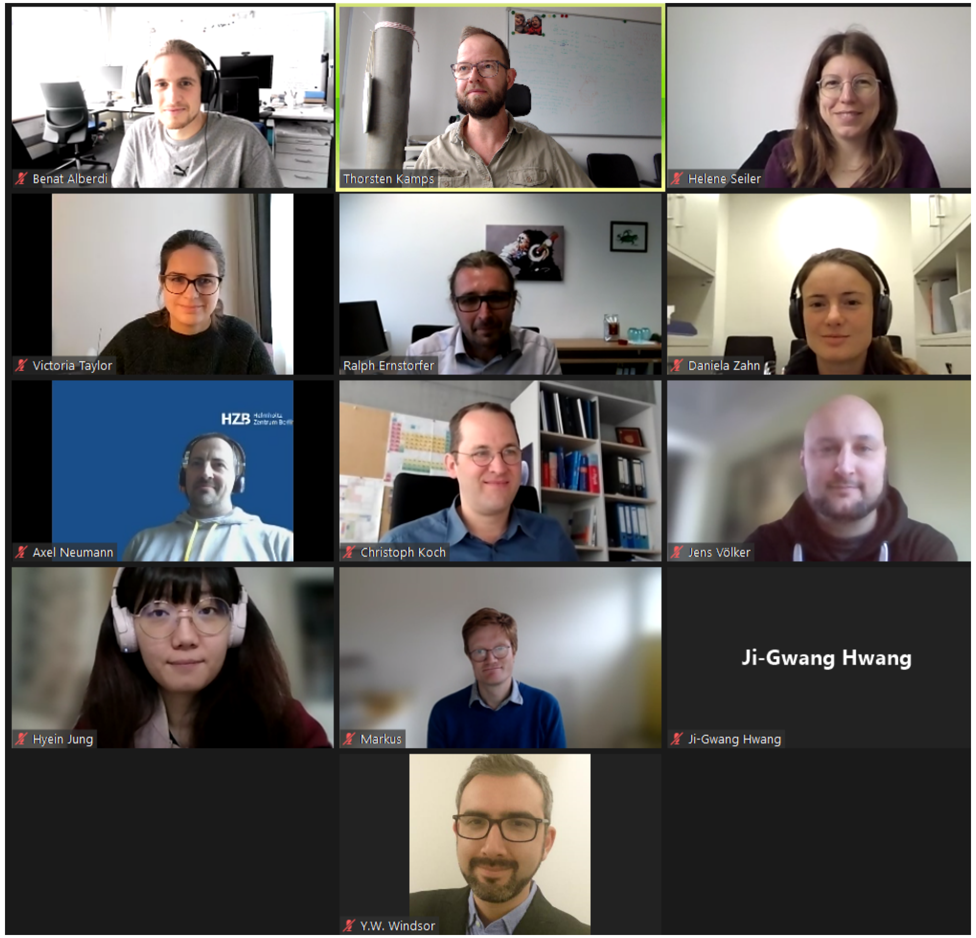
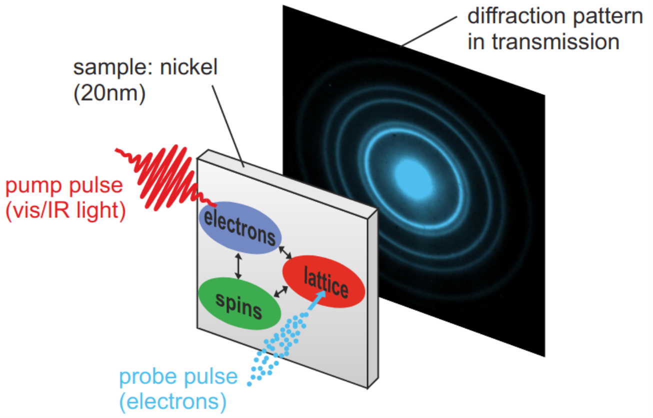
UED AT SEALAB – WORKSHOP WITH EXPERTS AND USERS



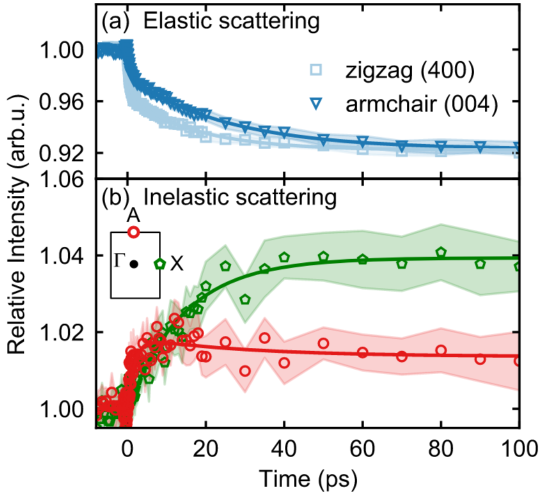
After the simulation results showing that the SRF Photoinjector was capable of achieving appropriate time and spatial resolutions for UED, a workshop was organized with experts and potential local users.

UED AT SEALAB – MAIN CONCLUSIONS

- **There is a very strong science case in the Berlin area for functional material studies with MHz repetition rate electron scattering experiments.**



D. Zahn, et al., arXiv:2008.04611 (2020)



H. Seiler, et al., arXiv:2006.12873 (2020)

- **Complementary to synchrotron radiation and FEL facilities with multi modal capabilities (Bessy III).**

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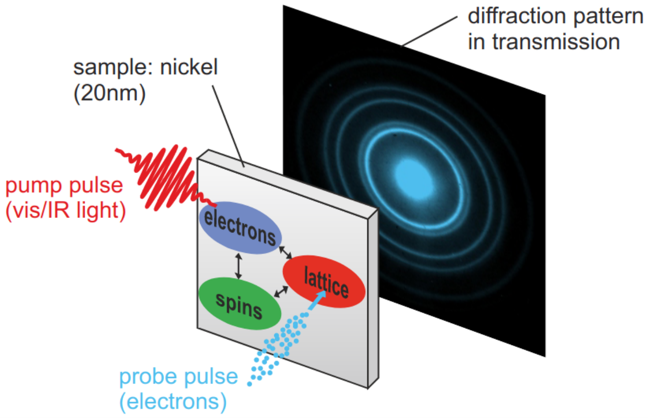

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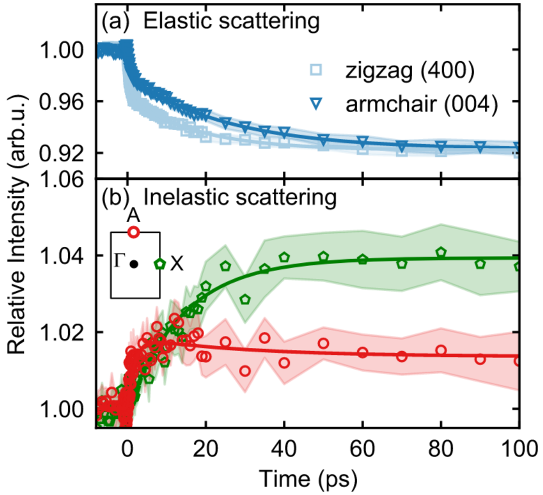

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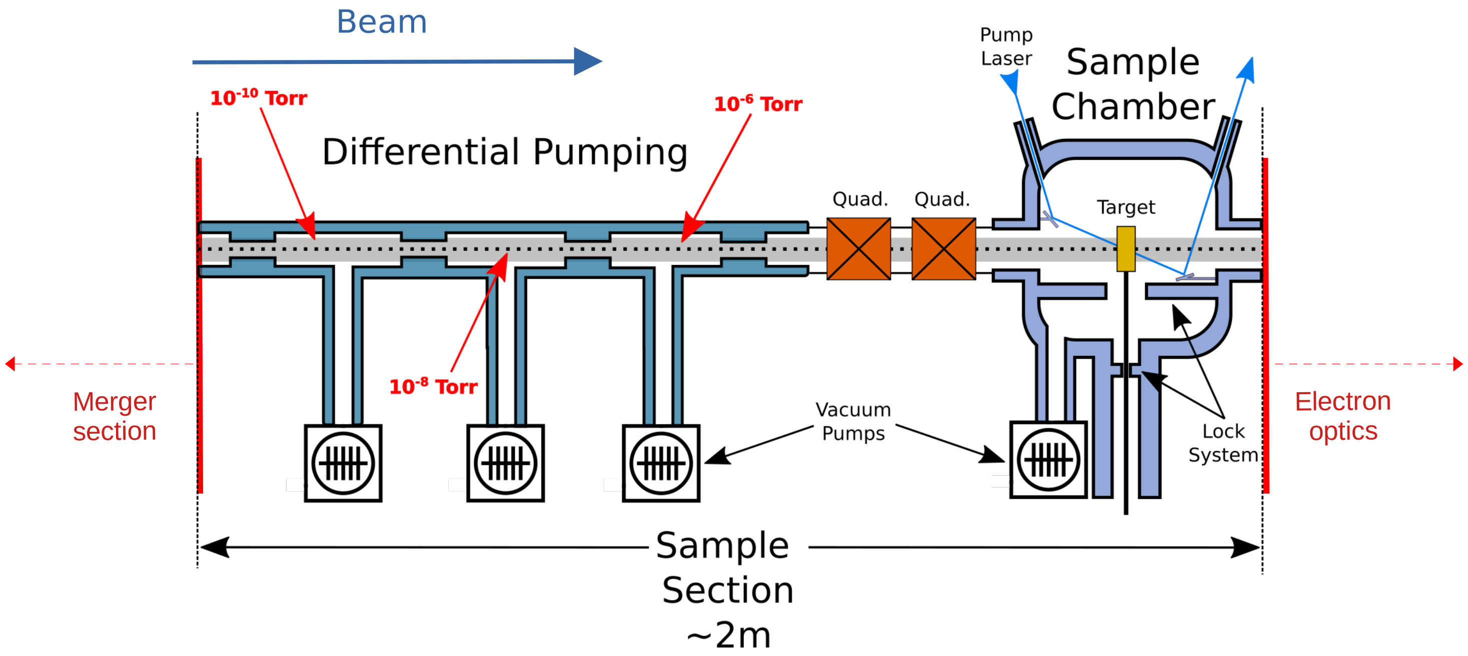
- **Complementary to synchrotron radiation and FEL facilities with multi modal capabilities (Bessy III).**

Machine Requirements

- The **time needed for the sample exchange should be reduced** from days to few hours or minutes.
- The capacity of **working in diffraction and imaging modes** together with very short pulses.
- **High magnification eletron optics** with low aberrations is required.
- A pump laser with suitable parameters and a synchronization system are needed.

SAMPLE SECTION

- The sample section will be **located downstream of the merger**.
- It consists of two main components:
  - **Differential pumping.**
  - **Sample chamber**.
- The differential pumping system separates the 10^{-10} Torr section upstream of the merger and the 10^{-6} Torr section downstream.



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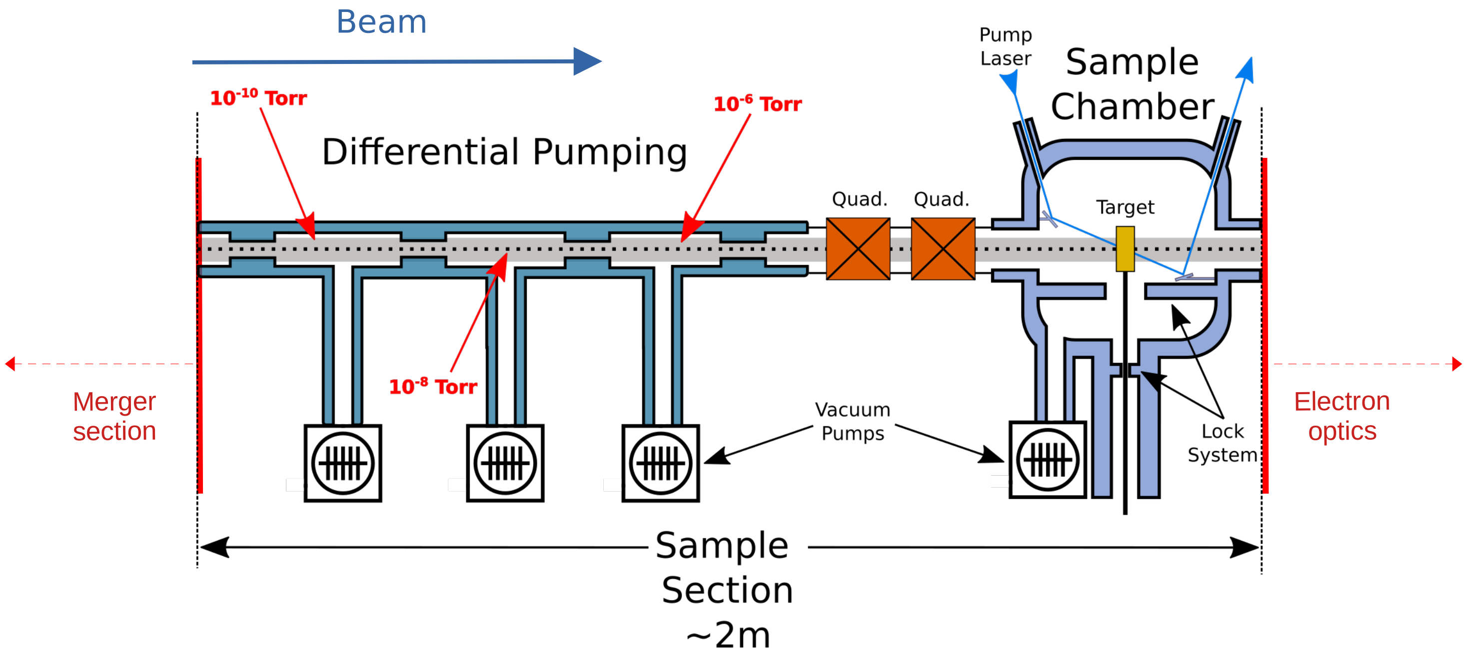
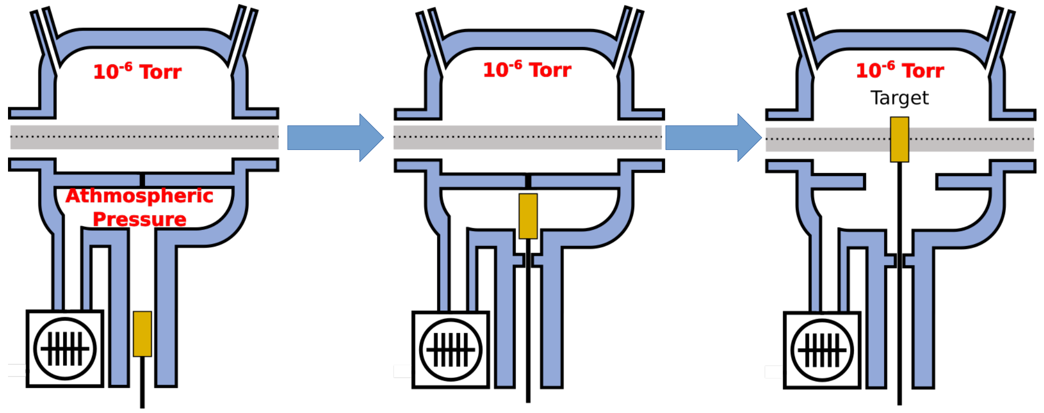
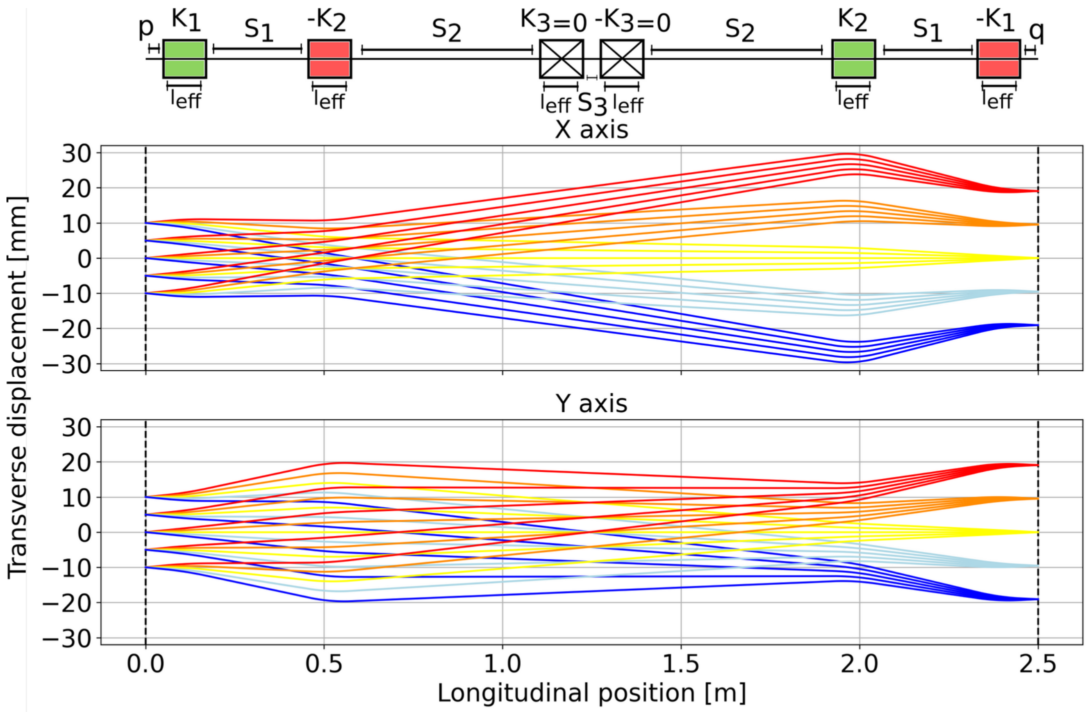
- The sample chamber enables quick exchange of the sample by using a lock system to keep relaxed vacuum conditions.

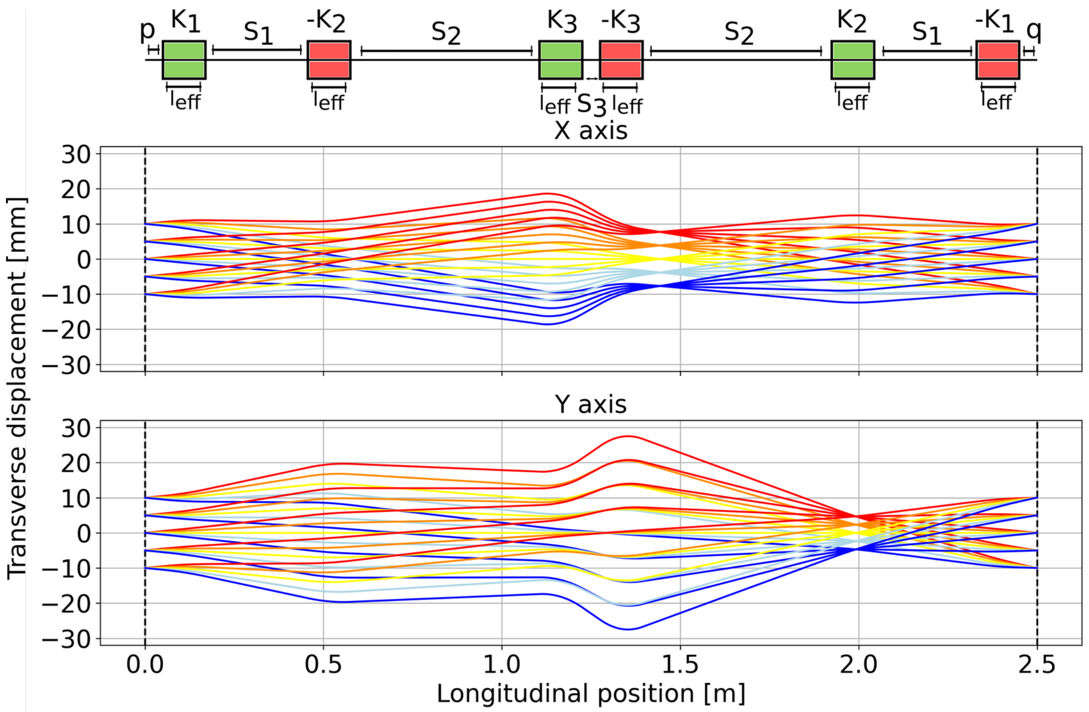




AXISYMMETRIC ZOOMING LENS WITH QUADRUPOLES

- The axisymmetric zooming lens produces point a **Fourier plane or an imaging plane** at 2.5m from the object.
- The lens **is axisymmetric**, keeping the symmetry between X and Y outside the quadrupoles.
- The change between the two operational modes happens by changing only one power supply value.





AXISYMMETRIC ZOO … UPOLES

- The axisymmetric zooming lens p… …ne at 2.5m from the object.
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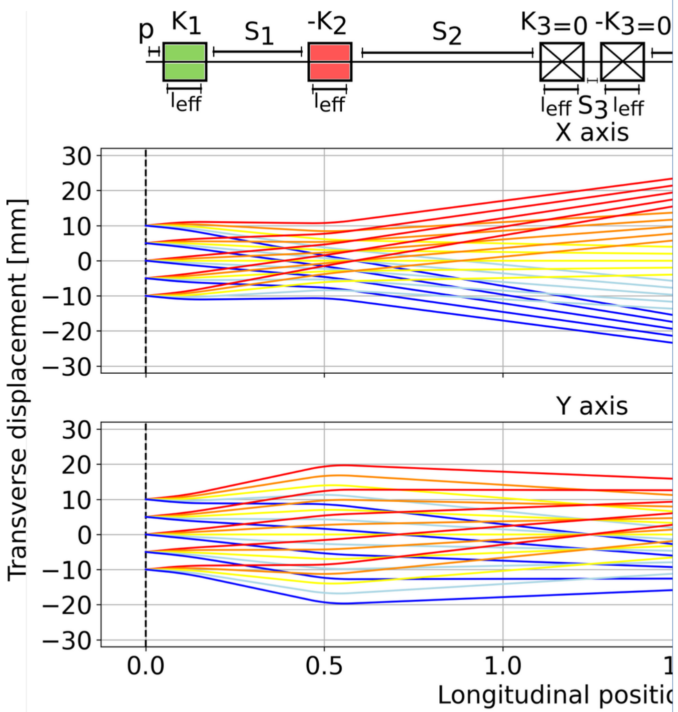
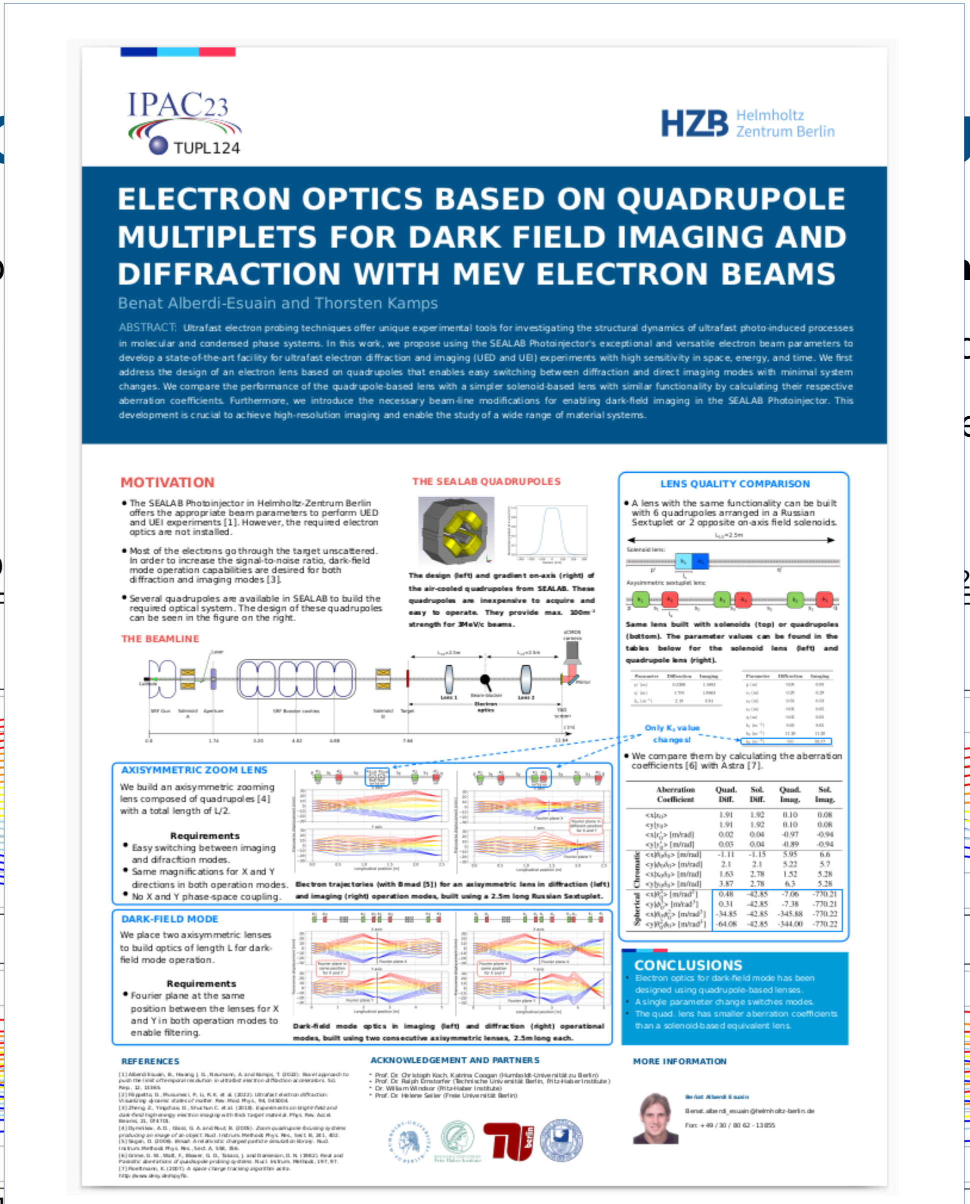
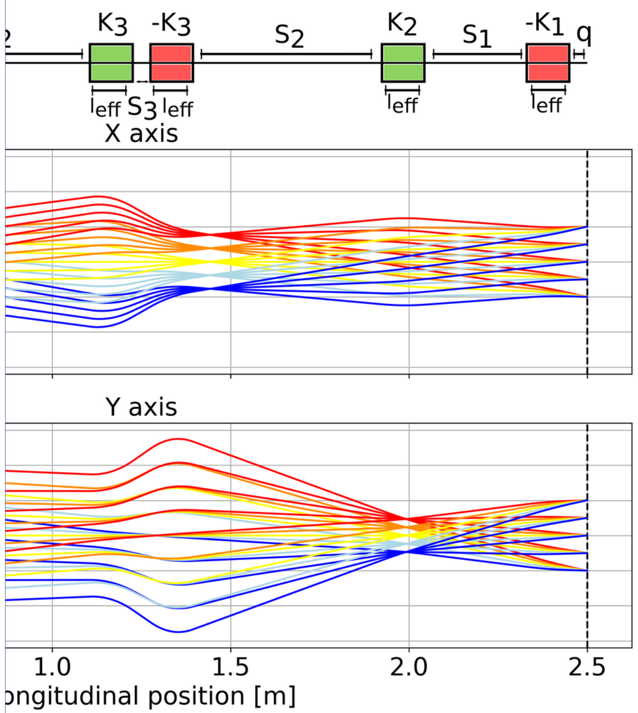


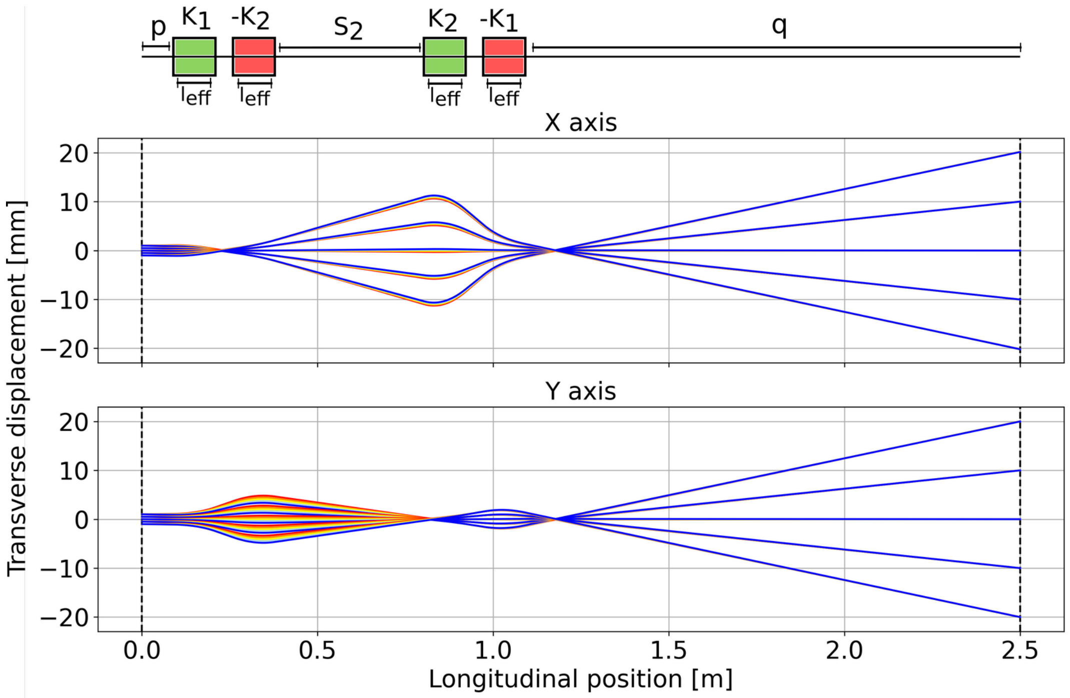


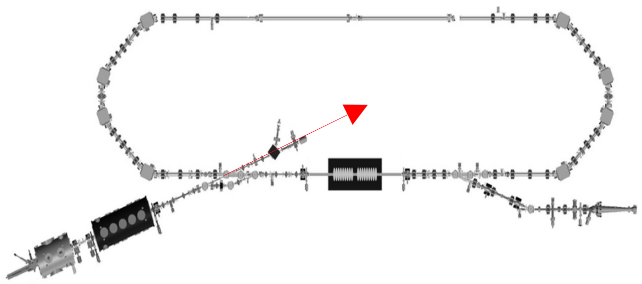
B. Alberdi and Thorsten Kamps, IPAC 2023 Proceedings.



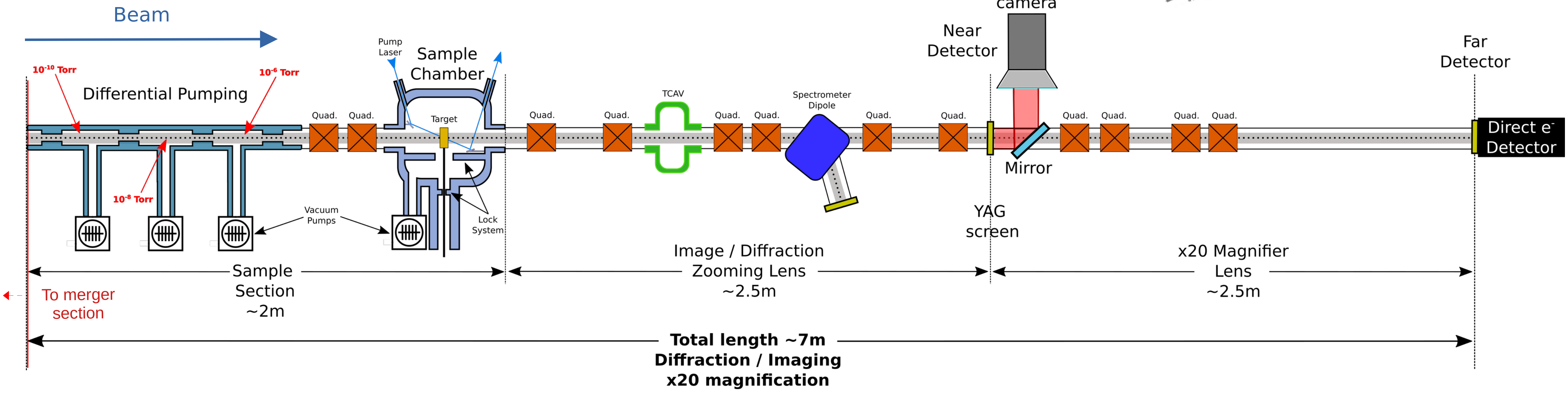
AXISYMMETRIC MAGNIFIER LENS WITH QUADRUPOLES

- **Symmetry between X and Y is conserved**: same magnification and same divergence at the end of the section.
- The axisymmetric magnifier lens produces **an image** of the object at 2.5m **with a magnification of 20**.
- An axisymmetric demagnifier lens with a demagnification of 20 has also been designed for beam focusing.

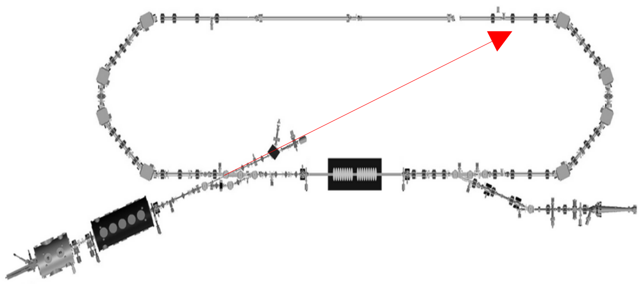




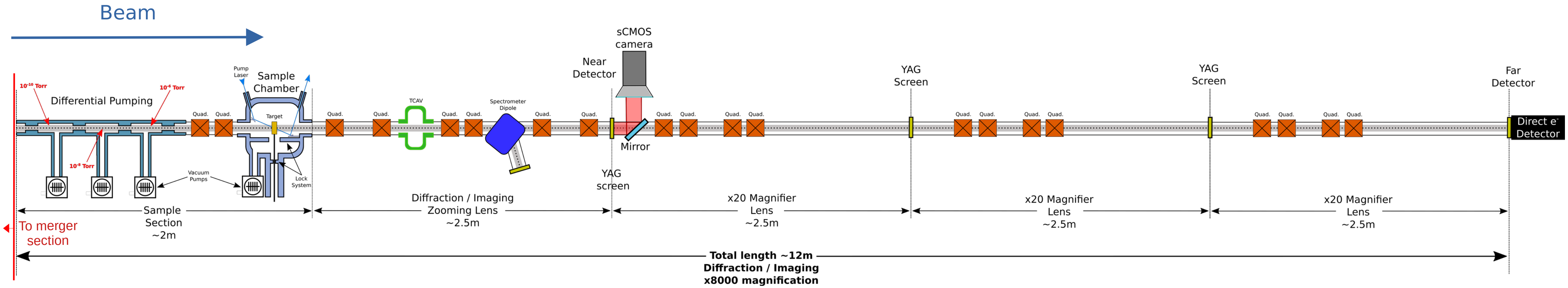
DIAGNOSTICS LINE – SHORT OPTION



- The beamline downstream of the merger is **in total 7m long**.
- It offers **both modalities diffraction / imaging in both detectors**: the near detector and the far detector.
- The **magnification** between both detectors is **of 20**.
- 12 quadrupoles needed for full implementation.



DIAGNOSTICS LINE – LONG OPTION



- The beamline downstream of the merger is **in total 12m long**.
- It offers **both modalities diffraction / imaging in both detectors**: the near detector and the far detector.
- The **magnification** between both detectors is **of 8000**.
- 20 quadrupoles needed for full implementation.

CONCLUSIONS

- Simulations show that the changes implemented to the SRF Photoinjector can reduce the transverse emittances to suitable values for electron scattering experiments. The changes to allow this have already been implemented in the beamine.
- This will be tested in an upcoming beamtime by measuring the emittance directly and indirectly using the diffraction pattern produced by a known target. The diagnostics techniques have been already tested in the KAERI beamline in Korea.
- The time resolution achievable in the SRF Photoinjector for pump-probe experiments is at least comparable to existing UED facilities.
- There is a big user base in Berlin who would like to perform MHz repetition rate UED and UEI experiments with solid state functional materials as target → This is the direction in which the SRF Photoinjector modifications will happen.
- **Current status:**
    - The commissioning of the SRF Photoinjector is planned for this year. We will soon see the first beams.
    - The design of the needed beamline modifications to allow pump-probe experiments is taking place right now, a final design will be ready soon. The changes will be implemented over the next years, with the goal of achieving first scientific results in 3 years time.

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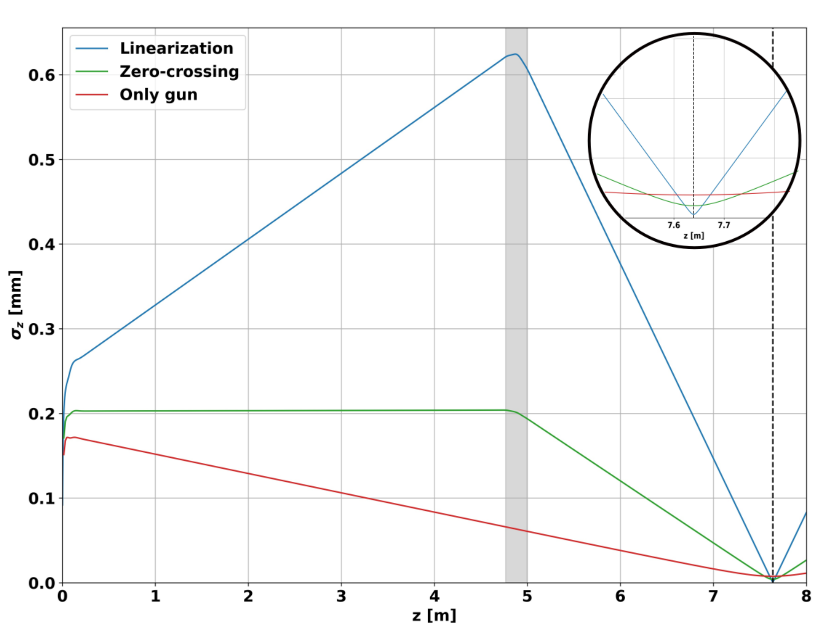
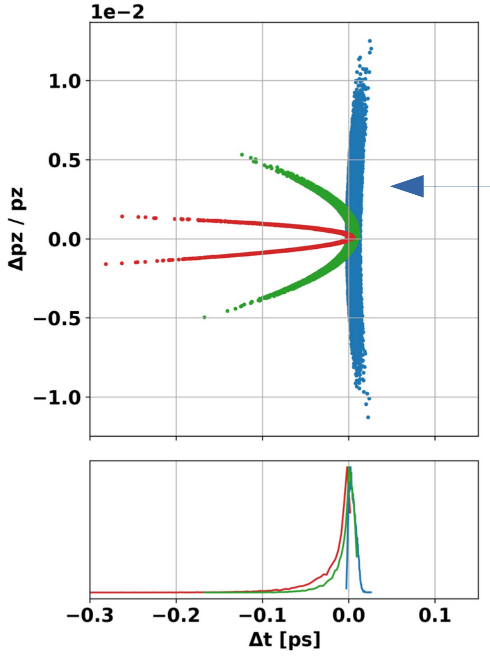
THIS IS ALL,
THANK YOU FOR YOUR ATTENTION

BACK-UP SLIDE - COMPRESSION W/O SPACE CHARGE

First, study a very simple case to achieve the shortest bunch possible at the target.

- Initial condition is 1ps laser pulse at the cathode, no space-charge forces for the moment.



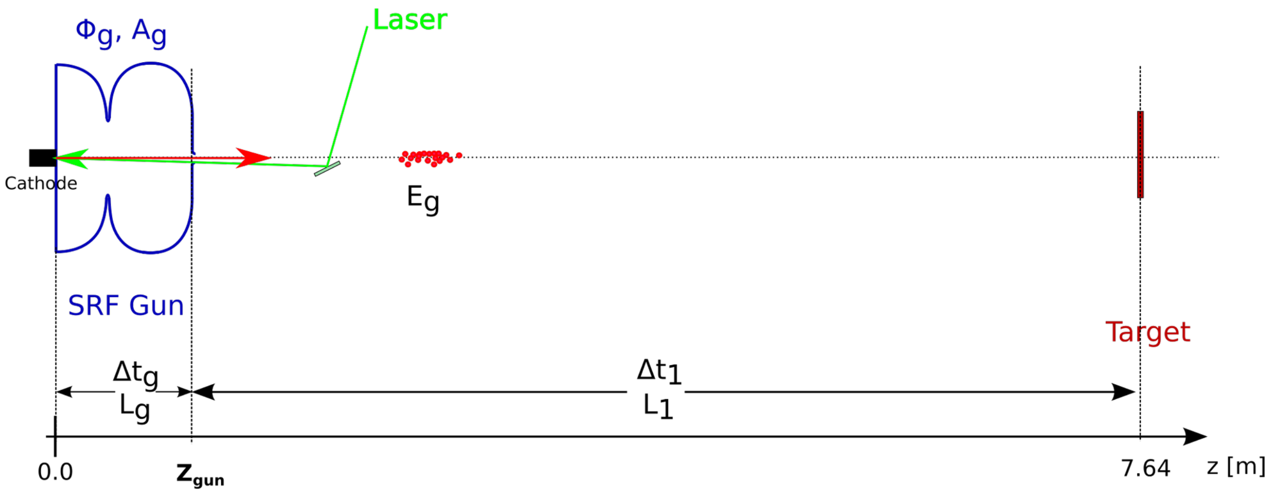


Linearization using the stretcher mode [1] provides the shortest bunch at target.

	Gun		Booster cav.		Target @
	ϕ_g [°]	A_g [MV m^{-1}]	ϕ_b [°]	A_b [MV m^{-1}]	τ_{bunch} [fs]
Direct compression	-7.41	20.0	X	X	26.7
Zero crossing	0.0	20.0	0.0	4.09	14.2
Linearization	14.5	20.0	-32.11	4.48	4.2

[1] B. Zeitler et al., Phys. Rev. ST Accel. Beams 18, 120102 (2015)

BACK-UP SLIDE – GUN JITTER



The electron bunches sample different fields than the nominal in the gun. The reasons are:

- The laser pulse arrival jitter at the cathode.
- The phase jitter in the gun.
- The amplitude jitter in the gun.

Parameter	Fluctuation	
Laser arrival [fs]	300	σ_L
RF Phase [°]	0.05	σ_ϕ
RF Amplitude	$1 \times 10^{-4} \cdot$ V	σ_A

Timing jitters in the gun can be combined:

$$\sigma_{RL} = \sqrt{(\sigma_\phi / w)^2 + \sigma_L^2} \sim 320\text{fs}$$

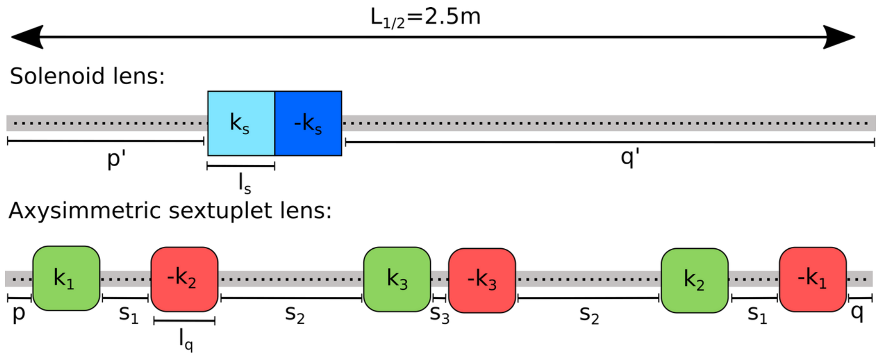
We develop an analytical model of the time of flight jitter:

- Astra simulations are used to calculate beam energy and time to exit the gun as a function of gun amplitude and phase

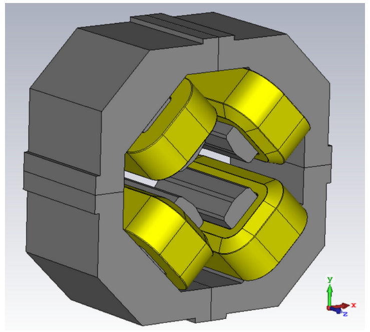
$$\sigma_{ToF}^2 = \left(\frac{\partial t_g}{\partial A_g} - \frac{L_1}{m_0 c^3 (\gamma_g^2 - 1)^{3/2}} \left(\frac{\partial E_g}{\partial A_g} \right) \right)^2 \sigma_{A_g}^2 + \left(\frac{\partial t_g}{\partial \phi_g} - \frac{L_1}{m_0 c^3 (\gamma_g^2 - 1)^{3/2}} \left(\frac{\partial E_g}{\partial \phi_g} \right) \right)^2 (\omega \sigma_{RL})^2$$

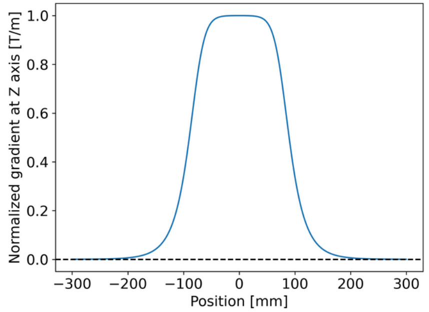
BACK-UP SLIDE – COMPARISON SOLENOID VS QUADRUPOLE

- A lens with the same functionality can be built with 6 quadrupoles arranged in a Russian Sextuplet or 2 opposite on-axis field solenoids.



THE SEALAB QUADRUPOLES





Parameter	Diffraction	Imaging
p (m)	0.05	0.05
s_1 (m)	0.29	0.29
s_2 (m)	0.53	0.53
s_3 (m)	0.05	0.05
q (m)	0.05	0.05
k_1 (m^{-2})	8.65	8.65
k_2 (m^{-2})	11.20	11.20
k_3 (m^{-2})	0.0	33.57

Parameter	Diffraction	Imaging
p' (m)	0.5206	1.1893
q' (m)	1.755	1.0863
k_s (m^{-1})	2.19	3.94

	Aberration Coefficient	Quad. Diff.	Sol. Diff.	Quad. Imag.	Sol. Imag.
	$\langle x\|x_0\rangle$	1.91	1.92	0.10	0.08
	$\langle y\|y_0\rangle$	1.91	1.92	0.10	0.08
	$\langle x\|x'_0\rangle$ [m/rad]	0.02	0.04	-0.97	-0.94
	$\langle y\|y'_0\rangle$ [m/rad]	0.03	0.04	-0.89	-0.94
Chromatic	$\langle x\|\theta_0\delta_0\rangle$ [m/rad]	-1.11	-1.15	5.95	6.6
	$\langle y\|\phi_0\delta_0\rangle$ [m/rad]	2.1	2.1	5.22	5.7
	$\langle x\|x_0\delta_0\rangle$ [m/rad]	1.63	2.78	1.52	5.28
	$\langle y\|y_0\delta_0\rangle$ [m/rad]	3.87	2.78	6.3	5.28
Spherical	$\langle x\|\theta_0^3\rangle$ [m/rad^3]	0.48	-42.85	-7.06	-770.21
	$\langle y\|\phi_0^3\rangle$ [m/rad^3]	0.31	-42.85	-7.38	-770.21
	$\langle x\|\theta_0\phi_0^2\rangle$ [m/rad^3]	-34.85	-42.85	-345.88	-770.22
	$\langle y\|\theta_0^2\phi_0\rangle$ [m/rad^3]	-64.08	-42.85	-344.00	-770.22