Laser cooling “taken to the extreme” at the FAIR SIS100

Danyal Winters

Laser cooling collaboration

- GSI Darmstadt
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- IMP-CAS, Lanzhou, China
  Dongyang Chen, Zhongkui Huang, Xinwen Ma, Hanbing Wang, Weiqiang Wen
- Uni Kassel
  Nils Kiefer, Arno Ehresmann

Why is our laser cooling interesting?

- laser cooling is frequently applied to atoms/ions in small traps (~cm)
- normally, several laser beams are used coming from different directions → 3D
- the laser light is mostly continuous (cw)
- typically, light atoms/ions (singly charged) are used (Be, Na, Mg, Ca …)
- the velocities of the atoms/ions is usually low

- we want to apply it to a very large accelerator (~1.1 km)
- our laser beams come from one direction only → 1D
- we will use cw and pulsed laser beams (MHz rep. rate)
- we will use heavy ions in very high charge states
- the ions have relativistic velocities (99% of c)

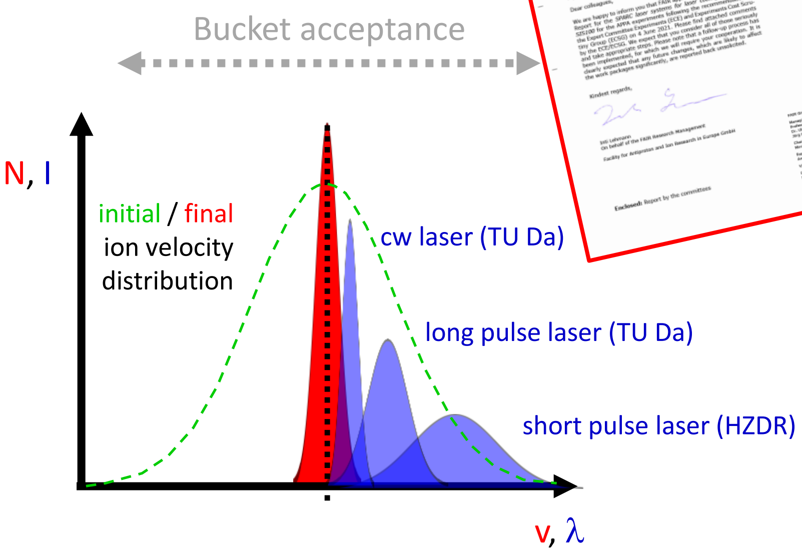
Motivation

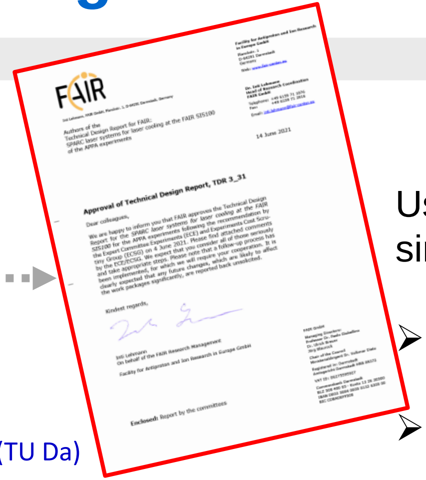
- create **worldwide unique** laser cooling facility @ FAIR SIS100
- **first application of laser cooling at a large synchrotron** using novel cw & pulsed laser and detection systems
- possibility to **deliver very cold & very short ion bunches** to FAIR experiments (*e.g.* plasma physics)

- "efficiency" of laser cooling increases with ion beam energy (γ)
- highly relativistic ion energies of the SIS100 allow **cooling of many ion species** by exploiting the huge Doppler shift (γ up to 13): Z = 10 – 54

- laser spectroscopy of the electronic structure of heavy ions

3-beam laser cooling at the SIS100





Authors of the
Technical Design Report for FAIR:
SPARC laser systems for laser cooling at the FAIR SIS100
of the APPA experiments

14 June 2021

Approval of Technical Design Report, TDR 3_31

Dear colleagues,

We are happy to inform you that FAIR approves the Technical Design Report for the SPARC laser systems for laser cooling at the FAIR SIS100 for the APPA experiments following the recommendation by the Expert Committee Experiments (ECE) and Experiments Cost Scrutiny Group (ECSG) on 4 June 2021. Please find attached comments by the ECE/ECSG. We expect that you consider all of those seriously and take appropriate steps. Please note that a follow-up process has been implemented, for which we will require your cooperation. It is clearly expected that any future changes, which are likely to affect the work packages significantly, are reported back unsolicited.

Kindest regards,

Inti Lehmann
On behalf of the FAIR Research Management

Facility for Antiproton and Ion Research in Europe GmbH

Enclosed: Report by the committees

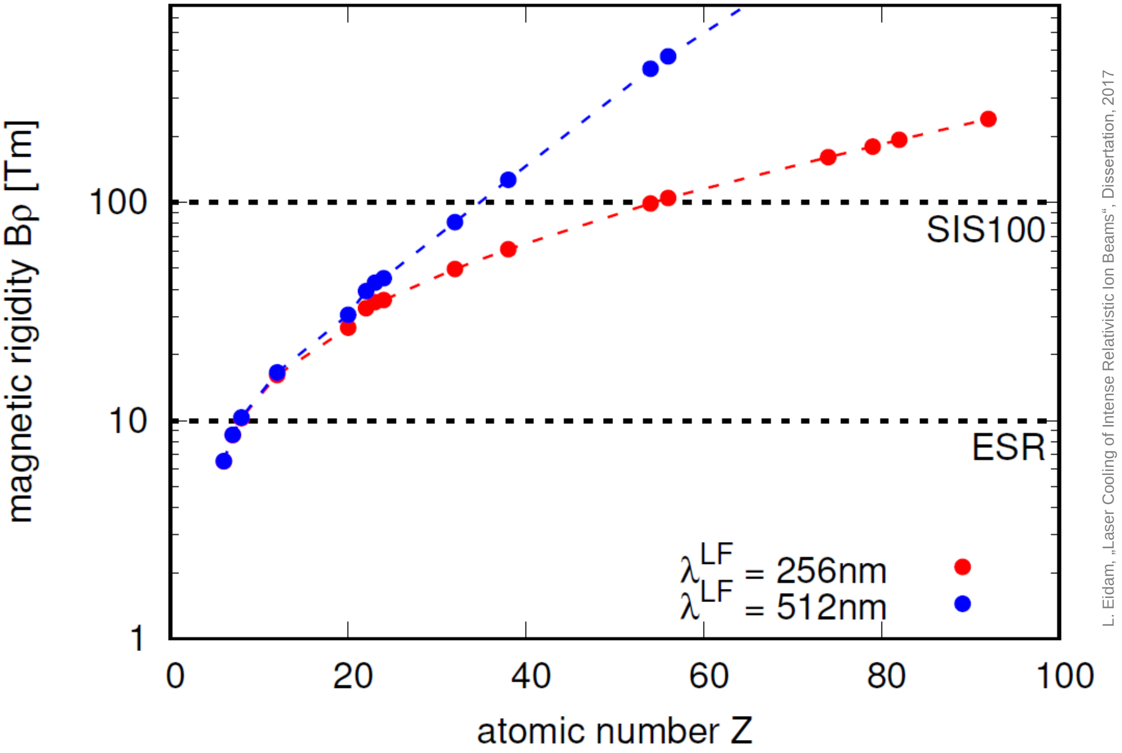
Using **three** laser systems at the SIS100 simultaneously combines the advantages of:

- covering a large ion velocity range
- suppressing heating effects like IBS
- fast cooling (order of seconds)
- lowest possible longitudinal ion momentum spread $\Delta p/p \sim 10^{-7}$
- shortest ion bunch lengths (order of ~10 ns)

But … requires overlap of ion and laser beams in space, time & energy !

Laser cooling of a large range of ions

(example: 2s – 2p transitions in Li-like ions)



calculations by Lewin Eidam

Ion species for laser cooling at SIS100 (green laser)

1. Regime: Bρ = 80 Tm, λ(laser) = 514 nm (2.412 eV)

El. sequence	Q/M range	Transition	j-j transition	ΔE laser, nm	Nucl. charge Z_n range
Li-like	0.25 – 0.43	2s – 2p	1/2 – 1/2	22 – 40	16 - 28
			1/2 – 3/2		16 - 24
Be-like	0.17 – 0.40	$2s^2$ – 2s2p	1/2 – 1/2	24 - 58	15 - 30
			1/2 – 3/2		14 - 23
B-like	0.08 – 0.40	$2s^22p$ – $2s2p^2$	1/2 – 1/2	25 - 120	8 - 27
			1/2 – 3/2		7 - 20
Na-like	0.04 – 0.34	3s – 3p	1/2 – 1/2	30 - 200	13 – 29
			1/2 – 3/2		13 - 27
K-like	0.025 – 0.30	4s – 4p	1/2 – 1/2	32 - 280	21 - 45
			1/2 – 3/2		21 - 40

these ions are the lighter ones

calculations by Slava Shevelko

Ion species for laser cooling at SIS100 (UV laser)

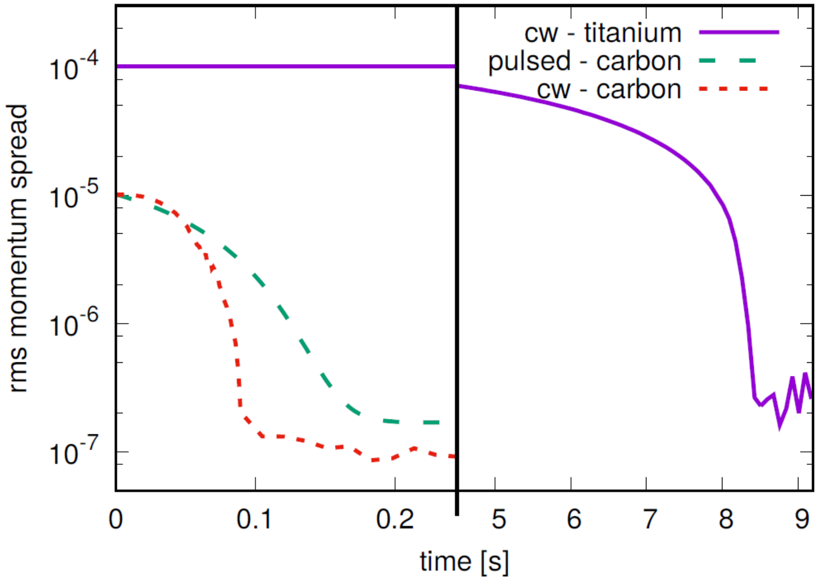
2. Regime: Bρ = 100 Tm, λ(laser) = 257 nm (4.824 eV)

El. sequence	Q/M range	Transition	j-j transition	ΔE laser, nm	Nucl. charge Z_n range
Li-like	0.25 – 0.43	2s – 2p	1/2 – 1/2	9 – 16	38 – 60
			1/2 – 3/2		28 - 36
Be-like	0.17 – 0.40	$2s^2$ – 2s2p	1/2 – 1/2	10 - 23	30 - 56
			1/2 – 3/2		25 - 36
B-like	0.08 – 0.40	$2s^22p$ – $2s2p^2$	1/2 – 1/2	10 - 48	17 - 56
			1/2 – 3/2		13 - 33
Na-like	0.04 – 0.34	3s – 3p	1/2 – 1/2	12 - 90	16 – 49
			1/2 – 3/2		16 - 40
K-like	0.025 – 0.30	4s – 4p	1/2 – 1/2	13 - 130	24 - 80
			1/2 – 3/2		24 - 58

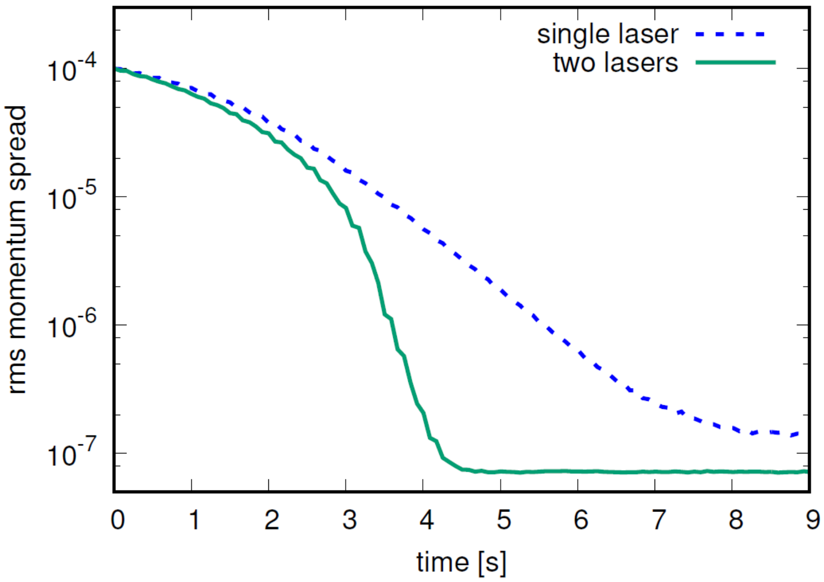
these ions are the heavier ones

calculations by Slava Shevelko

Expected cooling times and momentum spreads



@ESR @SIS100



@SIS100

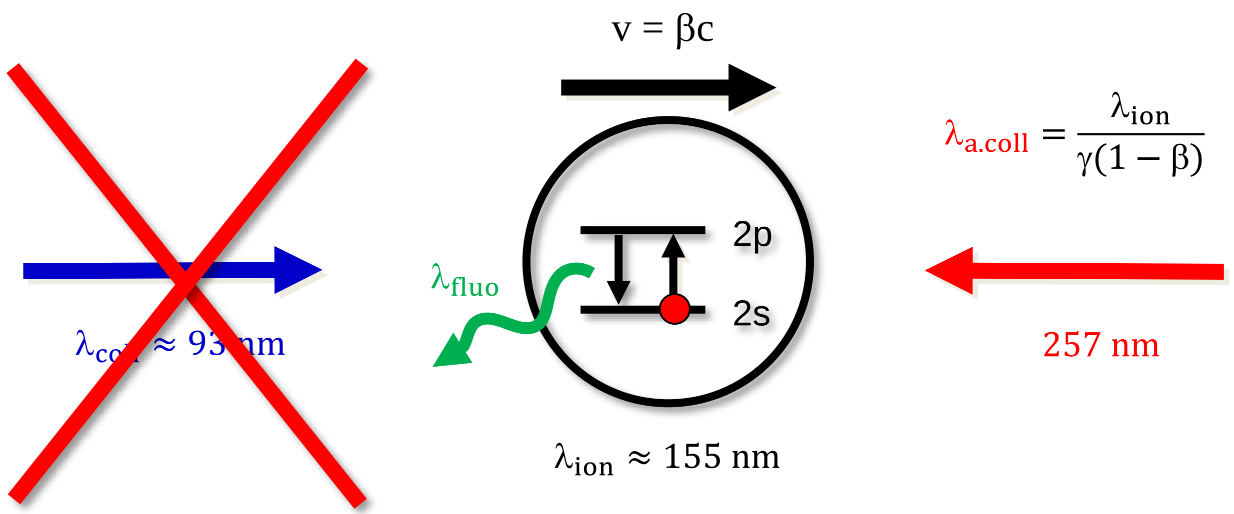
L. Eidam, „Laser Cooling of Intense Relativistic Ion Beams“, Dissertation, 2017

Simulations by Lewin Eidam

Principle: bunched beam laser cooling

ESR experiment (2021):
$^{12}C^{3+} \rightarrow \beta \approx 0.47, \gamma \approx 1.13$

only 1D laser cooling

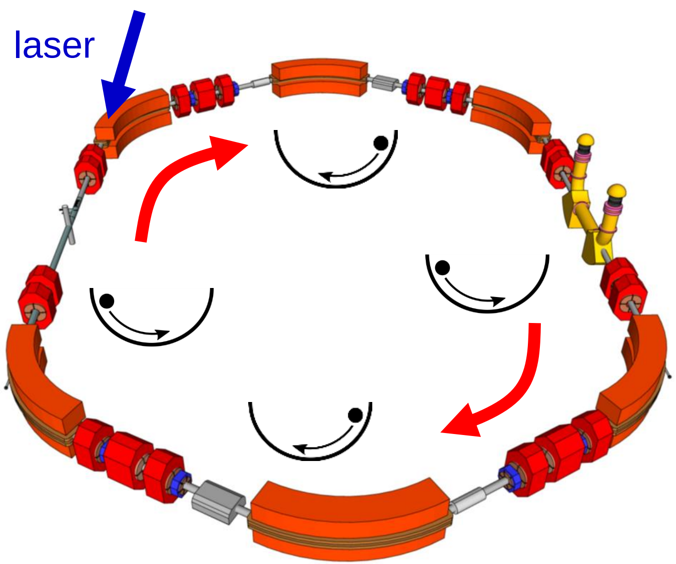


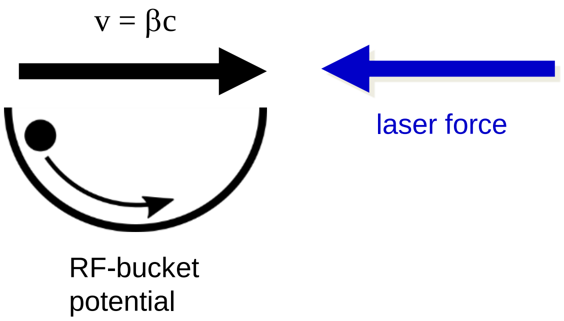
not feasible yet

The ion absorbs many directional momenta from the photons and decays each time with a random recoil, averaging out to zero.

Principle: bunched beam laser cooling

$$f_{bunching} = h \cdot f_{rev} \;\rightarrow\; h \text{ bunches}$$



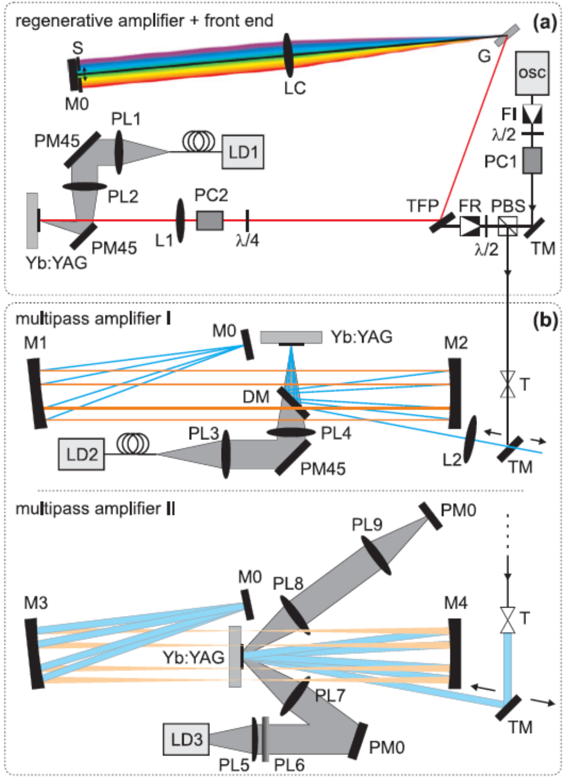


- the amplitudes of the synchrotron oscillations are damped

Short pulse laser system

- Transform limited pulses with **1-100 ps pulse duration** and up to **5 MHz repetition rate** using a regenerative amplifier
- Up to **10 W average power** @ 1028 nm using a single crystal fiber and **100 mW average power** @ 257 nm

Ref.: SPARC Collaboration, Technical Report. For the Design, Construction and Commissioning of the SPARC laser systems for laser cooling at the FAIR SIS100 (2020).



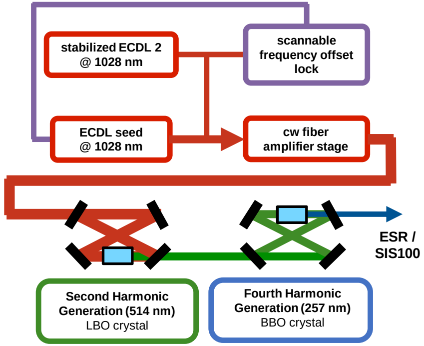
Siebold, M. et al. High energy Yb:YAG active mirror laser system for transform limited pulses bridging the picosecond gap. Laser Photonics Rev. **10**, 673–680 (2016).

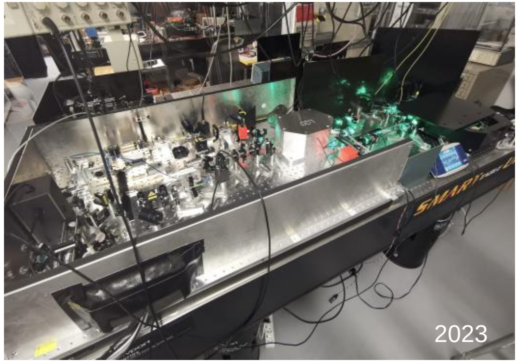
Continuous wave laser system

Federal Ministry of Education and Research

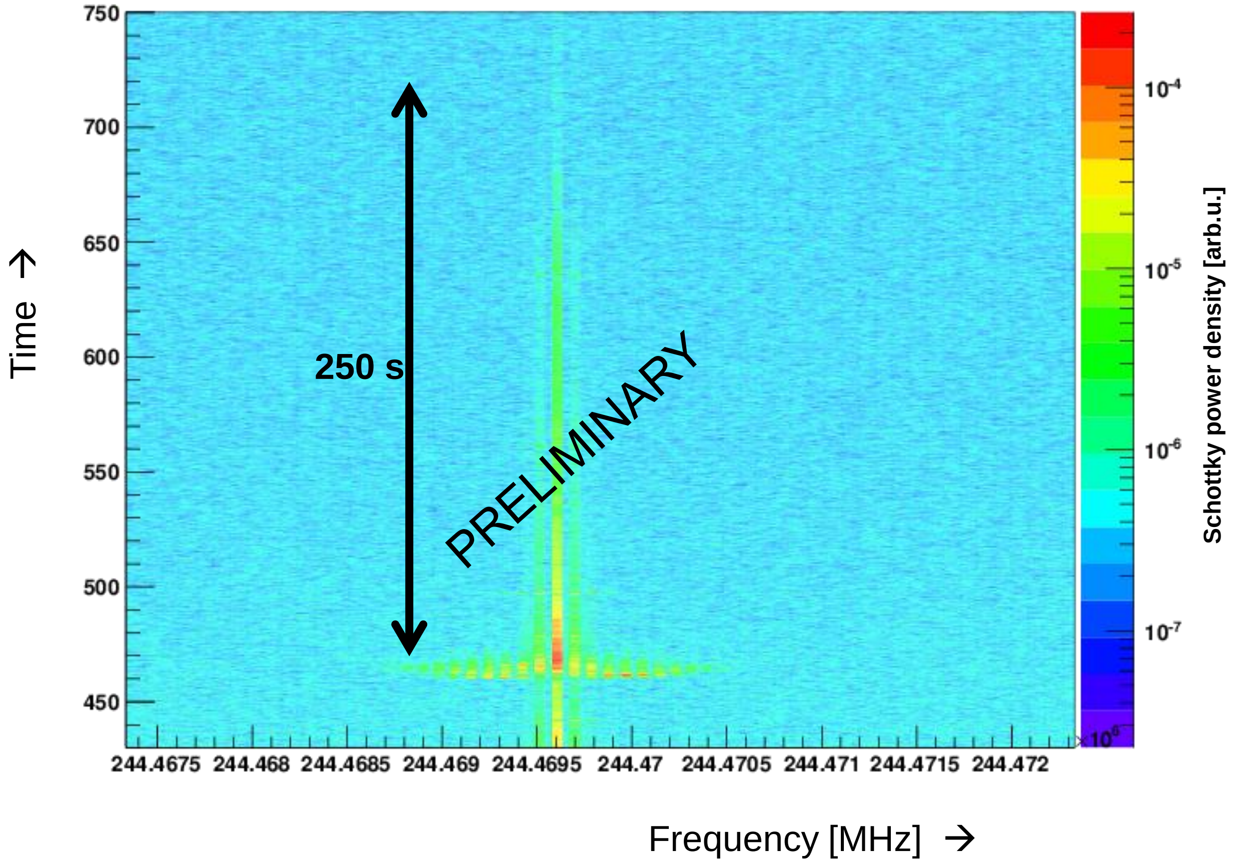
TECHNISCHE UNIVERSITÄT DARMSTADT

- IR laser system is seeded by Littrow-ECDL @ 1028 nm
- Bow-tie cavity for conversion to 514 nm and novel elliptical bow-tie cavity for conversion to **257 nm**
- **narrow linewidth** and mode hop free scanning over **20 GHz** (50 Hz scan rate) @ **257 nm**
- up to **1.6 W UV power** could be demonstrated





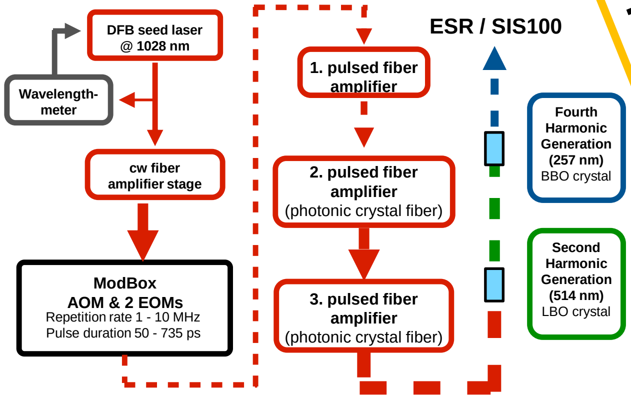
➢ successful demonstration of cw laser cooling at the ESR @ GSI in 2012 laser-cooling of the ion beam using cw laser scan, then keeping the ions cold for a long time

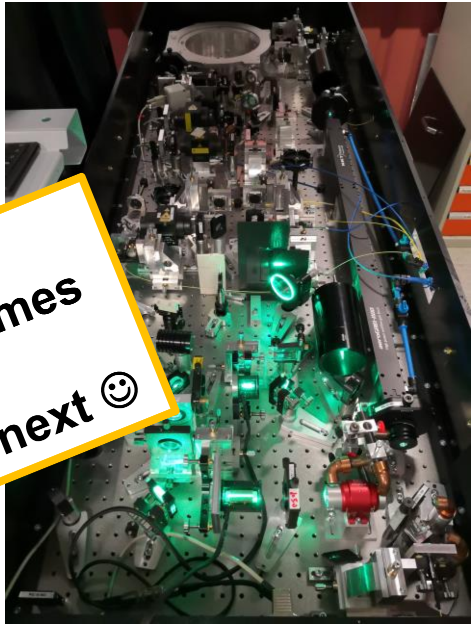


2012 ESR @ GSI

Long pulse laser system

- Tunable distributed feedback laser (DFB) as seed laser @ 1028 nm
- Transform limited pulses with **1-10 MHz repetition rate** and **50-740 ps pulse duration**
- Multi-stage pulsed fiber amplifiers to generate up to **60 W average IR power**
- Two single pass stages to generate 514 nm and 257 nm
- up to **4.1 W UV power** (115 ps, 10 MHz) could be demonstrated

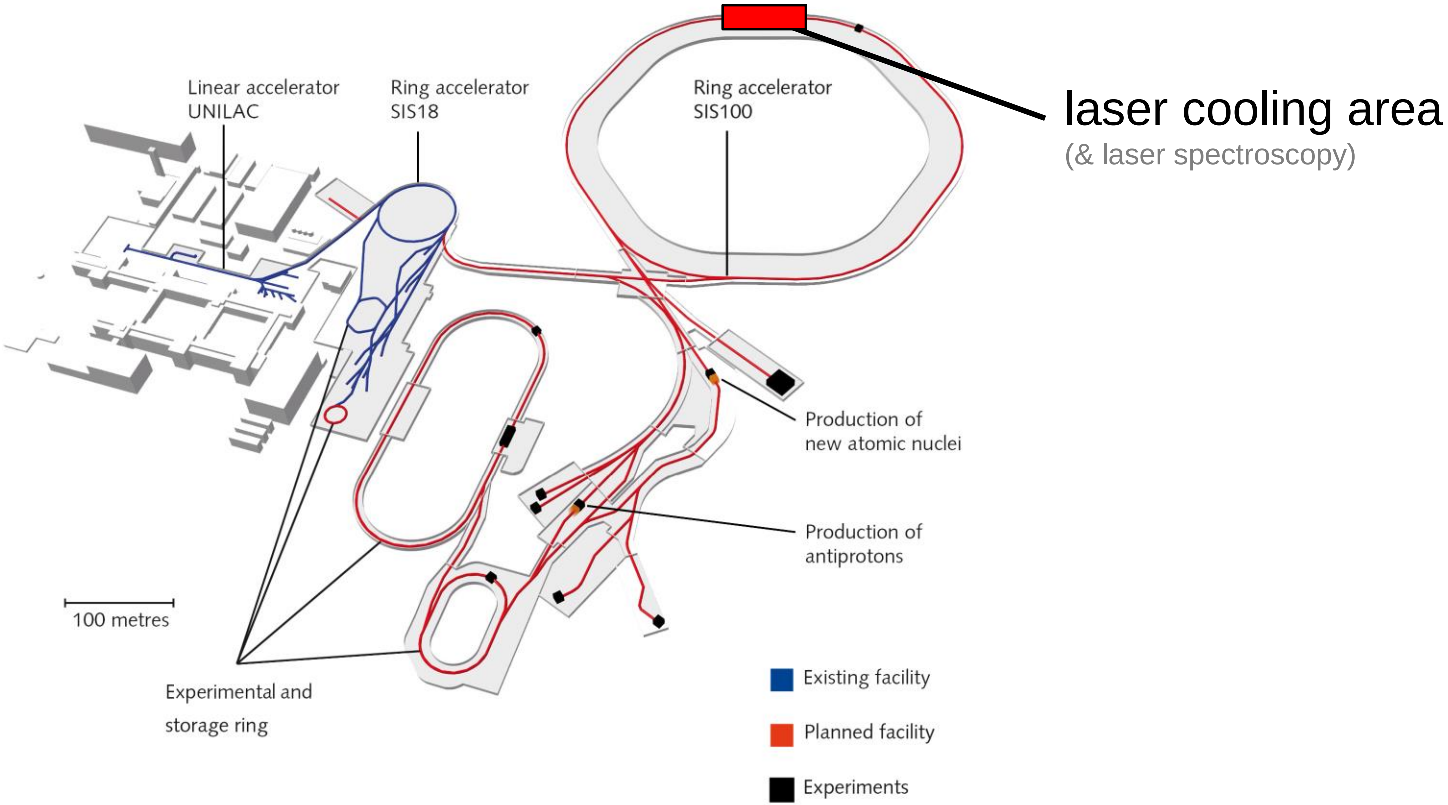




Talk by Sebastian Klammes … coming up next ☺

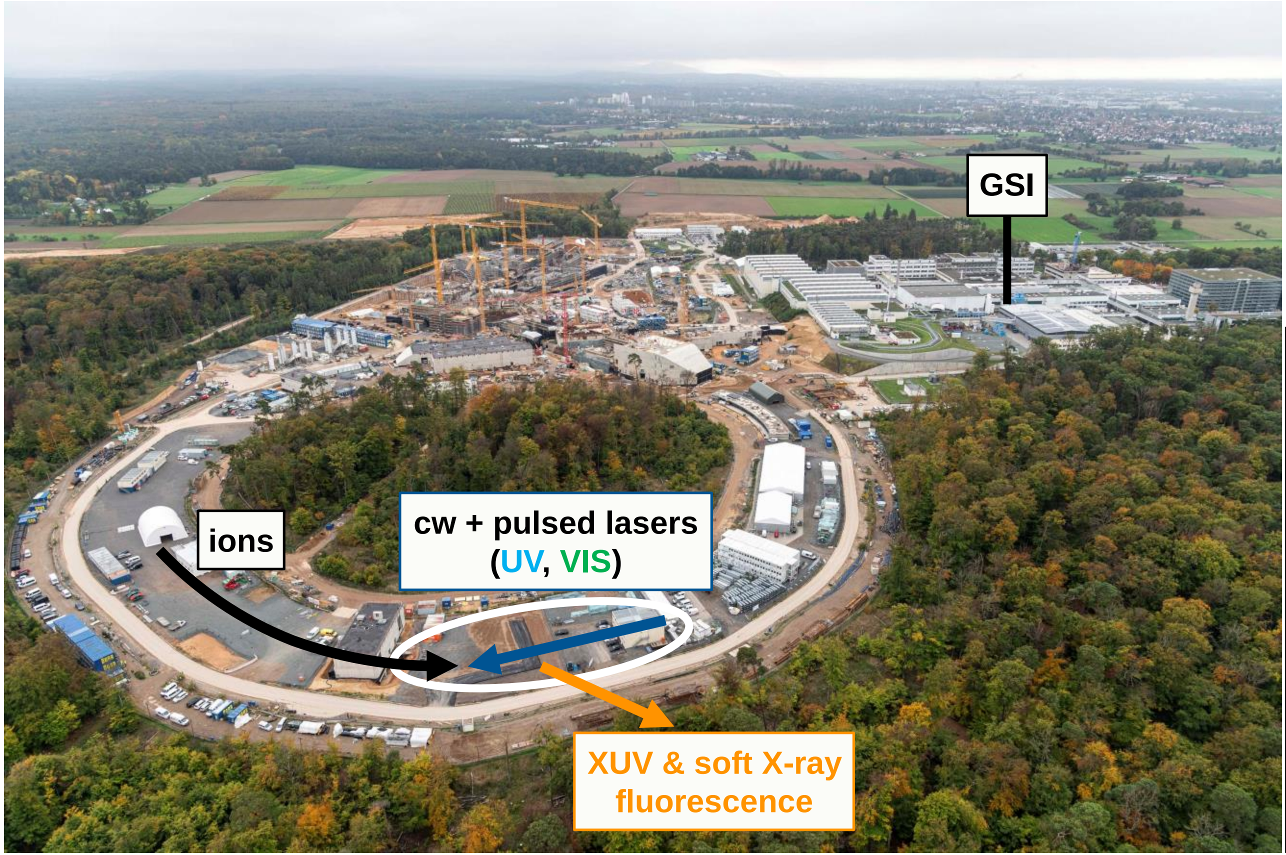
➢ successful demonstration of first broadband very high
➢ rep. rate laser cooling at the ESR @ GSI in 2021

FAIR SIS100



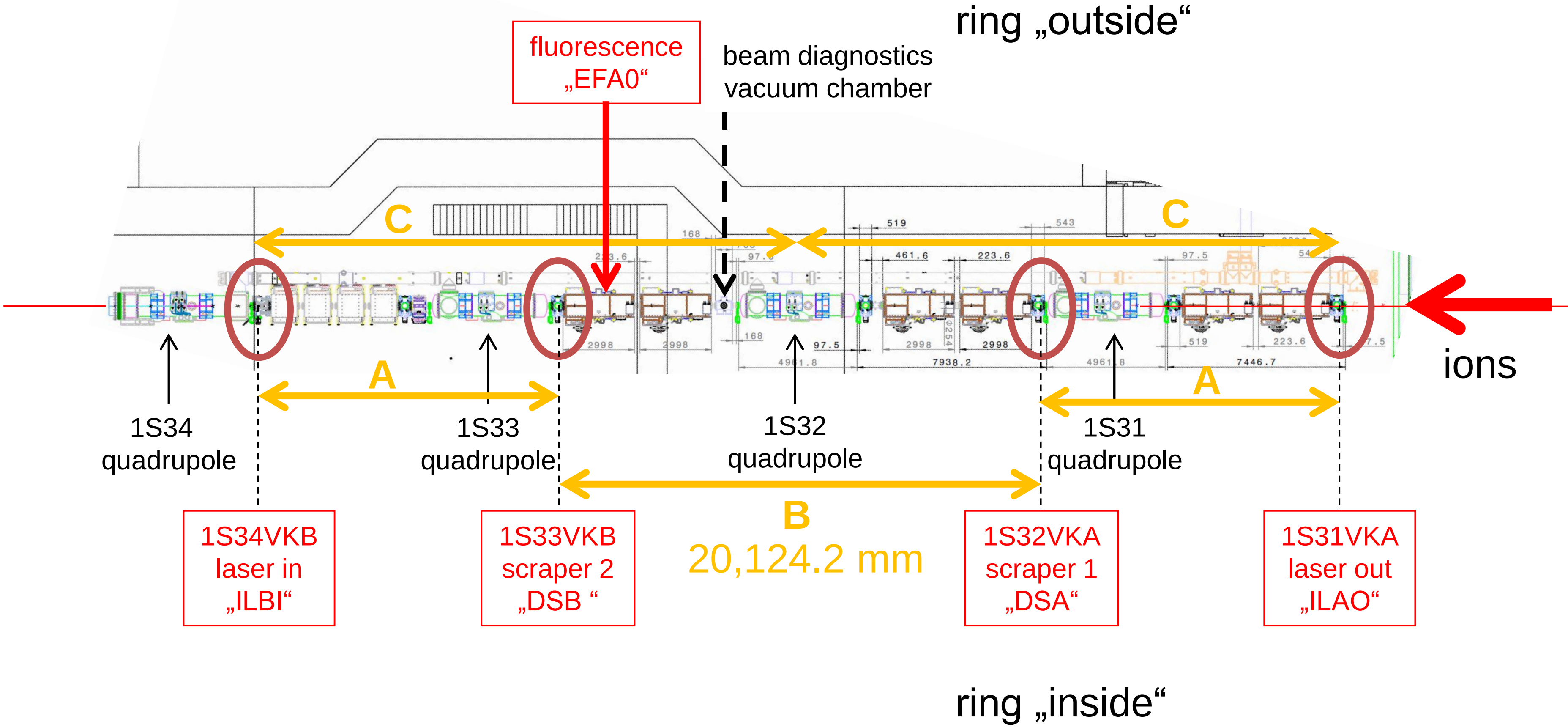
Linear accelerator
UNILAC
Ring accelerator
SIS18
Ring accelerator
SIS100
laser cooling area
(& laser spectroscopy)
Production of
new atomic nuclei
Production of
antiprotons
100 metres
Experimental and
storage ring
Existing facility
Planned facility
Experiments

SIS100 laser cooling pilot facility



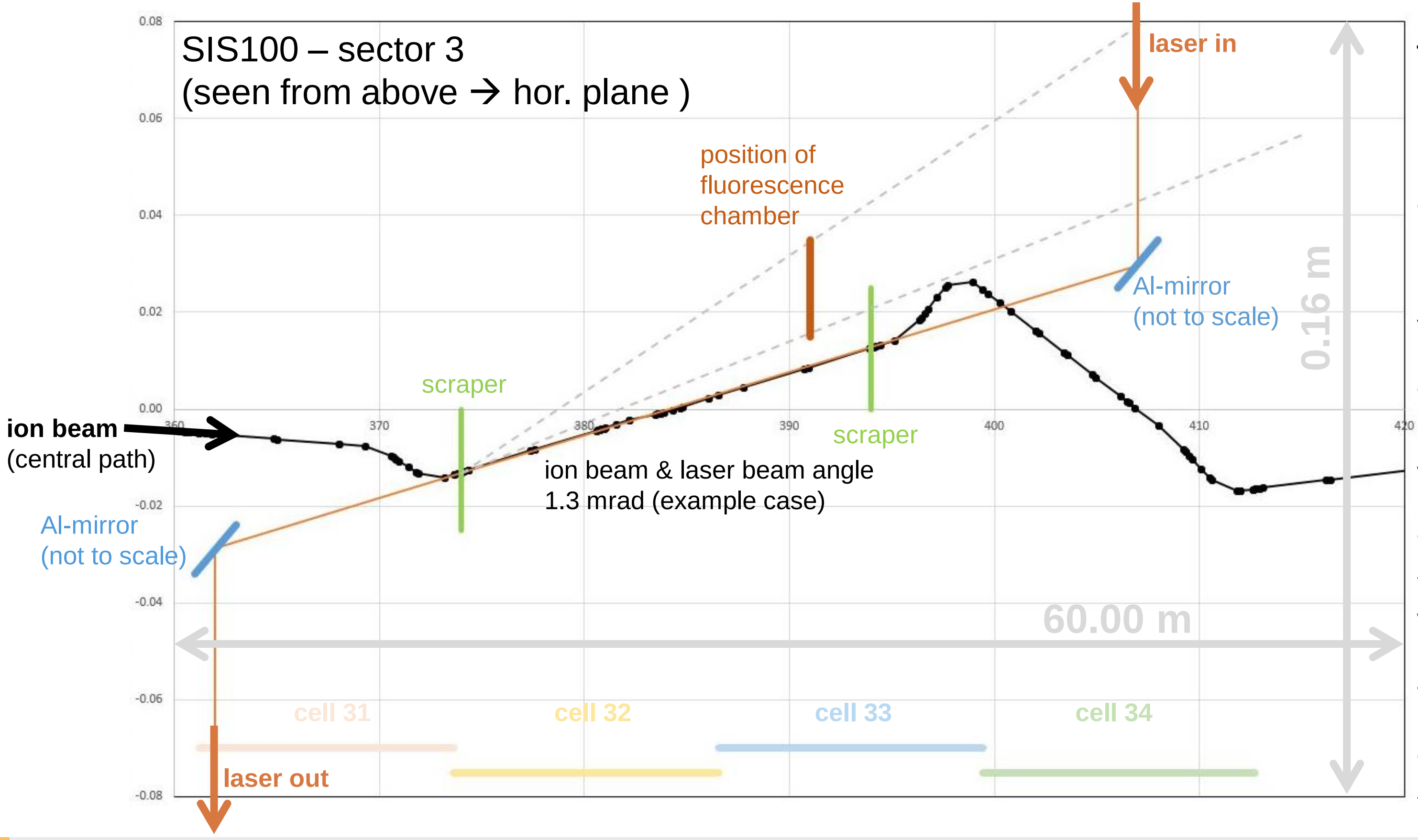
Picture: GSI Helmholtzzentrum für Schwerionenforschung, D. Fehrenz

SIS100 sector 3: scrapers , laser in & out, fluo chamber



spatial overlap ion & laser beams (slide added afterwards)

ion beam simulation by Youssef El Hayek (GSI)



Please note:

Different scales!
(horizontal & vertical)

The ion beam will make a very small (~2 mrad) angle to enable overlap with the laser beams.

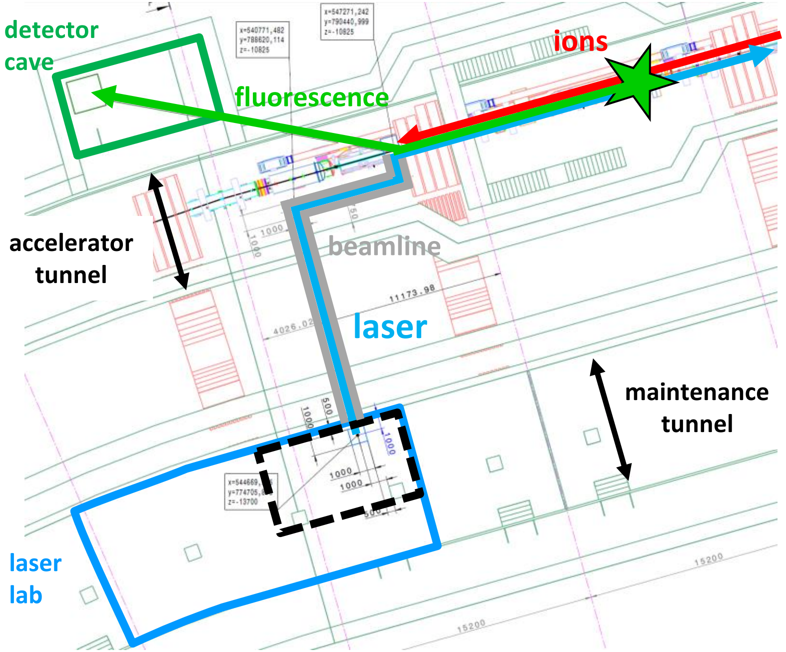
The Al-mirrors will move in from the outside and will not touch the ion beam.

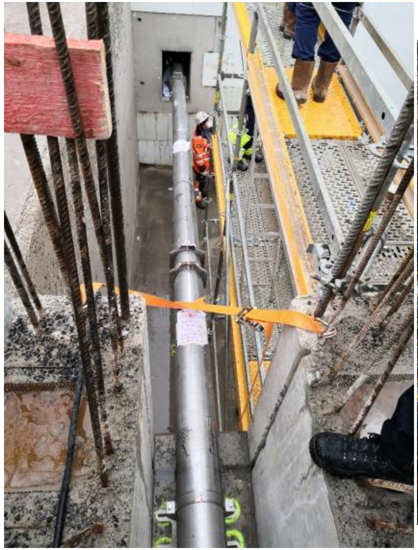
The components of the fluorescence chamber will also move in from the outside and will not touch the ion beam.

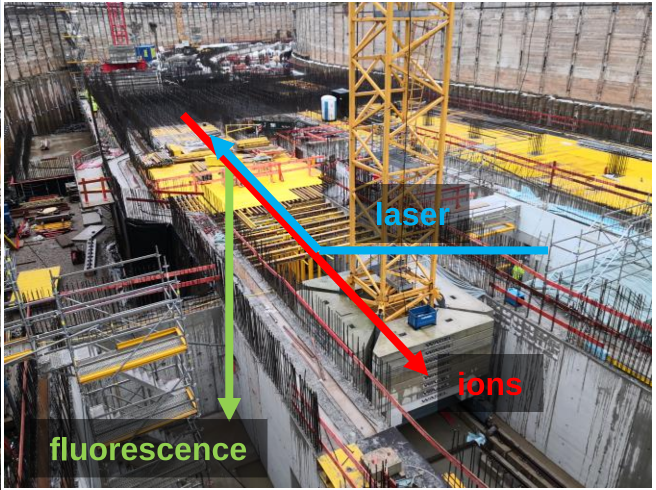
The two scrapers can move vertical and horizontal.

SIS100 laser beamline

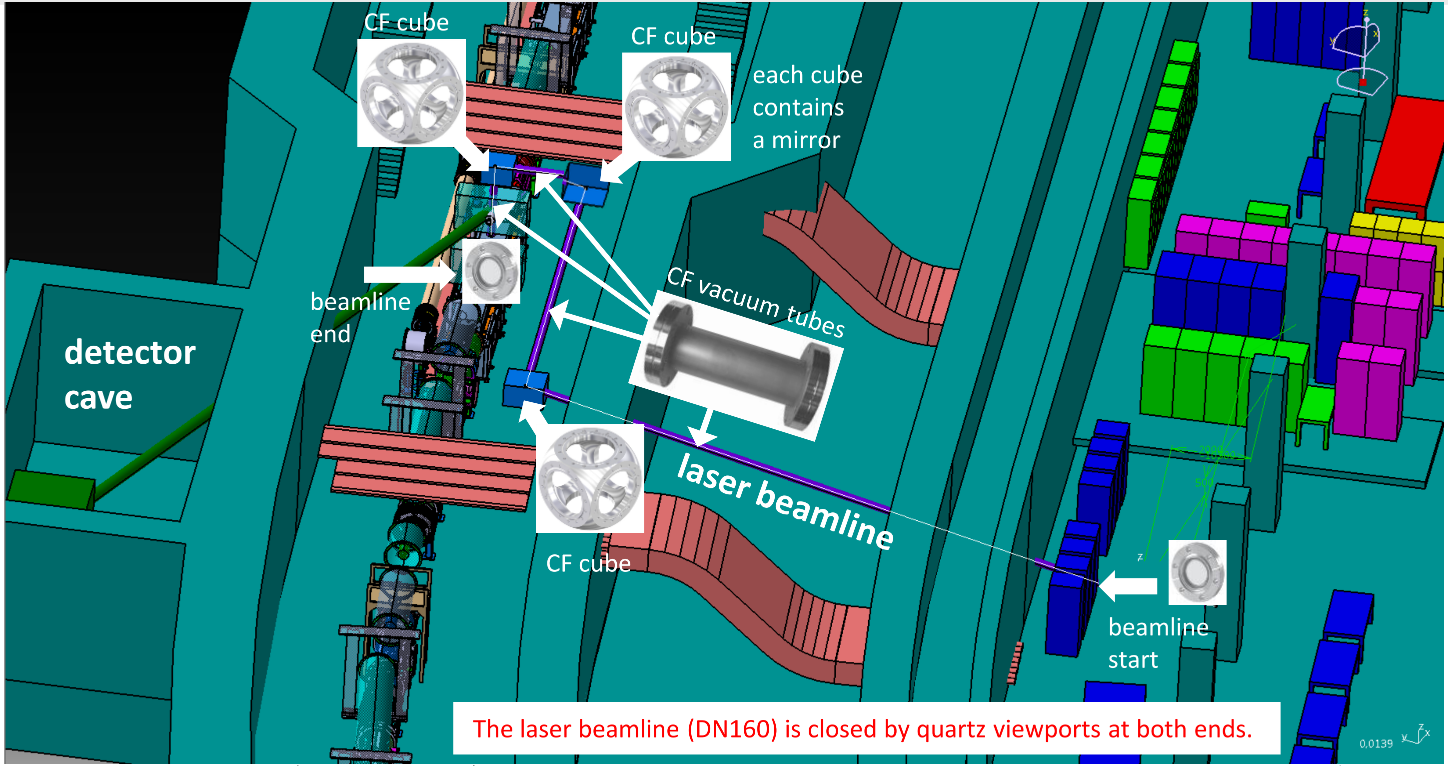
➢ first FAIR SIS100 experiment component installed







SIS100 laser beamline

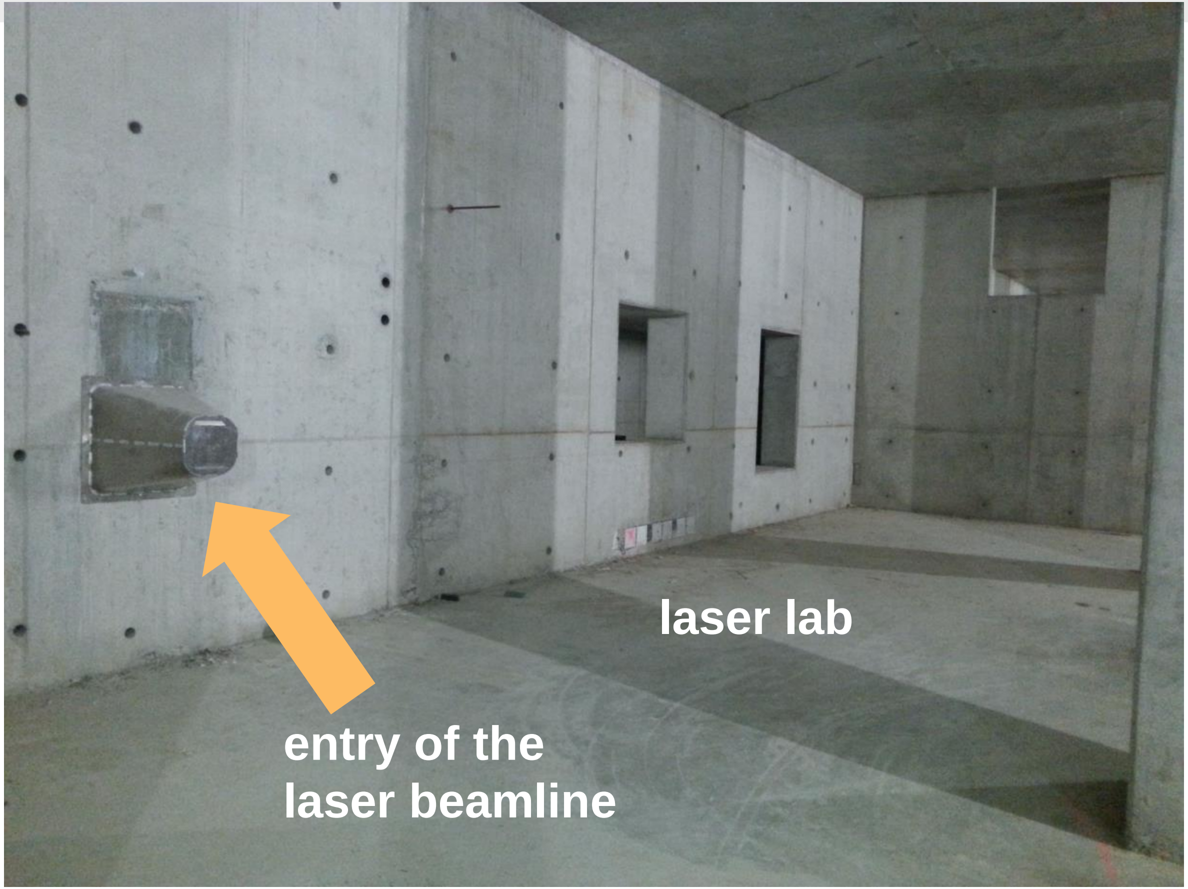


accelerator tunnel

maintenance tunnel

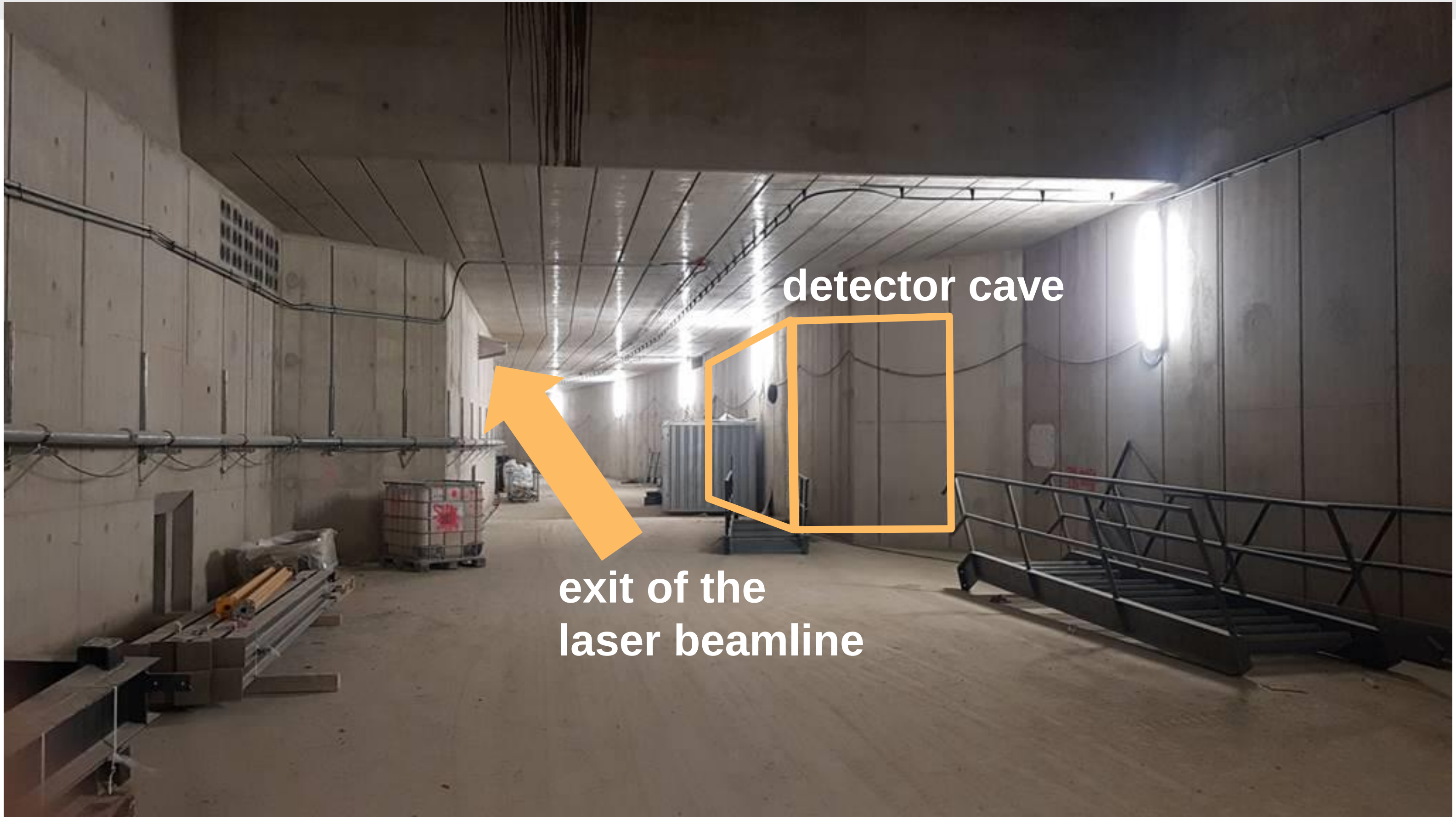
SIS100 maintenance tunnel

photo
2022



SIS100 accelerator tunnel

photo 2022



SIS100 accelerator tunnel

photo 2022

SIS100 accelerator tunnel

photo
2022

SIS100 accelerator tunnel

taken January 2023

Outlook

- Continue test measurements of components
  - Mirror box for SIS100 beamline, control systems, …

- SIS100 laser cooling infrastructure
  - Scrapers, UHV compatible laser mirrors (in/out), …

- Installation of components „*along the beamline*“ from 2024 onwards

- Work on data acquisition (Electronics, controls, cables, …)

- Dresden & Darmstadt groups have applied for funding (BMBF 2024 – 2027) to build the final laser systems (which will e.g. have more power)

`laser in´ chamber

Thank you for your attention!

detector cave