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STATUS OF BERLINPRO

FINAL COMMISSIONING PREPARATIONS

ERL 2024, 69th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

24/09/24,
KEK, つくば市

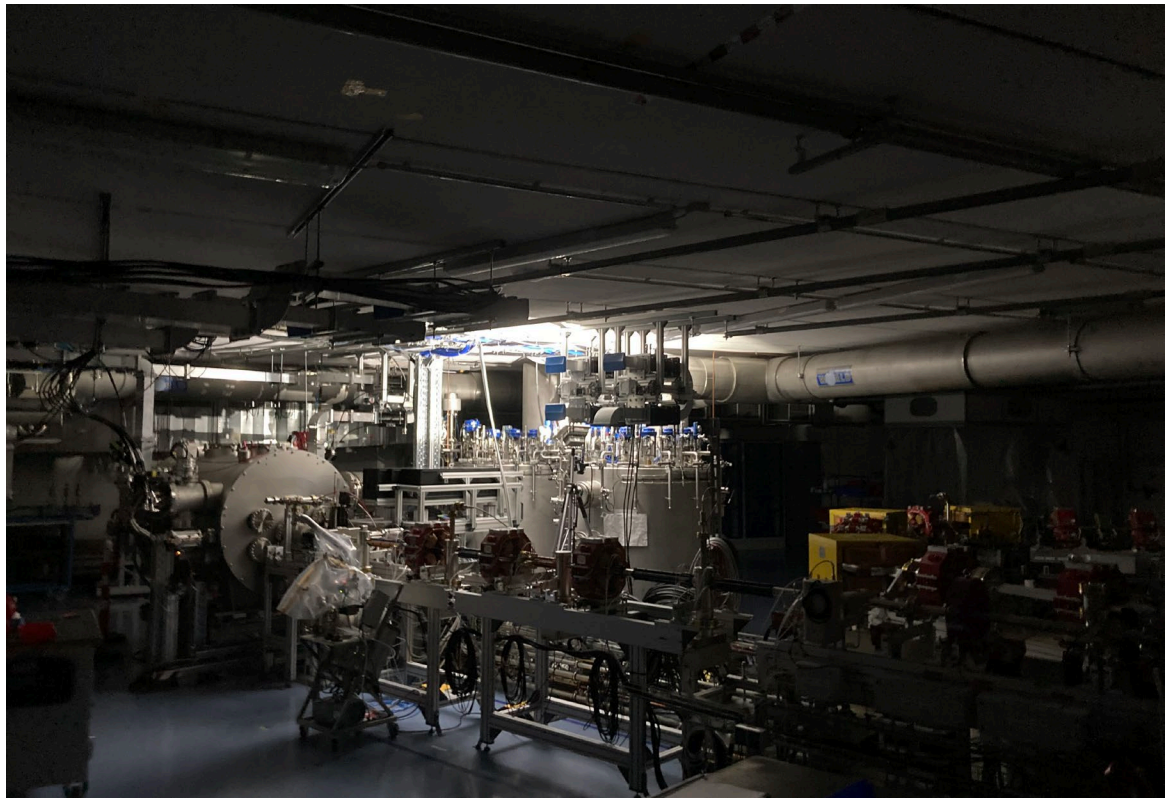
A. Neumann for the bERLinPro team @SEALAB

bERLinPro Beam Countdown

20d	21h	19m	52s

2024, AN EXITING AUTUMN AND WINTER ARE AHEAD OF US

- **Reminder: What was bERLinPro meant for and how far is it assembled and financed?**
- **Current status of the facility**
- **2024: Finally the year of first beam?**
  - Milestones:
    Final setup of the injector beamline
    First cooldown and RF tests
- **2024: Beam commissioning plan, a first insight**



The injector awakens

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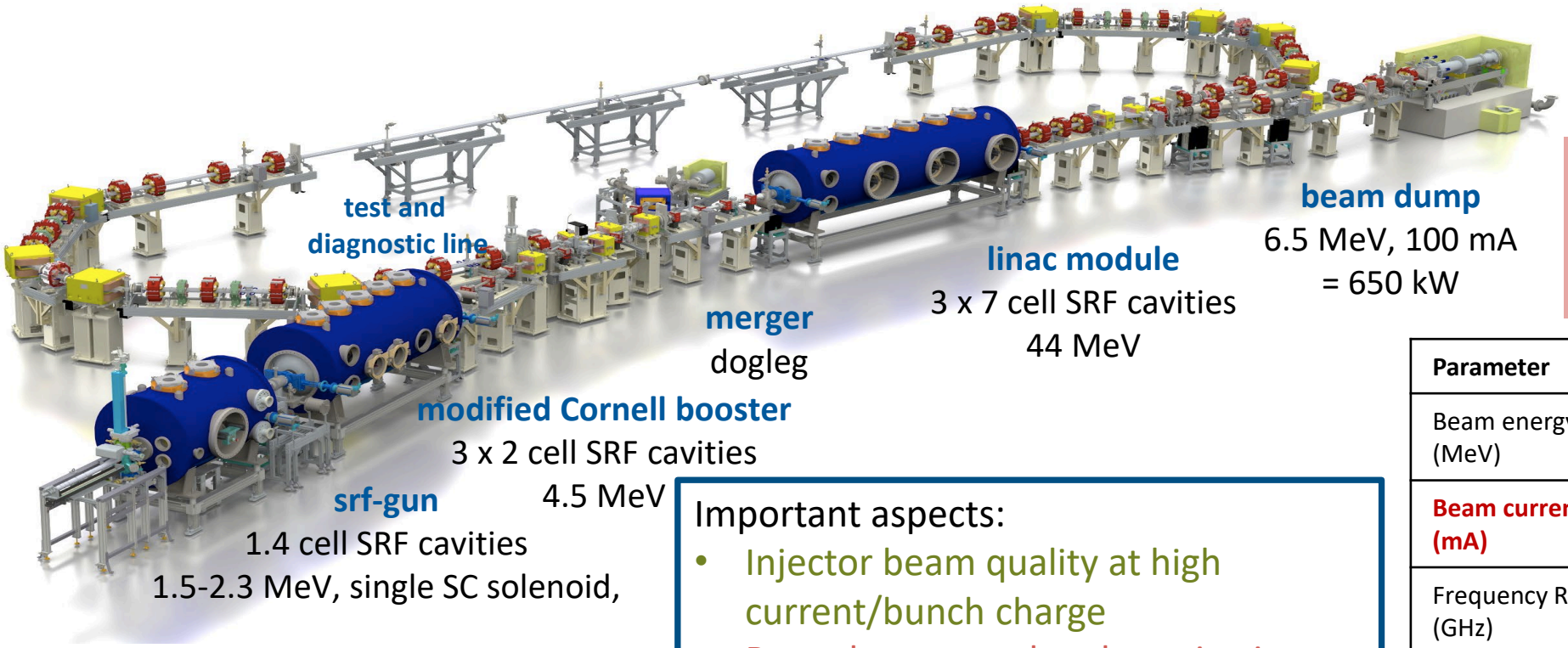
Evolution of bERLinPro

From 4th generation light source prototype (2011), via generic high intensity ERL prototype (2012-2020) towards *application driven* facility (today)



Single turn high intensity ERL
5 MW beam power
650 kW injector beam power

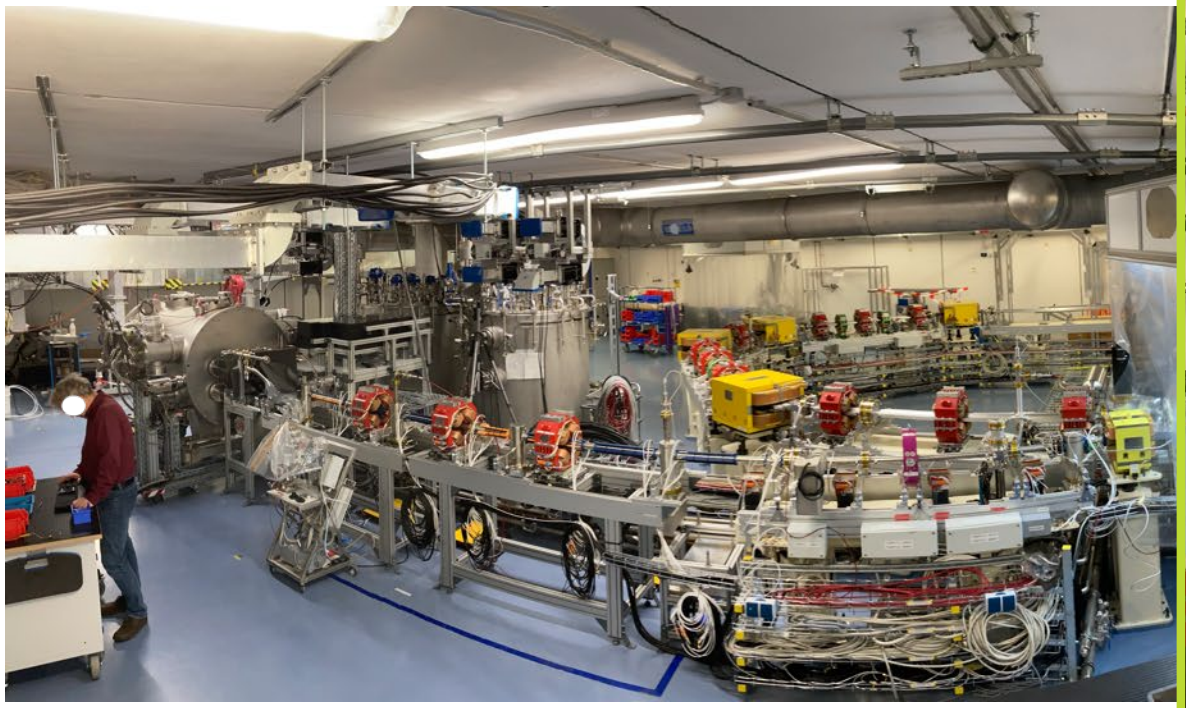
Important aspects:

- Injector beam quality at high current/bunch charge
- Beam loss control and monitoring
  → Radiation protection
- Beam break-up in main Linac
- Longitudinal control of beams for recovery process (low power margin)

Parameter	bERLinPro
Beam energy recirculator (MeV)	50
Beam current ERL mode (mA)	**100**
Frequency RF and Laser (GHz)	1.3
Normalized emittance (mm mrad)	**1 (< 0.6 in simulations)**
Bunch length (ps)	**< 2 (ERL mode), 100 fs @ 10 mA**
Beam losses	$<< 10^{-5}$ @ 100 mA

Stages at bERLinPro

Presently installed facility



- Installed: 10-mA SRF gun + merger + recirculation + dump
- Installed: Proof-of-principle UED experiment

} CW photoinjector studies < 10 mA
Long-pulse injector studies < 100 mA

- Funded: Booster module. Produced but assembly required

— High-power beam studies (“long pulse”)

- Not funded: LINAC module
- Not funded: 100-mA class photoinjector

} High-power energy recovery
Energy-efficient RF operation

Stages at bERLinPro

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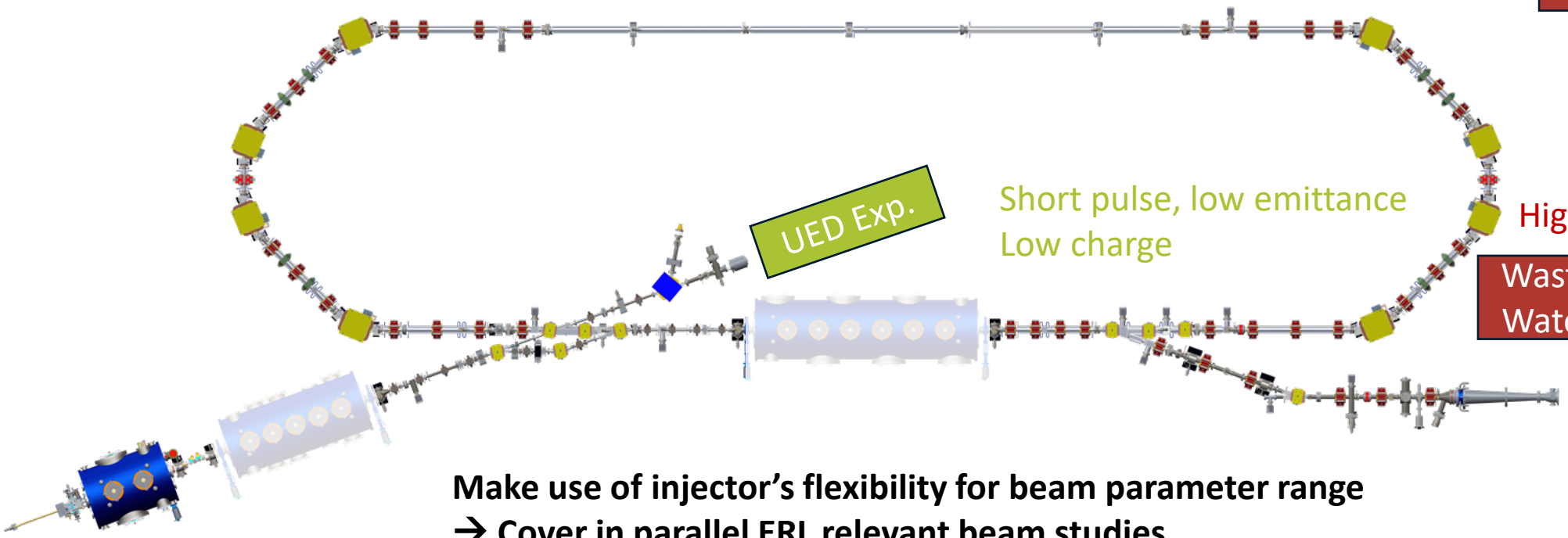
Presently installed facility

Applications



Make use of injector's flexibility for beam parameter range
→ Cover in parallel ERL relevant beam studies

- Installed: 10-mA SRF gun + merger + recirculation + dump
- Installed: Proof-of-principle UED experiment
- Planned: Waste water treatment demonstrator
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High-power beam studies ("long pulse")

High-power energy recovery
Energy-efficient RF operation

Stages at bERLinPro

Presently funded facility

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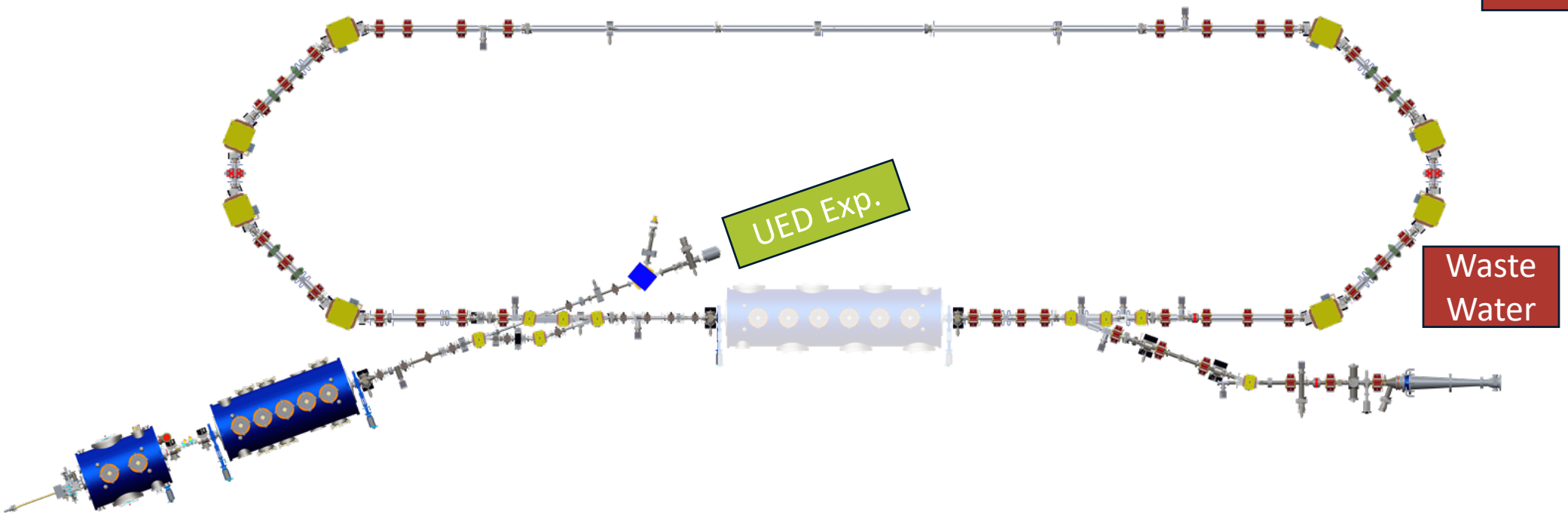

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Long-pulse injector studies < 100 mA

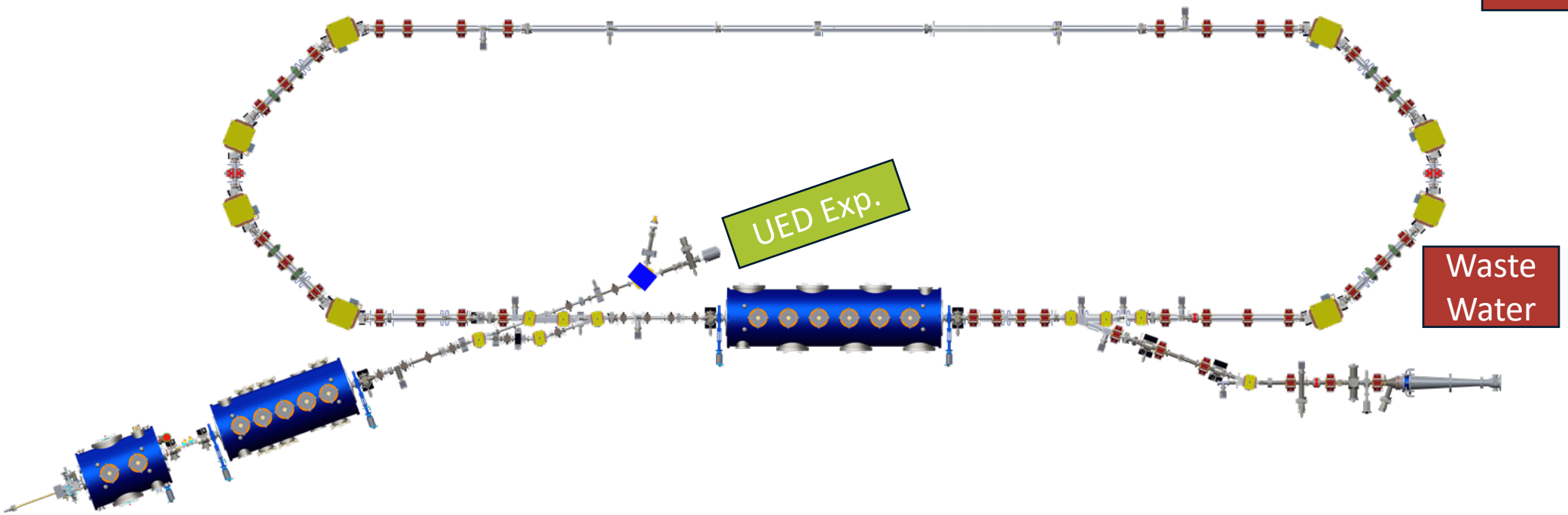
High-power beam studies (“long pulse”)

High-power energy recovery
Energy-efficient RF operation

Stages at bERLinPro

Full program (partially funded)

Applications



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High-power energy recovery
Energy-efficient RF operation

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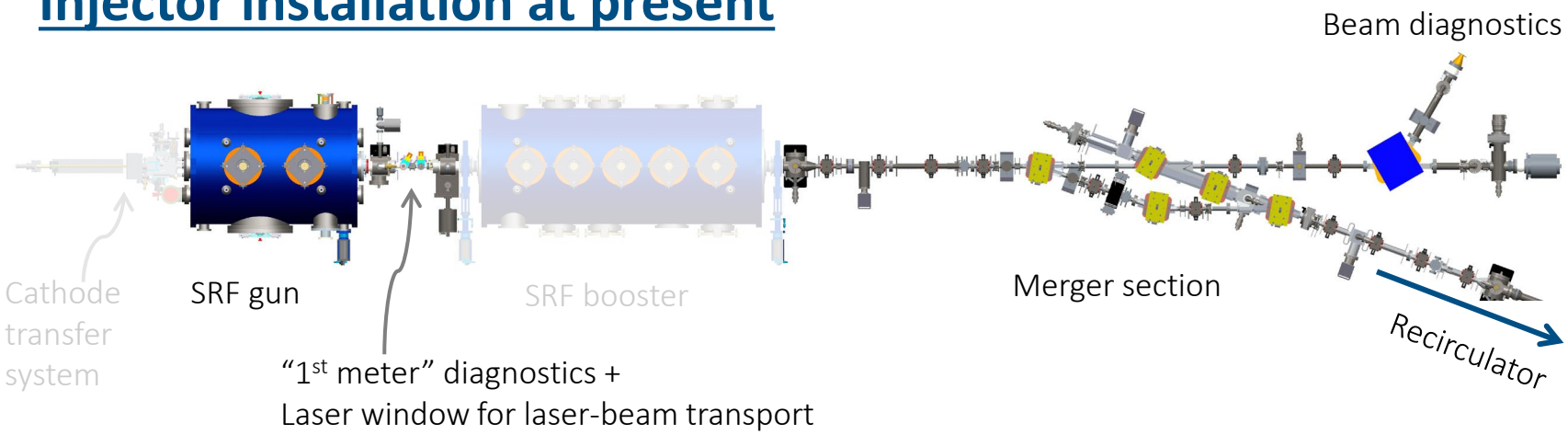
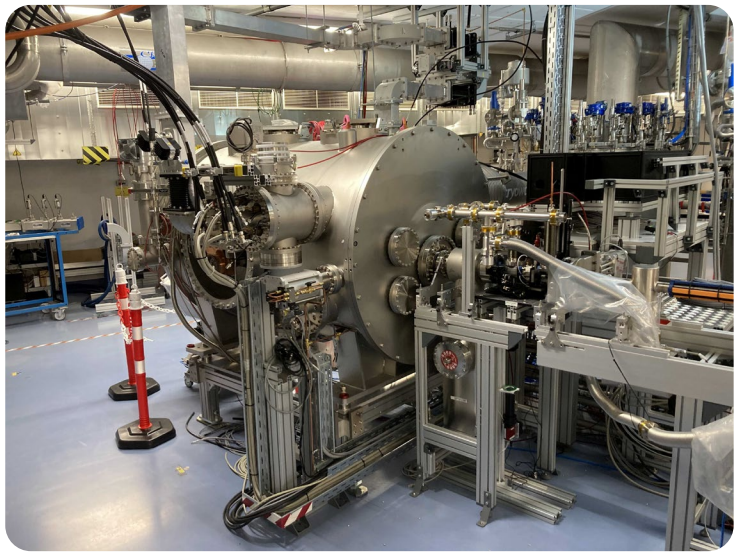
Status of bERLinPro@SEALAB

Injector installation at present





- SRF photo-injector and diagnostics ready for commissioning
- Cathode-laser beam transport tested, final alignment with cathode in cavity
- 1.3 GHz laser demonstrated 23 W CW → sufficient for 100 mA @ 2.5% QE
- **1st Cool-down in Jan. 2024** → successful
- **RF test of photoinjector Q2 2024** → Reached about 20 MV/m CW and 25 MV/m pulsed
- Cathode-transfer unit ready in final 120°C bake out these weeks
- **Beam operating permit expected Q3 2024 → First beam from SRF Gun around 10-11/2024**
- Start of Booster assembly H1/2024 (all parts in house)

Six+ month delay due to severe HZB cyber attack

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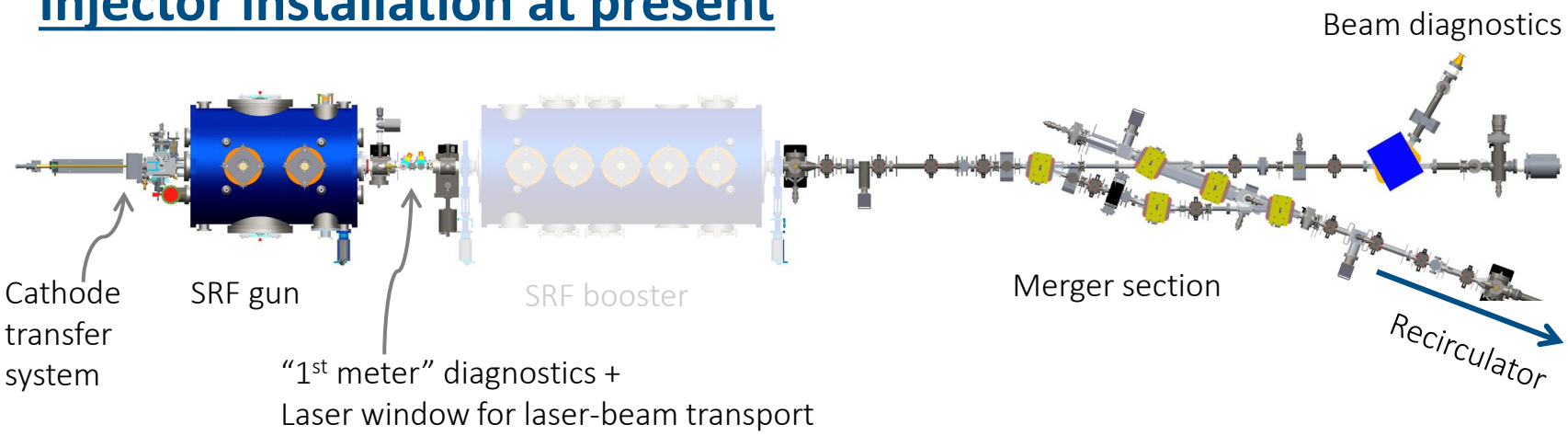

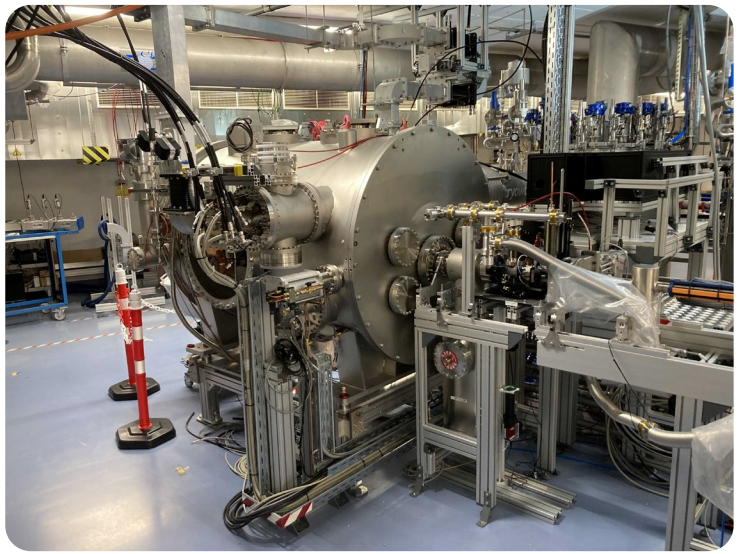

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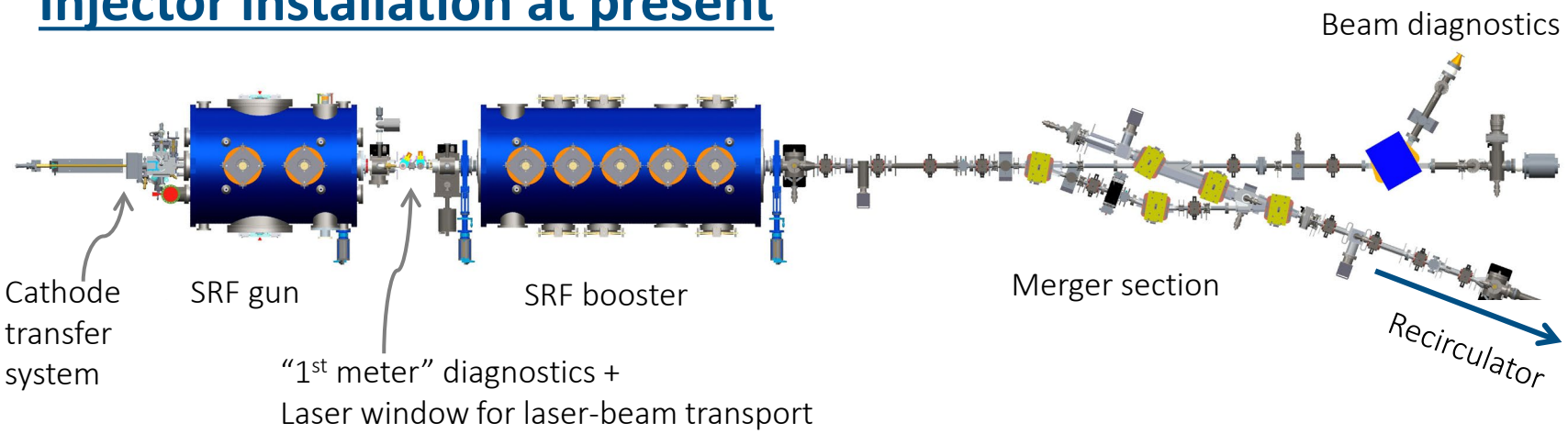

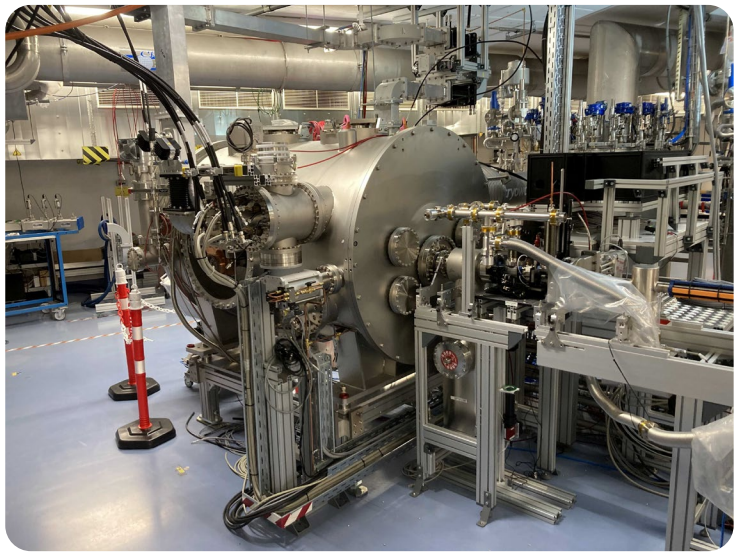

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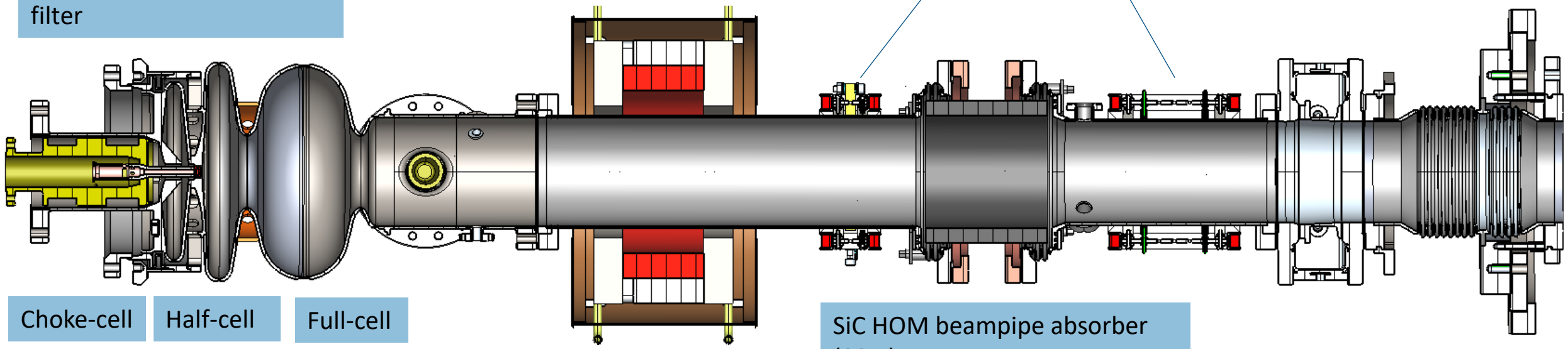
Reminder: The SRF Gun

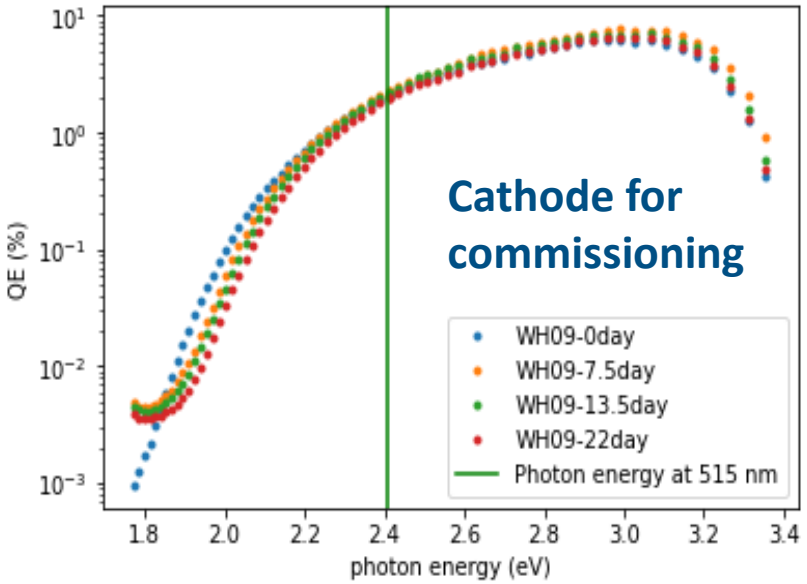


Cathodes: Na-K-Sb vs. Cs-K-Sb

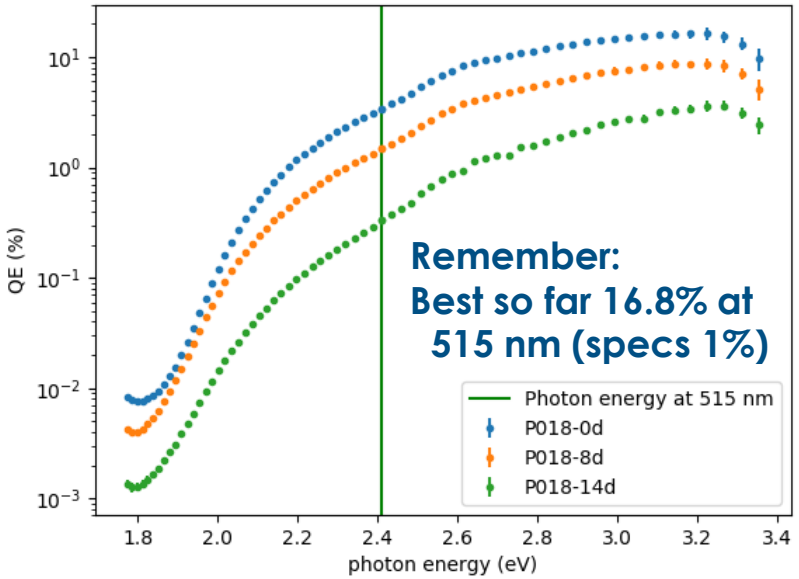
Investigations into Na-K-Sb as more temperature robust alternative to Cs-K-Sb (baseline cathode)

Photocathode Preparation & Analysis System

Sepctral Response Na-K-Sb (WH09)



Spectral response Cs-K-Sb (P18)



Time after deposition	Na-K-Sb (WH09) QE @ 515 nm	Cs-K-Sb (P18) QE @ 515 nm
0 days	2.0%	3.4 %
8 days	2.4%	1.5 %
14 days	2.2%	0.3 %
22 days	2.0%	-

Lifetime/Robustness

High QE photocathodes for SEALAB photoinjector: Explore multi-alkali Cs- and Na-K-Sb systems, from theoretical modeling (DFG fund), growth and characterization, towards operation in a SRF gun.

Complete infrastructure: growth and characterization system, UHV transport vessels, access to materials science lab EMIL at HZB, collaboration with theory.

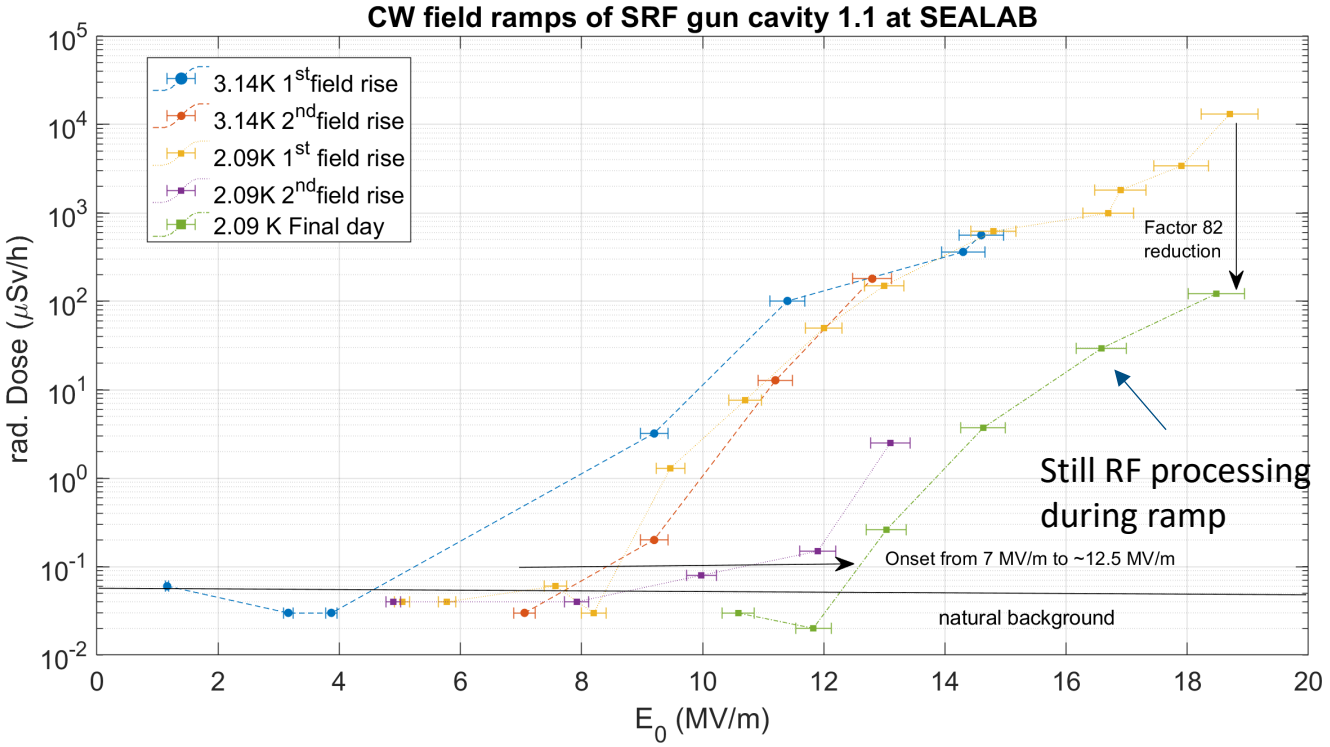
UNIVERSITÄT SIEGEN

DFG

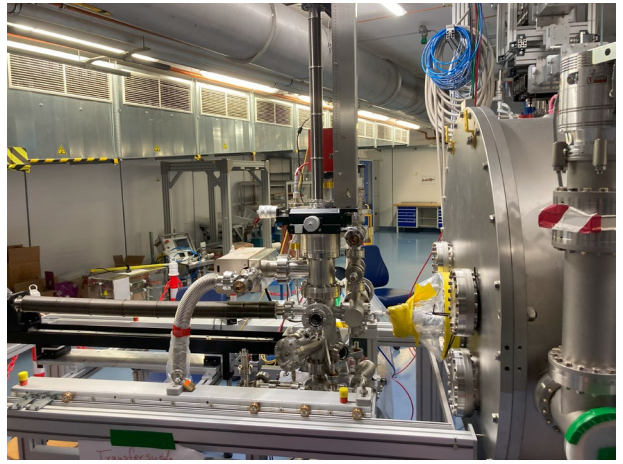
CARL VON OSSIETZKY UNIVERSITÄT OLDENBURG

J. Kühn, S. Mistry, C. Wang, J. Dube, C. Cocchi, R. Schier, H. Sassnick, et al.

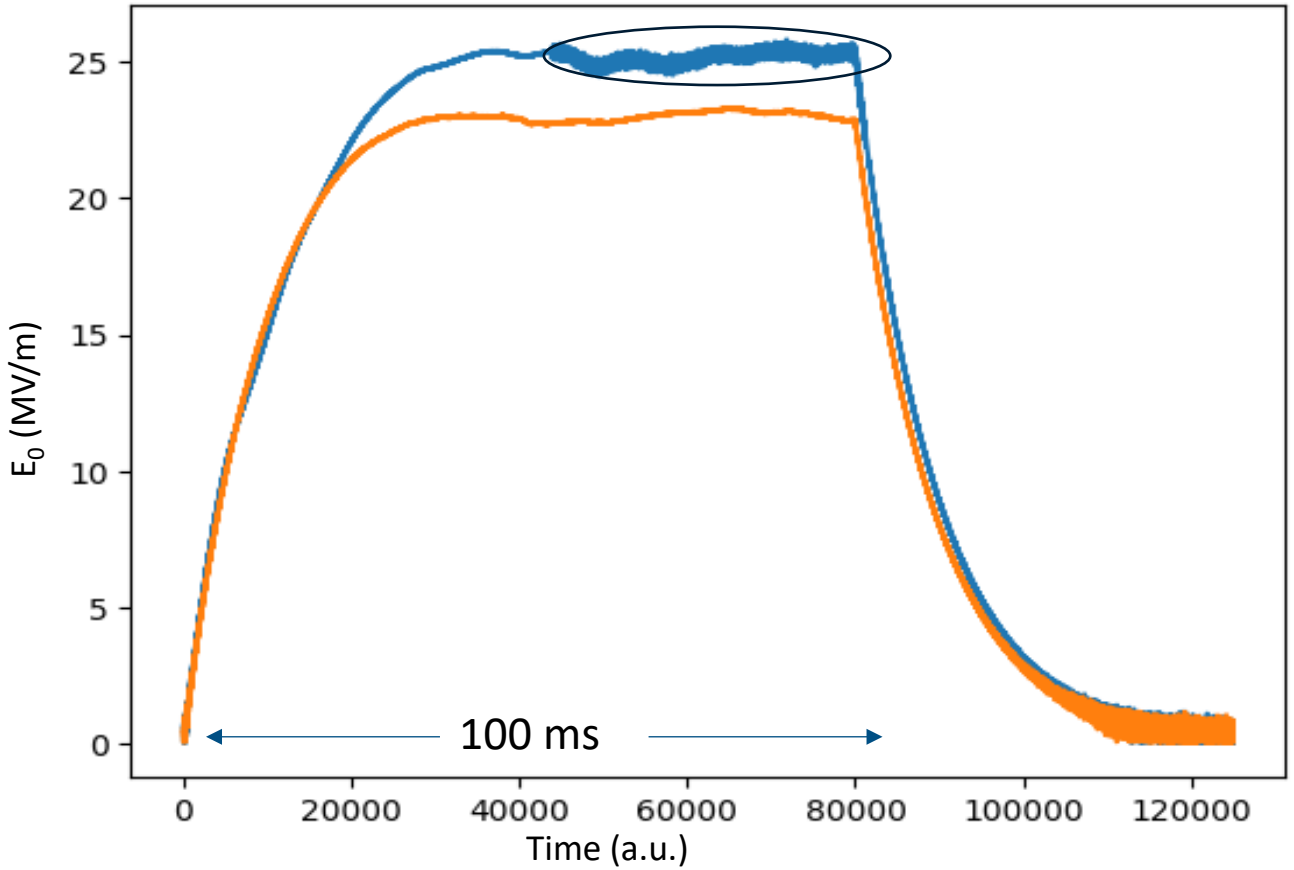
1st RF test at bERLinPro



- Successful RF test, beam energies up to 2.1 MeV → there is room for progress
- Field emission was present, but continuously being processed by RF
- Laser system, diagnostics, beam transport optics, beam loss monitoring (several systems) installed and ready
- Cathode transfer system in final bake out



Pulsed processing: Examples



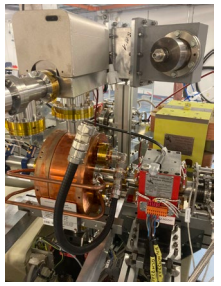
- RF processing at 1 Hz repetition rate
- Pulse length 30 and 100 ms
- Processing event at 14:35, 14th of May: Vacuum in 1st meter 2e-8 mbar
  → Above threshold for closing gate valve in module, no alarm handler
  → Processing continued not noticing this event
  → Explains also absence of any dark current measurement by Faraday Cup
- After event higher level pulsing showed this ripple effect, stopped and took last CW curve
- Reached: CW 20 MV/m, 25 MV/m pulsed

→ Beam energies between 1.7 to 2.1 MeV in reach

The Commissioning Setup

Capacitive sensors (cathode position)
HV DC bias
Cathode current

Faraday Cup
FOM
Stripline BPM



ToF?

Faraday Cup
FOM

TCAV

FOM

Q1

Q2

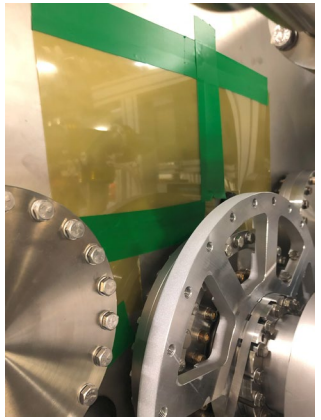
Spectrometer

FOM
BPM
F-Cup

2 cold steerer

Booster replacement quads

Quads with steerers
BPM-ICT-BPM



Gafchromic RTQA2
on Gun cryostat

Laser diagnostics:
Average Power
spot size and position on cathode

Pulse length
Pulse pattern

Beam loss monitors:

- PIN diode based systems
- Szintillator + PMT
- Dedicated LaBr Szintillator + PMT for energy spectrum of dark current

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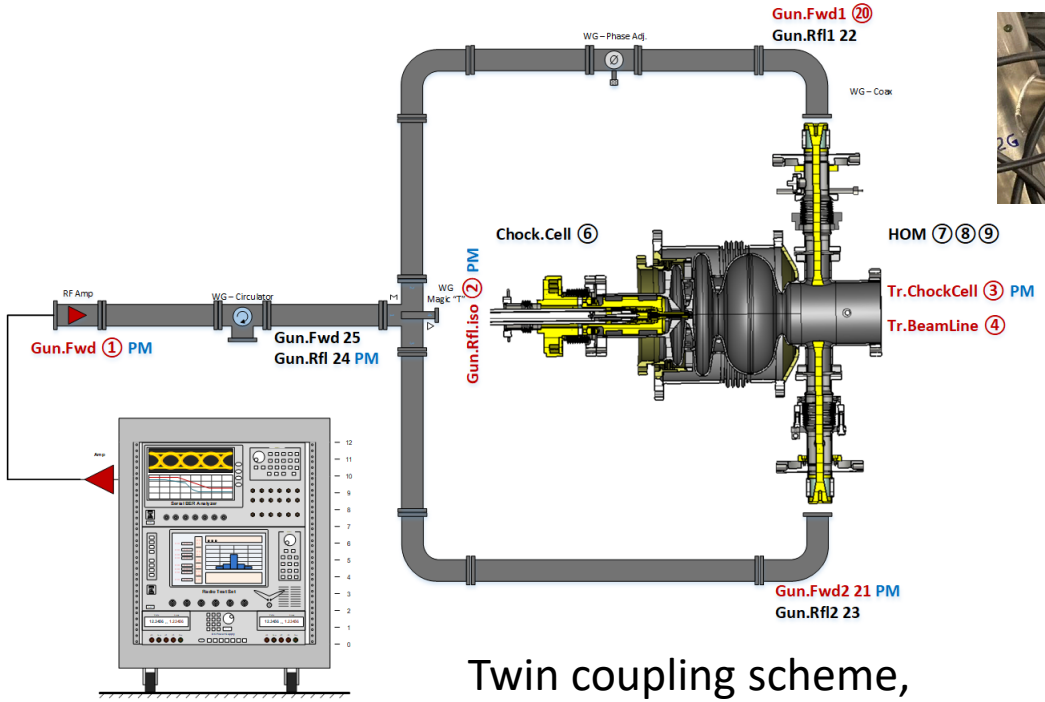
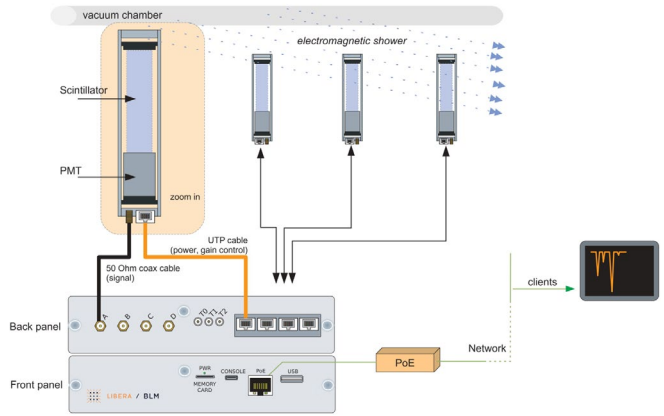
First Commissioning steps

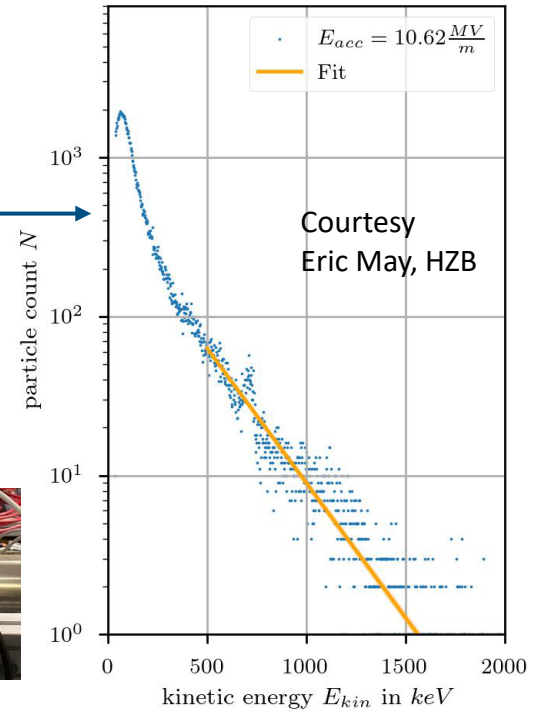
- 2nd RF test w/o cathode:
  - Demonstrate achievable field level with final installations of all beam vacuum systems
  - Measure dark current: Level, on-set field, energy range, determine source
    → Test beam loss monitoring system (PIN diodes, PMT based systems, Radiation sensitive films, Faraday Cup, foil monitor)
  - Determine field stability: Setup LLRF control system, twin coupler operation
    → Measure SRF cavity parameter for control: LF detuning, microphonics…



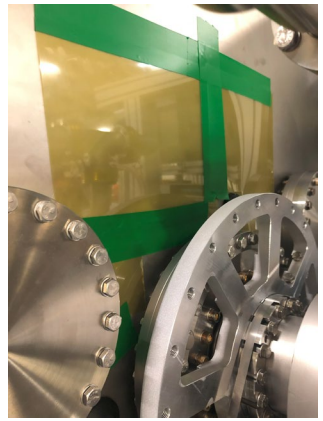
Twin coupling scheme,
Pic courtesy A. Ushakov, HZB



https://www.i-tech.si/products/libera-blm/



Courtesy
Eric May, HZB

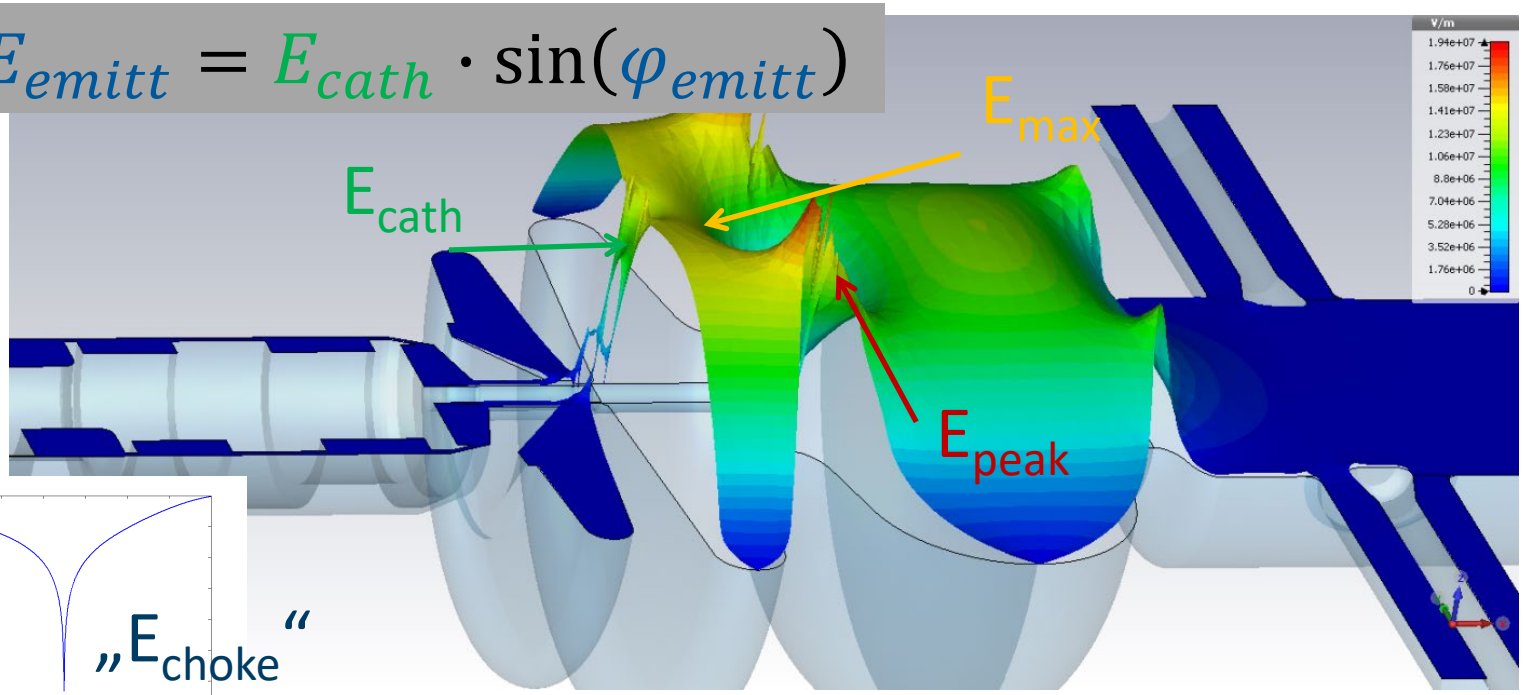


Gafchromic RTQA2
on Gun cryostat

First Commissioning steps

- 2nd RF test **with cathode**:
  - Demonstrate achievable field level with uncoated cathode → Measure position of cathode w.r.t. backwall: Impact on dark current, beam focusing, emission phase → Longitudinal and transverse beam dynamics……..training of cathode transfer into SRF gun
  - Measure dark current: Level, on-set field, energy range, determine source
    → How to handle co-propagating dark current, how to separate further down-stream?
  - Determine impact on cathode inserted on RF heating of cathode → adjust position
    Multipacting observed? DC bias as countermeasure → Impacts low field beam dynamics
  - Measure eventually microphonics by cathode insert

$$E_{emitt} = E_{cath} \cdot \sin(\varphi_{emitt})$$



- E_{emitt}: Beam emittance
- E_{max}: Beam energy
- E_{cath}: Beam emittance and level of dark current, eventually multipacting

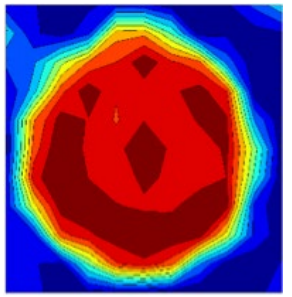
→ High current ERL issue:

Balance Beam quality vs. dark current

Beam losses all within power limit by high power operation

First Commissioning steps

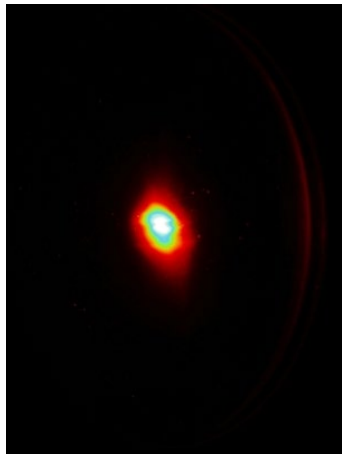
- **Cathode operation**:
  - Characterisation of cathode: Measure first beam, cathode quantum efficiency, QE maps
    → Cathode lifetime QE(t)
  - Determine zero phase ←→ on-crest phase, field calibration check
  - Measure dark current: Level, on-set field, energy range, determine source
    → How to handle co-propagating dark current, how to separate further down-stream?



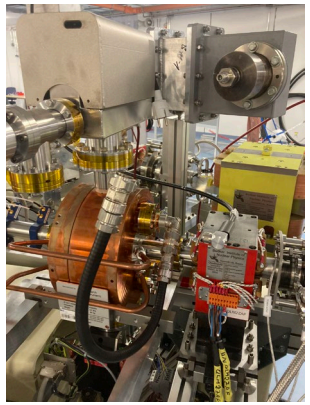
J. Kühn et al., IPAC 18
Cu cathode QE map

  - Measure multi-parameter beam phase space:
    - Beam based alignment of machine (Solenoid, steerer)
      Beam emittance vs. field level, emission phase, cathode position, pulse length, etc…
    - Longitudinal beam phase space: Bunch length studies, short beam studies (TCav)

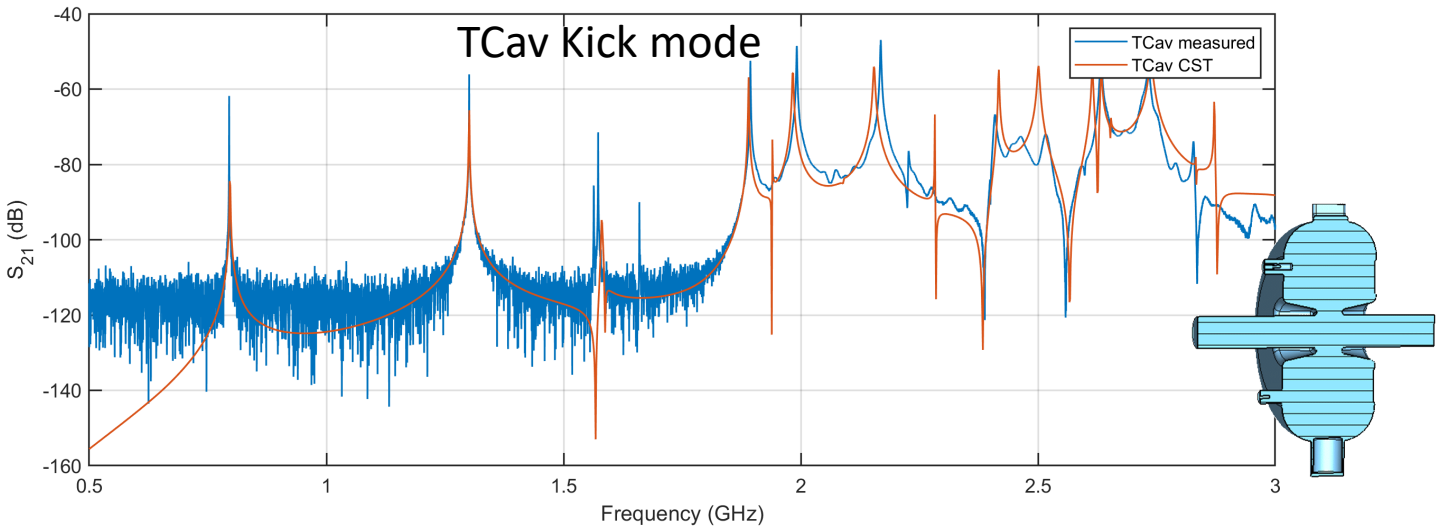
  - Impact of field stability on beam parameter: Jitter studies, beam based feedback



A. Neumann et al., IPAC 11
First beam from fully SRF gun with lead cathode

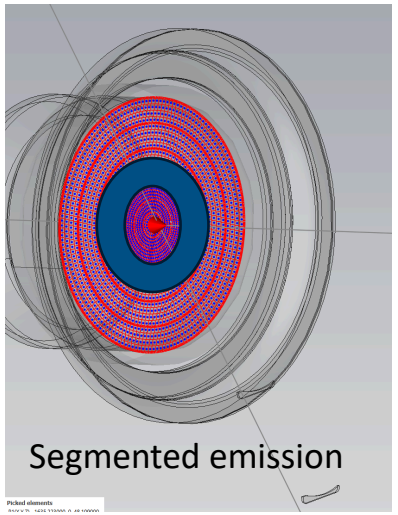


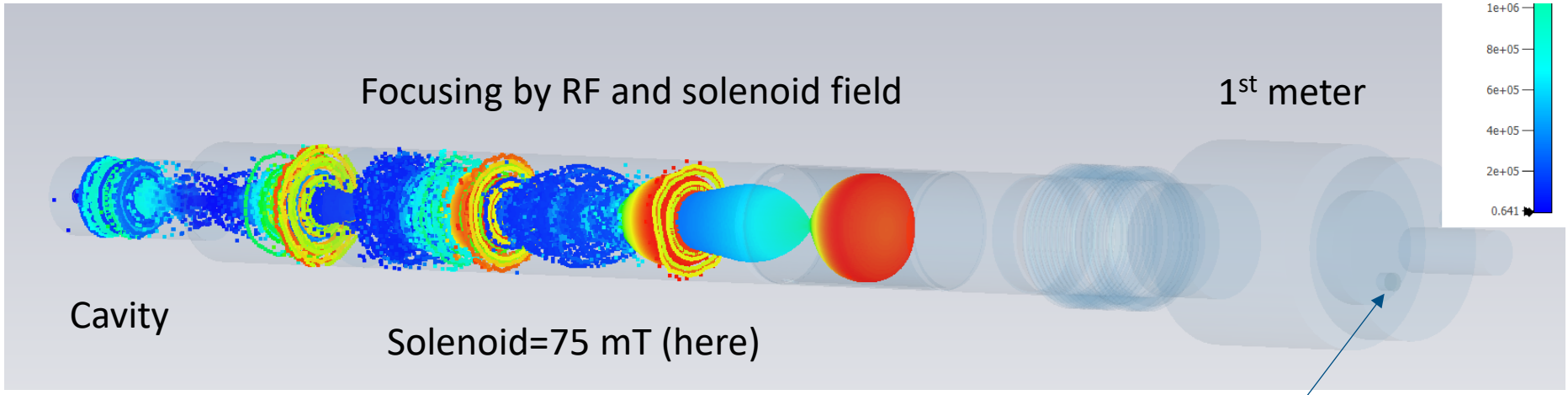
Tcav: see Linac 18
G. Kourkafas et al.



Field emission by cathode on laser windows

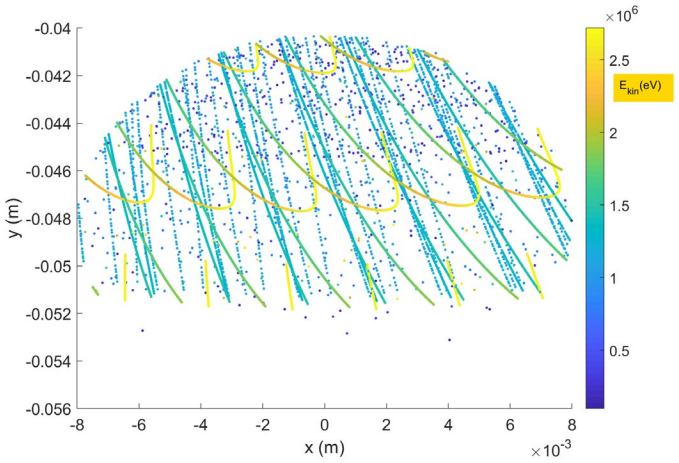
Some parameters: E_0=20 MV/m, elevated field in half cell, Solenoid off, 37 mT, 75 mT

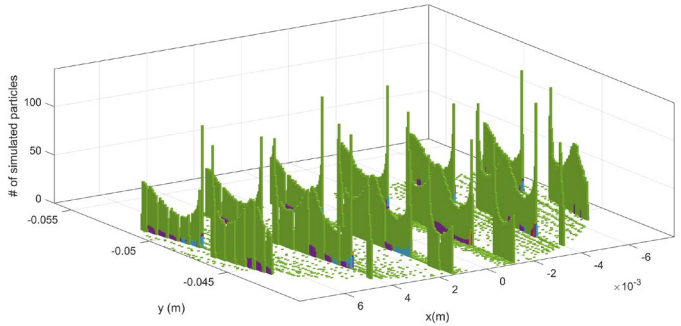




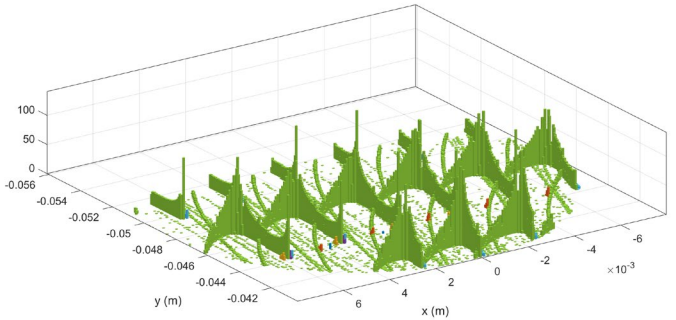
Fowler-Nordheim field emission model

Laser window





Solenoid off



Solenoid 37 mT

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bERLinPro@SEALAB injector studies

Parameter	Injector / UED	ERL
Beam energy (MeV)	6.5 – 10 / 2	50
Max. average current (mA)	10 / 0.0025	100
Bunch charge (pC)	0.05 – 400	77
RF Frequency (MHz)	1300	1300
Norm. Emittance (mm mrad)	0.6 / 0.03	1 (0.6)
RMS bunch length (ps)	0.02 – 2	2 (0.1)

Funded: SRF gun/booster ops & UED mode

Not funded: 100-mA CW gun cavity + couplers + LINAC module (existing design)

Medium-power gun (20kW) / booster program

- Explore full parameter space of SRF injector @ I_b < 10 mA
- 100 mA can be potentially studied in long-pulse* regime
- Bunch charge up to 0.5 nC with a high QE cathode
- Proof of cathode exchange concept, test of more robust cathode materials: Replace Cs by Na
- Studies of beam loss scenarios by dark current or beam halo formation by bunch tails
- Propagation of beam and unwanted beam from injector to dump
- Beam loss monitoring and machine protection concepts
- High dynamic range diagnostic concepts for low-current start-up to high-power operation (< µA → mA → 100 mA*)
- Beam arrival time and jitter studies
- Digital twins, ML+AI assisted control methods

A coarse 2024 schedule

RF operation permit ✓

Cooldown 2K ✓ — RF test 2K ✓ — Dry run injector ✓

January | February | March | April | May | June

- Setup Laser
- Setup transfer system
- Check for beam condition: FOMS, magnets,…

- LLRF ready ✓
- High power RF ready ✓
- Cryo ready ✓
- Module diagnostics ✓
- PSI operational ✓
- TCav ready ✓

- Readiness cathode transfer system, cathode laser
- Beamline magnets, steerer magnets
- Diagnostics: FOMs, Faraday Cups Camera tools, beam loss monitoring
- Control system fully implemented for needed devices, MPS functional

Final fixes, tests and repairs ✓

Beam operation permit

Beam operation injector

July | August | September | October | November | December

HZB Helmholtz Zentrum Berlin

ありがとう

If there is time left, questions are welcome or contact me at

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Please checks Emily‘s, Nick‘s and Thorsten‘s talks for more about bERLinPro related topics, visit Andriy‘s poster as well!

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