SEALAB/
bERLinPro

HZB Helmholtz
Zentrum Berlin

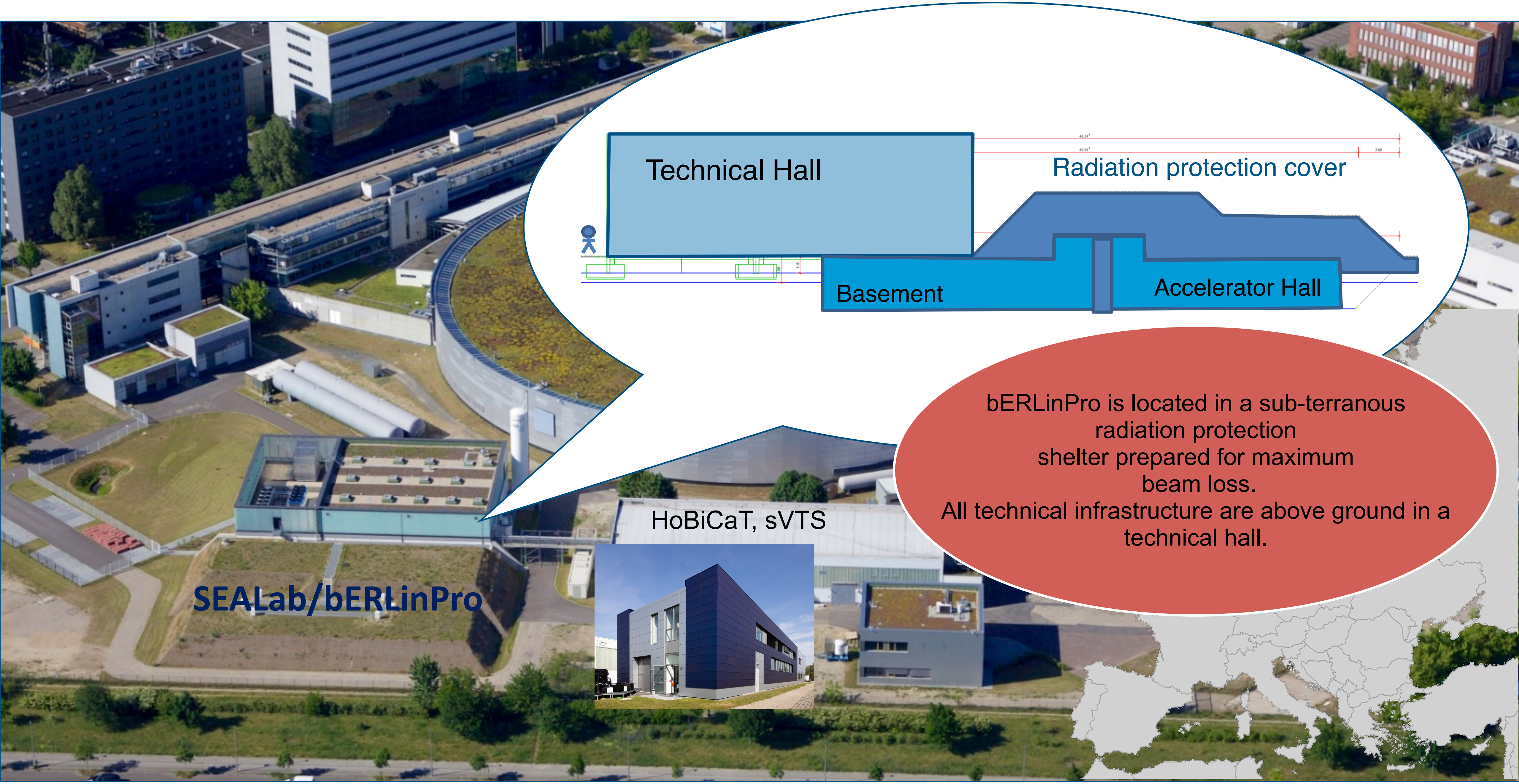
OVERVIEW, STATUS AND APPLICATIONS OF SEALAB(BERLINPRO)

27/06/24, Ezgi Ergenlik for the Sealab/bERLinPro Team

OUTLINE

What is ERL?
What is bERLinPro?
bERLinPro SRF
Beam vacuum system, magnets, cold boxes
Laser Modes and Infrastructure
Photocathode Lab.
bERLinPro to Sealab
Initial Commissioning And Further Applications
Stages of Sealab
First RF Tests
Schedule for 2024

bERLinPro in Berlin Adlershof



bERLinPro is located in a sub-terranous
radiation protection
shelter prepared for maximum
beam loss.
All technical infrastructure are above ground in a
technical hall.

Why bERLinPro, why ERLs?

From next generation Lightsource to many applications, e.g. HEP

Next generation multi-user light source
(e.g XFEL oscillators, multi-ID facility as former ARC-en-ciel or 4GLS)

Compact radiation sources, nuclear physics
(FEL, inverse Compton sources, next generation lithography, THz facility, MESA, Triumf)

ERLs allow efficient operation at high average brightness/luminosity with Linac class beam quality

High energy, high luminosity e^+e^- collider
(Two ERL based ring collider with larger luminosity than FCCee or ILC
proposal: Physics Letters B 804 (2020)

Ultra high luminosity electron – ion collider (EIC, LHeC)
(ERL serving as high intensity electron factory for electron
hadron collisions at

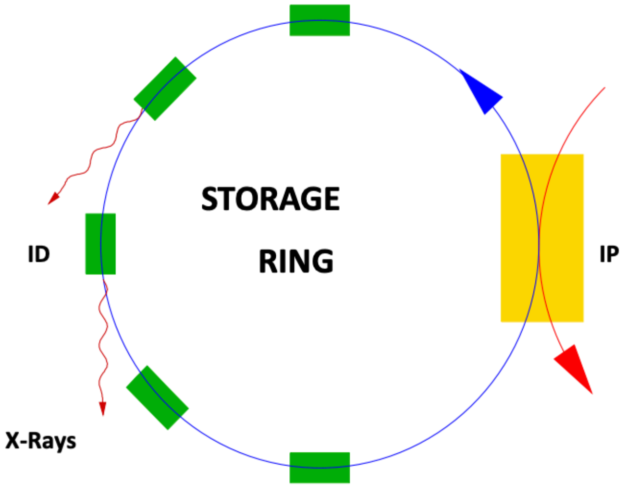
Reduces ecological footprint of large-scale science, especially when combining with higher SRF technology, vision of sustainable large-scale science driver

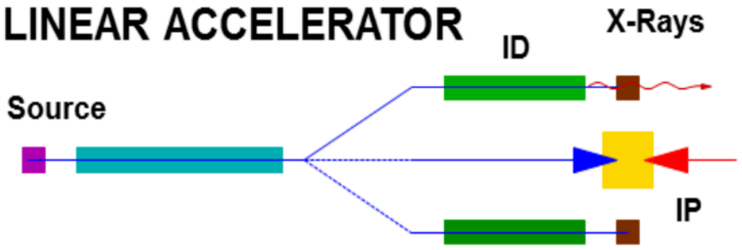
Ultra fast electron diffraction(by injector)

Waste Water Cleaning

More info:Scientific opportunies for bERLinPro 2020+, T.Kamps et all.(https://arxiv.org/abs/1910.00881)

What is ERL?

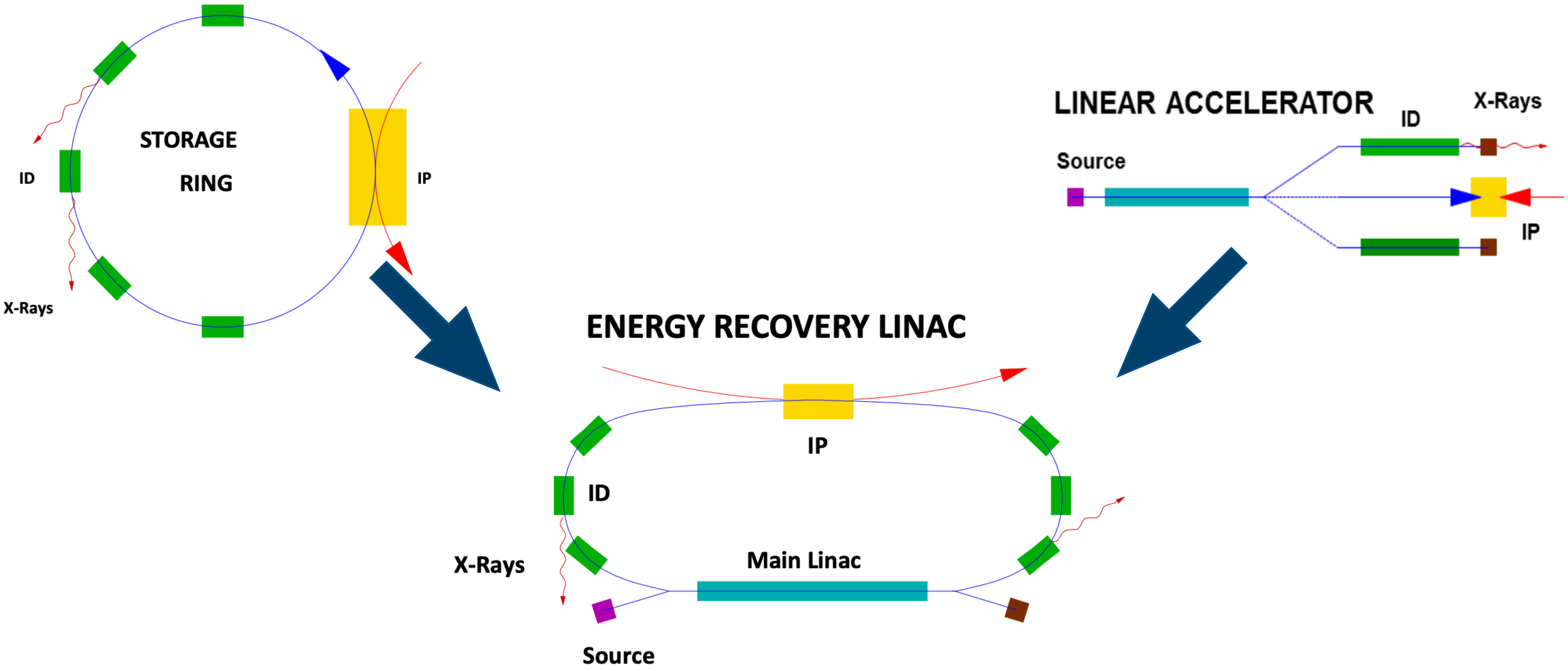




- Beam parameters defined by equilibrium
- Many user stations
- Limited flexibility – multi-pass
- High average beam power (A, few GeV)
- Typically long bunches (20 ps – 200 ps)
- Bigger areas

- Beam parameters defined by source
- Low number of user stations
- High flexibility – single-pass
- Low average beam power (<<mA)
- Achievable short bunches (sub ps)
- Comparable small areas

What is ERL?

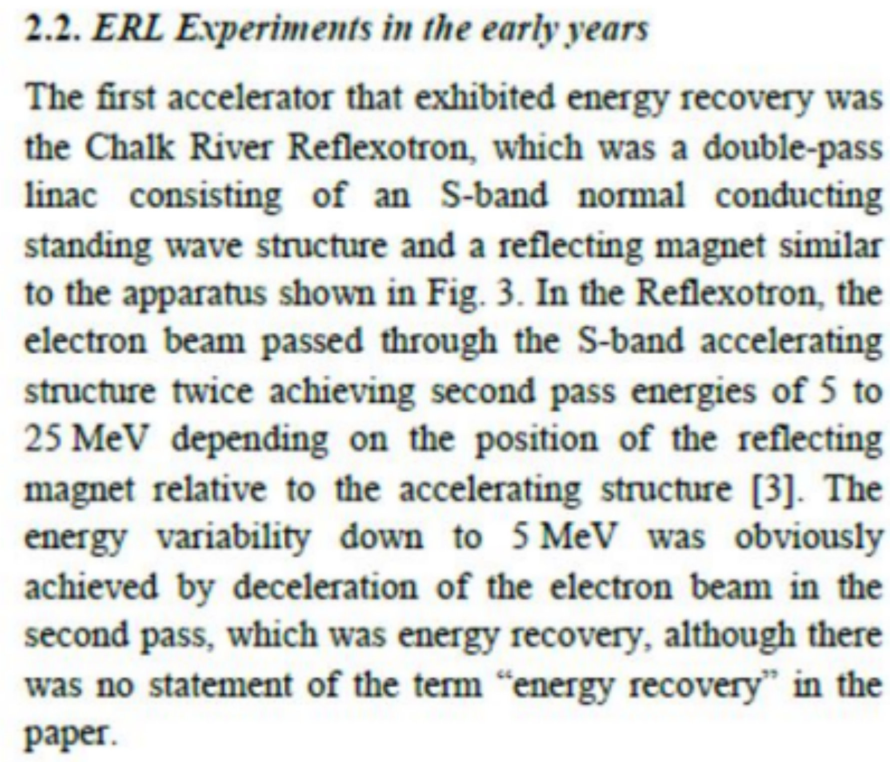


High average beam power (multi GeV @ some 100 mA) for single pass experiments, excellent beam parameters, high flexibility, multi user facility

What is ERL?

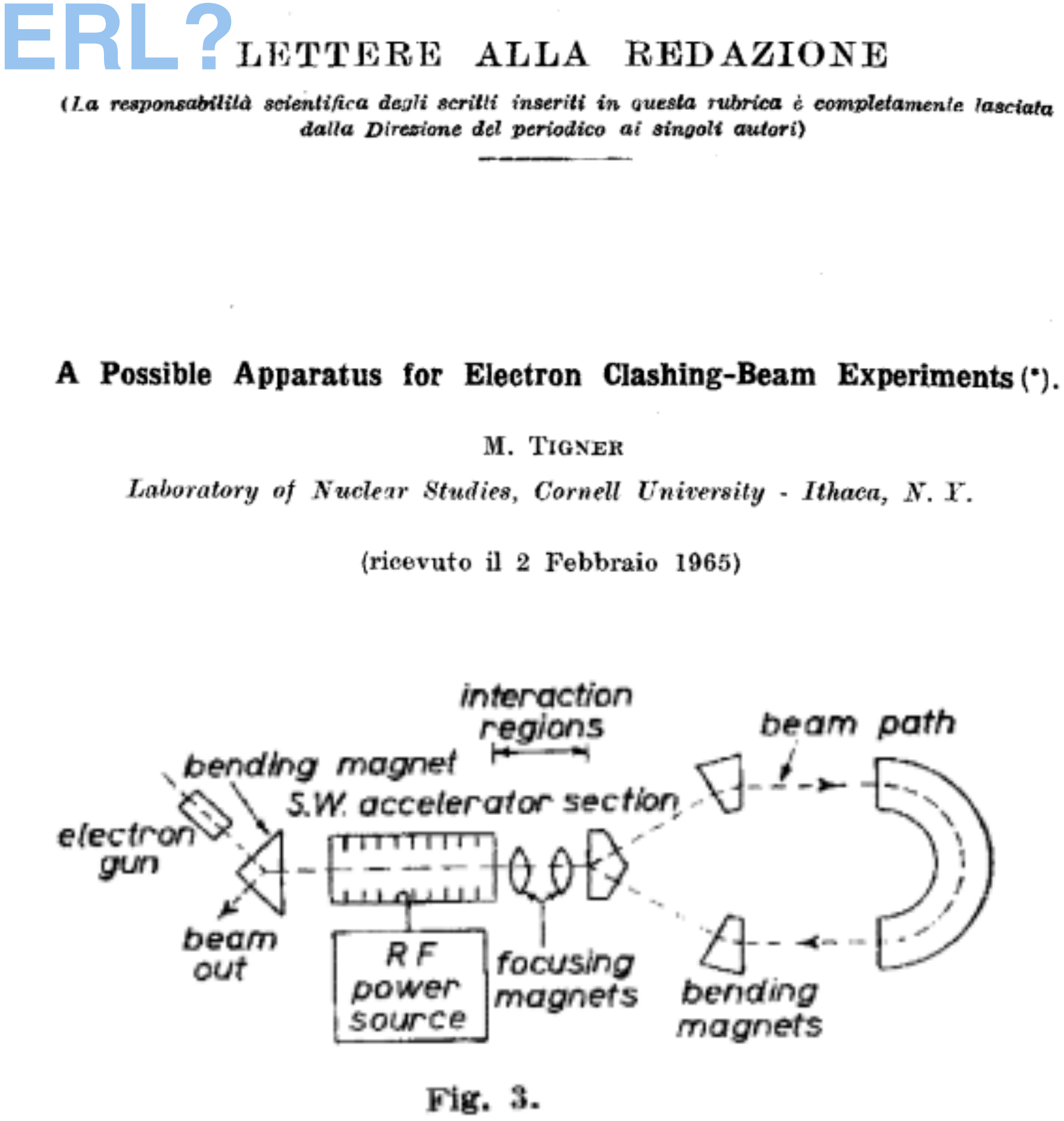
The ERL first proposed in 1965 by Maury Tiger

Tigner, M. *A POSSIBLE APPARATUS FOR ELECTRON CLASHING-BEAM EXPERIMENTS*.N. p., 1965. Web. doi:10.1007/BF02773204.



2.2. *ERL Experiments in the early years*

The first accelerator that exhibited energy recovery was the Chalk River Reflexotron, which was a double-pass linac consisting of an S-band normal conducting standing wave structure and a reflecting magnet similar to the apparatus shown in Fig. 3. In the Reflexotron, the electron beam passed through the S-band accelerating structure twice achieving second pass energies of 5 to 25 MeV depending on the position of the reflecting magnet relative to the accelerating structure [3]. The energy variability down to 5 MeV was obviously achieved by deceleration of the electron beam in the second pass, which was energy recovery, although there was no statement of the term "energy recovery" in the paper.



LETTERE ALLA REDAZIONE

(La responsabilità scientifica degli scritti inseriti in questa rubrica è completamente lasciata dalla Direzione del periodico ai singoli autori)

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

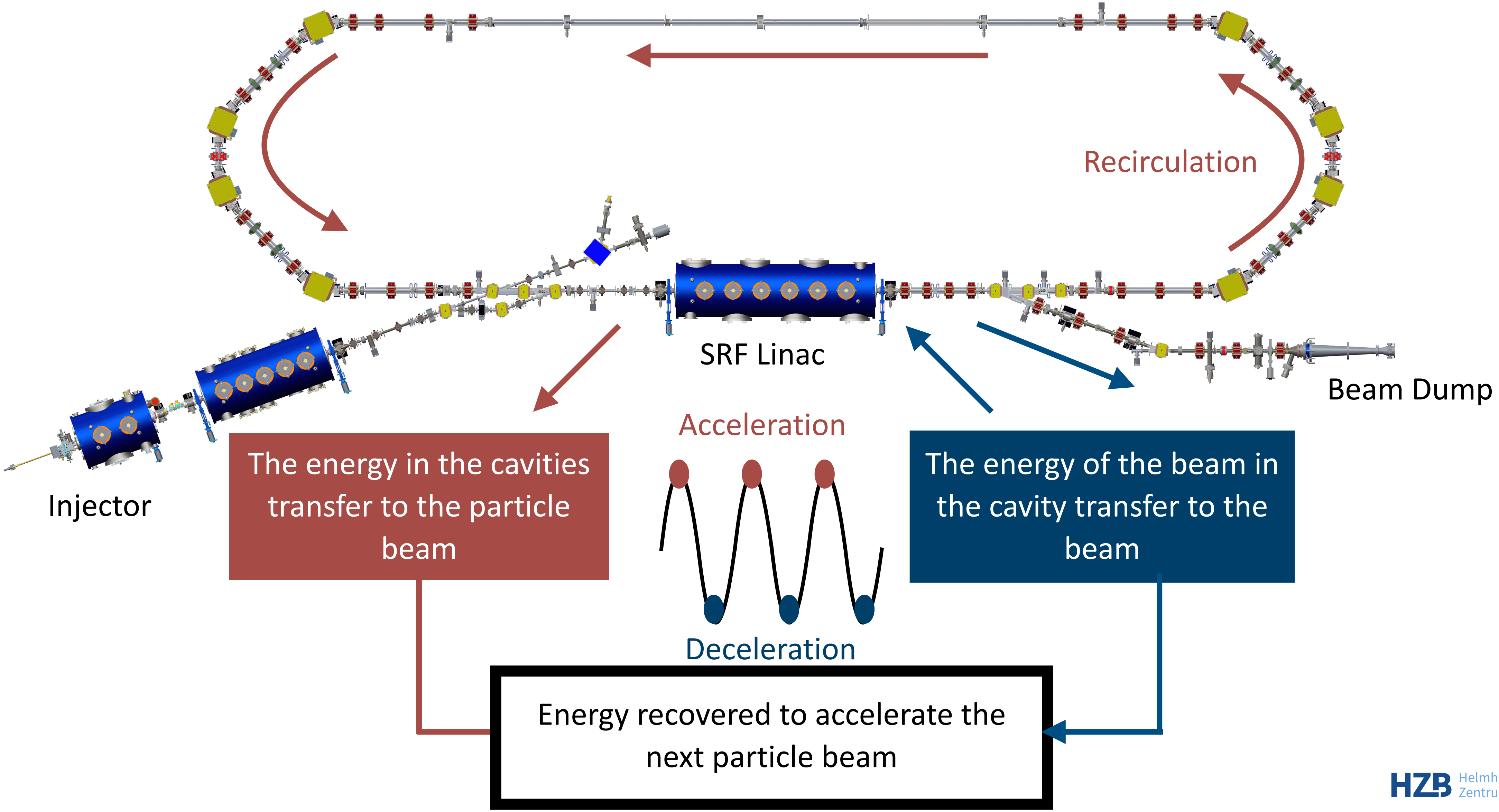
M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

Fig. 3.

What is ERL?



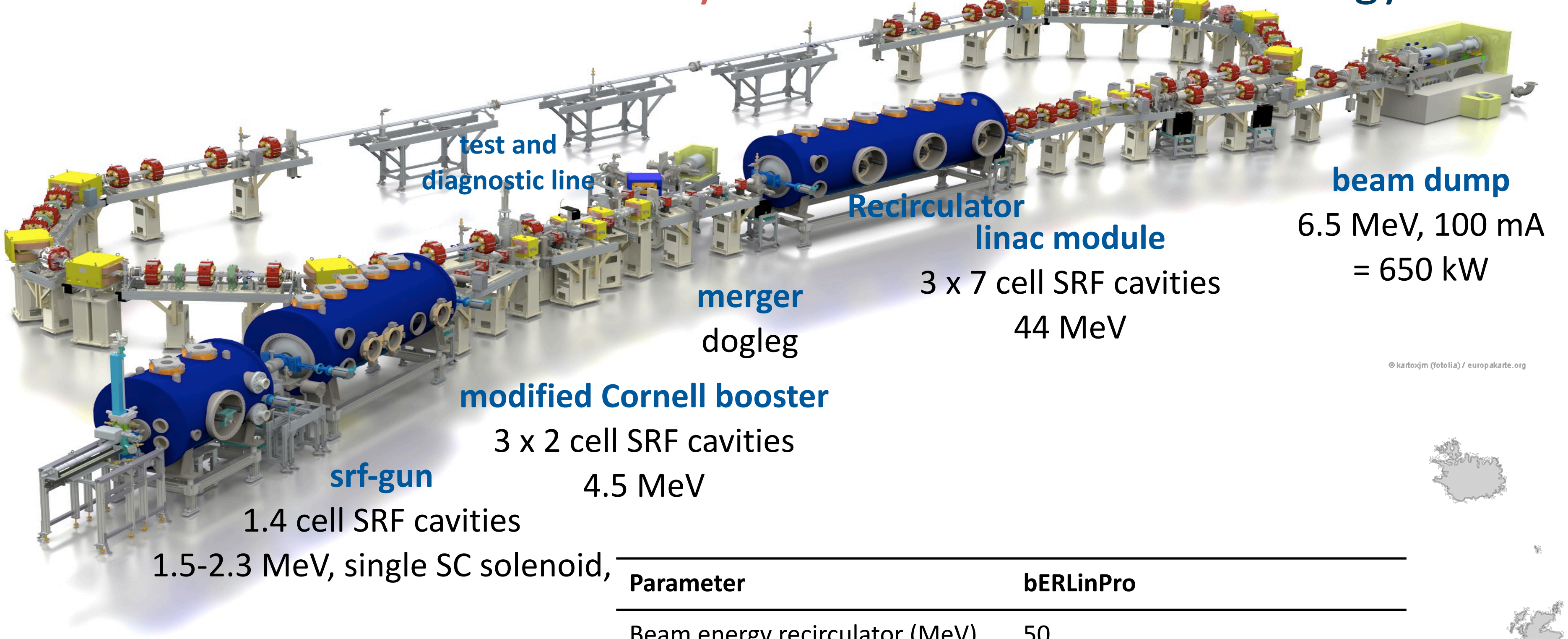
The energy in the cavities transfer to the particle beam

The energy of the beam in the cavity transfer to the beam

Energy recovered to accelerate the next particle beam

bERLinPro ERL

bERLinPro: A demonstration facility for ERL science and technology



test and diagnostic line

Recirculator linac module
3 x 7 cell SRF cavities
44 MeV

beam dump
6.5 MeV, 100 mA
= 650 kW

merger
dogleg

modified Cornell booster
3 x 2 cell SRF cavities
4.5 MeV

srf-gun
1.4 cell SRF cavities
1.5-2.3 MeV, single SC solenoid,

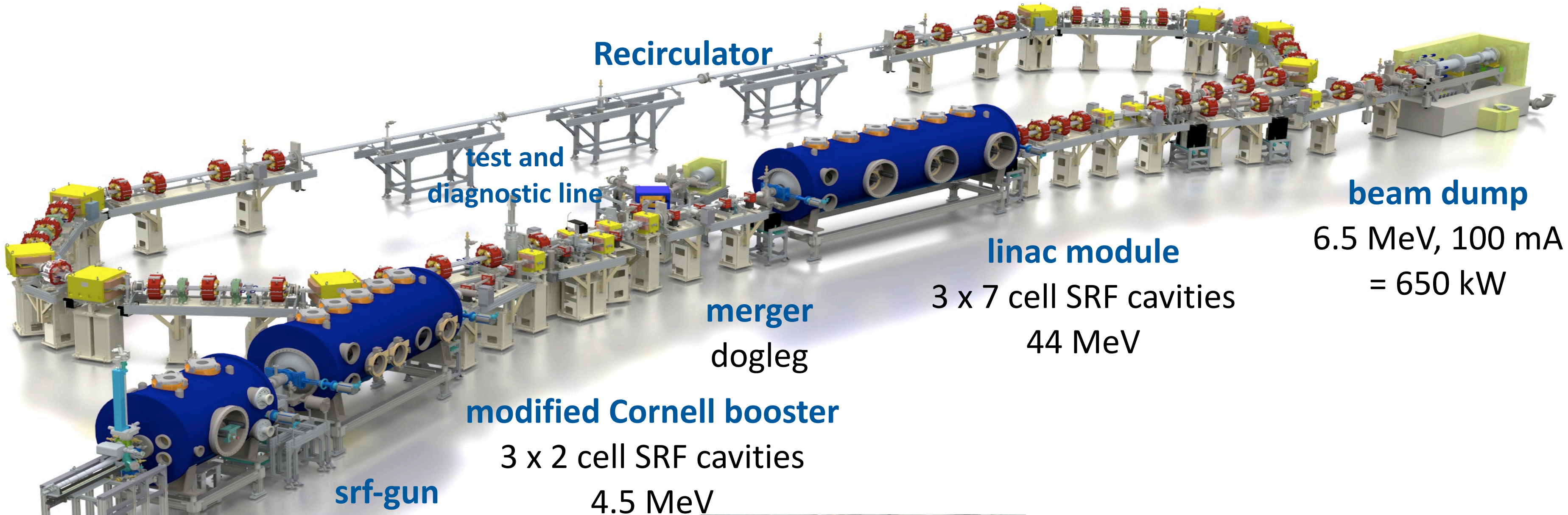
Parameter	**bERLinPro**
Beam energy recirculator (MeV)	50
Beam current ERL mode (mA)	**100**
Frequency RF and Laser (GHz)	1.3
Normalized emittance (mm mrad)	**1 (< 0.6 in simulations)**
Bunch length (ps)	**< 2 (ERL mode), 100 fs @ 10 mA**
Beam losses	<< 10^{-5} @ 100 mA

A fully funded 42 M€ project (including completely new building!)

© kartoxjm (fotolia) / europakarte.org

ERLs in Europe (past, present future)

bERLinPro SRF



Recirculator

test and diagnostic line

beam dump
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= 650 kW

linac module
3 x 7 cell SRF cavities
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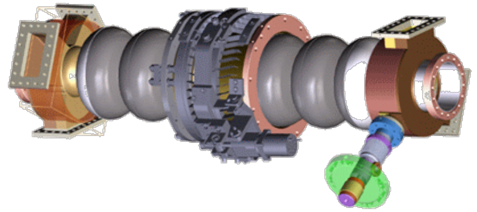
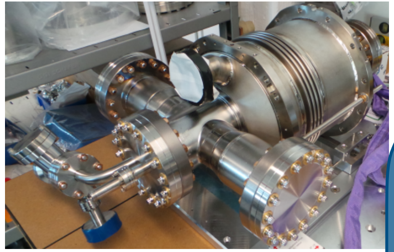




SRF Gun

2.3 MeV (100 mA)

- Low emittance high brightness beam
- Insertion of a thermally isolated high QE Cs-K-Sn cathode (particulate free)
- Control of field emission to avoid dark current based losses and halo formation
- High current, high beam power operation (HOM, FPCs)
- High emission RF field
- Synchronization Laser and RF, precise RF control

SRF booster cavity(Cornell)

+4.5 MeV (100 mA)

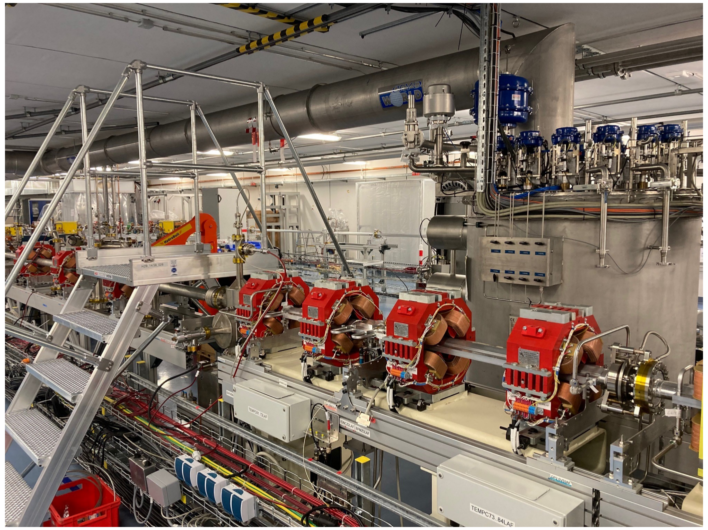
- High beam power
- High beam current
- Intermediate field levels 10 MV/m
- Low coupler kicks
- Zero-crossing operation

Main linac cavity

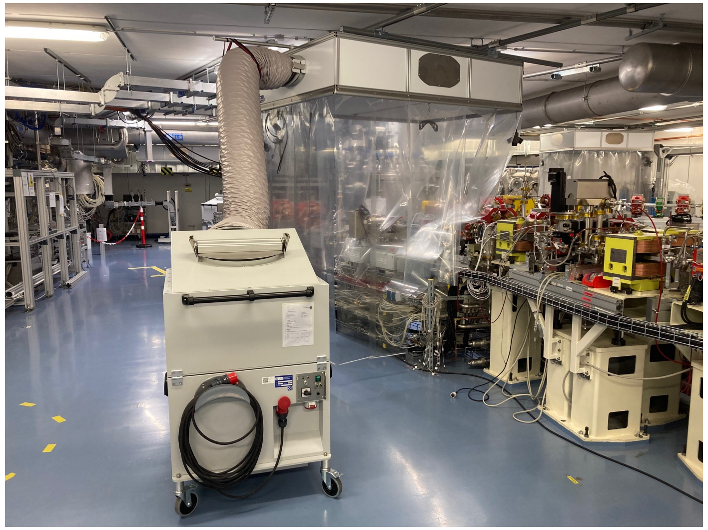
+45 MeV (2x 100 mA, recovered)

- Low beam power
- High beam current
- Strong higher order mode damping
- Higher field levels: 19 MV/m
- Multi-pass beam
- Precise field control and tuning

Beam vacuum system, magnets, cold boxes



Linac section with coldbox for cryogenics supplies



Rail system at ceiling to allow ISO5 flow-boxes everywhere at the machine to avoid particulates

Vacuum system complete, realigned with coordinate system adjusted to building (moved over the years)
Cabling of diagnostics well advanced

Laser Modes and Infrastructure

1.3 GHz laser is still in progress!

50 MHz Laser:
MP and CW modes

MP: 1 Hz … 100 kHz
77 pA … 7.7 µA

CW: 50 MHz, 5 mA

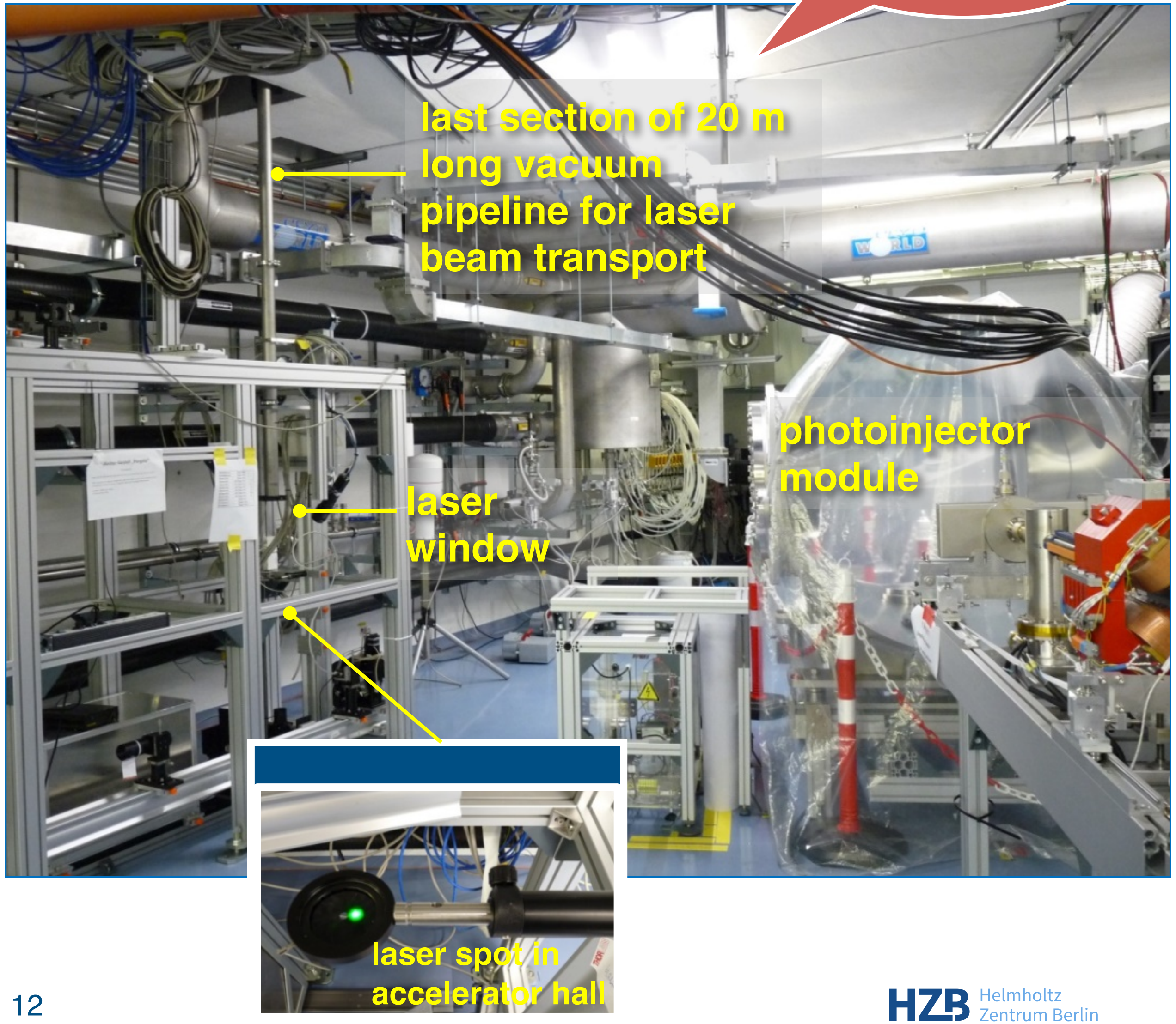
CW Mode	**MP Mode**
0.35uA 50 kHz 7 pC bunches	10 Hz 77pc (13 micropulses (with 1 nC)) 2ms bunch length
0.38uA 5 kHz 77 pC bunches	10 Hz 7pc (100 micropulses) 2ms bunch length

Initial Commissioning parameters for 2024-2025!

1.3 GHz Laser:
MP and CW modes

MP: 1 Hz … 1 kHz
60 – 200 ns

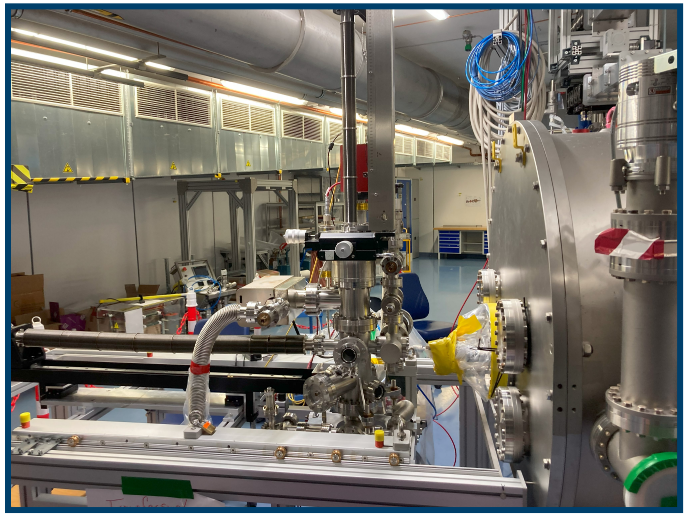
CW: 1.3 GHz, 100 mA



PhotoCathode Laboratory

Photocathode Preparation & Analysis System

Cathode transfer System (Still ongoing)



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.The laboratory contains whole structure of growth and characterization system and UHV transport vessels.

Transfer system at the SRF-photoinjector:
The system has been commissioned in the clean room and is now under UHV at the photoinjector module

Courtesy of J. Kühn and all the cathode team

From bERLinPro to **SEALAB** (**S**RF **E**lectron **A**ccelerator **LAB**oratory)

Map the complete attainable injector phase space for many applications: From FEL, UED to HEP

SRF Linac Funding search and check for possible external collaborations

Initial Goal

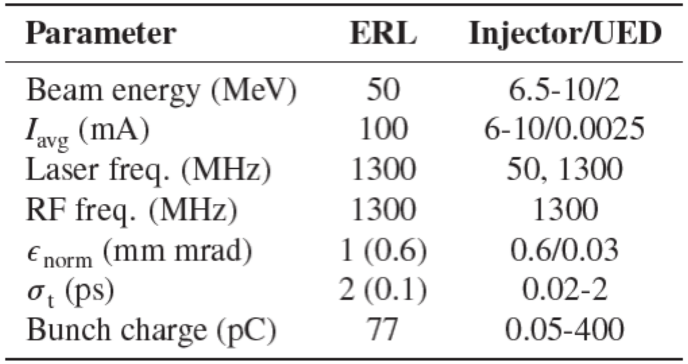
Completion of the injector and linac/dump lines: Commissioning Injector with beam (up to 5-10 mA, up to few 100 pC, up to 6.5 MeV)

Testing of new diagnostics, acceleration concepts

Waste Water Cleaning

New Development testbed

The injector can be used to test and commission AI/machine learning techniques, virtual accelerator twin. Also if it is possible :Test area for (S)RF cavities, modules (e.g. MESA)



Parameter	ERL	Injector/UED
Beam energy (MeV)	50	6.5-10/2
I_{avg} (mA)	100	6-10/0.0025
Laser freq. (MHz)	1300	50, 1300
RF freq. (MHz)	1300	1300
ϵ_{norm} (mm mrad)	1 (0.6)	0.6/0.03
σ_t (ps)	2 (0.1)	0.02-2
Bunch charge (pC)	77	0.05-400

UED experiment

Aiming for shortest pulses, synchronization, exact LLRF control

Initial Commissioning and Further Applications

Operation Modes

Unwanted Beam Studies

MPS system

Beam Loss Detectors

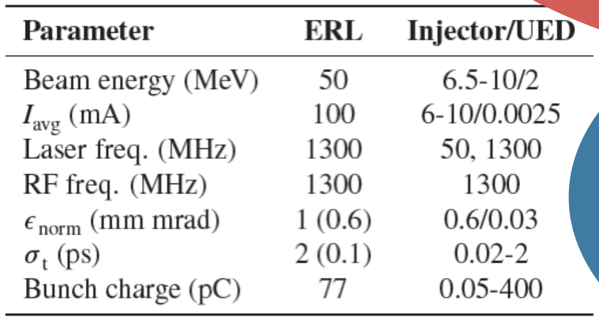
Diagnostic system

Control system

Optimization and Surrogate Mode

UED Experiment

bERLin pro with 100 mA will have approx. 1 µA at 50 MeV = **50 W** which is around 20k times bigger than the conventional storage rings such as BESSY II with 300 mA beam current and 5 hour beam lifetime, loses approx. 15 pA at 1.7 GeV = **0.025 W**



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RF freq. (MHz)	1300	1300
ϵ_{norm} (mm mrad)	1 (0.6)	0.6/0.03
σ_t (ps)	2 (0.1)	0.02-2
Bunch charge (pC)	77	0.05-400

bERLinPro needs fast and reliable MPS system, beam dynamics studies with optimization, surrogate models and unwanted beam studies for achieving stable machine.

Initial commissioning

Initial commissioning will be with ~2.5 MeV beam, 50 MHz laser (check the laser slide)

First goal of beam commissioning is to validate functionality of systems in injector and establish stable machine set points:

- Checkout of systems and components; dark current studies; test MPS
- Verify laser/RF timing stability checks; cavity phasing
- Cathode studies, beam-based alignment

Next goal is to characterize beam and establish ability to control beam parameters in injector:

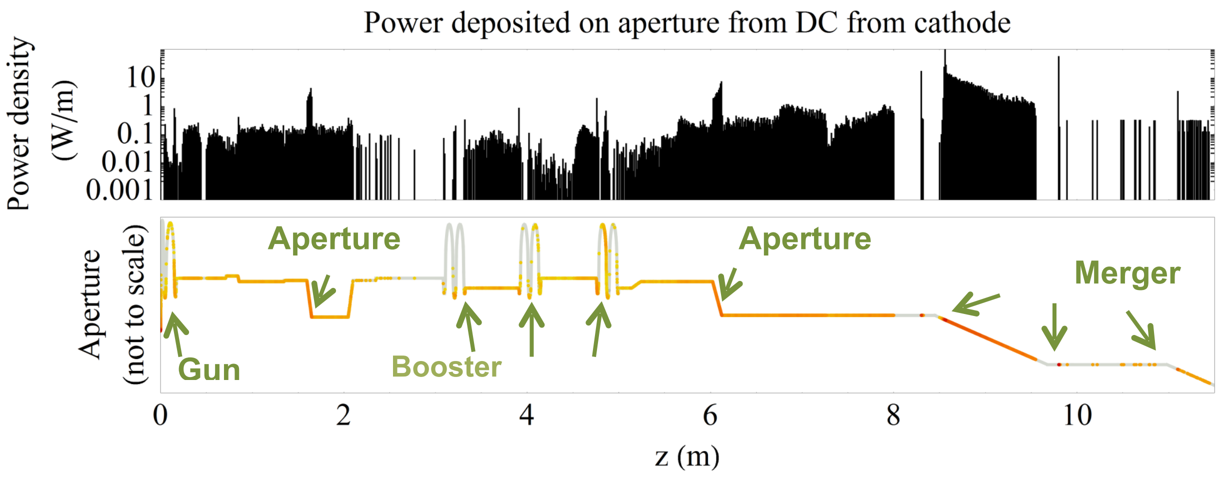
- 6D phase space measurements in diagnostics line
- Response measurements; model calibration; optics manipulation and correction
- Test of the surrogate models and other machine learning tools

Once stable set points and control of beam are established in injector, we can proceed with higher currents and with threading beam through banana.

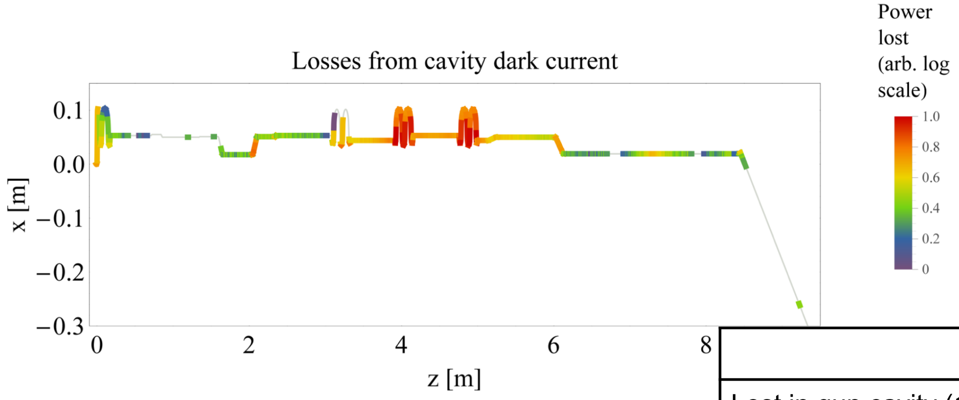
Unwanted beam Studies(ongoing)

Effects which typically generate unwanted beam in ERLs:

- Field emission from SRF cavites and cathode (“dark current “)
- Unwanted photons from laser
  - Stray light arriving at cathode out of phase
  - Incompletely blocked laser pulses (“ghost pulses”)
- Nonlinear dynamics within bunch



	% of e$^-$	P (W)	I (μA)
Lost in gun cavity (1.8K)	15%	0.5	
Strikes cathode	12%	0.4	
Lost in gun module (4K)	5%	0.12	
Exiting gun module	80%		3.6
Passes merger	17%		0.8



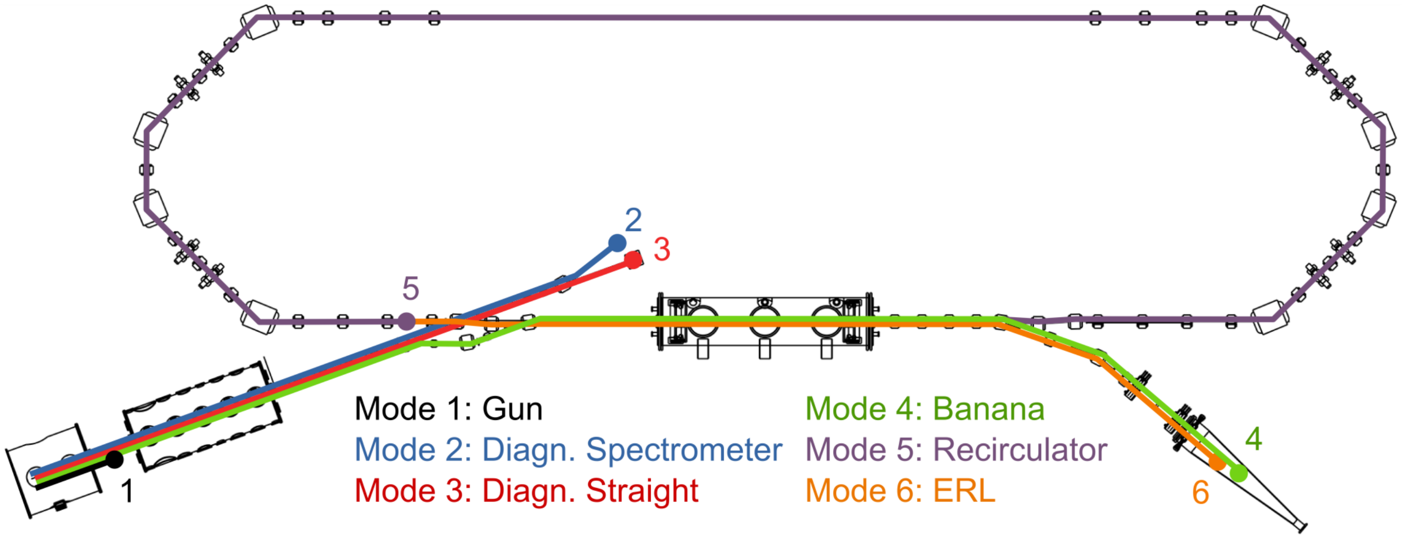
Dark current losses along injector

	% of e$^-$	P (W)	I (μA)
Lost in gun cavity (1.8K)	94%	2.0	
Strikes cathode	2%	0.03	
Lost in gun module (4K)	3%	0.16	
Exiting gun module	3%		0.085
Passes merger	0.1%		0.003

M. Abo-Bakr, M. McAteer, J. Völker
B. Kuske, M. Matveenko, E. Panofski et al.

Operation Modes

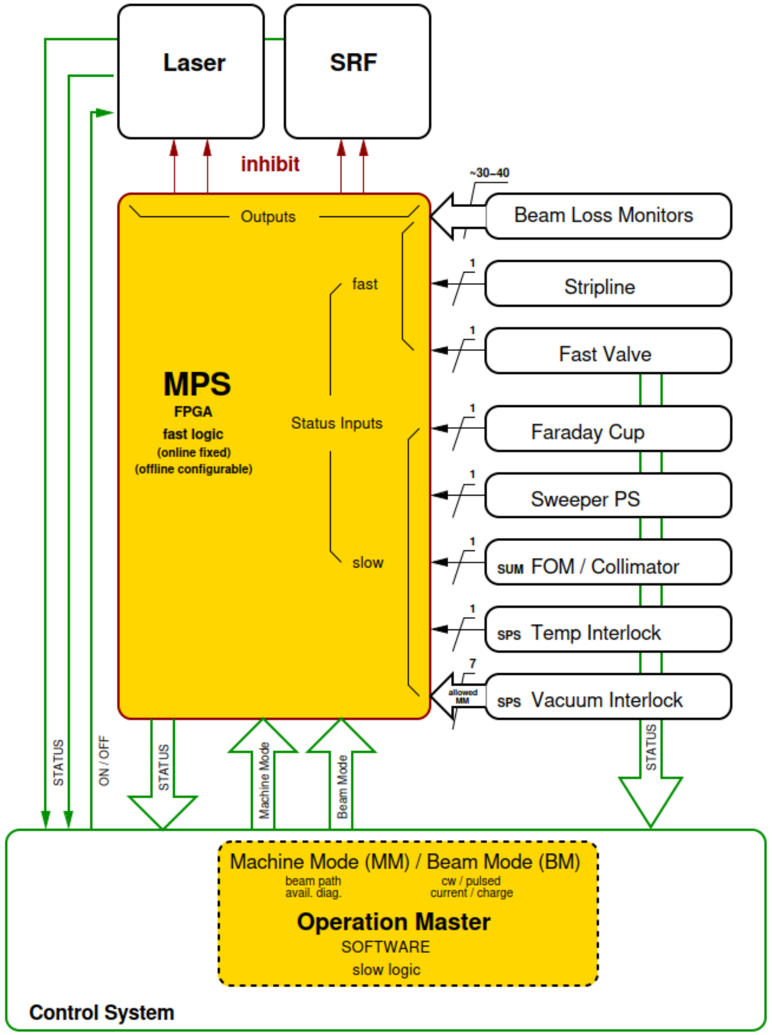
- Machine modes determine the path of the beam through the accelerator
- Current for each Machine Mode is limited by how much power can safely be deposited in each beam dumpTwo beam modes:
  - Diagnostics mode – 0.5 µA current limit (limited by FOM)
  - Full-current mode – 5 mA



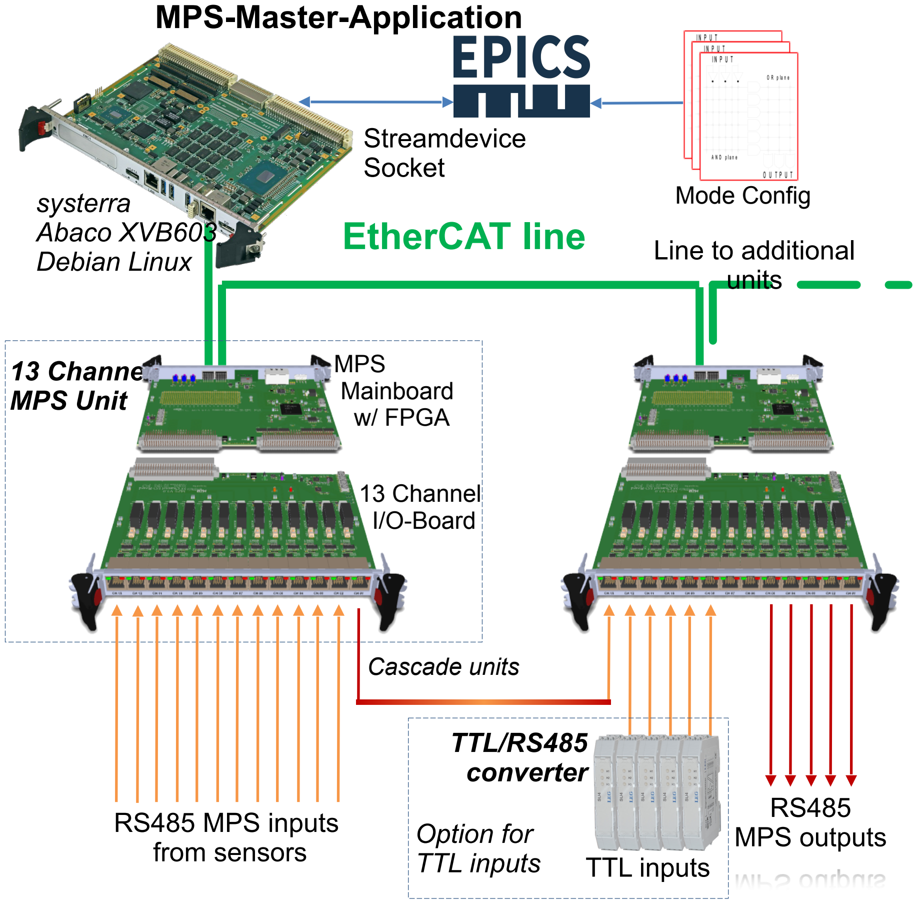
Beam Mode	Current Limit
BM1: Diagnostics Mode	0.5 µA
BM2: High-current	5 mA

#	Name	Dump	P_{max} (KW)	E_{kin} (MeV)	I_{max} (mA)
1	Gun	Faraday cup	0.3	2.7	0.1
2	Diagn. Spectr.	Faraday cup	0.3	6.5	0.045
3	Diagn. Straight	LEMP dump	35	6.5	5
4	Banana	LEHP dump	650	6.5	100
5	Recirculator	HELP absorber	0.050	50	0.001
6	ERL	LEHP dump	650	6.5	100

MPS



Courtesy of Thomas Birke



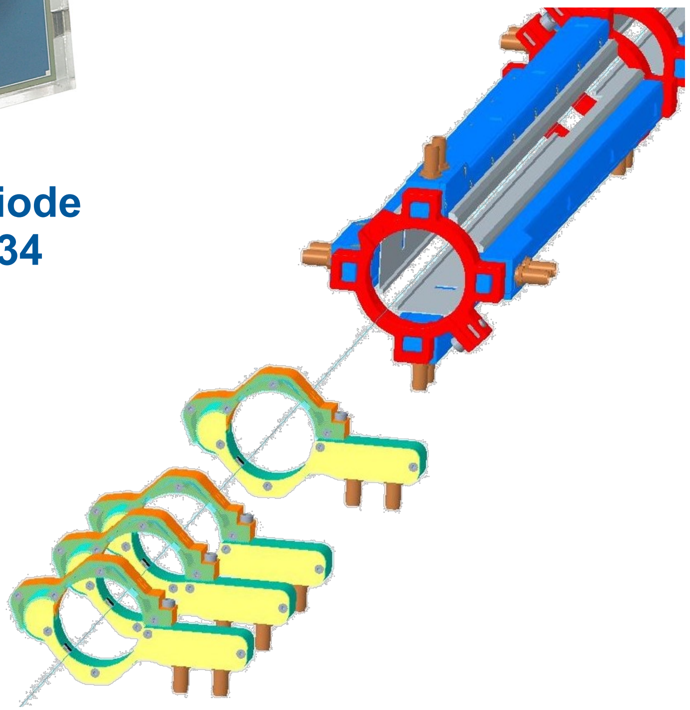
The MPS aims to detect beam losses using beam loss monitors and analyzing the signals with set thresholds. When the signal exceeds the threshold, it sends a signal to the relevant components to stop the beam.

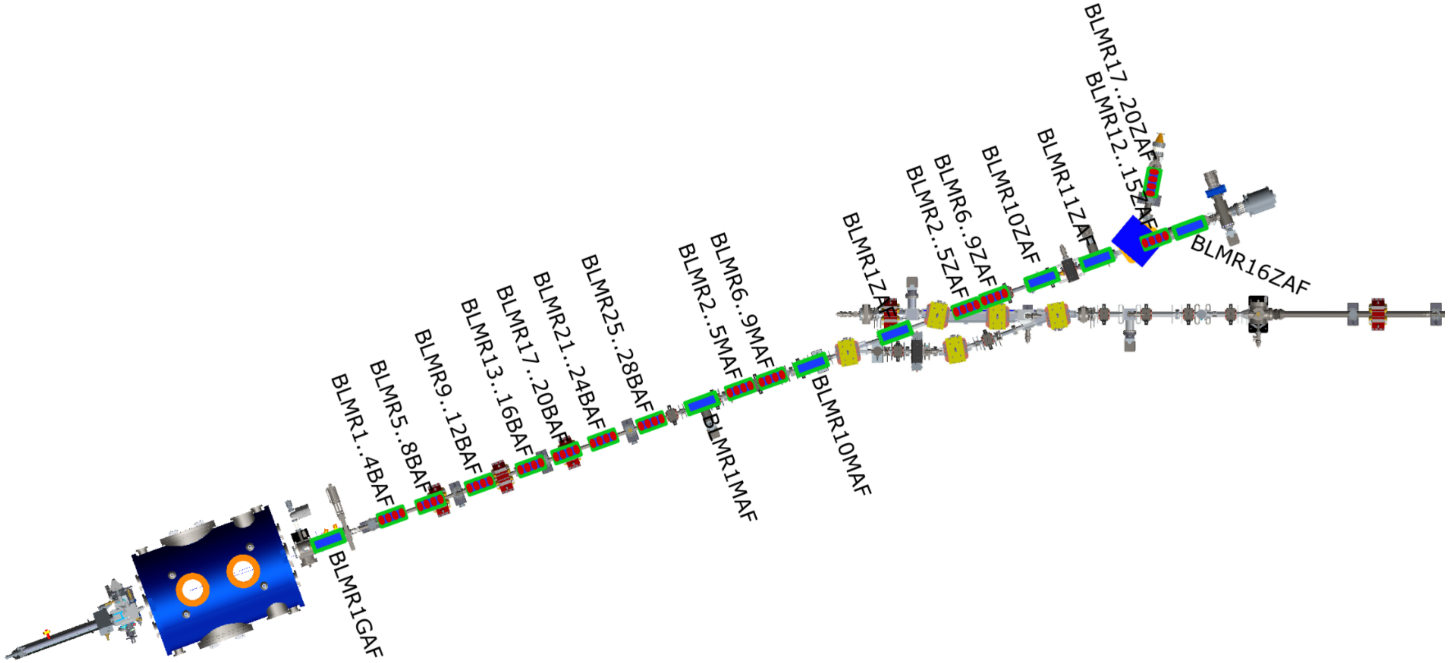
The MPS main board takes signals from BLMs and other tools and processes the signal according to the configuration files, and sends an output signal to the laser shutter or LLRF.

The main board is an FPGA unit that digitally checks every input signal (0 or 1).

Beam Loss Detectors

Si-PIN-diode VBPW34





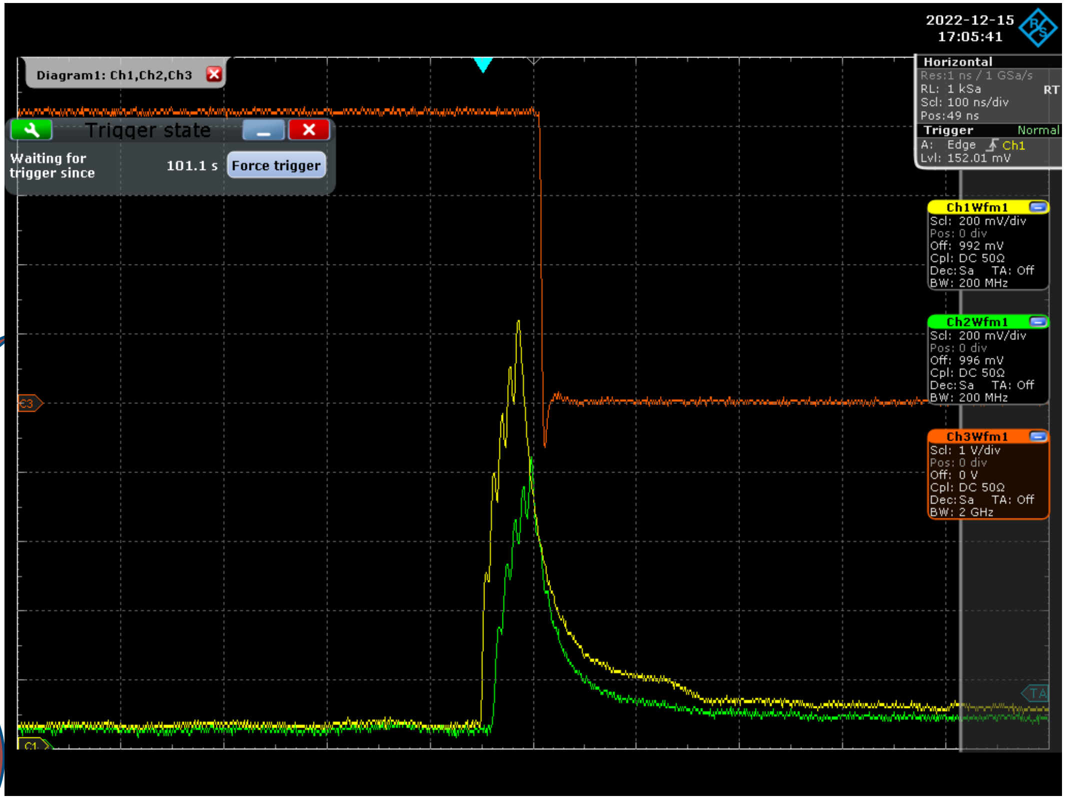
There is two types of Diode BLMs: **Circular**(Three to four rings longitudinally unequal distances mounted on the vacuum chambers with 4 sensors each are connected in series a BLM) and **Stripline**(Four strips, each with 4 sensors, are evenly distributed around the circumference so that they can provide a very good beam position at low current via the losses.)

BLMs embedded to MPS

Sensitivity : 13 mV / 0.35 nC = 37 μV / pC
Decay time : ~ 32 ns

Beam loss criterion : 5 μA/m (@ 50 MeV)
MPS working time : < 1 μs

Processing time for MPS
→ diode rise time (< 200 ns) + 80 m cable (270ns) + electronics (100 ns) < 600 ns



2022-12-15
17:05:41

Waiting for trigger since 101.1 s

Horizontal
Res:1 ns / 1 GSa/s
RL: 1 kSa RT
Scl: 100 ns/div
Pos:49 ns

Trigger Normal
A: Edge Ch1
Lvl: 152.01 mV

Ch1Wfm1
Scl: 200 mV/div
Pos: 0 div
Off: 992 mV
Cpl: DC 50Ω
Dec:Sa TA: Off
BW: 200 MHz

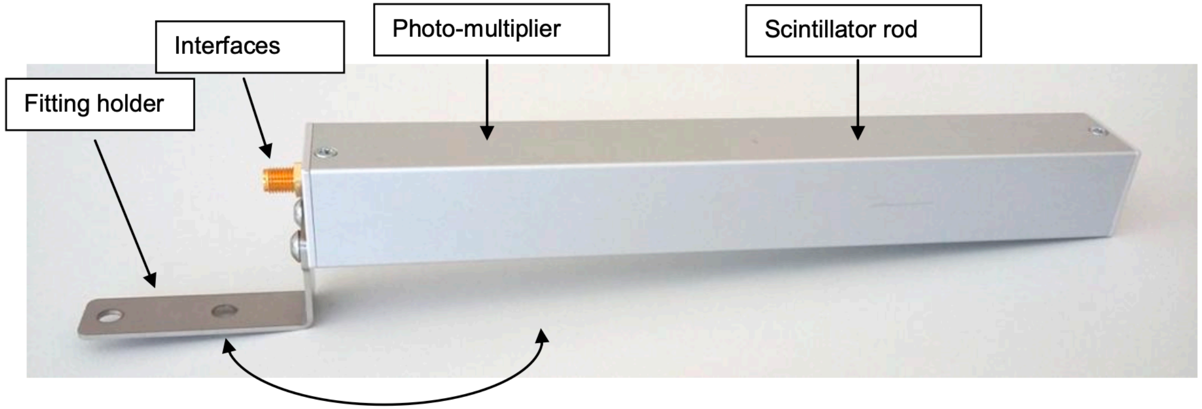
Ch2Wfm1
Scl: 200 mV/div
Pos: 0 div
Off: 996 mV
Cpl: DC 50Ω
Dec:Sa TA: Off
BW: 200 MHz

Ch3Wfm1
Scl: 1 V/div
Pos: 0 div
Off: 0 V
Cpl: DC 50Ω
Dec:Sa TA: Off
BW: 2 GHz

The yellow is the left sensor the green is the right. The orange is the interlock output. The beam is steered to the left.The measurement were performed with 5 bunch with 1500 pC and interlock is triggered due to the high amount of losses on the beam pipe.

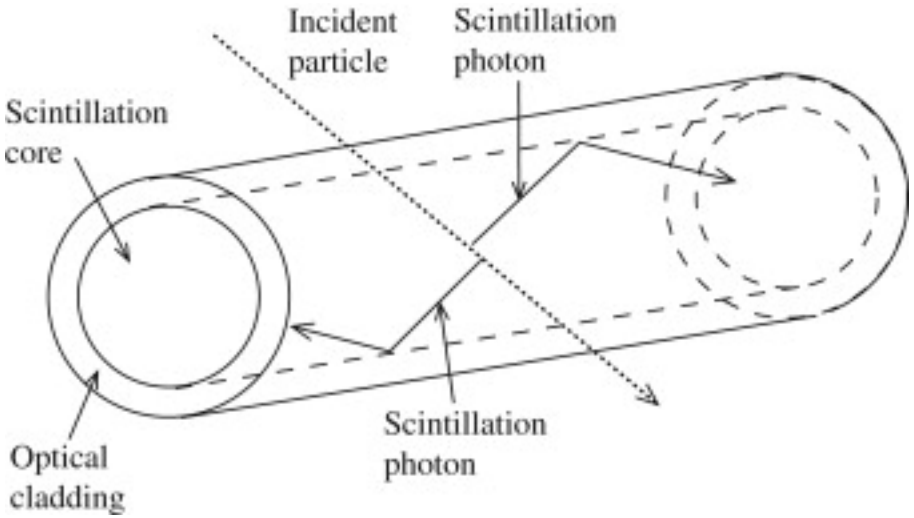
Beam Loss Detectors(Upgrade)

Scintillator-PMT based



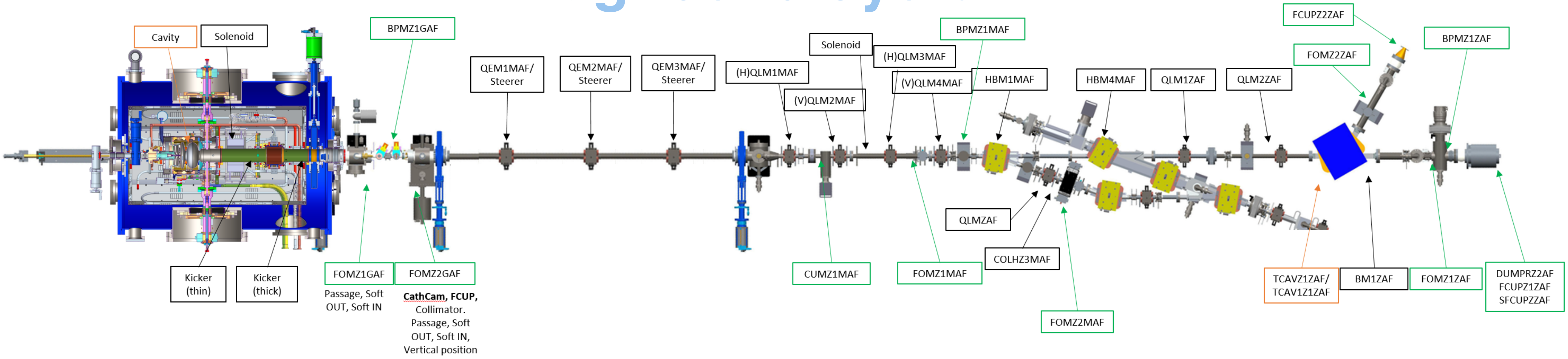
- 4 BLMs with readout system were ordered for the high loss expected areas
- The PMT calibration tests were performed with radiation sources
- The EPIICS control interface is ready

Scintillating fiber



- The Scintillating fibers will be replaced four sides throughout the accelerator.
- 4 PMTs with readout system were ordered.
- The suitable scintillating fiber research is ongoing due the low attenuation length of the fiber

Diagnostic System



4 Screen Monitors (i.e FOMZ2GAF)

1 Spectrometer Dipole

1 Transverse deflecting cavity(bunch length m.)

3 BPM for position measurements

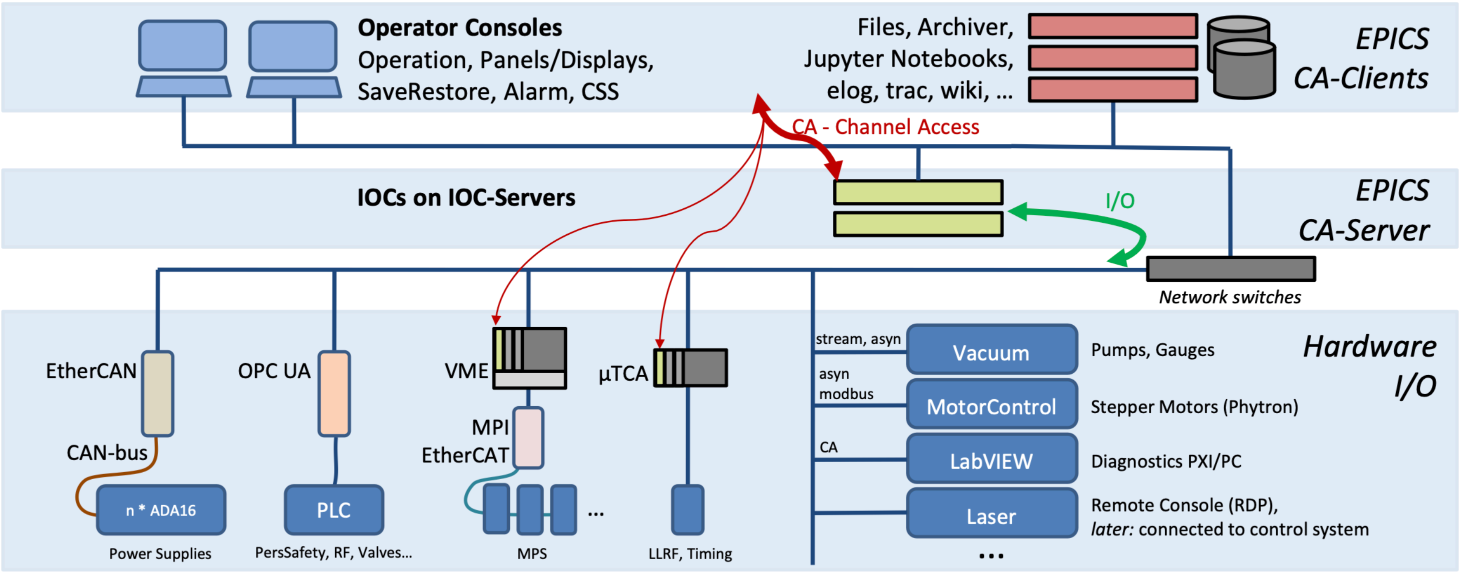
1 ICT for current measurements

3 Faraday cups(1 inserted 2 at the dumps)

Location	Beam conditions	E_{kin}	I_{avg}	Position measurement	Current measurement
1st meter	7 pC -77 pC macropulse	2.7 MeV	~0.5 µA	FOM BPMs (?) (to be tested)	Cathode Current Measurement,First Meter Faraday Cup
1st meter	CW, 7 pC or ramped from 0-77 pC	2.7 MeV	0-5 mA	FOM (I<~0.5 µA) BPM (I>1 mA)	Cathode Current M. Faraday Cup (I<~100 µA)
Injector/ Diagn. line	7 pC macro pulse	2.7 MeV	~0.5 µA	FOM BPMs (?)(to be tested)	Cathode Current M. Faraday Cup ICT
Injector/ Diagn. line	77 pC macro pulse at	6.5 MeV	~0.5 µA	FOM BPMs (?) (to be tested)	Cathode Current M. Faraday Cup ICT
Injector/ Diagn. line	7 pC or ramped from 0-77 pC, CW	6.5 MeV	0-5 mA	FOM (I<~0.5 µA) BPM (I>1 mA)	Cathode Current M. Faraday Cup (I<~45 µA)

Control System

Control System Structure



Operator Consoles
Operation, Panels/Displays,
SaveRestore, Alarm, CSS

Files, Archiver,
Jupyter Notebooks,
elog, trac, wiki, ...

EPICS
CA-Clients

CA - Channel Access

IOCs on IOC-Servers

I/O

EPICS
CA-Server

Network switches

EtherCAN
CAN-bus
n * ADA16
Power Supplies

OPC UA
PLC
PersSafety, RF, Valves...

VME
MPI
EtherCAT
...
MPS

µTCA
LLRF, Timing

stream, asyn
asyn
modbus
CA

Vacuum
Pumps, Gauges

MotorControl
Stepper Motors (Phytron)

LabVIEW
Diagnostics PXI/PC

Laser
Remote Console (RDP),
later: connected to control system

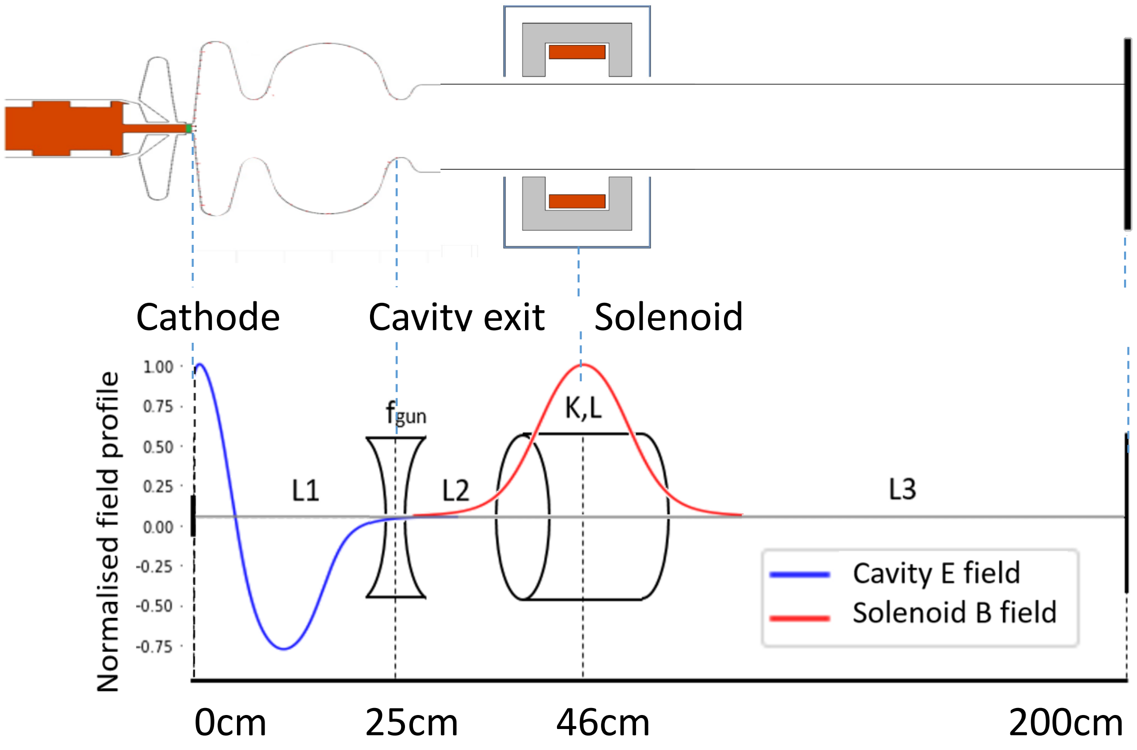
...

Hardware
I/O

courtesy of T. Birke

- EPICS based control system
- Most of the devices are connected(expected to test in July)
- General list of the panels were prepared and overview panels are still on progress.

Initial Optimization For the Gun



Courtesy of Emily Brookes

Follows principles from:
[1] T. Rao and D. H. Dowell, ‘An Engineering Guide To Photoinjectors’
[2] K.-J. Kim, ‘Rf and space-charge effects in laser-driven rf electron guns’

$$\begin{bmatrix} x_f \\ x'_f \\ y_f \\ y'_f \\ dE_i \\ dt_f \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & 0 & 0 \\ M_{21} & M_{22} & M_{23} & M_{24} & 0 & 0 \\ M_{31} & M_{32} & M_{33} & M_{34} & 0 & 0 \\ M_{41} & M_{42} & M_{43} & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M^2_{55} & M^2_{56} \\ 0 & 0 & 0 & 0 & M^2_{65} & M^2_{66} \end{bmatrix} \begin{bmatrix} x_i \\ x'_i \\ y_i \\ y'_i \\ dE_i \\ dt_i \end{bmatrix}$$

Model the gun as a drift space and an exit lens, and split the solenoid into slices

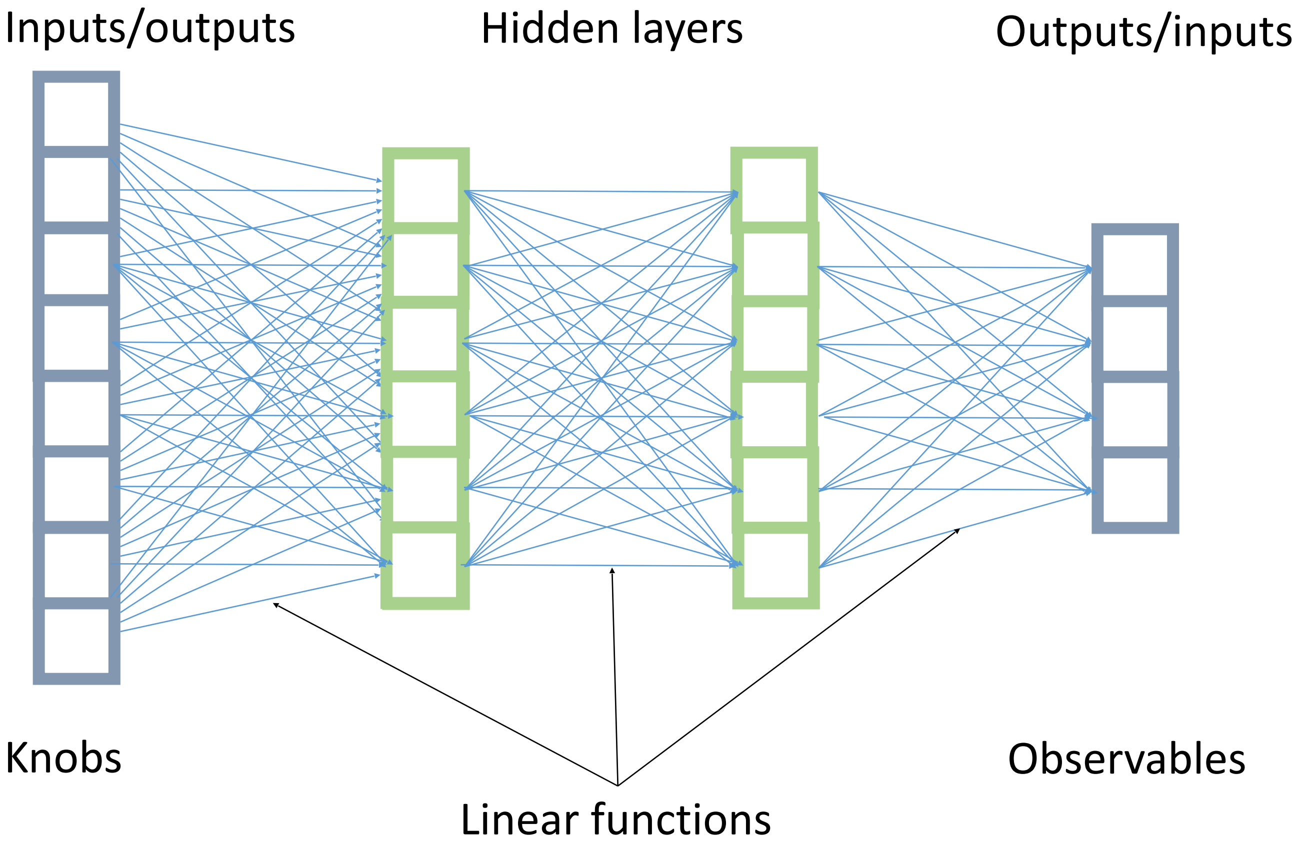
Analytical models provide fast insights into beam dynamics and derive dependencies between input parameters and observations

Considerations:

- Higher order effects are neglected (including space charge)
- All components are considered independent
- Assume constant momentum at relativistic speed (does not hold since particles start at near-rest)
- All fields are axisymmetric

Surrogate model (neural network) architecture

Neural networks



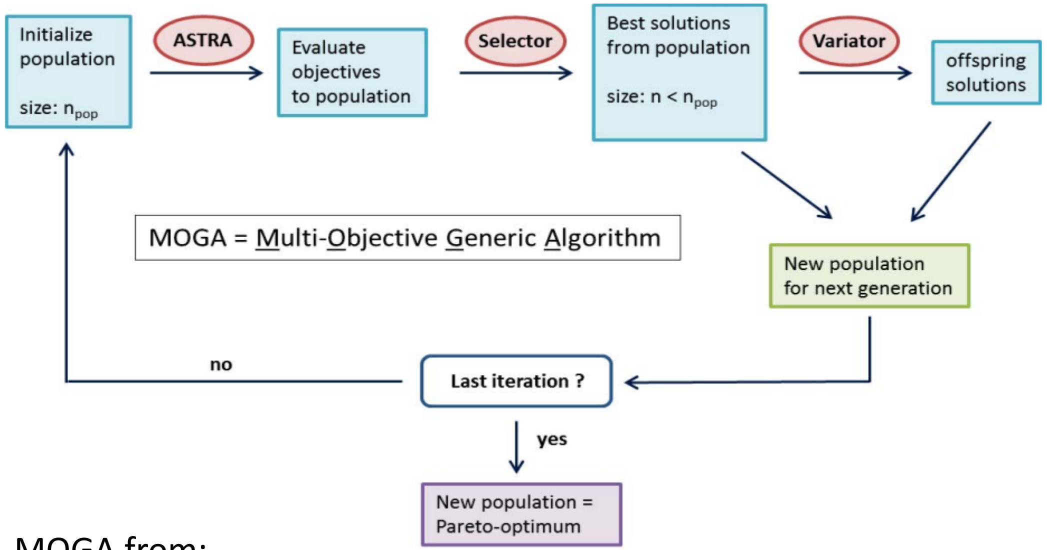
Train on a set of solutions from simulations or outputs from machine operation

Considerations:

- Learning rate
- Solver structure/loss function
- Training/validation set sizes
- Architecture for specific problem
  - Complexity of problem
  - Available data
  - Computing power
  - Over-fitting

Current architecture comes from previous work:
[3] D. Meier et al., ‘Reconstruction of offsets of an electron gun using deep learning and an optimization algorithm’
My model now uses 11 inputs, 4 hidden layers (sizes = 2002, 447, 100, 22), and 19 outputs (more NN optimisations to come)

Multi-Objective Genetic Algorithms vs Multi-Objective Bayesian Optimization



Initialize population

size: n_{pop}

ASTRA

Evaluate objectives to population

Selector

Best solutions from population

size: $n < n_{pop}$

Variator

offspring solutions

New population for next generation

MOGA = Multi-Objective Generic Algorithm

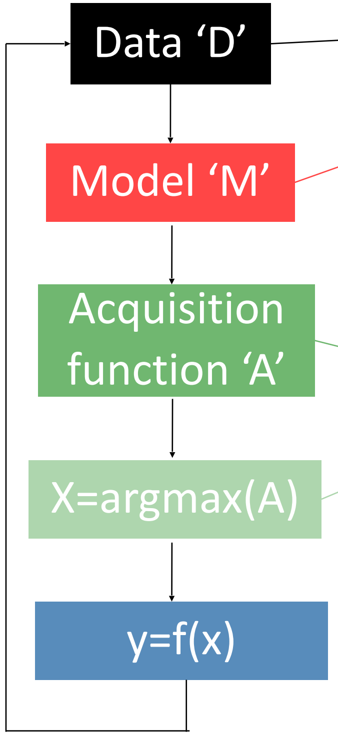
Last iteration ?

no

yes

New population = Pareto-optimum

MOGA from:
[4] E. Panofski, ‘Beam dynamics and limits for high brightness’



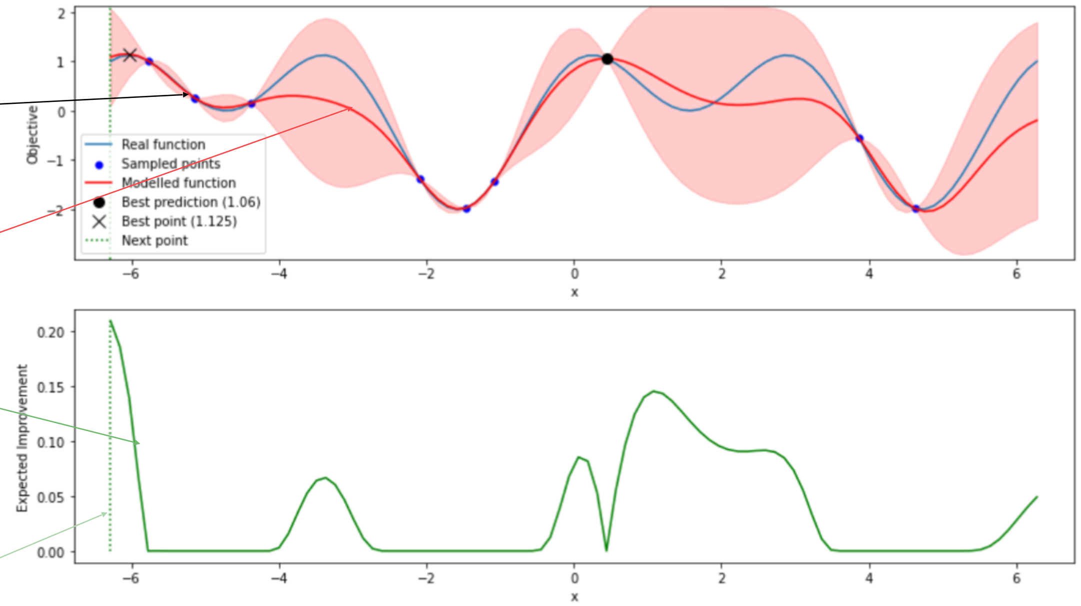
Data ‘D’

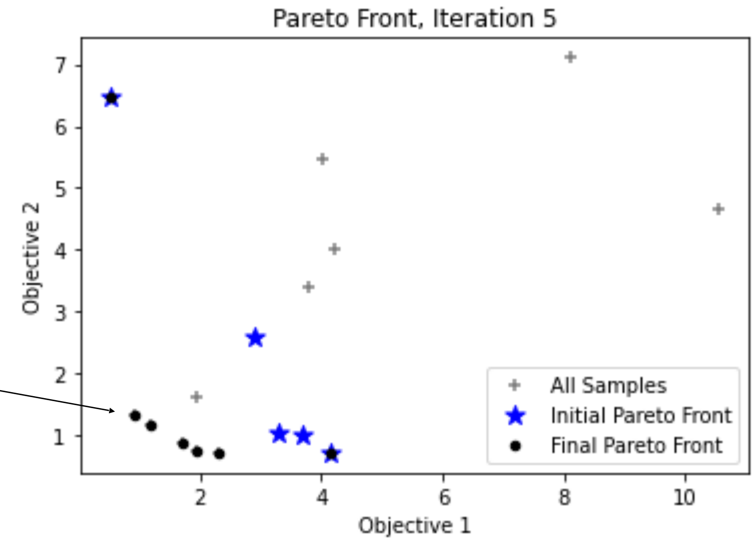
Model ‘M’

Acquisition function ‘A’

X=argmax(A)

y=f(x)



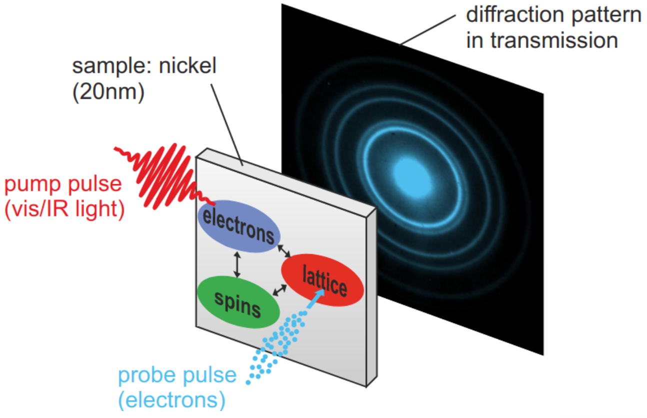


Both algorithms can be run with either ASTRA or a look-up to the surrogate model each iteration, and both aim to find the true Pareto front

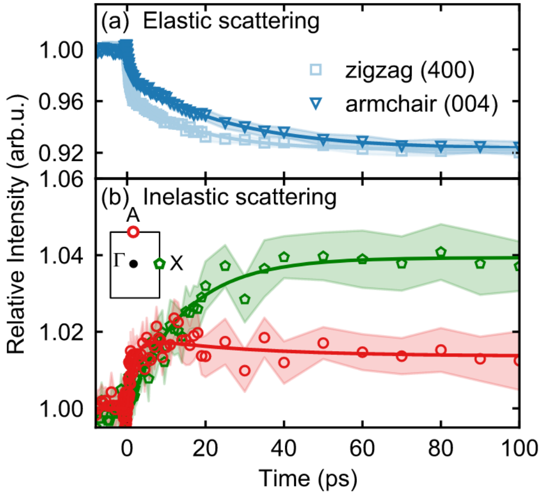
MOGA takes points and modifies them slightly with a variator to improve diversity, MOBO has an acquisition function which can be defined to balance exploitation-vs-exploration

UED Experiment

Ultra-fast Electron Diffraction (UED) can provide of real-time imaging of structural changes in atomic scales. Pump photon pulse excites the target structure, while a consequent probe electron bunch generates the diffraction pattern.



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



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

Spatial resolution is ultimately limited by the wavelength of the probing radiation → Visible light is not enough to reach atomic scales.

Neutrons

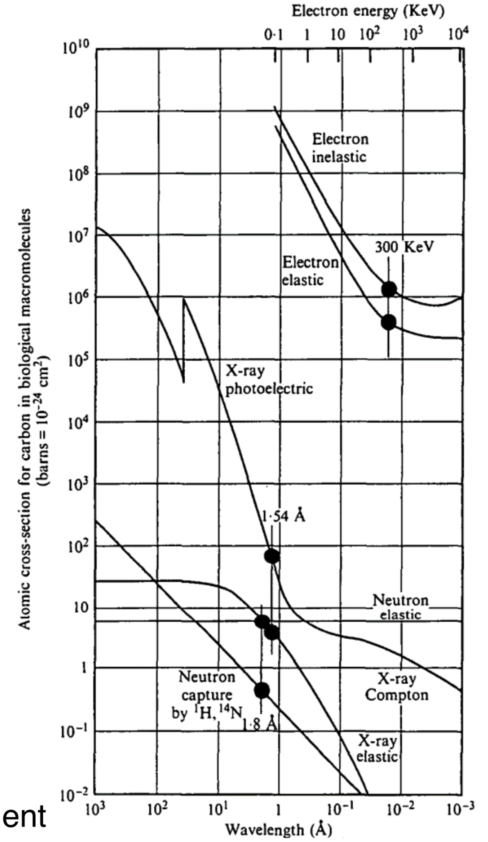
- High penetration depth due to small cross section.
- Interaction mostly with atomic nucleus and magnetic structure of the sample.

X-rays

- Interact mostly with electron clouds surrounding the atoms.
- Diffraction is possible, but imaging is not (only shadow imaging).

Electrons

- Interact with atomic nuclei of the target material.
- Both diffraction and imaging are possible with appropriate lenses.
- Due to the higher cross section than neutrons and X-rays, a lower incident flux is required → Radiation damage is then reduced.



R. Henderson, Q. Rev. Biophys. 28.2, 1995

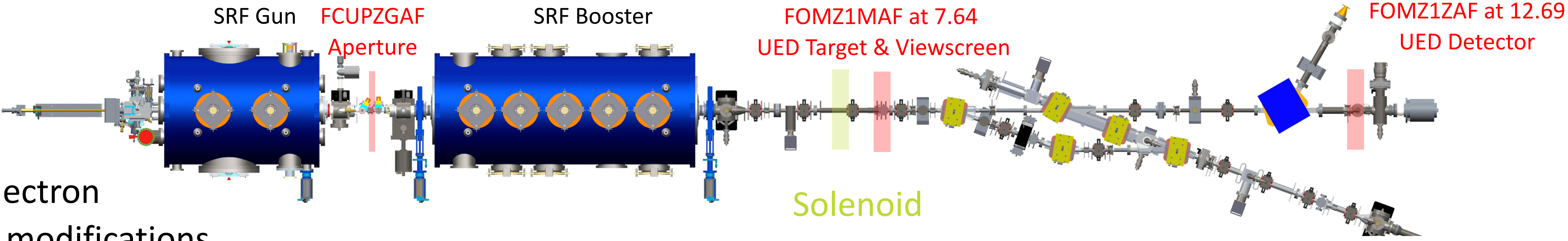
UED Experiment

For the MeV scattering experiments we need:

- 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.

The photoinjector has:
1 to 3.5 MeV beam energy with variable bunch charge (1 fC to 100 pC), pulse length (10 fs to 6 ps) and spot size (10 to 100s µm), high stability at MHz repetition rate.

Very flexible longitudinal accelerator/lens system: one gun cavity and three booster cavities, done optimization for bunching scheme.



Ultrafast Electron
Diffraction modifications

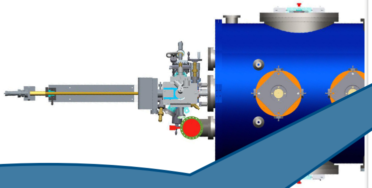
UED Experiment

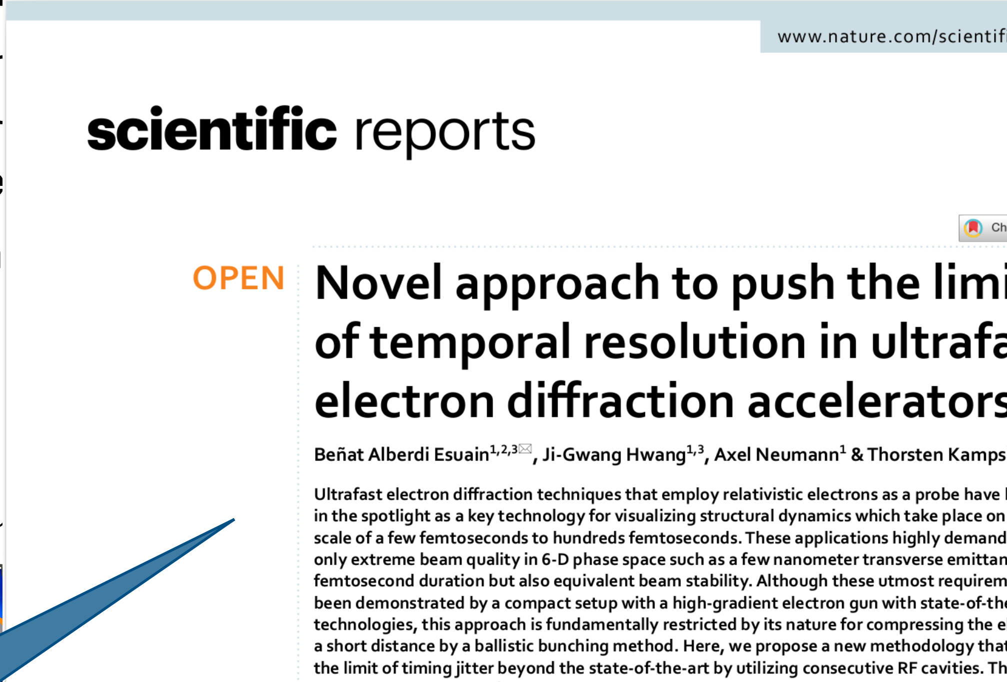
The phot
1 to 3.5 M

For the MeV scattering experiments we need:

- Emittance reduction fro
make sure we have eno
- Target station for sample
- Focusing element to con
at target.

SRF Gu





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scientific reports

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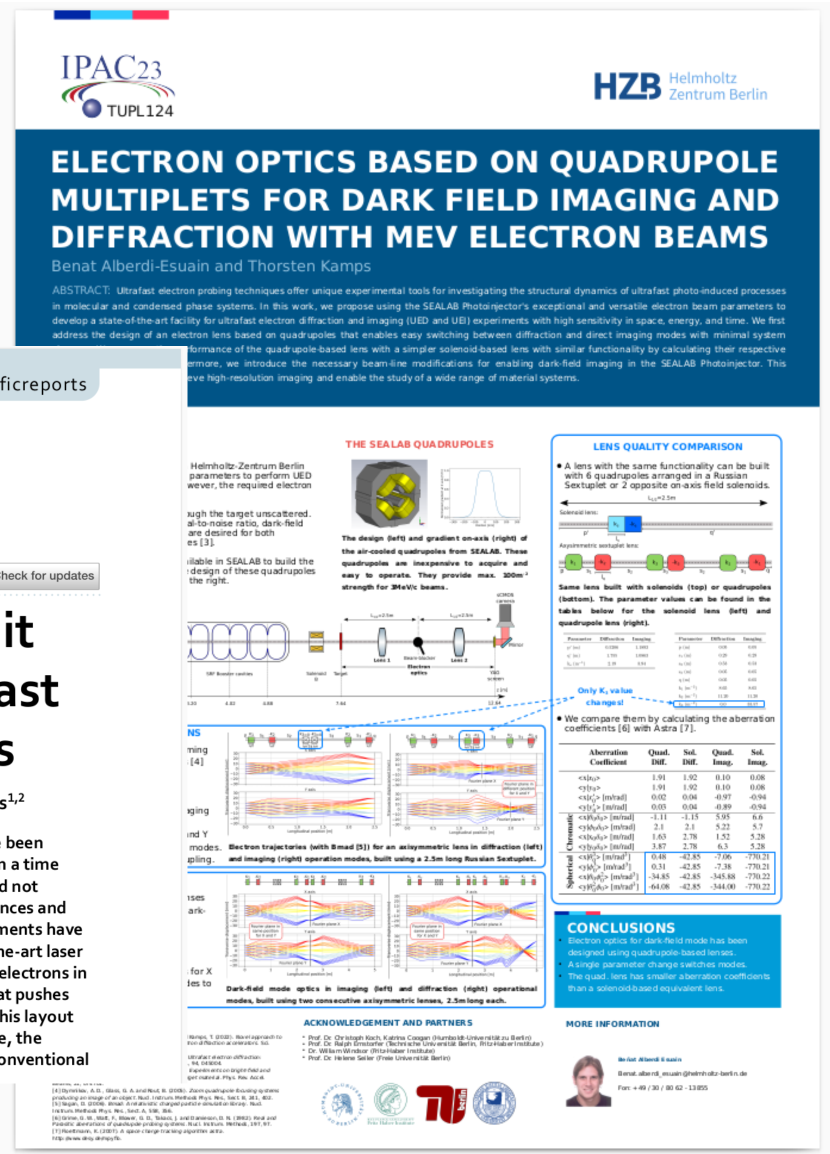
OPEN

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 high-gradient electron guns



IPAC23
TUPL124

HZB Helmholtz Zentrum Berlin

ELECTRON OPTICS BASED ON QUADRUPOLE MULTIPLETS FOR DARK FIELD IMAGING AND DIFFRACTION WITH MEV ELECTRON BEAMS

Benat Alberdi-Esuain and Thorsten Kamps

ABSTRACT: Ultrafast electron probing techniques offer unique experimental tools for investigating the structural dynamics of ultrafast photo-induced processes in molecular and condensed phase systems. In this work, we propose using the SEALAB Photoinjector's exceptional and versatile electron beam parameters to develop a state-of-the-art facility for ultrafast electron diffraction and imaging (UED and UEI) experiments with high sensitivity in space, energy, and time. We first address the design of an electron lens based on quadrupoles that enables easy switching between diffraction and direct imaging modes with minimal system
formance of the quadrupole-based lens with a simpler solenoid-based lens with similar functionality by calculating their respective
ermore, we introduce the necessary beam-line modifications for enabling dark-field imaging in the SEALAB Photoinjector. This
eve high-resolution imaging and enable the study of a wide range of material systems.

Helmholtz-Zentrum Berlin
parameters to perform UED
wever, the required electron

ugh the target unscattered.
al-to-noise ratio, dark-field
are desired for both
es [3].

ilable in SEALAB to build the
design of these quadrupoles
the right.

THE SEALAB QUADRUPOLES

The design (left) and gradient on-axis (right) of the air-cooled quadrupoles from SEALAB. These quadrupoles are inexpensive to acquire and easy to operate. They provide max. 300m⁻² strength for 3MeV/c beams.

Electron trajectories (with Bmad [5]) for an axisymmetric lens in diffraction (left) and imaging (right) operation modes, built using a 2.5m long Russian Sextuplet.

Dark-field mode optics in imaging (left) and diffraction (right) operational modes, built using two consecutive axisymmetric lenses, 2.5m long each.

LENS QUALITY COMPARISON

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

Same lens built with solenoids (top) or quadrupoles (bottom). The parameter values can be found in the tables below for the solenoid lens (left) and quadrupole lens (right).

Only K_3 value changes!

- We compare them by calculating the aberration coefficients [6] with Astra [7].

	Aberration Coefficient	Quad. Diff.	Sol. Diff.	Quad. Imag.	Sol. Imag.
	$<x\|x_0>$	1.91	1.92	0.10	0.08
	$<y\|y_0>$	1.91	1.92	0.10	0.08
	$<x\|x_0'>$ [m/rad]	0.02	0.04	-0.97	-0.94
	$<y\|y_0'>$ [m/rad]	0.03	0.04	-0.89	-0.94
Chromatic	$<x\|\theta_0\delta_0>$ [m/rad]	-1.11	-1.15	5.95	6.6
	$<y\|\phi_0\delta_0>$ [m/rad]	2.1	2.1	5.22	5.7
	$<x\|x_0\delta_0>$ [m/rad]	1.63	2.78	1.52	5.28
	$<y\|y_0\delta_0>$ [m/rad]	3.87	2.78	6.3	5.28
Spherical	$<x\|\theta_0^3>$ [m/rad³]	0.48	-42.85	-7.06	-770.21
	$<y\|\phi_0^3>$ [m/rad³]	0.31	-42.85	-7.38	-770.21
	$<x\|\theta_0\phi_0^2>$ [m/rad³]	-34.85	-42.85	-345.88	-770.22
	$<y\|\theta_0^2\phi_0>$ [m/rad³]	-64.08	-42.85	-344.00	-770.22

CONCLUSIONS

- Electron optics for dark-field mode has been designed using quadrupole-based lenses.
- A single parameter change switches modes.
- The quad. lens has smaller aberration coefficients than a solenoid-based equivalent lens.

ACKNOWLEDGEMENT AND PARTNERS

- Prof. Dr. Christoph Koch, Katrina Coogan (Humboldt-Universität zu Berlin)
- Prof. Dr. Ralph Ernstorfer (Technische Universität Berlin, Fritz-Haber Institute)
- Dr. William Windsor (Fritz-Haber Institute)
- Prof. Dr. Helene Seiler (Freie Universität Berlin)

MORE INFORMATION

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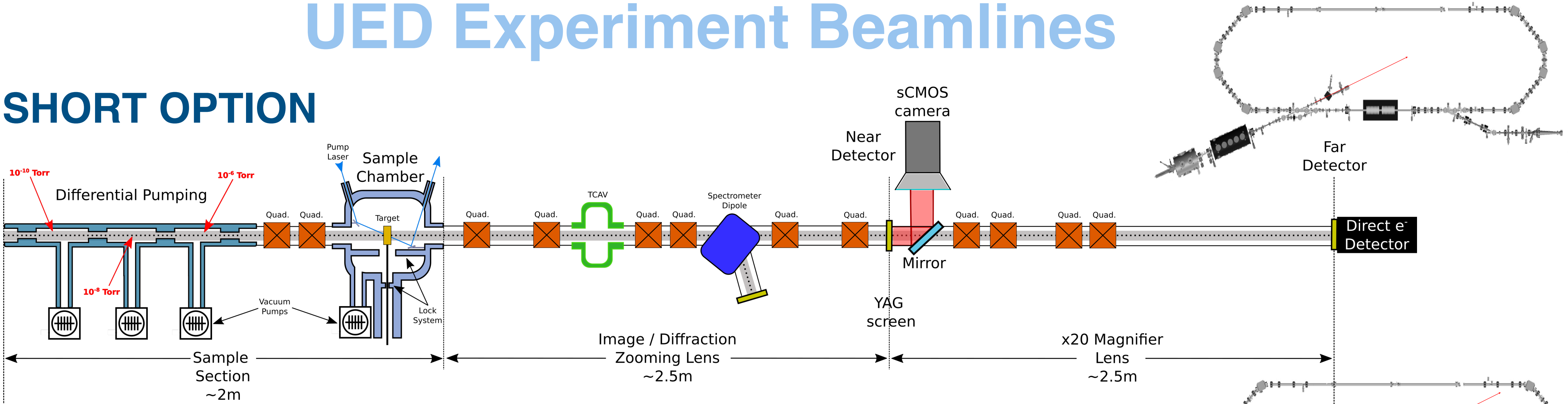
Solenoid

More information: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9349226/

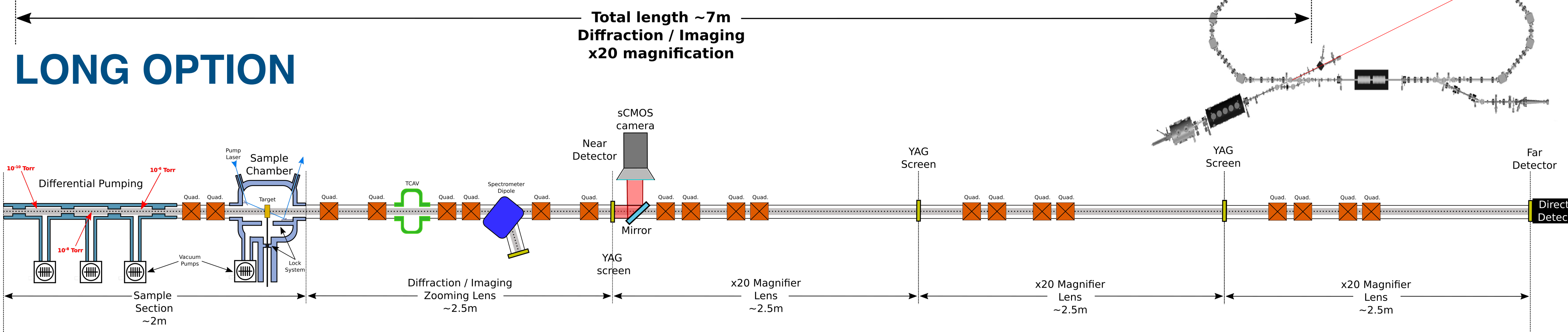
UED Experiment Beamlines

SHORT OPTION



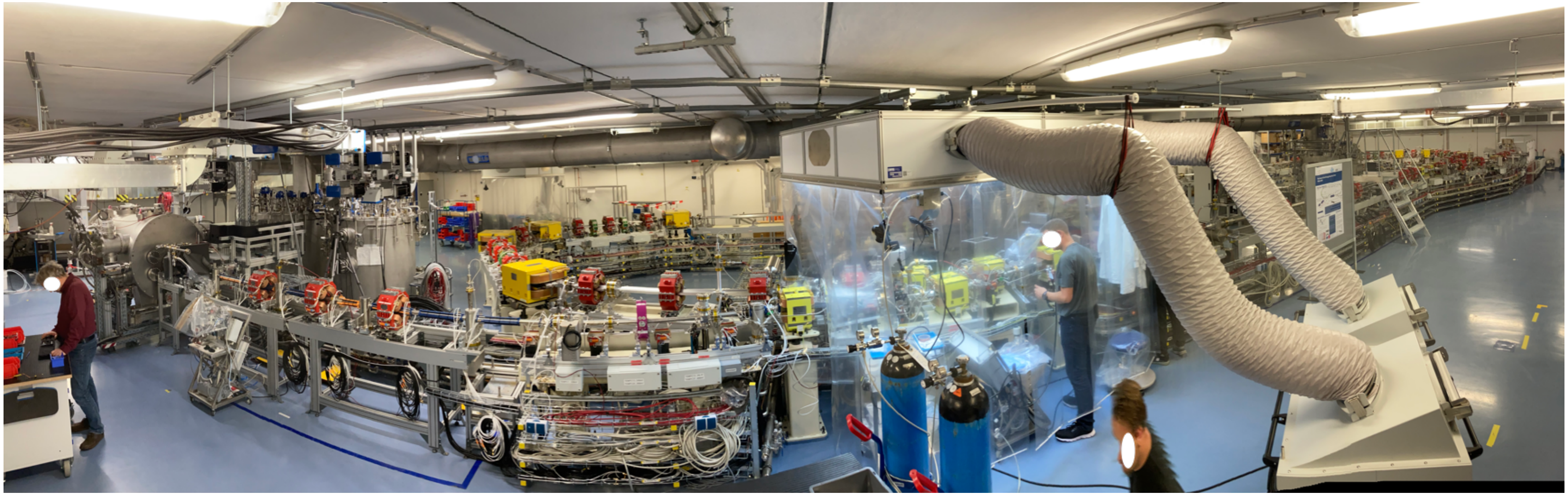
Total length ~7m
Diffraction / Imaging
x20 magnification

LONG OPTION



Total length ~12m
Diffraction / Imaging
x8000 magnification

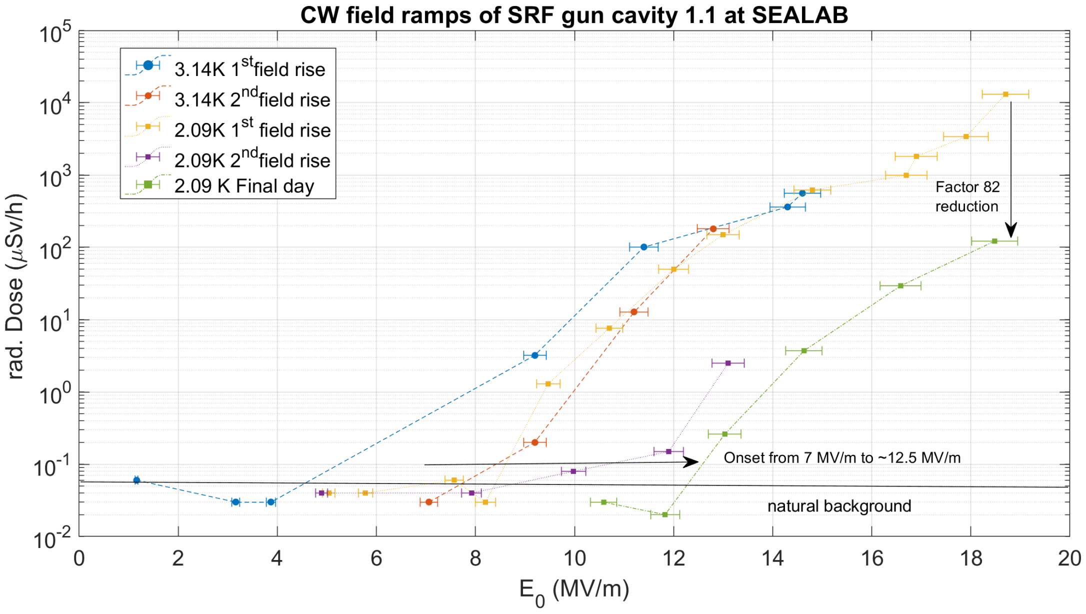
Stages at bERLinPro



Installed: 10-mA SRF gun + merger + recirculation + dump
Installed: Proof-of-principle UED experiment
Planned: Waster water treatment demonstrator
Funded: Booster module. Produced but assembly required
Not funded: LINAC module
Not funded: 100-mA class photoinjector

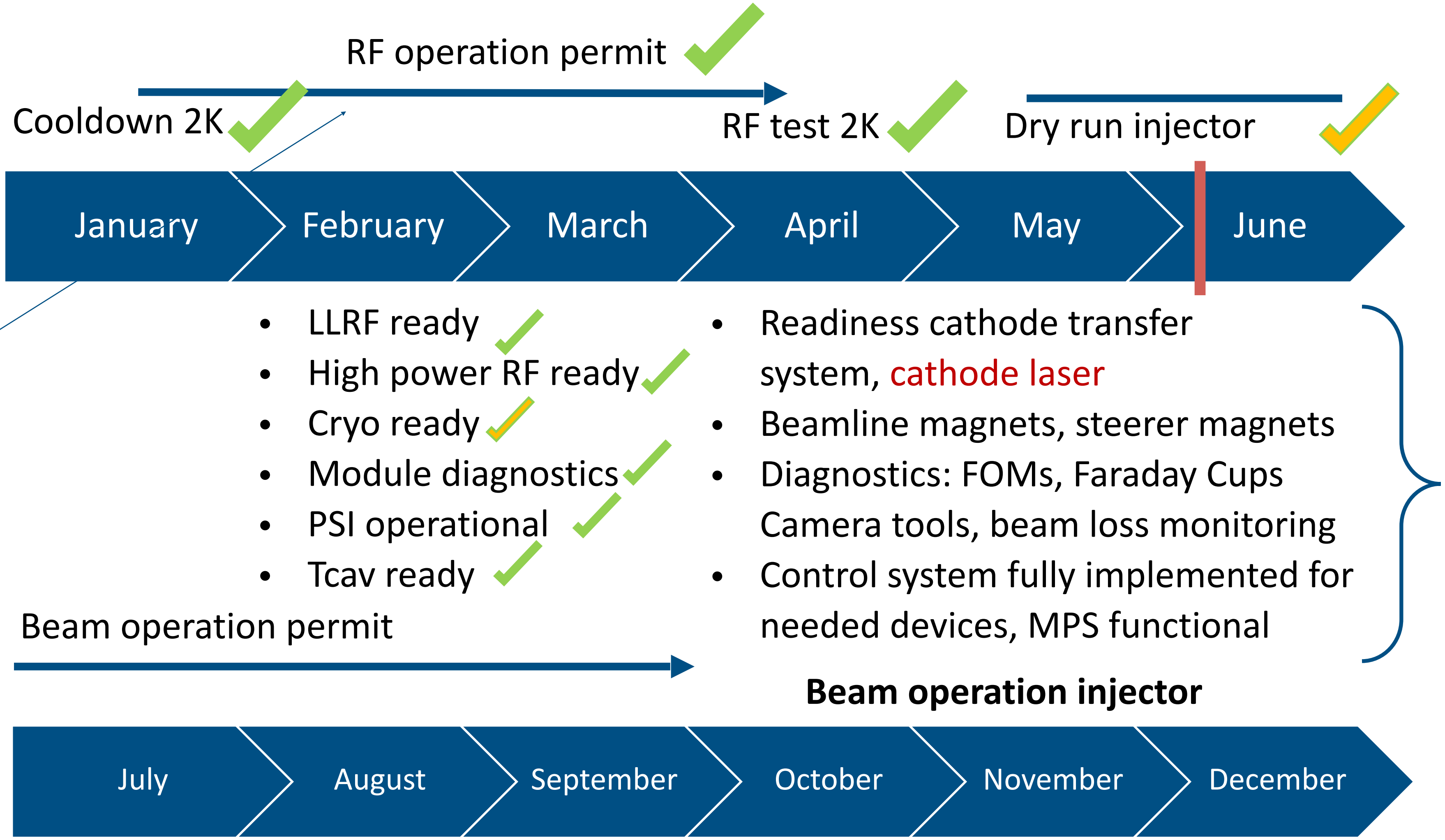
- SRF photo-injector and diagnostics ready for commissioning
- Final preparation of cathode-laser beam transport
- 1.3 GHz laser demonstrated 23 W CW → sufficient for 100 mA @ 2.5% QE
- **Beam operating permit expected Q3 2024 → First beam from SRF Gun around 10-11/2024**

RF Tests



- Successful RF test, beam energies up to 2.1 MeV
  → there is room for progress
- Laser system, diagnostics, beam transport optics, beam loss monitoring (several systems) installed and ready
- Cathode transfer system ongoing

A rough 2024 schedule



RF operation permit ✓

Cooldown 2K ✓

RF test 2K ✓

Dry run injector ✓

- 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 ✓

Beam operation permit

- 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

Ongoing

Beam operation injector

- Commissioning program beam ready, first measurement applications

Thank you for you attention!

Many thanks to:

HZB bERLinPro Team & friends
former colleagues
Team Sealab

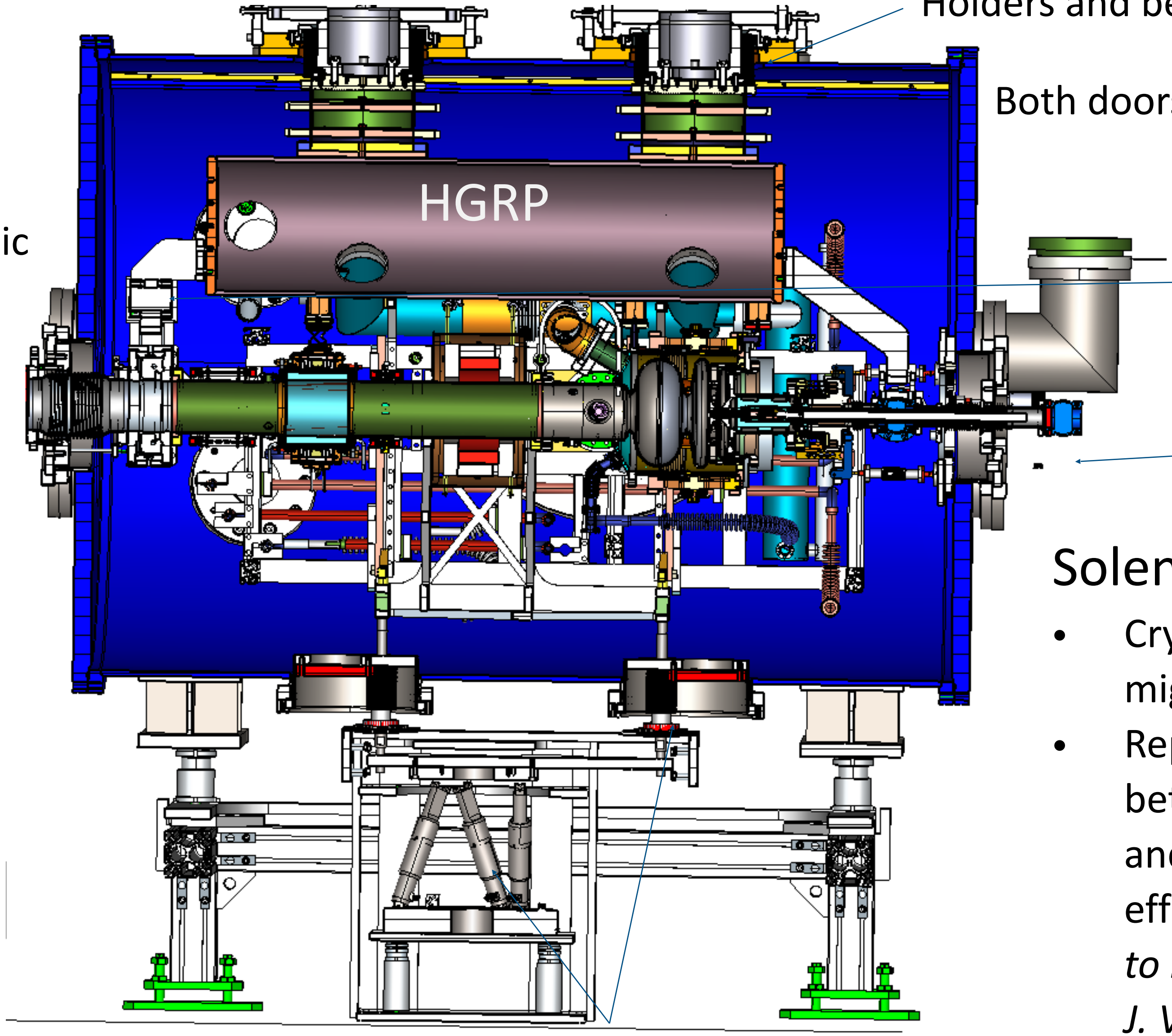
Backups

Module layout of bERLinPro SRF Gun

80K helium shield

2nd magnetic shield

Beam



Holders and bellows for alignment

Both doors can be opened

Modified: Issue with thermal short

Cathode transfer system port

External Solenoid hexapod mover with feedthroughs

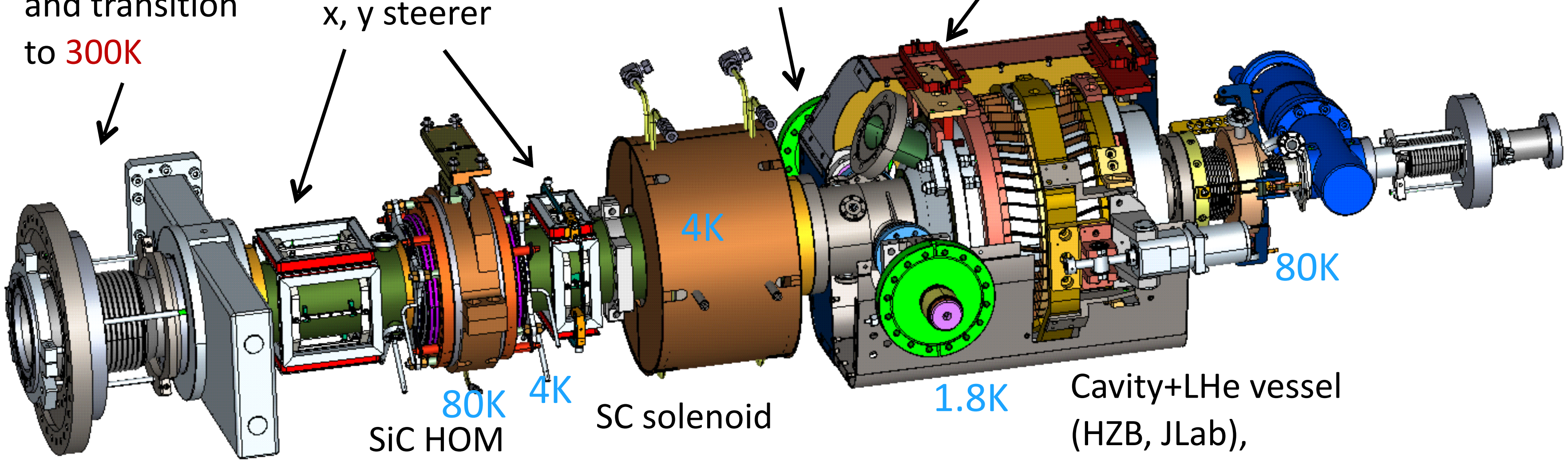
- 4K cooling:
    - Solenoid
    - HOM load
    - FPCs
- 4K filling line cavity
- 1.8 K JT line cavity
- 80K FPC and HOM
- 80 K shield and cathode

Solenoid shielding:

- Cryoperm around solenoid might saturate
- Replaced by Nb disc between Solenoid and cavity outer shield, efficiency factor 5-8 *to be published by J. Völker et al.*

Cold String layout of bERLinPro SRF Gun

Parameter	Design	As built
TM_{010} freq. (MHz)	1300	1300
$R/Q(\Omega)$ $\beta = 1$	150	132.5
$G(\Omega)$	174	154
P_{forward} max. (kW)	20	20
E_{peak}/E_0	1.45	1.66
$B_{\mathrm{peak}}/\mathrm{E}_{\mathrm{peak}}$ (mTMV^{-1}m)	2.27	2.18
E_{kin} (MeV)	3.5	2.5-3



Gate valve and transition to 300K

x, y steerer

Twin CW-modified TTF-III coupler up to 20 kW

Support structure

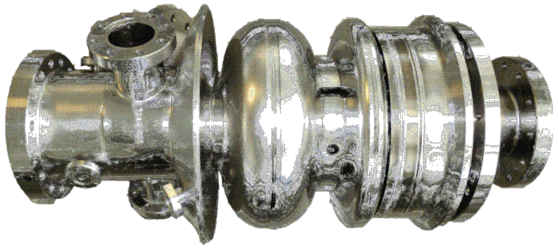
Cathode tube with tuner (HZDR)

SiC HOM absorber (Cornell)

SC solenoid

Cavity+LHe vessel (HZB, JLab), Cornell-type blade tuner, 2 layer magnetic shielding

1.4x$\lambda/2$ cells + Choke cell

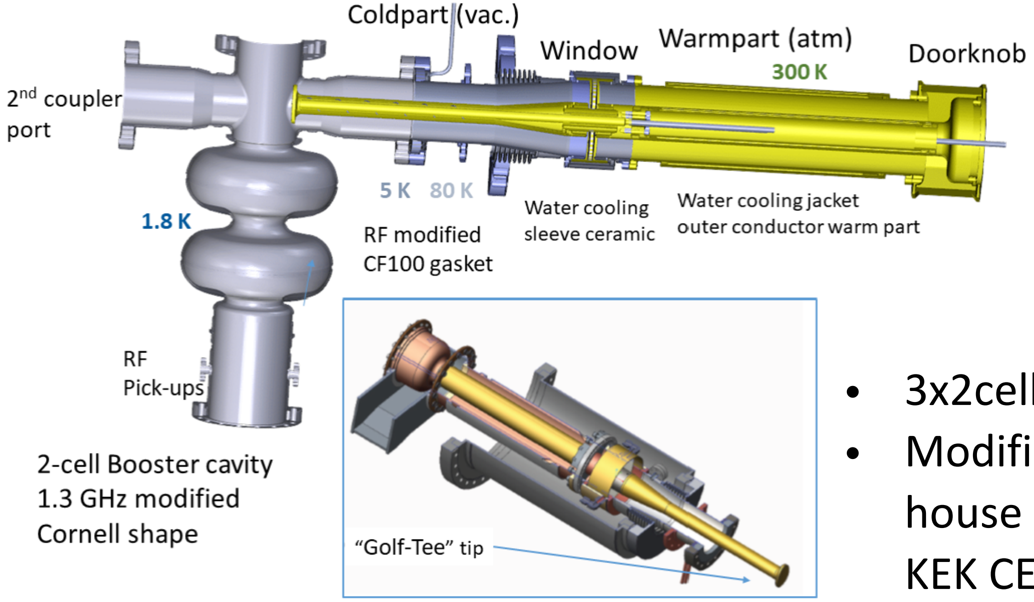


Prototype designed by HZB manufactured by JLab

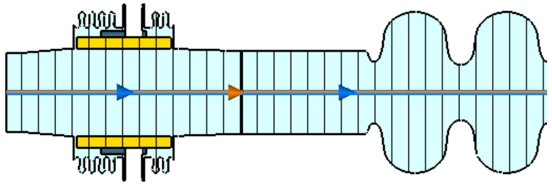
Parameter	VTA JLab*	HTA HZB*	Cold string HZB*
E_0 (MVm^{-1})	34.9	34.5	$28.5^{\ddagger}$
E_{peak} (MVm^{-1})	58	57.3	47.3
B_{peak} (mT)	111.8	110.4	91.2
low field Q_0	$1.2\cdot10^{10}$	$1.1\cdot10^{10}$	$9.6\cdot10^{9}$
$\Delta f/\Delta E_0^2$ (HzMV^{-1}m)^2	-4.7	-3.7	-3.4
$\Delta f/\Delta P_{\mathrm{LHe}}$ (Hzmbar^{-1})	-561	150	33

*15-20% higher found by beam energy measurements

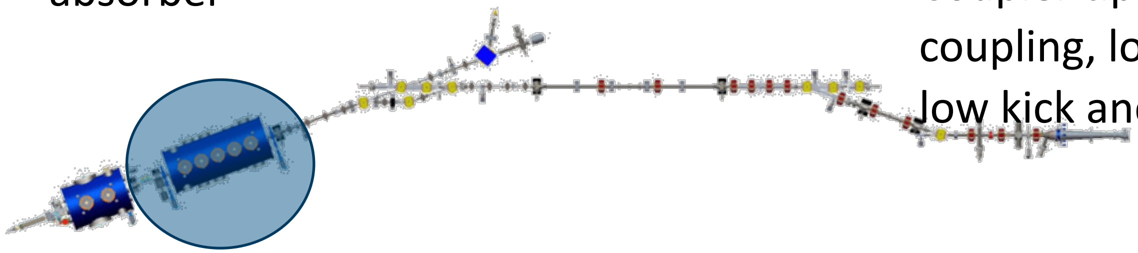
Status of the Booster



2-cell Booster cavity
1.3 GHz modified
Cornell shape

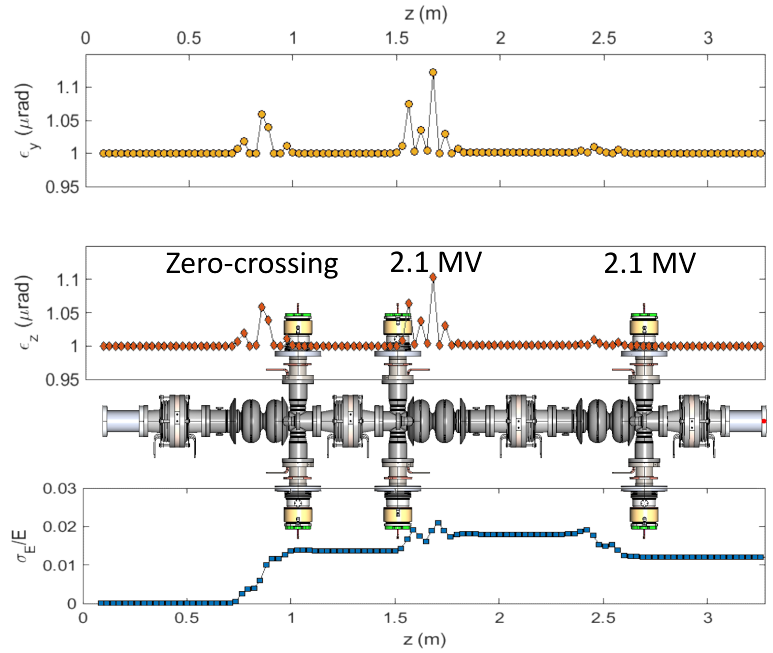


Cornell style SiC beamtube HOM absorber

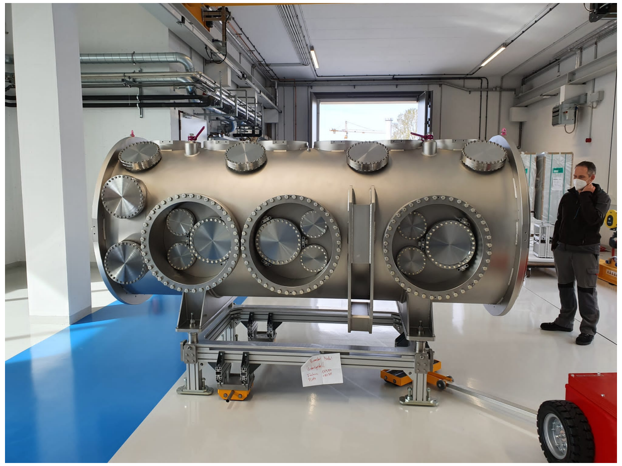


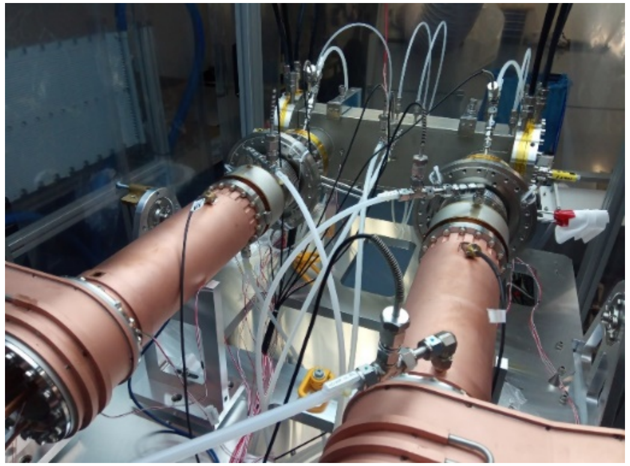
- 3x2cell Cornell style cavities
- Modified coupler section to house a redesigned version of the KEK CERL couplers
- 120 kW travelling wave per coupler at 100 mA
- For first stage, loaded Q is increased to be optimized for max. current of SRF gun
- Coupler tip optimized for improved coupling, low penetration depth, low kick and emittance dilution

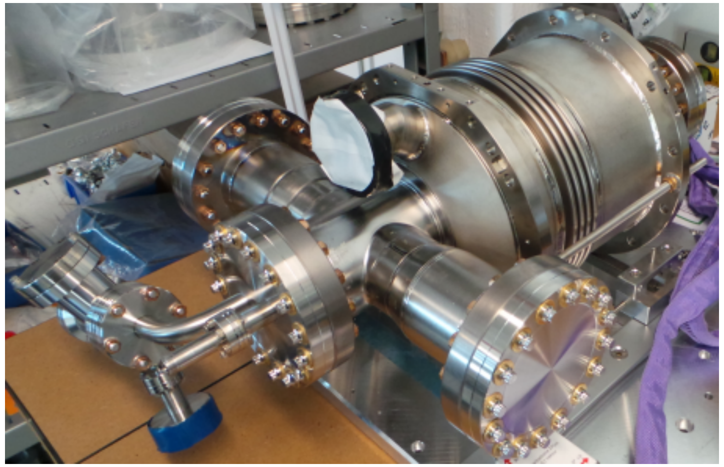
Parameter	**at 100 mA**	**at 6 mA**
Loaded Q	$1.05 \cdot 10^5$	$1.74 \cdot 10^6$
$f_{1/2}$	6.2 kHz	374 Hz
V_{acc}	0.56, 2.1 MV	0.56, 2.1 MV
E_0 (MV/m)	4.833, 19	4.833, 19
Φ_{acc}	-90, 0 deg	-90, 0 deg
Penetration depth	2 mm	–18 mm
P_{forward} TW	3.4, 220 kW	0.2, 13.8 kW
P_{forward} SW	3.4, 54 kW	0.2, 3.45 kW

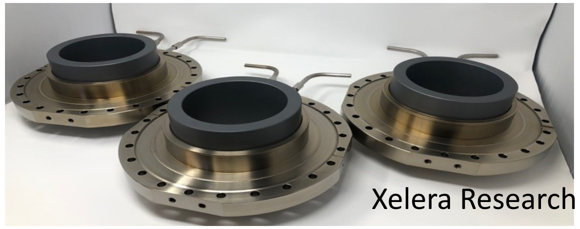


High power Booster module parts

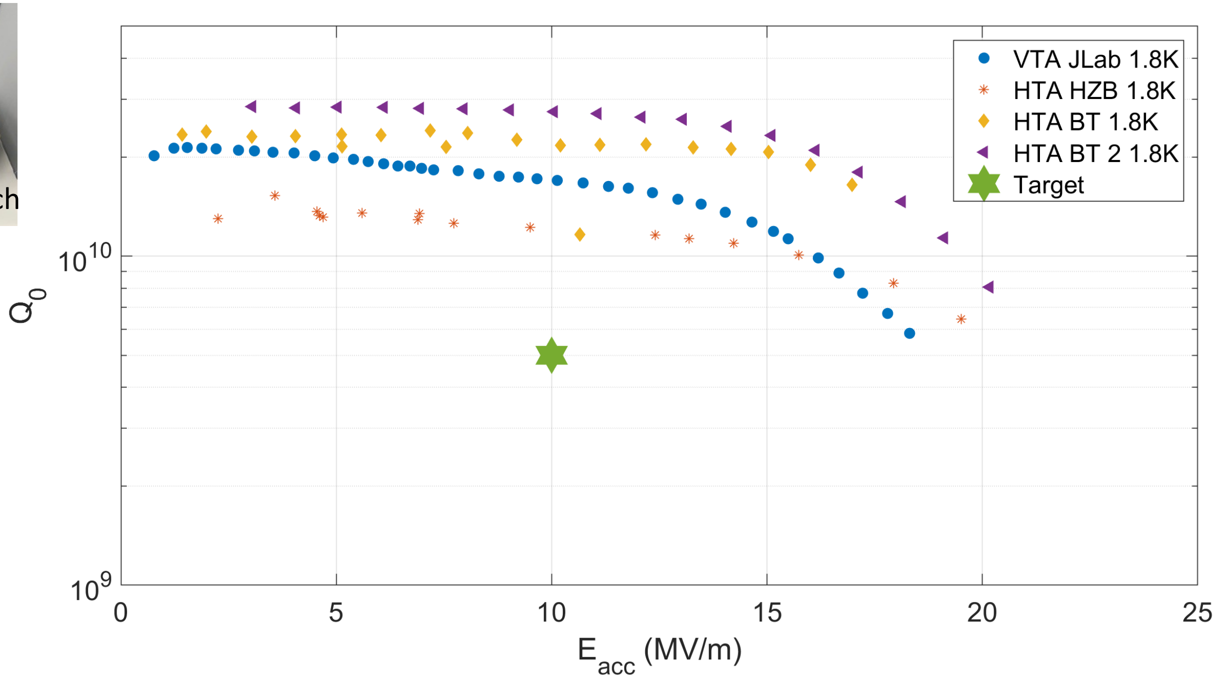








HOM absorber parts

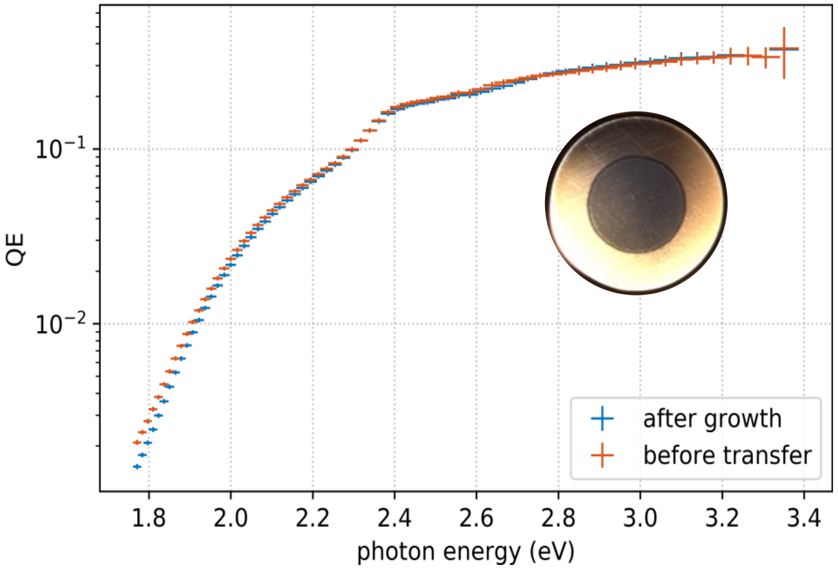


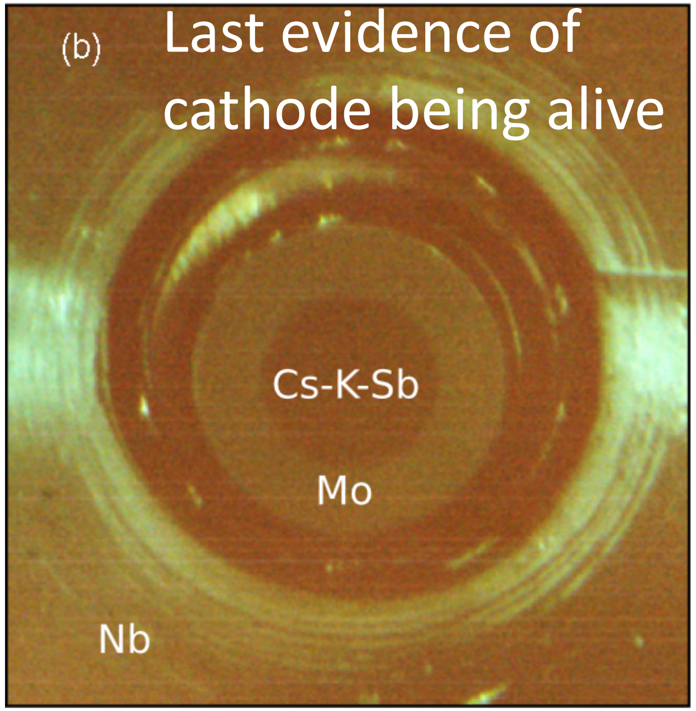
- Cavities outperform specs
- Coupler are being conditioned
- One cavity has been tested with tuner and magnetic shielding
- HOM arrival last winter→ all parts for cold string in house

Development of high QE cathode and drive Laser

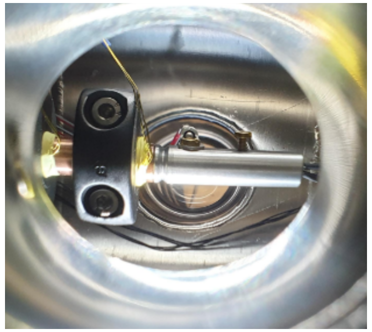
Photocathode preparation and analysis laboratory up and running since 2015

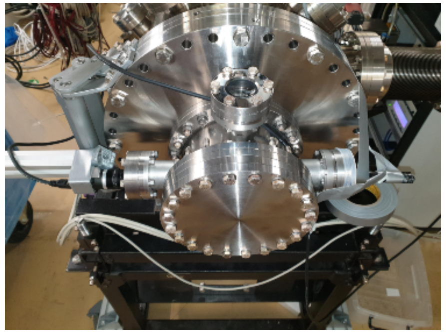
- insight into growth process with material science studies in parallel
- achieved quantum efficiency of 16.8% at 515 nm (specs 1%)
- successful transfer from cathode lab to SRF gun
- demonstrated, that cooling of cathode to 120 K do not harm quantum efficiency (unlike prediction by other researchers!)



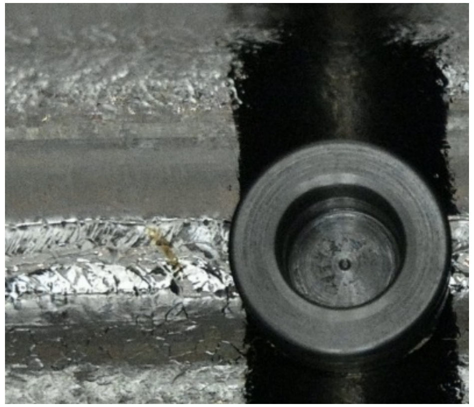

Last evidence of cathode being alive

doi:10.1103/PhysRevAccelBeams.21.113401





We were close to operate this record cathode in Gunlab…….



And learned from our fails…..

…cathode holder heating and shock experiments, Na based cathodes…..and the cavity?