SEALAB/ bERLinPro

HZB Helmholtz Zentrum Berlin

bERLinPro@SEALab

A contribution to European Accelerator Roadmap for ERLs

08/23/23, A. Neumann for the Sealab/bERLinPro Team

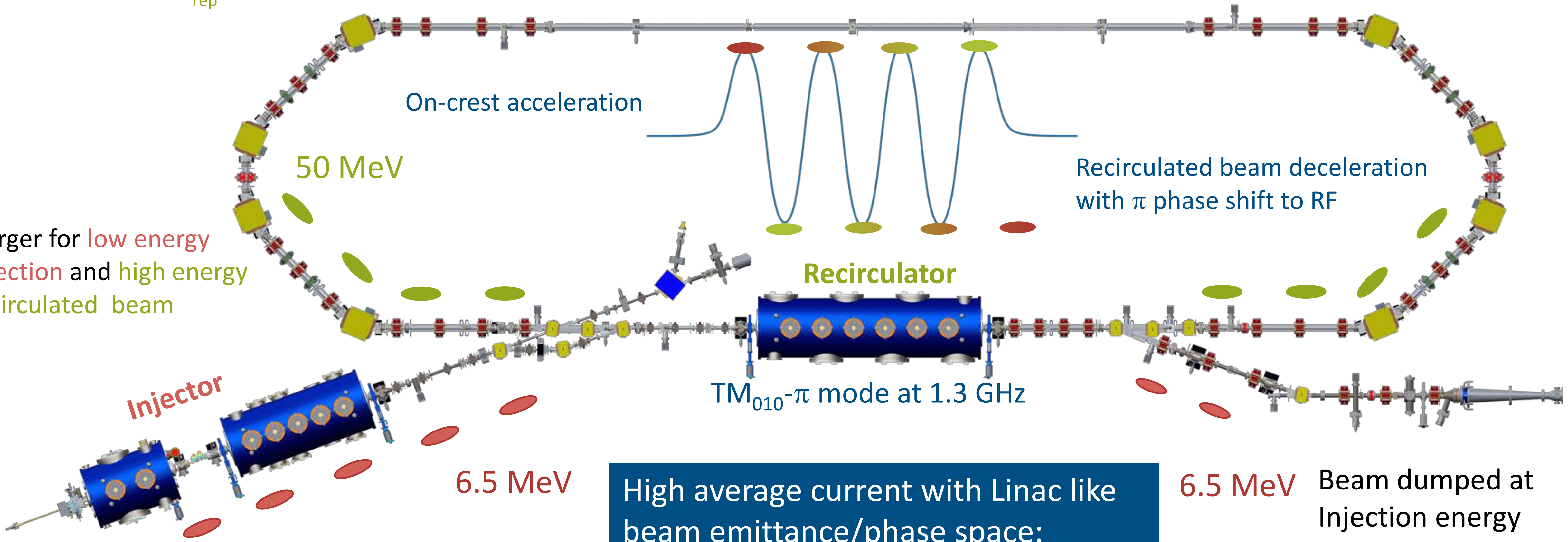
EPS-High Energy Physics 2023 Conference

Universität Hamburg, Hamburg, Germany

Do you want to know more?

THE ERL Principle: The Promise

Maury Tigner, A possible apparatus for electron clashing-beam experiments, Nuovo Cim., 37:1228–1231, 1965, http://doi.org/10.1007/BF02773204.



High average current with Linac like beam emittance/phase space:
No net beam power transfer in Linac!

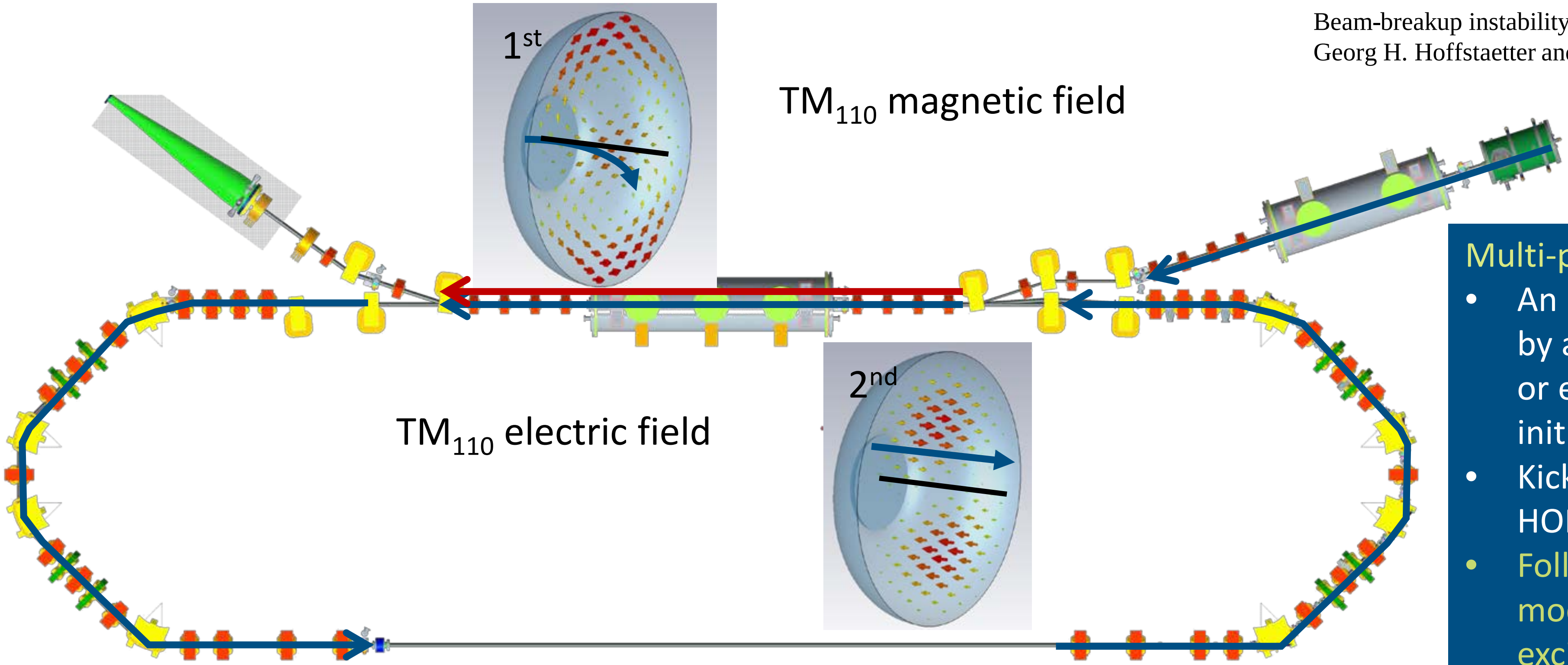
All perfect, can we start right away?

- No net power transfer between cavity and beam: tens to 100 mA beam current possible → Higher order mode issues*
  Note: SRF based machine record 10 mA (JLab)
- Only RF power required to sustain field in SRF cavity (+over-coupling for stability reasons, detuning control)
- Main power invest in the injector, which is also transferred to the beam dump → High power RF couplers, 100 kW class
- Beam losses in the recirculator need to be controlled to a low level → Beam halo formation, precise synchronization, beam loss diagnostics

*We roughly know from thermodynamics, nothing is for free in physics: The limits or, why do we need demonstrator facilities like PERLE and bERLinPro?

The limit: Beam Break-Up in ERLs

Beam-breakup instability theory for energy recovery linacs
Georg H. Hoffstaetter and Ivan V. Bazarov, PRST-AB, Vol. 7, 054401 (2004)



Multi-pass transverse beam breakup (BBU):

- An injected beam receives an initial kick by a given dipole higher-oder mode (HOM) or excites in first pass a dipole mode by its initial injection caused offset
- Kick→offset by optics, beam couples to HOM dipole electric field
- Following beam is deflected by the dipole mode and receives more offset → stronger excitation of HOM if phase advance by optics allows positive feedback
- Single mode BBU can be mitigated by proper setting of optics phase advance (while preserving recovery) or by RF feedback techniques within cavity or transverse optics manipulations
- Multi-mode problem usually tackled by proper HOM damping techniques
- **This is an intensity effect!**

Single cavity, single HOM case!

$$I_{\mathrm{th}} = -\frac{2\gamma}{e}\frac{c}{\frac{R}{Q}_{\perp} Q_{\mathrm{ext}}\omega M_{12}}\frac{1}{\sin(\omega t_{\mathrm{r}})}$$

Recirculation time

Cavity figure of merits: R/Q, w determined by shape

HOM damping

Sum and product of transport matrix, HOM polarization

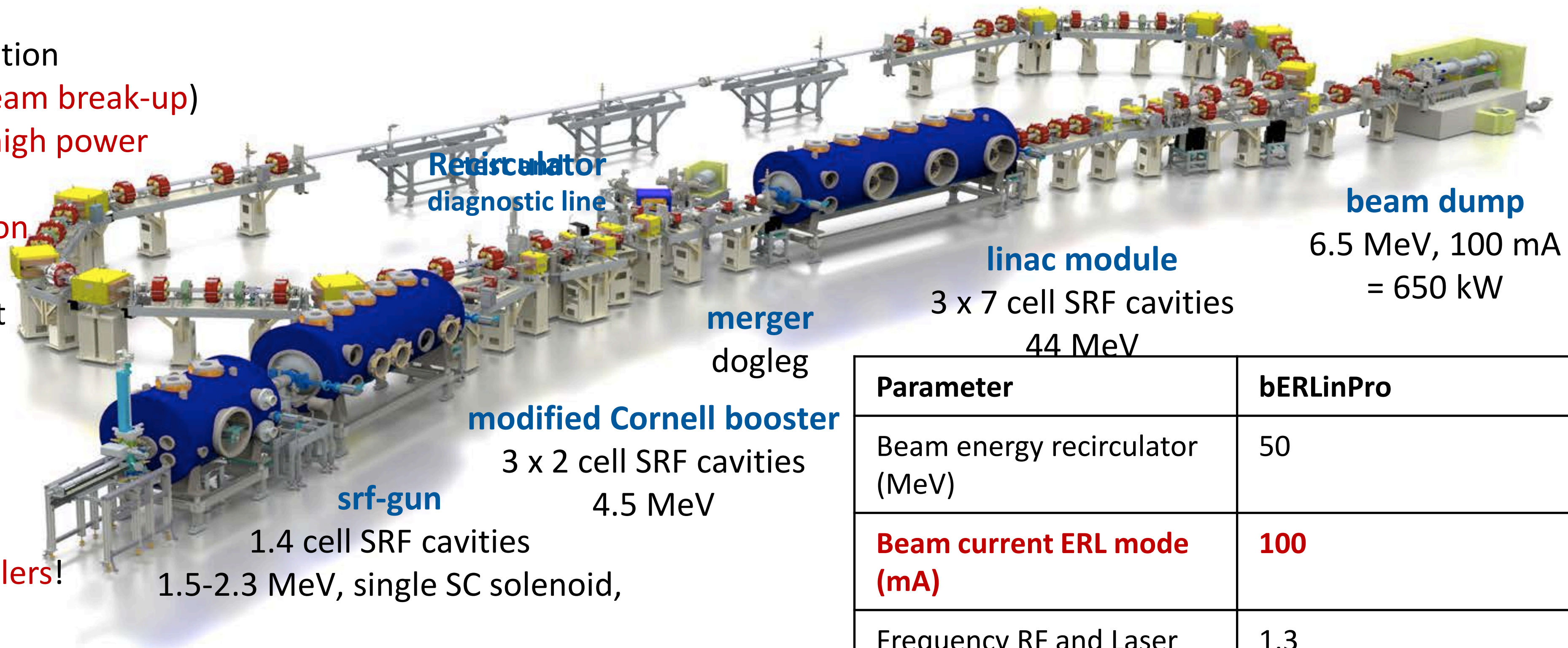
How did bERLinPro tackle this?

bERLinPro: A demonstration facility for ERL science and technology

bERLinPro
Helmholtz-Zentrum Berlin

New developments:

- Beam dynamics and manipulation (merger, recirculator, study beam break-up)
- SRF systems: Photo-injector, high power booster, HOM damped Linac
- Electron source: High repetition laser system
  high QE cathode development
- Control of beam losses and radiation protection
- High power beam dump
- High power CW RF
  - Few 100 kW class klystrons → Power couplers!
  - Some 10 kW solid state amplifier
- Diagnostics, synchronization machine protection, beam loss monitoring, LLRF and detuning control
- A stable, efficient Cryoplant



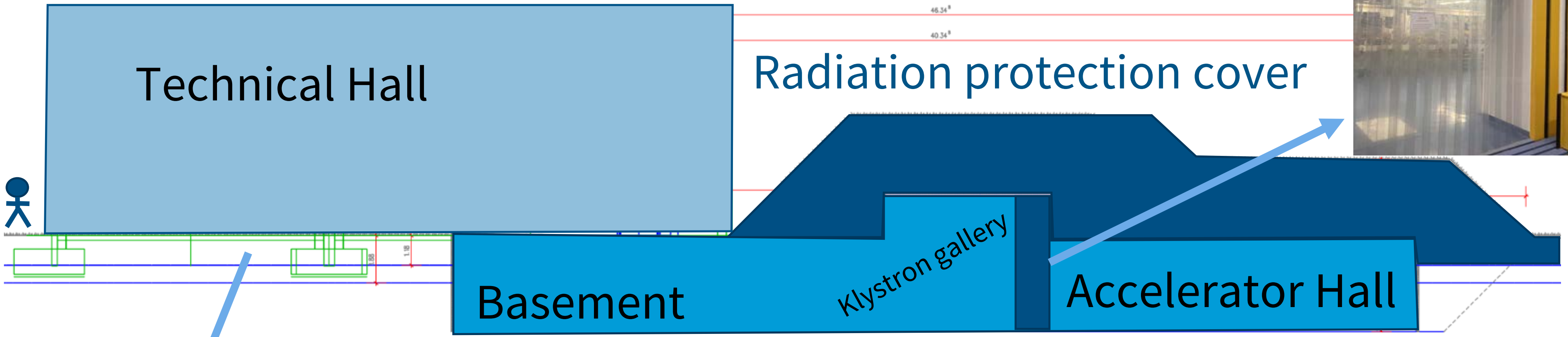
Parameter	bERLinPro
Beam energy recirculator (MeV)	50
Beam current ERL mode (mA)	**100**
Frequency RF and Laser (GHz)	1.3
Normalized emittance (mm mrad)	**1 (< 0.6 in simulations)**
Bunch length (ps)	**< 2 (ERL mode), 100 fs @ 10 mA**
Beam losses	$<< 10^{-5}$ @ 100 mA

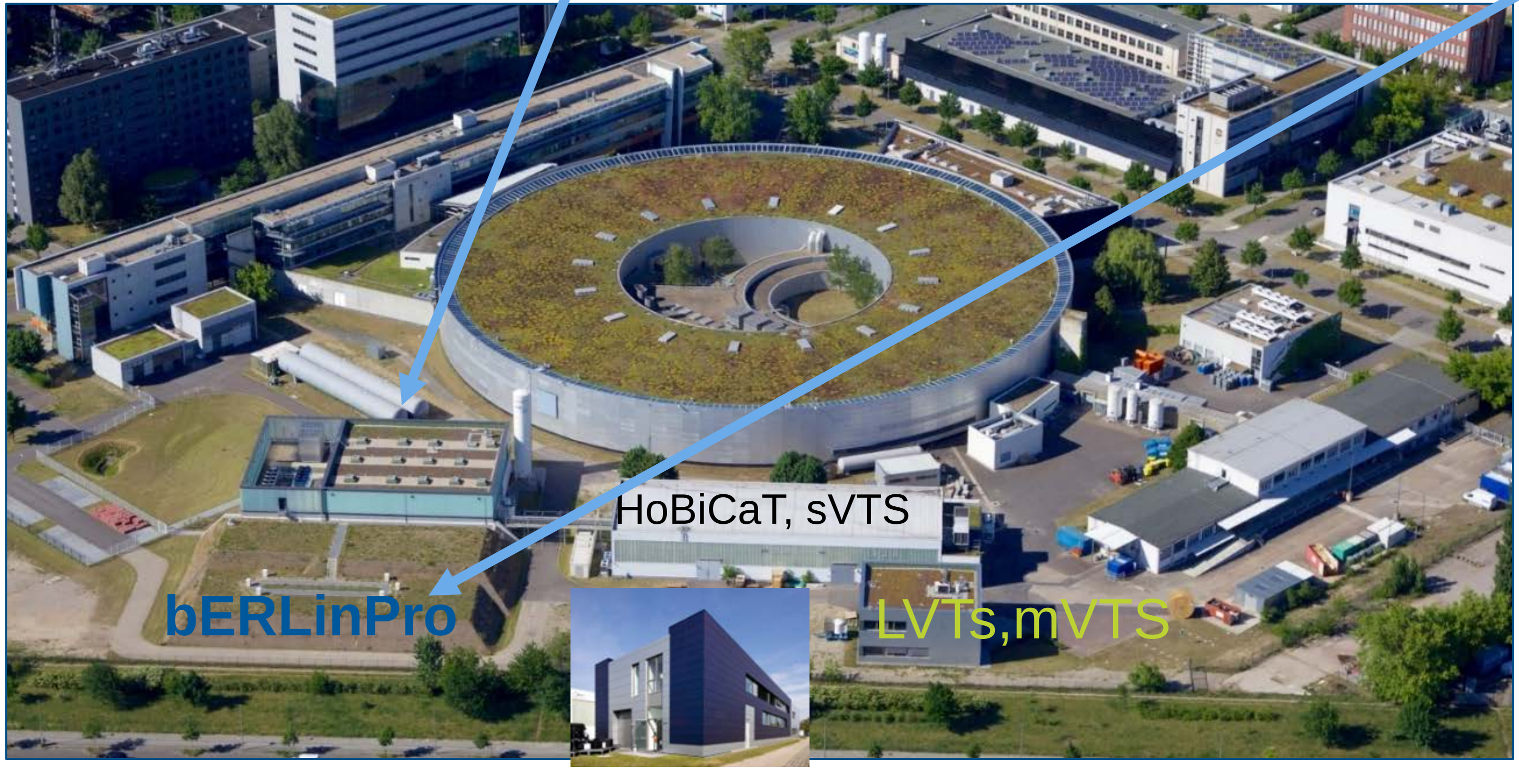
A fully funded 42 M€ project (including completely new building!)

bERLinPro in Berlin Adlershof

TH2, TH1: Cleanrooms, SRF Teststands

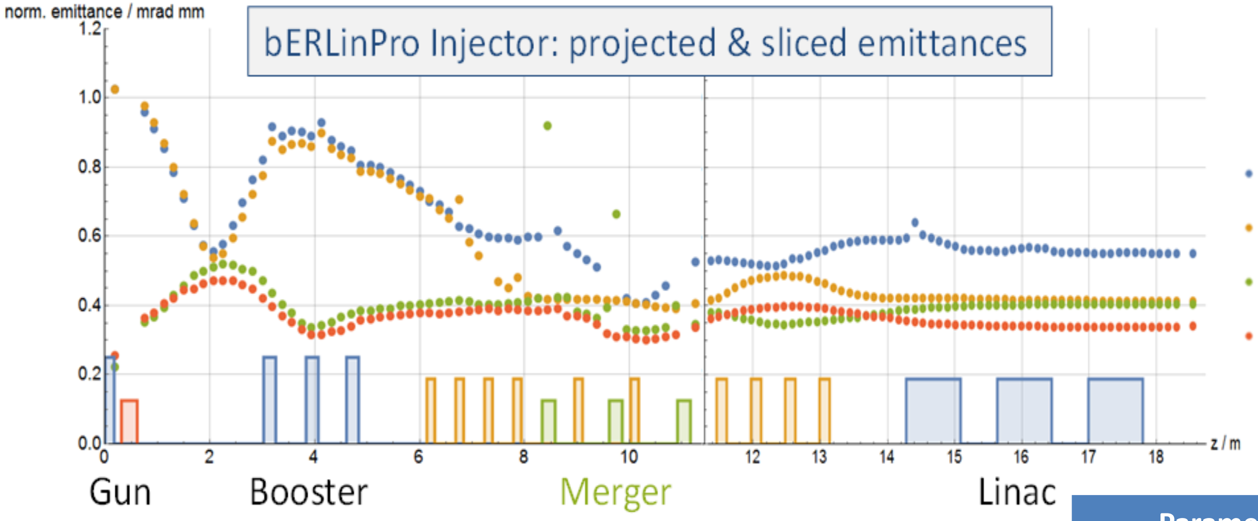
bERLinPro: A quick orientation



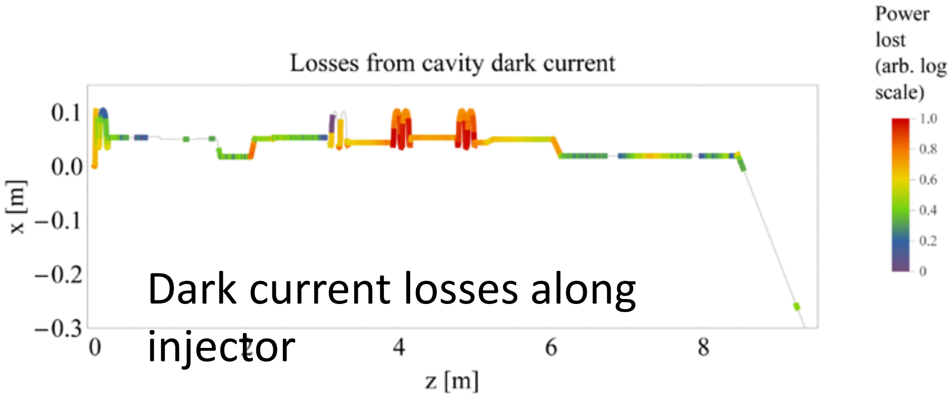


- bERLinPro is located in a subterraneous radiation protection shelter prepared for maximum beam loss (30 kW in theory)
- All technical infrastructure, besides the klystron and some cryogenic installations are above ground in a technical hall

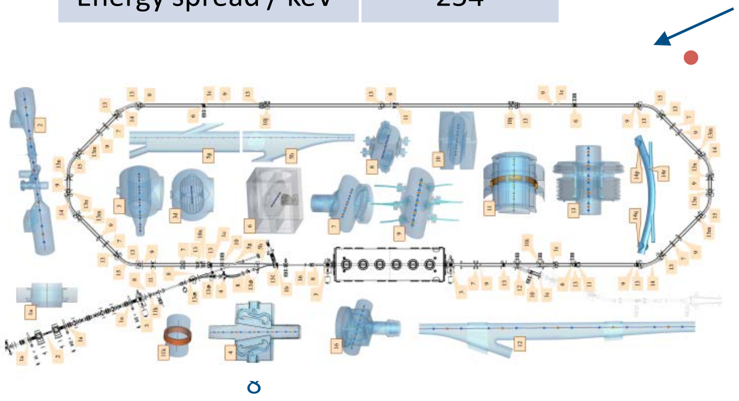
Beam optics studies



Parameters at LINAC exit	
Energy / MeV	50.1
Bunch length / ps	4.65
Emittance x,y / µm	**0.58/0.41**
Energy spread / keV	254



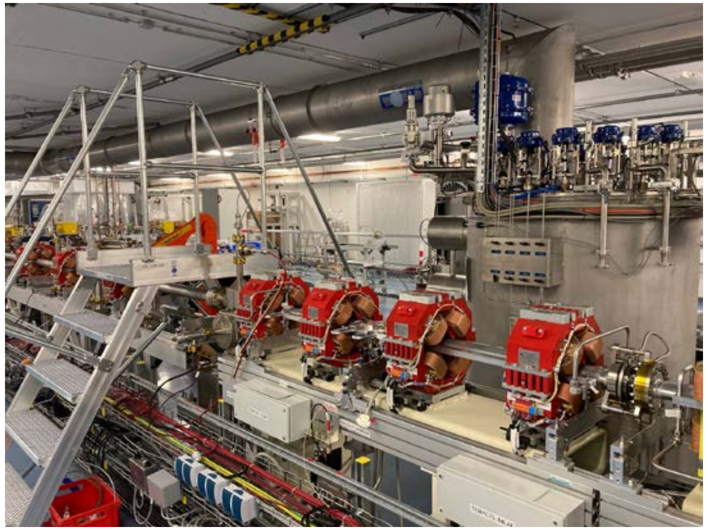
Dark current losses along injector



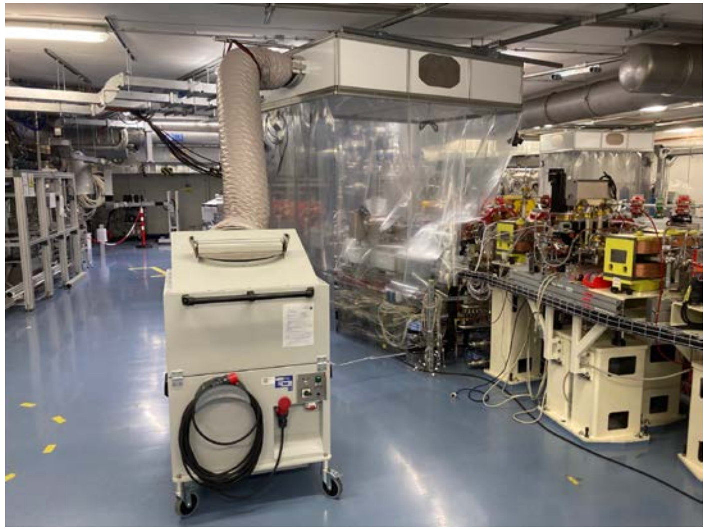
- Injector and recirculator optics design, magnet layout, collimators
- Start to end simulations (Astra+ Elegant), full 3D studies (OPAL), genetic optimization algorithms (MOGA), first look into ML
- Wanted vs. unwanted beam studies, dark current, halo formation,
- Beam break-up studies and countermeasures, wake analysis and component opt.
- Orientation of injector cavities optimized to:
  - Reduce coupler kick effects
  - Limit back travelling dark current towards cathode
  - Short pulse and low emittance modes

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

Beam vacuum system, magnets, cold boxes



Linac section with coldbox for cryogenics supplies

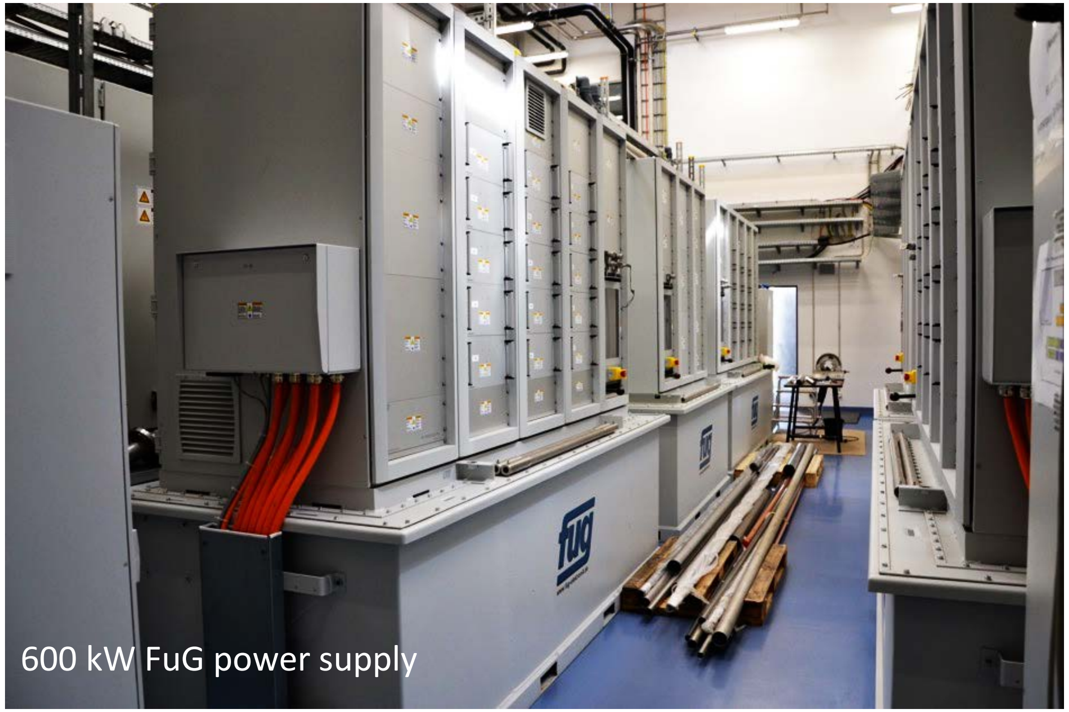


Rail system at ceiling to allow ISO5 flow-boxes everywhere at the machine to avoid particulates

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

RF and cryogenics installation status


1.3 GHz CW 270 kW Klystron
Second test in dummy load



600 kW FuG power supply

Pics courtesy W. Anders

- 3 Klystrons in house, 1 tested in SLH and at bERLinPro up to 270kW, currently in use for coupler conditioning
- 2 Klystrons will power Booster, 1 an high-power gun at some point
- 15 kW solid state amplifiers for Linac Tcav and 1st Booster (zero-crossing)

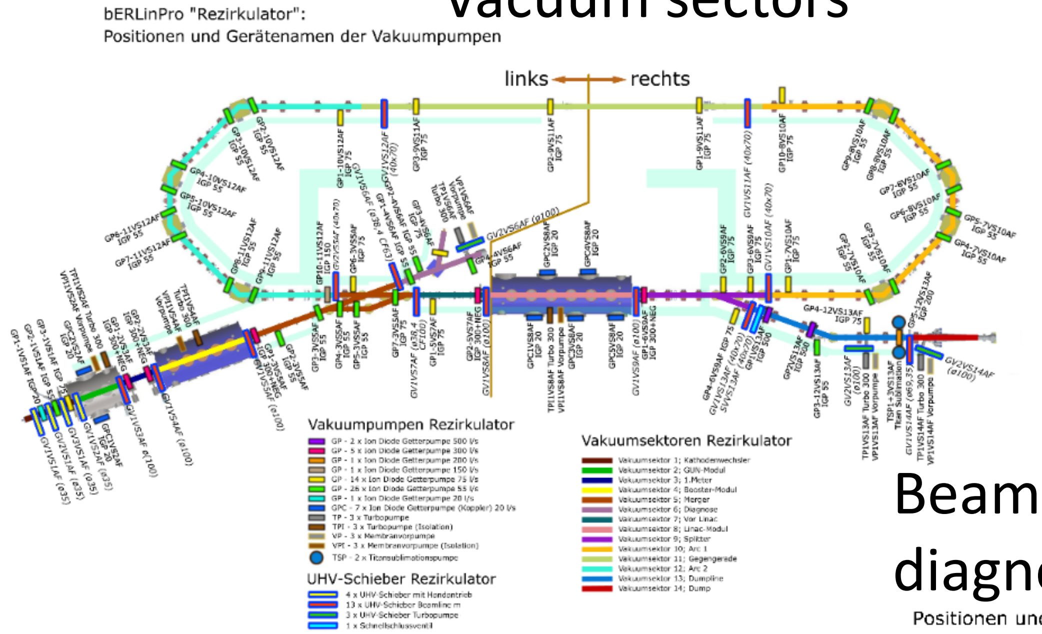

Booster+Gun coldbox

N_2 to cool L700

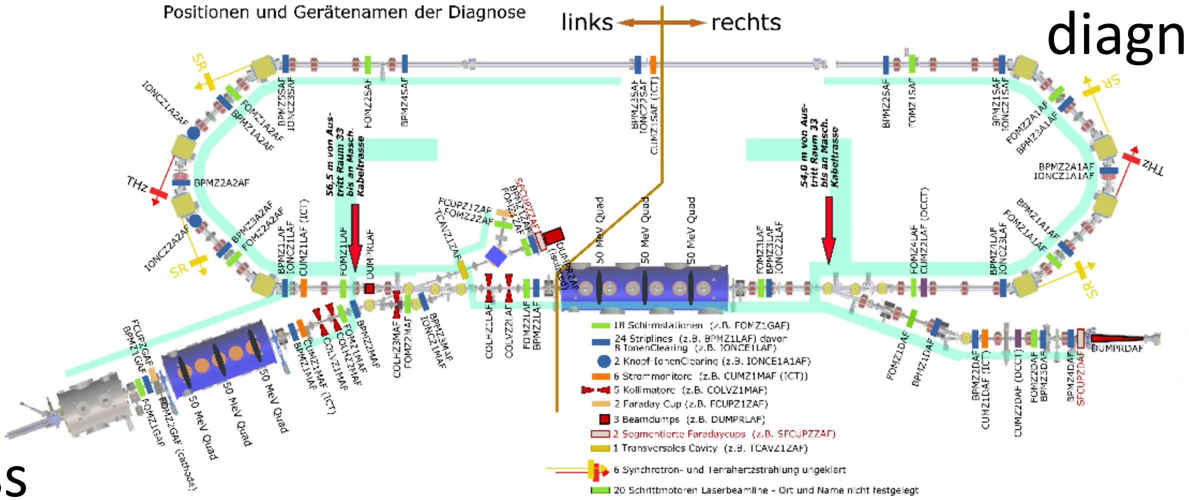
ACHIEVEMENTS

A glance at diagnostics and vacuum system

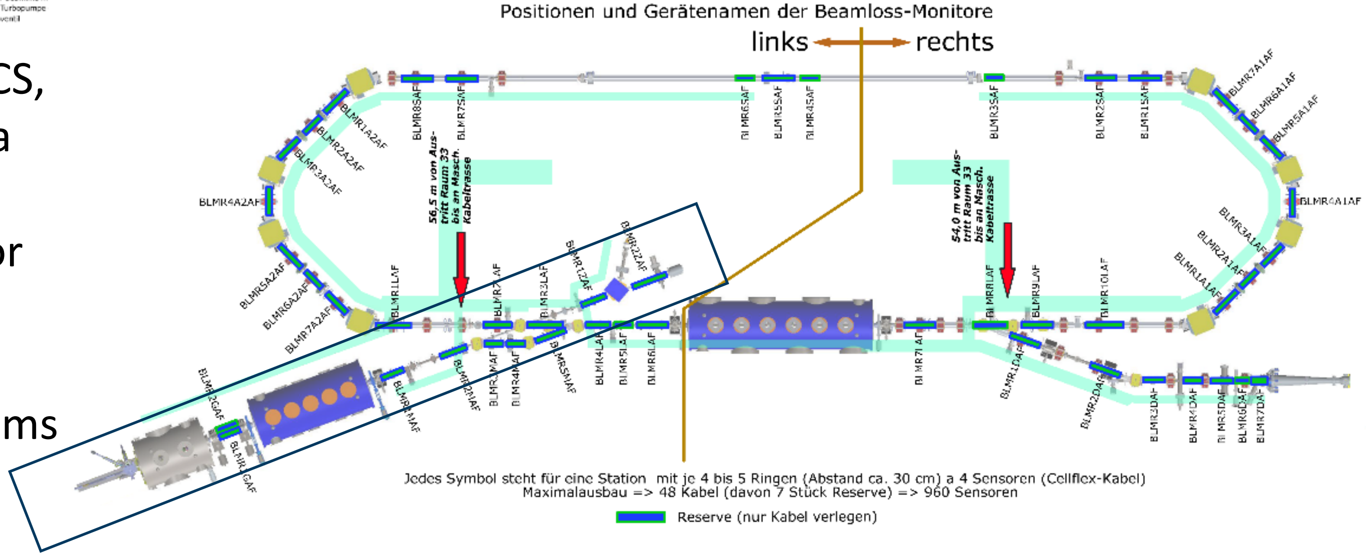
Vacuum sectors



Beam diagnostics



Beamloss diagnostics



+ Control system EPICS, visualization and data archiving
Jupyter Notebooks for Python based data analysis and measurement programs

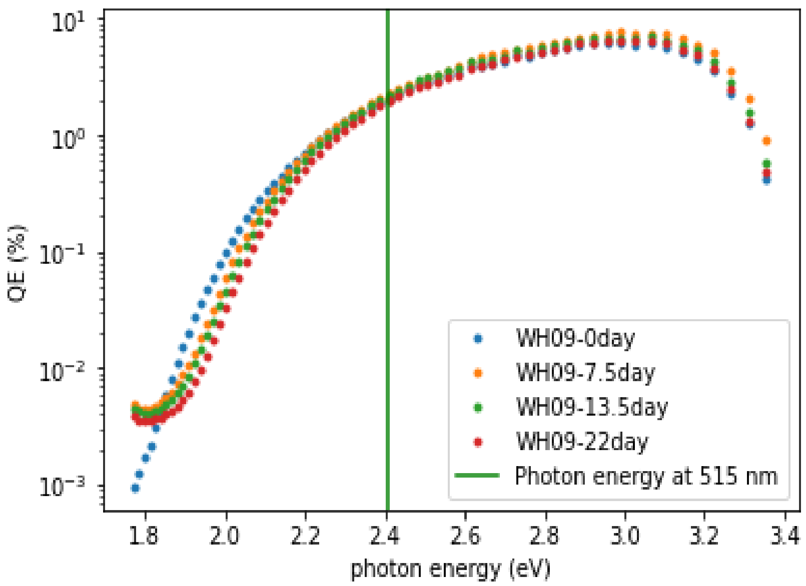
- 18x screen stations
- 24x Striplines, of which 8 with Ion clearing
- 2x button ion clearing
- 6x current monitors (ICT)
- 5x collimators
- 2x Faraday cups
- 3x Beam dumps
- 2 segmented Faraday cups
- 1 transverse defl. Cavity
- Option: 6x THz/Sync. Rad.

Optimizing the recipe for Na-K-Sb growth by QE and XPS measurements

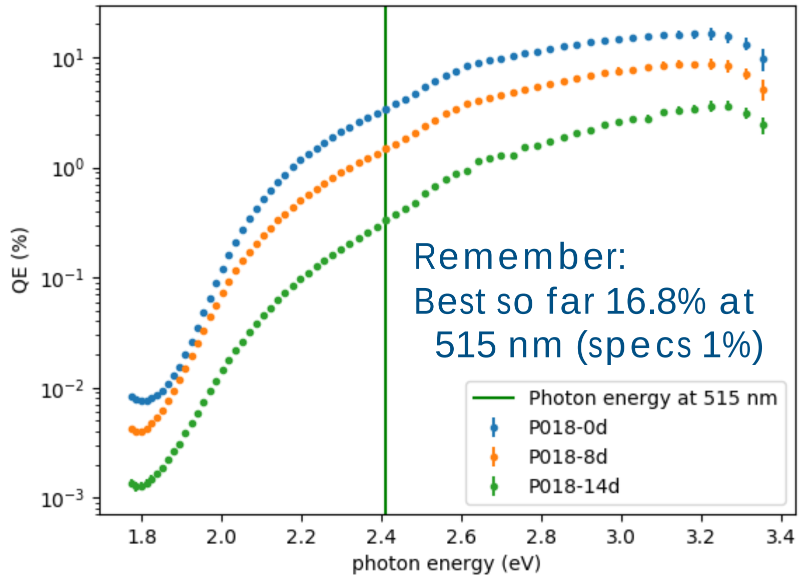
Investigations into Na-K-Sb as more temperature robust alternative to Cs-K-Sb (baseline cathode)

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%	-
	Lower QE, robust	High QE, sensitive

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.

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

UNIVERSITÄT SIEGEN

DFG

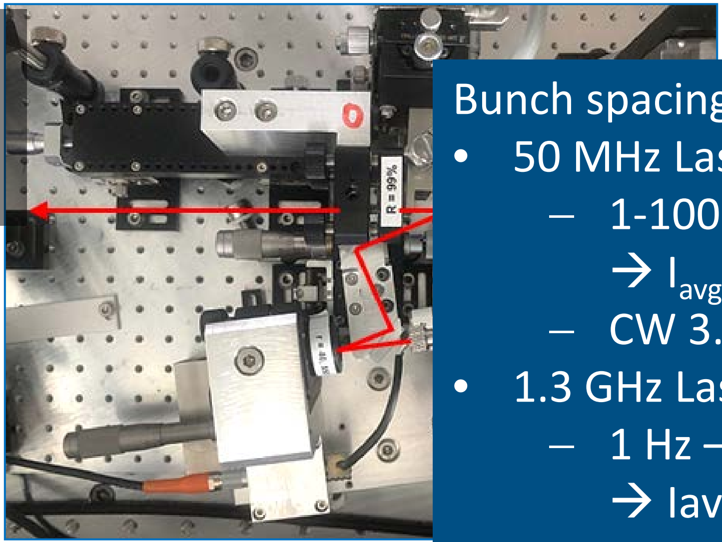
CARL VON OSSIETZKY UNIVERSITÄT OLDENBURG

HZB Helmholtz Zentrum Berlin

Drive laser ready for operation, laser beamline on-going (90% complete)

Two oscillators (50 MHz and 1.3 GHz), many pulse schemes, high average power (up to ~40 Watt) at 515 nm output

mode-locked (NIR) 1.3 GHz oscillator

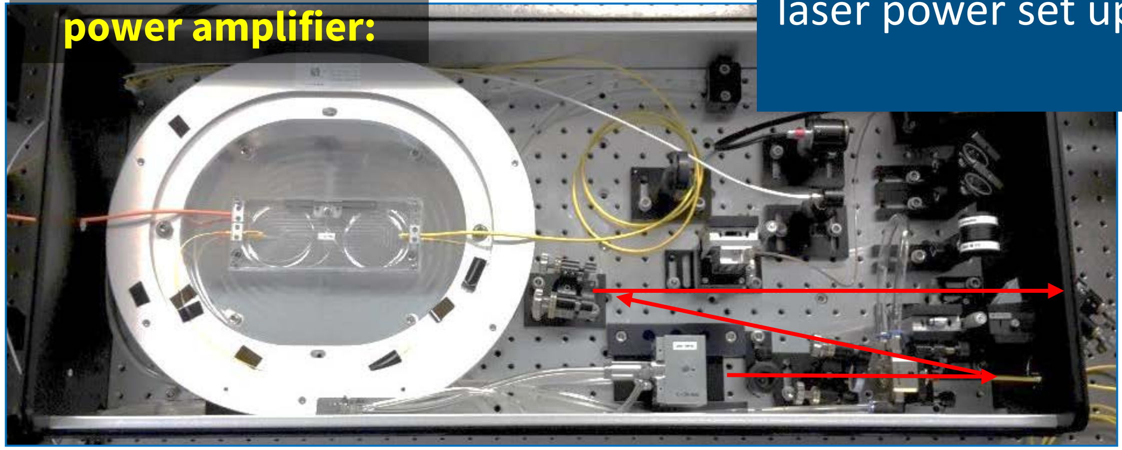


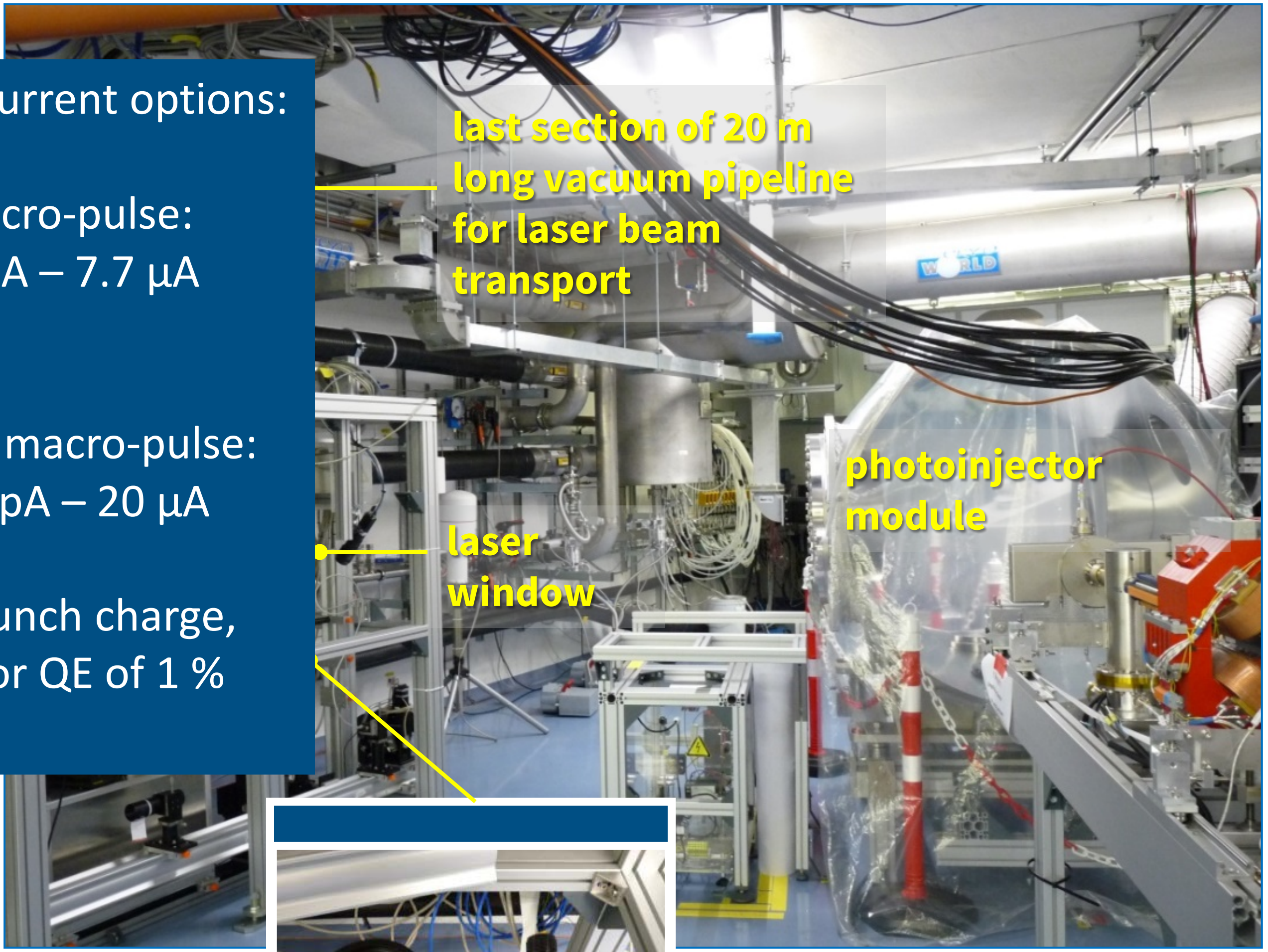
Bunch spacing and current options:

- 50 MHz Laser:
  - 1-100 Hz macro-pulse: → I_{avg} = 77 pA – 7.7 µA
  - CW 3.8 mA
- 1.3 GHz Laser:
  - 1 Hz – 1 kHz macro-pulse: → Iavg = 77 pA – 20 µA
  - CW 100 mA

All this with 77 pC bunch charge, laser power set up for QE of 1 %

Water cooled fiber power amplifier:





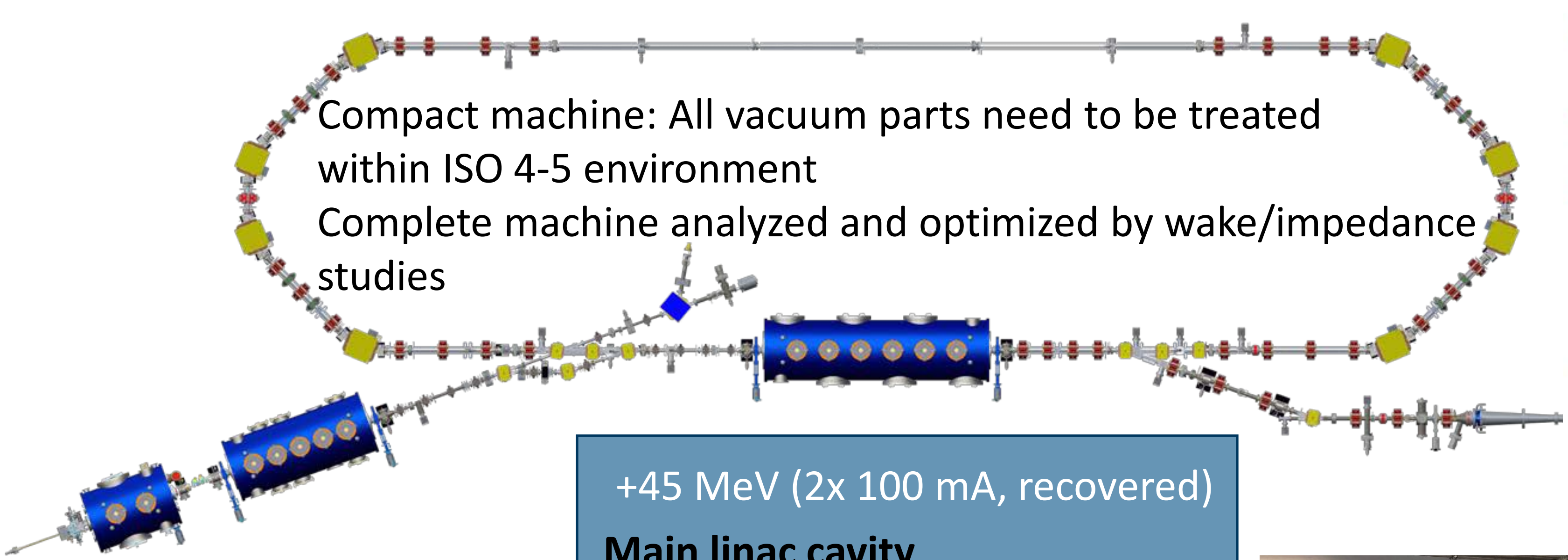
G. Klemz, I. Will, et al

Challenges for the SRF+vacuum systems

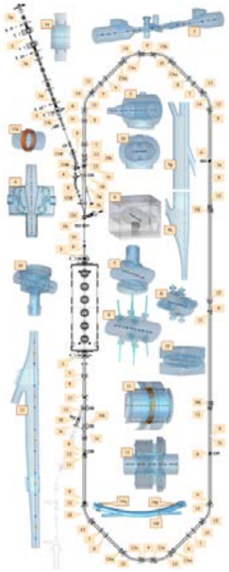
+4.5 MeV (100mA)

SRF booster cavity (Cornell)

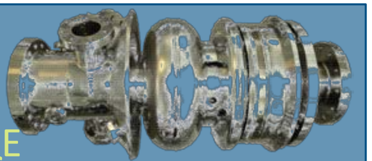
- High beam power
- High beam current
- Intermediate field levels 10 MV/m
- Low coupler kicks
- Zero-crossing operation



Compact machine: All vacuum parts need to be treated within ISO 4-5 environment
Complete machine analyzed and optimized by wake/impedance studies



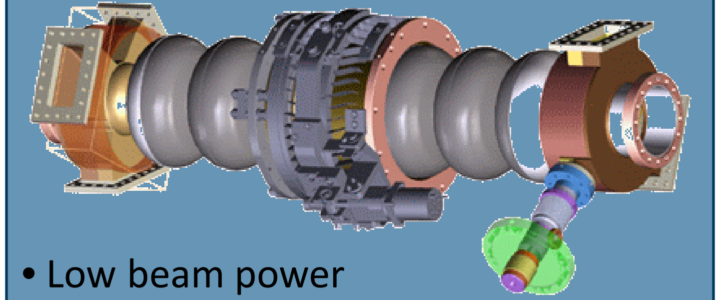
SRF Gun: 2.3 MeV, 100 mA



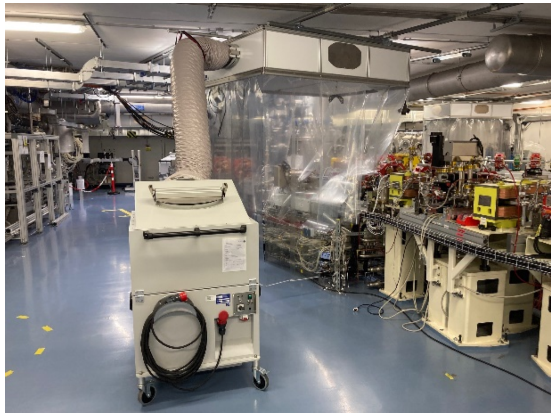
- Low emittance high brightness beam
- Insertion of a thermally isolated high QE Cs-K-Sn cathode (particulate free)
- Control of field emission to avoid dark current based losses and halo formation
- High current, high beam power operation (HOM, FPCs)
- High emission RF field → beam dynamics optimized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

+45 MeV (2x 100 mA, recovered)

Main linac cavity



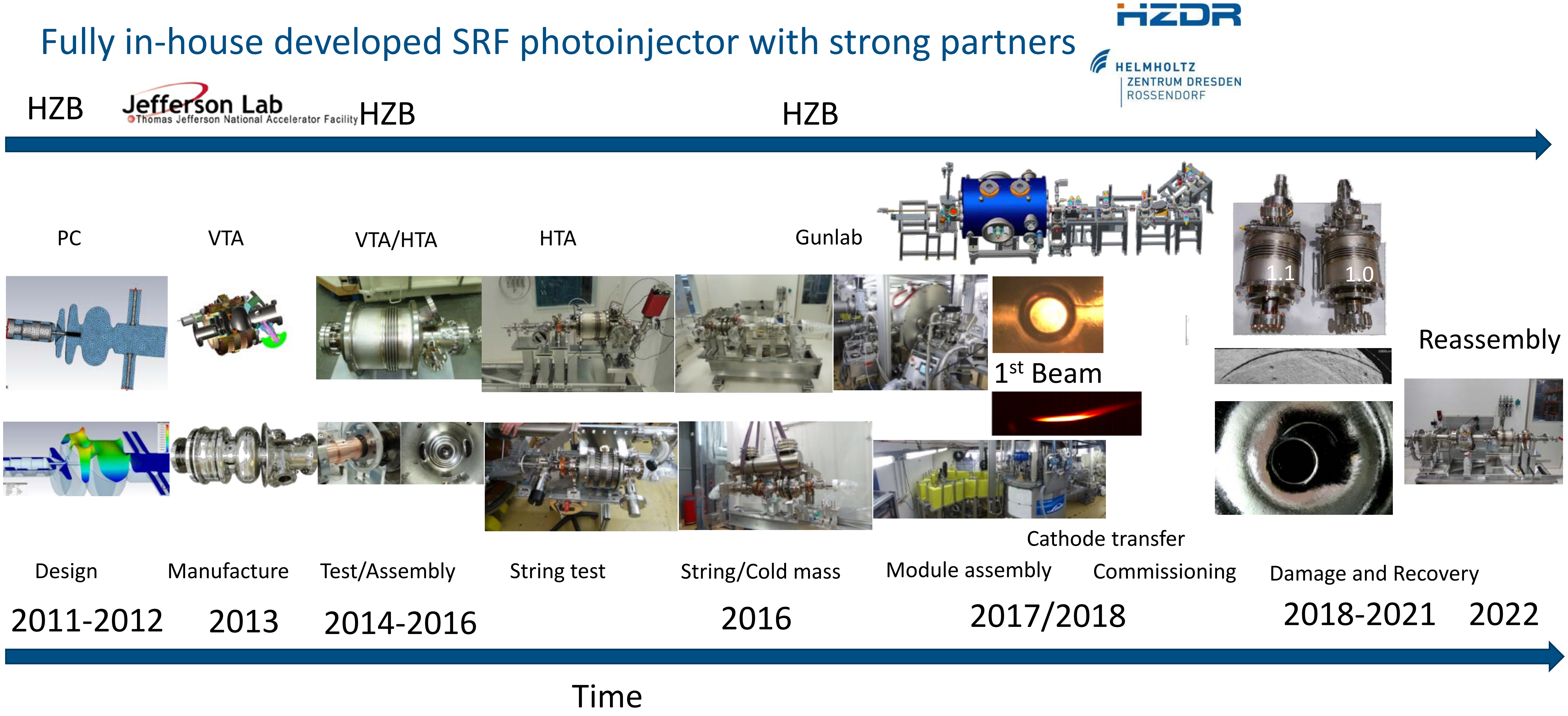
- Low beam power
- High beam current
- Strong higher order mode damping
- Higher field levels: 19 MV/m
- Multi-pass beam
- Precise field control and tuning



Movable local cleanrooms ISO 5, rail system on the ceiling for proper placement

Evolution of the SRF Gun at HZB

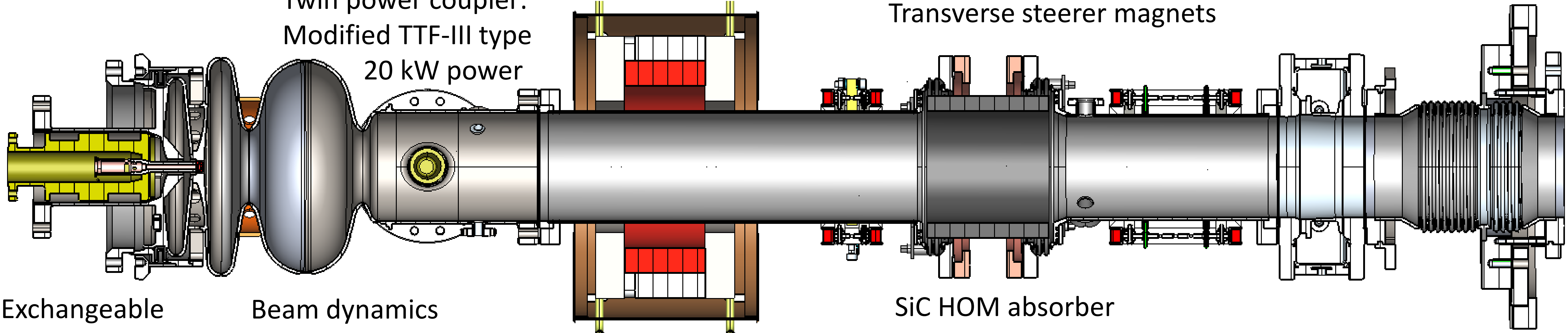
Fully in-house developed SRF photoinjector with strong partners



The SRF Injector 1.0

Twin power coupler:
Modified TTF-III type
20 kW power

Transverse steerer magnets



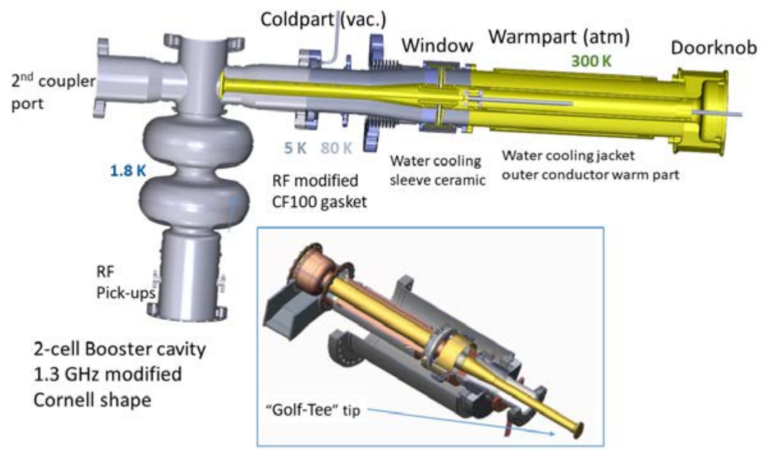
Exchangeable
Photocathode

Beam dynamics
+SRF optimized
1.4 $\lambda/2$ cell cavity

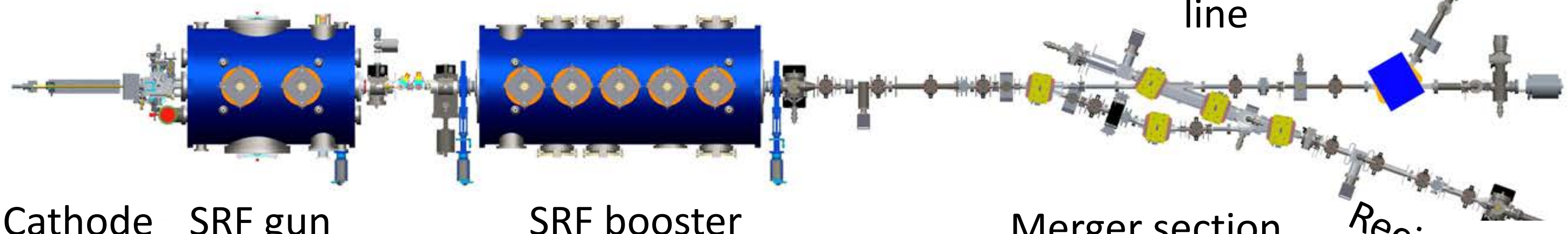
SC solenoid for
beam emittance

SiC HOM absorber

Booster cavity + couplers



Straight diagnostic
line



Cathode
transfer
system

SRF gun

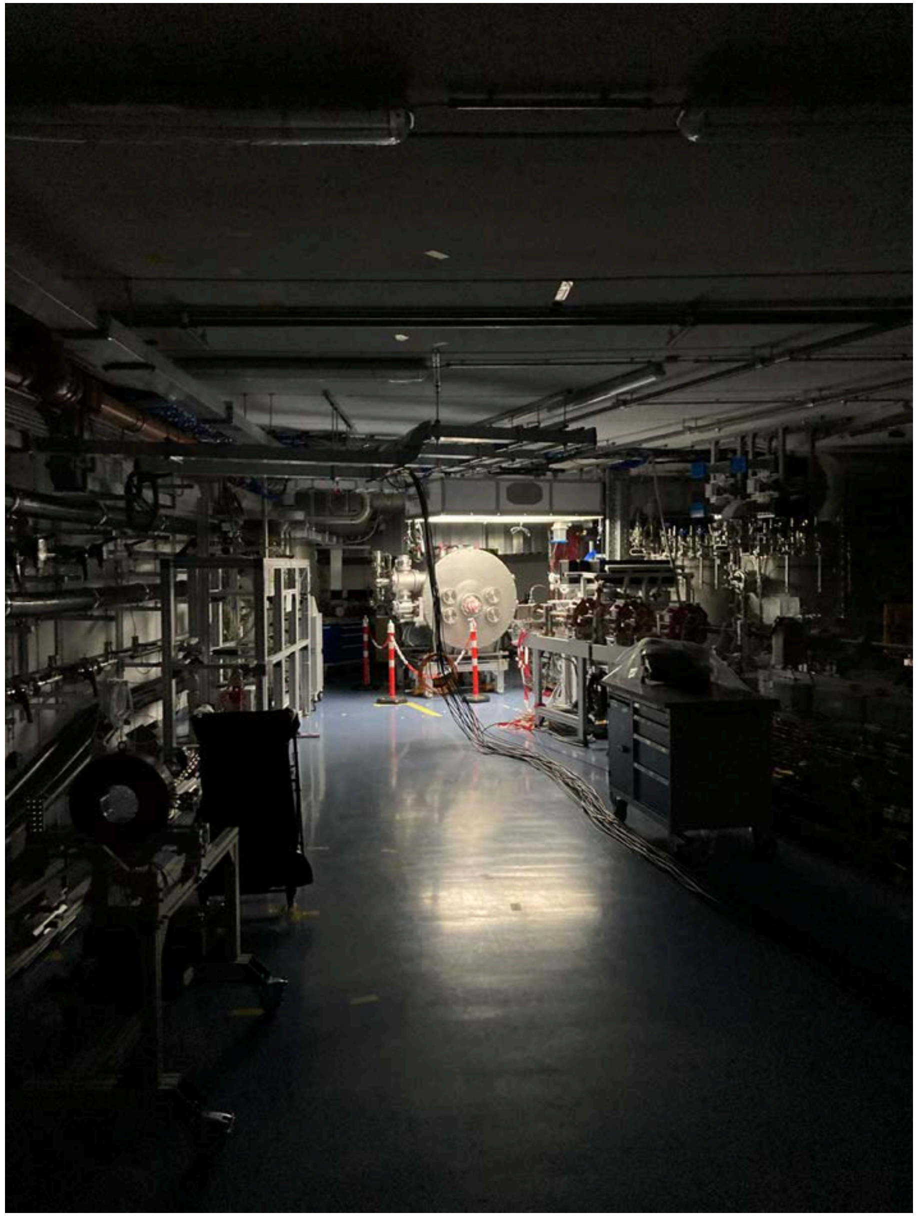
SRF booster

Merger section

Recirculator

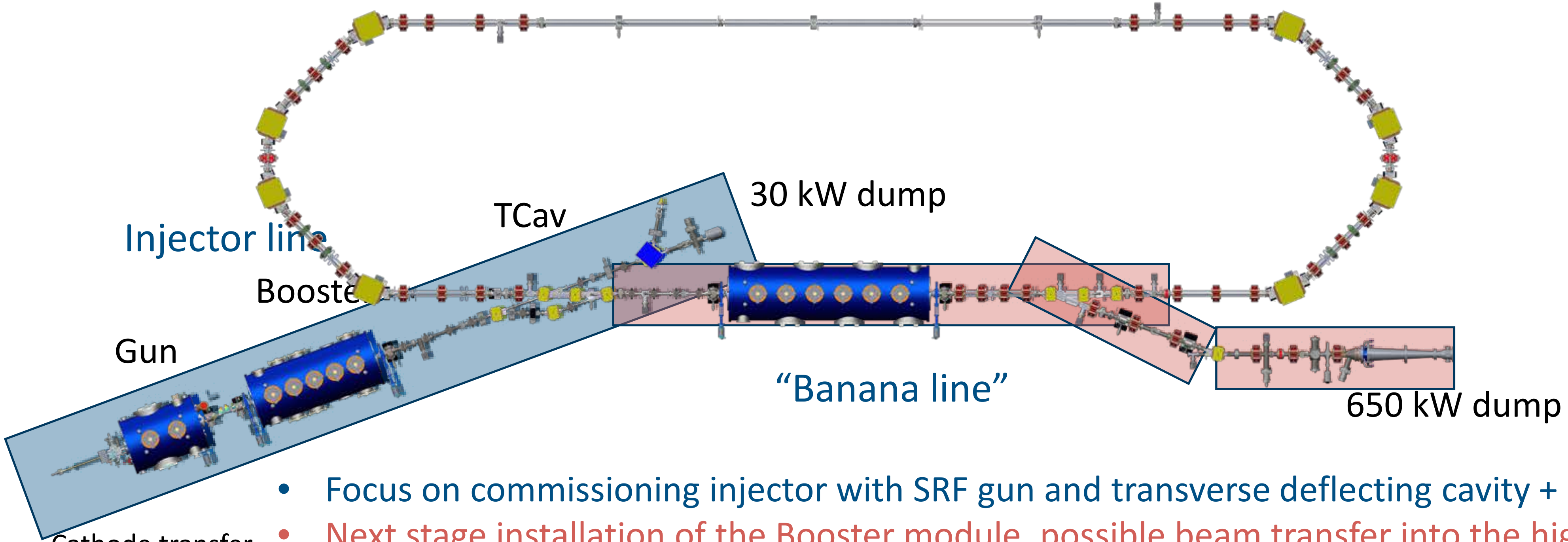
1st diagnostic
Laser window

Short to Midterm plans

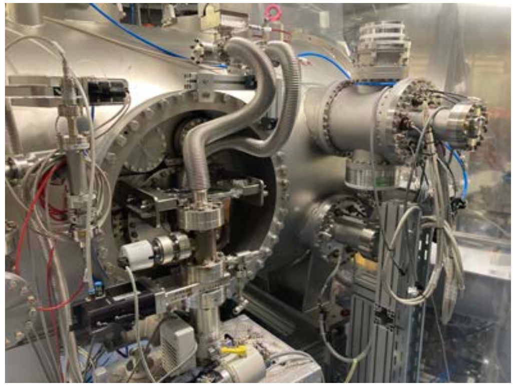


There is light at the end of the tunnel……

When will we have first beam?



- Focus on commissioning injector with SRF gun and transverse deflecting cavity + diagnostic line
- Next stage installation of the Booster module, possible beam transfer into the high power dump
- Recirculation, when Linac funding is secured or an interim arrangement can be found



- SRF gun module fully assembled, ready for cooldown and RF test, cathode transfer system on standby
- First beam planned for Christmas this year, but unclear because of attack on HZB's computing system
- Use the time to finalize all assemblies

First studies with bERLinPro (injector)

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

This comes all with the given budget and project status.

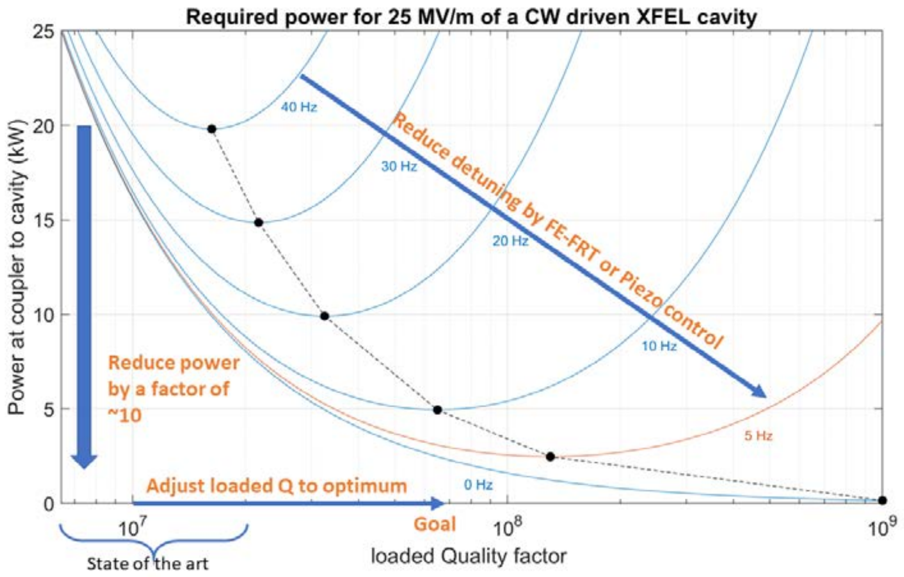
A Linac and a high power gun version still need new resources to be realized, though designs exist "in the drawer"

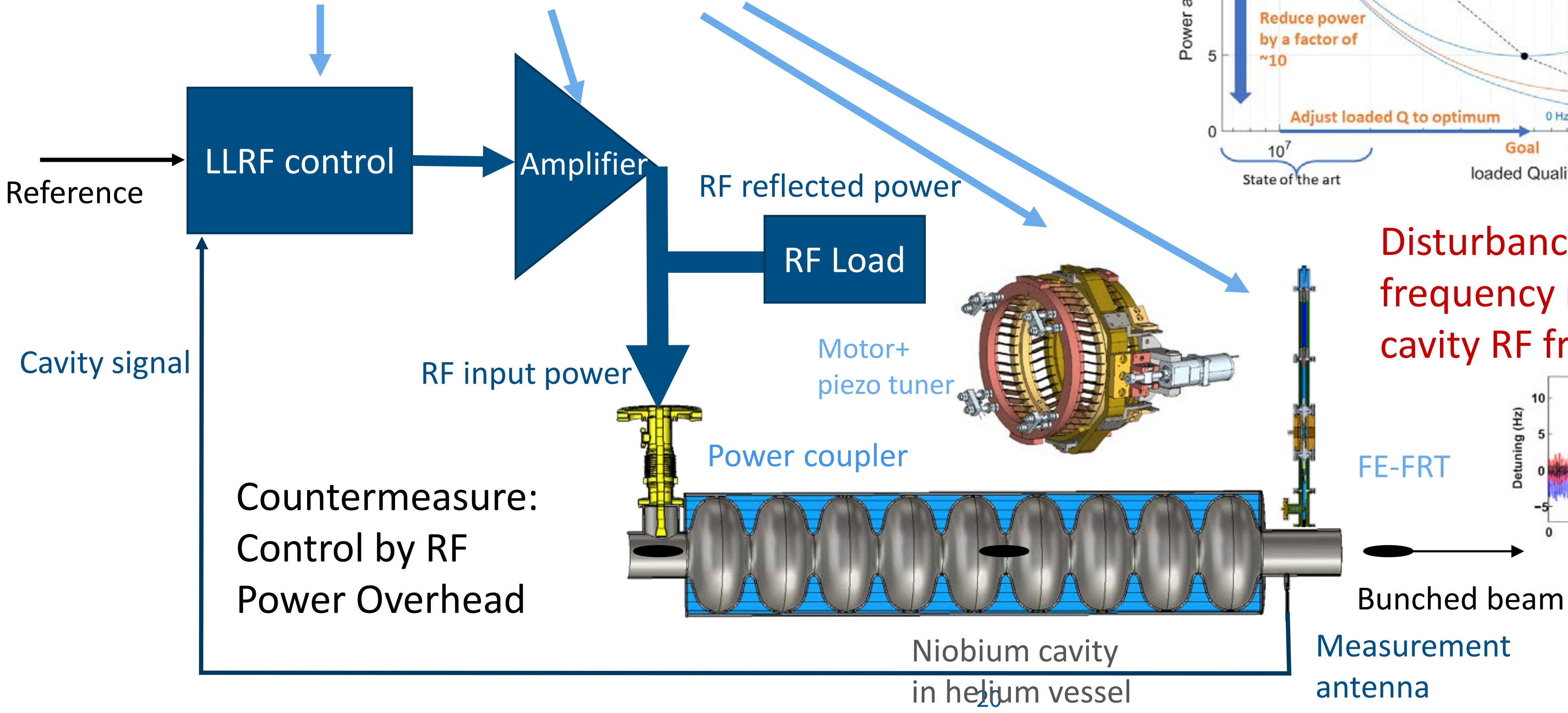
Even with the medium-power gun (20kW) cavity we can study:

- Up to 6-10 mA with the full injection energy
  → Explore the full parameter space of the SRF injector
- 100 mA can be potentially studied in macro-pulse regime (large power overhead by klystrons)
- Bunch charges up to 0.5 nC are in reach with a high QE cathode
- Proof of cathode exchange concept
- 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 and machine protection concepts
- Diagnostic concepts from low-current start-up to mid-power operation (sub µA to some mA)
- Beam arrival time and jitter studies
- Advanced control concepts, digital twins of the machine, ML+AI assisted control methods

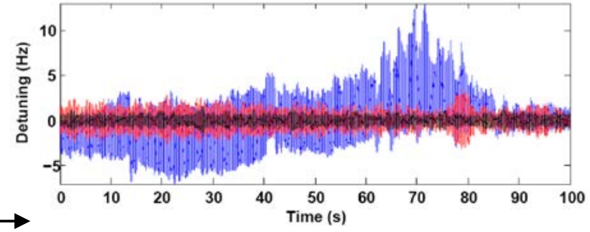
Even more efficient ERLs

iSAS approach:
- AI/ML assisted field control
- Improved detuning control by piezo and new FE-FRT
- Smart efficient amplifier control





Disturbances in the acoustic frequency regime modulate cavity RF frequency/field



Countermeasure:
Control by RF Power Overhead

Realize a Linac for SEALab/bERLinPro

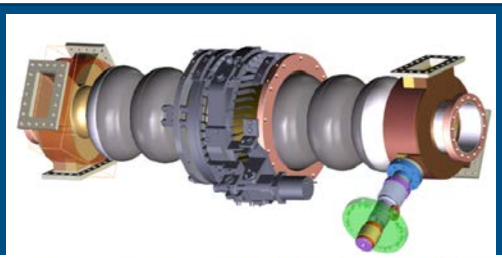
A bERLinPro Linac was developed

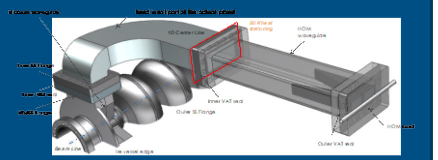
Funding

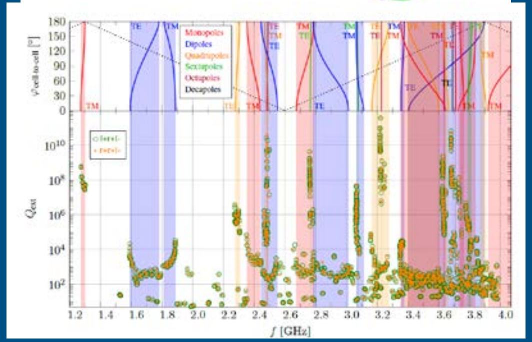
Limit

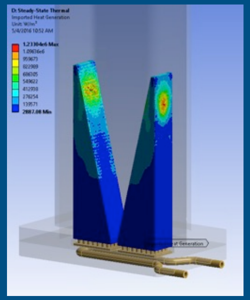
New baseline: Cut down to a simplified more cost saving, less complicated design

Simplified module concept, Cornell like, no room ...erature parts









- Full three-cavity string HOM analysed, coupler kick studies, manufacturing study etc....

→ For a BBU threshold of 2x 100 mA + margin this design is an overkill threshold current in the Ampère regime!

...s to ...n ERL ...map

HORIZON-INFRA-2023-TECH-01-01 iSAS funded!

Cryo allows to potentially operate one cavity at 4 K as new material demonstrator

- Cornell shap... cells
- No waveguides, TTF coupler + Fast reactive tuner port
- Beamtube HOM absorber like Booster/Gun

Acknowledgements

Many thanks to:

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+many more

HZB bERLinPro Team & friends
former colleagues, Team Sealab,
last but not least
iSAS collaboration members

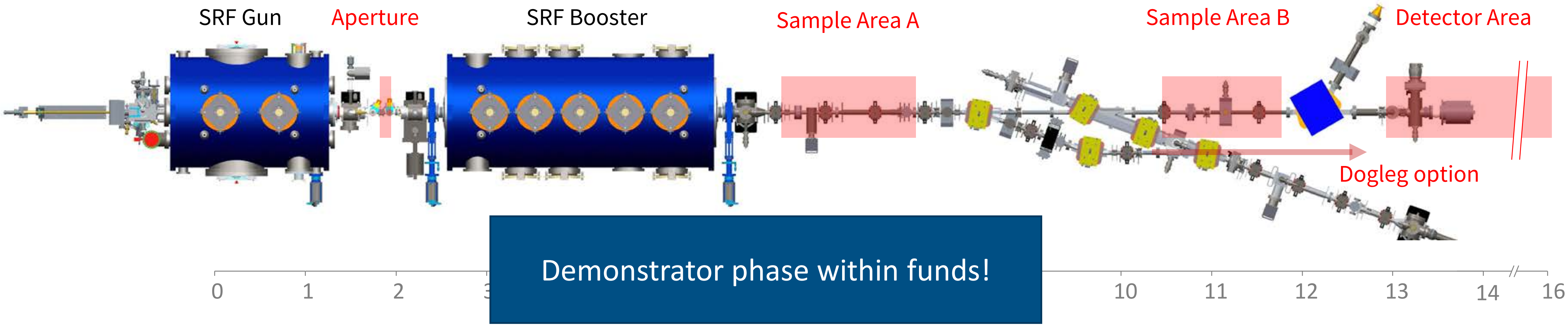
Thanks for your attention!

The Andrzej Sołtan Institute for Nuclear Studies
PL-05400 Otwock-Świerk
Poland

Funding: Bundesministerium für Bildung & Forschung
Bundesland Berlin, Helmholtz Gemeinschaft

Ultra-fast scattering experiments with the SRF photoinjector

Many ARD aspects: SRF, beam dynamics, instrumentation, controls, …

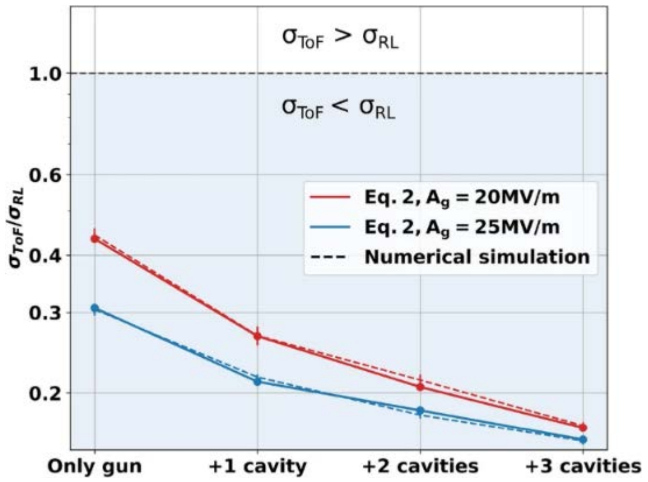


Capabilities of the photoinjector:
1 to 3.5 MeV beam energy with **variable** bunch charge (1 fC to 100 pC), pulse length (10 fs to 6 ps) and spot size (10 to 100s µm), **high stability at MHz repetition rate.**

Very **flexible longitudinal accelerator/lens system**: one gun cavity and three booster cavities, done optimization for bunching scheme, see B. Alberdi et al. [1].

[1] B. Alberdi, et al, Sci. Rep. 12, 13365 (2022)

TOF jitter at position A in units of initial jitter vs number of cavities in the photoinjector



Ultrafast science drivers:
Diffraction camera for **molecular movies** with MHz repetition rate (UED).
Imaging of **macromolecular structures** in liquid phase (UEI).

Complementary to SR and FEL light sources. Enabling **multi-modal capabilities** for Bessy II/III.

T. Kamps, B. Alberdi Esuain, J. Völker, T. Spohr, E. Ergenlik, A. Neumann, J.-G. Hwang, S. Barg, et al.