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bERLinPro
A demonstration Energy Recovery LINAC

Jens Knobloch
for the bERLinPro Project Team

June 8, 2015

bERLinPro layout

J. Knobloch, 2015-06-08

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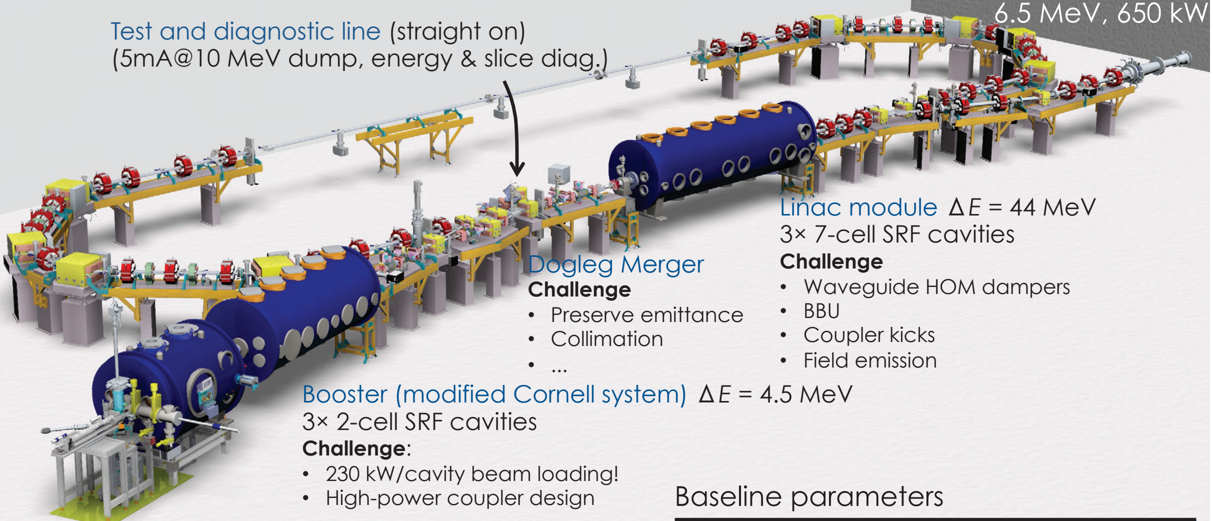
- M. Abo-Bakr et al., “Status of the HZB ERL project bERLinPro”, *Proc. IPAC2014*
- J. Knobloch et al., “bERLinPro – addressing the challenges of modern ERLs (a status report), *ICFA Beam Dynamics Newsletter* **58**, Aug. 2012, (http://www-bd.fnal.gov/icfabd/Newsletter58.pdf)



Beam dump
6.5 MeV, 650 kW

Test and diagnostic line (straight on)
(5mA@10 MeV dump, energy & slice diag.)

Linac module ΔE = 44 MeV
3× 7-cell SRF cavities
Challenge
- Waveguide HOM dampers
- BBU
- Coupler kicks
- Field emission

Dogleg Merger
Challenge
- Preserve emittance
- Collimation
- …

Booster (modified Cornell system) ΔE = 4.5 MeV
3× 2-cell SRF cavities
Challenge:
- 230 kW/cavity beam loading!
- High-power coupler design

SRF photoinjector, with SC solenoid, 1.5 – 2.3 MeV
Challenge:
- 30 MV/m CW operation with CsK_2Sb cathode
- Cathode performance @ 100 mA
- Dark current/halo control
- Emittance compensation
- …

Facility is fully funded (Helmholtz Assoc., HZB and State of Berlin)

Baseline parameters

Parameter	Design goal
max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
frequency	1.3 GHz
normalized emittance	1 mm (ca. 0.5 mm sim.)
bunch length (straight)	2 ps or smaller (100 fs)
losses	$< 10^{-5}$

bERLinPro goals (some of them)

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Develop the technology for high-current ERLs

- Build on experience/technology at other labs (Cornell, JLAB, KEK, BNL)
- E.g., SRF systems
  - SRF photoinjector/cathode development
  - Multi-100-mA class LINAC system with waveguide dampers
- E.g., Vacuum system & diagnostics
  - Impedance
  - High current, high dynamic range diagnostics
  - High-sensitivity beam loss
  - Machine protection …

Beam dynamics/"theory" of ERLs

- BBU suppression
- Recovery efficiency
- Beam manipulation, emittance compensation, compression (down to 100 fs)
- Orbit corrections
- Ion trapping …

Understanding and minimizing beam loss

- If an ERL should operate as user facility then losses must be significantly better than 1E-5/turn (compare with BESSY-II: ca. 1E-11/turn!!)
- Detection & avoidance
- Shielding designs / facility layouts suitable for user facilities

bERLinPro

Accelerator physics facility to mature ERLs to the point that one can seriously think about their application as a user facility

(and convince funding agencies to take them seriously)

Status: Optics/beam dynamics

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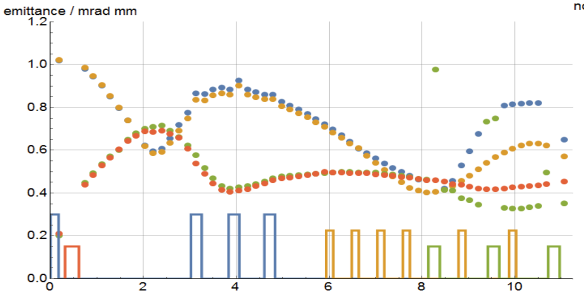
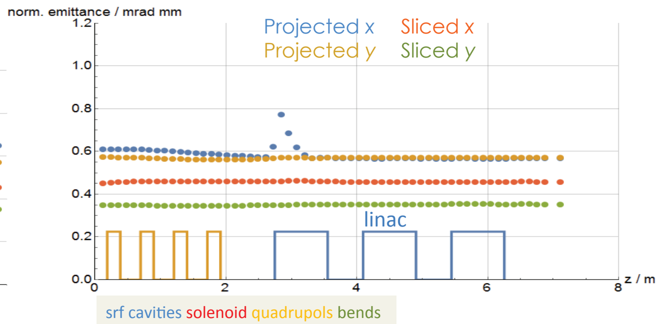
- B. Kuske, M. Abo-Bakr et al., "The injector layout of bERLinPro", *Proc. IPAC 2013*
- B. Kuske, J. Rudolph, "Beam positioning concept and tolerance considerations for bERLinPro", *Proc. IPAC 2014*
- M. Abo-Bakr et al., "Status of the HZB ERL project bERLinPro", *Proc. IPAC2014*

Optics settled, studies accompany physical facility design

- Entire facility layout in a data base … being updated continuously
- Generate automated input files for OPAL, ASTRA, ELEGENT etc.
- Automated tracking studies, e.g.,
  - effect of machine settings on beam parameters and recovery efficiency.
  - Study orbit correction schemes
- Emittance at LINAC exit about ×2 better than original design goal
- Short pulse operation also studied, current limited by CSR (5 kW max)





Warm Systems – Magnets & Girder

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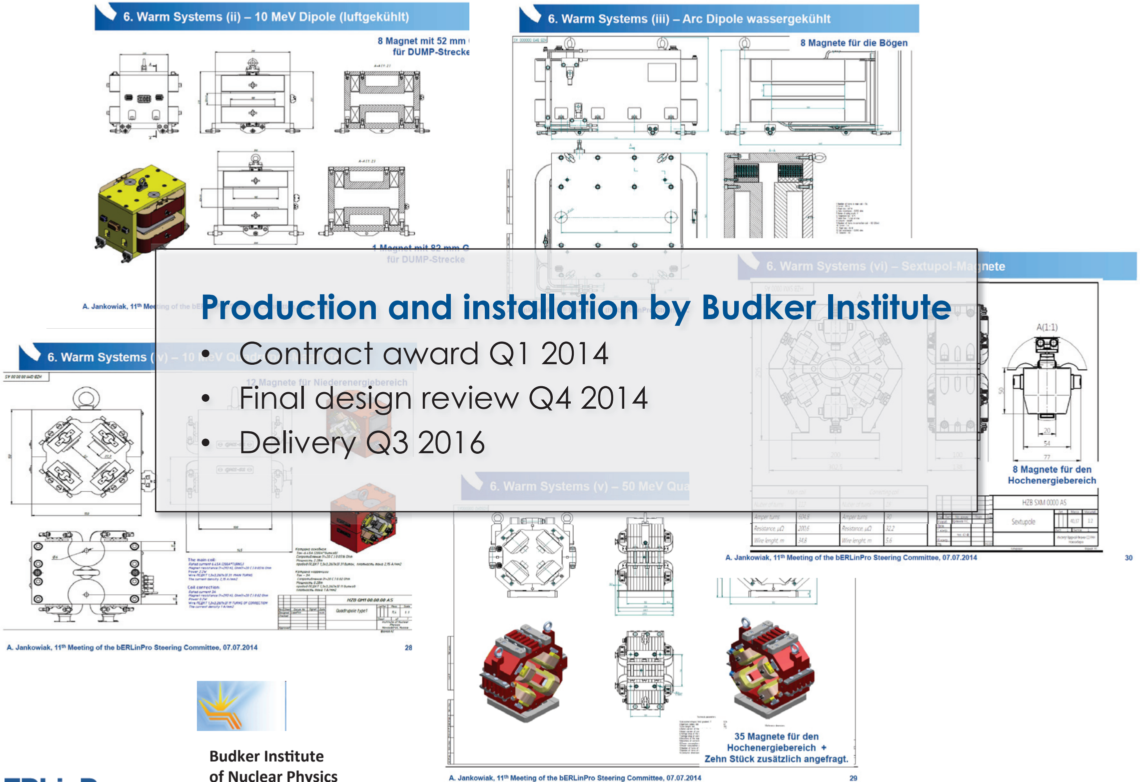


Production and installation by Budker Institute

- Contract award Q1 2014
- Final design review Q4 2014
- Delivery Q3 2016

Budker Institute of Nuclear Physics

Impedance analysis

– H.W. Glock et al, “Loss factor and impedance analysis of warm components of bERLinPro”, *Proc. IPAC 2015*

Vacuum system/diagnostics

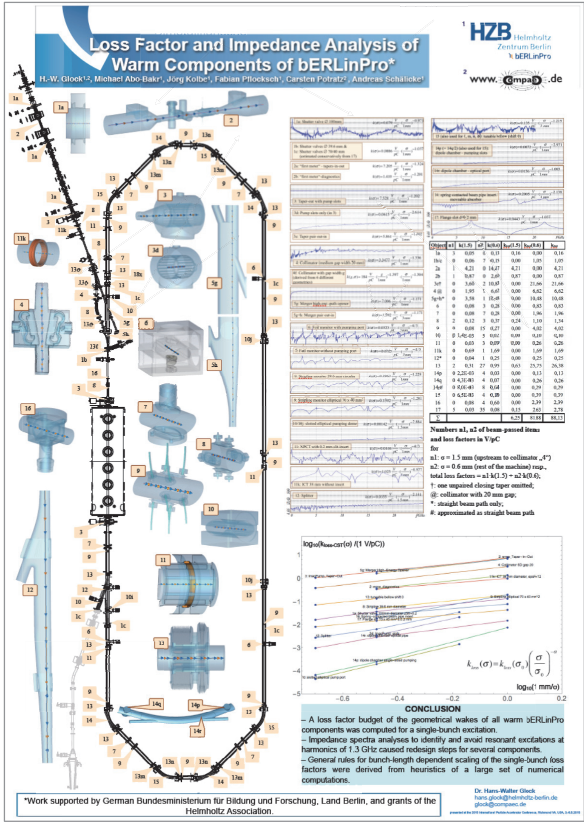
- Component types and layout is being settled & first prototypes are under production
- Aluminum vacuum chamber to limit activation.

Impedance analysis

- Impedance & loss-factor calculations for main components out to 100 GHz.

	resist.	geom.	roughn.	CSR
k_{total} (V/pC)	17	88	175	500

- Geometric wakes not dominant but also not negligible.
- Important: Interaction with drafting department for changes to minimize loss factor and avoid n×1.3 GHz resonances



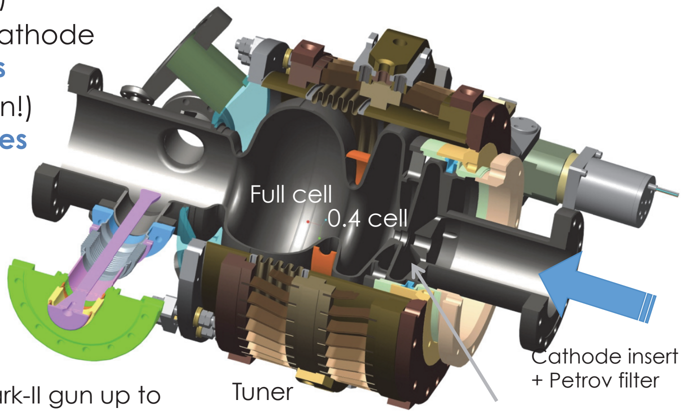
See poster

Status: RF photoinjector

- Neumann et al., "Towards a 100 mA superconducting RF photoinjector for bERLinPro", *Proc. SRF2013*
- T. Kamps et al., "Beam dynamics studies for SRF photoinjectors", *Proc. LINAC2012.*

New SRF gun, based in part on HZDR's design

- Potentially very powerful injector (CW operation + high field + high voltage + UHV simultaneously), but not demonstrated to date.
- 1.3 GHz, 1.4-cell SRF cavity
  - Compromise between RF voltage, RF field and beam loading (≤ 230 kW)
- CsK_2Sb Photocathode
  - Reasonable longevity, vacuum requirements, QE and laser wavelength (green)
  - Challenge: normal conducting cathode in the SRF cavity → **cooling issues**
  - Operating a cathode (low work-fn!) at high field → **field emission issues**



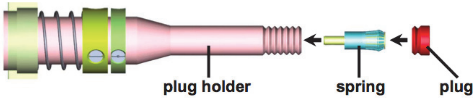
Twin CW RF couplers (Mark-II gun up to 115 kW. Shown here: Mark-I gun with CW modified TTF-III couplers for 10 kW CW)

SRF injector: photocathode

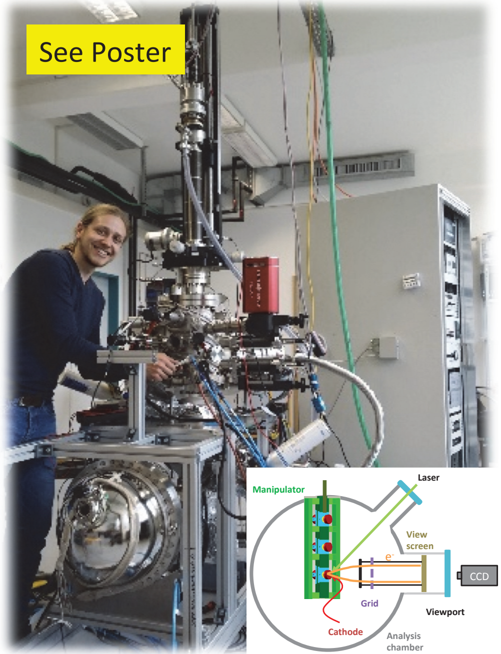
– M. Schmeißer et al., "In-situ characterization of K_2CsSb photocathodes", *Proc. IPAC 2014*

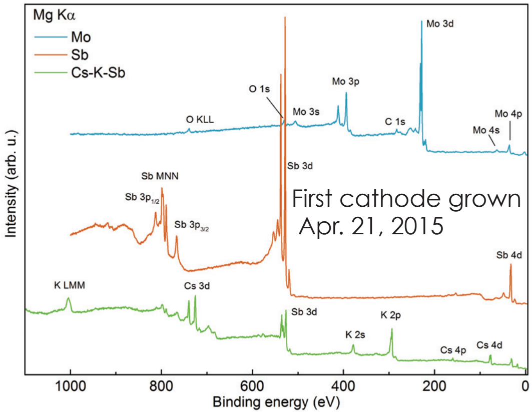
Photocathode production = "alchemy"

- → Develop a more systematic approach
- In situ analysis during production
  - XPS → electronic structure
  - LEIS → composition
  - QE v. wavelength
  - "Momentatron" → therm. emittance



"Standardized" cathode plug with HZDR





SRF photoinjector: 1.4-cell cavity

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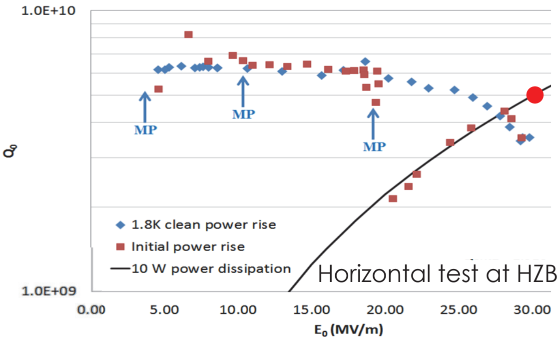
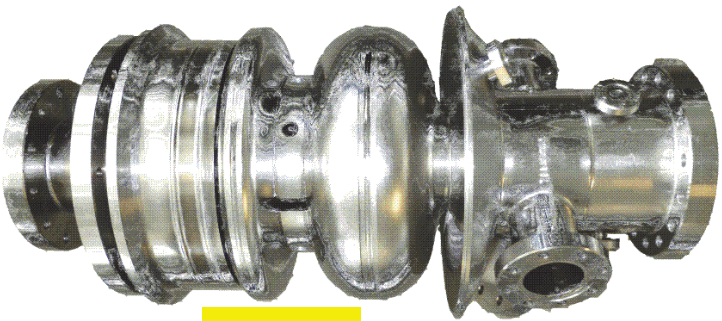
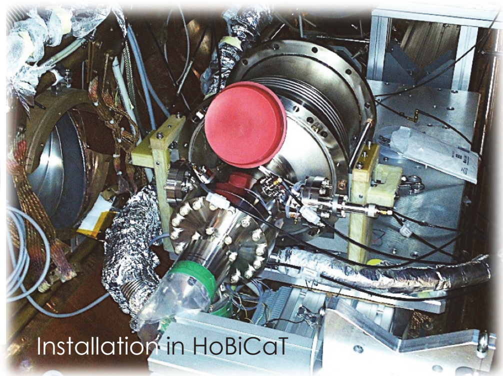
- A. Burrill et al.,"First Horizontal Test Results of the HZB SRF Photoinjector for bERLinPro", *Proc. IPAC2015*
- A. Neumann et al., "SRF photoinjector cavity for bERLinPro", *Proc. IPAC2013*

Production/vertical acceptance tests at Jefferson Laboratory

- Tolerance issues ("cavity short") that resulted in heavy multipacting in the 0.4 cell.
- Nevertheless, after initial difficulties design goal nearly reached.
- Installation in HoBiCaT facility following shipment to HZB.
- Performance maintained ☺







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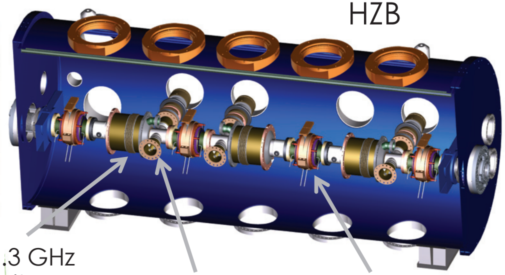
Booster module

- A. Burrill et al.,"BERLinPro Booster Cavity Design, Fabrication and Test Plans", *Proc. LINAC 2014*
- A. Neumann et al., "Booster cavity and fundamental power coupler design issues for bERLinPro", *Proc. IPAC 2014*
- V. Khan et al., "High-power RF input couplers and test stand for the bERLinPro project", *Proc. IPAC 2014*

Booster is based on the Cornell design (thank you for supplying the drawings!)

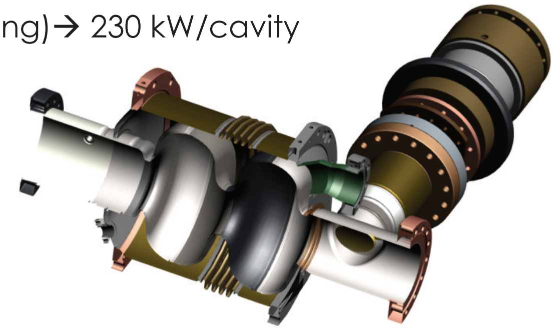
Cornell U.



Differences

- Only three cavities (one at zero crossing) → 230 kW/cavity
- Modified cavities (larger beam tube) to handle beam loading
- Different coupler system, based on KEK design but with improved cooling/horizontal installation

KEK-style coupler

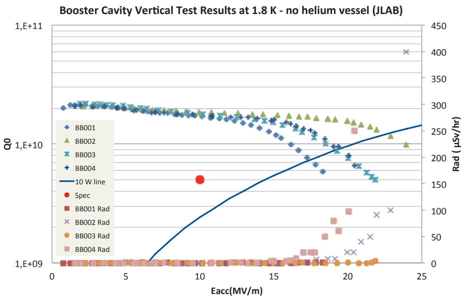


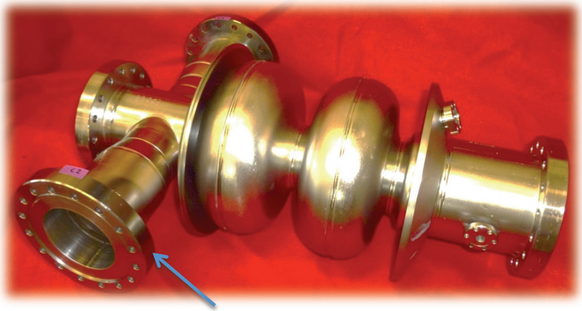
Booster Cryomodule

– A. Burrill et al.,"BERLinPro Booster Cavity Design, Fabrication and Test Plans", *Proc. LINAC 2014*

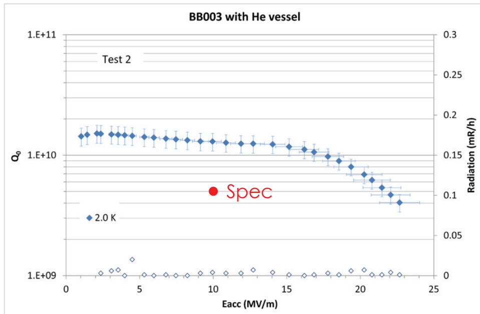
Production & processing of cavities under a CRADA at JLAB

- Four cavities produced, all four far exceeded design goal in VTA.
- First system passed vertical acceptance test with tank.
- **Integration in cryomodule in 2017**





Large coupling port for modified KEK high-power couplers



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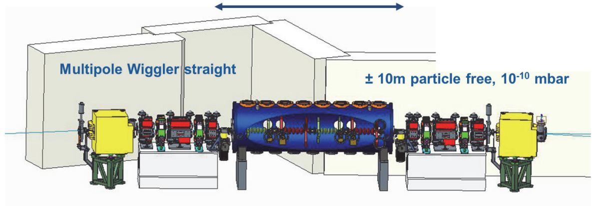
LINAC cavities

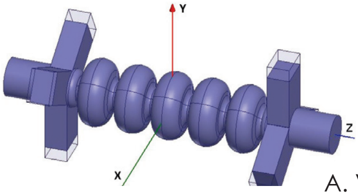
- A. Velez et al., “HOM Damping Optimization Design Studies for BESSY VSR”, *Proc. IPAC 2015*
- G. Wüstefeld et al.,”Simultaneous Long and Short Electron Bunches in the BESSY II Storage Ring, *Proc. IPAC2011*
- R. Rimmer et al., “Jlab high-current CW cryomodules for ERL and FEL applications”, *Proc. PAC 2007*

HZB developing a high-current design for BESSY-VSR. Criteria are:

- High current (300 mA), heavily HOM-damped: Order kW HOM power
- Tight space constraints in BESSY-II
- L-Band, CW operation at 20 MV/m
- Designs for WG-damped system based on JLAB’s original developm.

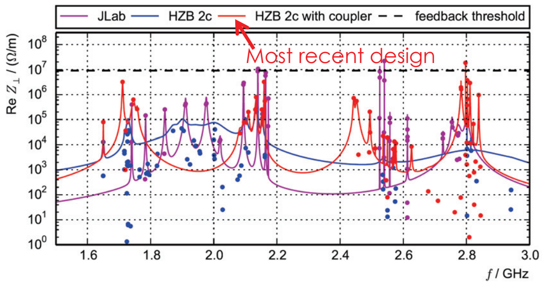
BESSY-II storage ring

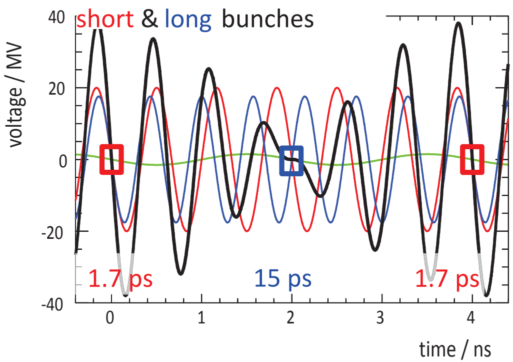




A. Velez

Transverse case





Installed voltage: 20 MV @ 1.5 GHz
17.1 MV @ 1.75 GHz

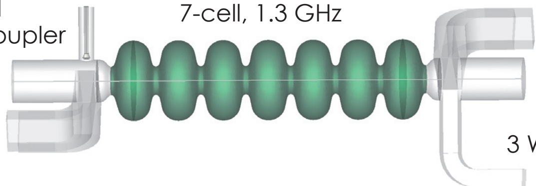
LINAC cavities

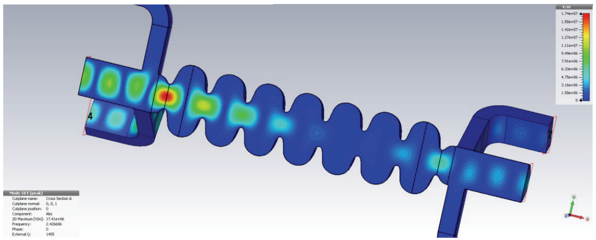
– A. Neumann et al., "Final design for the bERLinPro main LINAC cavity", *Proc. LINAC 2014*.
– O. Kugeler, et al., "Adapting TESLA technology for future CW light sources using HoBiCaT", *Rev. Sci. Inst.* **81**, 074701 (2010)

bERLinPro cavity will be a similar design to the BESSY-VSR system

- Take advantage of the synergy between SRF projects
- Module consists of three 7-cell cavities operating at 18 MV/m.
- Each cavity powered by 15 kW solid-state amplifier (10 kW @ cavity)
- 10 kW CW TTF-III-type input coupler + 5 waveguides for HOM damping

Design completed by Q4 2015





Number of cells	7
$R/Q_{\parallel}$	788 Ω
$f_{TM_{010}-\pi}$	1.3 GHz
E_{peak}/E_{acc}	2.08
B_{peak}/E_{acc}	4.4 mT/MVm^{-1}
Q_{ext} TM_{110} dipole	$\leq 8 \cdot 10^3$
Beam tube TE_{01} cutoff	1.596 GHz
Waveguide TE_{10} cutoff	1.576 GHz
Q_L for TM_{010}-π	$1 \cdot 10^7 - 1 \cdot 10^8$
$P_{forward}$ at $Q_L = 5 \cdot 10^7 (\Delta f = 0)$	1.4 kW

RF systems

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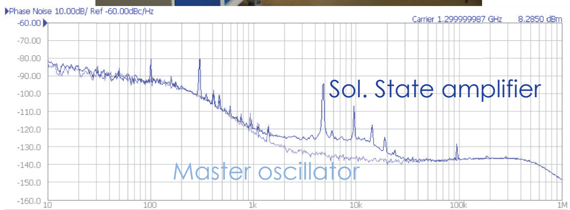
Photoinjector & booster RF

- 3x 270 kW klystron (CPI) + 600 kW power supply (FUG). First system beginning the test phase

LINAC RF

- 3x 15 kW solid state amplifier (SigmaPhi)
- Prototype currently operates HoBiCaT
- Very low noise.



Radiation safety

– K. Ott, M. Helmecke, “The shielding design of bERLinPro”, *Proc. IPAC 2011*

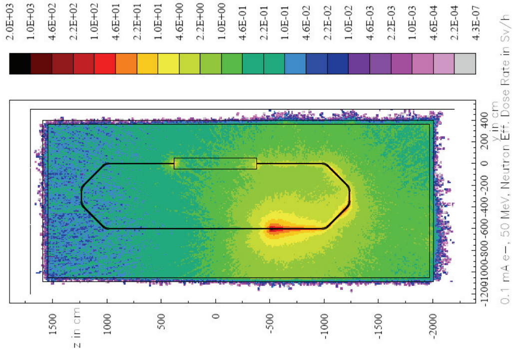
Gamma production, fast neutron production and activation issues

- ERLs are not “established” systems: What is a reasonable “worst-case scenario”?
  - Our case: max. sustainable loss @ 50 MeV = 30 kW installed LINAC RF (=0.6%)!
  - Our authorities: Radiation protection must be completely passive!
- Neutron production requires massive shielding in all directions (> 3 m).

→ Use underground building (if so, gamma shielding comes “for free” since it needs to be most extensive in the horizontal)

- Air activation requires under-pressure in accelerator building
- Aluminum vacuum system for reasonable access times

FLUKA calculation of neutron radiation field for one point source (5 kW)



Building: on paper

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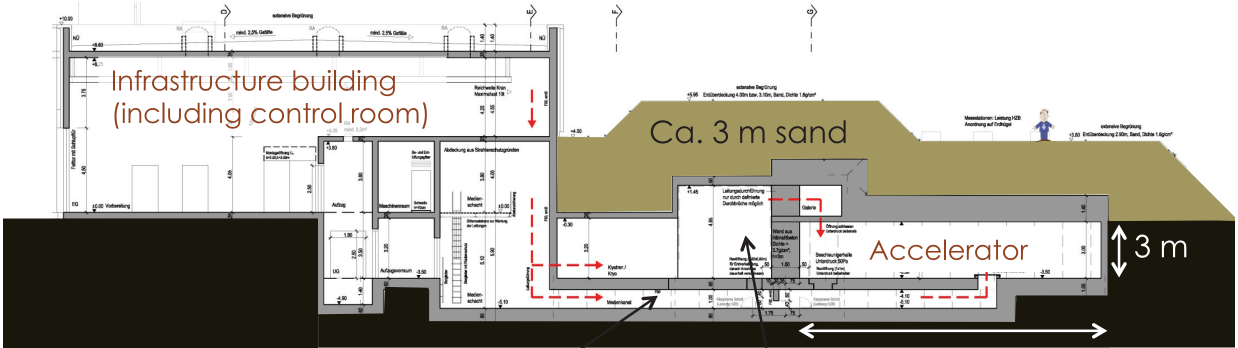
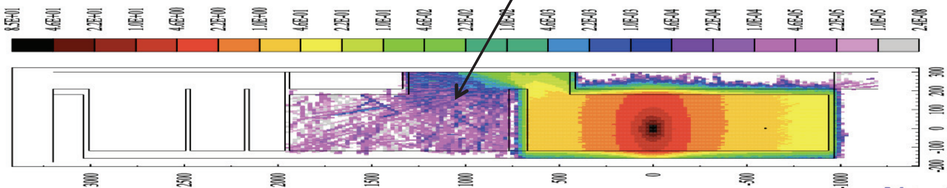


16 m

Utilities access underground

Partially shielded ante-room for equipment that must be close to accelerator (klystron, cold-compressor for cryogenics)

Fluka calculations
(K. Ott)



Neutrons

Building: in reality

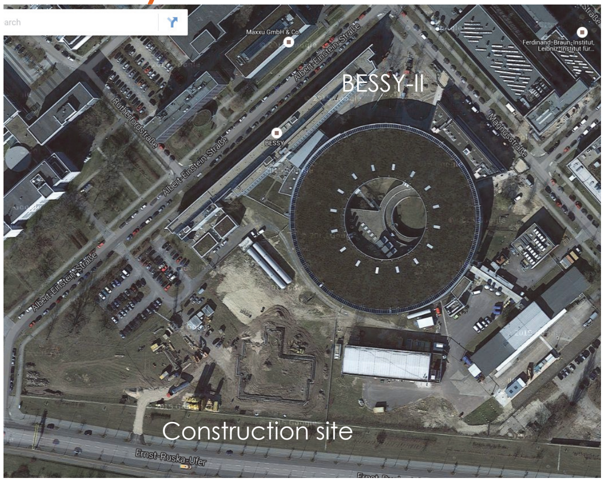
Construction commenced 11-Feb-2015
Underground construction complicated at Berlin site

- Sandy soil
- Ground water at only 1.5 m below grade
- Very strict water regulations in Berlin

→ Complicated and costly water management scheme

Building occupancy expected by End 2016

Quality control of concrete



bERLinPro staging: 1

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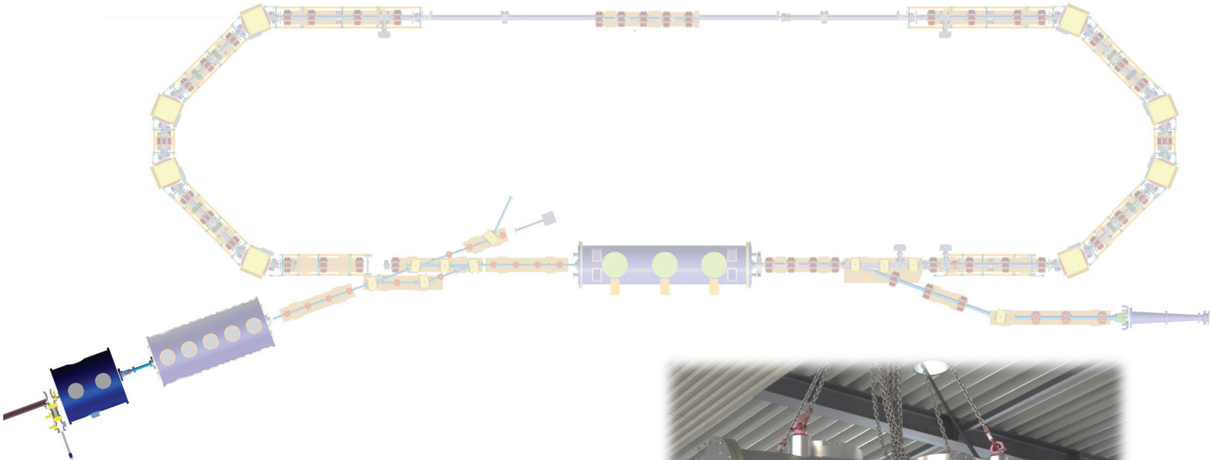

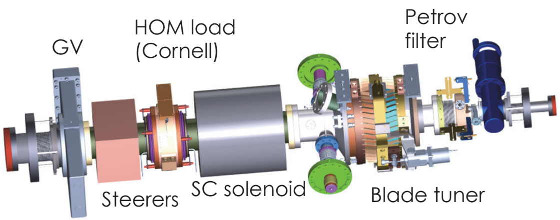

bERLinPro staging: 1

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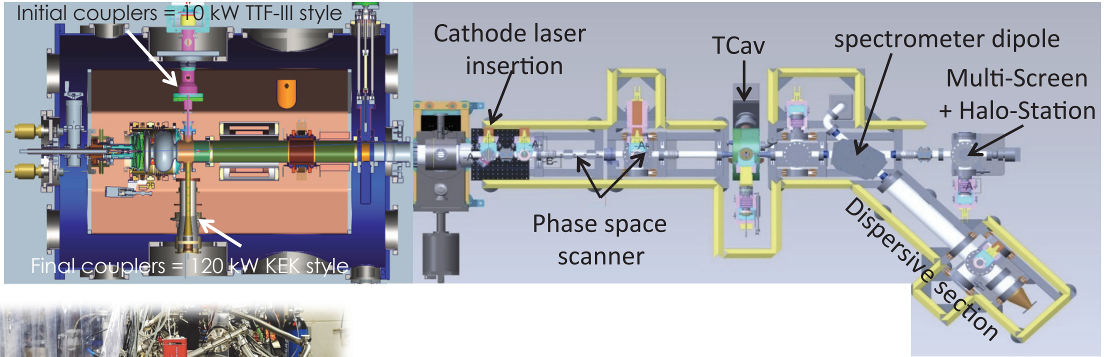
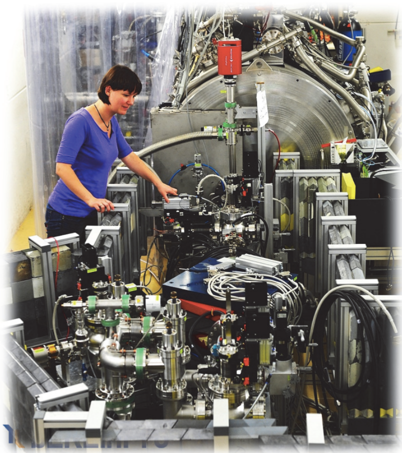
- J. Völker et al., “Introducing GunLab – A compact test facility for SRF photoinjectors”, *Proc. IPAC 2014*
- R. Barday et al., “Characterization of a superconducting Pb photocathode…“, *PRST-AB* **16**, 123402 (2013)
- M. Schmeißer et al., “Results from beam commissioning of an SRF plug-gun cavity photoinjector”, *Proc. IPAC 2013*





SRF photoinjector commissioning: ongoing

- Takes place off-line at HZB’s photoinjector beamline (“GunLab”) in HoBiCaT
- Limited radiation protect. → 5 µA admin. limit
- First tests in GunLab to begin **Q2 2016**.

bERLinPro staging: 2

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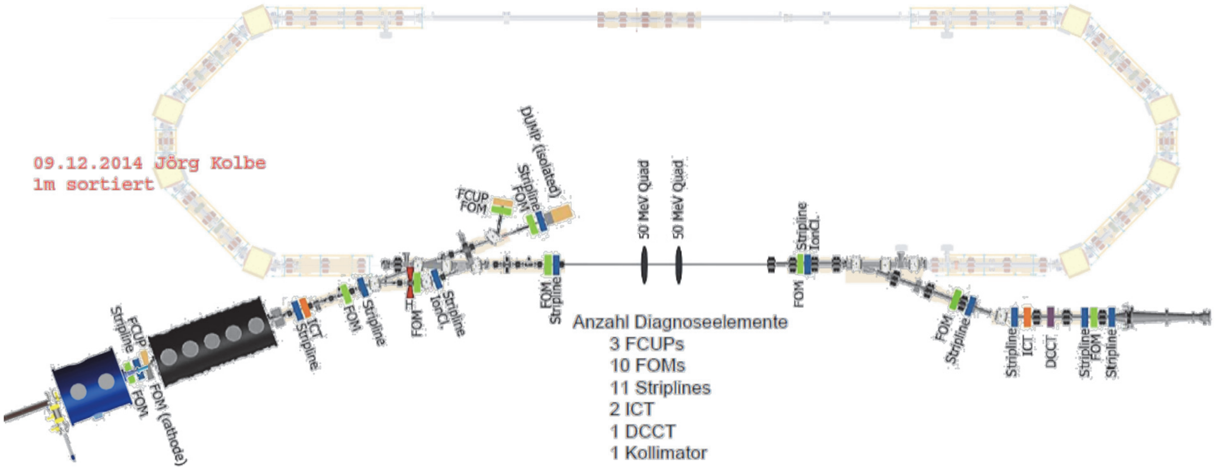
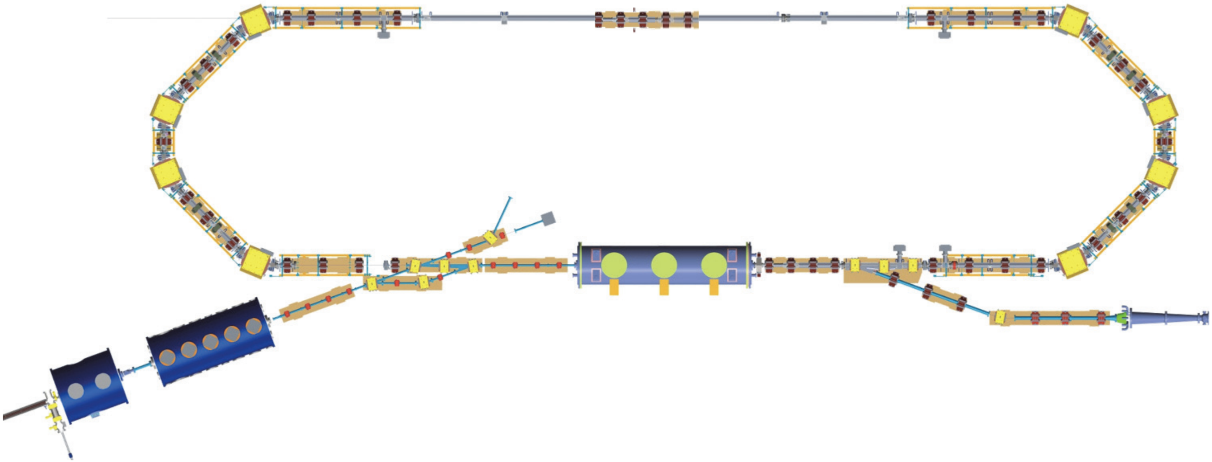


<10 MeV, high-current op. through "banana": start Q4 2017 / Q1 2018

- No energy recovery
- RF and cryogenics commissioning
- Commissioning of SRF photoinjector + booster for 5 μA < I_b < 5 mA (limit set by 10-kW couplers of the photoinjector)
- Commissioning high-power dump
- Commissioning of merger + beam characterization with dedicated diagn.

bERLinPro staging: 3



- Installation recirculation arcs & LINAC module Q3, 2018

Full energy recovery

- Commissioning of main LINAC module: Q2, 2019
- Energy recovery at I_b < 5 mA: Q3, 2019
- Installation Mk-II version of photoinjector with 115-kW couplers Q1 2020.
- ERL machine studies for currents up to 100 mA.

Acknowledgements

The bERLinPro Team

M. Abo-Bakr, W. Anders, R. Barday, A. Bondarenko, A. Burrill, A. Büchel, K. Bürkmann-Gehrlein, P. Echevarria, A. Frahm, H.-W. Glock, B. Hall, S. Heßler, A. Jankowiak, C. Kalus, T. Kamps, G. Klemz, J. Knobloch, J. Kolbe, J. Kühn, O. Kugeler, B. Kuske, P. Kuske, A. Matveenko, G. Meyer, A. Meseck, R. Müller, A. Neumann, N. Ohm, K. Ott, E. Panofski, Y. Petenev, F. Pflocksch, D. Pflückhahn, T. Quast, J. Rahn, S. Rotterdamm, J. Rudolph, M. Schmeißer, O. Schüler, J. Völker, S. Wesch ... + a number of people I have surely forgotten

+ Many collaborators around the world

P. Kneisel (JLAB), G. Ciovati (JLAB), R. Nietubyc (NCBJ), J. Sekutowicz (DESY), J. Smedley (BNL), J. Teichert (HZDR), A. Arnold (HZDR), P. Michel (HZDR), V. Volkov (BINP), I. Will (MBI), B. Riemann (TU Dortmund), A. Ferrarotto (TU Dortmund), T. Weis (TU Dortmund), G. Pöplau (U. Rostock), U. van Rienen (U. Rostock), T. Galek (U. Rostock), C. Brackenbusch (U. Rostock), K. Aulenbacher (JGU), Y. Mamaev (SPSPU), V. Shvedunov (MSU), E. Kako (KEK), R. Eichhorn (Cornell) + a number of people/labs I have surely forgotten …

Apologies for those who were forgotten on the list!