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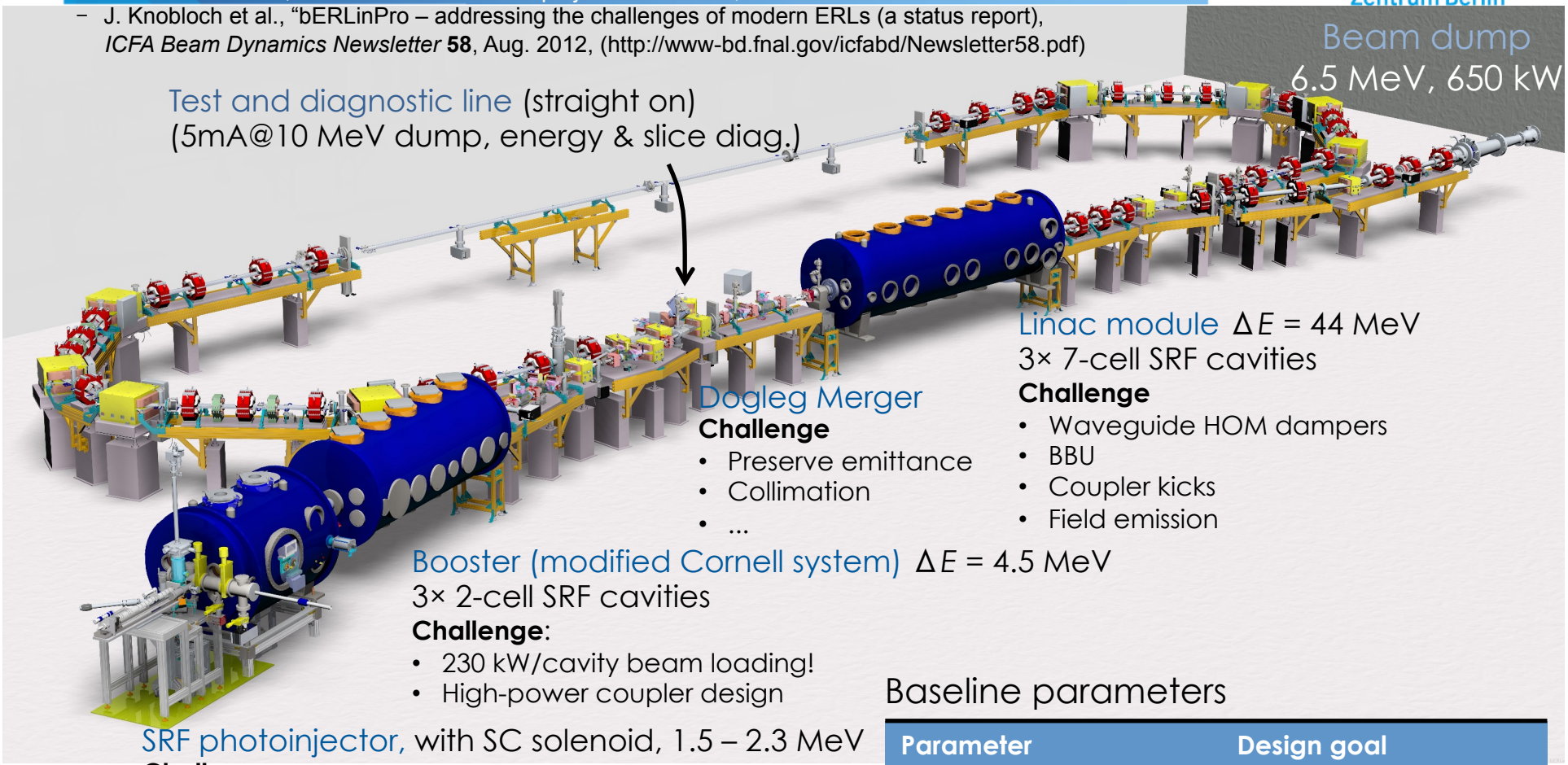
- M. Abo-Bakr et al., "Status of the HZB ERL project bERLinPro", *Proc. IPAC2014*
- J. Knobloch et al., "bERLinPro – addressing the challenges of modern ERLs (a status report), *ICFA Beam Dynamics Newsletter* **58**, Aug. 2012, (http://www-bd.fnal.gov/icfabd/Newsletter58.pdf)



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
- …

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	$< 10^{-5}$

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

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 …

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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)

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 <u>significantly</u> better than 1E-5/turn (compare with BESSY-II: ca. 1E-11/turn!!)
- Detection & avoidance
- Shielding designs / facility layouts suitable for user facilities

Status: Optics/beam dynamics

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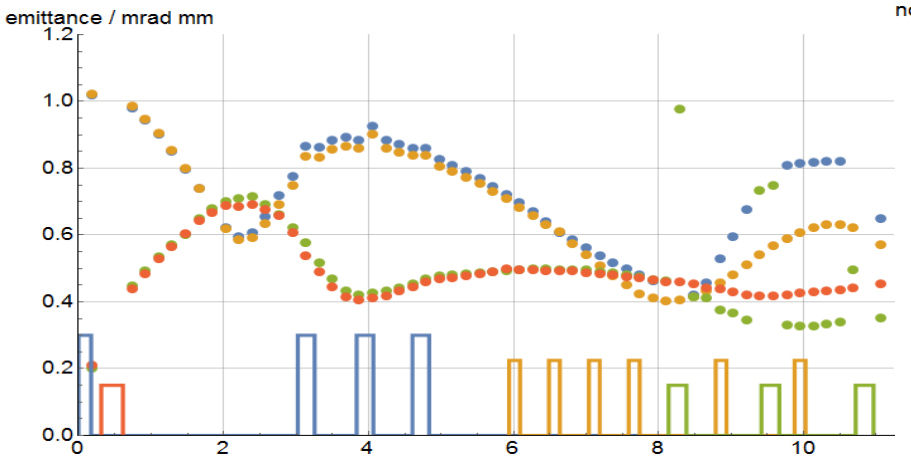
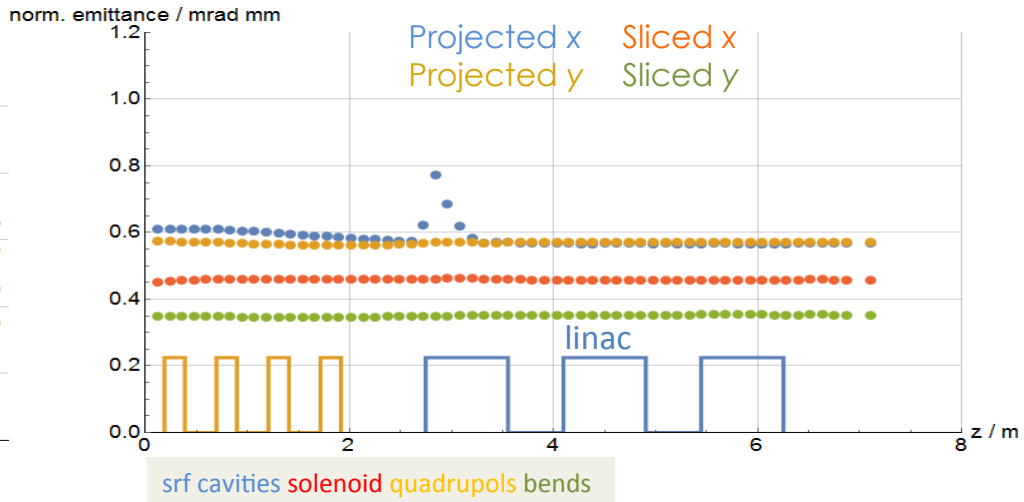
- B. Kuske, M. Abo-Bakr et al., "The injector layout of bERLinPro", *Proc. IPAC 2013*
- B. Kuske, J. Rudolph, "Beam positioning concept and tolerance considerations for bERLinPro", *Proc. IPAC 2014*
- M. Abo-Bakr et al., "Status of the HZB ERL project bERLinPro", *Proc. IPAC2014*

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)





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Warm Systems – Magnets & Girder

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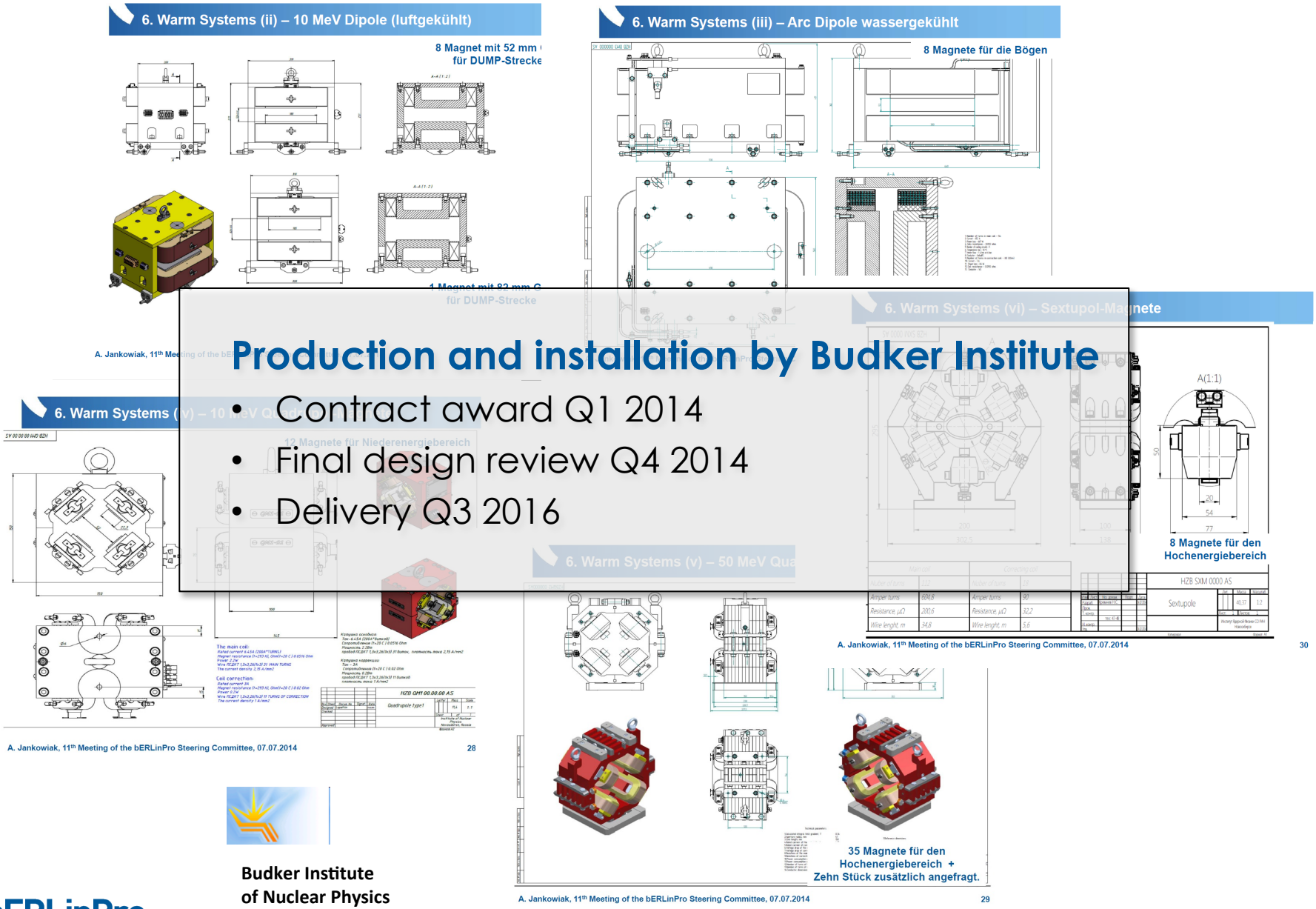

Production and installation by Budker Institute

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

Budker Institute of Nuclear Physics

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Impedance analysis

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

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Vacuum system/diagnostics

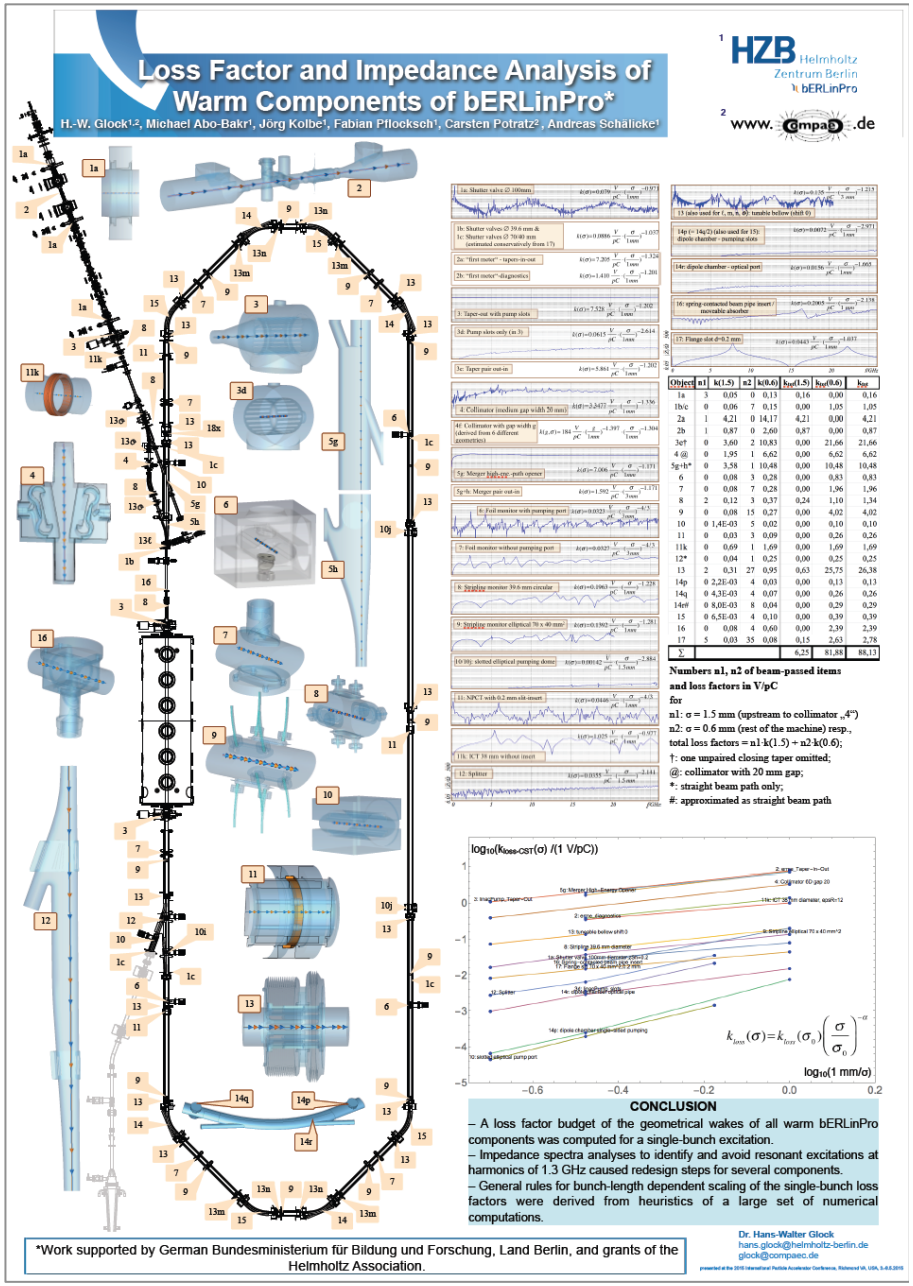
- Component types and layout is being settled & first prototypes are under production
- Aluminum vacuum chamber to limit activation.

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 $n\times1.3$ GHz resonances



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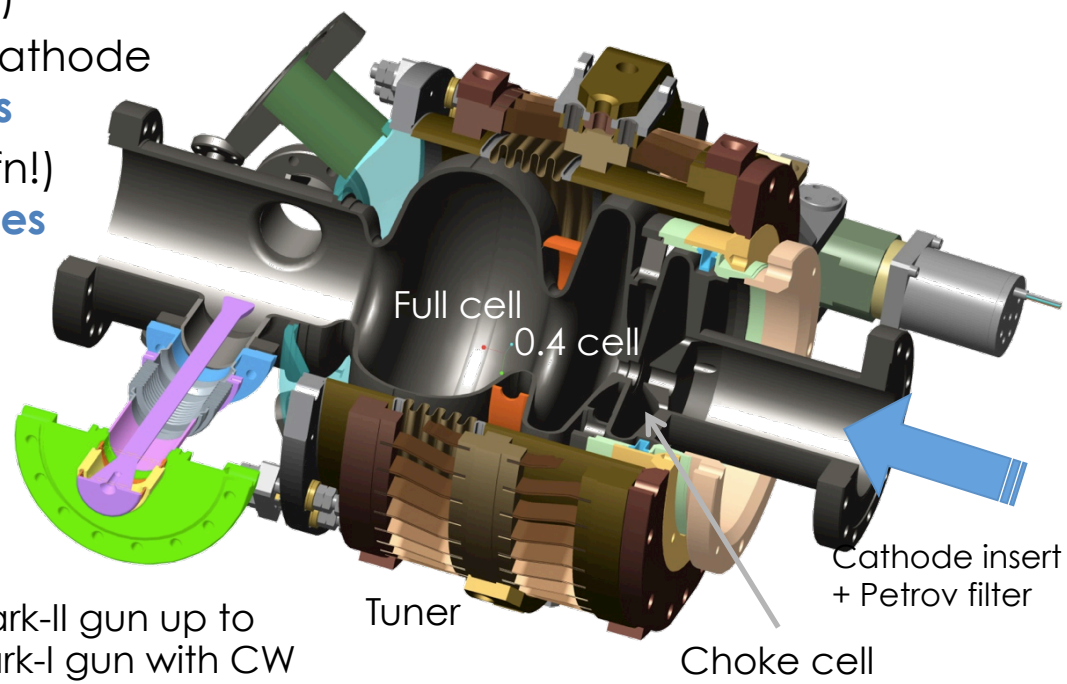
See poster

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*

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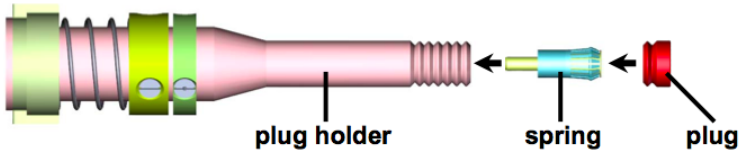
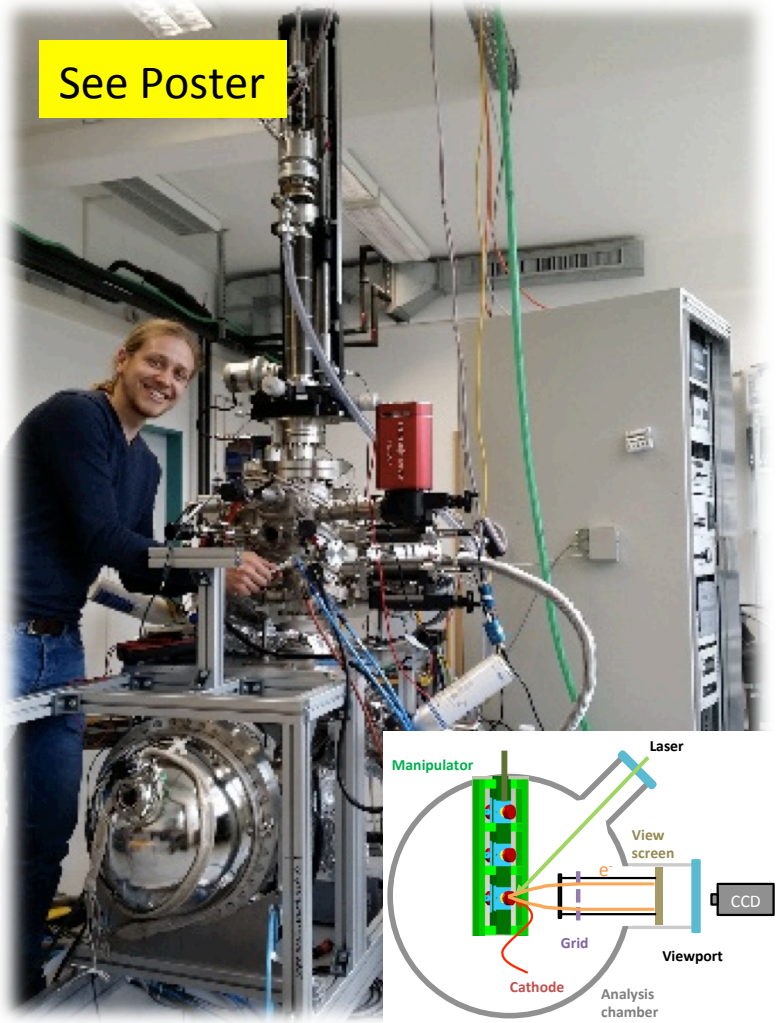
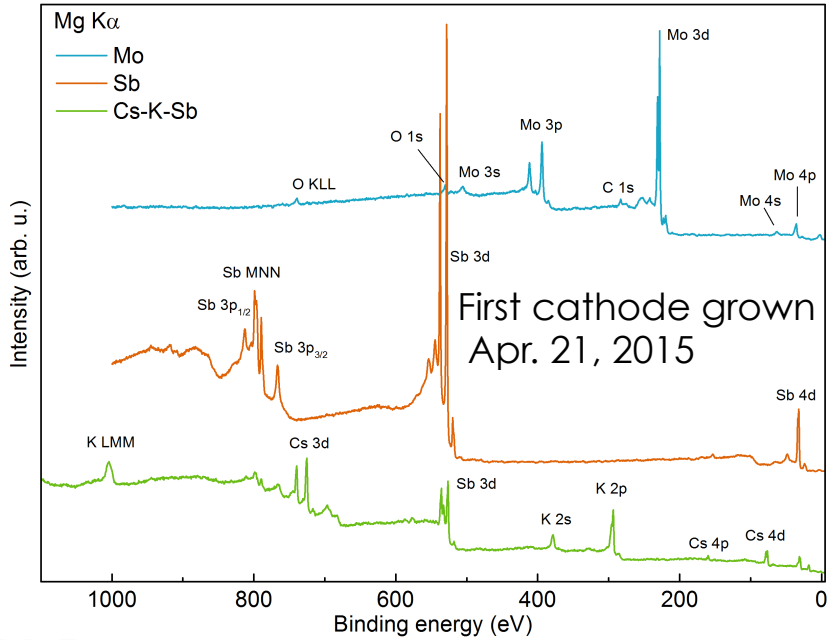
Photocathode production = "alchemy"

- → 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





First cathode grown Apr. 21, 2015

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SRF photoinjector: 1.4-cell cavity

- 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*

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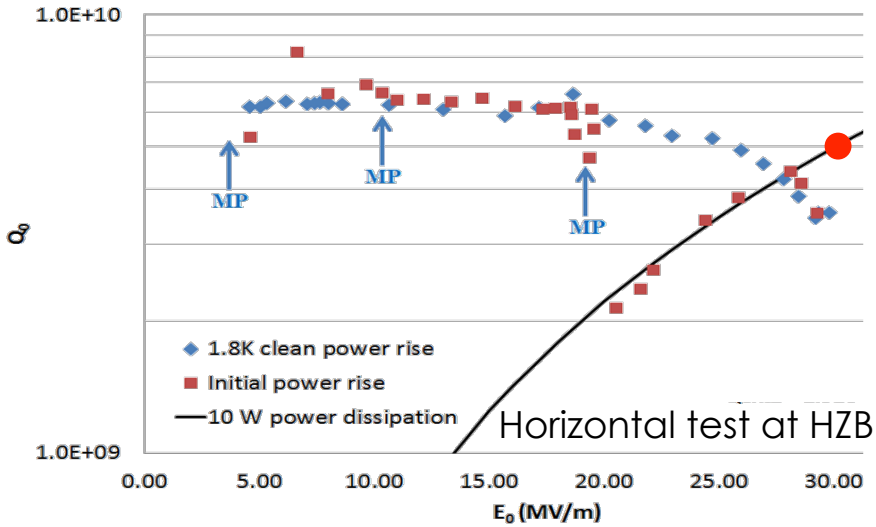
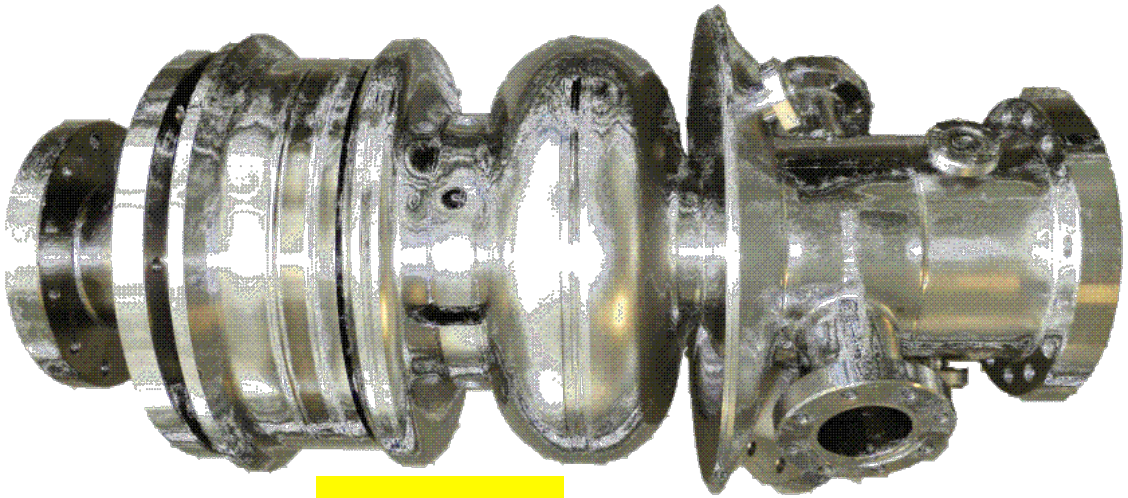
Production/vertical acceptance tests at Jefferson Laboratory

- 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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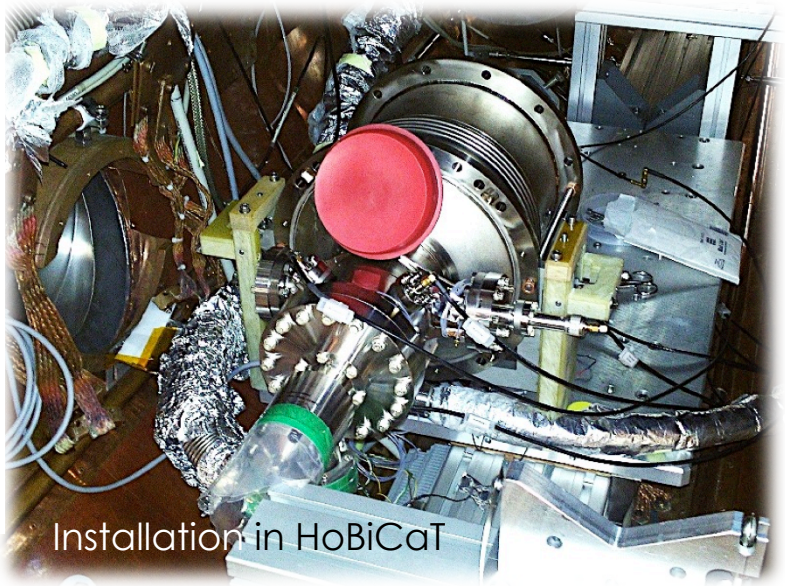

Booster module

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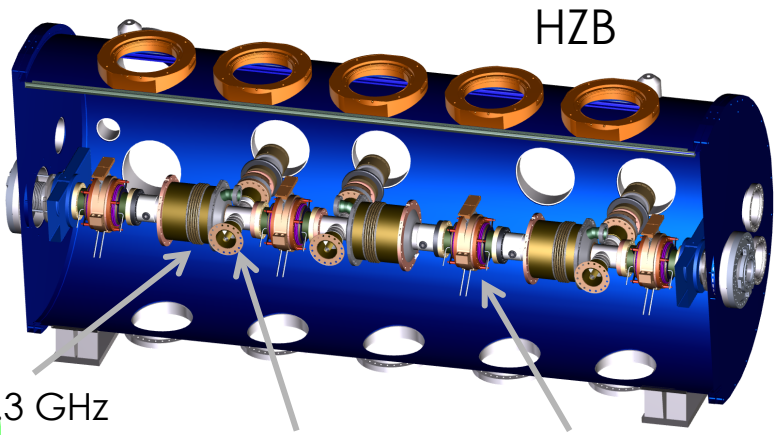
- A. Burrill et al.,"BERLinPro Booster Cavity Design, Fabrication and Test Plans", *Proc. LINAC 2014*
- A. Neumann et al., "Booster cavity and fundamental power coupler design issues for bERLinPro", *Proc. IPAC 2014*
- V. Khan et al., "High-power RF input couplers and test stand for the bERLinPro project",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

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

Cornell U.



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2-cell 1.3 GHz SRF Cavity

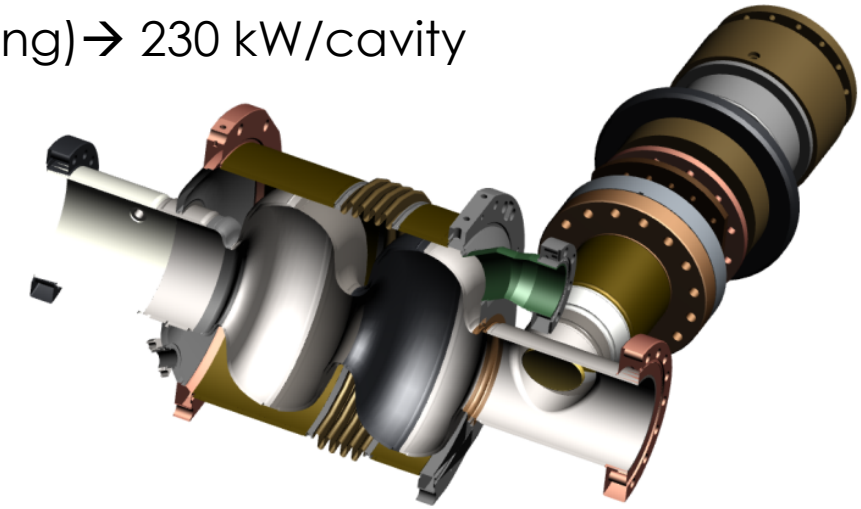
Twin 115 kW power couplers

Beamline HOM absorbers

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*

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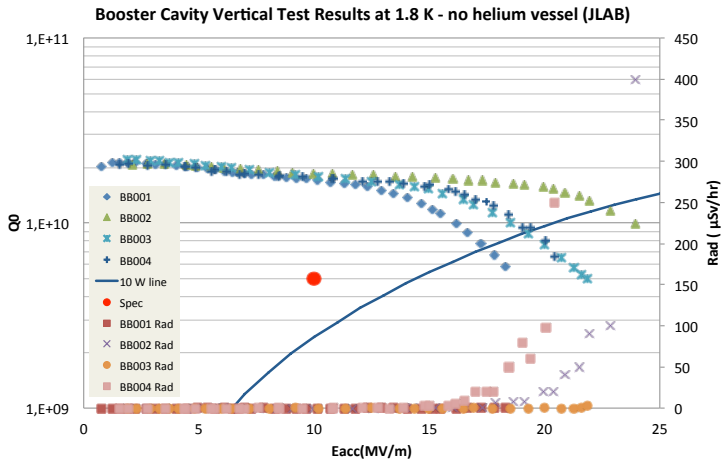
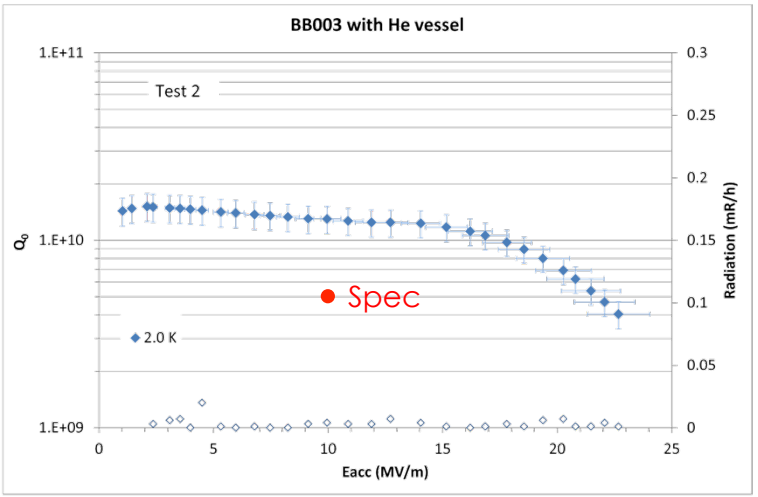
Production & processing of cavities under a CRADA at JLAB

- 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

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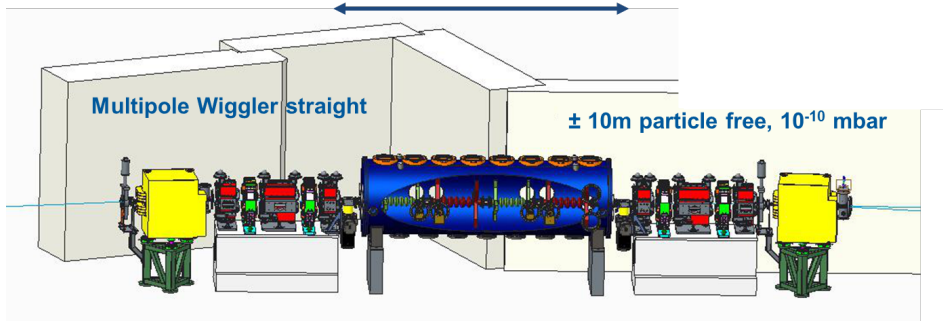
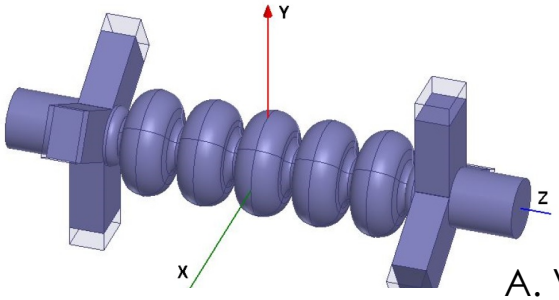
- A. Velez et al., "HOM Damping Optimization Design Studies for BESSY VSR", *Proc. IPAC 2015*
- G. Wüstefeld et al.,"Simultaneous Long and Short Electron Bunches in the BESSY II Storage Ring, *Proc. IPAC2011*
- R. Rimmer et al., "Jlab high-current CW cryomodules for ERL and FEL applications", *Proc.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

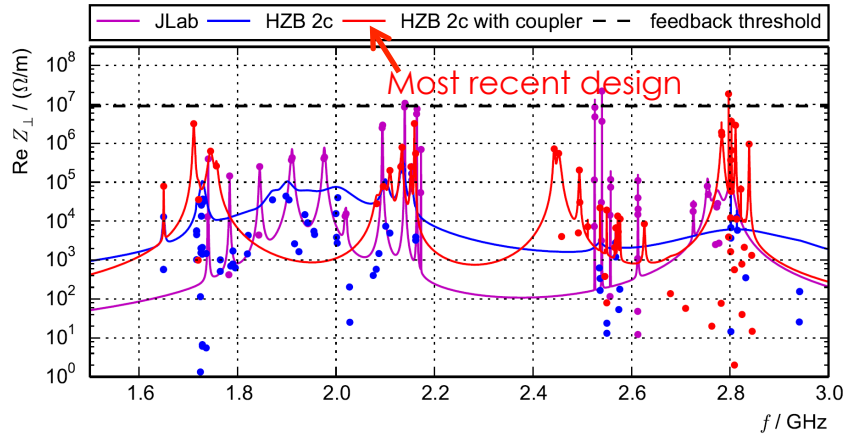
BESSY-II storage ring

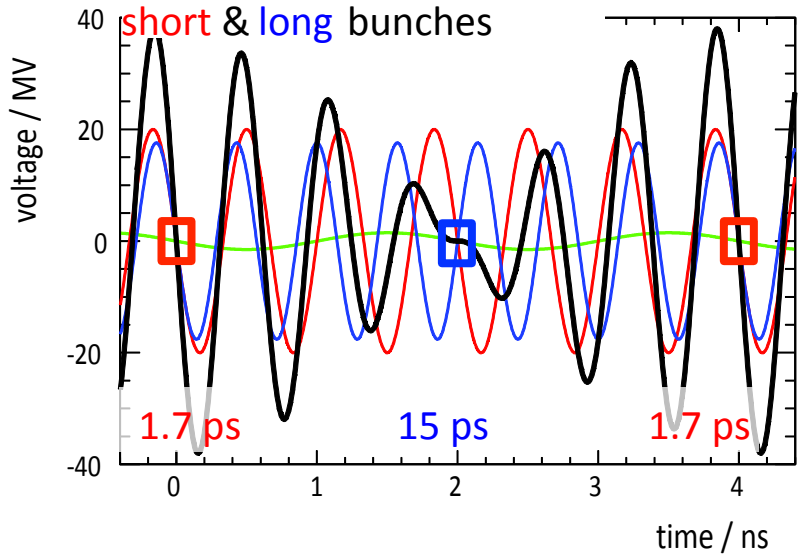




A. Velez

Transverse case





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

LINAC cavities

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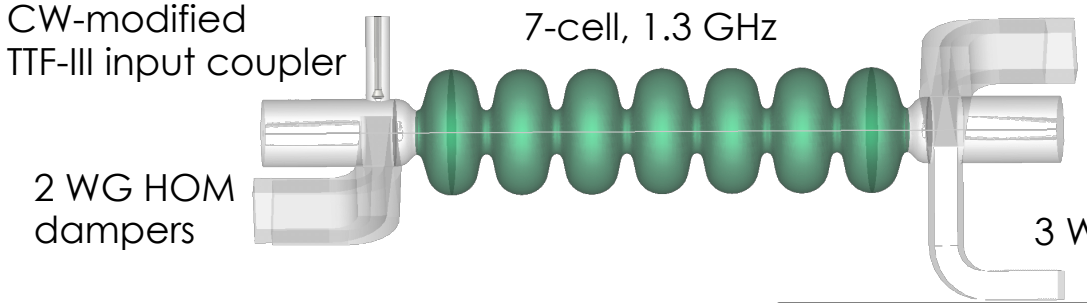
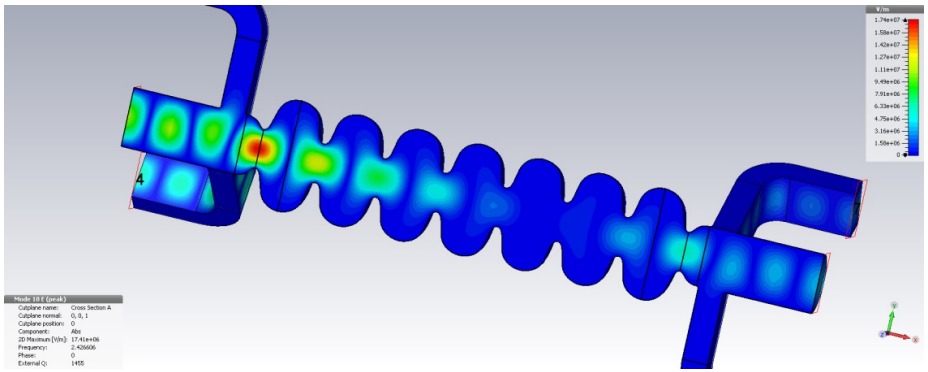
- A. Neumann et al., "Final design for the bERLinPro main LINAC cavity", *Proc. LINAC 2014.*
- O. Kugeler, et al., "Adapting TESLA technology for future CW light sources using HoBiCaT", *Rev. Sci. Inst.* **81**, 074701 (2010)

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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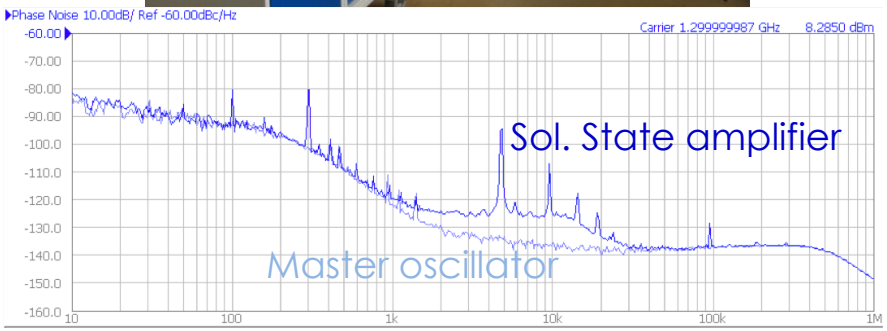
Photoinjector & booster RF

- 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*

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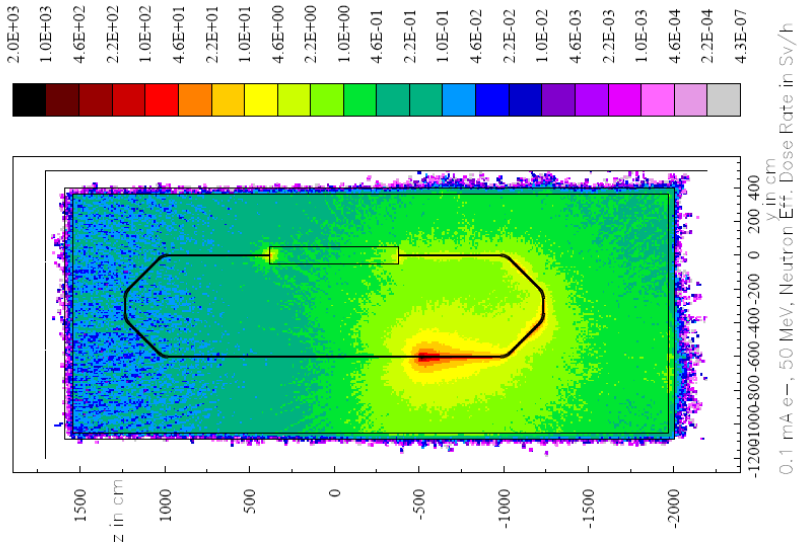
Gamma production, fast neutron production and activation issues

- 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)



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Building: on paper

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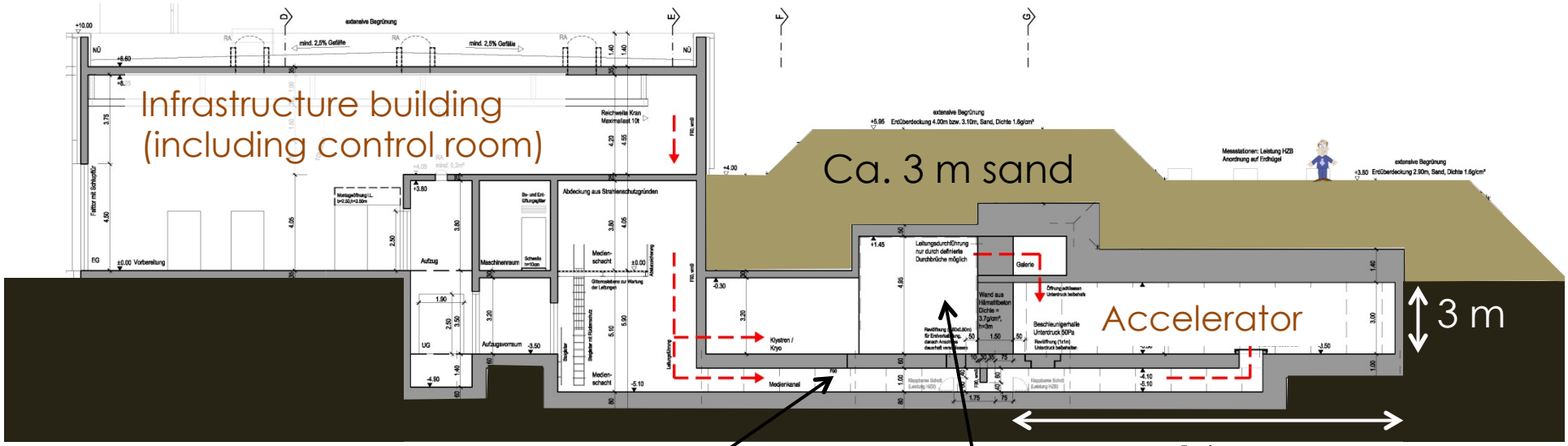
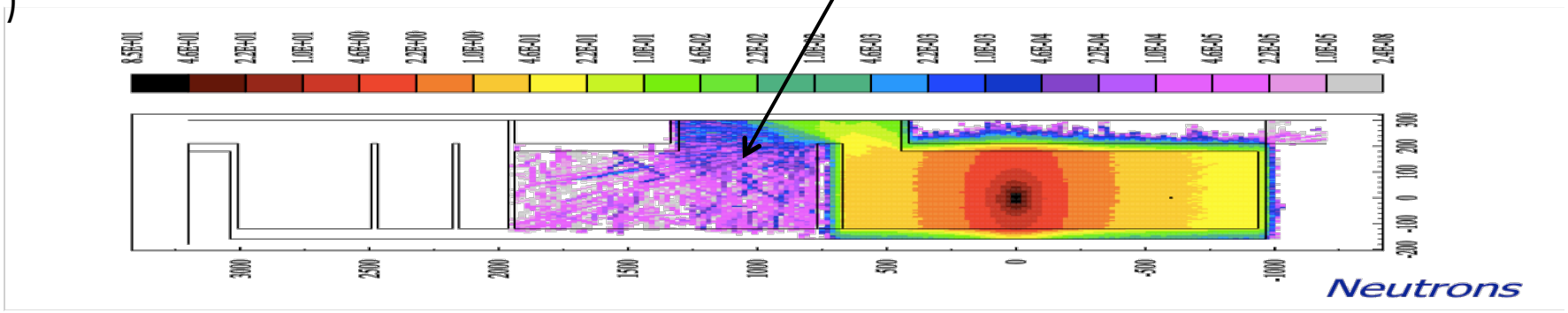


Utilities access underground

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

Fluka calculations
(K. Ott)



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Building: in reality

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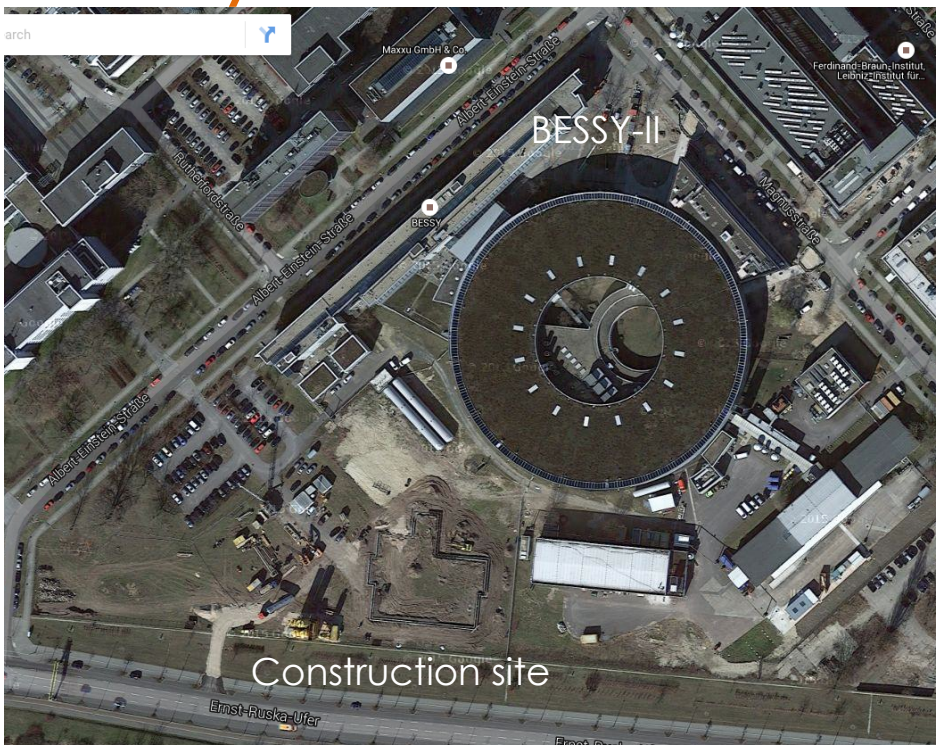
Construction commenced 11-Feb-2015
Underground construction complicated at Berlin site

- 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



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bERLinPro staging: 1

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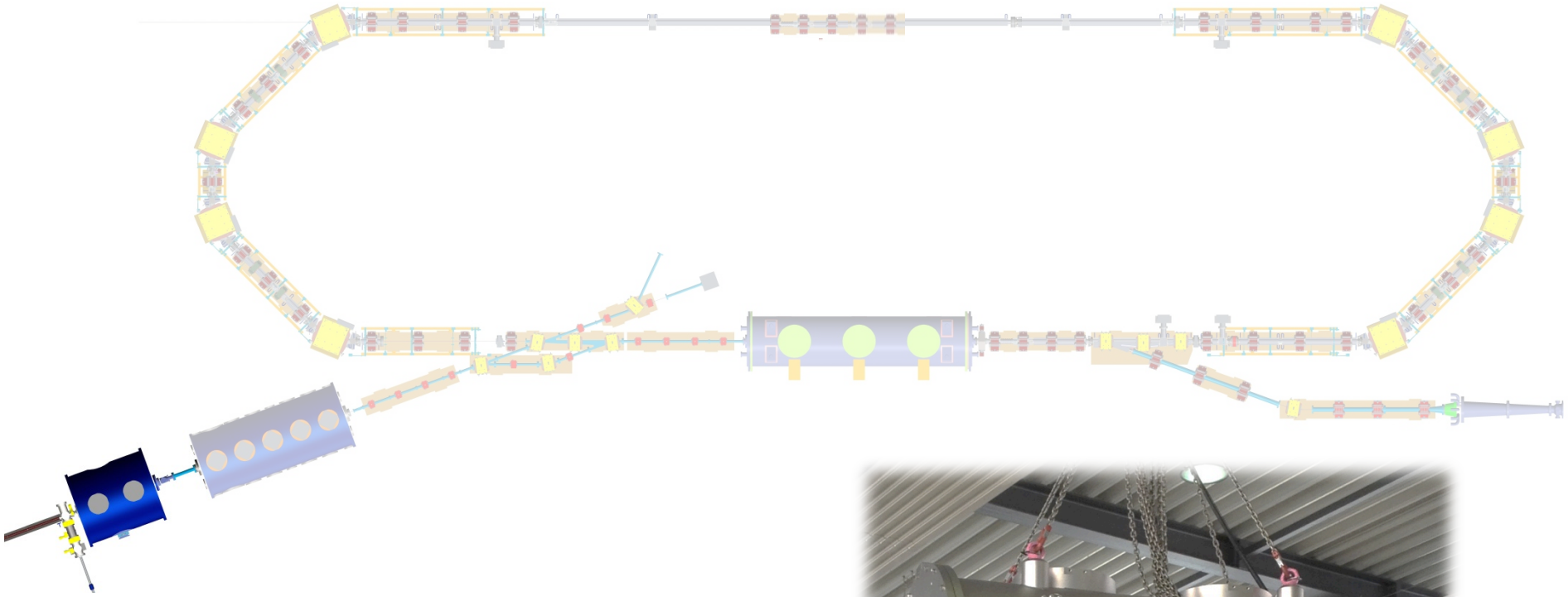

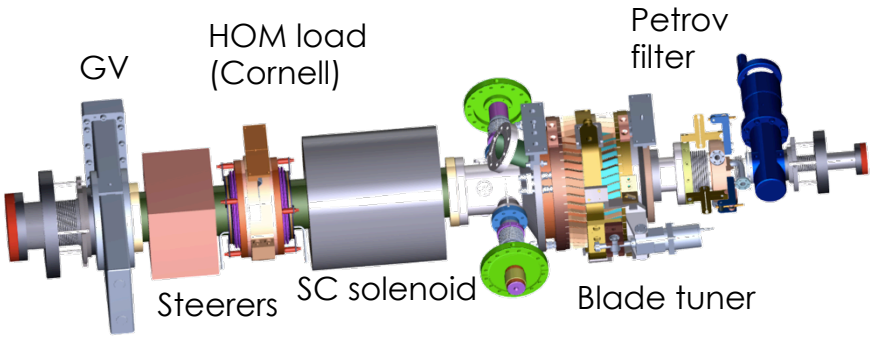

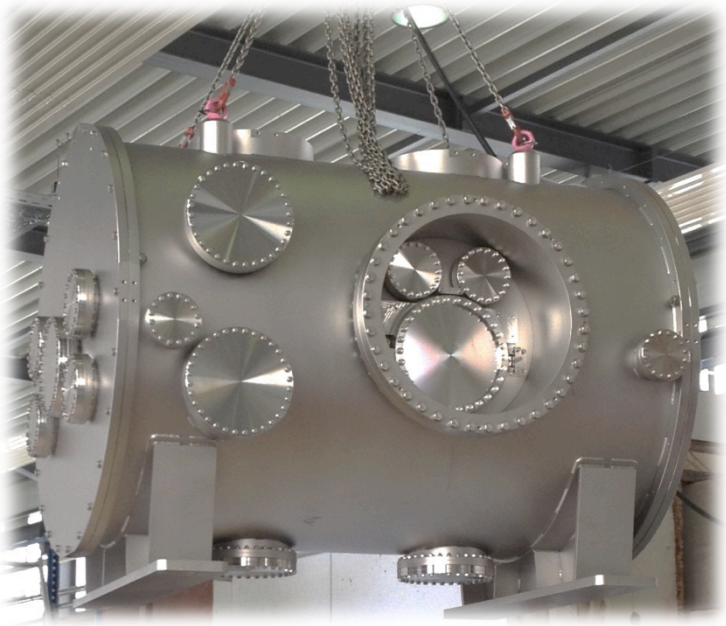

bERLinPro staging: 1

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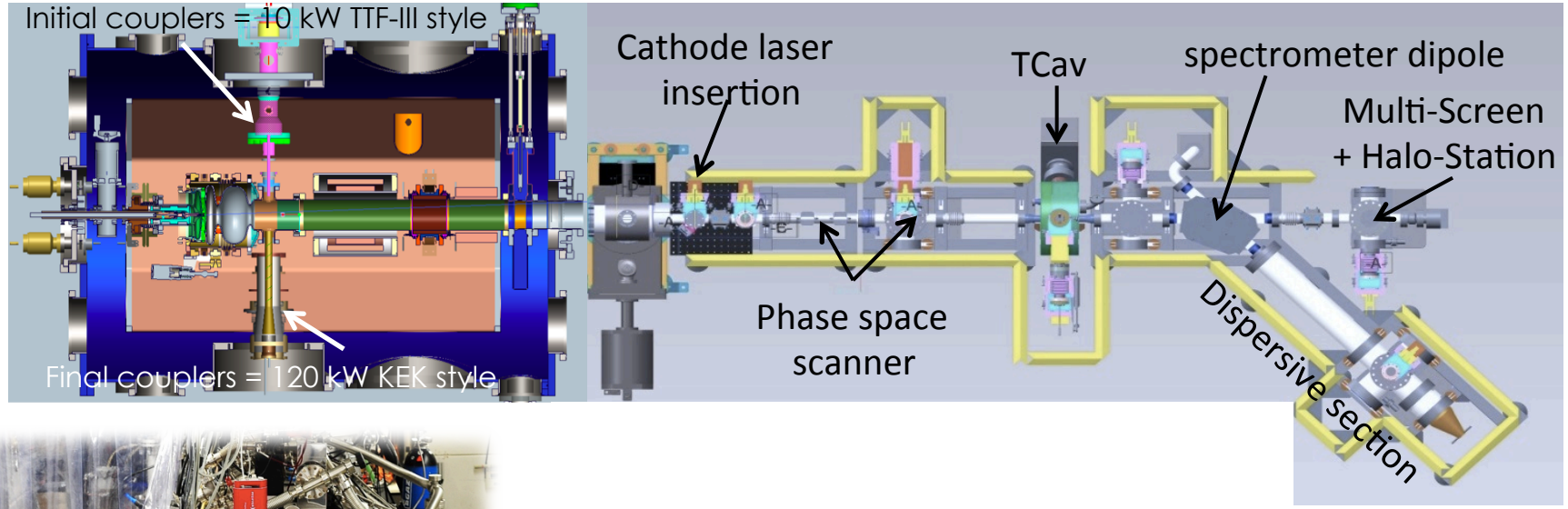
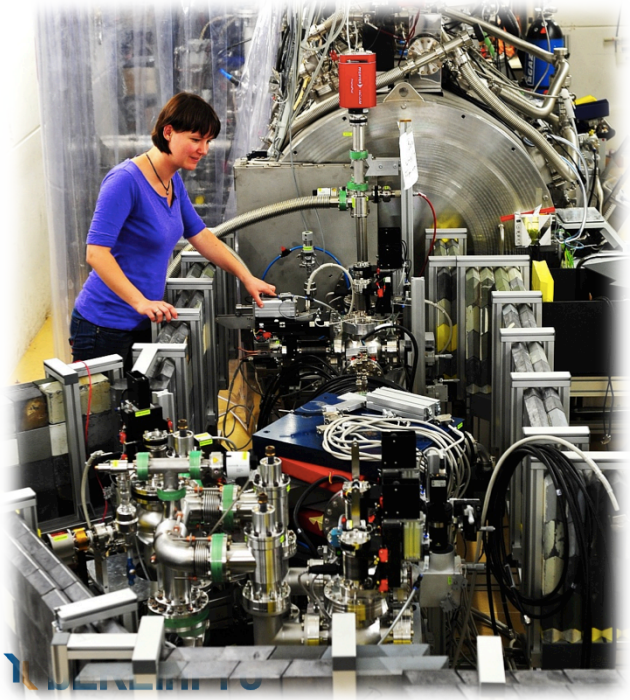
- J. Völker et al., "Introducing GunLab – A compact test facility for SRF photoinjectors", *Proc. IPAC 2014*
- R. Barday et al., "Characterization of a superconducting Pb photocathode…", *PRST-AB* **16**, 123402 (2013)
- M. Schmeißer et al., "Results from beam commissioning of an SRF plug-gun cavity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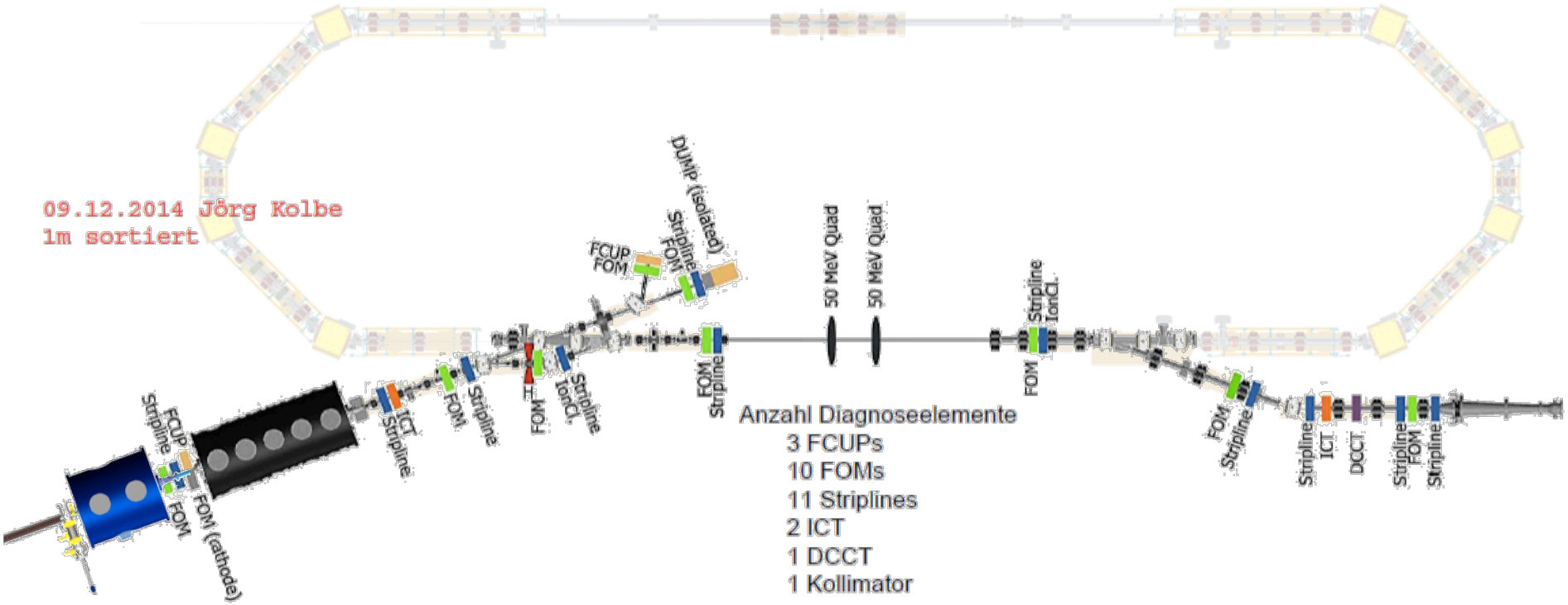
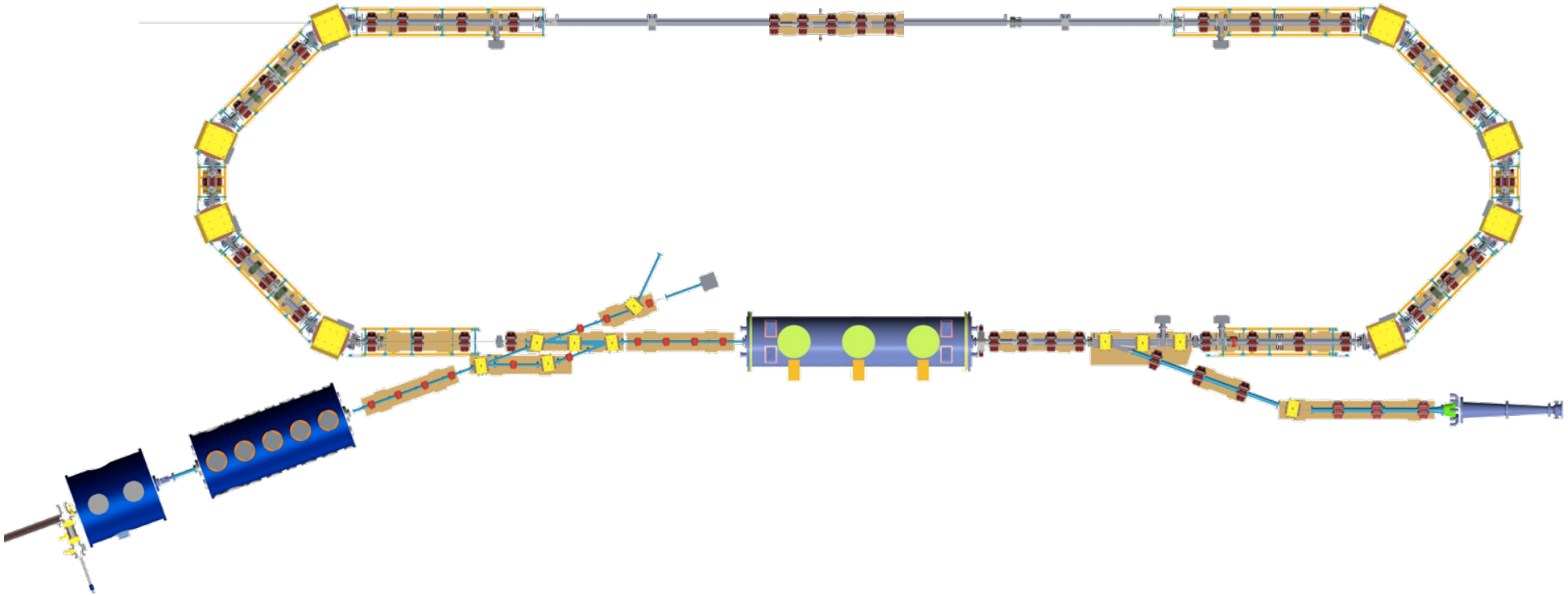


<10 MeV, high-current op. through "banana": start Q4 2017 / Q1 2018

- 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.

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The bERLinPro Team

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+ Many collaborators around the world

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