Radiation Protection Issues of bERLinPro

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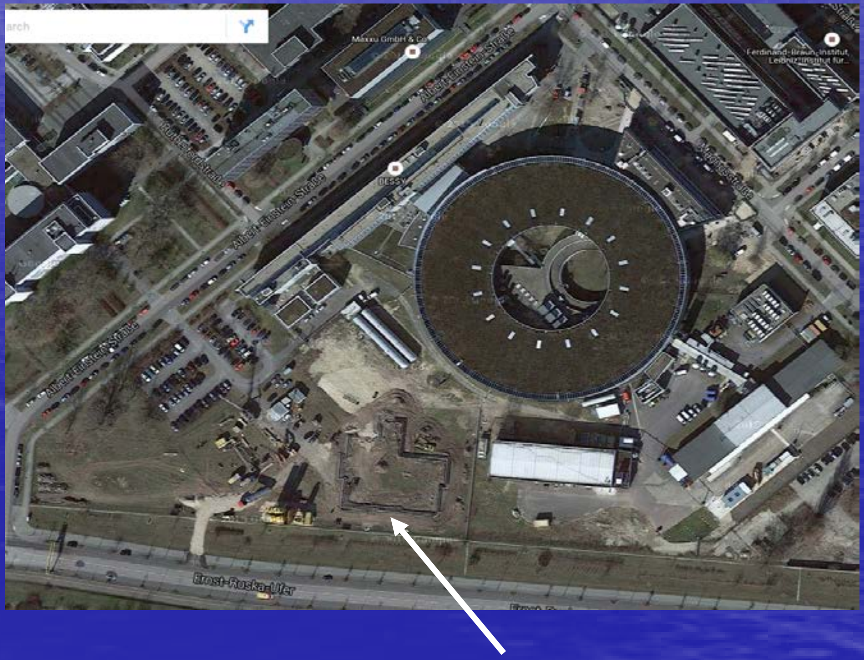
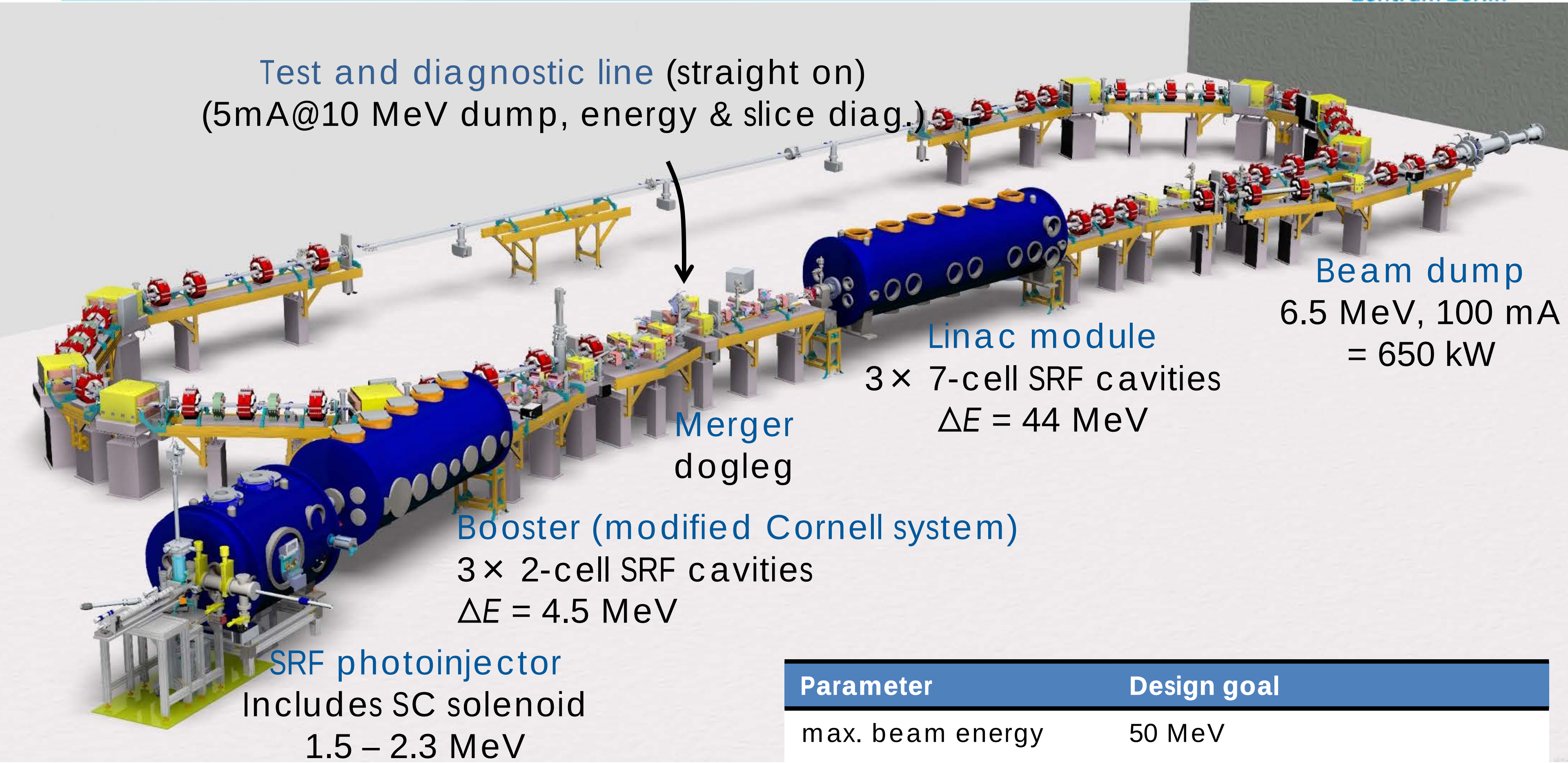
- **Overview**
- **Shielding results**
- **Dose calculations**
- **Activations**
- **Dosimetry**
- **Summary**



Location of bERLinPro

http://www.Helmholtz-berlin.de/projects/berlinpro/webcam/index_de.html

bERLinPro layout



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

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

Electron losses used for shielding calculations

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Electron losses for direct radiation

bERLinPro 0.6 % losses (0.1 % / point source)
(30 kW rf power)

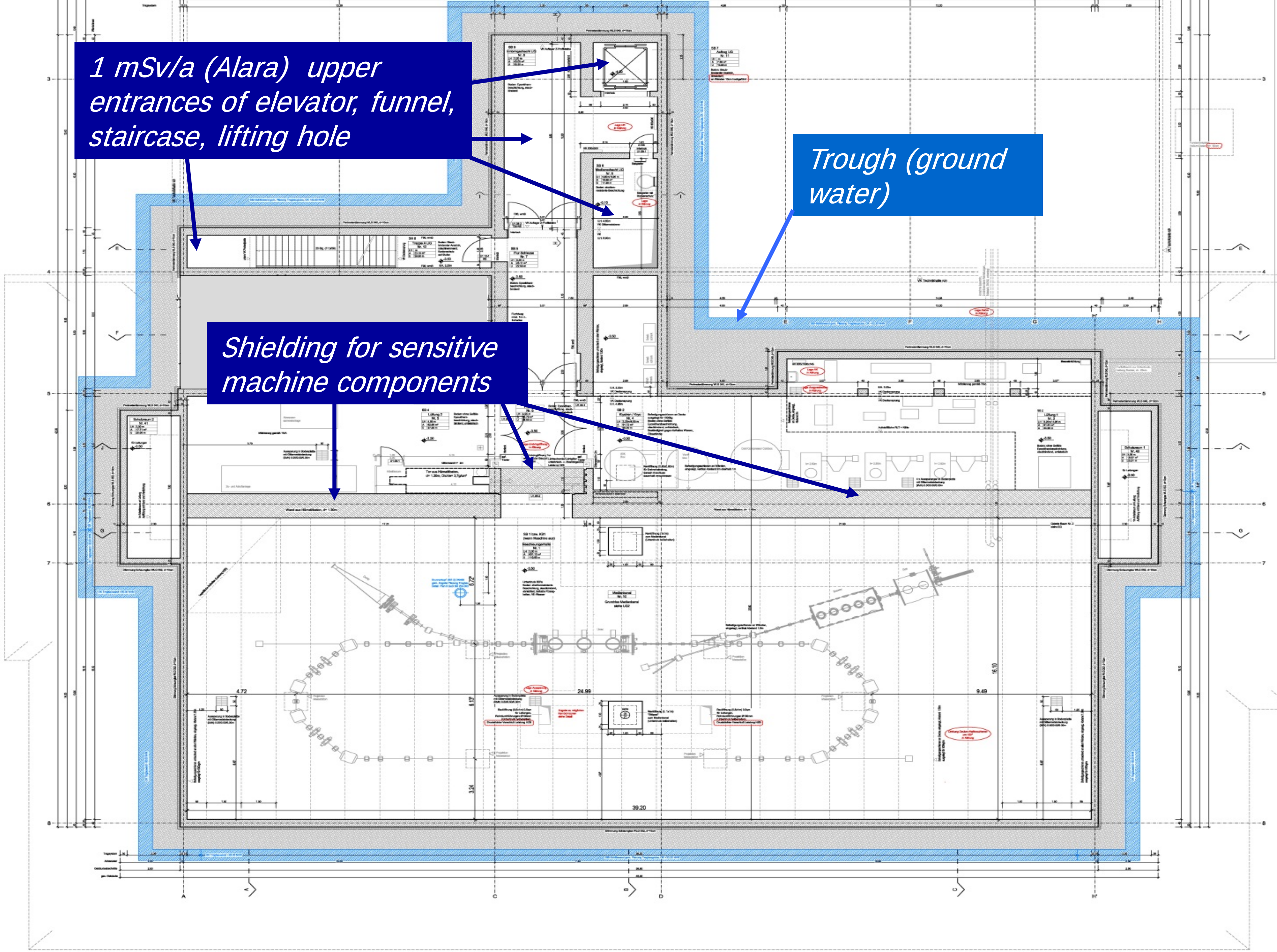
Electron losses for indirect radiation (activations)

5 µA/m
(machine protection system)
Beam parameter: 100 mA, 50 MeV

Reduction of electron losses should have highest priority for the development of ERLs

Future light sources as ERL (example BESSY 300 mA):
BESSYII injects 2E15 e-/a, as ERL 6000 h/a, 800 nsec convolution time = 74 e-/convoluton
= 4.9 E-11 losses / convolution

If losses are higher ERLs must be built subterraneously, synchrotron radiation deflected vertically (similar to FEL).
-> More expensive than storage rings, but better beam quality (emittance, pulse length, many beamlines could be used simultaneously)
Losses should be < 1E-7 / convolution otherwise serious problems with activations


1 mSv/a (Alara) upper entrances of elevator, funnel, staircase, lifting hole
Trough (ground water)
Shielding for sensitive machine components

Derivation of new formulas completed

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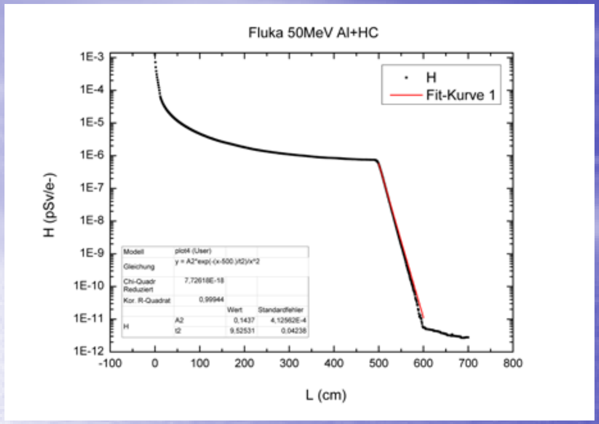
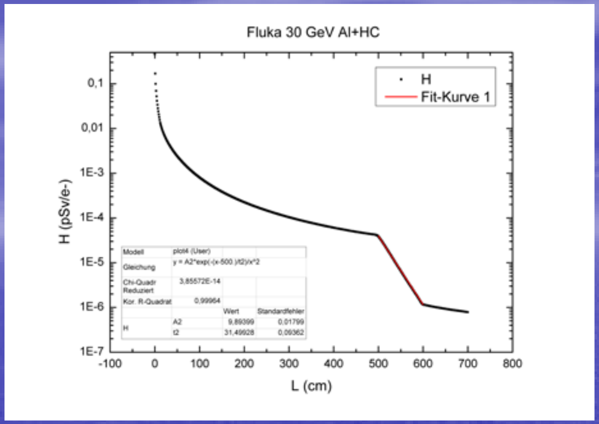


New: Neutron attenuation coefficients λ for haematit
λ (GN) = 35.2 g/cm²
λ (HN) = 116.5 g/cm²

Calculations by Y. Bergmann



$$H = H_A \cdot \ln Z \cdot t^{2.44} \cdot msc \cdot E \cdot \frac{1}{r^2} \cdot \exp(-(x \cdot \rho - 75\ g/cm^2)/\lambda)$$

$H_A = 3.45 \cdot 10^{-17}\ Sv/e^-;\ t = l/rad.len;\ msc = 1/54.95;\ E = 0.05\ GeV;\ r = 7.69\ m$

$\rho = 3.7\ g/cm^3; \lambda = 37.03\ g/cm^2$ heavy concrete

$rad.len(Al) = 8.9\ cm,\ (Fe) = 1.8\ cm$

Source term Al = 0.1 Fe

γ - radiation

$$Hr^2 = \frac{1}{r^2} \cdot a_1 \cdot E \cdot \exp(-d \cdot \rho / \lambda_g) + \frac{1}{r^2} \cdot K(E) \cdot a_2 \cdot E^{1.1} \cdot \exp(-d \cdot \rho / \lambda_h)$$

$a_1 = \eta \cdot 0.24 \cdot A^{2/3}$

$\lambda_g = 35.2\ g/cm^2$ heavy concrete $; E = 0.05\ GeV; r = 7.69\ m$

$a_2 = 4.453 \cdot A^{-2/3}$

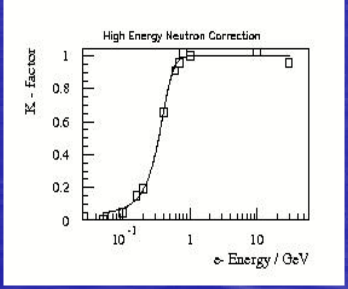
$\lambda_h = 116.5\ g/cm^2$ heavy concrete $\rho = 3.7\ g/cm^3$

Neutron – radiation

$$K(E) = 1 - \frac{1}{\exp(E \cdot a + b) + 1}$$

$a = 10.52, b = -3.59, E$ in GeV

Source term (GN) Al = 0.6 Fe
Source term (HN) Al = 1.6 Fe



K. Ott, M. Helmecke The Shielding Design of bERLinPro, IPAC 2011, San Sebastian, Spain

Direct radiation fields

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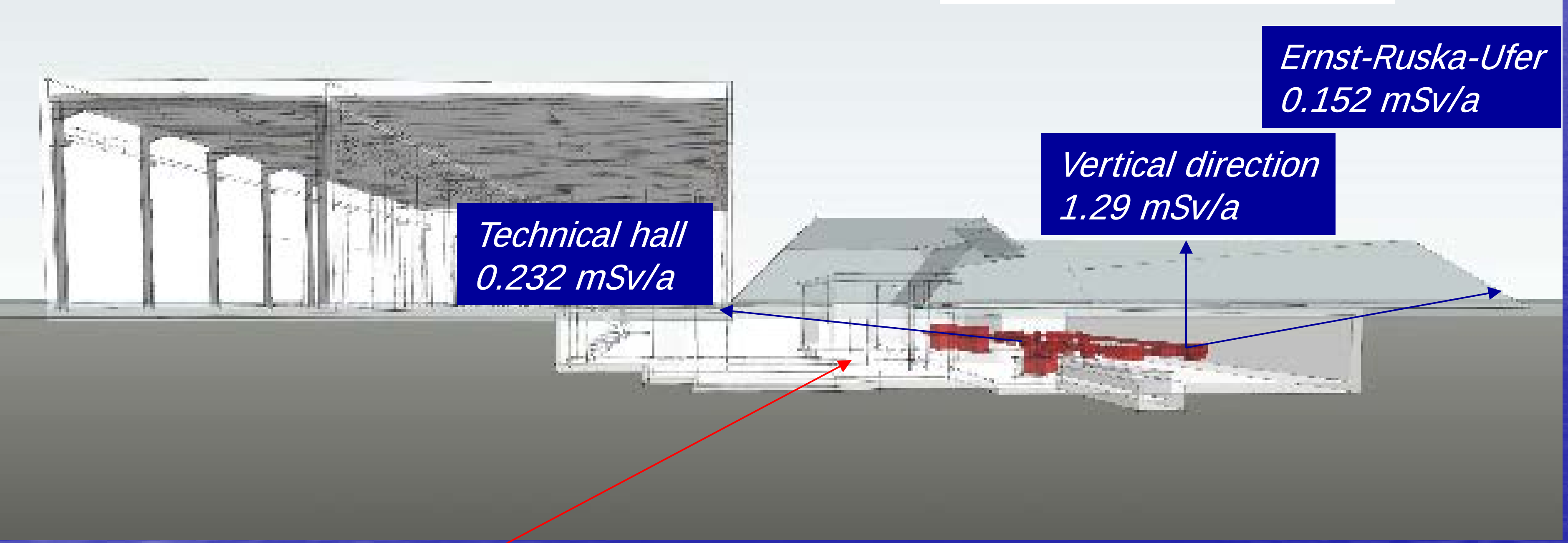
Analytical calculations with radp_mod.C (K. Ott)

$\gamma - \dot{H}_1$	$3.12e-01$	Sv/h	$\gamma - \dot{H}_S$	$1.82e-09$	Sv/h
$\gamma - H_N$	$3.64e-06$	Sv/a	$\gamma - H_M$	$0.00e+00$	Sv/a
$\gamma - \dot{H}_1^{tot}$	$3.12e+02$	Sv/h	$\gamma - \dot{H}_S^{tot}$	$1.82e-06$	Sv/h
$\gamma - H_N^{tot}$	$0.00e+00$	Sv/a	$\gamma - H_M^{tot}$	$0.00e+00$	Sv/a
$giant_n - \dot{H}_1$	$2.94e+00$	Sv/h	$giant_n - \dot{H}_S$	$4.55e-15$	Sv/h
$giant_n - H_N$	$9.11e-12$	Sv/a	$giant_n - H_M$	$0.00e+00$	Sv/a
$giant_n - \dot{H}_1^{tot}$	$2.94e+03$	Sv/h	$giant_n - \dot{H}_S^{tot}$	$4.55e-12$	Sv/h
$giant_n - H_N^{tot}$	$0.00e+00$	Sv/a	$giant_n - H_M^{tot}$	$0.00e+00$	Sv/a
$fast_n - \dot{H}_1$	$1.15e-01$	Sv/h	$fast_n - \dot{H}_S$	$6.45e-07$	Sv/h
$fast_n - H_N$	$1.29e-03$	Sv/a	$fast_n - H_M$	$0.00e+00$	Sv/a
$fast_n - \dot{H}_1^{tot}$	$1.15e+02$	Sv/h	$fast_n - \dot{H}_S^{tot}$	$6.45e-04$	Sv/h
$fast_n - H_N^{tot}$	$0.00e+00$	Sv/a	$fast_n - H_M^{tot}$	$0.00e+00$	Sv/a

Die gesamte Jahresdosis beträgt:

1.29e-03 Sv/a.



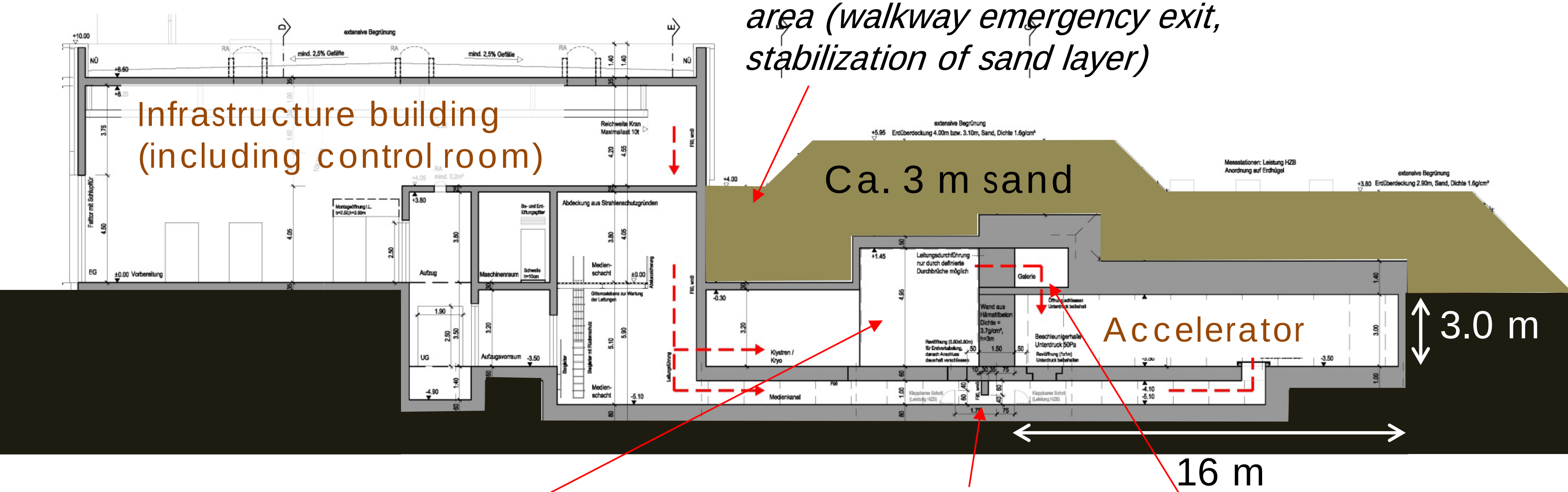
Radiation through the
Lifting hole, elevator, stair case

Doses through thick shielding by neutrons from quasi-deuteron fission

Constanze Tibes, DGI Bauwerk Gesellschaft von Architekten mbH (arcitect's office)

Building: on paper

Sand not for shielding in this area (walkway emergency exit, stabilization of sand layer)



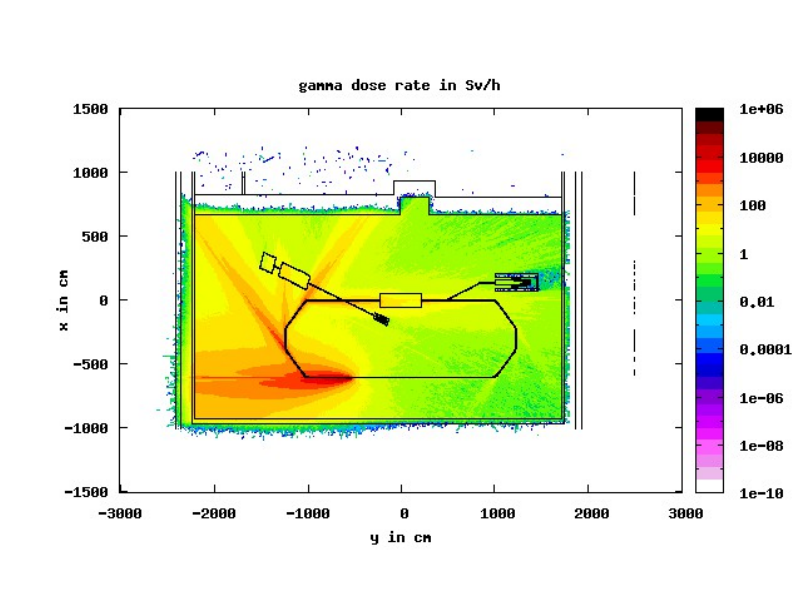
„gallery" for radiation sensitive components (cold box), air cooling that should be close to accelerator

Labyrinth in cable duct

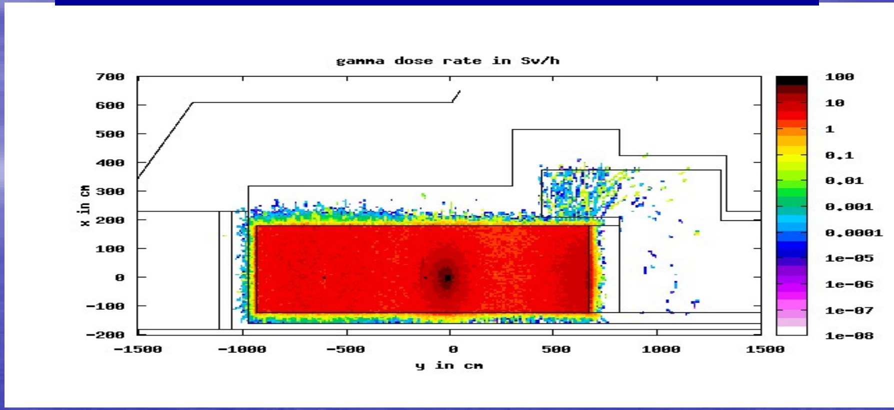
„balcony" laser tube and rf tubes

All subterraneous areas are interlock safed exclusion areas (Sperrbereiche) during operation, elevator is disabled and cabine is on ‚cellar' postion

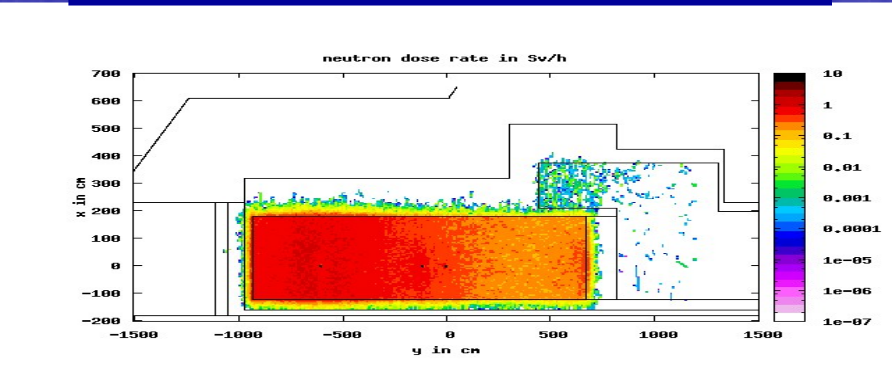
FLUKA calculations of doses through openings



γ dose rate through "balcony"



Neutron dose rate through "balcony"



0.1 mA losses, 50 MeV, 1 mrad, target Al 1 mrad

Modelling of bERLinPro with FLUKA completed

Calculation of activation: preliminiary considerations

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Activation rate:

$$\dot{N}^{+} = \rho \cdot N_L / A \int_0^{V_0} \int_0^{E_0} \sigma(E_P) \cdot \phi(E_P, \vec{r}) \cdot \mathrm{d}E_P \mathrm{d}V$$

Activation rate can be calculated by FLUKA

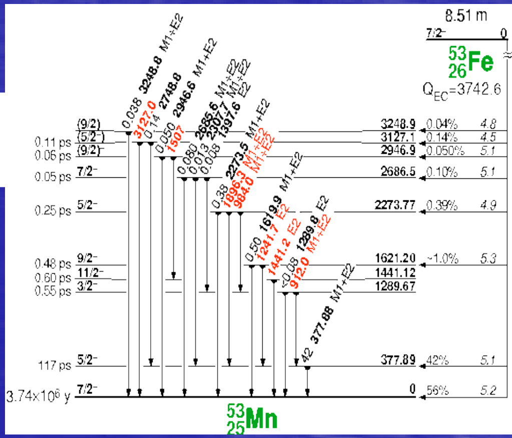
$\sigma(E_P)$: cross section
E_P: energy of photons
$\Phi(E_P, r) \cdot dE_P$: flux density of photons with energies between E_P and E_P+dE at r
$n=\rho \cdot N_L/A$: number of nuclei per volume
ρ: density of nuclei
N_L=6.023E23/mol
A: mass number of nucleus

Activation Equation:

$$A_\nu = \dot{N}^{+} \cdot [1 - \exp(-\lambda \cdot t_B)] \cdot \exp(-\lambda \cdot t_K) \cdot \frac{1 - \exp[-\nu \cdot \lambda(t_B + t_K)]}{1 - \exp[-\lambda(t_B + t_K)]}$$

ν: number of irradiation periods
$\lambda = (\ln 2)/T_{1/2}$
$T_{1/2}$: half-life of nucleus
t_B: irradtiation time
t_K: decay time

Dose calculation from activation and gamma energies from decay schemes

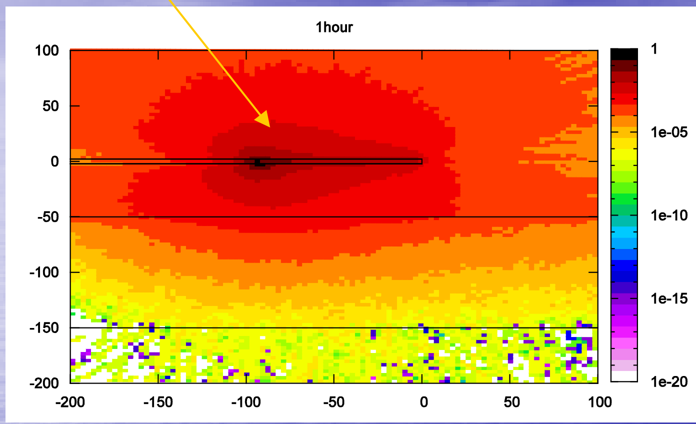


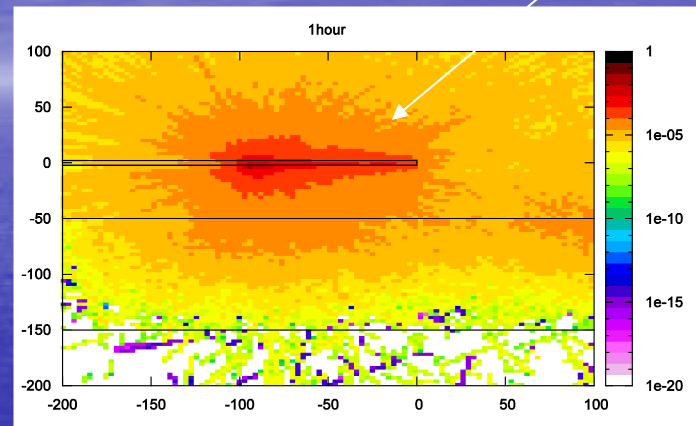
→ Method has been developed to automatize dose calculation by using the simulation code FLUKA without radiation constants from decay tables

Simulation of induced radioactivity

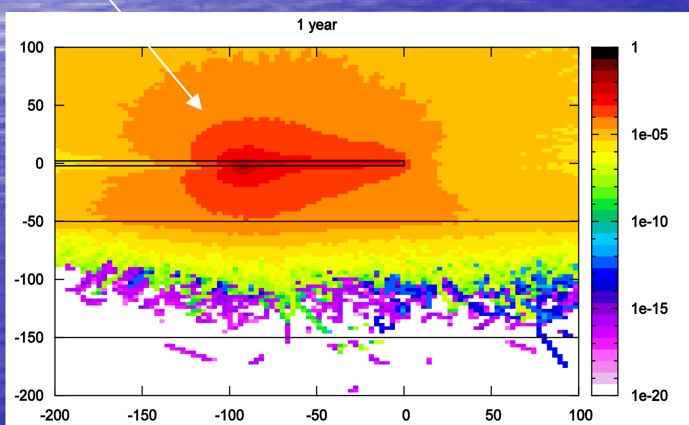
Electron loss of 5 µA/m for 2000 hours causes the following doses [Sv/h]:

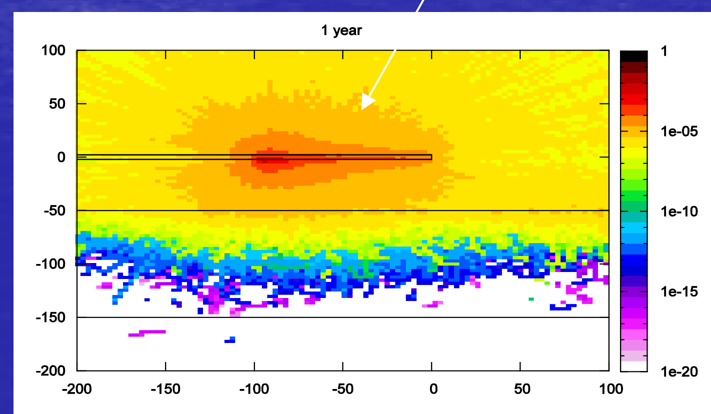
10 mSv/h After 1 hour of decay time *100 µSv/h*





1 mSv/h After 1 year of decay time *10 µSv/h*





Steel tube

Aluminium tube

Possible reduction of Ar41

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Ar41 is produced from
Ar40(nth,γ)Ar41
in the air

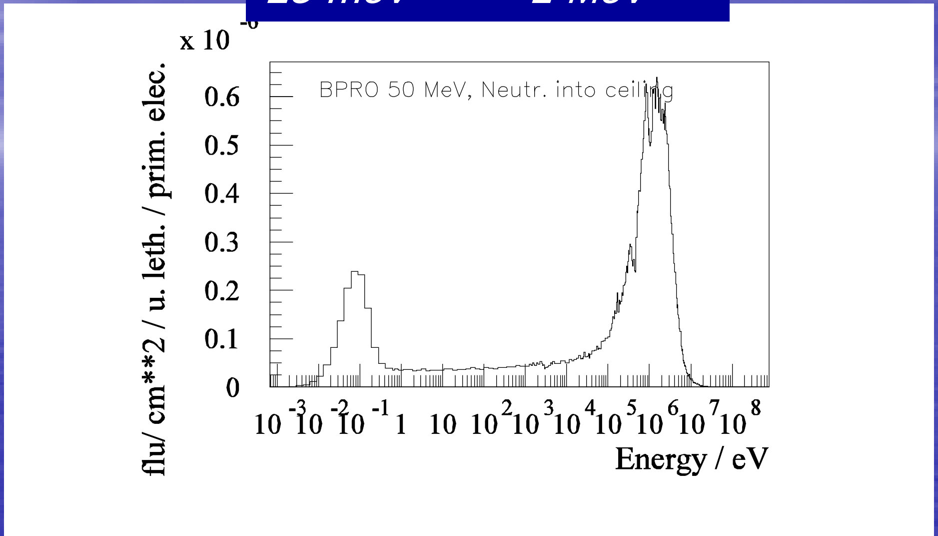
nth are neutrons that are thermalized (25 meV) in the wall

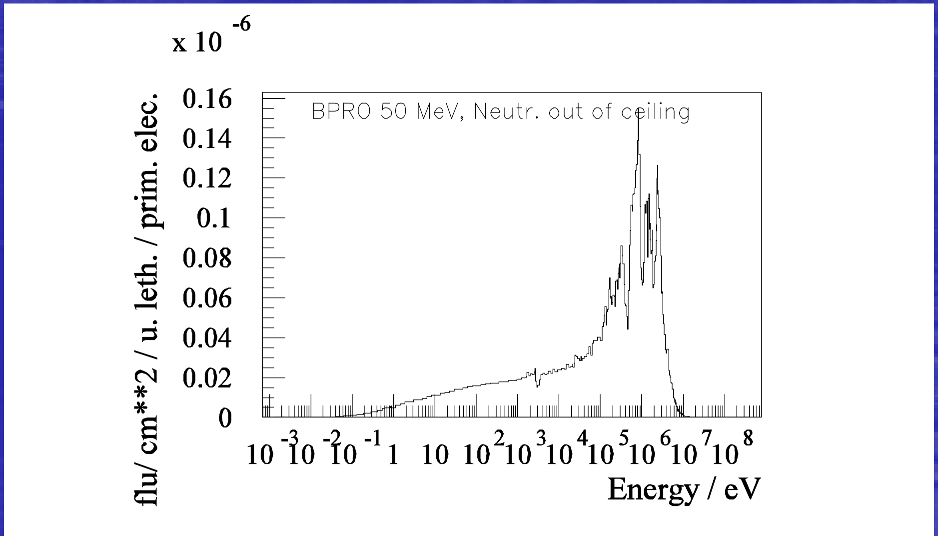
Test: inclusion of 0.5 % Boron
In concrete

0.5 mass % Boron in concrete reduces the Ar41 in the air by two orders of magnitude (steel) or a factor of 24 (Al)

Colemanit is chemical similar to cement (B2O3+CaO+H2O)
Cheep 50 k€ for bERLinPro, but the mechanical properties of concrete must be certified
Was not possible in time for bERLinPro

25 meV　　*1 MeV*





Activation of air inside accelerator hall

Nucleus	Bq/m³ steel	Bq/m³ aluminum	Bq/m³ Al Colemanit	Bq/m³ StrlSchV
Be7	133	252	175	6.0E3
C11	1.22E5	8.29E4	9.06E4	3.0E4
N13	5.26E5	2.71E5	2.67E5	2.0E4
O15	6.31E5	3.81E5	3.77E5	1.0E4
Cl39	7.53E3	4.54E3	4.61E3	6.0E3
Ar41	6.69E4	1.99E4	8.22E2	2.0E3

1) Underpressure -50 Pa in bunker during operation, 250 m³/h in environment
2) Area proportional counter in small air tube, chimney mounted at N – container
3) Activation concentration > limits (O15,N13,C11) but short half lifes (2,10,20 min)
4) Atmosperic dispersion modeling necessary (Ausbreitungsrechnung) to demonstrate that annual dose < 0.3 mSv. Emissions of EuroPet and IUT have to be added
5) Nucleii with longest half lifes below limit, nucleii in food has not to be considered, only doses due to submersion
6) During operation air cooling in gallery (closed circuit), after operation and after the activation < limit, air exchange with fresh air from outside (open circuit). Controlled by interlock system. Area proportional counter in large air tube too.

Atmospheric dispersion modeling

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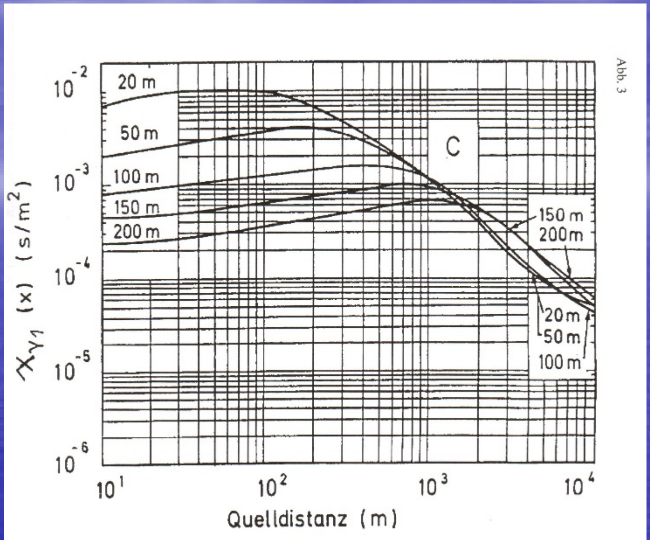
γ – submersion dose:

Height of chimney 21 m,
χ = 1E-2 s/m²,
>Double height of neighbor buildings

$$H_{T,\gamma,r} = A_r \cdot g_{\gamma,r,T} \cdot (\overline{\chi}_{\gamma 1}^{G} \cdot f_r \cdot c_{Geo,\gamma 1} + \overline{\chi}_{\gamma 2}^{G} \cdot (1 - f_r) \cdot c_{Geo,\gamma 2})$$



Nuclide	g/ (Sv/s)/(Bq/m²)	A/(Bq/a)	H/(Sv/a)
C11	3.4E-16	4.15E10	1.41E-7
N13	3.4E-16	1.36E11	4.62E-7
O15	3.4E-16	1.91E11	6.50E-7
Ar41	4.1E-16	5.99E09	2.46E-8
Sum (Al)			**1.28 µSv/a**

f spectrum factor = 1 for these nucleii

In Germany limit is 300 µSv/a but other emittents have to be added
EuroPET : 150 µSv/a, IUT : 100 µSv/a, bERLinPro < 50 µSv/a

β– submersion dose is two orders of magnitude lower (calculated for whole body dose)

Submersion doses within accelerator hall

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γ – submersion dose in accelerator hall:

A person stays within a radioactive cloud (half sphere) with a radius of R = 10 m, direct after operation

Nucleii	g/ (Sv/s)/(Bq/m³)	C/(Bq/m³)	H/(Sv/h)
C11	2.4E-15	8.29E04	7.17E-7
N13	2.4E-15	2.71E05	2.34E-6
O15	2.4E-15	3.81E05	3.29E-6
Ar41	2.9E-15	1.99E04	1.77E-8
Sum (Al)			**6.36 µSv/h**

$$H_{T,\gamma,r} = C_r \cdot g_{\gamma,r,T}$$

Same calculation for Fe targets: sum = 11.7 µSv/h

β – submersion dose in accelerator hall:

Nucleii	g/ (Sv/s)/(Bq/m³)	C/(Bq/m³)	H/(Sv/h)
C11	2.2E-14	8.29E04	7.17E-7
N13	2.9E-14	2.71E05	2.34E-6
O15	4.5E-14	3.81E05	3.29E-6
Ar41	2.7E-14	1.99E04	1.77E-8
Sum (Al)	**5.3 µSv/h** (eye lense)	**97.8 µSv/h** (skin)	**0.98 µSv/h** (whole body)

Same calculation for Fe targets: sum = 1.73 µSv/h

Earth activation

Wet sand $\rho = 1.8 /$ g/cm³ (DESY D3-114)

Layer: 10 cm thick, 3m height, 7.1 m width

Back wall: 30 cm concrete

Distance back wall - trough 1.2 m

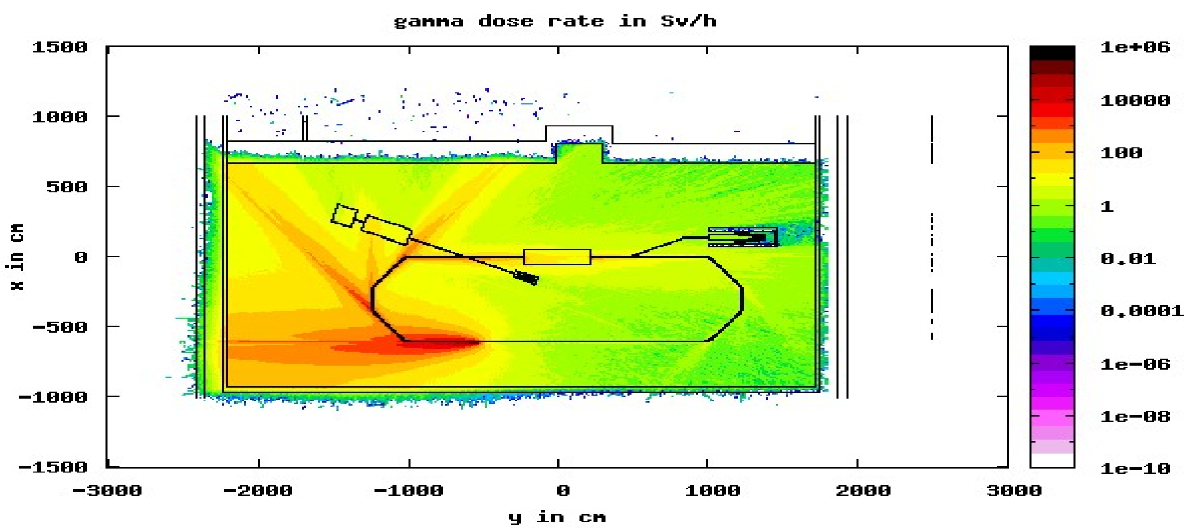
Trough : 60 cm concrete

50 MeV, 0.1 mA losses, 1 mrad ,Al target

One year irradiation (2000 h)

Nucleii	Mass %
H	3 %
O	62 %
Mg	2 %
Al	4 %
Si	23 %
Ca	4 %
Fe	2 %

Nucleii	Half lives	Activity
Be7	53.3 d	1.95E7
Na22	2.6 a	5.60E6
Mn54	312.6 d	1.18E7
Fe55	2.73 a	1.43E8
Ca45	163 d	6.56E6
H3	12.323 a	3.81E6
Ar39	269 a	2.98E3



Result: beyond trough activities < limits

Between backwall and trough <10*limits

(max layer 1, rel max

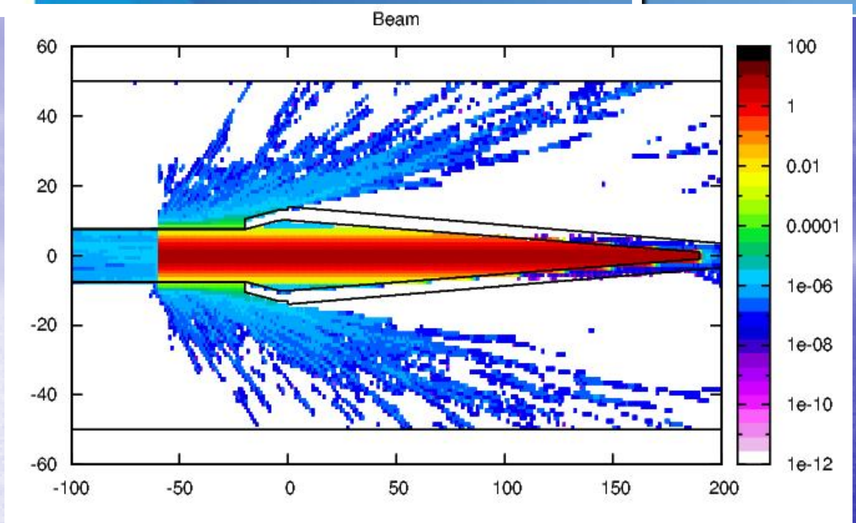
Na22 and Mn54)

Illumination of soil

1) Short living isomeric states (psec) are products of nuclear reactions during operation
2) Radiation equilibrium with bremsstrahlung
3) Dose contribution was calculated semi-analytically:
Nucleii with Fluka, dose with decay scheme for 1 MeV emitter
4) < 0.1 mSv/a at surface of sand
5) Doses due to isomeric states not yet included in Fluka

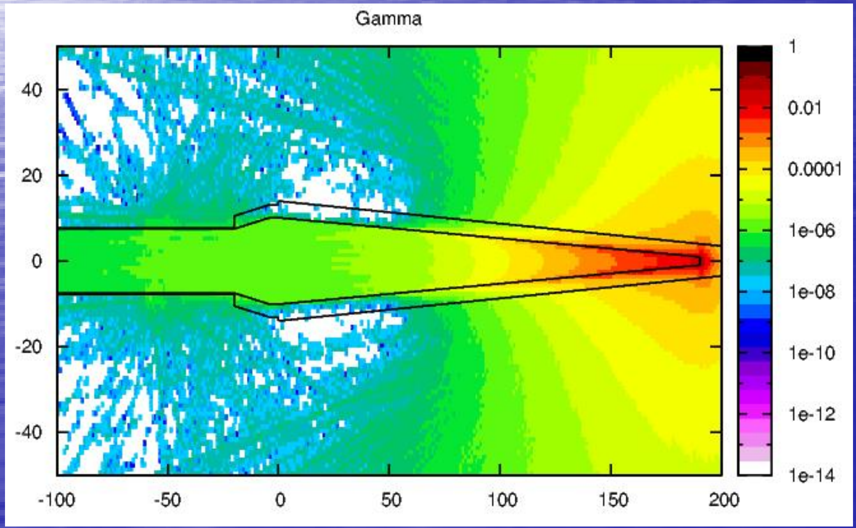
Nucleus stable groundstate	Activity/Bq
D2	6.98E11
He4	2.54E10
C12	4.77E9
N14	1.01E9
N15	3.79E9
Mg24	1.84E9
Mg26	1.13E9
Al27	5.19E9
Si28	9.11E8
Si29	7.33E8
K39	1.06E9

Beamdump calculations



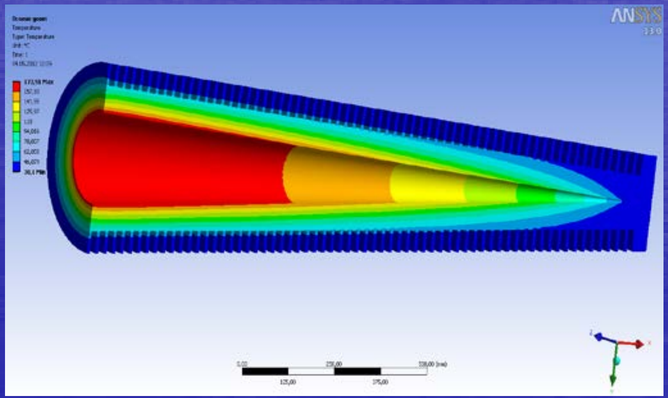
Electron beam with Gaussian distribution

Gamma doses



pSv/e-

Fluka calculations 0.6 MW (Yvonne Bergmann)
Dump material copper, water cooled
to calculate backscattered electrons, energy doses



ANSYS calculation (Marc Dirsat)

100 W/cm² reached (inner 1 cm layer)
Design close to completion

Beamdump must be able to absorb full beam power. Addtionally the beam will be moved

CERN reference field (CERF)

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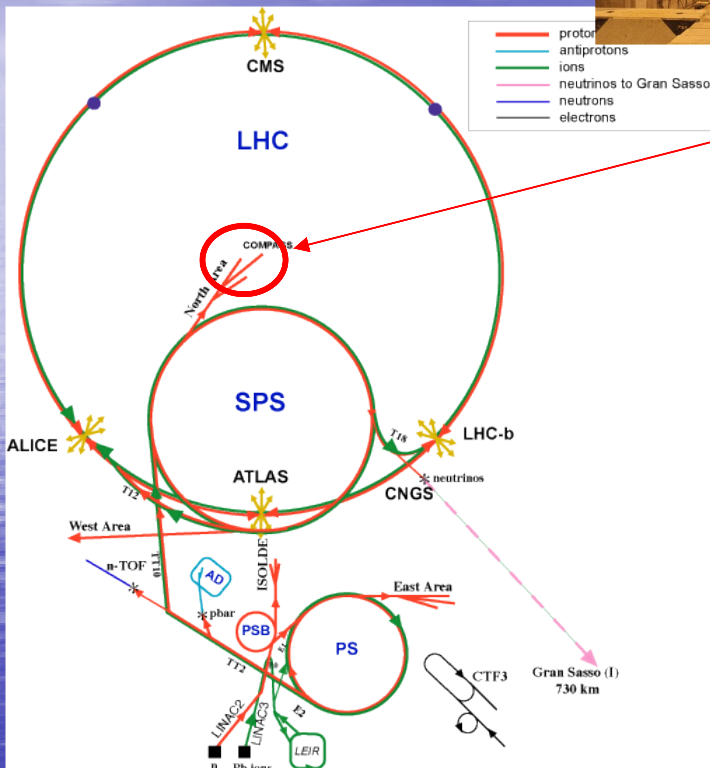
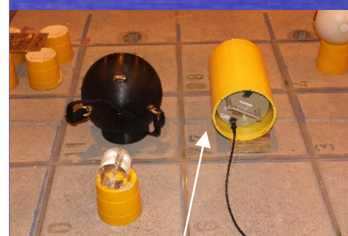


CERF location
(Prevessin cite)



Mixed beam
Protons 35%
Pions+ 61 %
Kaons+ 4 %
Momentum 120 GeV/c
Target Cu 50 cm

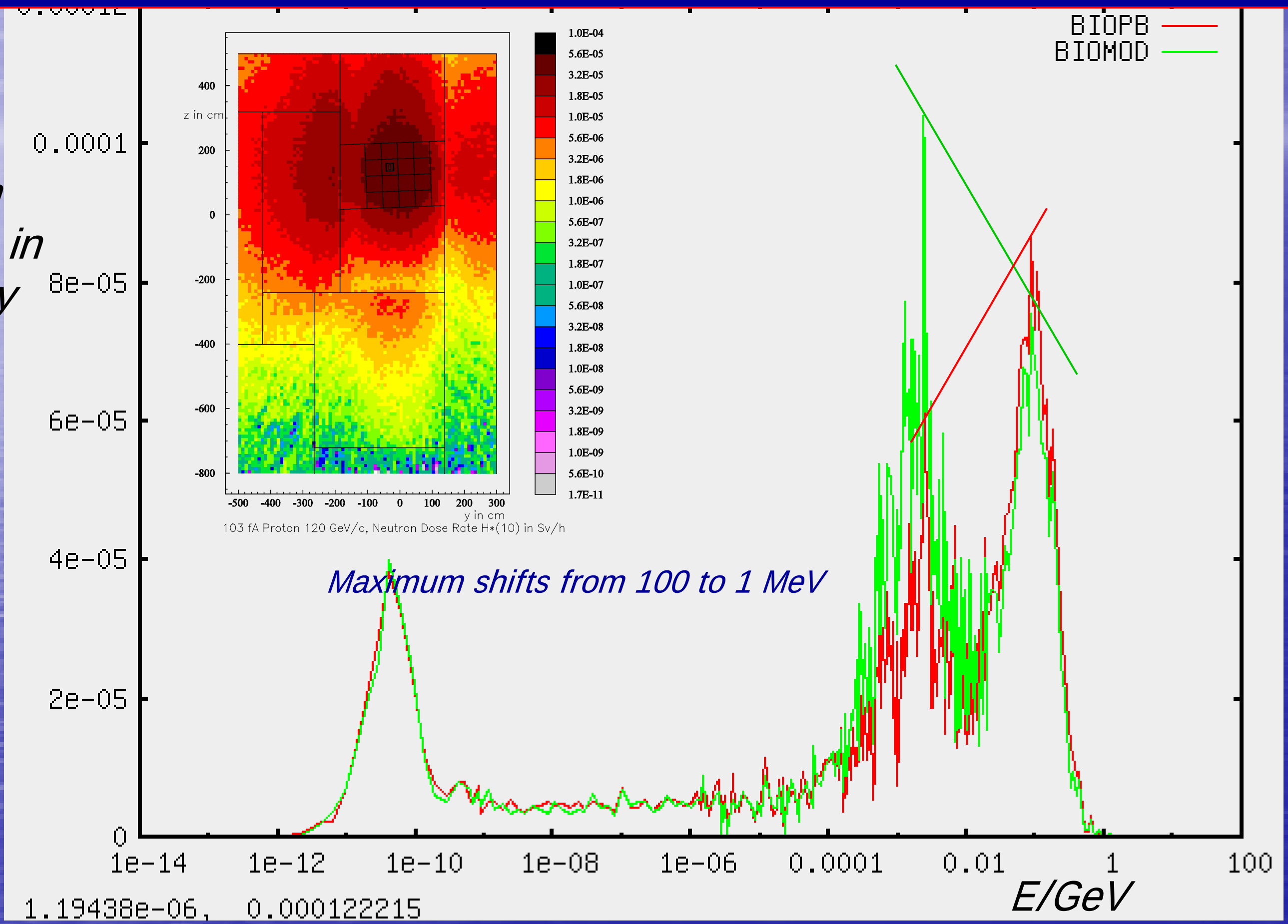
Biorem with
Pb Moderator
(own development)

Neutron spectrum similar to high energy electron or hadron accelerators

Effect of Pb moderator

Demonstrated that moderator expands measurement range from 10 MeV to 1 GeV
Patent light approved 24h Oct. 2013: Deutsches Gebrauchsmuster DE 20 2013 011 938

Neutron Fluence in Lethargy Units



E/GeV

Red: Spectrum at Pb, Green: Spectrum at PE , neutron spectum
Summarized from the three contributions (p, pi+, K+)
Beamtime at CERF in June 2012

Usage of Pb moderators at BESSY

Two examples:

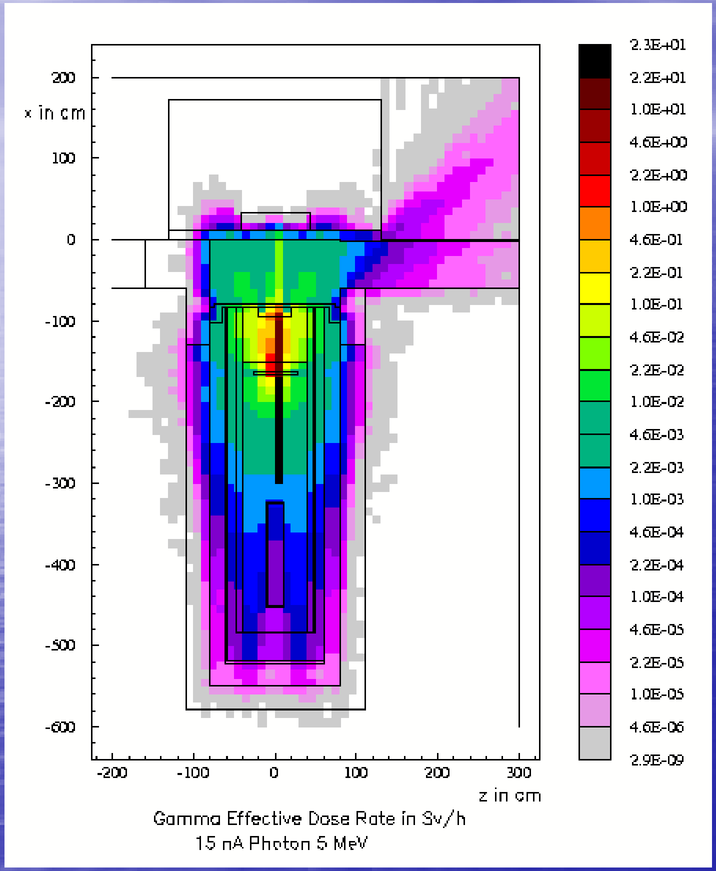
Close to front ends

Lead moderators will also be used for bERLinPro

At Booster entrance

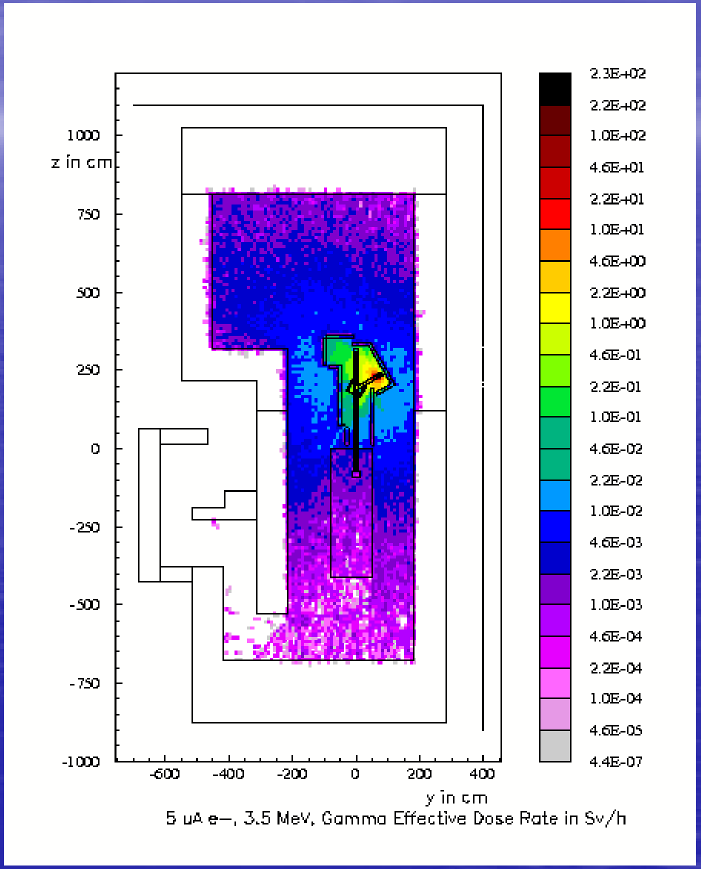
Further activities

Testing hall: vertical cavity teststand



Now funnel deeper and shielded ,
building starts in 2016,
operating licence in 2017

HoBiCaT: Gun0



Will be replaced by gun1:
new operating licence in 2015

Way to operation

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- Stage 1: Guncavity with photocathode (KCsSb) Tests in HoBiCat, current limited to 5 µA, E < 4 MeV, start Q2 2016
- Stage 2: Test of injector connected to large beam dump bERLinPro bunker „banana“, start Q4 2017
- Stage 3: Commissioning recirculator start Q2 2019 linac, Q3 2019 energy recovery with I < 5 mA, Q1 2020 Installation of MkII photo injector with 114 kW coupler, ERL machine studies up to 100 mA
- The three stages require three operation licences (radiation safety report, report by external expert, decision by state authority respectivly)

Summary

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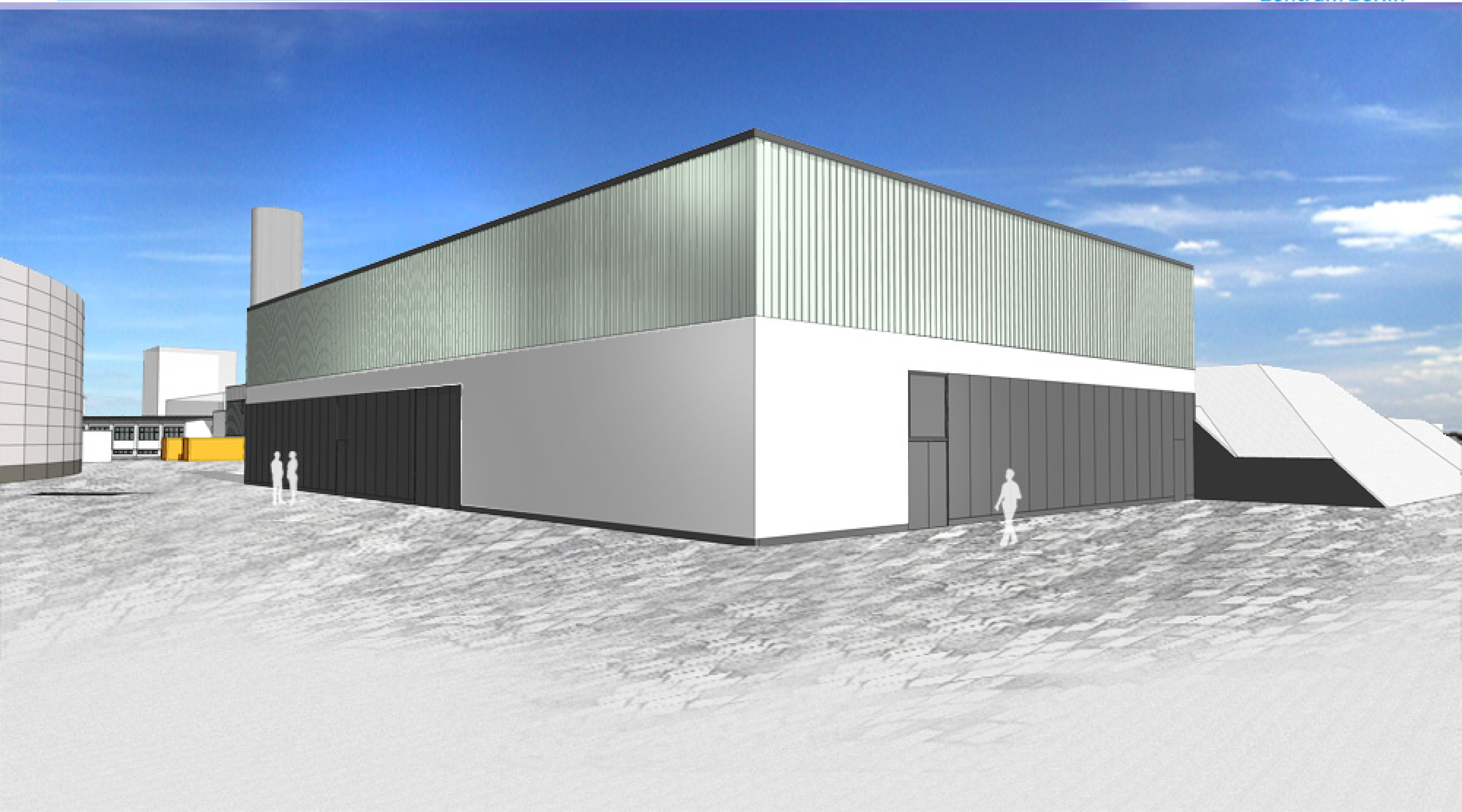
- 24th Oct. 2014: Patent light for new neutron moderators that expands measurement range from 10 MeV to 1 GeV: Deutsches Gebrauchsmuster DE 20 2013 011 938
- Beam dump calculations of energy doses to support construction group
- Set of analytical shielding formulas completed
- Modelling of bERLinPro with FLUKA completed
- Construction licence granted at 4th Sept. 2014, start of construction in Feb. 2015
- Planning for testing hall completed and planning for gun1 in progress
- Not shown in talk: Interlock functions specified, ambient dose measurement system delivered, leakage water measurement system specified, air measurement system ordered



Thanks for your attention