SRF 2021

HZB Helmholtz Zentrum Berlin

Industrial X-ray Tomography as a Tool for Shape and Integrity Control of SRF Cavities

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2021 Int. Conf. on RF Superconductivity (SRF'2021) – THOTEV07

Acknowledgements to:

– <u>*the trigger:*</u>

Michele Bertucci (INFN-LASA, Segrate, Italy) et al.:

"Test, diagnostics and computed tomographic inspection of a large grain 3.9 GHz prototype cavity", JACoW-IPAC2017-MOPVA062

– <u>*the industry partners:*</u>

J. Kinzinger (XRAY-LAB, Sachsenheim, Germany),

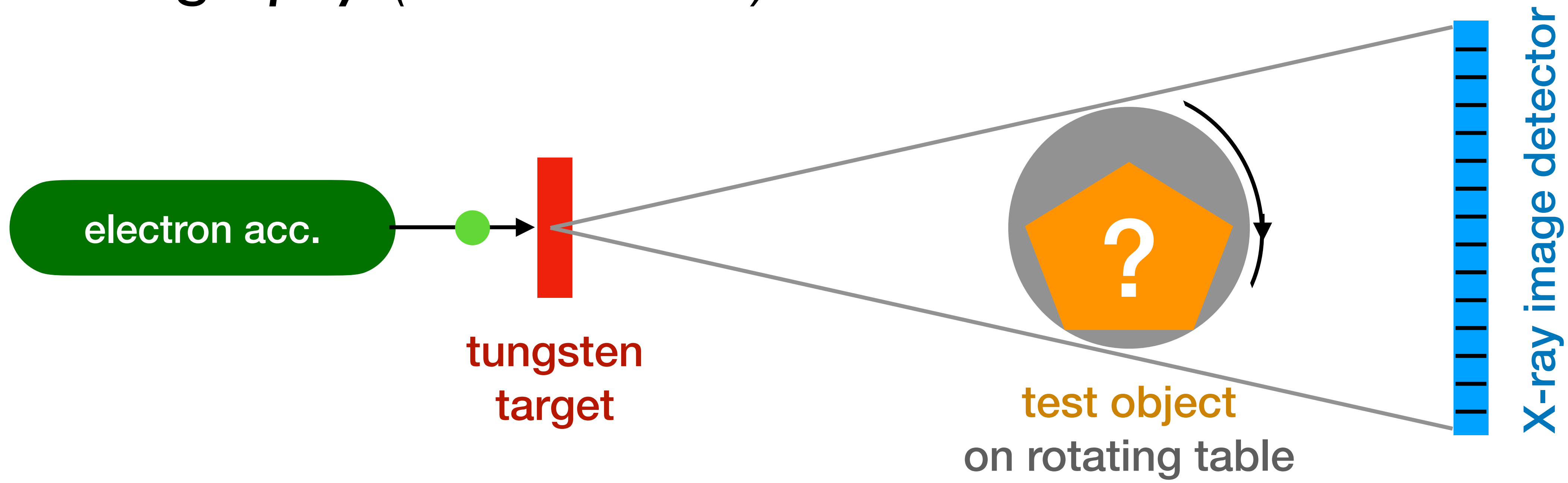
M. Böhnel, N. Reims, M. Salamon (Fraunhofer Institute for Integrated Circuits IIS, Development Center X-ray Technology EZRT, Fürth, Germany):

"Operational Experiences with X-ray Tomography for SRF Cavity Shape and Surface Control", JACoW-IPAC2019-WEPRB017

– <u>*the SRF'2021 Program Comittee …*</u>

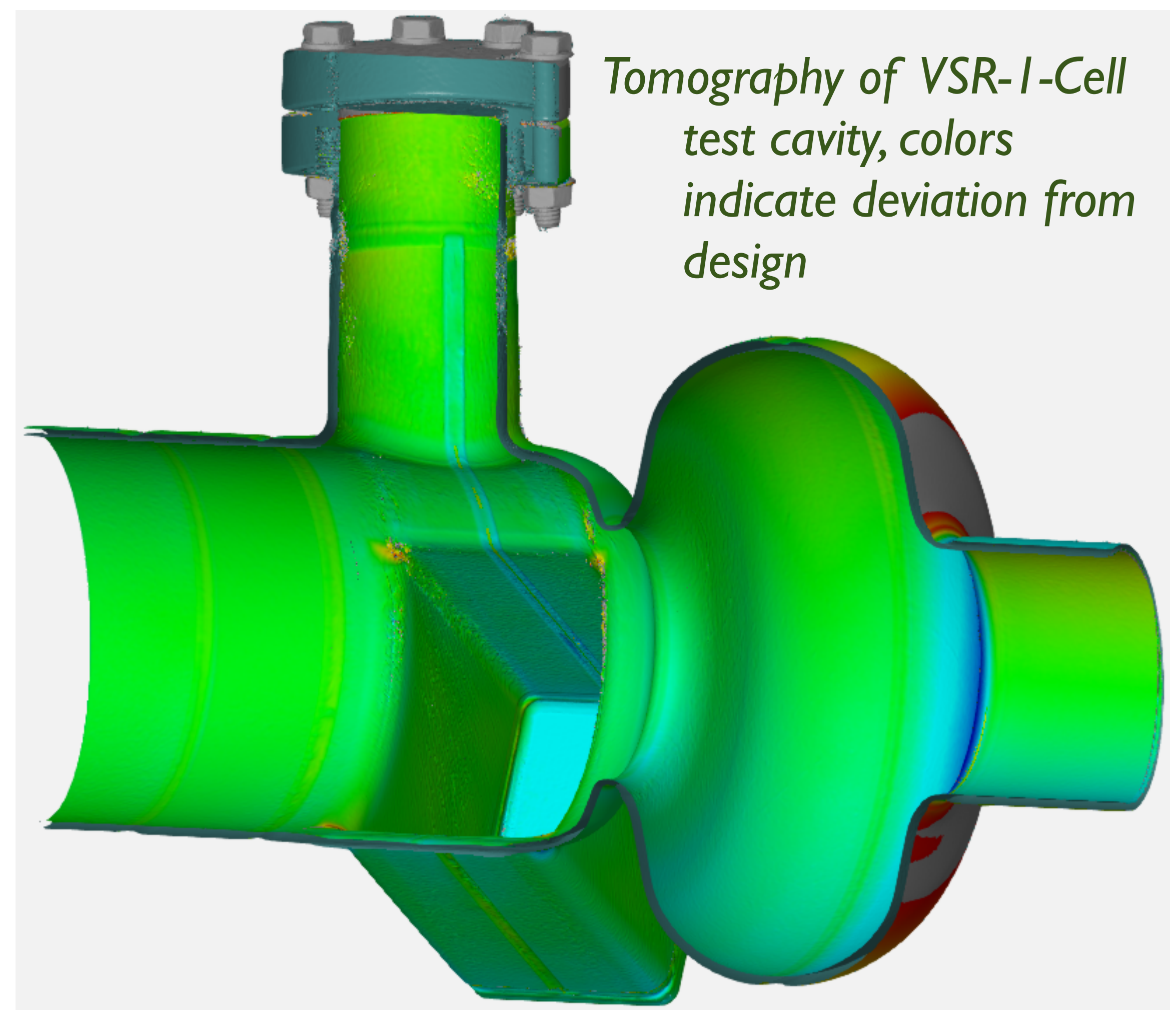
… who's talk invitation caused a reviewed and detailed summary of available data.

X-ray tomography (in a nutshell)



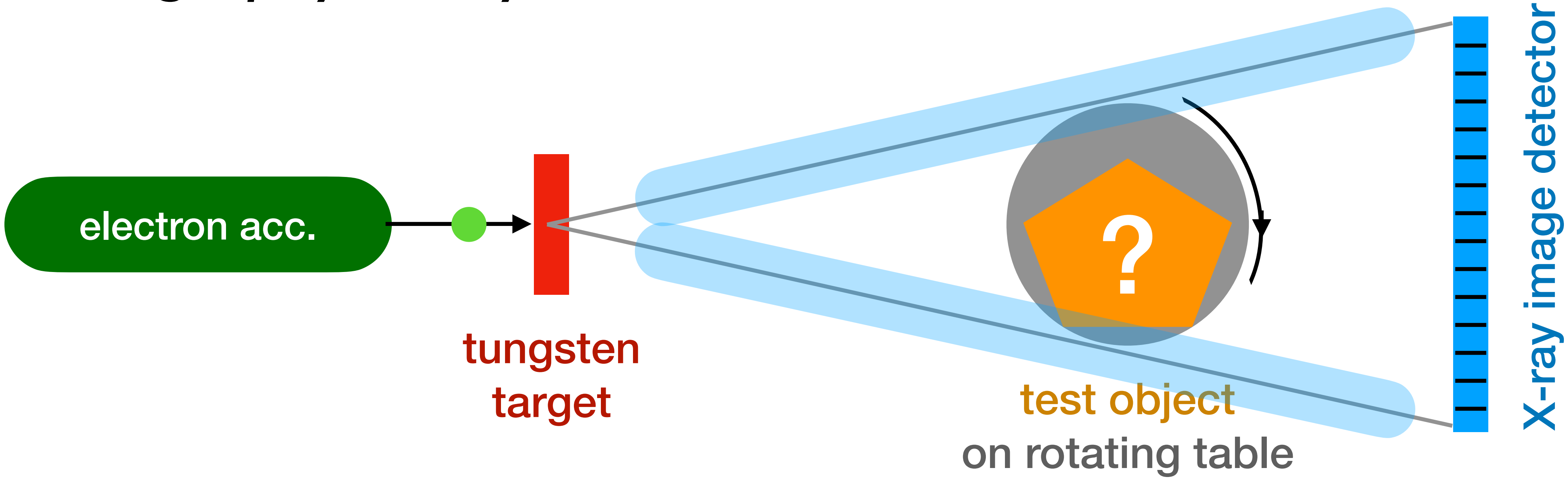
Is it a "magic eye" to look inside a cavity ?

"look" = surface inspection, weld integrity, thickness and shape control



Tomography of VSR-1-Cell test cavity, colors indicate deviation from design

X-ray tomography: X-rays



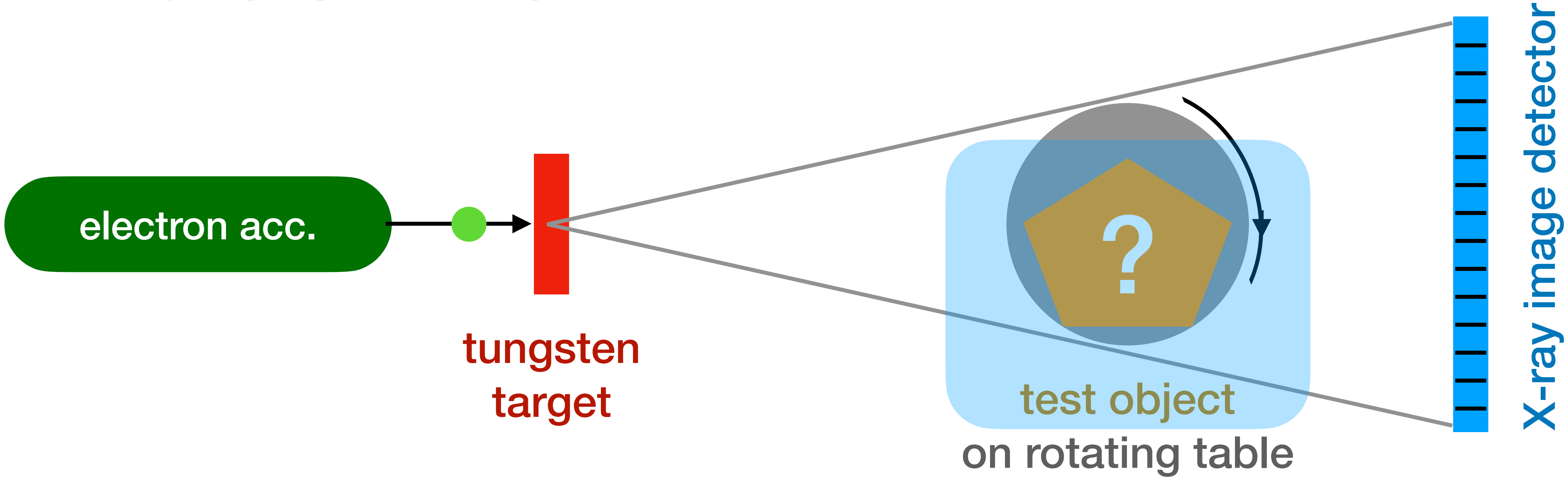
incoherent broadband (~10 keV … 10 MeV) X-rays,

core property is intensity-proportional absorption with material-dependent absorption coefficient μ

$$dI(x) = -\mu\, I(x)\, dx$$

assumed to happen along a straight line between source and detector.

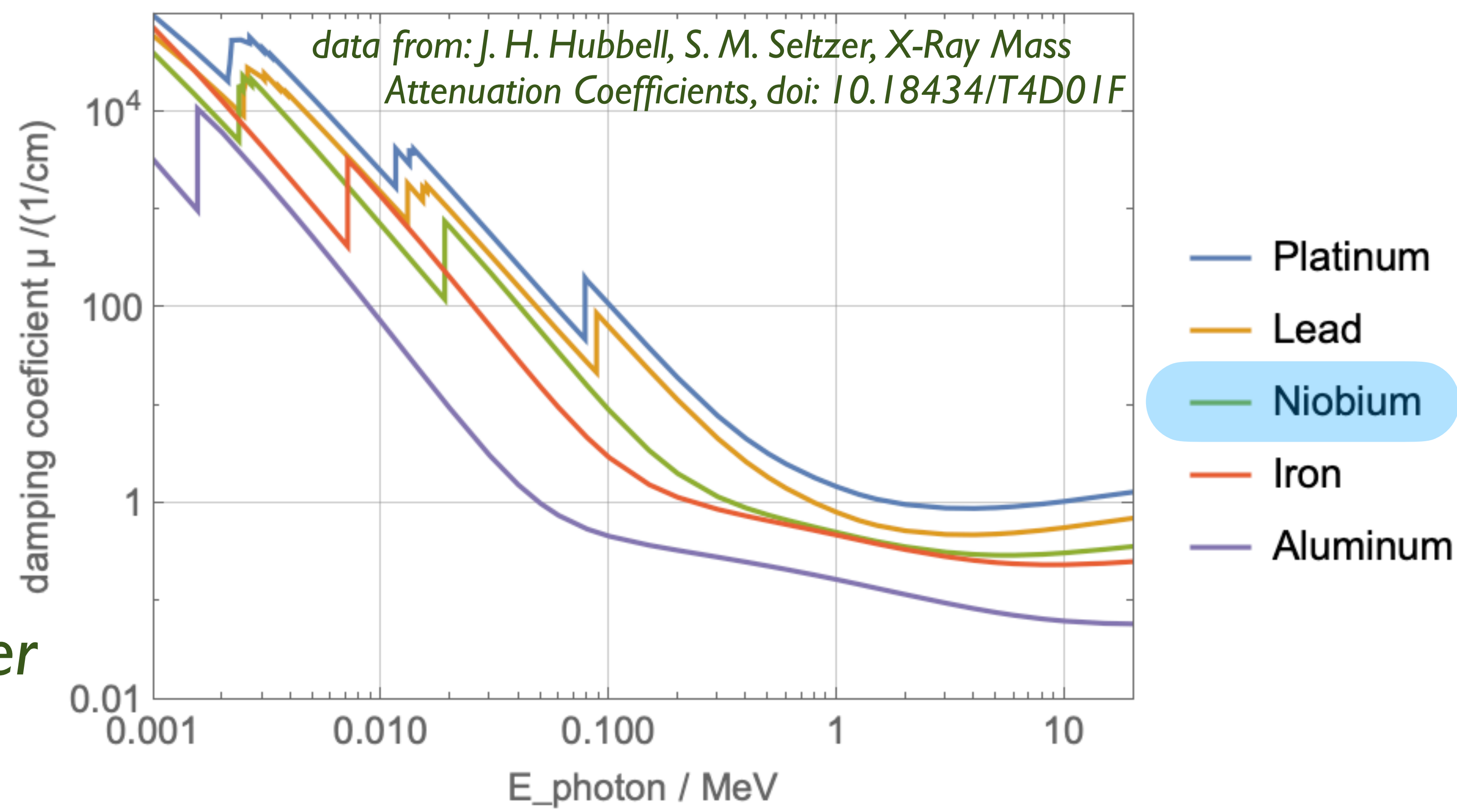
X-ray tomography: absorption



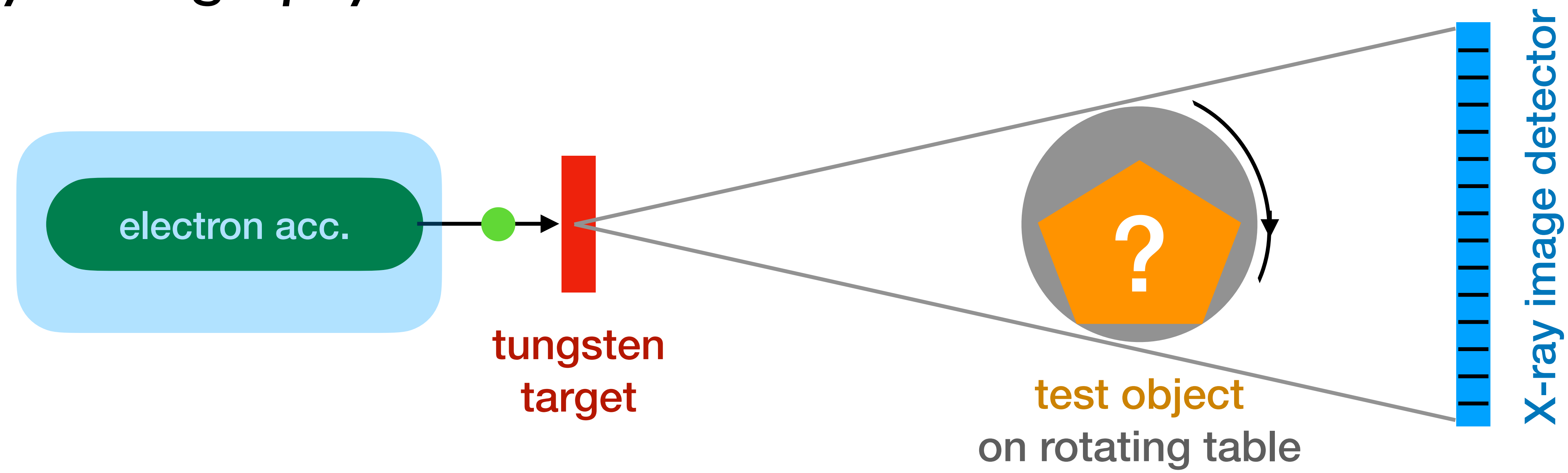
material-dependent absorption coefficient μ

$$dI(x) = -\mu\, I(x)\, dx$$

Niobium attenuates much stronger than iron up to 200 keV.



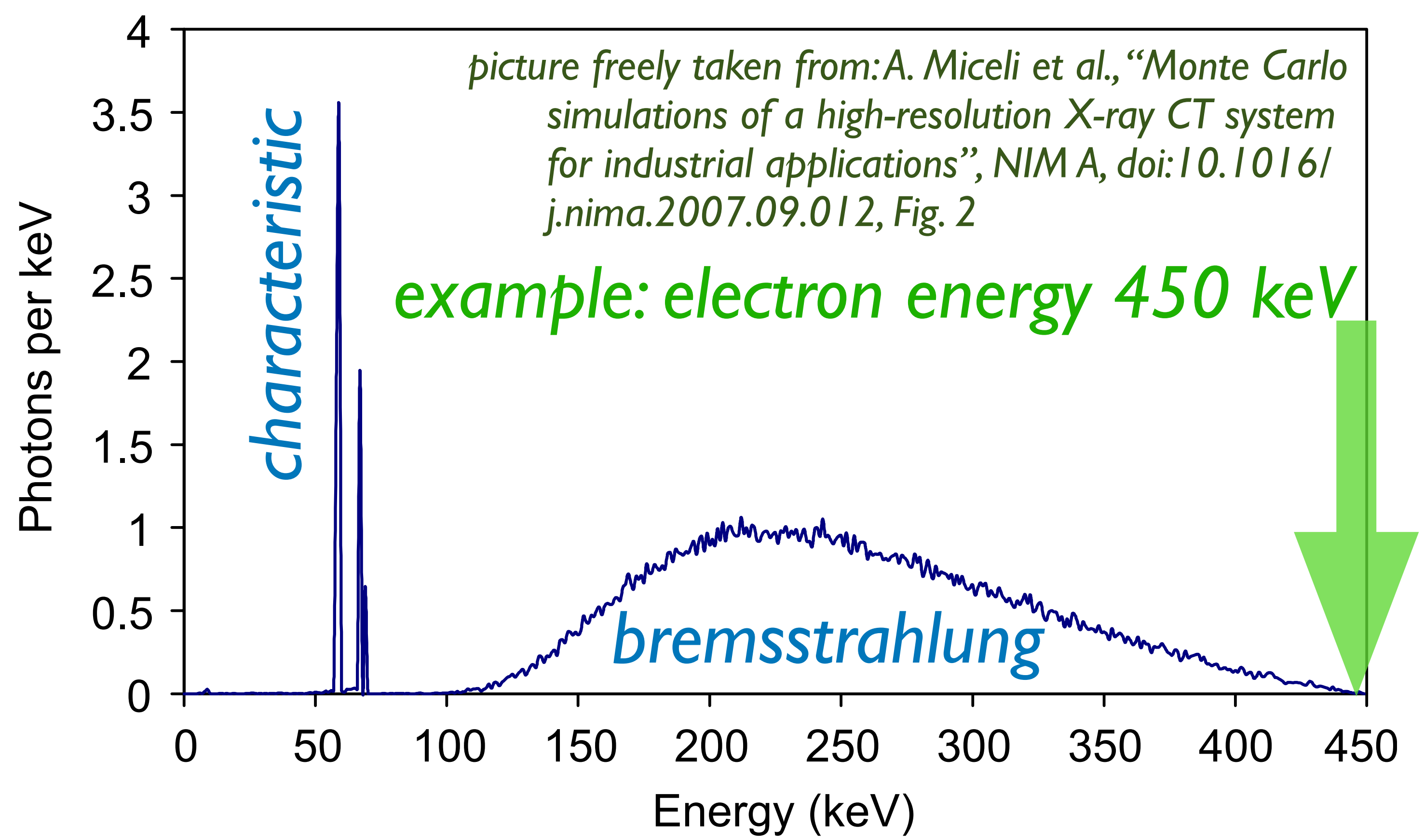
X-ray tomography: source



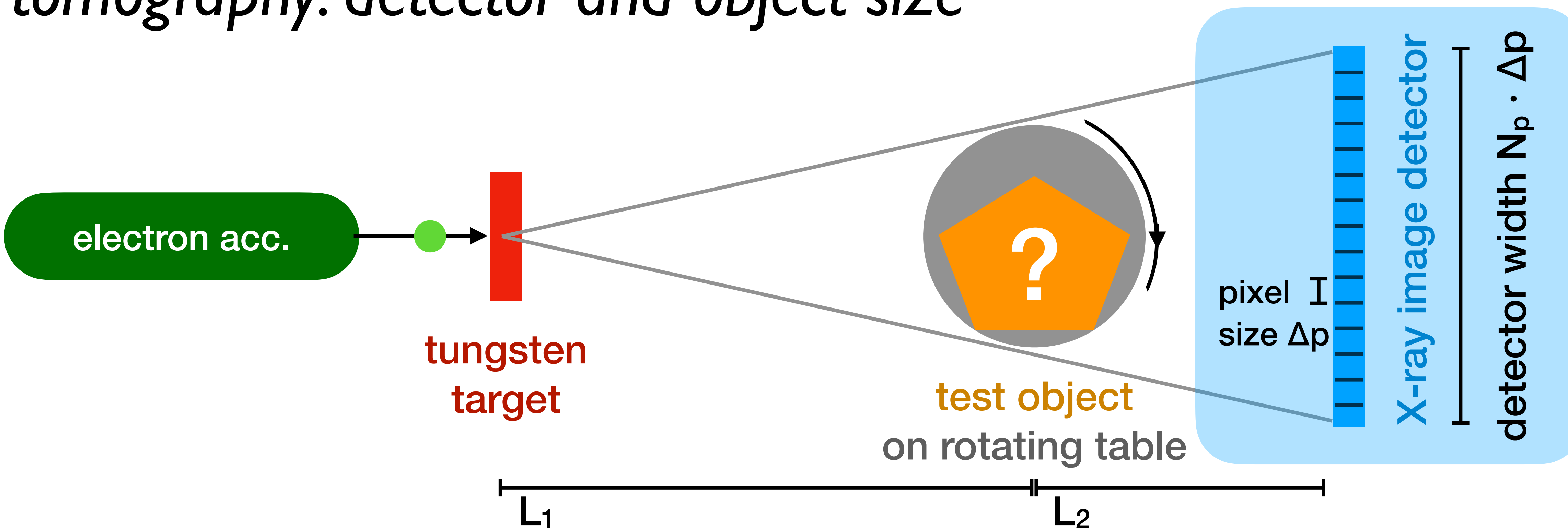
we tried:

- DC-gun 300 kV
- DC-gun 587 kV
- 9-MeV Linac (Siemens Silac)

Most photons have significantly less energy than the electron.



X-ray tomography: detector and object size



Detector panel width limits object diameter:

$$D_{obj} < \frac{L_1}{L_1 + L_2} \cdot N_d \cdot \Delta p$$

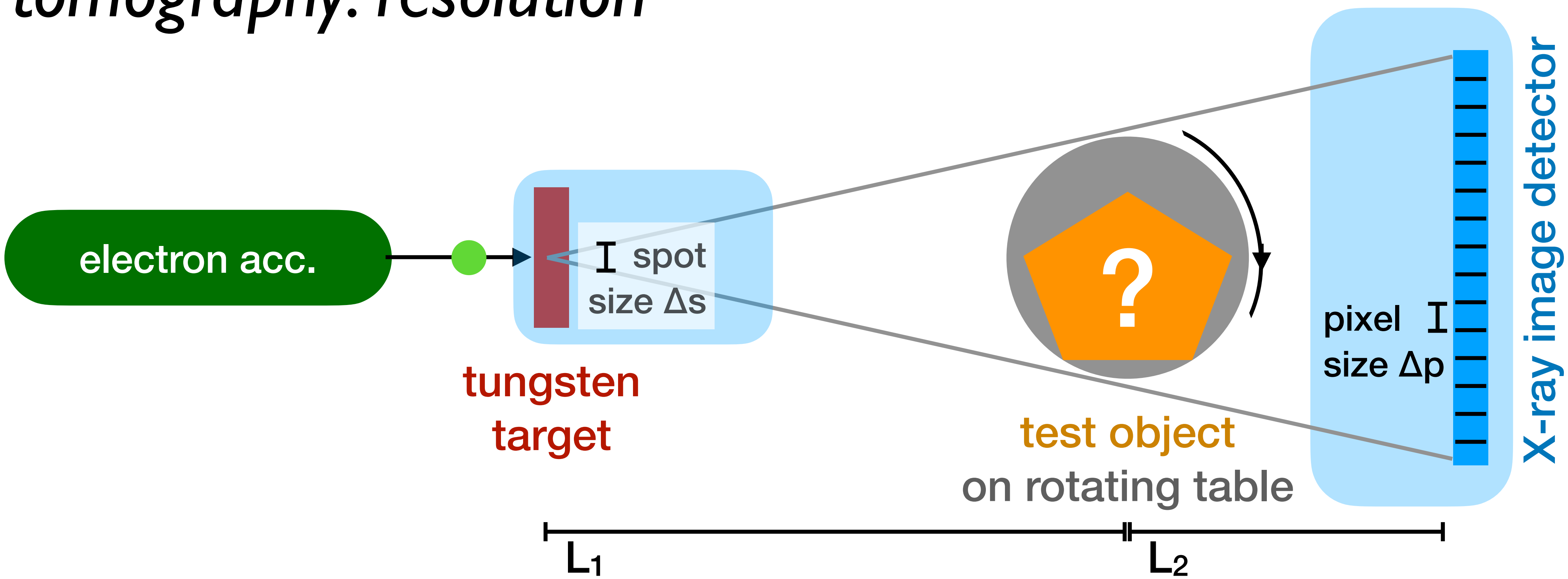
High resolution: L_1 small,

biggest practical D_{obj} ~ 0.9 detector width

we used square panels

- *~ (2000 x 2000) pixels*
- *~ (0.3 x 0.3) m^2 @ 300 kV,*
- *~ (0.4 x 0.4) m^2 @ 587 kV,*
- *~ (0.5 x 0.5) m^2 @ 9 MeV*

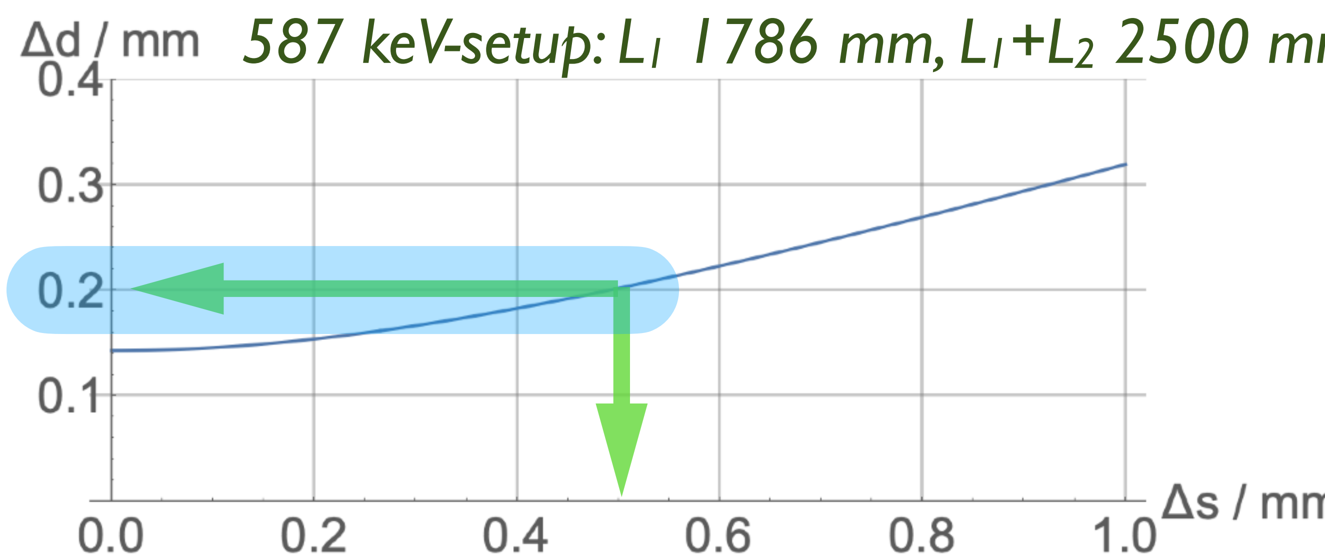
X-ray tomography: resolution



Finite width of X-ray source spot size Δs and detector pixel size Δp mix to effective beam path width:

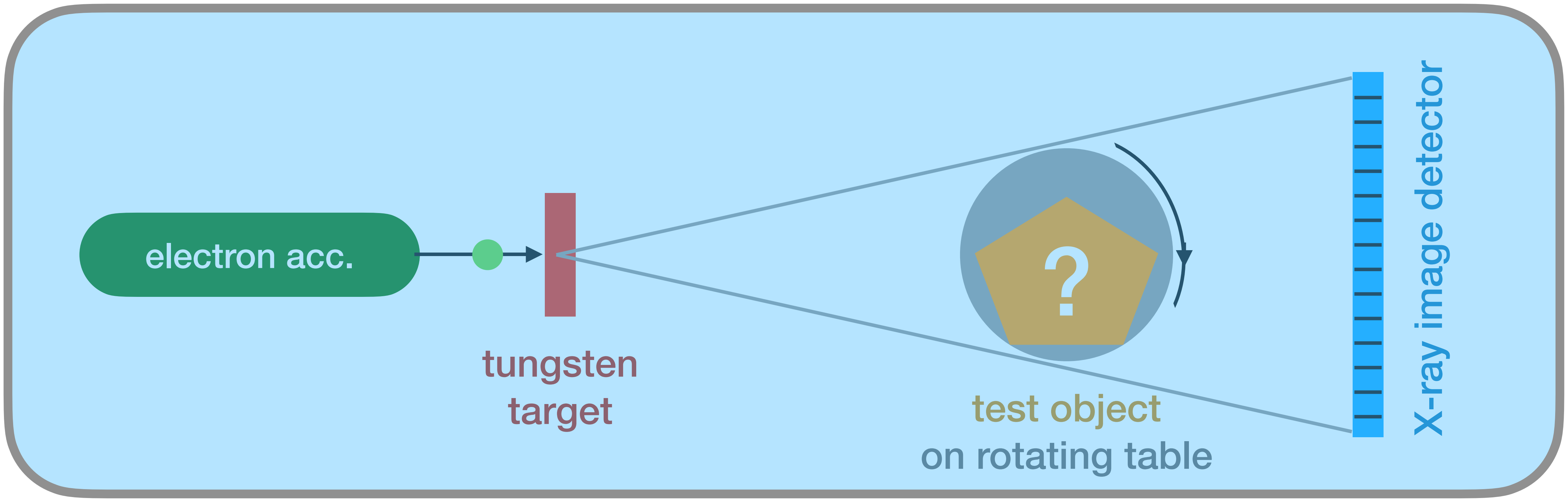
$$\Delta d = \frac{\sqrt{[L_2 \Delta s]^2 + [L_1 \Delta p]^2}}{L_1 + L_2}$$

587 keV-setup: L_1 1786 mm, L_1+L_2 2500 mm



resolution limit: 0.2 mm

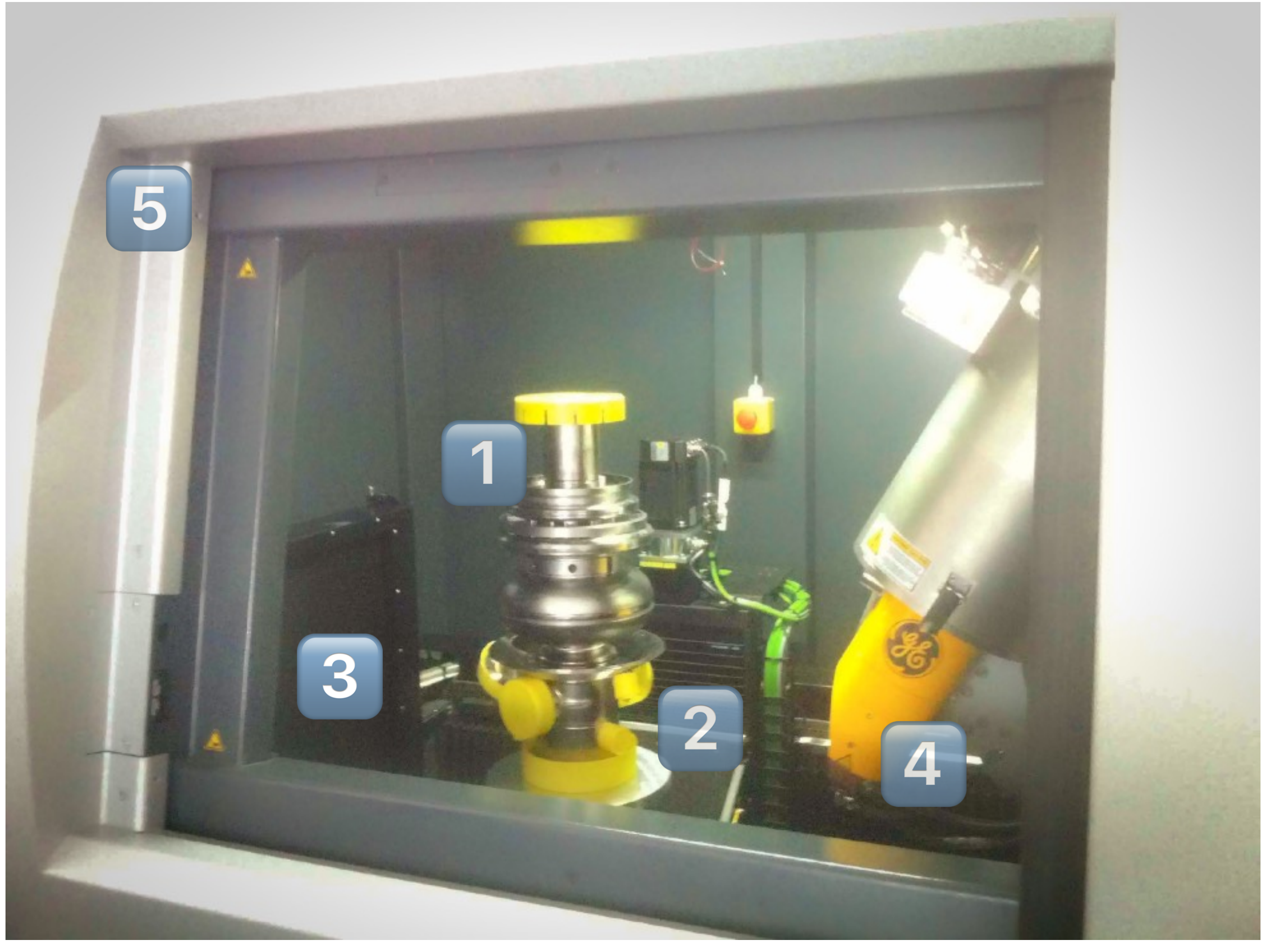
X-ray tomography: shielding, mechanics



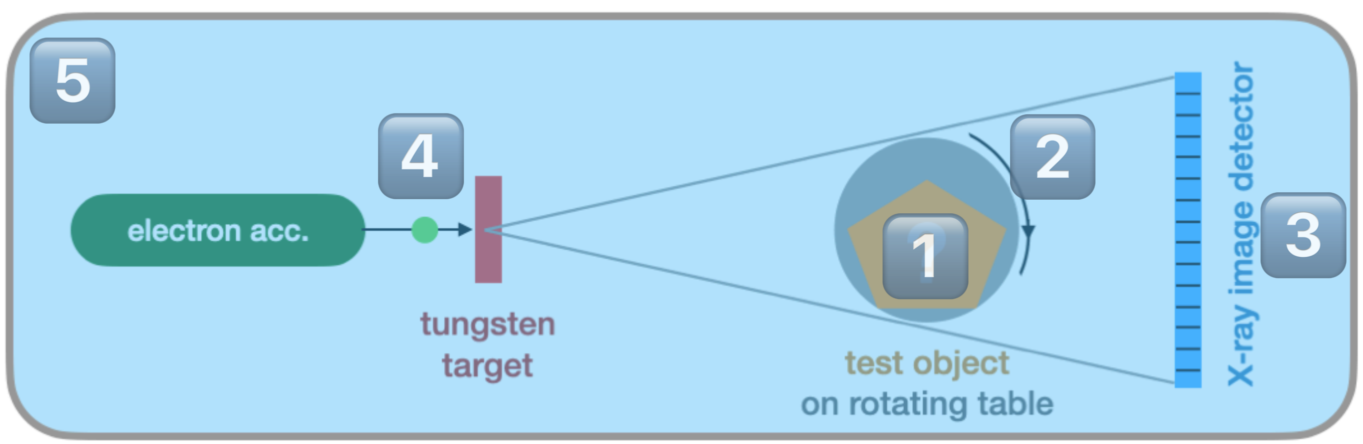
not to forget, since expensive:

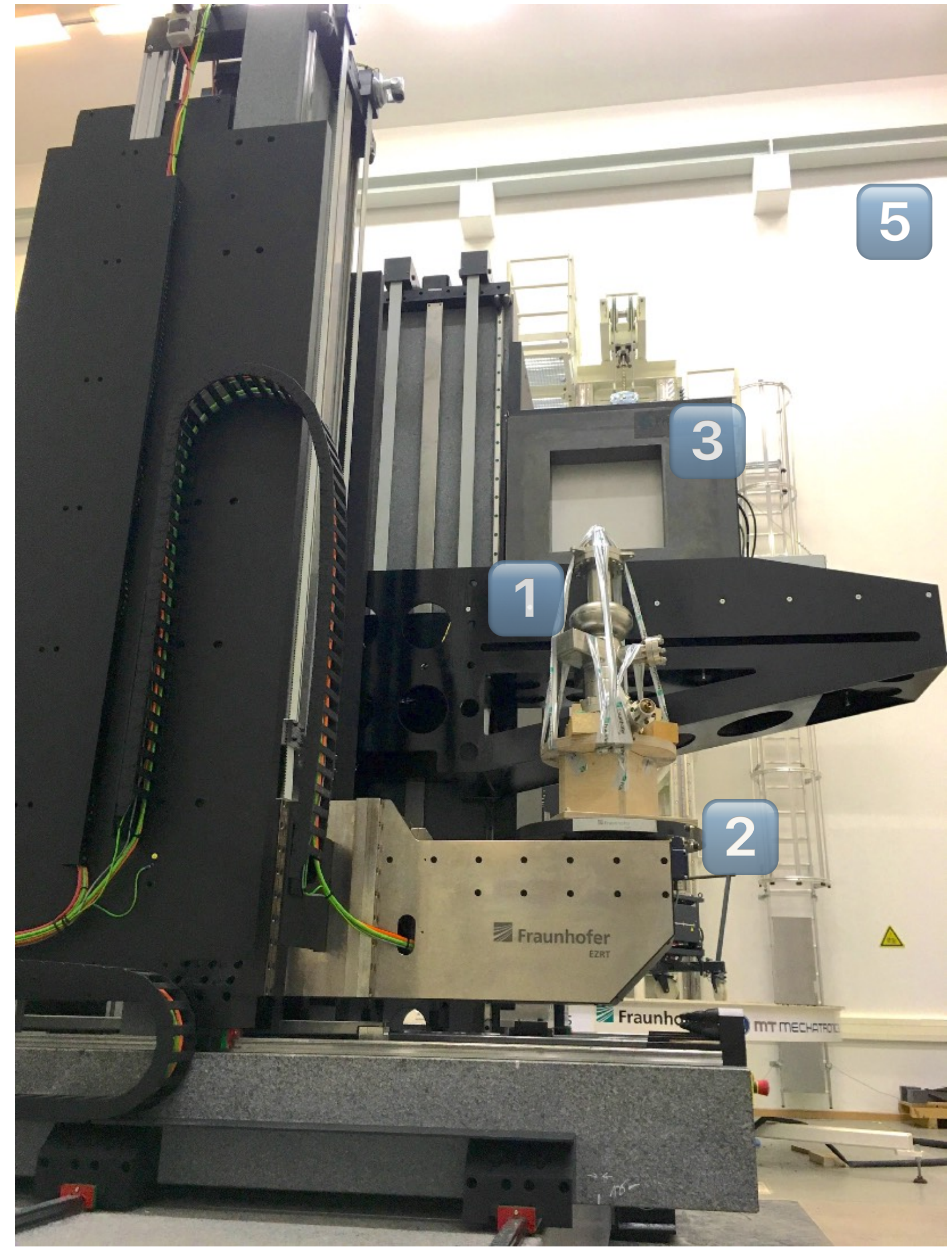
- *shielding for radiation safety (keep distance to object and detector to reduce ambient scattering)*
- *mechanical precision, thermal stability in the order of spatial resolution*

X-ray tomography: setups



bERLinPro Gun1.1 @XRAY-LAB, 300 keV



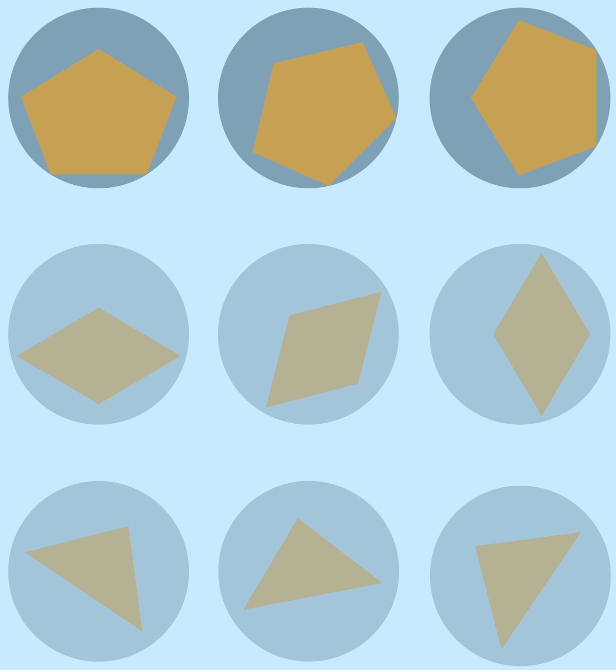


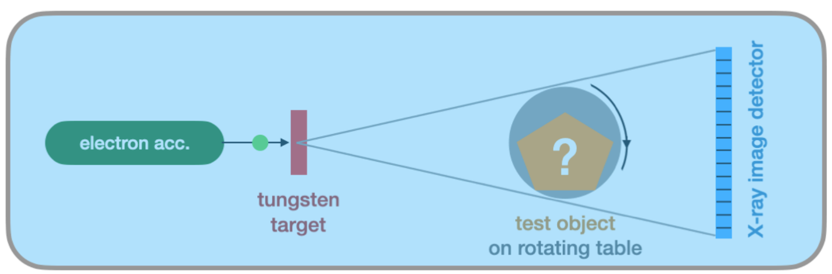
VSR-1-cell @Fraunhofer EZRT, 9 MeV 4

X-ray tomography: workflow I

X-ray pictures of ~10^3 different orientations

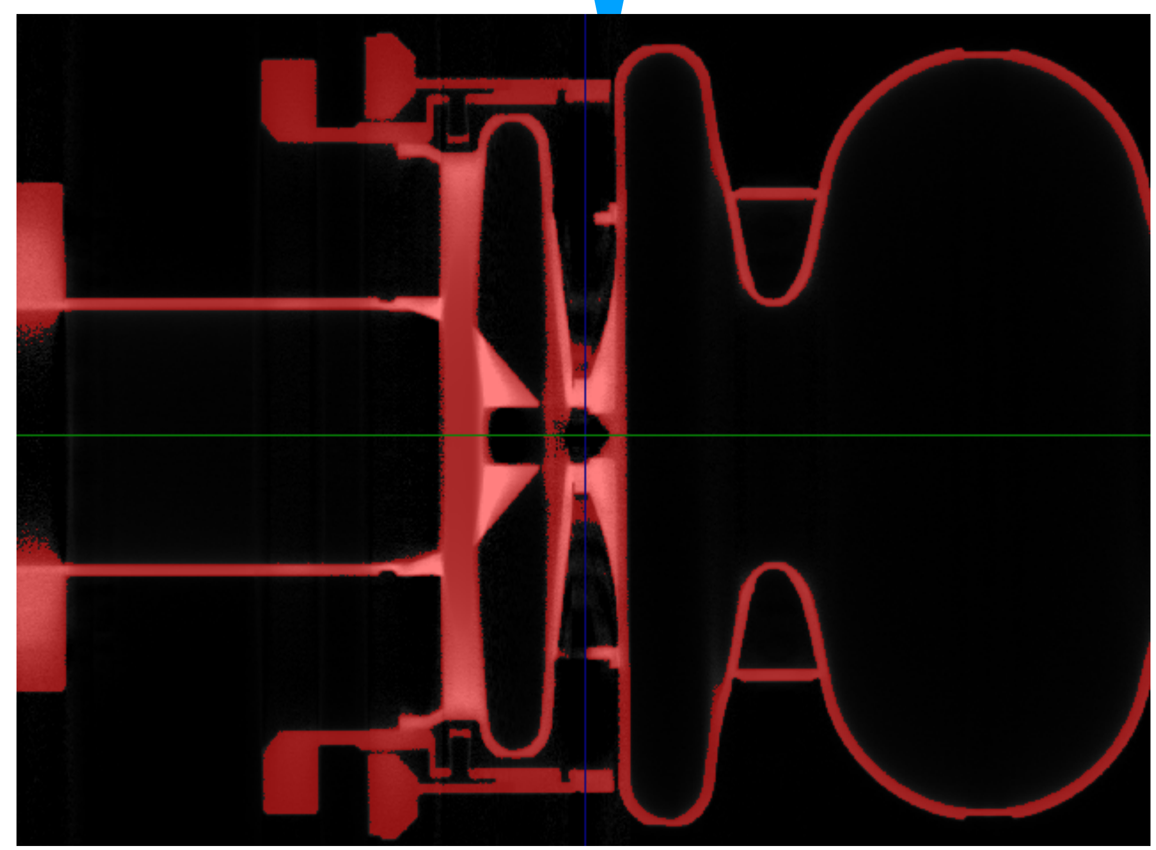
single to some vertical segments





Tomographic Inversion (proprietary algorithm)

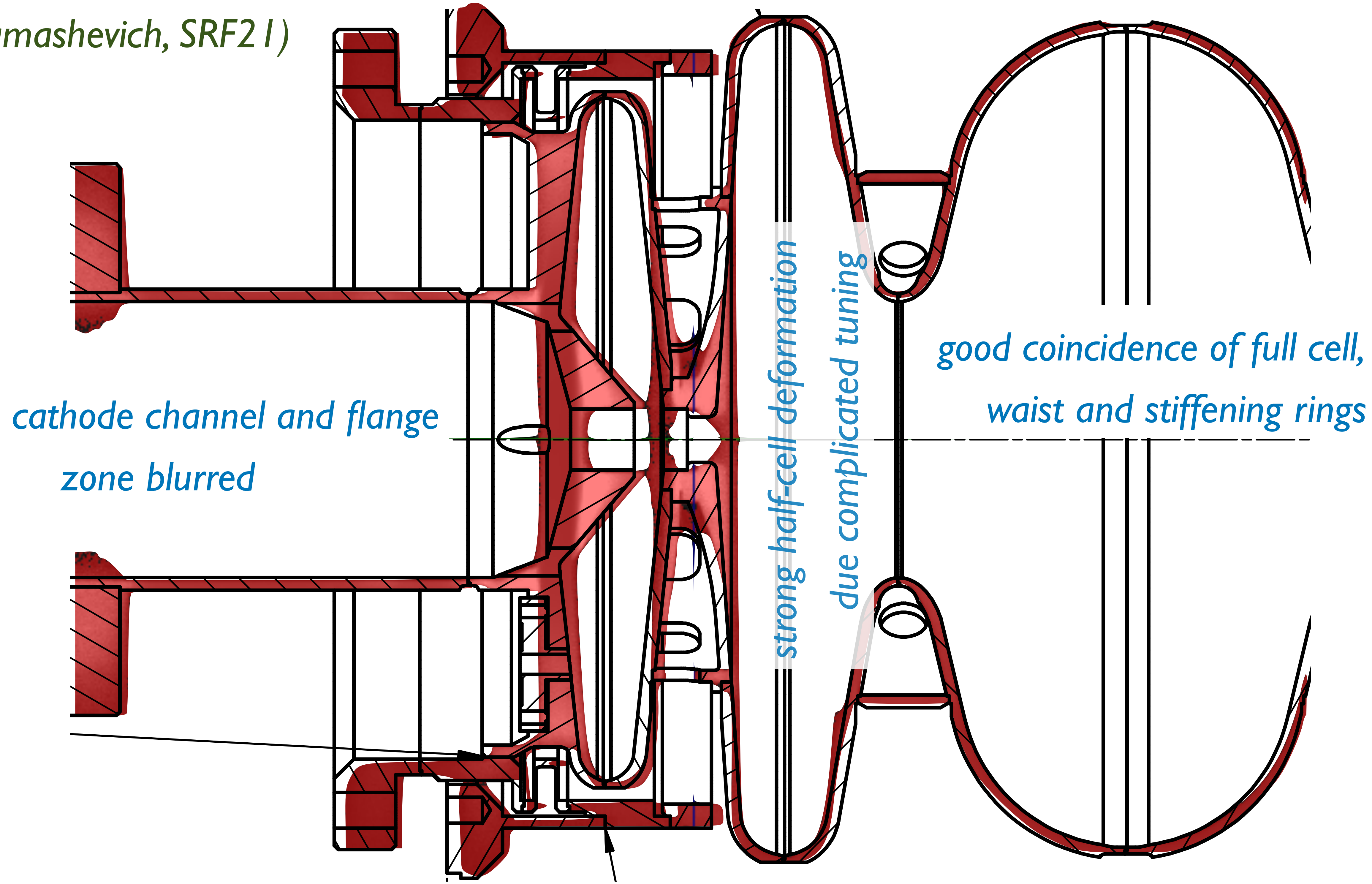
cubic voxel volume representation in 2^{16} intensity-scale values (.rek-file, ~ 10 GB)



bERLinPro Gun1.1 @Fraunhofer EZRT, 9 MeV

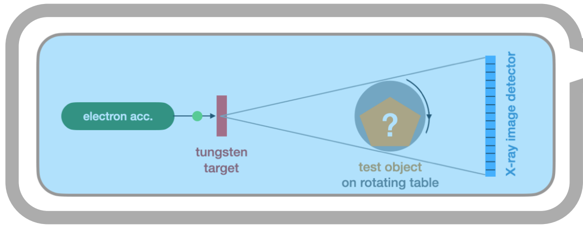
bERLinPro Gun1.1: 1.4-λ/2-cell @ 1.3 GHz, with tunable choke cell

(cf. Y.Tamashevich, SRF21)



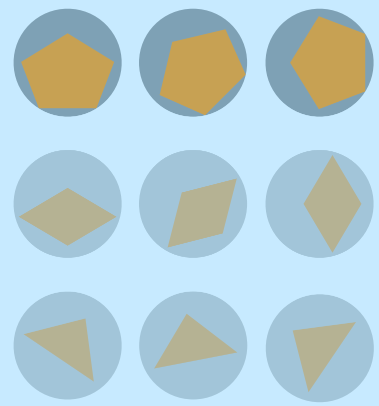
bERLinPro Gun1.1 (@Fraunhofer EZRT, 9 MeV, threshold 17464) vs. design

X-ray tomography: workflow II



X-ray pictures of ~10³ different orientations

single to some vertical segments



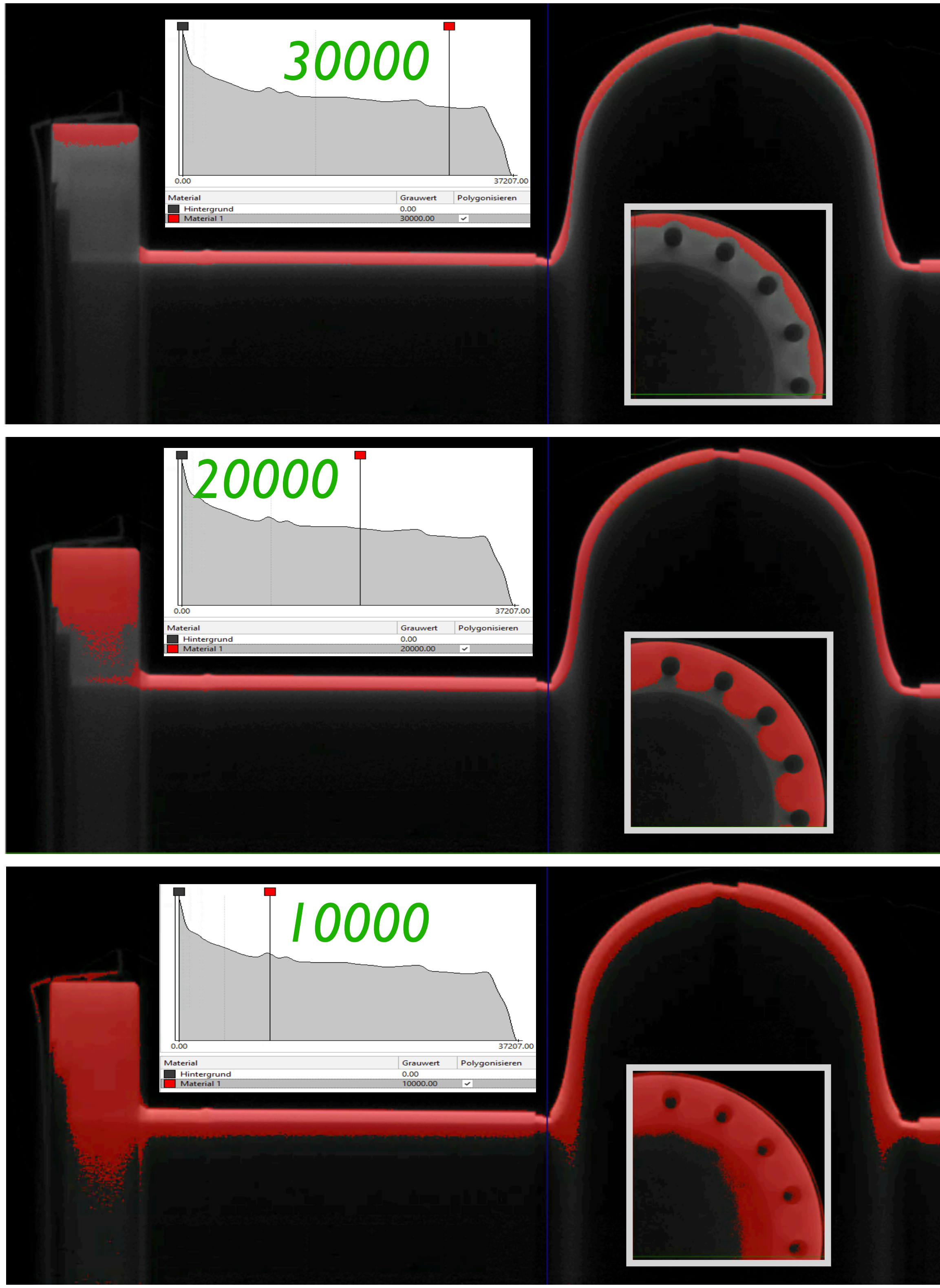
Tomographic Inversion (proprietary algorithm)

cubic voxel volume representation in 2^{16} intensity-scale values (.rek-file, ~ 10 GB)

bulk material volume construction by intensity-scale threshold (Volumegraphics©, GOM-Inspect©)

Generic 1-cell 1.3 GHz @Fraunhofer EZRT, 9 MeV

X-ray tomography: influence of threshold choice



bulk material volume construction by intensity-scale threshold (Volumegraphics©, GOM-Inspect©)

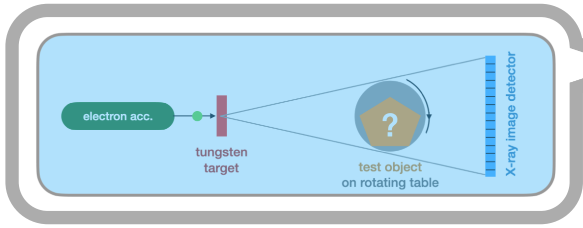
Threshold selection directly determines allocation of material borders.

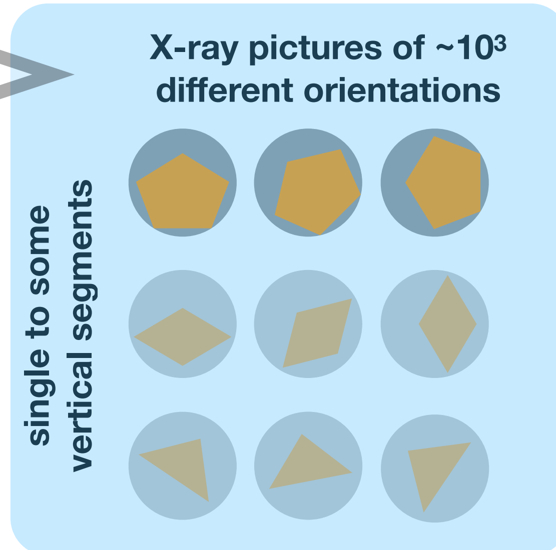
Choice happens by an educated guess!

(Approaches smarter than single constant value in use, but they also are based on additional assumptions.)

Generic 1-cell 1.3 GHz @Fraunhofer EZRT, 9 MeV

X-ray tomography: workflow III





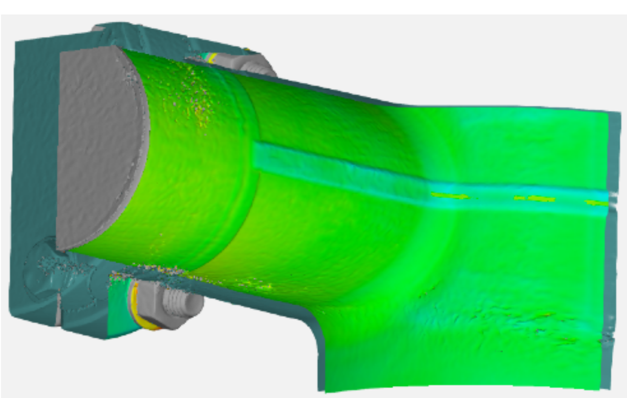
Tomographic Inversion (proprietary algorithm)

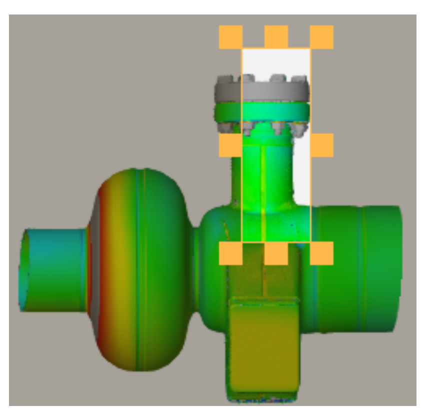
cubic voxel volume representation in 2^{16} intensity-scale values (.rek-file, ~ 10 GB)

bulk material volume construction by intensity-scale threshold (Volumegraphics©, GOM-Inspect©)

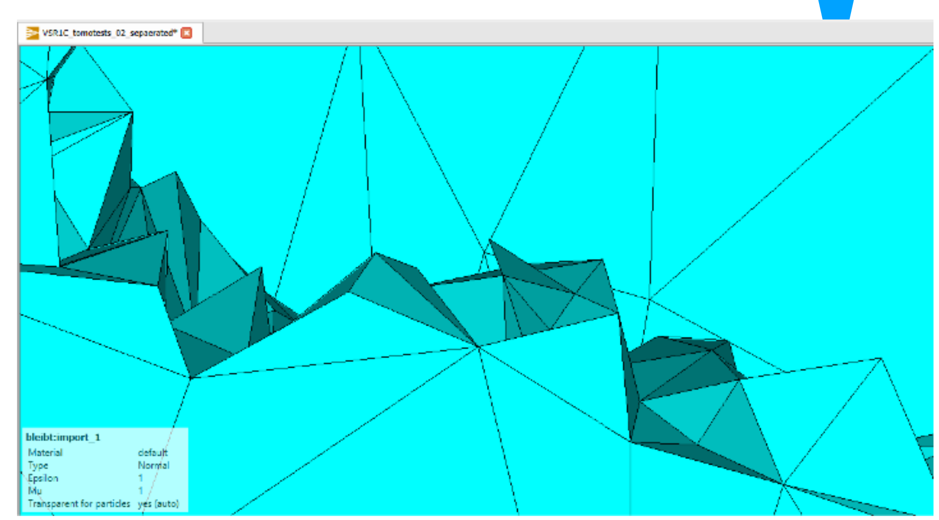
unpurified bulk material's surface description (.stl-file)

defect and shape accuracy check



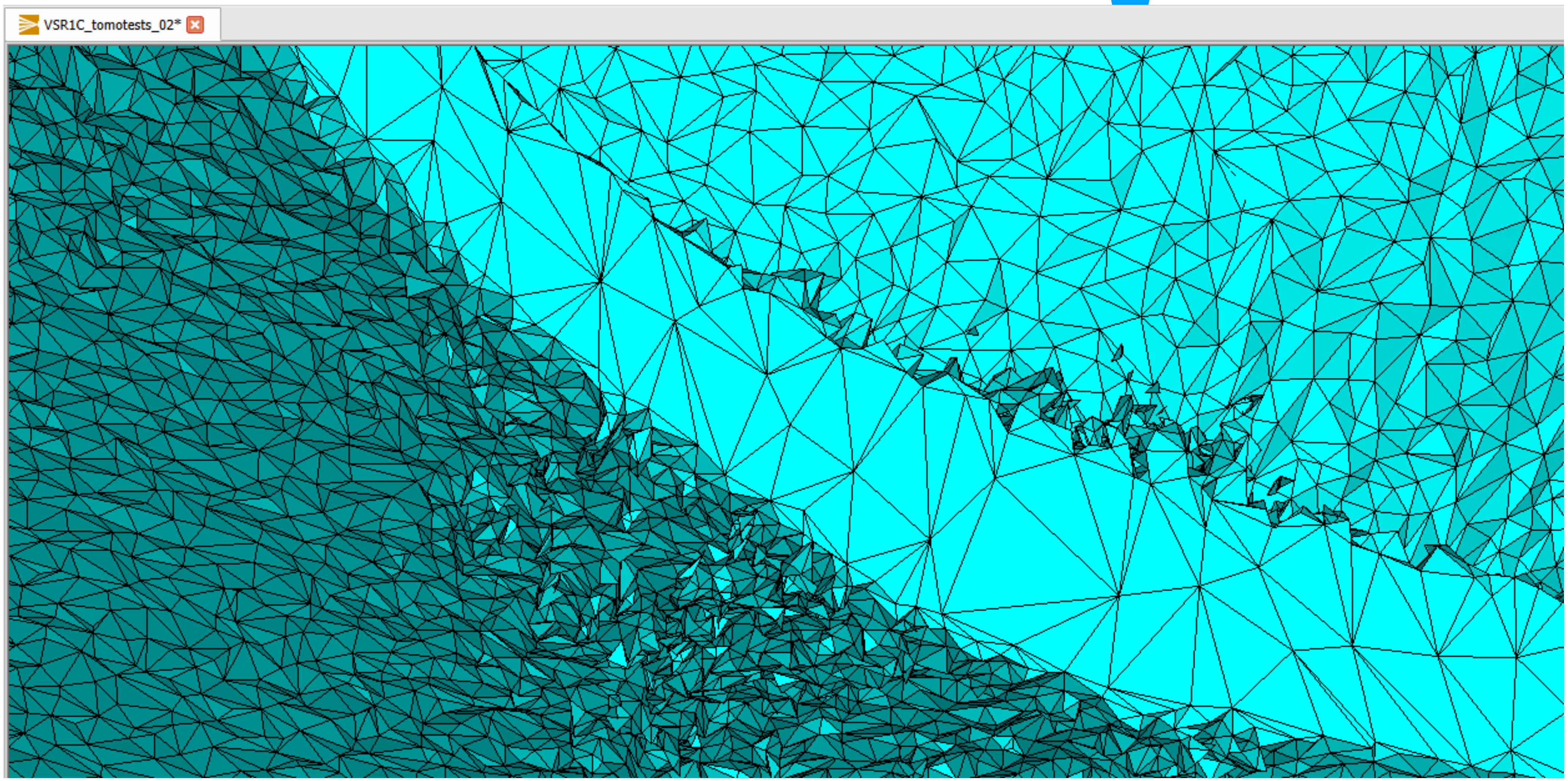


Example: overlapping interior welds of the coupler port of the VSR-1-cell



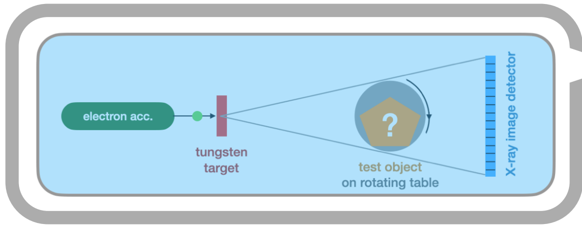
Issues with STL-files

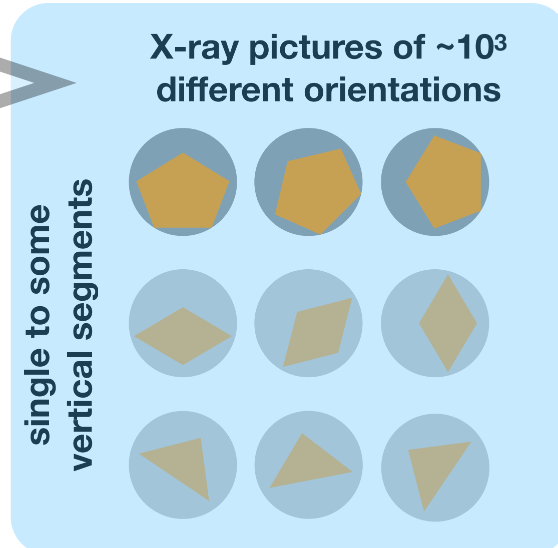
unpurified bulk material's surface description (.stl-file)



– *extremely big (~ 10^0 … 10^1 GB)*
– *isolated volumes, isolated/partially connected surfaces*
– *large surfaces not "watertight"*
– *not managed by field solvers*

X-ray tomography: workflow IV





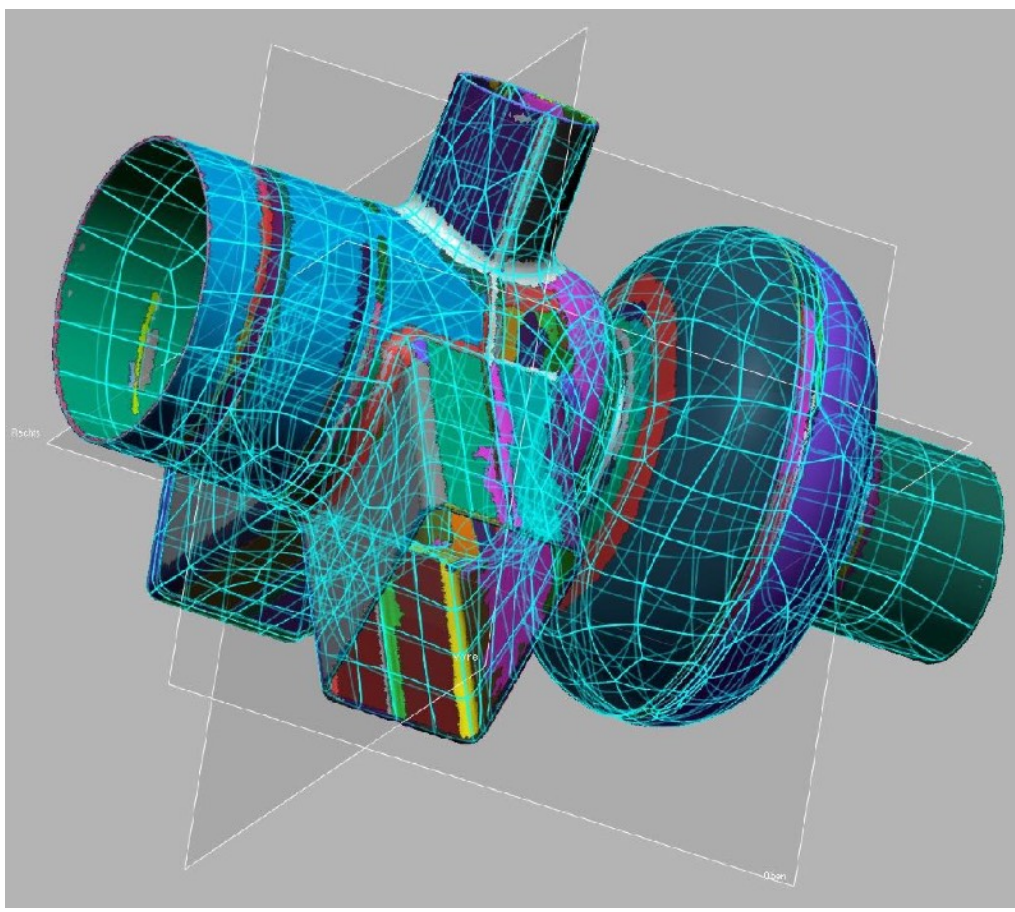
Tomographic Inversion (proprietary algorithm)

cubic voxel volume representation in 2^{16} intensity-scale values (.rek-file, ~ 10 GB)

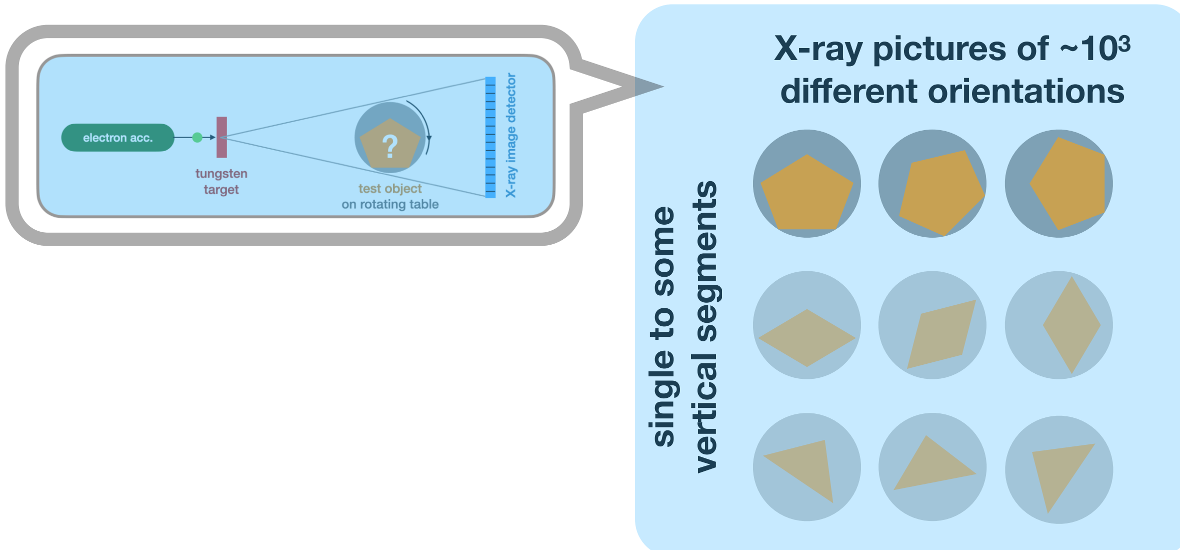
bulk material volume construction by intensity-scale threshold (Volumegraphics©, GOM-Inspect©)

unpurified bulk material's surface description (.stl-file)

conversion to NURBS-delimited volume representation (Geomagic Design X ©)



X-ray tomography: workflow V



Tomographic Inversion (proprietary algorithm)

cubic voxel volume representation in 2^{16} intensity-scale values (.rek-file, ~ 10 GB)

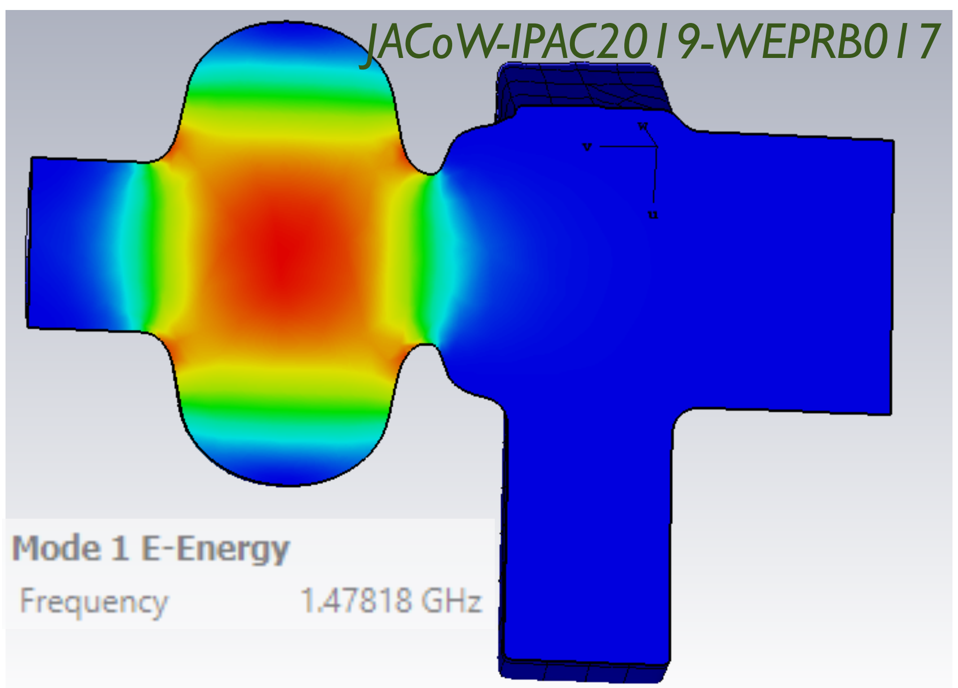
bulk material volume construction by intensity-scale threshold (Volumegraphics©, GOM-Inspect©)

unpurified bulk material's surface description (.stl-file)

conversion to NURBS-delimited volume representation (Geomagic Design X ©)

volume description (.step-file)

electromagnetic field solver (CST Studio ©)



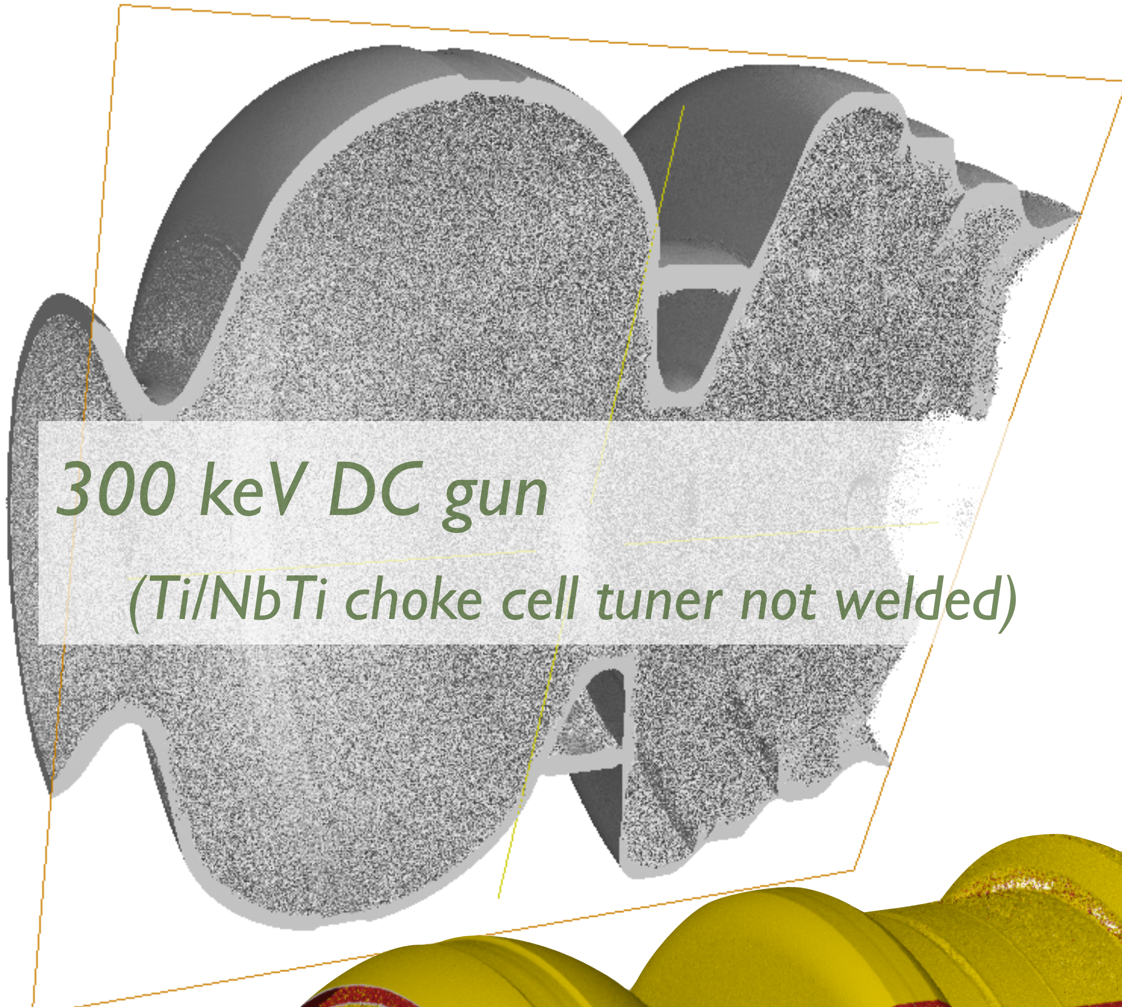
measured warm, air, 40% rel.hum.: 1476.979 MHz

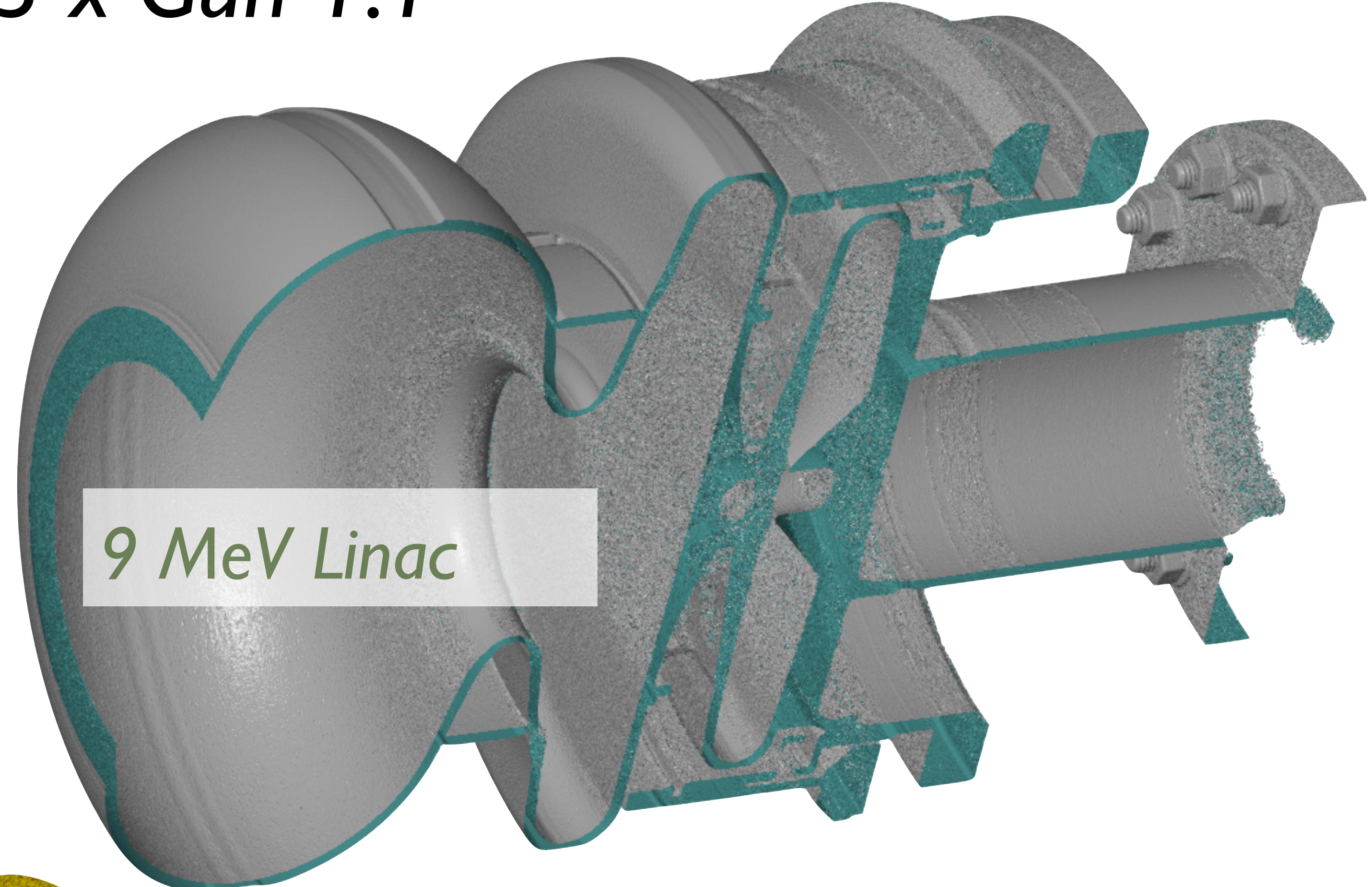
corrected $\varepsilon_r = \mu_r = 1$ as simulated: 1477.439 MHz

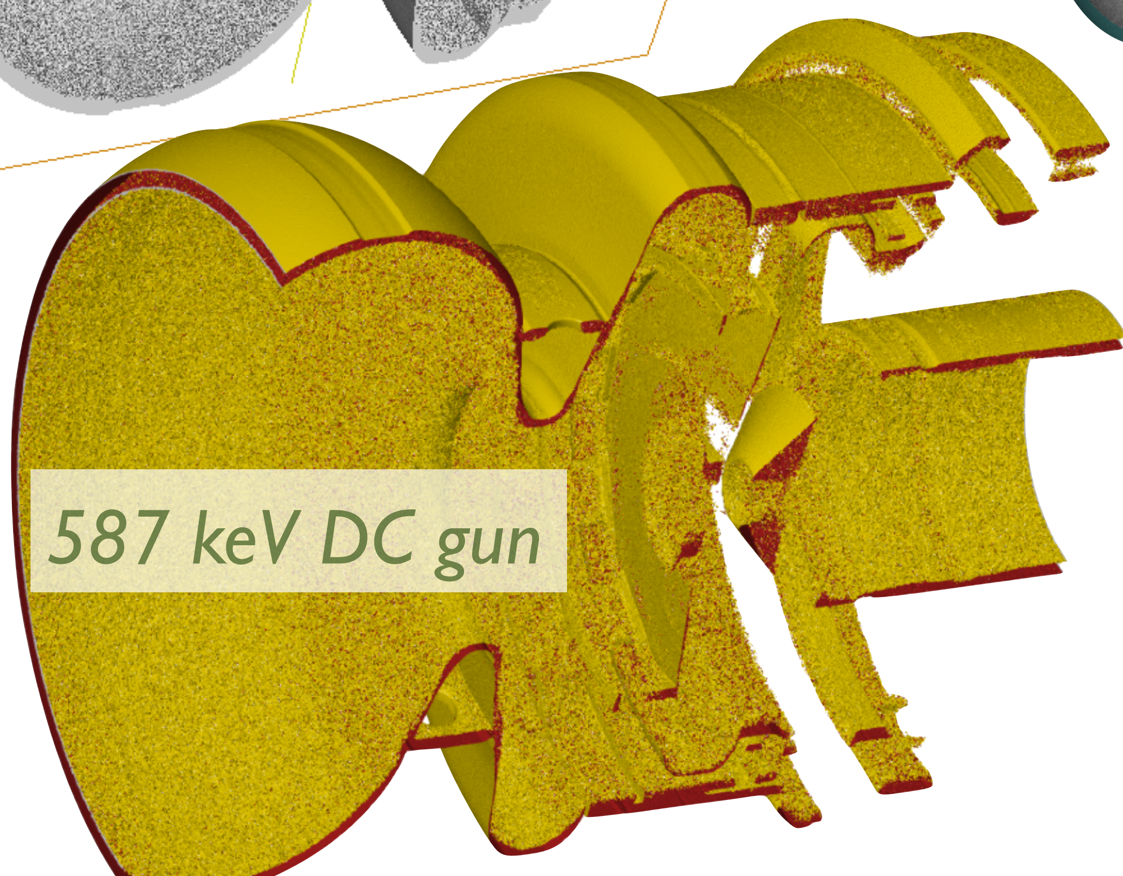
$\Delta f \,/\, f = 5.0 \cdot 10^{-4} = 92\ \mu m \,/\, D_{equator}$

Nice, but no statistics …

Benefit of high-energy X-rays: 3 x Gun 1.1

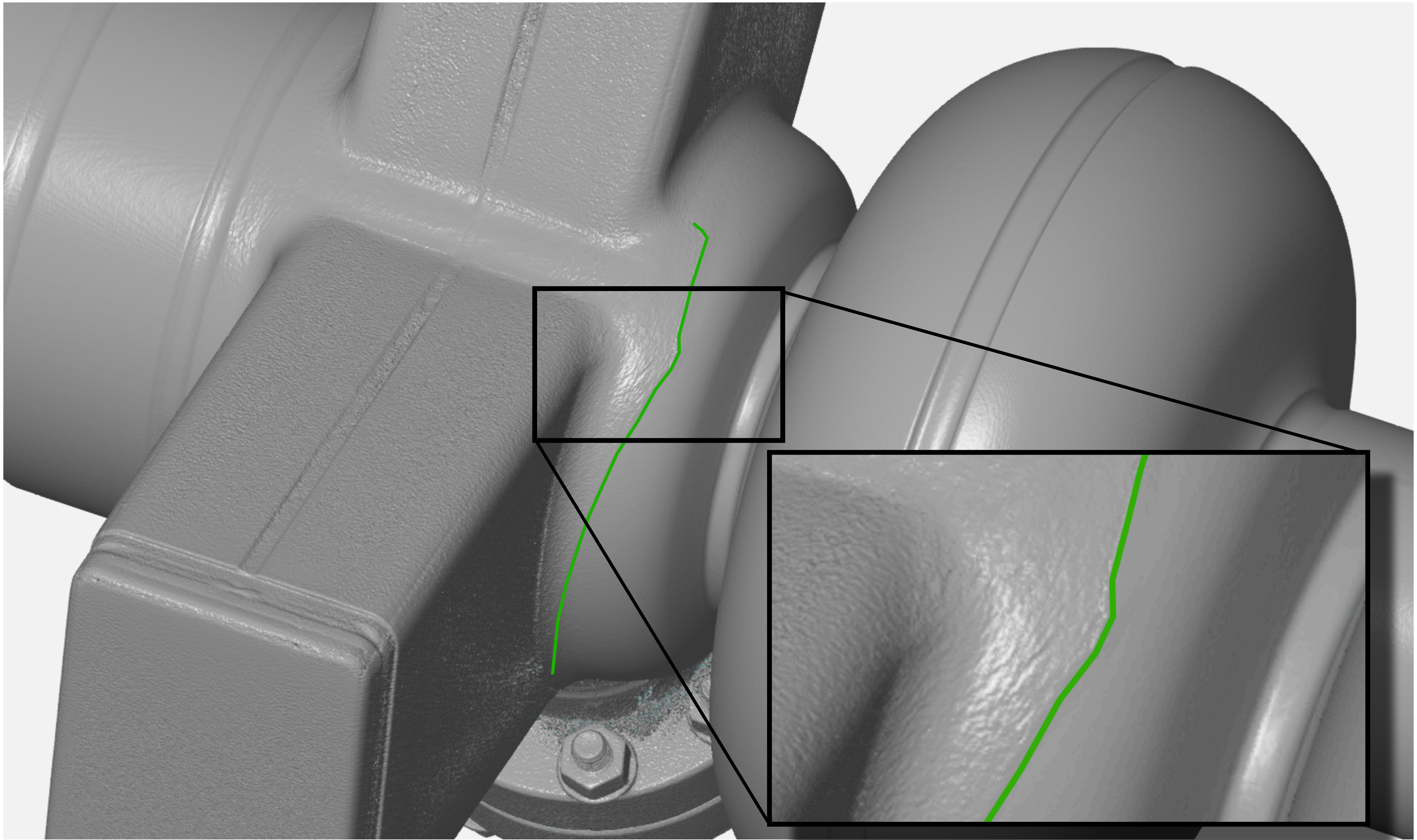






– *forget 300 keV for everything but outer surfaces*
– *600 keV-class guns resolve outer surfaces and some internal ones with noise*
– *9 MeV generated X-rays will resolve most, but not all internals, noise depending on overall attenuation*

Surface artifacts (though appearing rather authentic)



Example: VSR-1-cell, scanned with few degrees tilt. Artificially enhanced surface roughness in the shadow area of the waveguide extension, also noise around the screw nuts.

Conclusions - poor:

- *Meaningful X-ray tomography of niobium cavities need highest energies available, even beyond most "industrial" demands.*
- *Intrinsic calibration by additional knowledge is necessary to adjust threshold values needed for material border definition.*
- *Data evaluation requires capable resources, experience or/and good luck.*

Conclusions - optimistic:

- *X-ray tomography gives access to internals of fully processed and hermetically closed cavities.*
- *It does a good job in integrally capturing cavity shapes down to ~ 0.2 mm spatial resolution.*
- *As any emerging non-destructive testing procedure it has the potential to gain reliability with increasing practice.*