PAUL SCHERRER INSTITUT

PSI

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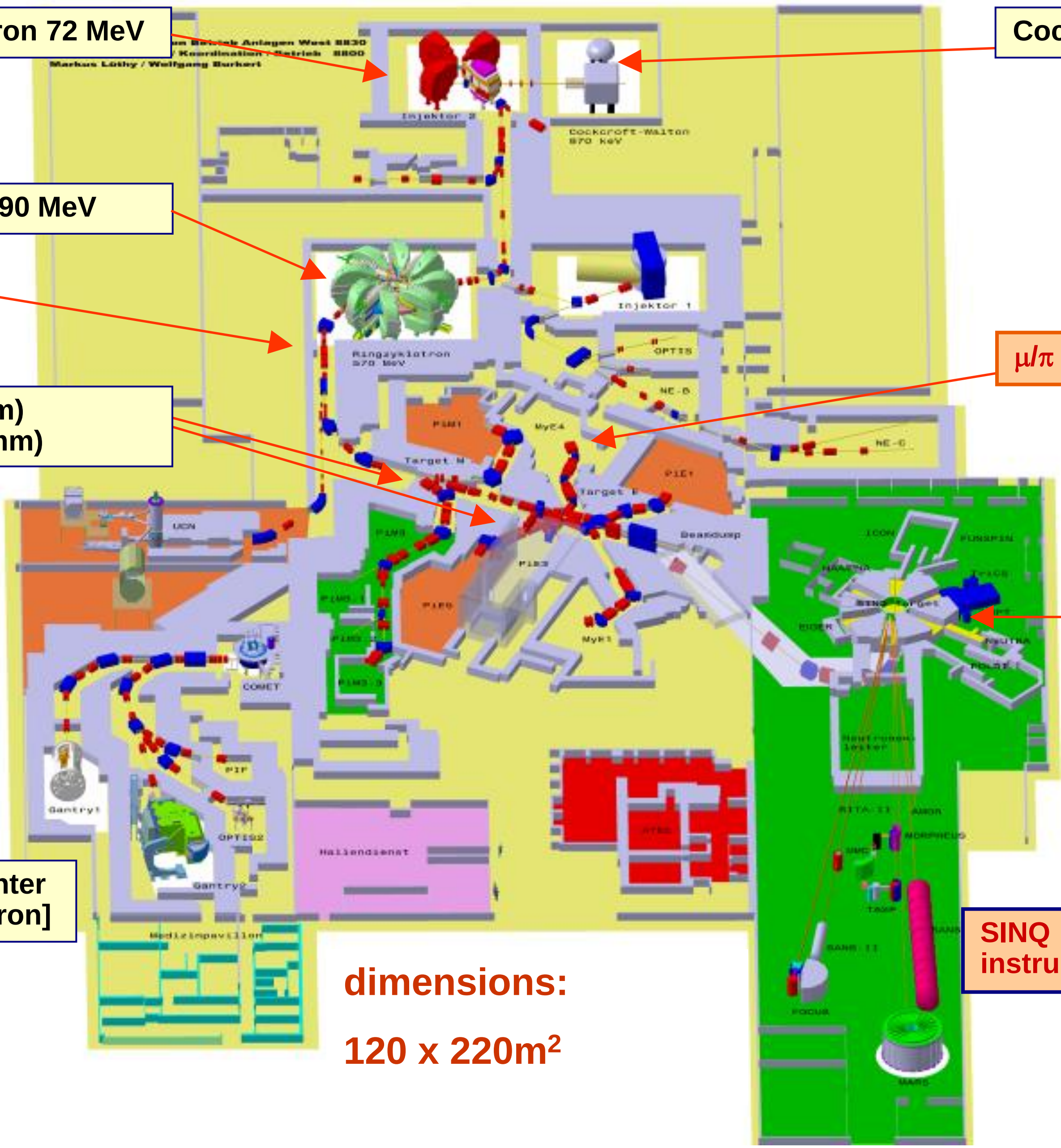
3D thermal-structural analyses of SINQ rod bundle target

13th International Topical Meeting on the Nuclear Applications of Accelerators

Outline

- Brief introduction to PSI HIPA facilities
- SINQ target and cooling system
- Thin / thick «Cannelloni» geometries
- **Goal of this study**
- Simulation procedures
- Results thick and thin «Cannelloni»
- Results 100% filling thick «Cannelloni»
- Ideas for future work

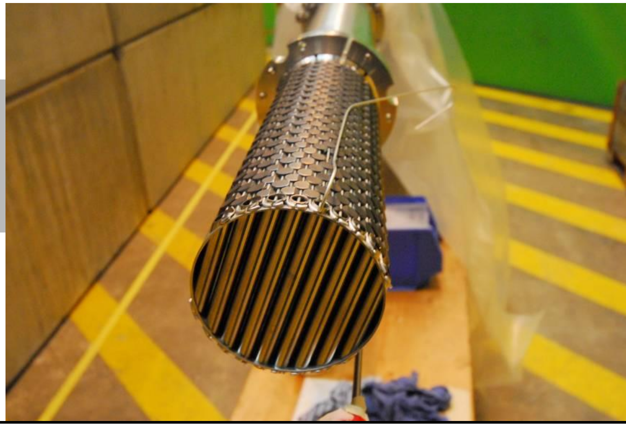
Overview HIPA



dimensions:

120 x 220m²

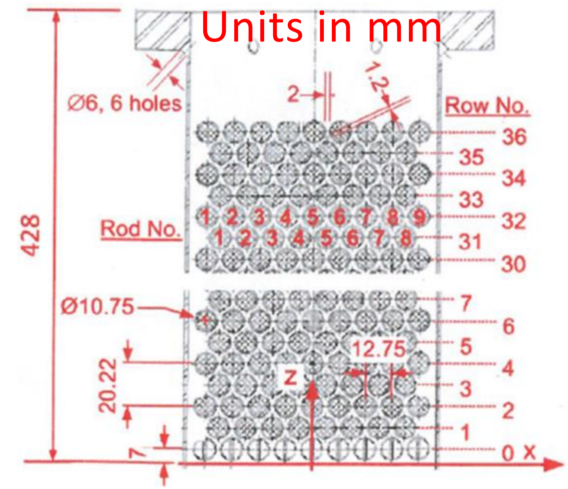
Cooling scheme of the SINQ Zr-2 - Pb «Cannelloni» target (CFD simulation from Sven Jollet)



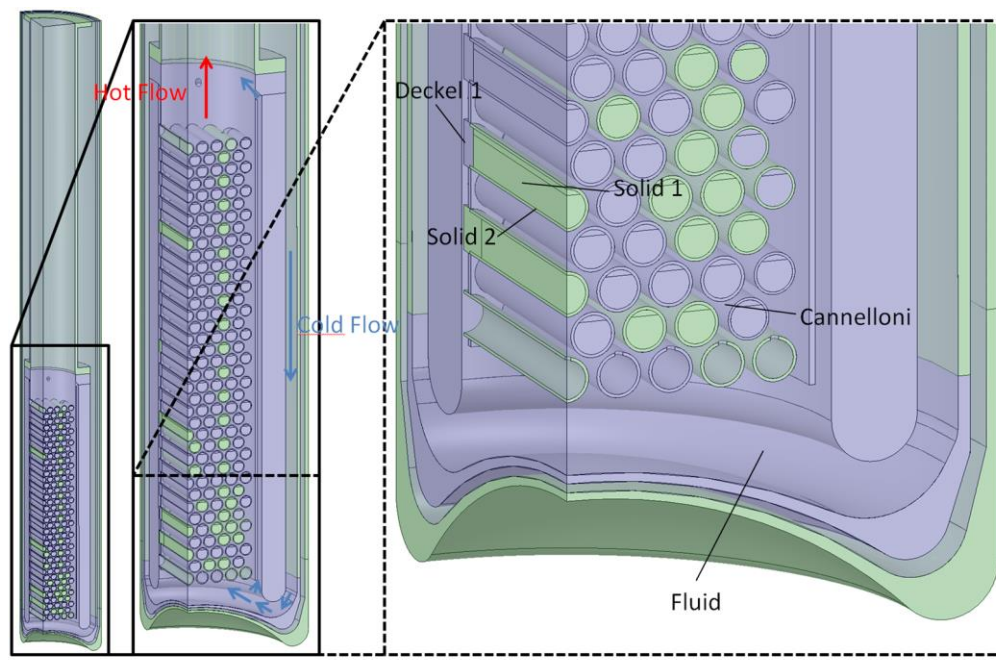
Zircaloy-2 - Pb « Cannelloni » array:

306 Lead filled « Cannelloni »

9 turbolizers



Cannelloni
Zircaloy-2 tube 90% filled with Lead



«Cannelloni» geometries

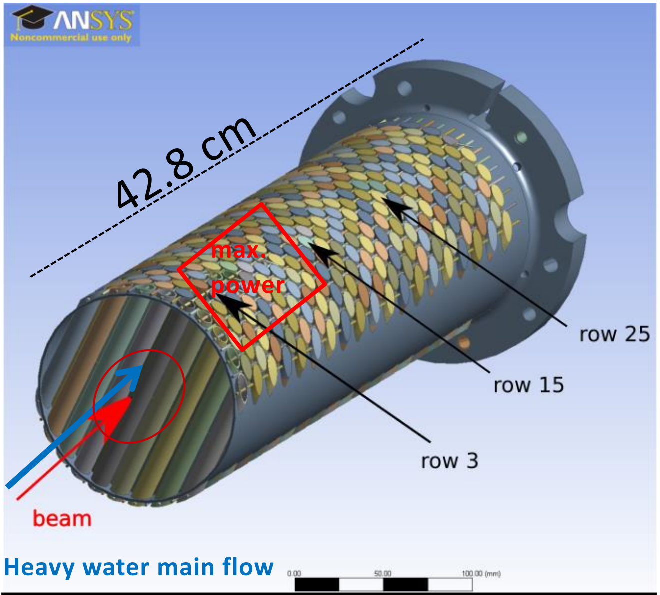
Thick (mm)

diameter Lead	9.25
radius Lead	4.625
diameter ext Zircaloy-2	10.75
radius ext Zircaloy-2	5.375
Zircaloy-2 thickness	**0.75**
thickness / internal radius	0.16

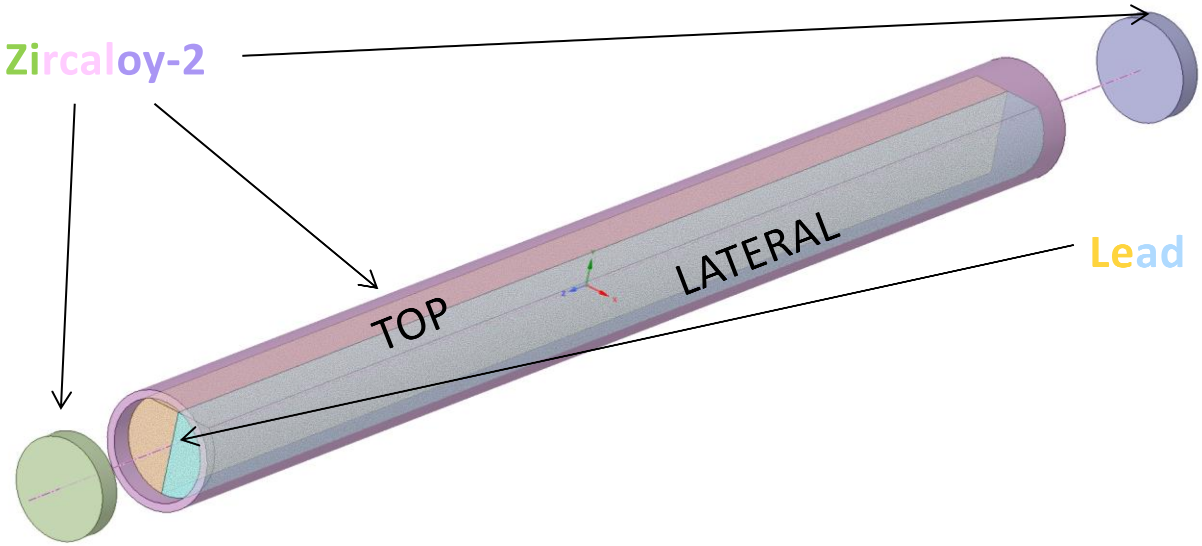
axial length Lead	116
axial length Zircaloy-2	120

Thin (mm)

diameter Lead	8.8
radius Lead	4.4
diameter ext Zircaloy-2	10.05
radius ext Zircaloy-2	5.025
Zircaloy-2 thickness	**0.606**
thickness / internal radius	0.14



306 filled « Cannelloni » + 9 turbolizers



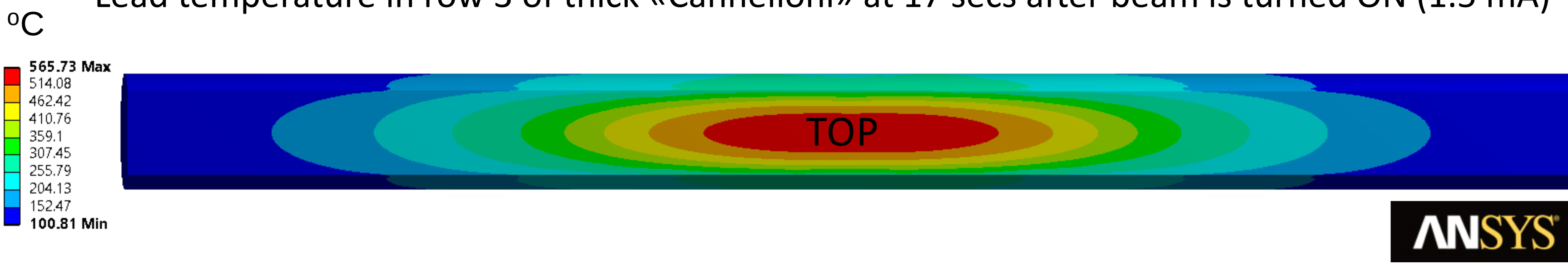
Damaged target tube – Target 8 row 16

Results focus on Zircaloy-2 to avoid «Cannelloni» failure:
spilling out of Lead + spallation products and blocking of cooling channels.

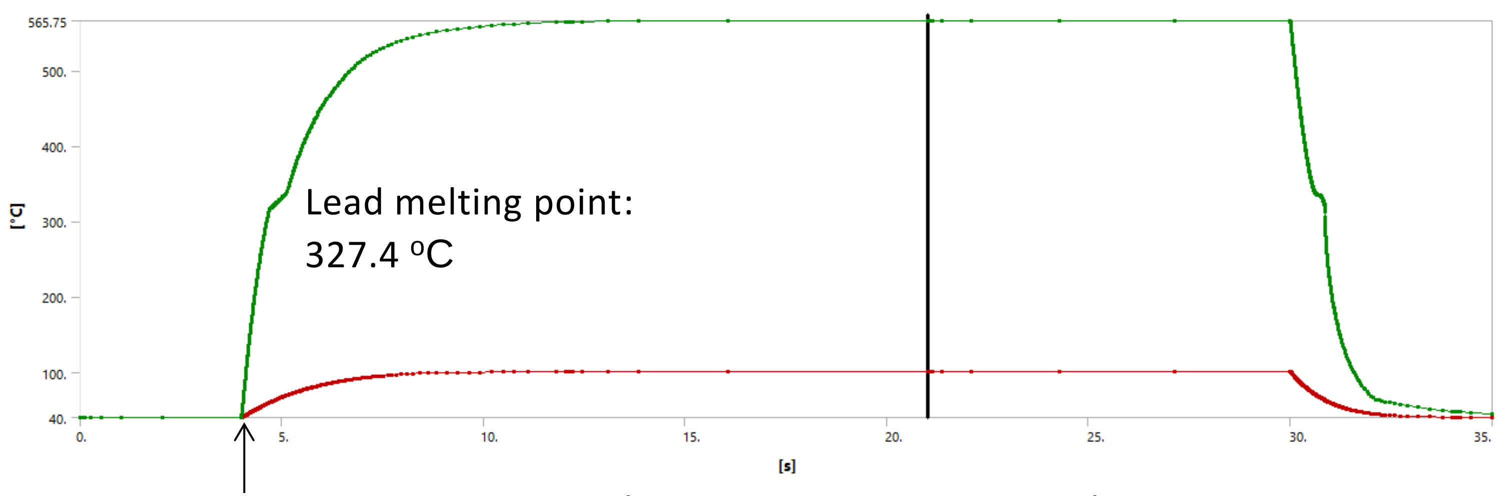
Simulation numerical procedure

- Simulations are done as **Transient thermal** and **Steady-state Structural analyses** In lower rows, phase change takes place which is a FULL THERMAL TRANSIENT process.

Lead temperature in row 3 of thick «Cannelloni» at 17 secs after beam is turned ON (1.5 mA)



Evolution in time of maximum temperaure in Lead for row 3 thick «Cannelloni» at 1.5 mA

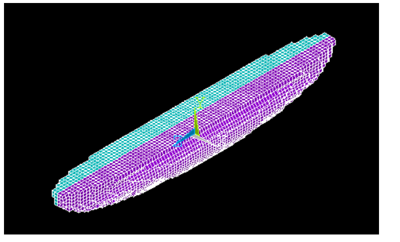


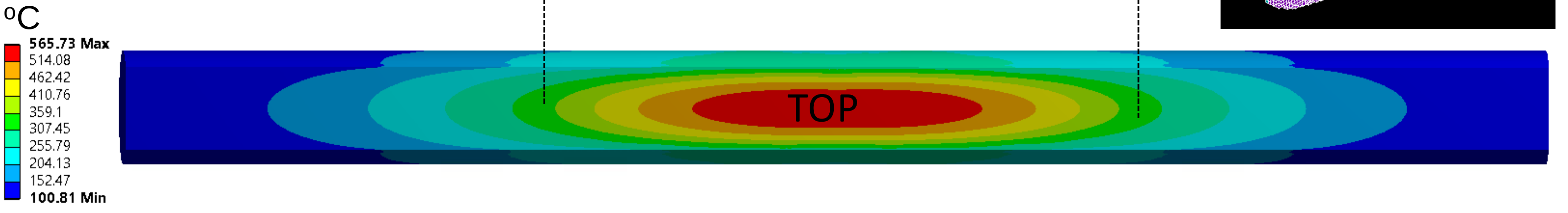
Beam ramping time= 1 ms (conservative approach)

Simulation numerical procedure

Automatic procedure to identify the **3D** liquid shape > 327.4 °C
and to make the corresponding mesh element «inert», no further contribution to results (molten Lead will also not flow → no Lead shape change):
stress → 0 (liquid produces no stress) , Temperature «frozen» at the present value, ...

Molten Lead shape row 3





Temperature in Lead in row 3 of thick «Cannelloni» at steady-state

The top flat surface of the Lead has been considered adiabatic.

Simulation physics assumptions

- Density
- Coefficient of thermal expansion
- Elastic coefficient (Young modulus) / plasticity
- Lead Kinematic hardening from experimental data
- Thermal conductivity
- Specific heat capacity

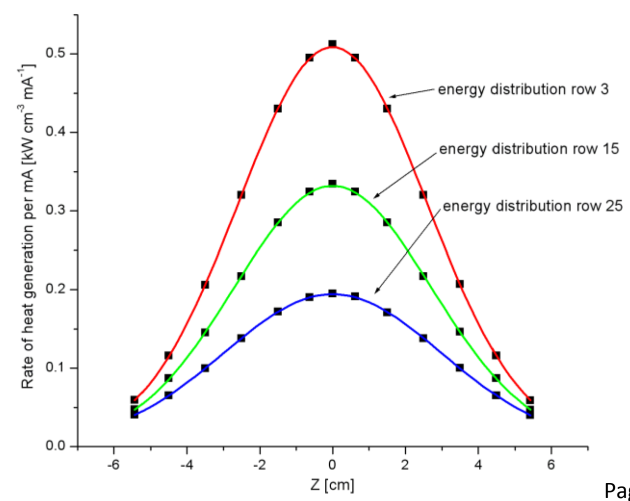
ARE FUNCTIONS OF TEMPERATURE

- **Beam current** = **1.5 mA** (correspond to about 2.2 mA on TARGET E 4 cm)
- **Power depositions** from Tibor Reiss / Michael Wohlmuther **Monte Carlo** calculations for TARGET10 (thick «Cannelloni»).
- Irradiated Zirc.2 data: irradiation dose is 20.3 dpa with about 1000 appm He and more than 10000 appm H. Irradiation temperature is 160+/-20 °C

For row 3 max rate of heat generation

for 1.5 mA:

$0.75\ [W / mm^3]$



Simulation physics assumptions: HTC

Heat transfer coefficient from SINQ CFD calculation (Sven Jollet)

Heavy water temperatures

row 3: 40.0 °C

row 15: 56.014 °C

row 25: 62.12 °C

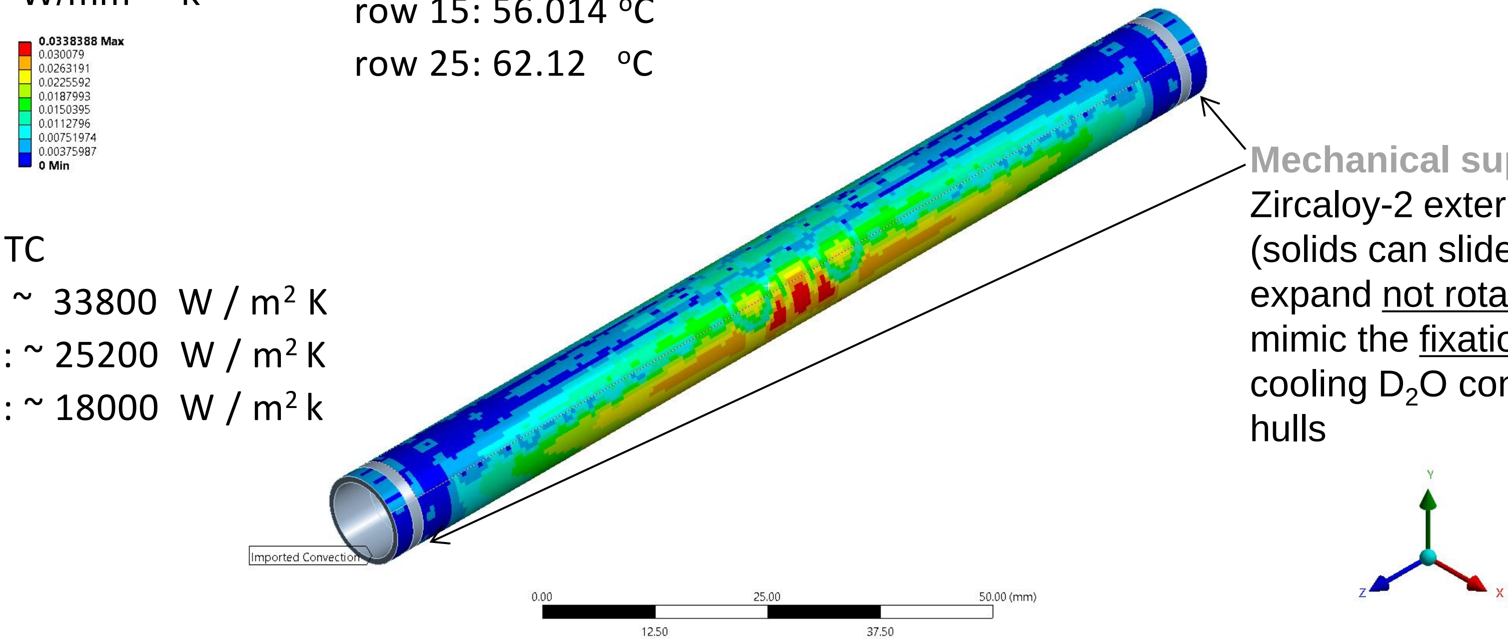
W/mm^2 - k

Max. HTC

row 3: ~ 33800 W / m^2 K

row 15: ~ 25200 W / m^2 K

row 25: ~ 18000 W / m^2 k



Mechanical support on Zircaloy-2 external surface (solids can slide and expand not rotate) to mimic the fixations on the cooling D_2O containing hulls

Heat transfer coefficient (HTC) row 3, 1.5 mA from **steady-state** CFD

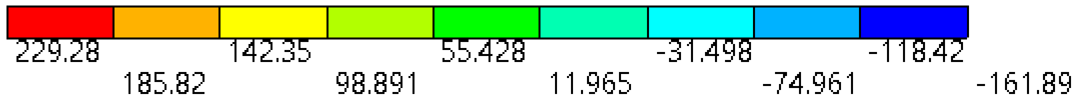
No evolution in time of HTC → strong approximation because

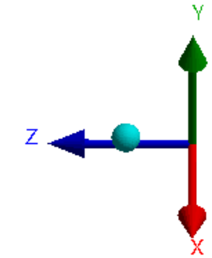
!!! Simulations really sensitive to HTC !!!

Results: thick «Cannelloni» at steady-state unirradiated Zircaloy-2 data

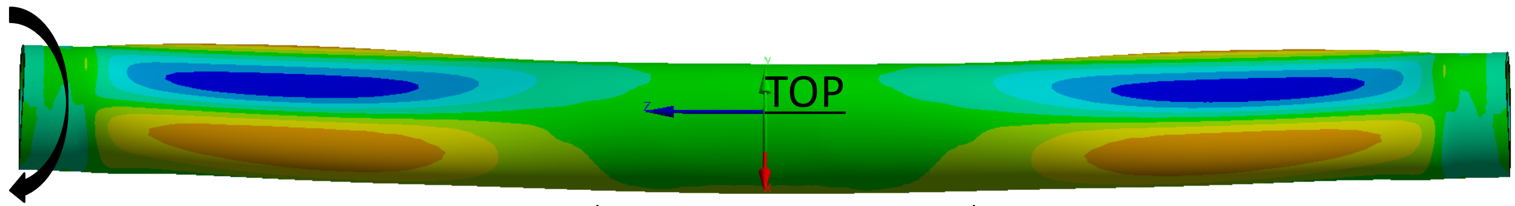
Results: **thick «Cannelloni»** <u>Hoop stresses</u> on Zirc.-2, 1.5 mA at steady-state with deformation (rescaled) – **rotated** LATERAL VIEW

MPa





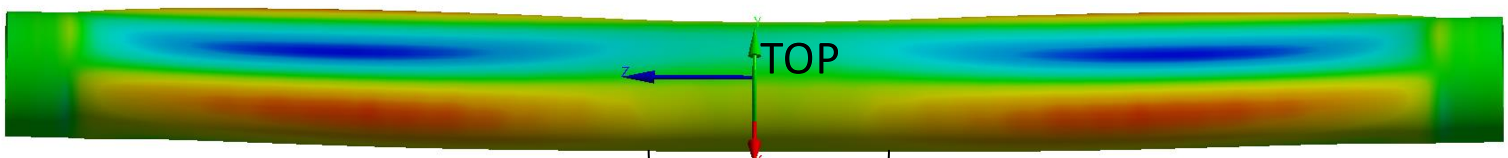
Row 3



Hoop stress = tangential stress

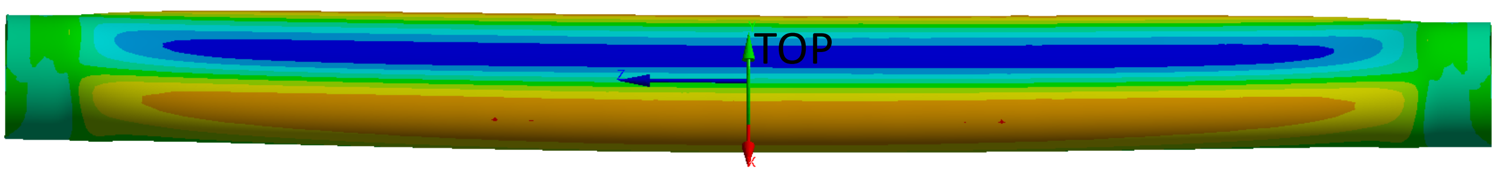
molten Lead

Row 15



molten Lead

Row 25



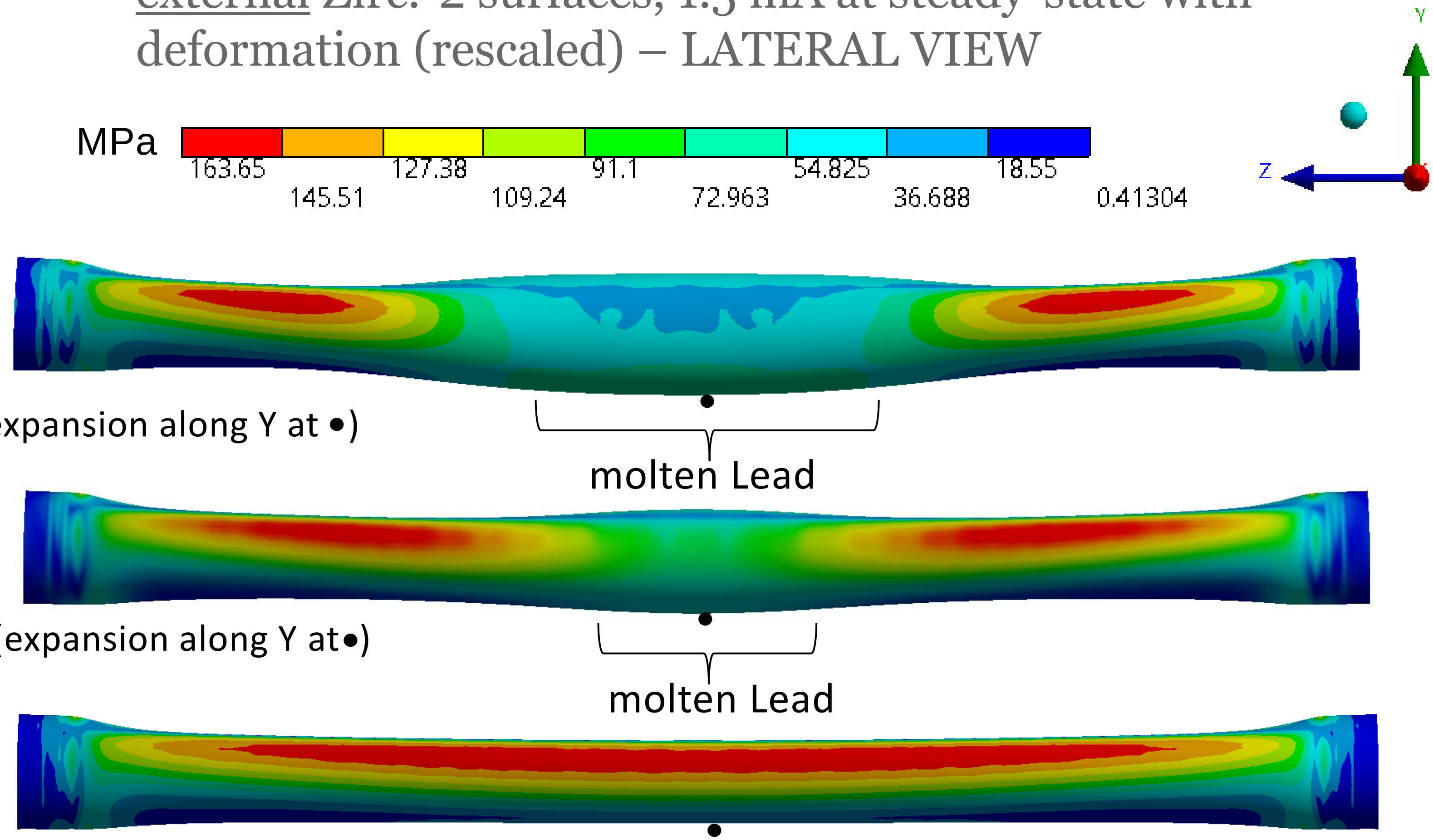
Positive values → tension

Max. positive internal surface

Negative values → compression

Max. negative internal surface

Results: **thick «Cannelloni»** von-Mises stresses on external Zirc.-2 surfaces, 1.5 mA at steady-state with deformation (rescaled) – LATERAL VIEW



Row 3
~161 MPa
~ 0.04 mm (expansion along Y at •)

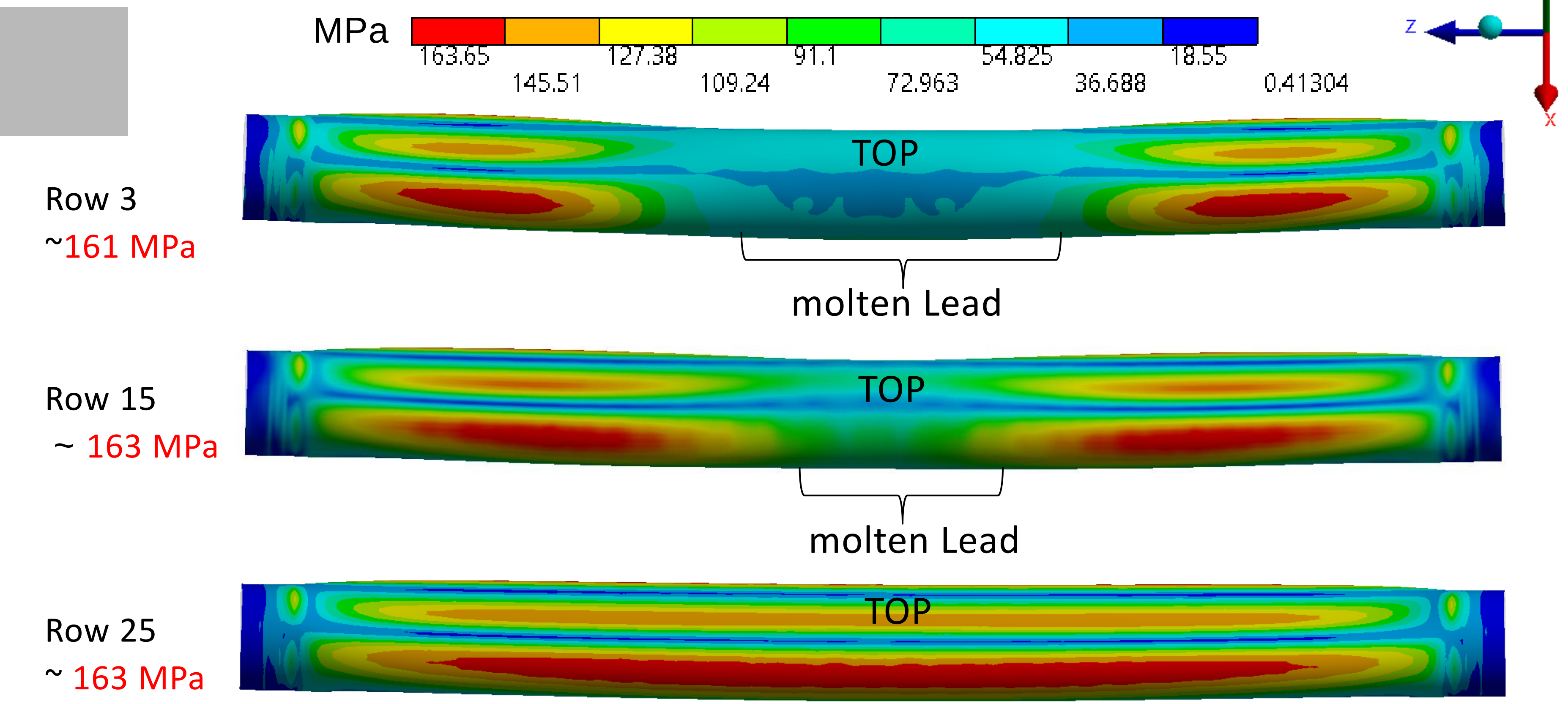
Row 15
~ 163 MPa
~ 0.015 mm (expansion along Y at•)

Row 25
~ 163 MPa
~ 0.005 mm (contraction along Y at •)

Similar stress amplitude even though max. beam deposition near row 3.

Stress behavior due to competition among Heat transfer coefficient – Heavy water temperature - Power deposition.

Results: **thick «Cannelloni»** von-Mises stresses on external Zirc.-2 surfaces, 1.5 mA at steady-state with deformation (rescaled) – **rotated** LATERAL VIEW



Similar stress amplitude even though max. beam deposition near row 3.

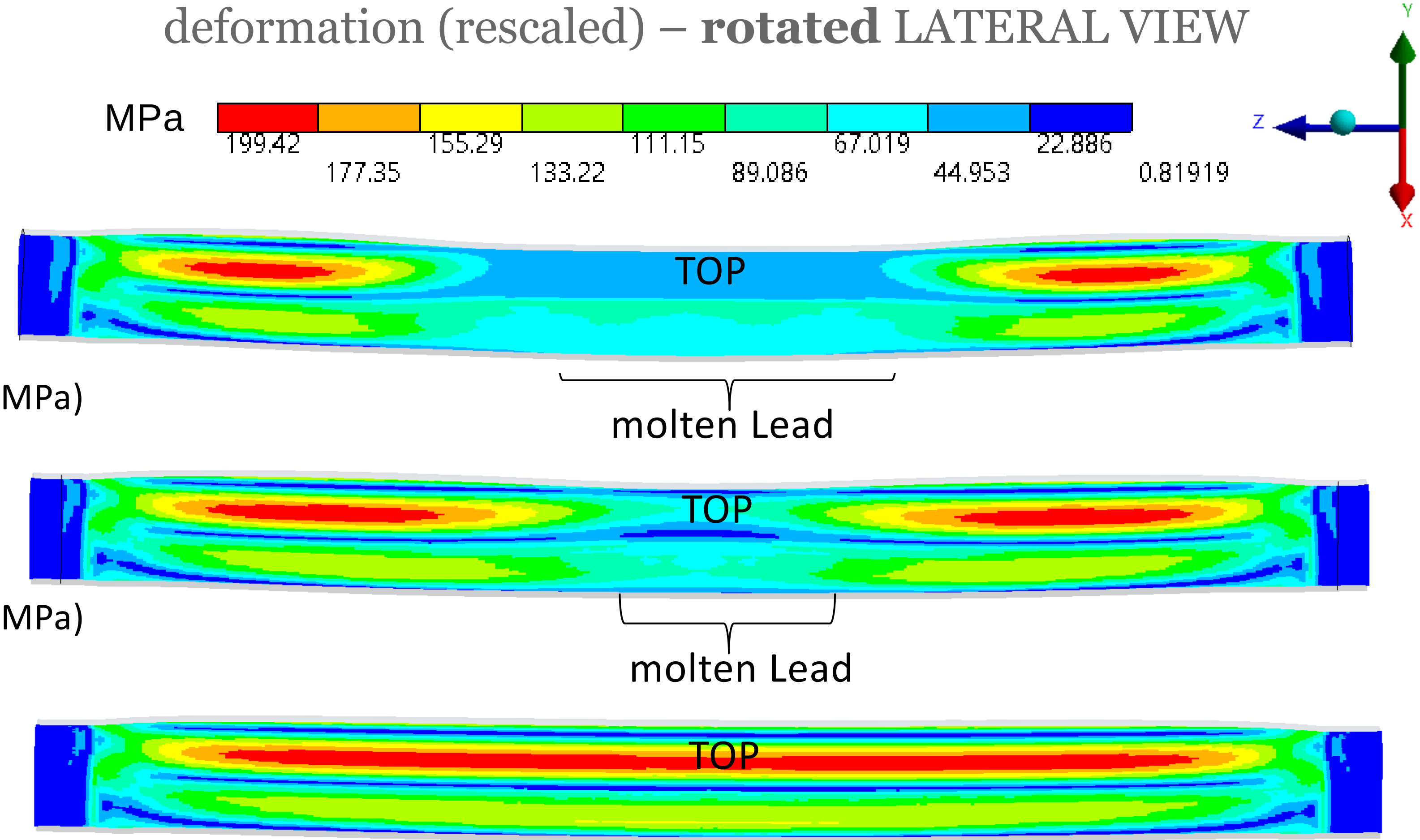
Stress behavior due to competition among Heat transfer coefficient – Heavy water temperature - Power deposition.

Results: **thick «Cannelloni»** von-Mises stresses on internal Zirc.-2 surfaces, 1.5 mA at steady-state with deformation (rescaled) – **rotated** LATERAL VIEW

Row 3
~195 Mpa
(ext. ~ 161 MPa)

Row 15
~ 199 MPa
(ext. ~ 163 MPa)

Row 25
~ 197 MPa
(ext. ~ 163 MPa)



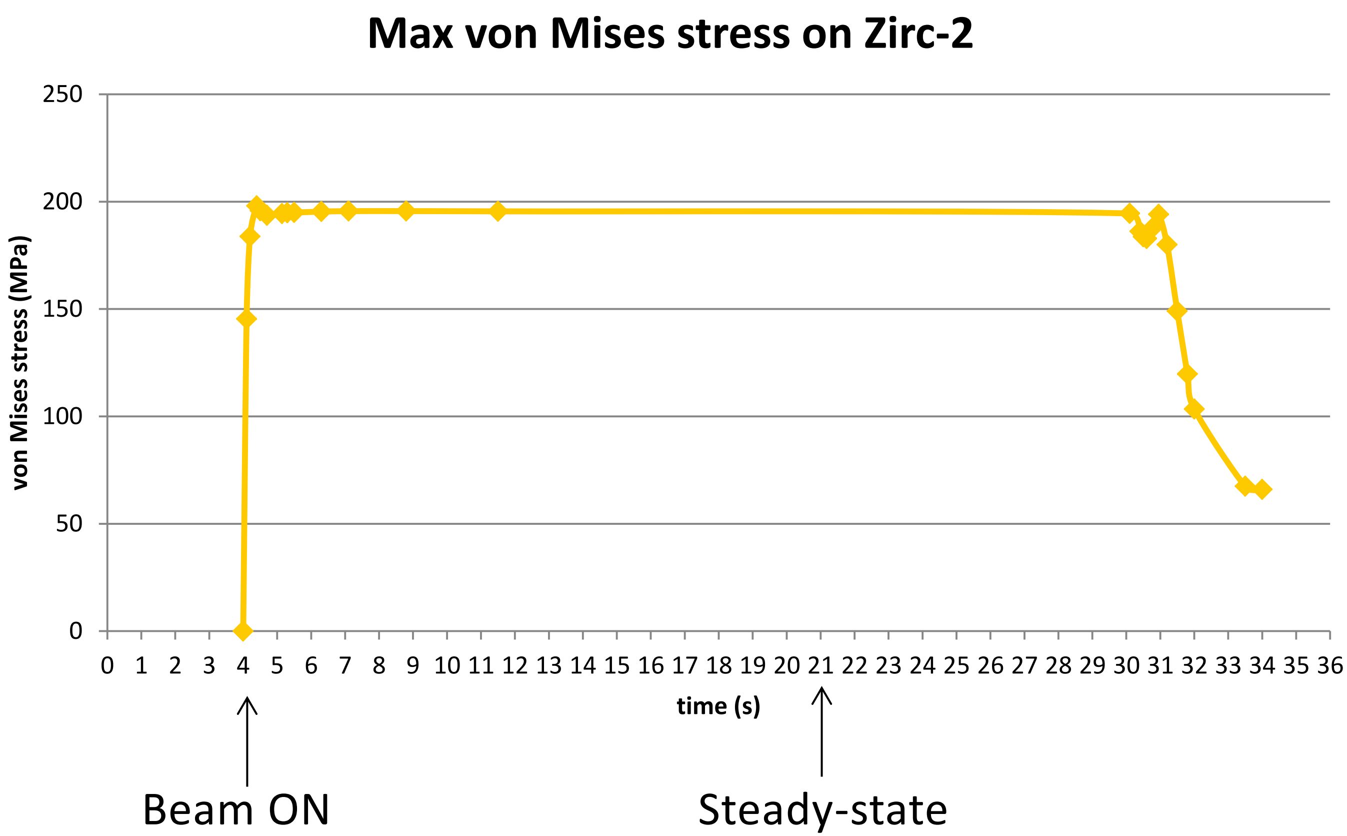
Similar stress amplitude even though max. beam deposition near row 3.

Higher stresses on internal Zirc.-2 surfaces with respect to the stresses on external surfaces!!!

Results: **thick «Cannelloni»** Von-Mises stresses on Zirc.-2, 1.5 mA function of time

200 MPa
Yielding point for unirradiated Zirc.-2:
from elastic to plastic.

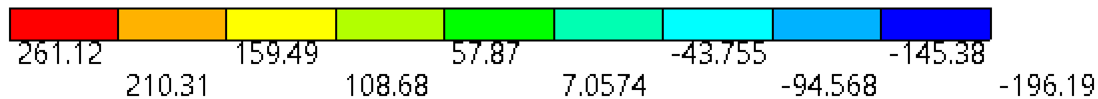
Calculations done with Zirc.-2 plasticity and irradiated data will show similar results.

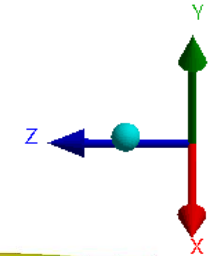


Results: thin «Cannelloni» at steady-state unirradiated Zircaloy-2 data

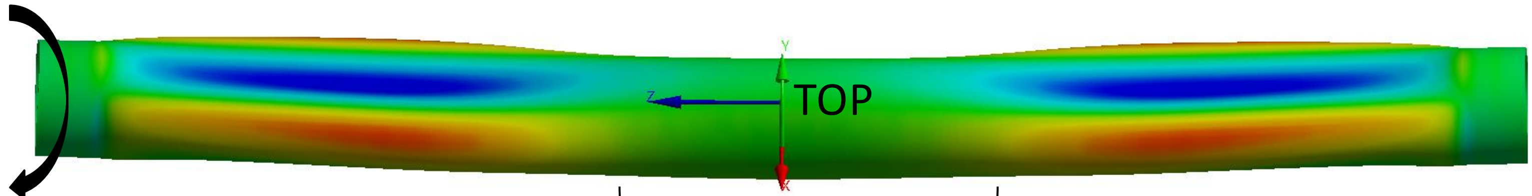
Results: **thin «Cannelloni»** <u>Hoop stresses</u> on Zirc.-2, 1.5 mA at steady-state with deformation (rescaled) – **rotated** LATERAL VIEW

MPa





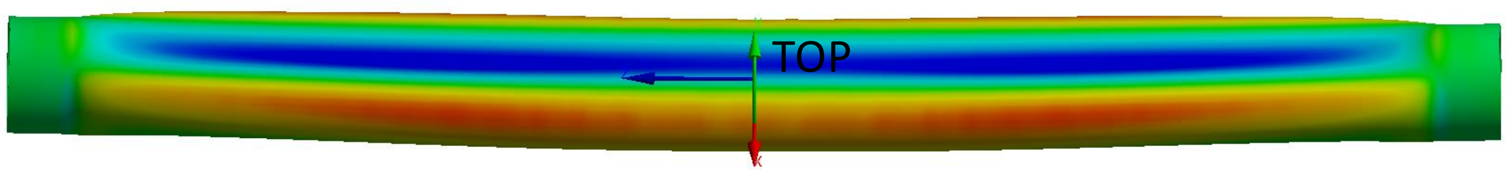
Row 3



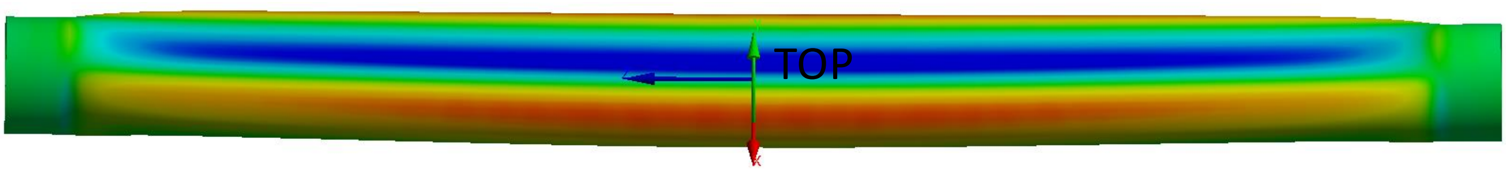
Hoop stress = tangential stress

molten Lead

Row 15



Row 25



Positive values → tension
Max. positive internal surface

Negative values → compression
Max. negative internal surface

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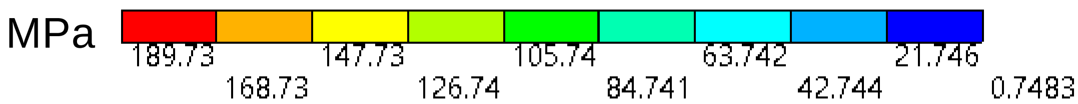
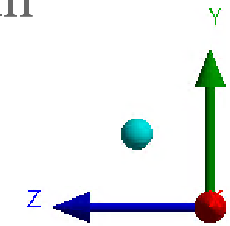
Results: : **thin «Cannelloni»** von-Mises stresses on external Zirc.-2 surfaces, 1.5 mA at steady-state with deformation (rescaled) – LATERAL VIEW

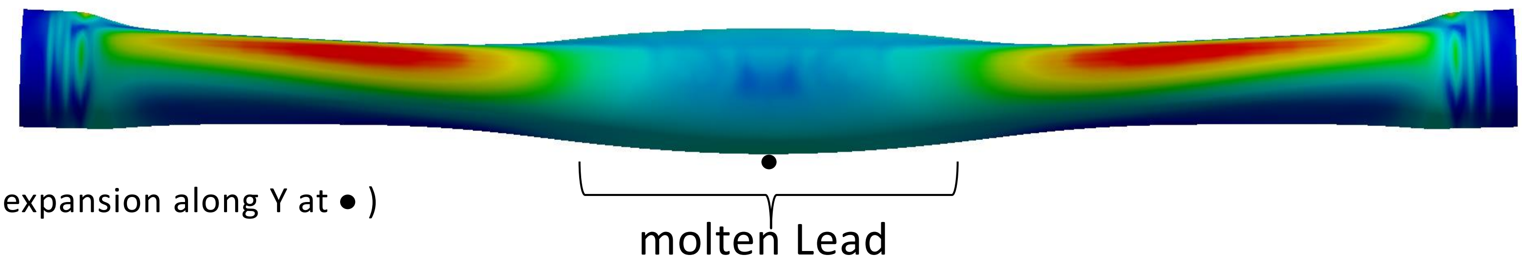




Row 3

~ 188 MPa

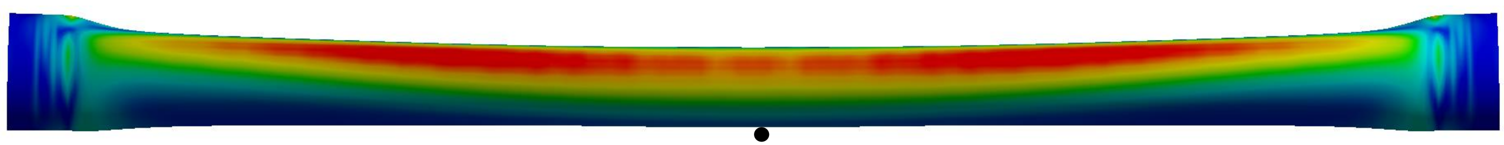
~ 0.035 mm (expansion along Y at ●)



Row 15

~ 189 MPa

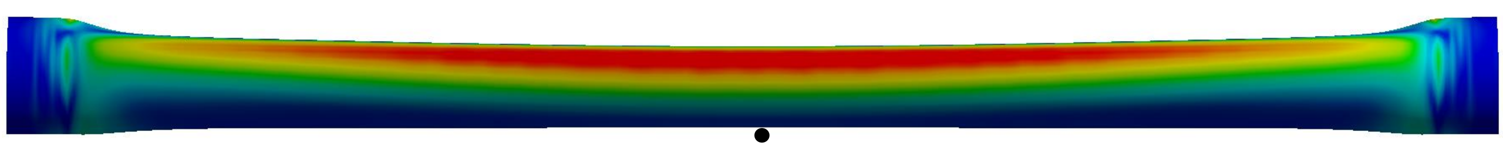
~ 0.0022 mm (contraction along Y at ●)



Row 25

~ 189 MPa

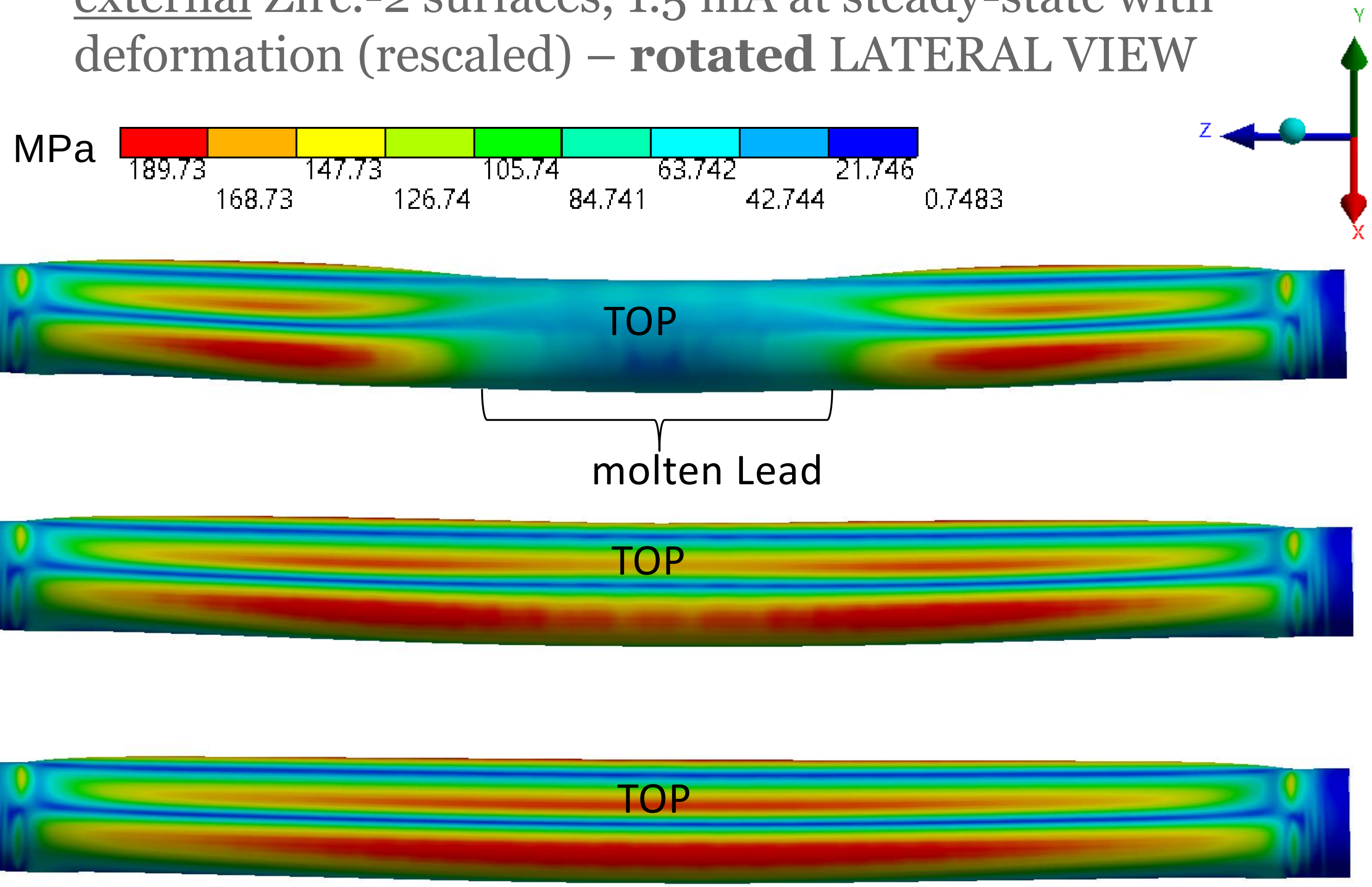
~ 0.0062 mm (contraction along Y at ●)



Similar stress amplitude even though max. beam deposition near row 3.

Stress behavior due to competition among Heat transfer coefficient – Heavy water temperature - Power deposition. Similar deformation also for thick «Cannelloni».

Results: **thin «Cannelloni»** von-Mises stresses on external Zirc.-2 surfaces, 1.5 mA at steady-state with deformation (rescaled) – **rotated** LATERAL VIEW



Row 3
~ 188 MPa

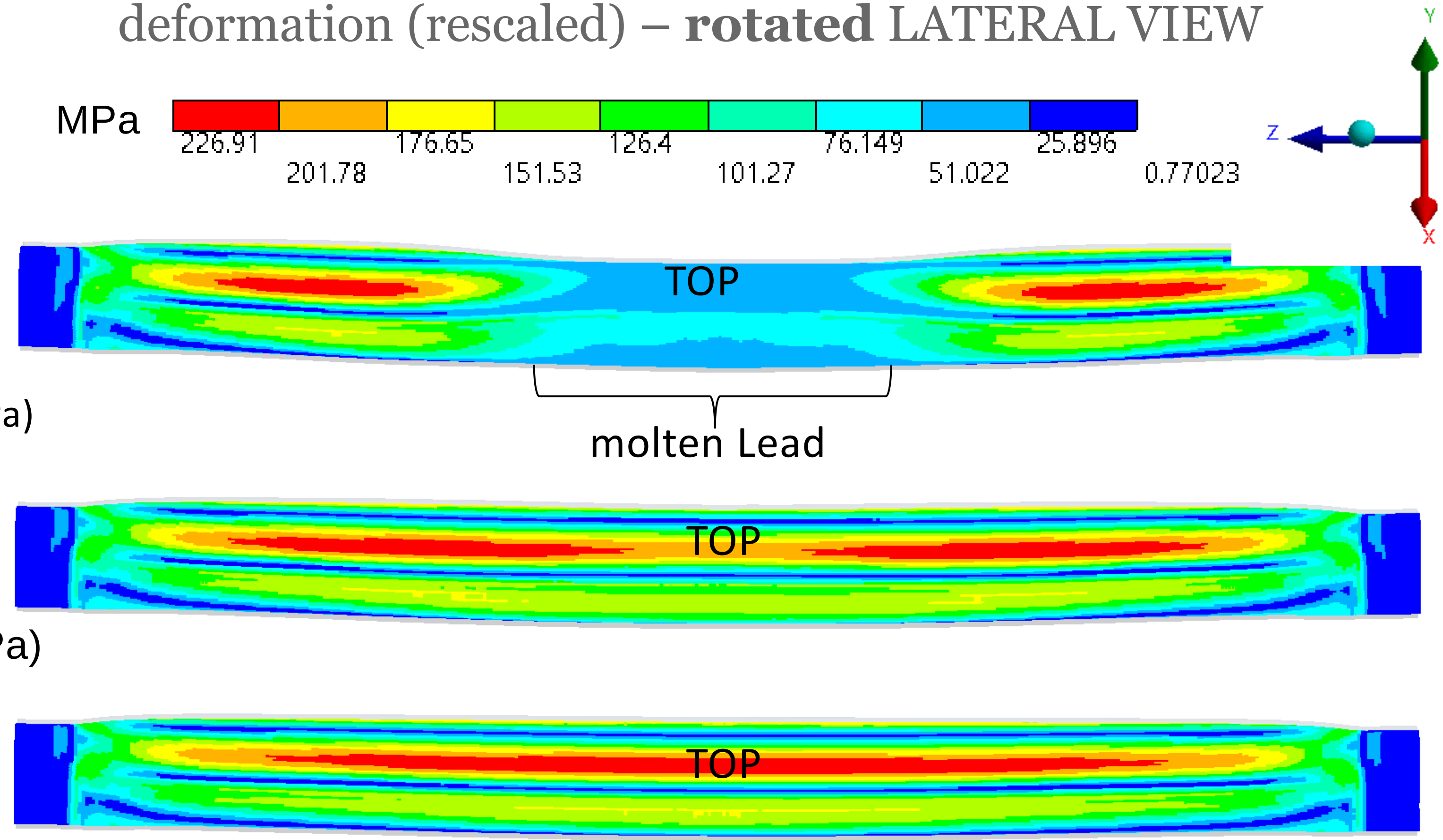
Row 15
~ 189 MPa

Row 25
~ 189 MPa

Similar stress amplitude even though max. beam deposition near row 3.

Stress behavior due to competition among Heat transfer coefficient – Heavy water temperature - Power deposition.

Results: **thin «Cannelloni»** von-Mises stresses on internal Zirc.-2 surfaces, 1.5 mA at steady-state with deformation (rescaled) – **rotated** LATERAL VIEW



Row 3
~ 224 MPa
(ext. ~ 188 MPa)

Row 15
~ 225 MPa
(ext.~189 MPa)

Row 25
~ 226 MPa
(ext. ~ 189 MPa)

Similar stress amplitude even though max. beam deposition near row 3.

Higher stresses on internal Zirc.-2 surfaces with respect to the stresses on external surfaces!!!

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Results: max. von Mises stress comparisons ext. surfaces **thick** «Cannelloni» vs **thin** «Cannelloni» unirradiated Zircaloy-2 data

	Thick (0.75 mm)	Thin (0.606 mm)	
row 3	161	188	MPa
row 15	163.15	189	MPa
row 25	163	189	MPa

Results: 100% filled thick «Cannelloni»

Can we explain this failure with the results shown (90% Lead filling)?
Not really because simulations for row 15 “thick” Cannelloni show max. stress on the sides and here crack forming in the center and propagates to the edges BUT …

Target 8 row 16

Physical considerations

Some neutron radiographies have shown that Lead was filling almost completely the empty space → previous results are valid at some point in time and space where some void regions still exist.

What will happen in case of 100% Lead filling?

If hot Lead → after expansion Lead will create thermal contact with Zirc.-2 then

strong thermal gradients → high stresses

Since under present hypotheses molten Lead produces no stress, simulations were performed with 100% Lead filling at a temperature just below Lead melting point (next slides).

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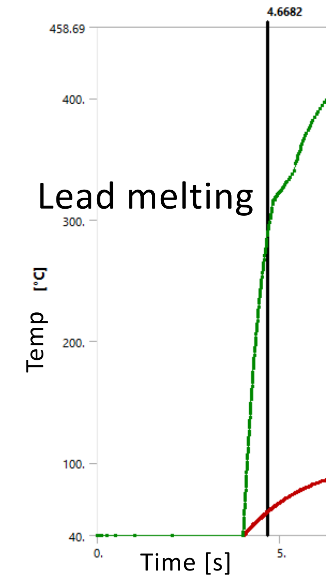
Results: 100% filled thick «Cannelloni» von Mises stress **row 3**, 1.5 mA **just before Lead melting** LATERAL view with deformation (rescaled)

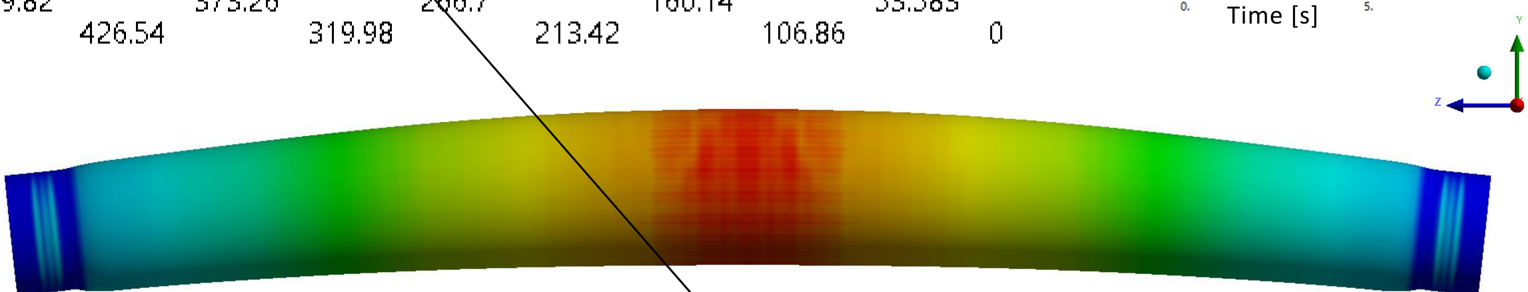
Target 8 **row 16**

Position of max. stress in the region of crack



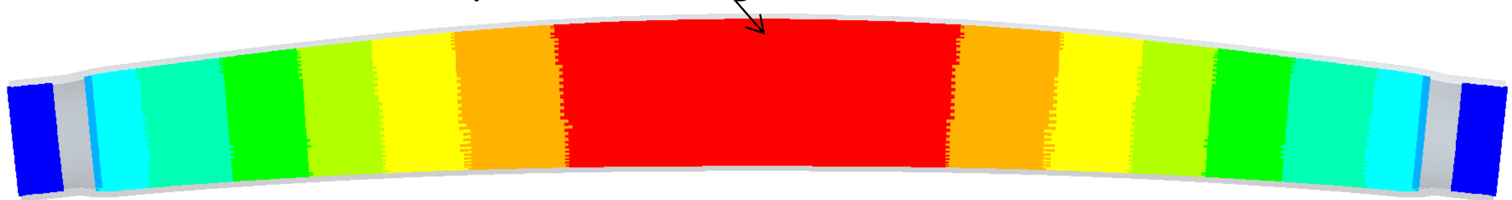
MPa

Row 3 ext. surf.
~ 410 MPa



Expansion along Y ~ 0.084 mm

Row 3 int. surf.
~ 479 MPa



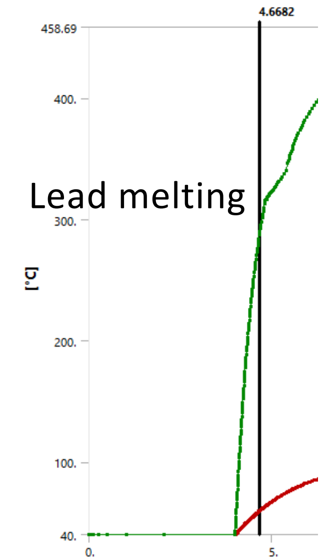
More than 2.5 times the stress when 90% filling (no upper contact)!!!

Zirc.-2 stress-strain data for **IRRADIATED Zirc.-2**.

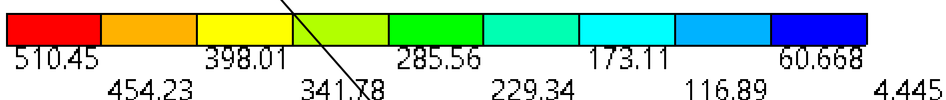
Results: 100% filled thick «Cannelloni» von Mises stress **row 15**, 1.5 mA **always SOLID Lead** LATERAL view with deformation (rescaled)

Target 8 **row 16**

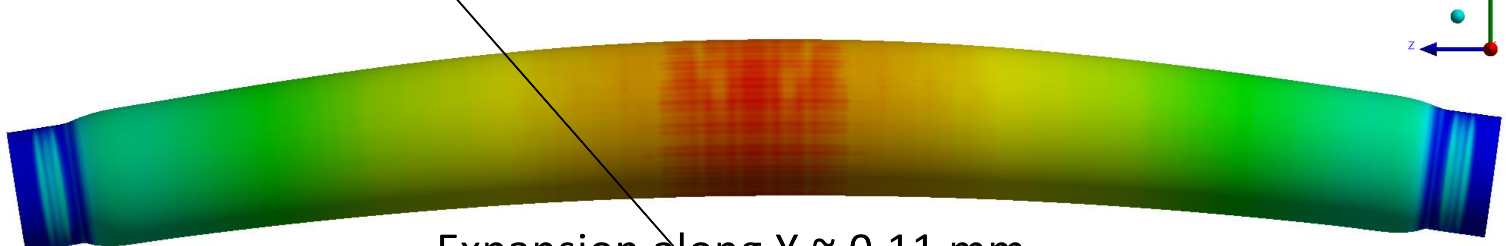
Position of max. stress in the region of crack



MPa



Row 15 ext. surf.
~ 427 MPa



Expansion along Y ~ 0.11 mm

Row 15 int. surf.
~ 510 MPa

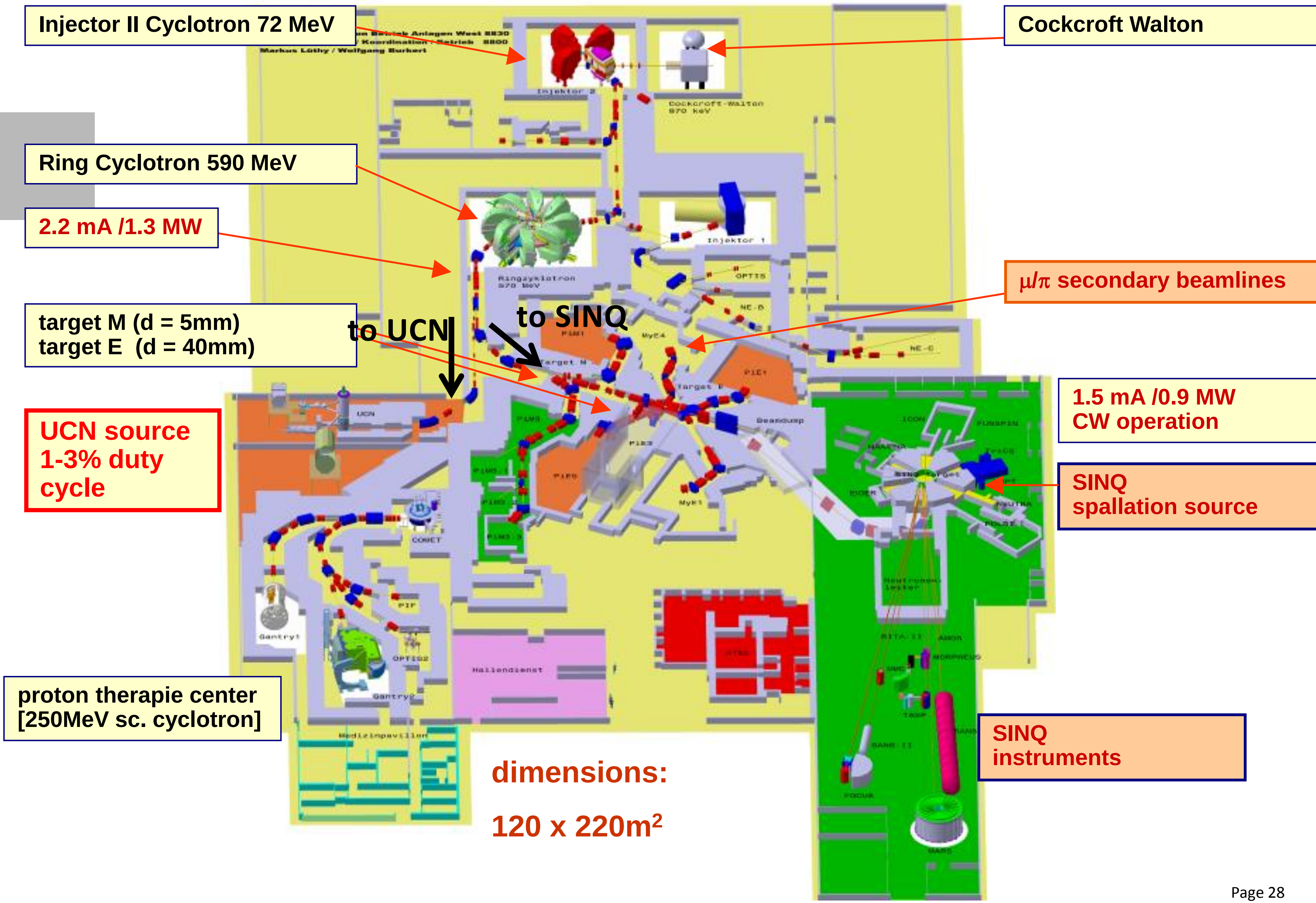
More than 2.5 times the stress when 90% filling (no upper contact)!!!

Zirc.-2 stress-strain data for **IRRADIATED Zirc.-2**.

some Physics still missing …

- Movement of molten Lead not taken into account (simulations: coupling CFD to Structural solvers, on going experiments)
- Radiation damage → embrittlement (partially taken into account via material data)
- Presence of hydrates - helium in material / corrosive environment → embrittlement + stress due to gas pressure
- FATIGUE (UCN kicks duty cycle of 1-3% - next slide)

Overview HIPA



Simulations have been performed to characterize stress behaviors of some SINQ «Cannelloni» (from full solid to molten Lead).

Specific configurations can lead to first insights of possible failure scenarios.

My thanks go to

- Co-authors
- Section 8590

- **You for your attention !!!**