Design and Optimisation of Aluminium Windows and Flanges for a High-Pressure Threshold Cherenkov Counter

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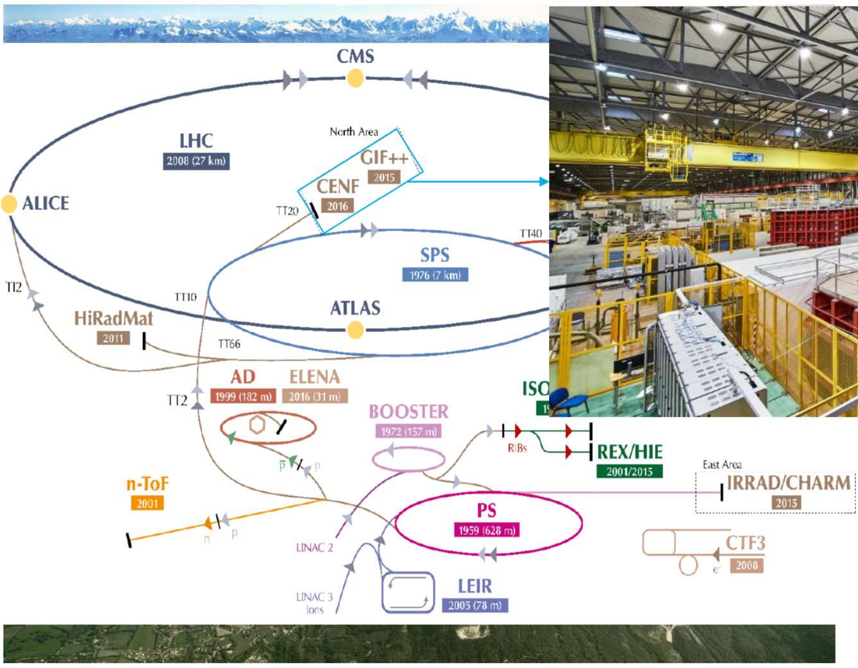
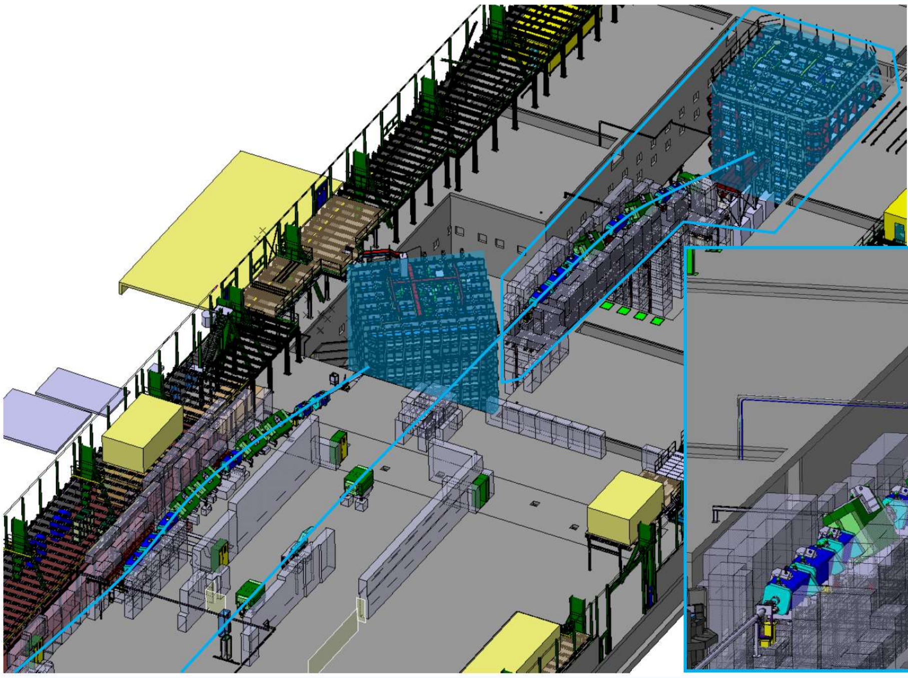
CERN (European Organization for Nuclear Research)



Neutrino Platform:

- Hosting collaborations and experiments from all over the world!
- Detector prototype validation for the Deep Underground Neutrino Experiment (DUNE) → USA/CERN Collaboration

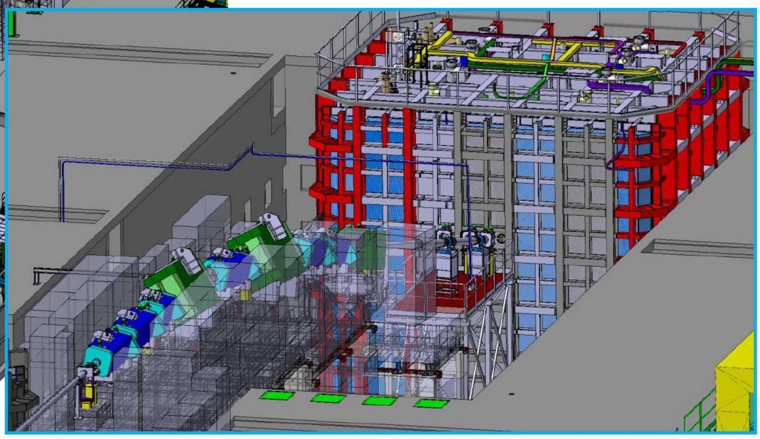
Neutrino platform



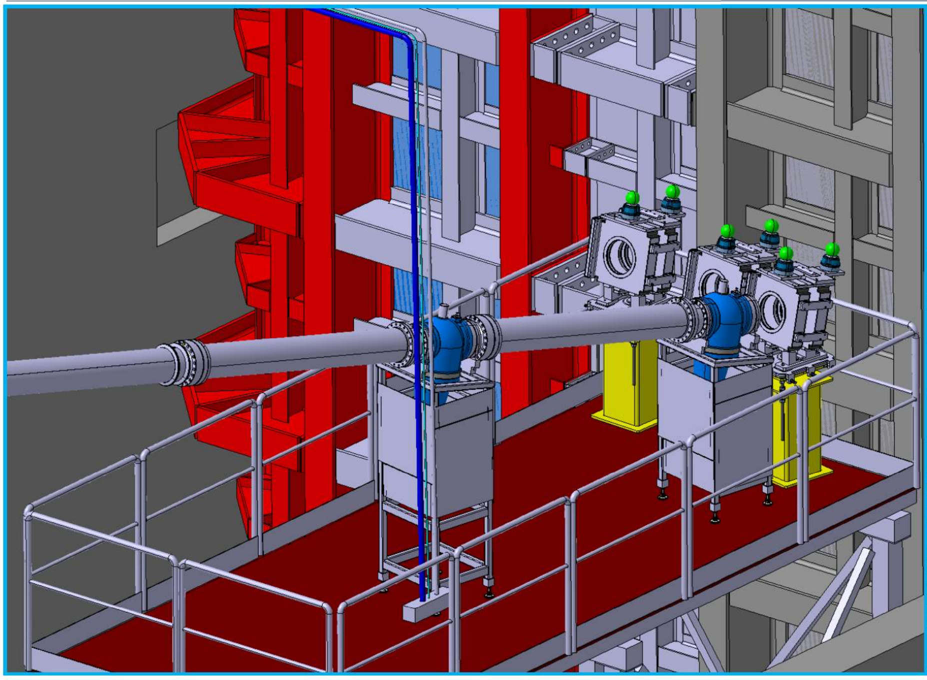
Two detectors → 800T liquid argon

Two beamlines providing the low energetic tertiary particles:

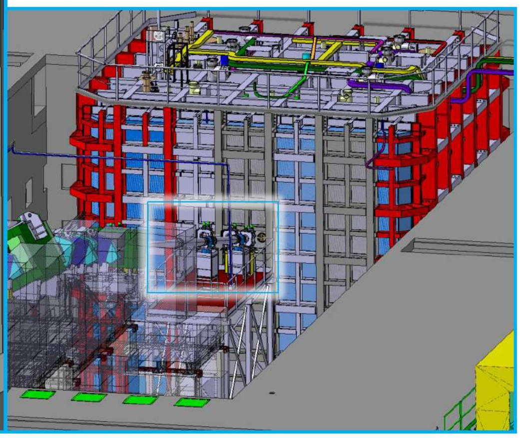
- H2 VLE Beamline
- H4 VLE Beamline



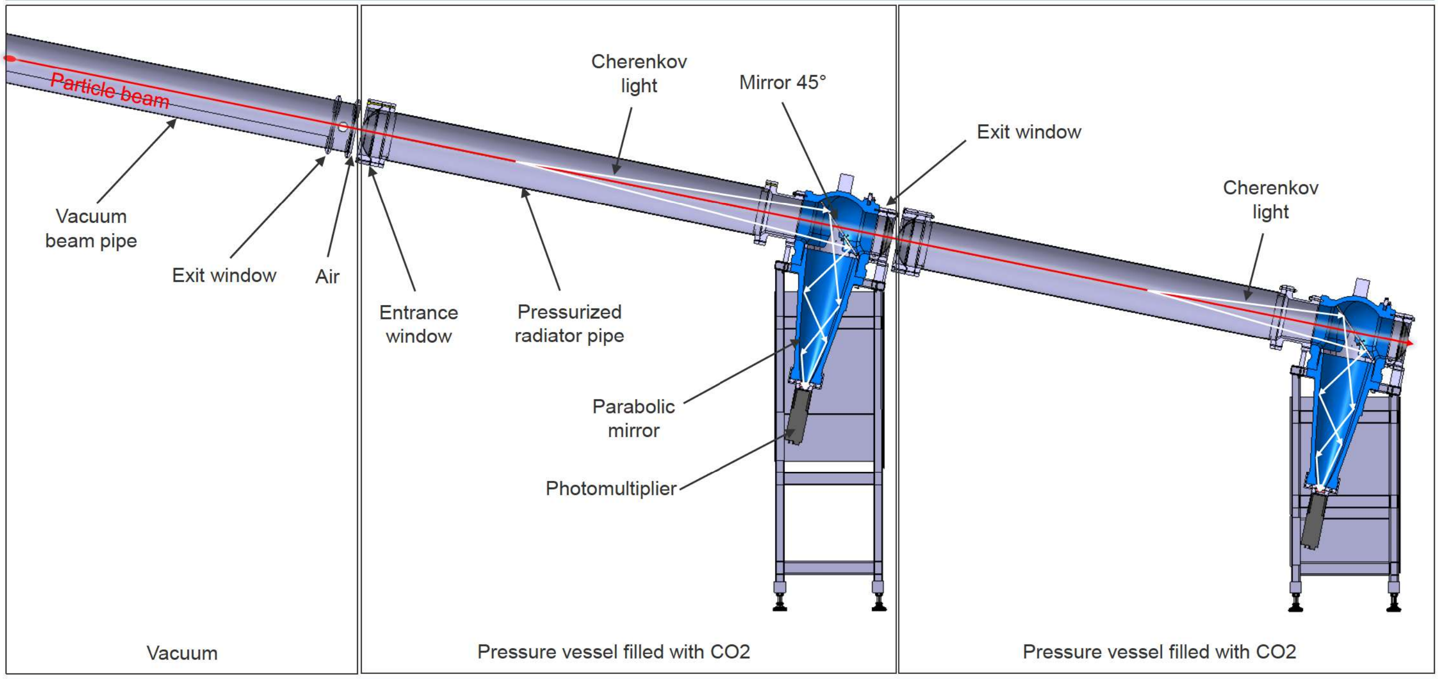
Neutrino platform



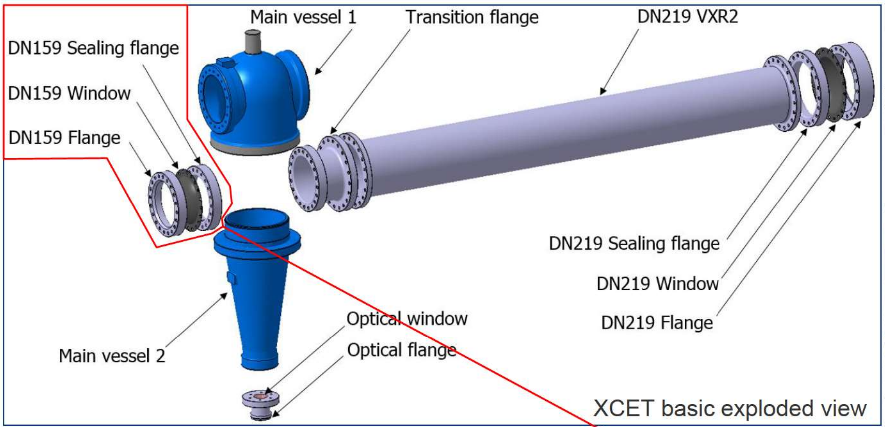
Two Threshold Cherenkov detectors equip the H4 VLE Beamline for particle species identification



Threshold Cherenkov Counters (XCET)



Threshold Cherenkov Counters (XCET)

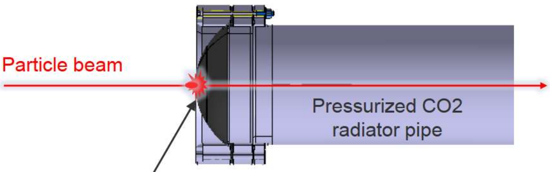


XCET Pressure vessel characteristics:

- Capacity:190 L
- Gas: CO_2, R134, N,
- Op. pressure:5 bar
- Op. temperature: ~20°C
- Pressure cycles: >500

The DN159 group of flanges/window is the focus of the design and validation study conducted

Thin aluminium windows



Considered materials for the windows				
	Units	Aluminium	Titanium	Beryllium
Density	[g/cm³]	2.700	4.500	1.850
Radiation length	[cm]	25.820	3.506	35.280
Nuclear collision length	[cm]	8.897	17.370	29.930
Tensile Strength	[MPa]	503 (7075-T6)	950 (grade 5)	370

→ A very thin window manufactured in a very 'light' material is needed!

↓

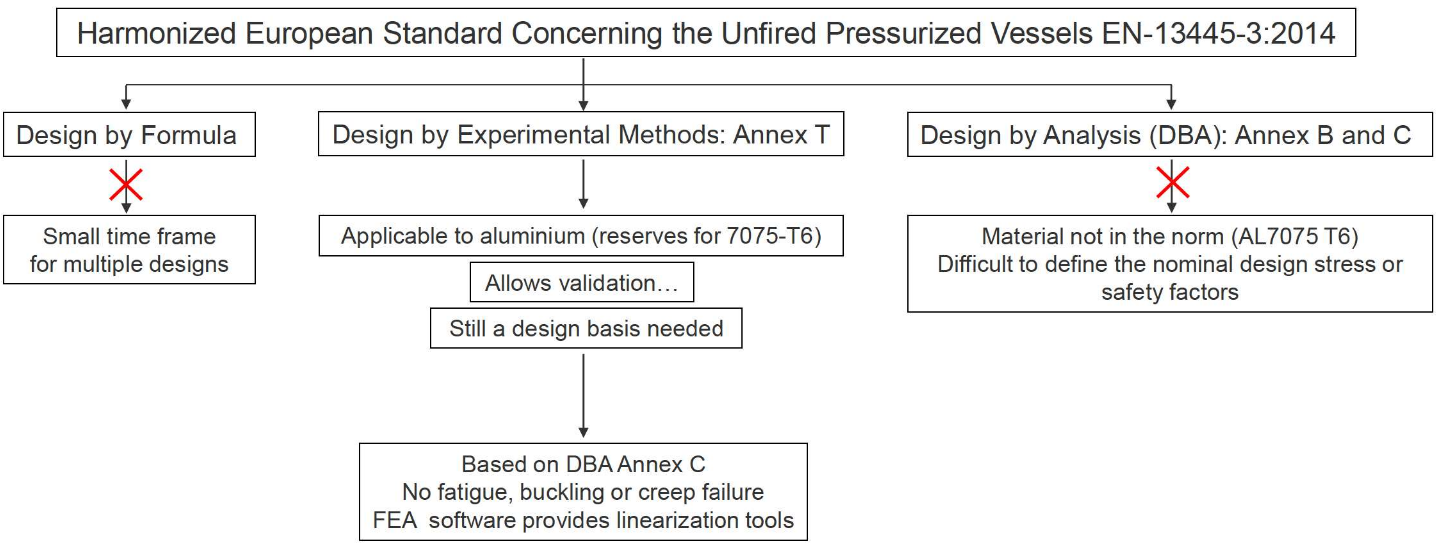
However a pressure of 5bar inside the XCET must be guaranteed <u>within reasonable safety limits</u>!

- Particles passing through a material are affected by: Nuclear collision and Radiation lengths
- Factors dependent on the particle specie

→ VLE beam: mixed particle beam

Aluminium is the material that satisfy in the best way all the requirements

Design validation strategy



Design validation strategy

Validation by Annex T → Burst test up to 25bar (5 x op. pressure)

Design based on Annex C → Window designed to withstand 25bar

↓

Failure criteria: yield/1.5

Expected high safety factor → 5x op. pressure + plastic deformation

↓ Ensure validation

Does the method allow a design (thickness) compliant with the physicist specifications?

↓ OK!

How big the safety factor added?
Pressure for plastic deformation?
Benchmark FEA simulations?

→ Digital Image Correlation (DIC)

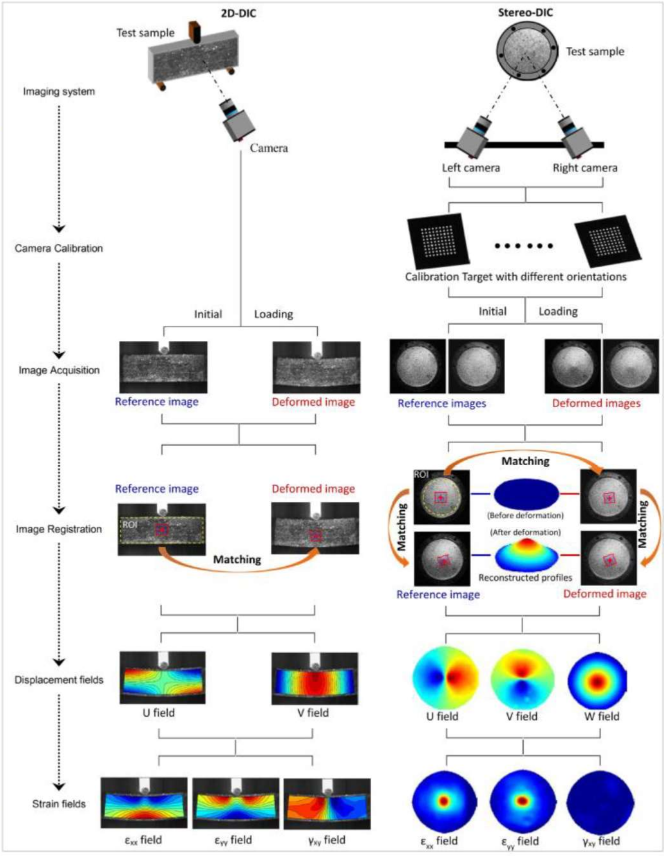
Design validation strategy

Digital Image correlation (DIC) → For FEA benchmarking

- Optical non-contact technique
- Measurement: shape, displacement, strain
- Hi-resolutions measurements
- Covers of a large surface area

For our scope…

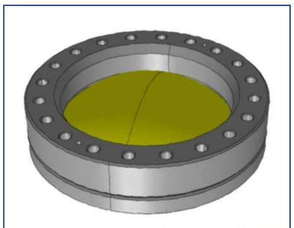
- Identification of areas that lead to failure
- Elastic to plastic deformation transition
- FEA benchmarking



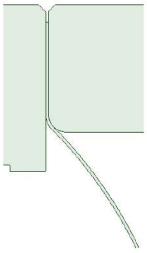
Source: Bing Pan 2018 Meas. Sci. Technol. 29 082001

Flanges/windows design

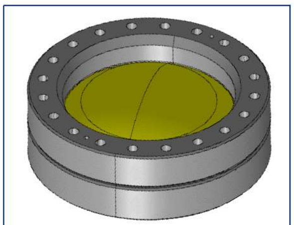
Two different designs were proposed:



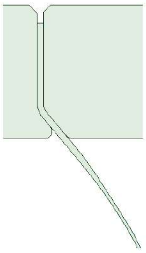
CATIA® 3D Model



Existent design



CATIA® 3D Model



New design

Existing design at CERN

- No official design validation existing for the required operational pressures

New design

- Driven by preliminary FEA simulations

Windows design parameters

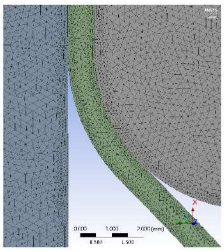
		Existing	New
Thickness	[mm]	0.85	0.8 to 1.7
Pressurized Diameter	[mm]	188	188
Operational Pressure	[bar]	5	5
Windows Material	-----	7075-T6	7075-T6
Flange Material	-----	6082-T6	6082-T6
Fab. Method	-----	Metal Spinning	Machining

Flanges/windows design

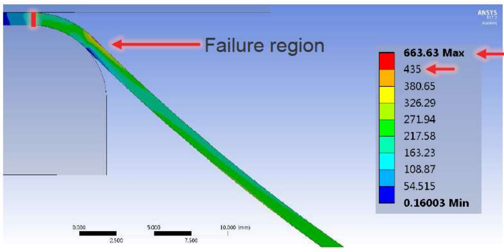
Linear static structural FEA

2D Axisymmetric

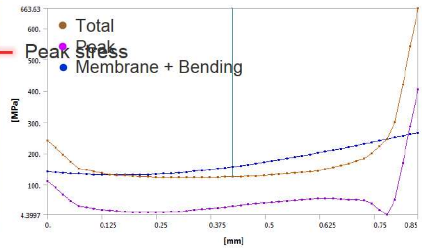
Existent design



Element quality avg.0.97

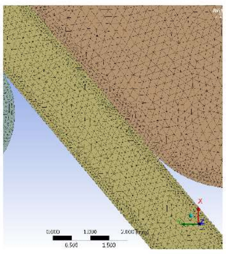


von-Mises stress at failure (7075-T6 yield) → 32bar



Linearized Eq. stress

New design



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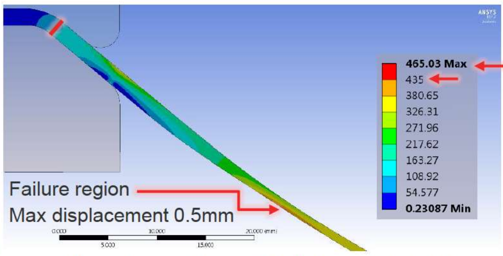
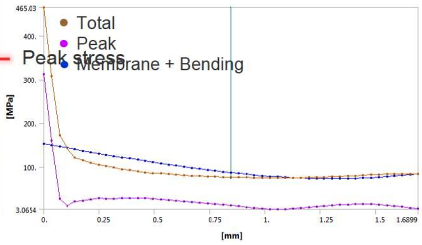


von-Mises stress at failure (7075-T6 yield) → 41bar



Linearized Eq. stress

Flanges/window validation

Experiment set up

Test subject preparation:

- Dimensional control
- Bolted connections (VDI2230)
- Window painted with a stochastic pattern

Pressurization:

- Hydro pneumatic pump: 0.25bar/s
- Two pressure sensors
    - Direct reading
    - DIC data/pressure sync.

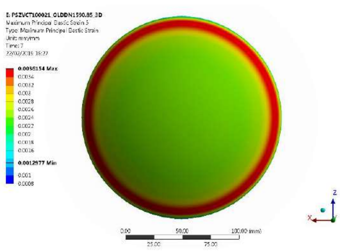
DIC set up:

- DANTEC Q-400 3D DIC system
- Acquisition rate of 0.5Hz
- Measurement uncertainty 3%

Flanges/window validation

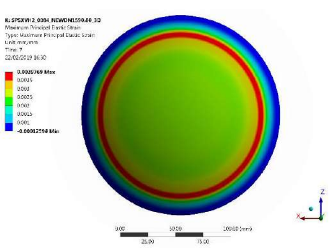
Expected failure modes → Simulations
Obtained failure modes → Experiments

Existent design



Max eq. strain at failure (7075-T6 yield) → 32 bar

New design



Max eq. strain at failure (7075-T6 yield) → 41 bar

Windows linear FEA and burst test results summary

	Existing	New
Window thicknes [mm]	0.85	0.80 to 1.7
Operational pressure [bar]	5	5
Min. burst pressure [S.F.5]	25	25
FEA DBA failure pressure [bar]	32	41
Burst test failure pressure [bar]	66	66
Difference (DBA vs tests) [%]	52	38

Validated!

- 13x the op. pressure (5bar)
- 2 x the design pressure (25bar)

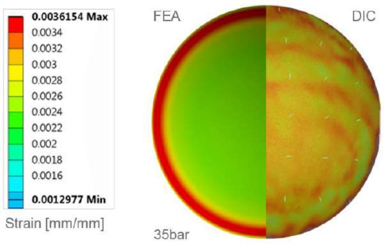
- Why the unexpected failure modes?
- Plastic deformation solely responsible for the observed effect?
- Is there an inconsistency in the simulations?

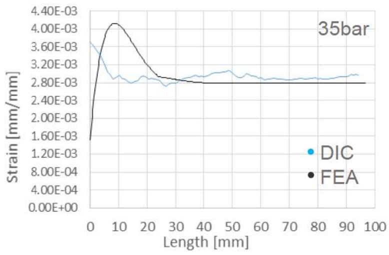
Benchmarking

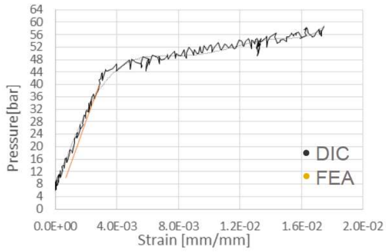
Study of the linear regime → DIC to linear FEA benchmarking

The agreement is good, specially for the new design
→ Linear FEA ok…

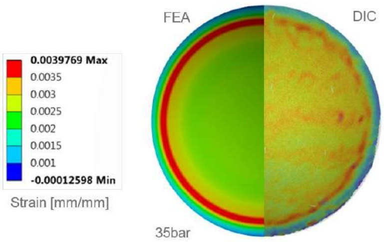
Existent design

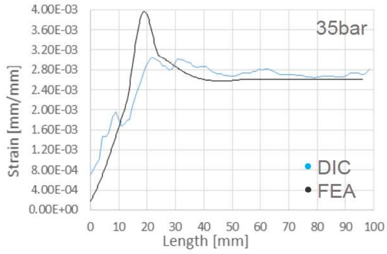


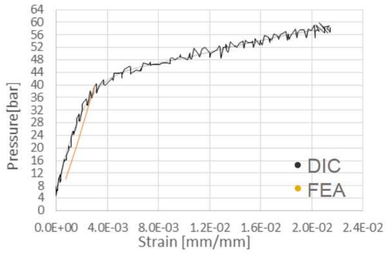




New design







Benchmarking

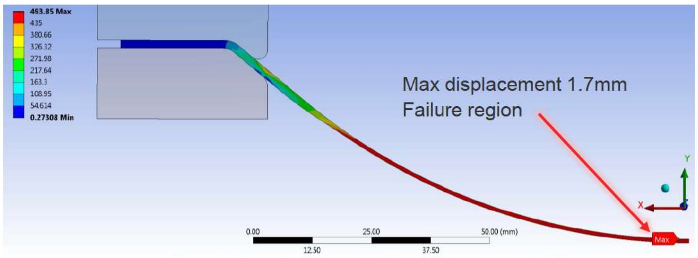
A look into the nonlinear regime → DIC to nonlinear FEA (not based on Annex B)

Window linear FEA, nonlinear FEA and pressure tests summary	
	New
Window thicknes [mm]	0.80 to 1.7
Operational pressure [bar]	5
Min. burst pressure [S.F.5]	25
FEA Linear DBA failure pressure [bar]	41
FEA Nonlinear DBA failure pressure [bar]	61
Burst test failure pressure [bar]	66
Difference (DBA Linear vs tests) [%]	38
Difference (DBA Nonlinear vs tests) [%]	8

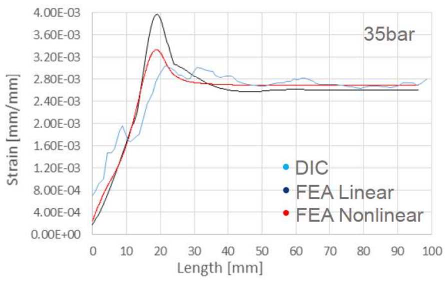
- Difference decrease to 8%
- Failure mode closer to burst
- High stress region mitigated
- Displacement in agreement with burst

Excellent fit with the experimental results

New design



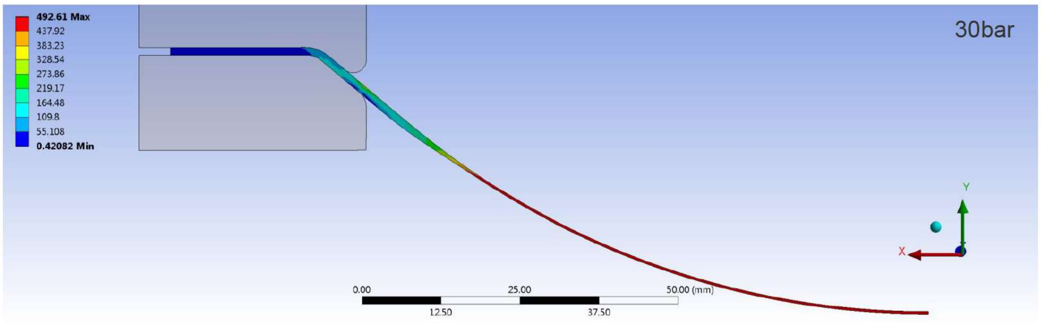
von-Mises stress at failure (7075-T6 tensile) → 61bar



Optimization (Rough study. not by Annex B)

Big safety factor obtained → Large margin for improvement!

Reminder: functional spec. → As thin as possibly achievable means better quality for the particle beam



von-Mises stress at failure (7075-T6 Tensile strength = 504MPa)
Thickness of 0.4 to 1.3mm in the periphery.

A possible thickness reduction of 50%! → A study according to Annex B is needed to properly evaluate…

Conclusions

- Method presented based on the EN-13445-3:2014 for the short (and budget restrained) period available
- Design and validation achieved for up to 66 bar. Max operational pressure possible up to 13 bar
- The new design proved to be slightly better for physics (thinner by 0.05mm)
- A high safety factor was obtained due to the nature of the proposed method. It was demonstrated that the nonlinear plastic deformation of the tested subjects cannot be neglected
- The DIC results revealed a good agreement between the linear simulations and the linear region of the experimental results indicating a correct construction of the simulation models
- A "basic" nonlinear analysis showed excellent agreement with the DIC experimental data leading the way for a possible optimization. Preliminary analysis show that the optimization can decrease the thickness by a factor 2
- No statistics were considered. Encouraging results but more tests needed…

THANK YOU VERY MUCH!