Shape Memory Alloy (SMA) connectors

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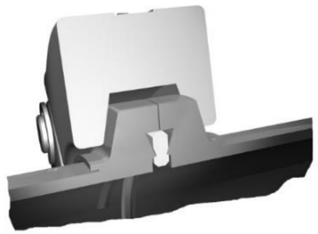
Outline

- Introduction: aim of the project
- Shape Memory Alloy behavior
- SMA connectors for UHV chambers: operation principle
- Advantages and potential applications at CERN
- SMA selection and ring training
- SMA couplers: design and experiments
- Possible applications outside of CERN and HEP
- Conclusions and future phases

AIM: A novel smart coupling technology for room temperature Ultra High Vacuum systems

- **Residual dose rate** in some critical areas of **HL-LHC**, **will increase by a factor of 16-30 in the next 20 years of operation**.

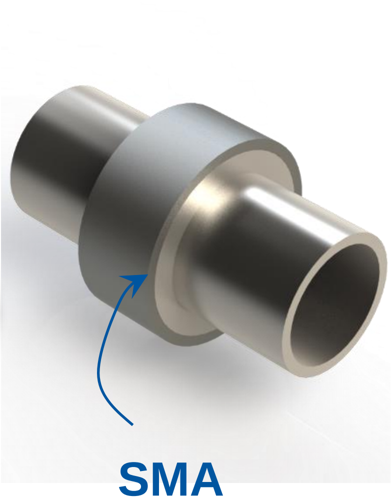
Standard vacuum coupling systems

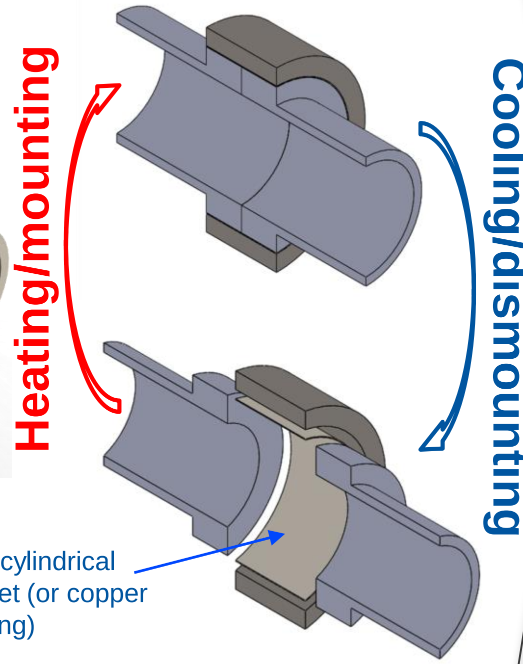


Soft/hard materials + mechanical force

Image source: web

Shape memory alloy couplers

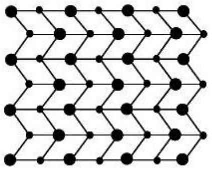




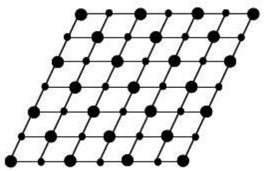
Soft/hard materials + temperature control

Shape Memory Alloy behavior

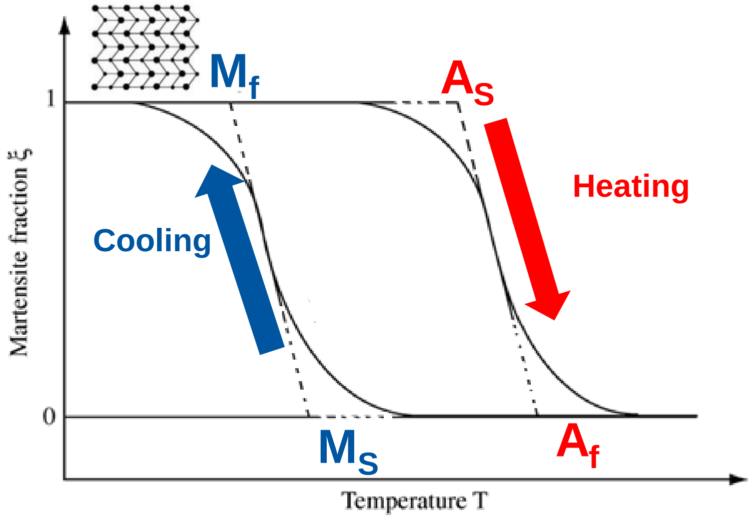
Martensite (B19'): stable at low temperature and high stress

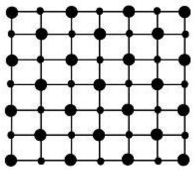


Twinned martensite (low stress)



Detwinned martensite (high stress)





Austenite (B2): stable at high temperature and low stress

Reversible phase transformation: displacive transformation without diffusion process

- **A_s**: Austenite start temperature
- **A_f**: Austenite finish temperature
- **M_s**: Martensite start temperature
- **M_f**: Martensite finish temperature

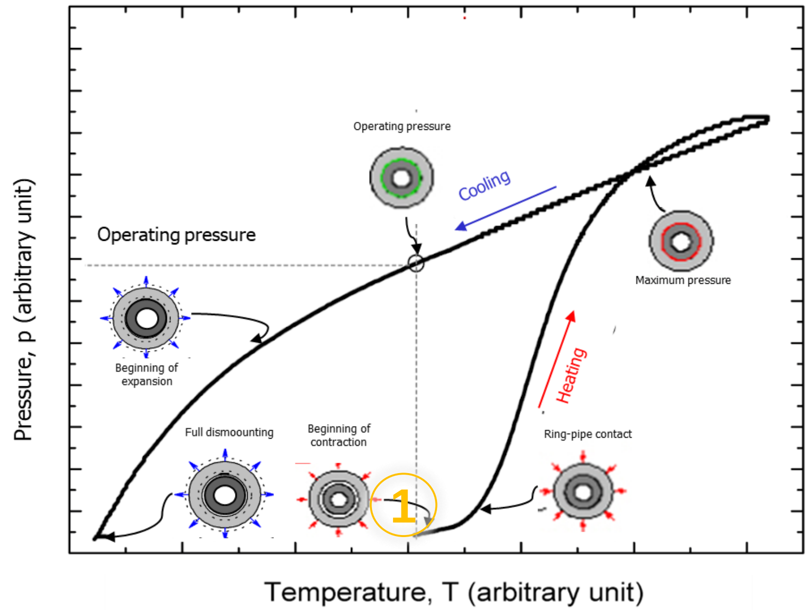
Transformation Temperatures (TTs) depend on:

- Chemical composition
- Internal stress/strain field (dislocation arrays/precipitates)
- Thermo-mechanical cycling

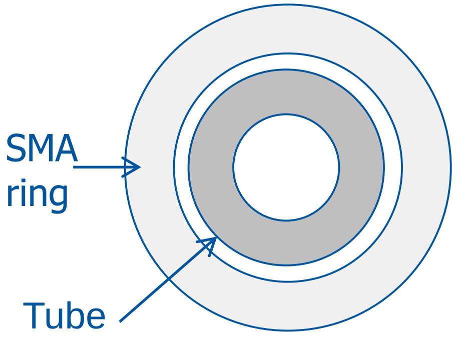
Operation principle

- A_s: Austenite start temperature (Ring contraction starts)
- A_f: Austenite finish temperature (Ring contraction ends)
- M_s: Martensite start temperature (Ring expansion starts)
- M_f: Martensite finish temperature (Ring expansion ends)

1. **Mounting at room temperature**
2. Tightening by heating above 100 °C
3. Leak Rate < 10^{-10} mbar·l·s^{-1} at room temperature
4. Dismounting by cooling down to -40°C



1: T<A_s (40 °C)



Mounting

Operation principle

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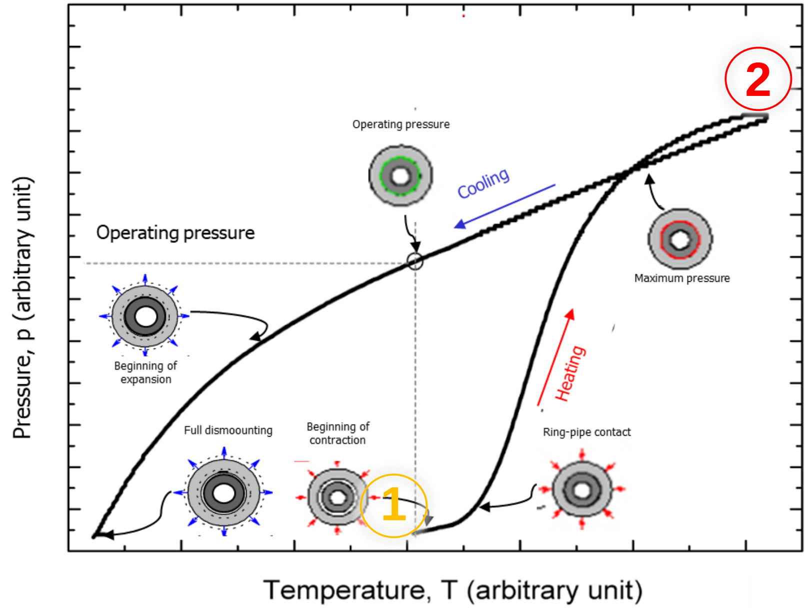

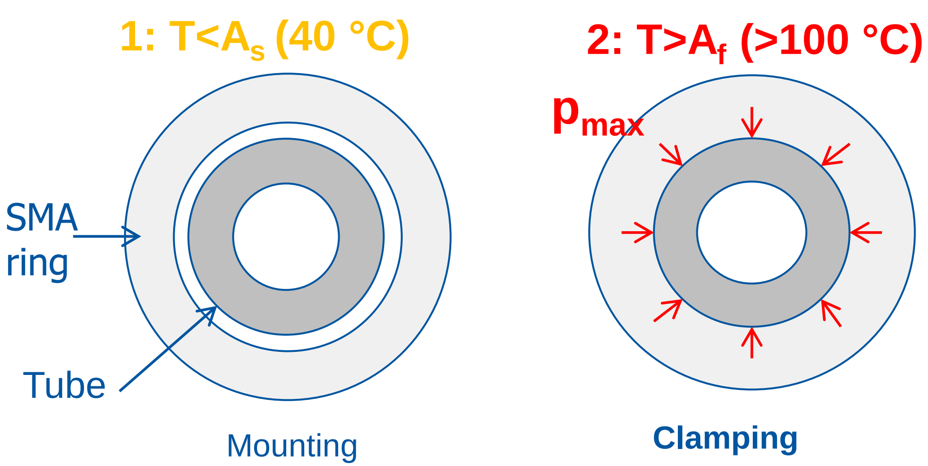

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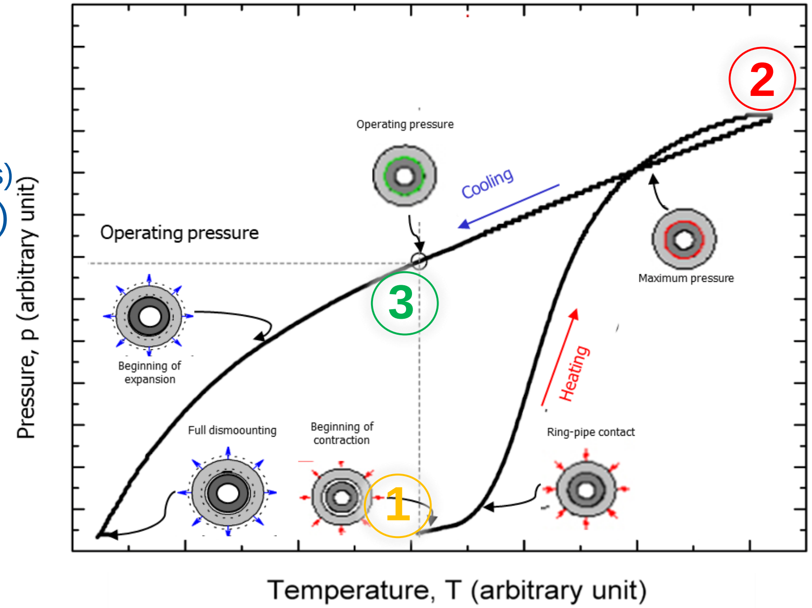

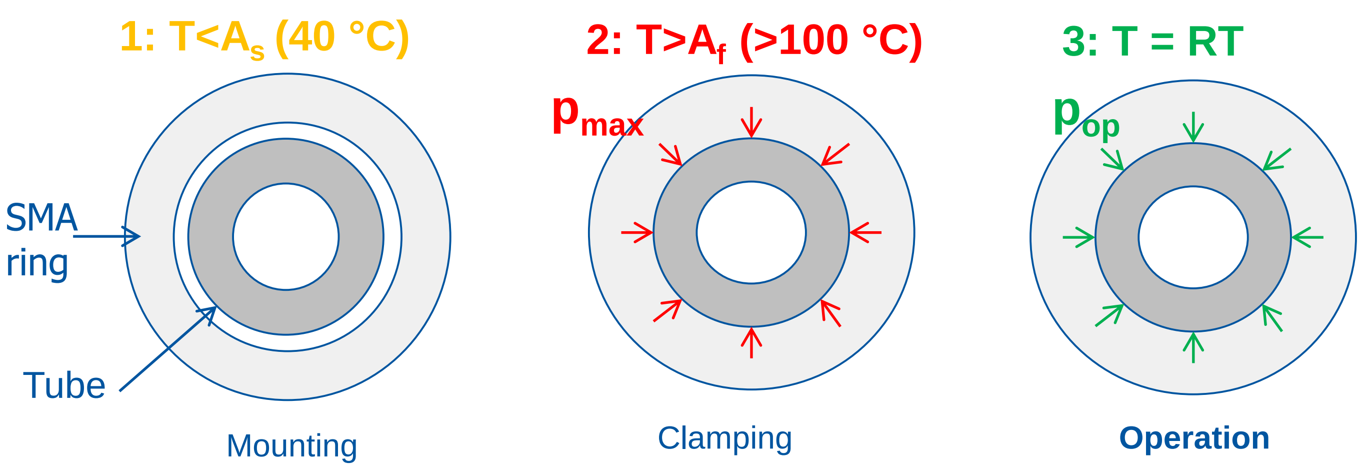

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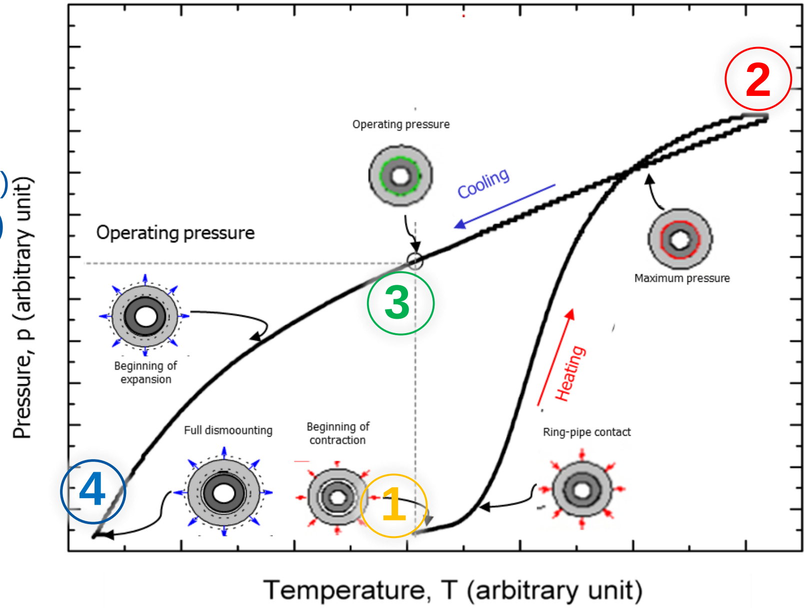
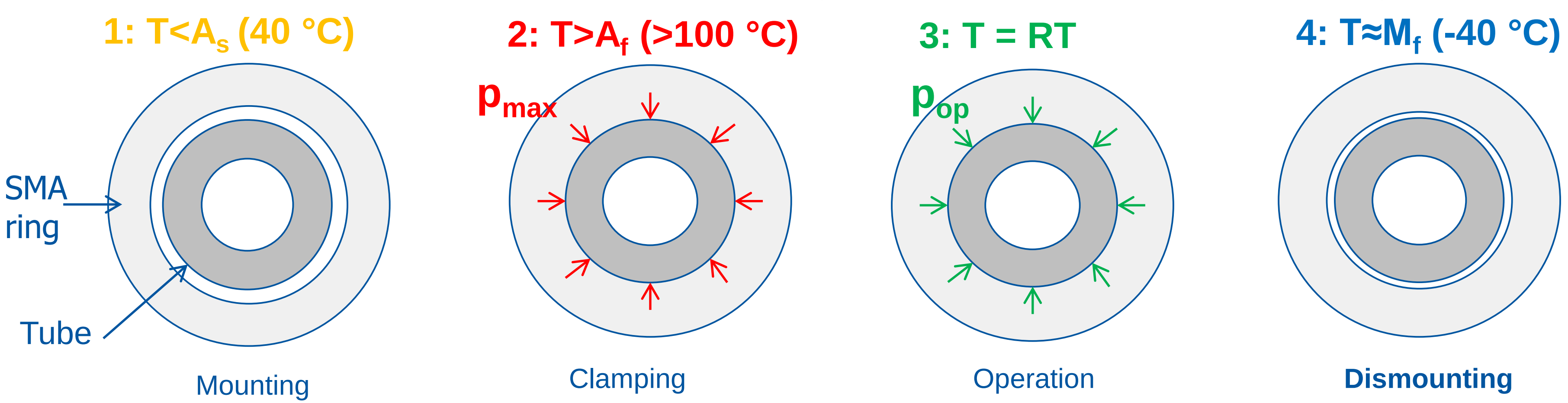
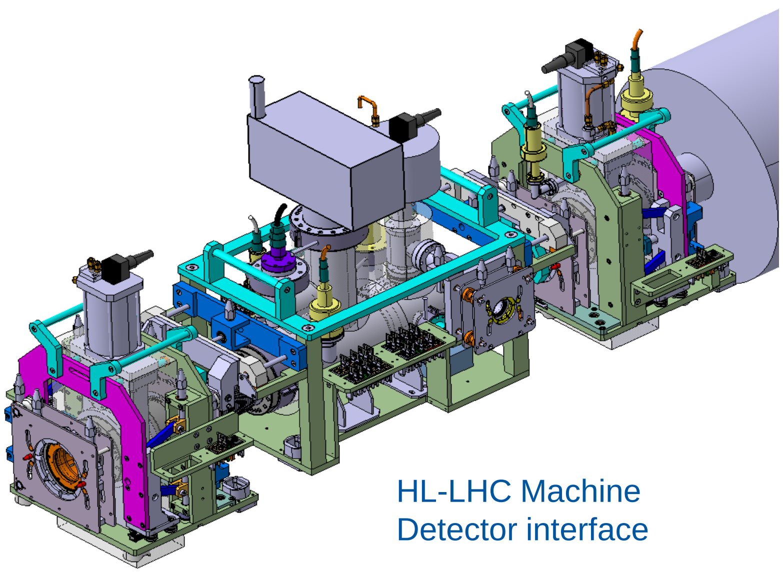


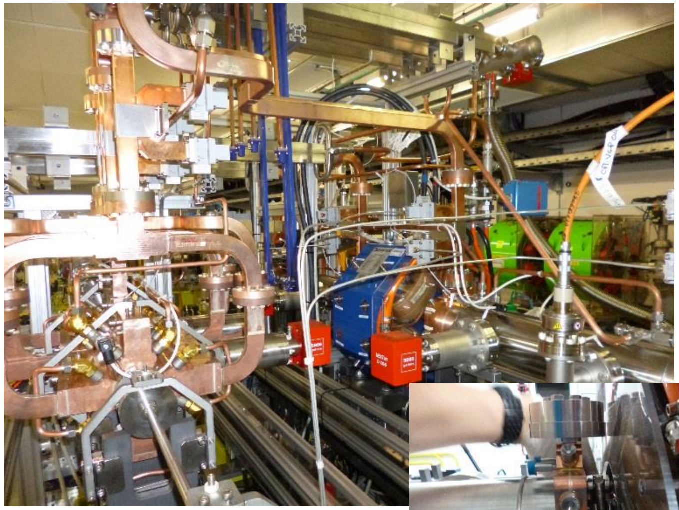


Advantages and potential applications

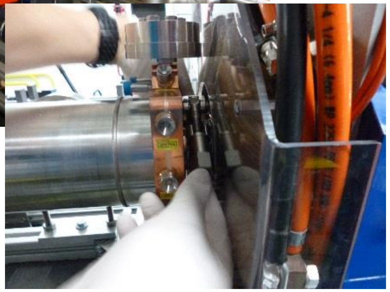
- A compact, bolt free, leak tight and easily mountable\dismountable connection system
- Possibility of remote controlling\activation
- Possibility to use in high demanding areas (e.g. collimator areas, machine/detector interface)
- Possibility to connect dissimilar materials



HL-LHC Machine Detector interface



CLIC main linac

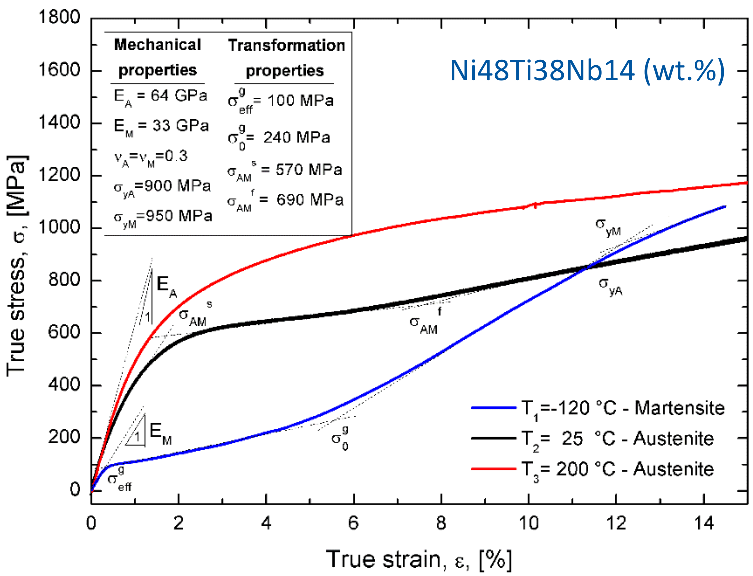


CLIC module installed in CLEX

Material selection - properties

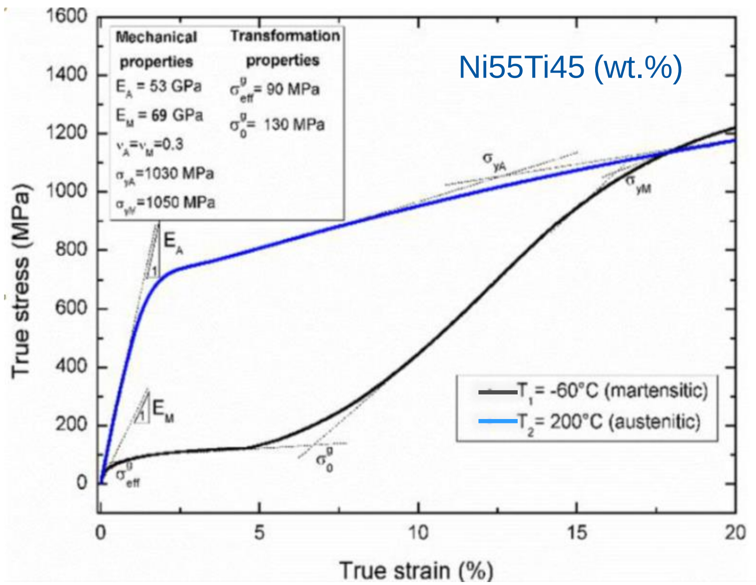
Material properties: **NiTi** and **NiTiNb**

- NiTi based alloys
- Magnetic permeability < 1.002
- Thermal outgassing: < 10^{-13} mbar·l·s^{-1}·cm^{-2}
- Radiation hard



Typical tensile curves of NiTiNb

- **Thermal Hysteresis: $A_f - M_S$ = 160 °C**
- High clamping pressure in a wide thermal range: **from -100 to 200 °C**
- Dismounting at very low temperatures **T_{dism} ≈ -150 °C**



Typical tensile curves of NiTi

- **Thermal Hysteresis: $A_f - M_S$ = 75 °C**
- High clamping pressure in a narrow thermal range: **from 0 to 200 °C**
- Dismounting at higher temperatures: **T_{dism} ≈ -40 °C**

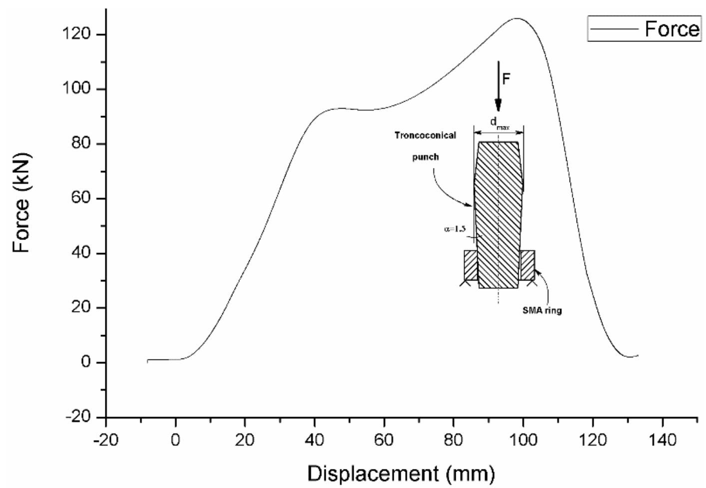
SMA Rings training

As-received SMA rings do not show any shape change by heating/cooling

(thermo-elastic deformation only)

By heat treatments and mechanical deformation (to give preferred orientation to the martensite variants), **the training aims at:**

- **Inducing the One Way (Hot shape) and Two Way (Cold shape) effects**
- **Meet the geometrical (ID after training) and functional requirements**



ε= circumferential strain at the internal diameter

Mechanical behaviour of trained SMA rings

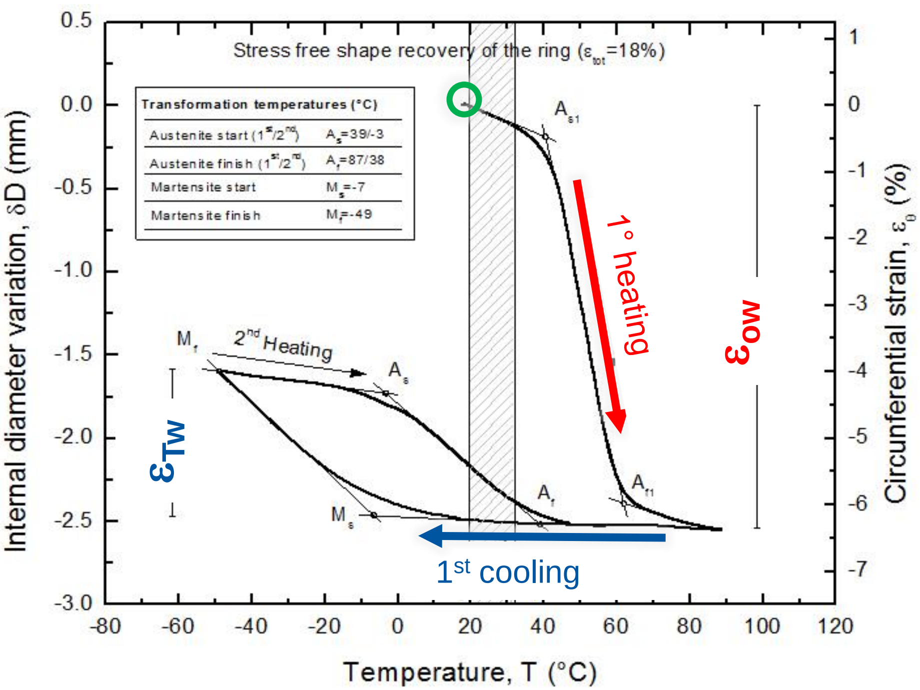
Stress-free condition

Stress free behaviour is measured with an extensometer.

Extensometer

ε_{OW}=One Way strain (heating)

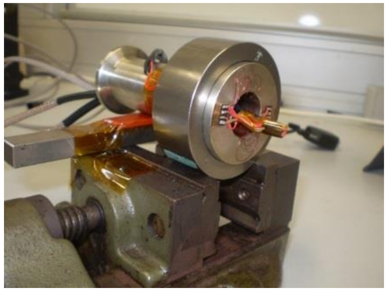
ε_{TW} =One Way strain (cooling)



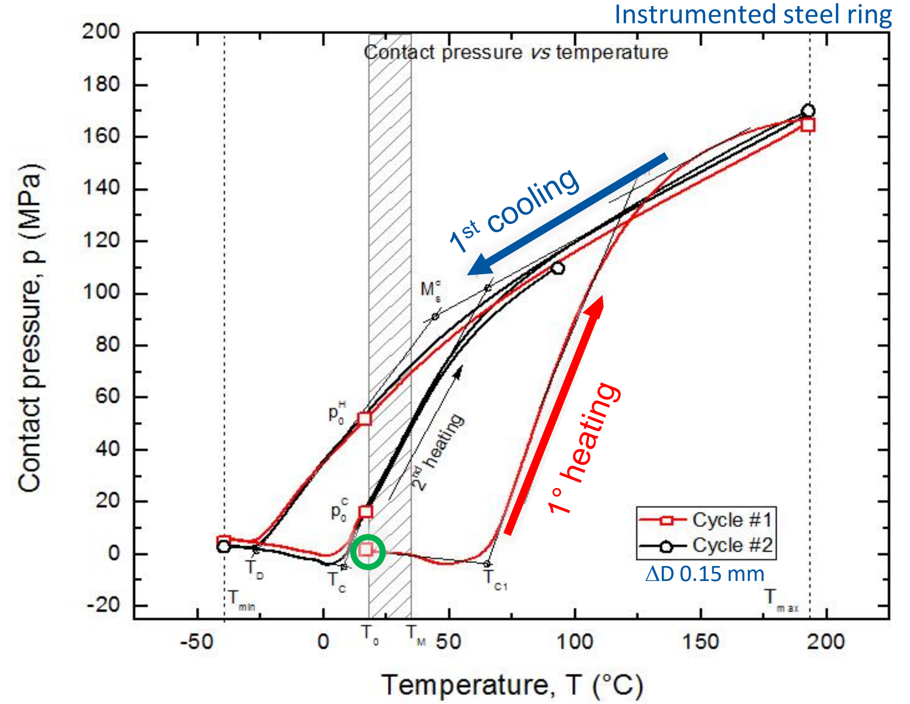
Stress-applied condition

Clamping pressure is assessed with instrumented ring under external pressure.

$$P = -\frac{E}{2(1+\nu)} \frac{De_{steel}^2 - Di_{steel}^2}{De_{steel}^2}(\varepsilon_\theta - \varepsilon_z)$$

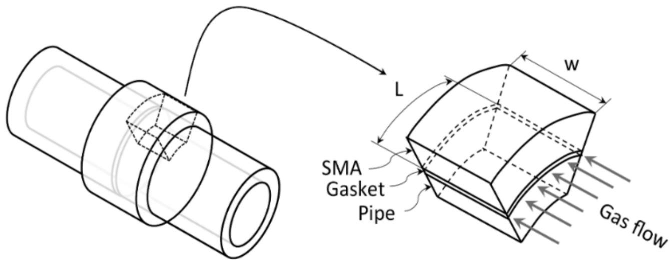


Instrumented steel ring



SMA ring\steel pipe interface design

The conductance C (free molecular flow) of a gas throughout a sealing surface can be calculated as follows [Roth, 1972]:

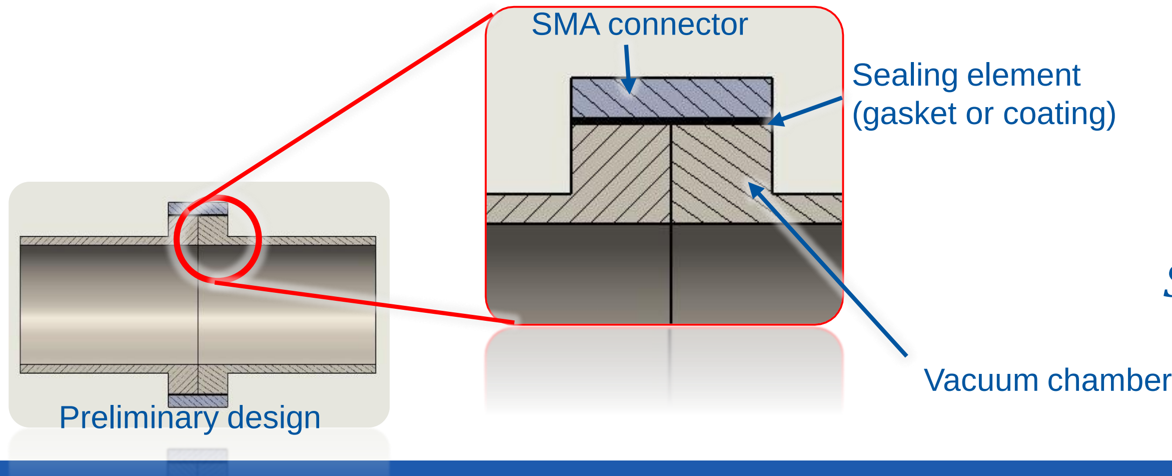


$$C = K\frac{L_e}{w_e}\exp(-3P/R)$$

- Effective length: L_e
- Contact pressure: P
- K=Cst(T,M,R_a…)
- Effective width: w_e
- Sealing ability of the material: R

A sealing performance parameter is defined:

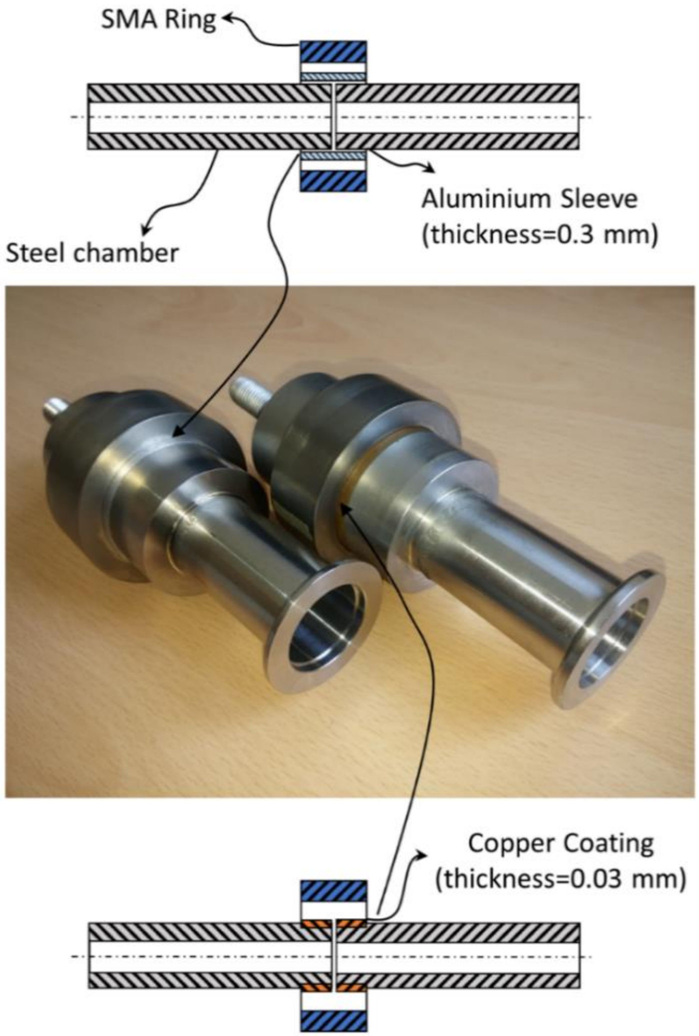
$$S = \left(\frac{C}{K}\right)^{-1} = \frac{w_e}{L_e}\exp(3P/R)$$



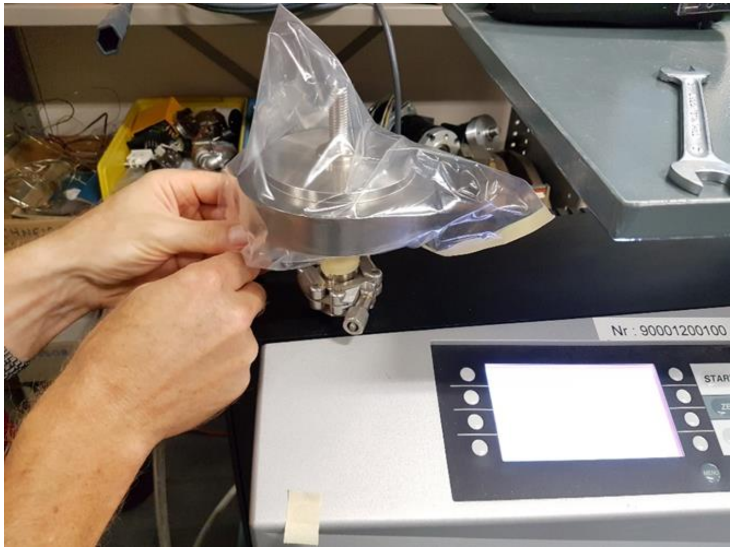
By integration of the contact pressure P along the gasket /pipe contact (FE results), assuming conductance in series, the sealing performance parameter reads:

$$S = (1/\pi d_e)\int_0^w exp(3\,P/R)ds$$

SMA\steel interface design: leak tightness tests



Proof of concept of SMA connectors for Ultra High Vacuum (UHV) chambers.

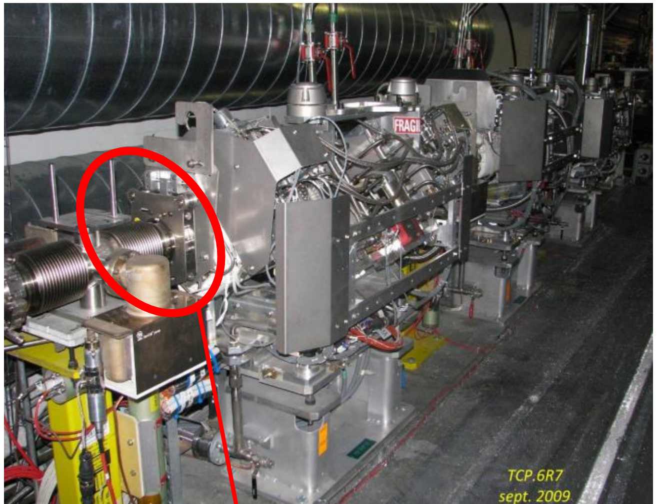


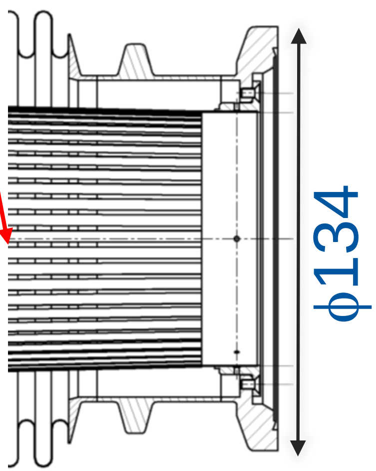
Leak detector

- About 20 assemblies tested in total (SMA ID from 40 to 135 mm)
- **All assemblies are leak tight** ($<10^{-10}$ mbar·l·s^{-1}), even after 1-year aging and complete thermal cycles.

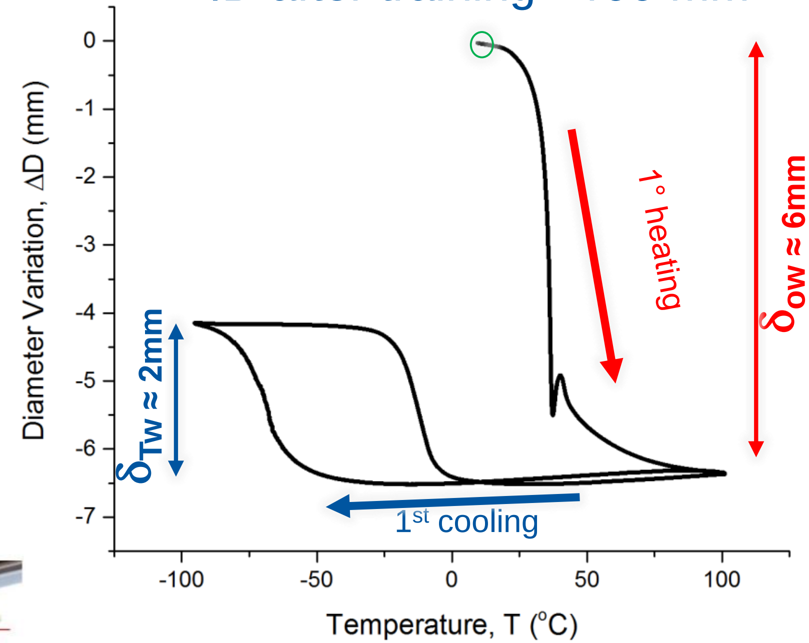
Large rings

SMA ring dimensions are compatible with LHC collimator flanges.





ID after training ≈135 mm



Stress free curve of a trained large ring (ID≈135 mm,OD≈10 mm)

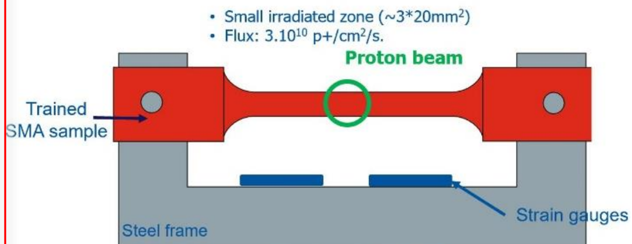
Large ring training has been performed successfully (ongoing optimization). Validation by leak tests performed.

Radiation-induced damage

Aim: analysis of possible stress-assisted radiation damage in terms of transformation temperatures variation and creep-like relaxation effects

Proton irradiation @ IRRAD

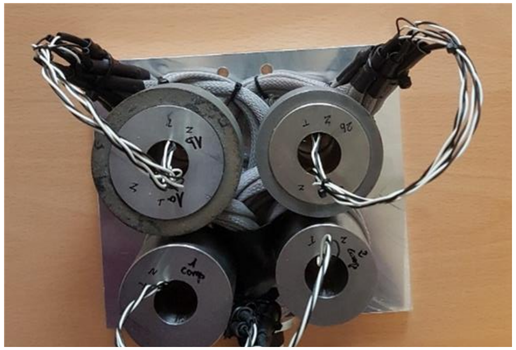
Absorbed dose > 1MGy (April – August 2018).

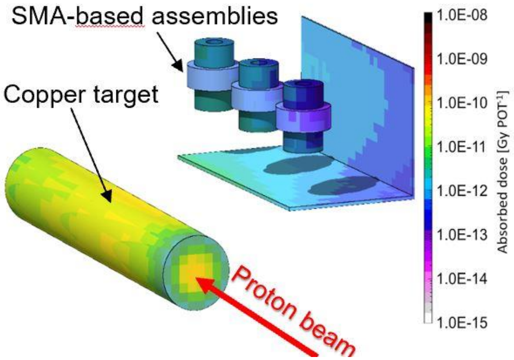


Test set-up used in IRRAD

Mixed-field irradiation @ CHARM

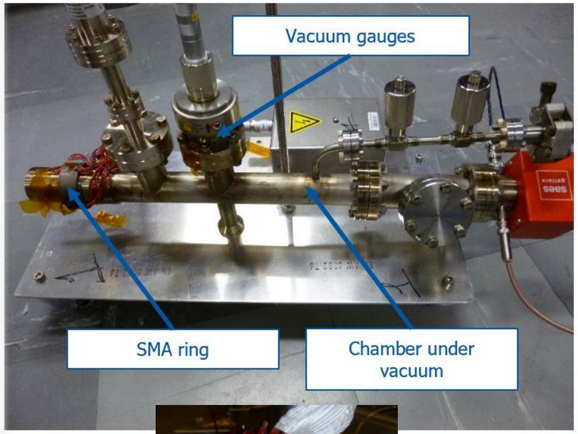
Expected dose 200-250 kGy (up to Dec 2018).





SMA vacuum set-ups in TDC2 (SPS North Area)

Expected dose 200-250 kGy (up to Dec 2018).



Main results

No significant variation of recovery stress\contact pressure (IRRAD\CHARM setups) **and leak rate\pressure** (TDC2 setups) **during the exposure**

Potential applications outside of CERN\HEP

- Where extreme operating conditions are needed, from Ultra-High Vacuum (UHV) to High Pressure (HP) conditions.

- In critical/readiactive/harsh environments, where human intervention must be limited or avoided

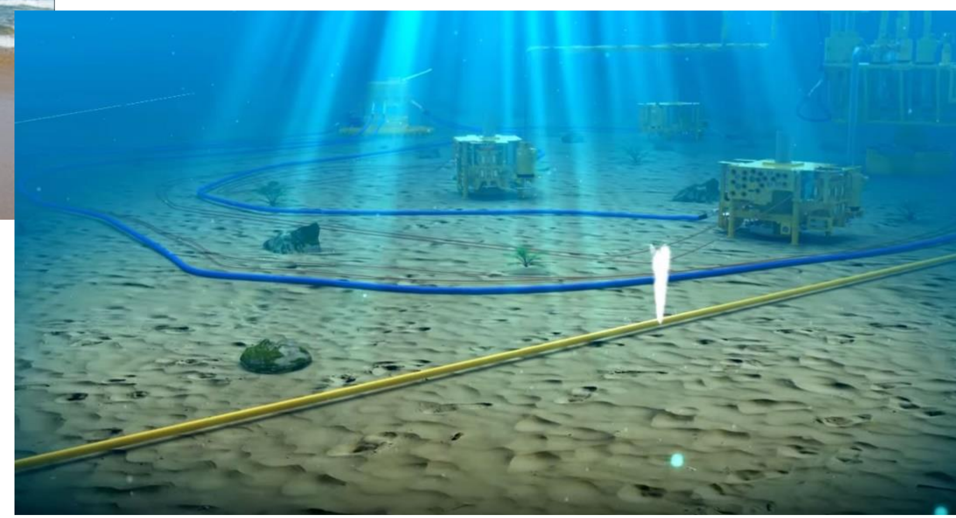
- Where maintenance/repairing operations are extremely complex and/or very expensive (e.g. oil and gas, nuclear industry, aerospace sectors).

- For smart bi-material joining (alternative to welding, brazing etc.)

Potential applications outside of CERN\HEP

Subsea pipe connections systems for Oil and Gas

The extreme locations and harsh conditions in oil and gas applications make maintenance/repairing operations very complex and enormously expensive



SMA-connectors Pros

- Corrosion resistence
- Thermo-actuation (remote)

Potential applications outside of CERN\HEP

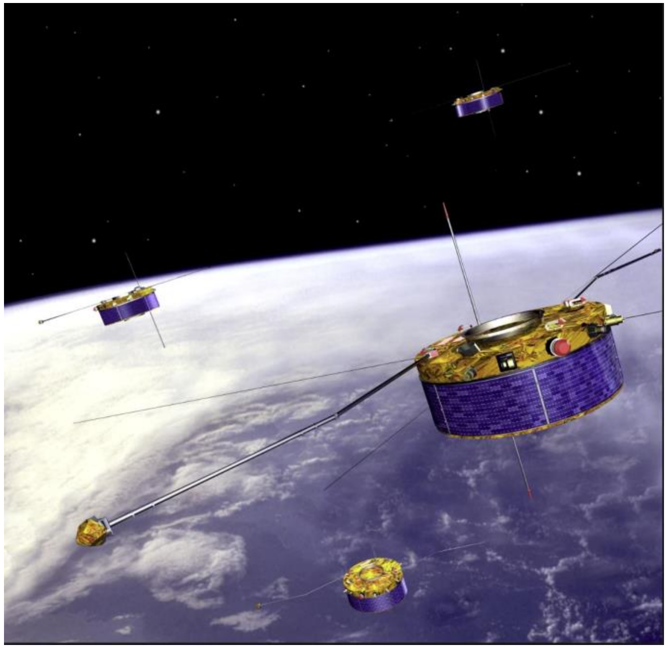
Nuclear reactors

SMA-connectors Pros

- Thermo-actuation (remote)
- Radiation hardness

Potential applications outside CERN\HEP

<u>Aerospace</u>: propulsion\hydraulic systems of <u>aircrafts and/or spacecrafts</u>
(e.g. rocket engine valves\actuators)



ESA satellites

Pyrotecnic valves for space propulsion systems

SMA-connectors Pros

- Thermoactuation
- Compactness
- Limited weight

Conclusion and future developments

SMA project

CERN

Role: Research partner & main user
Expertises: Vacuum technologies, irradiation damage

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DIPARTIMENTO DI INGEGNERIA MECCANICA, ENERGETICA E GESTIONALE
DIMEG

Role: Research partner
Expertises: Material science & Engineering Design

Roadmap

2014 – 2017

✓ **Phase #1: From idea to proof of concept (3 years - concluded)**

- **#1.1**: Material selection (Two types of alloys identified)
- **#1.2**: Design of thermo-mechanical process (Training successfully designed)
- **#1.3**: Validation by leak detection (Sealing properties verified)

2017 – 2023

Phase #2: From proof of concept to implementation in LHC (6 years - ongoing)

- **#2.1**: Assessment of material and ring performance (NiTi): narrow hysteresis NiTi successfully verified)

Today

- **#2.2**: Material modelling and numerical simulations (novel constitutive model under development)
- **#2.3**: Long term behaviour of selected material in accelerator environment (under investigation at CERN)
- **#2.4**: Clamping and unclamping device: in-situ heating/cooling devices for remote actuation (ongoing development)
- **#2.5**: Implementation in accelerators (before 2022)

Conclusion and future developments

2014

Phase #1: 3 years - concluded

#1.1: Material selection
#1.2: Design of thermo-mechanical process
#1.3: Validation by leak detection

2017

Phase #2: 6 years - ongoing

#2.1: Assessment of material and ring performance (NiTi)

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2023

Conclusion and future developments

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#2.4: Clamping and unclamping device (In situ remote heating/cooling device)

#2.5: Implementation in accelerators (before 2022)

2023

Phase #3: Developments for use outside of CERN and HEP

#3.1: Analysis of material damage in radiation/corrosive/harsh environments (e.g. for deep sea applications in oil & gas and/or nuclear industry);

#3.2: Development of new thermo-mechanical processes for manufacturing and training of very large couplers (diameter>200 mm) at industrial scale;

#3.3: Design, development and prototyping of in situ heating\cooling devices and\or robotic systems for mounting and dismounting in critical environments

2023

Publications

Preliminary results about this technology (commercial SMA rings employed) have been published in two journal papers, results on ad-hoc developed SMA connectors have not been disclosed yet:

- Niccoli, F., Garion, C., Maletta, C., Chiggiato, P. Shape-memory alloy rings as tight couplers between ultrahigh-vacuum pipes: Design and experimental assessment. (2017) Journal of Vacuum Science and Technology A: Vacuum, Surfaces and Films, 35 (3), art. no. 031601, DOI: 10.1116/1.49780449
- Niccoli, F., Garion, C., Maletta, C., Sgambitterra, E., Furgiuele, F., Chiggiato, P. Beam-pipe coupling in particle accelerators by shape memory alloy rings. (2017) Materials and Design, 114, pp. 603-611. DOI: 10.1016/j.matdes.2016.11.101

Other publications:

- Schaeffer A., Pandolfi S. “Shape Memory material provides a solution for the High-Luminosity LHC”,CERNBullettin,IssueNo.15-16,2016. (https://cds.cern.ch/journal/CERNBulletin/2016/15/News%20Articles/2144535?ln=en)
- F.Niccoli, Shape Memory Alloy connectors for Ultra High Vacuum applications: a breakthrough for accelerator technologies, CERN-THESIS-2017-335.

THANKS !

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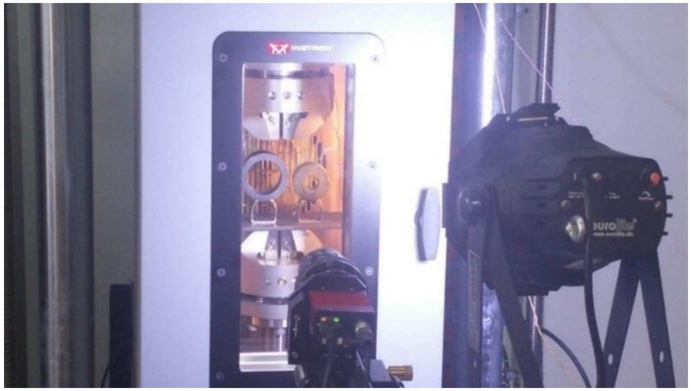
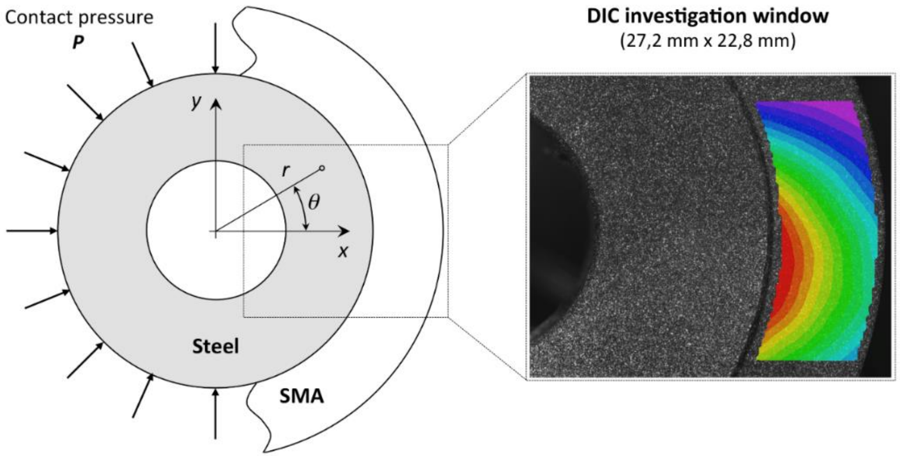
EXTRA SLIDES

Mechanical behaviour of SMA rings

Digital Image Correlation (DIC) measurements



Digital Image Correlation (DIC) experimental set-up



DIC observation window of the SMA-steel rings coupling

Displacement field in the elastic steel ring:

$$\begin{bmatrix} u_x(r,\theta) \\ u_y(r,\theta) \end{bmatrix} = -P\left[K_1 \cdot r + \frac{K_2}{r}\right]\begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} + \alpha\,\Delta T\, r\begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} + A\, r\begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix} + \begin{bmatrix} B_{ux} \\ B_{uy} \end{bmatrix}$$

$$K_1 = \frac{1-\nu}{E}\,\frac{D^2_{e.Steel}}{D^2_{e\_Steel} - D^2_{i\_Steel}}$$

$$K_2 = \frac{1+\nu}{E}\,\frac{D^2_{e\_Steel} \cdot D^2_{i\_Steel}}{D^2_{e\_Steel} - D^2_{i\_Steel}}$$

B_{ux},B_{uy} = horizontal (x) and vertical (y) rigid body motions
A = rigid body rotation parameter
P= contact pressure
α= thermal expansion coefficient of the steel

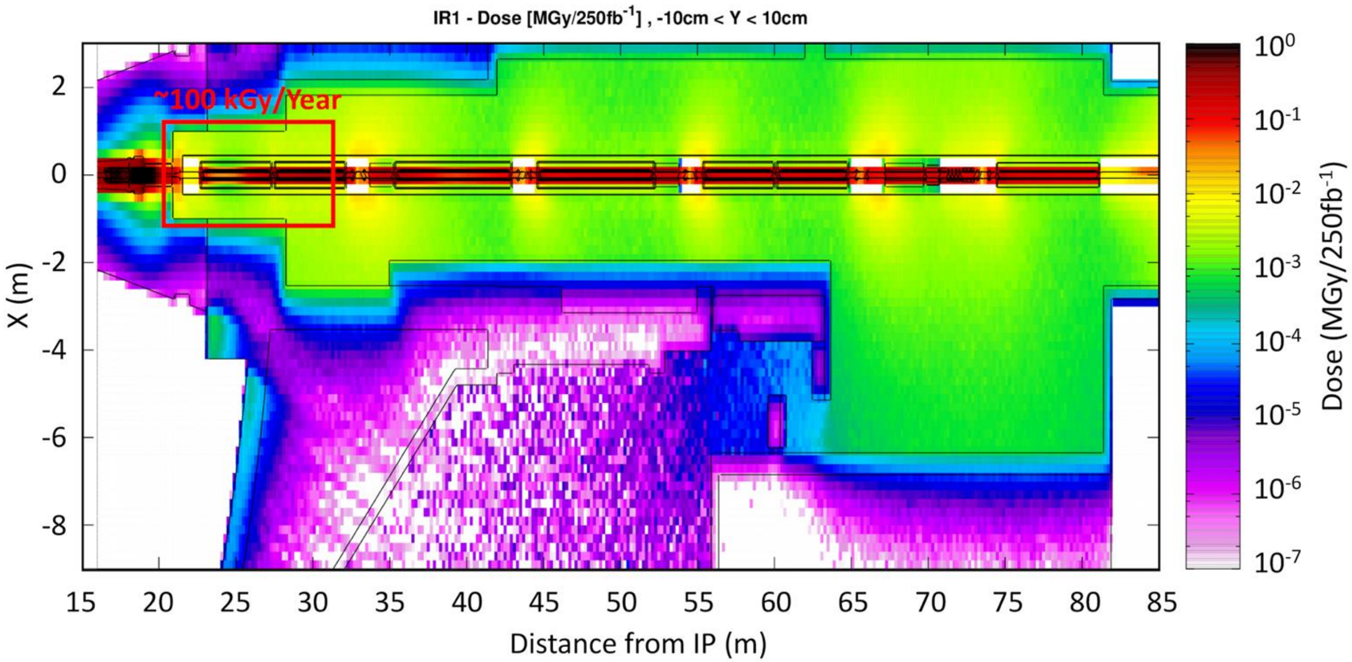
Clamping pressure and other parameters estimated from DIC data (displacements) by least square regression (numerical procedure implemented in Matlab)

Irradiation tests design

Irradiation experiments designed based on the expected accumulated dose in critical areas of HL-LHC

Predictions obtained by Fluka

(~100 kGy/Year close to ATLAS experiment)

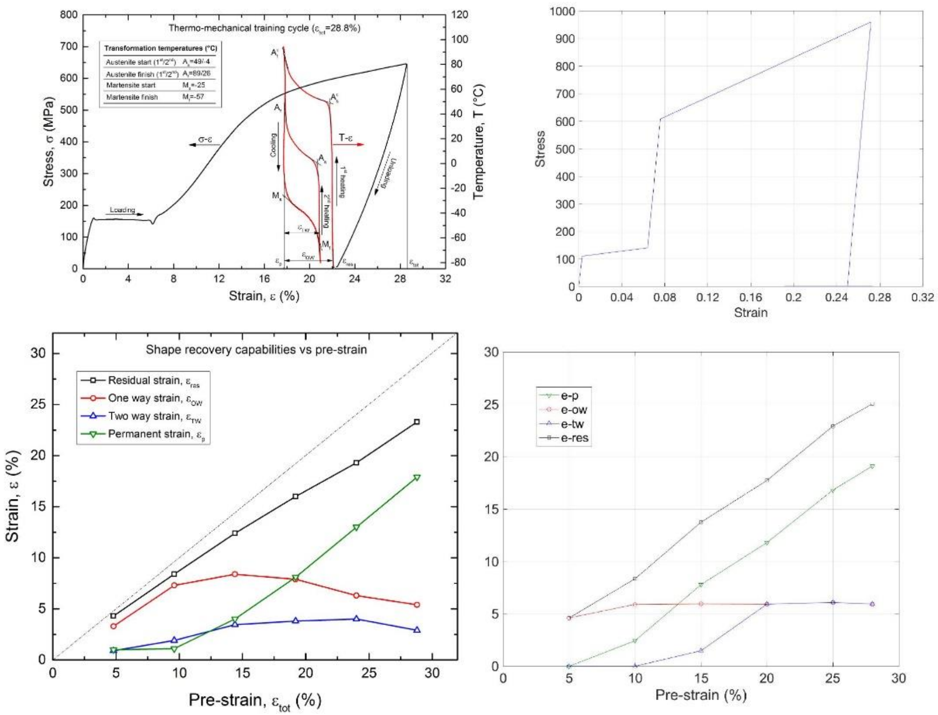


Dose map in the IT area right side of ATLAS for HL-LHC operation. (courtesy of F. Cerutti)

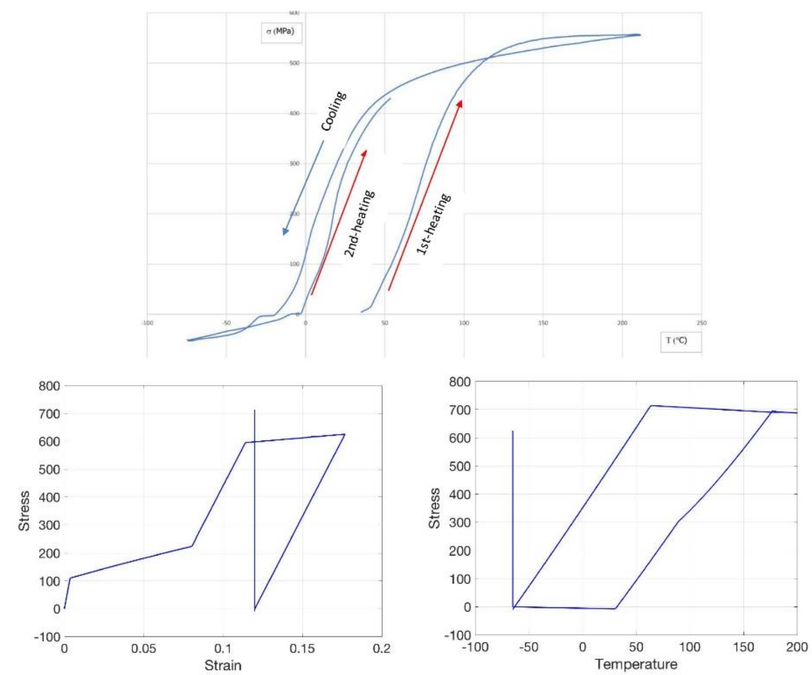
Simulations

Development of a constitutive model suitable for training, OWE and TWE*:

- Kinematic: $\varepsilon = \varepsilon^e + \varepsilon^{th} + \varepsilon^p + \varepsilon^{tr}$ (decomposition of the strain).
- Constitutive equation: $\sigma = E \cdot \varepsilon^e$ (Hooke's law).
- Yield surface (plasticity based on Von Mises criterion).
- Memory surface in the strain space.
- Evolution laws for plasticity and phase transformation.
- Consistency equations.



Training simulations compared to measurements

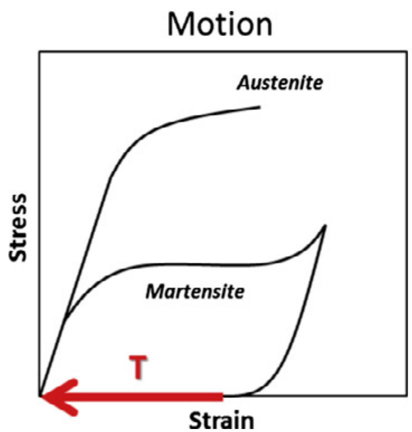


Stress applied and stress free behaviour

*: In collaboration with University of Calabria and University of Pavia

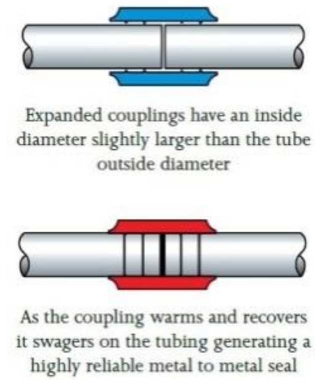
Nickel Titanium-based alloys: SME applications

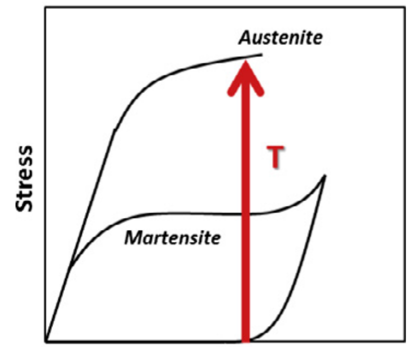
Free recovery



SMA element function: motion or strain generation by heating\cooling

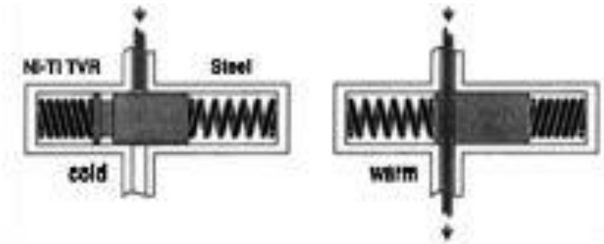
Constrained recovery

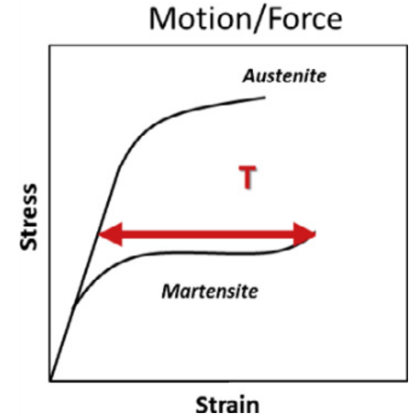




SMA element function: force generation by heating\cooling

Actuator or work production



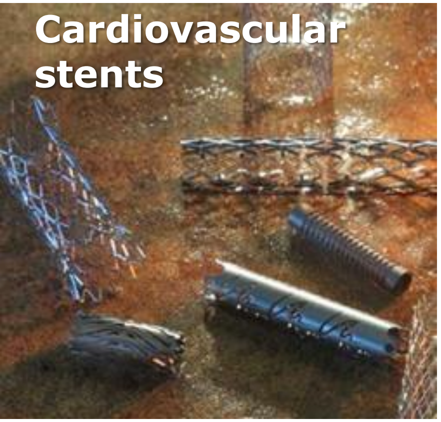


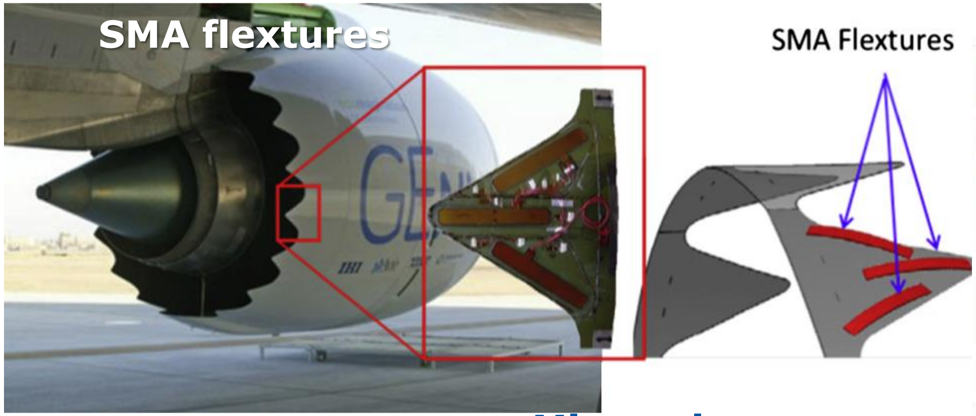
SMA element function: motion\force generation (work generation) **by heating\cooling**
Most of applications fall in this category (OWSME or TWSME):

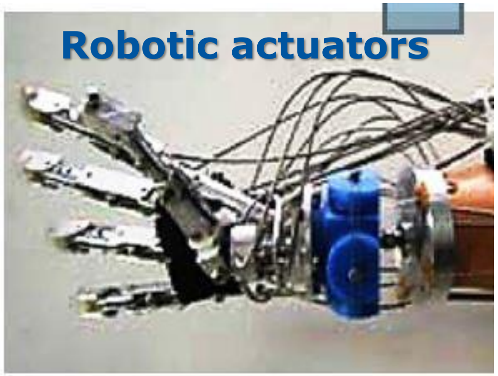
Nickel Titanium-based alloys: applications

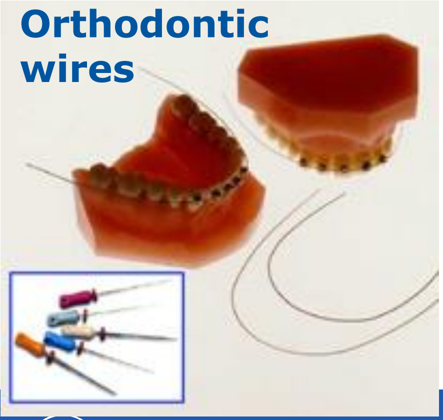
Biomedical
Aerospace
Automotive

Robotics
Communication
Consumer goods

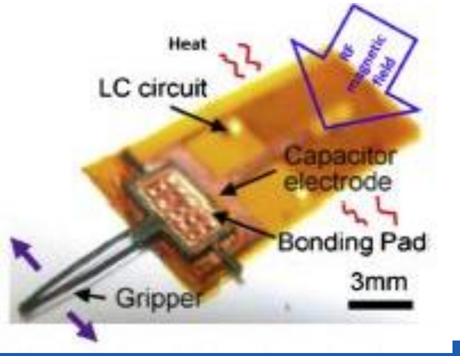


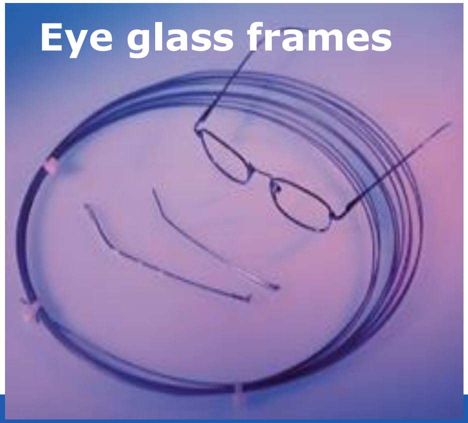




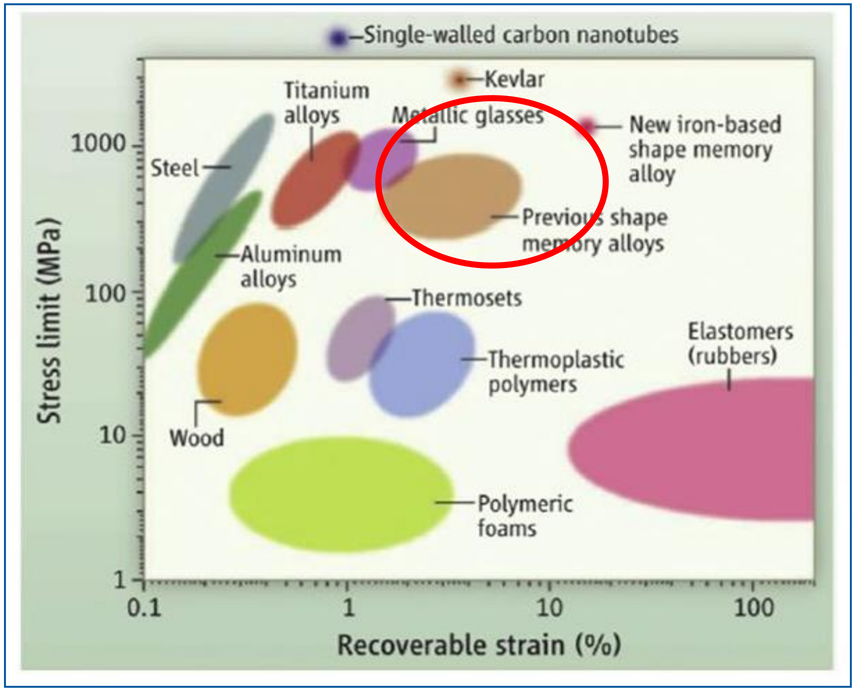


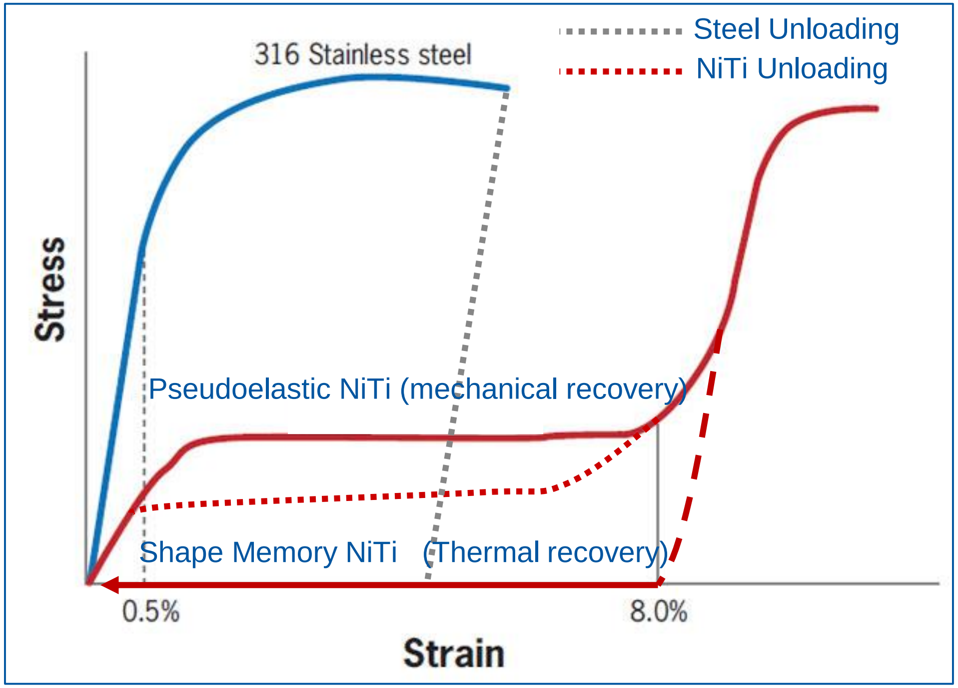
Micrograppers





SMA Properties and Classification



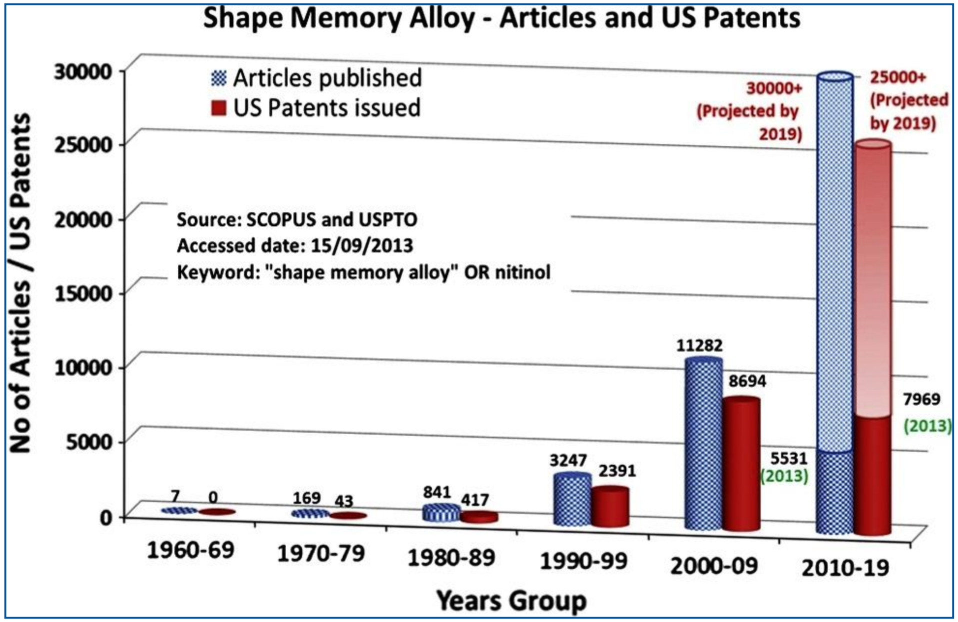


Comparison between the stress and recoverable strain limits of new developed SMA with other materials

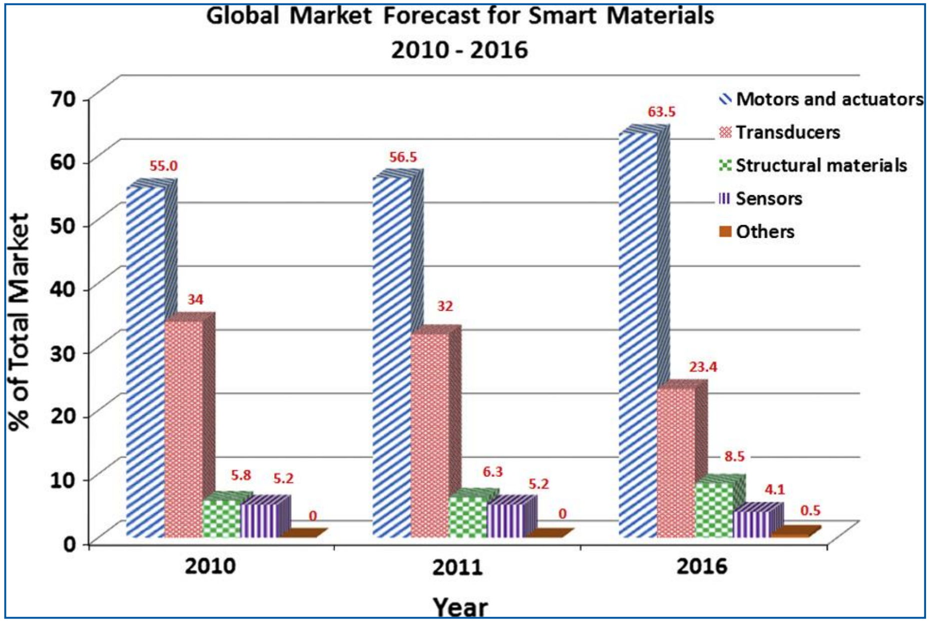
Comparison between the stress-strain responses of a pseudoelastic or shape memory NiTi and a traditional steel

Nickel Titanium-based alloys: applications

Scientific and industrial interests on SMA: some statistics



Number of ''Shape Memory Alloy'' articles and patents by years-group [3] .



Global market forecast for smart materials for 2010–2016 [3] .

1962: Buehler and his co-workers at the U.S. Naval Ordnance Laboratory (Maryland) discovered the shape memory effect in an equiatomic alloy of Nickel and Titanium.This alloy was named Nitinol (Nickel Titanium Naval Ordnance Laboratory)

Breakthrough in the field of shape memory materials.

- **Number of commercial applications growing each year**
- **Cost decreased significantly, from approximately US$1100 per kilogram in 1996 to less than US$111 per kilogram today (indicative trend)**
- **price strictly depending on composition, casting, manufacturing, training processes etc.)**