Mechanics and Materials for

Beam Instrumentation

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CERN Accelerator School on Mechanics and Materials Engineering for Particle Accelerators and Detectors
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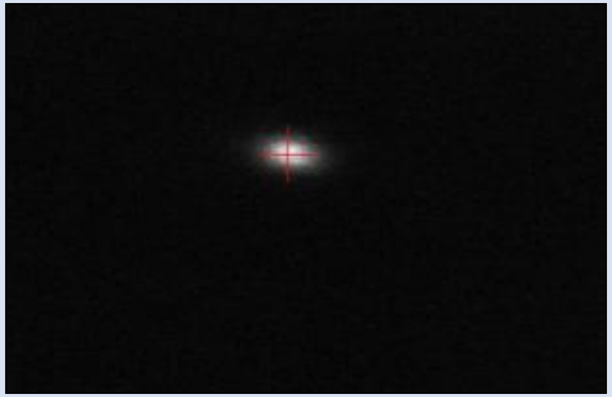
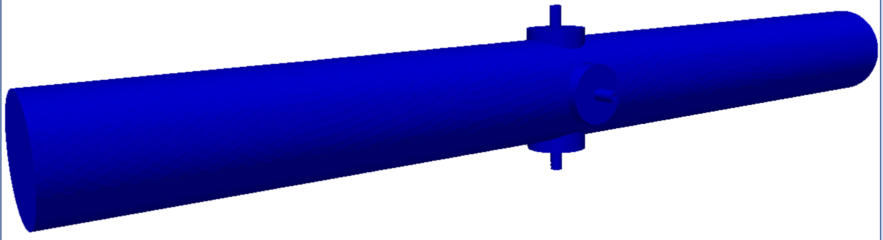
Beam Instrumentation

The EYES



Beam induced Light

The EARS



Electro-magnetic field

The HANDS

Beam interceptive devices

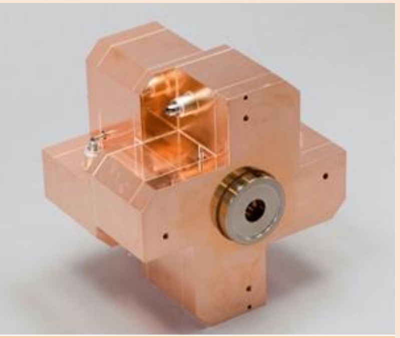
So, not including: instruments for experimental physics, instruments needed to operate accelerator systems (eg, temperature probes…), nor instruments for the infrastructure or services

Why do we need it?

Keeping the beams on-track

Examples:

Beam observation screen



Position monitor (cavity BPM)

Key words:
Scaleable, Direct

Safe Operations

Examples:

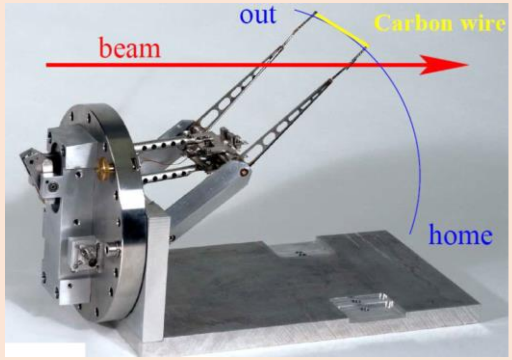
Fast beam current transformer

Beam-loss monitor (ionisation chamber)

Key words:
Reliable, Fast

Optimising and diagnosing

Examples:



Wire scanner

Beam-gas curtain

“If we don’t understand what’s wrong, we probably need a new instrument”

Where do we need it (at CERN)?

LHC Collider *(~8’500 instruments)*

Synchrotrons and storage rings *(1020 instruments)*

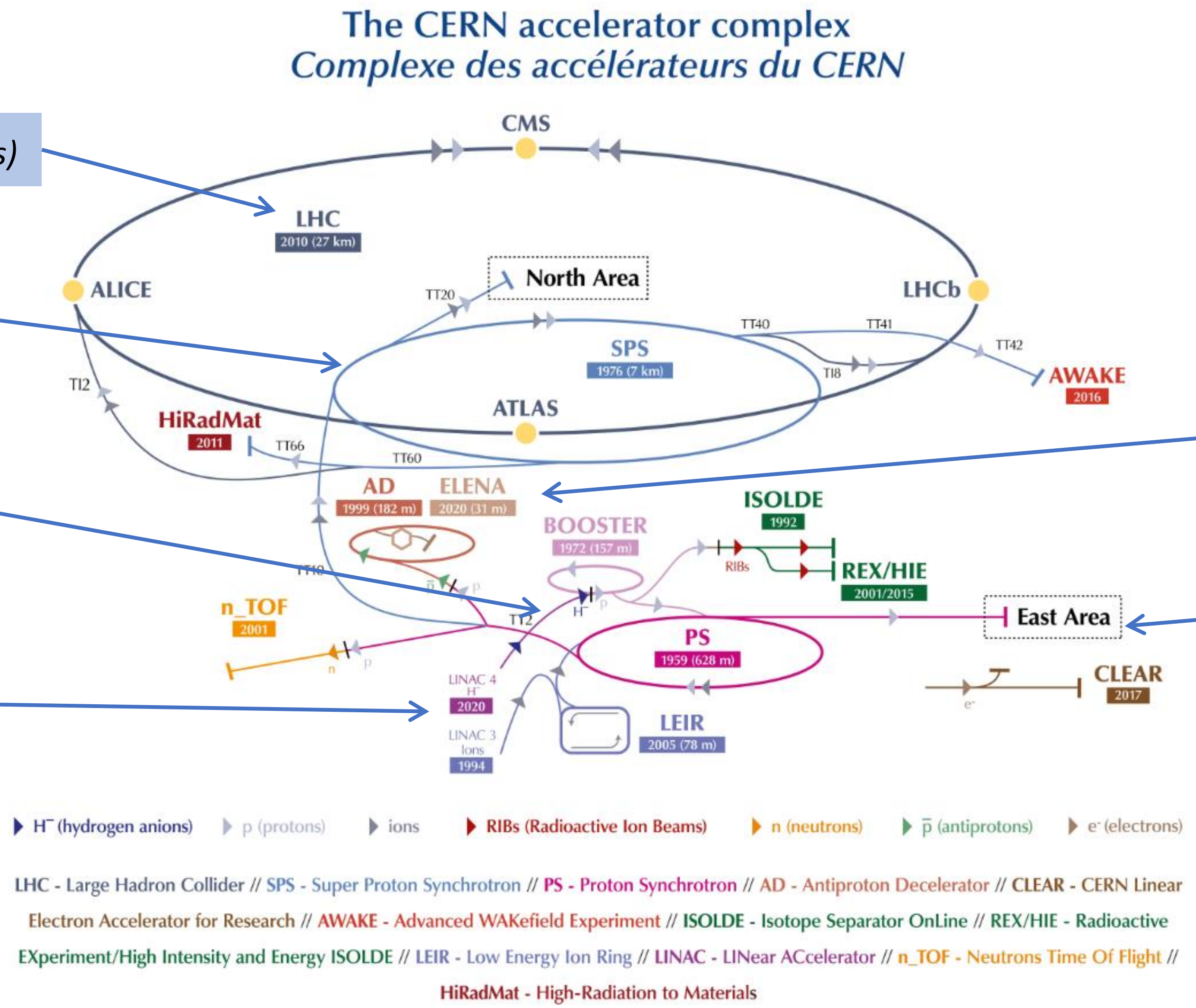
Transfer lines and switchyards *(829 instruments)*

Low energy: ion sources, LINACs *(119 instruments)*

Low energy and intensity: antiprotons *(107 instruments)*

Fixed target experimental beamlines *(368 instruments)*

Total: ~**10’900** beam instruments operating in the CERN accelerator complex



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

What am I going to cover?

- Huge and diverse range of instrument applications and needs
  - Different beam types (charges, mass, intensities, energies)
  - Different measurement needs (position, loss, intensity, profile, tune…)
- Many different physical principles for measurement are used
  - Electro-magnetic, electro-static, direct particle measurement, electron emission, scintillation, visible light, synchrotron light, optical transition radiation…

CAS Introduction and Advanced physics schools

- I will focus on the engineering challenges rather than physical principles or operational uses
  - Take three example instruments and **deconstruct** them to show the key engineering components:
    - (i) Beam observation screen, (ii) Fast wire scanner, (iii) Secondary emission grid
  - My apologies if your ‘favorite’ instrument is not covered!
- Use CERN accelerator complex for examples
  - Challenges are similar for light sources, proton drivers, (linear colliders)

Beam ‘TV’ observation screen

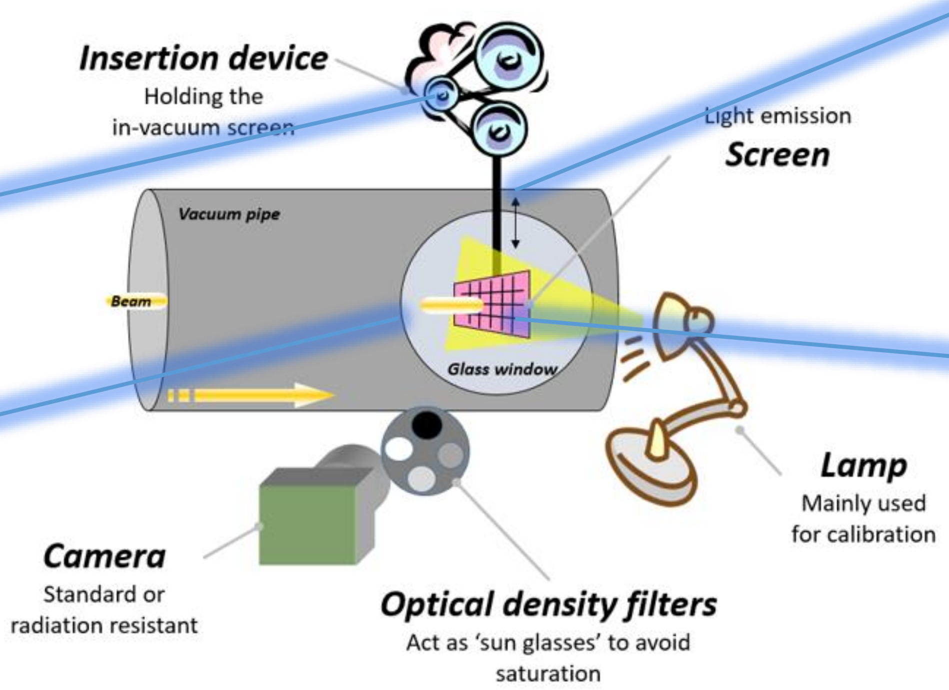
(i) Deconstruct: a beam TV observation screen

Precision measurement: **end switches** are sufficient as we only need to know the 'in' and 'out' positions

Transmit movement to vacuum: **Bellows** or **magnetic coupling**

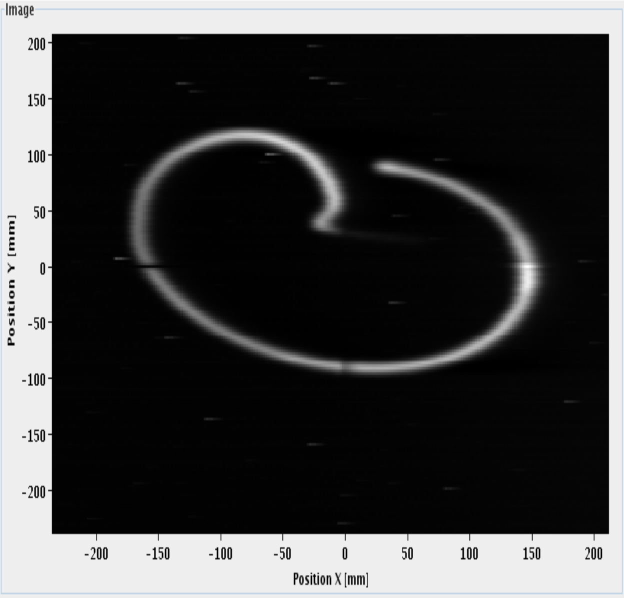
Signal transmission: **Viewport** and **camera**

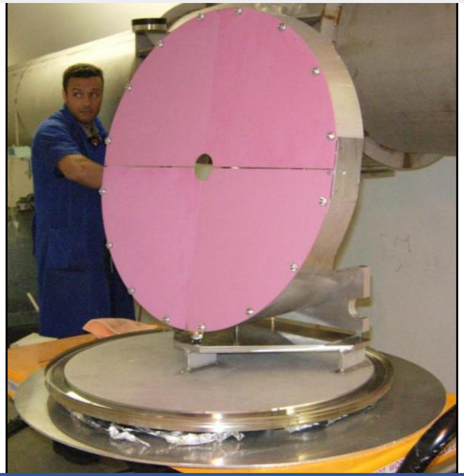
Beam intercepting material: '**functional material' screen**

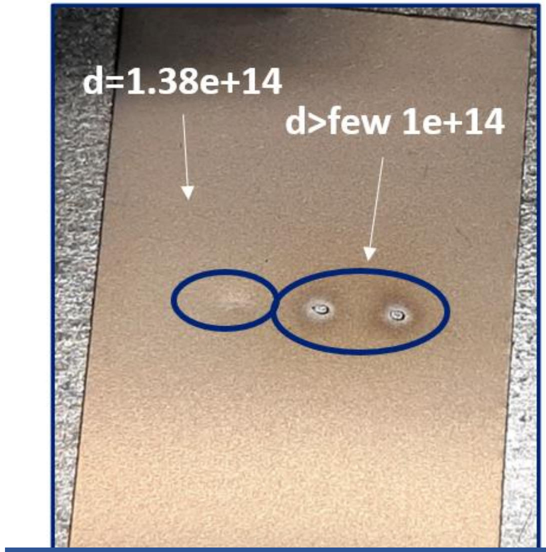


Beam intercepting materials: Screens

- Beam intercepting instruments
  - The most 'direct' way of probing a beam is by physically interacting with some particles
  - Widely used at low energy/intensity
    - but there is always a push to extend reach
- Diverse range of sizes, materials and 'measurables' *[this is a major field in instrumentation physics!]*
  - Scintillation, fluorescence, optical transition radiation
  - Alumina, chromox, YAG, quartz, metal…
- Issues
  - Radiation and mechanical resistance
  - Direct beam heating and impedance induced heating
    - See later slides
- Solutions
  - Testing and qualification of new materials
  - Interlocks to limit machine parameters when screens are inserted




600 mm diameter LHC beam dump screen



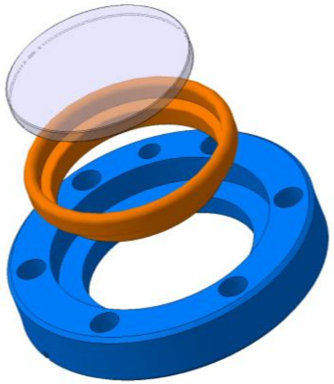
Ti screen damaged by a 440 GeV proton beam (HiRadMat)

Signal transmission: Viewports - introduction

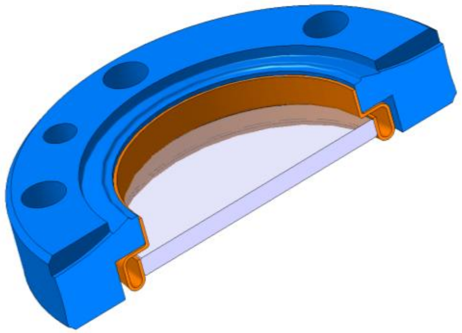
- Viewport: a section of vacuum envelope transparent to ‘light’
  - Visible light observation (observation screens)
  - Laser diagnostic signals
  - Synchroton light diagnostics
- Design challenges:
  - Window materials are brittle and not Coefficient of Thermal Expansion (CTE) matched to most metals
  - Making a leak-tight join with the window means glueing (not normally acceptable) or brazing (at high temperature)
  - Designs include a transition, requiring:
    - Intermediate CTE between window and flange, weldability to flange, brazability to window and a stress relieving shape
- Specificities
  - Glasses (borosilicate, fused silica, sapphire…) and coatings for the application
  - Flanges (conflat, ISO, KF…), diameter
  - Bakeability is very design dependent (material choice and transition design)

1: Choose the window material and coating

2: Choose the flange type and material



3: Braze/glue the flange to the transition



4: Weld the transition into the flange

Signal transmission: Viewports – issues and solutions

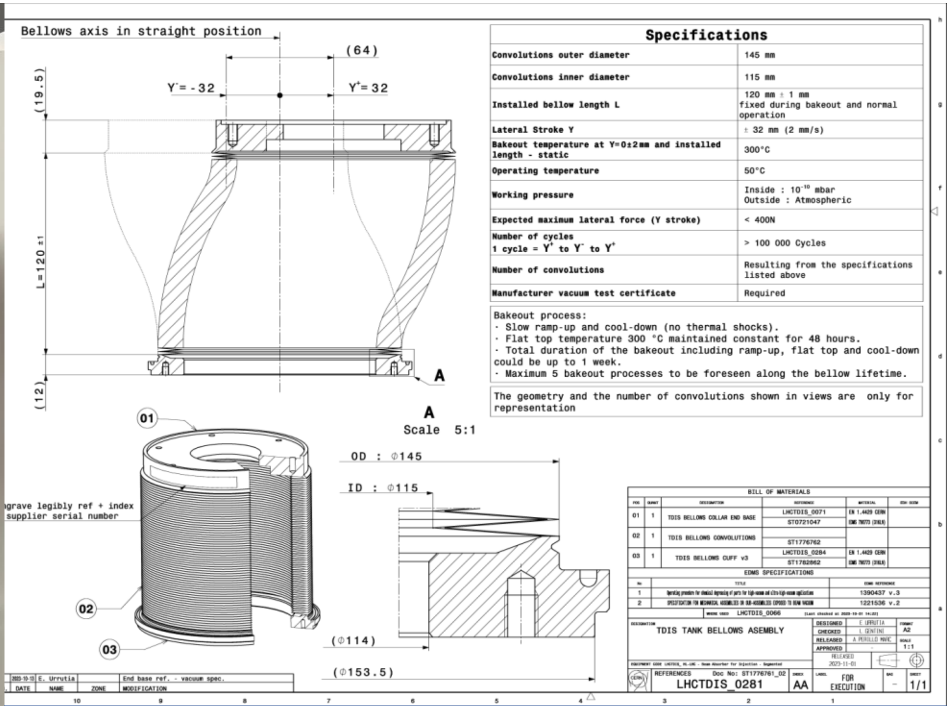
- Issues
  - Inherently fragile system with high impact of failure
  - Specialist manufacture with ‘proprietary’ processes and materials
    - Every manufacturer has their own detailed design, particularly for the transition and brazing
  - Few manufacturers but many stockists, often with product ranges drawn from different manufacturers
- Failures
  - Most failures occur during assembly
    - Supplies can try to impose the use of annealed Conflat seals
  - …or bakeout
    - Suppliers often impose strict bakeout ramp rates
  - …but sometimes you find cyclic crack growth in the glass leading to unexpected failures during pumpdown or operation
    - VIRGO gravitational wave experiment in Pisa
  - Optical damage due to radiation can make these ‘consumable’
- Solutions
  - Ideally, oblige a supplier to make and test to your specification (OK if you are a large customer)
    - Otherwise, understand the design and supplier of each diameter
  - You tend to get what you pay for

Failed PS viewport glass after some vacuum cycles

Transmit movement to vacuum: edge-welded bellows

- Why moveable instruments?
  - Many instruments are ‘invasive’ and cannot remain in the beam
    - Used for machine set-up or ‘machine development’
  - High intensity beams are destructive and will damage detectors
- Why edge-welded bellows?
  - Large stroke/length ratio, high flexibility, compared with formed bellows
  - Commercially available and widely used in many applications
- Issues
  - One typical bellows will have 15 meters of micro-welds, all single point failures
  - Particulate contamination (eg, swarf) can peirce the plys
  - These operate as elasto-plastic structures and are designed for fatigue and crack growth
  - Asymmetric forces when pushing or pulling against atmosphere
- Solutions
  - Detailed designs are proprietary, so very complete functional specification and qualification of potential suppliers required
    - QA is critical, limited cyclic lifetime, so testing advised

Edge welded bellows for LINAC4 wire scanner at CERN



Specifications	
Convolutions outer diameter	145 mm
Convolutions inner diameter	115 mm
Installed bellow length L	120 mm ± 1 mm fixed during bakeout and normal operation
Lateral Stroke Y	± 32 mm (2 mm/s)
Bakeout temperature at Y=0±2mm and installed length - static	300°C
Operating temperature	50°C
Working pressure	Inside : 10^{-10} mbar Outside : Atmospheric
Expected maximum lateral force (Y stroke)	< 400N
Number of cycles 1 cycle = Y^+ to Y^- to Y^+	> 100 000 Cycles
Number of convolutions	Resulting from the specifications listed above
Manufacturer vacuum test certificate	Required

Bakeout process:
- Slow ramp-up and cool-down (no thermal shocks).
- Flat top temperature 300 °C maintained constant for 48 hours.
- Total duration of the bakeout including ramp-up, flat top and cool-down could be up to 1 week.
- Maximum 5 bakeout processes to be foreseen along the bellow lifetime.

The geometry and the number of convolutions shown in views are only for representation

BILL OF MATERIALS

01	1	TDIS BELLOWS COLLAR END BASE	LHCTDIS_0071 ST0721047	EN 1.4429 CERN [illegible]	
02	1	TDIS BELLOWS CONVOLUTIONS	ST1776762		
03	1	TDIS BELLOWS CUFF v3	LHCTDIS_0284 ST1782862	EN 1.4429 CERN [illegible]	

EDMS SPECIFICATIONS

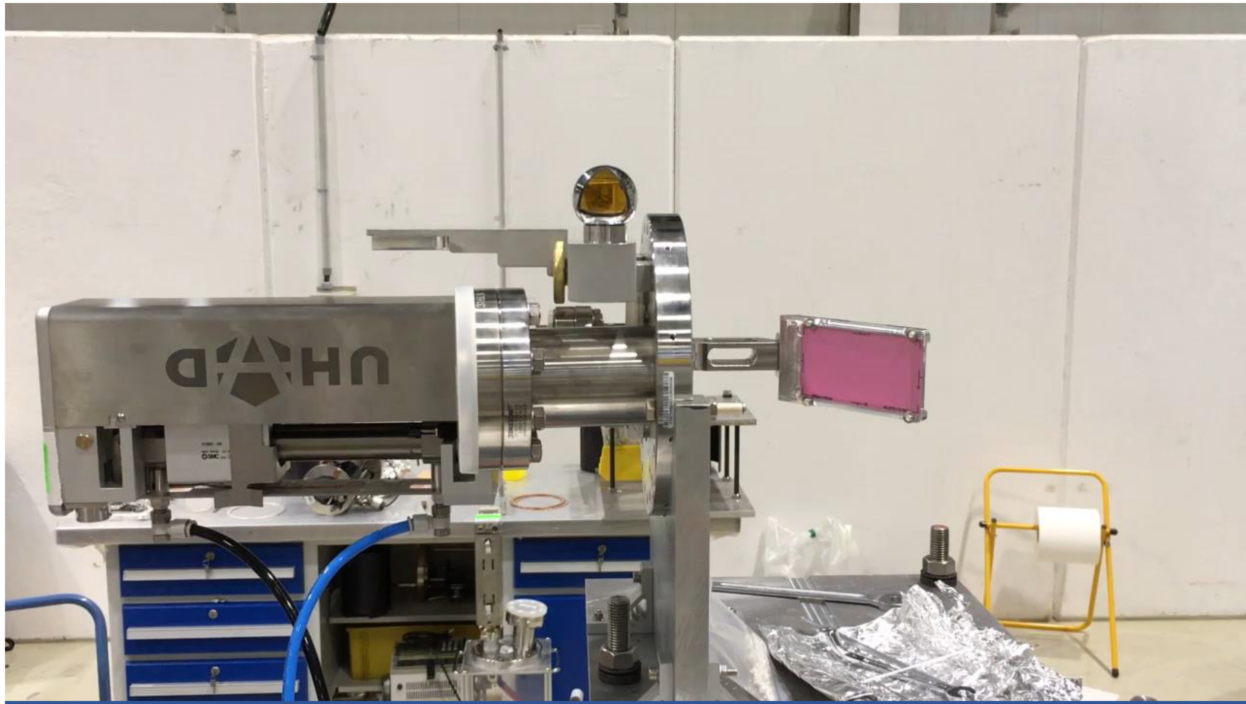
1	[illegible]	1390437 v.3
2	[illegible]	1221536 v.2

LHCTDIS_0066

Recent functional drawing for edge welded bellows for a collimator movement system at CERN

Transmit movement to vacuum: magnetic coupling

- Principles
  - Powerful (SmCo) magnets coupled via a thin vacuum chamber
  - Movement of the outside magnet drives a movement on the vacuum side
- Possible implementations
  - Commercial magnetically-coupled ‘push-pull’
  - Rotary (or linear) electric motor, with thin vacuum chamber between stator coils (in air) and permanent magnet rotor (under vacuum)
- Advantages
  - Static vacuum boundary
  - Inherently more robust than welded bellows with ‘graceful degredation’ (unlikely to leak)
- Issues
  - Position in vacuum is not intrinsically defined during the movement
    - Either used in instruments where only the ‘in’ and ‘out’ position are needed, or in conjunction with an in-vacuum position sensor
  - Requires some in-vacuum bearings or sliders which will limit lifetime and reliability

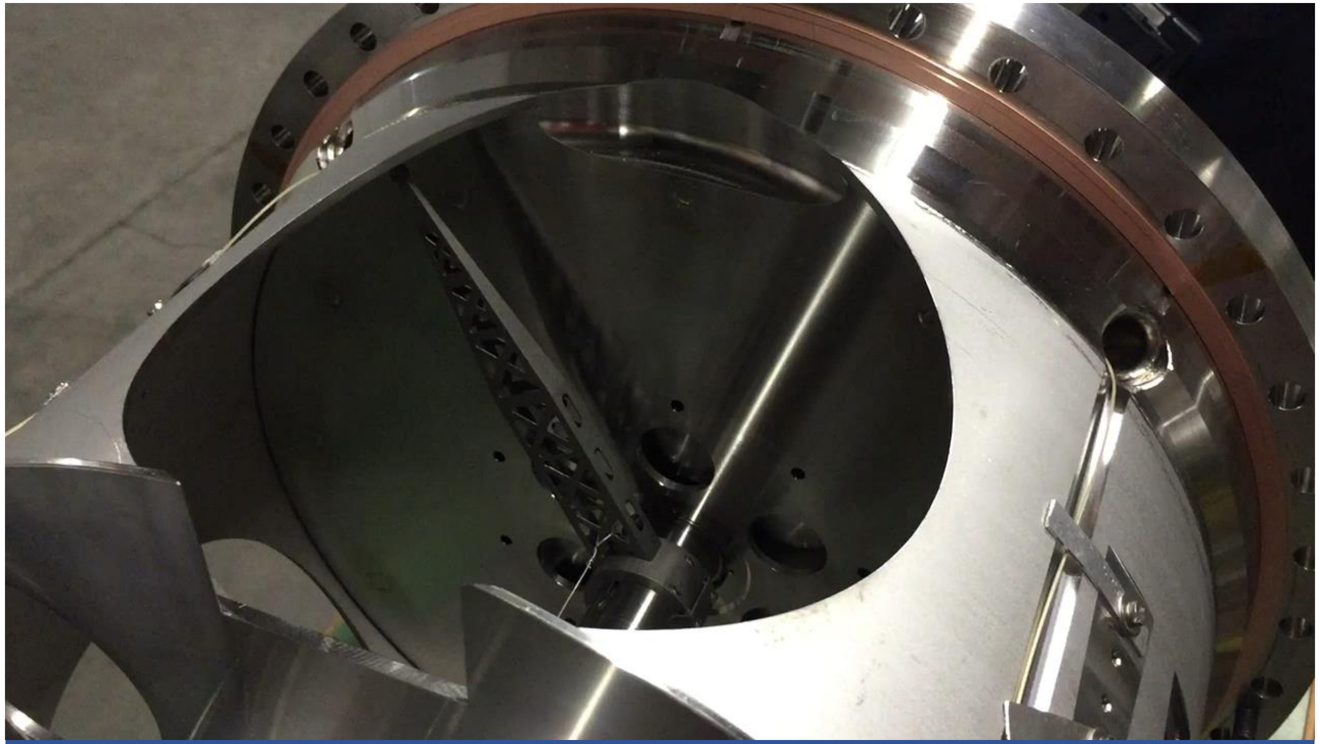


Commercial magnetically coupled ‘push-pull’ on a CERN beam observation screen

‘Fast’ wire scanner principle

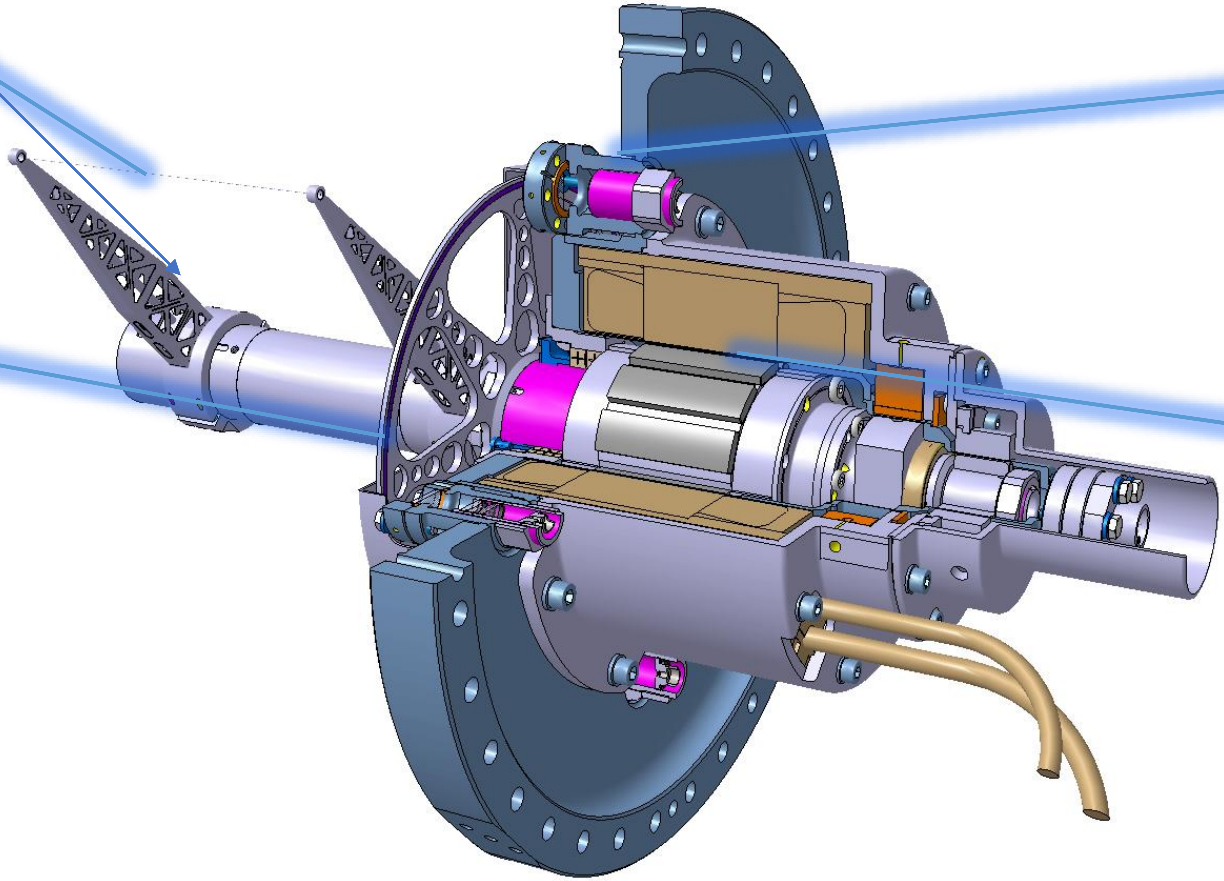
New fast wire scanners in PSB, PS and SPS rings

Latest instrument technology, operating since 2021



Fast means fast: Upto 20 ms^{-1} scanning speed with ~10 um precision

(ii) Deconstruct: a fast wire Scanner



Beam intercepting material: **carbon filament**

Precision position measurement: **optical disc**

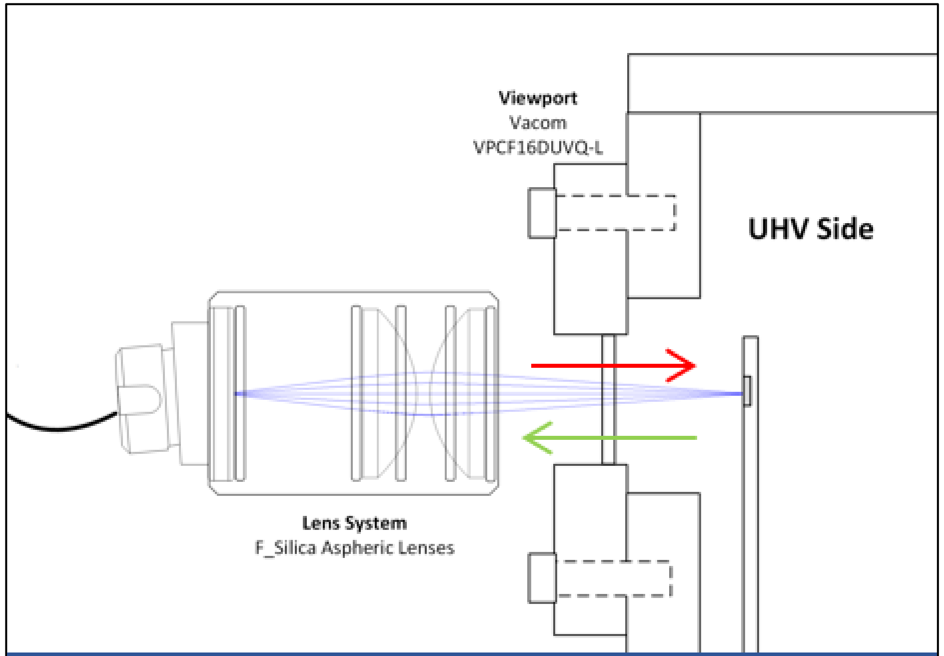
Beam induced heating

Transmit signal from the instrument: **Viewport and laser**

Generate and transmit movement to vacuum: **Magnetically coupled** (Electric motor with stator and rotor separated by a thin vacuum chamber)

Precision measurement: in-vacuum optical disc

- Non-defined (eg, magnetically coupled) or very high precision systems need a dedicated in-vacuum position measurement
- There are some commercial solutions, but not for UHV and radioactive environments

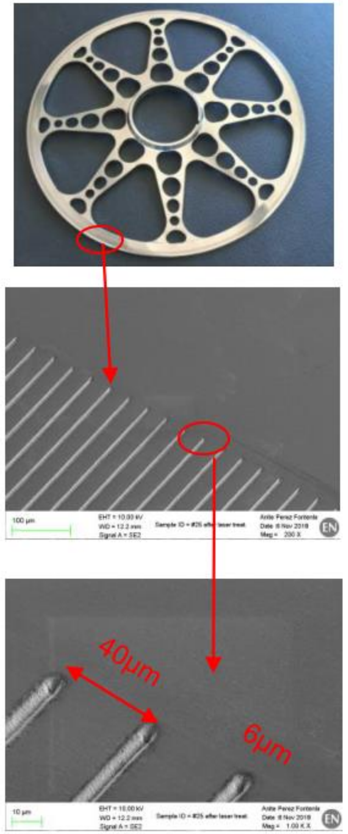


New fast wire scanner uses in-air laser, reading an in-vacuum optical disc fixed to the detector head

Optical grade aluminium with inertia-optimized geometry

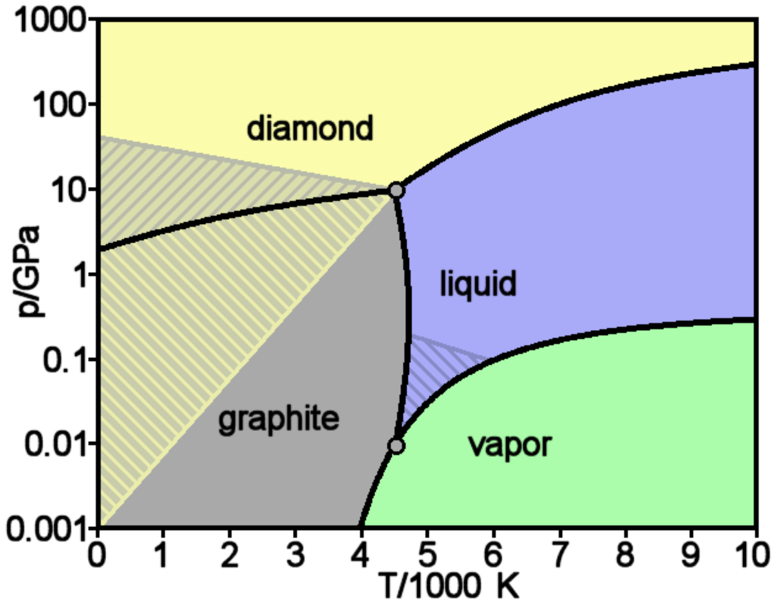
Locally machined the surface to a mirror finish

Laser engraved grating around the circumference

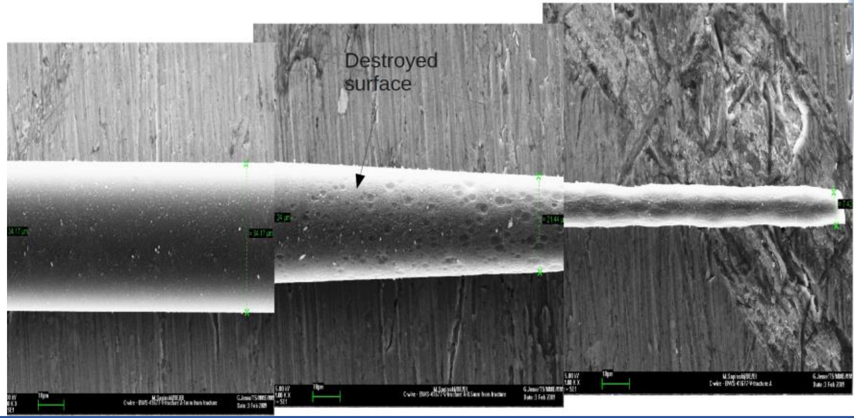


Beam intercepting materials : **wires**

- Why wires:
  - Wire scanners and grids use small diameter (7-100 µm) wires to probe the beam
    - ‘Minimally invasive’ design allows instrument use to monitor performance
    - Smaller diameters give better position resolution
  - Variety of materials (C, W, Be, B, Fe) depending on beam parameters
    - Intensity frontier devices converge on C and B wires
- Issues
  - Wire damage from beam heating
    - Already limiting applications in both SPS and LHC at CERN
  - Particle loss leading to accelerator irradiation or heating (in superconducting machines)
    - Limiting use in parts of the LHC
- Can we improve these extreme beam intercepting materials??



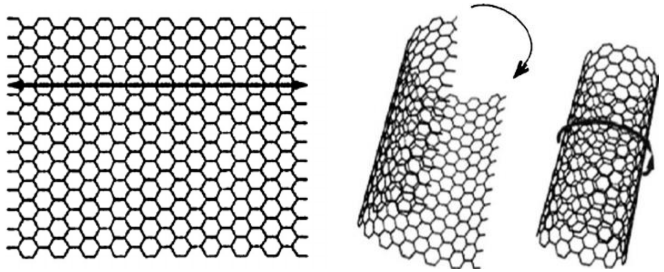
Carbon transition diagram



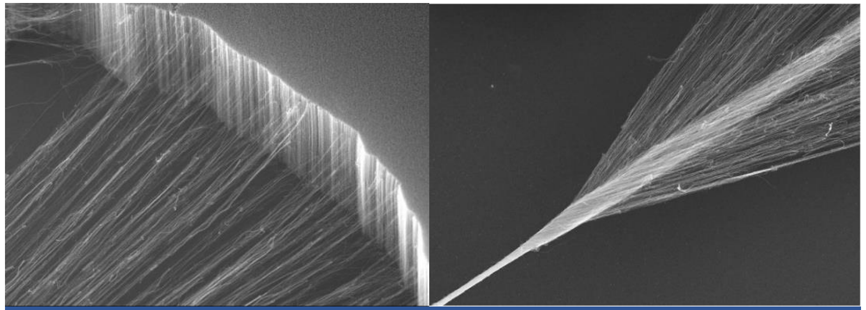
Carbon wire scanner wire test in the SPS

Beam intercepting materials: research

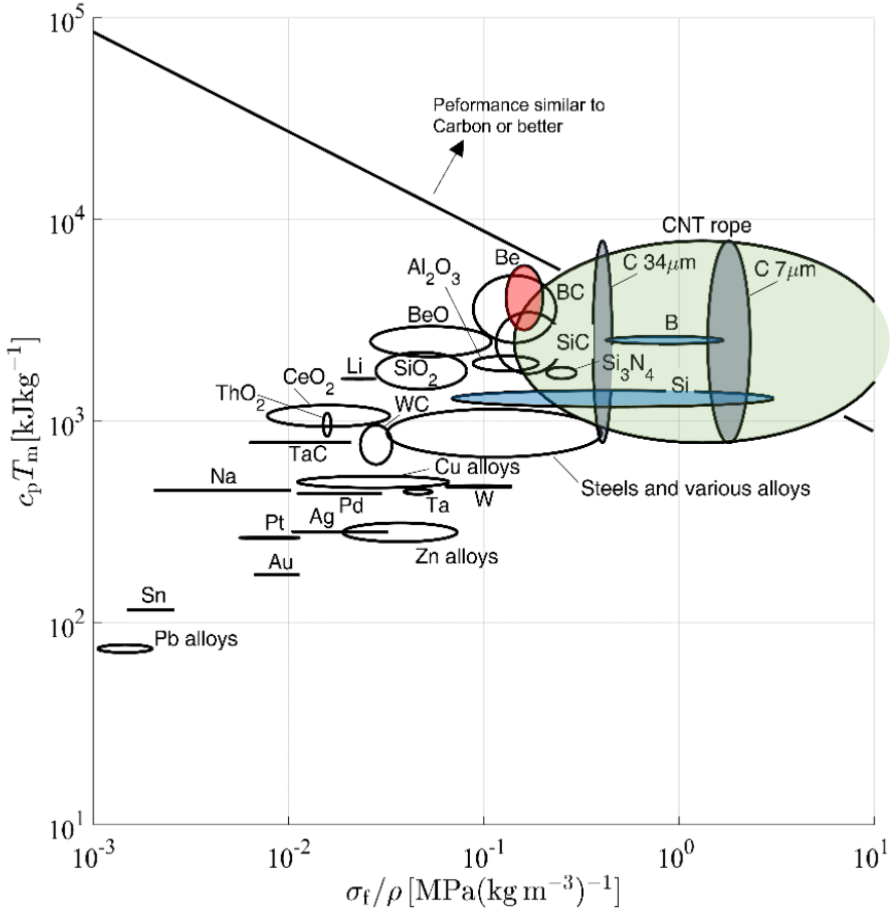
- Material requirements for pushing the frontiers with wire scanners and screens
  - Low density/atomic number (intercepts less beam)
  - High strength (needs less material)
  - High heat capacity (lower temperatures for same energy)
  - High melting/sublimation temperature (resisting more beam)
  - Functional material properties (it has to work as an instrument)
- Research – is it worth the investment?
  - ‘Real research’ is resource and time consuming
    - Requires expert personnel (PhDs and doctoral students)
  - Try to do this as collaborations with universities and institutes



From graphene to carbon nano-tube (CNT)



From a CNT forest to a CNT rope, or wire



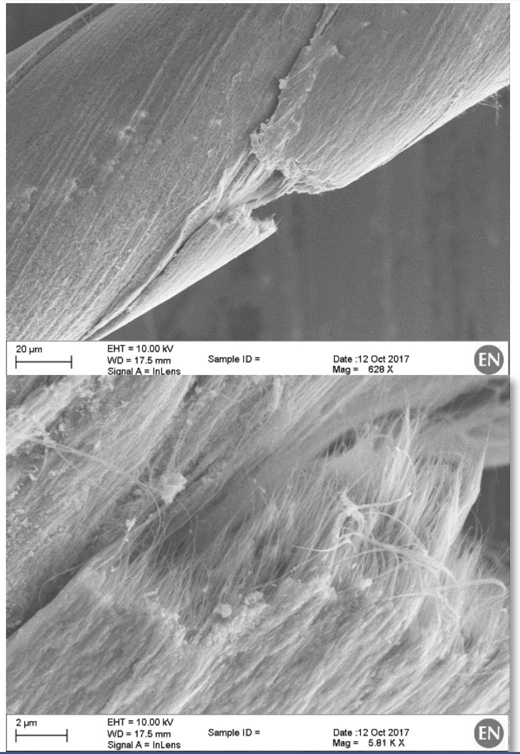
‘Ashby plot’ method (in collaboration with Oxford University Engineering Science) for identifying potential new materials for wire scanners*

*https://doi.org/10.1002/adem.201900927

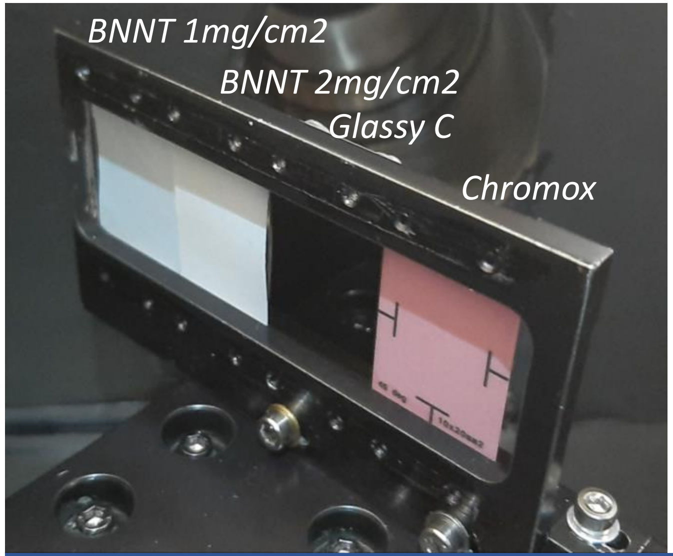
Beam intercepting materials – nano materials

	Mechanical			Thermal			Electrical
Material	**ρ [g.cm^{-3}]** **Density**	**E [GPa]** **Young modulus**	**UTS [MPa]** **Tensile strength**	**k [W.m^{-1}.K^{-1}]** **Conductivity**	**c_p [J.kg^{-1}.K^{-1}]** **Specific heat capacity**	**T_f [K]** **Transition temperature**	**σ_{el} [Ω^{-1}.m^{-1}]** **Conductivity**
CNT (SWNT)	0.02-0.04	1000-5000	120000	3000-6600	10	3500	10^8
Carbon fiber	1.7-2.5	60-500	600-4500	140	720	3500	5.10^6
Stainless Steel	7.8	200	500-600	15-30	430-500	1600	$1.2\text{-}1.8.10^6$

- Recent advances in low density materials (graphene, nano-tubes) give the potential for orders of magnitude improvements over existing materials
  - Lower densities, higher strength
- Existing materials are getting better, but not made using the right processes
  - Woven strands rather than long single tubes
  - High density (Fe) impurities used as catalysts
- Follow/direct materials producers and test in accelerator conditions
  - HiRadMat at CERN used for both screen and wire testing
- Can we improve the materials?: **WATCH THIS SPACE**



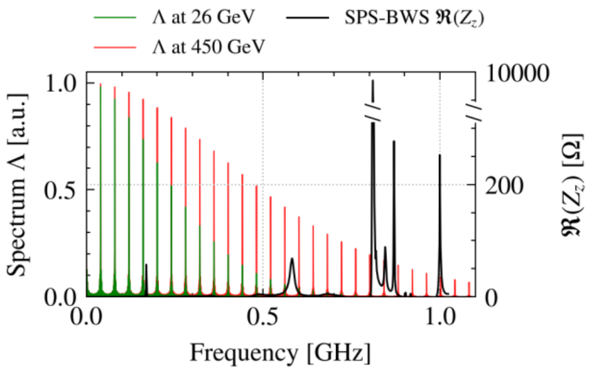
SEM images showing testing of CNT wires at CERN



Screen materials test set-up in high intensity beamline (HiRadMat)

Beam induced heating – the problems

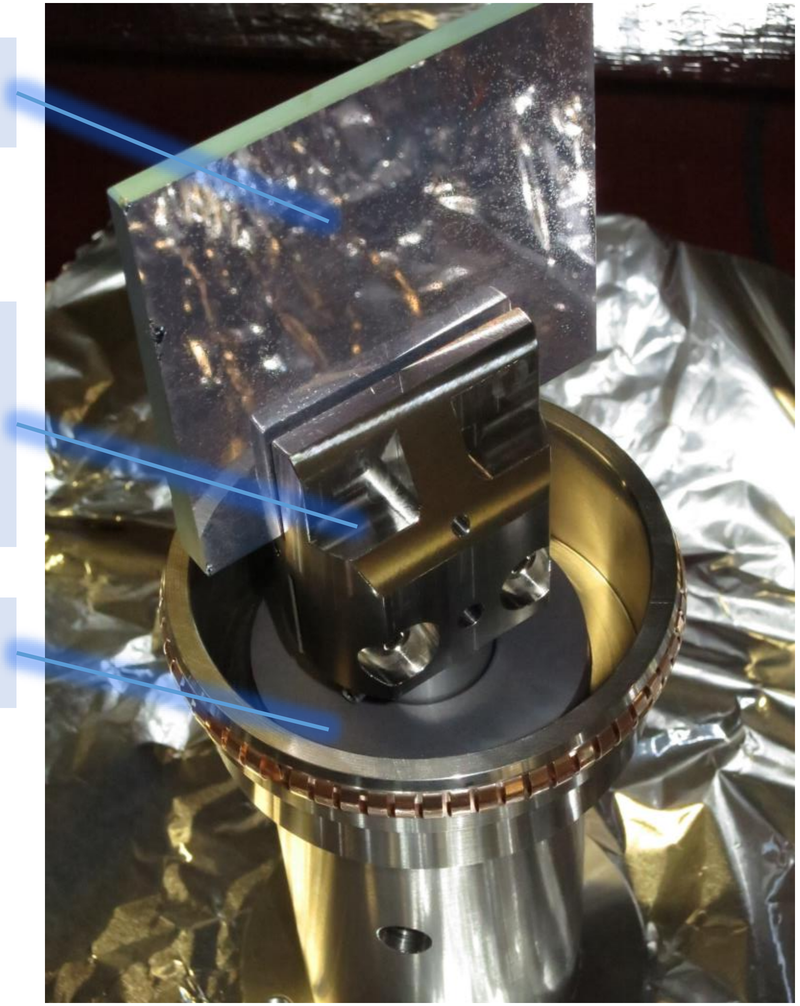
- Some instruments have specific space or volume requirements in the beam envelope
  - This shape can ‘ring’ with the circulating beam depending on details of beam and vacuum tank
  - This transmits energy (heat) to the vacuum chamber
- Some instruments need to ‘probe’ close to circulating beams
  - This makes them resonate like a radio antenna and pick up energy from the beam (as well as causing beam instabilities)
- Simulating and predicting the extent of this heating is a specialist skill
  - Combination of details of the circulating beams and precise geometry of the structure
  - Heating is sometimes caused by sharp ‘resonances’ that can be detuned even by thermal expansion of a vacuum tank
  - Uncertianties in the simulations can be orders of magnitude



Beam spectrum (green) and SPS wire scanner modes (black)*

*’Impedance and thermal studies of the CERN SPS wirescanners and mitigation of wire heating’. IPAC-2024

Beam heating example: LHC synchrotron light mirror



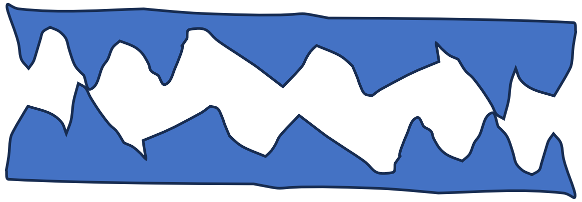
Mirror surface blistered and mirror damage

Cu-Be springs heating to softening temperature and released force on mirror

Ferrite disc cracked into pieces

Beam induced heating : heat transfer

- Mechanical structures in vacuum are difficult to cool
  - No convection in vacuum
  - Conduction is very limited and unreliable, without careful design
    - Actual surface contact between hard metals can be as little as 0.1% of the nominal surface
    - Conduction in air relies (mainly) on ‘micro convection’ between close surfaces, which does not occur under vacuum
    - Design for conduction under vacuum implies soft, smooth surfaces and high clamping forces (plus testing!)
  - Thermal radiation only starts be effective at high temperatures
    - Thermal radiation scales with 4th power of absolute temperature difference, so large ΔT for any significant heat transfer
    - Eg, 5cm x 5cm surface, radiating to room temperature (293 K) space will emit 0.5 W for 50 °C and 16 W at 300 °C



Actual conducting area can be orders of magnitude lower than nominal surface under vacuum

$$Q = A\,\sigma\,\varepsilon\,(T_1^4 - T_2^4)$$

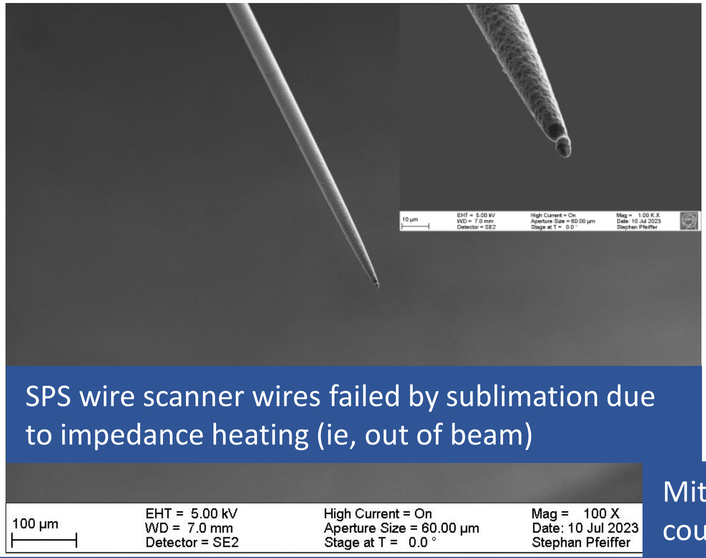
Where:
Q is the heat radiated
A is the surface area
σ is Stefan’s constant
ε is the thermal emissivity (1= black body)
T_1 is the source temperature
T_2 is the sink temperature

Heat transfer by thermal radiation is very non-linear: large temperature differences are needed for significant power transfer

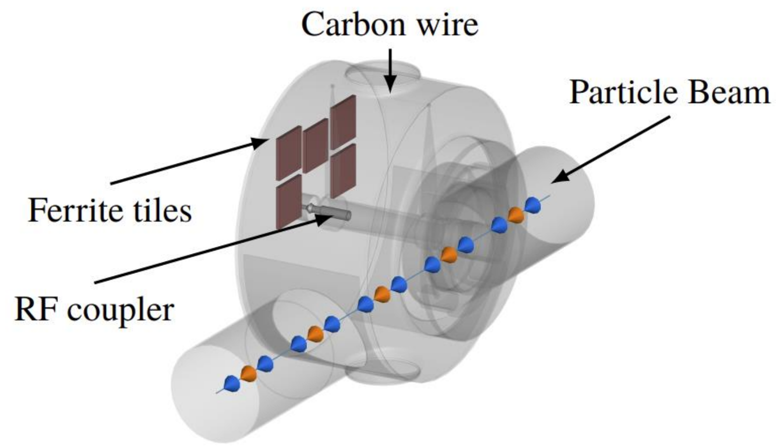
Beam induced heating: concequences and solutions

- Due to the large inherent uncertainties in simulation and cooling design, impedance heating is a recurrent problem in most high brightness machines
  - Designing for a worst-case can be expensive, or impossible
- Solutions
  - Try to avoid by design (LHC screens)
  - Work at the concept design stage with impedance experts on shapes and materials in the structure
  - Consider RF absorbing materials (ferrites) and other structures (couplers) where needed
  - Mechanical designs for cooling include:
    - active (eg, water),
    - radiation (design to get hot!),
    - direct (non-bolted) path from heat source to air
    - Bolted connections with deformable interface materials
  - Testing and thermocouples
  - Have a ‘plan B’ to cope with uncertainties

LHC screen retracted during normal operations



SPS wire scanner wires failed by sublimation due to impedance heating (ie, out of beam)



Mitigation of wire heating in SPS wire scanner (ferrites and coupler)*

*’Overview of beam intensity issues and mitigations in the CERN-SPS fast wire scanners’. IPAC-2024

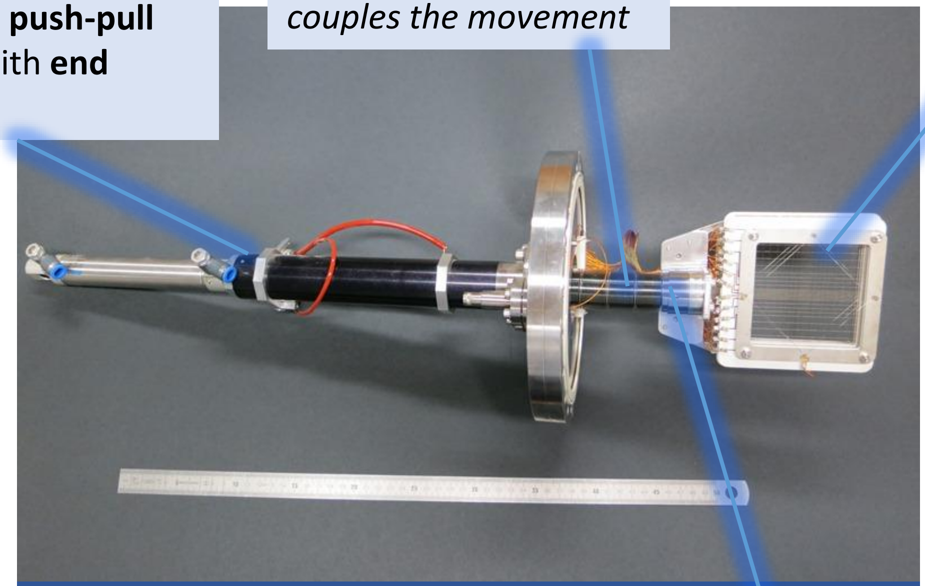
(iii) Deconstructing: wire grid monitor

- Secondary Emission Monitors (SEM)
  - Measures the electrical current produced when the beam intercepts the wires

Pneumatic push-pull *actuator* with **end switches**

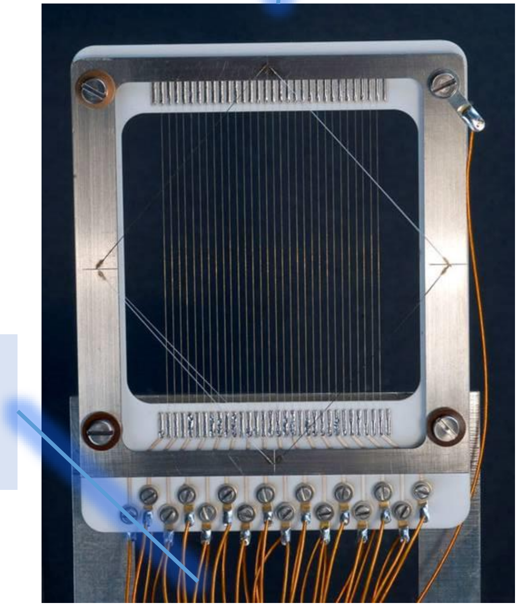
Edge-welded bellows *couples the movement*

Beam intercepting material: **Wire grid** with multiple, independently wired channels

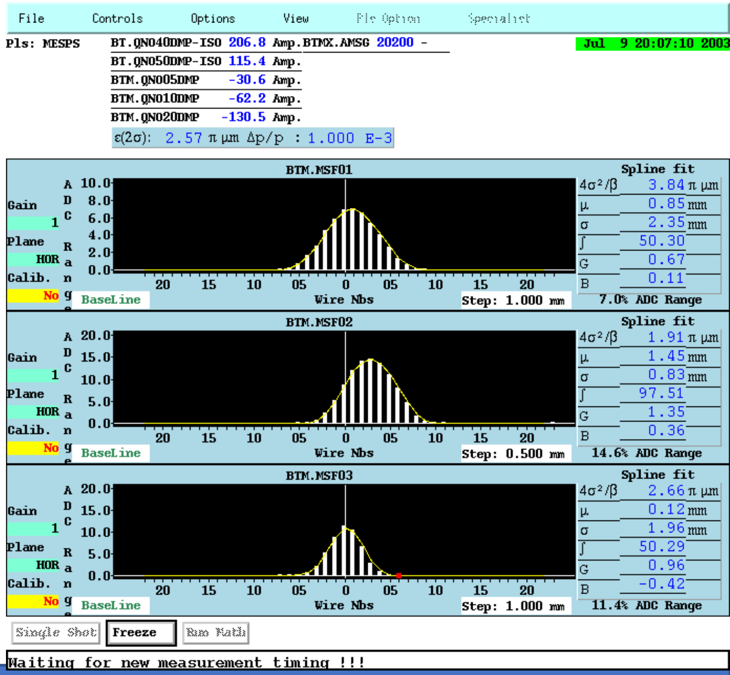


LINAC4 Secondary emission wire grid monitor

Insulated *signal wires* pass through **multi-pin electrical feedthrough**



Direct display of beam profile and intensity



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Pls: MESPS   BT.QN040DMP-ISO  206.8 Amp.BTMX.AMSG 20200 -      Jul  9 20:07:10 2003
             BT.QN050DMP-ISO  115.4 Amp.
             BTM.QN005DMP     -30.6 Amp.
             BTM.QN010DMP     -62.2 Amp.
             BTM.QN020DMP    -130.5 Amp.
             ε(2σ):  2.57 π μm Δp/p : 1.000 E-3

BTM.MSF01                                   Spline fit
Gain 1     ADC 10.0 8.0 6.0 4.0 2.0 0.0     4σ²/β  3.84 π μm
Plane HOR                                   μ      0.85 mm
Calib. No                                   σ      2.35 mm
                                            ∫     50.30
                                            G      0.67
                                            B      0.11
BaseLine   Step: 1.000 mm                   7.0% ADC Range

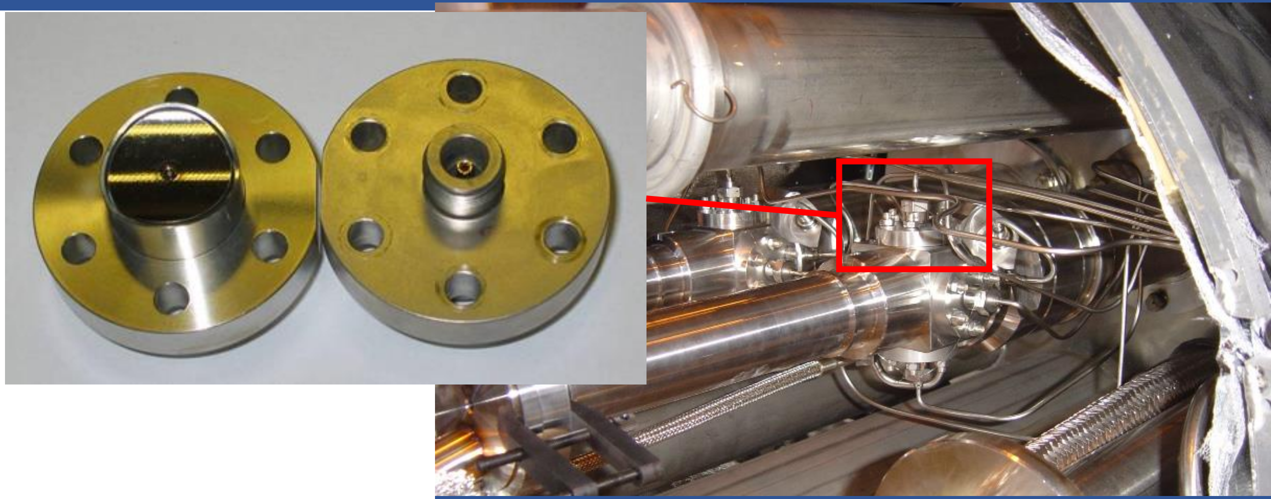
BTM.MSF02                                   Spline fit
Gain 1     ADC 20.0 15.0 10.0 5.0 0.0       4σ²/β  1.91 π μm
Plane HOR                                   μ      1.45 mm
Calib. No                                   σ      0.83 mm
                                            ∫     97.51
                                            G      1.35
                                            B      0.36
BaseLine   Step: 0.500 mm                   14.6% ADC Range

BTM.MSF03                                   Spline fit
Gain 1     ADC 20.0 15.0 10.0 5.0 0.0       4σ²/β  2.66 π μm
Plane HOR                                   μ      0.12 mm
Calib. No                                   σ      1.96 mm
                                            ∫     50.29
                                            G      0.96
                                            B     -0.42
BaseLine   Step: 1.000 mm                   11.4% ADC Range

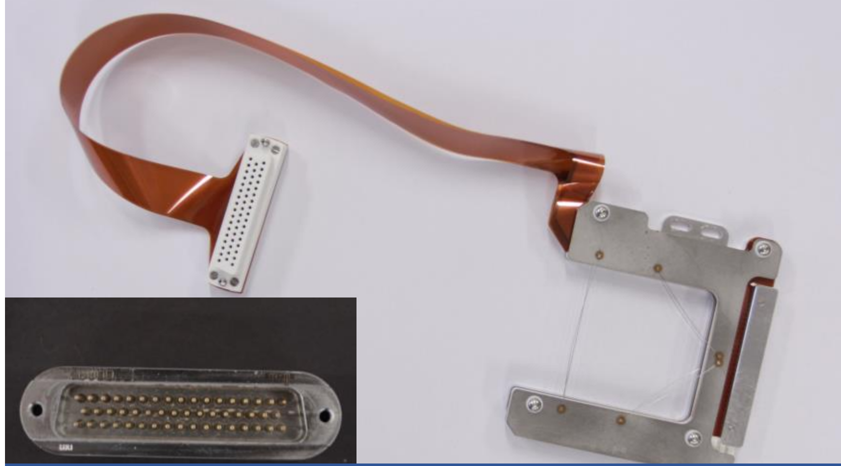
Waiting for new measurement timing !!!
```

Transmit signals: Electrical Feedthroughs

- Variety of signals
  - Electromagnetic/RF, signal, multi-pin,
- Specificities
  - Signal transmission is often linked-to/degrades instrument performance, eg beam pickups
  - Requirement sometimes for ‘as many channels as possible’
- Issues
  - Few manufactuers, and most with no real experience for accelerators, and frequent change in suppliers and their expertise
  - Frequent source of instrument failure
    - Braze leaks after welding, material quality issues,
- Solutions
  - Understand specific functional needs
  - Careful design of weld methods and preparations
  - Supplier selection and qualification
  - Expect some failures, so buy spares!



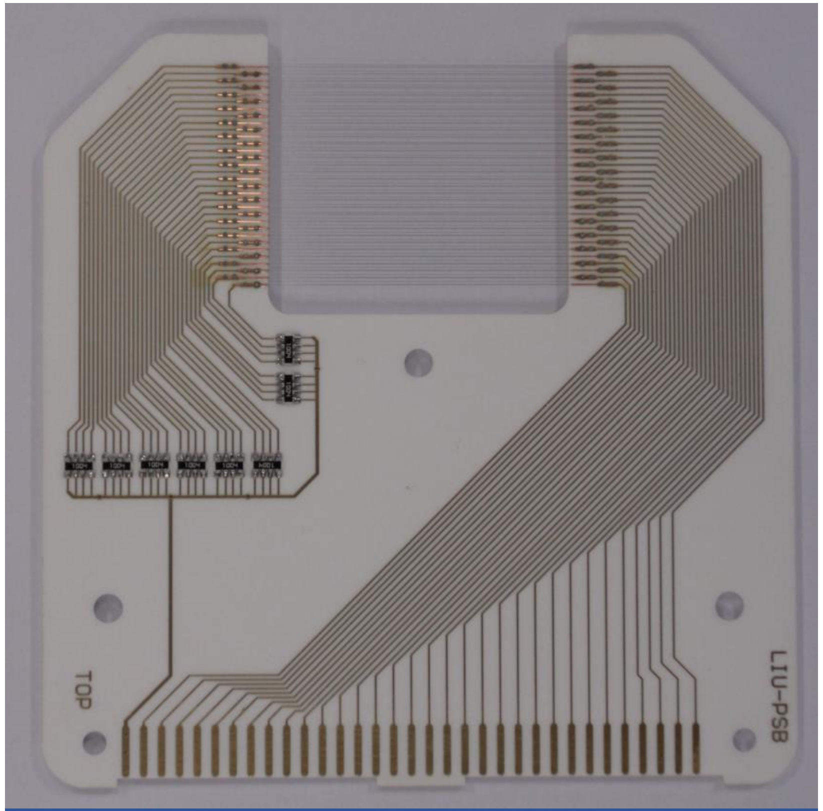
Cryogenic LHC pickups with feedthroughs and cryo signal cables



nToF SEM grid with 64-pin feedthrough

Beam intercepting grid: Micro-mechanics

- Small beam sizes and needs for higher resolutions push towards micro-mechanics
  - Requires special skills and equipment
- Follow the state-of the art in the semiconductor industry
  - Ceramic SEM supports using PCB (photo lithography) methods
  - Specialist wire attachment tooling (bump bonding)
- Synergies also with high-energy physics instrumentation

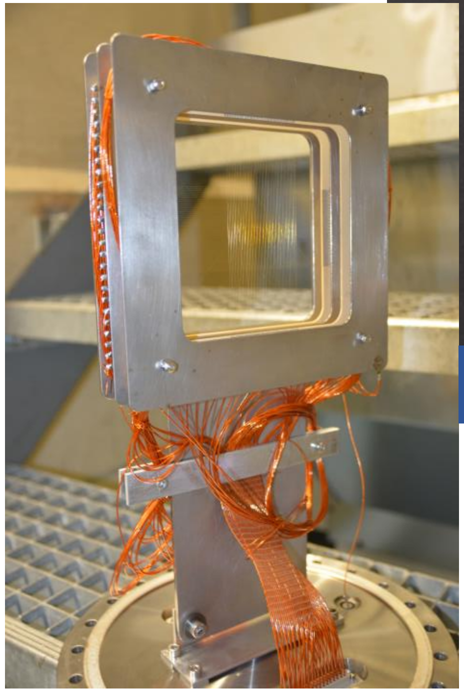


SEM grid with 0.4mm spacing

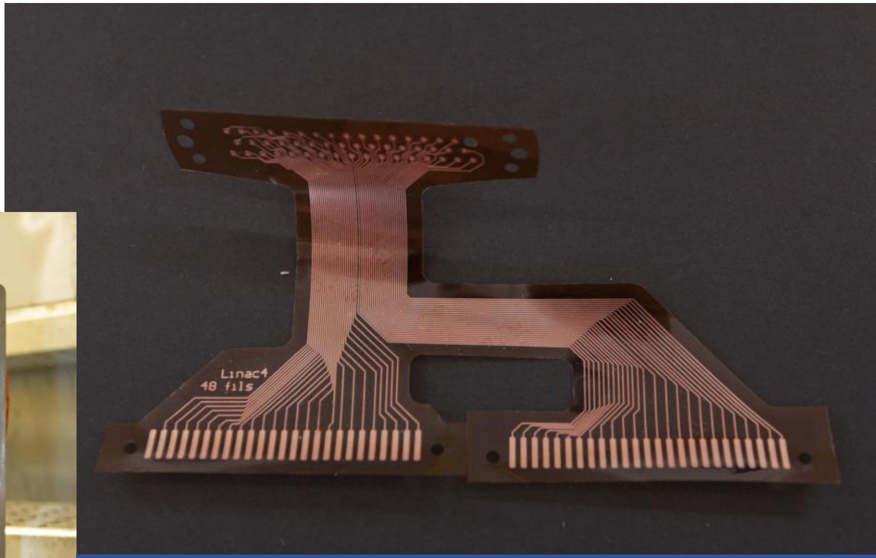
Wire bump bonding machine

Beam intercepting materials: Vacuum compatibility

- Many beam instruments are inherently challenging for accelerator vacuum
  - Large in-vacuum surface/volume ratio and possibilities for trapped volumes
  - Materials are not optimum for vacuum
    - Multiple (polymer) insulated signal wires
    - Detector materials – including semiconductors
  - Instruments operating at elevated temperatures
    - Non-bakeable designs and materials
- Solutions
  - Talk early with vacuum experts
    - Design details for venting surfaces etc.
    - Vacuum degassing treatments, (eg., for ferrites)
    - Incorporate additional local pumping
  - Outgassing testing of proposed materials, plus R&D on new materials
    - Move from individual insulated cables to electro-deposited flex strips



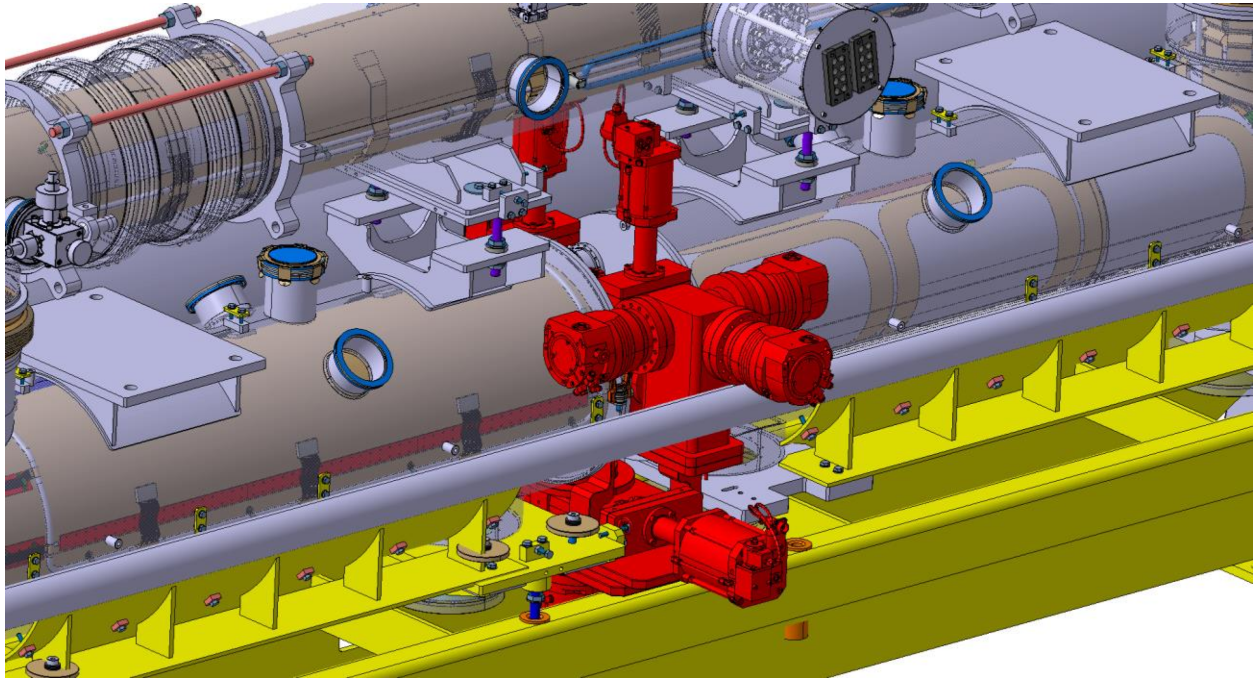
Individual signal cables



…being replaced by 'flex strips'

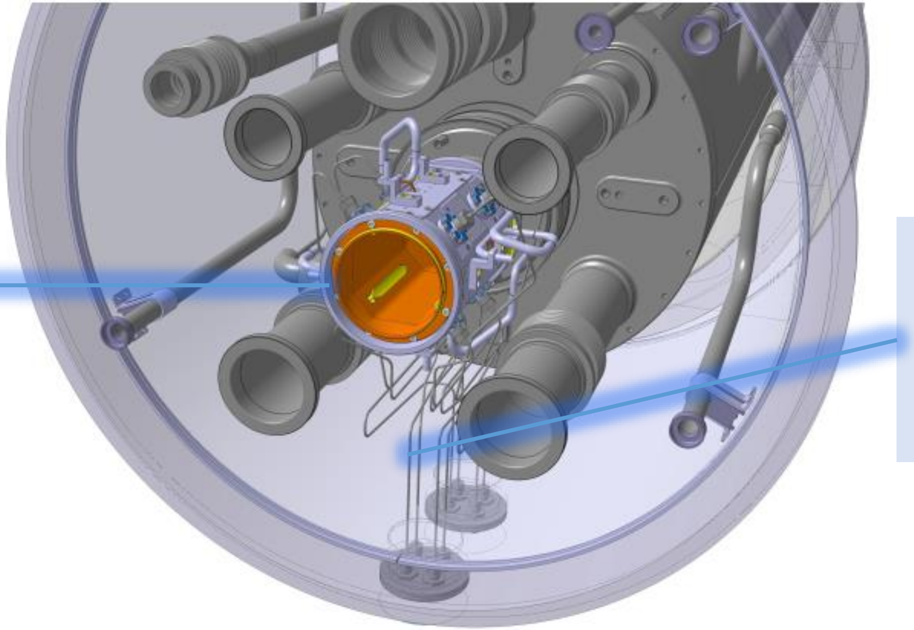
Integration and space

- Integration constraints
  - Beam instruments are normally constrained to be placed in a specific location, either for beam size/geometry or for proximity to other active equipment
- Impact on instrument design
  - Instrumentation is often needed to be inserted in small spaces, or inside other equipment, leading to special component design
  - In some cases, the whole instrument concept is driven by integration constraints
    - Eg, Beam Gas Curtain, specifically designed for use in a strong magnetic field, with a high SR light background, in a very confined space!
- Solutions
  - Know before you start where your instrument will be installed (functional specifications)
  - Plan for simulation and testing with all significant envonmental factors (radiation, temperature, fields, EM noise…)



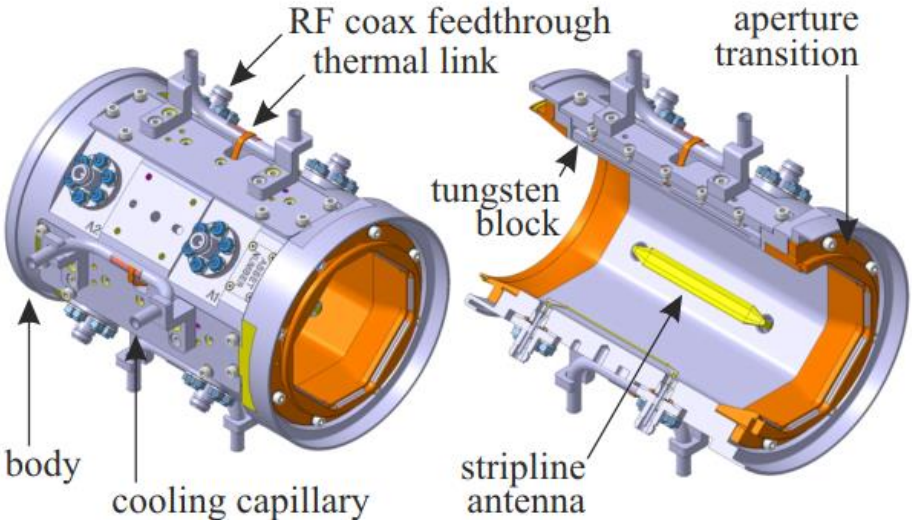
Beam-gas curtain monitor (shown in red) integration study. Designed for installation between two solenoid magnets and within the LHC tunnel environment

Beam instrumentation integration challenge: HL-LHC cold pickups



Beam pickup needs to be installed close to the magnet, inside the cryostat

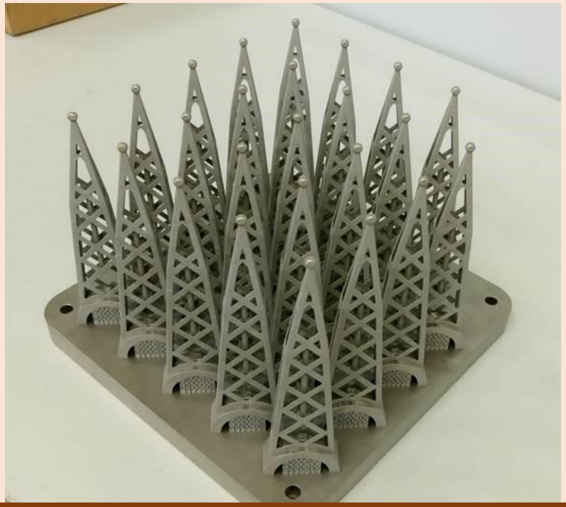
Signal cables are semi-rigid stainless steel tubes with a defined RF performance transmit the signals out to air via an electrical feedthrough



Future of beam instrumentation

- New methods, tools and materials
  - Small physical sizes and small series make beam instruments well-adapted for additive machining
  - Micro (and nano-) scale manipulation opens new doors for high precision, minimally invasive devices
  - New, low-density nano-materials could breathe new life into intensity limited intercepting materials
- Challenges for future machines
  - High brightness (small, intense beams)
    - Favour non-invasive (eg, beam-gas, electro-magnetic) instruments
  - Most planned large next generation machines (FCC, CECP, ILC, CLIC, G4 light sources) are lepton accelerators
    - Differences in instrumentation needs, but many mechanics challenges are the same
    - Very large machines need new thinking to optimize production methods

Topological optimisation to optimise mass and inertia for the rigid forks



Cost-efficient series production in titanium using 3D additive machining

Summary

- Beam instrumentation is a very diverse field
  - Large number of instruments across all accelerator rings, transfer lines and extraction lines
  - Variety of measurables and technology
    - I have tried to pick-out some engineering-specific **Beam Instrumentation technologies** and common **(recurring) issues**
- You cannot be an expert in it all
  - Even when restricted to the mechanical instrument, it is difficult to be an expert in every aspect
    - You need to develop **friends with other competencies**
    - There is a high degree of **collaboration** between different institutes
- The push towards more powerful, precise machines continually drives this exciting field
  - "An accelerator is only as good as it's instrumentation"

Thank you for your attention

Thanks for material from:
Benjamin Moser, Gerhard Schneider, Christophe Vuitton, Chiara Pasquino, John Huber, Stephane Burger, Peter Forck, Thibaut Lefevre, Rhodri Jones, Mariusz Sapinski, Alexandre Mariet, Gerard Aliana Cervera, Benoit Salvant, Christine Vollinger, Hikmet Bursali

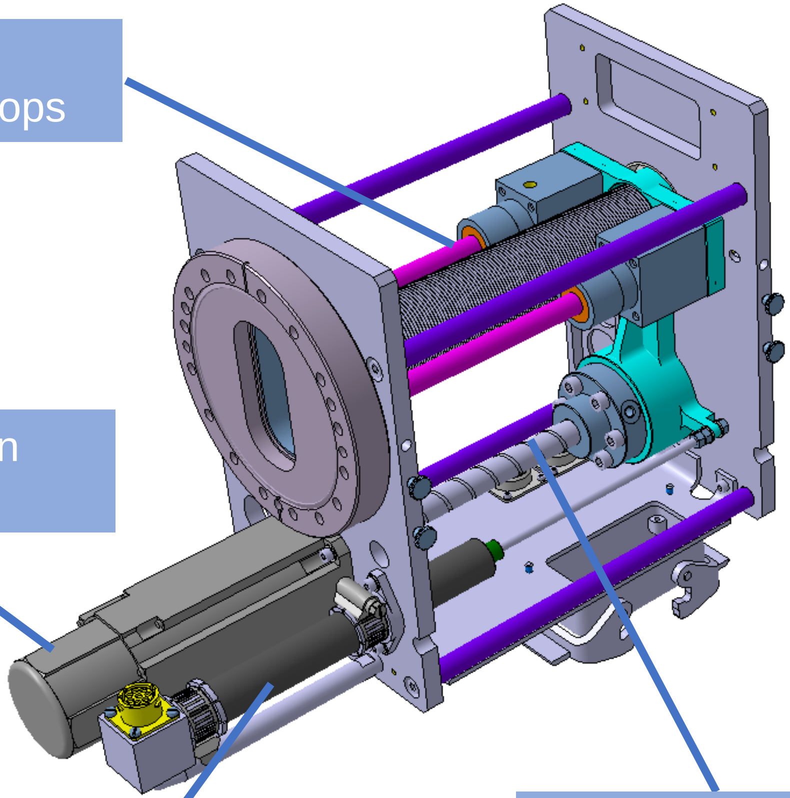
Plus, of course, all of my friends and colleagues in this field around the world.

Useful resources

- CAS School ‘Introduction to Accelerator Physics’ October 2021, P.Forck’s talk on BI
    - https://indico.cern.ch/event/1022988/
- ARIES workshop on ‘Materials and Engineering Technologies for Particle Accelerator Beam Diagnostic Instruments’ June 2021
    - https://indico.cern.ch/event/1031708/timetable/#20210621
- MEDSI Conference ‘Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation’
    - https://www.medsi2025.com/
- CERN Workshop on ‘Low density materials for beam instrumentation’, June 2023
    - https://indico.cern.ch/event/1275649/

Generate and control movement

- Motion systems
  - Stepping motors
    - Typically 200 steps/revolution, allowing also for position measurement
  - Permanent magnet synchronous motors (PMSM)
    - Modern, small, controllable
  - Pneumatic actuators
    - For push-pull applications
- Transmission
  - Ball screw/worm drive
  - Guiding shafts
  - Reducers/gearing
  - Bearings/sliders
- (Mechanical) control
  - End switches
  - Adjustable stops
  - Torque couplings
- Comments:
  - These are normally commercial (radiation resistant) components
  - End switches/couplings protect your system from control and software issues



Guide shafts with adjustable end-stops

PMSM with built-in position resolver

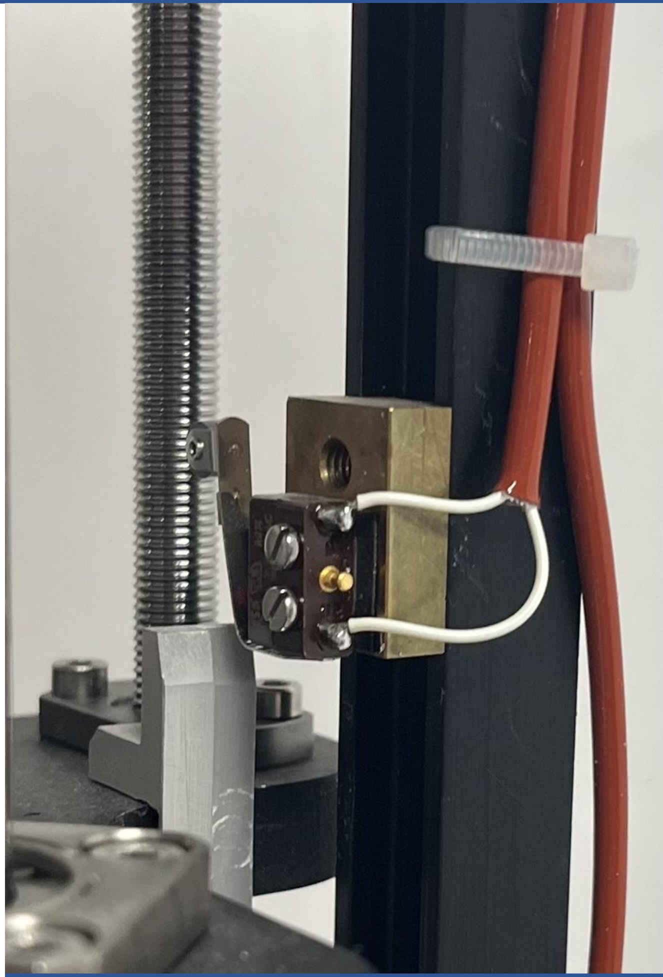
Ball screw driven by PMSM

Linear encoder for precision position measurement

‘Hybrid’ LHC wirescanner design components

Precision position measurement: Switches

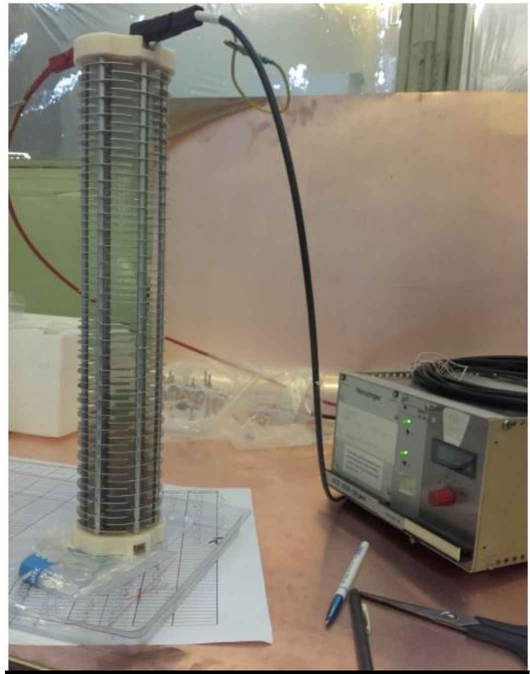
- In-out instruments
  - Many moveable instruments just move between ‘in’ and ‘out’ positions, eg, screens, grids
  - These can rely on end stops or switches that are linked to external references by feudalization before installation
- Scanning instruments
  - Some instruments rely on the precise position of the detector as part of the measurement, eg. Wire scanners, slits
  - Where the drive is mechanically linked to the detector, the position measurement can be on the air-side
  - Where there is some compliance, the measurement must be made at the detector head, ie., in vacuum
- Technical solutions
  - Rad-hard switches, and position transducers exist in commerce for air
  - Some vacuum compatible solutions, exist, but with limited application



LINAC4 wire scanner end-switch

Beam loss monitor ionization chamber production

- CERN is planning a new production of ionization chambers
  - This consists of precise aluminium discs mounted on ceramic supports for ~10 keV electrical operation, inside a chamber with partial gas pressure
- Production tooling for large series
  - As some ‘000s of chambers are needed, a series production tooling will be procured with vacuum, heating and gas injection

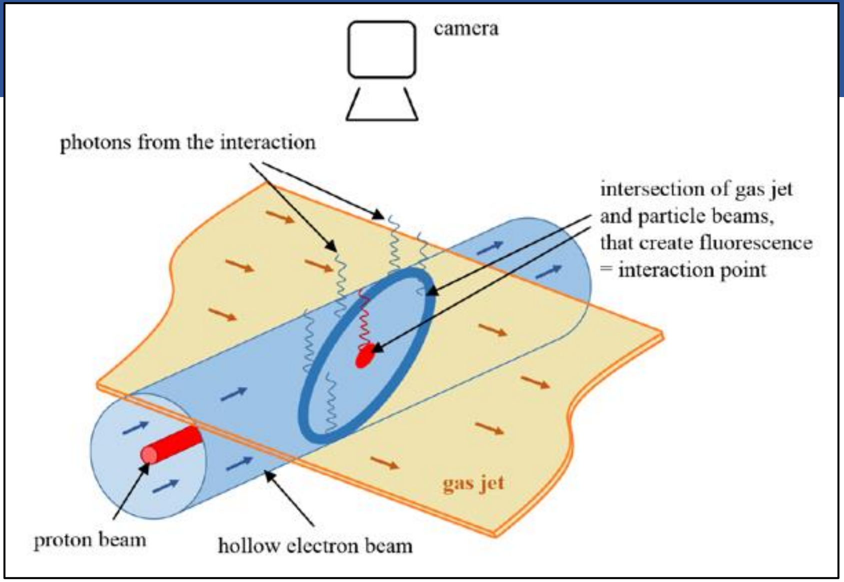

Internal structure

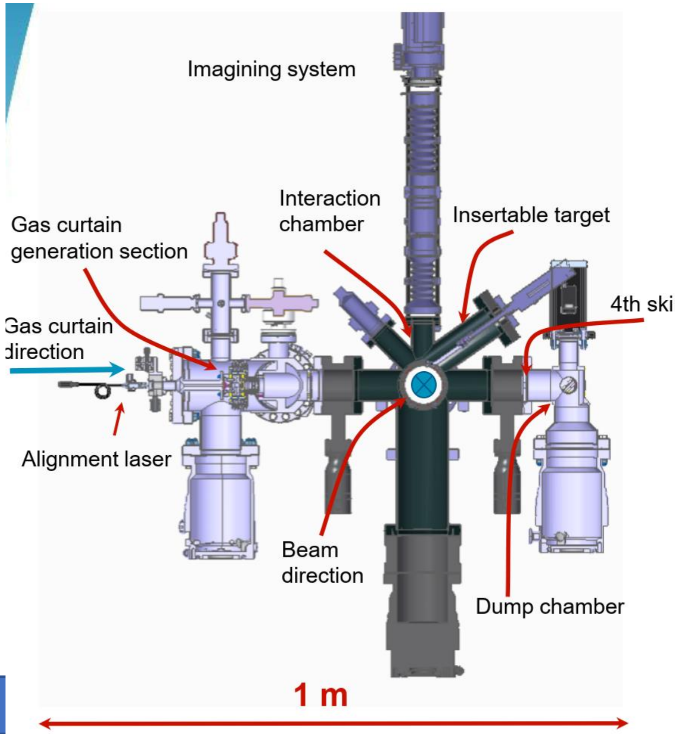

Ionisation chambers in the LHC tunnel


Production tooling

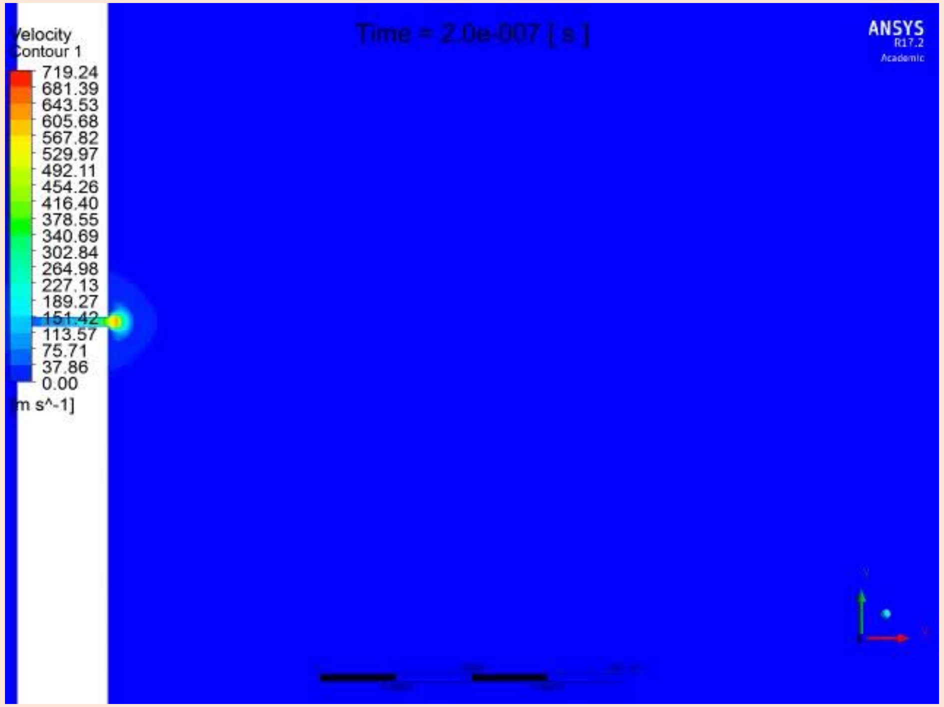
Beam Gas Curtain

- The challenge:
  - Monitor the ‘overlap’ between coaxial LHC proton beam and a ‘hollow’ electron beam, used for beam cleaning
  - The whole instrument must be integrated and operational adjacent to a superconducting solenoid which maintains the hollow electron beam
- The technique:
  - A 2-D gas ‘screen’ crossing the beams at 45° creates beam-induced which is directly observed by a camera
- A supersonic gas jet
  - The selected gas is expanded through a nozzle then passed through 3 micro-machined skimmers to shape the quasi-2D curtain 12 orders of pressure lower within the ultra-high vacuum of the LHC. The gas curtain molecules are then collected in a dump
- Optical system
  - State of the art blackened surfaces to minimize SR light background. Ex-vacu optical system with intensified camera using single photon counting and image analysis

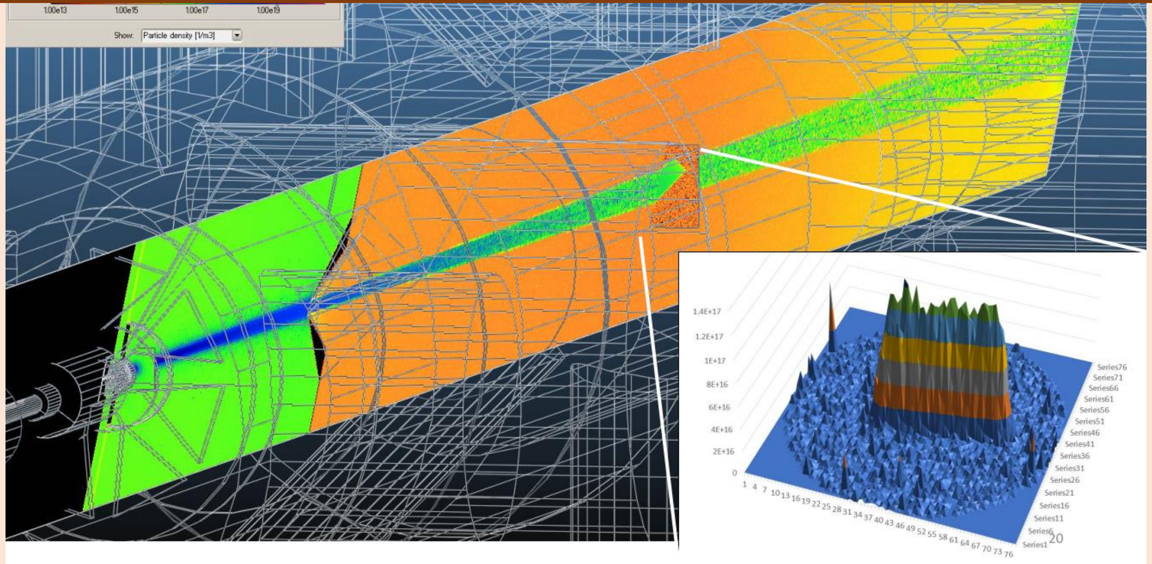


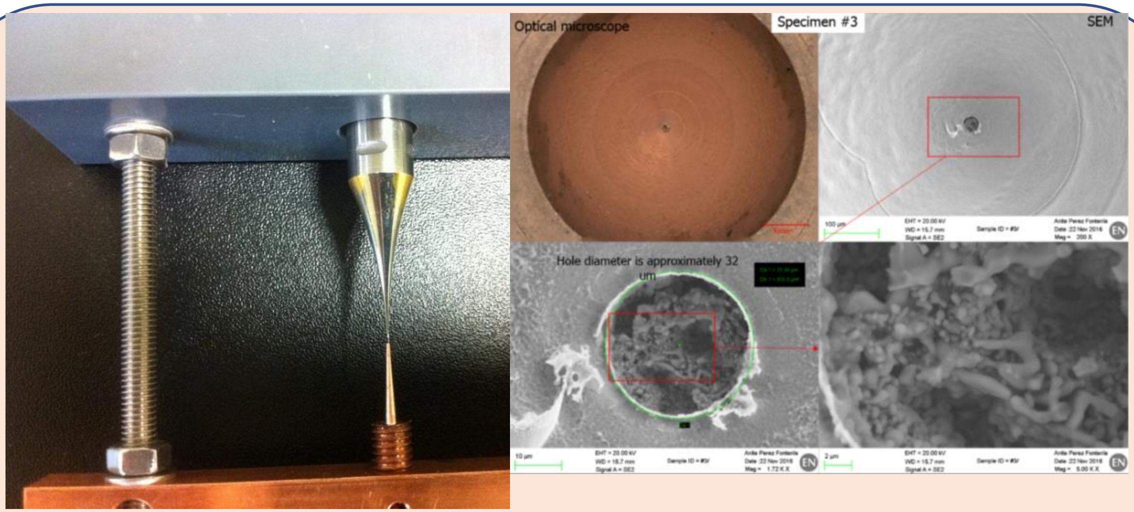


Computational fluid dynamics calculations of gas jet expansion

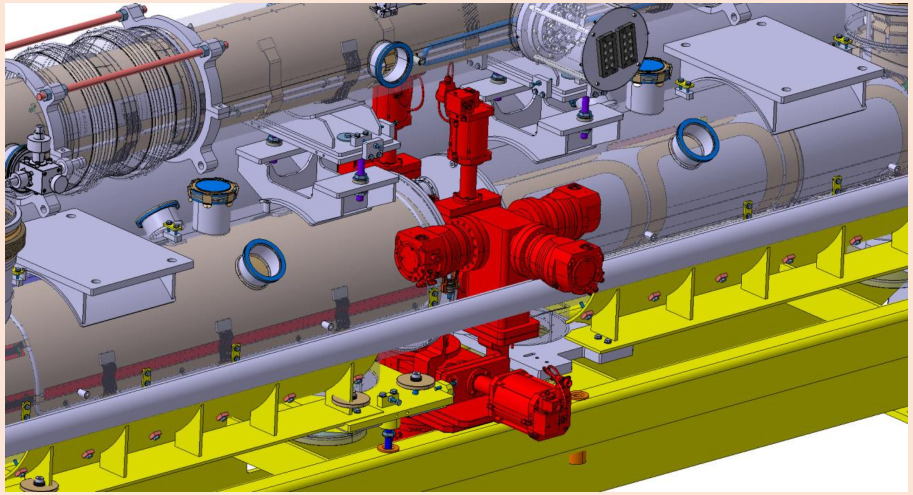


Monte-Carlo molecular flow simulations of gas skimming, with predicted gas curtain geometry





Development of 30 µm convergent-divergent nozzle



Instrument integration into a very tight space in the LHC tunnel