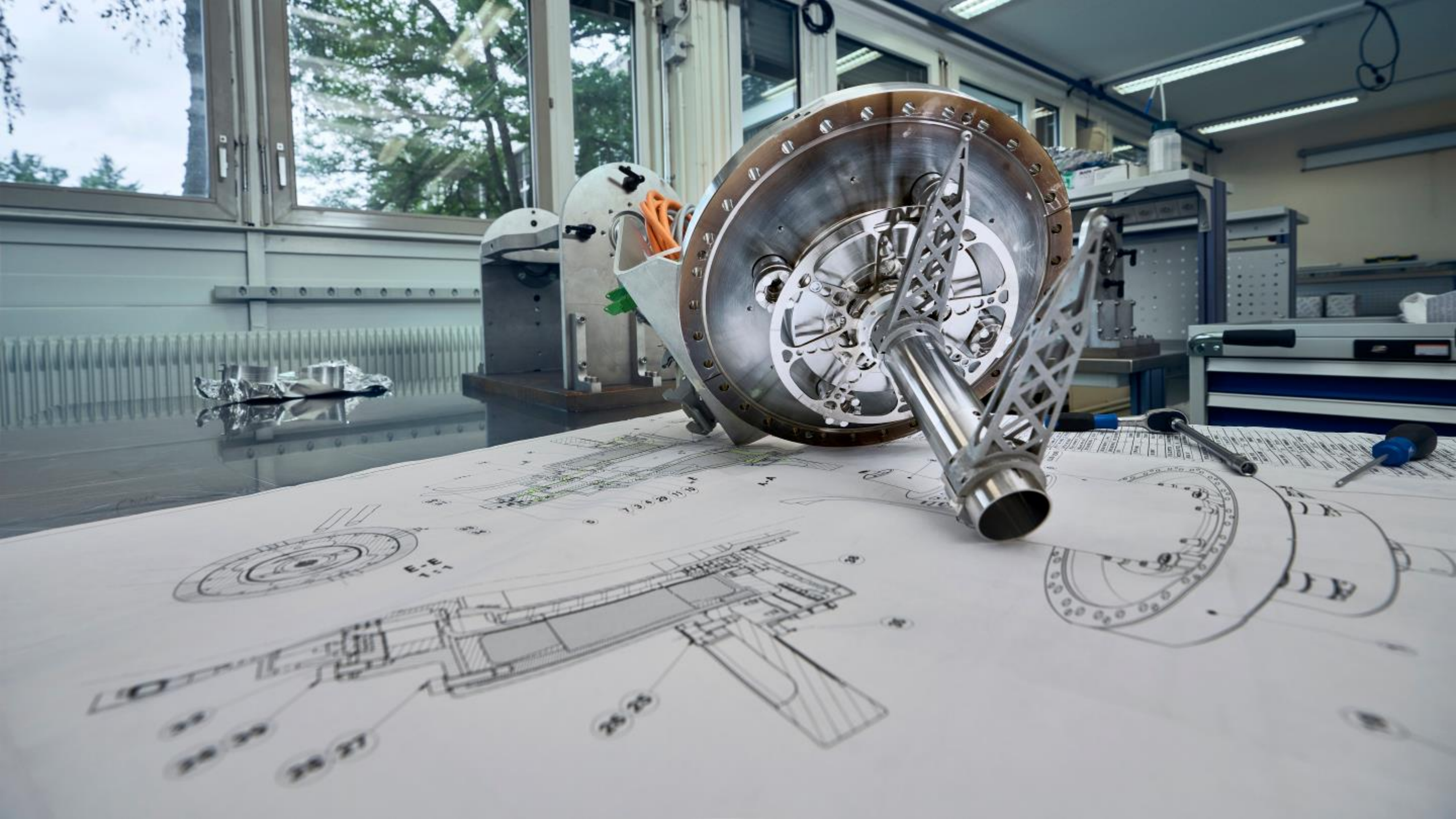

A-A
E-E
1:1

Wire scanners for the HL-LHC era

Ray VENESS / BE-BI

With many thanks to:

Aurelie GOLDBLATT, Dmitry GUDKOV, Anton LECHNER, Alexandre MARIET, Ioannis PAPAZOGLOU, Federico RONCAROLO, Georges TRAD,

Wire scanners for HL-LHC

- Primary aim is to keep a working system suitable for calibrating other instruments
  - Control system is being consolidated with the new LIU electronics
  - What is the 'operability' status of the instrument mechanics?
  - What will be required to maintain required performance for HL beams?
- Then, if we are making changes, what should we do?
  - What are the options for a replacement instrument?
  - What performance can we expect to achieve?
- What are the future expectations for performance improvements?

Overview

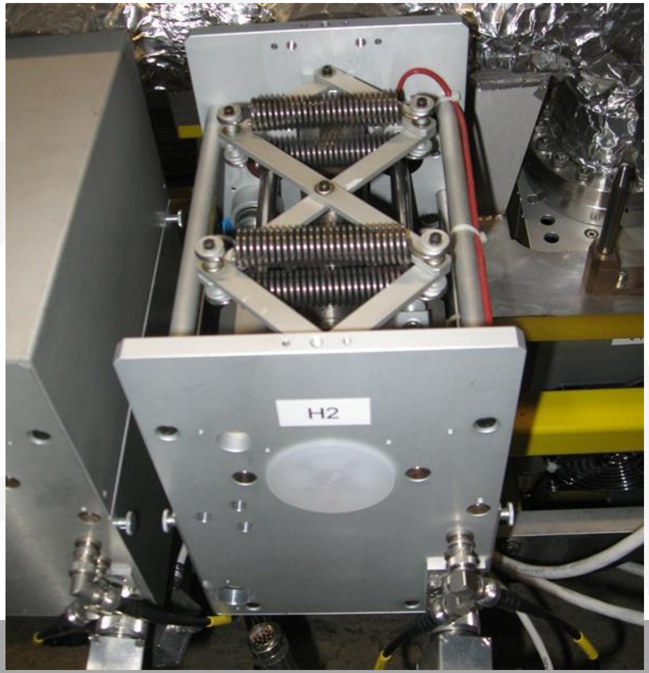
- Status of the existing wire scanner mechanics
- Options for a replacement
  - Upgraded linear scanner
  - LIU fast rotary scanner
  - Change of location or shielding of magnets
- Operational limits for HL-LHC
- Improving the operational reach of scanners
  - Multiple fast scans
  - Wire studies
- Summary and conclusions
- Future work and resources

Identification of the problem

Bellows leak in 2012, attributed to fatigue in the original bellows after 10’000+ cycles

Bellows were re-designed for 40’000 cycles, but this caused an issue with the ‘pantograph’ springs that took many man/months to fix

- Identification of the problem
  - BI, VSC piquet and RP piquet went into the machine at 01h00
  - A leak was rapidly localised in the 5R4.B1.H2 scanner
  - Leak appears to be near the non-beam end of the long edge-welded bellows which allows for the linear movement of the fork
  - Direct access to leak location not possible

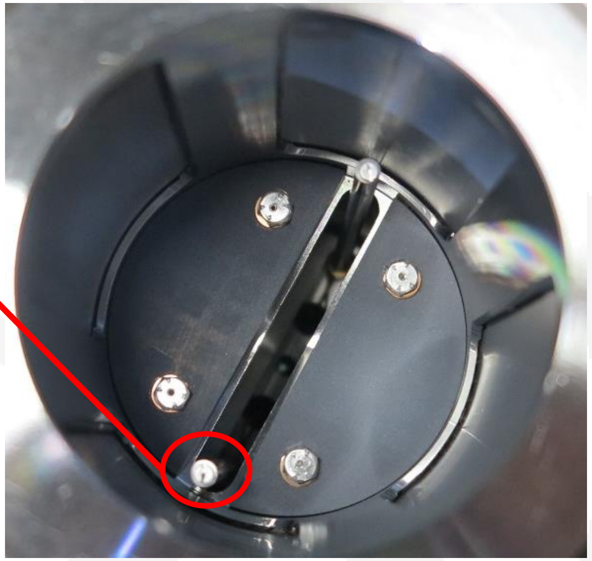


BWS Ferrite and Holder Issue

- **2015 issue**
  - Contact between fork and ferrite holder stopped BWS operation in B1-H1 in April 2015 (see LMC 220 of 6/2015)
  - Design issue identified. The clearance between fork and ferrite holder was too small
  - Ferrites and holders in all 4 Beam 1 scanners were corrected during YETS 15-16
  - Beam 2 scanners were not modified during the YETS, so this is an outstanding action

Movement was blocked by interference between the fork and the ferrite holder.

The ferrite holder was re-machined to increase the clearance, but this was a 'quick fix' for a fundamental problem with the fork rigidity

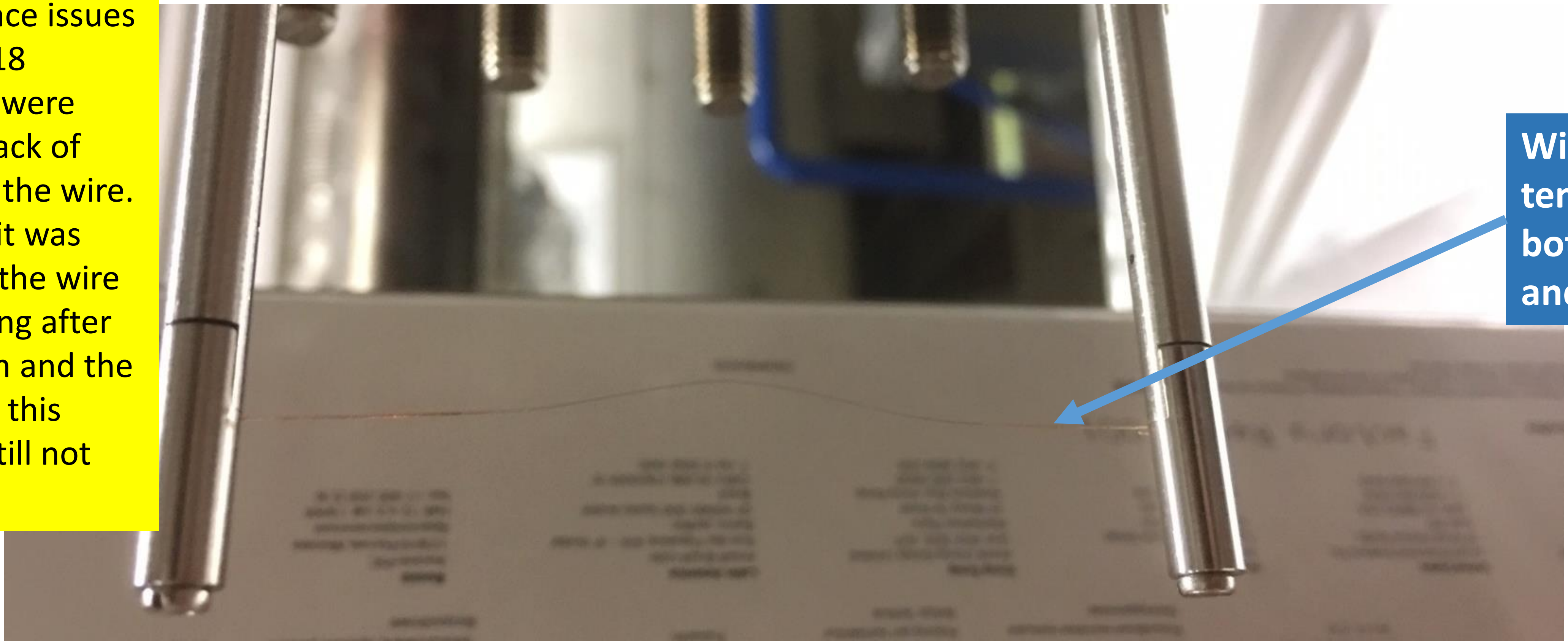


Contact between fork and ferrite holder during 2015 operation

Photo of the scanner, showing ferrites (black) and clearance between fork and ferrite holder

Visual and electrical inspections during LS2

Performance issues during 2018 operation were linked to lack of tension in the wire. However, it was clear that the wire was working after installation and the reason for this failure is still not identified.



Wire not tensioned in both B2-H1 and B2-V2

Wire-scanner B2-H1

Deflection ~= 2,7 mm

Length increase~= +240 µm

Electrical resistance in the wire circuit of both B2-H1 and B2-V2 measured ~30% lower than other six scanners

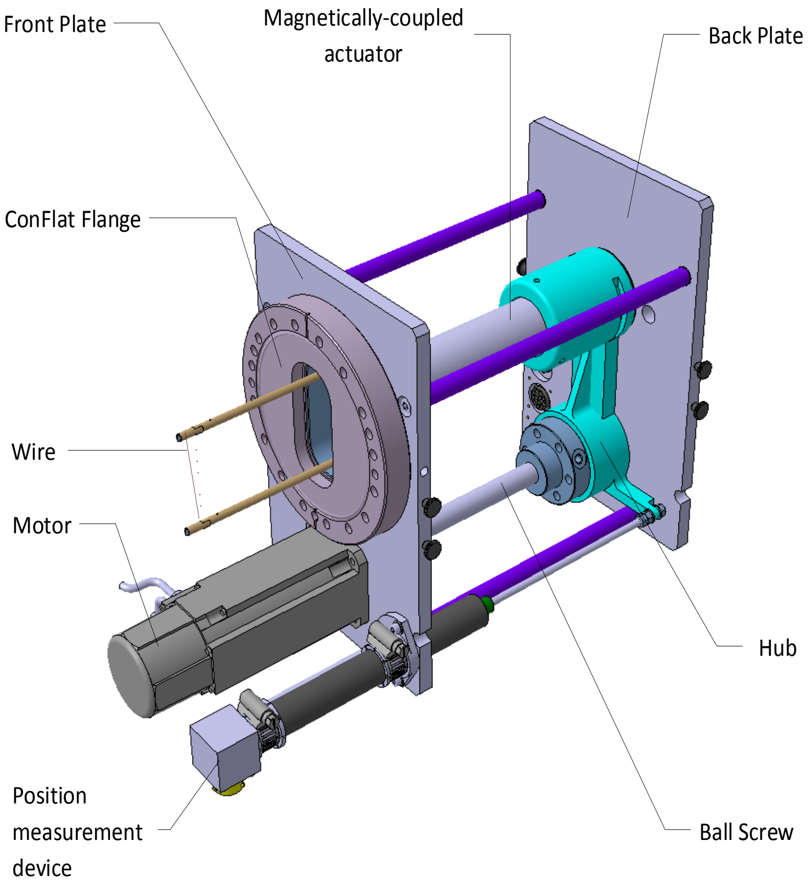
Courtesy A.Mariet/B.Moser / BE-BI

Status of existing wire scanner mechanics

- Current mechanics are a pre-LEP non-CERN designed instrument
  - They have seen three significant mechanical failures in recent years, two resulting in machine stoppage (2012, 2015) and one with reduced performance (2018)
  - In all cases, solutions have been found, but design is shown to be outdated and with ongoing reliability issues
- CONS request for mechanics
  - BI initially request full replacement based on cost of the LIU mechanics starting immediately post-LS2
  - Agreed with CONS to postponed the request for funding to 2022-24 due to manpower and budget limitations
  - Pending approval by CONS

Replacement Option 1: New linear scanner

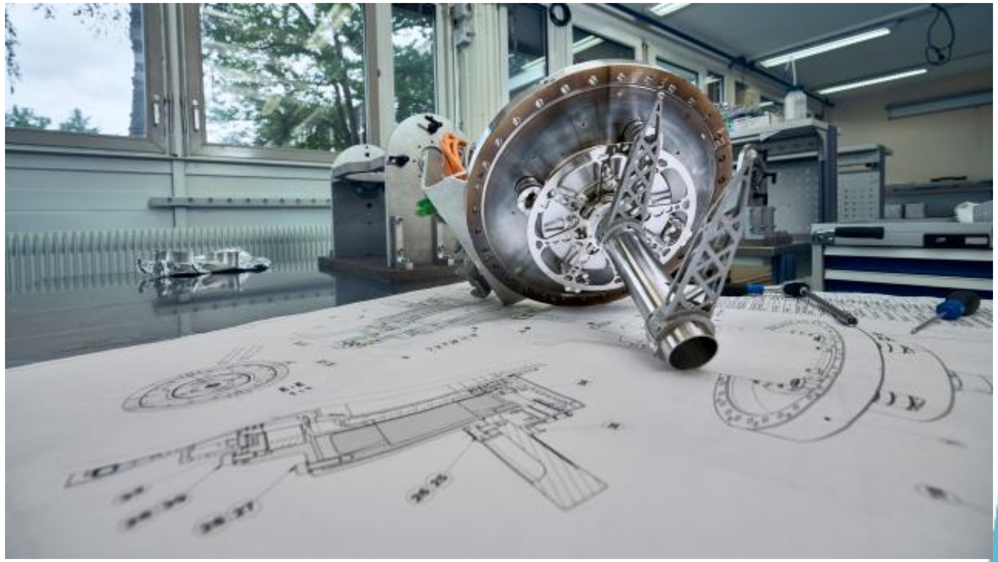
- Advantages:
  - Potentially use new bellows-free technology, modern ball-screw movement and motors
  - Would re-design the forks and in-vacuum components
  - Relatively inexpensive to manufacture
  - Possible compatibility with existing structures and vacuum system
  - Can be made compliant with new LIU control electronics
- Disadvantages
  - Will require full new LHC-specific instrument design and validation
  - Likely to be always be limited to ~1 ms^{-1}



Preliminary study of a new bellows-free linear scanner (Courtesy D.Gudkov)

Replacement option 2: LIU Scanner

- Advantages
  - Any scan speed upto 20 ms^{-1} achievable
    - Native instrument precision is consistent with HL demands for 1-2% absolute accuracy at 7 TeV, even at 20 ms-1
    - High scan speeds improve the magnet quench constraint
  - New, state-of-the-art design
    - Prototypes tested in all injector rings, 17 being installed for LIU
    - Fully compatible with new consolidated control and acquisition electronics
- Disadvantages
  - LHC compatibility of LIU instrument
    - Designed with LHC in mind, but will need review/changes for vacuum and impedance
  - Unit cost higher than a 1 ms^{-1} instrument
  - Issue with scan speed vs. rotation frequency



Scanning speed (rads.s^{-1})	Average wire position error (um)	Standard deviation (um)
55	2.2	1.2
110	2.5	0.9
130	4.4	2.1

Average wire position measurement error for 8 LIU-PSB scanners (total 2400 scans). Courtesy A.Goldblatt

Other possible options (in combination with 1 or 2)

- Move the scanner
  - Move to a location less sensitive to particle showers or quench
    - Further from SC magnets, in a collimation IR…
  - Would require studies for:
    - Possible gains in quench limits for nearby magnets
    - Measurement errors due to optics transfer to IR4 instruments
- Shield the SC magnets
  - Add downstream shielding to protect from particle shower
  - Would require studies for:
    - Shielding performance optimisation
    - Design and Integration of new shielding

What are the operational limits for HL?

- Extrapolating scenarios in-use today imply:
  - Safe scans of ~6 bunches for HL flat-top for a 1 ms^{-1} scanner
  - A single scan at 20 ms^{-1} with same wire would allow ~130 bunches
- Assumption that:
  - Quench limit is independent of scanning speed (!!)
- Similar extrapolations can be made at injection
  - Gives result that nearly the full beam could be scanned at injection
  - However, wire damage model is unlikely to scale linearly with scanner speed and number of bunches, so more detailed studies required

Currently used 'safe limits' for the number of proton charges that can be scanned in the LHC (courtesy G.Trad):
2.7x10^{13} at 450 GeV [wire damage limit]
1.5x10^{12} at 6.5 TeV [magnet quench limit]

Beam energy	**Safe number of bunches**			
	Run 2 @1 ms^{-1} (1.2x10^{11})	End run 3 @1ms^{-1} (1.8x10^{11})	Run 4 @1 ms^{-1} (2.3x10^{11})	Run 4 single @20 ms^{-1} (2.3x10^{11})
450 GeV	225	150	117	(2348)
6.5 TeV	12	8	6	130

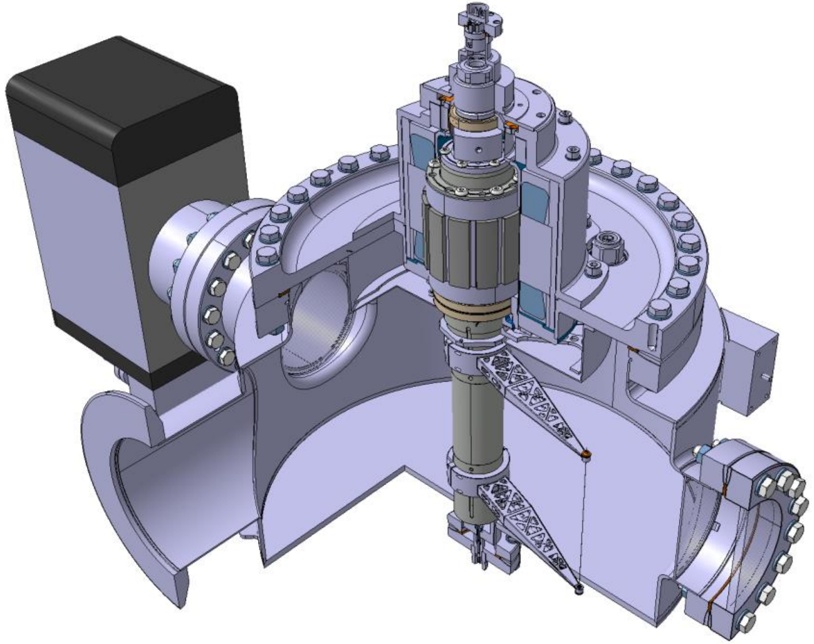
Operational Scenarios with a 20 ms-1 scanner

- Accuracy limitations due to accelerator rotation frequency
  - To obtain accurate bunch-by-bunch measurements, a given bunch must pass the wire a number of times (~3+ per beam sigma) to reconstruct a profile
  - This condition is just fulfilled at 1 ms^{-1} for the small HL beams at top energy, but a single scan at 20 ms^{-1} would not yield enough points for a profile
- Re-construct multiple scans?
  - The new LIU scanner mechanics is designed to rotate freely, so it could scan the beam twice per rotation and continue spinning, performing 20 scans in ~0.5 seconds
    - Could make bunch-by-bunch with less than 20 scans by synchronising rotation frequencies
  - This data could be reconstructed to produce bunch-by-bunch profiles with the same accuracy as a 1 ms^{-1} scan, or greater with more rotations
    - Assuming no losses from reconstruction, beam jitter etc.

Points-per-sigma (pps) obtained by a single scan at different speeds for injection and top energy beam size (σ)

Speed	1 ms-1	20 ms-1
σ= 0.9 mm @450 GeV	10 pps	0.5 pps
σ= 0.26 mm @ TeV	2.9 pps	0.15 pps

LIU wire scanner in a vacuum tank (part-section)



Ray VENESS, Beam Size Review, October 2019

Inelastic collisions of beam protons in the wire

Assuming the wire moves with constant speed v_w through the beam, the **total number of inelastic proton-nucleus collisions in the wire per scan,** N_i, can be expressed as:

$$N_i = I_b \frac{f_r d_w^2 \pi \rho_w N_A \sigma_i}{4 v_w M}, \tag{1}$$

where:

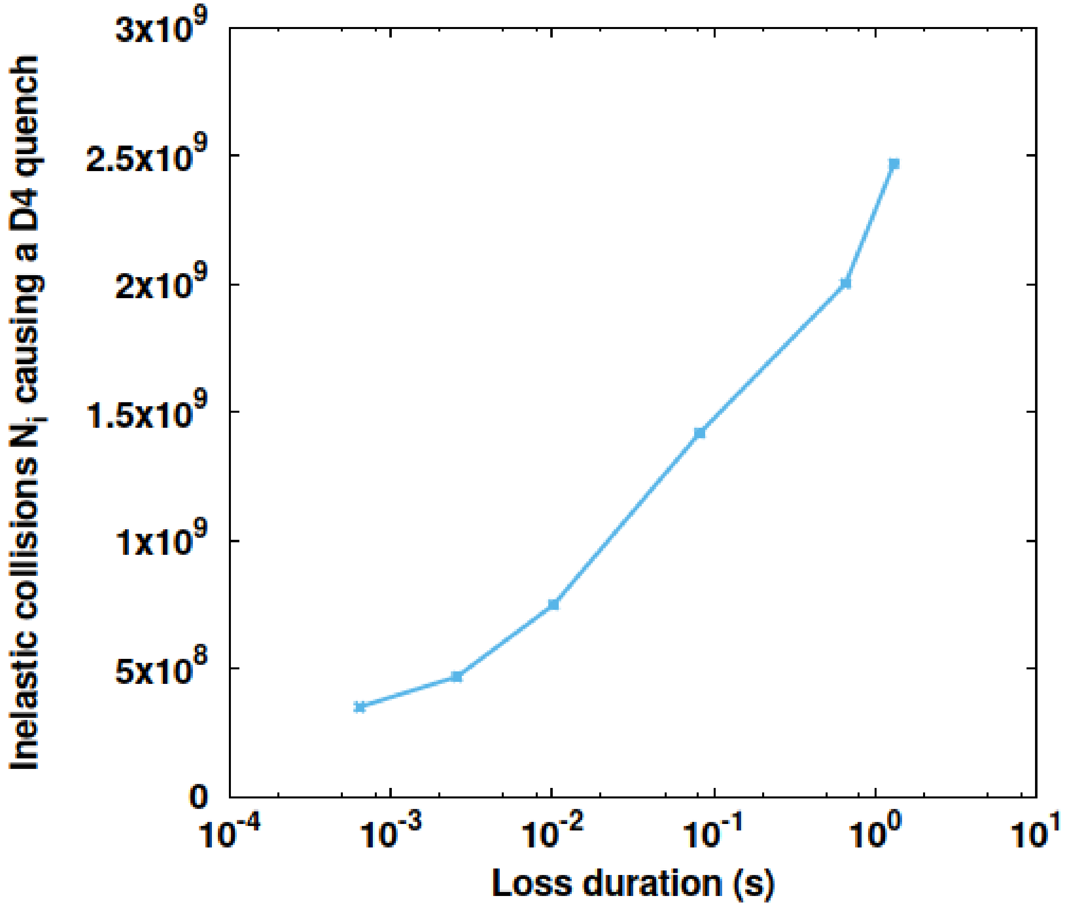
- I_b is the number of circulating protons,
- f_r is the LHC revolution frequency (11245 Hz),
- d_w is the wire diameter,
- M is the molar mass of the wire material,
- ρ_w is the wire density,
- N_A is the Avogardo constant ($6.02214086 \times 10^{23}$ mol^{-1}),
- σ_i is the inelastic nuclear cross section of beam protons in the wire.

(note: the wire is assumed to be round)

Slide courtesy of A.Lechner (PRELININARY)

Number of inelastic collisions in the wire leading to a quench

Assuming the wire scanner remains at the present location (about 35 m upstream of the D4 in IR4) then the number of proton-nucleus collisions in the wire, which lead to a D4 quench, is given by (as a function of the loss duration):



Simulation based on quench level calculations with the QP3 code (A.Verweij), performed by B.Auchmann.
Combined by A.Lechner with FLUKA simulations to translate quench level into inelastic proton collisions.

Slide courtesy of A.Lechner (PRELININARY)

Example 1 (single scan with the present C wire scanner):

- **Assumptions**:
  - Round carbon wire with a diameter of 34 μm and a density of 1.63 g/cm^3
  - Scanning speed of 100 cm/s (loss duration roughly 0.5 ms)
  - Inelastic cross section for 7 TeV proton collisions with carbon nucleus: 267 mb

$$N_i = I_b \frac{11245\,[s^{-1}] \cdot 0.0034^2\,[cm^2] \cdot 3.1415 \cdot 1.63\,[g \cdot cm^{-3}] \cdot 6.02214086 \times 10^{23}\,[mol^{-1}] \cdot 267 \times 10^{-27}\,[cm^2]}{4 \cdot 100\,[cm \cdot s^{-1}] \cdot 12.0107[g \cdot mol^{-1}]}, \tag{2}$$

$$= I_b \cdot 2.25 \times 10^{-5} \tag{3}$$

- **Which beam intensity I_b can be scanned without quenching (at 7 TeV):**
  - Number of inelastic collisions leading to a quench: 4×10^8 (see plot on previous page)
  - Using above formula, one gets I_b=1.77×10^{13}, i.e. about 80 HL-LHC bunches with a bunch intensity of 2.2×10^{11} protons can be scanned without quenching (no safety margin taking into account)

Slide courtesy of A.Lechner (PRELININARY)

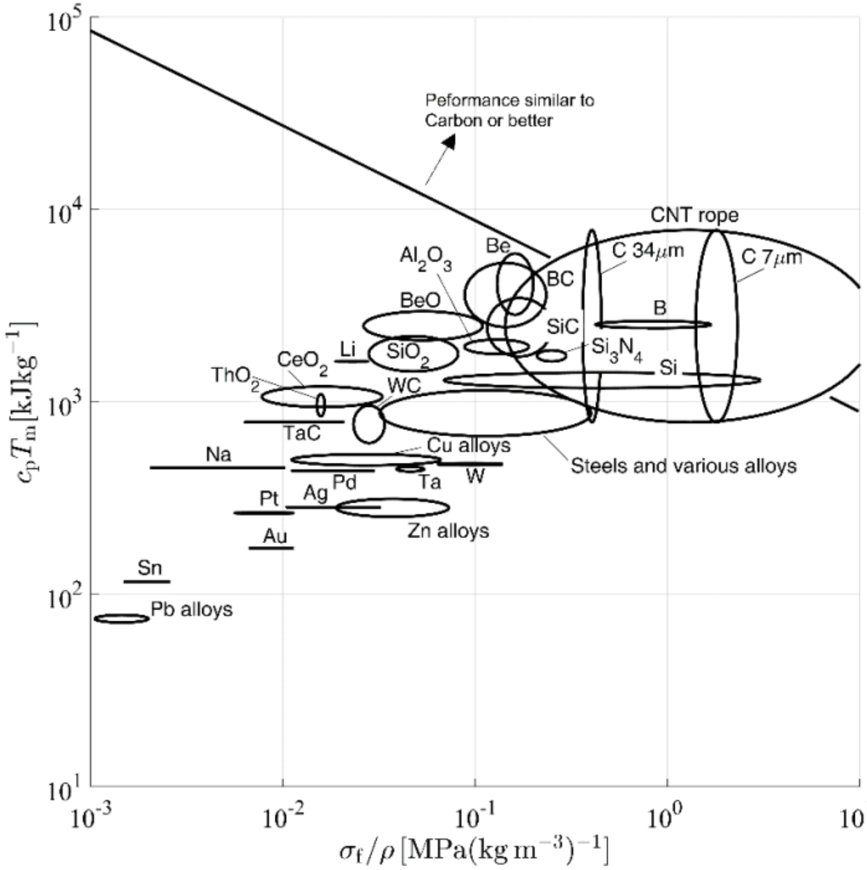
Comparison between ‘safe scans’ and time-dependent simulations

Beam energy	~~Safe~~ number of bunches				
	Run 2 @1 ms^{-1} ($1.2x10^{11}$)	End run 3 @1ms^{-1} ($1.8x10^{11}$)	Run 4 @1 ms^{-1} ($2.3x10^{11}$)	Run 4 single @20 ms^{-1} ($2.3x10^{11}$)	Run 4 20 scans at 20 ms^{-1} ($2.3x10^{11}$)
450 GeV	225	150	117	2348	n/a
6.5 TeV	12	8	6	130	n/a
7 TeV Simulation			80	1600	410

- Preliminary simulations with multiple (20) fast scans, taking into account loss duration suggest that 410/80 = **~5x more bunches** can be scanned compared with a 1 ms^{-1} scanner, whilst achieving the same number of points-per-sigma (pps)
- In addition, multiple fast scans allow for other operational options to balance:
  - Required accuracy (ie, more scans to increase the pps, slower, more precise scans)
  - Wire preservation (ie, many fast scans allow for additional wire cooling mechanisms)
  - Quench levels

Introduction to wire studies

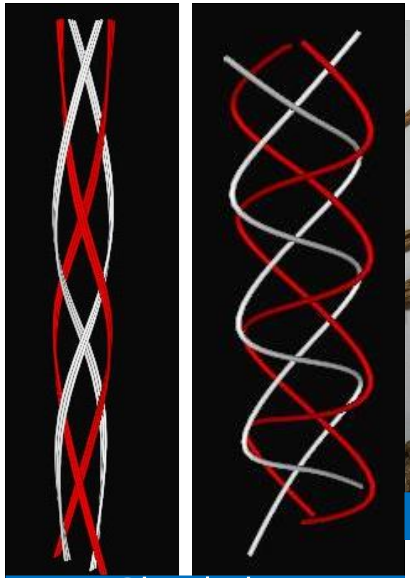
- Change wire material
  - Studes continue to show that carbon has the best combination of low density, low atomic number, good mechanical strength and high temperature resistance
- Reduce wire diameter
  - Quench limit scales with d^{-2}, so smaller is better when there is no issue with signal strength
  - Practical limits on lower diameters due to failure load and manipulation
  - Smaller diameter fibres have a higher tensile strength (UTS), so a braid of smaller wires is a good compromise.
- Improve wire properties
  - Carbon nano-tubes (CNT) have potential for ‘game changing’ lower density and higher UTS
  - Preliminary test in the SPS with the currently available multi-wall long-strand materials
  - Medium-term perspective for long-strand single-walled nano-tubes with impressive mechanical and thermal properties



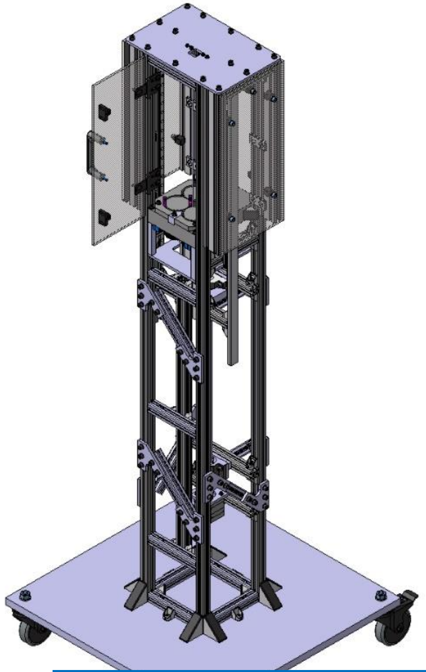
Materials selection chart from an article recently submitted to ‘Journal of Advanced Engineering Materials’

Braided Wires

- Why braiding?
  - Carbon filaments (normal and CNT) are only available in certain diameters
  - Smaller diameters have a better UTS than larger
  - CERN has used ‘twisted’ multiple wires, but difficult to produce and tendency to separate
- Studies, design and construction
  - Studies of optimal wire diameters made with Oxford University collaboration
  - Braid optimisation, machine design and production by HL funded technical student
  - Assembly in progress. Should allow braiding of 3x1 carbon filaments


Simulation


Trials

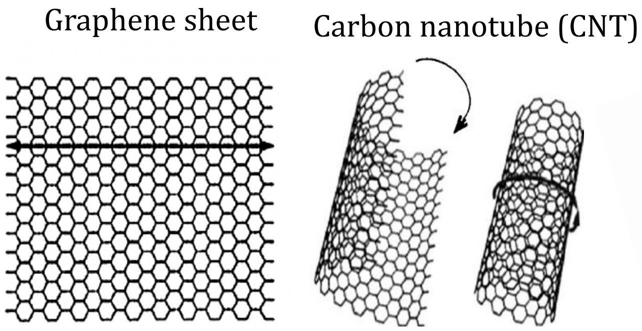

Design


Construction

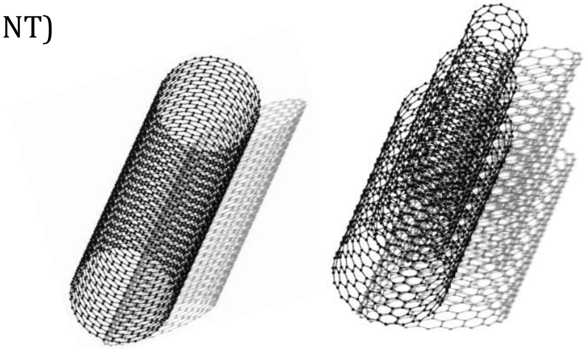
Carbon Nano-Tube (CNT) Introduction

Composed of walls formed by sheets of graphene:

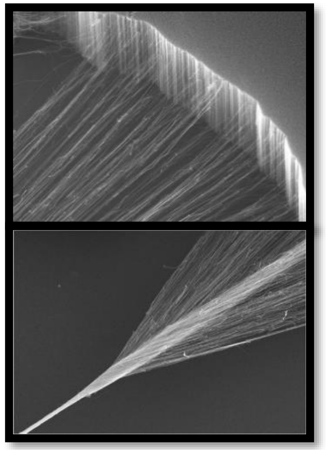
- Several walls -> Multi Wall NanoTube (MWNT)
  - Properties limited by Van de Waals bonding between many short CNTs
  - Density depends on bundle diameter and number of walls
  - Currently available to buy in long spool length
- A single wall -> Single Wall NanoTube (SWNT)
  - Properties defined by inter-atomic bonding
  - Density should be defined just by tube diameter
  - Not yet available in lengths greater than ~ mm, but a major research topic worldwide



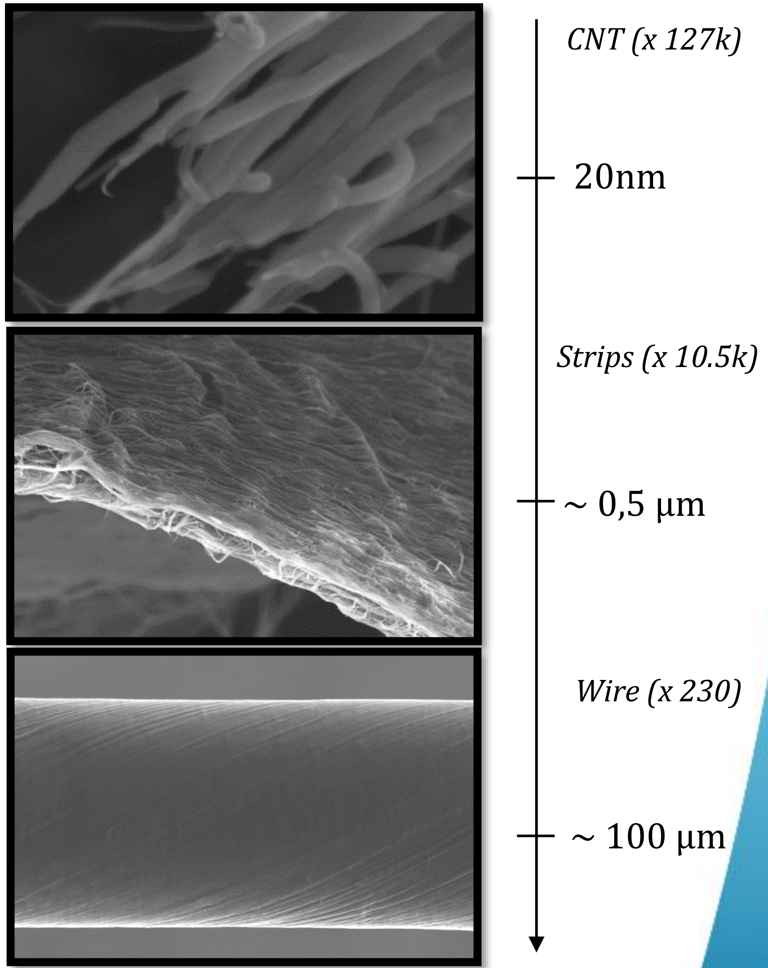
From graphene to CNT [1]



A SWNT and a MWNT



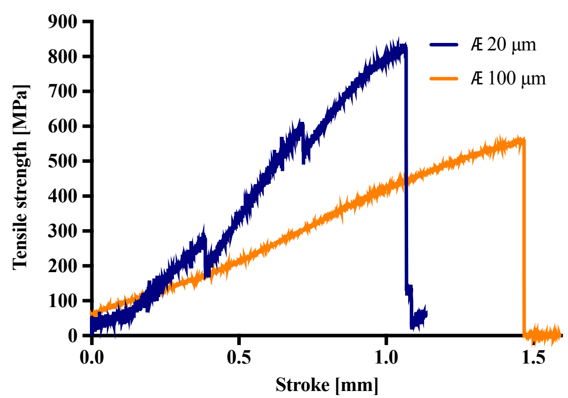
Getting the wire



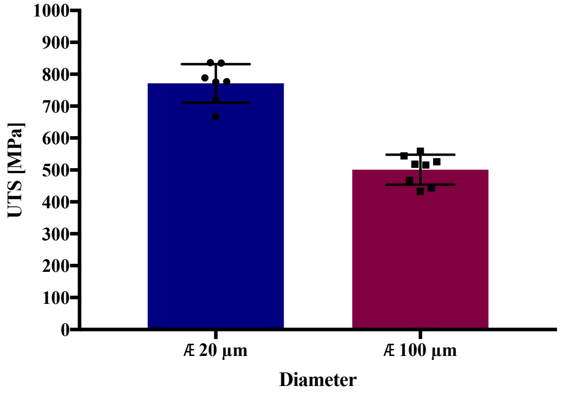
Images M. Meyer (EN/MME-MM)

Slide courtesy of A.Mariet (LIU Fellowship)

CNT tests and future perspectives

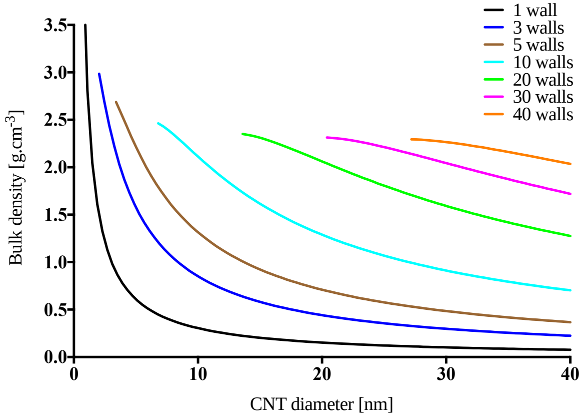


Tensile test curves



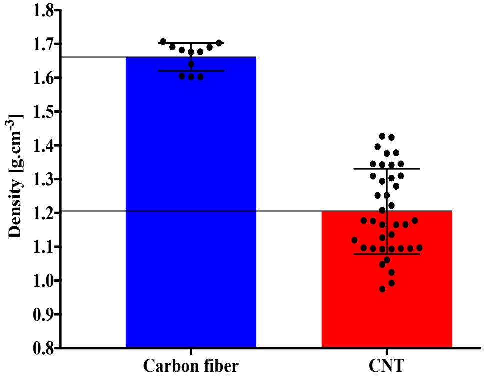
Ultimate Tensile Strength

Mechanical Characterisation of MWNT at CERN (20, 30, 100 um)



Bulk density

Simulations confirm variation of bulk density with number of walls



Preliminary tests with beam in SPS linear BWS show ~factor of 2 lower 'beam density' than existing carbon fibres

Properties of SWNT in the literature– waiting for the development of 20cm long strands

	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	$1.2\text{-}1.8.10^6$

Slide courtesy of A.Mariet (LIU Fellowship)

Summary and Conclusions

- Existing LHC mechanics is obsolete and should be replaced in LS3 at the latest
  - Request made to CONS, pending approval
- Could replace either with the LIU fast rotary scanner or a to-be-designed linear scanner
  - Fast LIU scanner, using multiple fast scans (FMS), will allow more (5x?) bunches to be scanned, but units costs higher
  - Preliminary simulations of FMS also support many more operating options to adjust accuracy, preserve wire and prevent quench
- Wire studies
  - Using braided strands, either of conventional fibres or CNTs allow the failure loads of wires and quantity of material seen by the beam to be optimized. This technology is being prototyped.
  - Carbon still seems the optimum material for high energy and intensity machine scanners
  - Commercial MWNT materials already give a factor ~2 in quench limits compared with existing carbon fibres. Future SWNT (research materials) could give much more.
  - Using braided strands, either of conventional fibres or CNTs allow the failure loads of wires and quantity of material seen by the beam to be optimized. This technology is being prototyped.

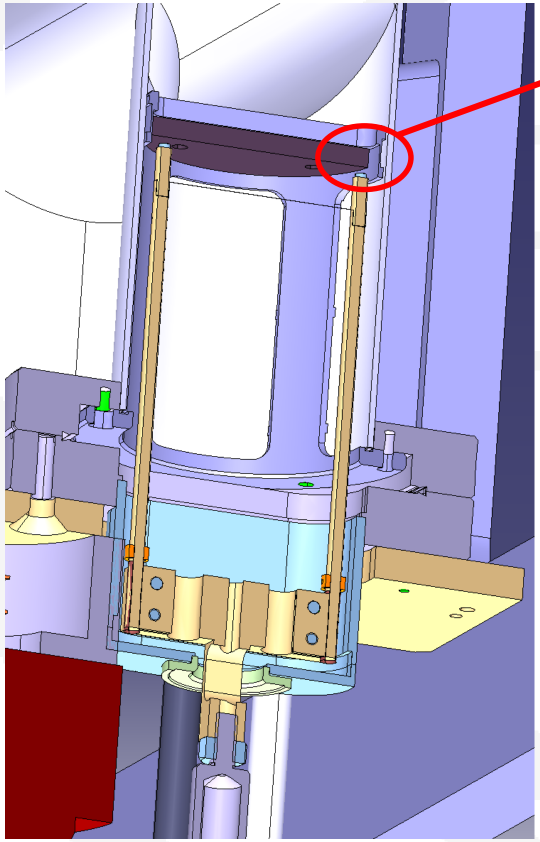
Future Work Resources

- Budget and manpower for design and production of new wire scanner mechanics
  - Request for CONS funding pending approval
- MDs in the SPS to:
  - Cross-calibrate the new LIU scanner with the linear scanner
  - Continue wire material studies with (non-operational) linear scanners
- Studies and possible MDs in the LHC for
  - Validating new magnet quench scenarios for multiple faster scans
  - Validating impedance and LHC vacuum compatibility
  - Possible other scanner locations and magnet shielding
    - Neither of these options are currently on the BI work list
- Resources for new wire material studies
  - CERN PhD on testing of CNT materials (FCC funded)
    - Started 1/10/19 with University of Bourgogne Franche Comte
  - CERN PhD on simulations (targeted for SEMs, synergies for BWS)
    - Recently started in BI-PM section

Thanks for your attention!

Backup material

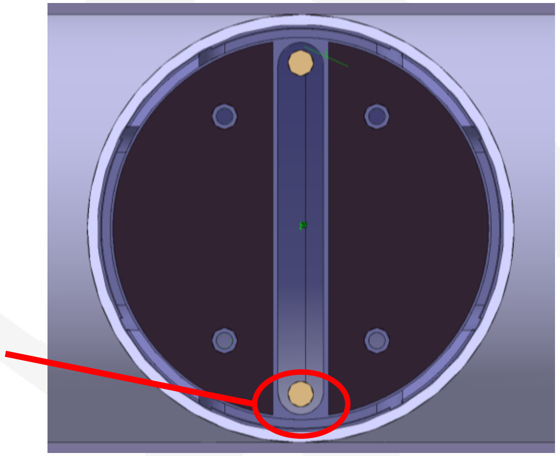
B1 H1 – Contact Between Fork and Ferrite holder



Fork in the 'out' position

6.5 mm nominal movement to ferrite

1.5 – 2 mm nominal clearance between fork and ferrite holder



Section, looking from beam axis showing fork and ferrites

Origin of the problem:

Contact between fork and ferrite holder

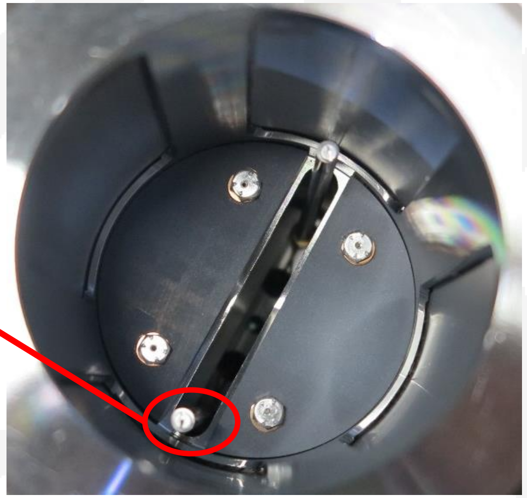


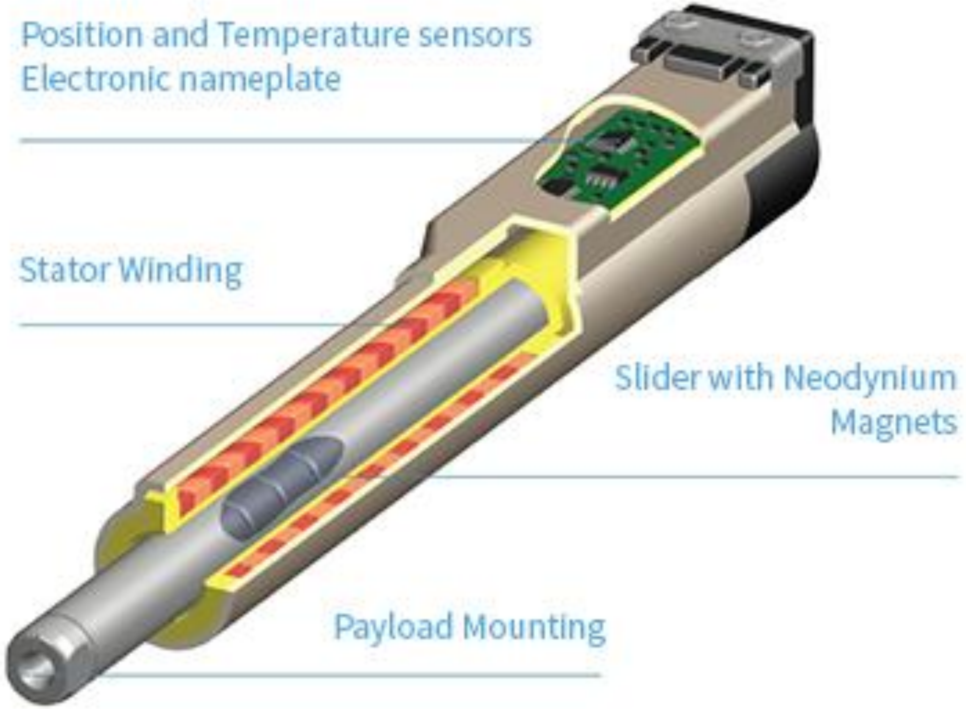
Photo of the scanner, showing ferrites (black) and clearance between fork and ferrite holder

Linear motors

DEMO

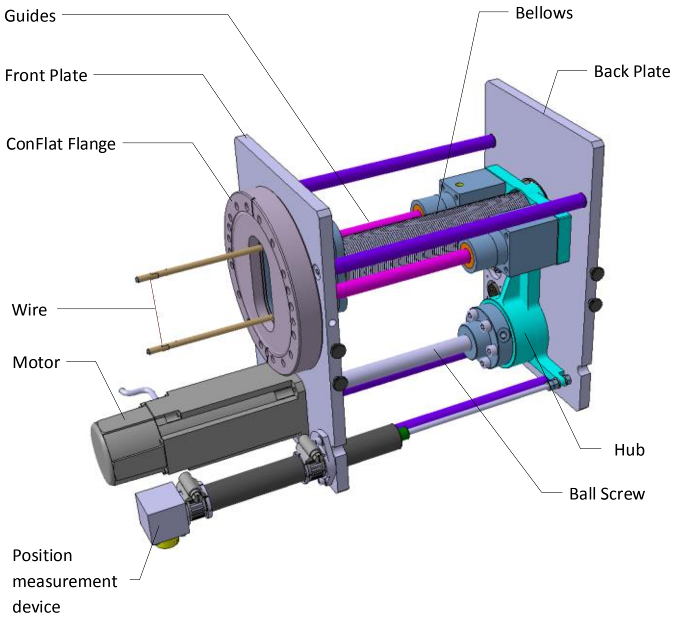
- Direct linear drive
- No ballscrew is needed
- Linear guide is not needed in case high accuracy is not required
- Can work in two modes:
  - Shaft slides inside the stator
  - Slider moves along the shaft (stator becomes slider)
- Both solution can be used in beam instrumentation

<u>Electronic module can be located far from the bea</u>

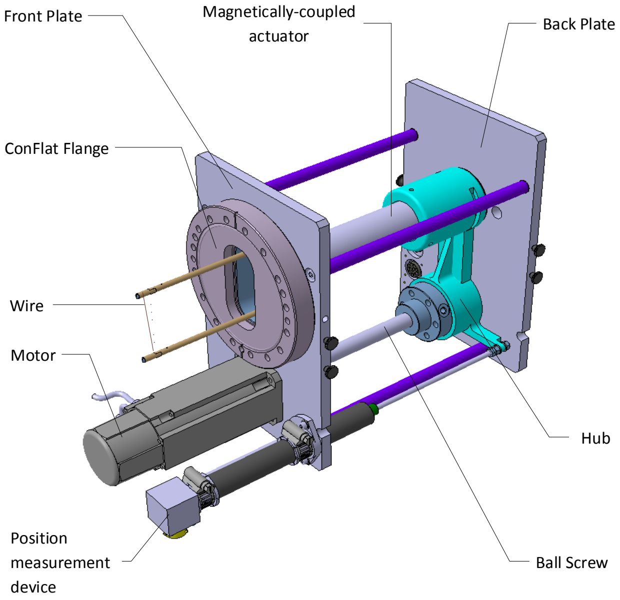


Future Linear BWS Alternatives and Study

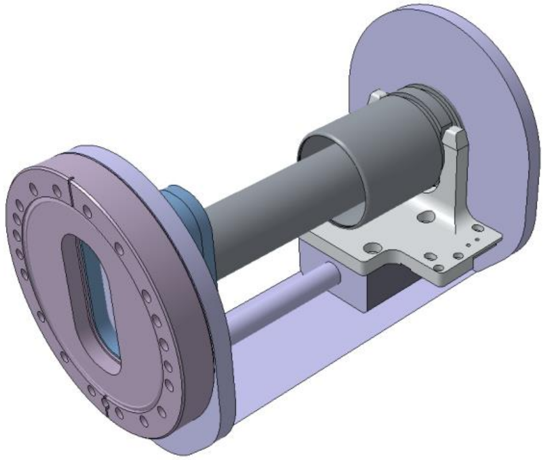
Bellows/Ballscrew/Rot. motor



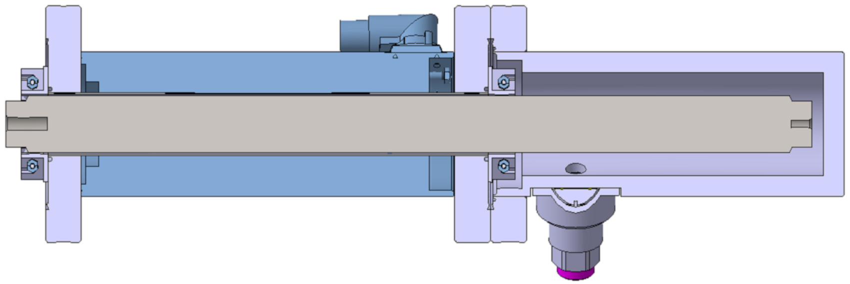
Magnetically-coupled/Ballscrew/Rot. motor



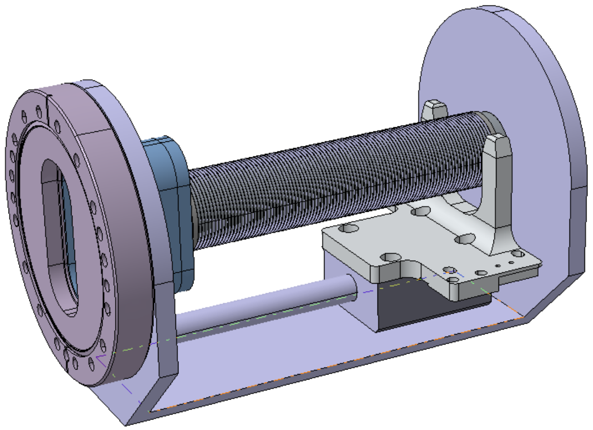
Magnetically-coupled/Lin. motor

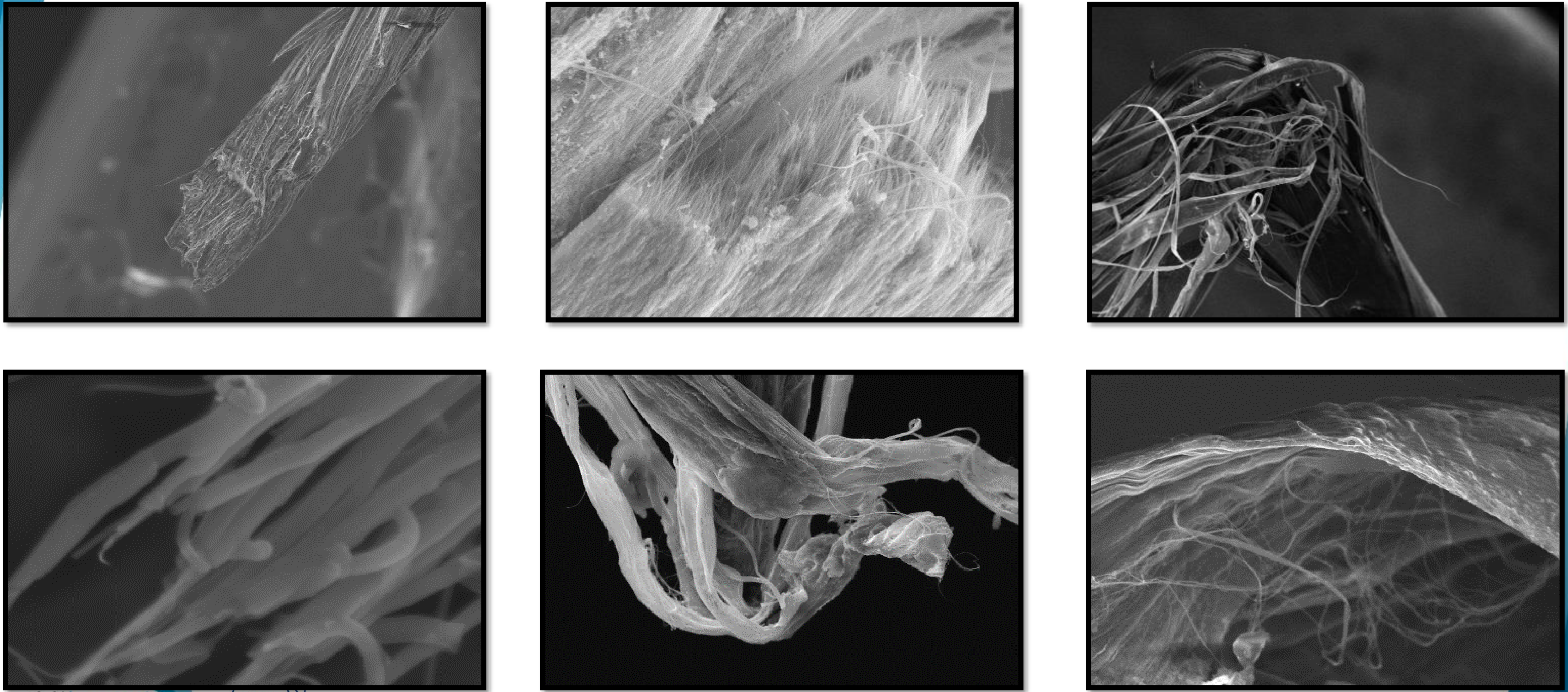


Direct Drive/Lin. Motor/thin wall vac. chamber



Bellows/Lin. motor





Optimal Packing

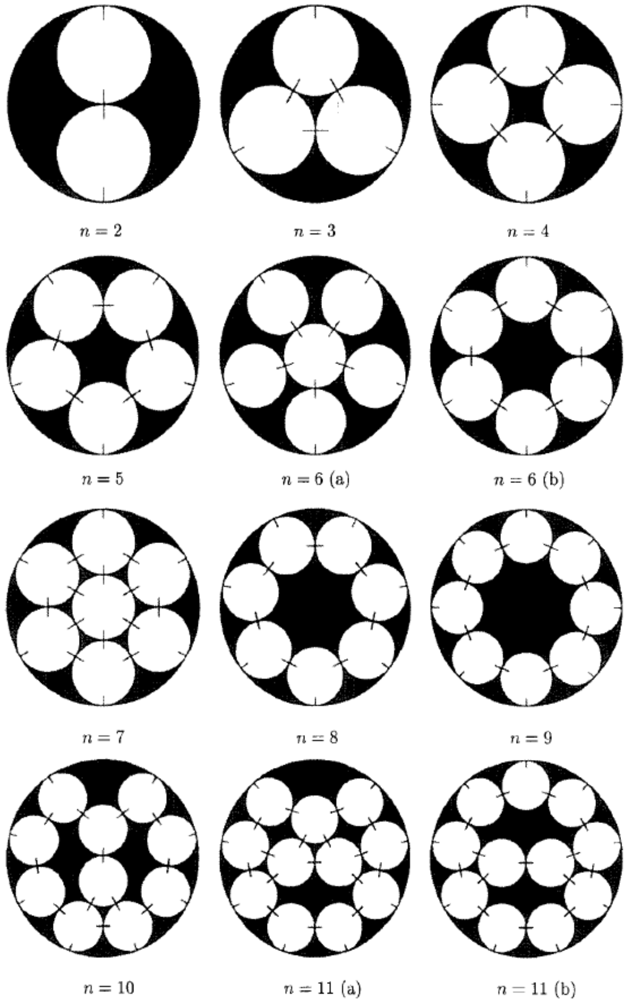


Fig. 1. Optimal packings of 2–11 circles in a circle.

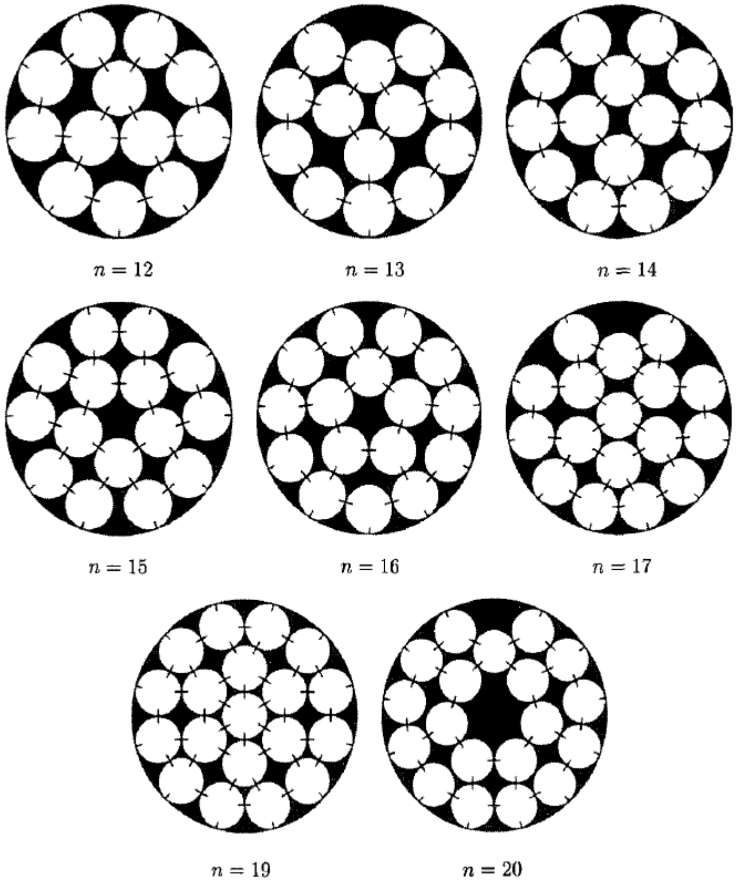


Fig. 2. Conjecturally optimal packings of 12–17 and 19–20 circles in a circle.