HENAPIX
HEat pipe **NA**no Fiber **PIX**el detectors

Proposal for R&D to INFN

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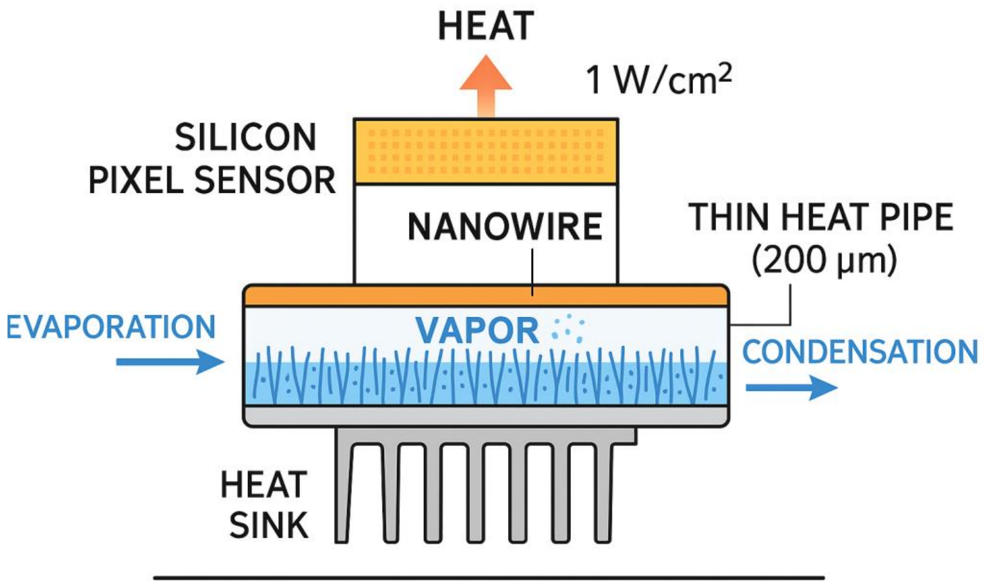
Abstract

- **HENAPIX** (**HE**at pipe **NA**no Fiber **PIX**el detectors) is a multi-institutional R&D initiative focused on developing a self-cooled, ultra-lightweight mechanical structure for silicon pixel sensors in next-generation high-energy physics (HEP) detectors, such as those foreseen for the Future Circular Collider. The project addresses the growing thermal demands imposed by localized power densities reaching 1 W/cm^2, particularly for high speed alectronics and timing detectors with high channel count. HENAPIX proposes a novel cooling approach based on an integrated nanofibre-enhanced heat pipe system, constructed from few 100 µm carbon fibre envelopes embedded with high-capillarity nanowires (~200 nm diameter). The targeted structure aims to remove ≥1 W/cm^2 across several cm^2 while preserving a material budget below a fraction of a percent X_0 per layer.
- The project is organized into four work packages: WP1 develops high-fidelity CFD/CHT simulations incorporating capillary action and phase-change phenomena to determine optimal design parameters; WP2 fabricates and characterizes nanofibre tissues via electrospinning, evaluating morphology, thermal conductivity, and radiation hardness; WP3 handles mechanical integration, module sealing, and prototype assembly; and WP4 validates system performance through thermal and mechanical stress testing. HENAPIX directly contributes to low-mass, high-performance vertex detector technologies for future collider experiments.

Heat pipe as “supeconductor” of heat

A HEAT PIPE IS A DEVICE WITH VERY HIGH THERMAL CONDUCTIVITY

- Up to now two-phase heat-transfer devices such as cylindrical heat pipes (HPs), planar (i.e., flattened heat pipes (FHPs) and vapor chambers (VCs) have been widely used for the thermal management of high-power density electronic devices such as desktop computers, laptops, spacecraft components, and LED modules and provide temperature uniformity and eliminate local hotspots generated in such devices.
- The reason is the heat transfer capabilities of such passive cooling devices with heat pipes exhibiting thermal conductivities up to 100.000 W/m K in theory, whereas for solid copper thermal conductivity is approximately 390 W/m K.
- The need for thin (<1mm) or ultrathin (<500 μm) and flexible vapour chambers (UTHPs) has seen developments using micro- and nano-fabrication devices



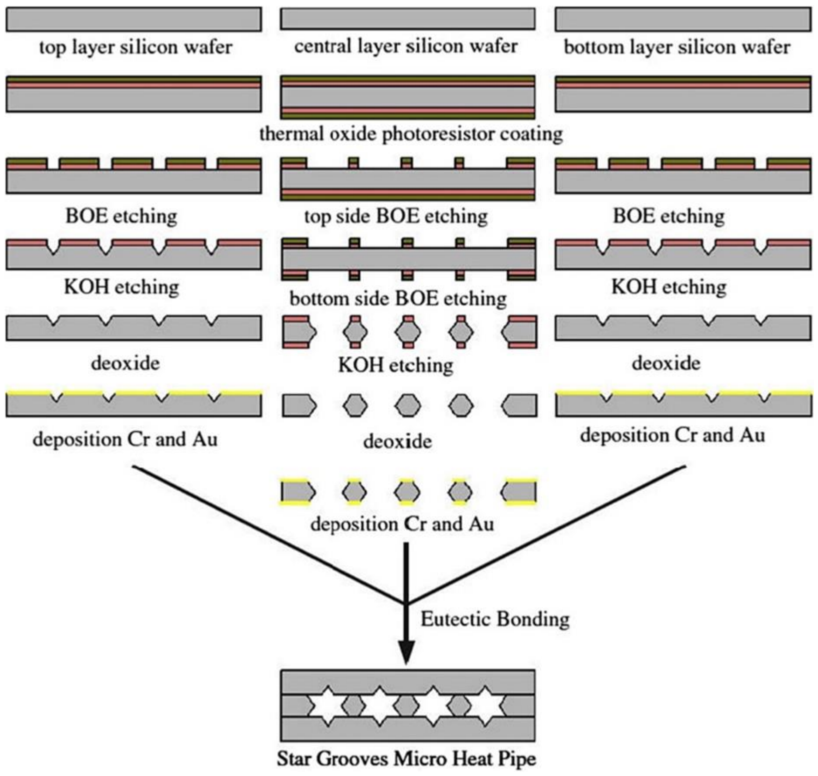
HEAT PIPE FILLED WITH NANOWIRES

Review of methods used

Thickness (mm)	Encasing material	Heat transfer capacity (W)	Thermal resistance (°C/W)	Wick structure	Type of Device
1	Copper	5	0,74	Copper foam-mesh	Flattened heat pipe
0.35-0.6	Copper	0,48	10,3	Copper Fibers	Heat pipe
3.5	Copper	-	0,868	Copper columns	Vapor chamber
3	Aluminum	180	0,197	Micro-grooves	Flattened heat pipe
8	Copper	-	0,02	Sintered Copper powder in Grooves	Heat pipe
0.7 & 1	Copper	20	0,2	Oxidized-reduced Copper Mesh	Heat pipe
2	Copper	120	0,196	Copper Powder	Flattened heat pipe
0.95	Copper	-	1	5-layer Hydrophilic Copper Mesh	Heat pipe
0.55	Copper	6,5	0,46	Copper Powder	Vapor chamber
0.2	Copper	-	0,205	Stainless steel mesh covered with copper	Vapor chamber
2	Copper	6	0,38	Copper mesh in channels	Vapor chamber
1	Copper	14	0,74	Sintered Copper Powder and Mesh	Flattened heat pipe
0.5	Copper	9,06	0,37	4 Spiral Woven Meshes	Vapor chamber
0.4	Copper	4,5	0,99	Copper mesh	Vapor chamber
0.6	Titanium	6,4	7,19	Titanium pillars	Flattened heat pipe
4	Aluminum	6	0,1	Metallic powder in Grooves	Heat pipe
1	Silicon	50-70	0,9	Radial grooves	Heat pipe
1.5	Silicon	60	0,8	Grooves	Heat pipe
1.25	Silicon	-	0,53	Micropillars	Vapor chamber
1.3	Silicon	-	1	Micropillars	Vapor chamber
0.72	Silicon	-	2,5	Copper powder	Vapor chamber
4	Silicon rubber	12,67	5	Copper mesh	Heat pipe
1	Kapton and Polyimide	-	~0,07	3-layer copper mesh	Vapor chamber
5	Polyurethane and Copper	-	0,01	Copper mesh	Heat pipe
1.31	Polyethylene terephthalate and Aluminum	20	1,2	3-layer sintered copper woven mesh	Heat pipe
0.3	Kapton	5	11,92	Micropillars	Vapor chamber
2	Liquid-crystal polymer films (LCP)	-	1,02	Sintered Copper mesh on grooves	Heat pipe
10	Polycarbonate Board and Copper	-	0,81	Sintered Copper powder	Vapor chamber
~6	Fluororubber and Copper	-	0,16	Copper mesh	Heat pipe
1	Low-density Polyethylene (LDPE)	-	2,41	Grooves	Heat pipe

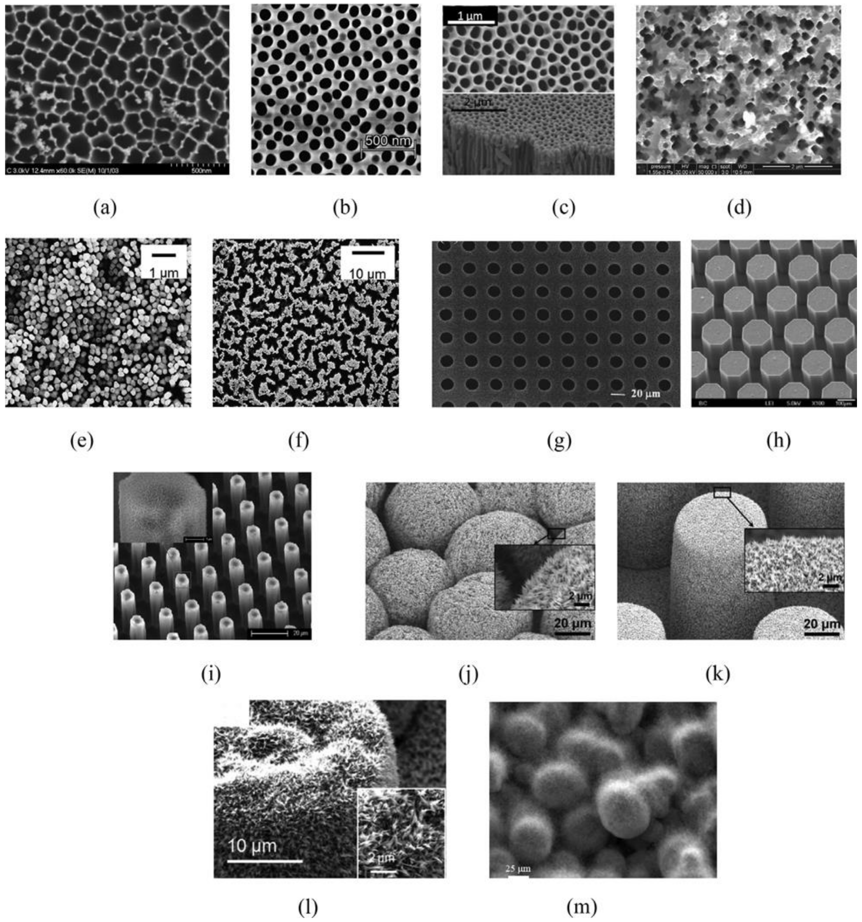
Silicon as an advantage (compared to metallic VC/HP)

- Plus
  - The compatibility of silicon micro heat pipes with the coefficient of thermal expansion (CTE) of numerous electrical components, as well as their mechanical properties and the availability of various working liquids, renders them a promising option for heat dissipation.
  - Can use DRIE process
- Minus (from the past experience)
  - Channel clogging
  - Corrosion
  - Leakage



Nano structures

- Fabrication of MEMS VC with CNT or nanowires has been already demonstrated in several research with different results
  - Important issues were linked to the permeability of the nano-arrays
  - Bio-inspired wick structures can solve the problem

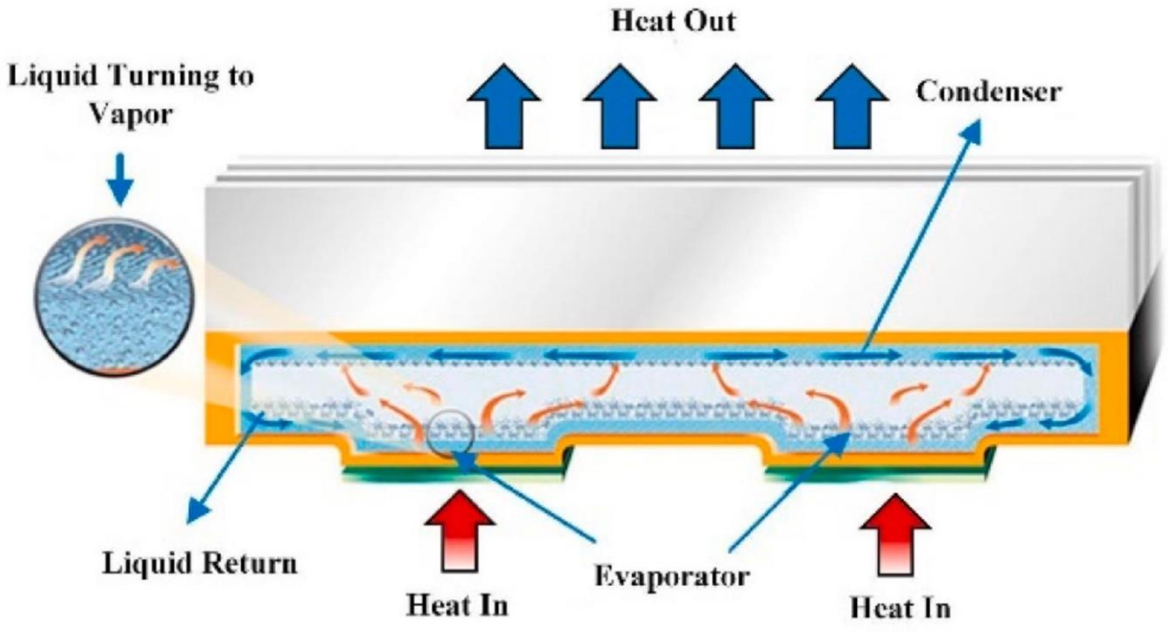


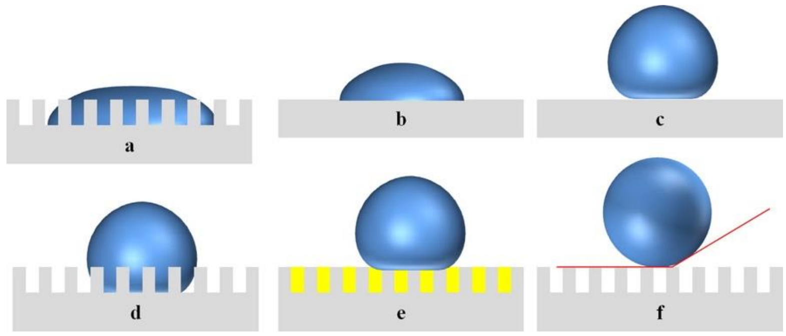
Advantages

- Compared to microchannel
  - No need of connections for fluid nor piping
  - More efficient thermal conductivity
  - Less material budget
- Compared to “traditional” CO_2 bi-phase
  - No need to go to -30 ºC
  - No need of connections

Project rationale

- Flattened heat pipes (vapour chambers) with fibres
  - Sintered wick structure made of nanofibres
    - Hydrophilic to absorb water
    - Hydrophobic to repel water
  - Liquid water stays in the hydrophilic section, while it is repelled from the section with hydrophobic fibers
  - Water vapour is then transferred to the hydophobic section where it condensate.
- Fibres will have a diameter of ~200 nm
- In a ~100 μm thickness we could have hundreds of fibres with high capillarity
  - Porosity of nanofibres increases capillary pumping pressure
- Target power density is >1 Watt/cm^2
- The clear advantage of such a system is the removal of any piping in the detector area

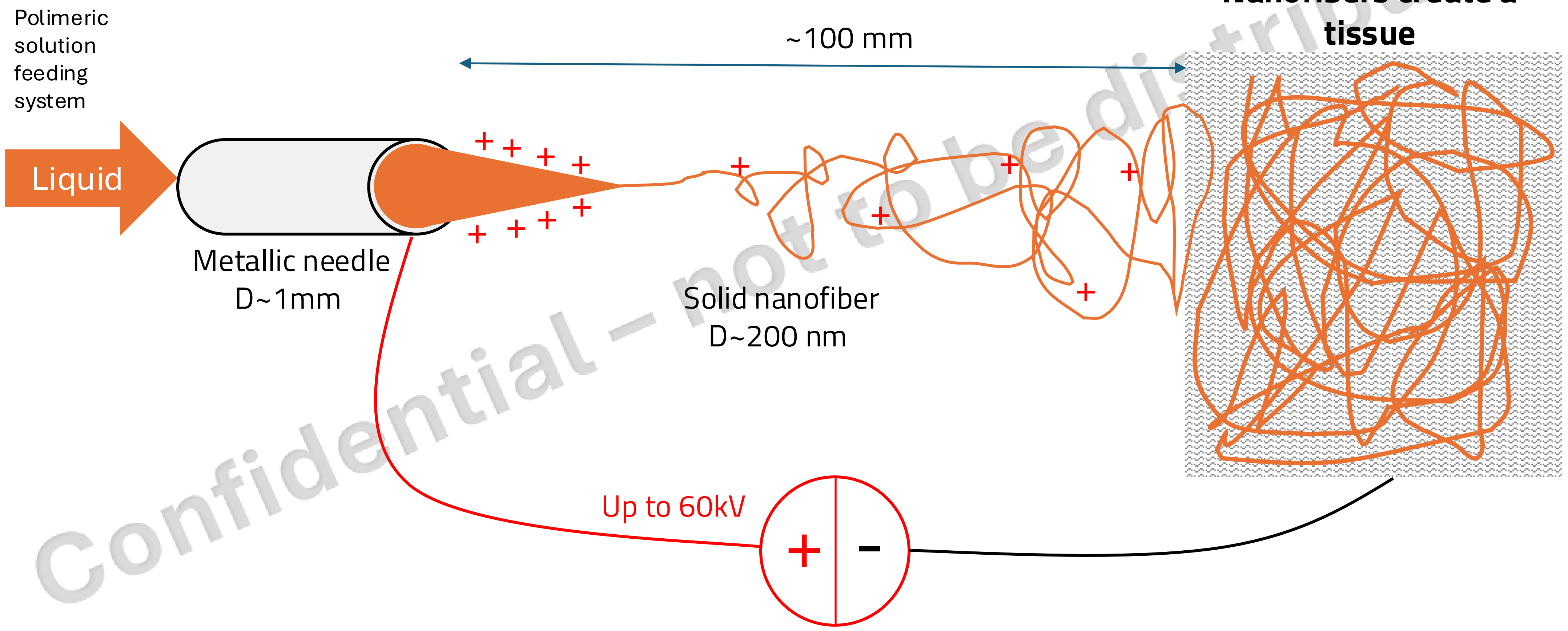




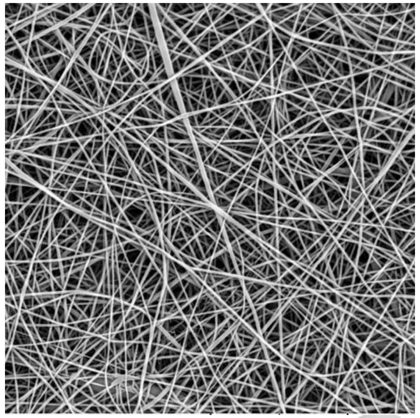
System aspects

- Vacuum chambers efficiently works with minimal power density. Given that the trend in sensors and electronics developments is given emphasis on reducing the power density, it is important that the simulation should determine the minimal power density of the electronics
- To allow efficient condensation, one needs to study the positioning of an external plate with a fin that acts as a radiator thanks to an air flow, and to calculate the minimum surface area needed.

How electrospinning works

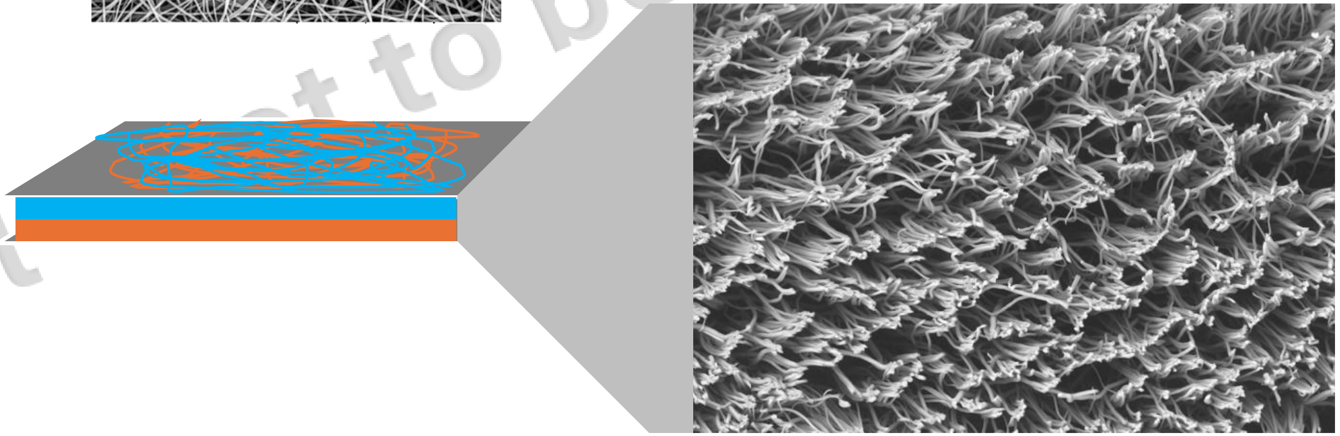


Nano composites at tissue scale: stacked materials



Top View

Double layer nanofibers in
a sealed cooling channel



Cross section View

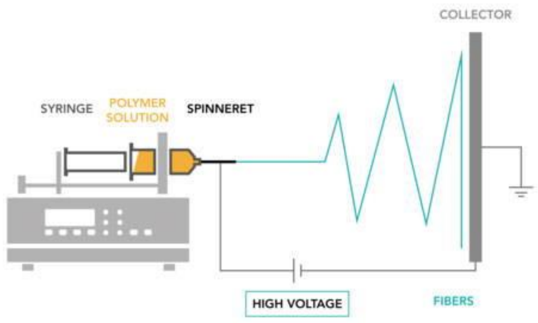
Companies

- Linari engineering s.r.l.
  - Nano wires fabrication

- FBK Trento
  - Microchannel fabrication
  - R&D on materials

Proposed WP

- **WP1 – Simulation (Uni Pisa)**
  - high-fidelity numerical model of the heat pipe system using Computational Fluid Dynamics (CFD) simulations coupled with Conjugate Heat Transfer (CHT) models
- **WP2 – Nanofibres fabrication (Linari and INFN)**
  - Use electrospinning technology (Linari)
  - Material characterization (Linari)
  - Radiation hardness tests (INFN)
- **WP3 – Module fabrication (FBK, INFN and Linari)**
  - Design and integation of nanofibers with silicon module
  - Microchannel processing
  - Silicon passivation characterisation
  - Fluid choice
- **WP4 – System test (Uni Pisa and INFN)**



Anagrafica

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TOTALE			**100%**

Richieste in sezione

- Alte tecnologie – misure di termofluidodinamica: 2 settimane/anno
- Irraggiamento a raggi X: 2 settimane/anno
- Disegni meccanici: 2 settimane/anno

References

- https://www.linarinanotech.com/
- https://doi.org/10.1016/j.mne.2023.100235 (and references therein)
- https://doi.org/10.1016/j.ijheatmasstransfer.2017.03.034.