RD_FCC

Romualdo Santoro

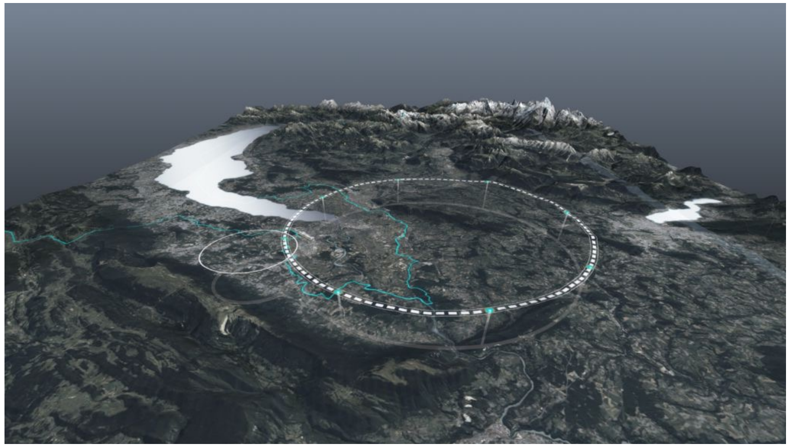
RD_FCC

- In questa sigla confluiscono gli R&D per i futuri collisionatori leptonici circolari
  - Coordinata a livello nazionale da Paolo Giacomelli (INFN-Bologna)
- L'interesse della sezione di Milano continua a crescere con contributi importanti sulle seguenti attività:
  - Studi su High Tempetature Superconductors (HTS)
    - Utilizzo di quadrupoli e sextupoli in FCC-ee
    - Utilizzo di un solenoide HTS in IDEA
  - Studi di beam dynamics
  - Rivelatori monolitici a pixel di silicio
    - Sensori sviluppati in ARCADIA
    - Sensori sviluppati in HVR_CCPD (ATLASPIX3)
  - Calorimetro Dual Readout (sinergica con Hidra2 - Call Gr5)
  - dSiPM per la fisica delle alte energie (SPIDES – richiesta nuova sigla GR5)
- Tabelle riassuntive: FTE e richieste

FCC-ee Collider Magnets

Motivation of the contribution:

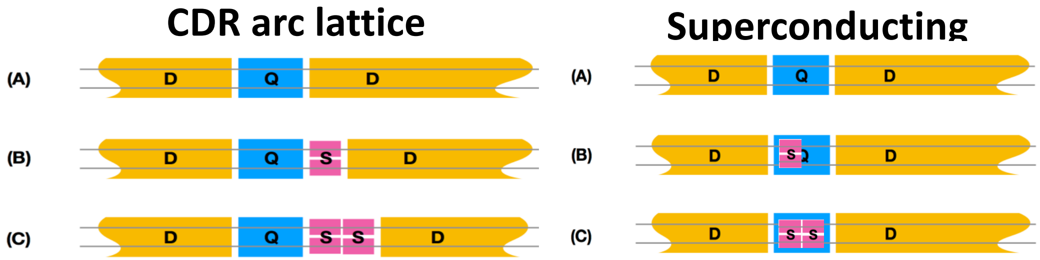
- FCC-ee energy consumption 20 TWh (14 y)
  DC collider operation (high power consumption)
- **90+ km ring tunnel**: thousands of resistive magnets
- <u>*European Strategy for Particle Physics 2020*</u>
  Need for «Improvement of energy efficiency»



PROPOSAL of INFN-Mi-LASA:

"Study for replacement of 2900 quadrupoles and 4700 sextupoles in the 80 km ARC cells"

1. **HTS** Superferric Magnets
2. Combined Magnets (**reduced length**)
3. High operating temperature (up to **50 K**)



New proposal of INFN-Mi-LASA: “Study of an HTS based Solenoid for the IDEA detector”

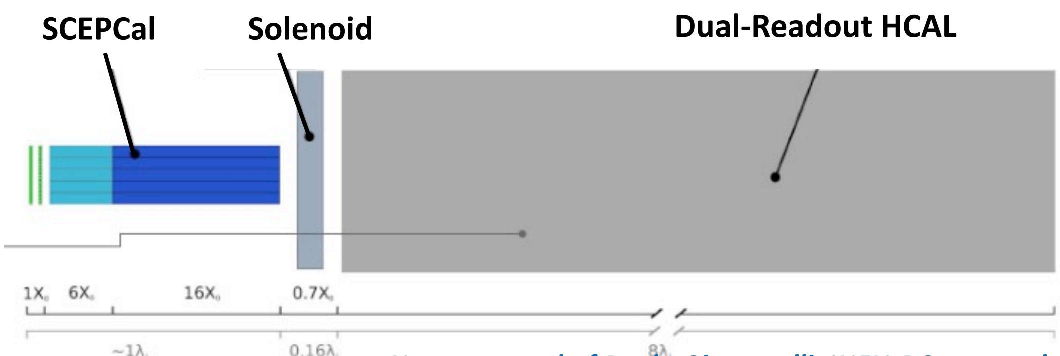
Setector magnets are all based on aluminum-stabilized NbTi: but:

NO Commercially available nowadays

- Need of re-establishing conductor technology in industry

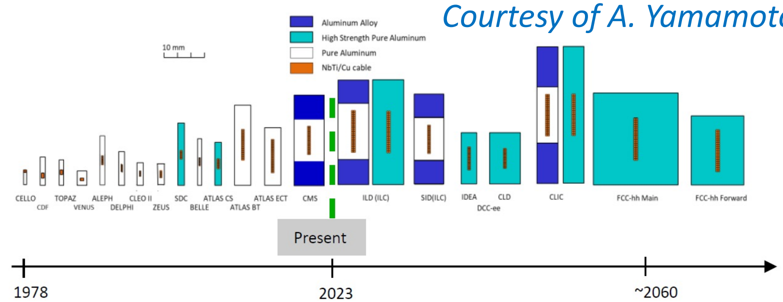
- **Required low temperature operation (< 5 K)**
  - Large energy consumption (cost and not sustainabile)
  - Large inventory of LHe (scarcity of He and no sustainable)

“NEED OF NEW CONCEPTS OF DETECTOR MAGNETS”



New proposal of Paolo Giacomelli, INFN-BO: move the em calo inside solenoid! → change of paradigm

Aluminum-stabilized Nb-Ti conductors: Courtesy of A. Yamamoto



Property	IDEA	CLD	Unit
Conductor			
Conductor material	Nb-Ti/Cu in Al/Ni cladding		
Conductor height	36	36	mm
Conductor width	10	22	mm
Turn-to-turn insulation	1	1	mm
Number of strands	30	26	
Strand diameter	1.1		mm
Cu:SC ratio	1: 1		
Operating current	20		kA
Operating temperature	4.5		K
Coil			
Inner radius	2.235	4.02	m
Length	5.8	7.2	m
Weight	12.5	49.5	t
Number of turns x layers	530 x 1	300 x 1	
Support cylinder thickness	12	25	mm
Total coil thickness	53	102	mm
Central field	2		T
Stored energy	170	600	MJ
Energy density	14	12	kJ/kg

Richieste ed FTE

- L'attività di quest'anno sarà principalmente focalizzata su studio di fattibilità. Non c'è necessita di fondi specifici, ma solo il contributo per trasferte (meeting di collaborazione).
- In futuro potrebbero arrivare richieste specifiche per R&D.

Update 28Giugno'24 (Lucio)		Gr1	Gr1	Gr1	Gr 1		NOTE
		exp.LHC	**FCC**	**HiLumi**	**Muon Coll**		
Ric & Tecnologi UNIMI		TwoCryst	R&D_FCC	HL-SHOC	HE-MuCol	**TOT**	
Lucio Rossi	PO		15%		15%	30%	
Massimo Sorbi	PA	10%	10%		10%	30%	
Samuele Mariotto	RTDA		50%		30%	80%	
Stefano Sorti	RTDA		20%		20%	40%	
Enrico Beneduce	T (D3)		20%		20%	40%	
Lorenzo Balconi	PhD Unimi		20%		20%	40%	
Ric & Tecnologi INFN							
Marco Statera	T2		10%	10%	10%	30%	**compilerà time sheet INFN EU-MuCol**
Carlo Santini	T3 TD				10%	10%	Attenzione time sheet 100% IRIS INFN --> Sinergia
Antonio Bianchi	T3 TD	50%				50%	Attenzione time sheet 100% IRIS INFN --> Sinergia
Gabriele Crespi	T3 TD				20%	20%	Attenzione time sheet 100% IRIS INFN --> Sinergia
Francesco Mariani	PhD RM1		90%		10%	100%	100% IRIS (no time sheet)
Simone Busatto	PhD RM1		50%				100% IRIS (no time sheet)
Giuseppe Scarantino	PhD RM1				100%	100%	
TOT Ricercatori		**60%**	**285%**	**10%**	**265%**	**570%**	
TECNICI							
Danilo Pedrini	C4				10%	10%	**Compilerà time Sheet EU-MuCol INFN**
Augusto Leone	C4				10%	10%	**Compilerà time Sheet EU-MuCol INFN**
Alessandro Pasini	C6				10%	10%	**Compilerà time Sheet EU-MuCol INFN**
Mattia Castoldi	C6 TD				40%	40%	Attenzione time sheet 100% IRIS INFN --> Sinergia
Ahmed Gad	C6 TD		10%		10%	20%	Attenzione time sheet 100% IRIS INFN --> Sinergia
Leonardo Carletto	C1 UNIMI		20%			20%	
TOT Tecnici		**0%**	**30%**	**0%**	**80%**	**110%**	

Beam dynamics

- Main activities
  - Inverse Compton scattering on FCC beam: beam-cleaning & flip-flop instability
  - Complex beam line design in collaboration with IJCLab (ex. LAL), PSI and LNF
  - Beam line design for beam tests @ p-cubed (a PSI experiment) –new–
  - Optimization methods comparison –new–

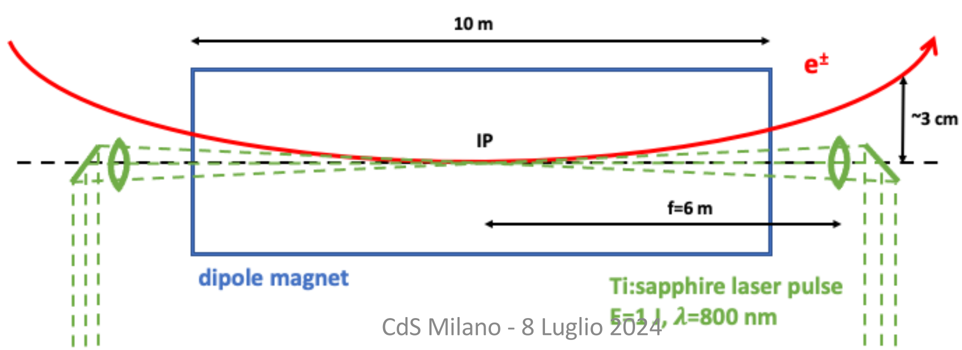
Inverse Compton scattering techniques

ICS – FCC beam control

Work in progress :

- Improve IP (LASER / e^- e^+ beams interaction) inside the bending magnet
- Find optimum between bunch charge reduction (flip-flop instability) VS emittance degradation
- e^-e^+ energy optimization exploiting the dispersion inside IP bending magnet
- Study possibility to reduce beam halo using Donuts-shaped laser beam

Sketch: e+ beam vs laser interaction inside a dipole magnet



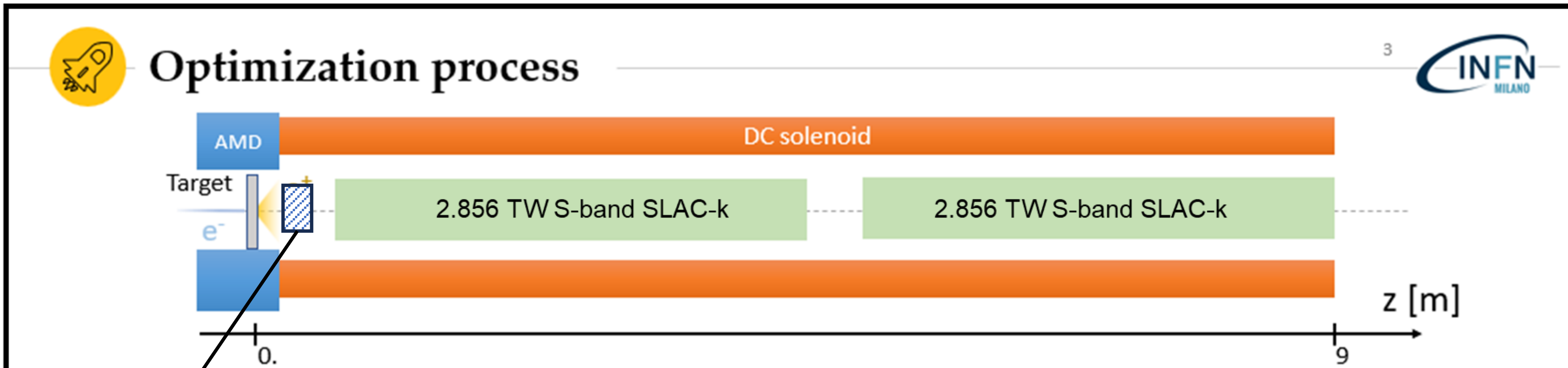
FCC beam line design

A <u>low-β RF buncher with long acceleration bucket</u> & couplet to standard S-banc cavities

the e+ trapping channel

1- Use of a low-β bucher as first trapping device

2- Use of a more standard TW S-band SLAC cavity with a larger airis (r = 16.5 mm) *VS* 2.0 GHz TW $\frac{9}{10}\pi$ mode (r = 30.0 mm)



325 MHz Buncher
$v_p = \beta = 0.74$

Low β Bunchers exploit I_o, I_1 modified Bessel function, for non-linear distribution corrections

F. LEMERY *et al.* , PRAB **21**, 051302 (2018)

$$E_z = E_0 I_0(rk_1)\sin(\omega t - k_z z + \psi),$$

$$E_r = \frac{E_0 k_z}{k_1} I_1(rk_1)\cos(\omega t - k_z z + \psi),$$

$$B_\phi = \frac{\omega \epsilon_0 \mu_0 E_0}{k_1} I_1(rk_1)\cos(\omega t - k_z z + \psi)$$

Alberto Bacci

Richieste ed FTE

- Richieste di missione (13 keuro)
  - Illya:
    - 2 settimane al CERN in due momenti diversi, per collaborazione su ICS-beam controll, studio e pratica software: Xsuite
  - Alberto e Marcello:
    - 8 giorni, Incontri e primi test al PSI per attività su P-qubed (2 persone)
  - Alberto, Illya e Marcello:
    - 1 settimana a LNF: corso sul software RF-Track (3 persone)
    - 1 giorno, 2-3 incontri di gruppo in persona tra Ferrara, LNF, JCLAB (2 persone)
    - Due eventi x 2 persone: FCC_week e/o IPAC2025 (2 persone)

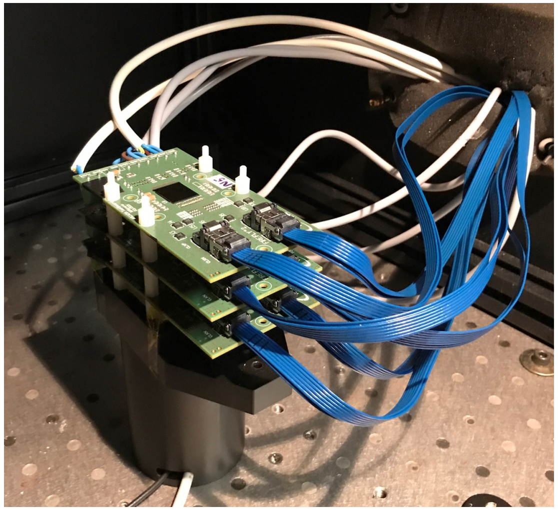
- FTE: tutti passati dal 15% al 30%
  - Marcello, Illya, Alberto

Rivelatori monolitici a pixel di silicio

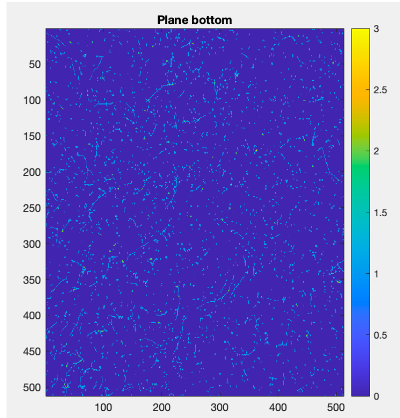
- ARCADIA (Call Gr5: 2019-2021): Tecnologia monolitica Fully Depleted Lfoundry (CMOS 110 nm)
  - MD3 consegnato nel 2023: raggiunto il consumo di potenza di design ≈ 10 mW/cm^2
  - Diversi telescopi sono in fase di qualifica sia con cosmici che su fascio

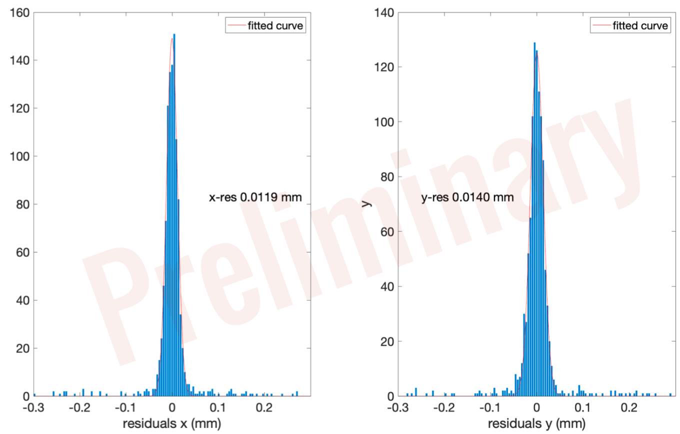
- ATLASPIX3: Tecnologia TSI 180 nm HVCMOS (chip full-reticle size $20 \times 21\ mm^2$)
  - Qualifiche con sorgenti, su fascio e studi di integrazione in moduli con più chip

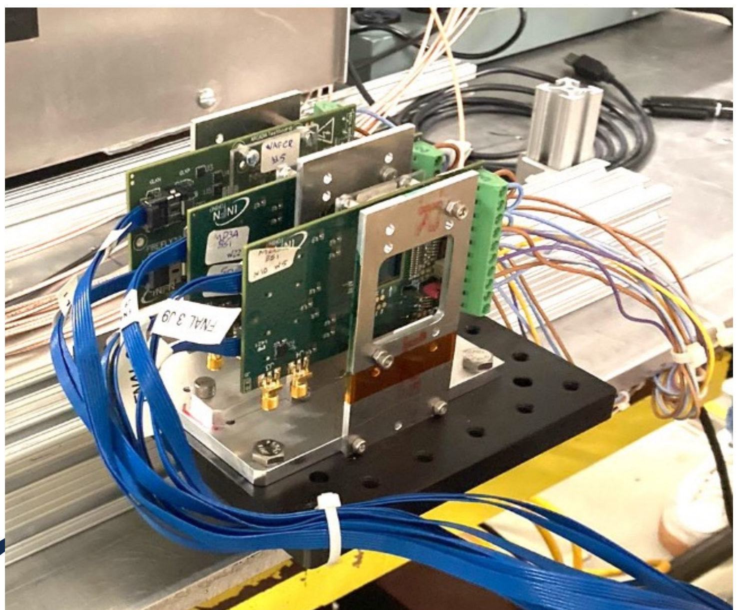
MD3- Arcadia



Data with cosmics

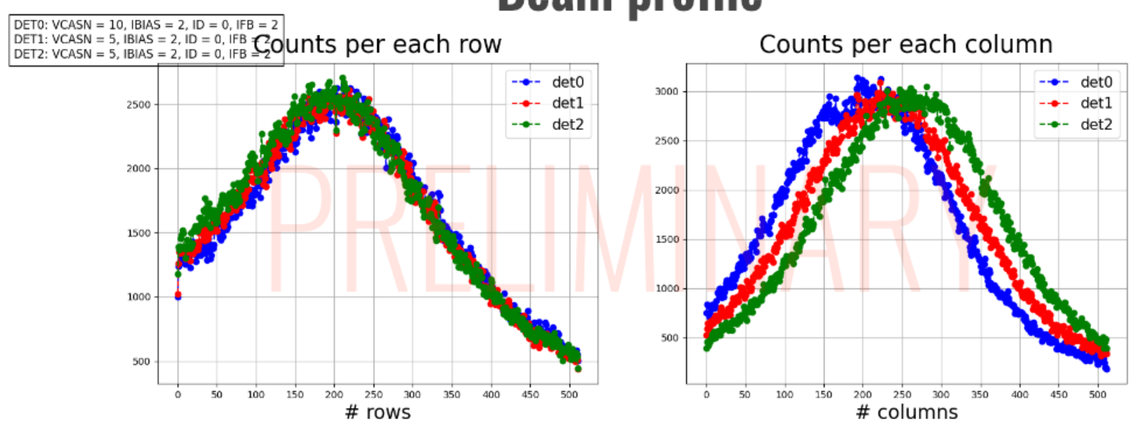




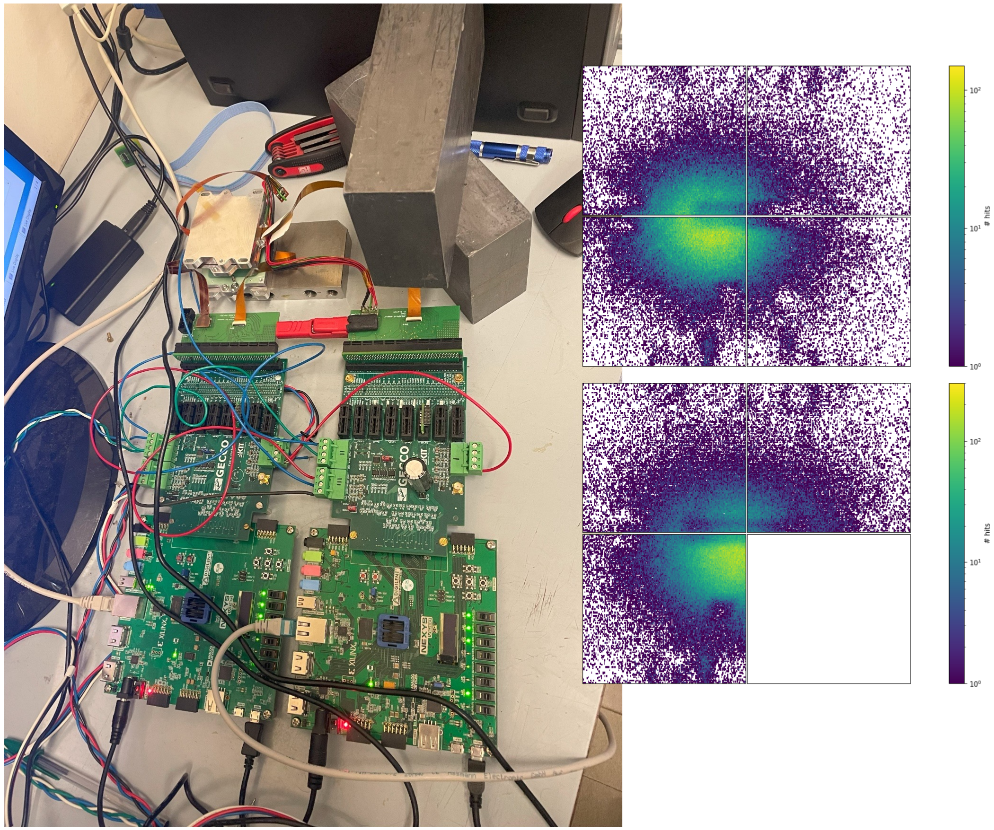


Test beam @ FNAL (120 GeV protons)

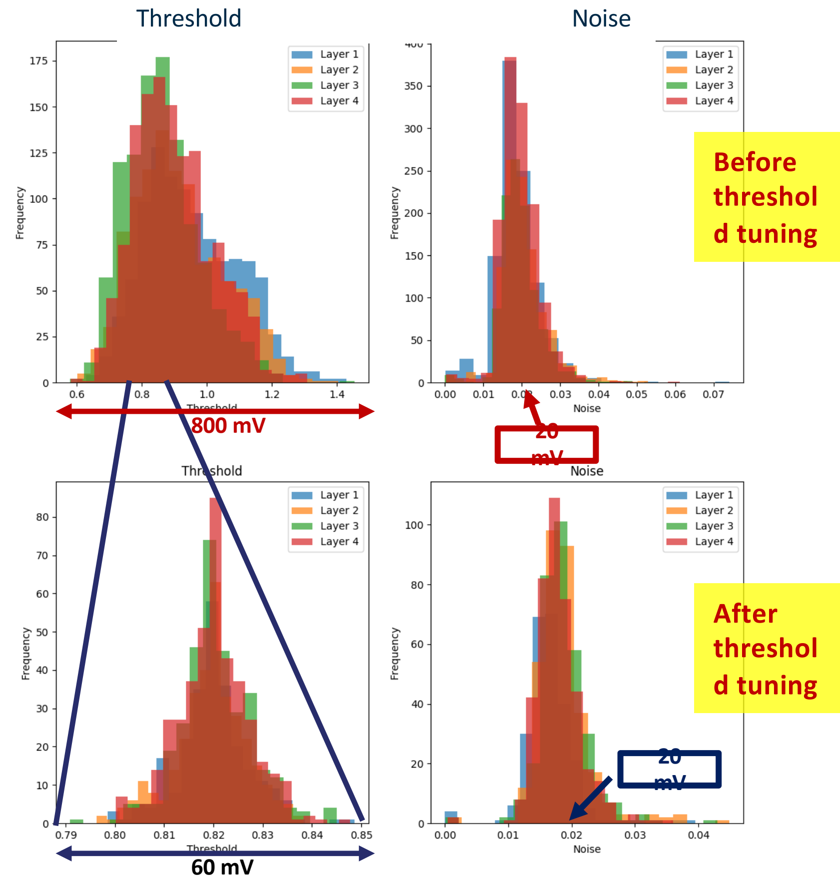
Beam profile



ATLASPIX3 Quad-module performance



Two modules taking data with a 90Sr source
Visible are the shadows of the data connectors



Threshold tuning and noise measurement on modules
No change in performance compared to single chips

Attilio Andreazza

ATLASPIX3 Stave electrical bus

UNIVERSITÀ DEGLI STUDI DI MILANO

Distribution of power and data signals along the stave

- reducing power dissipation on the distribution lines
- minimize the number of connections

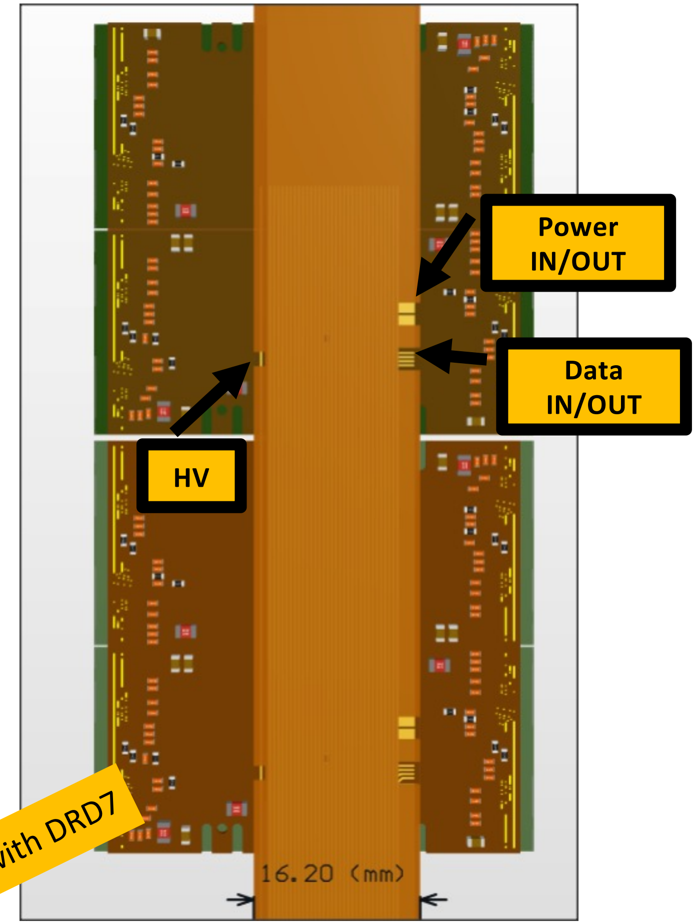
Read-out units are:

- **multi-chip modules** (example 2x2 quad modules)
- large stitched detectors
- bias is in parallel within the components of a module

Minimal I/O connection on chip requires:

- Serial powering chain: all biases generated internally by shunt-LDO regulators
- chip-to-chip data transmissions: local data aggregation on module
- clock data recovery

Reduce material by developing PCB with Al as conductor
Module flex compatible with serial power, just delivered
Al electrical bus in design/



Attilio Andreazza

Rivelatori a pixel di silicio con sensori monolitici

- Richieste
  - ATLASPIX3: Moduli di serial power per ATLASpix (DRD7) -> 20keuro SBJ
  - Arcadia / ATLASPIX3: missioni per Test beam 4 Persone per 1 settimana SBJ alla conferma del test
  - 6 mesi di elettronica per progettazione pcb e test elettrici.
  - 1 mese di officina

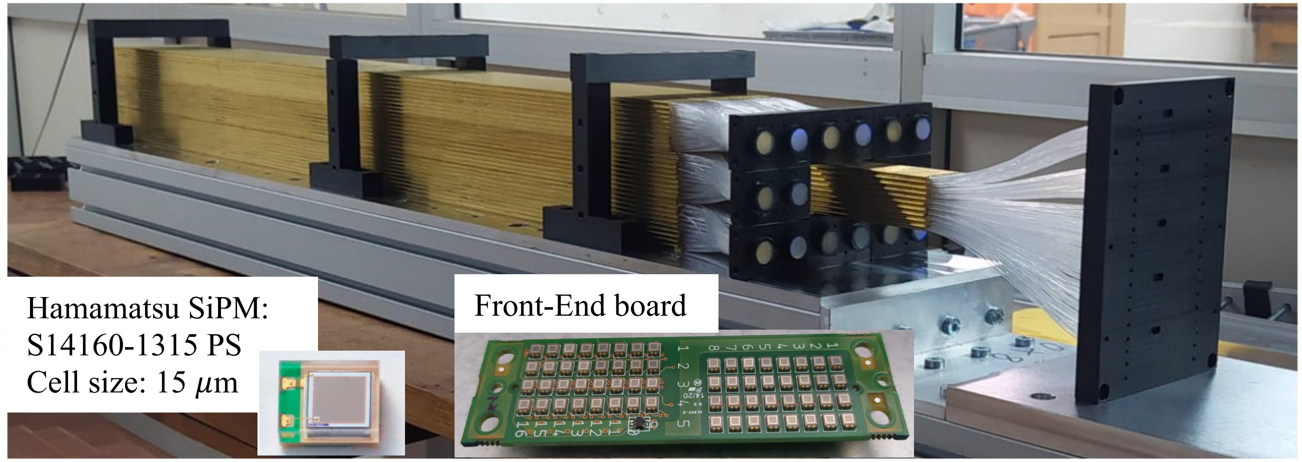
- FTE:
  - Romualdo Santoro
  - Massimo Caccia
  - Attilio Andreazza
  - Riccardo Zanzottera

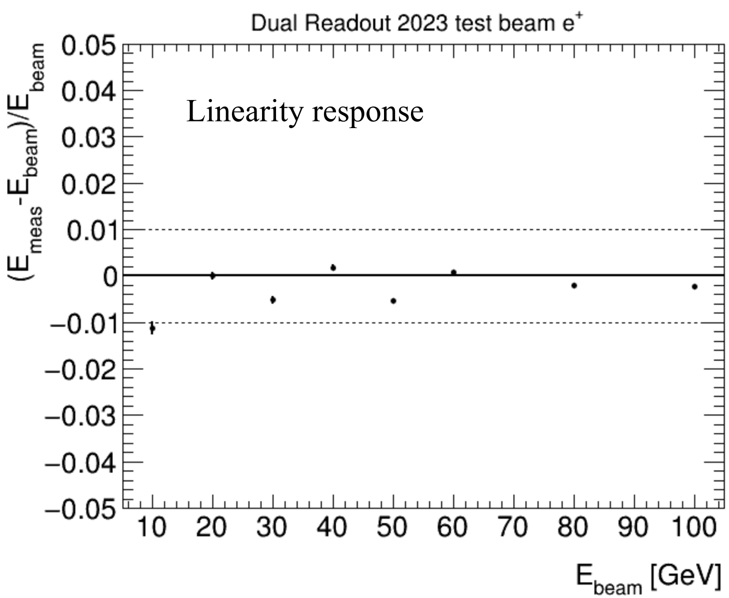
Calorimetria Dual Readout

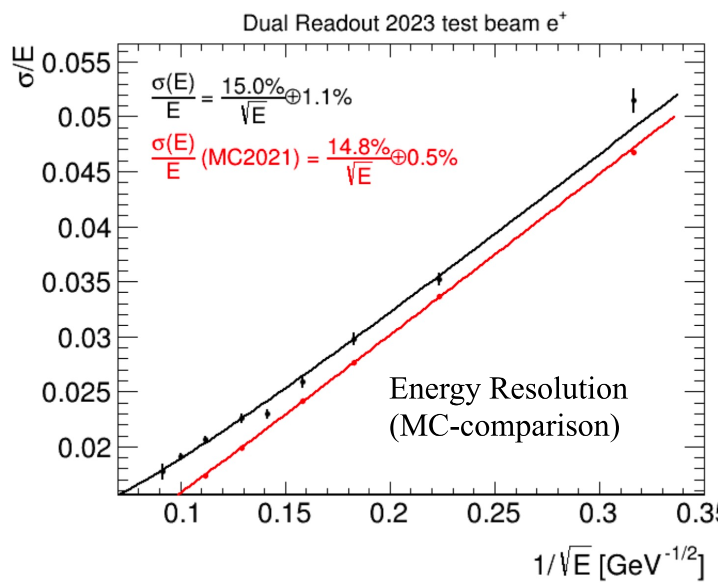
- Attività finanziata dalla call di GR5 (Hidra2: stiamo chiedendo estensione del progetto, 1 anno) – DRD6
  - Design, costruzione e qualifica su fascio di un prototipo scalabile e grande abbastanza da contenere sciami adronici
  - PI: Roberto Ferrari (Pavia)
- Attività svolte nel 2024:
  - Design e qualifica front-end board patch panel ed interconnessioni necessarie per la costruzione dei moduli ad alta granularità (pre-produzione)
  - Contributo al Test beam e analisi dati
- Attività prevista per il 2025:
  - Produzione e qualifica dei componenti necessari alla costruzione dei moduli ad alta granularità in collaborazione con le altre sedi coinvolte (BO e CT)
  - Contributo al Test beam e analisi dati

Test beam results (previous prototype)

- EM-size prototype ($10x10x100\ cm^3$)
- 9 modules made of 16 x 20 capillaries (160 C and 160 Sc)
- Core module readout by SiPMs
- TB in 2021 and 2023





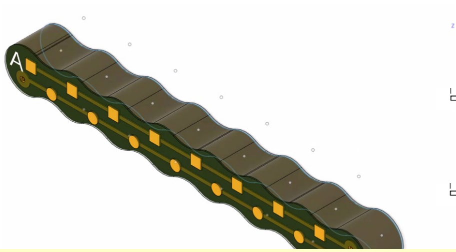


Results from 2021:
N. Ampilogov et al JINST 18 P09021 (2023)

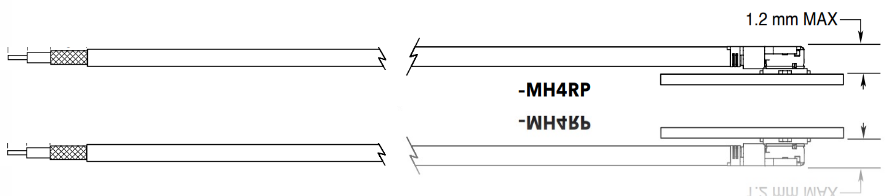
Results from 2023: paper in preparation

Mechanical integration and cabling of the Highly granular modules

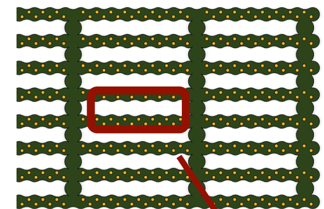
mini FE-board with integrated grouping (8 SiPMs)

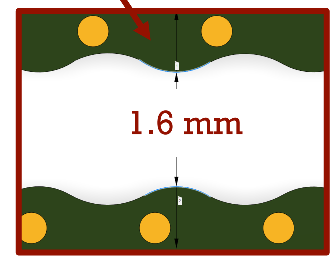


MH081: shielded micro-coax RF cables from Samtec

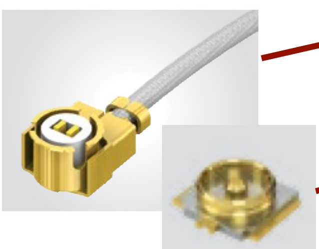


Large FE-board equipped with 16 SiPM-bars

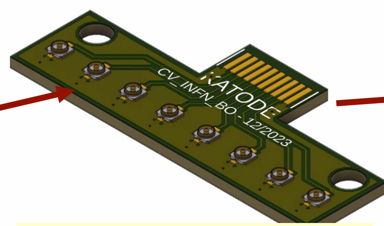




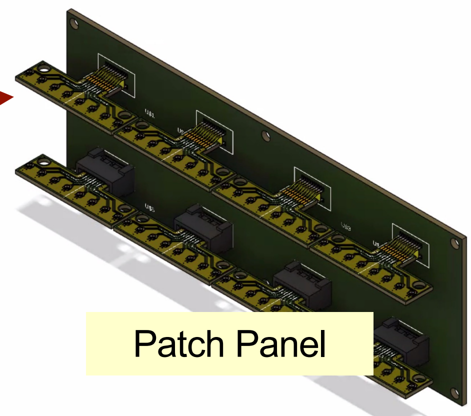
SiPM bar mounted on the front and two-pin cable on the back



connectors fitting into the PCB holes

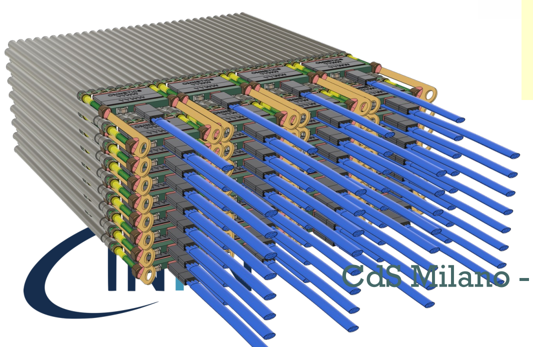


Bridge board: serves 8 SiPM-bars



Patch Panel

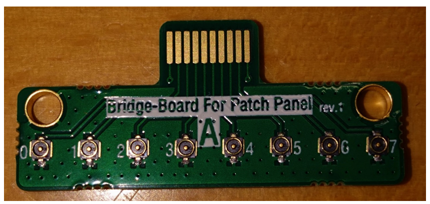
A5202-Board: serves half-minimodule



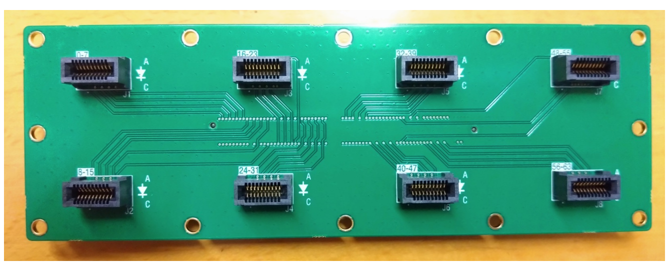
Preproduction and first qualification (Milano)

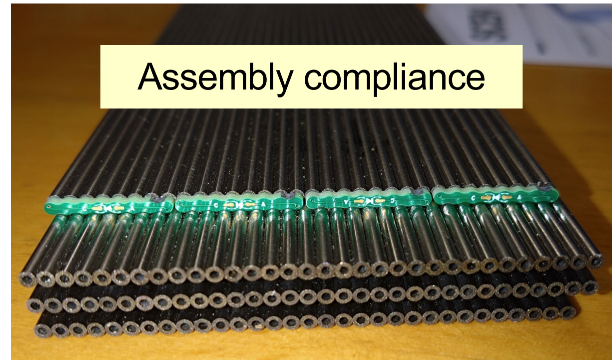
- Mini front-end board (40 prototypes)

- Bridge board (10 prototypes)

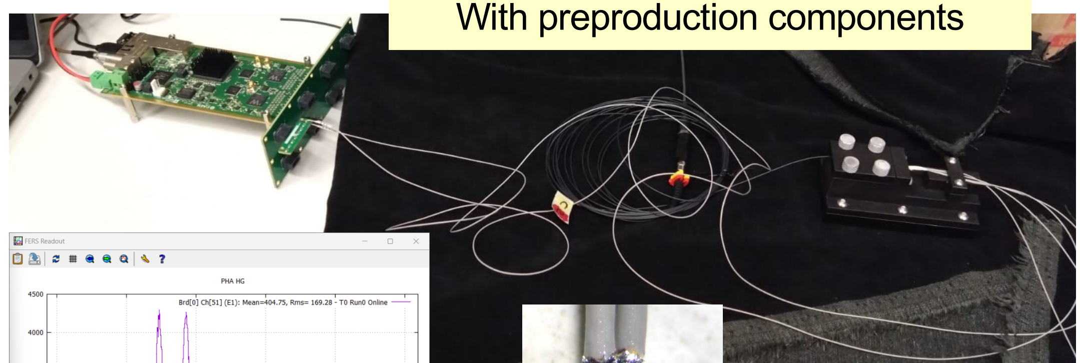


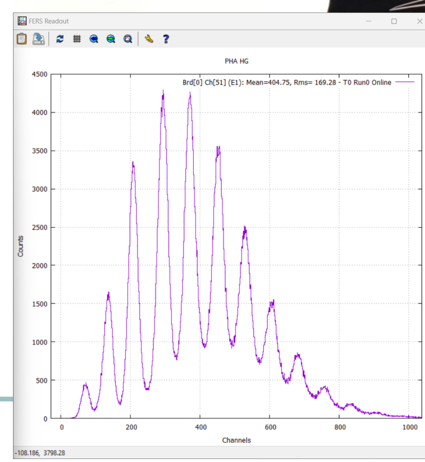
- Patch panel (4 prototypes)

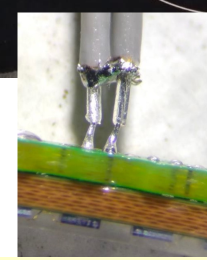




Multi-photon quality assessment
With preproduction components







Ready for production!

Calorimetria Dual Readout

- Richieste:
  - Test beam: 4 Persone per 1 settimana SBJ alla conferma del test
- Partecipanti della sezione di Milano
  - Romualdo Santoro
  - Massimo Caccia
  - Aleksandr Burdyko
  - Leonardo Carminati
  - Ruggero Turra
  - Laura Nasella

ASPIDES

Nuova sigla GR5 (sinergica RD_FCC – DRD4):

PI: Lodovico Ratti (INFN - PV)

Main Goal:

Develop digital SiPMs in CMOS technology for high dynamic range counting and high accuracy timing, targeting dual readout calorimetry, RICH and detectors for dark matter and neutrino experiments

Participating units:

Bari (N. Mazziotta), Bologna (L. Rignanese), Milano (R. Santoro), Pavia (L. Ratti), Trento (L. Pancheri), Napoli (G. Fiorillo), Padova (G. Collazuol), Torino (M. Da Rocha Rolo)

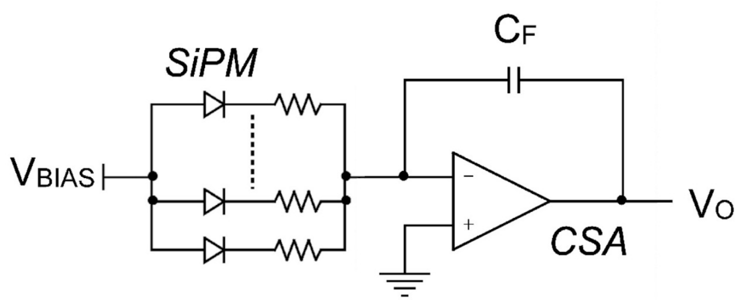
Research area:

Detectors and electronics

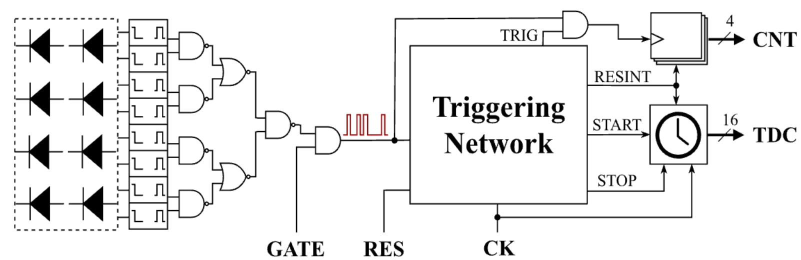
Duration: 3 years

SiPMs: analog vs digital

SiPMs: analogue signal proportional to number of fired cells. Readout performed externally



Digital (CMOS) SiPMs: readout functionalities implemented in the sensor substrate (e.g. binary counters, SPAD masking, TDCs …)



M. Perenzoni et al. 2017 – IEEE JSSC

- SPAD array in CMOS technologies may offer the following benefits:
  - Front-end can be optimized to preserve signal integrity (especially useful for timing)
  - Easier linearization and calibration – direct digital output vs digital/analog (including noise + non uniformity)/digital conversion
  - The monolithic structure simplifies the assembly for large area detectors
  - Development costs can be kept relatively low if the design is based on standard process

ASPIDES

- Richieste:
  - Nessuna in RD_FCC
- Partecipanti della sezione di Milano
  - Romualdo Santoro
  - Massimo Caccia
  - Aleksandr Burdyko

Sintesi anagrafica RD_FCC + sinergie

Update 28Giugno'24 (Lucio)		Gr1	Gr1	Gr1	Gr 1		NOTE
		exp.LHC	**FCC**	**HiLumi**	**Muon Coll**		
Ric & Tecnologi UNIMI		TwoCryst	R&D_FCC	HL-SHOC	HE-MuCol	**TOT**	
Lucio Rossi	PO		15%		15%	30%	
Massimo Sorbi	PA	10%	10%		10%	30%	
Samuele Mariotto	RTDA		50%		30%	80%	
Stefano Sorti	RTDA		20%		20%	40%	
Enrico Beneduce	T (D3)		20%		20%	40%	
Lorenzo Balconi	PhD Unimi		20%		20%	40%	
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Augusto Leone	C4				10%	10%	**Compilerà time Sheet EU-MuCol INFN**
Alessandro Pasini	C6				10%	10%	**Compilerà time Sheet EU-MuCol INFN**
Mattia Castoldi	C6 TD				40%	40%	Attenzione time sheet 100% IRIS INFN --> Sinergia
Ahmed Gad	C6 TD		10%		10%	20%	Attenzione time sheet 100% IRIS INFN --> Sinergia
Leonardo Carletto	C1 UNIMI		20%			20%	
TOT Tecnici		**0%**	**30%**	**0%**	**80%**	**110%**	

Sintesi anagrafica RD_FCC + sinergie

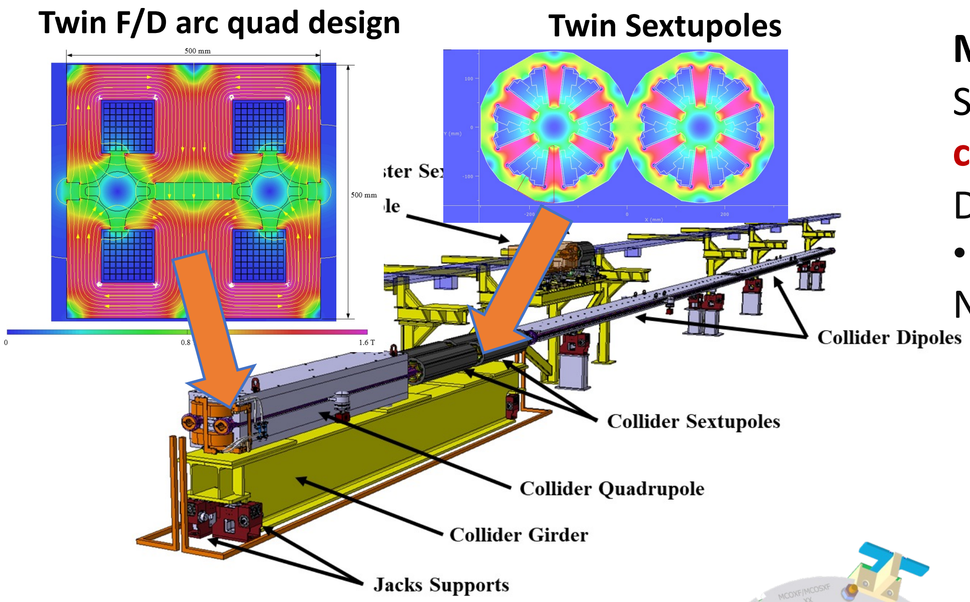
	ASPIDES (GR5 - to be submetted) (DRD4)	Hydra2 (Possible extension) (DRD6)	RD_FCC	Percentuali / persona	commenti:
Romualdo Santoro (PA)	40	30	10	80	Hidra2 ed ASPIDES sinergiche con RD_FCC
Massimo Caccia (PO)	10	20	20	50	Hidra2 ed ASPIDES sinergiche con RD_FCC
Aleksandr Burdyko (assegnista/PhD)	50	50	0	100	Hidra2 ed ASPIDES sinergiche con RD_FCC
Attilio Andreazza (PO)			30	30	
Zanzottera Riccardo (PhD)			20	20	
Alberto Bacci			30	30	
Illya Drebot			30	30	
Marcello Rossetti Conti			30	30	
Leonardo Carminati (PA)			10	10	attività sinergiche con Hidra2
Ruggero Turra (Ric)			10	10	attività sinergiche con Hidra2
Laura Nasella (PhD)			10	10	attività sinergiche con Hidra2
FTE - Totali	1	1	2	4	

Sintesi richieste RD_FCC

consumo	Moduli di serial power per ATLASpix (DRD7)	0.00	20.00			0	20
missioni	Test beam per rivelatori di vertice (Arcadia e AtlasPix). 4 Persone per 1 settimana SBJ alla conferma del test	0.00	4.00			13	8
	Test beam per calorimetria dual readout. 4 Persone per 1 settimana SBJ alla conferma del test	0.00	4.00				
	Bunch intensity control by Compton backscattering: 2 trasferte di 1 settimana per imparare ad utilizzare un codice specifico sviluppato al CERN	3.00	0.00				
	Riunioni di collaborazione e test per ottimizzare la linea a singola e/o doppia targhetta per l'esperimento da svolgersi presso il PSI (P-cubed): propedeutico per FCC (PSI ed JCLAB-Orsay)	10.00	0.00				
Totale						13	28

Backup

Leverage on the HTS superferric magnets experience



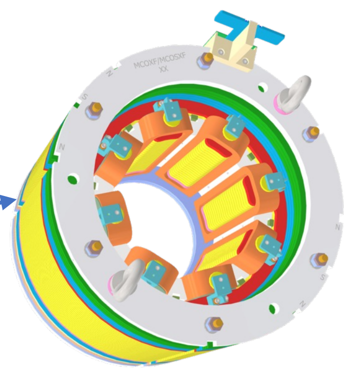
MAIN IDEA:

Superconducting 4P+6P might save **1-2 TWh (to be confirmed AFTER a careful cryogenic system evaluation)**

Different F/D Quadrupoles in **Z-mode and tt-mode**

- **Independent** tunable quadrupole and sextupoles

Need of light-distributed cryogenic/Single cryocoolers



In-Kind contribution to HL-LHC Project: Sextupole developed by INFN-Mi-LASA

Experience from HL-LHC corrector magnet:

Several families of magnets from 4P up to 12P

- Racetrack coils suitable for HTS
- Modular design
- Easy mechanical assembly
- Optimal Field Quality
- Very good reproducibility (several magnets)

New proposal of INFN-Mi-LASA: “Study of an HTS based Solenoid for the IDEA detector”

N. Deelen, "High Temperature Superconductor Detector Magnets for Future Particle Physics Experiments“

Higher Operating temperatures (20-50 K)

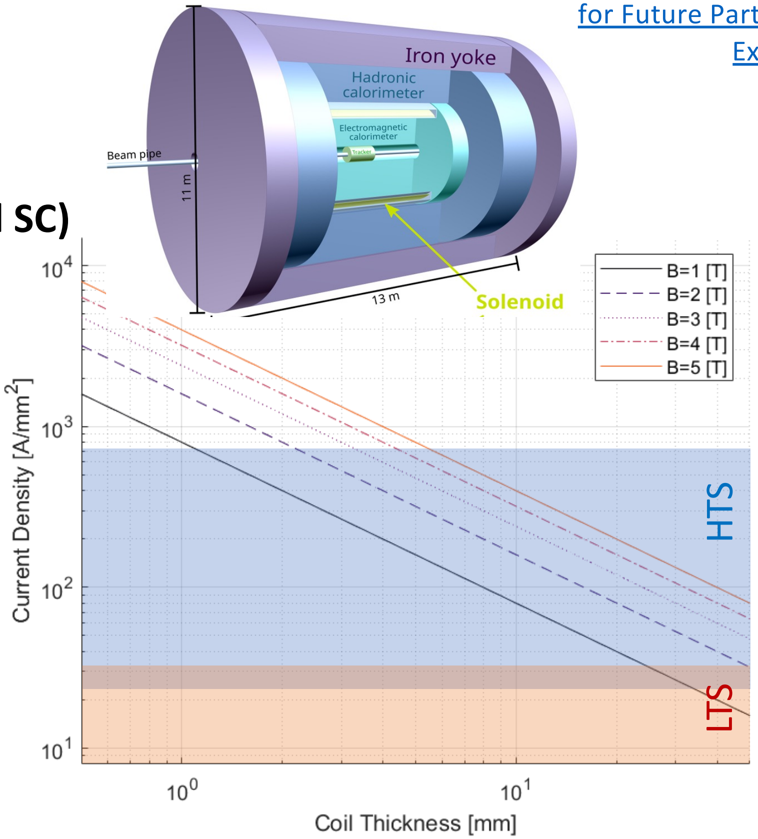
- Reduction of power consumption
- Reduce helium inventory (He is becoming scarce)
- Reduction of cold mass

Thin HTS Coil (higher HTS current densities than classical SC)

- Lighter solenoidal magnets
- Preliminary coil thickness required (< 1 or 2 cm)
- HIGHER FIELD (3T) → better momentum resolution

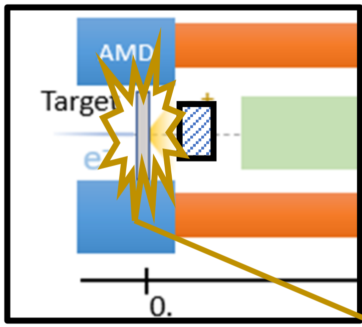
Synergies: with Fusion reactors; needs for HTS tapes

- Massive production of HTS for Fusion
- Huge R&D and production quality effort in industry
- 5 qualified vendors world-wide (more are coming)

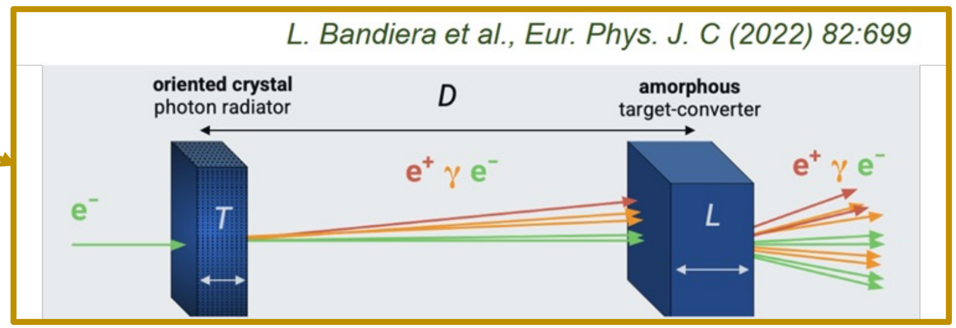


MAIN GOAL of the proposal:
(B= 3 T, T= 20-50 K) solenoid for IDEA detector with HTS cables for >10 y operation

FCC: New targets kind to be tested in 2026 @ PSI for P^3 beam line



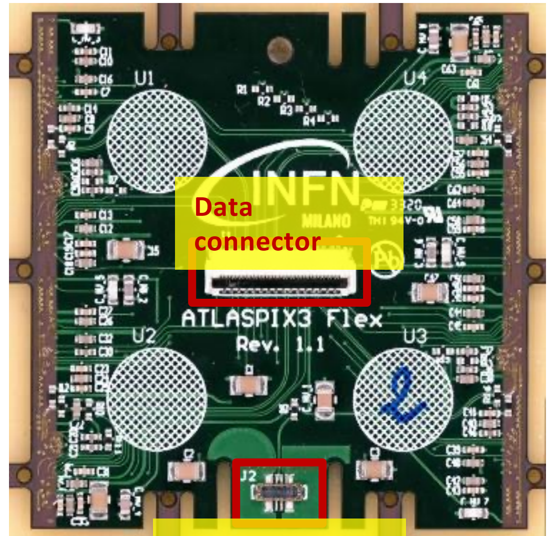
AI methods to optimize different layouts are under study, with the aim of the e+ source optimization, and further to compare different optimization techniques

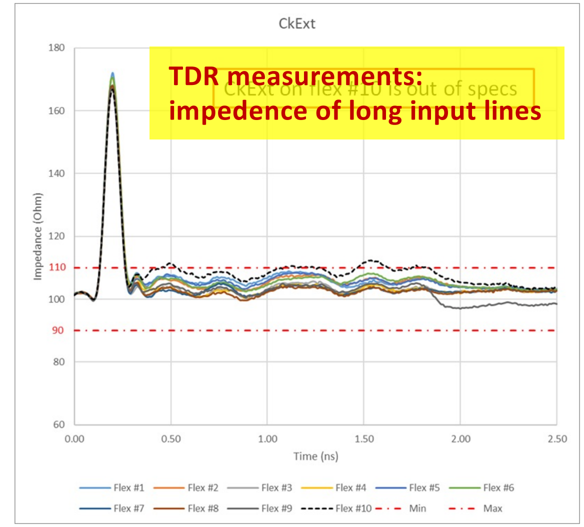


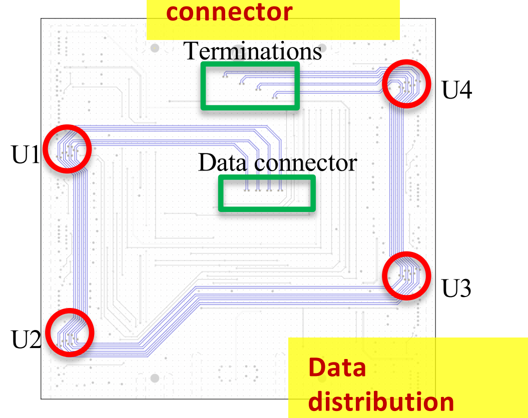
T, L and D are parameters that needs to be tuned in function of the final e+ source performance.

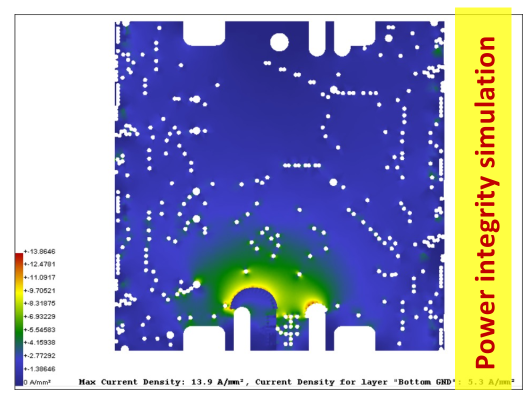
Module concept

- **Readout unit based on 4 chips**
  - shared services among 4 sensors by common power connections and configuration lines
  - benefits of in-chip regulators to reduce connections
  - avoids complications with stitching
  - design based on ATLAS quad-modules
- **Two configuration options**
  - command decoder (LVDS, default)
  - SPI (backup)
- **4-layer flex hybrid**
  - 2 power layers
  - 2 signal layers, impedance-matched lines









Shunt-LDO regulators

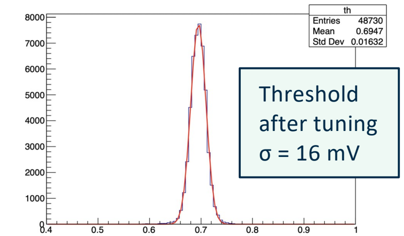
ATLASPIX3.1 can be powered serially using two shunt/low dropout regulators

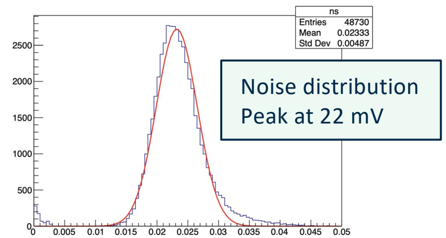
- VinA -> VDDA / VinD -> VDDD
- GND of the analog and digital circuits are shorted.
- Regulator outputs are connected to VDDD/A.

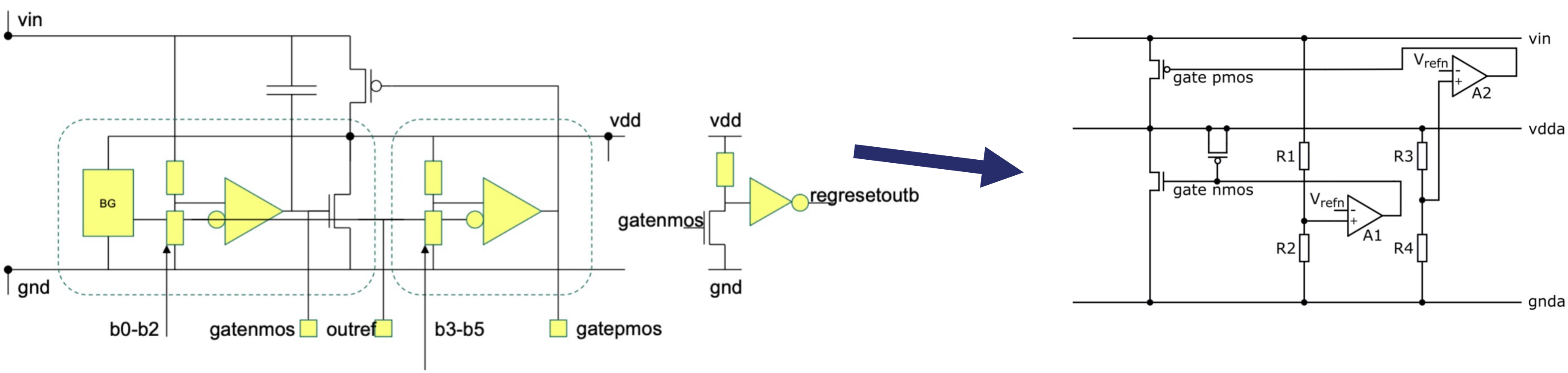
Each regulator 6-bit DAC to adjust the threshold and output voltage:

- b0-b2(3-bit) -> the shunt threshold (nominal value ~ 2.34V),
- b3-b5(3-bit) -> the VDDD/A output tuning (nominal value ~ 1.92V)

Analog performance independent from biasing scheme

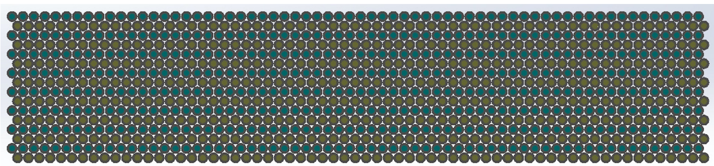






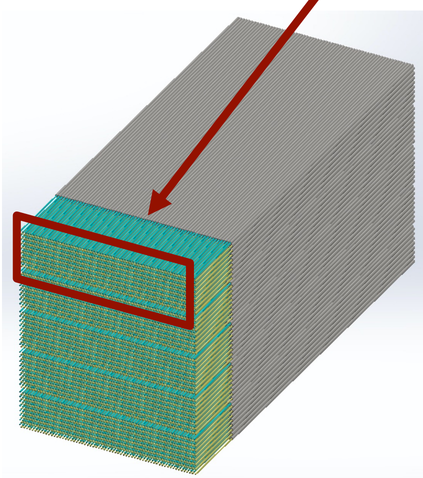
HiDRa: prototipo con contenimento adronico

The BiMini-Module



64 x 16 capillaries

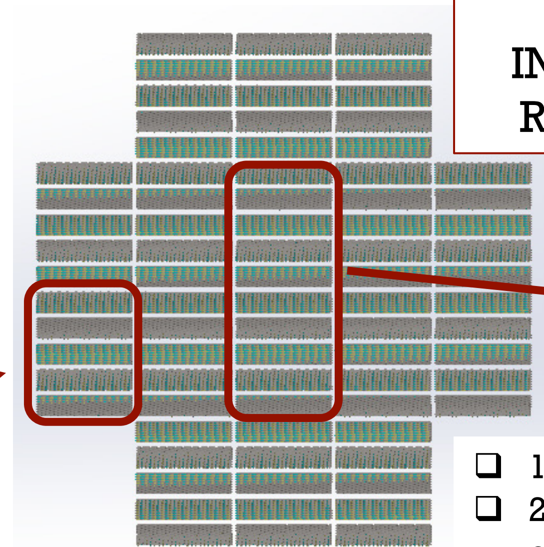
The Module



5 BiMini-modules
~ 13 x 13 x 250 cm^3

The hadronic prototype

HiDRa
INFN-funded
R&D project



The highly granular modules

- 16 modules in total
- 2 central modules equipped with SiPMs
- 14 modules equipped with PMTs
- ~ 65 x 65 x 250 cm^3

The challenge:

We have10240 SiPMs, fitting the back side of the detector

ASPIDES Requirements

Requirements	Dual readout calorimetry	Cherenkov (eg RICH, IACT)	DM	neutrino
SiPM Unit area (mm^2)	1x1	mm scale	10x10	6x6
Micro-cell pitch (um)	10-15	40-50	25-30	50-150
Macro-pixel area (μm^2)	500x500			
PDE (%)	>20	> 40	>45	>35
DCR (kHz)	<100 kHz/mm^2	very low for single pe detection	<0.1 Hz/mm^2 (at LN)	<0.2 Hz/mm^2 (at LN)
AP (%)	<1	Few	Total Correlated Noise Probability (Xtalk + AP) < 60 %	<5%
Xtalk (%)	few			<35%
Trigger	external, self	self, external	self	
Output data: light intensity	no. of fired cells in 1 or 2 time windows (10's of ns long)			
Output data: time	time of arrival of the first photon in the window, possibly of the last photon (TOT)	ToA and ToT	ToA and TOT	
Time resolution (ps)	<100	< 100 single pe		
Module size and form factor	strip with 8 units (1mm x 16 mm), pitch of 2 mm			