F. Cappuzzello
Università di Catania and INFN LNS

The NUMEN project at INFN-LNS: R&D activity on new detection technologies

GDS Topical Meeting: GDS coupling to auxiliary detection systems

25-27 January 2017, INFN Laboratori Nazionali di Legnaro

The NUMEN project

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$$1/T^{0\nu}_{1/2}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

The NUMEN framework

TeBe: PI M.Cavallaro

Other regional projects

CS-upgrade: PI D. Rifuggiato

NURE: PI M.Cavallaro

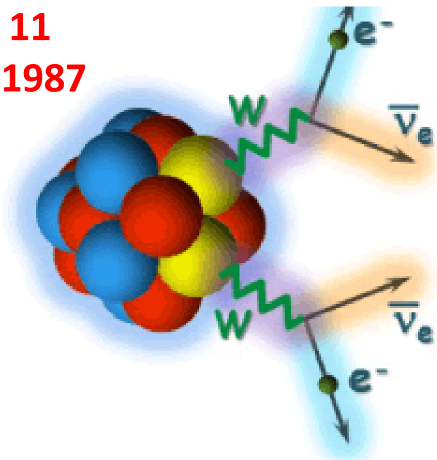
SiCILIA: S. Tudisco

Physics case tutorial

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



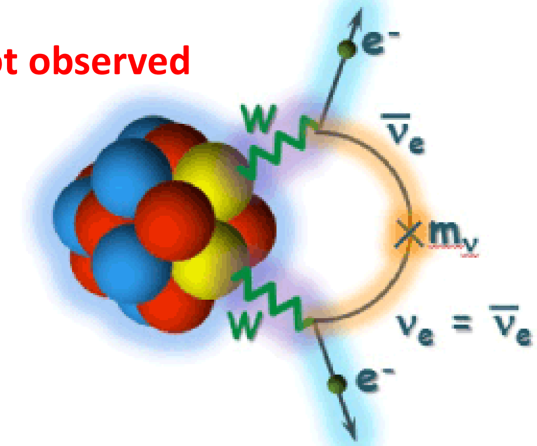
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

1. **Within standard model**
2. **$T_{1/2} \approx 10^{19}$ to $2*10^{21}$ yr**

$$1/T_{1/2}^{2\nu}(0^+ \rightarrow 0^+) = G_{2\nu}\left|M^{\beta\beta 2\nu}\right|^2$$

Neutrinoless double beta decay

Still not observed



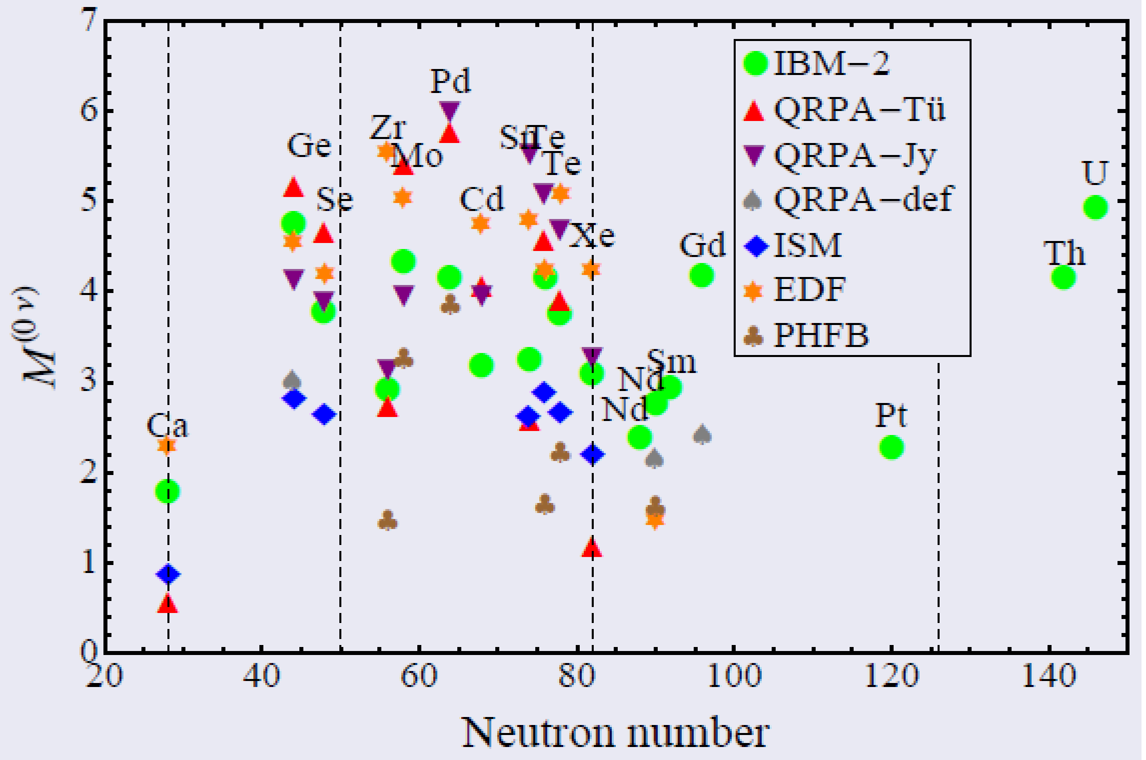
E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184

1. **Beyond standard model**
2. **Access to effective neutrino mass**
3. **Violation of lepton number conservation**
4. **CP violation in lepton sector**
5. **A way to leptogenesis and GUT**

$$1/T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e^5}\right|^2$$

State of the art NME calculations

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$



Courtesy of Prof. F.Iachello

Heavy-ion DCE

- ✓ Induced by strong interaction
- ✓ Sequential nucleon transfer mechanism 4th order:

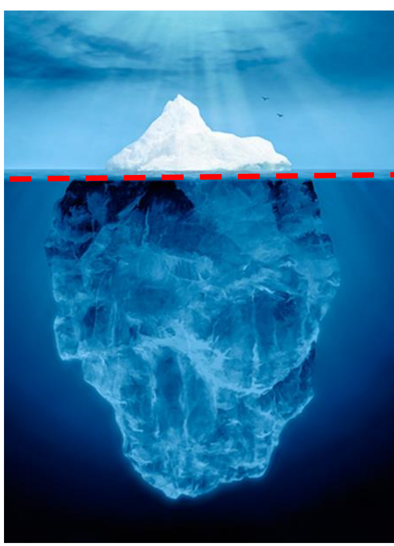
  Brink's Kinematical matching conditions *D.M.Brink, et al., Phys. Lett. B 40 (1972) 37*

- ✓ Meson exchange mechanism 2nd order
- ✓ Possibility to go in both directions

NUMEN

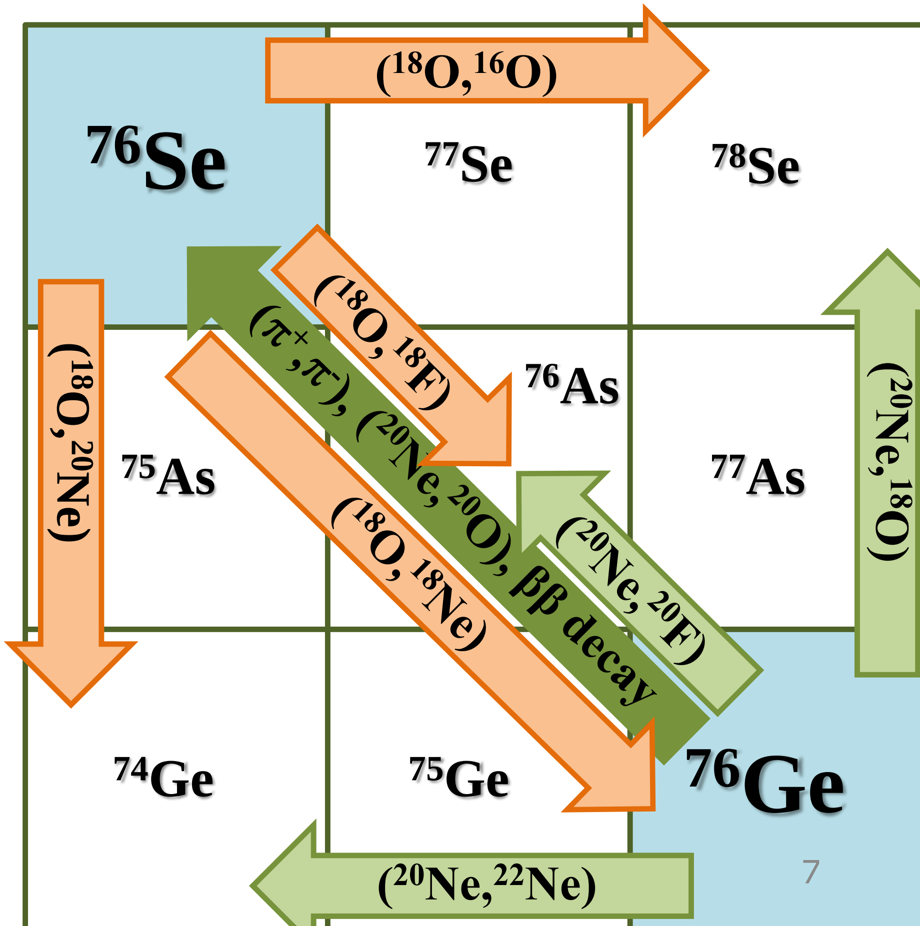
RIKEN

RCNP



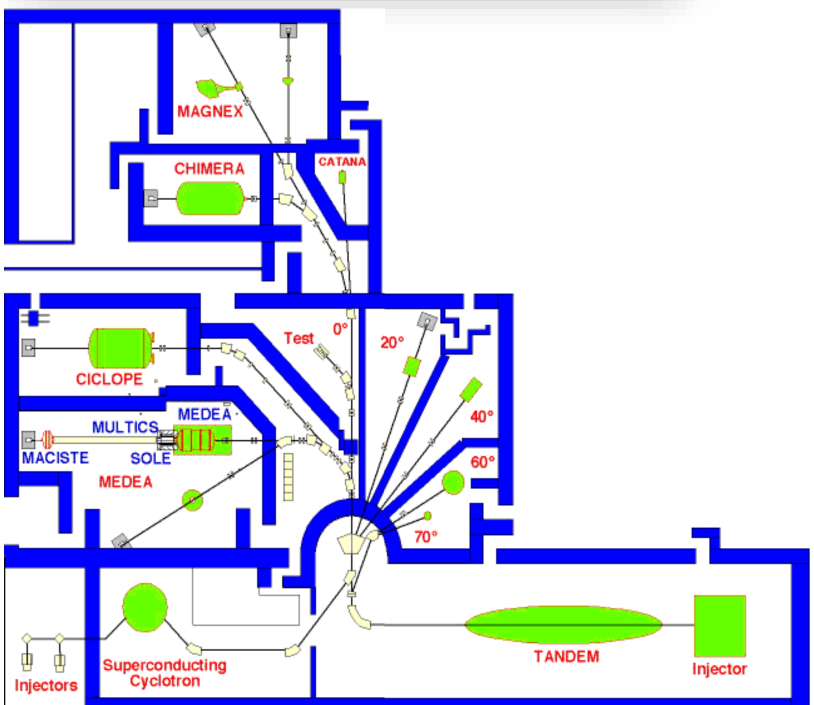
Tiny amount of DGT strenght in low lying states

Sum rule almost exhausted by DGT Giant Mode



DCE @ INFN-LNS

The LNS laboratory in Catania



Superconducting Cyclotron and MAGNEX spectrometer @ LNS

crucial for the experimental challanges

Superconducting Cyclotron

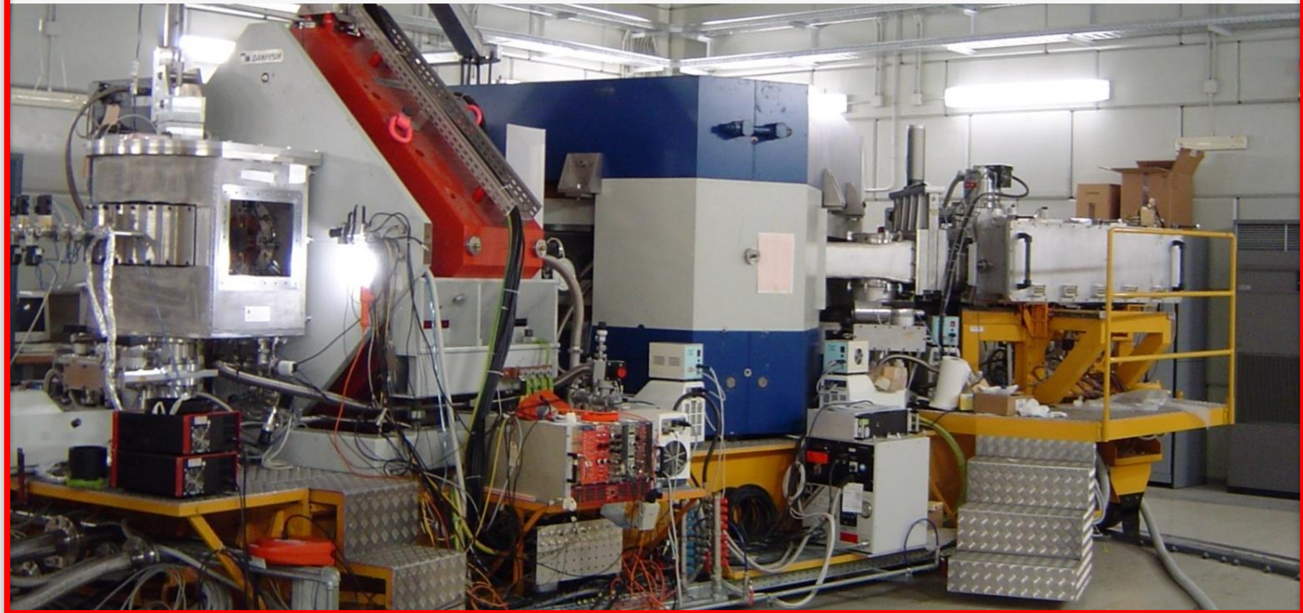
- **K800 Superconducting Cyclotron in full operation since 1996.**
- **It can accelerate from Hydrogen to Uranium.**
- **Maximum nominal energy is 80 MeV/u.**

MAGNEX spectrometer

F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167

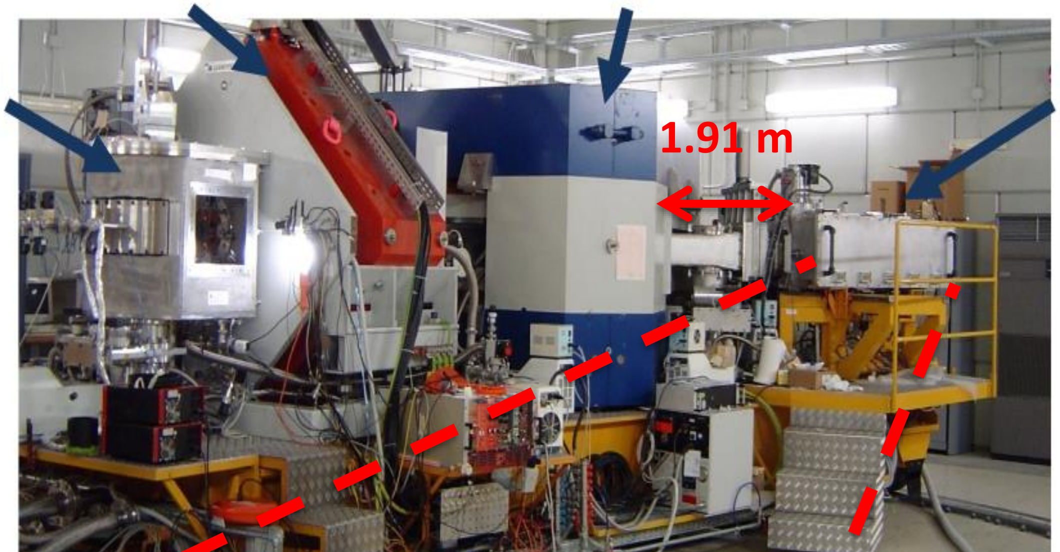
Achieved resolution
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.2^{\circ}$
Mass $\Delta m/m \sim 1/160$

Optical characteristics	Measured values
Maximum magnetic rigidity	1.8 T m
Solid angle	**50 msr**
Momentum acceptance	**-14.3%, +10.3%**
Momentum dispersion for k= - 0.104 (cm/%)	3.68



The MAGNEX FPD

M. Cavallaro et al., Eur. Phys. J. A (2016) 48: 59

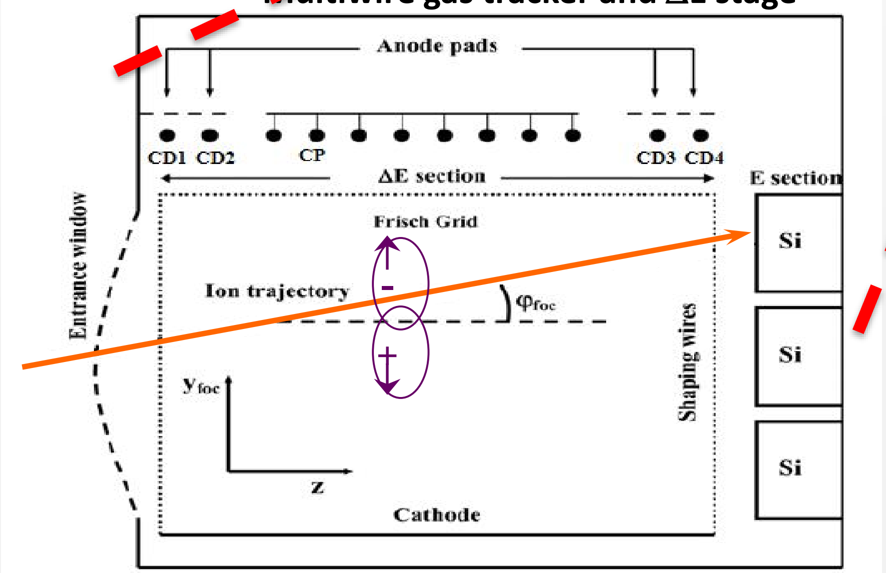


active area **140 x 20 cm²**

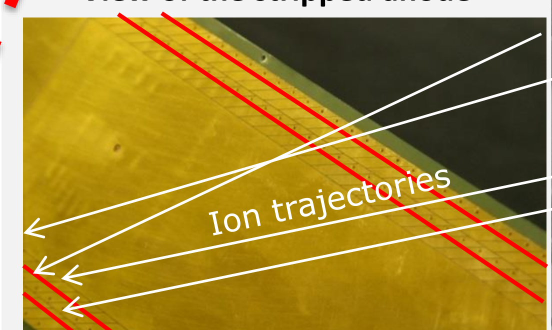
Ionization drift chamber, five independent proportional counters, four of which are position-sensitive and a **wall** of **stopping silicon detectors**

Pure isobutane; pressure range: 5-100 mbar; 600-800 V, wires ϕ =20 μm

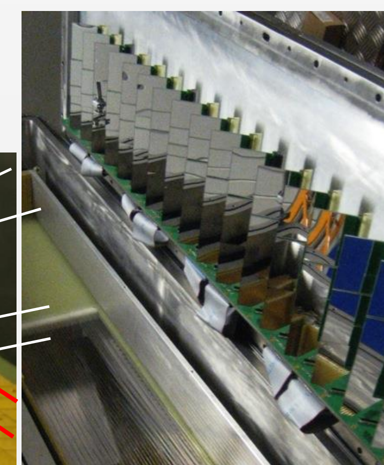
Multiwire gas tracker and ΔE stage



View of the stripped anode



Wall of 60 stopping 7 X 5 cm² Silicon detectors

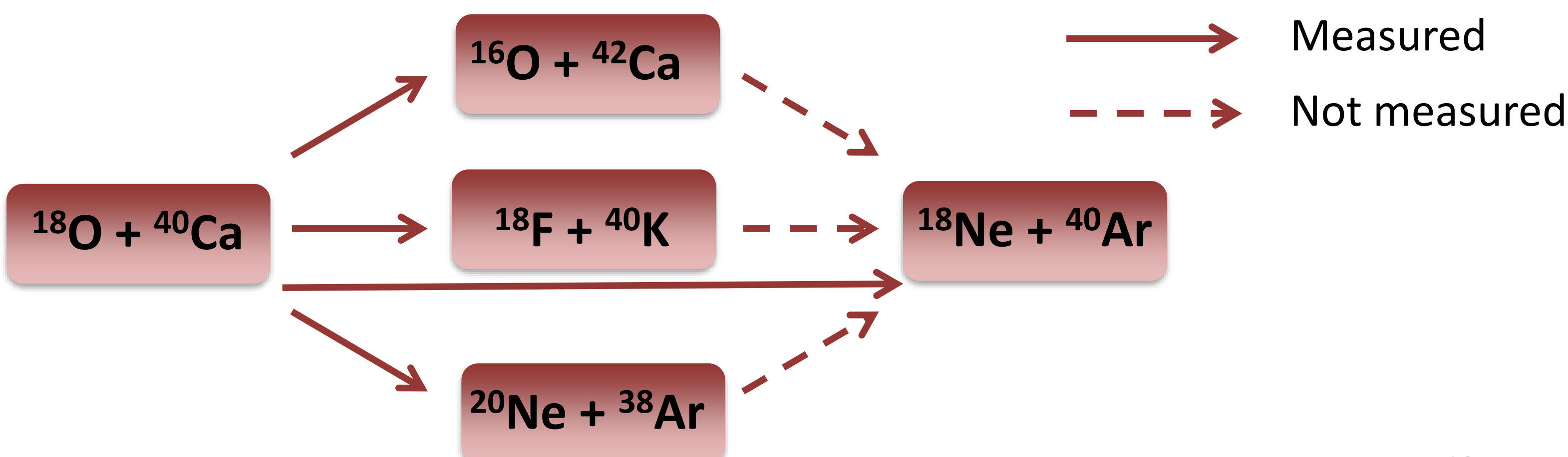


(^{18}O,^{18}Ne) DCE reactions at LNS

^{40}Ca(^{18}O,^{18}Ne)^{40}Ar @ 270 MeV

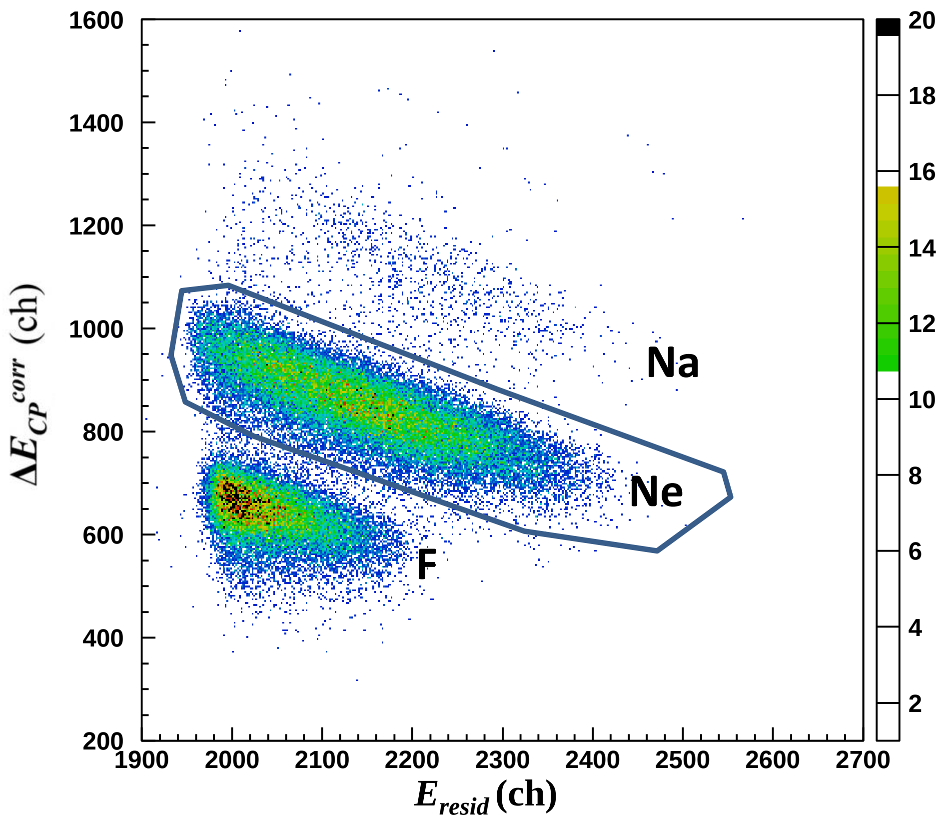
First pilot experiment

- $^{18}O^{7+}$ beam from Cyclotron at **270 MeV (10 pnA, 3300 μC in 10 days)**
- **^{40}Ca** solid target 300 μg/cm^2
- Ejectiles detected by the MAGNEX spectrometer ($0° < \vartheta_{lab} < 10°$)
- Unique angular setting: $-2° < \theta_{lab} < 10°$ corresponding to a momentum transfer range **from 0.17 fm^{-1} to about 2.2 fm^{-1}**



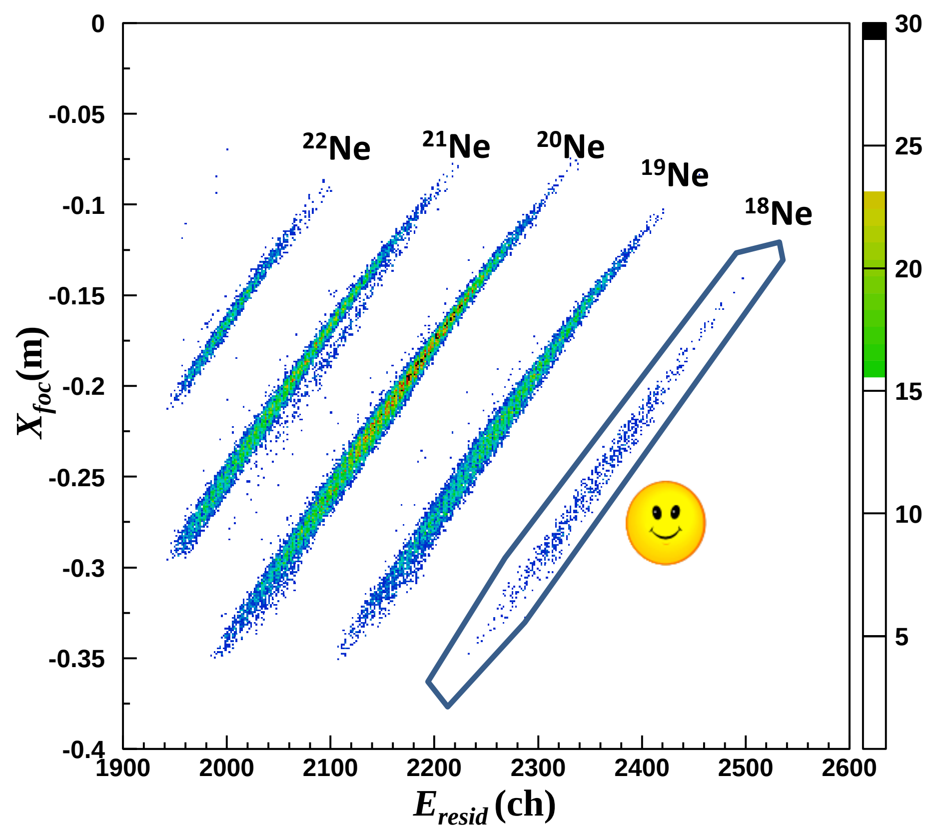
Particle Identification

Z identification



A identification

$$B\rho = \frac{p}{q} \quad \rightarrow \quad X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$



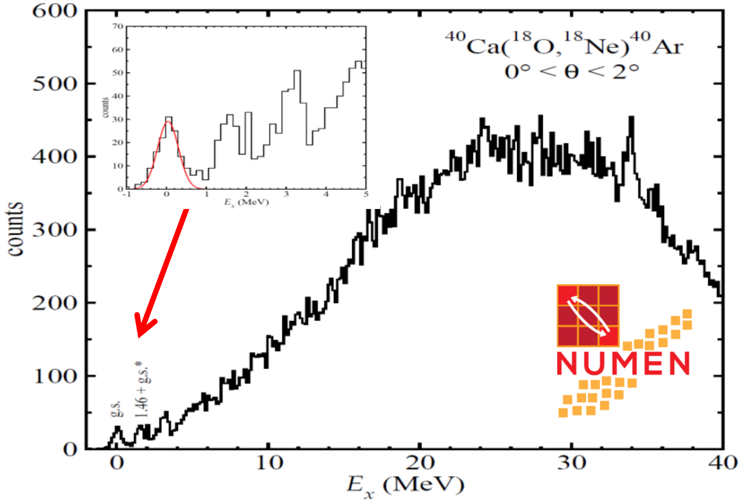
F. Cappuzzello et al., NIMA621 (2010) 419

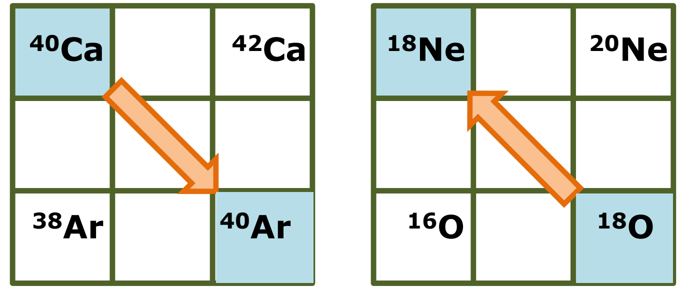
F. Cappuzzello, et al. NIMA638 (2011) 74

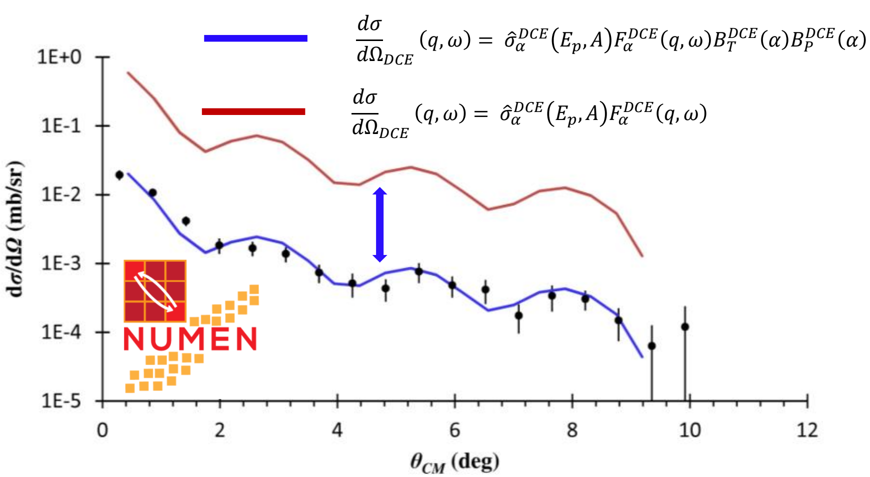
M.Cavallaro et al. EPJ A (2012) 48: 59

D.Carbone et al. EPJ A (2012) 48: 60

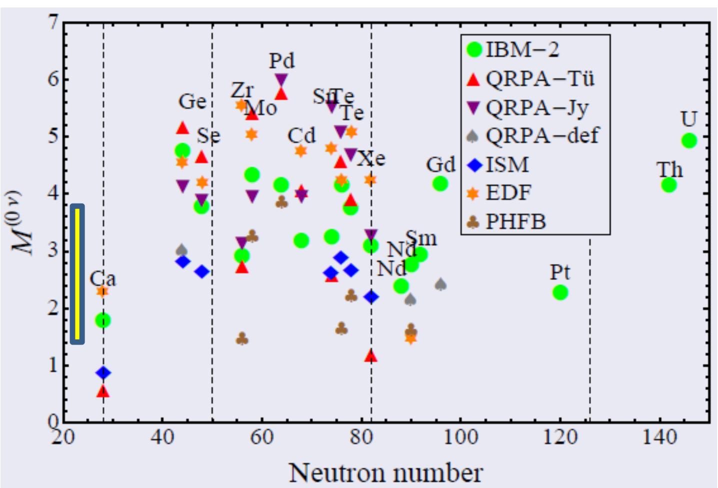
$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV







F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145



$$\left|M^{0\nu\beta\beta}\left(^{40}Ca\right)\right|^2 = 0.37 \pm 0.18$$

Pauli blocking about 0.14 for F and GT

Status and perspectives of NUMEN

Moving towards hot-cases:

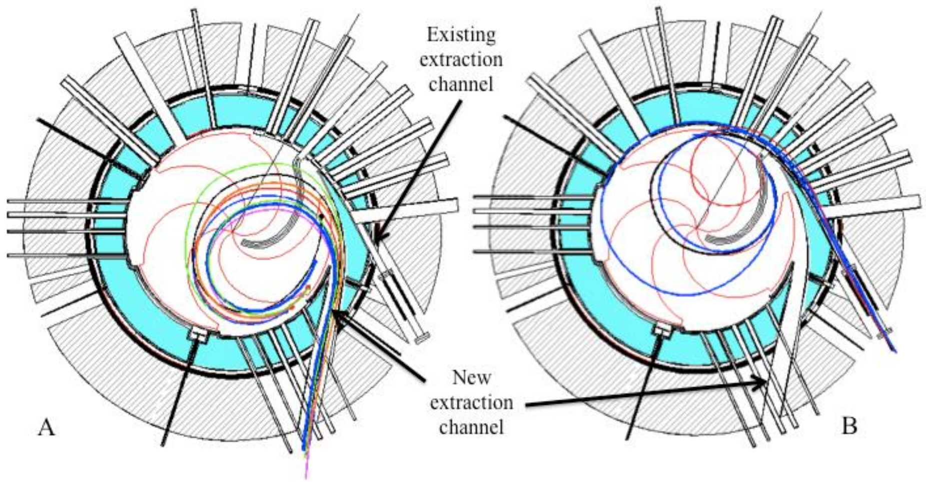
Caveat

- The $(^{18}O,^{18}Ne)$ reaction is particularly advantageous, but it is of $\beta^+\beta^+$ kind;
- None of the reactions of $\beta^-\beta^-$ kind looks like as favourable as the $(^{18}O,^{18}Ne)$.
  - $(^{18}Ne,^{18}O)$ requires a radioactive beam
  - $(^{20}Ne,^{20}O)$ or $(^{12}C,^{12}Be)$ have smaller B(GT)
- The reaction Q-values are normally more negative than in the ^{40}Ca case
- In some cases gas or implanted target will be necessary, e.g. ^{136}Xe or ^{130}Xe
- In some cases the energy resolution is not enough to separate the g.s. from the excited states in the final nucleus $\rightarrow$ Coincident detection of γ-rays

Much higher beam current is needed

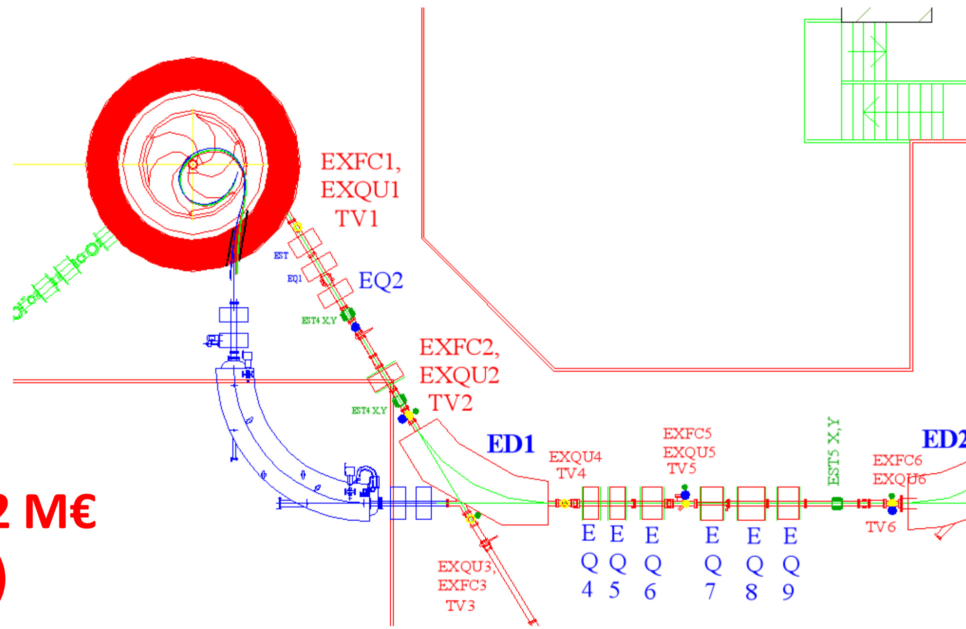
Major upgrade of LNS facilities: The CS accelerator

- The **CS** accelerator current (from 100 W to 5-10 kW);



Extraction by stripping

- The **beam transport line** transmission efficiency to nearly 100%



TDR of the project approved 11.2 M€
Cryostat tender started (~4.1M€)

Studied cases – expected intensities

Ion	Energy	Isource	Iacc	Iextr	Iextr	Pextr
	MeV/u	eμA	eμA	eμA	pps	watt
^{12}C q=5+	30	200	30 (4+)	45 (6+)	$4.7 \cdot 10^{13}$	2700
^{12}C q=4+	45	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	8100
^{12}C q=4+	60	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	10800
^{18}O q=6+	20	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	3600
^{18}O q=6+	29	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	5220
^{18}O q=6+	45	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	8100
^{18}O q=6+	60	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	10800
^{18}O q=7+	70	200	30 (7+)	34.3 (8+)	$2.7 \cdot 10^{13}$	5400
^{20}Ne q=7+	28	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	4800
^{20}Ne q=7+	70	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	10280
^{40}Ar q=14+	60	400	60 (14+)	77.1 (18+)	$2.7 \cdot 10^{13}$	10280

Purchase of the SC Magnet

Cost and technical analysis
Dec. 2015 -> completed in Sett. 2016
(RUP appointed in Sept. 2016)

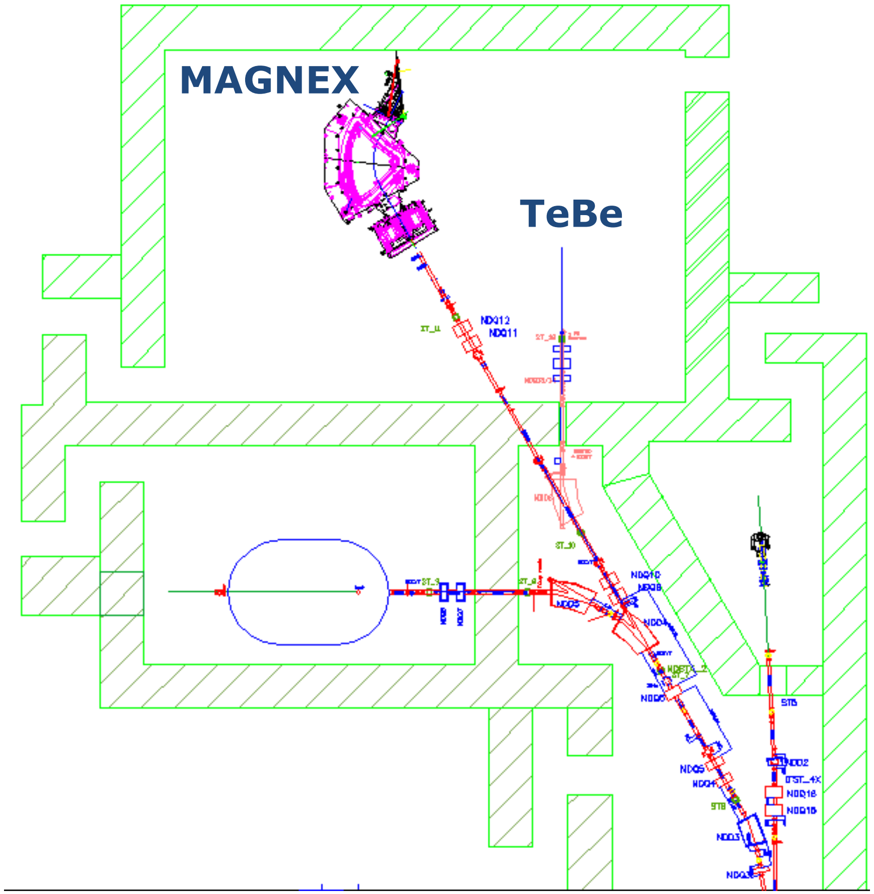
Tender and contract:
Nov. 2016 -> Sept. 2017

Design and Construction:
Oct. 2017 -> June 2020

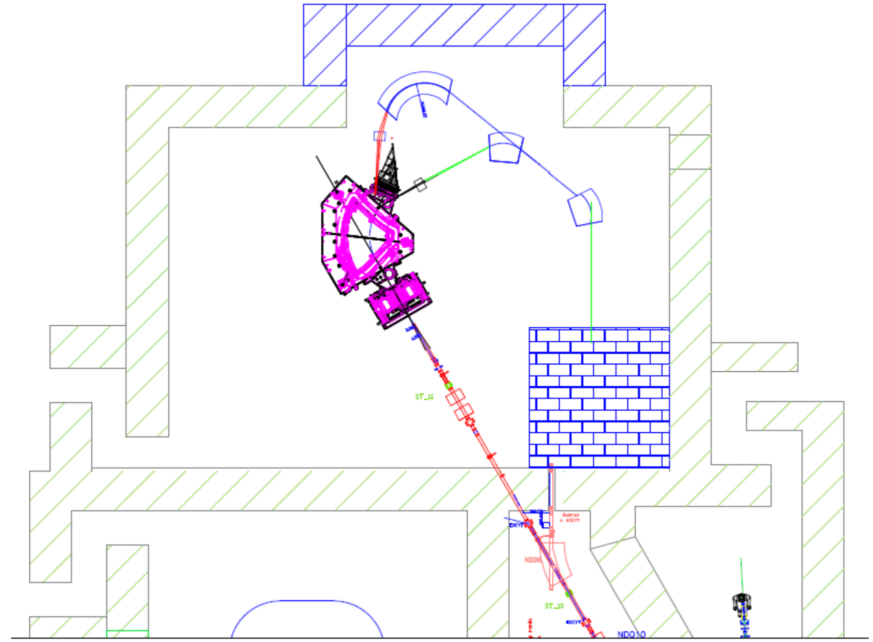
Installation - Test and Commissioning
July 2020 -> Apr. 2021

A challenging beam dump inside the MAGNEX hall

Present MAGNEX hall

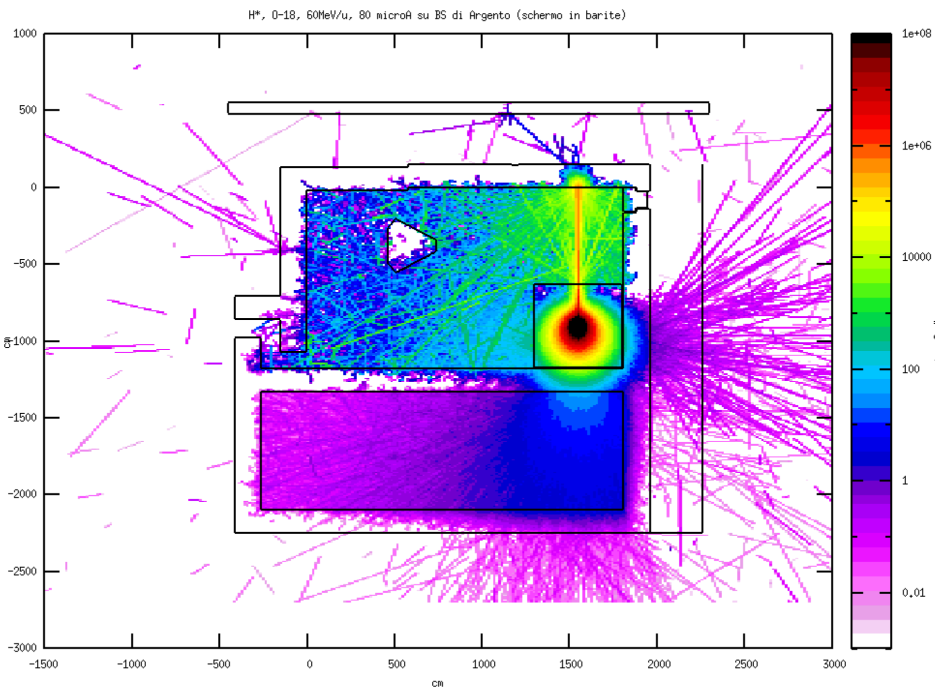


Future MAGNEX hall

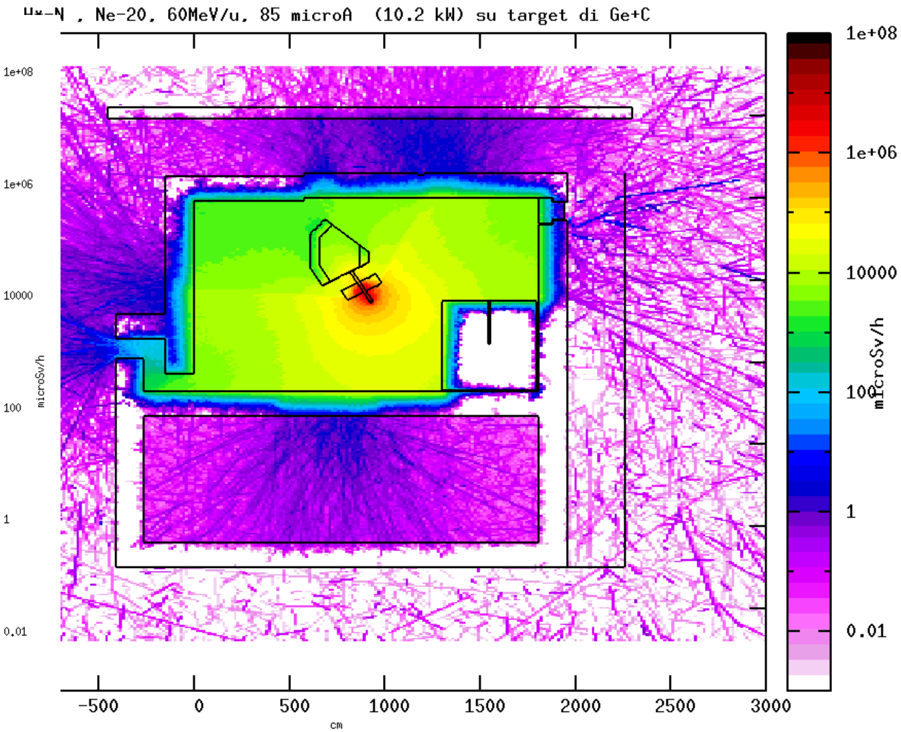


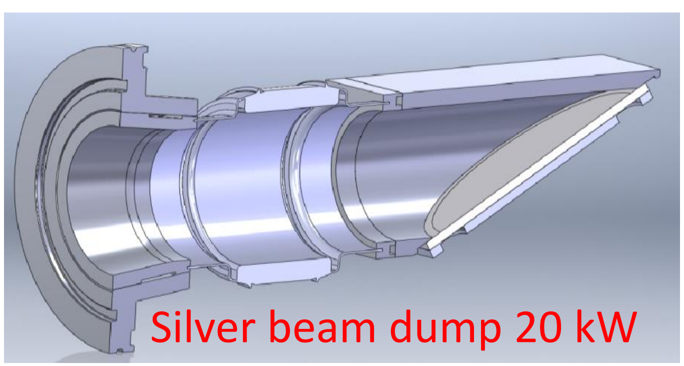
A challenging beam dump inside the MAGNEX hall

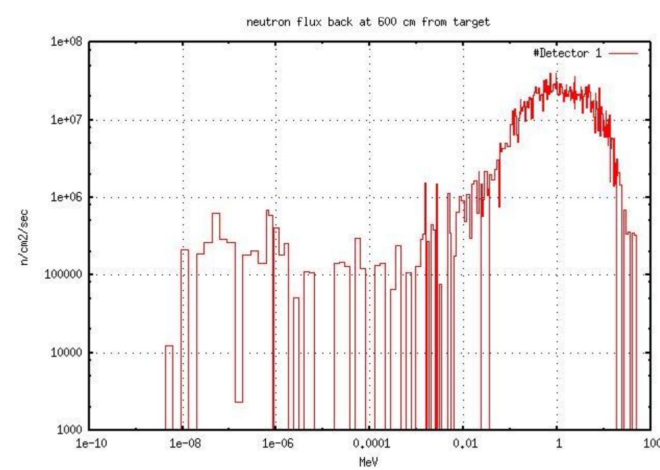
85 μA beam of ^{18}O on Ag



85 μA beam of ^{20}Ne on ^{76}Ge+C







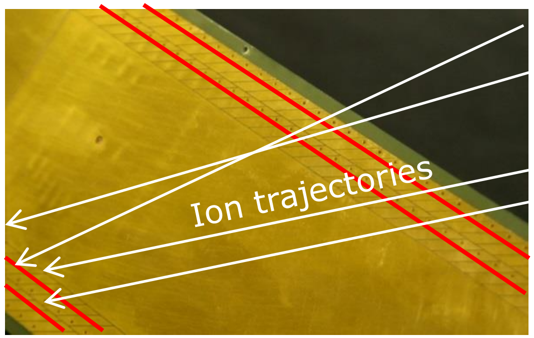
From S.Russo (LNS radioprotection service)

The new focal plane detector

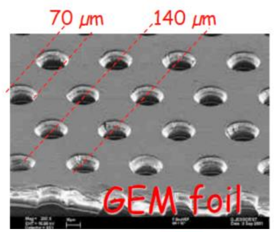
Major upgrade of LNS facilities: MAGNEX

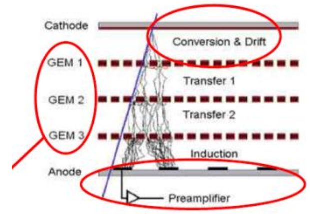
- The **MAGNEX focal plane** detector rate (from 2 kHz to several MHz)

From multi-wire tracker



To micro-pattern tracker



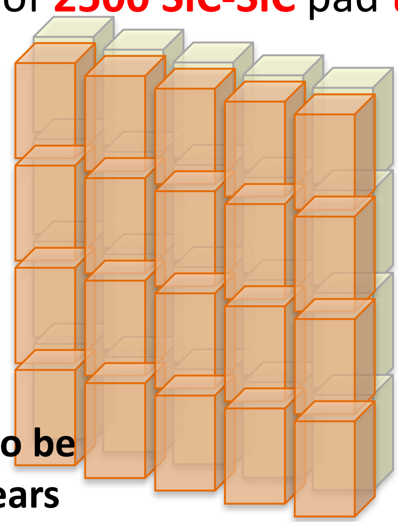


Up to MHz/mm² of primary electrons for ^{20}Ne 30 MeV/u on C_4H_{10} 20 mbar

- ➢ **R&D key issue : MPGD-based tracker at low pressure and wide dynamic range**
- ➢ **INFN-LNS (M. Cavallaro), collaboration with INFN-CT, UNAM**

From wall of **60** Si pad

To wall of **2500 SiC-SiC** pad **telescopes**



About 10^{14} ions to be collected in 10 years

A big challenge!

0.9 M€ call approved by INFN CSN5 (SICILIA)
P.I. S.Tudisco, collaboration with CNR, STM, FBK

SiC for radiation detectors

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.28**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$3\text{-}4 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$\mathbf{2 \cdot 10^7}$	$\mathbf{0.8 \cdot 10^7}$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**30-40**	**13-15**

- Wide band-gap (3.3eV)

⇒ Visible blind

⇒ Lower Leakage current

- High Breakdown

⇒ Advantage for Radiations hardness

- Different e-h mobility

⇒ Charge Identification pulse shape analysis

- Fast devices

⇒ Timing applications

- Signal

⇒ Less charge than Si, SiC≈Si/2

- Higher displacement threshold

⇒ Radiation harder then Silicon

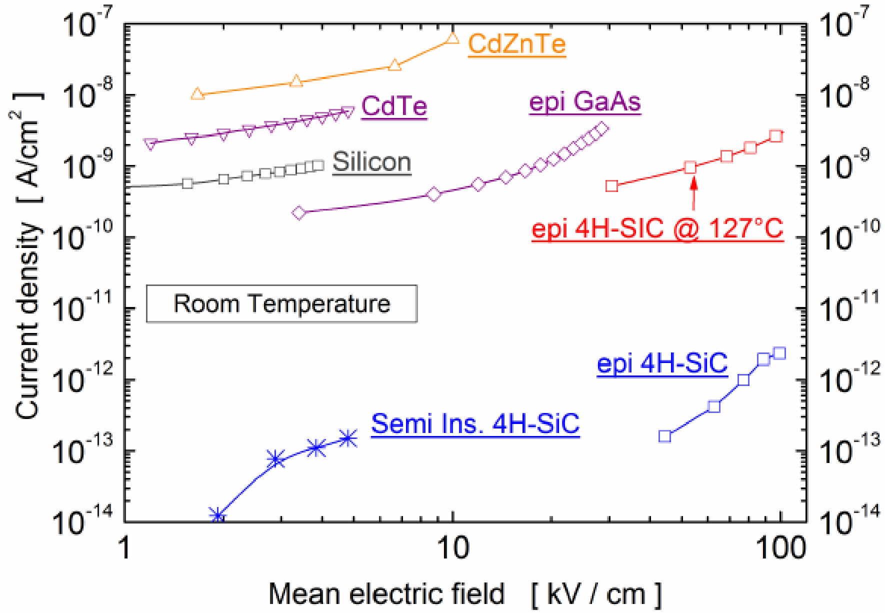
Leakage current

p-n => $J_L = J_{diff} + J_{gen}$

Schottky => $J_L = J_S + J_{gen}$

$J_{gen} \approx N_t (V_{bi}+V)^{1/2}$

Schottky device



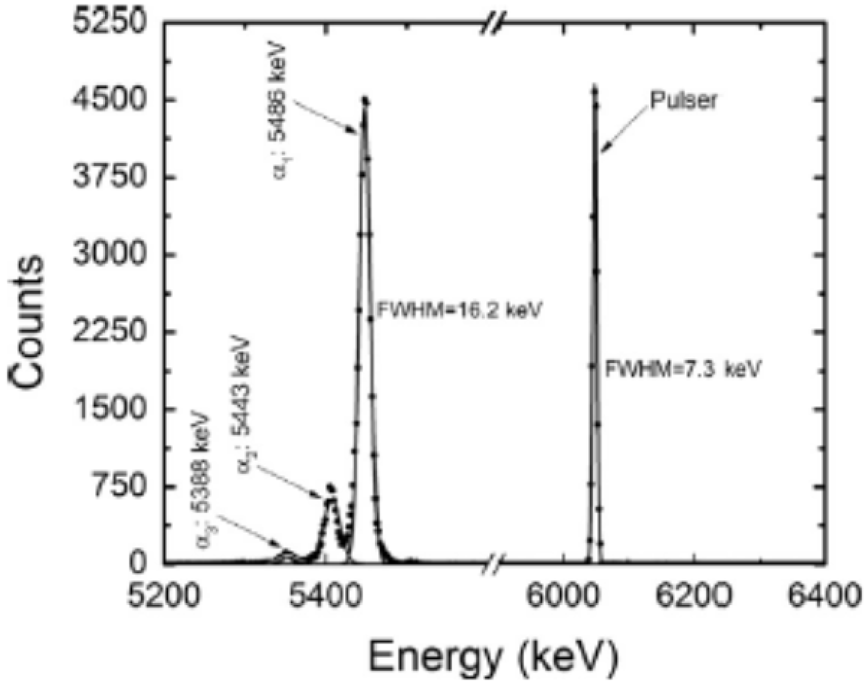
$J_S \approx A^{**}T^2 \exp(-q(\Phi_B+\Delta\Phi_B)/KT)$

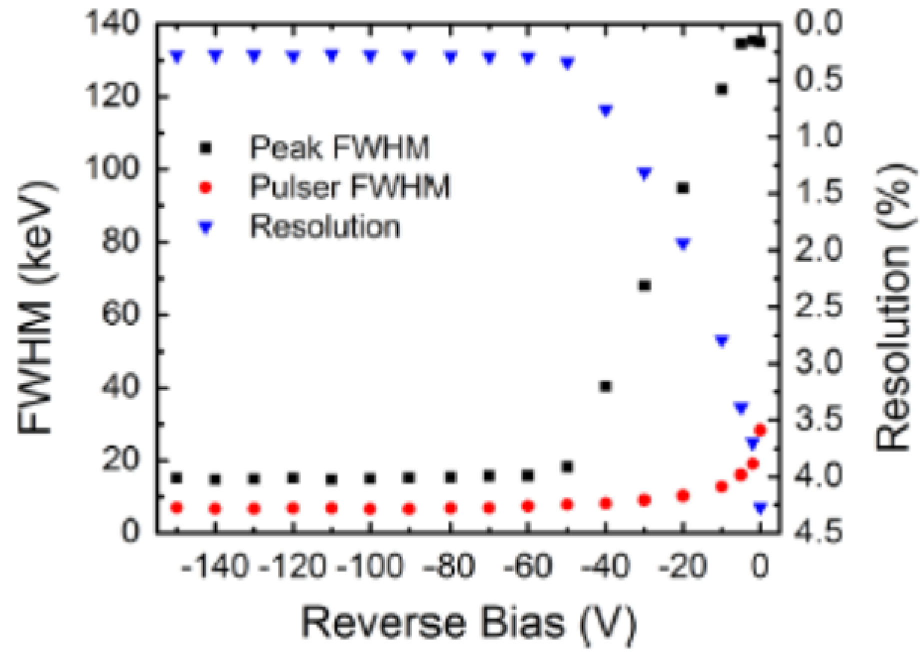
$$J_L^{(SiC)} \approx 10^{-3} J_L^{(Si)}$$

$J_{diff} \approx T^{(3+\gamma/2)} \exp(-E_g/KT)$

$$J_L^{(SiC)} \approx 10^{-4} - 10^{-5} J_L^{(Si)}$$

SiC detectors



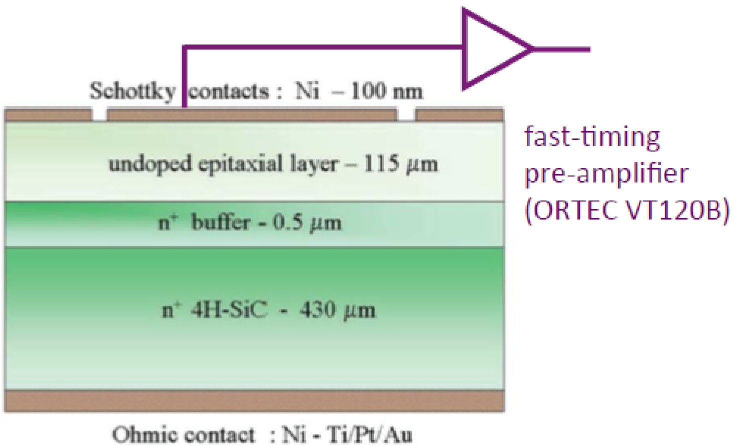


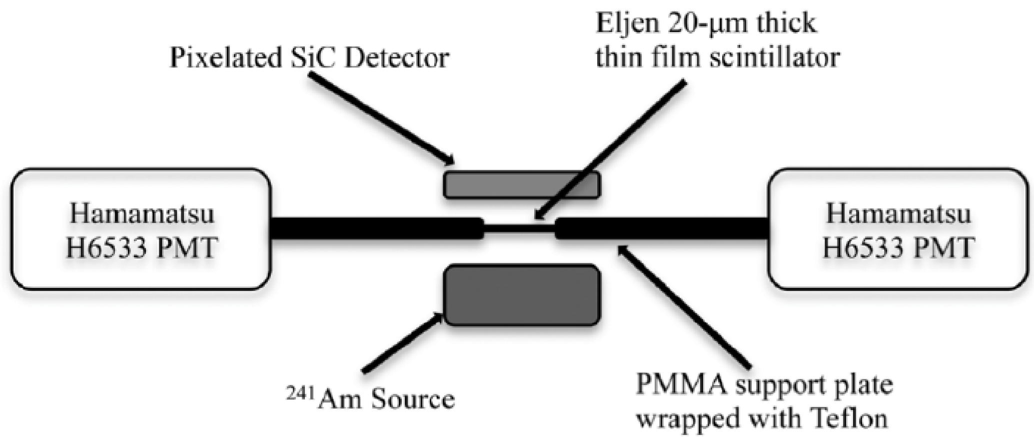
S.K. Chaudhuri et al. / Nuclear Instruments and Methods in Physics Research A 728 (2013) 97–101

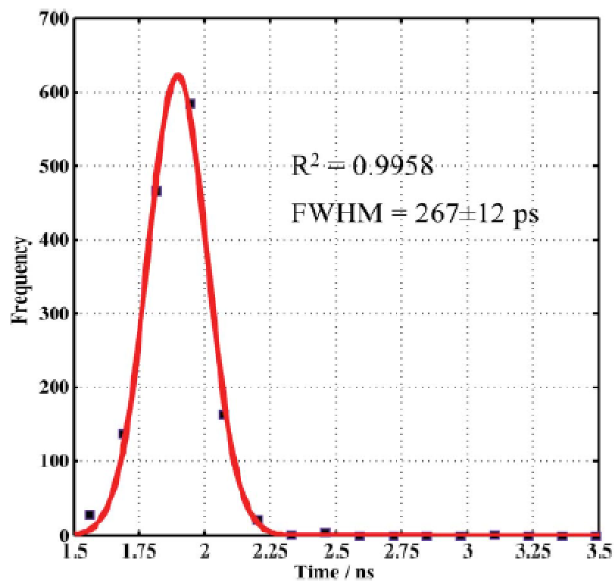
Intrinsic detector resolution 14.5 KeV (0.2%)

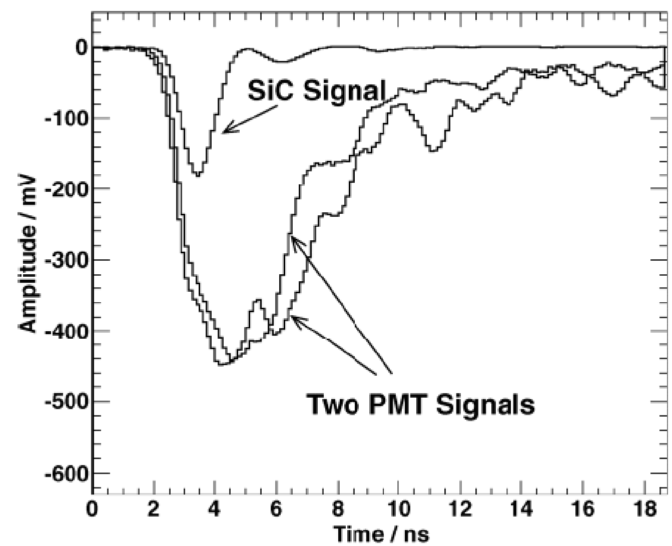
SiC detector: state-of-Art

✓ Timing







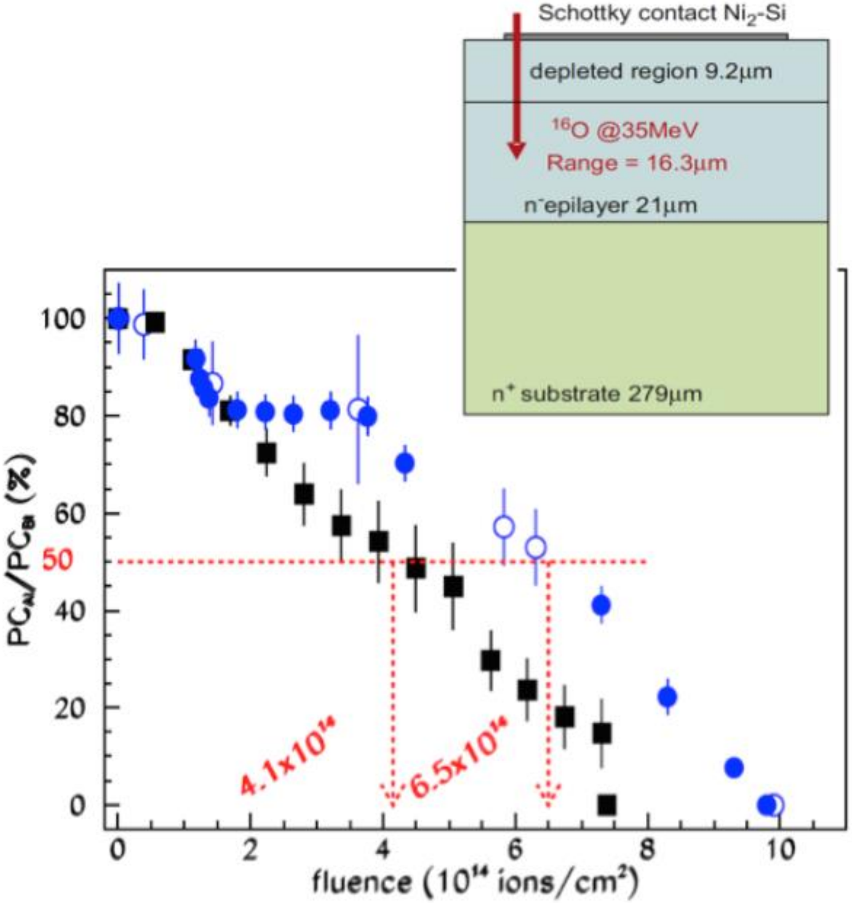


Snapshot of signals obtained from the SiC detector and the two PMTs.

Xiaodong Zhang IEEE Trans. Nucl. Scie. VOL. 60, NO. 3, JUNE 2013

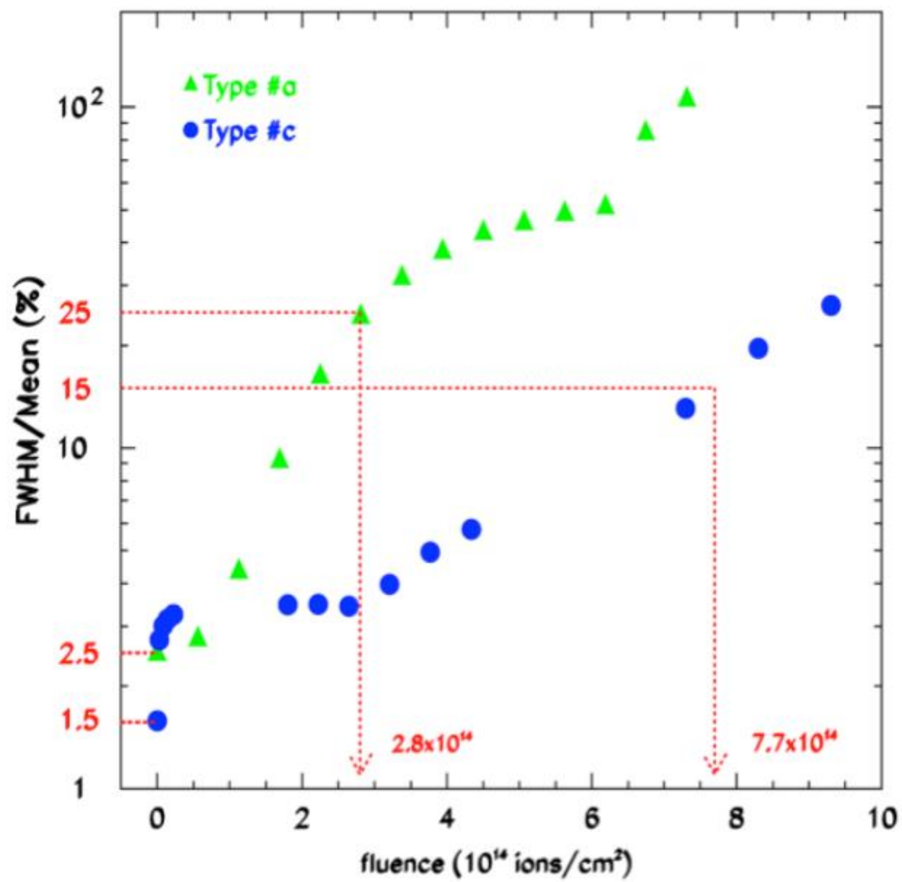
SiC detector: state-of-Art

✓ Radiation Hardeness



Ratio of peak centroid of ^{16}O energy spectrum after (PC_{AI}) and before irradiation (PC_{BI})

^{16}O @ 35 MeV



Relative Energy resolution

G. Raciti et al. Nuclear Physics A 834 (2010) 784
M. De Napoli et al. NIMA 600 (2009) 618

SiC detectors in INFN

SiCILIA

Si**l**icon **C**arbide Detectors for **I**ntense **L**uminosity **I**nvestigations and **A**pplications

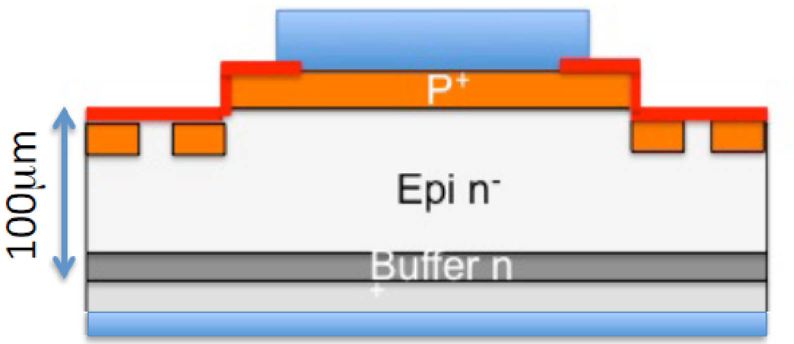
Call INFN 2016 PI: S. Tudisco

SiCilia strategy

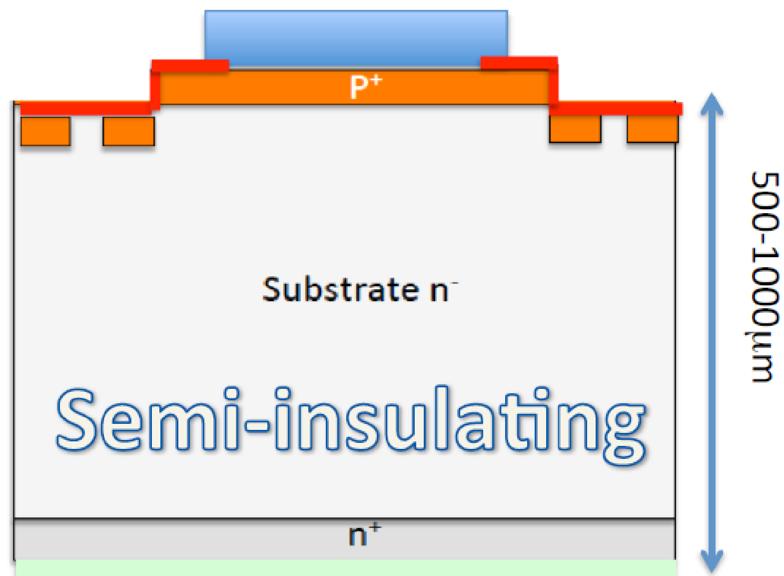
Schottky junctions => FONDAZIONE BRUNO KESSLER

p-n junctions => STMicroelectronics

Detector Δ E



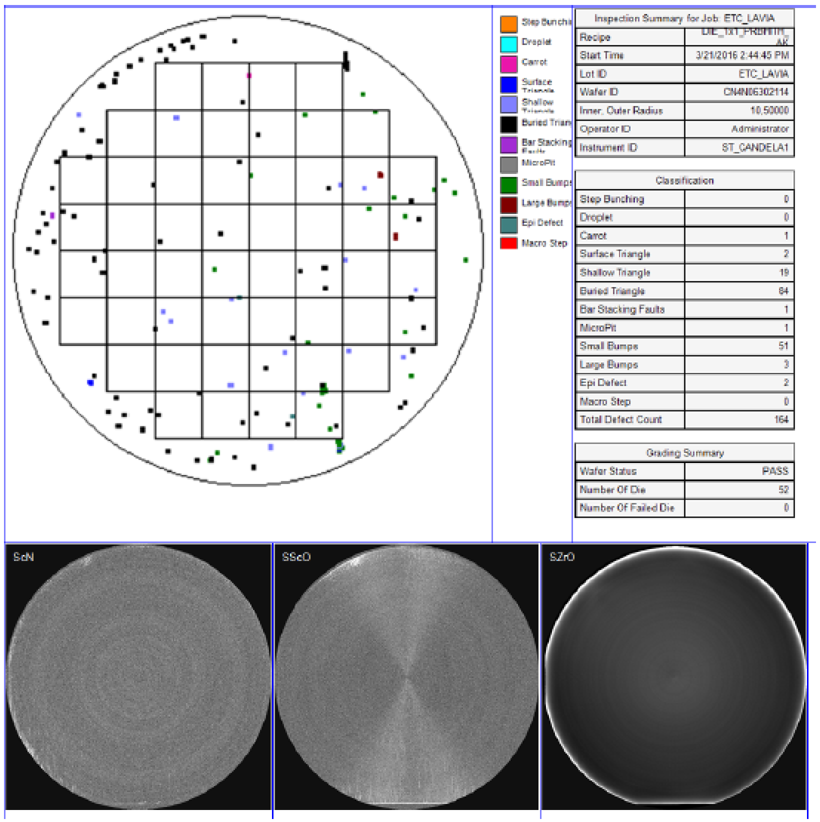
Detector E



SiCilia activity 2016

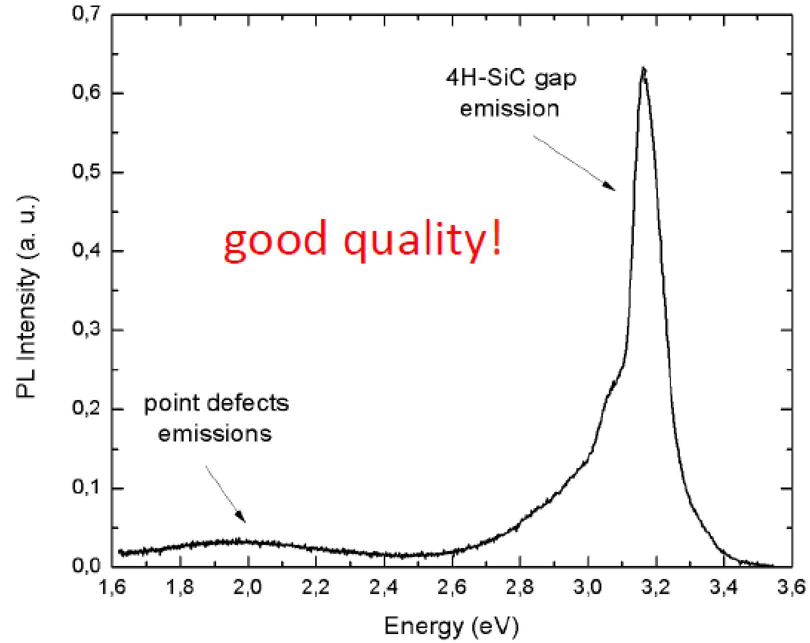
Epitaxial grows

10 μm epitaxial layers grown in LPE



CANDELA Analysis

PL Spectroscopy @325 nm



Expected Yield 85 -100 % @ 10 μm Epi

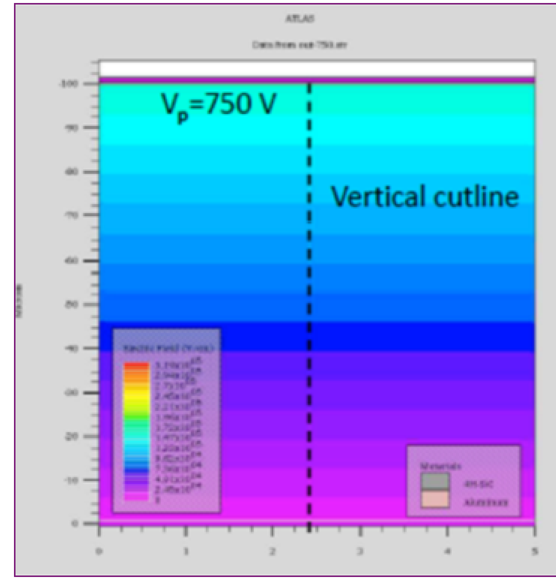
=> 50% @ 100 μm Epi

SiCilia activity 2016

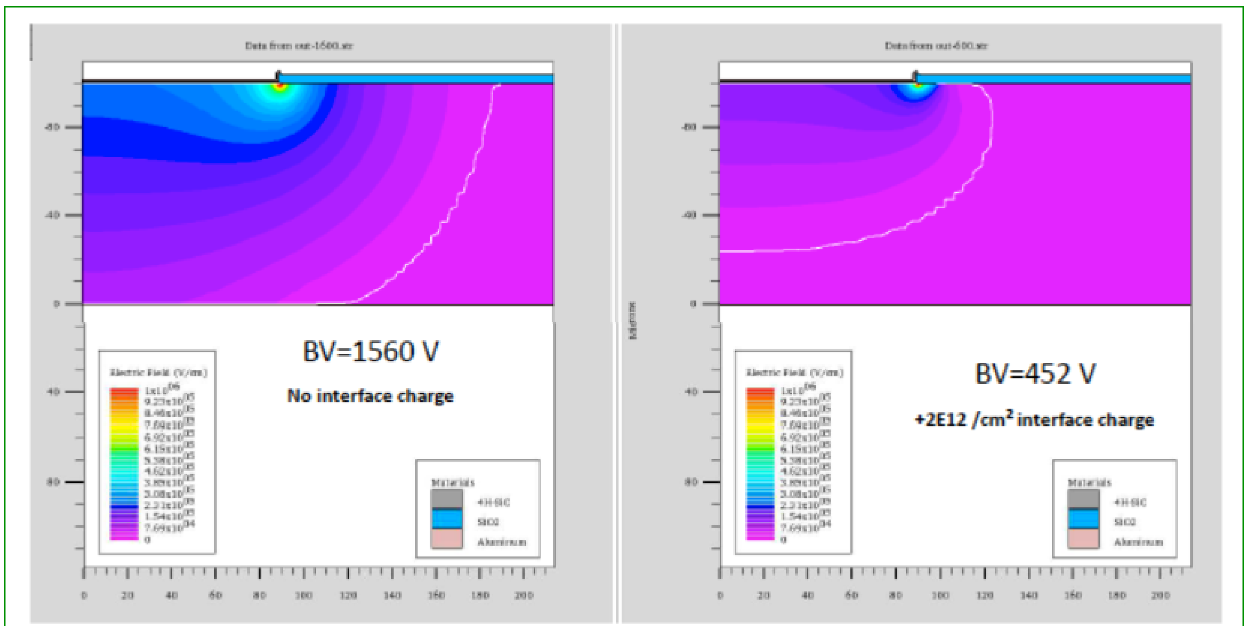
Simulations

for 100 micron EPI is 750 V

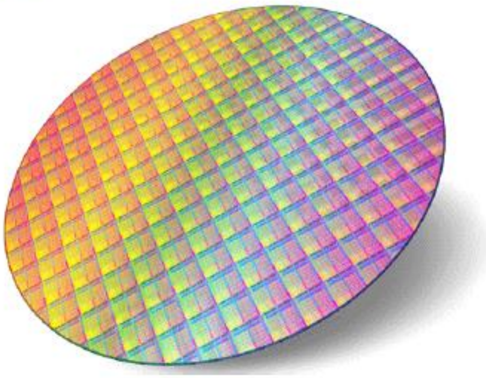
Breakdown > 10kV infinite planar junction



Oxide and Interface Trapped Charges



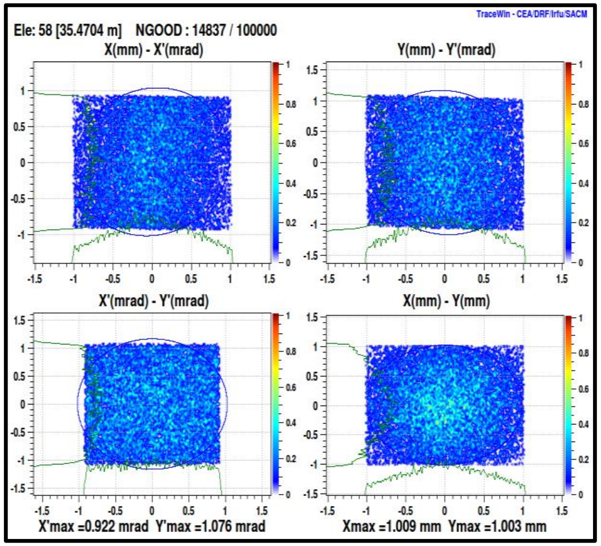
Silicon Carbide detectors

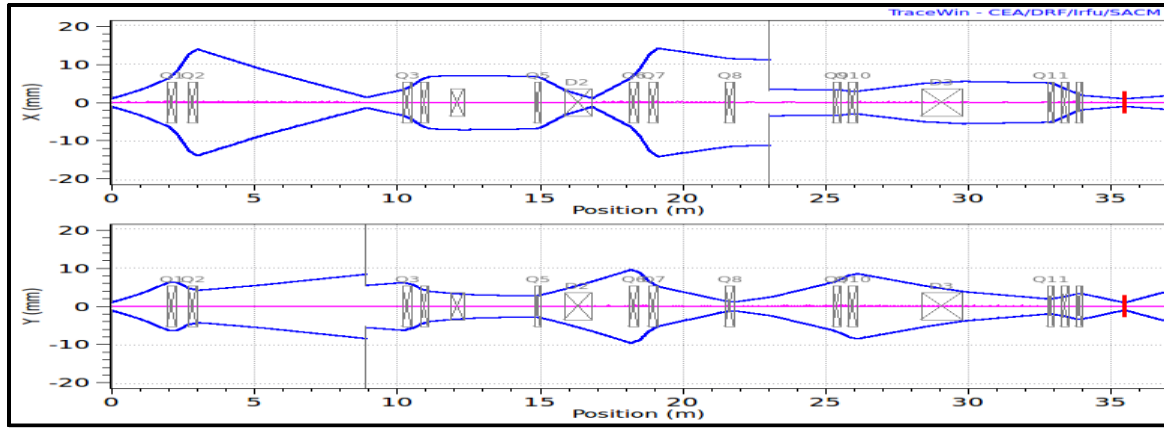


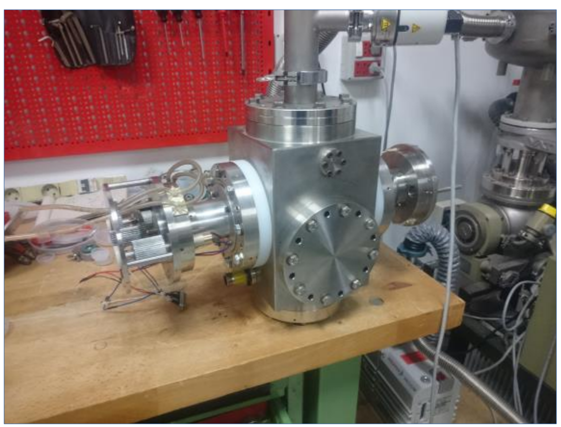
In 2017 first new detector prototypes for STM to be tested under beam

The new Test Bench (TeBe)

TeBe Experimental point in the MAGNEX Hall



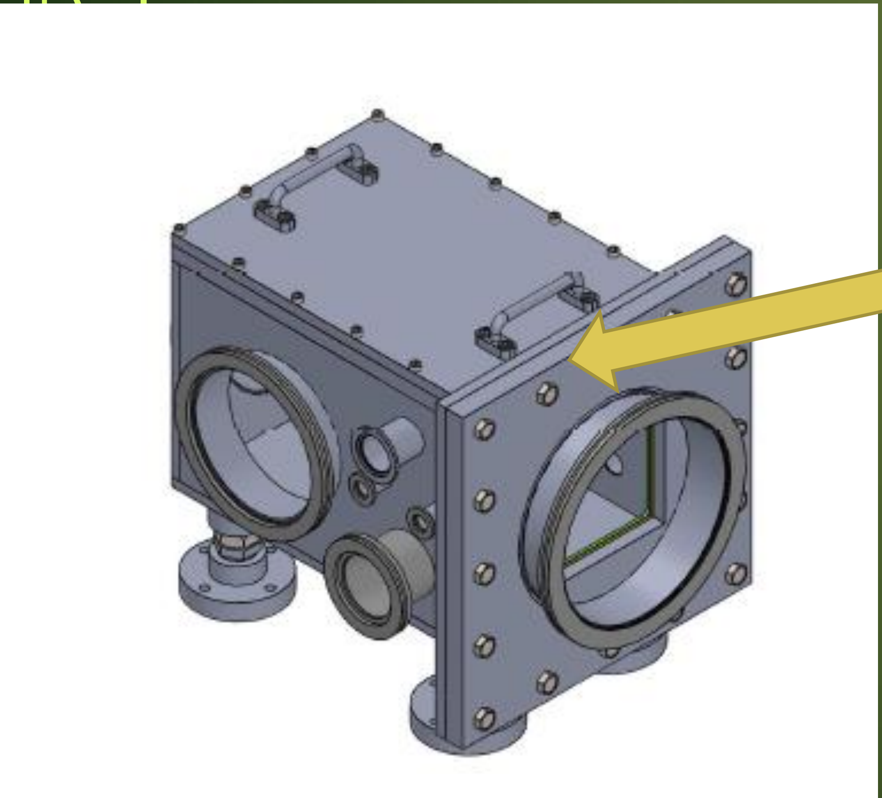


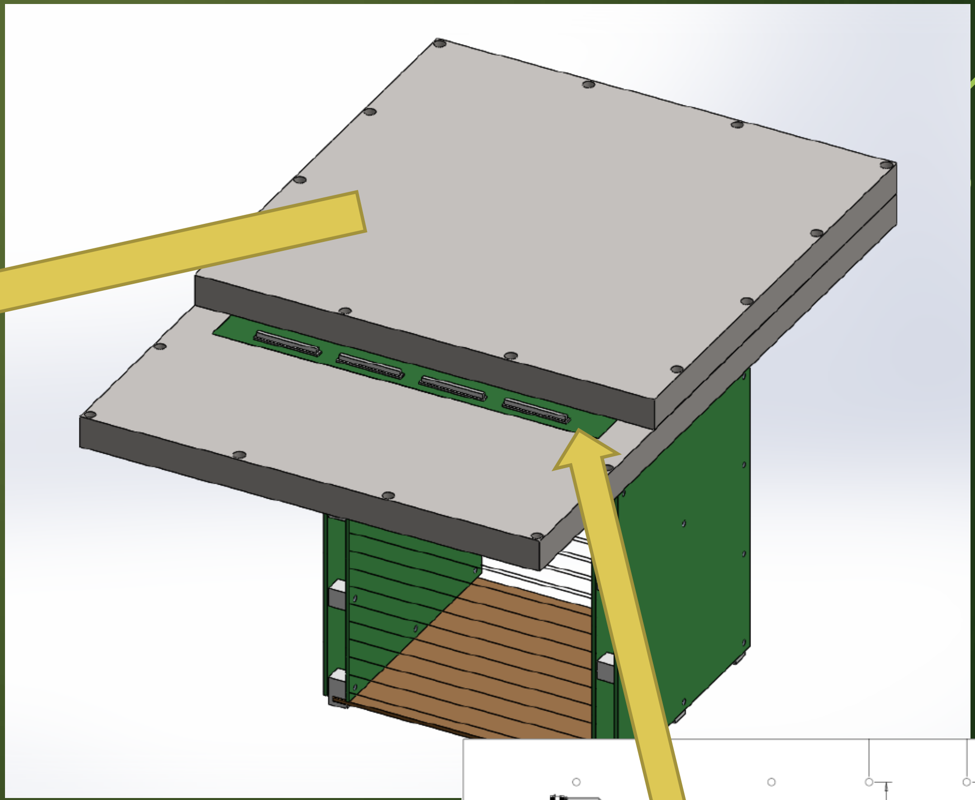


Low emittance beam line for test of tracking detectors

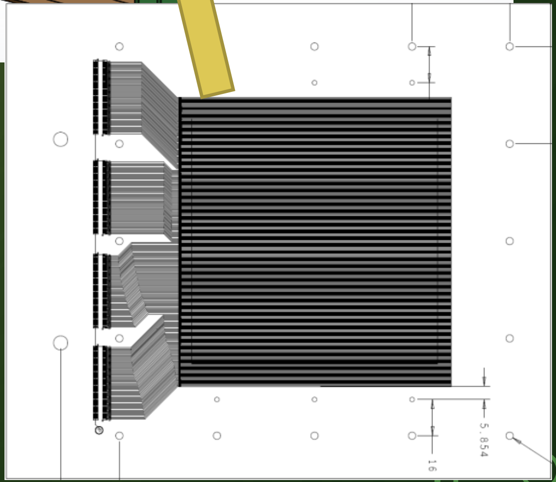
DETECTOR CHAMBER PROTOTYPE

TEST PLATFORM FOR ALL BRAND NEW SOLUTIONS

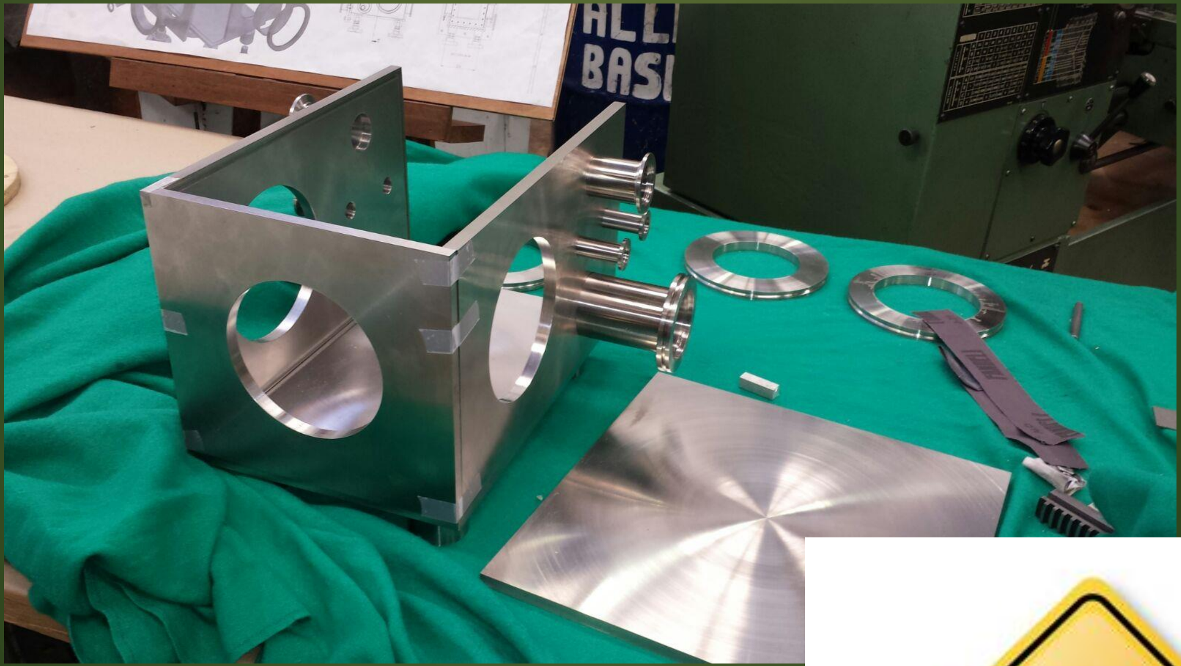




- Scalable to final size;
- Minimization of FE-RO Electronics;
- No need for vacuum connector;
- Read-out Electronics in air;
- Optimization of the electric field;
- Easy of maintenance.



DETECTOR CHAMBER PROTOTYPE

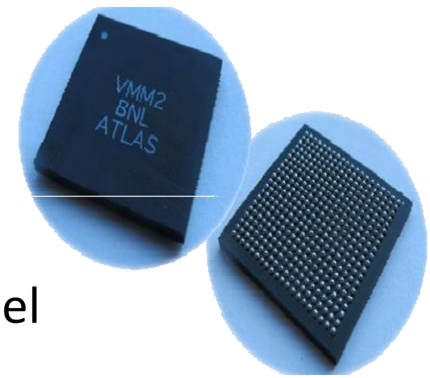


Final assembly and installation next weeks

The new electronics

Front-end and read-out electronics

ELECTRONICS PROTOTYPES (D. LoPresti)



1) ASIC front–end chip:

for FPD chip **VMM2(3)** in collaboration with Brookhaven National Laboratory (8x10^4 transistor/channel for 64 channels)

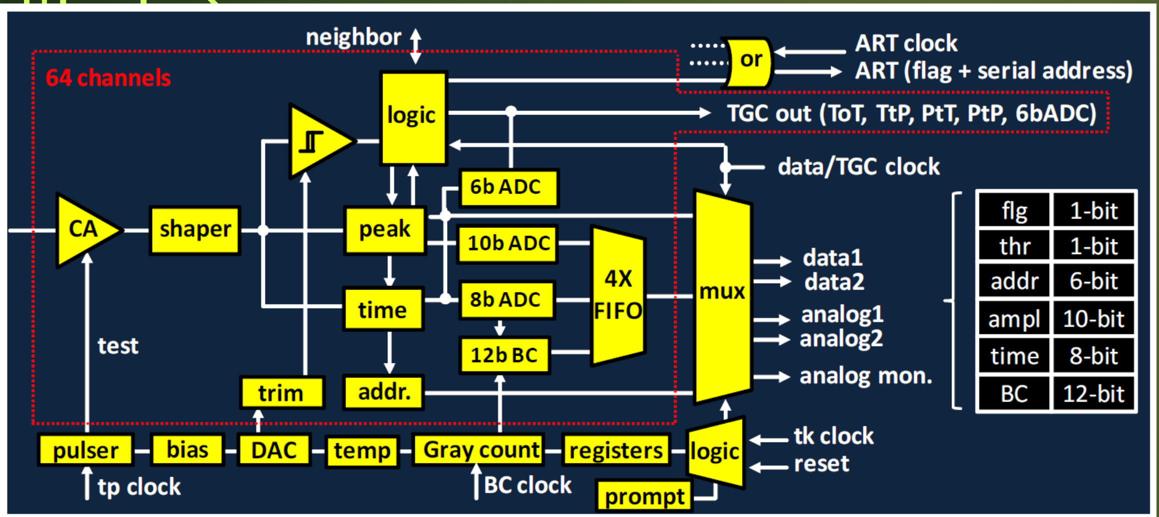
2) Read – out: new generation of **FPGA** and System On Module (**SOM**)

Number of channels

- Gas tracker ~ 2000 ch
- SiC-SiC ~ 6000 ch
- γ-ray calorimeter ~ 2500 ch

Tot ~ 10500 ch

VMM2 CHIP – BROOKHAVEN NATIONAL LABORATORIES



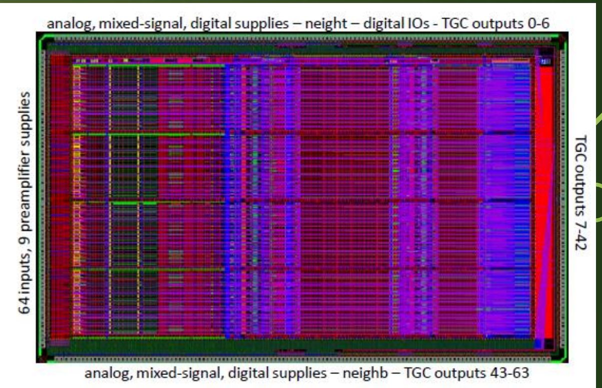


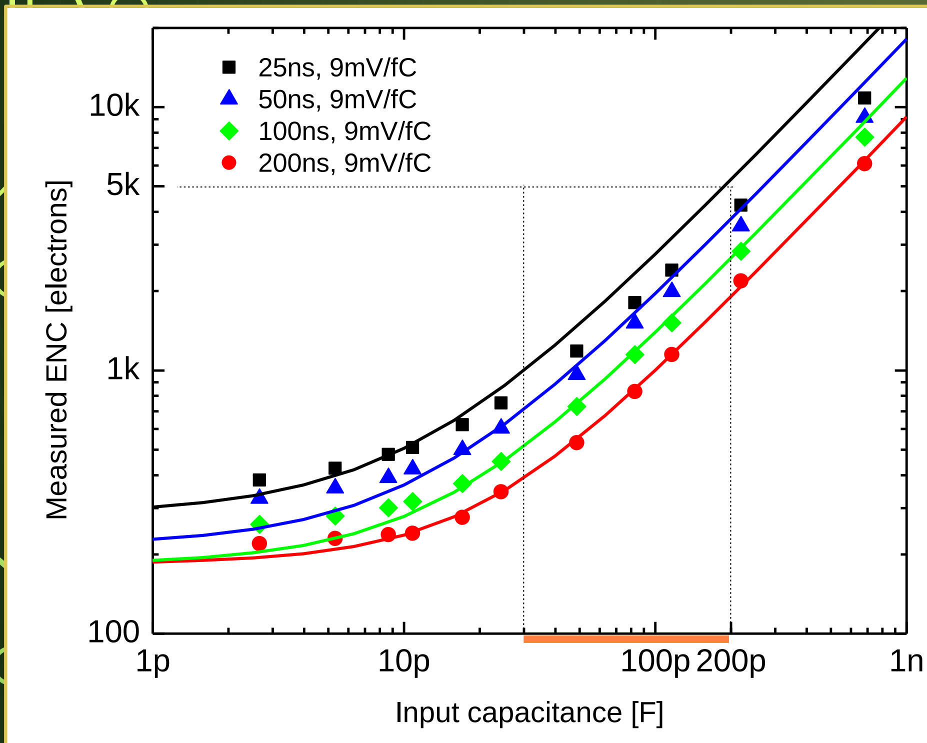
Fig. 2 – Physical layout of VMM2, size 13.5×8.4 mm² pad count 392.

130nm 1.2V 8-metal CMOS technology from IBM

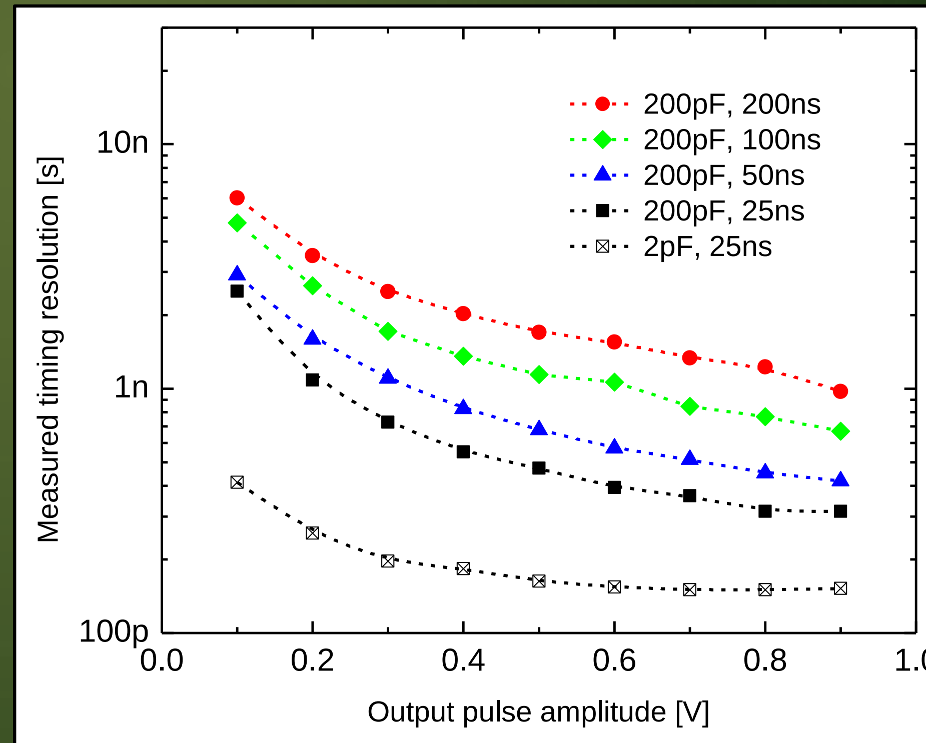
- *64 linear front-end channels:*
- *low-noise charge amplifier (CA) with adaptive feedback;*
- *test capacitor and pulse generator for calibration;*
- *adjustable polarity;*
- *optimized for a capacitance of 200pF and a peaking time of 25 ns.*
- *third-order shaper (DDF) – adjustable peaking time in four values (25, 50, 100, and 200 ns);*
- *Stabilized band-gap referenced baseline;*
- *Gain adjustable in eight values (0.5, 1, 3, 4.5, 6, 9, 12, 16 mV/fC).*
- *Many mode of operation, selected "continuous digital":*
  - *38 bit generated for each event read-out @ about 200 MHz;*
  - *Id channel-peak amplitude (10b) – time stamp (10b);*
  - *4-event deep de-randomizing FIFO per channel, read-out token ring;*
  - *8 LVDS digital channel required for the read-out and control of the chip;*
- *Power dissipation 4 mW per channel.*

Resolution Measurements (VMM2)

charge resolution



timing resolution



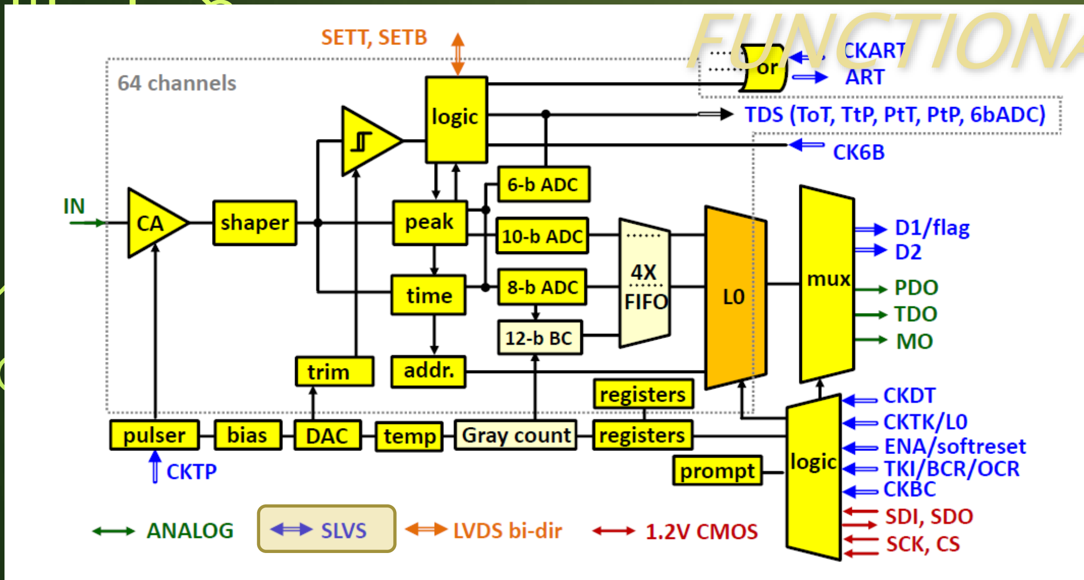
- *charge resolution ENC < 5,000 e⁻ at 25 ns, 200 pF*
- *analog dynamic range Q_{max} / ENC > 12,000 → DDF*
- *timing resolution < 1 ns (at peak-detect)*

$$\sigma_t \approx \frac{ENC\ \tau_P}{Q} \frac{\lambda_P}{\rho_P}$$

≈ 0.3-0.8

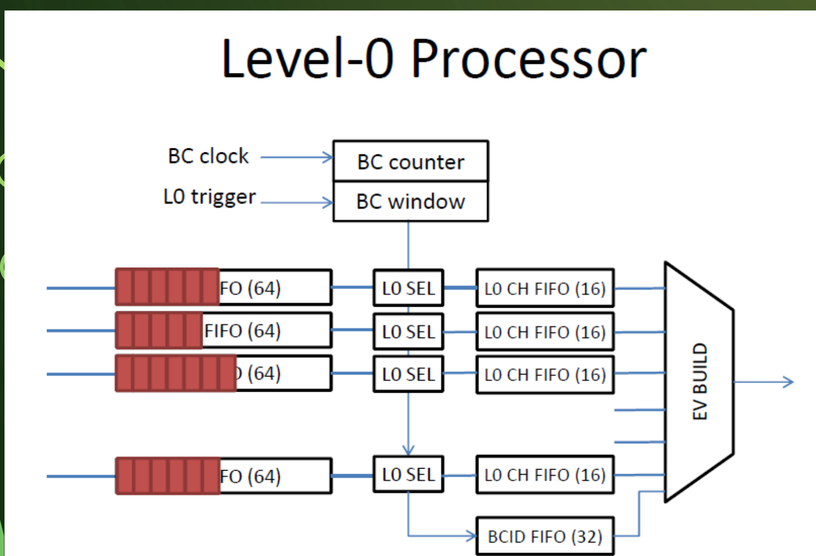
G. De Geronimo,
in "Medical Imaging" by Iniewski

VMM3 ARCHITECTURE AND FUNCTIONALITY



Additional Circuits

- Dynamic discharge circuit (DDC) for improved high rate operation with AC coupled sensors
- Fast recovery circuit (FRC) for reduced recovery time at very high charge (60 pC)



Latency FIFO takes data from the mixed-signal front-end

- FIFO designed to accommodate 4 MHz data in a 10 μs latency window
- Threshold, amplitude (ADC), timing (ADC)

At **L0 trigger** builds BC trigger window and **selects data** for the L0 CH FIFO:

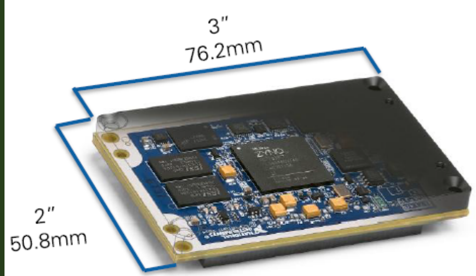
- flushes old data
- fills non-valid data as needed (for simultaneous overflow)
- builds BCID FIFO

Builds event

- BCID followed by valid data with address
- header
- event built in < 1μs

Sends data through dual data link (DDR, 640MB/s)

NI System on Module (SOM) Specifications



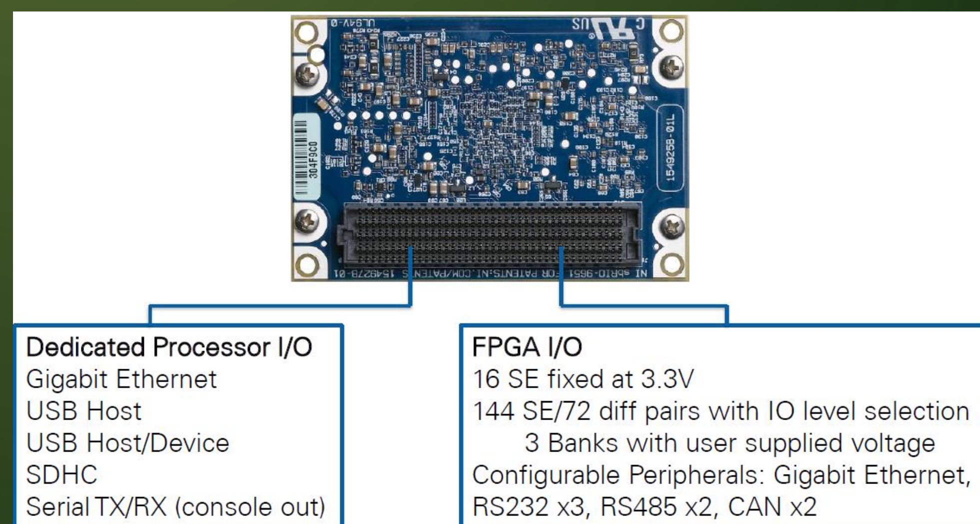
Processor SoC
Xilinx Zynq-7020 667 MH Dual-Core ARM Cortex-A9 Artix-7 FPGA Fabric
Size and Power
50.8mm x 78.2mm (2 in. X 3 in.) Typical Power: 3 W to 5 W
Memory
Nonvolatile: 512 MB DRAM: 512 MB
Operating Temperature
-40 °C to 85 °C Local Ambient

Read-out of VMMx chips will be performed by a SOM based board, custom designed for the experimental demands:

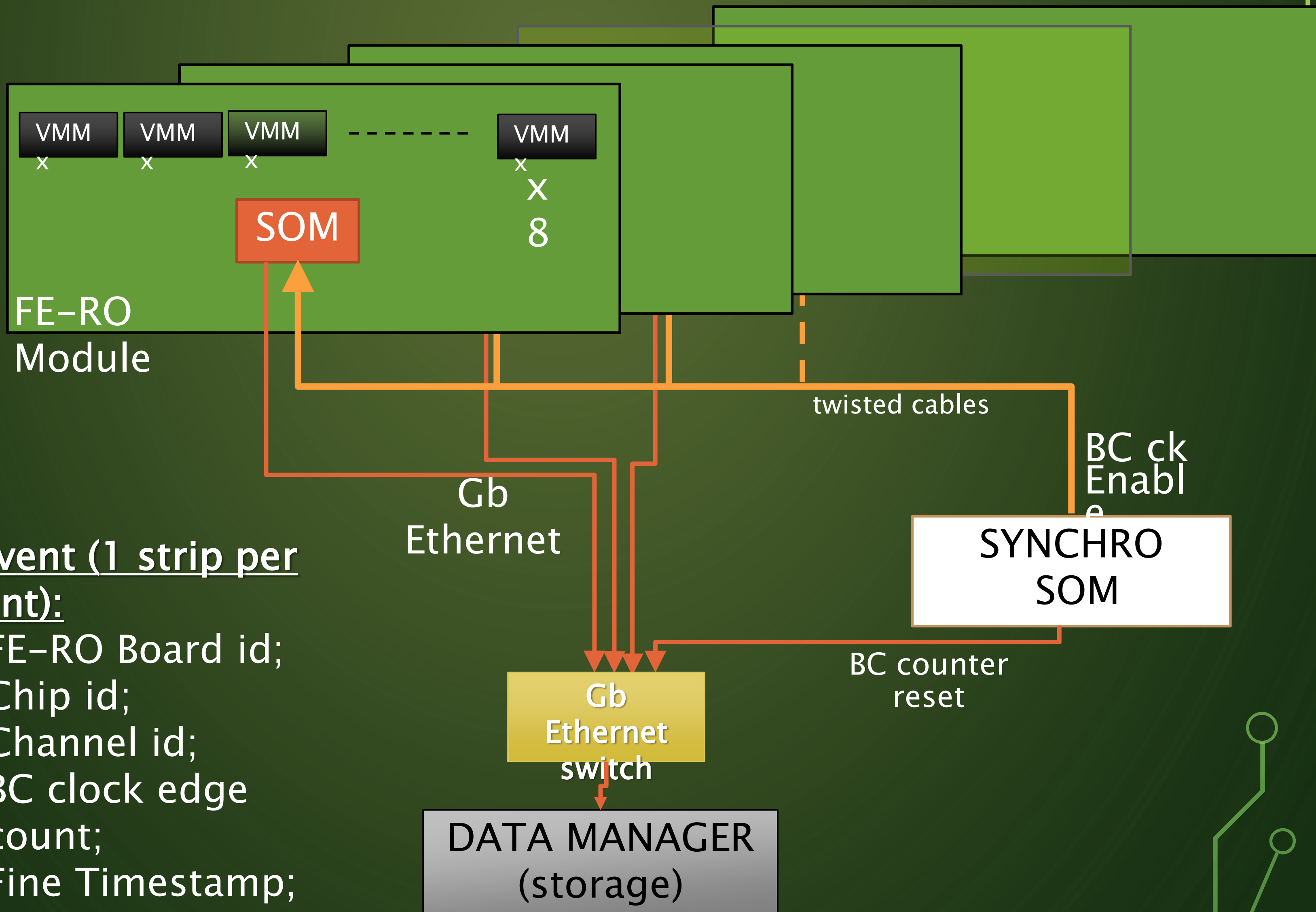
- *Low Power;*
- *Radiation Tolerance;*
- *Low Cost;*
- *Re-configurability;*

Re-programmable Intelligence on board will allow for:

- *composite trigger strategies;*
- *Slow control;*
- *Calibration;*
- *Overall synchronization;*
- *Gigabit Ethernet to maximize data throughput.*



FE-RO ARCHITECTURE



<u>**1 event (1 strip per event):**</u>

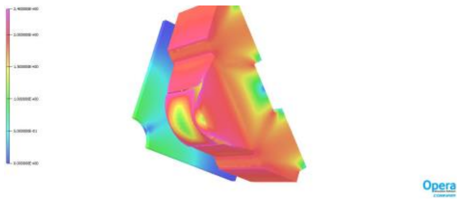
- FE-RO Board id;
- Chip id;
- Channel id;
- BC clock edge count;
- Fine Timestamp;
- Charge measurement;

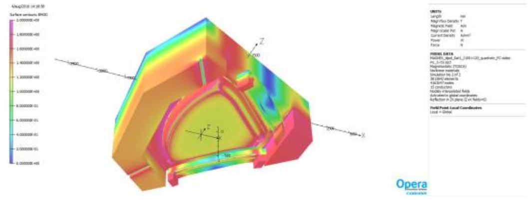
Next steps

- February: The VMM2 FE board and the Segmented Anode prototype will be available and test will start
- March/April: The scaled-size FPD prototype will be assembled and characterized
- March/April: The gas-mixing and fluxing system will be assembled and tested
- April: Test of the VMM2 interfaced to SiC PiD
- May/June: Test of the complete scaled-size FPD prototype

Other upgrades

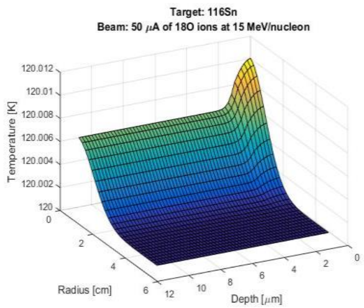
- The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.5 Tm)

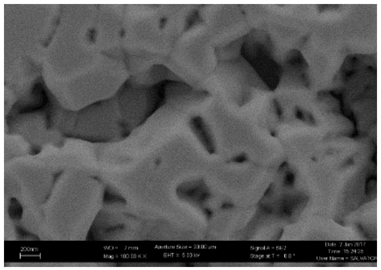




- An **array of LaBr(Ce) detectors for γ-rays** measurement in coincidence with MAGNEX

- The **target** technology for intense heavy-ion beams





- **Plan_B for particle identification**

- **Data Acquisition**

- **Data Reduction**

- **Nuclear reaction theory** (formal development and calculations)

The Phases of NUMEN project

- **Phase1**: The experimental feasibility
- **Phase2**: “hot” cases optimizing the experimental conditions and getting first results (approved). Synergy with ERC granted NURE project (PI: M. Cavallaro)
- **Phase3**: The facility Upgrade (Cyclotron, MAGNEX, beam lines, …..)
- **Phase4** : The systematic experimental campaign

Time table

year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Phase1	done									
Phase2				Approved						
Phase3										
Phase4										

Conclusions and Outlooks

- **NUMEN represents a challenging perspective** for the future of LNS in nuclear science
- **The project** turns around the MAGNEX and the Cyclotron upgrade toward high intensity
- It is playing an important role for **attracting worldwide researchers at the LNS**
- It is playing an important role for nuclear physics in Italy. **INFN-LNS was recently included** in the restricted list of **italian strategical reserach projects**
- **Results** of relevance for $0\nu\beta\beta$ physics already achieved in **2016 campaigns**
- **A big technological challenge**