The Magnex spectrometer for double charge exchange reactions

Manuela Cavallaro

INFN – Laboratori Nazionali del Sud

(Italy)

INTERNATIONAL CONFERENCE ON ELECTROMAGNETIC ISOTOPE SEPARATORS AND RELATED TOPICS

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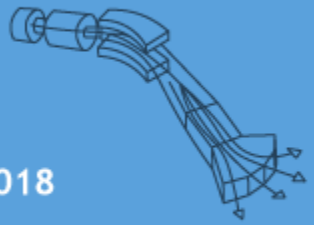
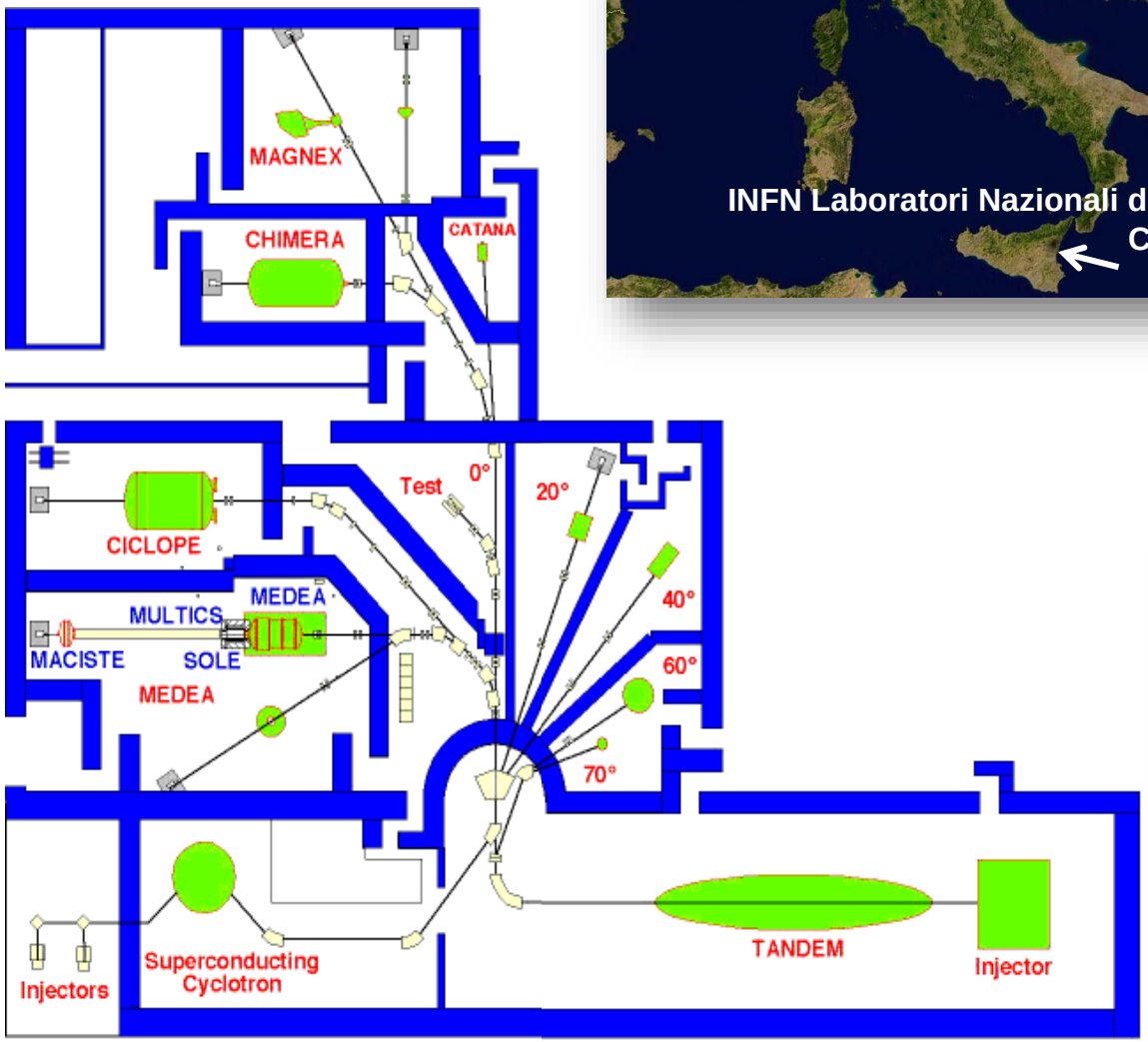
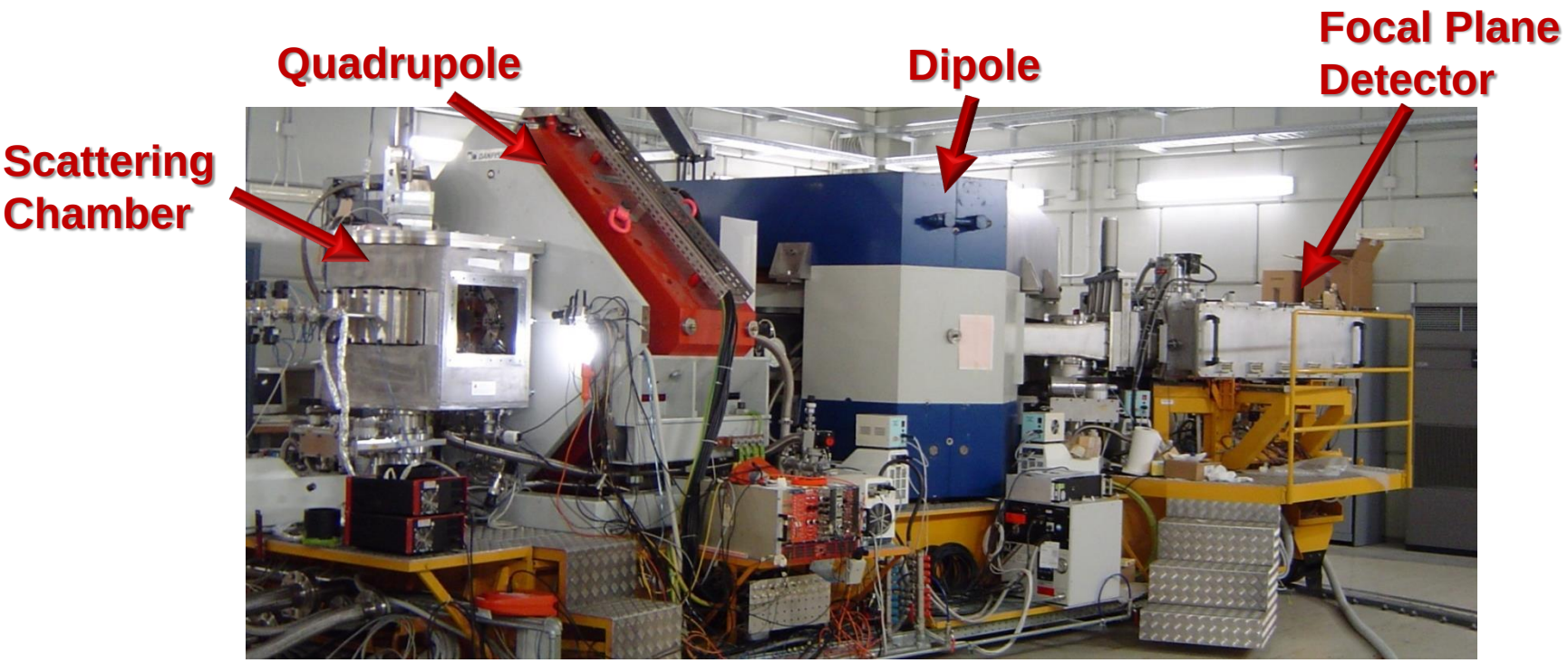


The INFN-LNS laboratory in Catania



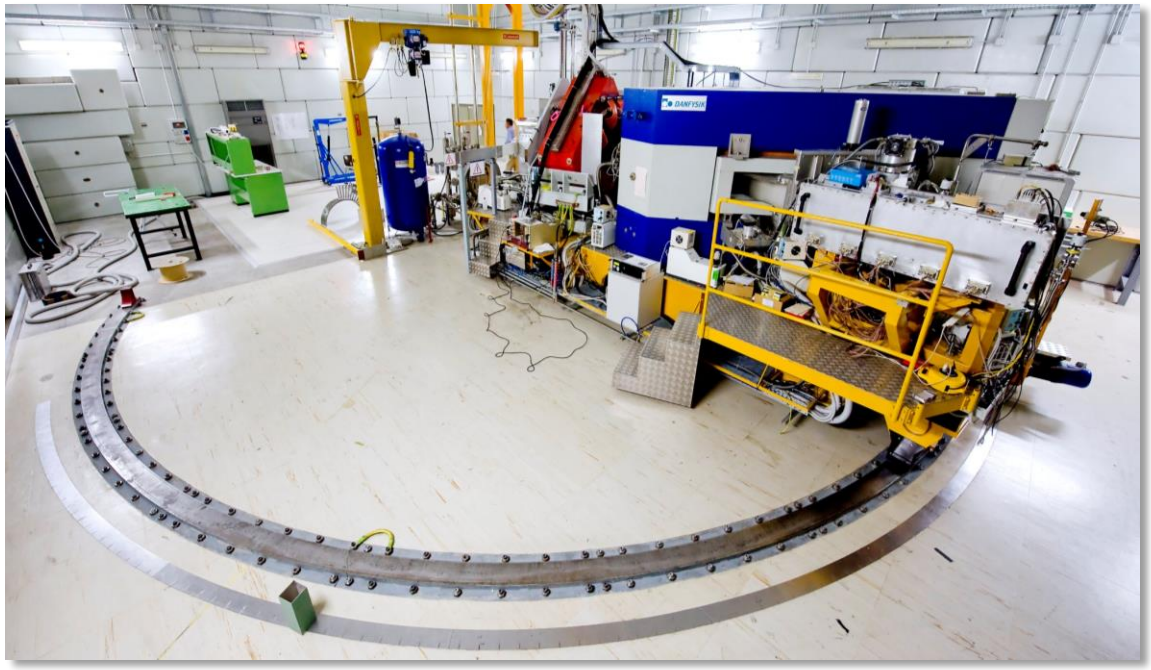
MAGNEX: a large acceptance QD spectrometer

1996 - Conceptual design (from an idea of A. Cunsolo)
2007 - Commissioning
Since 2008 – nuclear physics experiments



- **The Quadrupole**: vertically focusing
  (Aperture radius 20 cm, effective length 58 cm, Maximum field strength 5 T/m)
- **The Dipole**: momentum dispersion (and horizontal focus)
  (Mean bending angle 55°, radius 1.60 m, Maximum field ~ 1.15 T)

MAGNEX characteristics



Measured resolution:
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.3^\circ$
Mass $\Delta m/m \sim 1/160$

We have measured in a **wide mass range** (from protons to medium-mass nuclei)

Optical characteristics	Measured values
Angular acceptance (Solid angle)	50 msr
Angular range	–20° - +85° (including 0°)
Momentum (energy) acceptance	-14%, +10% (-28%,+20%)
Momentum dispersion for k= - 0.104 (cm/%)	3.68
Maximum magnetic rigidity	1.8 T m

F. Cappuzzello et al., Eur. Phys. Journ. A (2016) 52:167
A. Cunsolo et al., EPJ ST, 150 (2007) 343

The large acceptance problem

$$F: \vec{X}_i \rightarrow \vec{X}_f$$

F transport matrix

Large acceptance

Aberrations

$$x_i(f) = \sum_j R_{ij} x_j(i) + \sum_{j,k} T_{ijk} x_j(i) x_k(i) + \ldots\ldots$$

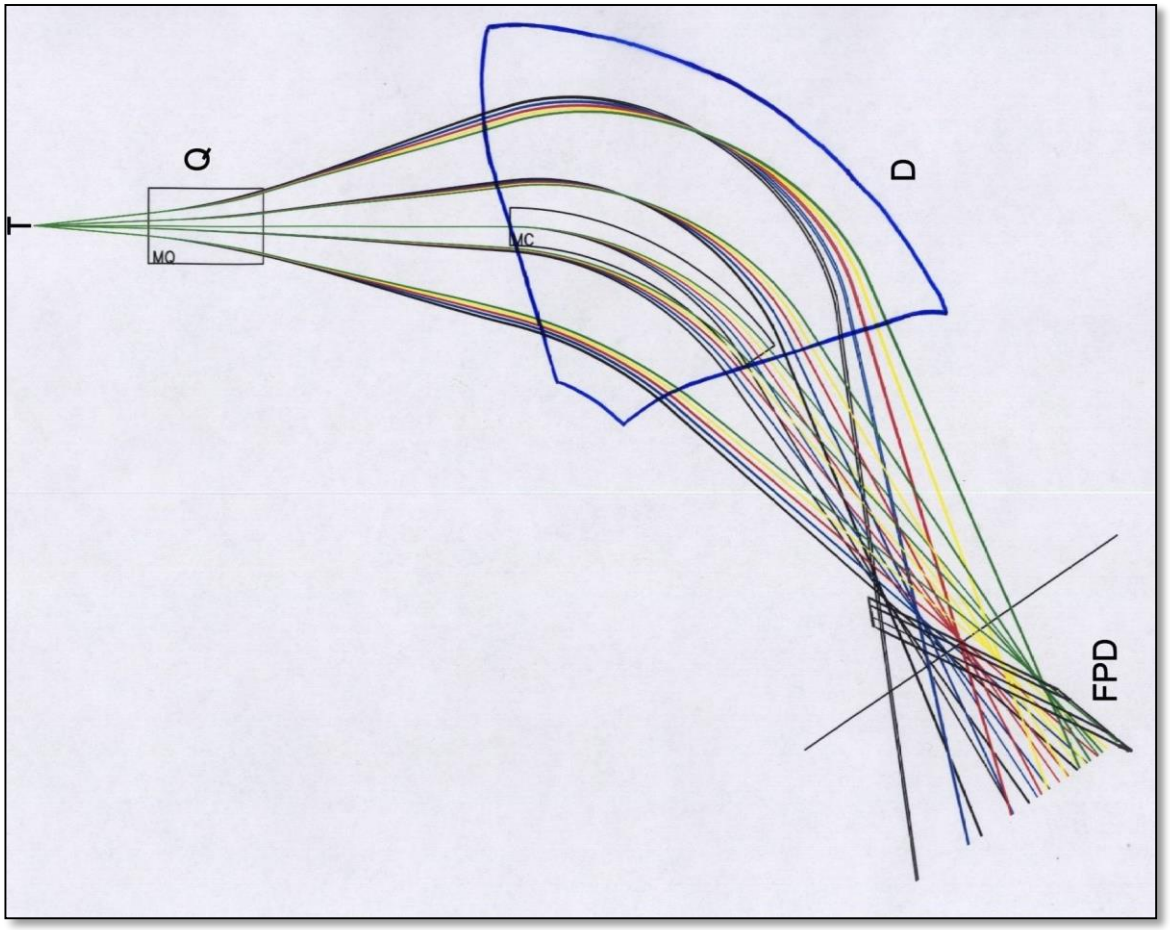
Up to 10° order

Careful hardware design
(to minimize the aberrations)

Software ray-reconstruction
(to know the aberrations)

Hardware minimisation of aberrations

- Rotation of the focal plane detector of 59°
- Shift of the focal plane detector



Hardware minimisation of aberrations

- Introduction of surface coils located between the dipole pole faces and the inner high vacuum chamber, giving tunable quadrupolar and sextupolar corrections

- Shaping of dipole entrance and exit boundaries (8th order polynomial)

Software ray-reconstruction

ALGEBRIC RAY-RECONSTRUCTION

✓ Solution of the equation of motion for each detected particle
✓ Inversion of the transport map
✓ Application to the final measured parameters

$F : \vec{\mathbf{X}}_i \rightarrow \vec{\mathbf{X}}_f$

Inversion of the transport map

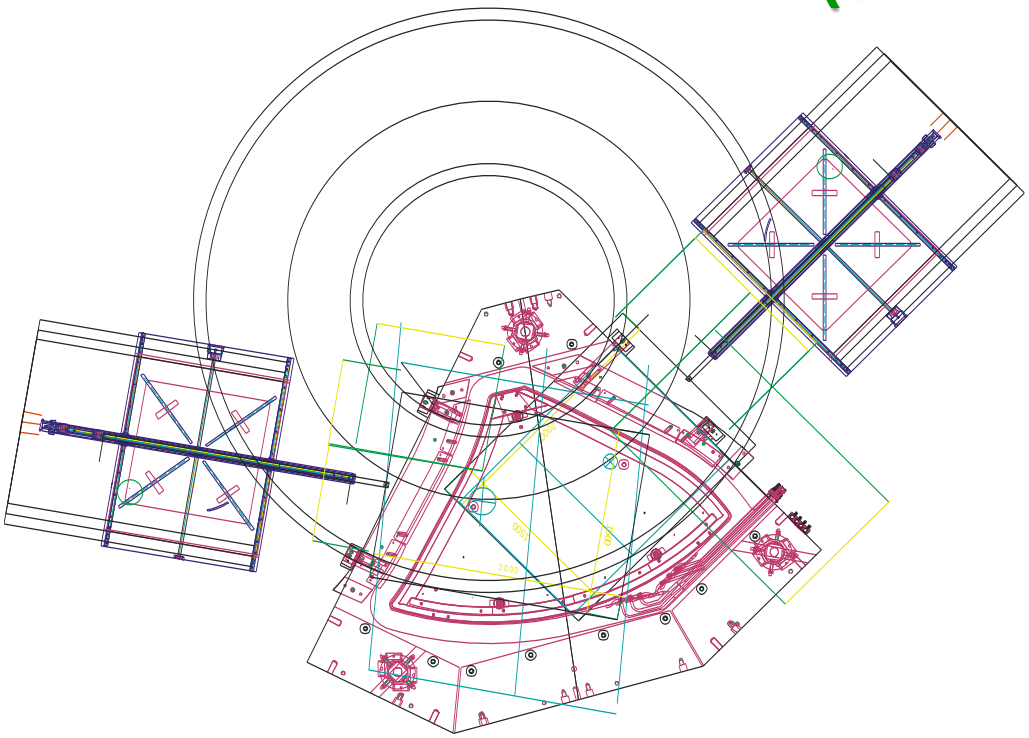
$F^{-1} : \vec{\mathbf{X}}_f \rightarrow \vec{\mathbf{X}}_i$

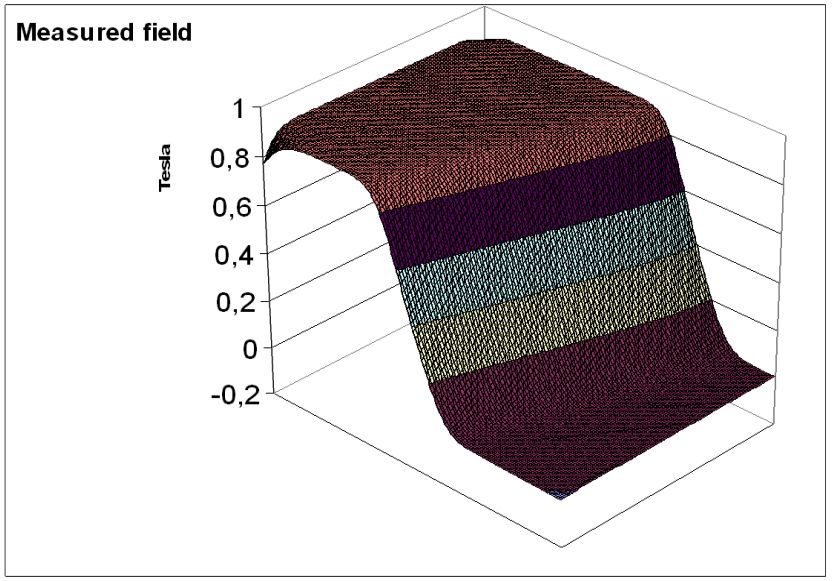
1) Detailed knowledge of the geometry and magnetic field

1) Detailed knowledge of the magnetic field

Measurement of the field (3D map)

Measurements at Danfysik
240000 points





Interpolation of the field

Regular function up to 10° order

A.Lazzaro et al., NIMA 570 (2007) 192

A.Lazzaro et al., NIMA 585 (2008) 136

A.Lazzaro et al., NIMA 591 (2008) 394

A.Lazzaro et al., NIMA 602 (2009) 494

Software ray-reconstruction

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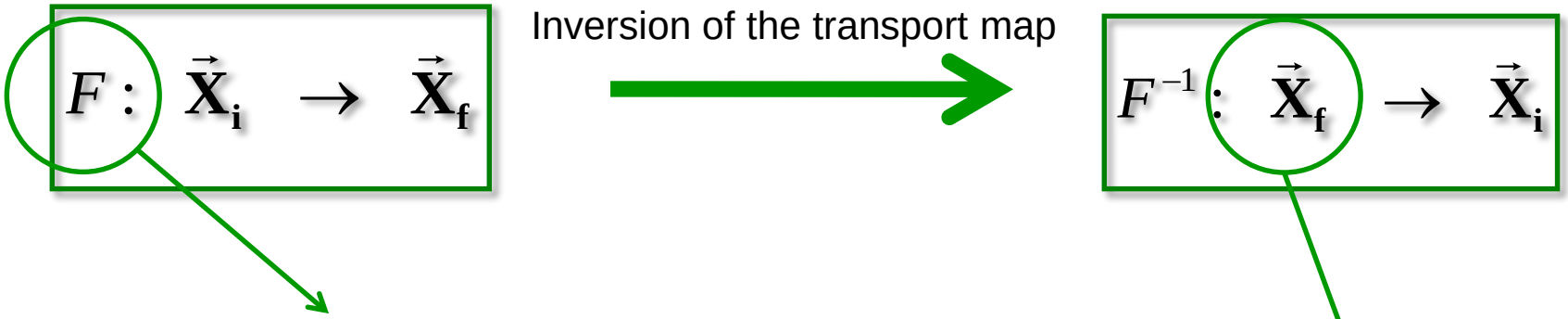


1) Detailed knowledge of the geometry and magnetic field

2) High resolution measurement at the focal plane (highly performing detectors)

2) MAGNEX Focal Plane Detector

M. Cavallaro et al., Eur. Phys. J. A, (2012) 48:59

Two tasks to accomplish:

1) Identification of the reaction ejectiles (Z, A) - crucial aspect for heavy ions

2) High resolution measurement at the focal plane of the phase space parameters (X_{foc}, Y_{foc}, θ_{foc}, ϕ_{foc})

FPD characteristics

Horizontal and vertical position resolution (FWHM)	0.6 mm
Horizontal and vertical angular resolution (FWHM)	0.3°
Mass resolution[a]	0.6%
Explored ion mass range	from $A = 1$ to $A = 48$
Energy loss resolution[b]	6.3%
Maximum incident ion rate (uniform distribution)	5 kHz
Maximum incident ion rate (localized in $\sim$ 1 cm)	2 kHz

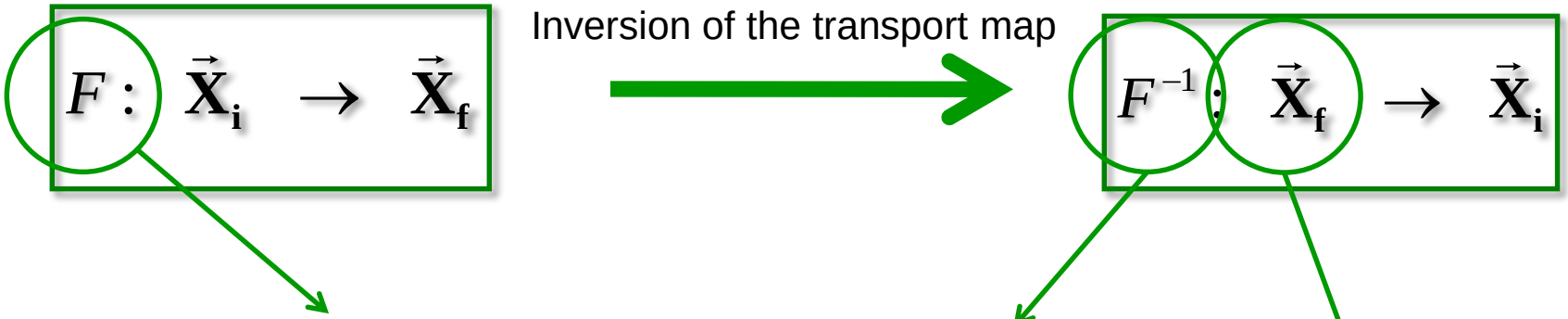
Hybrid detector:
Gas section: proportional wires and drift chambers
+
Stopping wall of silicon detectors

For O at 300 MeV
10^4 Hz/mm^2

Software ray-reconstruction

ALGEBRIC RAY-RECONSTRUCTION

✓ Solution of the equation of motion for each detected particle
✓ Inversion of the transport map
✓ Application to the final measured parameters



1) Detailed knowledge of the geometry and magnetic field

3) Algorithm to transport and invert

2) High resolution measurement at the focal plane (highly performing detectors)

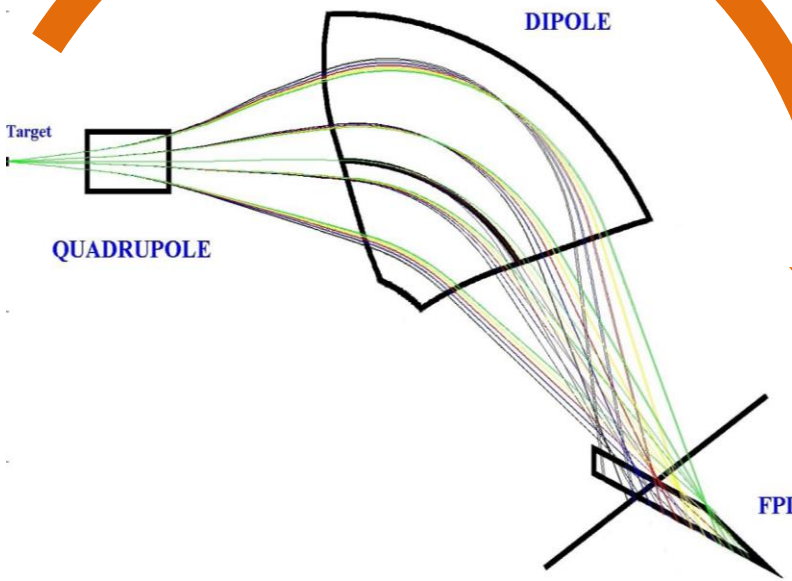
3) Algorithm to transport and invert

ALGEBRIC
RAY-RECONSTRUCTION
(*Differential Algebras*)
COSY-INFINITY

$$F : \vec{X}_i \rightarrow \vec{X}_f$$

Direct transport map

$\vec{P}_i\left(E^*, \theta_{lab}\right)$
Physical Parameters at the target



$\vec{P}_f\left(X_{foc}, Y_{foc}, \theta_{foc}, \varphi_{foc}\right)$
Geometrical Parameters at the FPD

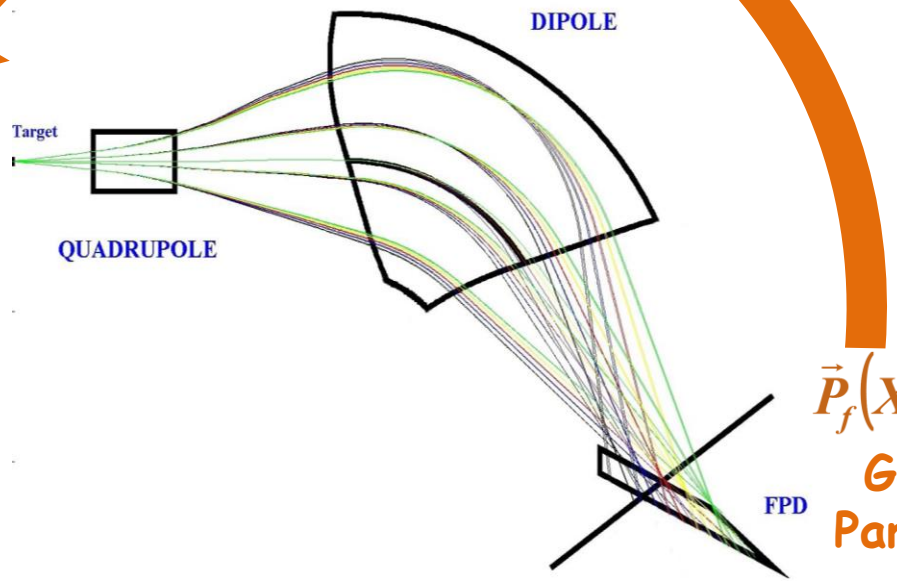
F. Cappuzzello, et al., NIM A 638, (2011) 74

3) Algorithm to transport and invert

ALGEBRIC
RAY-RECONSTRUCTION
(*Differential Algebras*)
COSY-INFINITY

$$F^{-1} : \vec{X}_f \rightarrow \vec{X}_i$$

Inverted transport map



$\vec{P}_i\left(E^*, \theta_{lab}\right)$
Physical Parameters at the target

$\vec{P}_f\left(X_{foc}, Y_{foc}, \theta_{foc}, \varphi_{foc}\right)$
Geometrical Parameters at the FPD

F. Cappuzzello, et al., NIM A 638, (2011) 74

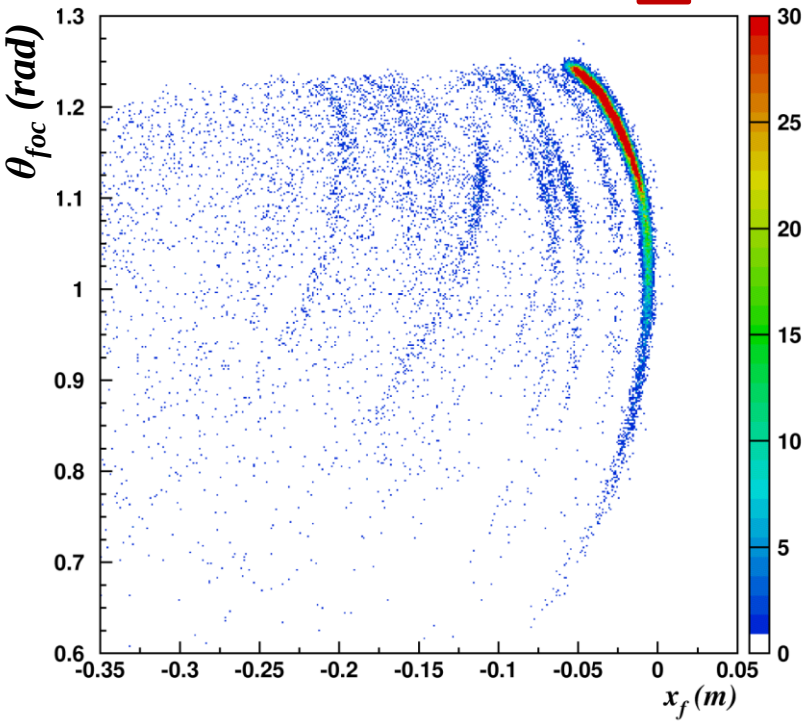
Example of ray reconstruction

$^{27}Al(^{16}O,^{16}O)^{27}Al$ at 100 MeV

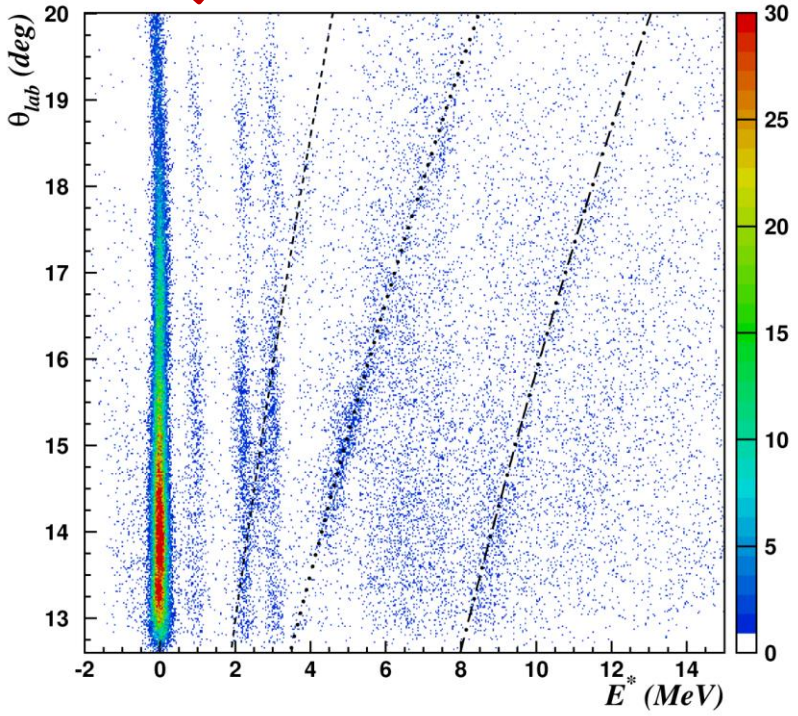
$13° < \theta_{lab} < 20°$

F^{-1}

measured



reconstructed



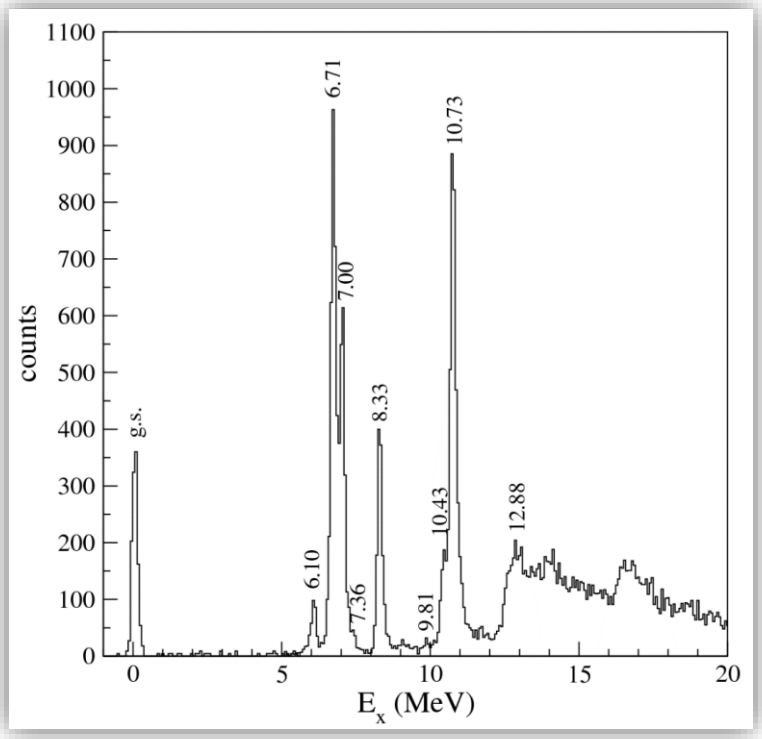
$$E^* = Q - K\left(1 + \frac{M_{ejectile}}{M_{residual}}\right) + E_{beam}\left(1 - \frac{M_{beam}}{M_{residual}}\right) + 2\frac{\sqrt{M_{beam}M_{ejectile}}}{M_{residual}}\sqrt{E_{beam}K}\cos\theta_{lab}$$

M. Cavallaro et al., NIMA 648 (2011) 46-51

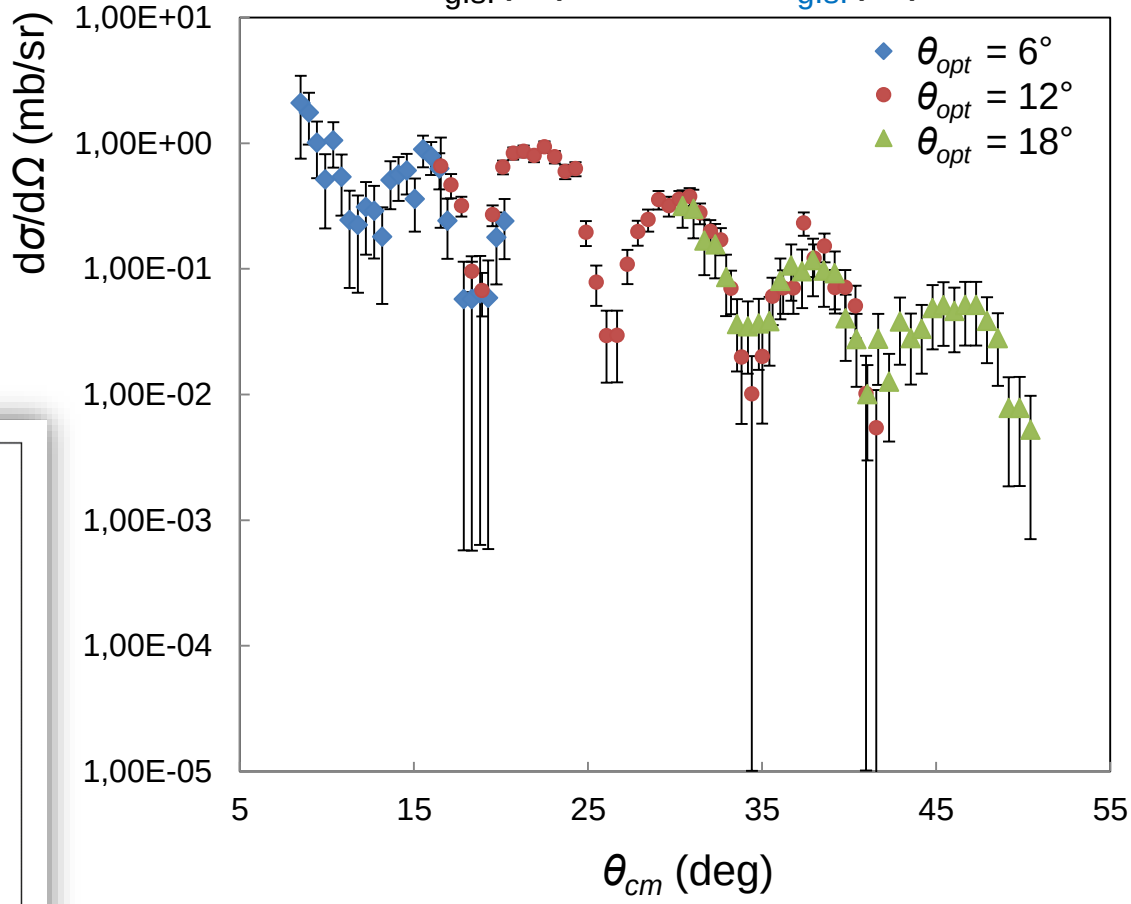
F. Cappuzzello et al., NIMA 638 (2011) 74-82

Typical energy spectra and angular distributions

$^{12}C(^{18}O,^{16}O)^{14}C$
E = 84 MeV



$^{18}O + ^{12}C_{g.s.}(0^+) \rightarrow ^{18}O + ^{14}C_{g.s.}(0^+)$ ***L* = 0**



M. Cavallaro et al, Phys. Rev. C, 88 (2013) 054601
F. Cappuzzello et al., Nature Comm. 6, 6743 (2015)

A recent physics case for MAGNEX:

Nuclear Reactions for Neutrinoless Double Beta Decay

NUclear **M**atrix **E**lements for
Neutrinoless double beta decay

0νββ decay

Open problem in modern physics:

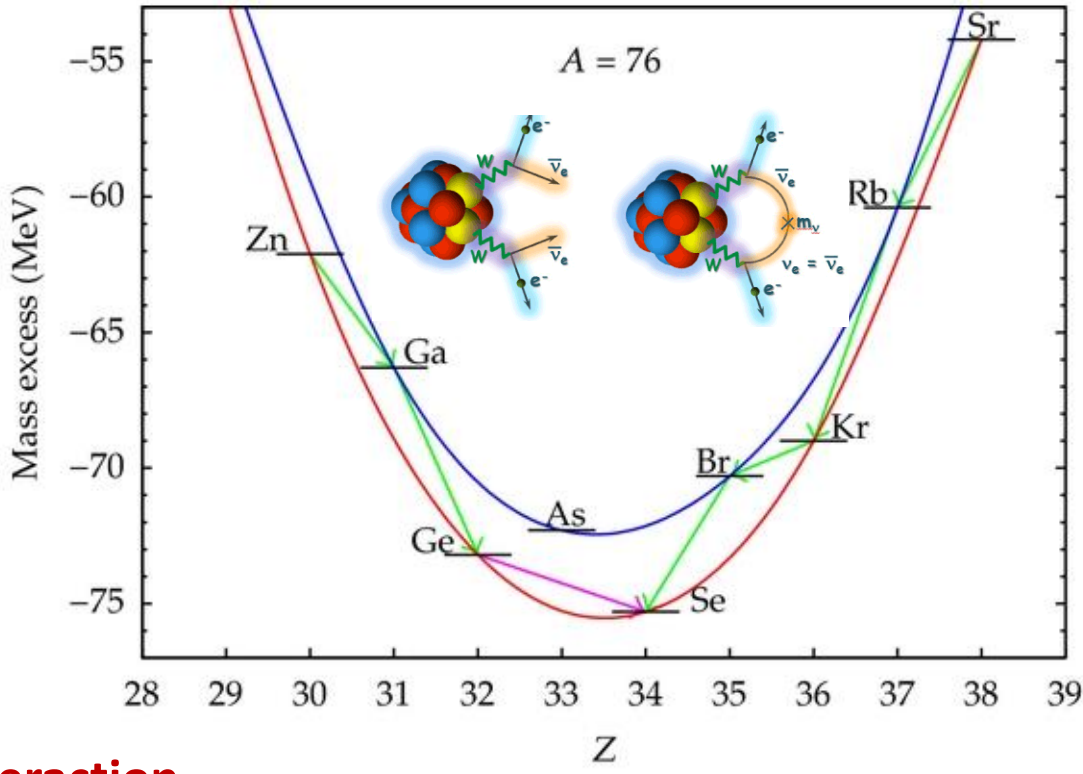
Neutrino absolute mass scale

Neutrino nature

→ **0νββ** is considered the **most promising approach**

$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} + (2\bar{\nu})$$

^{76}Br	^{77}Br	^{78}Br	^{79}Br	^{80}Br
^{75}Se	^{76}Se	^{77}Se	^{78}Se	^{79}Se
^{74}As	^{75}As	^{76}As	^{77}As	^{78}As
^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge	^{77}Ge
^{72}Ga	^{73}Ga	^{74}Ga	^{75}Ga	^{76}Ga



- ✓ Process mediated by the **weak interaction**
- ✓ Observable in even-even nuclei where the **single β-decay** is energetically **forbidden**

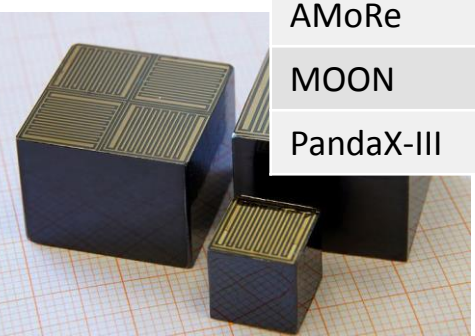
Search for 0νββ decay. A worldwide race

Experiment	Isotope	Lab
GERDA	^{76}Ge	LNGS [Italy]
CUORE	^{130}Te	LNGS [Italy]
Majorana	^{76}Ge	SURF [USA]
KamLAND-Zen	^{136}Xe	Kamioka [Japan]
EXO/nEXO	^{136}Xe	WIPP [USA]
CUPID - Lucifer	^{82}Se, ^{100}Mo	LNGS [Italy]
SNO+	^{130}Te	Sudbury [Canada]
SuperNEMO	^{82}Se	LSM [France]
CANDLES	^{48}Ca	Kamioka [Japan]
COBRA	^{116}Cd	LNGS [Italy]
DCBA	many	[Japan]
AMoRe	^{100}Mo	[Korea]
MOON	^{100}Mo	[Japan]
PandaX-III	^{136}Xe	CJPL [China]

Still not observed

Consequences of 0νββ observation

- Beyond standard model
- Neutrino is its own anti-particle
- Access to effective neutrino mass
- Violation of lepton number conservation
- CP violation in lepton sector
- A way to leptogenesis and GUT
- …



List not complete…

Nuclear Matrix Elements

0νββ decay **half-life**

Phase space factor

contains the average neutrino **mass**

$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Nuclear Matrix Element (NME)

$$\left|M_{\varepsilon}^{0\nu\beta\beta}\right|^2 = \left|\left\langle \Psi_f \left| \hat{O}_{\varepsilon}^{0\nu\beta\beta} \right| \Psi_i \right\rangle\right|^2$$

Transition probability of a **nuclear** process

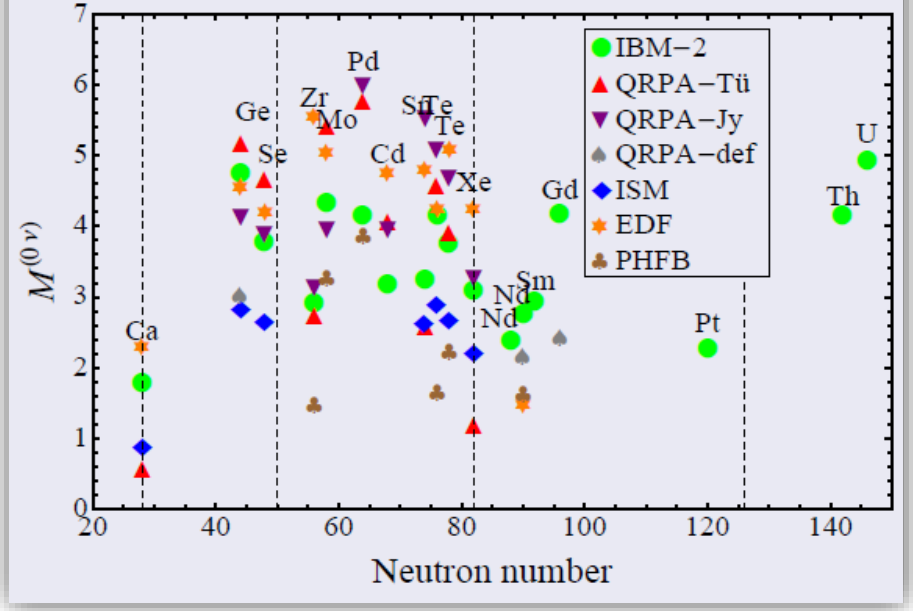
Nuclear physics plays a key role!

Nuclear Matrix Elements

Nuclear Matrix Element (NME)

$$\left|M_{\varepsilon}^{0\nu\beta\beta}\right|^2 = \left|\left\langle \Psi_f \left| \hat{O}_{\varepsilon}^{0\nu\beta\beta} \right| \Psi_i \right\rangle\right|^2$$

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



Calculations (still sizeable uncertainties):
QRPA, Large scale shell model, IBM, EDF, AB-INITIO …

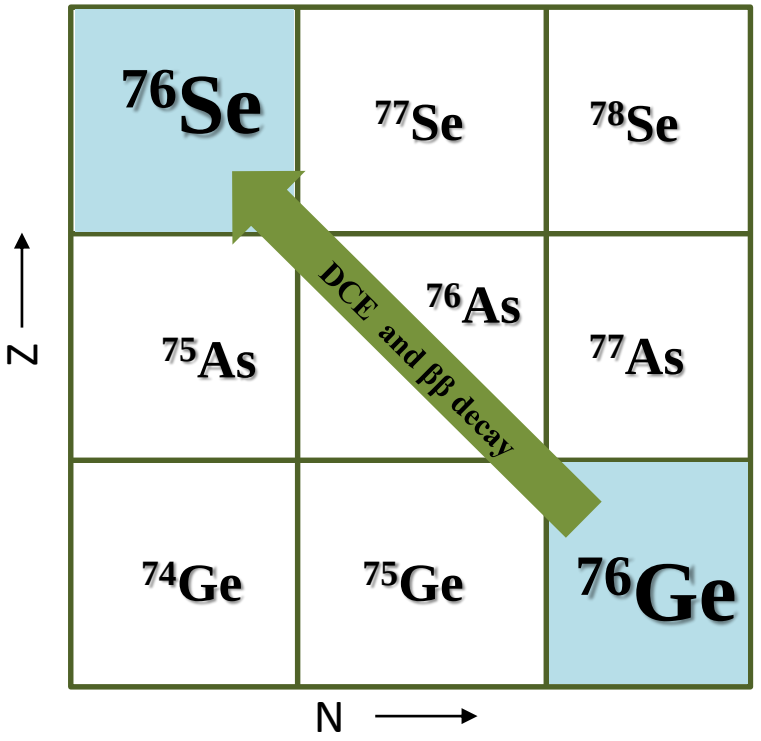
Many body WaveFunctions!

A new experimental tool

Nuclear reactions
Double Charge Exchange reactions (DCE) to stimulate in the laboratory the same nuclear transition (g.s. to g.s.) occurring in 0νββ

NUMEN

European Commission
erc
NURE



F. Cappuzzello et al., EPJ A 2018 54:72

The project

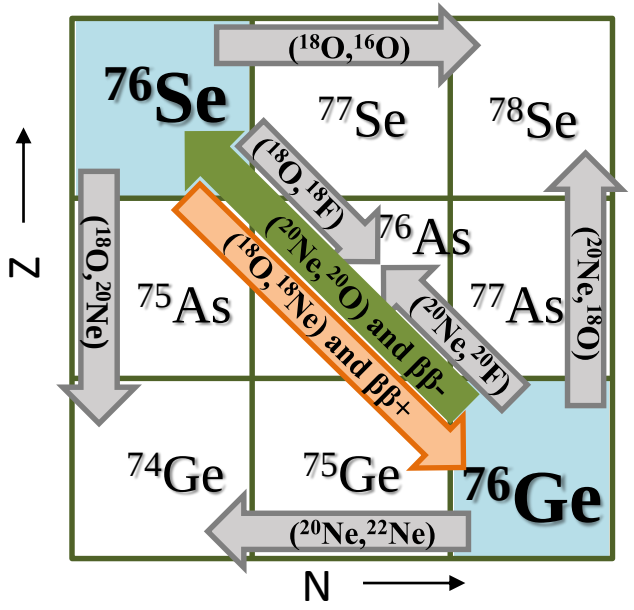
Main goal (Holy Grail):

Extraction from measured cross-sections of *"data-driven"* information on NME for all the systems candidate for 0νββ

- **Transitions of interest for 0νββ:**
  $^{76}Ge \leftrightarrow {}^{76}Se$, $^{116}Cd \leftrightarrow {}^{116}Sn$, $^{130}Te \rightarrow {}^{130}Xe$

- **Two directions**:
  $\beta\beta^+$ via (^{18}O,^{18}Ne) and $\beta\beta^-$ via (^{20}Ne,^{20}O)

- **Complete net** of reactions which can contribute to the DCE cross-section:
  1p-, 2p-, 1n-, 2n-transfer, single cex, DCE

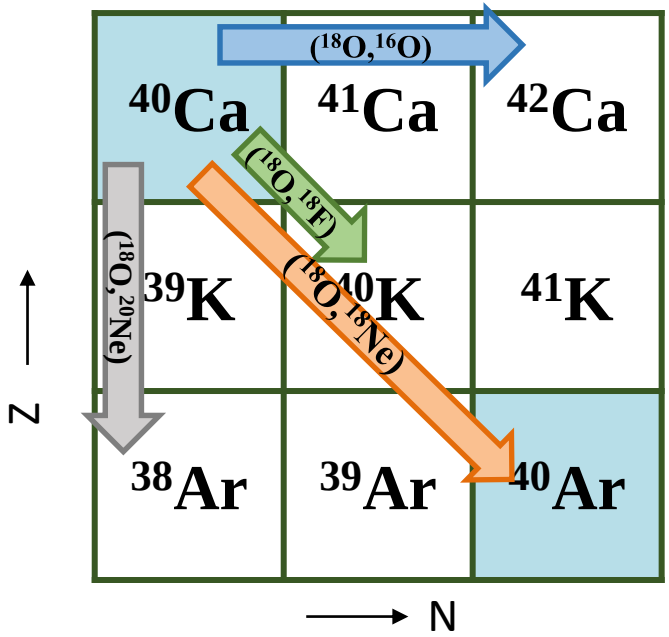


The pilot experiment

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

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

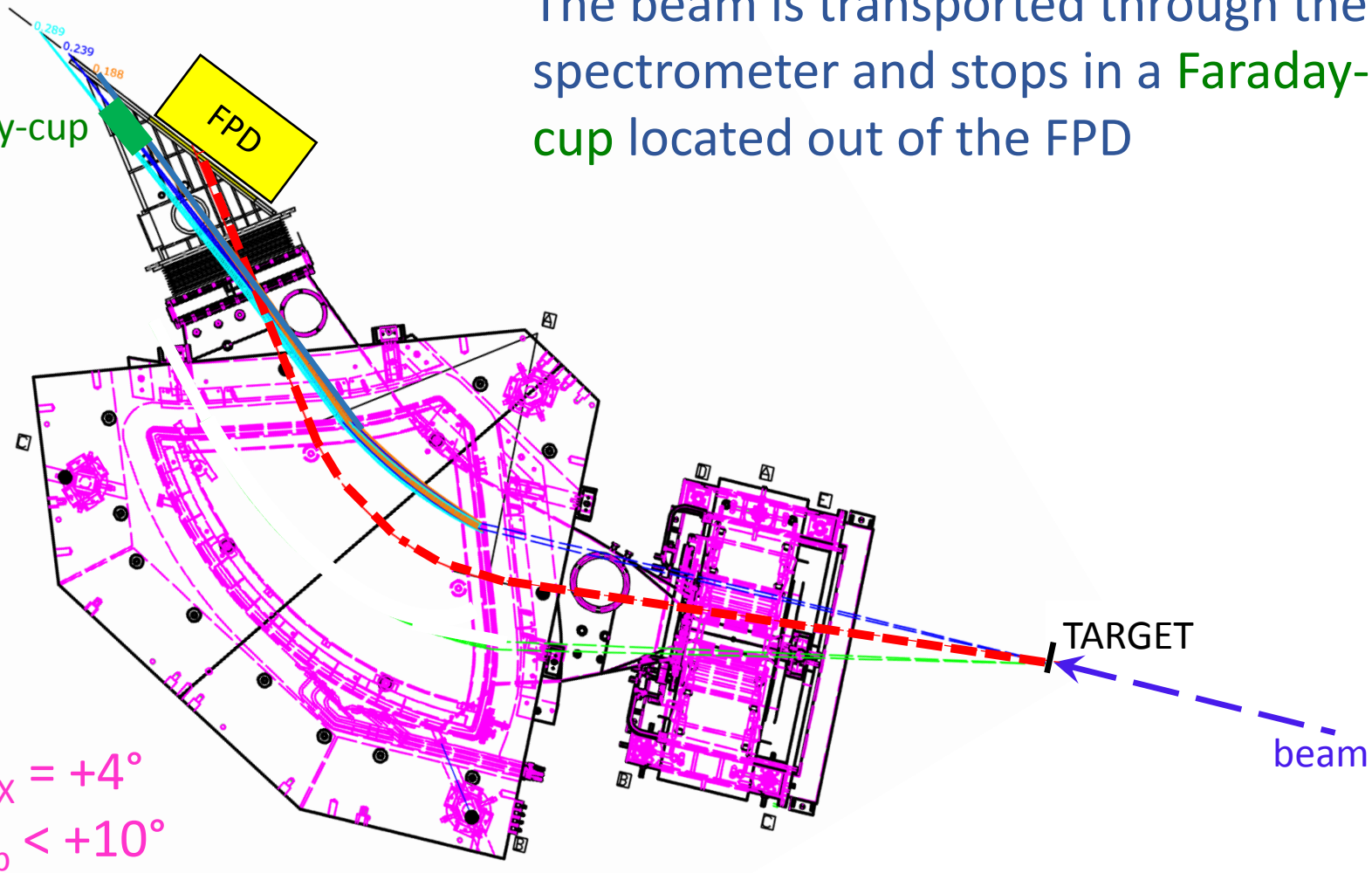
- $^{18}O^{7+}$ beam from Cyclotron at **270 MeV** (10 pnA, 3300 μC in 10 days)
- **^{40}Ca** target 300 μg/cm^2
- Ejectiles detected by the MAGNEX spectrometer $0° < \vartheta_{lab} < 10°$



Zero-degree measurement

The reaction ejectiles reach the FPD

The beam is transported through the spectrometer and stops in a Faraday-cup located out of the FPD



$\Theta_{MAGNEX} = +4°$

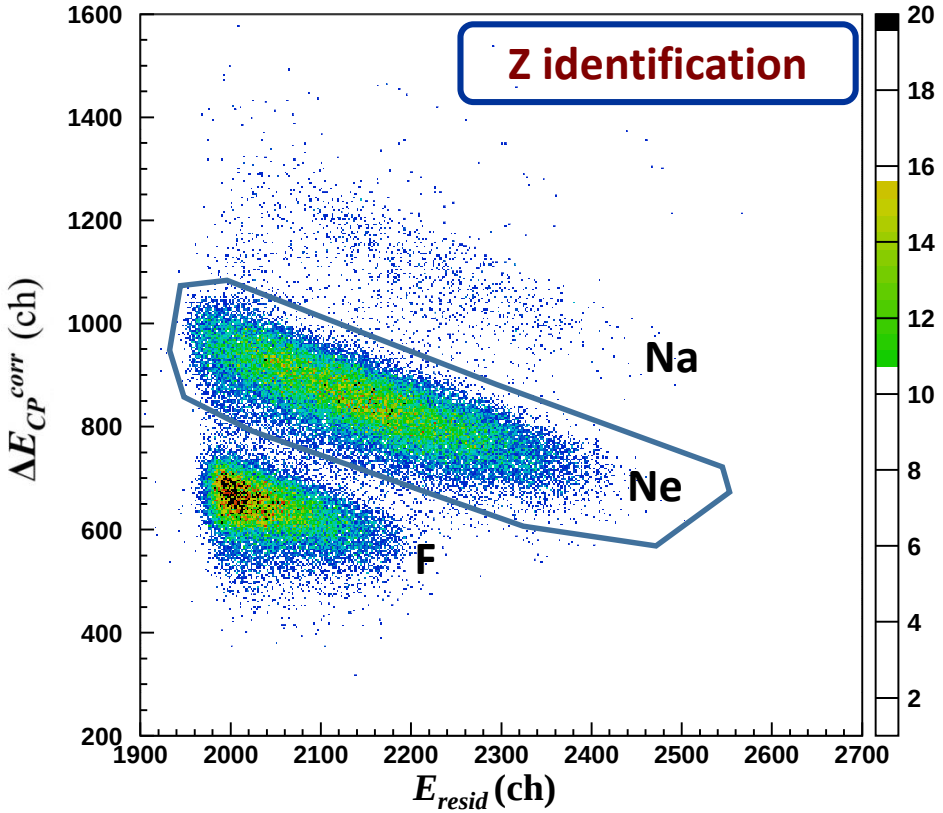
$-1° < \theta_{lab} < +10°$

Particle Identification

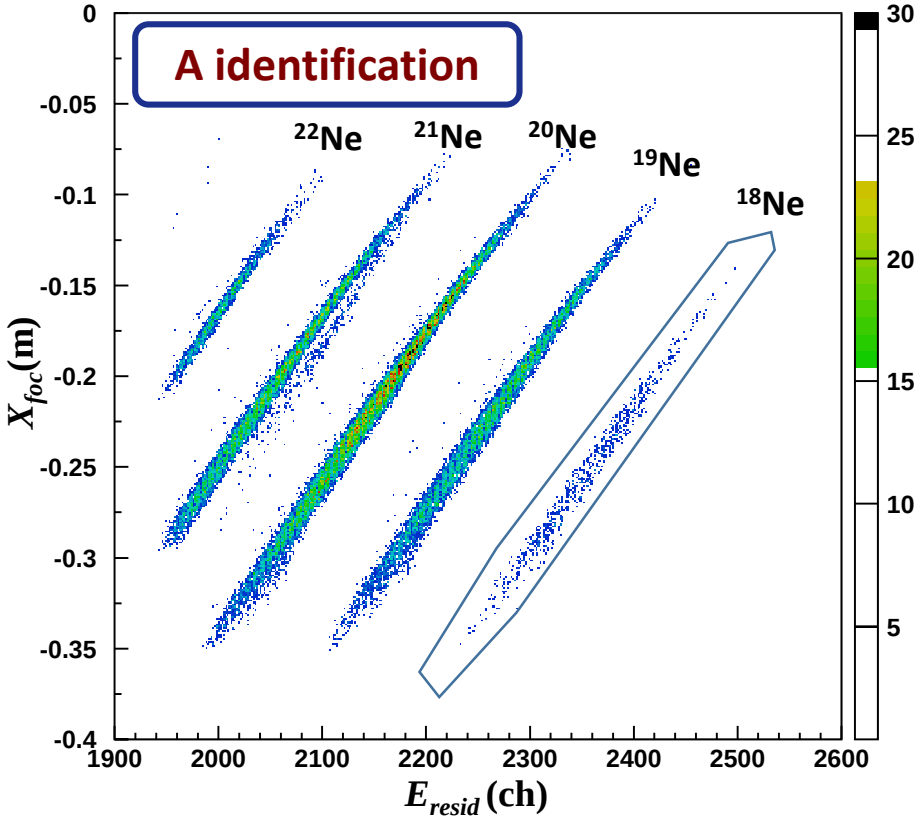
No TOF

$\Delta m/m \sim 1/160$

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



$$Br = \frac{p}{q} \rightarrow X_{foc}^2 \mu \frac{m}{q^2} E_{resid}$$



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

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

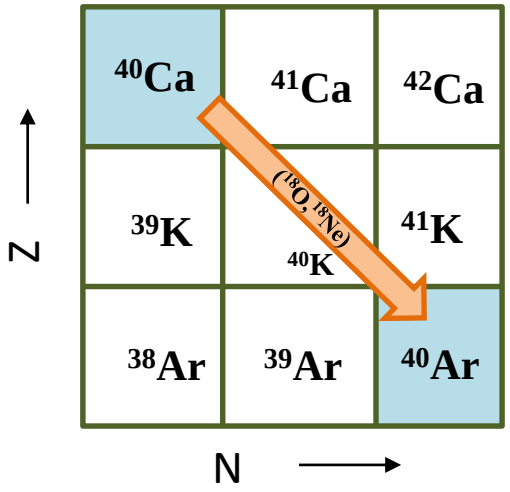
M.Cavallaro et al. EPJ A 48: 59 (2012)

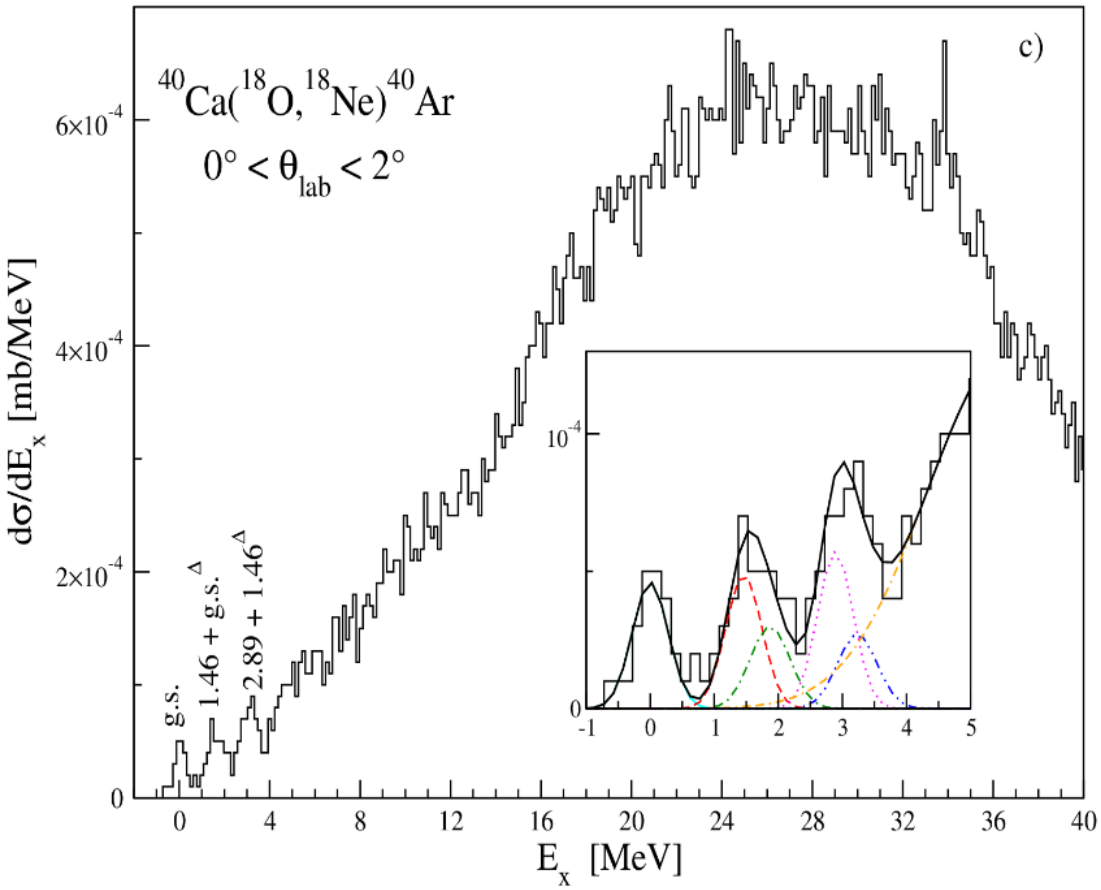
D.Carbone et al. EPJ A 48: 60 (2012)

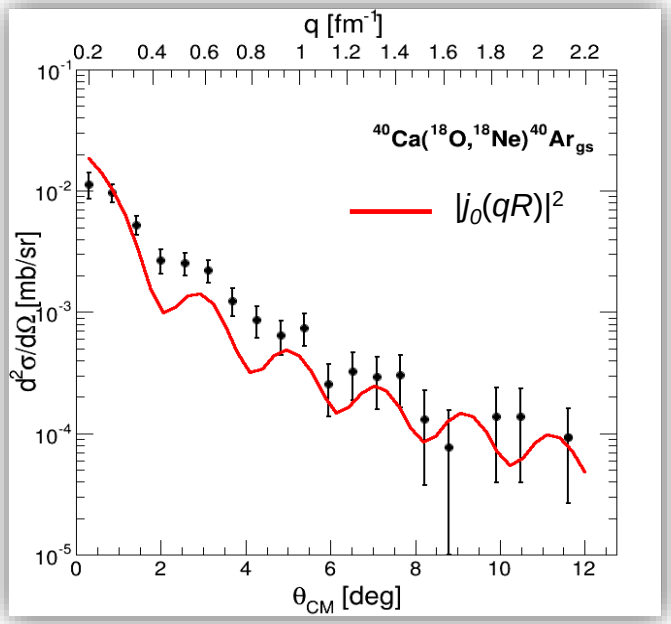
The pilot experiment

$^{18}O + {}^{40}Ca$ at 270 MeV

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







Experimental feasibility: zero-deg, resolution (500 keV), low cross-section (µb/sr)

Limitations of the past HI-DCE experiments are overcome!

Present limitations

- An accurate job on the **theory** is mandatory
- Only few systems can be studied in the present condition (due to the **low cross-sections**)

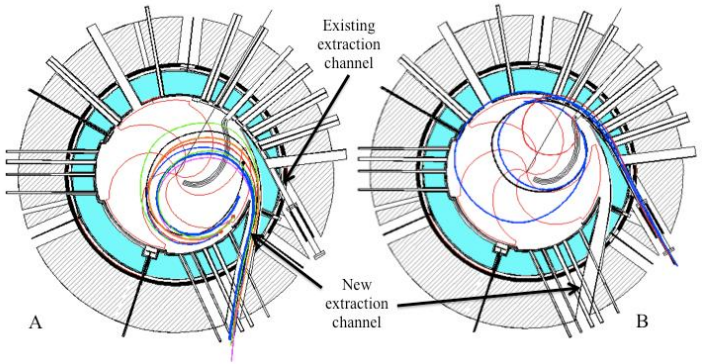
Moving towards hot-cases requires much higher beam intensity

Facility upgrade (Cyclotron and beam lines + MAGNEX) to work with two orders of magnitude more intense beam

Funded by National Grant (PON)

Upgrade of the LNS facility

➢ Upgrade of the LNS accelerator and beam lines



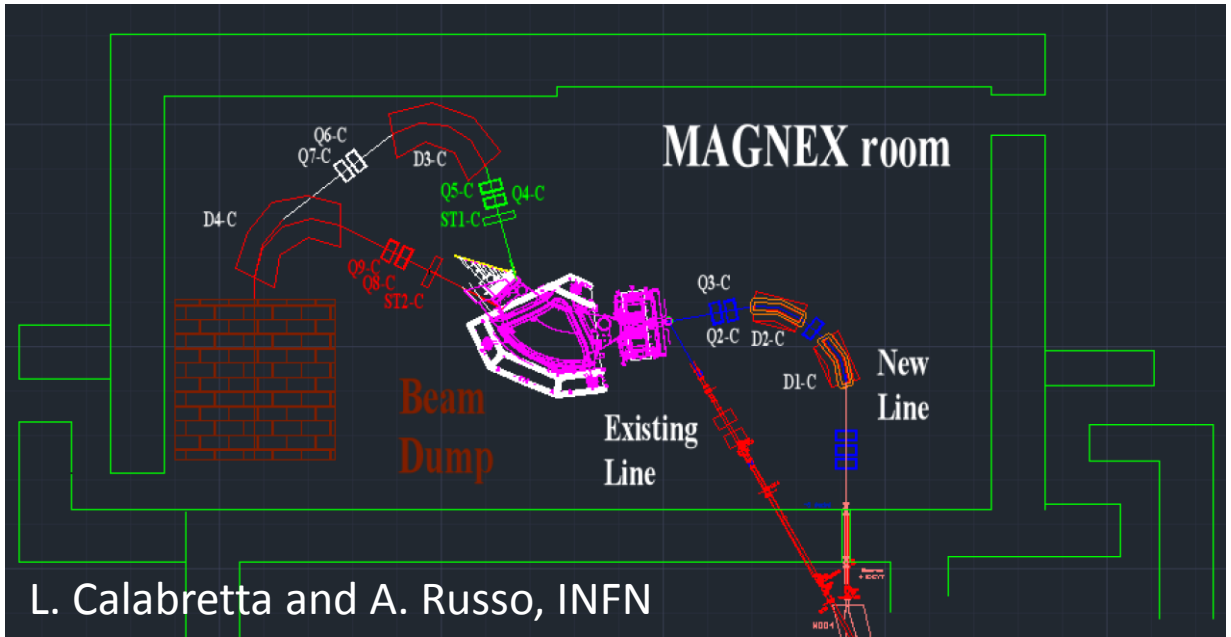
- **Cyclotron** power (from 100 W to 5-10 kW)

from extraction by deflector to extraction by stripping

- **beam transport line** transmission efficiency to nearly 100%
- Maintaining the present **beam energy resolution**

(see poster A. Russo)

➢ Beam dump for the MAGNEX hall



Two exit lines:

- (^{20}Ne,^{20}O) reactions ($\beta^-\beta^-$ kind)

Beam with Bρ lower than ejectiles

- (^{18}O,^{18}Ne) reactions ($\beta^+\beta^+$ kind)

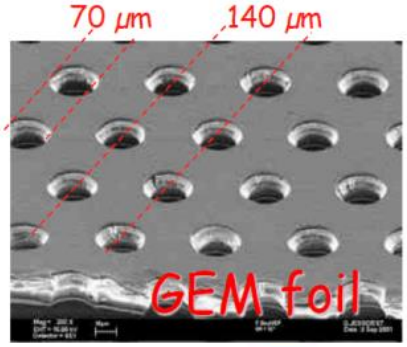
Beam with Bρ higher than ejectiles

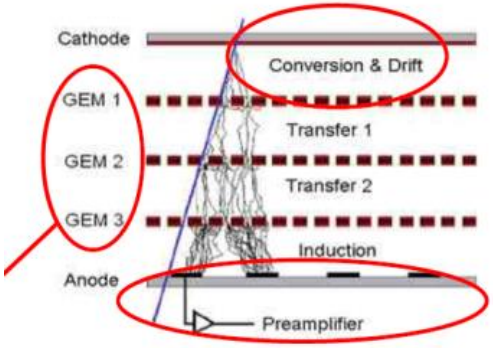
Upgrade of MAGNEX

➢ The Focal Plane Detector

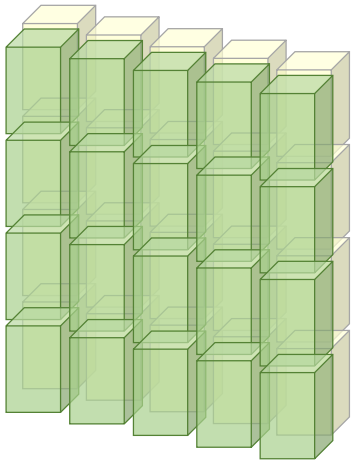
Rate
from few kHz to MHz
preserving low-pressure operation

Radiation hardness
expected 10^{13} ions/cm^2 in 10 years activity
(silicon detectors dead at 10^9 implanted ions/cm^2
heavy ions not MIP!!)





Micro-pattern gas tracker



- Radiation hard
- Heavy ions
- Working in gas environment
- Large area
- High energy resolution (2%)
- Timing resolution (few ns)

➢ SiC-SiC pad telescopes
➢ SiC (ΔE) + scintillator (E)

A challenging program

Theory:
Formal development and calculations

Accelerator and beam lines:
Upgrade of the Superconducting Cyclotron for high power

Detectors:
- Gas tracker for high rate heavy ions at low pressure (MPGD)
- PID wall covering a large area made of radiation hard and high resolution detectors (SiC)
- Gamma detectors

Mechanics:
Beam dump for zero-degree beam downstream of the spectrometer

Targets:
For intense heavy-ion beams

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The NUMEN project

Spokespersons: F. Cappuzzello (cappuzzello@lns.infn.it) and C. Agodi (agodi@lns.infn.it)

93 Researchers
30 Institutions
14 Countries

Proponents: C. Agodi, J. Bellone, D. Bonanno, D. Bongiovanni, V. Branchina, S. Brasolin, G. Brischetto, O. Brunasso, S. Burrello, S. Calabrese, L. Calabretta, D. Calvo, V. Capirossi, F. Cappuzzello, D. Carbone, M. Cavallaro, I. Ciraldo, M. Colonna, G. D'Agostino, N. Deshmukh, P. Finocchiaro, M. Fisichella, A. Foti, G. Gallo, U. Garcia-Tecocoatsi, F. Iazzi, G. Lanzalone, F. La Via, F. Longhitano, D. Lo Presti, P. Mereu, L. Pandola, F. Pinna, S. Reito, A.D. Russo, G. Russo, E. Santopinto, O. Sgouros, V. Soukeras, A. Spatafora, D. Torresi, S. Tudisco, R.I.M. Vsevolodovna

Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Italy
Dipartimento di Fisica e Astronomia, Università di Catania, Italy
Dipartimento di Fisica, Università di Genova, Italy
DISAT, Politecnico di Torino, Italy
Università degli Studi di Enna "Kore", Enna, Italy
CNR-IMM, Sezione di Catania, Italy

T. Borello-Lewin, P.N. de Faria, J.L. Ferreira, R. Linares, J. Lubian, N. Medina, D.R. Mendes, M. Moralles, J. R. B. Oliveira, M.R.D. Rodrigues, R.B.B. Santos, M.A.G. da Silveira, V.A.B. Zagatto

Instituto de Fisica, Universidade de Sao Paulo, Brazil
Instituto de Fisica, Universidade Federal Fluminense, Niteroi, Brazil
Instituto de Pesquisas Energeticas e Nucleares IPEN/CNEN, Brazil
Centro Universitario FEI Sao Bernardo do Brazil, Brazil

I. Boztosun, H. Djapo, A. Hacisalihoglu, S. Hazar, S.O. Solakcı, A. Yildirim
Akdeniz University, Antalya, Turkey
Institute of Natural Sciences, Karadeniz Teknik University, Turkey

L. Acosta, P. Amador, R. Bijker, E.R. Chávez Lomelí, R. Espejel, A. Huerta, H. Vargas, A. Flores, S. Martínez, C. Ordoñez, D. Marín, B. Góngora, G. Reza, J. Mas, G. Vega, D. Belmont, S. Sandoval
Instituto de Fìsica, Universidad Nacional Autónoma de México, México
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, México Instituto Nacional de Investigaciones Nucleares, México

A. Pakou, G. Souliotis
Department of Physics, University of Ioannina, Greece
Department of Chemistry, National and Kapodistrian University of Athens, Greece

H. Lenske, V. Werner, N. Pietralla
Department of Physics, University of Giessen, Germany
Institut fur Kernphysik, Technische Universitat Darmstadt, Germany

N. Auerbach
School of Physics and Astronomy Tel Aviv University, Israel

H. Petrascu,
IFIN-HH, Bucarest, Romania

J.A. Lay
Departamento de FAMN, University of Seville, Spain

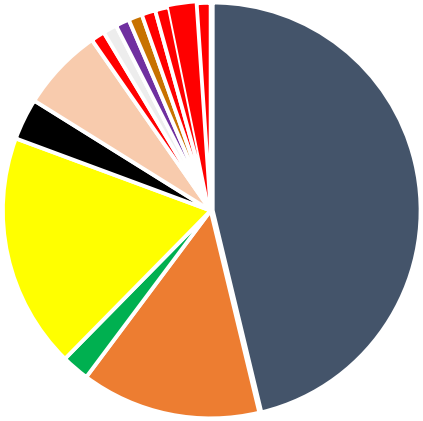
F. Delaunay,
LPC Caen, Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, France

Z.J. Kotila,
University of Jyväskylä, Jyväskylä, Finland

G. De Geronimo
Stony Brook University, US

J. Barea
Universidad de Conception, Chile

R. Chen, J.S. Wang
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China



Conclusions and Outlooks

- Many **experimental facilities** for 0νββ half-life, but not for the **NME**
- Pioneering experiments shown that **DCE cross sections can be suitably measured** and **cross-section extracted**
- The use of the **MAGNEX** magnetic spectrometer is crucial
- **Experimental campaign** and work on the **theory** is going on within the NUMEN project
- The **upgrade** of the INFN-LNS cyclotron and MAGNEX will allow to build a **unique facility** for a systematic exploration of all the nuclei candidate for 0νββ
- Exciting new physics requiring **high intensity beams**

Thank you