Design and test of an Accelerator Driven Neutron Activator at the Joint Research Centre of the European Commission

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Outline

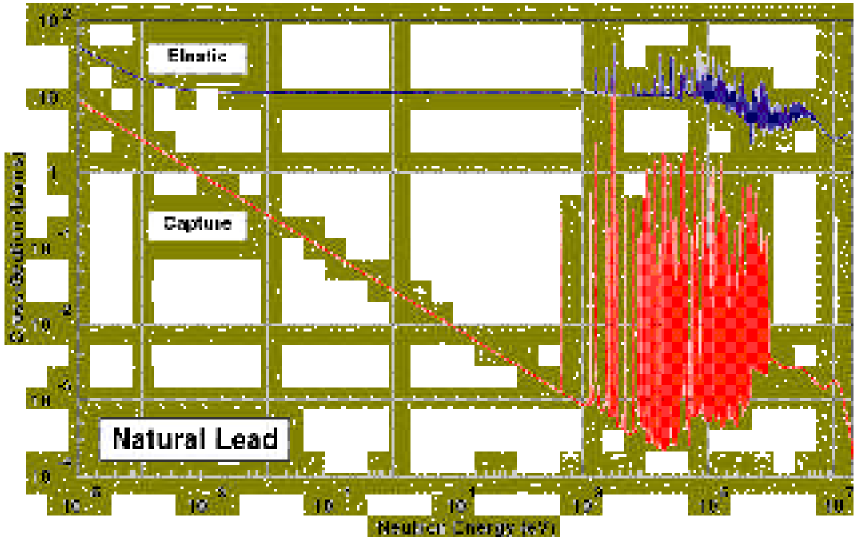
- ARC concept and previous experiments
- Motivation – the INBARCA project
- New design for an ARC neutron activator
- Installation and preliminary results
- Concluding remarks

Adiabatic Resonance Crossing (ARC) concept

- ARC was introduced by C. Rubbia for transmutation and radioisotope production (by neutron capture)

- The ARC method consists of moderating neutrons in lead

- Pb has the lowest capture cross section in the fast neutron field



- In Pb fast neutrons are moderated in small energy degradation steps therefore neutron capture in the epithermal range (resonance range) is enhanced

Use of ARC Concept for Transmutation or Radioisotope Production

1 - Fast neutrons are generated in a target bombarded with accelerated charged particles

2 - Then they are incrementally slowed by scattering with relatively little energy absorption in lead down to the resonance energy range of the material to be transmuted

3 - Finally, they are captured in the material to be transmuted (neutron captures take place)

Transmutation by Adiabatic Resonance Crossing (TARC) Experiment at CERN (1996-1999)

1 - Facility installed in the CERN PS proton beam line

2 - Neutrons produced by spallation with proton beam (2.5-3.5 GeV)

3 - Neutrons slowed down in Lead (3.3 m x 3.3 m x 3 m, ~ 334 tons)

4 - TARC Conclusions:

- **ARC can be used to transmute large amounts of ^{99}Tc or ^{129}I (long lived f. products)**
- **ARC can be used as an alternative method (alternative to nuclear reactors) for radioisotope production for medical or other applications**

ARC experiment at the Cyclotron of Louvain-La-Neuve (Belgium)

1 – Aim: Feasibility study for industrial production of ^{99}Mo (generator of ^{99m}Tc) and ^{125}I using the ARC concept in a cyclotron (University of Louvain)

2 – Neutron generated by proton beam (65-75 MeV) bombarding Be target

3 – Neutron slowing down in pure lead (1.6 m x 1.6 m x 1.63 m, 47 tons)

4 – Conclusion: The results were very encouraging and seem to confirm that the ARC concept can be used for radioisotope production for nuclear medicine

Aim of the current project

- partially funded by the EUREKA programme, project INBARCA -

(Innovative Nanosphere Brachytherapy by Adiabatic Resonance Crossing with Accelerators)

1 – Test of a new ARC design concept at low energy (Cyclotron)

2 – Measurement of activation yields and validation of MC calculations

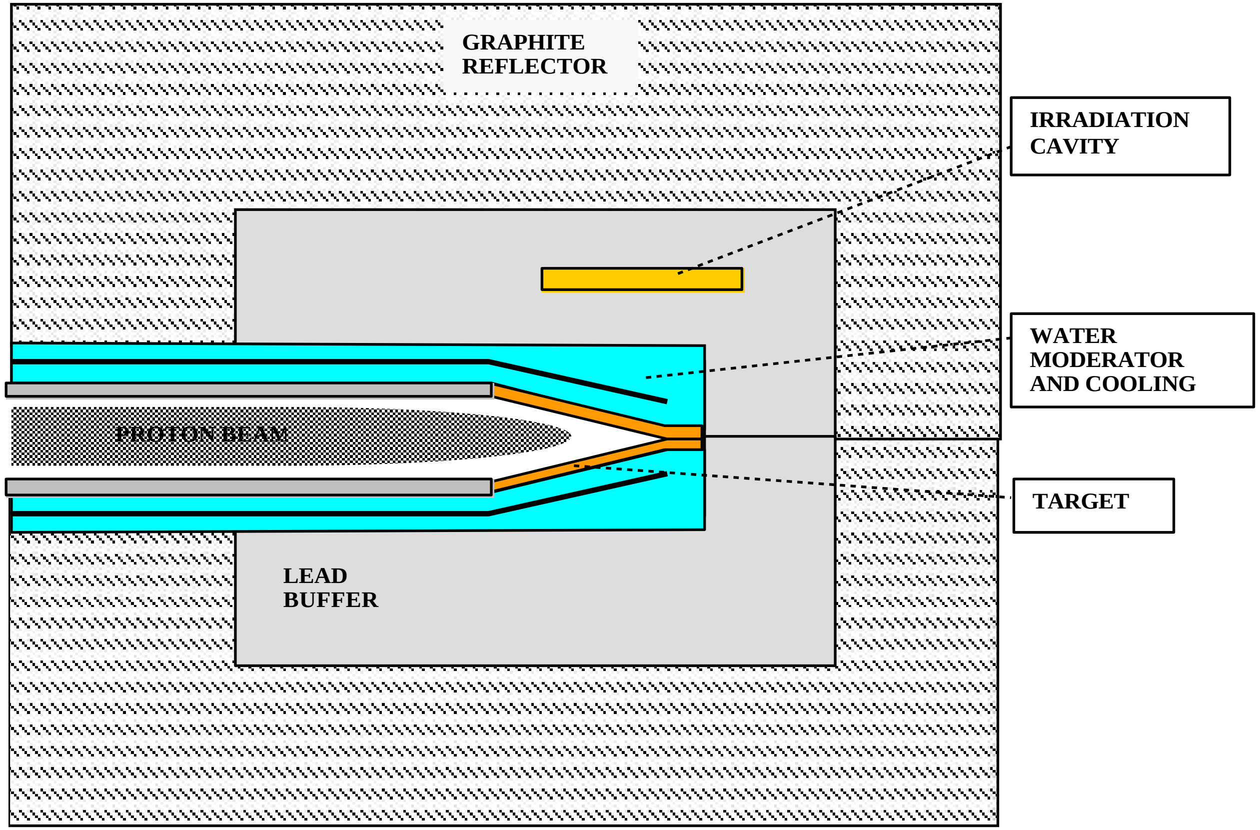
3 – Activation of nanoparticles for Brachytherapy (Ho and Re)

4 – Investigation of other potential uses (other radioisotopes, activation of nanoparticles for tracer studies, etc.)

List of radioisotopes used in brachytherapy (in black) and the ones proposed in this project (in red)

Radioisotope	Symbol	$T_{1/2}$ (h)	Decay mode	Mean energy	Current production method	Main applications
125-Iodine	^{125}I	1425.6	e	35 keV	Reactor	Prostate cancer
103-Palladium	^{103}Pd	407.76	ec	21 keV	Reactor & Accelerator	Prostate cancer
90g-Yttrium	^{90g}Y	64.104	b-	930 keV	Reactor	Live cancer
192g-Iridium	^{192g}Ir	1771.92	b-(95.24%) b+(4.76%)	317 keV	Reactor	HDR brachytherapy
188g-Rhenium	^{188g}Re	16.98	b-	2 MeV	Reactor	Bone cancer, rheumatoid arthritis, prostate...
186g-Rhenium	^{186g}Re	89.25	b-	1 MeV	Reactor	Bone cancer, rheumatoid arthritis, prostate...
166-Holmium	^{166}Ho	26.80	b-	2 MeV	Reactor	Liver Tumour

New design for an ARC neutron activator

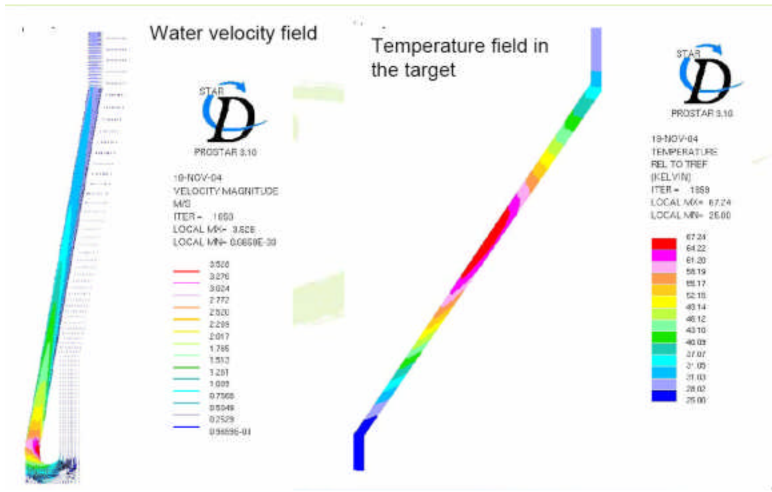


System design: calculations

MCNPX, FLUKA and STAR-CD codes were used for designing the new ARC facility

Components taken into account in the simulations:

- **Be target (quality, thickness, shape)**
- **Proton irradiation (energy, charge, shape)**
- **The cooling water of the Be target (shape, flow)**
- **The lead buffer and Graphite reflector (quality, shape)**
- **Irradiation channels (positions)**

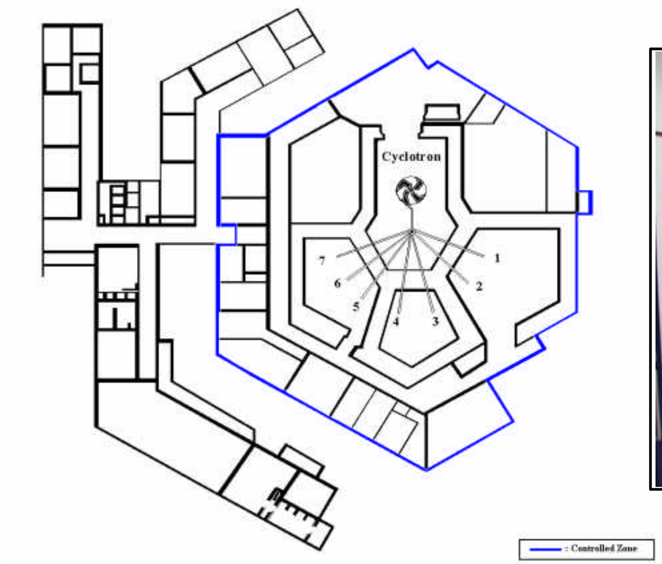


The final design was optimised for maximum activation yield (with thermal and epithermal neutrons) of Ho and Re in the irradiation channels

JRC Cyclotron (Ispra, Italy)

Scanditronix MC 40

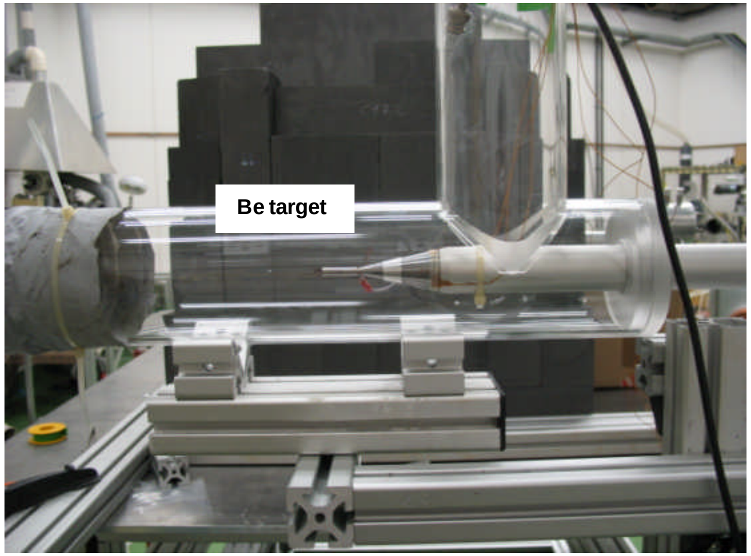
Particles	Minimum Energy (MeV)	Maximum Energy (MeV)	Maximum Extracted Current (mA)
p	8	40	60
a	8	40	30
$^{3}He^{2+}$	8	53	30
d	4	20	60

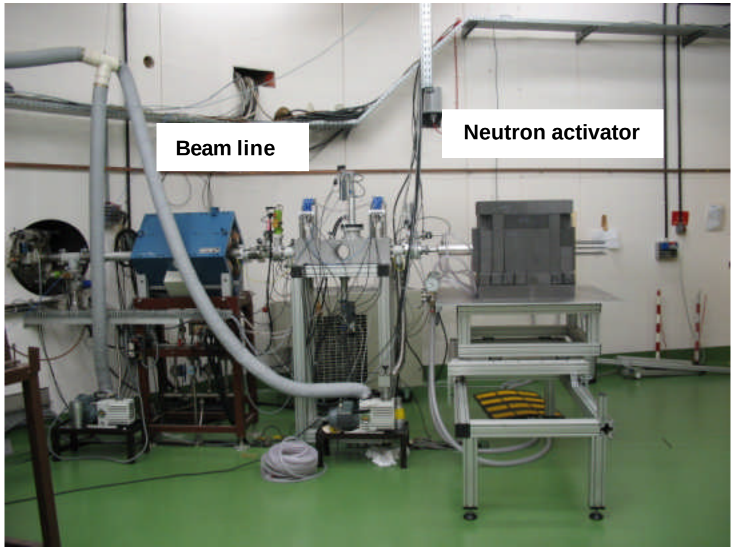


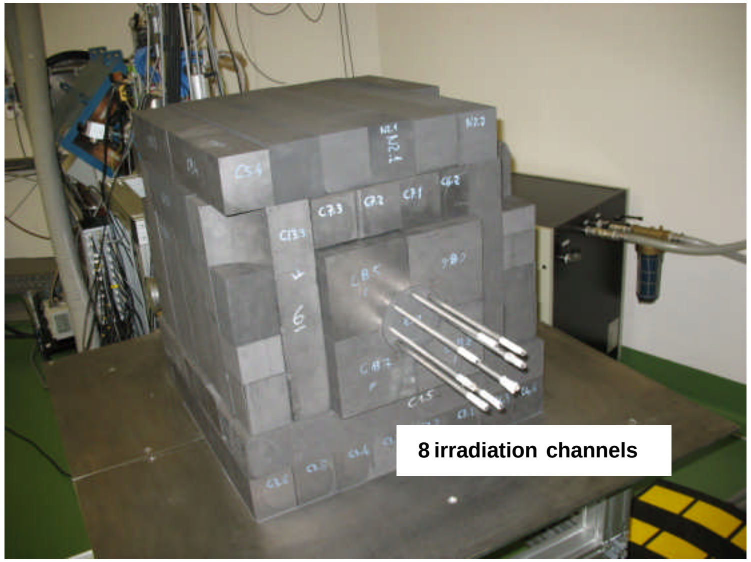
RF cavities	2, lombda/4
Dees	2, 90 degrees
Beam aperture	20 mm
Tuning	Moving shorts/trim cap.
RF range	12.5 –27 MHz
Frequency stability	$< 10^{-6}$
Amplitude stability	$< 10^{-3}$
Max. Dee peak voltage	44 kV
Ion source	P.I.G. Type

Pole diameter	115 cm
Magnet weight	60 tons
Main coils Max. Curr.	850 A
Sectors	3
Hill gap	100 mm
Valley gap	180 mm
Max. magnetic field	2.1 Tesla
Extraction radius	50 cm
Trim coils	8
Harmonic coils	84 sets

Installation of the neutron activator

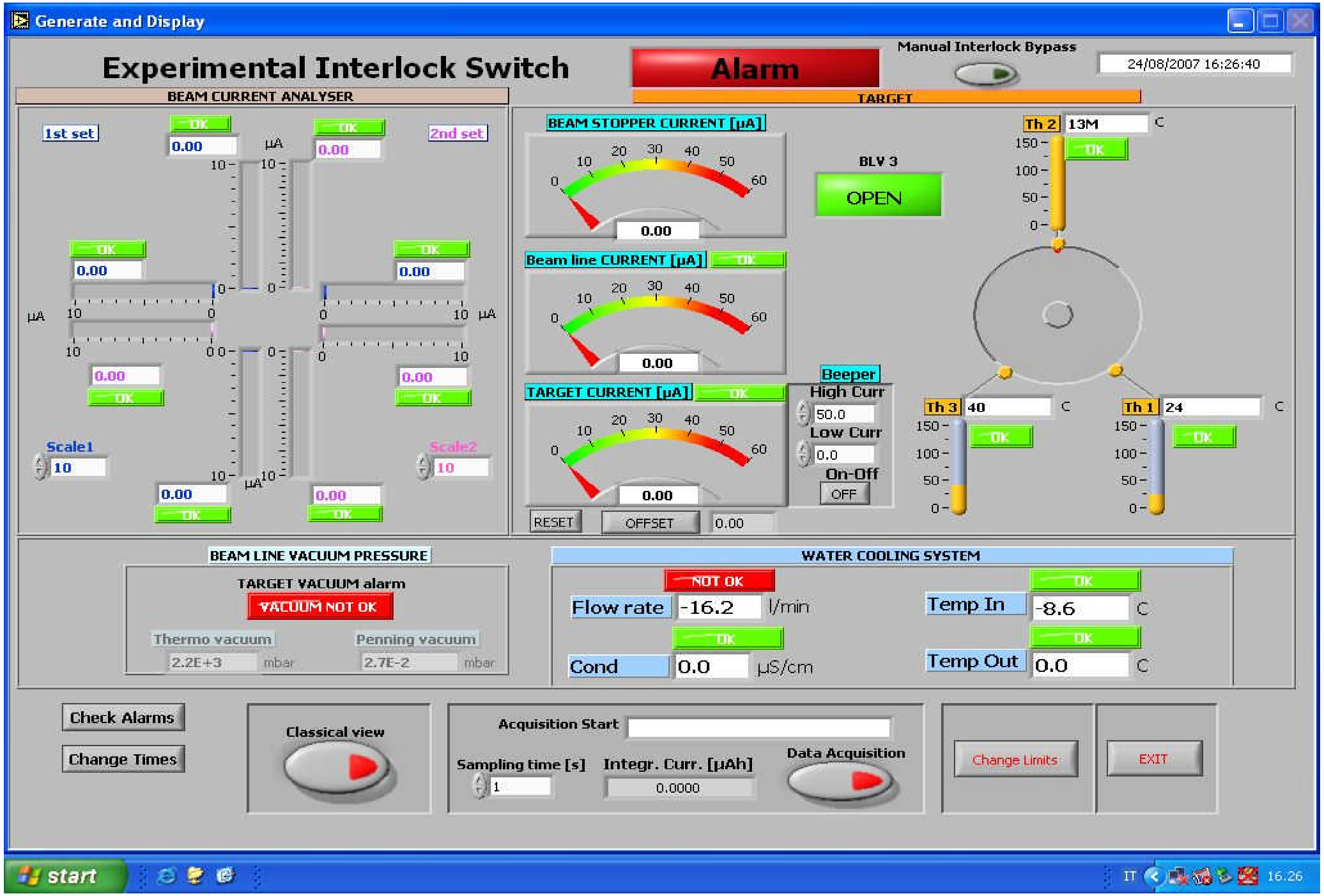






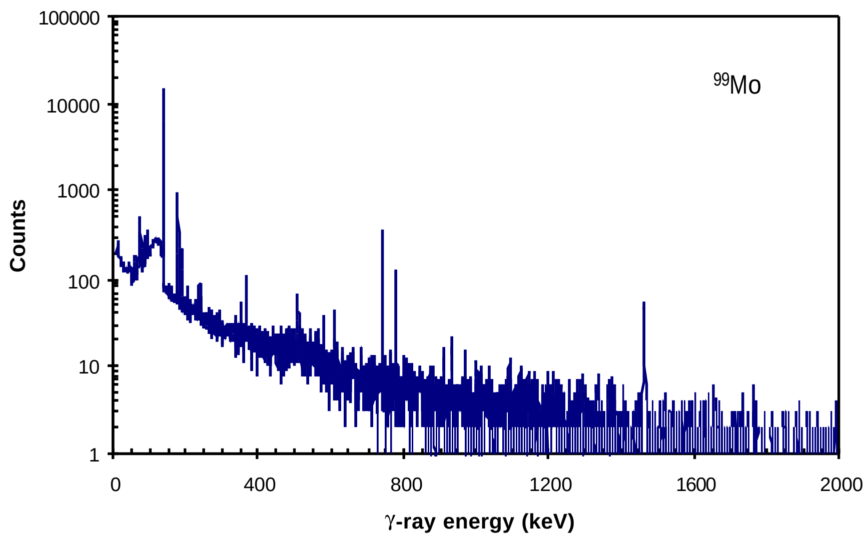
Dimension: 60 cm x 60 cm x 60 cm
Weight: ~ 600 kg

Control system of the neutron activator

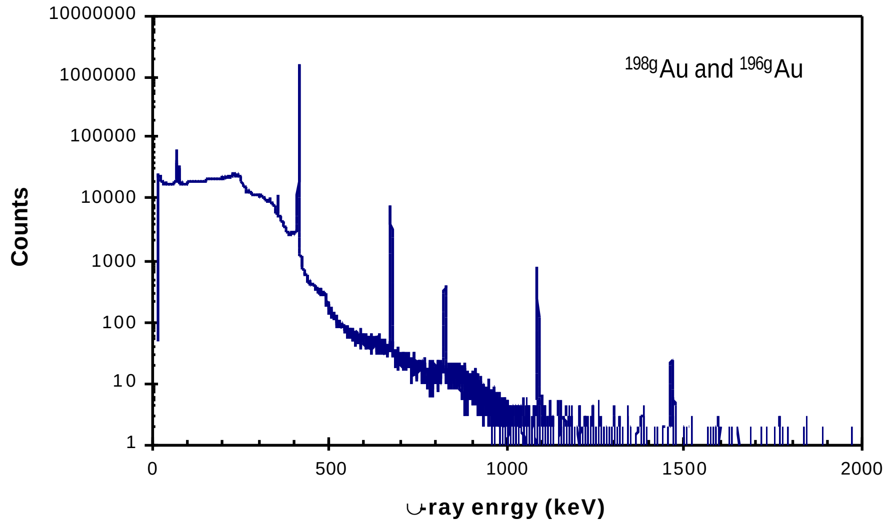


Preliminary Results

Activation of foils of Mo and Au



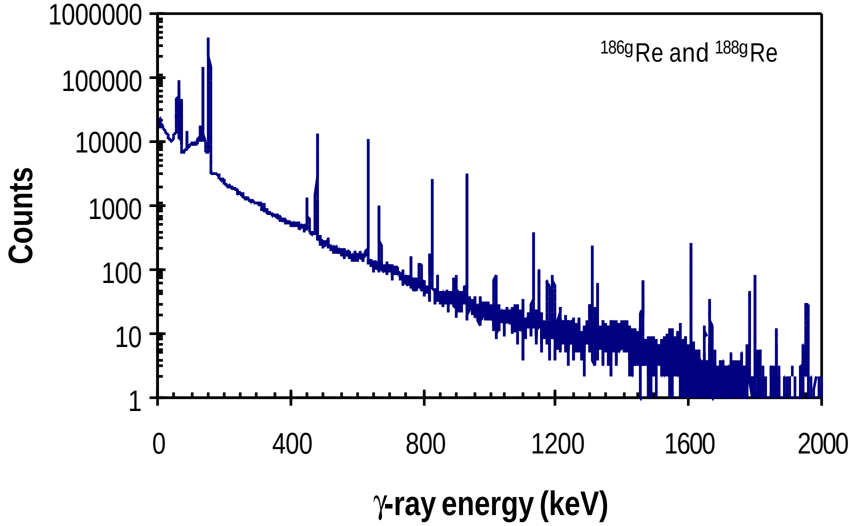
$^{98/100}Mo(n,g/2n)^{99}Mo$

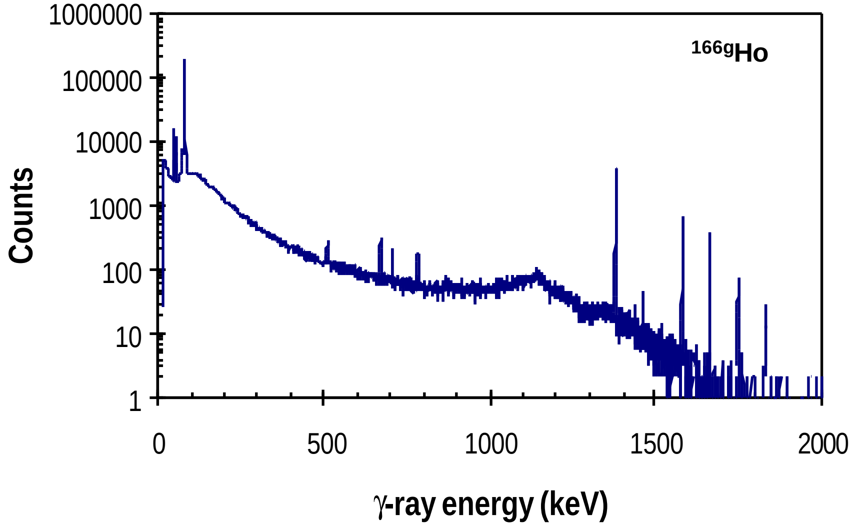


$^{197}Au(n,g)^{198g}Au$

$^{197}Au(n,2n)^{196g}Au$

Preliminary Results
Activation of foils of Re and Ho





$^{185/187}Re(n,g/2n)^{186g}Re$

$^{187}Re(n,g)^{188g}Re$

$^{165}Ho(n,g)^{166g}Ho$

Preliminary Results Summary

Radioisotope	$T_{1/2}$	Reaction	Yield (MCNPX)	Yield Measured (Ispra)	Yield Measured (LLN)
^{198}Au		^{197}Au(n,g)^{198}Au	553.83		
^{196}Au		^{197}Au(n,2n)^{196}Au	1.99		
^{198g}Au	**2.69 d**	**^{197}Au(n,g)^{198g}Au**		**724.20**	**194.46 * (526.99 **)**
^{196g}Au	6.2 d	^{197}Au(n,2n)^{196g}Au		1.58	
^{24g}Na	14.96 h	^{27}Al(n,α)^{24g}Na		5.37	
^{99}Mo	**66 h**	**$^{98/100}$Mo(n,g/2n)^{99}Mo**		**7.13**	**1.85 * (5.02 **)**
^{166}Ho		^{165} Ho(n,γ)^{166}Ho	1650.00		
^{166g}Ho	**26.8 h**	**^{165}Ho(n,g)^{166g}Ho**		**2520.00**	
^{186}Re		^{185}Re(n,γ)^{186}Re	693.00		
^{188}Re		^{187}Re(n,γ)^{188}Re	1150.00		
^{186g}Re	**3.7 d**	**$^{185/187}$Re(n,g/2n)^{186g}Re**		**385.00**	
^{188g}Re	**0.71 d**	**^{187}Re(n,g)^{188g}Re**		**2100.00**	

*Yield corrected for proton energy bombardment, ** Yield for 65 MeV proton energy as published (LLN),

- Yield unit: kBq/(μA.h.g), Measured yield uncertainties: < 10%

Conclusions

1 - A new concept of an ARC neutron activator was designed and tested. With respect to previous designs it is much more compact (60 x 60 x 60 cm^3, weight ~ 600 kg)

2 - Preliminary results on activations of foils of various materials were in good agreement with calculations

3 - With reference to previous work, slightly higher production yields of ^{99}Mo (generator ^{99m}Tc) and ^{198g}Au were obtained (factor ~4)

4 - The promising activation yields accomplished in this work open interesting perspectives for brachytherapy studies using Ho and Re based radioactive nanoparticles

5 - The ARC activator developed in this work may constitute an attractive alternative to nuclear reactors for production of certain radioisotopes for medical or other applications

THANK YOU FOR YOUR ATTENTION