Status of ATW technology and research needs from the Swedish perspective and opportunities for international collaboration

Waclaw Gudowski
Royal Institute of Technology
Stockholm, Sweden

Program

- **Roadmap activities - some concerns how I (we) am supposed to help?**
- **Nuclear power in Sweden from US perspective. Can transmutation (accelerator-driven) solve some of the nuclear energy problems**
- **ATW - state of the art (from different perspectives)**
- **Critical areas of ATW technology requiring further R&D**
- **The opportunities for ATW collaboration**
  - **Synergy with European activities**
  - **Synergy with other international activities : ISTC, IAEA**
- **Conclusions**

Acronym dictionary:

ATW - Accelerator-Driven Transmutation of Wastes

ADTT - Accelerator-Driven Transmutation Technologies

ADS - Accelerator-Driven Systems

AE - Energy Amplifier

EC - European Commission ("Government of EU")

EU - European Union

IAEA - International Atomic Energy Agency

ISTC - International Science and Technology Centre

MA - Minor Actinides (Np,Am, Cu, Cf etc.)

SKB - Swedish Nuclear Fuel and Waste Managament Co.

TRU - Transuranium elements (Np,Pu, Am, Cu, Cf etc.)

Sketching a road map

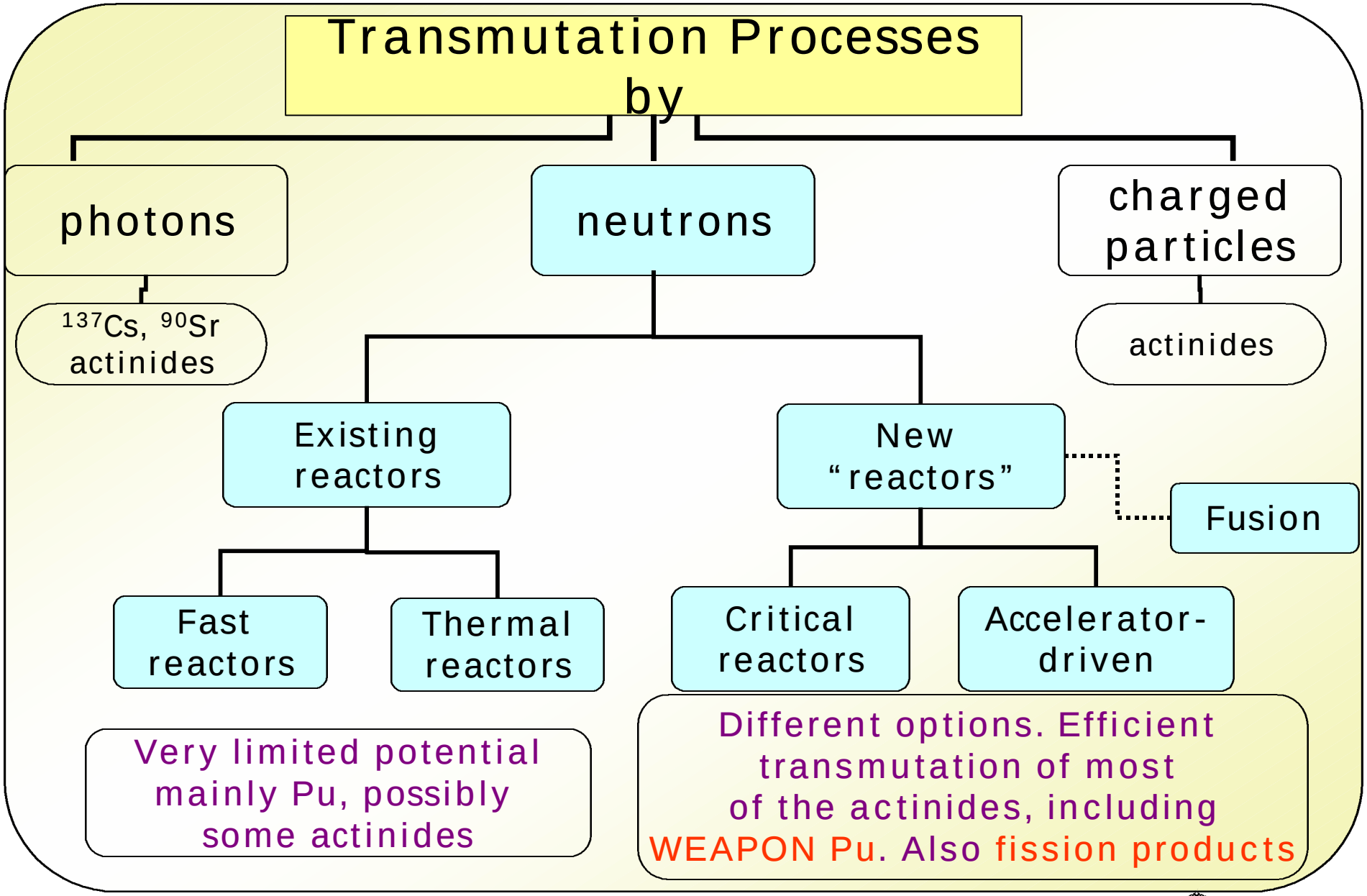
The agenda for "road mapping" activities:

- the technical issues that must be resolved,
- a proposed time schedule and program to resolve the technical issues,
- the estimated cost of such a program, its elements and certainty of cost estimates,
- a plan for collaboration with
  - (a) other countries developing ATW, and
  - (b) other accelerator programs (e.g., the Spallation Neutron Source project)
- an assessment of the institutional challenges of an ATW program in the U.S.,
- the possible impact of ATW on the current civilian spent fuel program,
- areas of ATW development which could benefit other ongoing programs,
- the estimated capital and operational life cycle costs for ATW treatment of the civilian spent fuel.

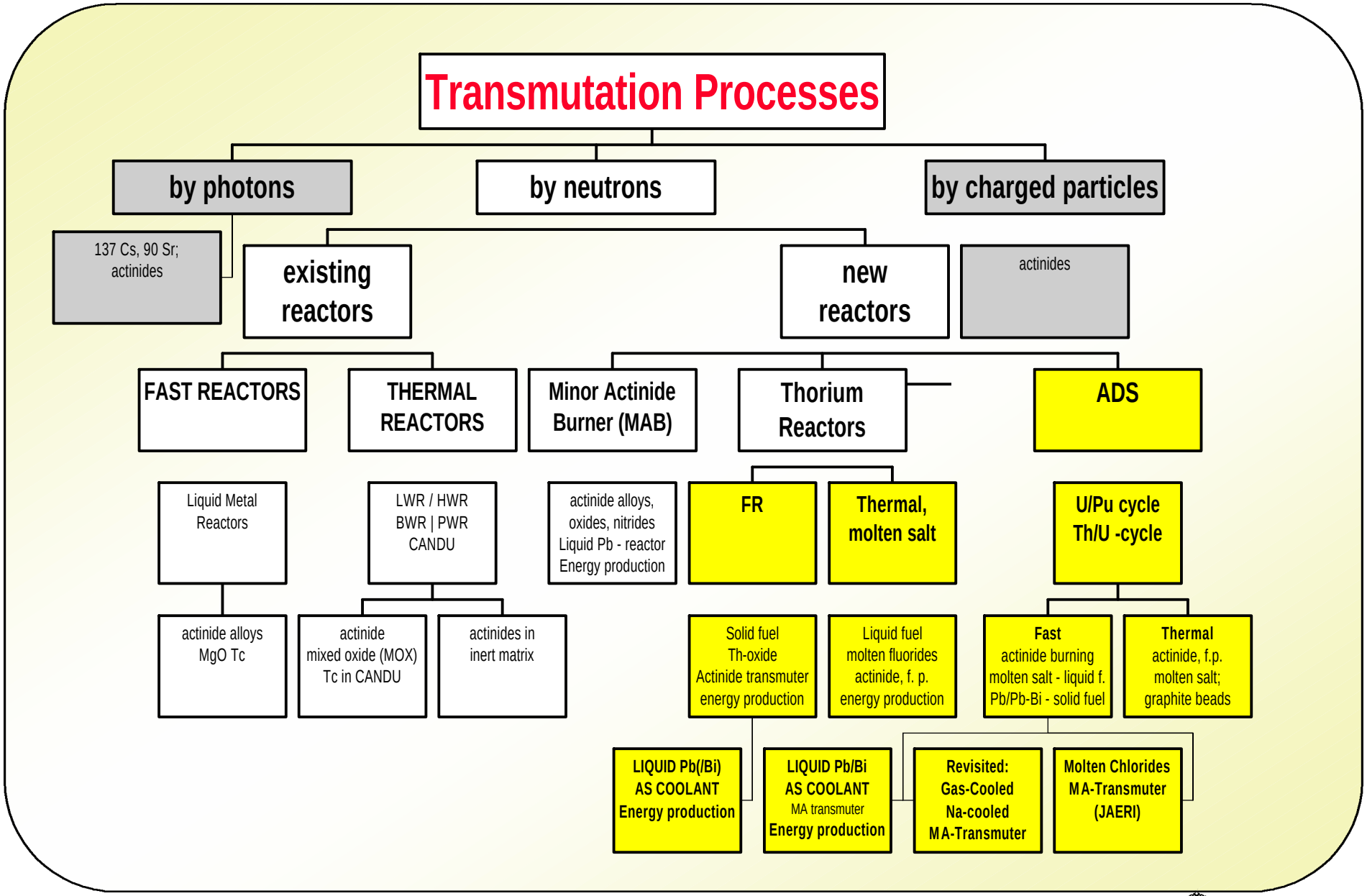
indicates that there is a genuine will to launch the ATW program (am I right ?? That is what we hoped for since 1991-92.) and “road mapping” is to plan the optimal way to shape this program. However the two principal questions have to be asked and answered at the very beginning of “road mapping” activities:

- **Do we need transmutation?**
- **If so, is Accelerator-Driven Transmutation the best choice?**

If the expert community do not reach a solid consensus on these 2 questions we have very small chances to convince the public & politicians.



SCIENCE AND ART THE ROYAL INSTITUTE OF TECHNOLOGY



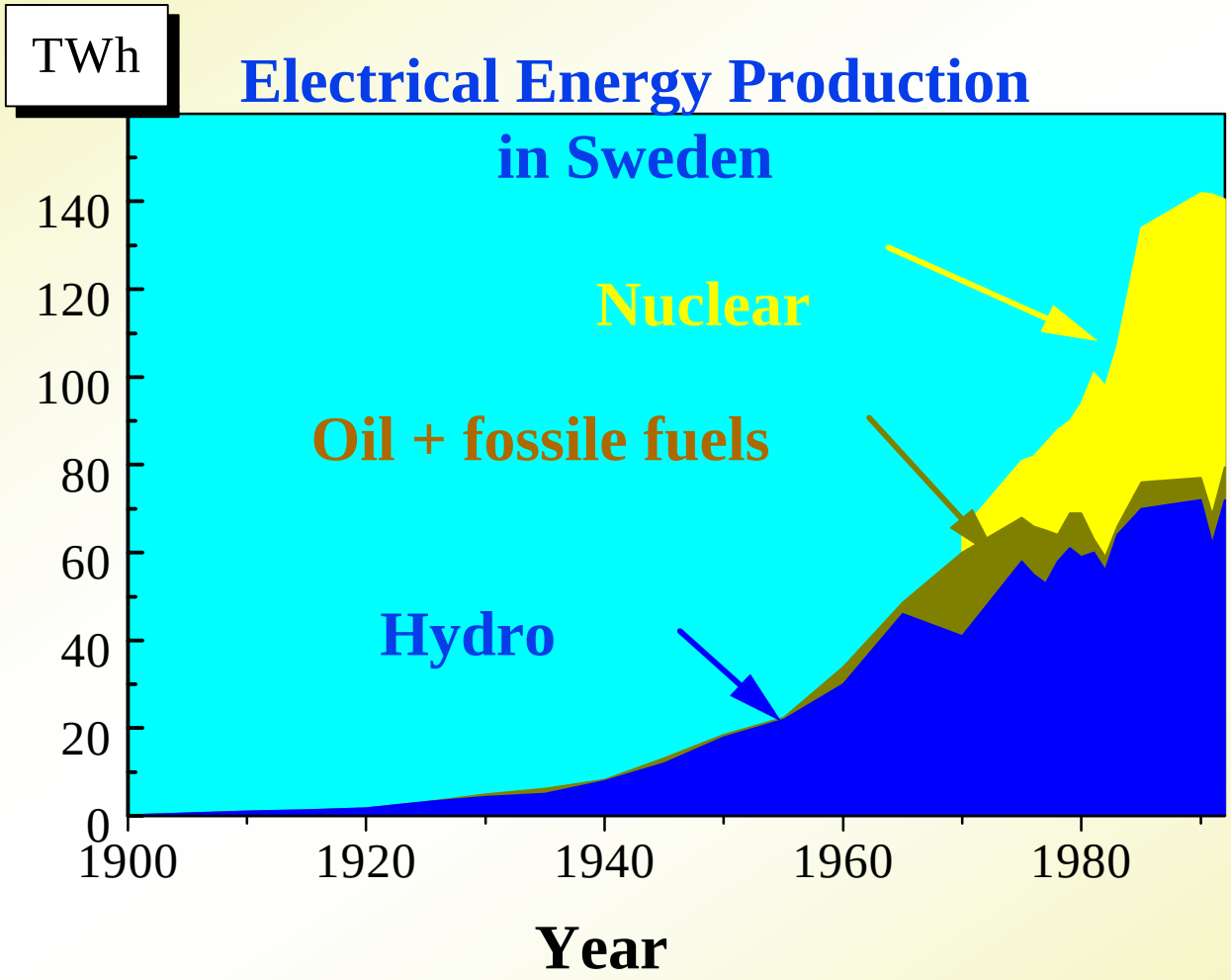
SCIENCE AND ART THE ROYAL INSTITUTE OF TECHNOLOGY

Swedish Nuclear Power -

Comparison to the US situation:

	Sweden	USA
Nuclear Power (GW_{el} & TWh/a)	10 & 66.5	107.7 & ~673
Number of reactors	12	~107
Share of NP in electricity production	~50% (46% – 1997)	20%
Waste handling policy	Central interim storage in place, geological disposal program	Storage at reactor sites, geological disposal program

SCIENCE AND ART THE ROYAL INSTITUTE OF TECHNOLOGY



SCIENCE AND ART
THE ROYAL INSTITUTE OF TECHNOLOGY

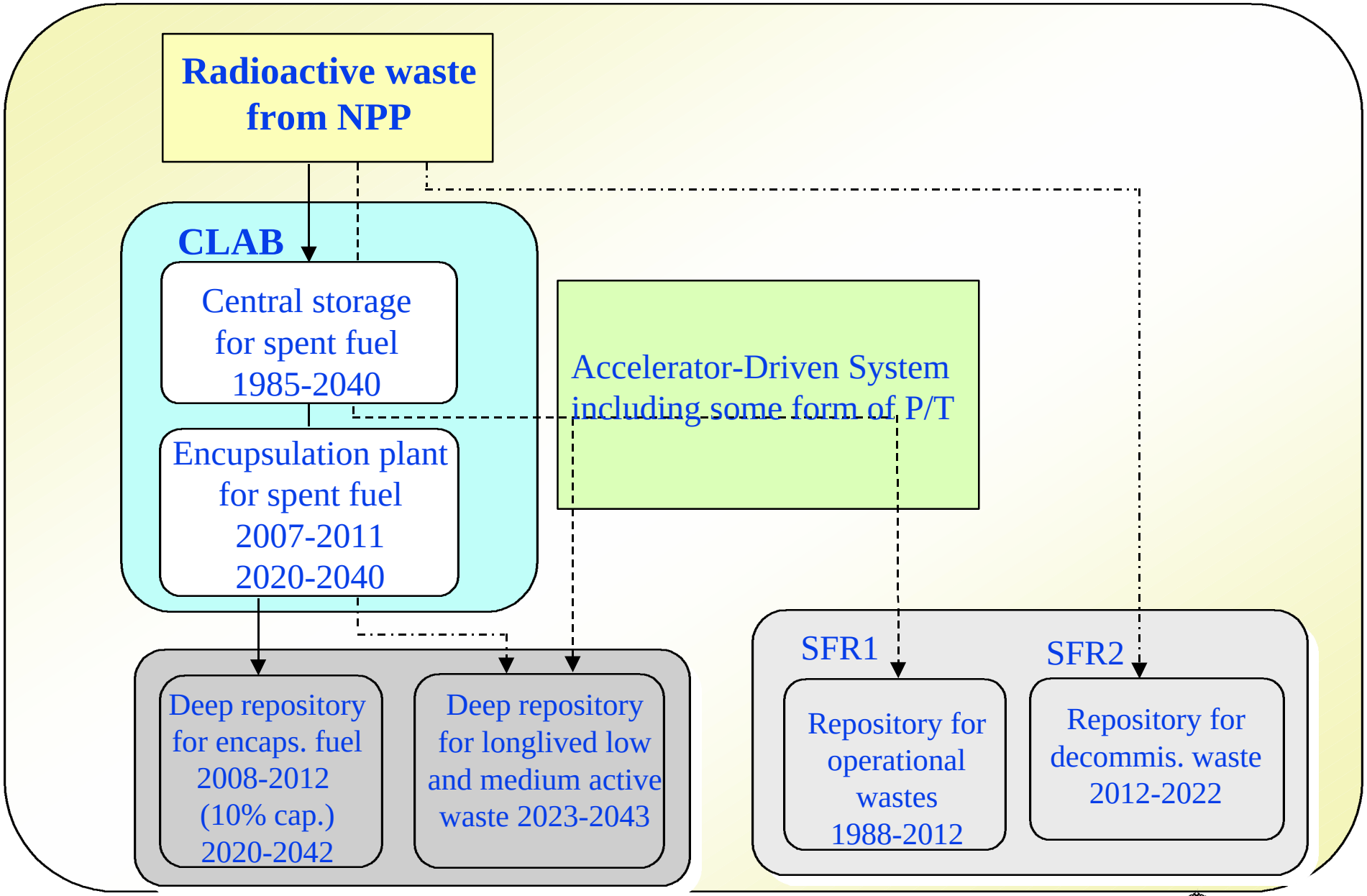
Fuel Consumption for Different Nuclear Power Scenarios Sweden & USA

Scenario	*Total Energy Production (TWh)*	*Total Uranium Consumption (ton U)*	*US – Spent fuel inventory (ton U)*
Operation up to and included 2010	2010	7840	54890 + 2 500 DOE
Operation 25 years of all reactors	1630	6530	
Operation 40 years of all reactors	2630	9890	
			70 000 at year 2020

Future costs of the radioactive waste handling for the different alternatives (MSEK)

	Operation through 2010	25 years of operation	40 years of operation
CLAB	**5586**	**5143**	**6360**
Encapsulation plant	**7908**	**6880**	**9658**
Deep Repository - Above Ground	**6957**	**6433**	**7486**
Deep Repository - Spent Fuel	**8661**	**7508**	**10662**
Deep Repository - Other Waste	**780**	**748**	**934**
Final Repository for Operating and Decomm. Wastes - SFR 1 + SFR 3	**779**	**891**	**920**
TOTAL	**30671**	**27603**	**36020**

(1$ ~7.5 - 8 SEK.)


Radioactive waste from NPP
CLAB
Central storage for spent fuel 1985-2040
Encupsulation plant for spent fuel 2007-2011 2020-2040
Accelerator-Driven System including some form of P/T
Deep repository for encaps. fuel 2008-2012 (10% cap.) 2020-2042
Deep repository for longlived low and medium active waste 2023-2043
SFR1
SFR2
Repository for operational wastes 1988-2012
Repository for decommis. waste 2012-2022

Why (Accelerator-Driven) Transmutation? (arguments used in Sweden)

- Social and technical reasons:
  - Conventional nuclear power with its once-through fuel cycle has very low public acceptance because:
    - excess of electricity on the market (important reason!!) and perceived risks related to nuclear reactors:
      - radioactive contamination risks due to potential reactivity excursion hazards, core meltdown or intentional terrorist handling
    - necessity of a geological disposal of spent fuel with its unimaginable time scale. Licensing of such facility can be very difficult mainly due to non-technical concerns. Typical example: critical review of SKB geological disposal program because of negligible perspective on socio-geographical, psychological and ethical aspects of geological storage.
    - concerns about increasing worldwide Pu-inventory.
  - low competitiveness of NP due to increasing safety requirements for big industrial facilities and very high investment costs for nuclear reactors

- Social and technical reasons (cont.):
  - most of the arguments in favor of NP (with or without transmutation) which appeal to scientists and researchers are not convincing for "general public", particularly:
    - exhaustion of fossile fuels (***there is always another 25 years for oil ...).*** Ethical arguments are used selectively, one criterion for geological repository, another one for e.g. coal mining or oil exploitation
    - global warming and climate changes are on the political agenda but politicians believe that :
      - problems are not that serious
      - "environmentally adjusted" taxation system can solve the problems by energy saving measures and by inducing technological progress and inventions.
- It is believed that transmutation, if successfully developed and implemented, can changed the perception of NP by addressing some of above mentioned concerns, can increase attractiveness of nuclear technology and ensure preserving of competence in this field for a current and future generations (very important arguments in Sweden).

- Technical arguments for ATW:
  - Accelerator-driven system addresses criticality concerns: power control not linked to reactivity feedbacks, delayed neutrons (or to control rods), but only to the accelerator drive
  - It permits purely transuranic cores or other “exotic” fuels
    - subcritical systems work independently of the fuel composition
    - allows constant power during burn-up through variable beam power
    - allows very deep burnup of Pu and other actinides, EOL inventory not limited by criticality conditions
  - Neutronics and thermohydraulics are effectively decoupled
  - Possibilities for implementation of passive safety features
  - New possibilities of closing of the fuel cycle, dedicated waste burners adjusted to the different national fuel cycle policies: dedicated MA-burners, Pu + MA burners, possibilities (if necessary) of “a soft introduction” of a Th-fuel cycle. This flexibility makes a broad international collaboration possible!

Last but not least:

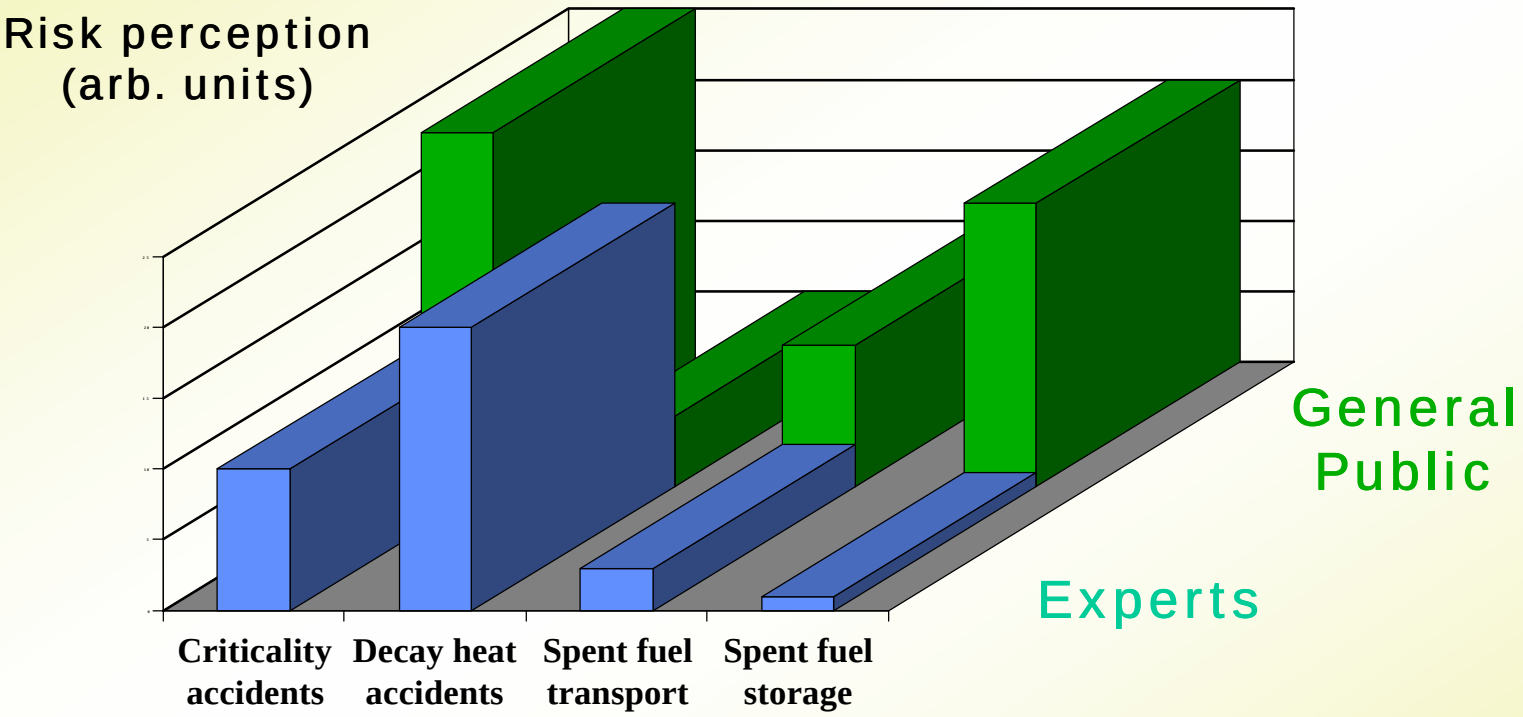
ATW is considered as technology which can assist a geological/underground waste repository by reducing the volume, time scales and possibly by “conditioning” of the final waste forms.

ATW research in Sweden is financed mainly by SKB, because:

- of genuine technological and “political” interest
- by its regulations, SKB is obliged to prove every 3 years that geological storage is the most feasible and sound technical solution for Swedish waste disposal. SKB’s R&D program is reviewed by independent bodies every 3 years and approved by the government.
- SKB can afford this!

It is also clear that a radical change of Swedish waste management program could happen only if there is a visible and convincing technological break-through in transmutation technology. However, there is a genuine will to join international efforts to achieve this break-through.

Risk perception for accidents related to nuclear power



Type of accidents/concerns

SCIENCE AND ART
THE ROYAL INSTITUTE OF TECHNOLOGY

ADS - system cost analysis (1$~8 SEK.)

Unit	Value/Basis Development scenario		
	autonomic	international	
Accelerators			
• **Number req.**	1	10-20	
• **Capital costs BSeK**	3	0.8	
ADS Target/Blankets			150% cost of LWR - 5000 Sek/kW_{th} for first 3 units, 100% for 6 -10, for many units - 75 %
• **Number req.**	3-6	100	
• **Capital costs BSeK**	16.5	9.9	
On-site ADS Fuel processing			
• **No. of ADS Pyro FPP req.**	1	10-20	
• **Capital costs BSeK**	.5	.4	
LWR Fuel Processing 8 000 t of fuel BSeK	10	10	COGEMA and BNFL
Repository BSeK	1	1	130% SFR 1 cost
ADS-R&D	1	.5	
TOTAL CAPITAL COST with 1 target/blanket unit - BSeK	**32**	**22.6**	

State of the art.
Technical issues of ATW:

Components of the ATW system

Accelerator

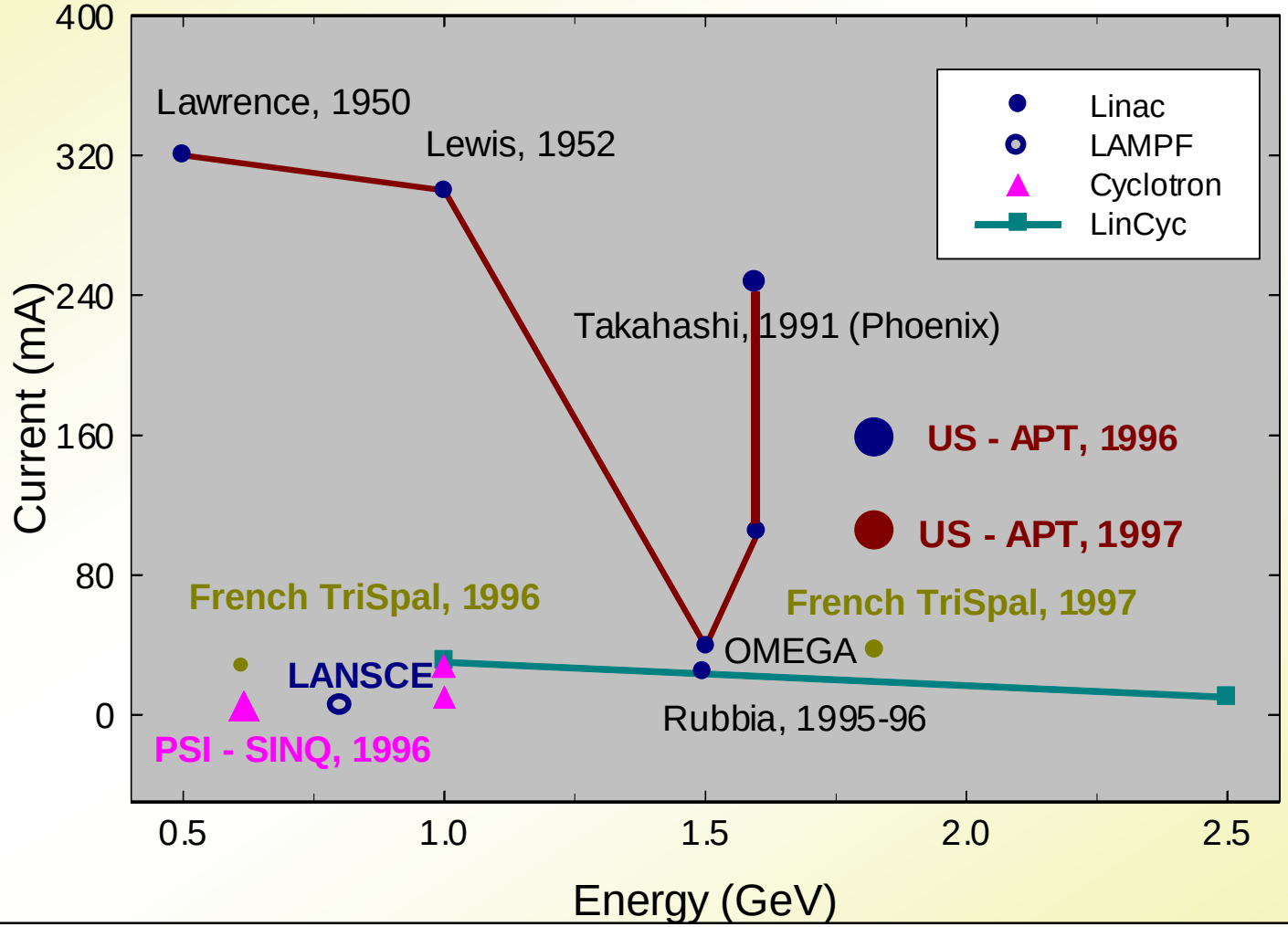
Target

Subcritical core (blanket)

Fuel preparation, partitioning & separation chemistry

Final waste/tailings treatment

Accelerators proposed for ADS



THE ROYAL INSTITUTE OF TECHNOLOGY

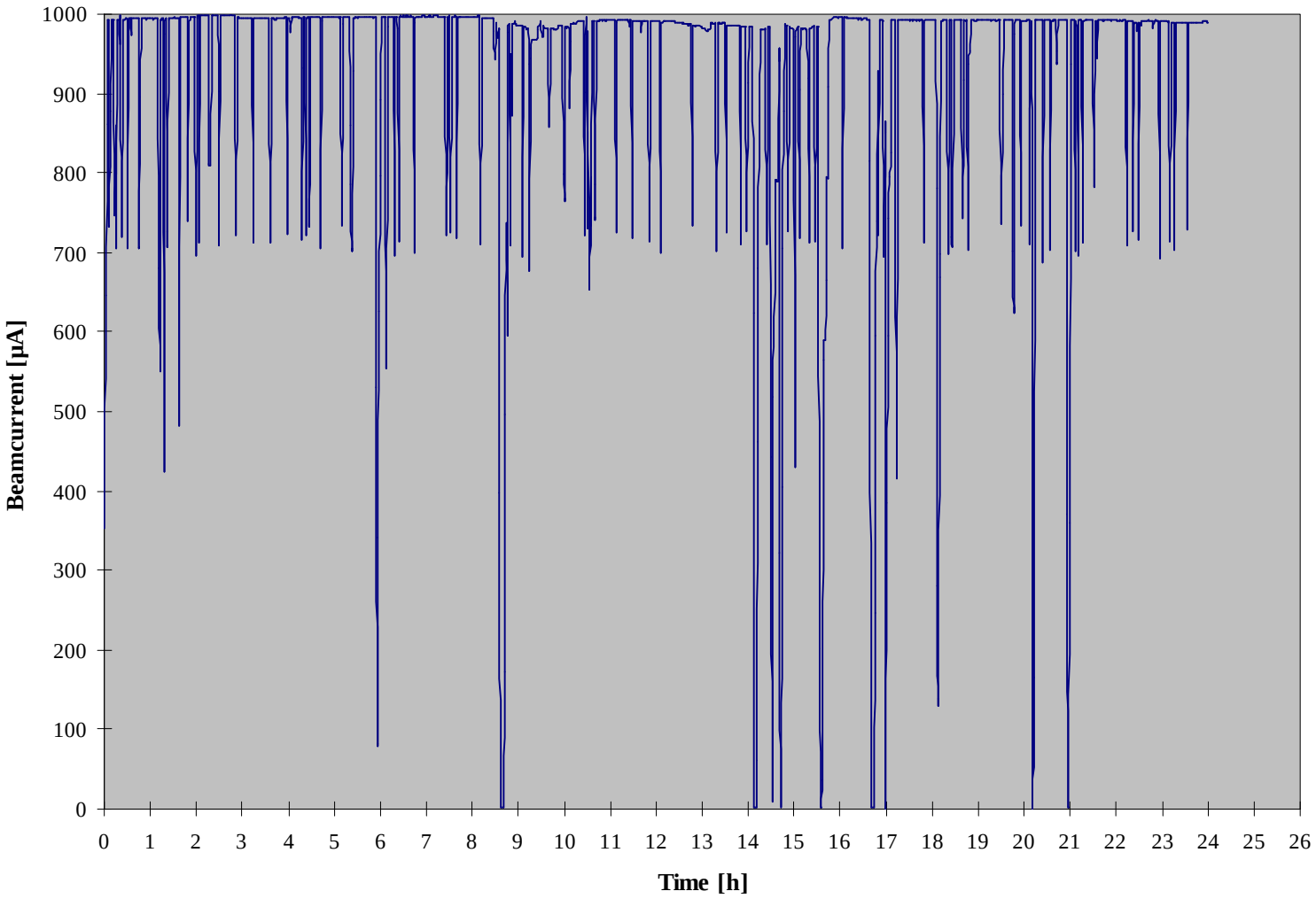
Accelerators need extensive development

- Linacs:
  - Improved reliability and trip-free performance
  - Extensive use of superconductors
  - Increase of electrical field gradients leading to reducing the size
  - Increase of current and possibly beam splitting/sharing to share accelerators in development stage

- Cyclotrons
  - Improved reliability and trip-free performance
  - Increase of beam current - novel concepts highly desired, space charge challenges
  - Cost reduction through compactness and robust constructions

BEAMCURRENT FLUCTUATIONS AT LANSCE

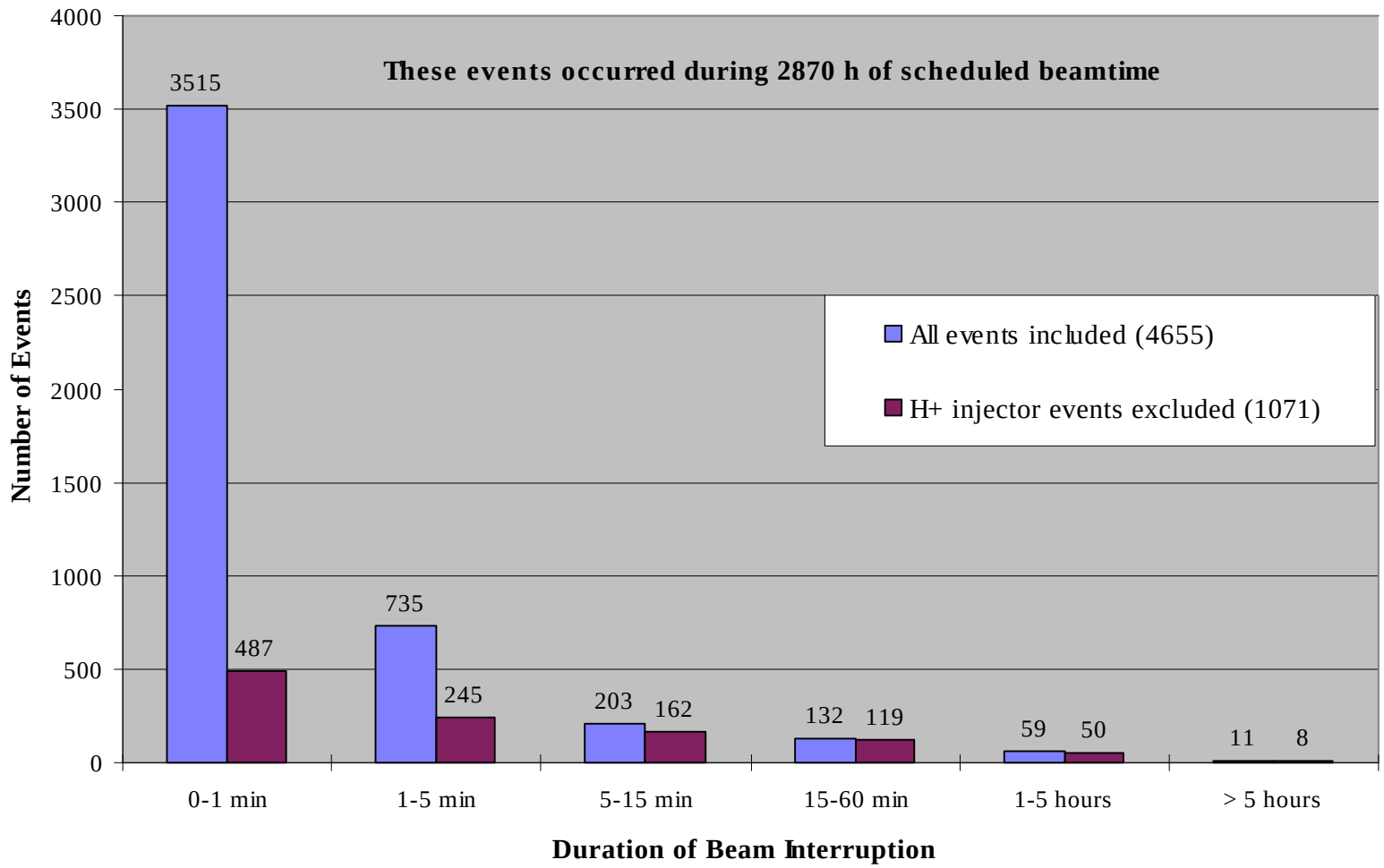
(H+ current during 24 h of full production)



SCIENCE AND ART
THE ROYAL INSTITUTE OF TECHNOLOGY

BEAM INTERRUPTION EVENTS OF H+ BEAMLINE AT LANSCE

(Period 18 Mar - 27 Jul 1997)



SCIENCE AND ART
THE ROYAL INSTITUTE OF TECHNOLOGY

Spallation Target (extensively reviewed at MIT):

Successful, so far, collaboration between LANL/IPPE-RIT-CEA in the frame of ISTC (#559).

One of the crucial projects in this technology today. Can give important answers:

- **Is liquid Pb/Bi spallation target feasible for ATW and/or other neutron research?**
- **Is liquid Pb/Bi (and finally liquid Pb) technology licenseable in nuclear facilities (critical or subcritical)?**
- **Is oxygen control method affected by spallation products?**
- **Is radioactivity control (Po) and monitoring system for liquid spallation target licenseable?**
- **Are there important spin off effects for other applications?**

Serious concerns:

There is no doubtless commitment of LANL that irradiation experiment will take place as planned. It affects the progress of this project!

Serious preparations for this experiment should already begin in order to gain as much data as possible from the irradiation (funding??)

Back-up target in case of target failure must be seriously prepared.

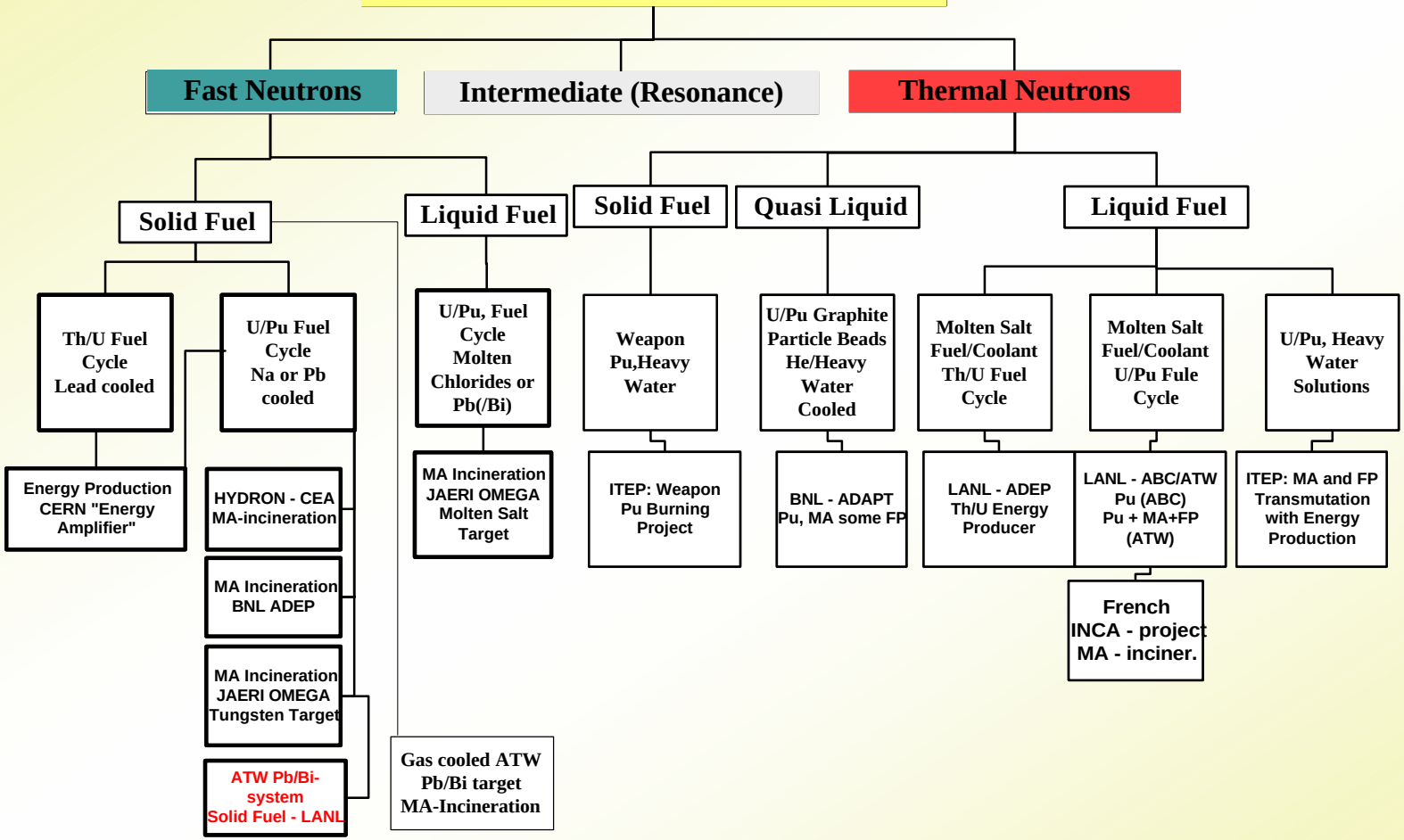
Spallation Target (cont.)

- Solid target should be prepared as a next-choice (and back-up) option
- An extensive collaboration with neutron-user community should be established (some good experiences already exist in collaboration with European Spallation Source project) to optimize R&D efforts
- Material compatibility studies for liquid Pb(/Bi) should be seriously undertaken
- Windowless target design should be developed.

Collaborators (Sweden, France, EU - ??) are ready to contribute seriously to this experiment.

Subcritical core

Accelerator-Driven Systems



Cyclotron driven

Linac driven

SCIENCE AND ART THE ROYAL INSTITUTE OF TECHNOLOGY

Remarkable convergence to the fast neutron, solid fuel and heavy metal cooled ATW system is, in my opinion, caused by:

- **technological compromises:**
  - **solid fuel is a more conservative design (solid fuel is not easily applicable in a thermal spectrum system), a lot of experiences from conventional nuclear technology can be relatively easy adopted,**
  - **molten salt system is much more dependent on (separation) chemistry; first LANL molten salt systems had extremely high thermal neutron fluxes (to ensure Np and Am transmutation) requiring Pa and FP on-line separation and continuous injection of the fuel. JAERI "integral" molten chloride system had material compatibility problems and serious reactivity swings (moreover spallation process directly on molten salt fuel is much less effective neutron source than a heavy metal target)**
- **compatibility with existing fuel cycle policy in "pro-nuclear countries" (France, Japan and also Russia)**
- **in a lesser extent by physical reasons (cross section) or estimated parameters of the systems**

However:

- Molten salt systems have appealing features, like very deep burn-up and consequently high incineration efficiency, potentially low inventories, design flexibility, compatibility with separation chemistry etc. These systems should be studied as back-up options and possibly as a final stage of the advanced fuel cycle.
- Requires: revisiting of Molten Salt Reactor experiments, some basic chemistry research (solubility of Pu and MA fluorides) - could be a good topic for international collaboration (growing interest in pyrochemistry)

Nuclear data needs for ADS

(a very good example of well coordinated international collaboration)

- First priority elements: Pb, Bi, minor actinides, constructional materials (radiation damage)
- First priority data: neutron/proton cross sections (improved data below 20 MeV, mostly new data above 20 MeV (first - 150 MeV, then - 300 MeV - pion production treshold)
  - activation, fission, and transmutation cross sections for daughter products
  - decay half-lives and branching ratios
  - absorption cross-sections
- Much data is from an earlier period and is sometimes suspected, will not satisfy regulatory scrutiny
- Data required will depend upon the chosen design
- Importance of proton-induced reactions (target, constructional materials)

- There are large similarities between fast (or other) reactors and ADS concept, there are also some important differences.
  - chain reactions begin not with fission neutron, but with a spallation neutron. The transport of the neutrons from localised source to the rest of the subcritical core must be well understood and modeled accurately. Fundamental modes which drive critical reactors practically are not achievable in ADS - transient modes determine the behaviour of ADS.
- Formation and decay of metastable isomers
- Physics of high energy fission (fission product yields and spallation product yields vs neutron/proton energy), improved spallation models
- Physics of radiation damages, code development (nuclear physics - material physics)
- Development of Monte-Carlo burnup codes to integrate calculations

The opportunities for ATW collaboration

ATW may have strong interactions with other technologies and possible spin off:

- Process Chemistry: partitioning, separation and segregation
- Nuclear Fuel Technology
- Material Sciences - material compatibility, corrosion, radiation stability
- Mechanical engineering: thermal hydraulics etc

In more fundamental physics

- Intense neutron sources
- Accelerator technology
- Spallation and nuclear reaction physics
- Advanced nuclear systems

European Community is getting momentum in ADS research:

- In IV Framework Programme:
  - 2 projects on Accelerator Driven Systems:
    - TARC coordinated by C. Rubbia
    - IABAT coordinated by W. Gudowski
  - and some aspects of ADS in other projects on advanced nuclear systems
- On the eve of V Framework Programme starting 1999 remarkable activities in preparation of ADS-related proposals: more then 200 scientists working on project proposals, projected (expected) EC-financing of the order of 30 - 40 MECU in shared cost projects (i.e. 60 - 80 MECU in real life)

- Emerging multilateral projects in EU: French-Italian-Spanish collaboration
- Growing national activities in some countries: France, Sweden, Belgium, Italy, Germany

The role of ISTC

- ISTC can play and already plays an important role in creating an ATW collaboration platform with Russian institutes in full compliance with ISTC-objectives :
  - #17 (“Feasibility of Accelerator Based Conversion for weapon Pu-incineration”) identified a number of research groups and organized an effective network of collaboration inside Russia and with foreign partners
  - #559 - manufacturing of liquid Pb/Bi spallation target. Can lead to customization and commercialization of Pb/Bi technology. (A difficult way full of ice-bergs!!)
  - a number of important nuclear data projects accomplished, under way or waiting for approval

The role of ISTC - cont.

- ISTC Contact Expert Group on ADS-related project (formed last year) plays already an important role in coordination and stimulation of the ISTC ADS projects:
  - Strong US and European involvement with Steve Gitomer (LANL) and D. Gambier (EC) as an effective bridge to ISTC-board
  - Balancing financing efforts between major research areas important for ADS (see a draft of White Paper)
  - May become a seed of an effective international harmonization and co-ordination of the projects. However a lot of difficulties to overcome, like : propriety rights, effective communication between “competing” groups and institutes etc.

IAEA and NEA/OECD

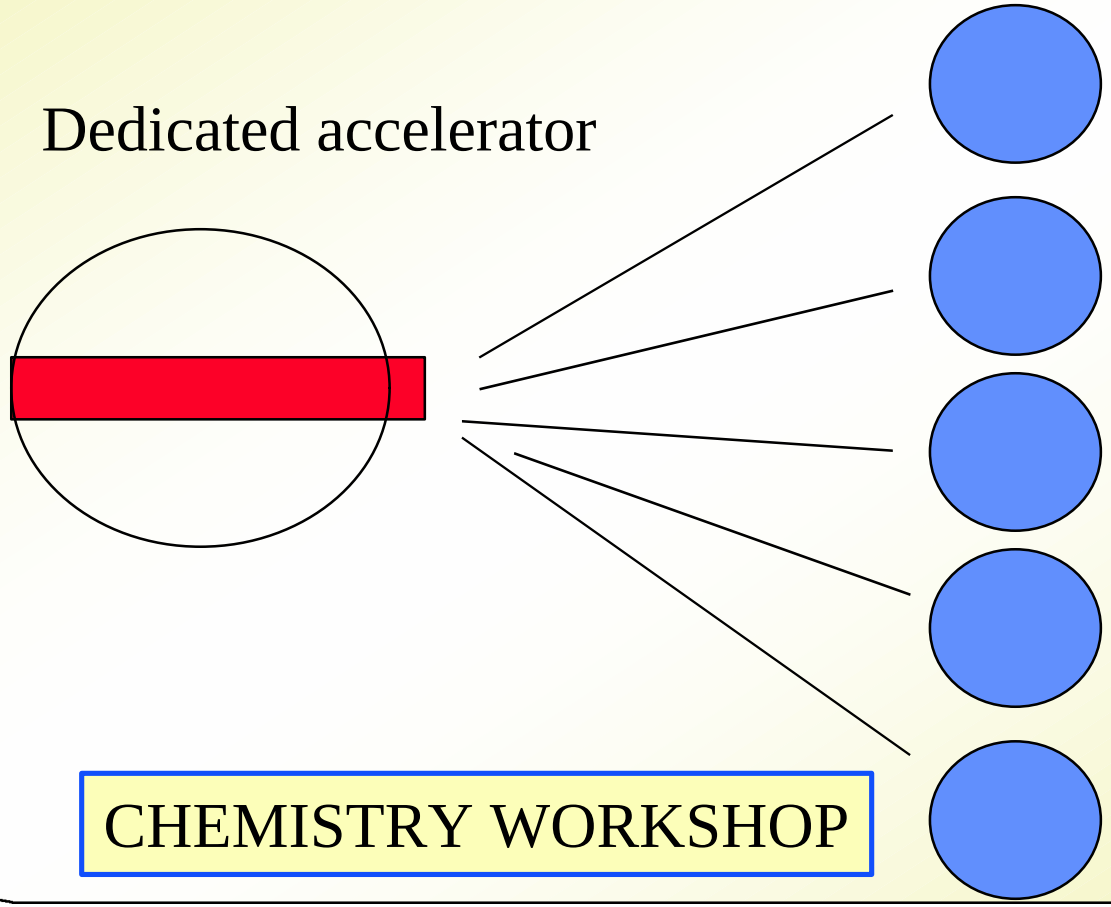
IAEA showed from the very beginning a strong interest in ADS (e.g. see ADS Status Report, CRP - Coordinated Research Programme on Th-fuelled ADS benchmark, data-base on ADS relevant research facilities and tools in Russia).

Some competition and overlapping activities between IAEA and NEA/OECD but it may be easily avoided:

- Proliferation issues related to ATW and powerful accelerators in general should be an important activity for IAEA
- Benchmarking activities make no harm if duplicated
- If MEGASCIENCE FORUM puts transmutation on its agenda NEA/OECD is a natural forum for coordination of MEGASCIENCE scale projects.

Conclusion 1. Picture from my summary of The Second ADTT Conference in Kalmar, 1996

Vision of the ATW experiment



CHEMISTRY WORKSHOP

SCIENCE AND ART
THE ROYAL INSTITUTE OF TECHNOLOGY

Conclusions - 2

- Accelerator-driven transmutation of nuclear waste has emerged in last few years to be potentially a complementary technology for radioactive waste handling by transmuting the longest-lived isotopes into short-lived or stable ones. Transmutation of nuclear wastes, if successful, can change public opinion concerning nuclear energy. Therefore the key experiments important for development of this technology should be performed in international collaboration using extensively existing facilities and carefully planning dedicated new experimental facilities. The construction of the needed demonstration facility with its accelerator is of a such scale that it would strongly benefit from international collaboration.
- This technology has a significant synergy with more fundamental research like spallation neutron sources, high intensity accelerators and even advanced nuclear systems.

Conclusions - 3

- Nuclear technology field is highly regulated and intensively scrutinized by many authorities and agencies in every country. Moreover, there are very different nuclear power and fuel cycle policies. International collaboration should be based on respect for “national constraints” of collaborating parties and on strong respect for non-proliferation principles.

Probably, some conflicts are unavoidable - it should not discourage, neither frustrate too much any of the collaborating partners.