Overview of specifications and issues of ADS-drivers

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caveat emptor

- this short presentation **is not** a well-structured introduction to the session
- it **neither is** a **review** of the field, requiring much more time, and the **focus is for high-power developing systems**, thus the drivers for the **coupling experiments, of utmost scientific importance,** will **not** be treated here
- because of these **time constraints** it is **incomplete** and furthermore some transparencies will just be **flashed** on
- it **however is a personally biased** selection of facts, perception of some decisive events, and what **main ingredients of reactor physics** are determining for Accelerators for ADS
- partly destined to convey also some observations/messages
- but first I want to thank the organizers, Giulia, CERN, and EUCARD2 for the invitation

(some) Prehistory

1941:
Glenn Seaborg produces Plutonium by means of an accelerator

1950 – 1954:
Material Testing Accelerator (MTA) research program at Livermore,
Use of McGill cyclotron in Canada for spallation neutron yields

Late 80's:
A research group at BNL (H. Takahashi & G. van Tuyle) develops a Concept for an ADS in today's meaning (focused on Safety and/or Waste Transmutation)

1991:
Detailed design of the ATW at Los Alamos by group of C. Bowman

Some Historical Highlights since the past 25 years

1993 :
CERN group of Carlo Rubbia presents the "Energy Amplifier"
(U-Th cycle driven by high intensity accelerator) and performs the supporting experiments FEAT (1994) and TARC (1997-1998) at the CERN PS accelerator

During the decennia of the 1990's:
Launching of

- **J-PARC in Japan**
- **SNS Project in US**
- **French Law on Research for Nuclear Waste Transmutation (CEA + <u>CNRS + Academia!)</u>**
- **European Collaborative Research substantially funded by EURATOM**
- **Decision of OECD-NEA Working Party on the fuel cycle for HPPA conferences Since 1998**

08:00 - 08:30	**REGISTRATION**	
	OPENING SESSION	Chairpersons: C. NORDBORG
08:30 - 08:45	- Welcome	A. TOURNYOL DU CLOS
08:45 - 09:00	- Meeting format, scope and objectives	M. SALVATORES
09:00 - 09:30	- Key note : "Utilisation and future development of high power accelerators	C. DETRAZ
	SESSION 1 (Invited papers) : Recent developments and Ongoing Accelerator programs. Experience of relevance for ADS	Chairpersons: A. MUELLER, Y. CHO
09:30 - 10:00	- Joint project of JAERI and KEK for high power proton accelerator	T. MUKAIYAMA
10:00 - 10:30	- Reliability Considerations in Design of High Power Linacs	G. LAWRENCE
10:30 - 11:00	***Break***	
11:00 - 11:30	- Scientific issues and status of Franco-Italian collaboration in ADS	C. PAGANI
11:30 - 12:00	- Status of the proposal for a Superconducting Proton Linac at CERN	R. GAROBY
12:00 - 12:45	- Design and Status of the SNS project, and - Availability consideration of the Spallation Neutron Source	Y. CHO

Extract from the program of HPPA-2 Aix-en-Provence 1999

Key issues:
Debate on the design of SNS NC or SC.
Strong opinion voiced by J.L. Laclare (SNS-MAC): SC!

Laclare, builder of ESRF, also showed how to implement reliability, and, note ESRF has today ADS-class reliability

At the same time:
(E)TWG report on ADS demanded by European Science Ministers, chaired by Carlo Rubbia (ENEA)

Triggering European ADS collaboration PDS-XADS, (leader Bernard Carluec Framatome) 2002-2006

and launch of word-wide collaboration for MEGAPIE Spallation Target
Europe - Japan - Korea - US

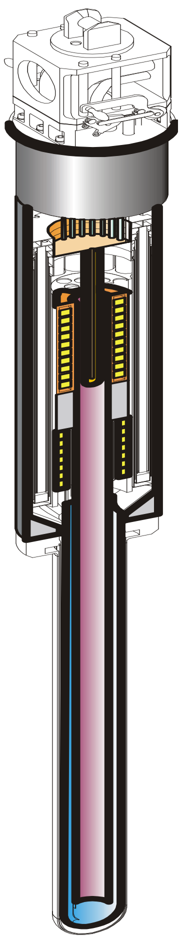
Progress discussed and reported in HPPA-3, Santa-Fe (NM) with important findings for the suited accelerator technology:
Only SC-LINAC suited for full-scale ADS
and (existing) cyclotrons for preliminary experiments

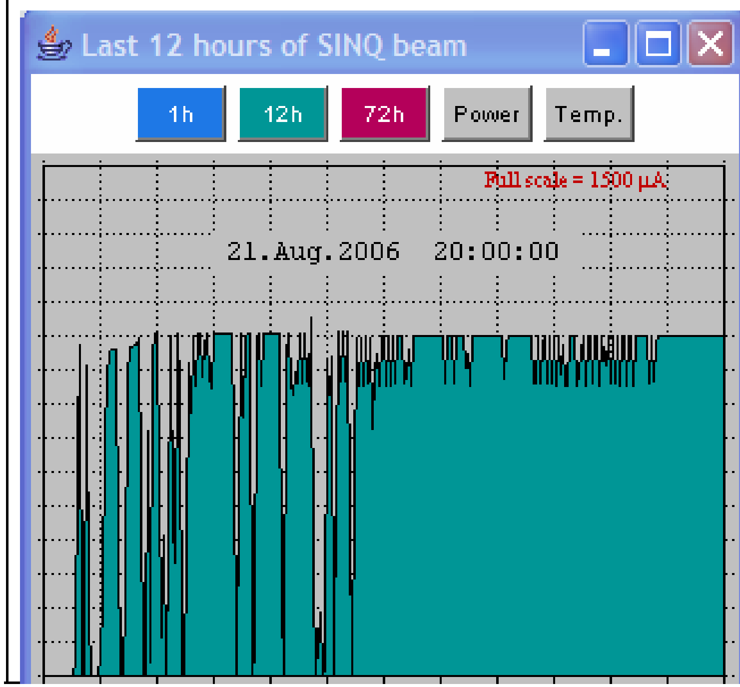
Some memories from TWG (final session approving the report to the ministries)
And and also a tribute to nuclear data community for a "grande première" (first nTOF data from CERN)

Period 2005 -2010:

- Construction of SNS and J-PARC facilities
- China enters with strong accelerator programme
- European EUROTRANS research programme
- Success of the MEGAPIE experiment
- ESS is going from fiction to reality
- MYRRHA on the "ESFRI-list"

2006: Succes of the Megapie experiment at PSI





Start of Normal User operation.

Normal user operation was started on August 21st around 8:30 and is planned to continue until the normal annual winter shut-down starting on December 23rd 2006.

The first 12 hours of proton beam is seen to the left.

590 MeV cyclotron
1.3 MW beam power

The EUROTRANS programme

- EURopean research programme for the TRANSmutation of high level nuclear waste in an Accelerator Driven System
- EU FP6 programme (2005-2010)
- 31 research agencies & industries, 16 universities
- Expands the EU FP5 project PDS-XADS (2001-2004)
- 5 Domains (Design, Coupling Experimnts
- Fuels, Materials and Nuclear Data)

<u>Main GOAL of the EUROTRANS programme</u>

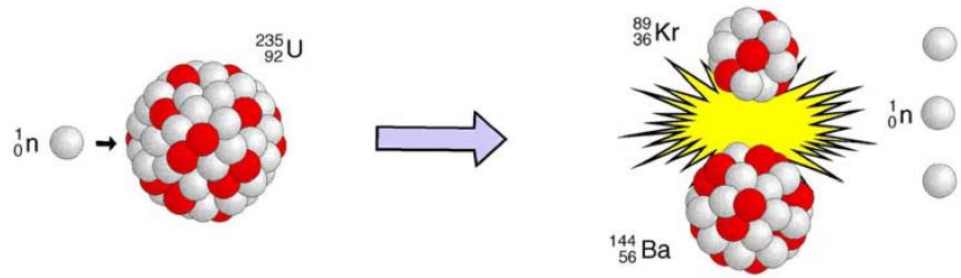
- Advanced design of a 50-100 MWth eXperimental facility demonstrating the technical feasibility of Transmutation on an ADS (XT-ADS, short-term realisation)
- Generic conceptual design (several 100 MWth) of a European Facility for Industrial Transmutation (EFIT, long-term realisation)

Period 2010 - today:

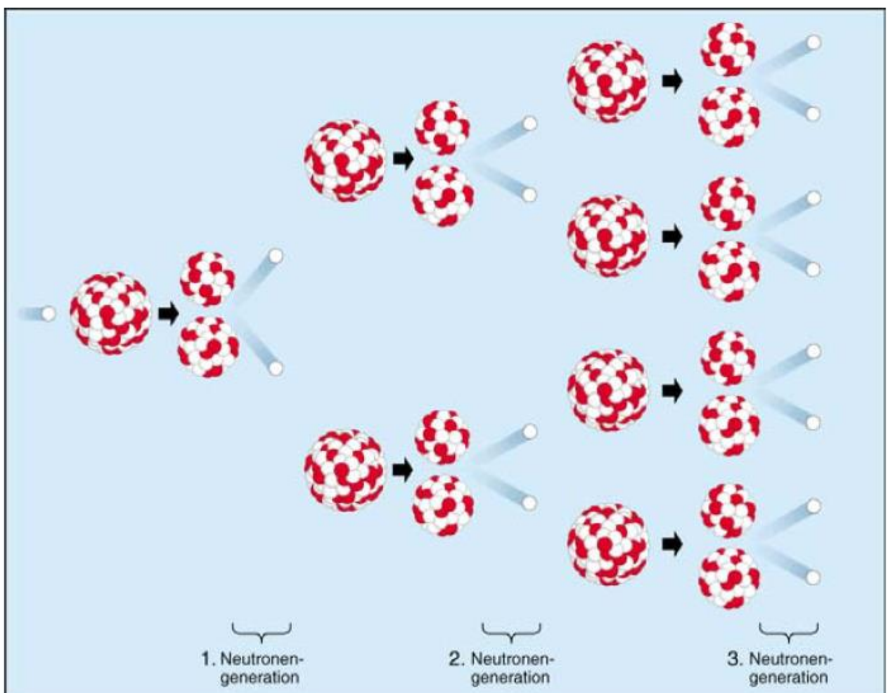
- Operational Experience from running facilities SNS and J-PARC
- Construction of ESS SC-linac
- EURATOM funding for MYRRHA R&D and GUINEVERE at SCK Mol
- Construction of first stage of MYRRHA
- Construction in China of ADS-linacs at 2 sites
- PIE of MEGAPIE
- Ukraine program
- International Thorium Energy Committee
- Construction of Linac components is INDIA focused on Thorium ADS

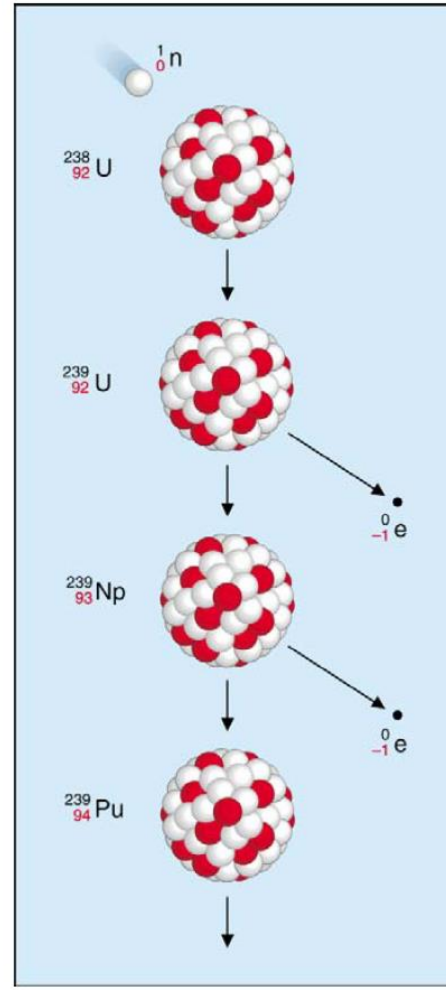
Pictorial View of Nuclear Reactions

Fission of U235 (below) liberating new neutrons that in turn fission other U235 nuclei giving rise to a chain reaction



$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{89}_{36}Kr + ^{144}_{56}Ba + 3\,^{1}_{0}n + 210\ \text{MeV}$$





Neutron capture of U238, followed by beta-decay of U239 and continuation of this process leading to Pu239 (and beyond)

(Figures from the Karlsruhe Lexikon zur Kernenergie)

Fundamental Difference between Critical Reactor and ADS

A critical reactor is piloted by (neutron absorbing) rods, which, **inserted**, keep the criticality below k <1. See below the gradual start-up (note time!). The divergent phase stabilizes at k=1 because of thermal expansion decreasing reactivity. The delayed neutron fraction (from radioactive) decay ensures that the prompt criticality stays below 1.

Energy by Strong Interaction
Controlability by Weak Interaction

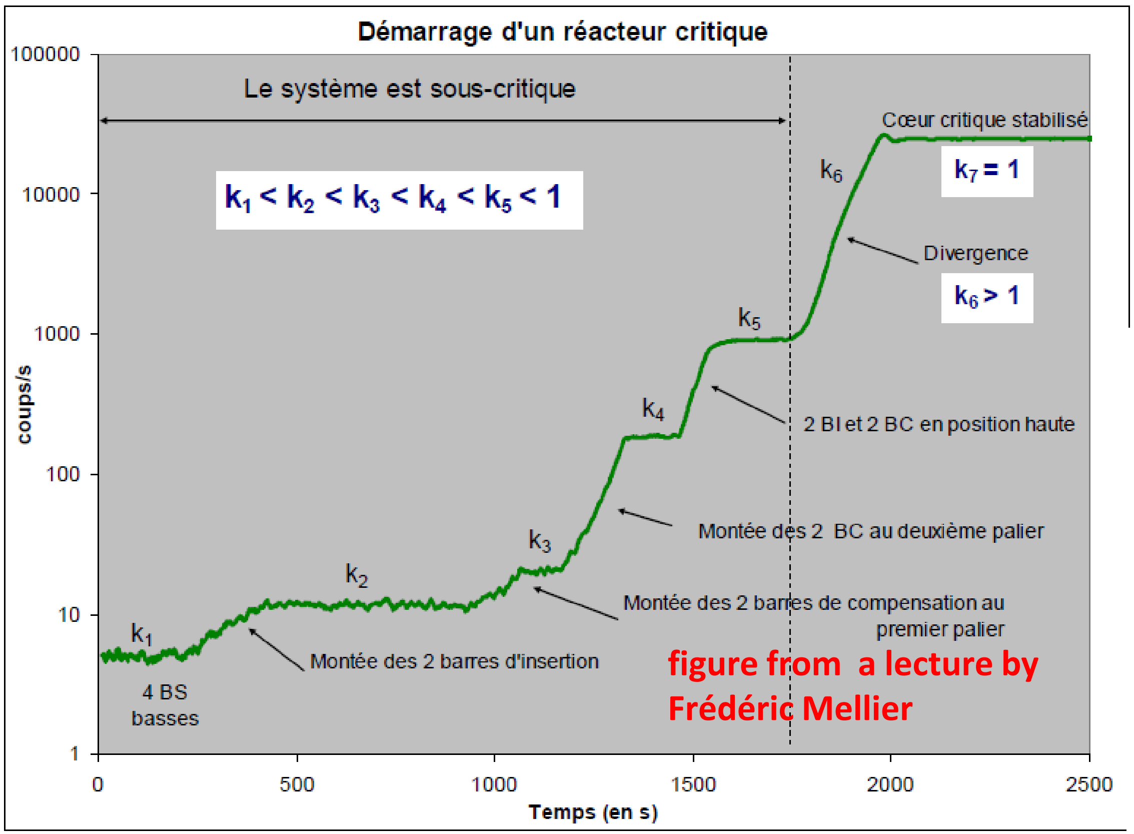
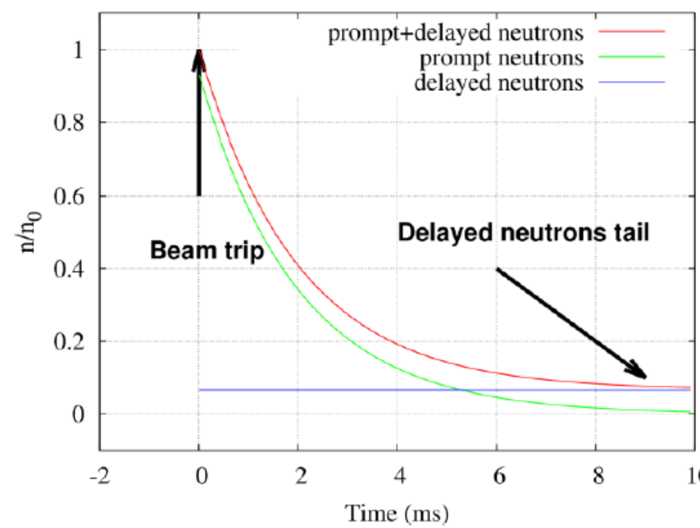


figure from a lecture by Frédéric Mellier

An ADS is (and has to stay!) sub-critical at all times. The thermal output P is determined by the driving source S.

$$P \sim \frac{S}{1 - k_{eff}}$$

effective criticaltity k_{eff}, Typically **0,92 – 0,98**

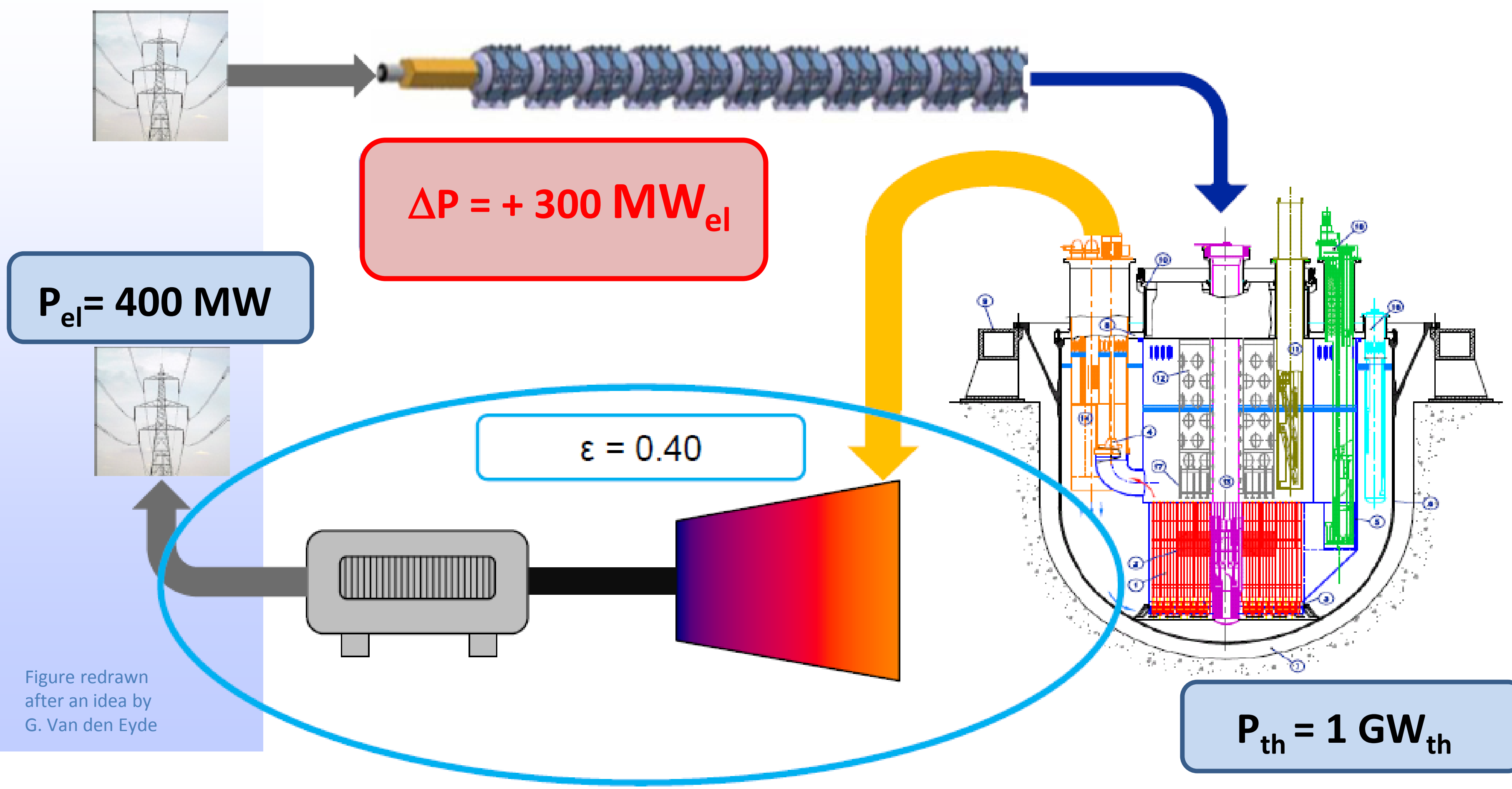


Characteristic Numbers for a Power ADS

$$P \sim \frac{S}{1 - k_{eff}}$$

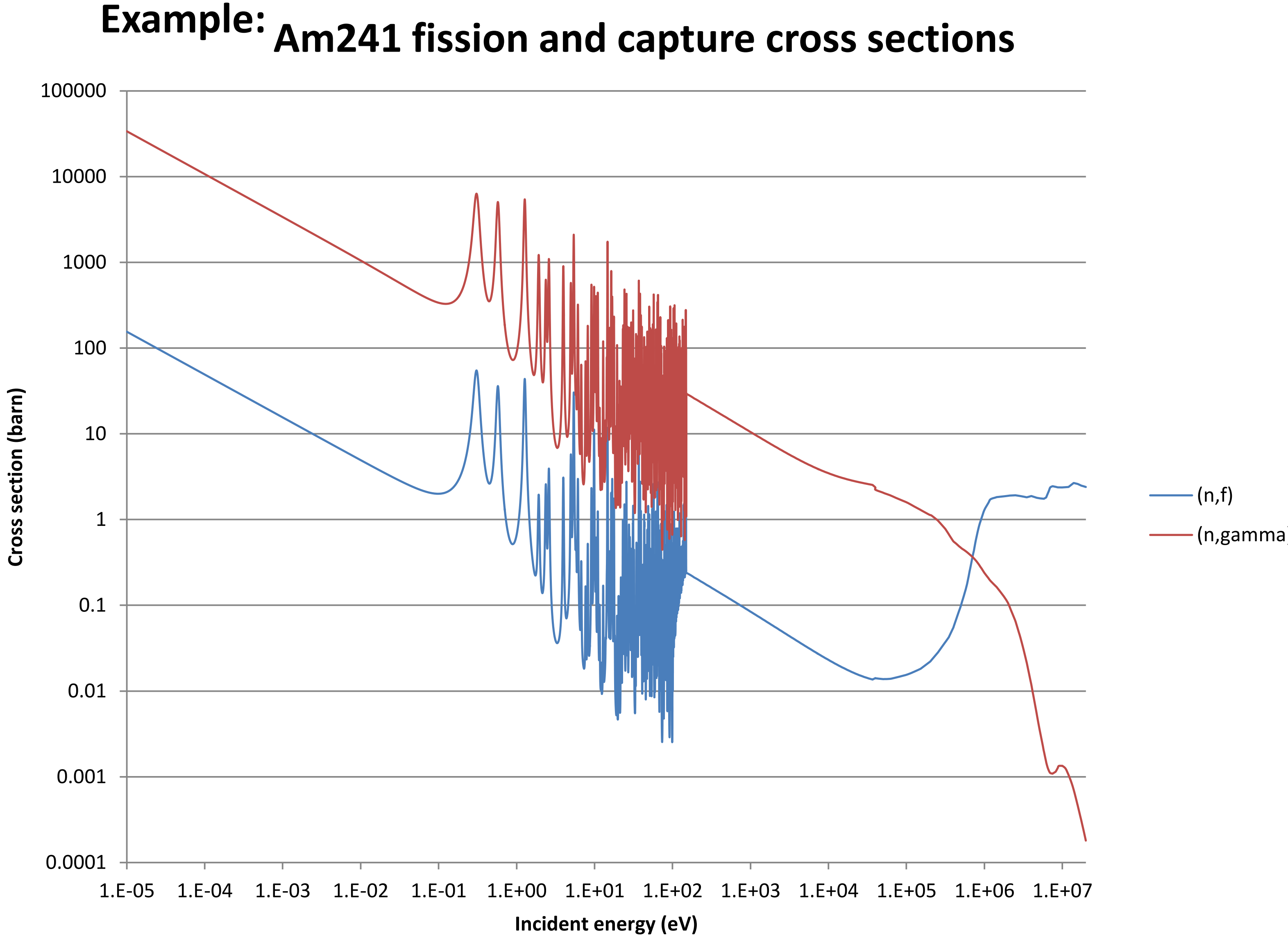
k_{eff} = 0.93 - 0.97

$P_{acc\ el}$ = 100 MW ⟺ ε_{Acc} = 0.3 ⟺ $P_{acc\ beam}$ = 1 GeV x 30mA = 30 MW

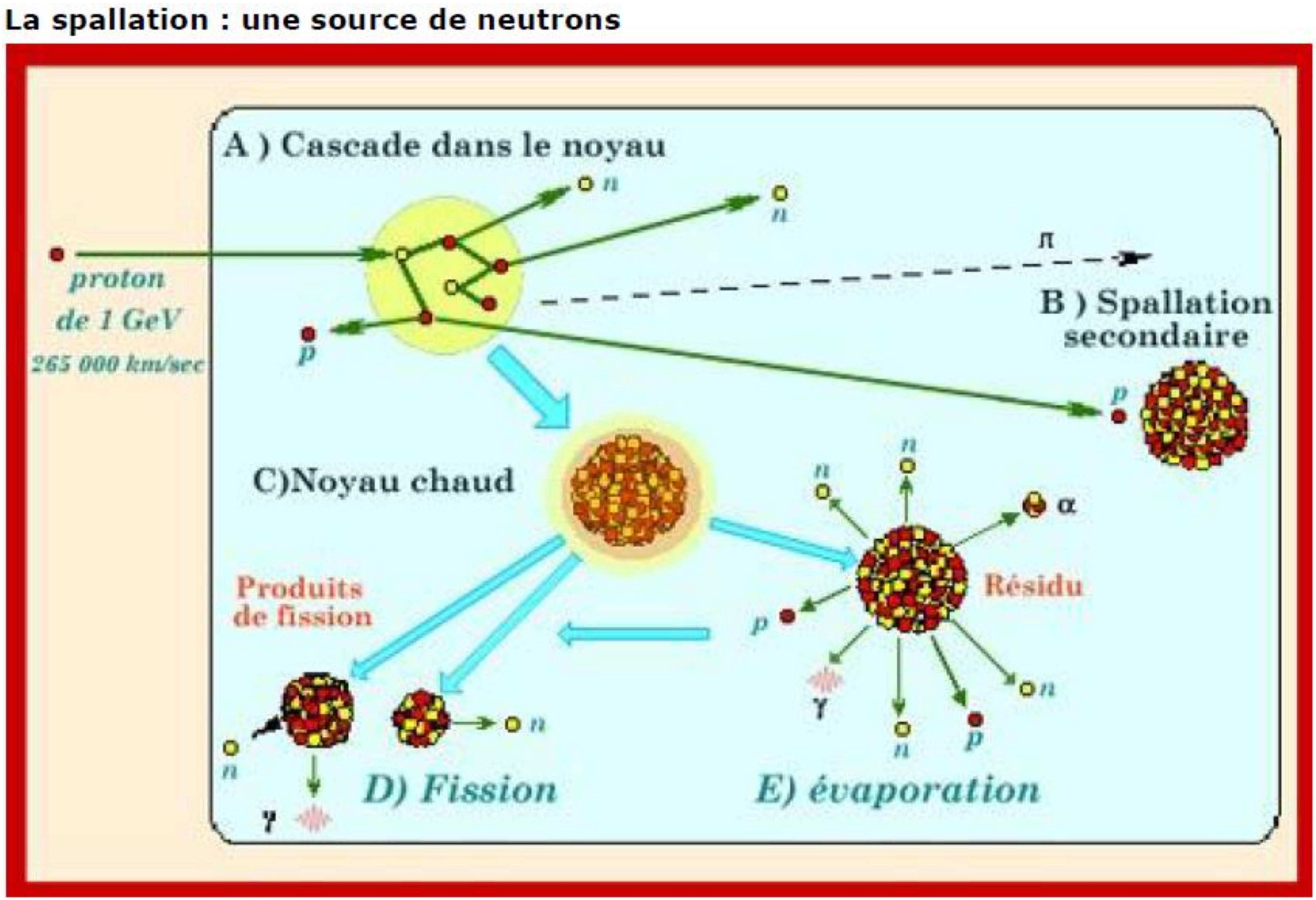


Fast Neutrons are needed to incinerate actinide waste (or breed U233 from Thorium)

Example:

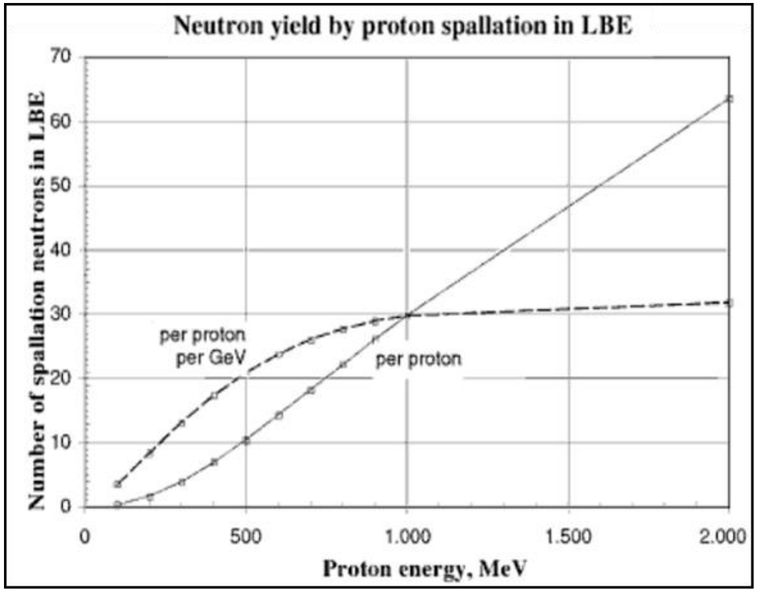


Pictorial: the nuclear reactions underlying Spallation



taken from the site "laradioactivite.com" (IN2P3 & EDP Sciences)

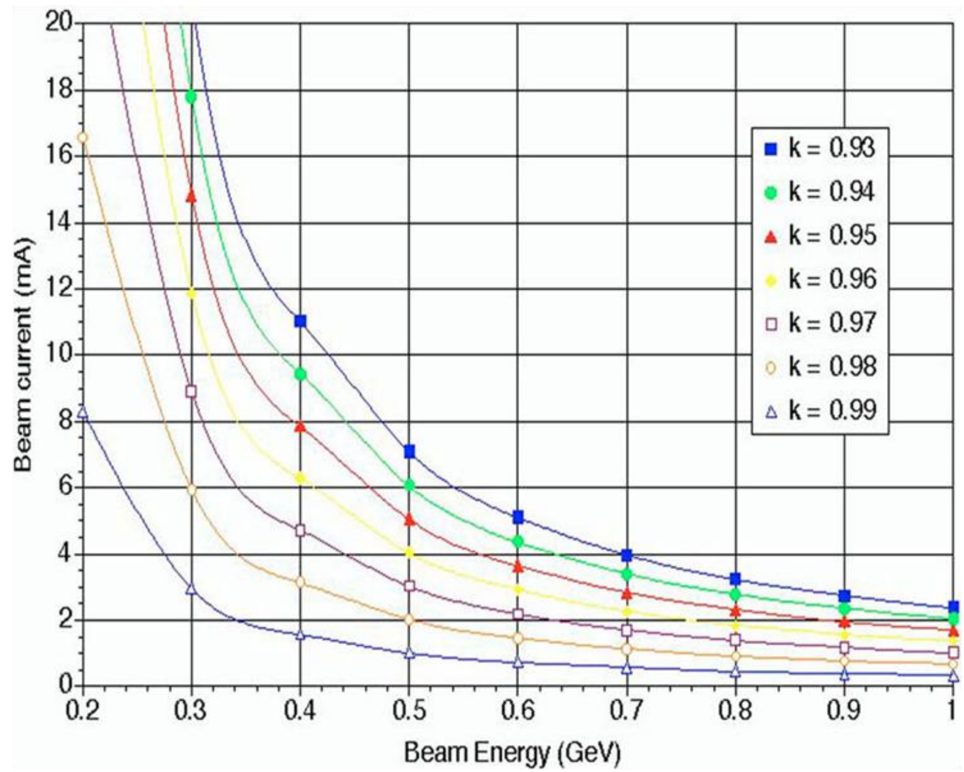
Spallation physics and technology defining accelerator parameters



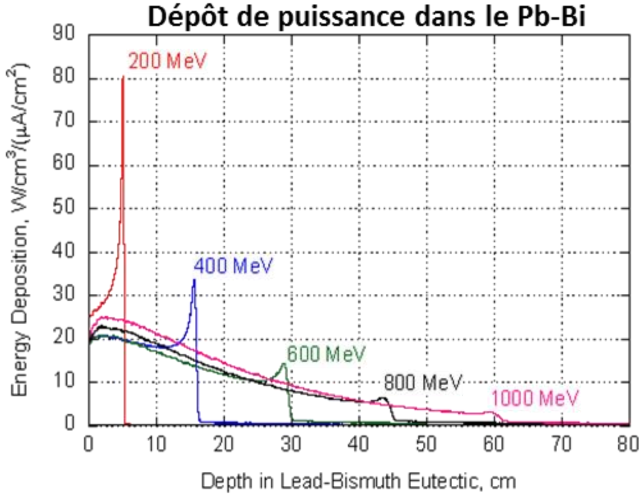
Abaques Courant/Energie/Sous-Criticité

pour un démonstrateur de 80 MW_{therm}

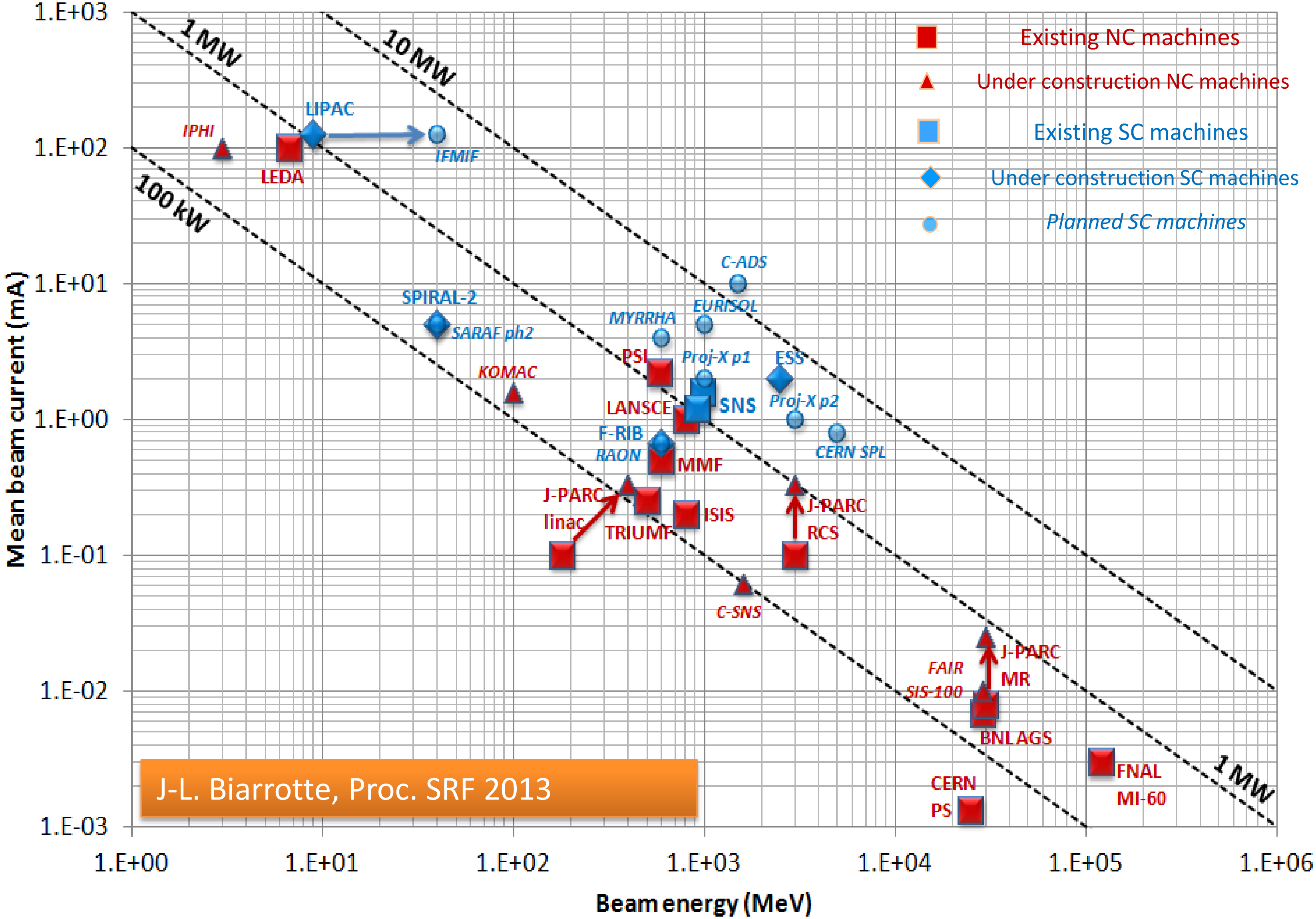
(simulation par ANSALDO)



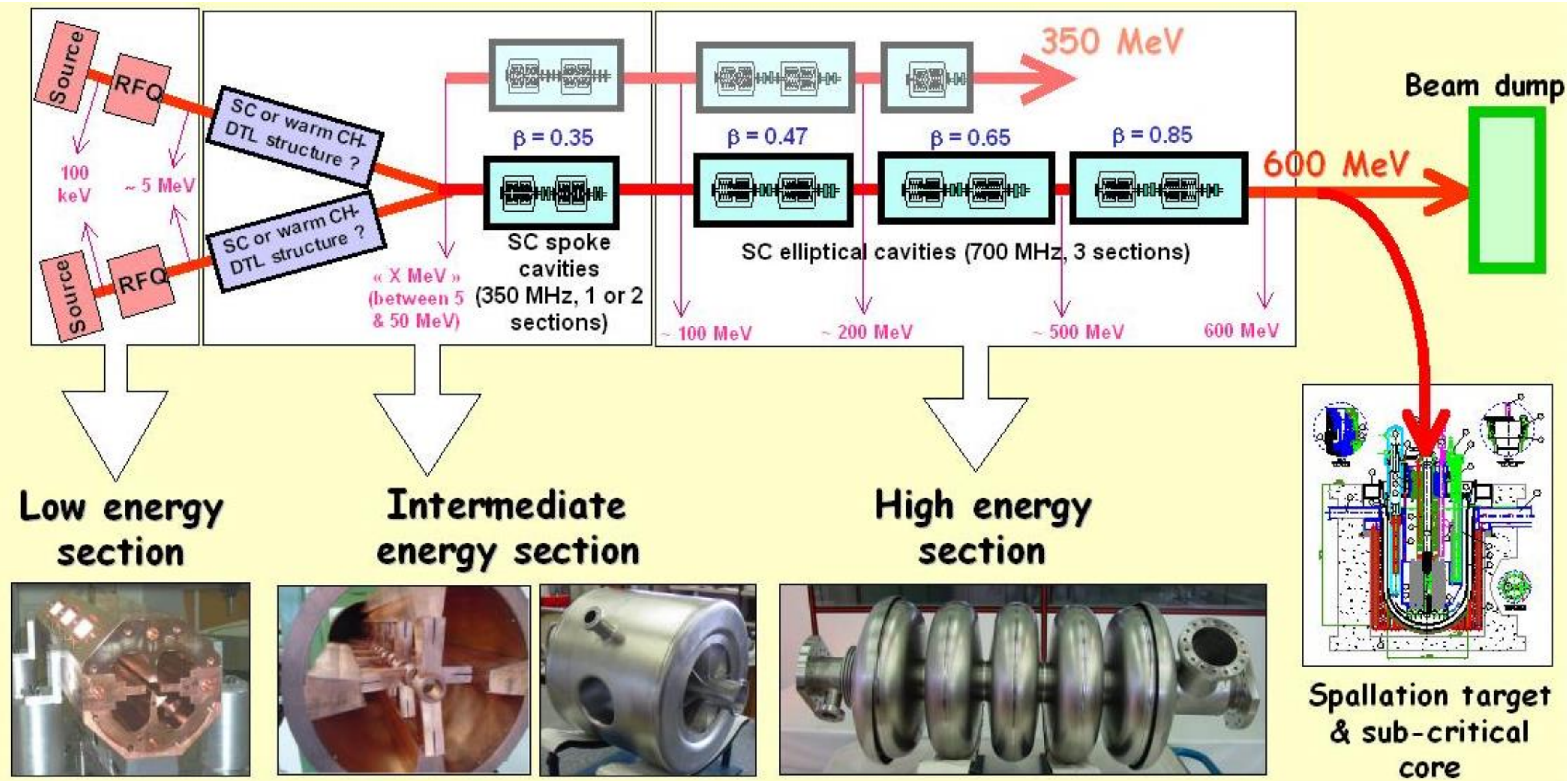
Dépôt de puissance dans le Pb-Bi



High Power Accelerator Projects in the World

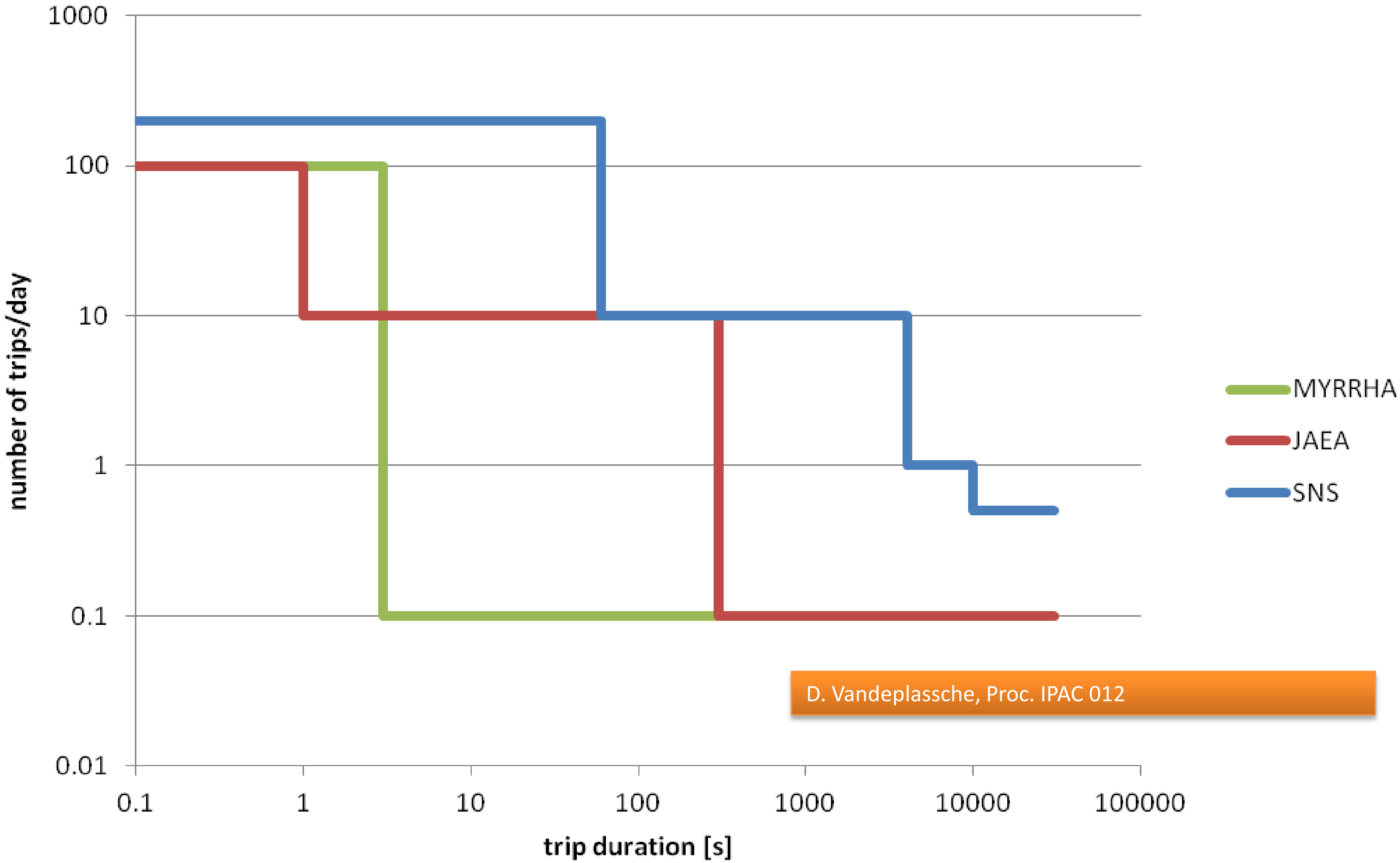


PDS-XADS Reference Accelerator Layout



Strong R&D & construction programs for LINACs underway worldwide for many applications
(Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)

Reliability
as required by reactor physics, technology and safety



D. Vandeplassche, Proc. IPAC 012

The 3 principles for reliability improvement

- **Overdesign**
  - basically only possible for linacs not running against or exceeding
    - the limits of energy (relativistic effects)
    - The limits of intensity (weak focusing)

- **Redundancy**
  - basically only possible for linacs
    - because of their modularity
    - at the expense of efficiency (components used once)

- **Fault tolerance**
  - basically only possible for linacs
    - requires modularity
    - a very innovative concept

Fault Tolerance, a new concept uniquely applicable in a modular SC-Linac

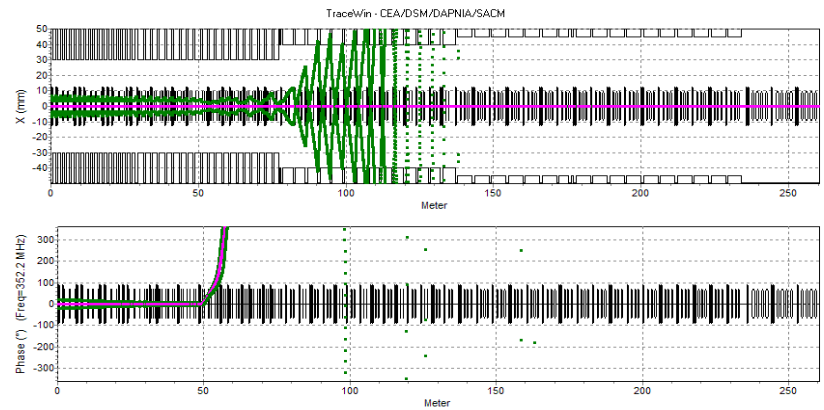
- first proposed in PDS-XADS study in 2002 by Biarrotte, Mueller et al.
- experimental verification by Galambos et al with SNS in 2007

Fault tolerance in the independently phased SC sections is a crucial point because a few tens of RF systems failures are foreseen per year.

1. Consequences of the failure of a superconducting RF cavity

→An RF system failure induces phase slip (non relativistic beam)

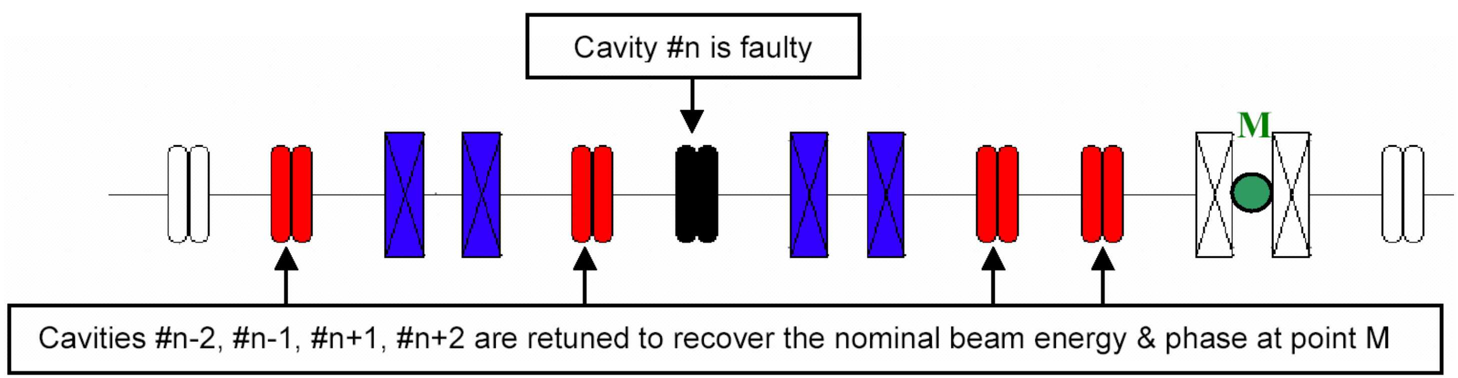
→ If nothing is done, the beam is always LOST



2. Linac retuning after the failure of a RF cavity or of a quadrupole

→ Local compensation philosophy is used

→ In every case, the beam can be transported up to the high energy end without beam loss



Exotic hybride concepts?

- In contrast to cyclotrons, FFAG exhibit
  - strong focusing and they overcome the relativistic limitations **+**
- In contrast to cyclotrons, FFAG
  - are pulsed machines, with intrinsically (much) lower intensity **--**
- In contrast to cyclotrons and linac's, FFAG are
  - very complicated to build
  - No "real machine" existing since the 60 years after invention **--**
- In contrast to linacs, FFAG exhibit
  - no potential for implementing the 3 basic principles of reliability improvement **---**

- To my assessment,
  - FFAG are therefore unsuited for ADS

Accelerator choice assessment: NEA was and still is right!

- **Main technical answers**
  - Superconducting linac
    - No limitation in energy & in intensity
    - Highly modular and upgradeable (industrial transmuter)
    - Excellent potential for reliability (fault-tolerance)
    - High efficiency (optimized operation cost)
  - Cyclotron
    - Attractive (construction) cost (?)
    - Required parameters well above limits of feasibility ("dream machine"=10 mA)
    - Compact, but therefore not modular

- **In complete agreement with findings of the NEA report:**
  - **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice **for preliminary low power experiments**, where availability and reliability requirements are less stringent.
  - **CW linear accelerators must be chosen for demonstrators and full scale plants**, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.

Concluding Remarks

- **From early conceptional considerations and studies the field has grown to maturity with large-scale experiments, dedicated R&D, and major realisations**
- **The choice of the accelerator type directly depends from nuclear physics and technology**
- **I am eager to see the progress that will be reported at the present meeting**
- **Good luck for all for the future of the field that truly lends to international collaboration and as European I of course look forward to MYRRHA**
- **Warm thanks again to Giulia, CERN and EUCARD2**