international Thorium Energy Committee

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17, rue François-Dussaud CH 1227 Acacias-Genève

A Proposal for a First ADS Demonstrator

October 14, 2015
ThEC15 Parallel
Mumbai, India

Jean-Pierre Revol
Centro Fermi, Rome, Italy
iThEC, Geneva, Switzerland

International Thorium Energy Committee (iThEC)

- The goal of iThEC is to **"Promote innovation, more specifically, in the development of thorium nuclear technologies"**
  - **September 2012**: Creation of iThEC in Geneva Switzerland
  - **October 2013**: Organization of the ThEC13 conference at CERN, in Geneva Switzerland
  - **Spring 2015**: MoU signed with IBeL (industrial partner)
  - **October 2015**: A first concrete step towards the exploitation of thorium – **couple a proton accelerator to a subcritical core of significant power**

Why thorium ($^{232}Th_{90}$)?

- *"Thorium is a sustainable source of energy on a human time scale"* *Carlo Rubbia*

Monazite sample containing 2 to 3% of thorium mixed with rare earths (from the Steenkamp-skraal mine, South Africa – Trevor Blench)

Energy intensity

to generate 1 GWe during one year takes:

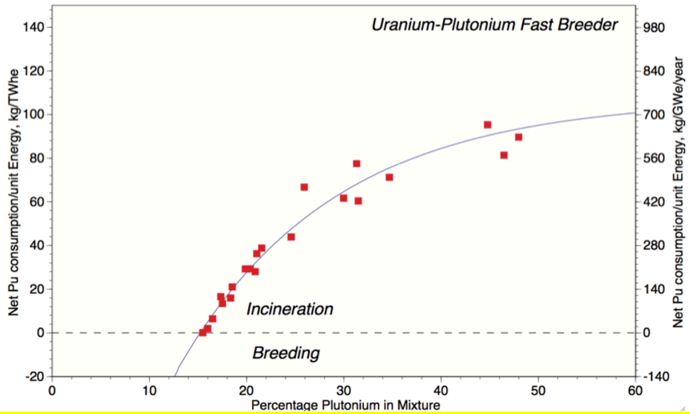
– 2.5 million tons of coal (13t of Th)

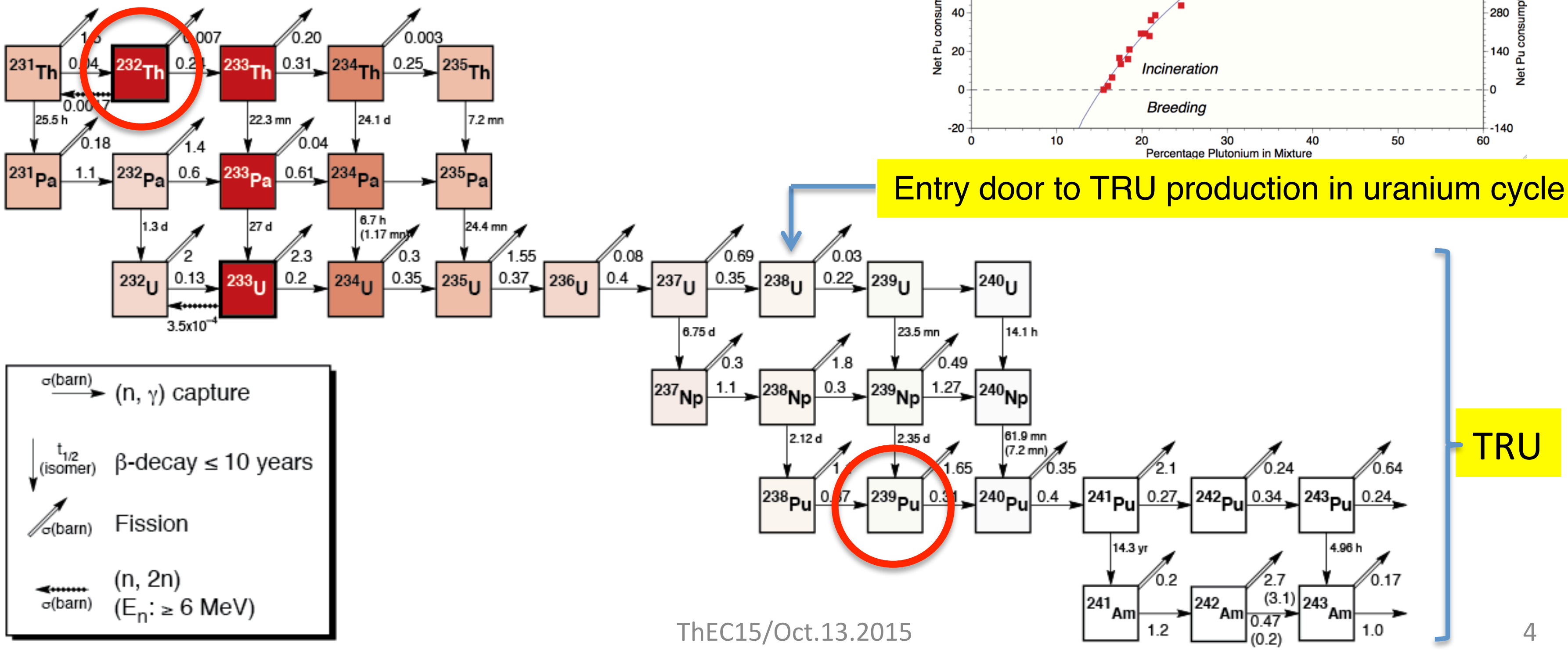
– 1 ton of thorium in an Energy Amplifier

In view of the dramatic effect of burning fossil fuels on atmospheric pollution, the much better energy intensity is **in itself a very strong incentive to try to use thorium**

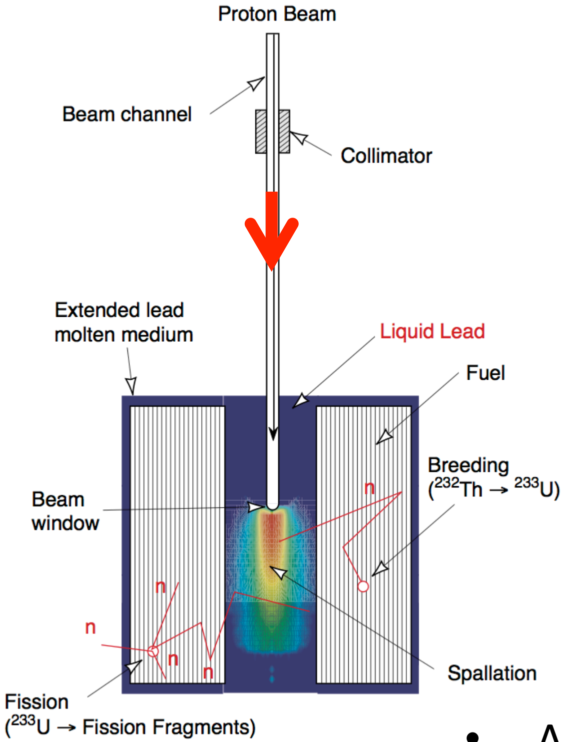
Destroying nuclear waste with $^{232}Th_{90}$

- Thorium minimizes TRU production, as it is 7 neutron captures away from ^{239}Pu
- **For the same reason, it can be used to destroy nuclear waste**
- With **efficient recycling** and **fast neutron flux**, one can make the TRU inventory as small as wanted



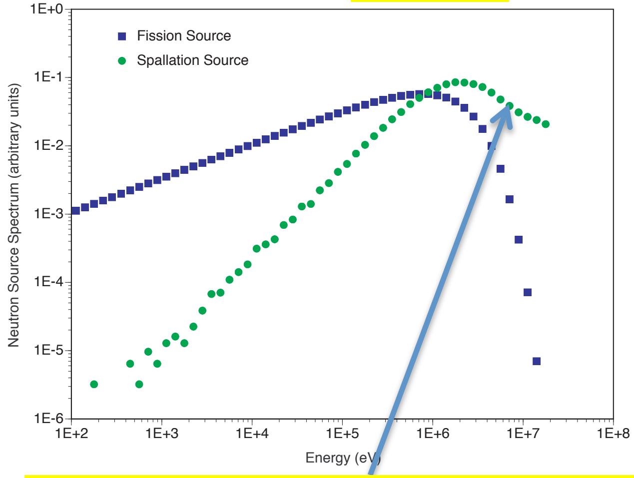


iThEC's interest is ADS



Fission

Spallation

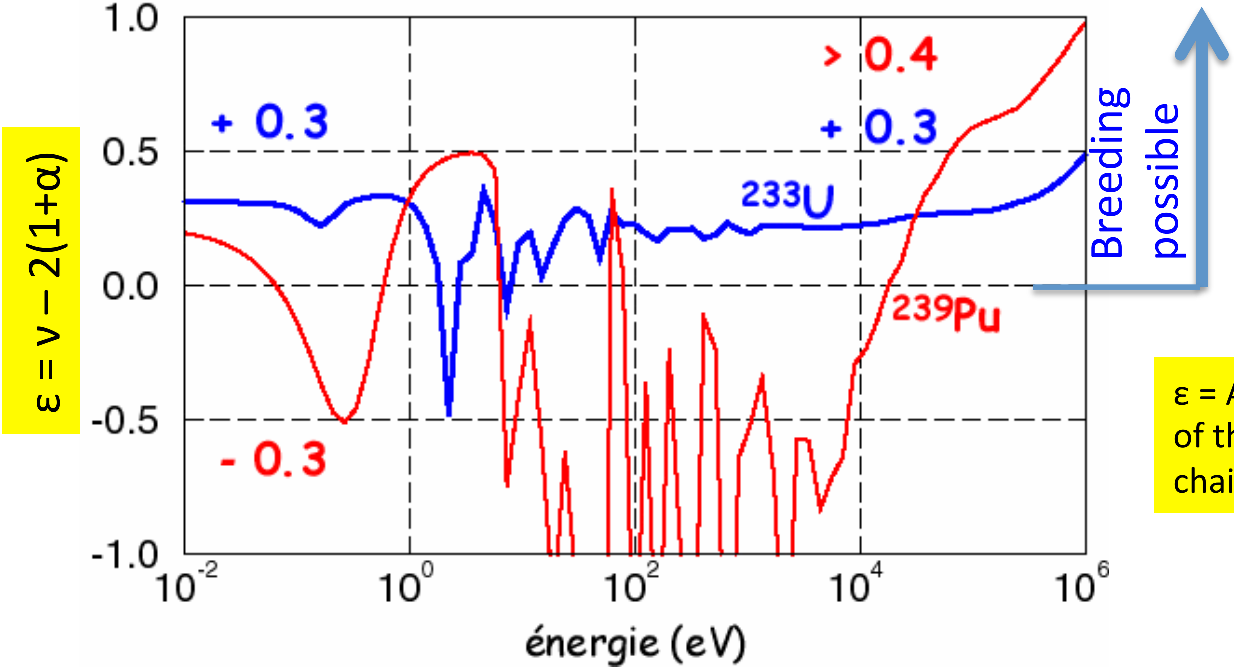


Non negligible contribution from the high energy tail (n,xn) reactions on Pb.

- A **particle accelerator** to provide a **neutron source through spallation** (Pb, Pb-Bi, U targets)
- A **core** in which both source neutrons and fission neutrons are at work – with a **moderator least moderating** to allow for a fast neutron spectrum
- **Combine with passive processes for heat removal and for safety**

ADS

- The accelerator allows to breed in the fast neutron region where breeding is not favourable compare to Pu, this in turn allows to destroy TRU



ε = Average number of neutrons in excess of the 2 neutrons needed to run the fission chain

- **An ADS can fit in various nuclear scenarios:**
  - In combination with U-Pu fast reactors as a dedicated burner of Minor Actinides
  - As a ^{233}U breeder burning TRU
- In addition, the accelerator allows to modulate the power (complementarity with fluctuating renewable energies)

Theory of subcritical systems

- **Theory of subcritical systems** well known. Properties are quite different from those of critical systems (*C. Rubbia, CERN/AT/ET/Internal Note 94-036*)
- MC simulations are needed for quantitive properties. Neutron flux geometry important to determine the generated power distribution and the uniformity of fuel burnup
- Analytical approach interesting to get insight into the physics. The basic equation similar to that of a critical reactor, but **with an external neutron source term in addition,** and obtain the qualitative properties of the system:

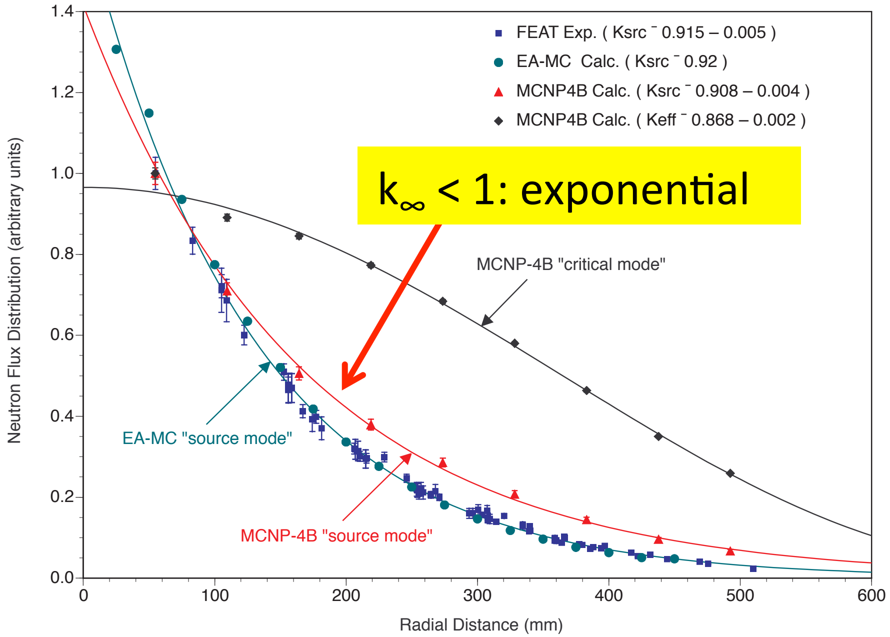
$$\frac{\partial n(\vec{r},t)}{\partial t} = \nu \Sigma_f \Phi(\vec{r},t) + C(\vec{r},t) - \Sigma_a \Phi(\vec{r},t) + D\nabla^2 \Phi(\vec{r},t)$$

Fission | **Source** | Absorption | Leakage

$$k_s \approx \frac{\nu' \Sigma_f \Phi(\vec{r},t) + C(\vec{r},t)}{\Sigma_a \Phi(\vec{r},t) - D\nabla^2 \Phi(\vec{r},t)} > k_{eff}$$

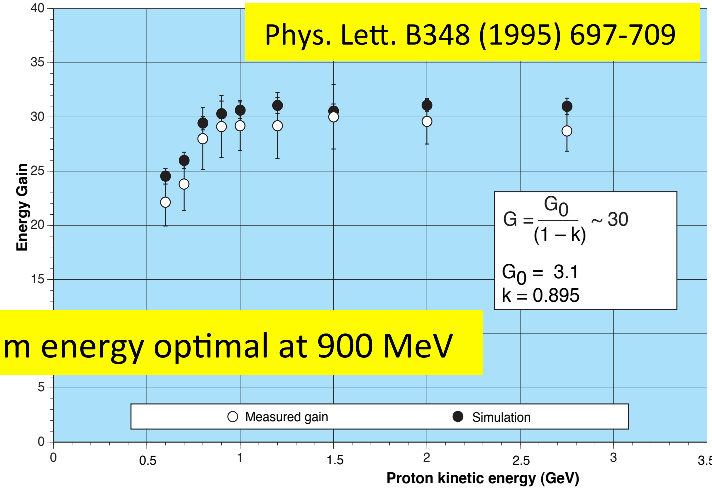
Switching off the neutron source not only stops the main power generation, but also moves the system further away from prompt criticality, k_s to k_{eff}.

FEAT and TARC experiments at CERN



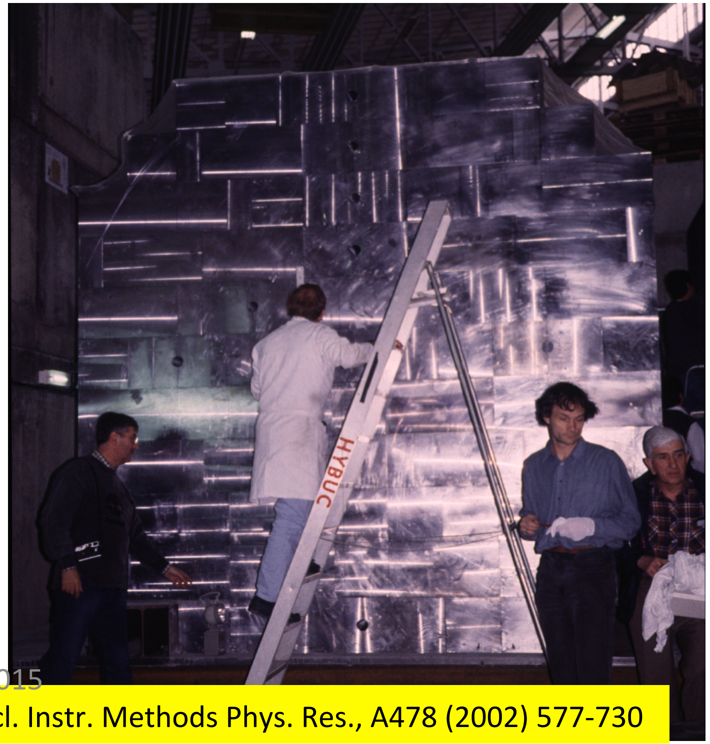
$k_\infty < 1$: exponential

Phys. Lett. B348 (1995) 697-709



Beam energy optimal at 900 MeV

3.62 t of natural uranium at CERN PS; k_{eff} ~ 0.9



Nucl. Instr. Methods Phys. Res., A478 (2002) 577-730

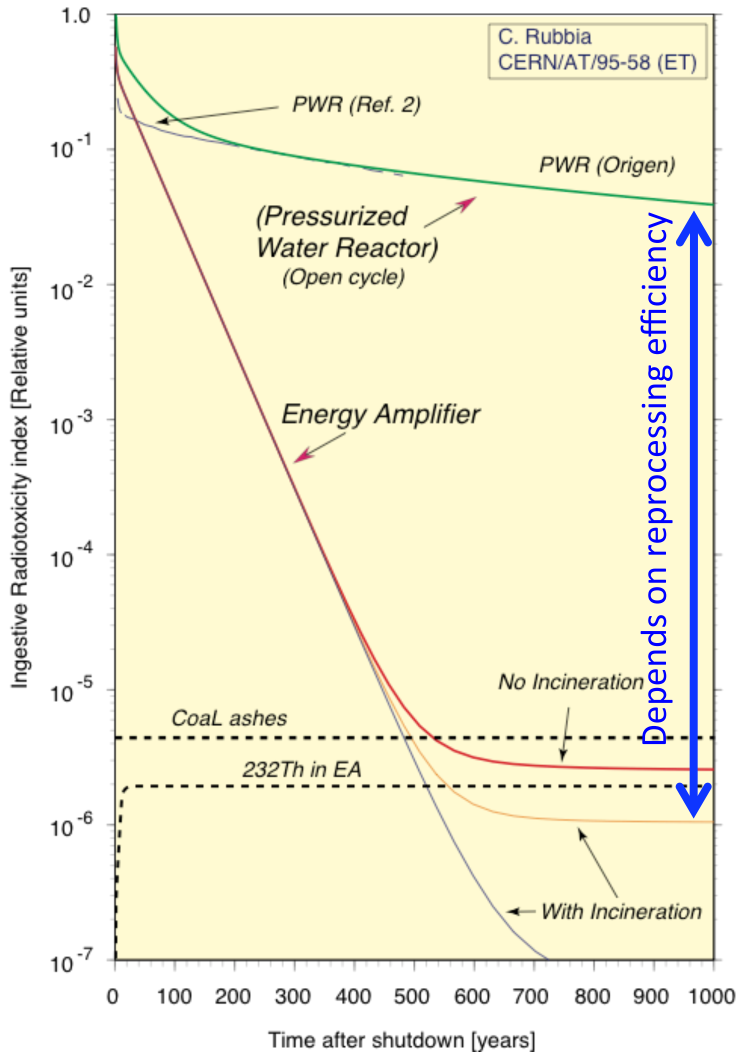
Transmutation performance of ADS

- **C. Rubbia's EA can destroy** 36 kg of TRU/TW_{th}.h (A PWR **produces** 14 kg of TRU/TW_{th}.h)

- Calculations of specific transmutation rates (Y. Kadi)

Transmutation rates (kg/TW_{th}h) of plutonium and minor actinides and LLFPs

Nuclides	EADF (ThPuO2) ENDF/B-VI	EADF (UPuO2) ENDF/B-VI	EADF (UPuO2) JENDL-3.2	PWR (UO2)
^{233}U	+ 31.0			
Pu	– 42.8	– 7.39	– 5.55	+ 11.0
Np	+ 0.03	+ 0.25	+ 0.24	+ 0.57
Am	+ 0.24	+ 0.17	+ 0.14	+ 0.54
Cm	+ 0.007	+ 0.017	+ 0.020	+ 0.044
^{99}Tc prod	+ 0.99	+ 1.07	+1.22	+ 0.99
^{99}Tc trans	– 3.77	– 3.77		
^{129}I prod	+ 0.30	+ 0.31		+ 0.17
^{129}I trans	– 3.01	– 3.01		



The PSI Cyclotron

1.3MW@0.59GeV, 94% reliability

Mike Seidel

High Level Baseline Parameters for the SNS

Proton beam energy on target	**1.0**	**GeV**	SC linac output energy	1.0	GeV
Proton beam current on target	**1.4**	**mA**	HEBT length	170	m
Power on target	**1.4**	**MW**	Accumulator ring circ.	248	m
Pulse repetition rate	60	Hz	Ring fill time	1.0	ms
Beam macropulse duty factor	6.0	%	Ring beam extraction gap	250	ns
Ave. current in macro-pulse	26	mA	RF systems	h=1 +h=2	
H^- peak current front end	38	mA	RTBT length	150	m
Chopper beam-on duty factor	68	%	Protons per pulse on target	$1.5x10^{14}$	
RFQ output energy	2.5	MeV	Proton pulse width on target	695	ns
FE + Linac length	335	m	Target material	Hg	
DTL output energy	87	MeV			
CCL output energy	185	MeV			

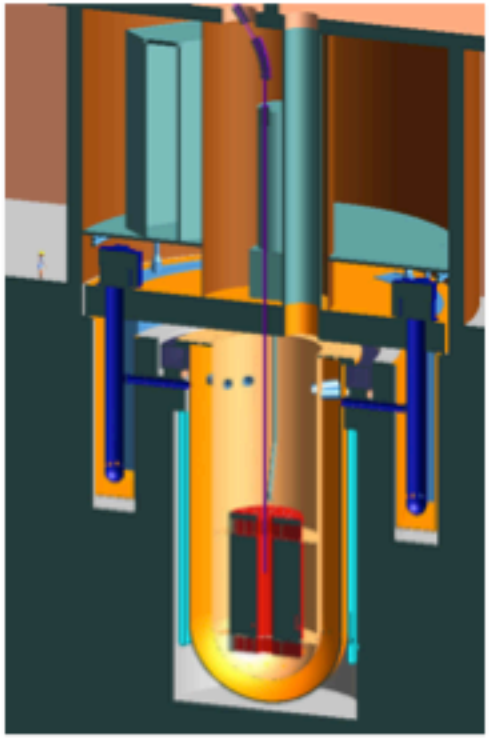
Industrialized ADS

EA Feasibility Study: Aker ASA and Aker Solutions ASA (2010)

AkerSolutions

- 1500MWTh/600MWe
- Sub-critical core
- Thorium oxide fuel
- Accelerator driven via central beam tube
- Molten lead coolant
- Coolant temp 400-540°C
- 2 Axial flow pumps
- 4 Annular heat exchangers
- Direct lead/water heat exchange

- *It may be modified to a Minor Actinide burner (ADS)*



A Thorium fuelled reactor for power generation

Jacobs Engineering Group Inc.

Carlo Rubbia

CERN_Oct_2013

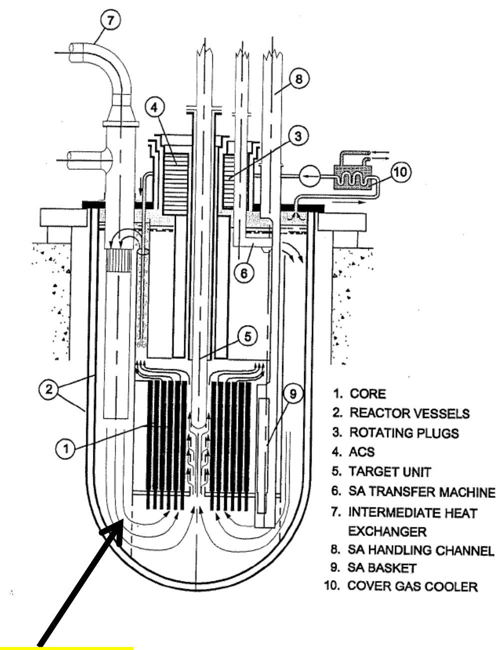
Simplified reprocessing (U & Pu by fluorination)

lide# : 23

The next step for ADS

- Before building a system on an industrial scale, it is necessary to build a first demonstrator of significant power
- Many attempts in the past
- So far no ADS exceeded 1 kW of thermal power, which is too small to learn useful lesson in view of an industrial exploitation
- The minimum power requires is 1 MW

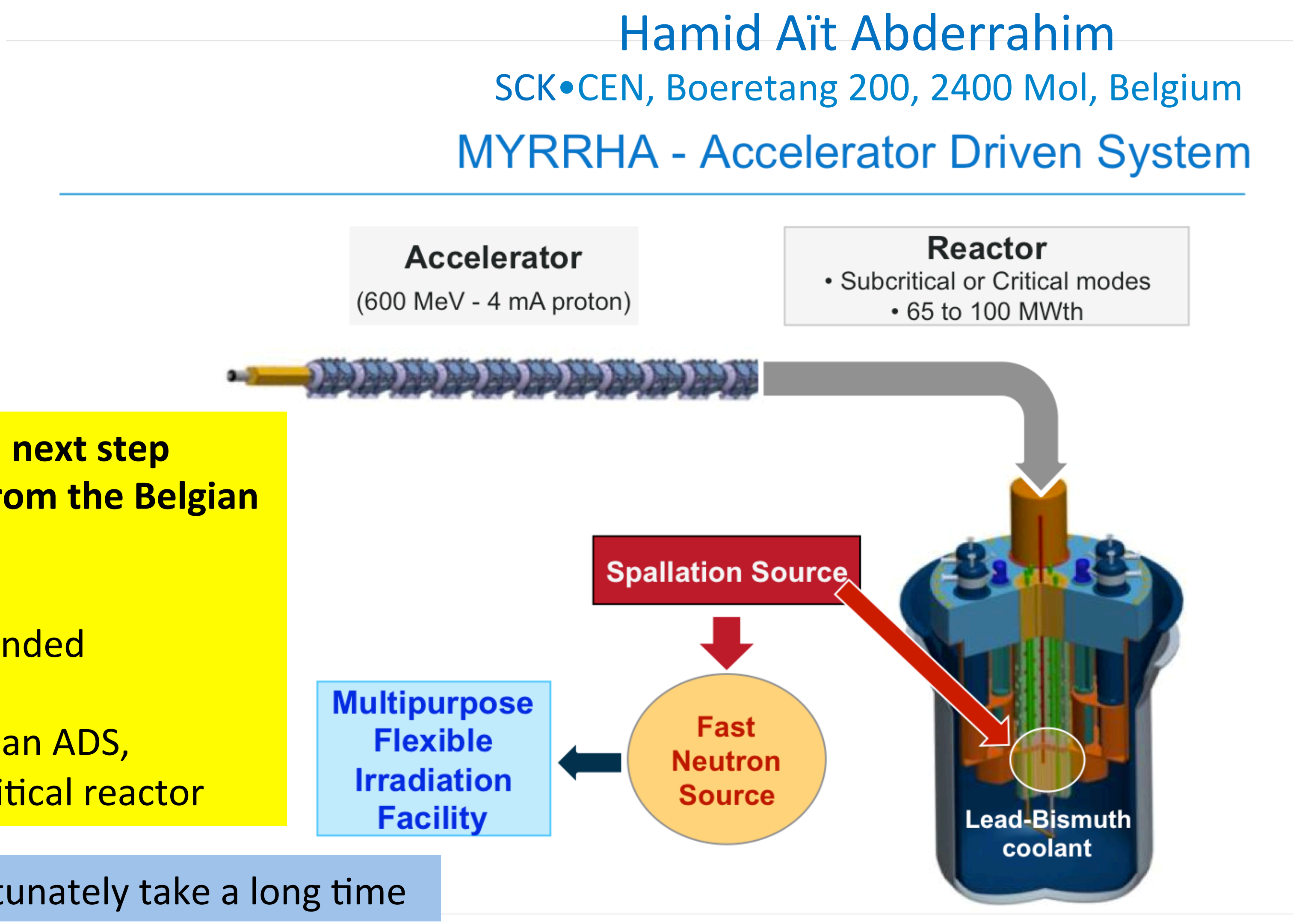
First proposal by C. Rubbia et al., in 1999
Ansaldo engineering design for the Energy Amplifier Demonstration Facility
EA B0.00 1 200 (Jan. 1999)



ADS demo projects

Project	Neutron Source	Core	Purpose
FEAT (CERN)	Proton (0.6 to 2.75 GeV) (~10^{10}p/s)	Thermal (≈ 1 W)	Reactor physics of thermal subcritical system (k≈0.9) with spallation source - **done**
TARC (CERN)	Proton (0.6 to 2.75 GeV) (~10^{10}p/s)	Fast (≈ 1 W)	Lead slowing down spectrometry and transmutation of LLFP - **done**
MUSE (France)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of fast subcritical system - **done**
YALINA (Belorus)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of thermal & fast subcritical system - **done**
MEGAPIE (Switzerland)	Proton (600 Me) + Pb-Bi (1MW)	-----	Demonstration of 1MW target for short period - **done**
TRADE (Italy)	Proton (140 MeV) + Ta (40 kW)	Thermal (200 kW)	Demonstration of ADS with thermal feedback - **cancelled**
TEF-P (Japan)	Proton (600 MeV) + Pb-Bi (10W, ~10^{12}n/s)	Fast (< 1 kW)	Coupling of fast subcritical system with spallation source including MA fuelled configuration - **postponed**
SAD (Russia)	Proton (660 MeV) + Pb-Bi (1 kW)	Fast (20 kW)	Coupling of fast subcritical system with spallation source - **cancelled**
TEF-T (Japan)	Proton (600 MeV) + Pb-Bi (200 kW)	-----	Dedicated facility for demonstration and accumulation of material data base for long term - **postponed**
MYRRHA (Belgium)	Proton (600 MeV) + Pb-Bi (1.8 MW)	Fast (60-100 MW)	Experimental ADS – **under design**
CADS (China)	Protons (0.6 – 1.5 GeV)	Fast (100–>1000MW)	**Four phase project: 2011 – 2031**
U-ADS (Ukraine)	Electrons	200 kW	Uranium-based ADS prototype (KIPT)
ADS (Russia)	Protons (250-500 MeV)	1-5 MW	**Sidorkin et al., Using an existing facility at INR, Troitsk**

ADS demonstrator: MYRRHA

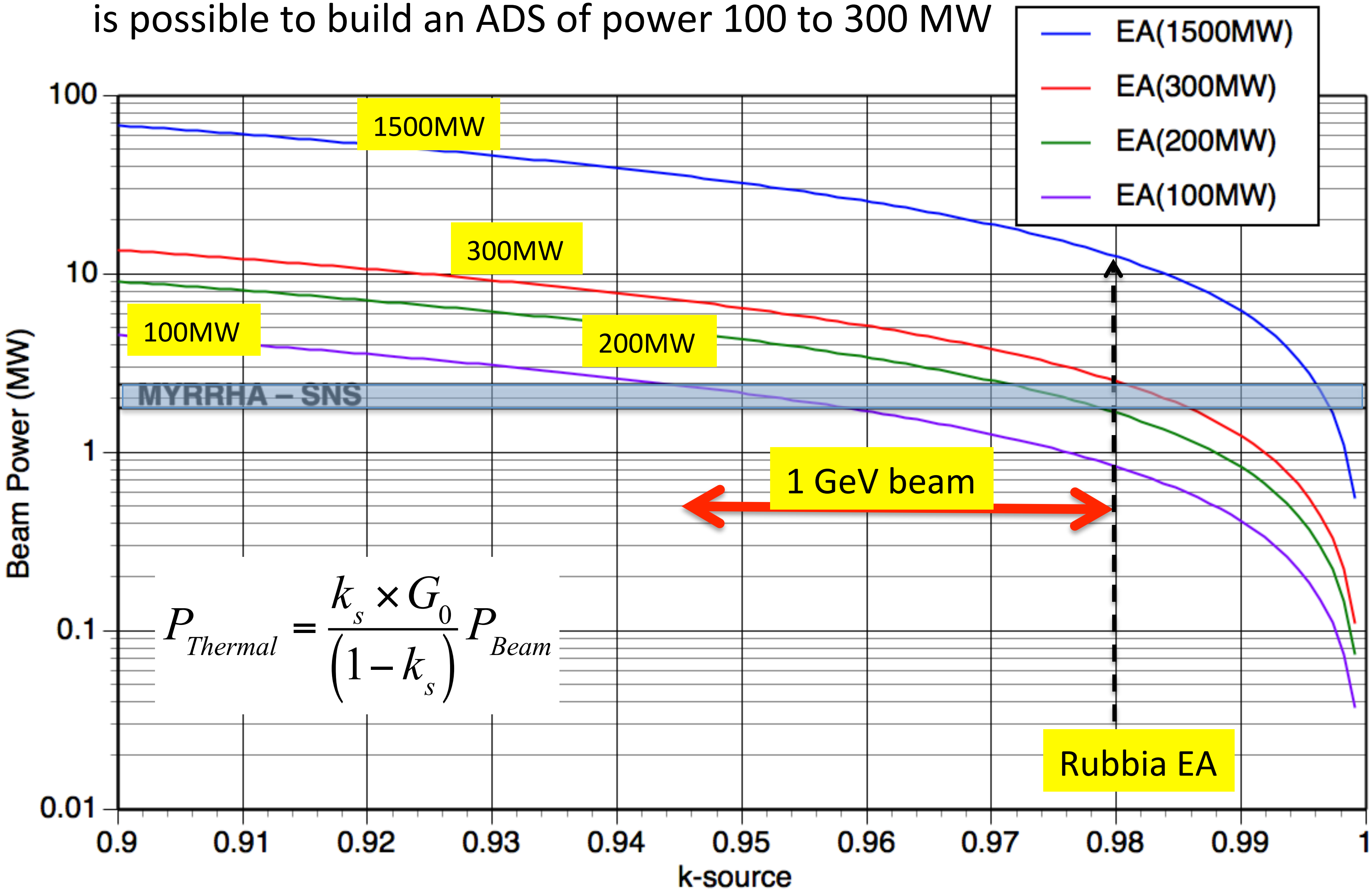


The most natural next step
Strong support from the Belgian government
However:
– only partially funded
– no thorium
– will not remain an ADS,
will turn into a critical reactor

MYRRHA will unfortunately take a long time

What could be done today?

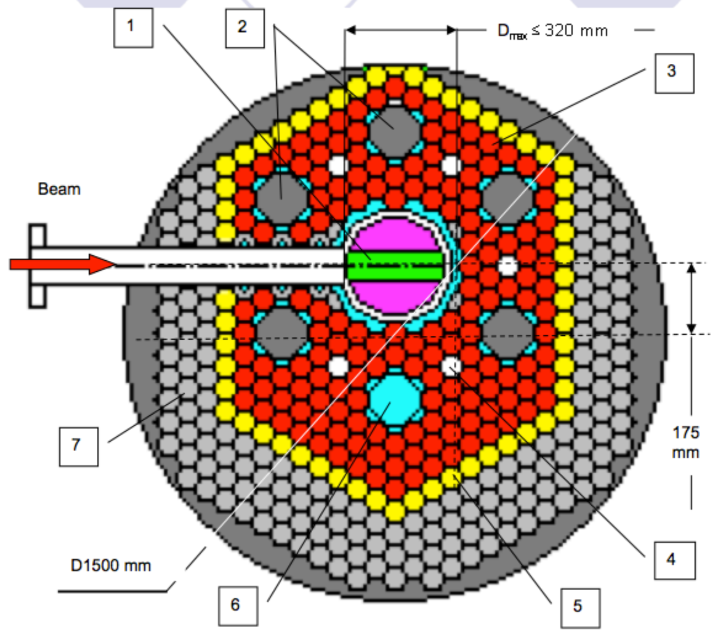
- With present accelerators and neutrons spallation sources (1 to 2 MW) it is possible to build an ADS of power 100 to 300 MW



A Proposal at Troitsk

- At ThEC13 Stanislav Sidorkin presented a proposal of an ADS demonstrator at Troitsk, using the Moscow Meson Factory, at the Institute for Nuclear Research (INR)

Conceptual scheme of research ADS



1 –target module;
2 – hermetical PbBi capsules with high enriched fuel and minor actinides;
3 – the cassettes of the water-cooled part of blanket with MOX fuel (~ 25% enr.);
4 – the module of controlled systems;
5 – decoupler (if it is required);
6 – traps of thermal neutrons (moderator) can construct in any place ;
7 – reflector.

iThEC recognized that it could be a realistic possibility of having a first ADS demonstrator

iThEC delegation on site

Evaluation of the potential of the facility

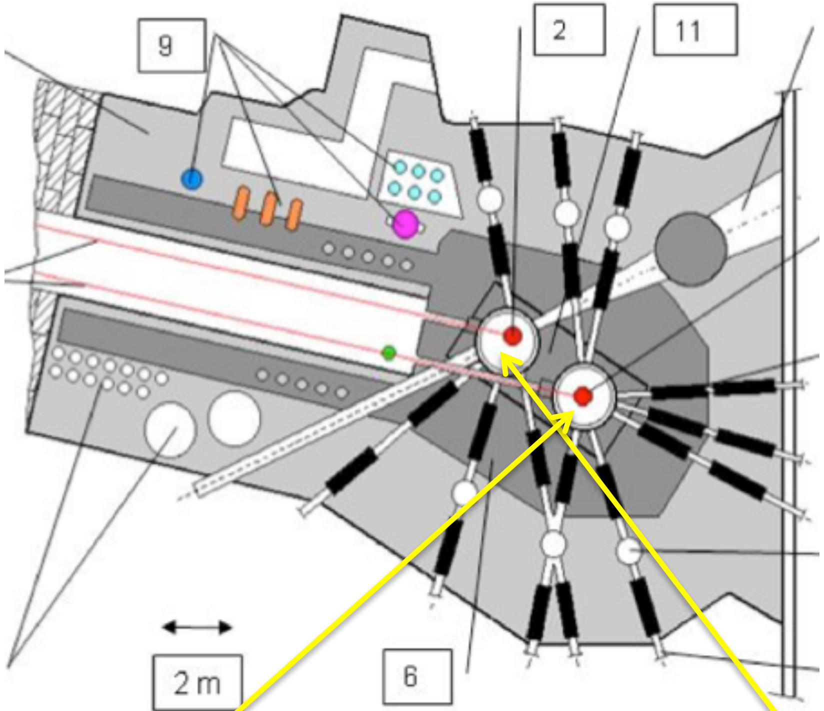
Photo taken at the entrance of the Troitsk Laboratory (July 13, 2015): From left to right: Valeri Kalinin, Frank Gerigk, Karel Samec, Yacine Kadi, Anatol Rogov, Stanislav Sidorkin.

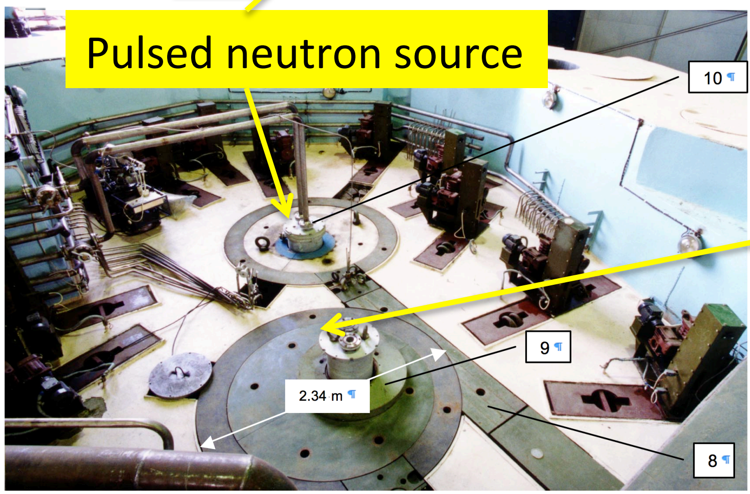
The LINAC

The LINAC

INR Deputy Director Dr. Alexander Feschenko
iThEC mebers Yacine Kadi and Frank Gerigk

The target area





Evaluation of the Troitsk Facility

- The iThEC delegation with experts in accelerator and reactor technology, in nuclear safety, and in ADS concluded that an ADS at Troitsk can fullfill the requirements for a useful ADS demonstrator
- The facility once commissioned would be used for studies in material sciences, nuclear physics, nuclear technologies, liquid-metal cooling, fuel composition and processing, instrumentation and control, computer simulation techniques.
- In its meeting on October 8, iThEC decided to proceed, in collaboration with Troitsk management, to the next step which is a detailed feasibility study, in parallel with the constitution of a collaboration, on the CERN experiment model.

ADS demonstrator

- What do we want to achieve with an ADS demonstrator?:
  - Demonstrate ADS at a substantial power (at least 1 MW thermal) the coupling of an accelerator with a subcritical core;
  - Learn how to operate an ADS of substantial power, in particular define and demonstrate the safety features for a future industrial prototype;
  - Prepare the design of a prototype of an energy producing unit of industrial power (a few hundred MW);
  - Demonstrate the destruction of Minor Actinides.

The Troitsk accelerator

Linac parameters

S. Sidorkin@ThEC13

	The design parameters	Running characteristic	Maximum reached value
Accelerated particles	p, H^-	p, H^-	p, H^-
Maximal proton energy, MeV	600	209	502 (1996)
The maximal average current, μA	500	150	180
Pulse current, mA	50	16	22
Pulse repetition rate up to, Hz	100	50 - 100	50
The pulse duration, μs	1-100	0.5-200	0.5-200

The Troitsk infrastructure

- The **accelerator** exists but needs to be refurbished (250-300 MeV perhaps 550 MeV, 25 to 75kW of average beam power (a few MW of thermal power) with a repetition rate of 100Hz – the accelerator upgrade is however far less costly than a new installation.
- It is only a lack of spare parts, mainly klystrons which prevents from going to the nominal parameters (600 MeV; 500 μA)
- The **spallation neutron source** exists (one pulse source in operation). The neutron source could be optimised to reflect latest developments in this field (one iThEC member participated in MEGAPIE)
- There is a **design of the core** which could be further optimized. The design and construction of the core requires collaboration with ROSATOM.
- The ancillaries and supporting equipment at Troitsk would be submitted to a thorough safety review and – where needed – upgraded. However the presence of significant amounts of nuclear fuel, may imply the need for a new containment structure.

Troitsk Project parameters

- For a beam power of **24.8 kW** at **247 MeV** (G_0 = 1.15)

C. Rubbia's EA design parameter

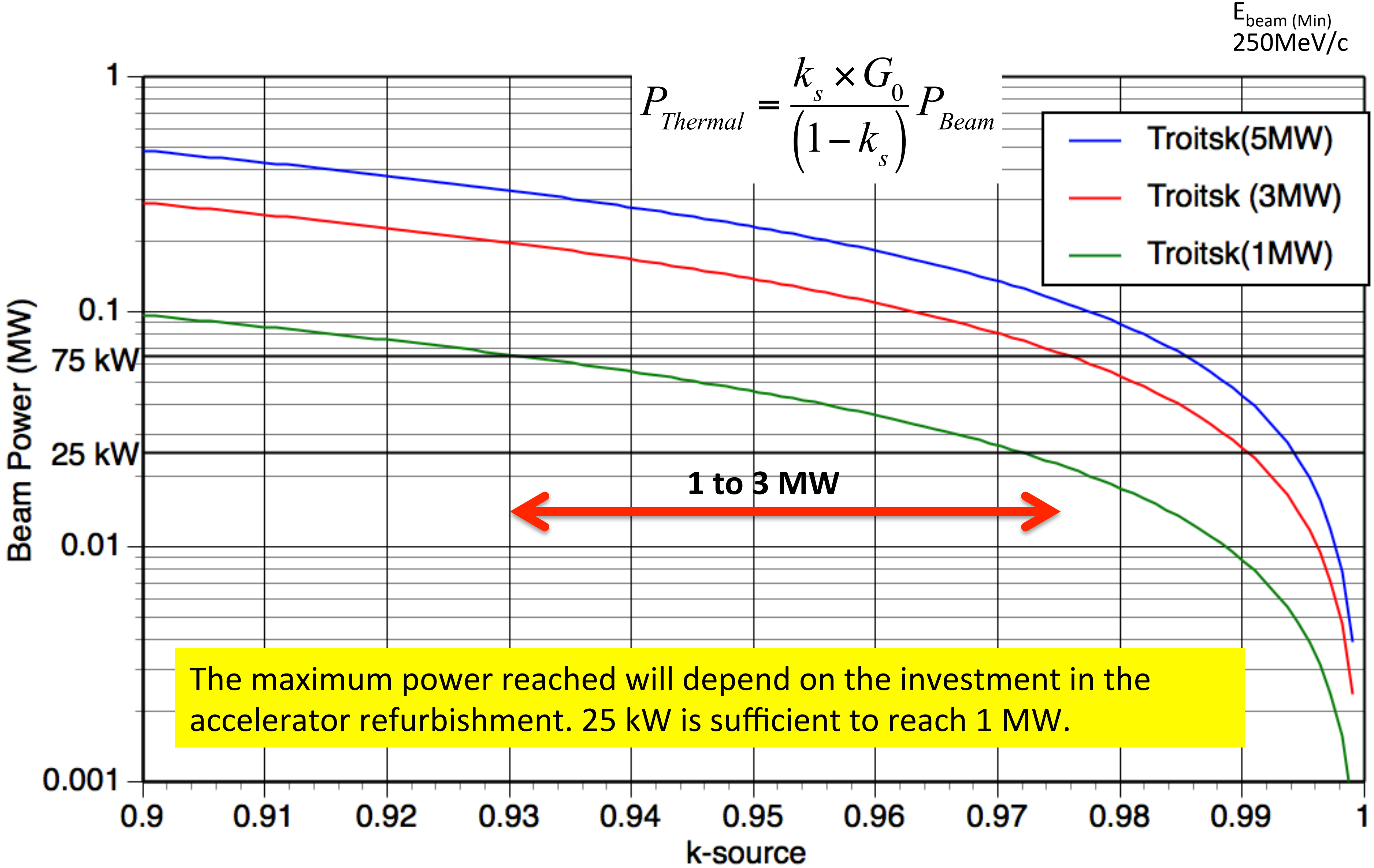
k	0.95	0.96	0.97	0.98	0.99
Gain	21.85	27.6	37.2	56.3	113.3
$P_{thermal)}$ (MW)	0.542	0.684	0.922	1.396	2.81

- For a beam power of **50 kW** at **247 MeV** (G_0 = 1.15)

k	0.95	0.96	0.97	0.98	0.99
Gain	21.85	27.6	37.2	56.3	113.3
$P_{thermal}$ (MW)	1.09	1.38	1.86	2.81	5.66

With 300 MeV protons and an intensity be 50% higher, a beam power of **50 to 75 kW should be possible**, even if not available initially.
It is only a matter of investment to achieve higher beam energy and power

What can be done at Troitsk?



The maximum power reached will depend on the investment in the accelerator refurbishment. 25 kW is sufficient to reach 1 MW.

Physics of ADS at Troitsk

- Measuring the core physical properties will be the first stage – the fact that the system is subcritical will simplify life:
  - Neutron Spectrum and flux density mapping
  - Neutron source dynamics, k-source, keff, etc. (pulse beam)
  - Delayed neutron percentage (beta factor)
  - Fuel evolution during power cycle
  - Peak pin power along the burn cycle
  - Cycles to equilibrium with Thorium (Breeding characteristics, fuel doubling time)
  - Reactivity feedback coefficients due to geometric effects
  - Characteristics of waste-containing fuel pins such as Doppler effect
  - etc.

CONCLUSION

- The Troitsk project would be the first ADS of significant power, a long awaited and necessary step in view of the design of an industrial system
- Its power 1 to 3MW (5MW?) is sufficient to fulfill the iThEC program and can allow many more measurements of general interest. It will constitute an ADS test facility
- The project costs 5% of the cost of MYRRHA and can be achieved in 5 year
- Collaborators are welcome

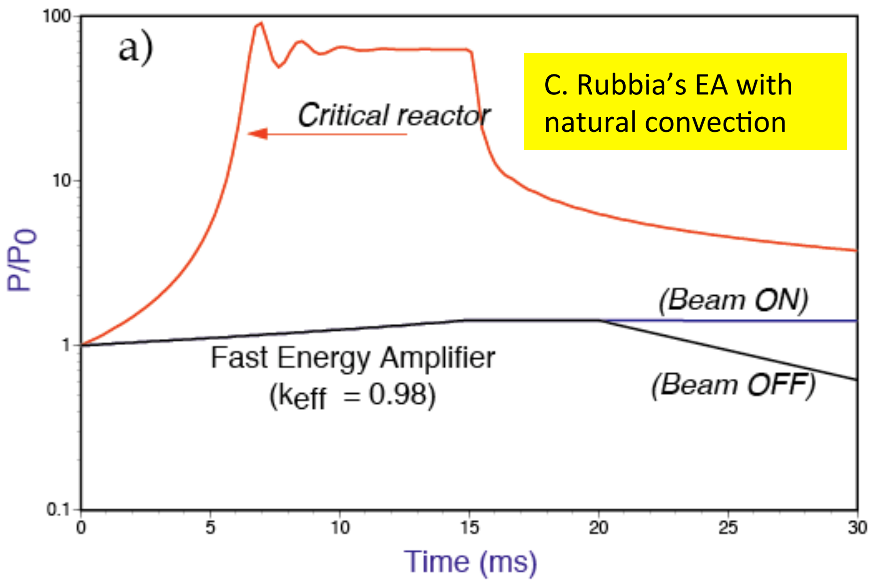
RESERVE

Physics of subcritical systems

- Subcritical systems are insensitive to delayed neutron fraction (β); **safety margin** (distance from prompt criticality) **is a design choice**, it is not imposed by Nature!

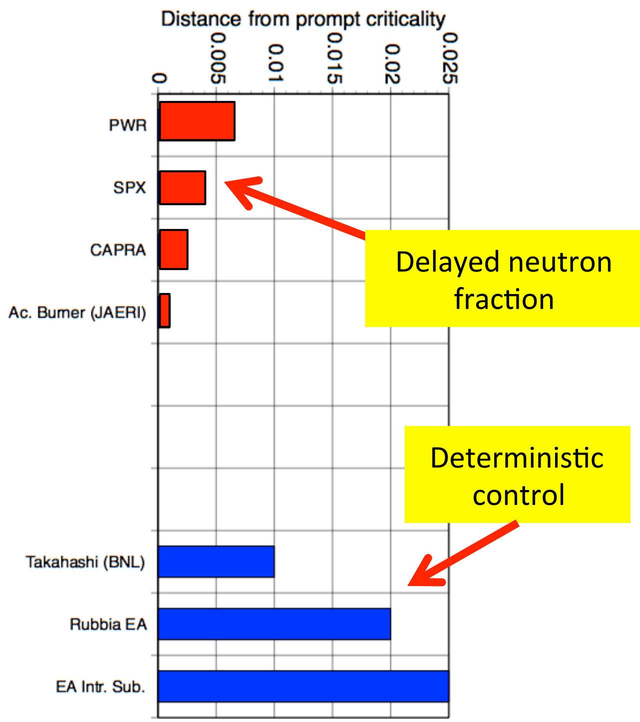
- The reactivity changes only very slowly; the beam can be switched off very quickly, reducing k_s to k_{eff}. It is possible to choose a higher k_s in order to reduce the load on the accelerator (Takahashi at BNL, k_s = 0.99)

Comparative response to reactivity insertion



There is enough time for the natural convection to adapt

The CERN LHC beam can be switched off in 270μs, the CERN SPS in 46 μs, and a smaller accelerator for ADS, even much faster.

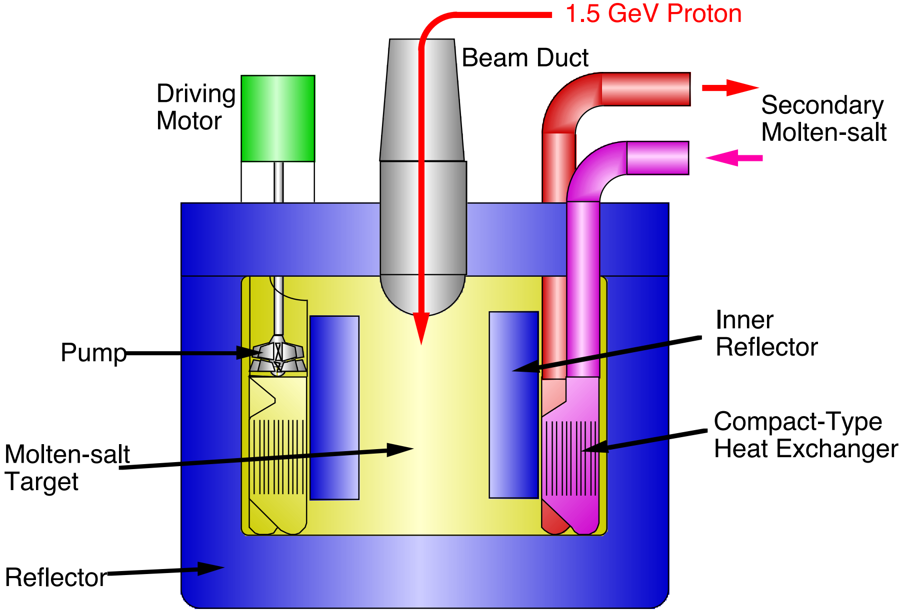


Other ADS concepts

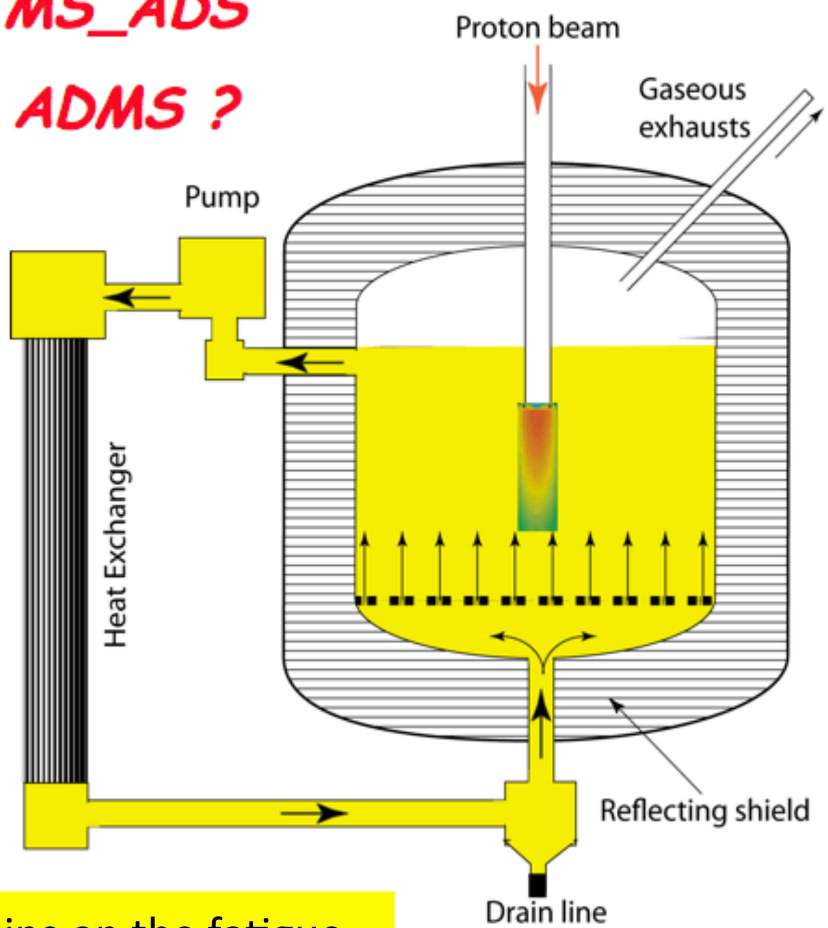
- Several **Molten Salt ADS concepts** are being studied: Carlo Rubbia, Toshinobu Sasa and Laszlo Sajo-Bohus, presented such possibilities at ThEC13.

MS_ADS

ADMS ?



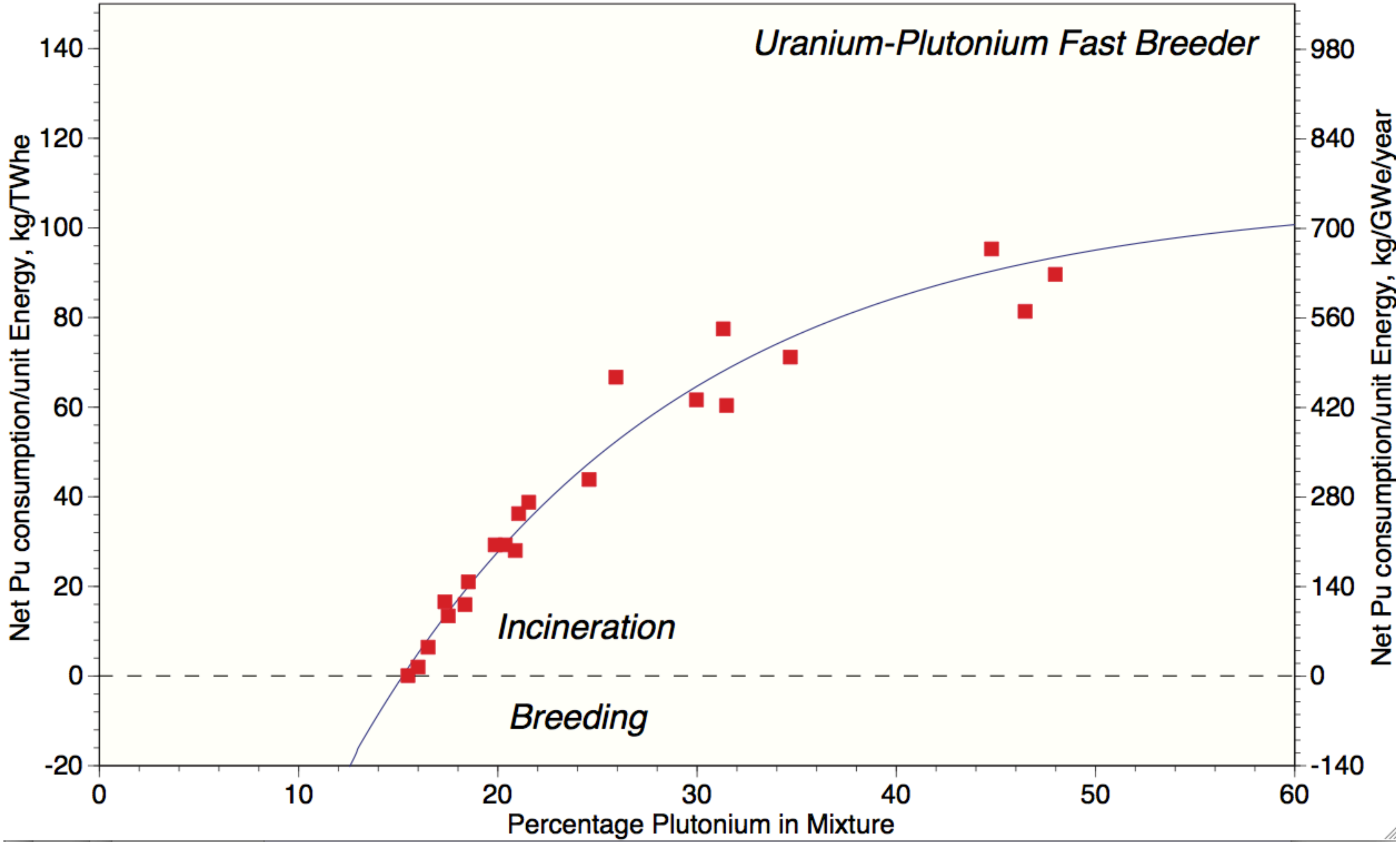
Toshinobu Sasa



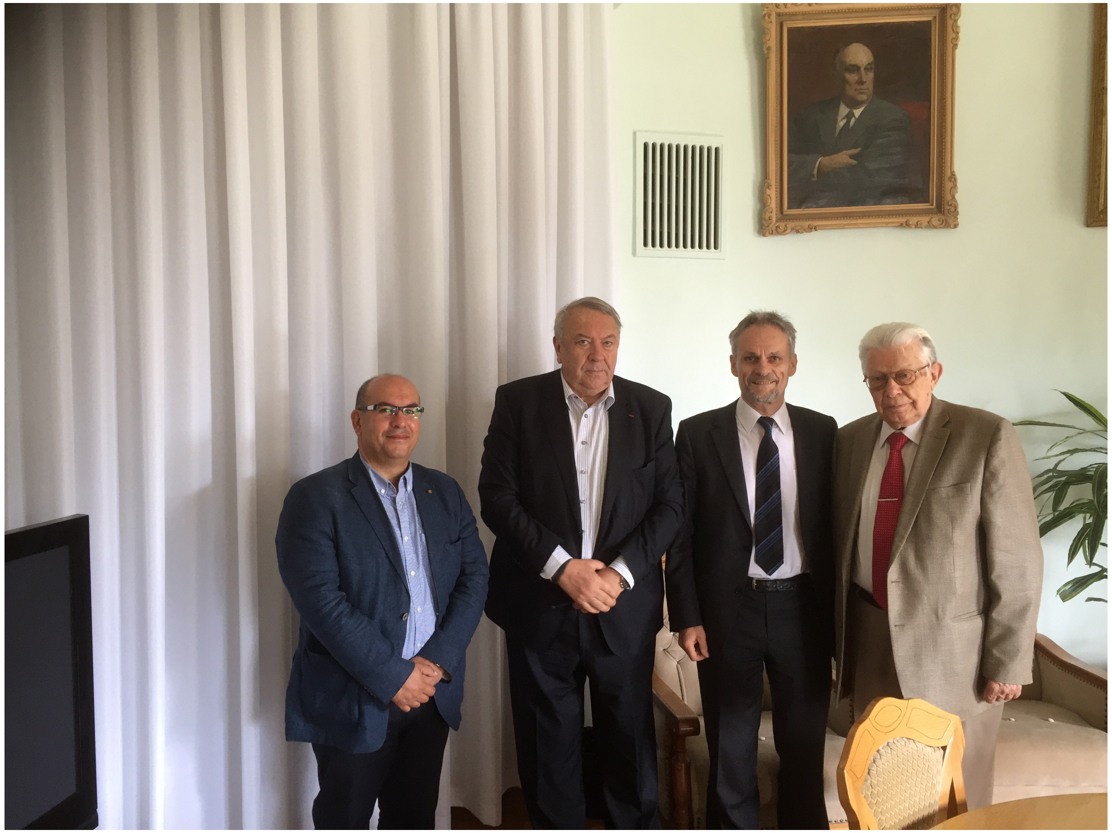
Carlo Rubbia

This relaxes the constrains on the fatigue induced in the fuel structure by the accelerator trips

CAPRA CEA France



iThEC's strategy



**Yacine Kadi, Vladimir E. Fortov (President of RAS),
Jean-Pierre Revol (President of iThEC),
Boris F. Myasoedov (In charge of Thorium at RAS)**

Evaluation of the Troitsk facility in Russia (done)

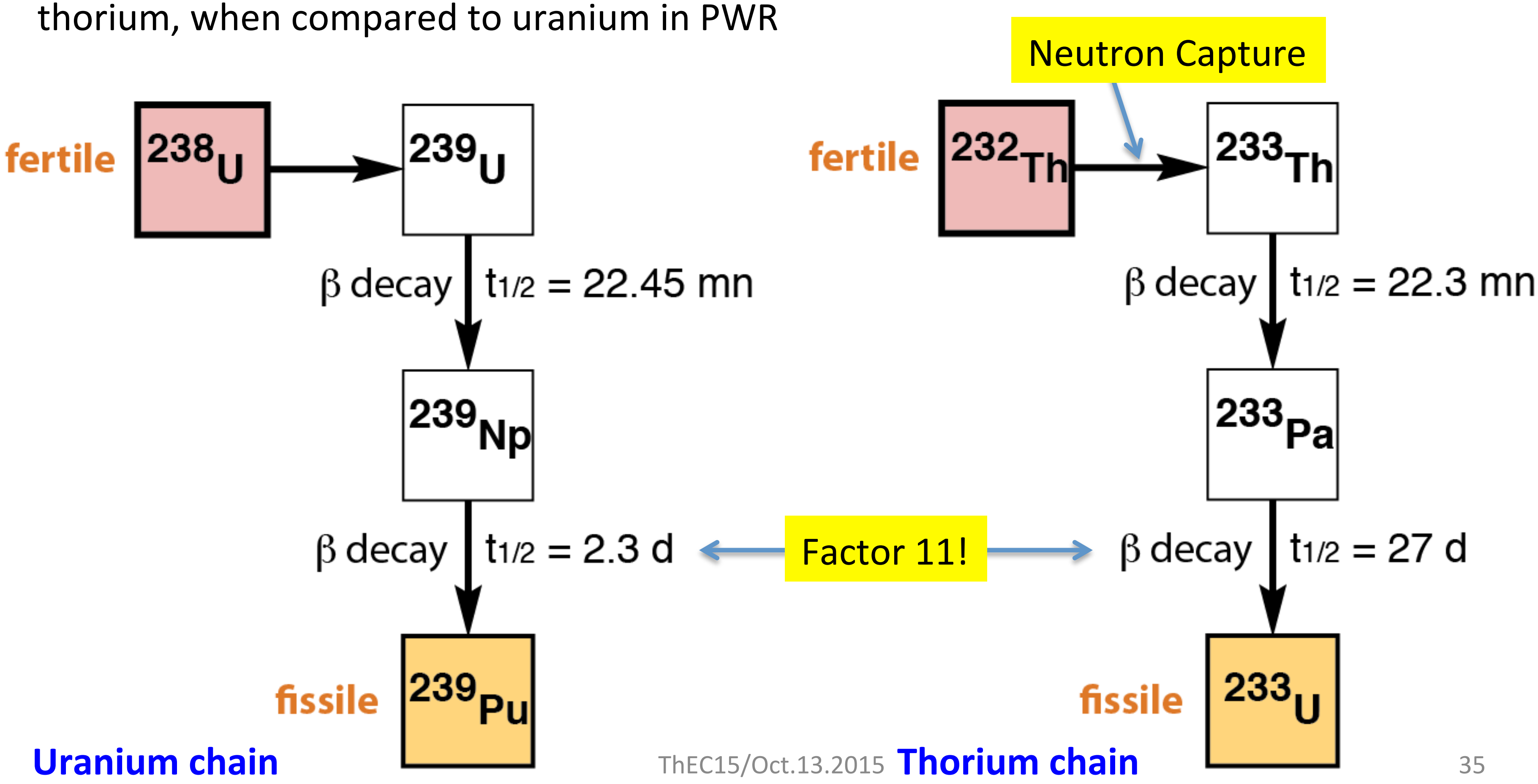
Discussions with partners in Russia:
– Troitsk management
– Russian Academy of Sciences
– ROSATOM

MoU signed with IBeL, an industrial partner, with international connections

Decision by iThEC last week to start a feasibility study, and at the same time form an international collaboration

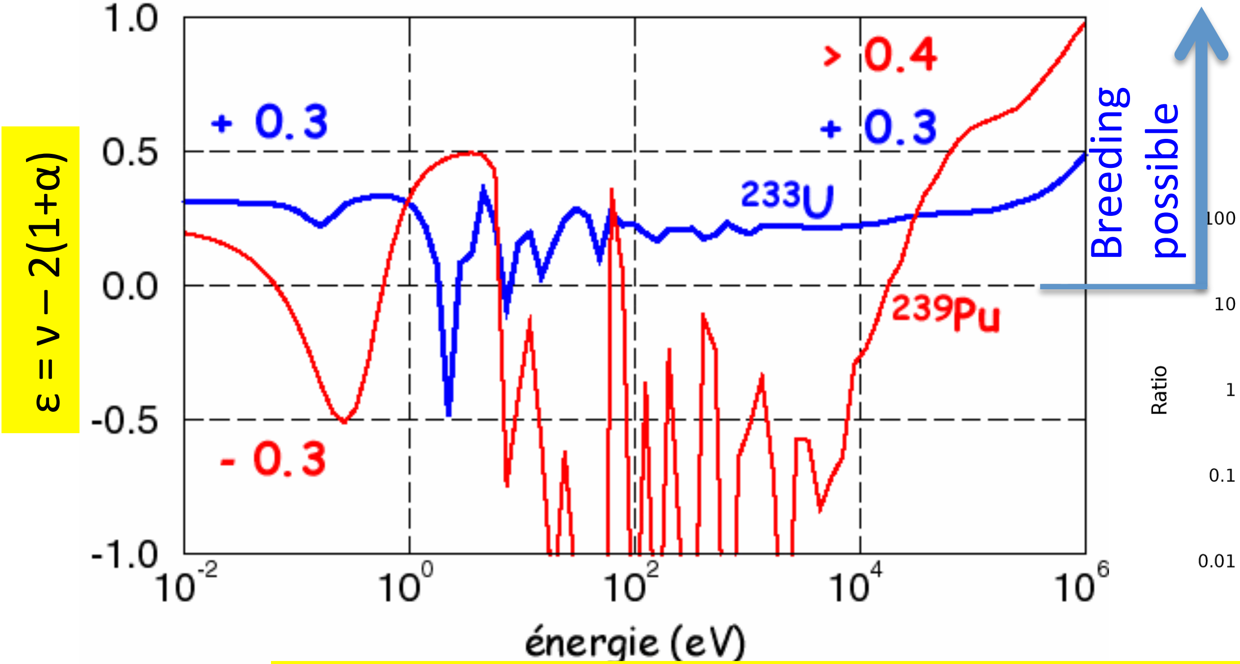
Fission energy from $^{232}Th_{90}$

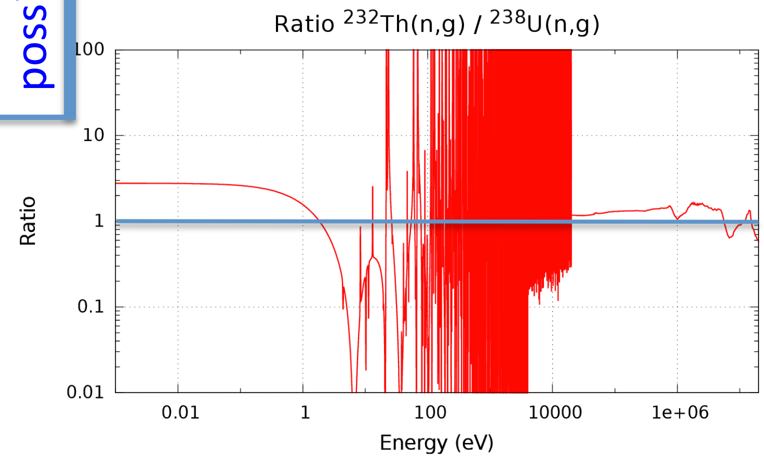
- The fact that most of the thorium is used through breeding gives a factor 140 gain compared to ^{235}U in PWRs
- Combining with the factor 3 to 4 in abundance, gives an **overall factor 500** in favour of thorium, when compared to uranium in PWR



Fission energy from $^{232}Th_{90}$

- **Breeding potential**: For most of the neutron spectrum ^{233}U is better than ^{239}Pu, However, not for fast neutrons





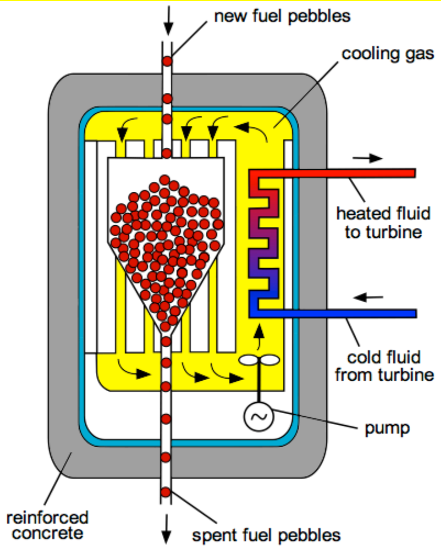
ε = Average number of neutrons in excess of the 2 neutrons needed to run the fission chain

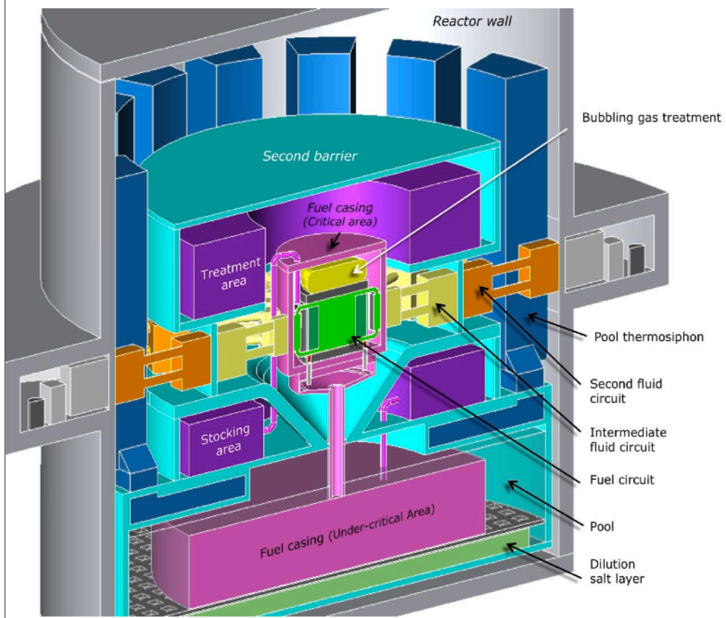
- As thorium has a higher capture cross section than ^{238}U, and it takes much longer to breed the fuel (^{233}U) because of the long half-life of ^{233}Pa, **one cannot simply replace ^{238}U by ^{232}Th in current reactors.**

How to use thorium in practice?

- **Thorium blankets around fast critical reactors to breed ^{233}U**: the Indian approach, most advanced, complicated but it should work
- **Continuously circulating fuel to always have fresh fuel in the core**
  Pebble bed or molten salt critical reactors (MSR)

Pebble-bed Reactor scheme



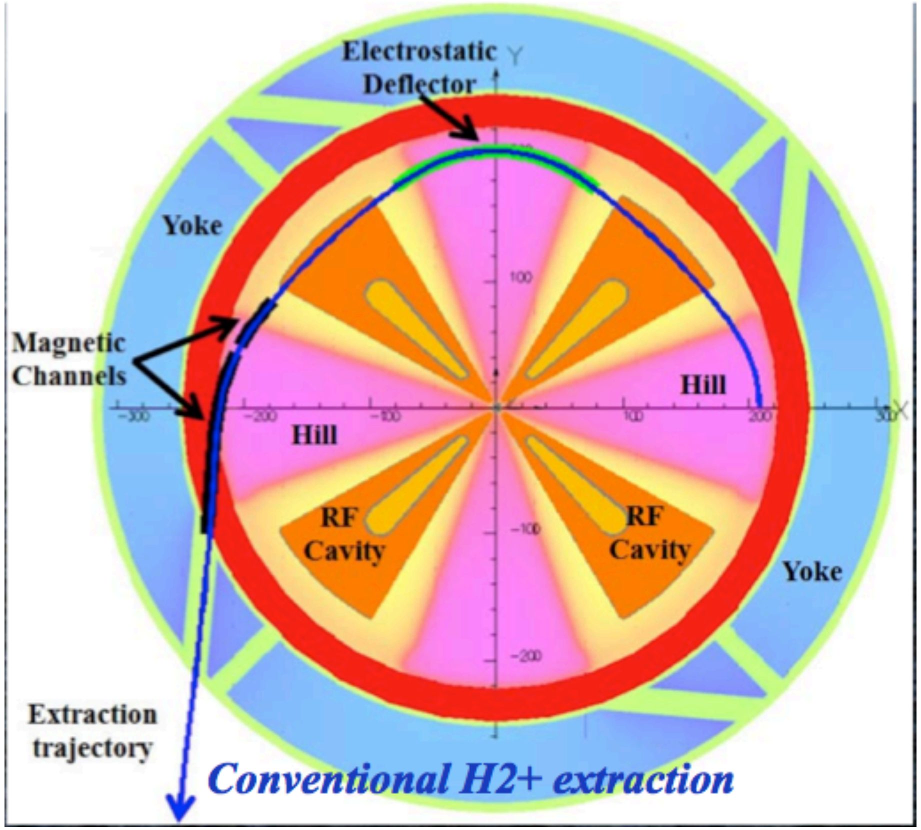


Molten Salt Reactor scheme

- **Provide extra neutrons with an accelerator: Accelerator-Driven Systems (ADS)**

Next generation of cyclotrons

Separate turn Cyclotron



H_2^+ Cyclotron with reverse bend and multiple (3) injections, 1.6 MW at 800 MeV should bring the number of trips within the ADS requirement

At the same time progress on core configuration should make it more tolerant to trips

P. Mandrillon (AIMA)

MEGAPIE TARGET

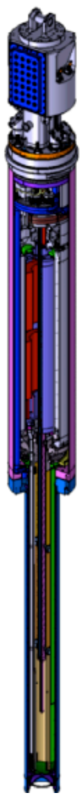
Heat Exchanger (Oil)
10 i/s, 5.5 m/s
140-175°C inside

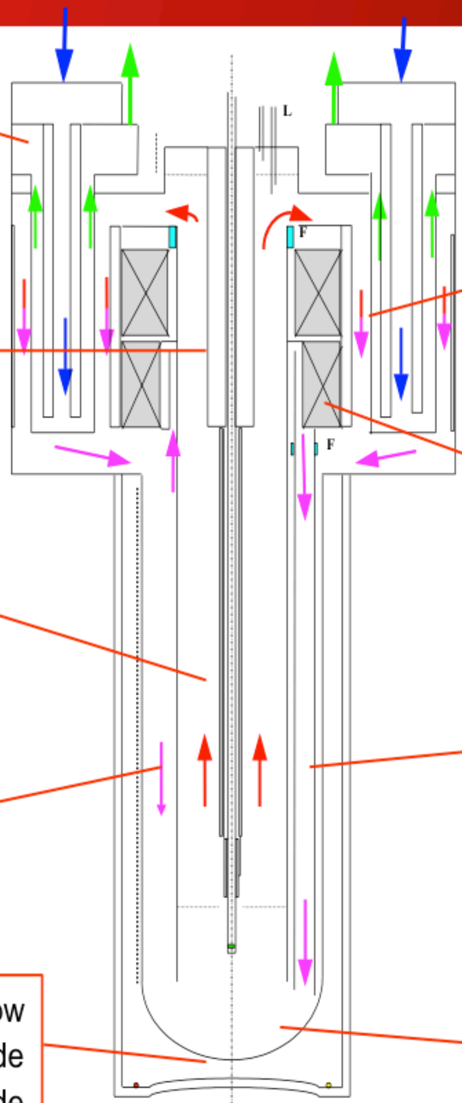
Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

Beam Window
380°C outside
330°C inside





Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
380-230°C inside

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1m/s
230-240°C

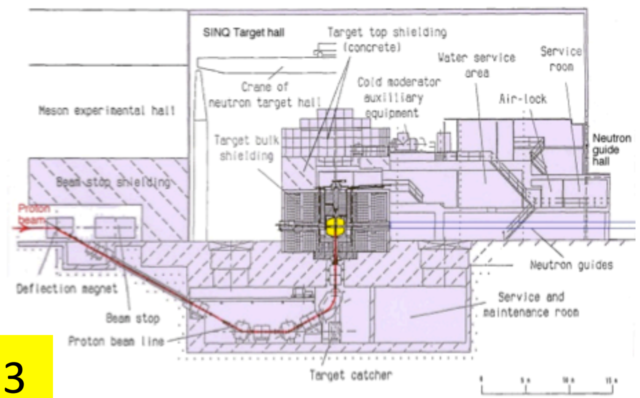
Nozzle 1.2 m/s
Beam Window 1 m/s

Design parameters:

p-beam energy: 575 MeV
p-current: 1.74 mA
Heat removal: 650 kW
Design pressure: 16/10 bar
Design temp.: 400°C
Cover gas press: 3.2 bar
Operation: 1 year
with max 6000 mAh
Radiation damage: 20-25 dpa

Dimensions

Length: 5.35 m
Weight: 1.5 t
LBE-Volume: 89 l



Ch. Latge (CEA) France @ ThEC13

Tentative schedule

The basic stages	Distribution on years from the beginning of funding				
	1	2	3	4	5
Development of the conceptual and draft designs. Choice and substantiation of key parameters and technical decisions. Preparation of requirements specifications on the fuel elements the fuel cassettes the PbBi capsules and target. The project of the window diagnostic system. Examination. The state license for placement.					
Detail design of stand. Detail designs of the fuel elements the fuel cassettes the PbBi capsules and the diagnostic systems included to the main units. The co-ordination with State Committee for Nuclear Safety.					
Project of State Special Design Institute – SSDI (placement and varies connections of stand, building part). The project of the security guard for nuclear-danger object. The obtaining of the building license for stand.					
The working draft (the working drawings of facility).					
Production of the equipment, Development testing of PbBi capsules, Building and assembly jobs.					
Balancing and commissioning. The obtaining of the license for operation.					
The beginning of operation. Stage-by-stage increase of power.					