Accelerators and Nuclear Energy

-- a brief history concerned in Japan --

Makoto Inoue

FFAG School (FFAG'10), Kumatori, Oct. 26, 2010

World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)	
Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

Japanese accelerators (except ion implanters), for electron E>1MeV

1.2.3 発生装置の使用許可台数（種類別、機関別）
Number of Radiation Generators in Use (as of March 31,2008)

機関 Category / 発生装置 Radiation Generators	総数 Total	構成比 Ratio(%)	医療機関 Hospitals &Clinics	教育機関 Educational Organizations	研究機関 Reseach Institutions	民間企業 Industrial Firms	その他の機関 Other Organizations
総数 Total	1,433		1,039	66	141	146	41
構成比 Ratio %		100%	72.5	4.6	9.8	10.2	2.9
サイクロトロン Cyclotrons	198	13.8	131	2	22	39	4
シンクロトロン Synchrotrons	28	2.0	3	3	17	4	1
シンクロサイクロトロン Synchrocyclotrons	2	0.1	1	−	−	1	−
直線加速装置 Linear Accelerators	1,042	72.7	890	22	39	55	36
ベータトロン Betatrons	4	0.3	1	1	2	−	−
ファン・デ・グラーフ加速装置 Van de Graaff Accelerators	40	2.8	−	16	23	1	−
コッククロフト・ワルトン加速装置 Cockcroft-Walton Accelerators	82	5.7	−	20	26	36	−
変圧器型加速装置 Transformer-type Accelerators	17	1.2	−	−	10	7	−
マイクロトロン Microtrons	19	1.3	13	2	1	3	−
プラズマ発生装置 Plasma Generators	1	0.1	−	−	1	−	−

Good readings:

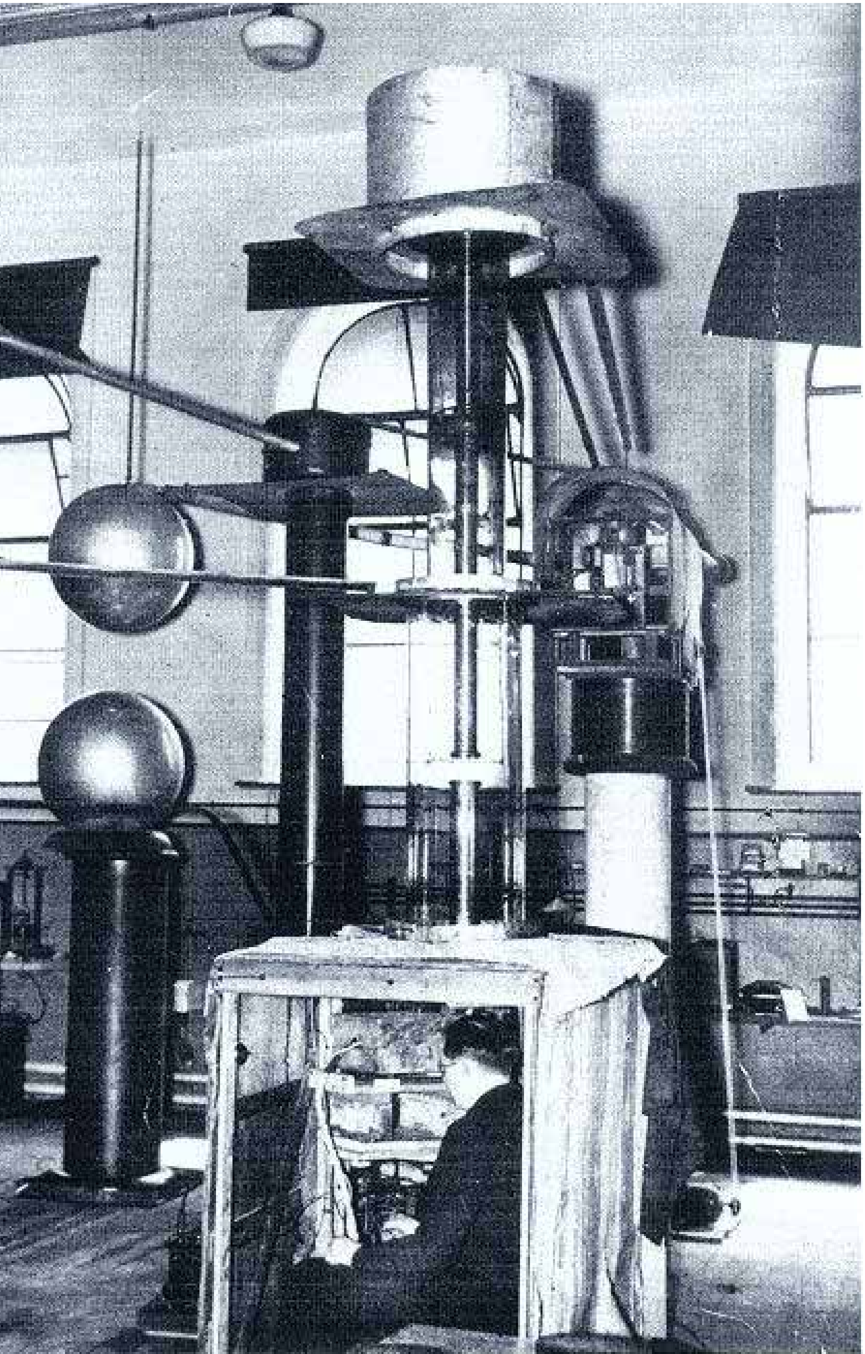
A.Sessler and E. Wilson, Engines of Discovery —A Century of Particle Accelerators—(World Scientific 2007)

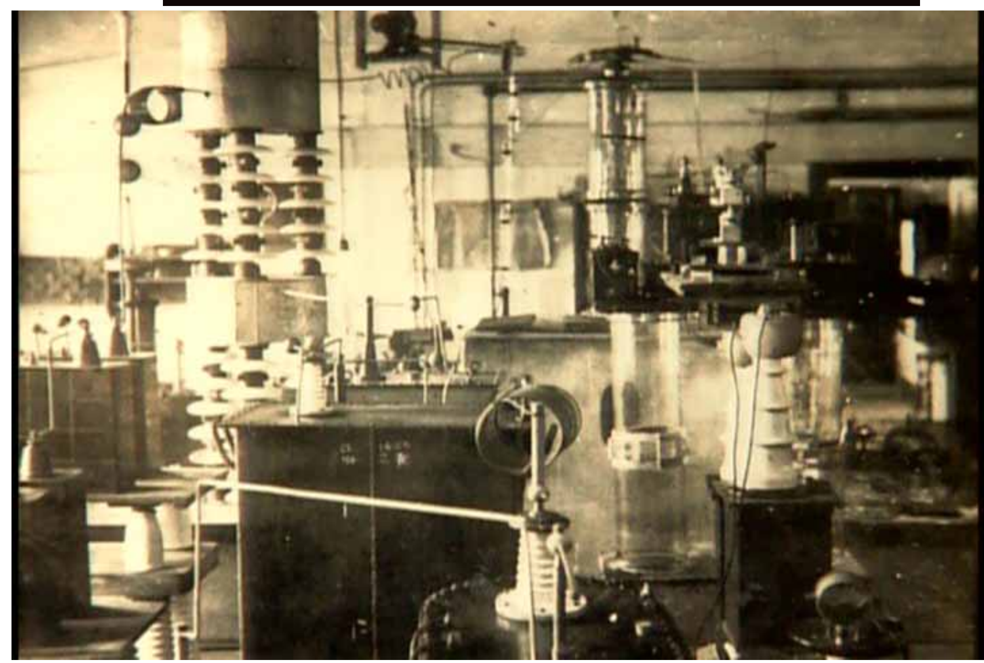
F.T. Cole, Oh Camelot —A Memoir of the MURA Years— (Proceedings of the Cyclotron conference2001, supplement)

(Japanese translated version; http://hadron.kek.jp/FFAG/)

M.K. Craddock, Eighty Years of Cyclotrons (Proceedings of the Cyclotron conference 2010, MOM1CIO02)

Cockcroft and Walton’s accelerator (1932)

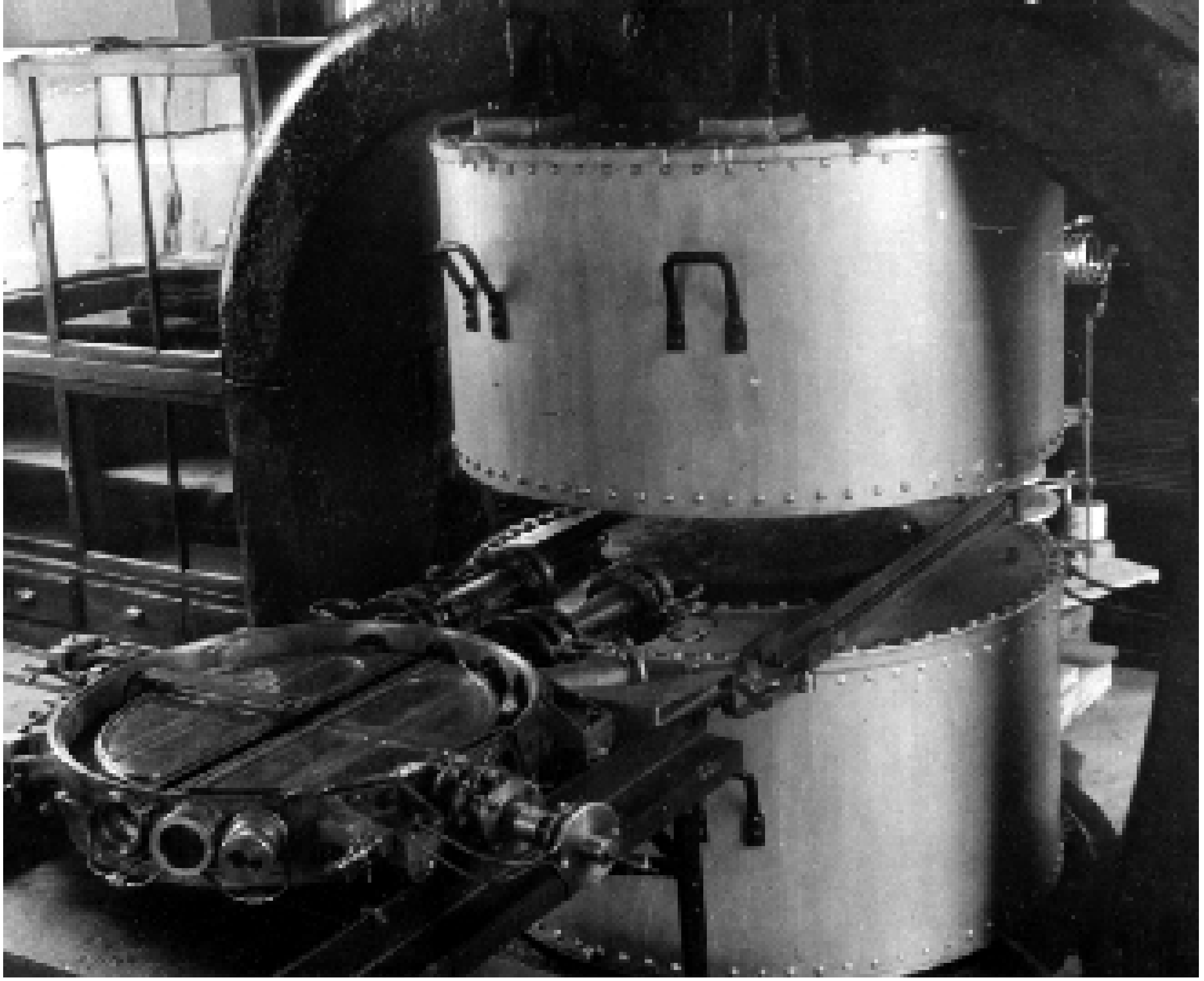




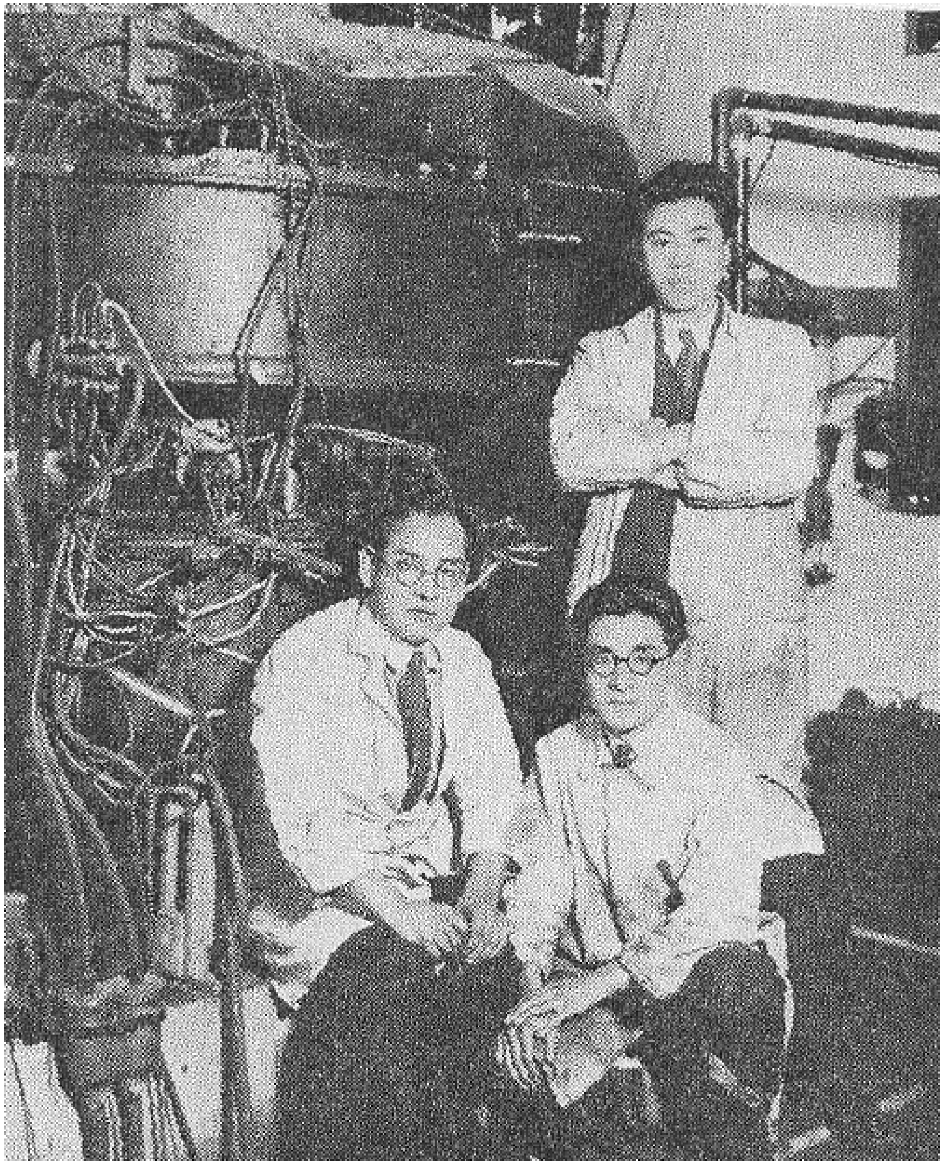
Arakatsu and Kimura and their machine

at Taihoku Imperial University (Taiwan University) 1934

27inch 5MeV-deuteron cyclotron (1934)
Livingston (left) and Lawrence (right)

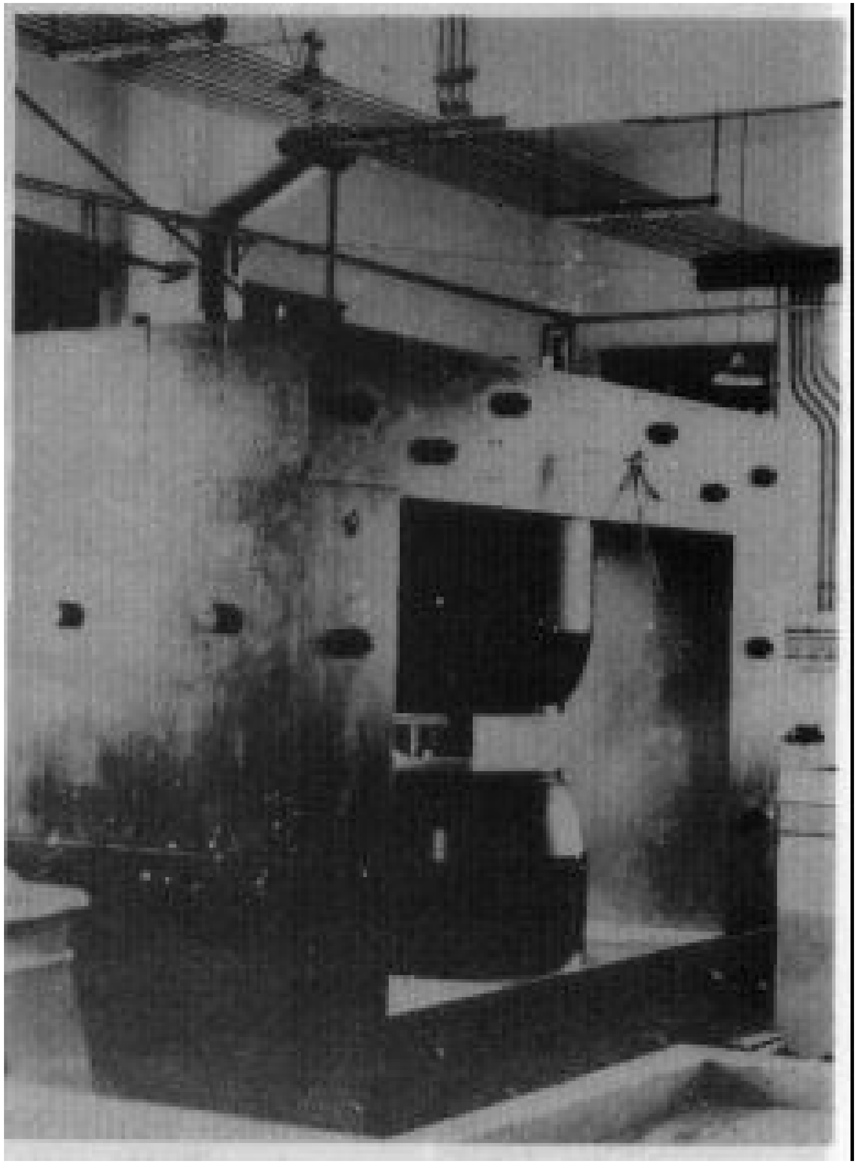


RIKEN small cyclotron(1937) Nishina lab.



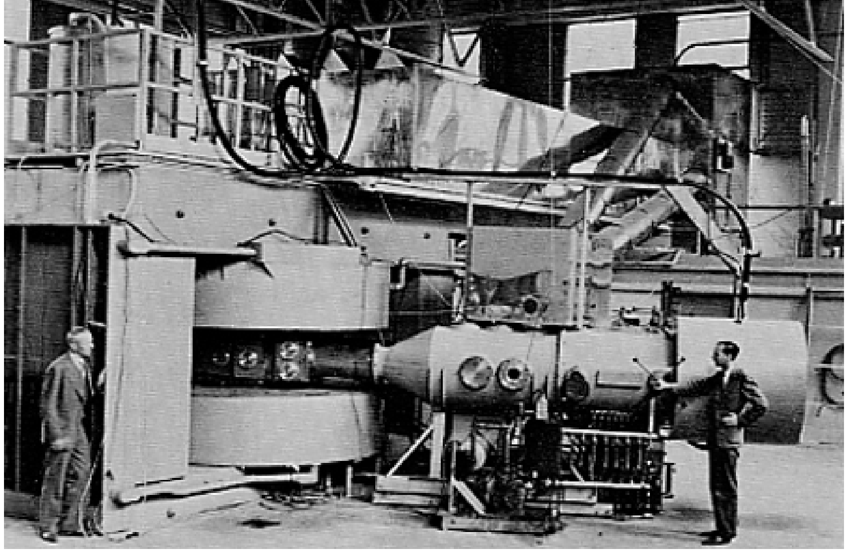
Osaka U. cyclotron

Kikuchi lab.

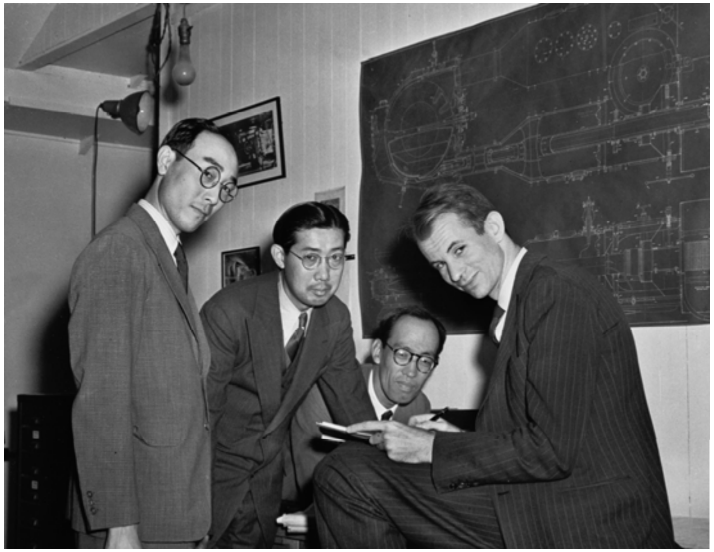


Kyoto U. cyclotron

Arakatsu lab.



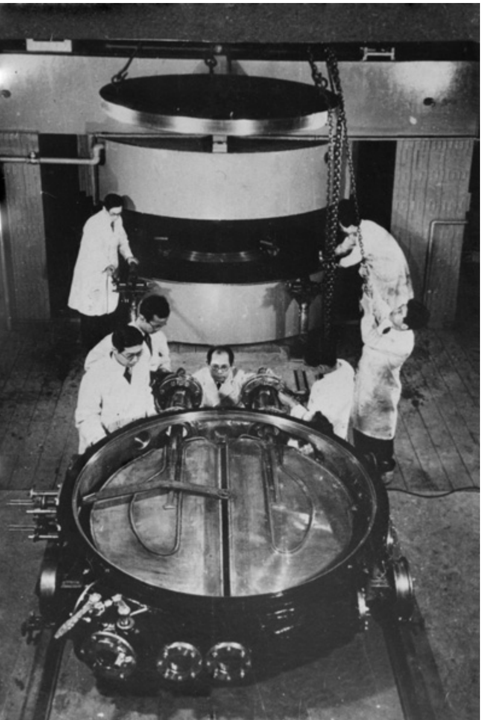
Berkeley 60 inch cyclotron

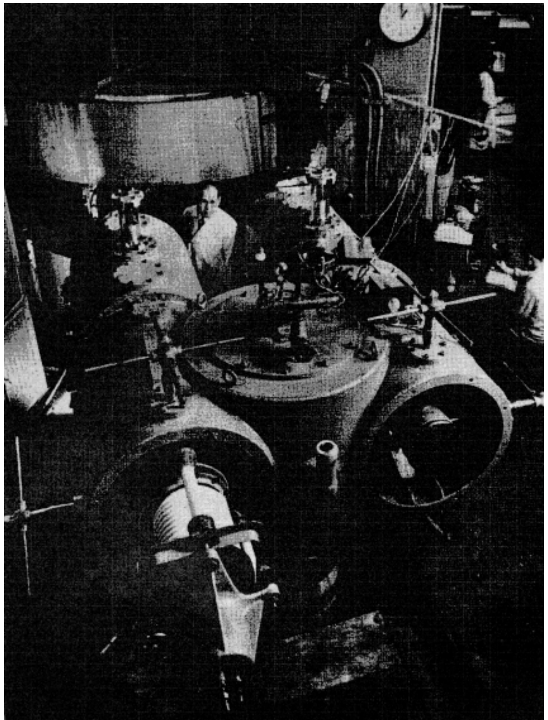


Coaxial resonator is essential

before

after





RIKEN staffs and McMillan

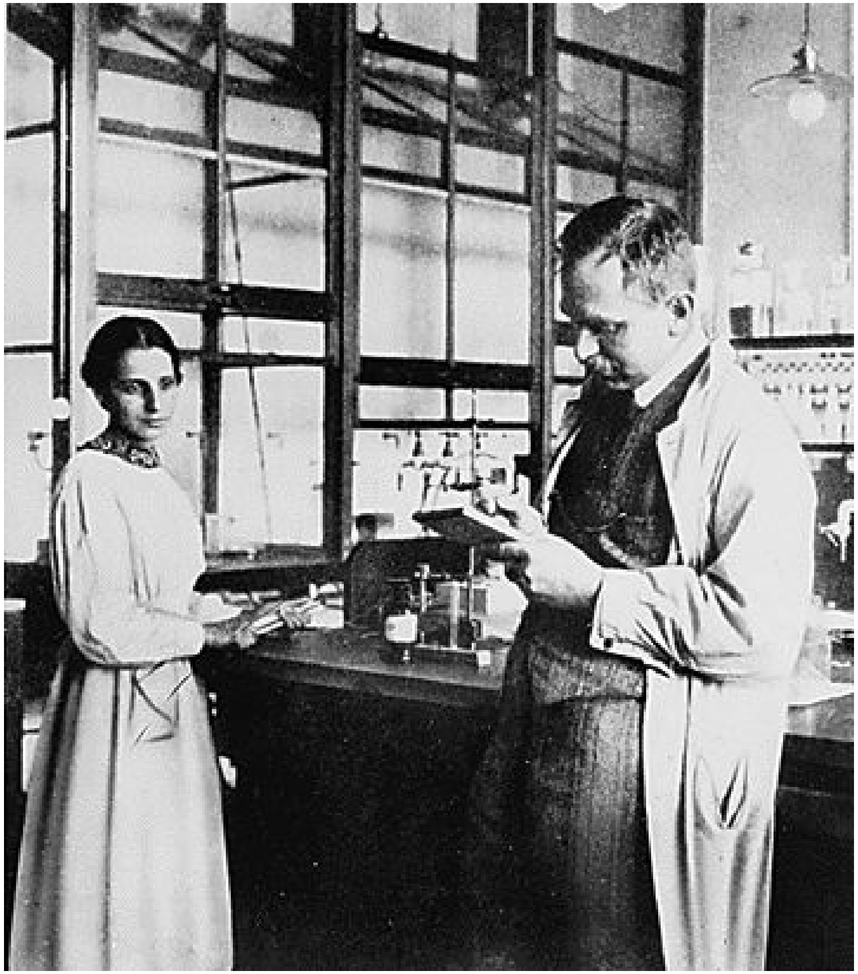
Sep.2, 1940, Berkeley

S. Hinokawa, “Cyclotron to A-bomb”,
Sekibundo,p.45, (2009)

RIKEN 60 inch cyclotron

RF system was changed

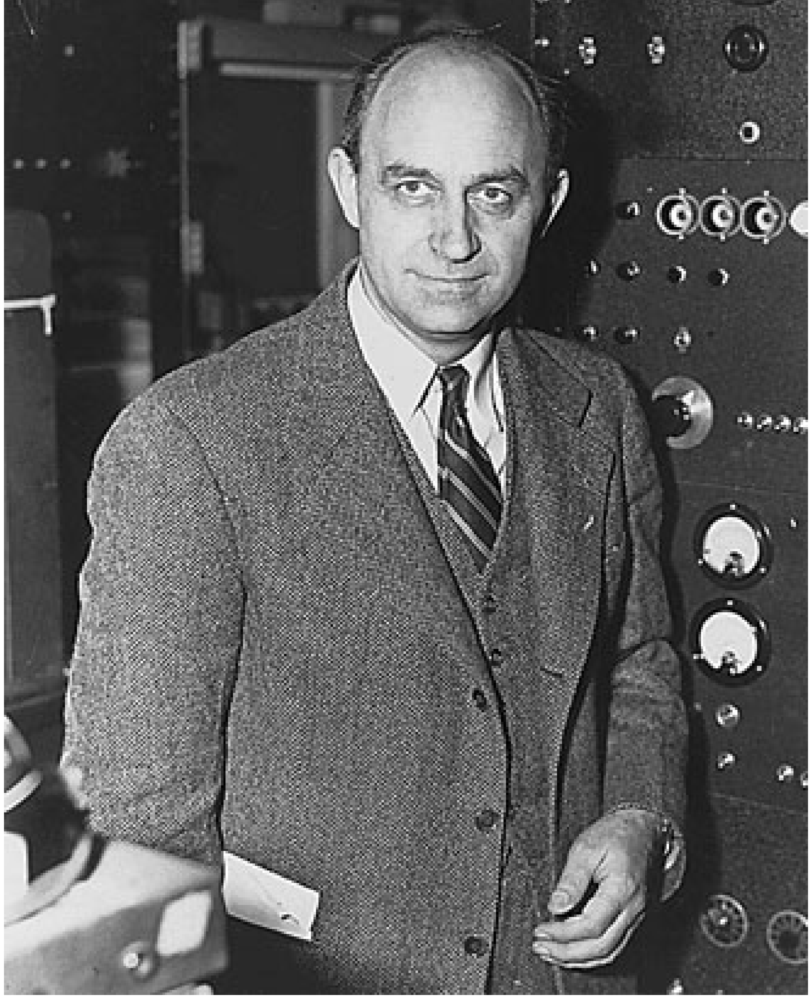
1938 Otto Hahn and Fritz Strassmann discover the process of fission in uranium.
1938 Lise Meitner and Otto Frisch confirm the Hahn-Strassmann discovery and communicate their findings to Niels Bohr.

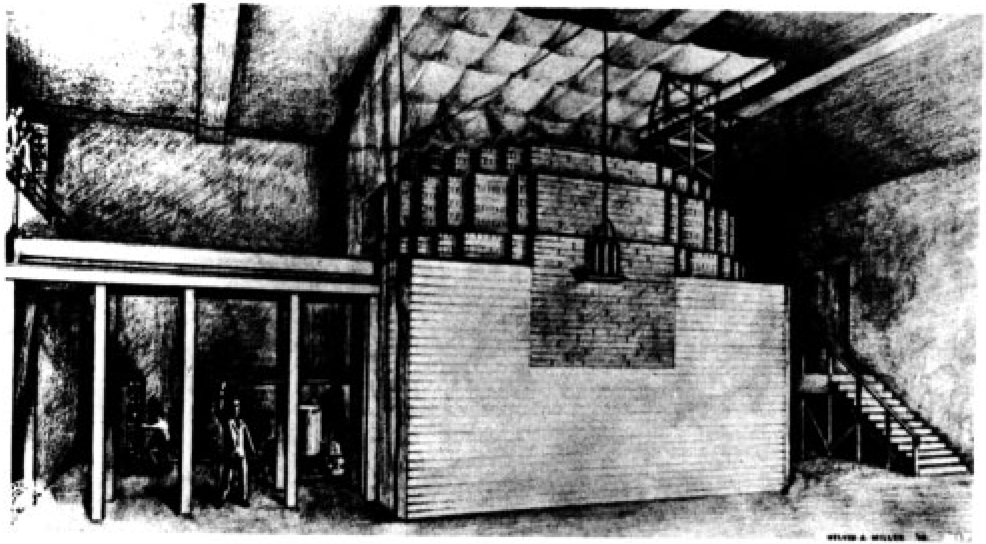


Lise Meitner Otto Hahn

January 26,1939
Bohr reports on the Hahn-Strassmann results at a meeting on theoretical physics in Washington, D. C

August 2, 1939
Albert Einstein writes President Franklin D. Roosevelt, alerting the President to the importance of research on chain reactions and the possibility that research might lead to developing powerful bombs.



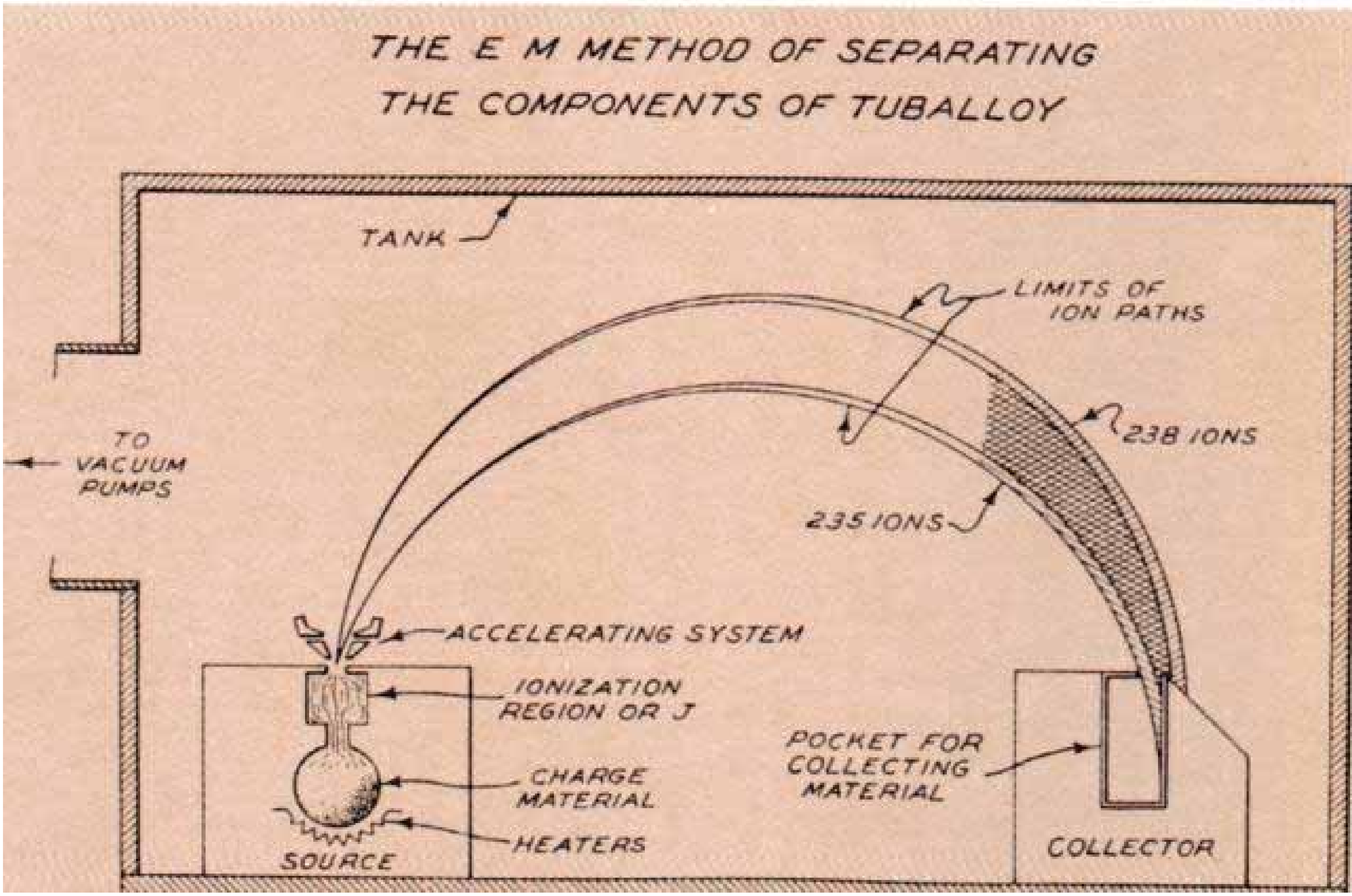


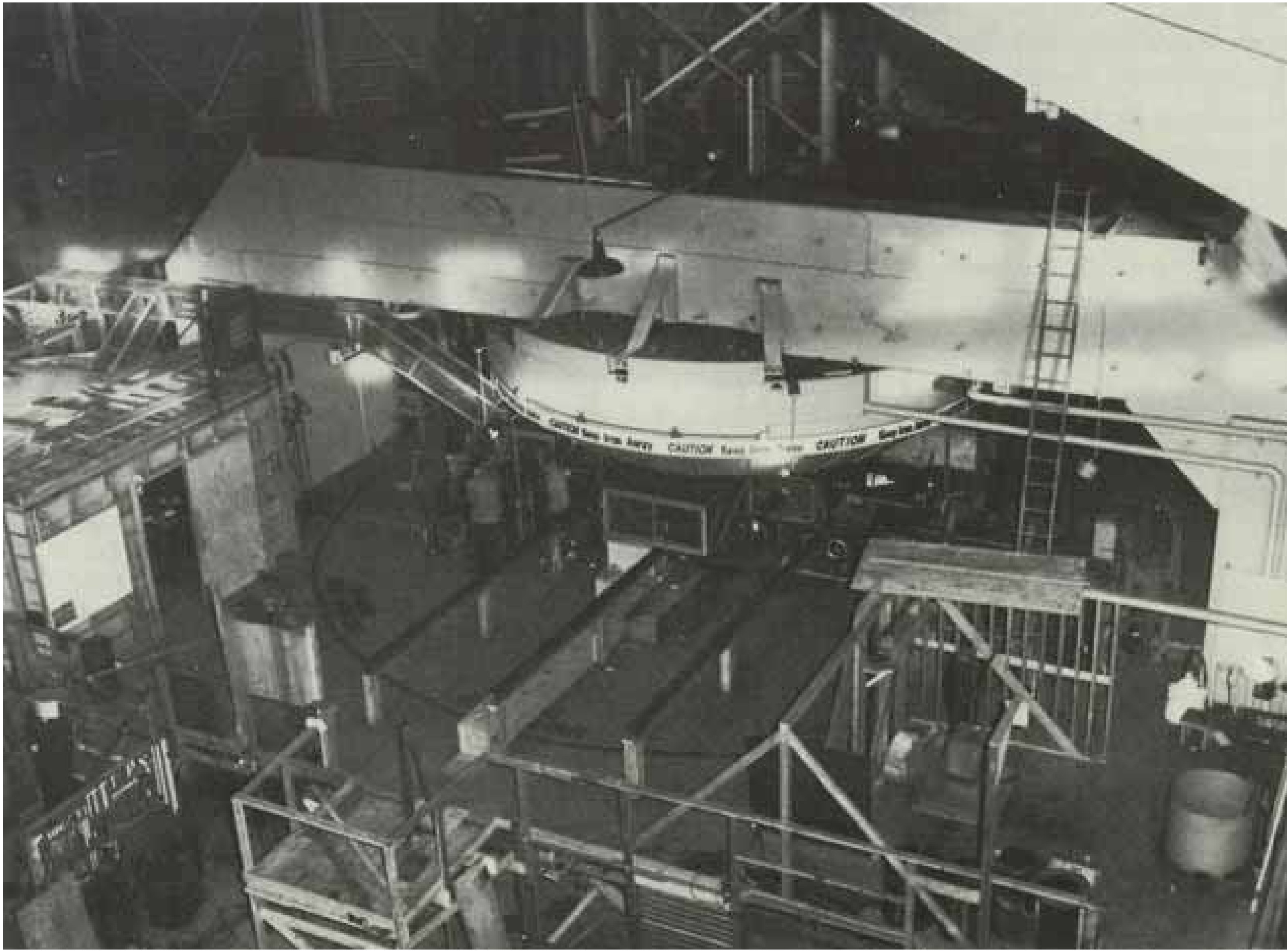
Fermi and Chicago pile

February 24, 1941 Glenn T. Seaborg's research group discovers plutonium.
November 25, 1942 Groves selects Los Alamos, New Mexico as the bomb laboratory (codenamed Project Y). Oppenheimer is chosen laboratory director.
December 2, 1942 Scientists led by Enrico Fermi achieve the first self-sustained nuclear chain reaction in Chicago.
February 1943 Groundbreaking for the X-10 plutonium pilot plant takes place at Oak Ridge.

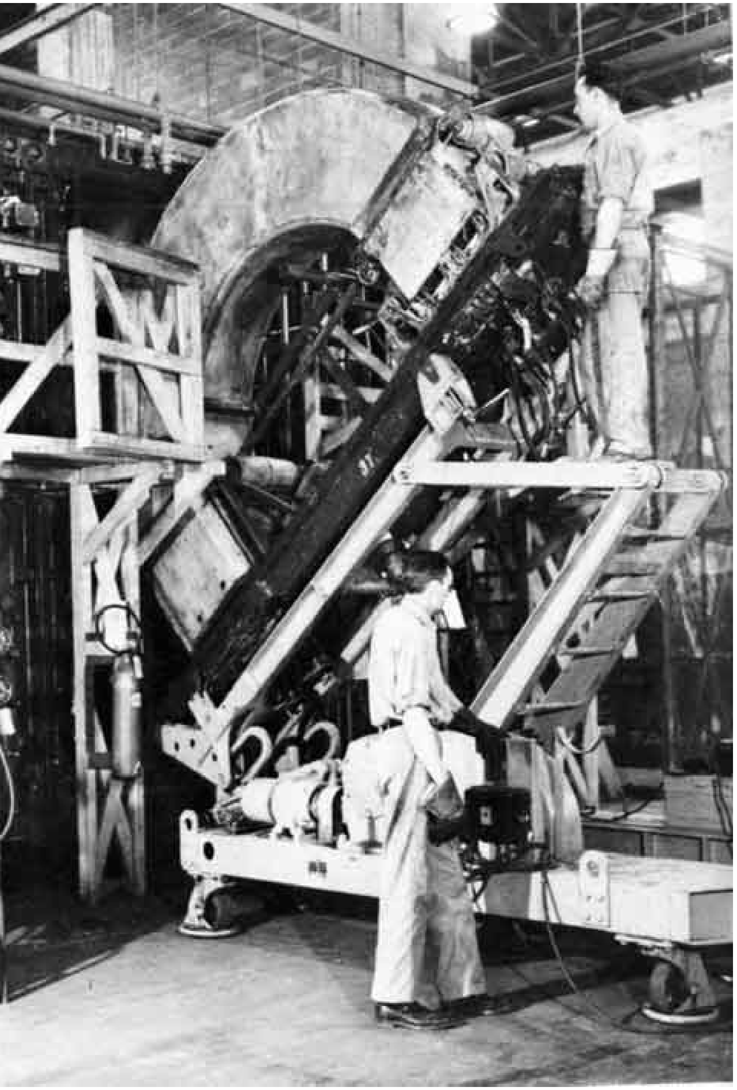
(L to R) **J. Robert Oppenheimer, E. Fermi, and Ernest O. Lawrence**

Principle of the Calutron

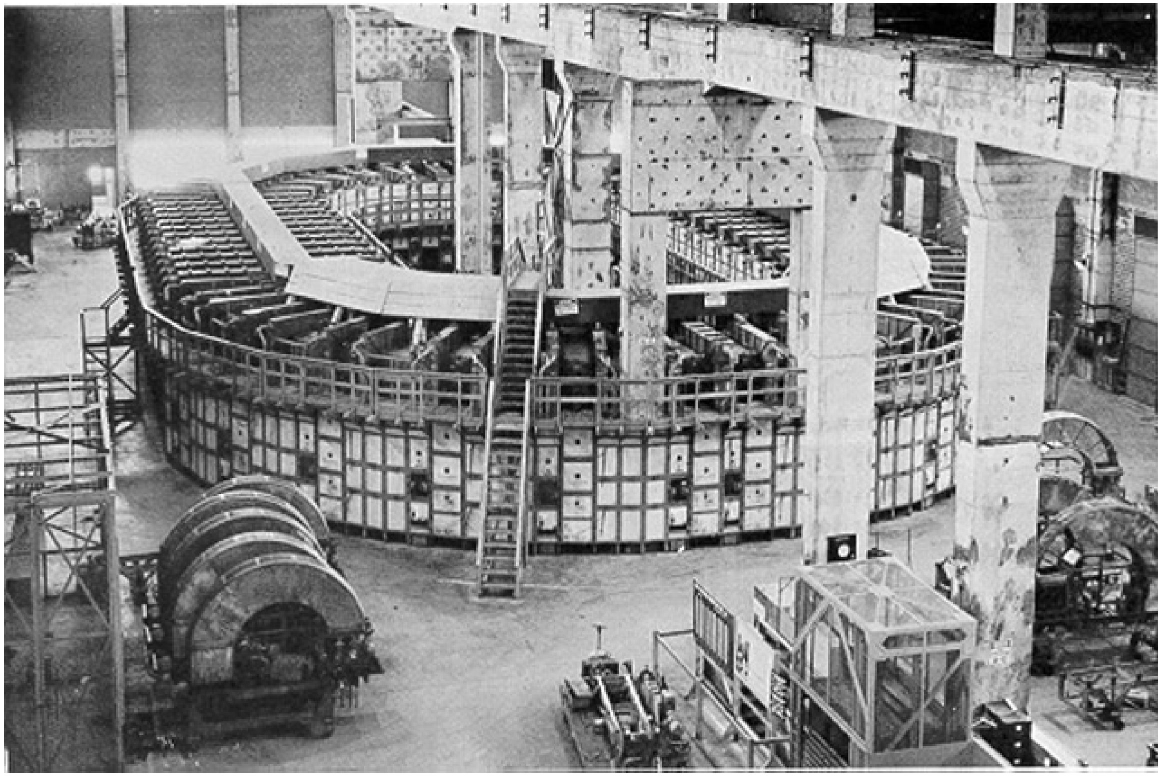




The to-be 184inch cyclotron magnet modified to prove the principle of the Calutron



One of the Calutron tanks

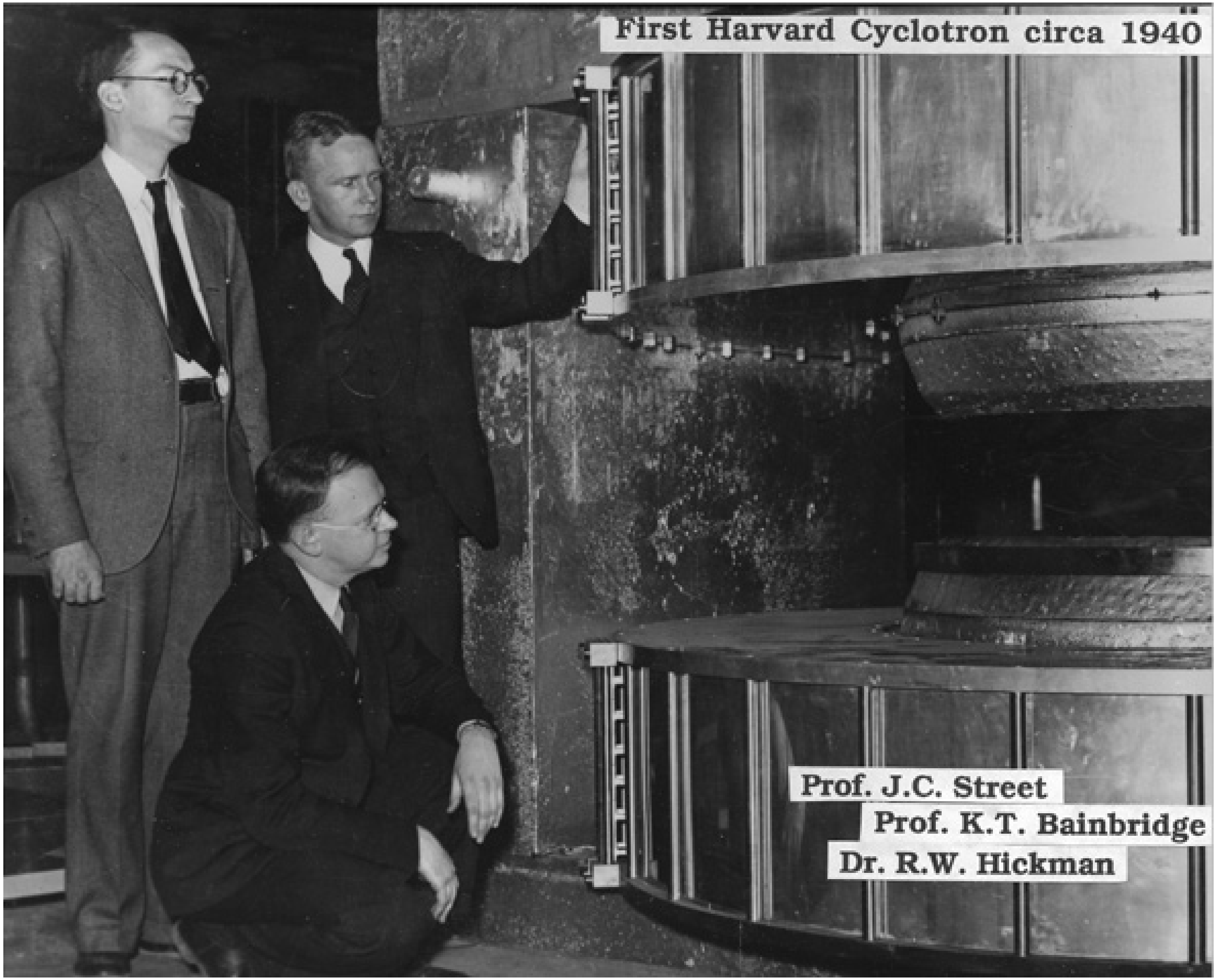


One of the nine alpha-Calutron race trucks

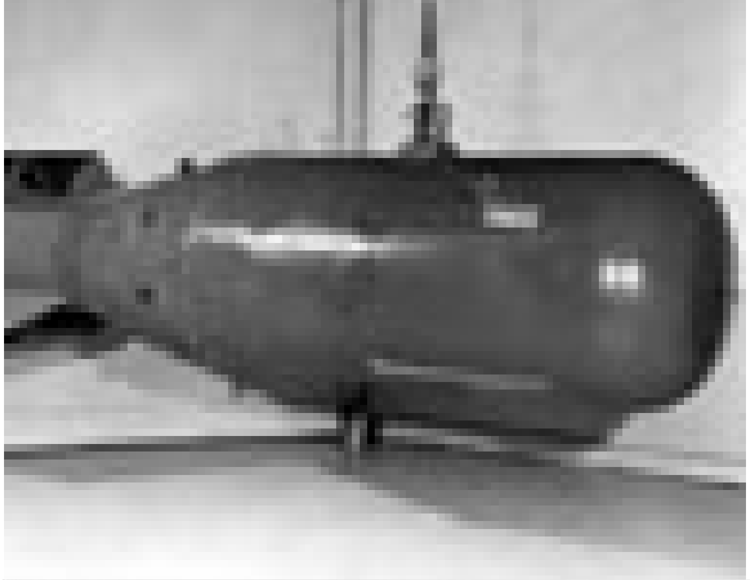
Each race truck contains 96 Calutron tanks

February 18, 1943   Construction of Y-12 (Calutron plant) begins at Oak Ridge

March 1943 Researchers begin arriving at Los Alamos.

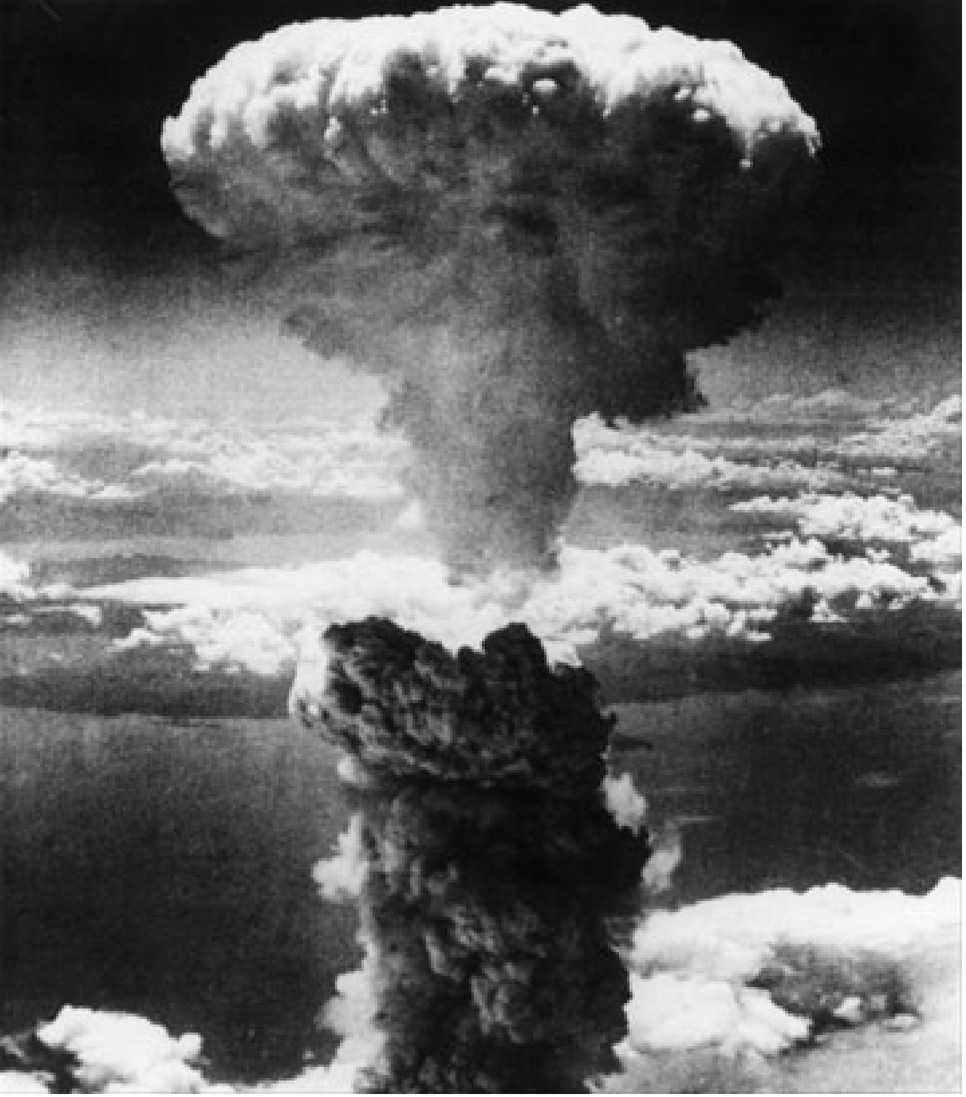


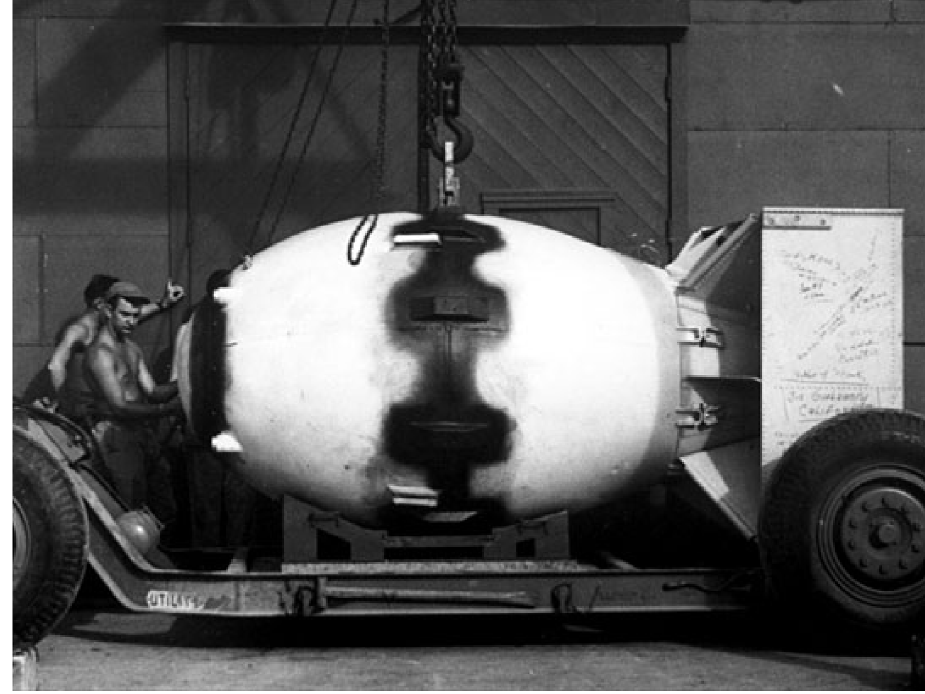
Harvard cyclotron was sent to Los Alamos



Uranium bomb

1945.8.6 Hiroshima





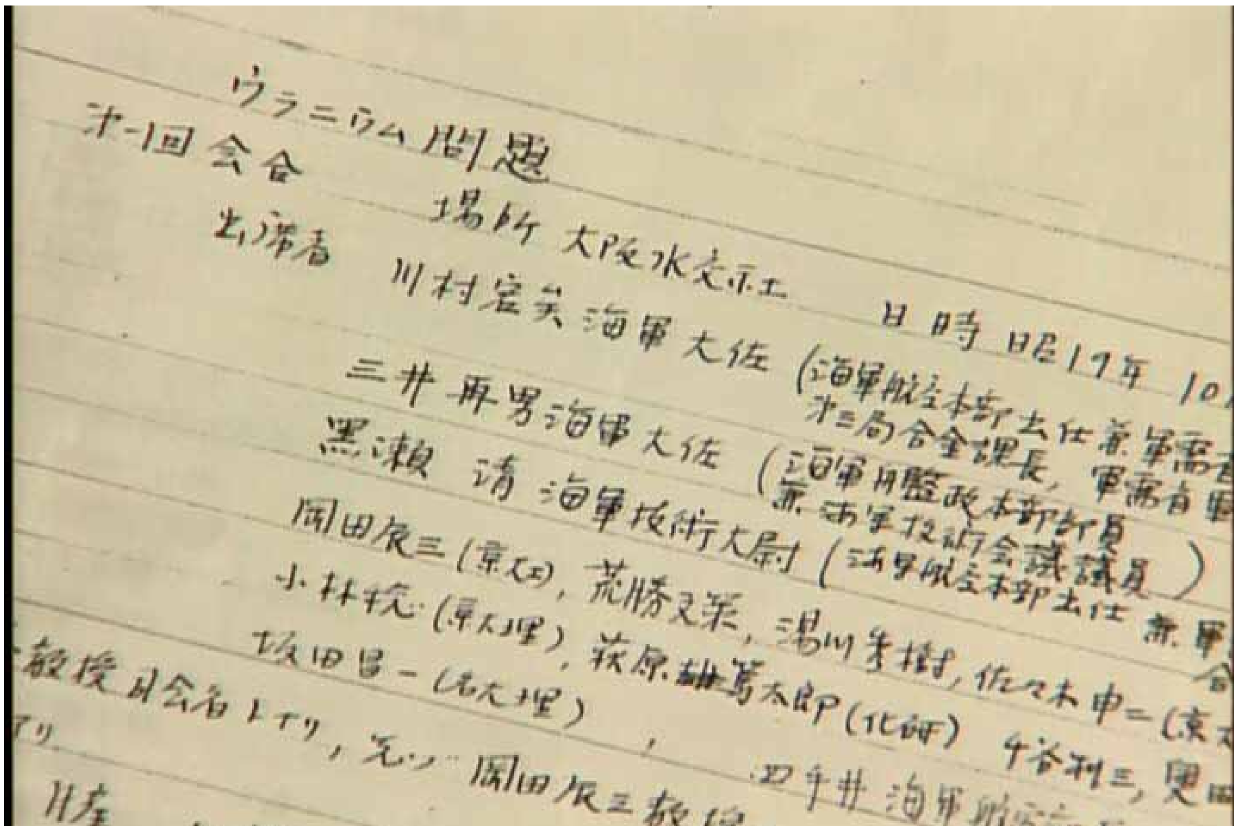
Plutonium bomb

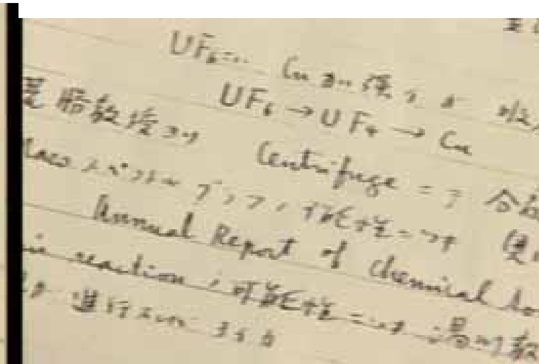
1945.8.9 Nagasaki

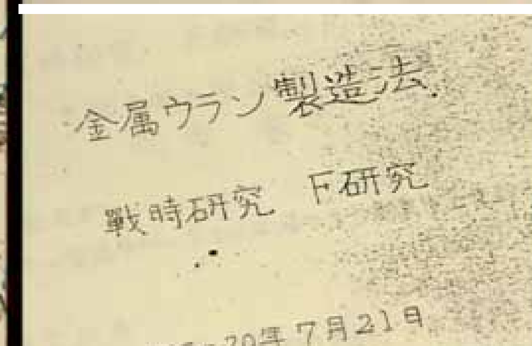
Japanese research of the atomic bomb

(Army)-(Nishina) Ni-gou project; A thermal diffusion method for uranium enrichment (not completed)

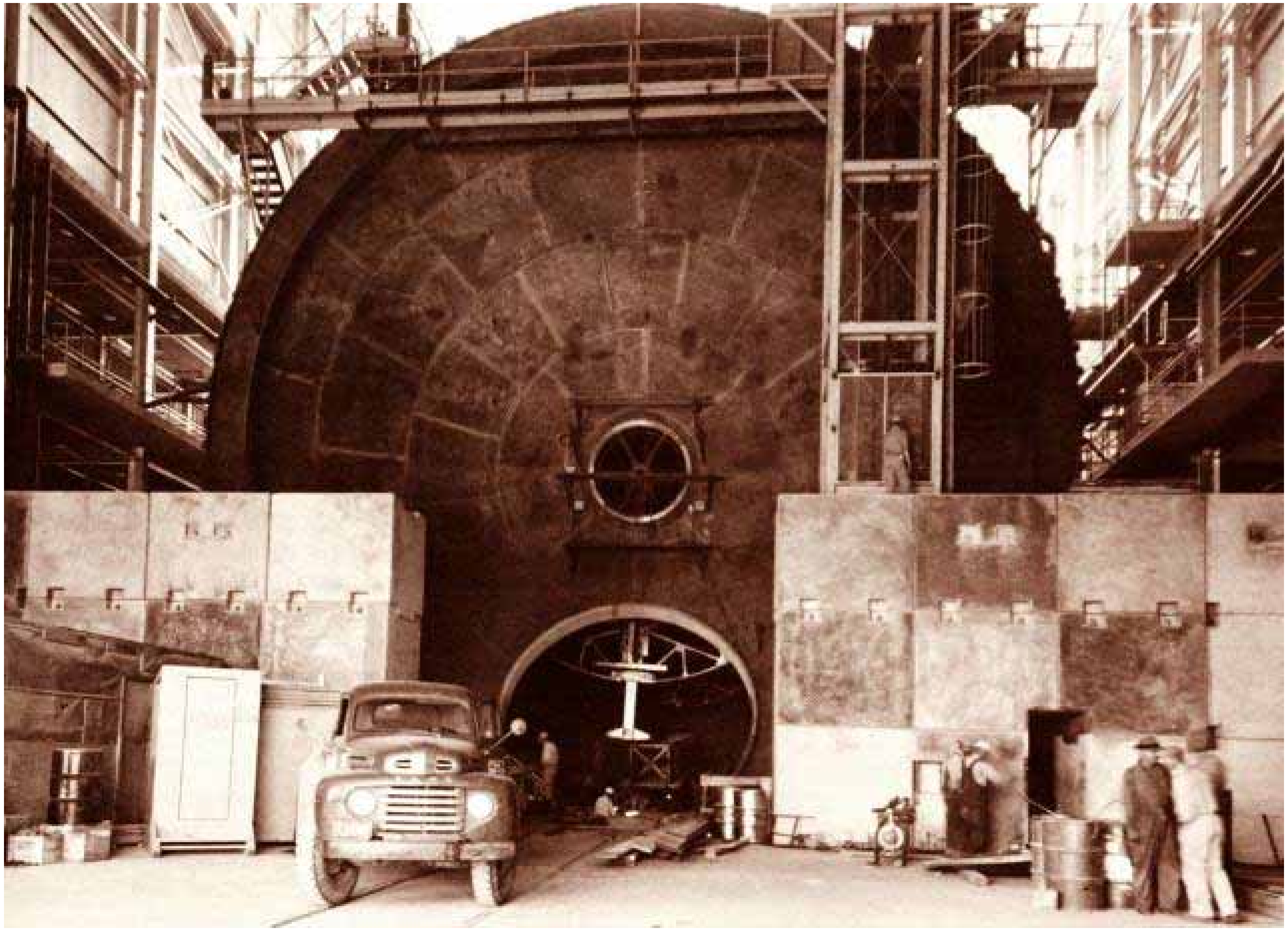
(Navy)-(Arakatsu) F project; A centrifugal method for the enrichment (not fabricated)





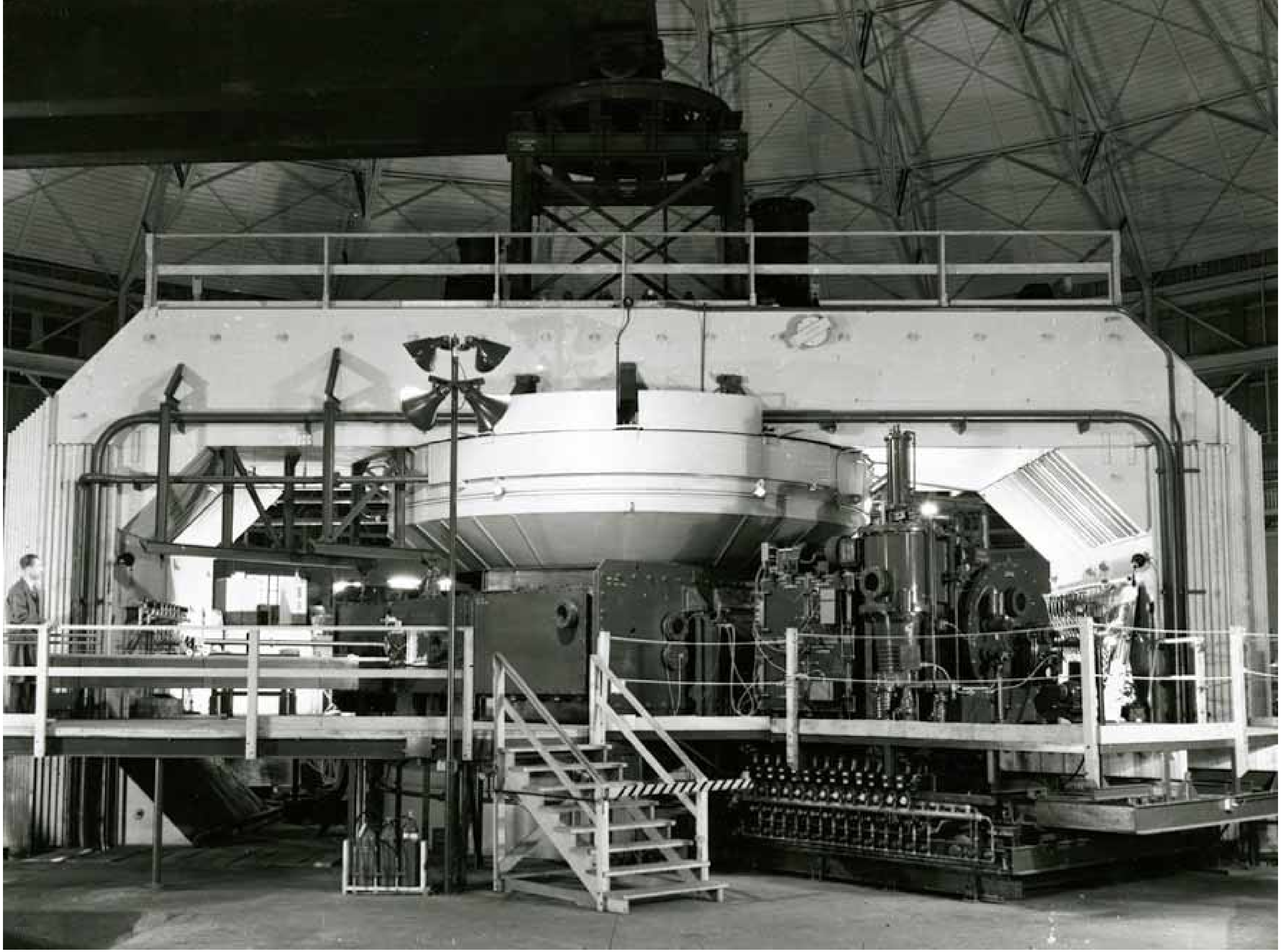


Kimura’s note of the F-project meeting

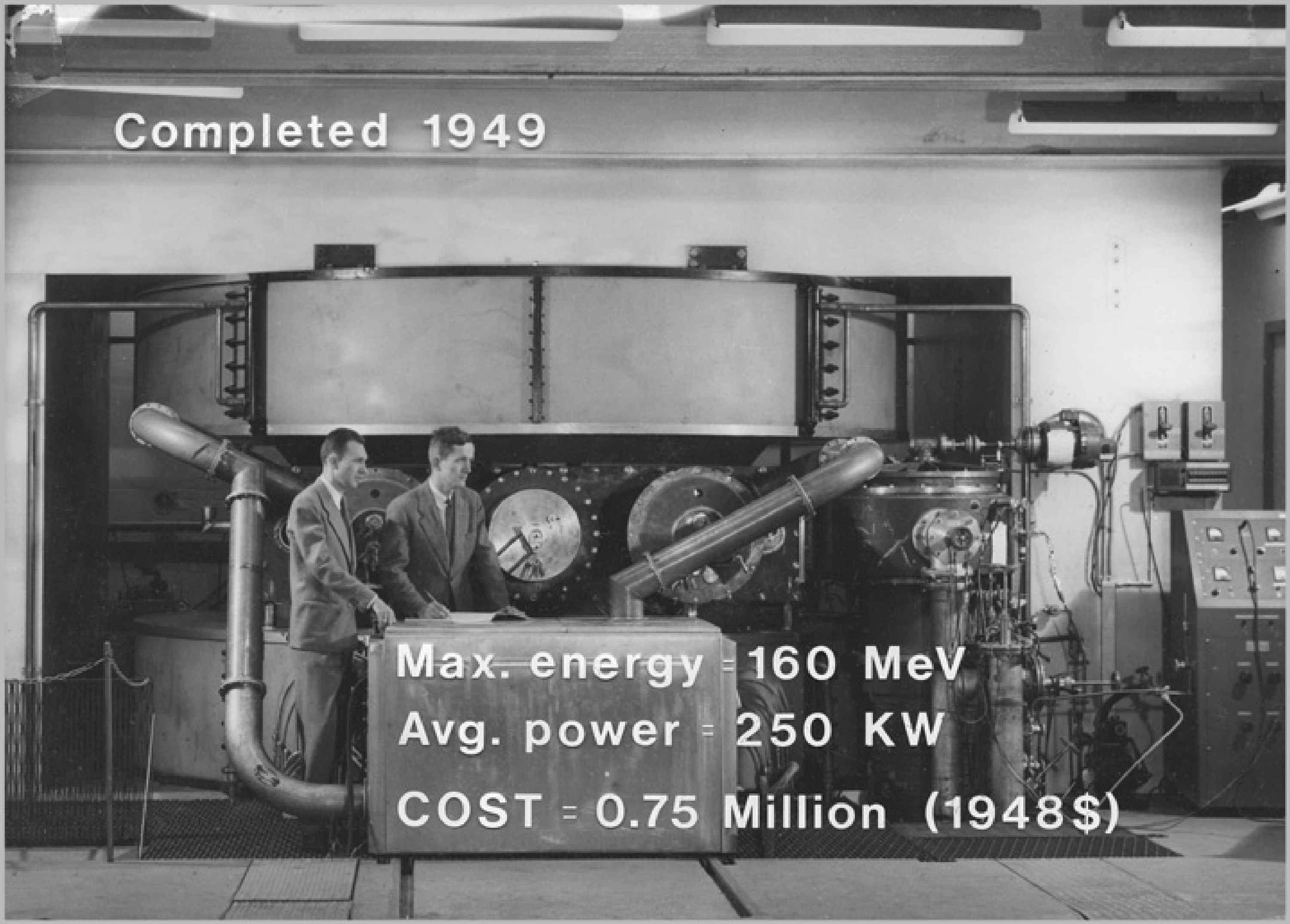


MTA mark I (25MeV deuteron linac 18m-18m)

Materials Testing Accelerator (MTA), was founded at the Livermore Auxiliary Naval Air Station



Berkeley 184 inch synchrocyclotron, 340MeV proton (1946)



(L) Dr. Lee Davenport (R) Dr. Norman Ramsey
June 10 1949

The Harvard cyclotron was rebuilt after the war.

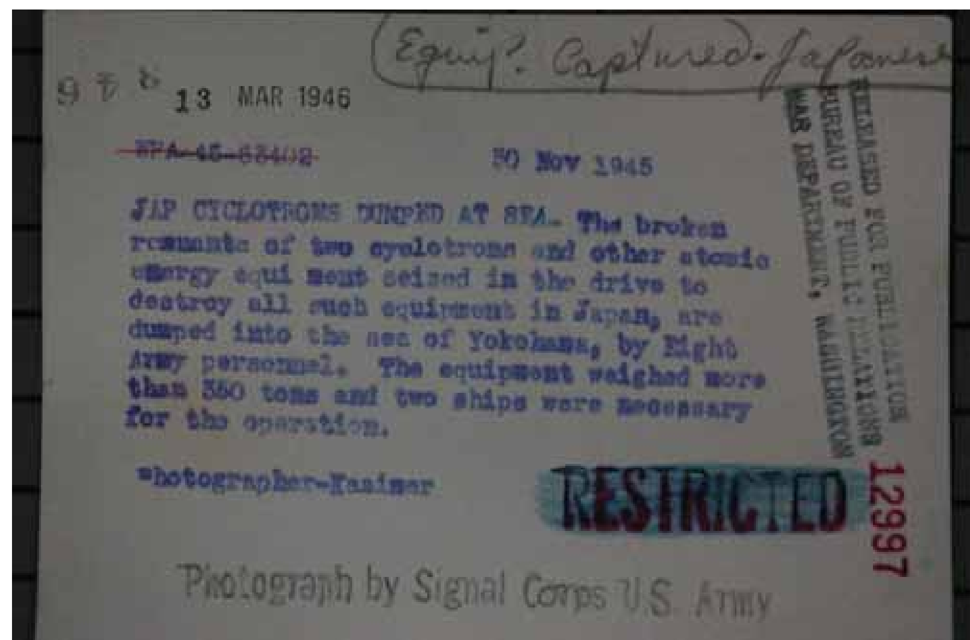
It became a proton therapy machine later.

RIKEN cyclotron destroyed by the occupation forces

1945 Nov.

Photo by U.S. Army 1945 Nov. 30, Yokohama. (U.S. National Archives)

Photo reported by LIFE 1945



Equip. Captured-Japanese

13 MAR 1946

~~SPA-45-63402~~

30 Nov 1945

JAP CYCLOTRONS DUMPED AT SEA. The broken remnants of two cyclotrons and other atomic energy equipment seized in the drive to destroy all such equipment in Japan, are dumped into the sea of Yokohama, by Eight Army personnel. The equipment weighed more than 380 tons and two ships were necessary for the operation.

Photographer-Kasimer

RELEASED FOR PUBLICATION
BUREAU OF PUBLIC RELATIONS
WAR DEPARTMENT, WASHINGTON

RESTRICTED

12997

Photograph by Signal Corps U.S. Army

U：Osaka U. cyclotron destroyed (1945.11.24)

D：Kyoto U. cyclotron destroyed (1945.11.24)

（U.S. National Archives）

Reconstruction in Japan

Lawrence recommended to the GHQ to restart fundamental nuclear science in Japan, and came to Japan to encourage Japanese physicists.

RIKEN reconstructed the small cyclotron
Osaka university and Kyoto University also reconstructed their cyclotrons.

Later the Institute for Nuclear Study (INS) was established at University of Tokyo as a joint-use laboratory to open all Japanese scientists.
A classical cyclotron which could also operated as a synchrocyclotron was built at the INS.

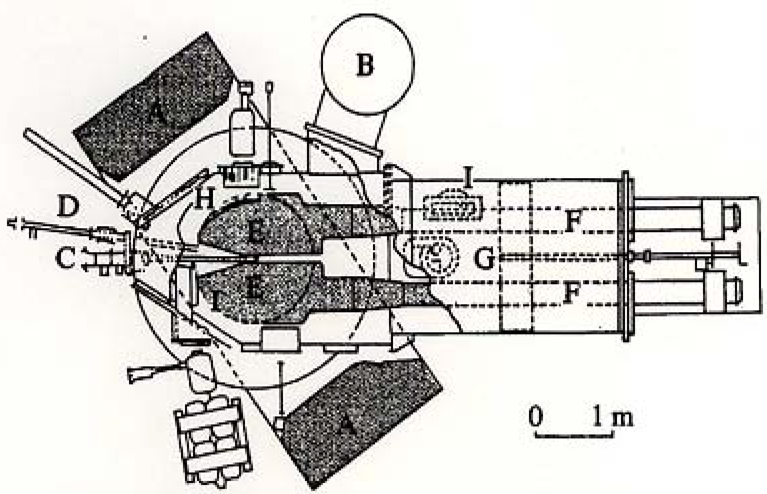


図1 FF（周波数固定）モードのサイクロトロン構造. 主たる部分; A: 磁気ヨーク, B: 32インチ拡散ポンプ, C: イオン源, D: ビームプローブ, E: ディー, F: ステム, G: 短絡板, H: rf デフレクター, I: 磁気チャンネル.

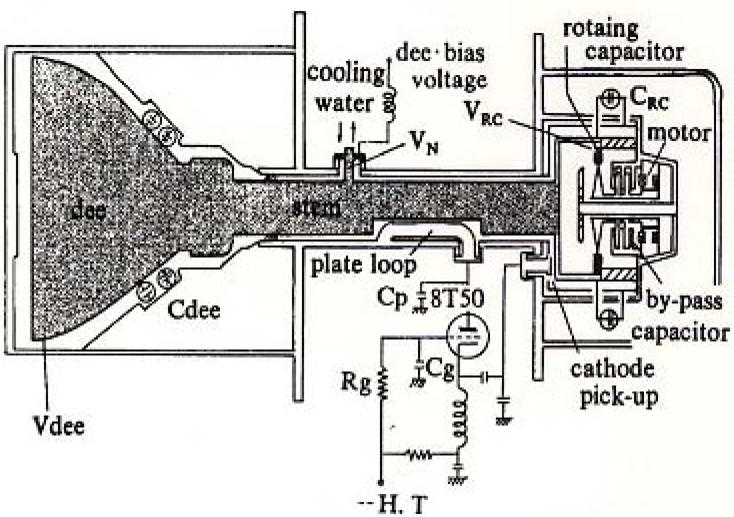


図2 FM（周波数可変）モードのサイクロトロン高周波系概念図.

Low energy nuclear physicists hope high quality and high intensity accelerator -- large electrostatic tandem accelerators and isochronous cyclotrons.

Intermediate energy physics -- Meson factory (PSI, TRIUMF, LAMPF)

Heavy ion physics -- MSU, GANIL, RIKEN, Lanzhou

Progress in accelerators for high energy physics

Higher intensity -- FFAG synchrotron (MURA study by electron analogues)

Higher energy -- Large synchrotron (separated-function and cascade machine proposed by Kitagaki) (FNAL and CERN-SPS, KEK-PS)

Much higher energy at CM system -- Collider machine (LHC, KEK-B …..)

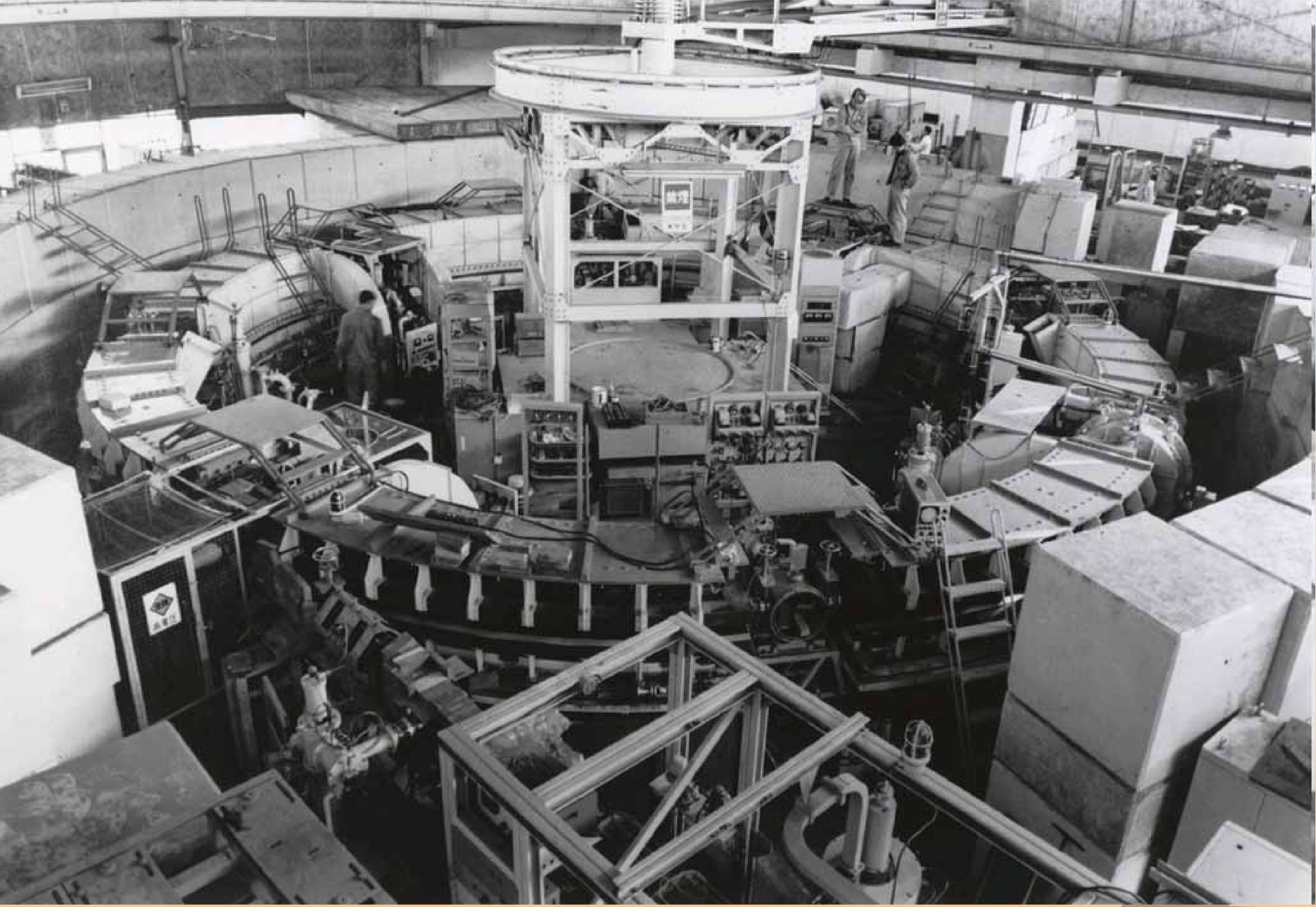
CERN LHC

In Japan – future plan age after establishment of the INS

Particle physicists began to construct the 1.3GeV electron synchrotron at the INS for design study of a future proton synchrotron. Later they established KEK in 1971 and constructed the12GeV proton synchrotron.

Nuclear physicists established also in 1971 another center at Osaka (RCNP), where a 230cm AVF cyclotron was constructed. Later using this cyclotron as an injector, the RCNP built a ring cyclotron.

Then the high energy physicists hoped to build an electron-positron collider (TRISTAN) at KEK, and nuclear physicists hoped a high-energy heavy-ion synchrotron (NUMATRON) at INS. TRISTAN won. NUMATRON was not funded

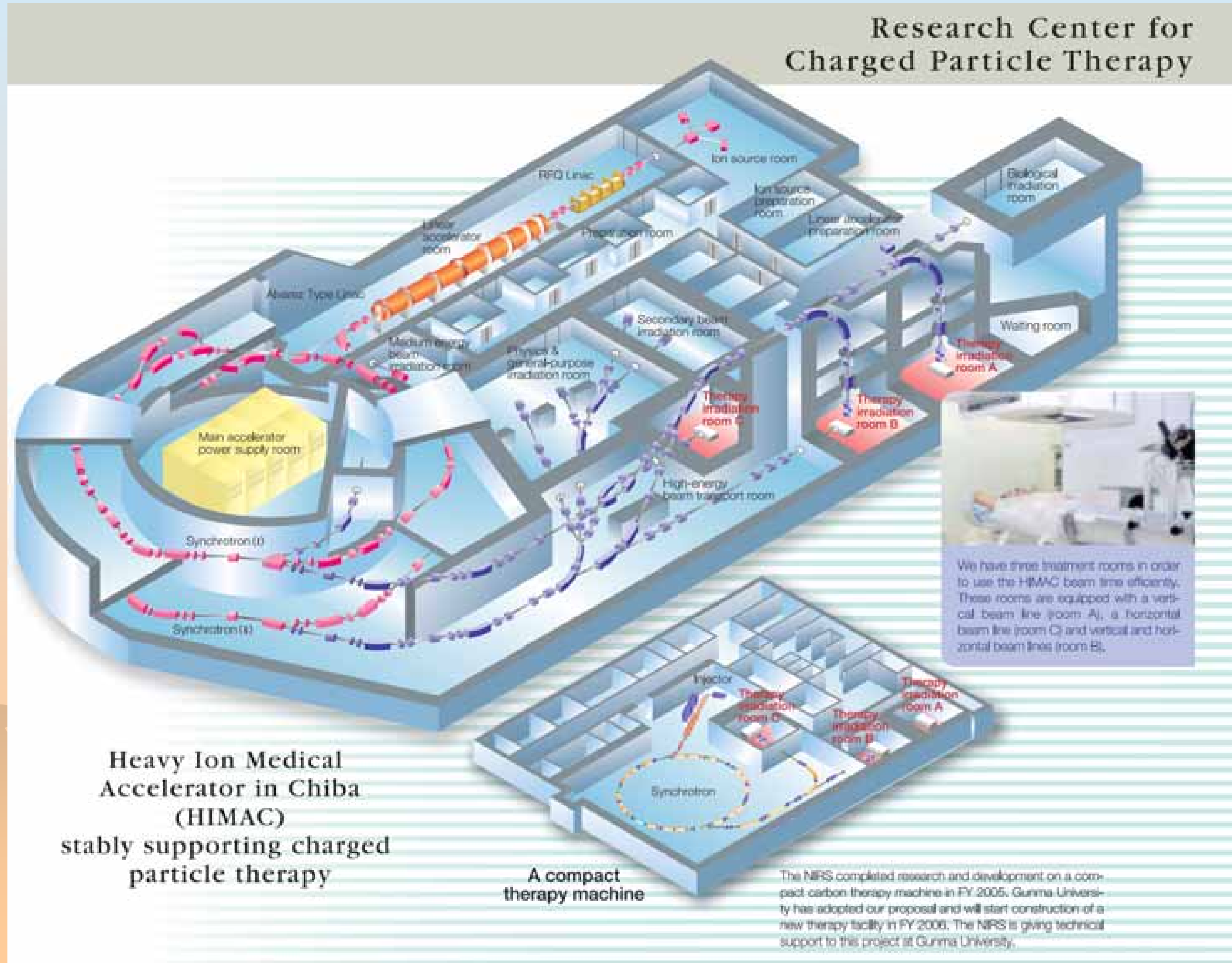


INS 1.3GeV electron synchrotron

KEK

Science and Technology Agency (STA) comes to build advanced large accelerators.

Some members of NUMATRON group moved from INS to NIRS to build a heavy ion therapy synchrotron **HIMAC**, Then STA established **Spring-8**. Another heavy ion group constructed a heavy ion separated sector cyclotron at RIKEN, which is now followed by **RIBF**.



XFEL and SPring-8

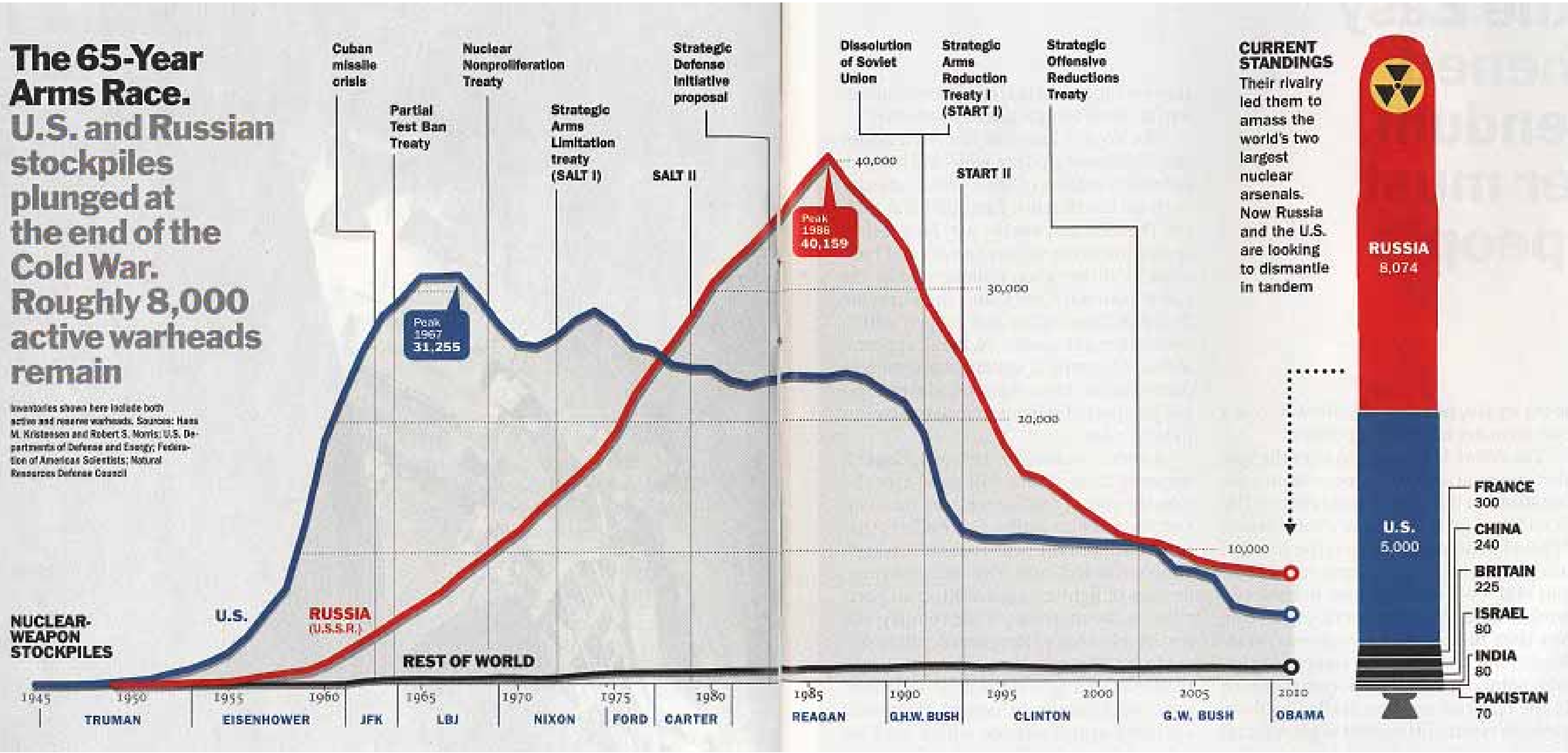
RIKEN super-conducting separated-sector cyclotron of RIBF

On the other hand, nuclear physicists at INS planned a high-intensity proton-accelerator for multi-purpose as a future plan of the INS after abandon of NUMATRON project. After KEK-B started as TRISTAN-II, the INS merged in the KEK to promote the future plan of the INS. Then after STA merged in Ministry of Education, the KEK collaborated to establish J-PARC with JAERI, which had so far planned to construct a high intensity proton linac as a future plan,.

J-PARC

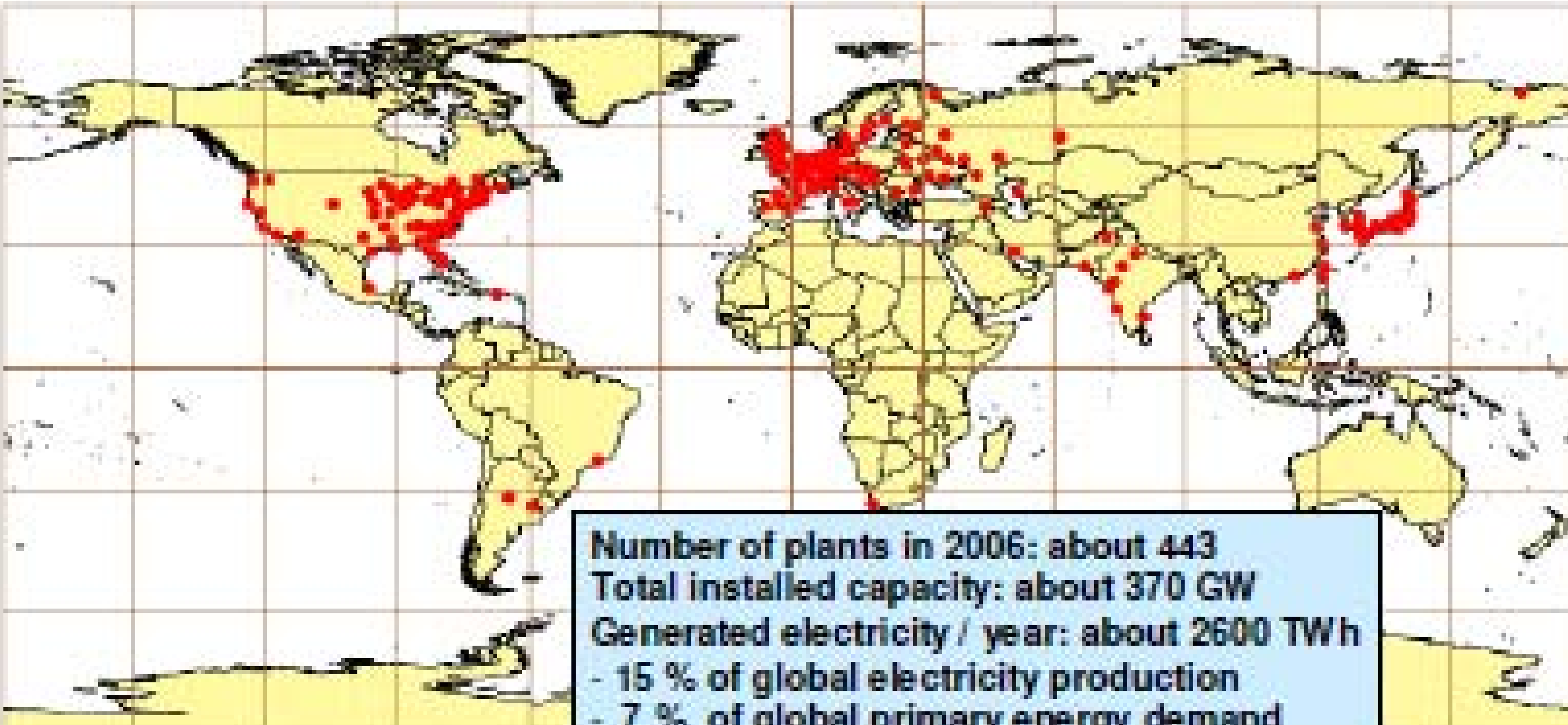
Atoms for Peace

President Eisenhower's speech at the UN general assembly in 1953



TIME, vol. 176, no. 13, pp30-31, Sep. 27, 2010

Nuclear Power Sites of the World



Number of plants in 2006: about 443
Total installed capacity: about 370 GW
Generated electricity / year: about 2600 TWh
- 15 % of global electricity production
- 7 % of global primary energy demand

UNEP/DEWA/GRID-Geneva

Copernicus Institute
Sustainable Development and Innovation

Japanese fundamental law of atomic energy (1955)

Only for peace

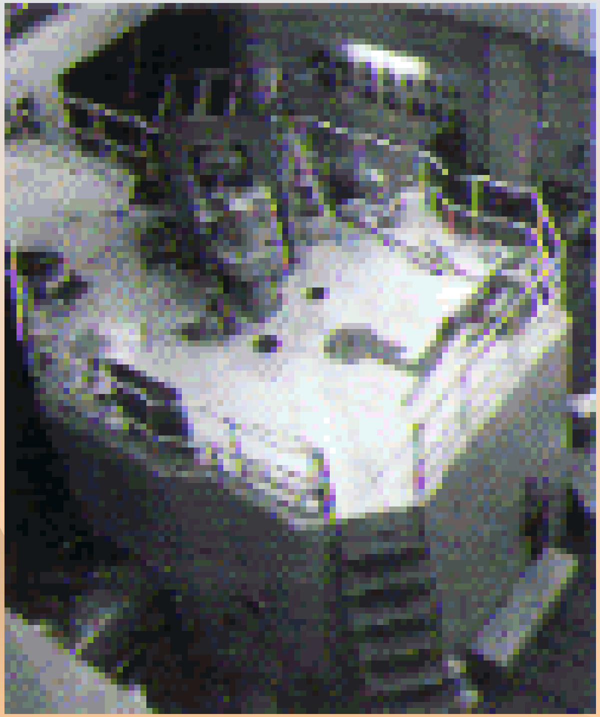
Yukawa Tomonaga Sakata

Leading particle physicists concerned nuclear science and engineering in the beginning
Then the nuclear engineering researcher began to lead the policy of the atomic energy.

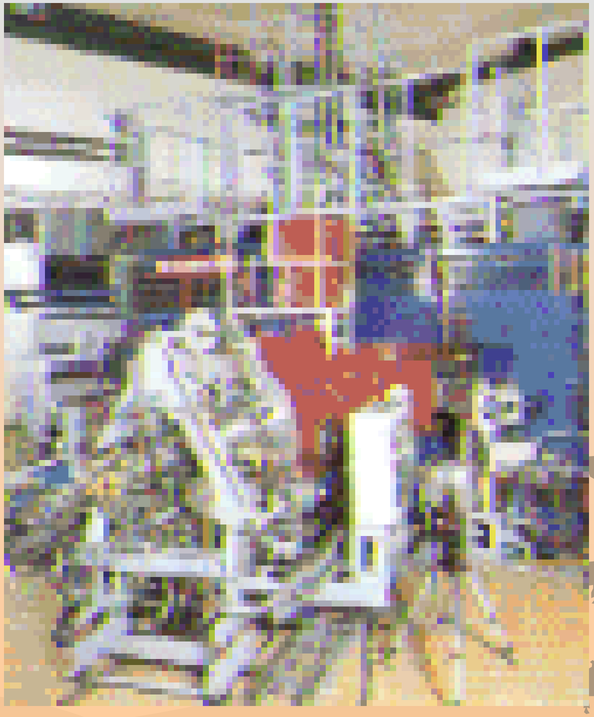
Science and Technology Agency (STA) and Japan Atomic Energy Research Institute (JAERI) were established in 1956 to promote the ‘atoms for peace’ of Japan. (STA does not financially support the universities)

At the JAERI

Not only nuclear reactors (neutron source, power station) but also accelerators (electron linac as a neutron source, a large electrostatic Tandem accelerator for nuclear science, AVF cyclotron for irradiation, etc) were built.



JRR-1(1957)



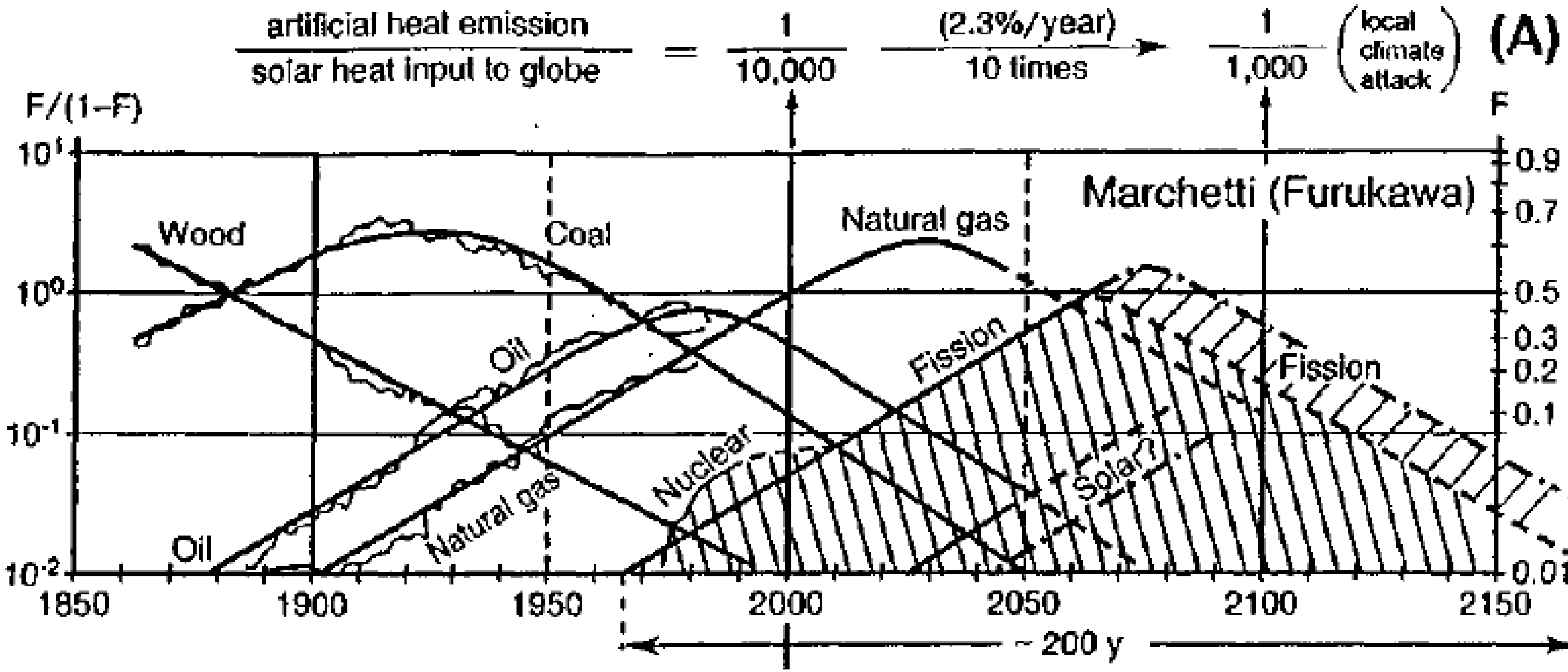
AVF cyclotron (1990)

Japan Nuclear Cycle development Institute (JNC) established in 1998 modifying the Power Reactor and Nuclear Fuel Development Corporation (PNC) that was established in 1967.

A main facility of the JNC is ‘Monju’, which is an FBR.

JNC merged in JAERI and became Japan Atomic Energy Agency (JAEA) in 2005.

FBR ‘Monju’



Furukawa’s view of energy resource

IAEA-TECDOC-1319 (2002)

Proposals of accelerator driver

In 1950, Ernest O. Lawrence proposed the Material Testing Accelerator (MTA). The project was abandoned in 1954.
In 1952, W. B. Lewisin proposed to use an accelerator to produce 233U from thorium, soon abandoned.

In the 1980's and beginning of the 1990's
In Japan (OMEGA project at Japan Atomic Energy Research Institute).
In the USA (Hiroshi Takahashi et al. A proposal of a fast neutron hybrid system at Brookhaven for minor actinide transmutation. Charles Bowman a thermal neutron molten salt system based on the thorium cycle at Los Alamos).

“Neutron multiplication factor” M

The number of fissions produced by a single fission in the proceeding cycle : reproduction factor; k

$$M = 1 + k_{eff} + k_{eff}{}^{2} + k_{eff}{}^{3} + k_{eff}{}^{4} + \ldots\ldots = \frac{1}{1 - k_{eff}}$$

k_{eff}**<1; subcritical**

k_{eff}**=1; critical**

The OMEGA project

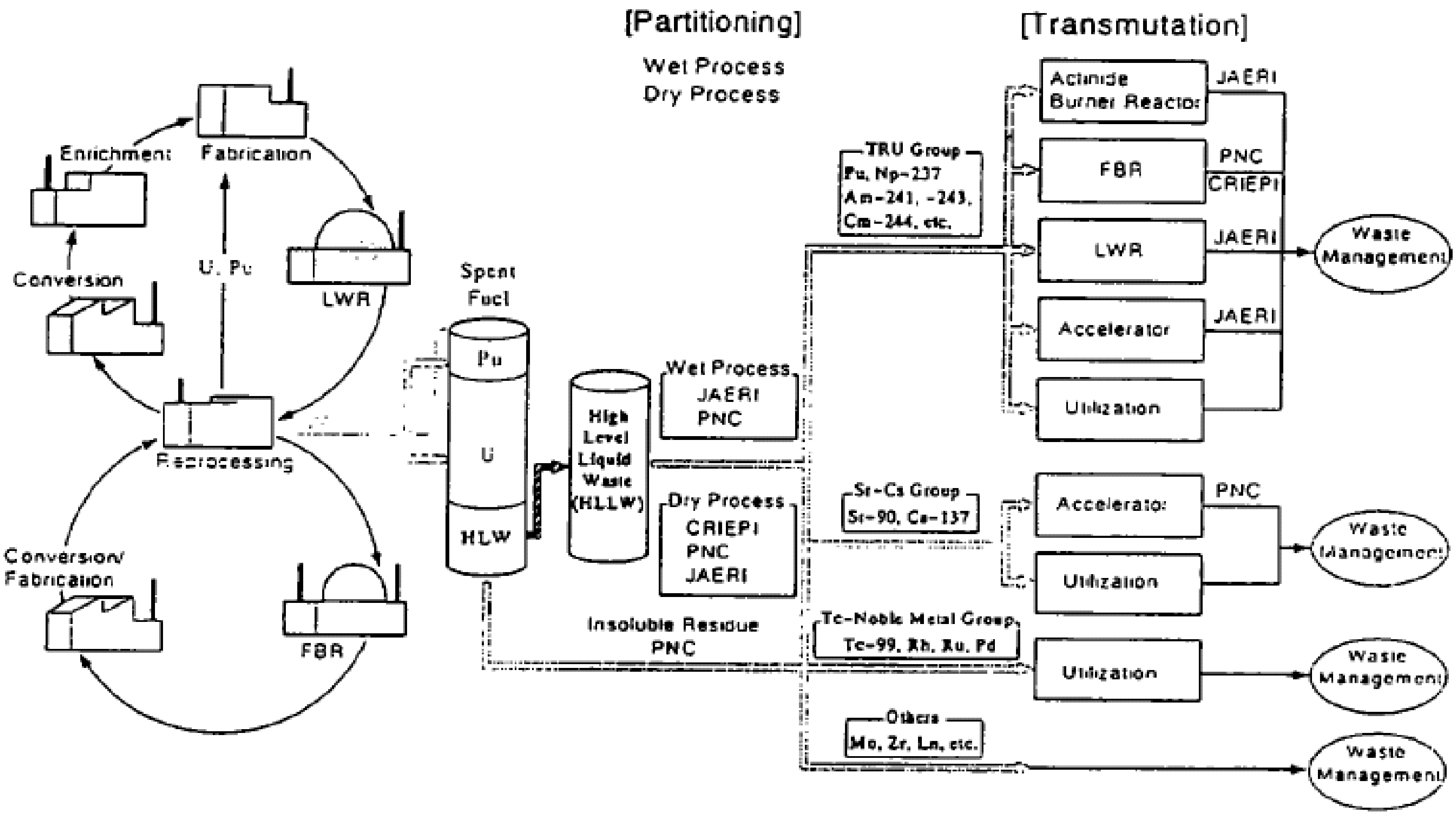


FIG. 1. P-T R&D activities under OMEGA Program.

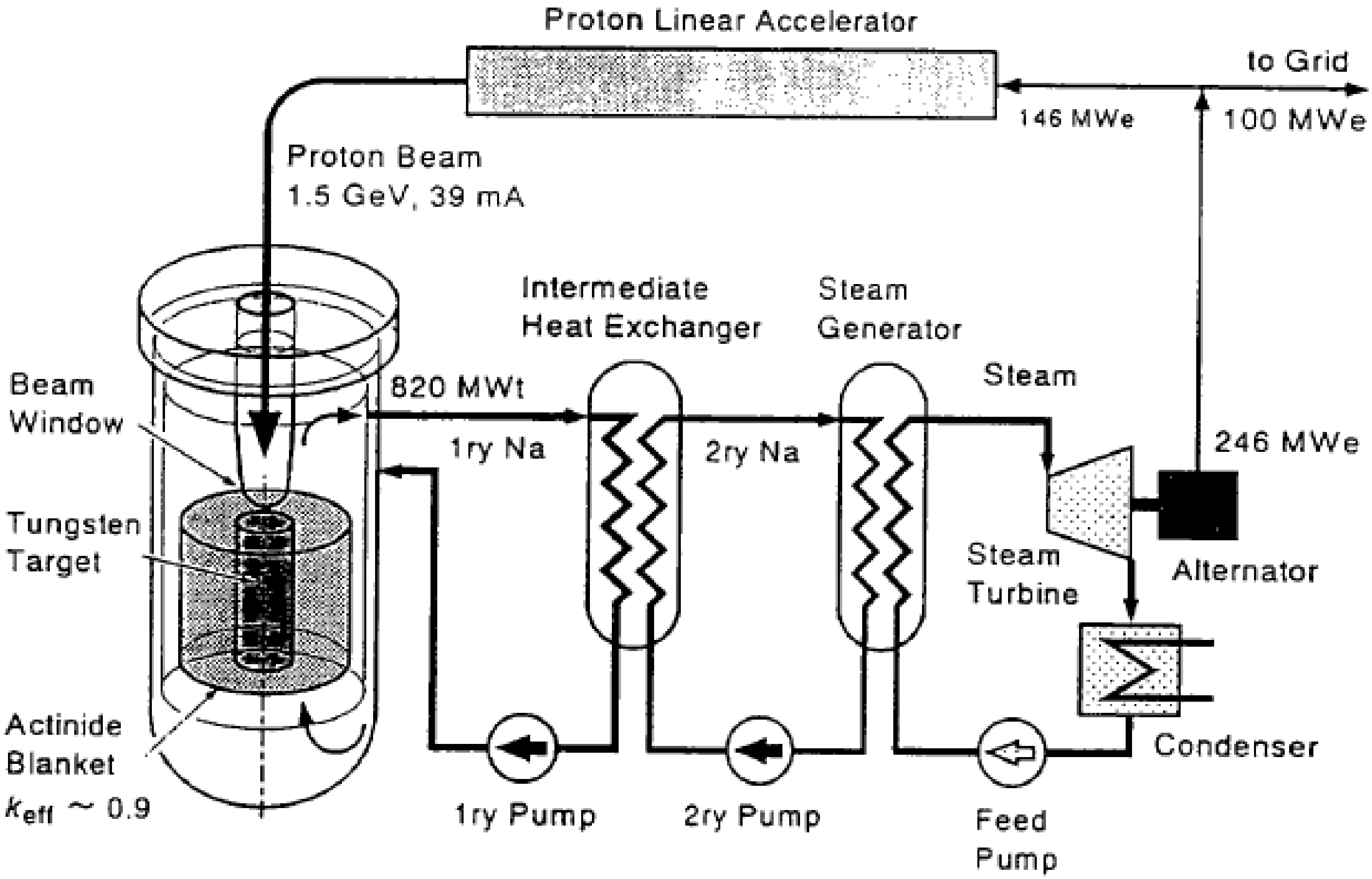
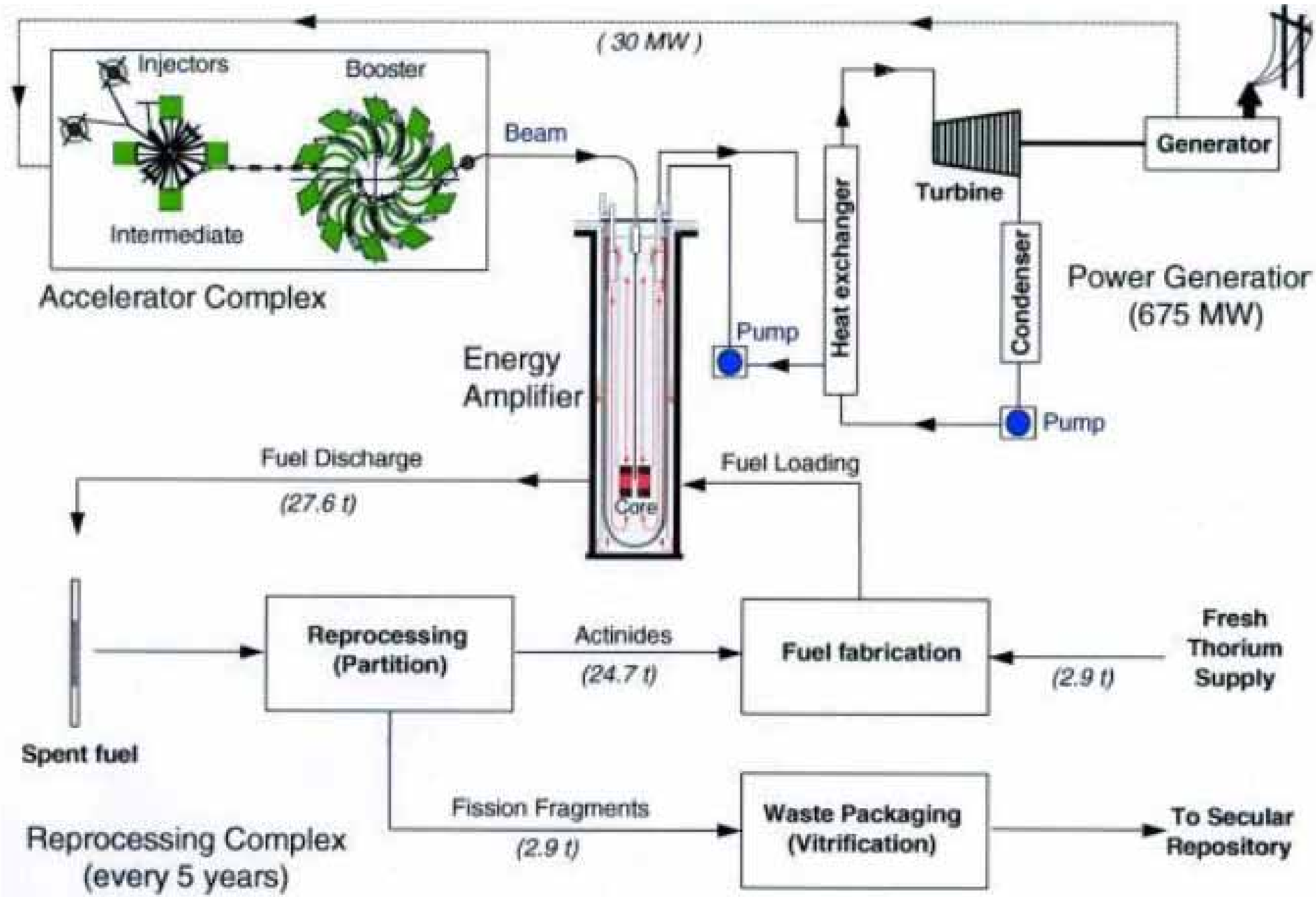


FIG. 3. Concept of accelerator-driven transmutation system.

In 1993, Carlo Rubbia proposed, in an exploratory phase, a first Thermal neutron Energy Amplifier system based on the thorium cycle, with a view to energy production.

Rubbia's energy amplifier



ADS research and development

What was claimed to be the world's first ADS experiment was begun in March 2009 at the Kyoto University Research Reactor Institute (KURRI), utilizing the Kyoto University Critical Assembly (KUCA). The research project was commissioned by Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) six years earlier. The experiment irradiates a high-energy proton beam (100 MeV) from the accelerator on to a heavy metal target set within the critical assembly, after which the neutrons produced by spallation are bombarded into a subcritical fuel core.

The Indian Atomic Energy Commission is proceeding with design studies for a 200 MWe PHWR accelerator-driven system (ADS) fuelled by natural uranium and thorium. Uranium fuel bundles would be changed after about 7 GWd/t burn-up, but thorium bundles would stay longer, with the U-233 formed adding reactivity. This would be compensated for by progressively replacing some uranium with thorium, so that ultimately there is a fully-thorium core with in situ breeding and burning of thorium. This is expected to mean that the reactor needs only 140 tU through its life and achieves a high burn up of thorium - about 100 GWd/t. A 30 MW accelerator would be required to run it.

http://ww.world-nuclear.org/info/inf35.html

Kyoto University Critical Assembly (KUCA)

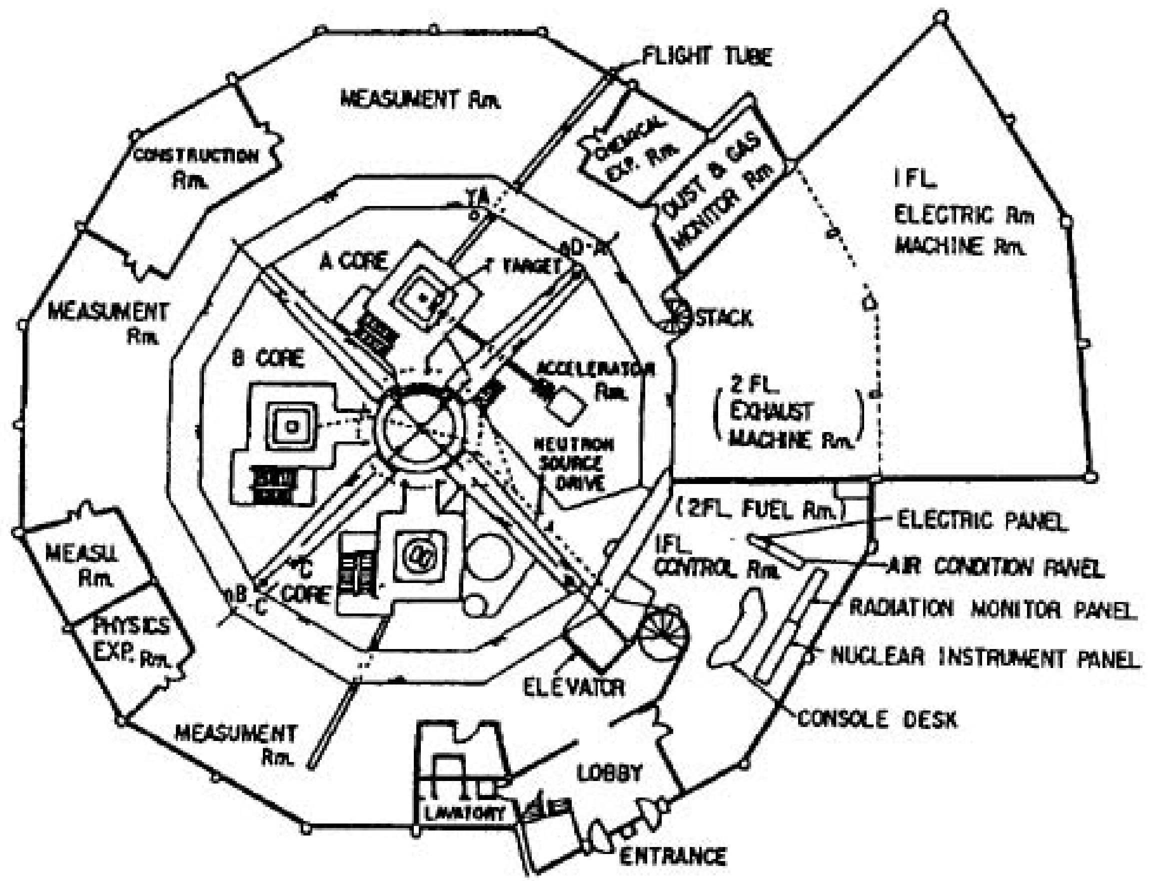


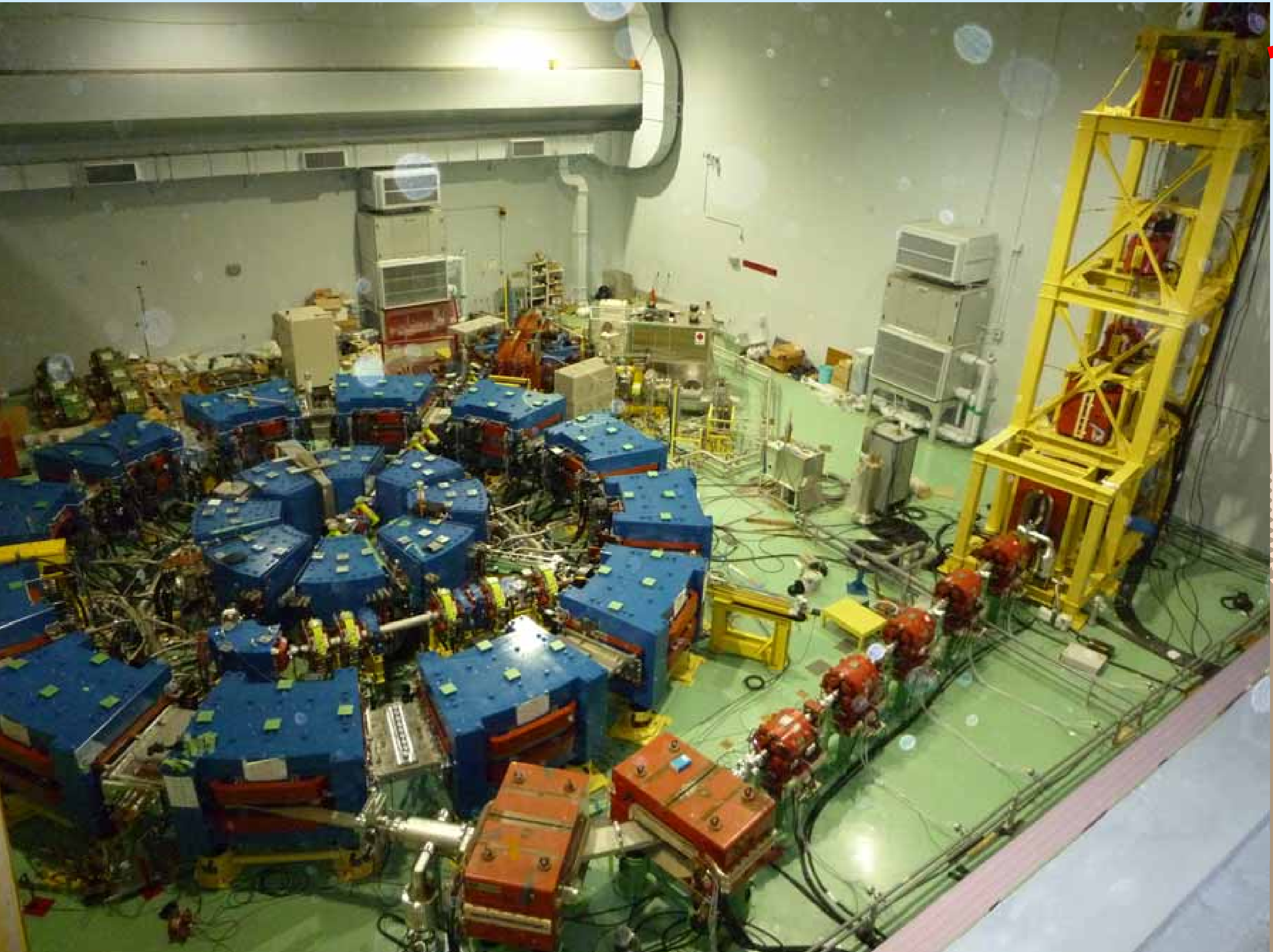
Figure 1. Horizontal cross section of the KUCA building

ASSESSMENT OF ^{232}TH NUCLEAR DATA THROUGH CRITICAL EXPERIMENTS USING THE KYOTO UNIVERSITY CRITICAL ASSEMBLY*

S. SHIROYA, H. UNESAKI, T. MISAWA
Kyoto University,

IAEA-TECDOC-1319 (2002)

FFAG complex at KURRI



Beam to KUCA

KUCA as a sub-critical target of the ADS

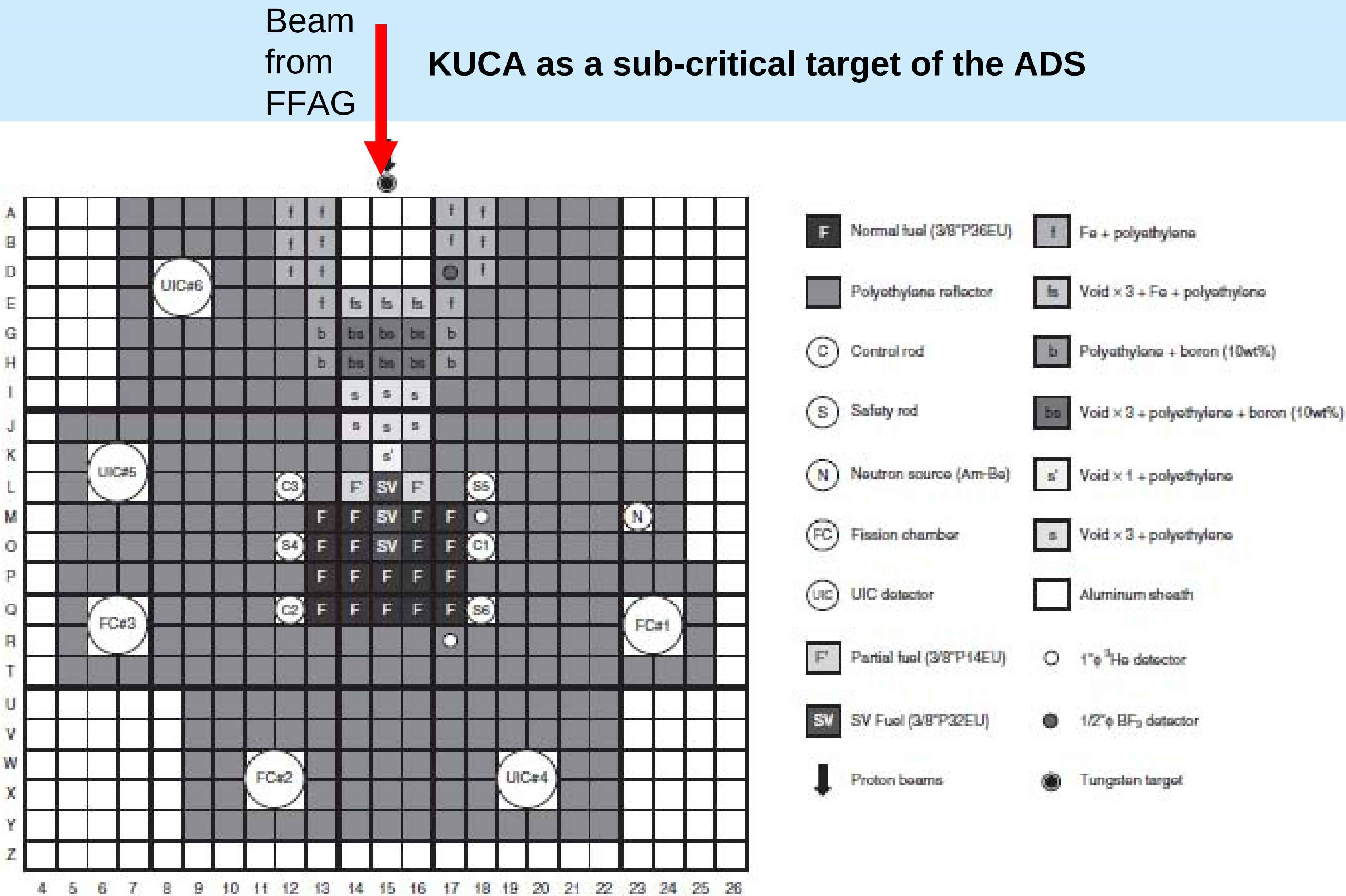
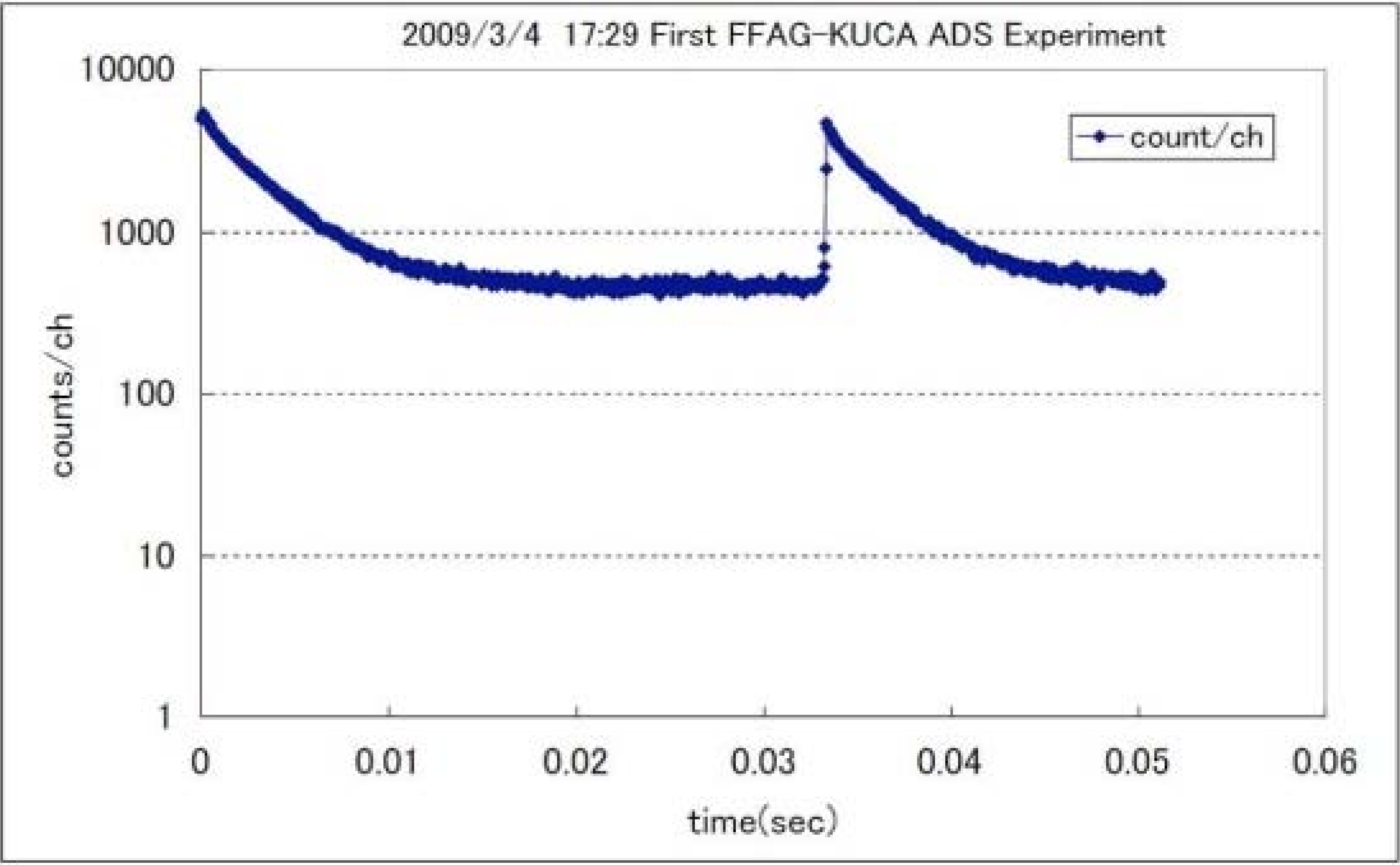


Fig. 1 Top view of the configuration of A-core in the ADS experiments with 100 MeV protons


2009/3/4 17:29 First FFAG-KUCA ADS Experiment
count/ch
counts/ch
10000
1000
100
10
1
0
0.01
0.02
0.03
0.04
0.05
0.06
time(sec)

European ADS project

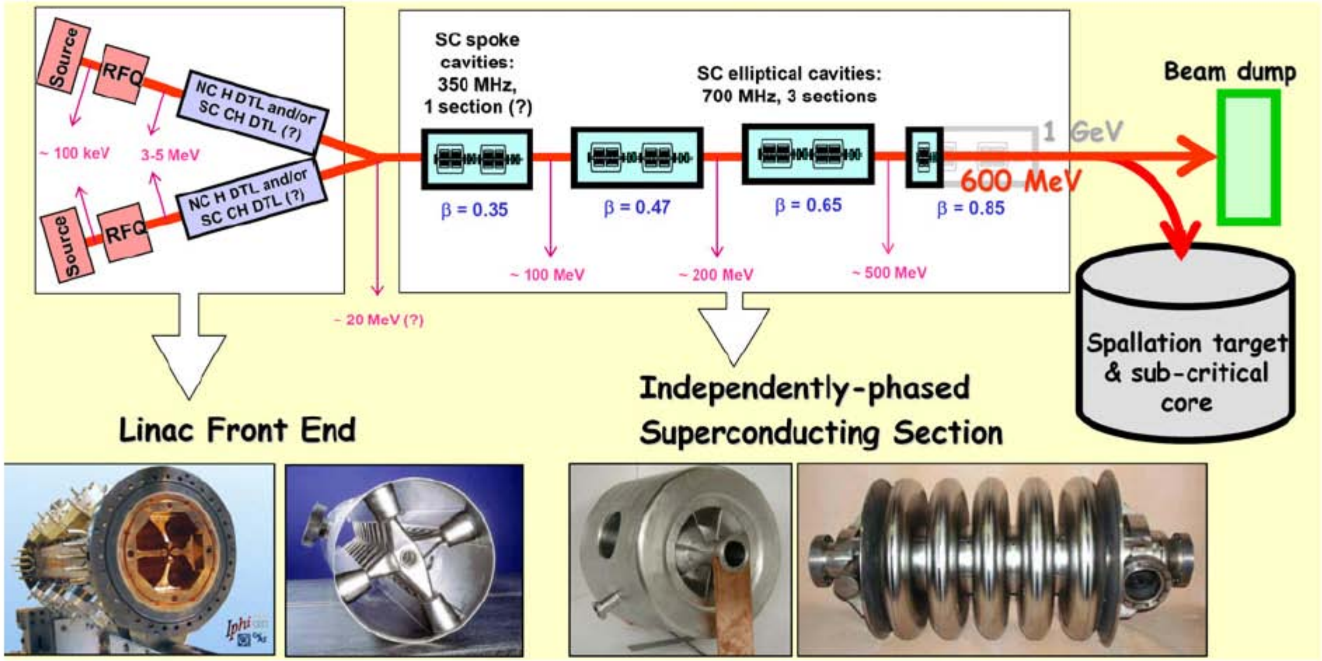


Figure 1: European ADS accelerator conceptual scheme.

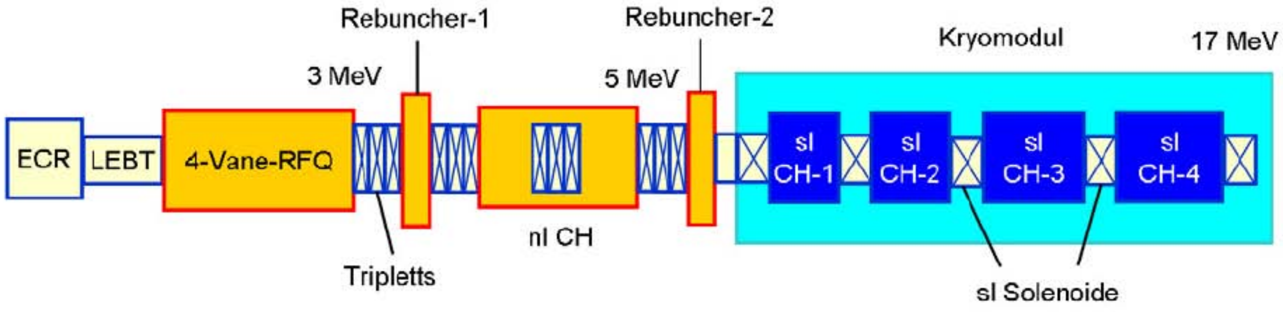
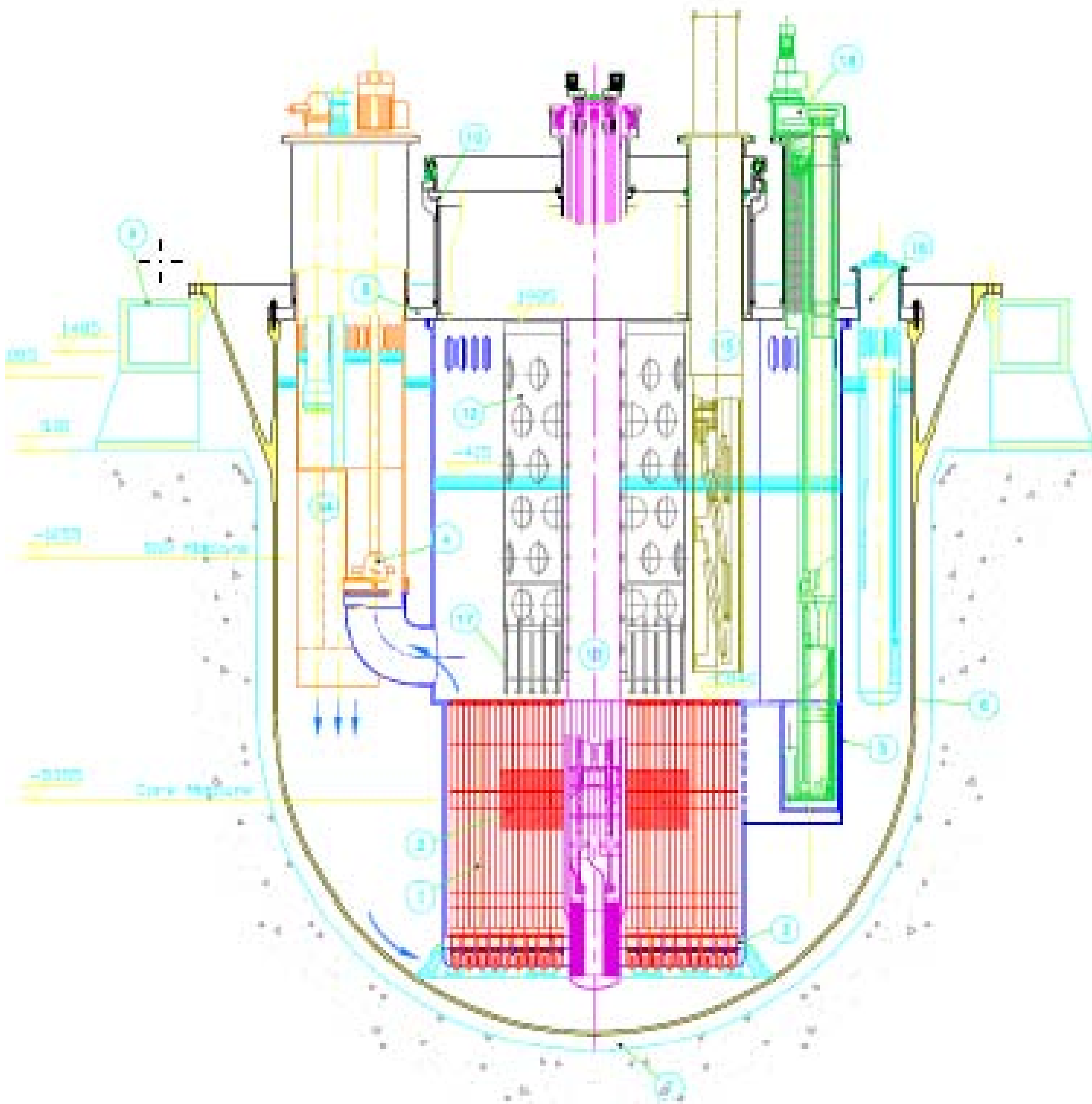


Figure 2: The reference linac front-end.

Table 1: European Transmuter Main Specifications

Transmuter demo (XT-ADS / MYRRHA project)	**Industrial transmuter (EFIT)**
50 – 100 MWth power	Several 100 MWth power
k_{eff} value ~ 0.95	k_{eff} value ~ 0.97
Highly-enriched MOX fuel	Minor Actinide fuel
Pb-Bi Eutectic coolant & target	Pb coolant & target



European-ADS EFIT (lead coolant pool type, 400MWt)

GENEPI-3C is a neutron generator for ADS purposes.

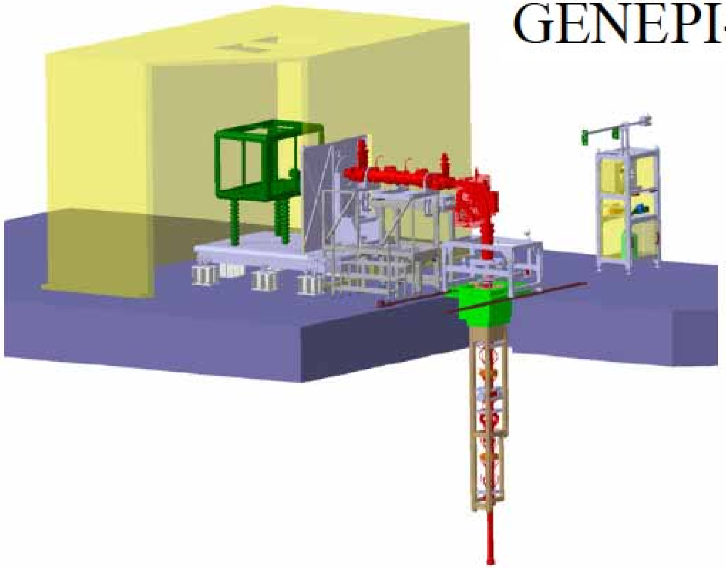


Figure 1: General layout of the GENEPI-3C machine.

Table 1: Characteristics in pulsed and continuous mode.

Parameters	Values
Energy	140 up to 240 keV (deuterons)
Pulsed mode	Peak current: 40 mA on target pulse duration (FWHM) < 1µs Repetition rate up to 5 kHz
Continuous mode	DC current: 1 mA on target Beam interruptions: 20 µs to 10 ms Beam trip rate: 0.1 to 100 Hz Rise/drop times: ~ 1 µs
Beam diameter	~ 20 mm on target
Stability	~ 1%
Beam power	240 W on target (continuous mode)

Figure 6: Accelerator GENEPI-3C assembled at LPSC (March 09).

It will be installed at Mol (Belgium) after commissioning at Grenoble (FRANCE).

Neutron sources for nuclear data

facility		driver and energy	repetition rate	n source	n energy range	flight path length
FZK TIT ...	Karlsruhe Tokyo ...	varii in the MeV range	MHz	$^{7}Li(p,n)$ & others	few keV up to 1 MeV monoE above	10s cm
GELINA	EC-JRC Geel	electron linac 150 MeV	800 Hz	photo-n photo-f	10 meV – 20 MeV	10m to 400m
LANSCE	Los Alamos National Laboratory	proton linac 800 MeV	20 Hz	spallation	< 500 keV (DANCE)	20m
n_TOF	CERN	PS 20 GeV	0.4 Hz (average)	spallation	10 meV – 250 MeV (or wider)	200m

TABLE I. Main features of the n_TOF facility

Neutron energy range	1 eV-250 MeV
Proton beam energy and intensity	20 GeV/c; 7×10^{12} p/pulse
Pulse repetition frequency	0.25 s^{-1}(average in dedicated mode)
Neutron flux at 187.5 m (uncollimated)	4×10^5 n/cm^2/pulse
Neutron flux with Φ=1.9 cm collimator	1.4×10^5 n/cm^2/pulse
Fraction of flux in 1 eV - 1 Mev range	2/3
Resolution $\Delta E/E$	3×10^{-4} at 1 eV; 1.5×10^{-3} at 30 KeV
Background (fluence out/in beam)	10^{-5}

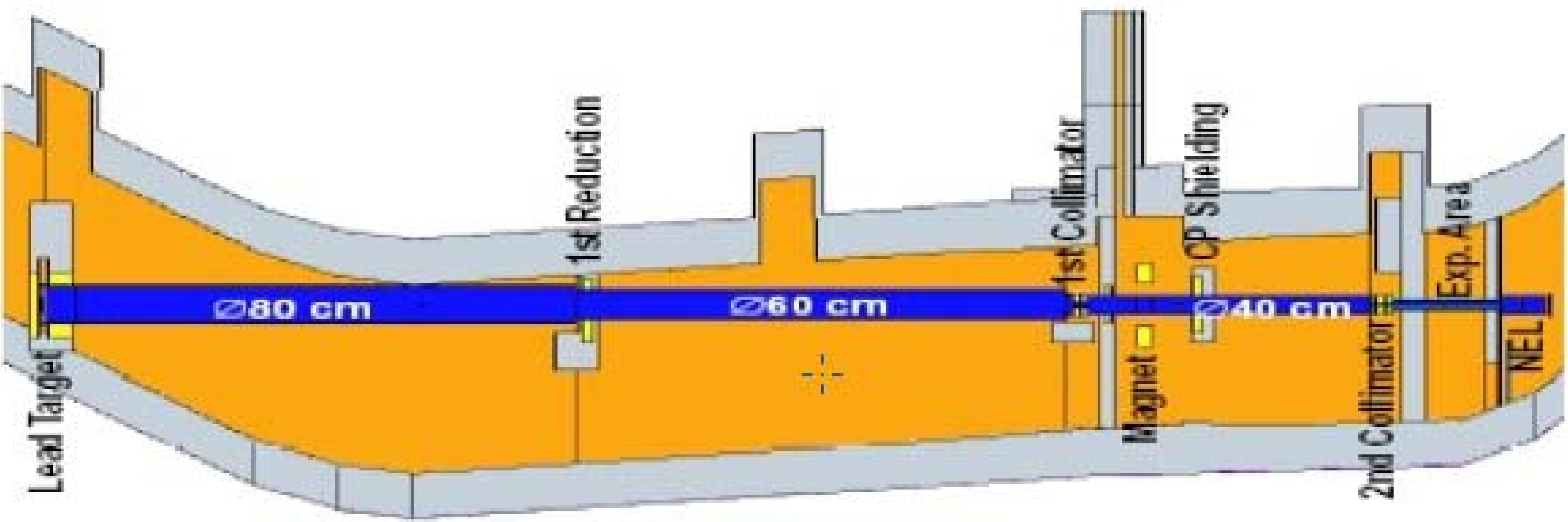
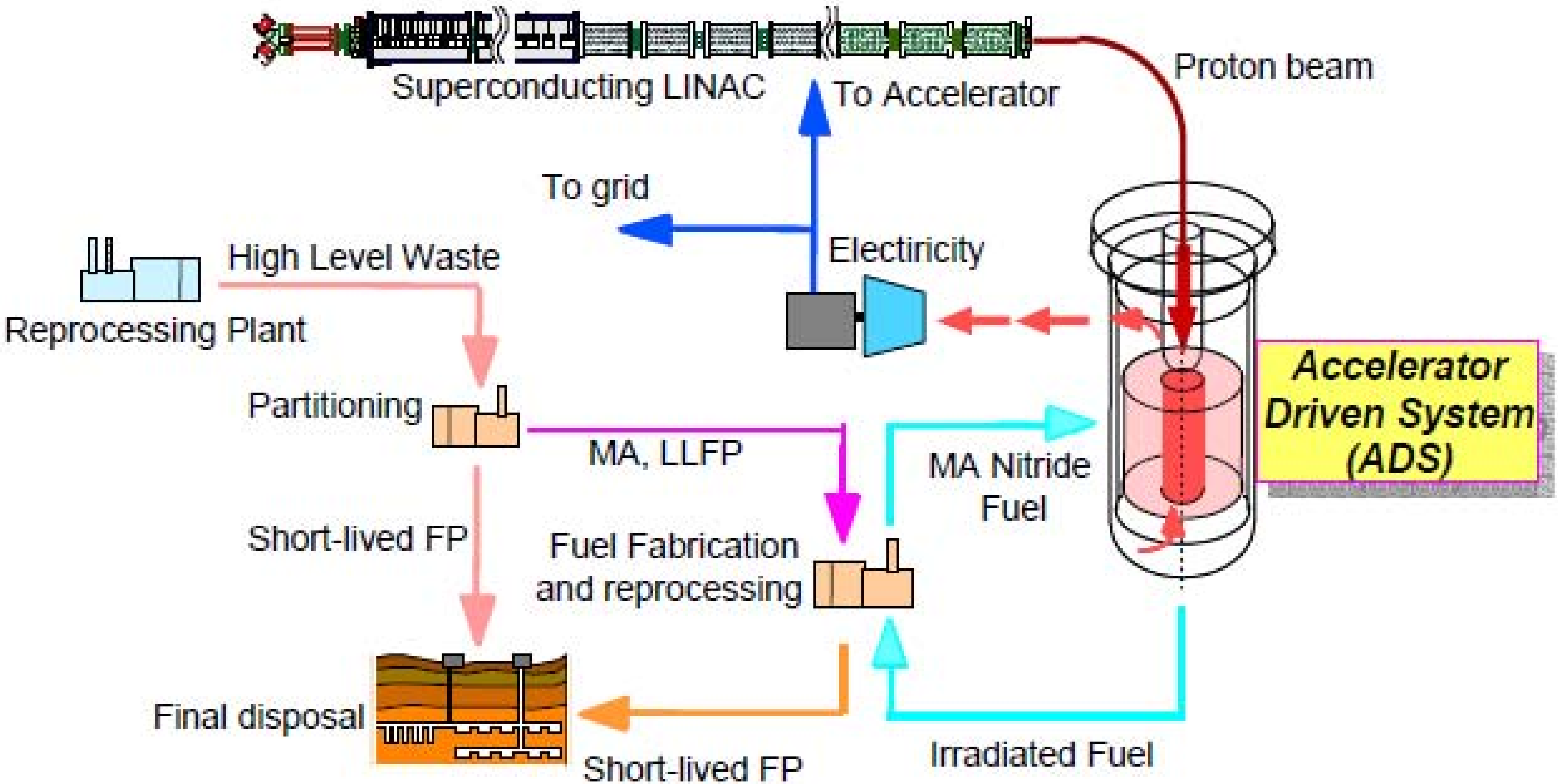
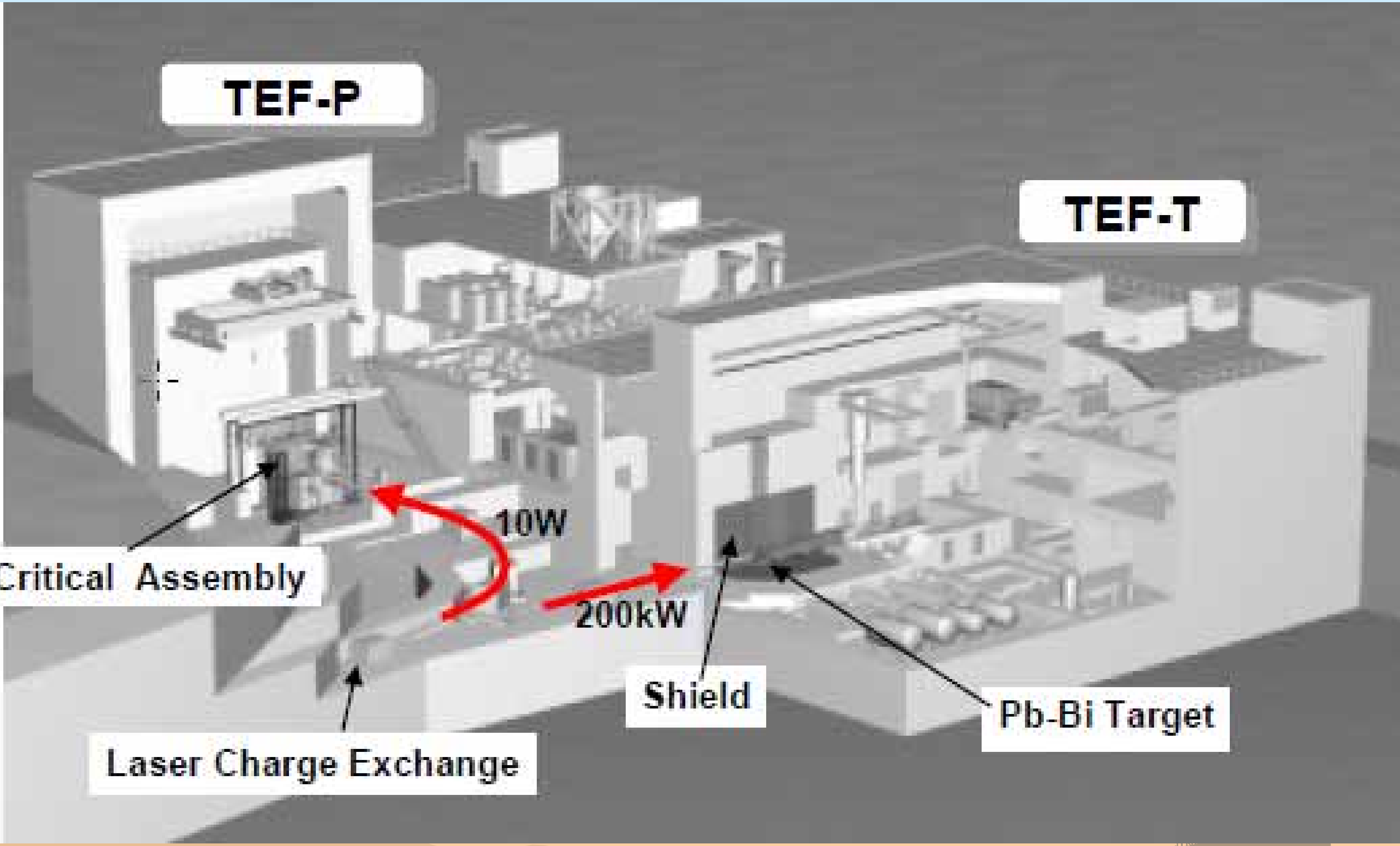


Figure 1. Lay out of the TOF tube.

JAEA ADS plan



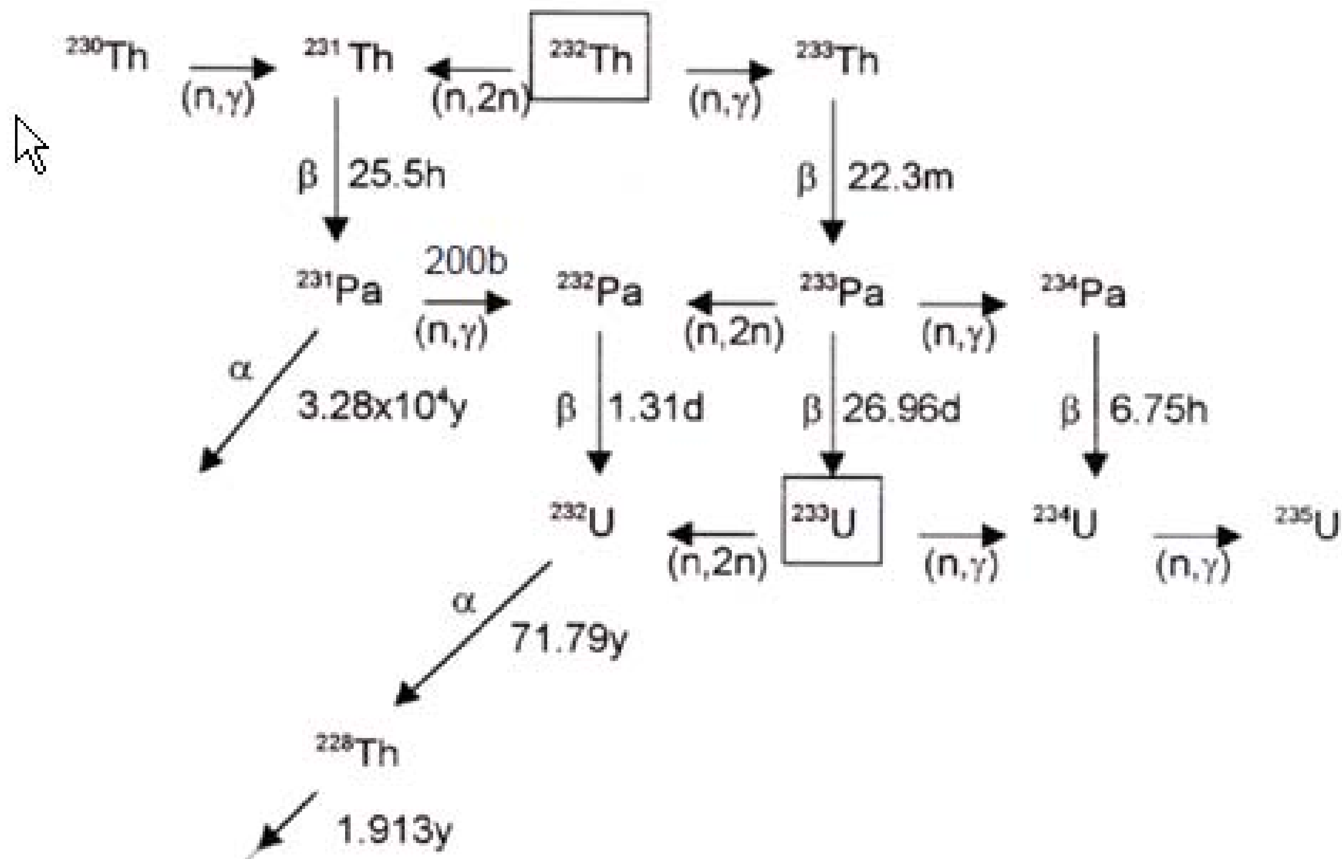
Oigawa JAEA



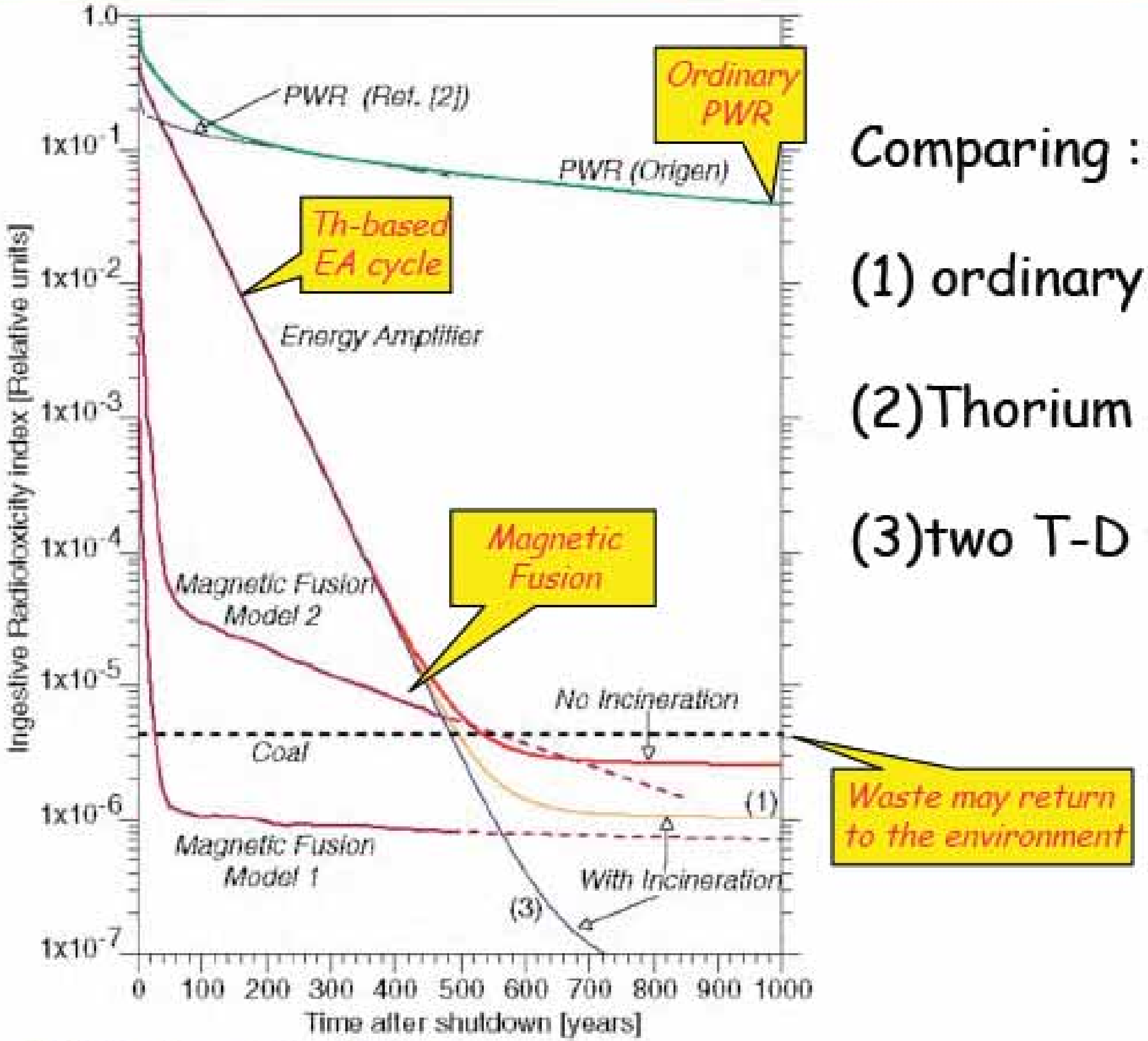
J-PARC the to-be 2nd stage project

The thorium cycle

$$n + {}^{232}_{90}\mathrm{Th} \rightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow{\beta^-} {}^{233}_{92}\mathrm{U}$$



Residual radio-toxicity of waste as function of time

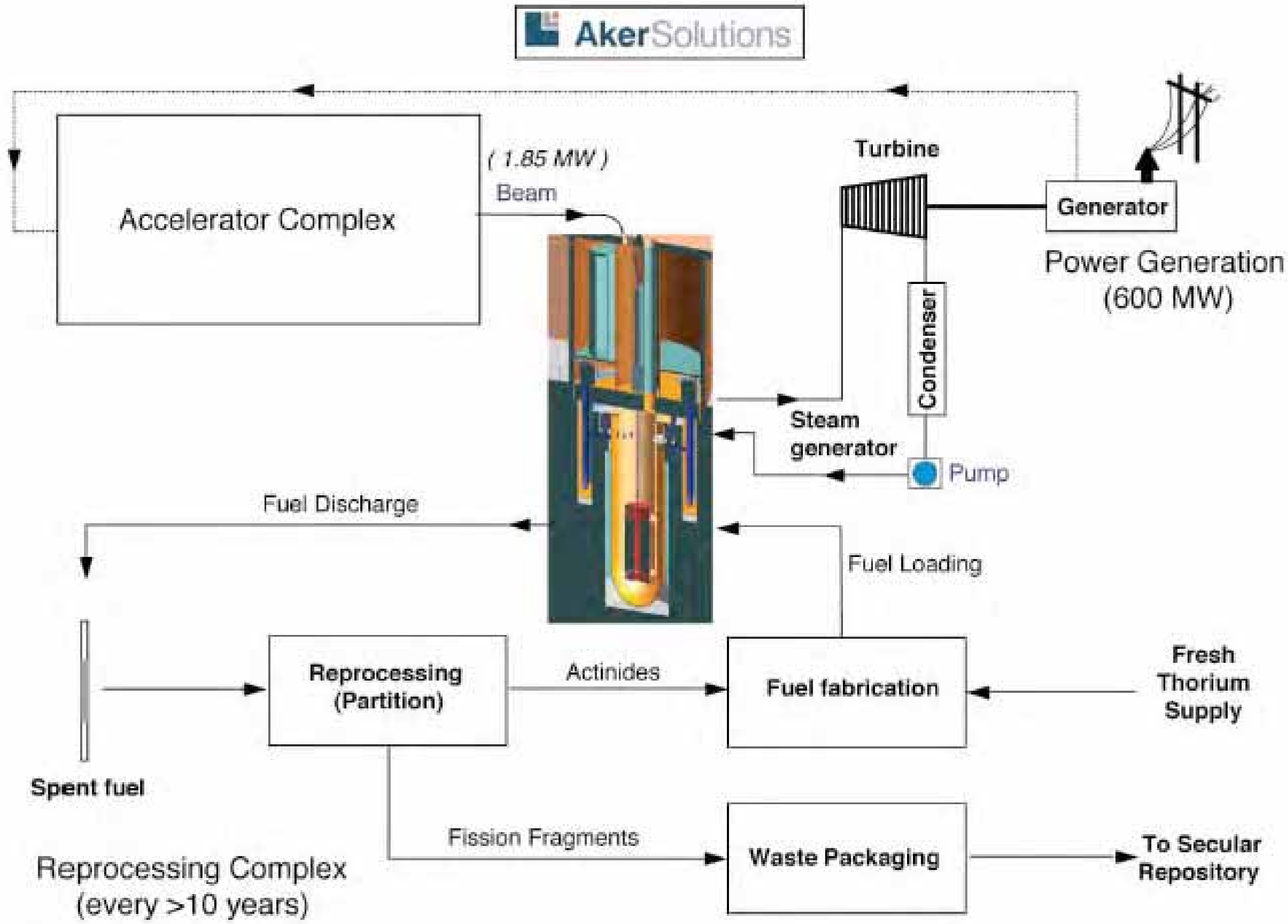


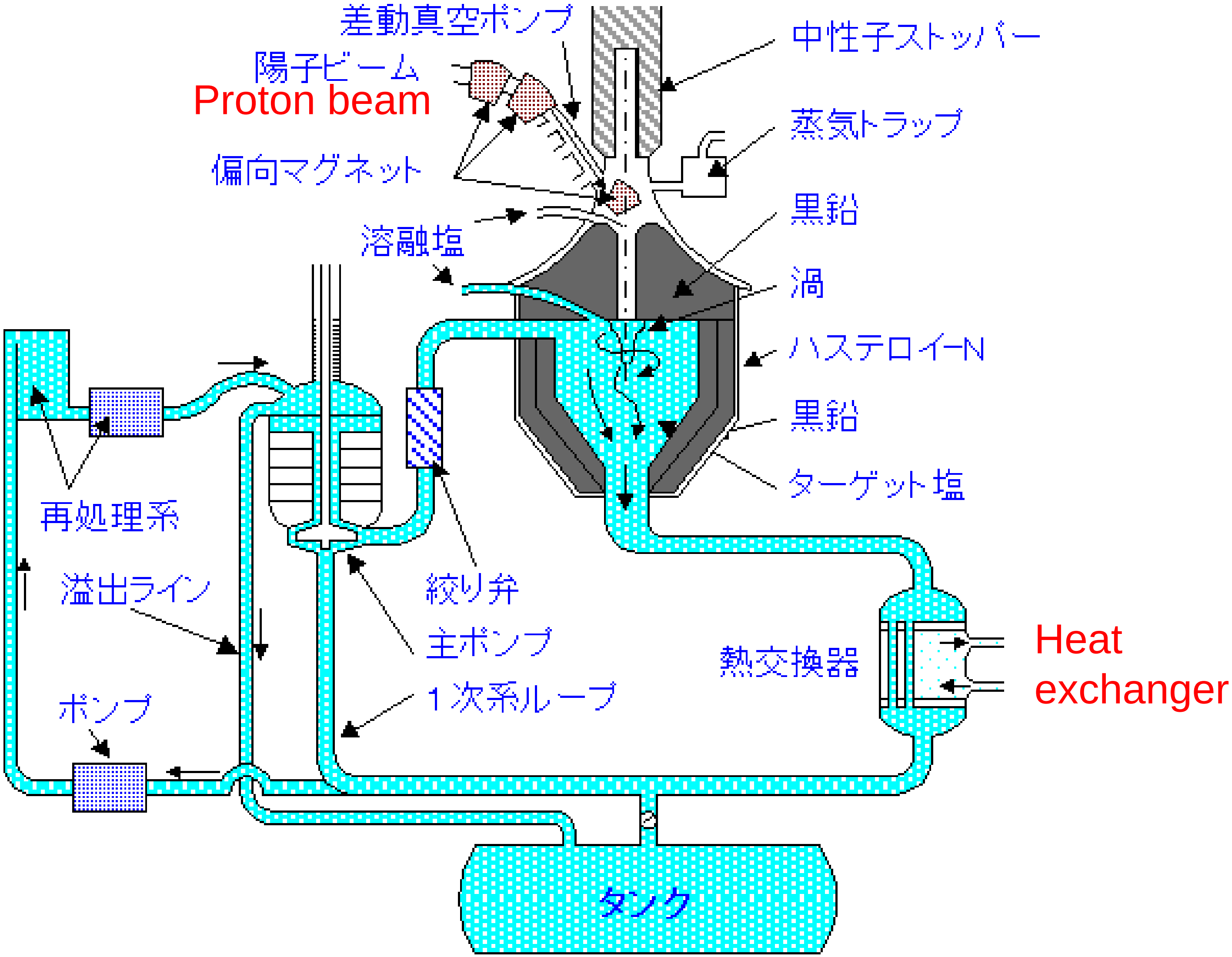
Comparing :

(1) ordinary reactor (PWR)

(2) Thorium based EA

(3) two T-D fusion models


AkerSolutions
Accelerator Complex
(1.85 MW)
Beam
Turbine
Generator
Power Generation
(600 MW)
Condenser
Steam
generator
Pump
Fuel Discharge
Fuel Loading
Spent fuel
Reprocessing
(Partition)
Actinides
Fuel fabrication
Fresh
Thorium
Supply
Fission Fragments
Waste Packaging
To Secular
Repository
Reprocessing Complex
(every >10 years)

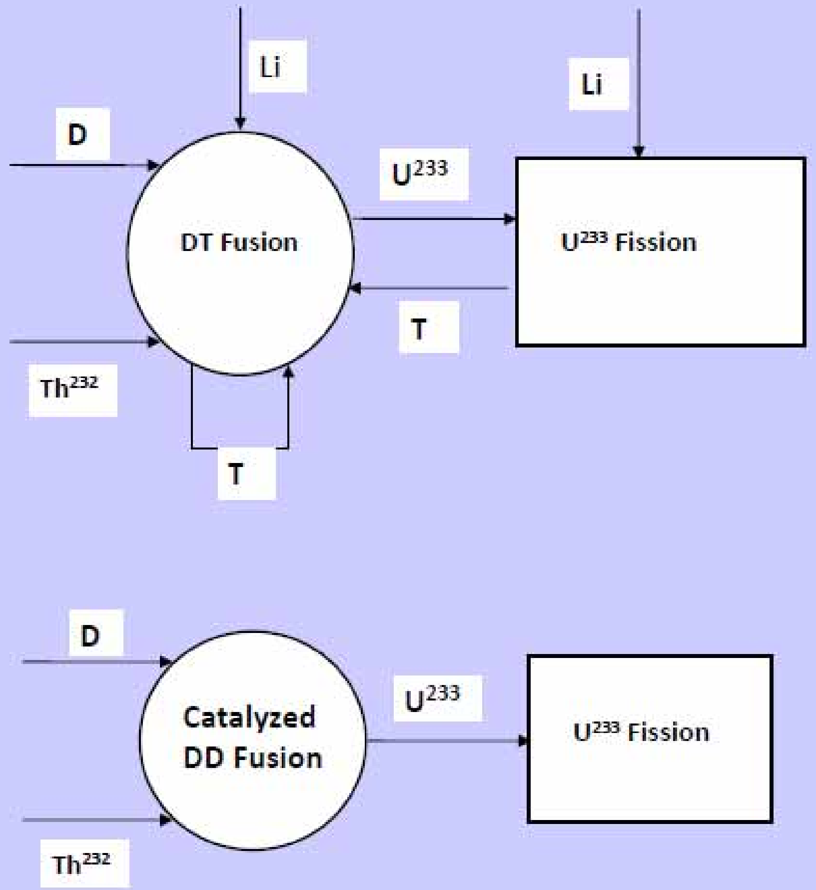


Accelerator driven MSR (Furukawa)

図8 加速器駆動増殖炉の概念図

［出典］IAEA: IAEA WORKING MATERIAL, THE STATUS OF THORIUM-BASED FUEL OPTIONS (to be published as IAEA TECDOC), (1996年) p.163

Fusion-fission hybrid thorium fuel cycle alternative

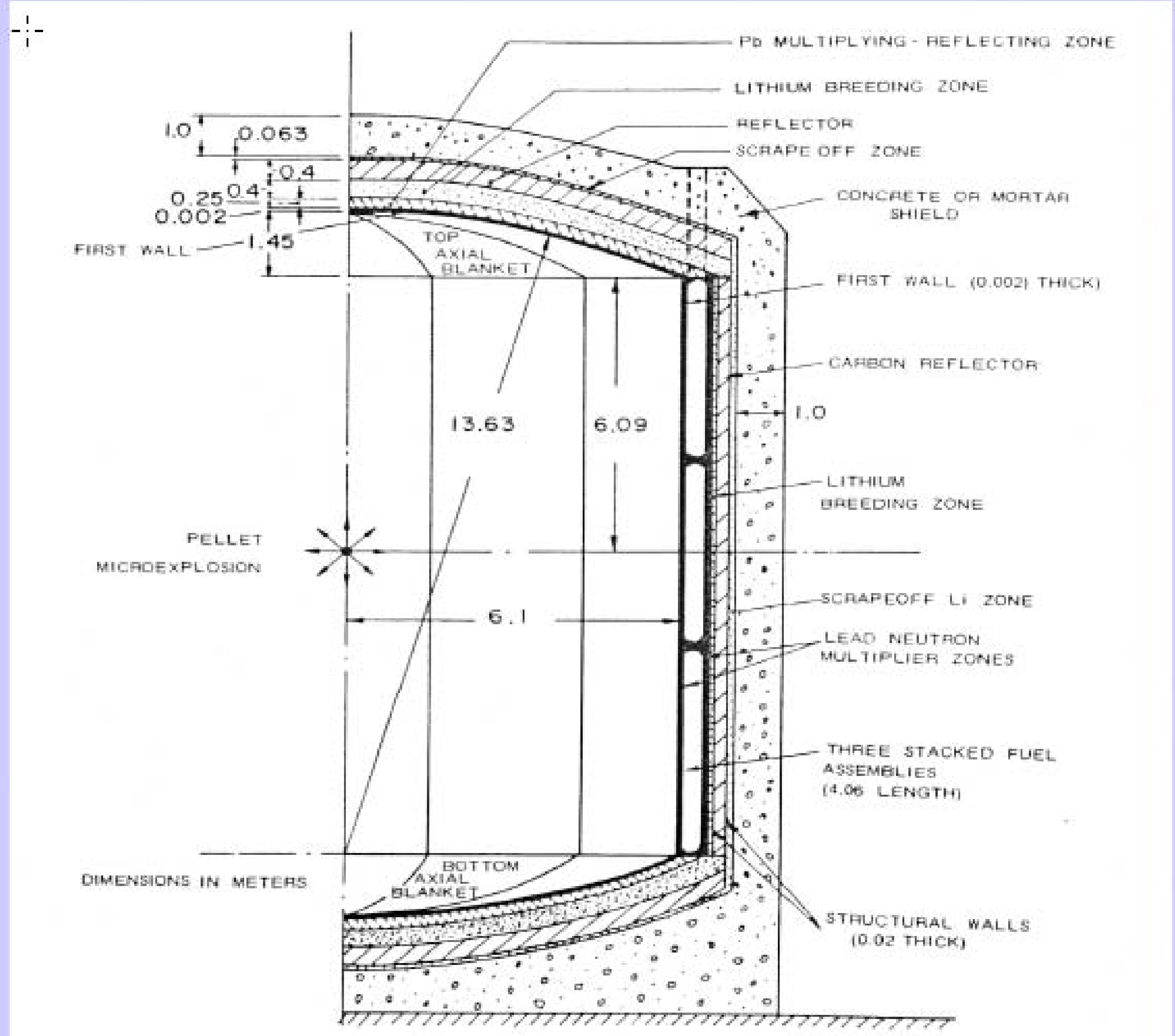


Material flows in the DT (top) and Catalyzed DD fusion-fission hybrid (bottom) Fuel Factory alternatives with U^{233} breeding from Th^{232}.

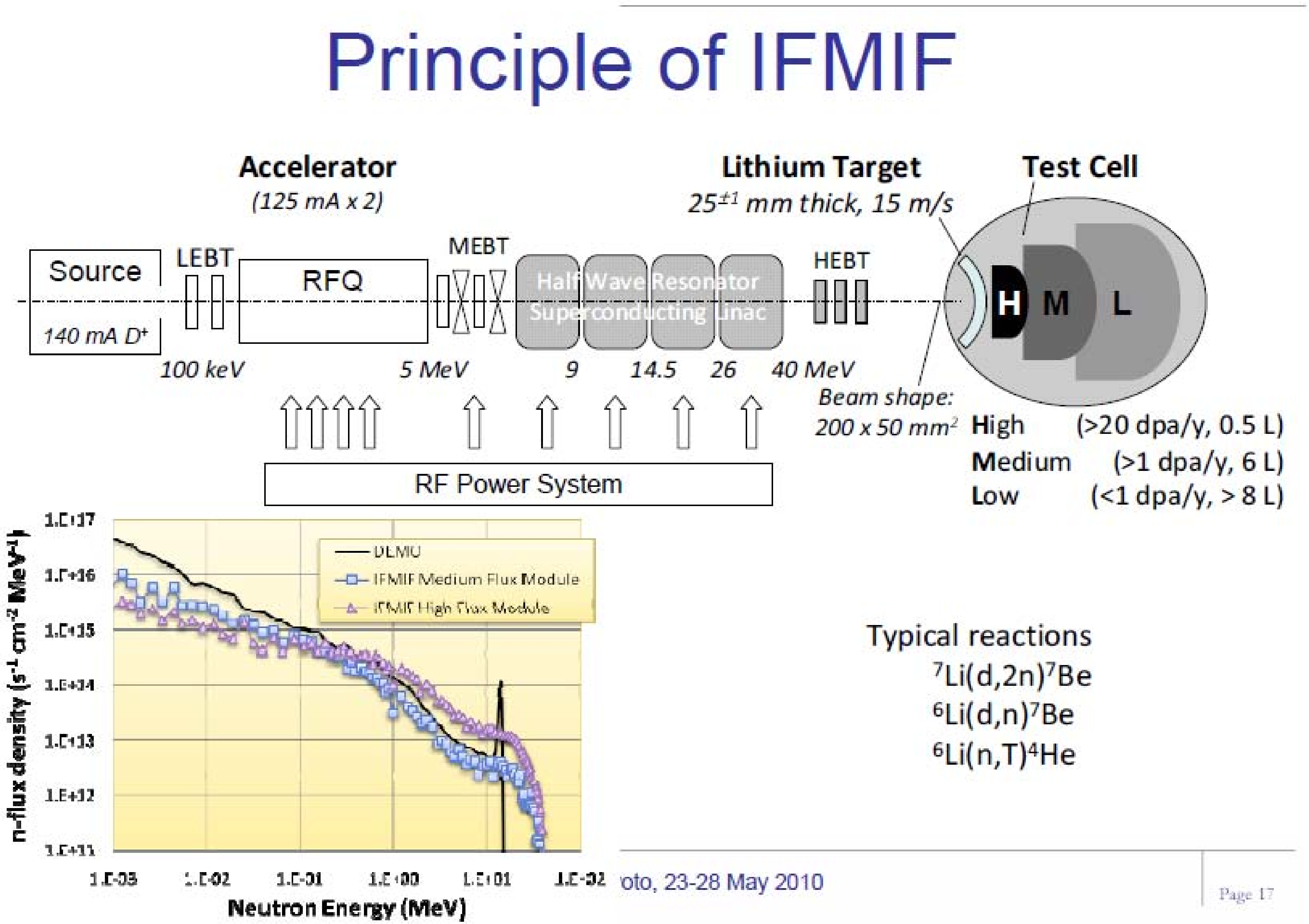
Magdi Ragheb

Graduate seminar, department of nuclear, plasma and radiological engineering, University of Illinois at Urbana-Champaign, 103 Talbot laboratory, USA, February 10, 2010

Laser fusion fissile generator plant with U^{233} breeding.



Accelerator of the ITER (neutron irradiation source for material test)



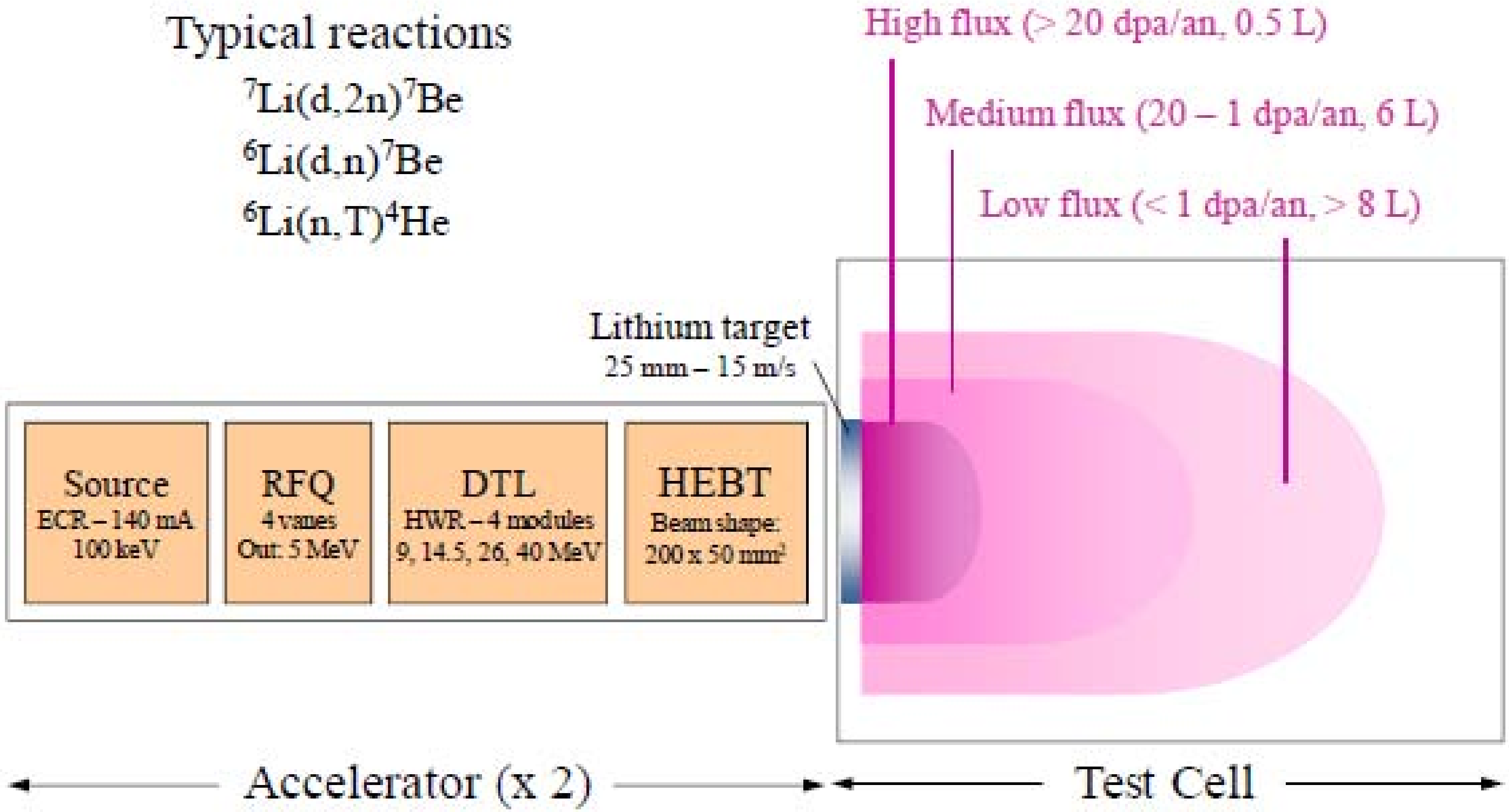
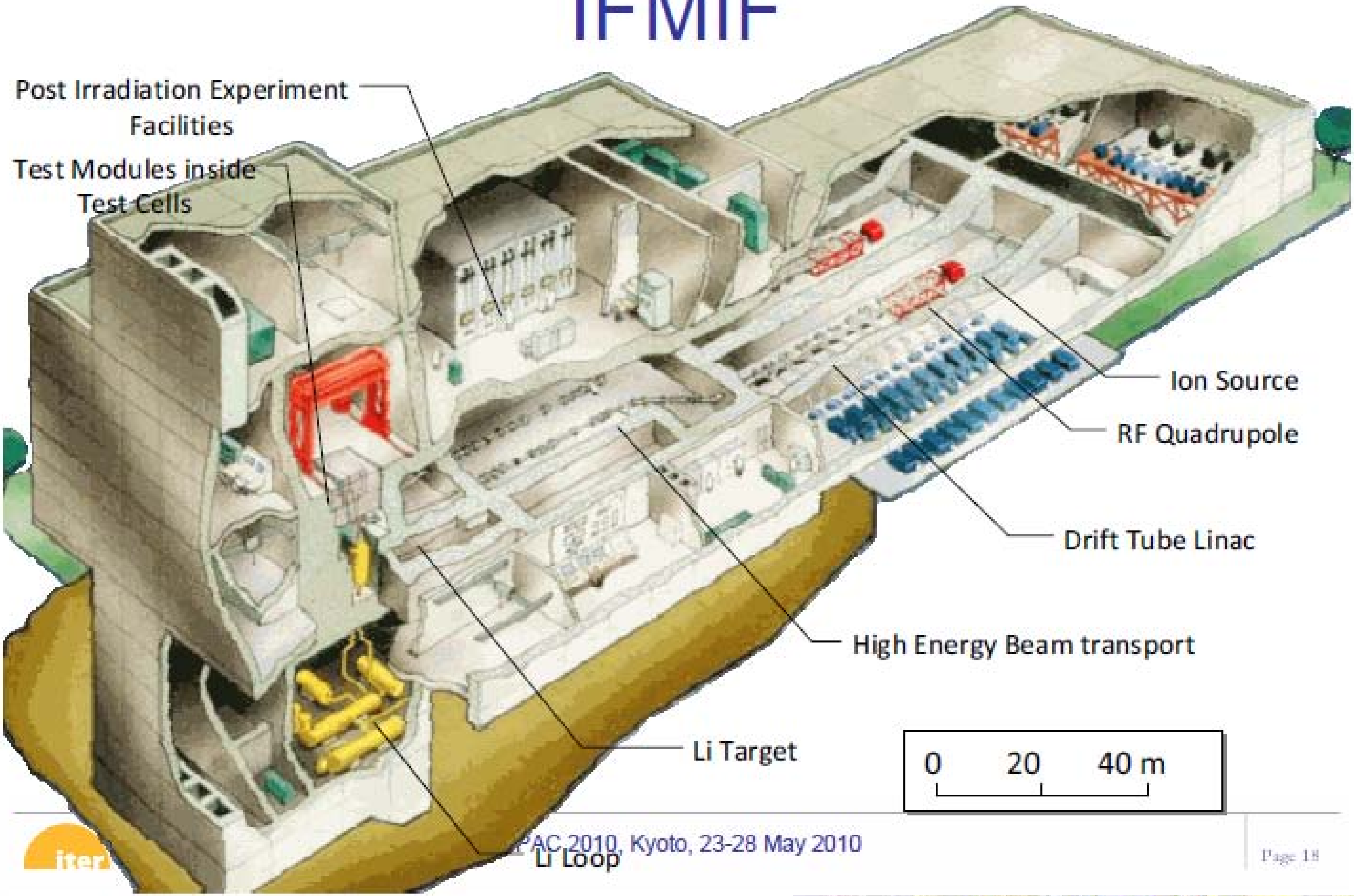


Figure 1: IFMIF is constituted of 3 main systems:
the Accelerator Facility, the Lithium Target Facility and Test Facilities

The IFMIF/EVEDA Project: Outcome of the first Engineering Studies

Pascal Garin[1], Masayoshi Sugimoto[2],
on behalf of the Project Team and the numerous Institutes involved

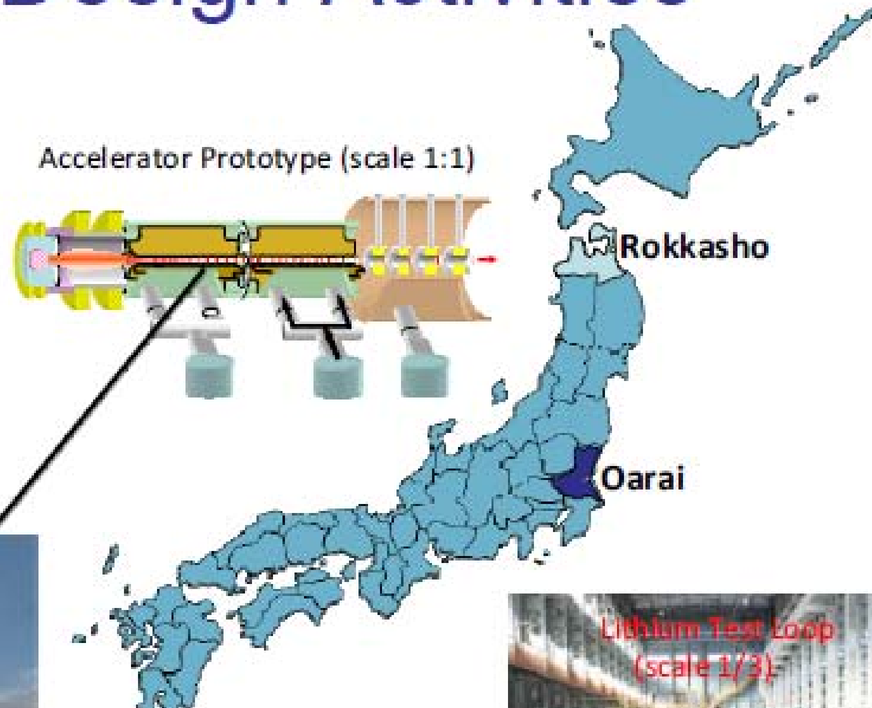
IFMIF



Norbert Holtkamp
Principal Deputy Director General
28 May 2010

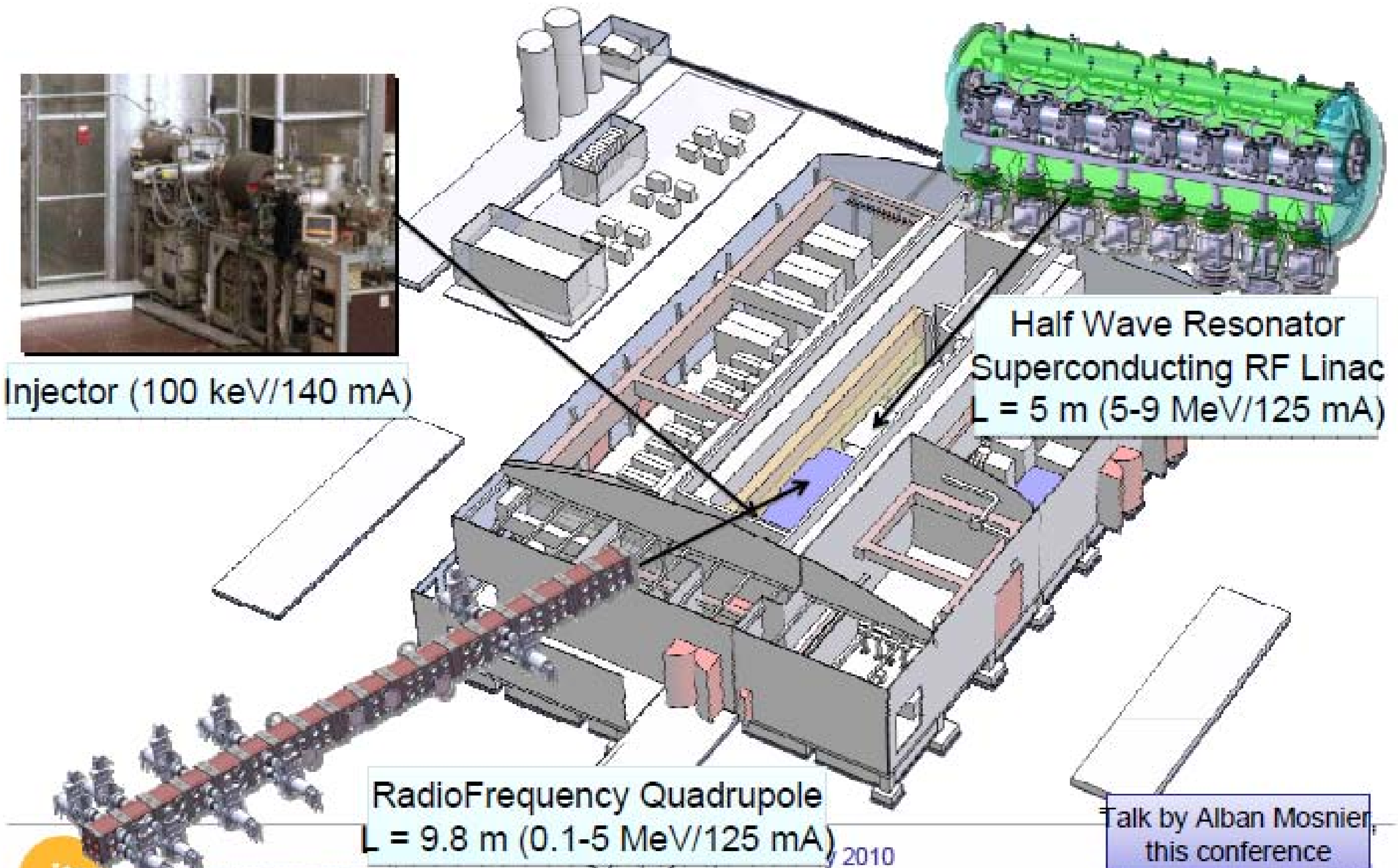
Engineering Validation & Engineering Design Activities

- Engineering Validation
  - The Accelerator Prototype
  - The Lithium Test Loop
  - High Flux Test Modules
- Engineering Design
  - Of the whole IFMIF Plant



Norbert Holtkamp
Principal Deputy Director General
28 May 2010

IFMIF/EVEDA Project – Accelerator Development



Norbert Holtkamp
Principal Deputy Director General
28 May 2010

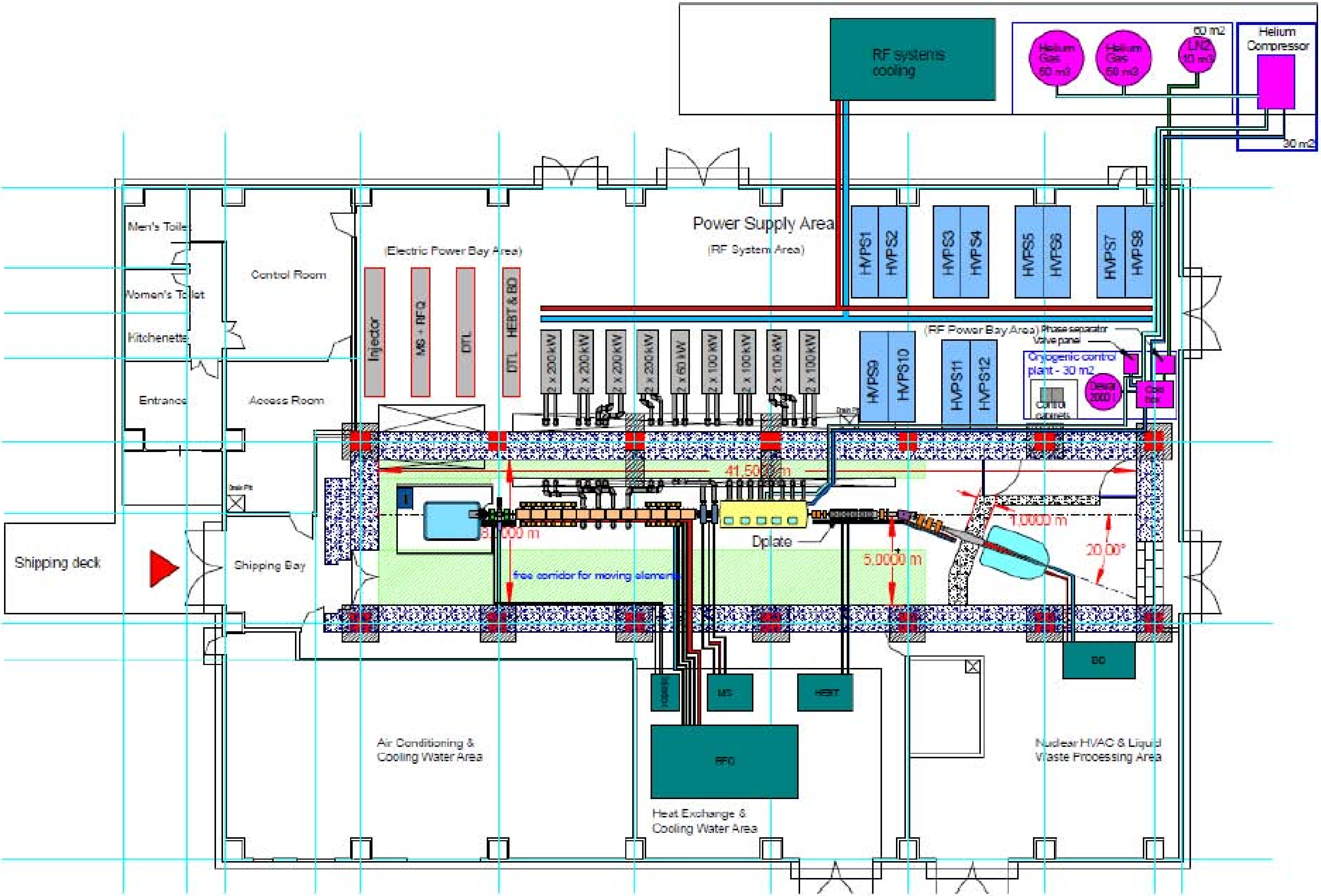


Figure 11: Layout of the prototype accelerator in the IFMIF/EVEDA accelerator building.

Accelerator physicists could/should contribute to the atoms for peace in order to develop a safer and useful nuclear technology.

Younger physicists be ambitious!

Thank you for your attention.