High Intensity Low Energy Electron Accelerators for Sub Critical Micro Nuclear Reactors

Kailash C Mittal* and Ganapati Myneni

BSCE Systems, Inc.,Yorktown, Virginia 23693, US

*Retired from BARC India (2014)

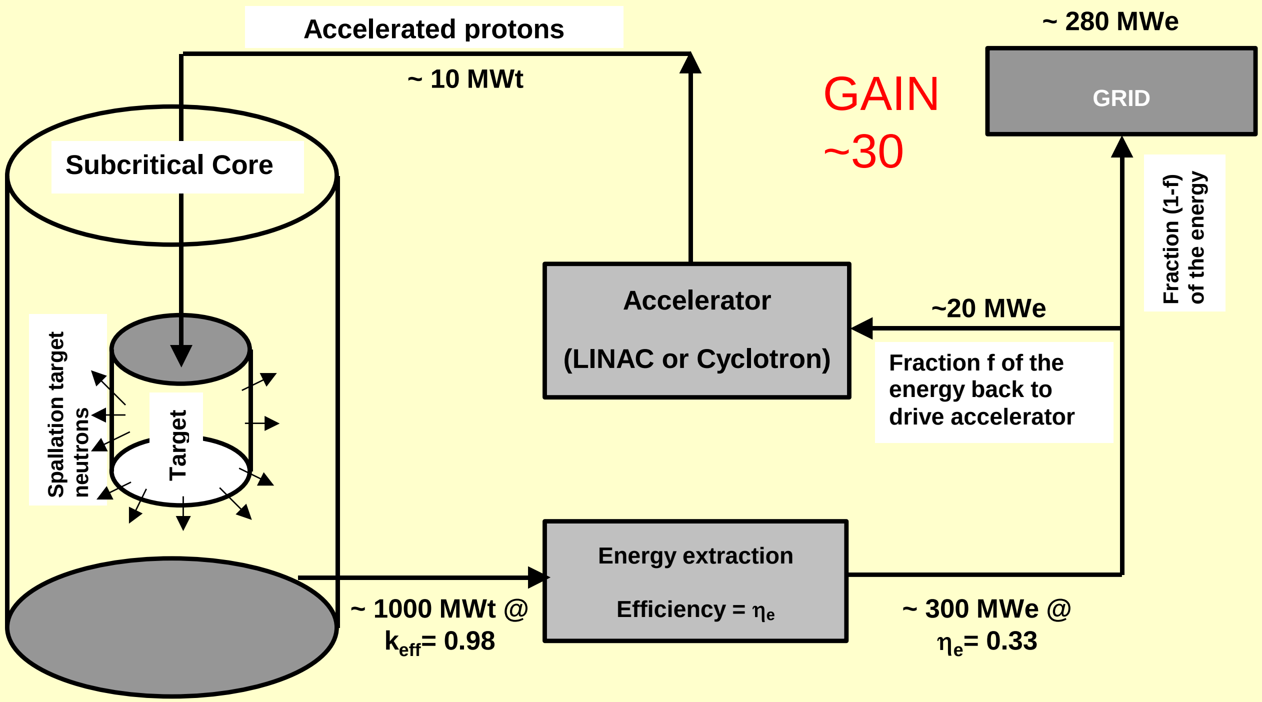
smkcm@rediffmail.com

Nov 6, 2019 @SCK.CEN Mol Belgium

Plan of Talk

- Introduction: ADS with Proton Beam
- Electron Beam Applications (1 – 100 MeV)
- ADS with 100 MeV Electron Beam
- High Intensity Photo neutrons at 10 MeV
- **Photo neutron Target Design Considerations at 10 MeV**
- Industrial Status of 10 MeV Electron Sources
- Proposal to develop 10 MeV, 1-10 MW ADS for Micro Reactors and Isotope Production

Accelerator-Driven System for thorium fuel and waste transmutation



Schematic of ADSS

ADSS has exclusive niche in:

- **Thorium fueled reactor due to enhanced availability of non-fission neutrons of spallation target for faster breeding.**

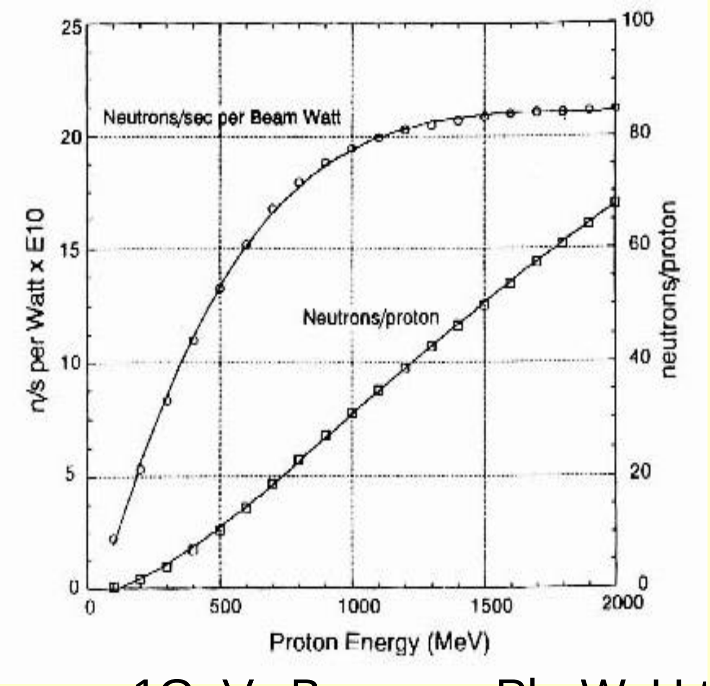
  (This will enable early introduction and faster growth of thorium fuel-based power reactors in the country.)

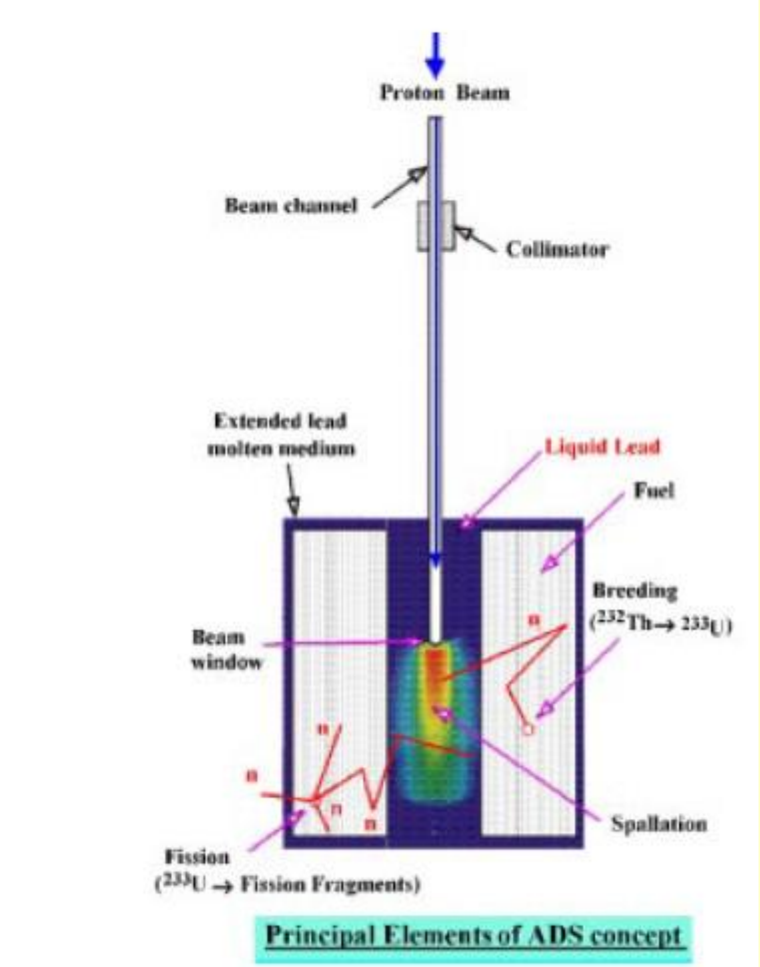
- **Transmuting transuranic (TRU) elements in the spent fuel with enhanced safety with sub-critical operation, that is otherwise difficult in a conventional fast reactor.**

  (This will reduce/eliminate need for geologic repository to dispose spent fuel.)

Proton Beam as a Driver for ADSS

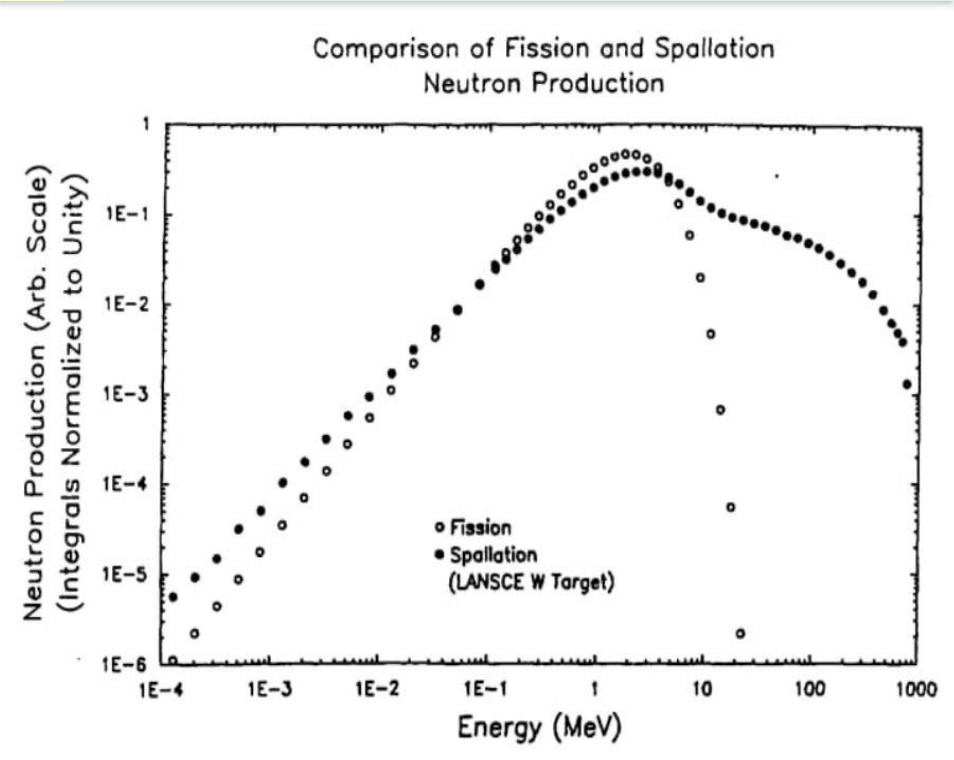
- **By Spallation process with GeV energy protons striking on high Z target.**
- **Number of neutrons per proton per Watt of beam power reaches a plateau just above 1 GeV.**

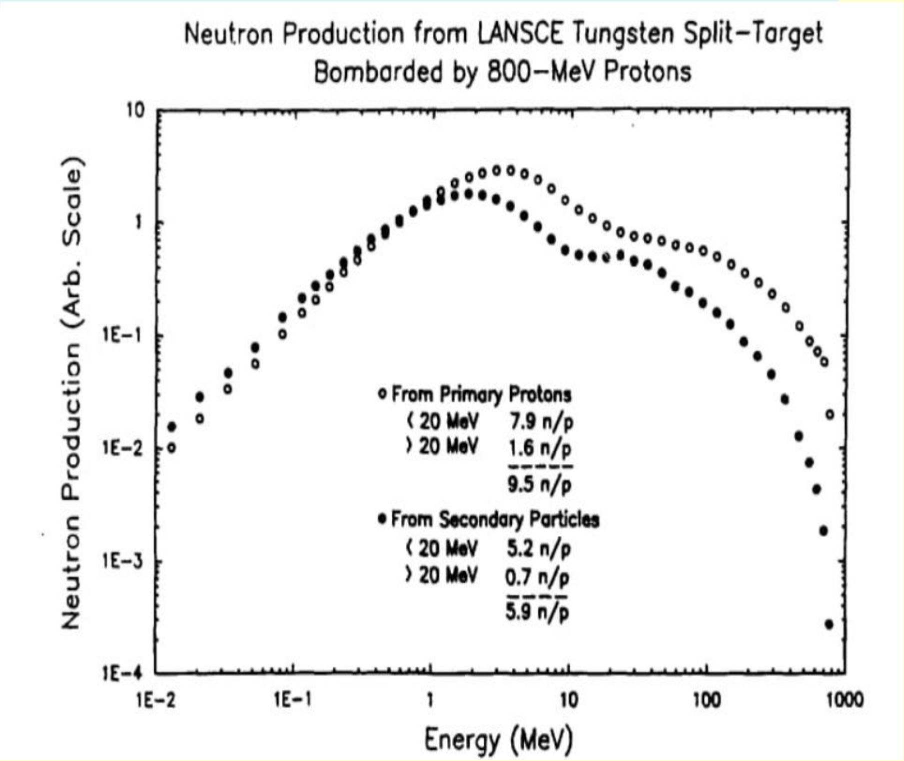




1GeV, Beam on Pb, W, U targets, produce ~ $2X10^{11}$ n/s/W.
1GeV, 10 mA, 10 MW Beam will produce ~ $2 X10^{18}$ n/s.

Neutron Energy Spectra from 800 MeV Proton Beam



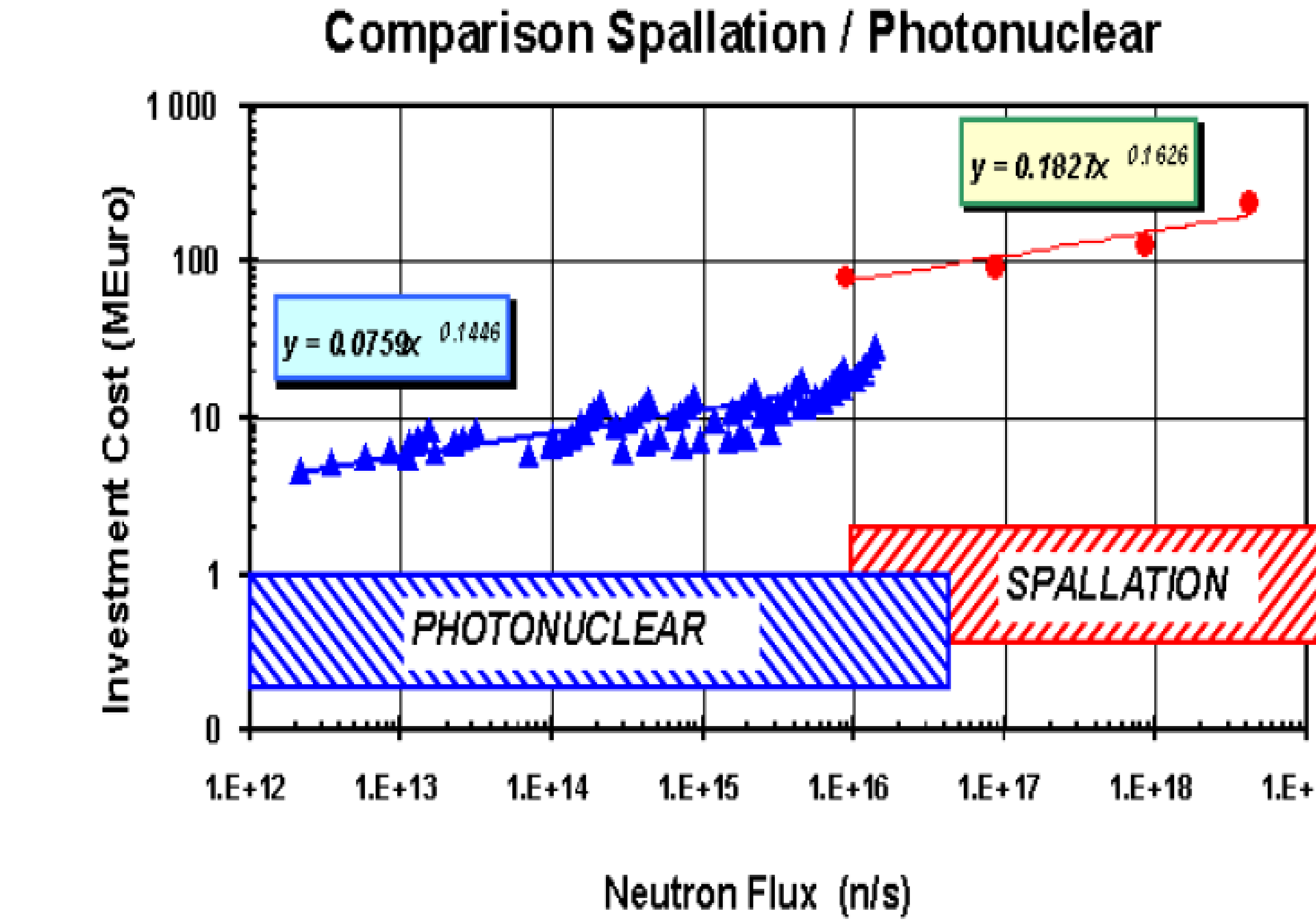


Neutron Energy at Max Intensity: 1 – 2 MeV

Number of n/p with <20 MeV energy: 13.1 (85%)

Number of n/p with >20 MeV energy: 02.3 (15%)

Gary J Russell: ICANS XI Intl Coll Adv Neutron Sources
KEK Tsukuba, Oct 22 -26 1990


Comparison Spallation / Photonuclear
y = 0.1827x 0.1626
y = 0.0759x 0.1446
PHOTONUCLEAR
SPALLATION
Investment Cost (MEuro)
1 000
100
10
1
0
1.E+12
1.E+13
1.E+14
1.E+15
1.E+16
1.E+17
1.E+18
Neutron Flux (n/s)

Industrial Applications of Electron Beams for < 10 MeV

Application	Energy	Dose
○Cross Linking of Polyethylene	0.3-10 MeV	50-300 kGy
○Thermo Shrinkable Plastics	0.5-4	100-250
○Teflon Degradation	2	
○Curing of Coatings on wood	0.15-0.5	20-500
○Exotic Colors in Diamonds	2-10	few MGy
○Sewage & Sludge Treatment	0.5-4	0.5-1.0
○Food Preservation	5-10	5-10
○Disinfestation of Grain	1	0.5-1.0
○Purification of Exhaust Gases	0.3-1.5	10-15
○Sterilization of Medical Prods	1-10	20-50
○Vulcanization of Rubber	0.5-1.5	20-500
○Graft polymerization	0.3-2.5	10-300

Applications of Electron Beams (10 -100 MeV)

- **Neutron Generator** for studying the sub critical core of a reactor as an **Energy driver, Breeder of fuel, Transmutator of Radioactive Waste etc (ADS Applications).**
- **Production of Radio-nuclides: treatment of Cancers, Diagnostics, Imaging of the Explosives** buried as landmines,
- **225Ac, ^{99m}Tc (daughter nucleus of ^{99}mo). ^{186}Re, ^{188}Re, ^{11}C, ^{13}N, ^{15}O, and ^{18}F for cancer treatment and medical imaging.**

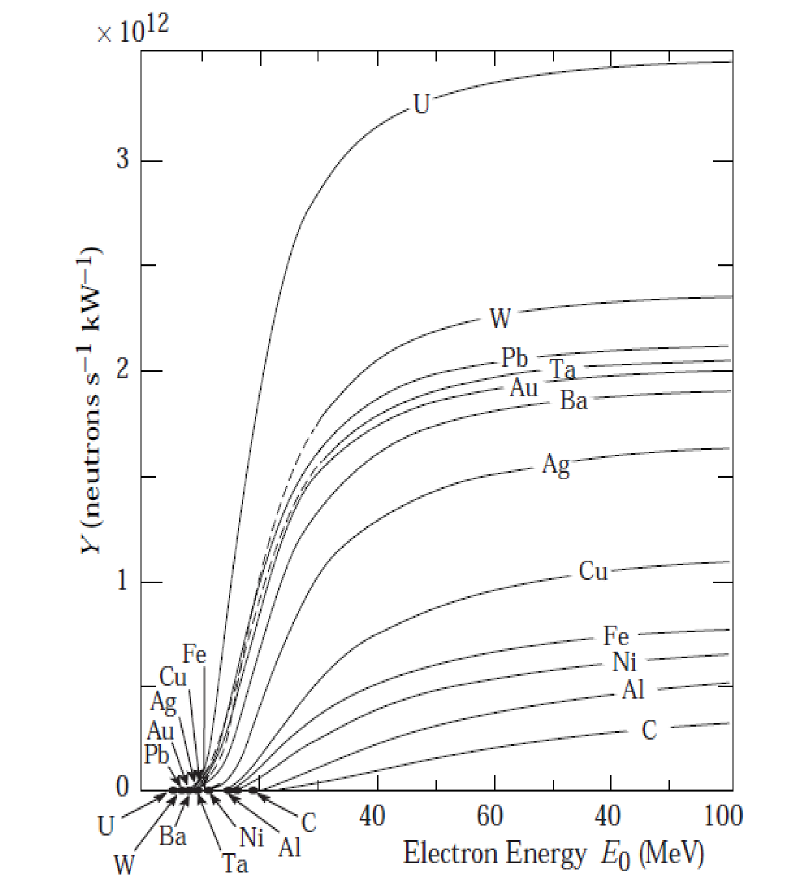
^{57}co used for calibration of scintillation detector.

- **Production of Neutron rich Radioactive Nuclei**, for doing Research in **Basic sciences**.

❑ **Target optimization for photo neutron production.**

Electron Beam as a Driver for ADSS

- neutrons are generated via photonuclear and photo fission reactions from Bremsstrahlung photons.
- In the photon energy range from threshold (few MeV) to about 30 MeV, neutron production is via the Giant Dipole Resonance (GDR) mechanism.



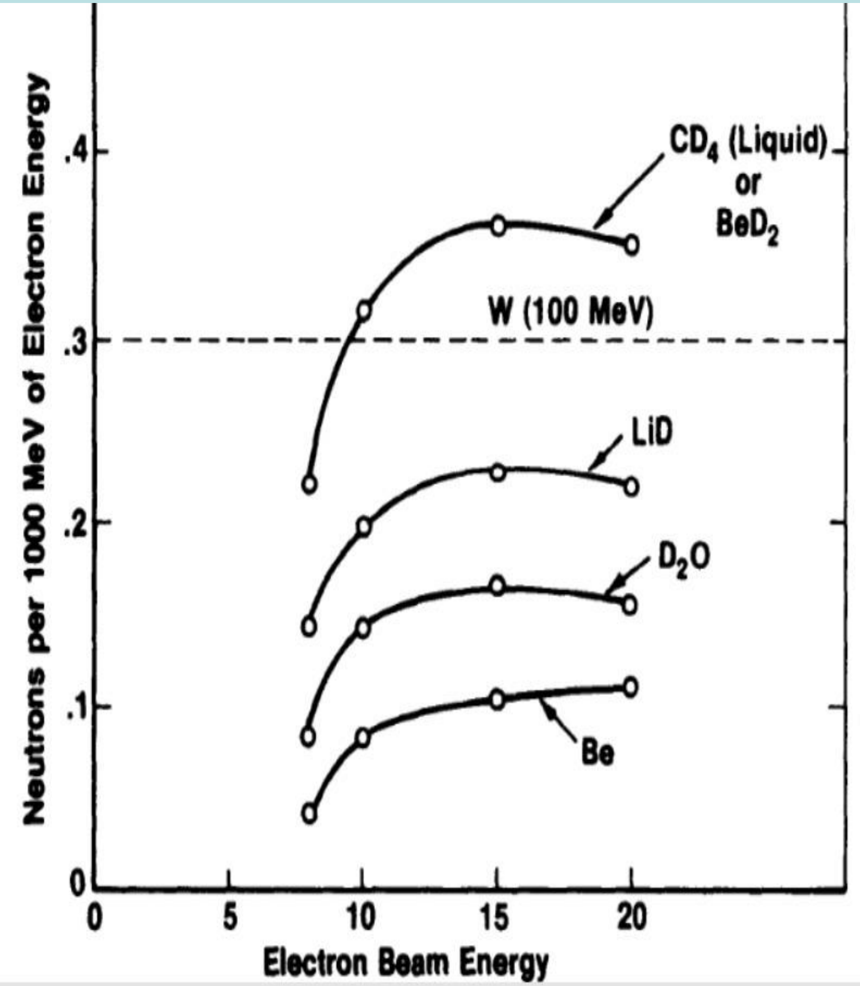
Beam Energy (MeV)	Neutron Yeild ($n\ s^{-1}\ kW^{-1}$)	Beam Current (mA)	Beam Power (MW)	Neutron Flux (n/s)
50 (U – Target)	$3.25X10^{12}$	100-200	5-10	$1.625\text{-}3.2X10^{16}$
50 (W –Target)	$2.17X10^{12}$	100-200	5-10	$1.085\text{-}2.17X10^{16}$
50 (Pb – Taget)	$1.97X10^{12}$	100-200	5-10	$0.985\text{-}1.97X10^{16}$
50 (Ta–Target)	$1.91X10^{12}$	100-200	5-10	$0.955\text{-}1.91X10^{16}$

10 MeV Electron Beams as ADS Driver

- High Intensity Protons (~ 800 MeV) and Electrons (~100 MeV) have been considered as Neutron Sources for ADS

- We propose to evaluate ~10 MeV Electrons as Neutron Sources utilizing low threshold energy targets like Be and Deuterium.

Photo Neutron Targets for Low Energy Electrons



Neutron Yield for Beryllium & Deuterium targets as a function of Electron Energy

Low Threshold Reactions

Nuclide	*Threshold(MeV)*	*Reaction*
^{2}D	2.225	$^{2}H(\gamma,n)^{1}H$
^{6}Li	3.697	$^{6}Li(\gamma,n+p)^{4}He$
^{6}Li	5.67	$^{6}Li(\gamma,n)^{5}Li$
^{7}Li	7.251	$^{7}Li(\gamma,n)^{6}Li$
^{9}Be	1.667	$^{9}Be(\gamma,n)^{8}Be$
^{13}C	4.9	$^{13}C(\gamma,n)^{12}C$

High Threshold Reactions

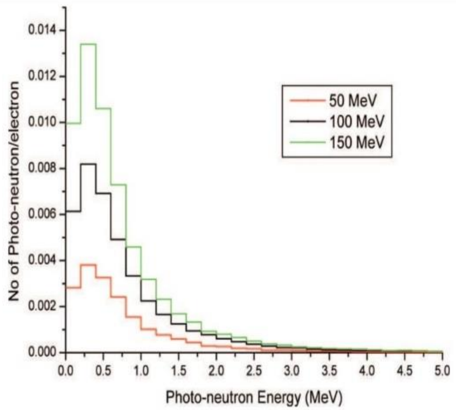
Nuclide	**Threshold (MeV)**	**Isotope Abundance (%)**
^{206}Pb	8.09	24.10
^{207}Pb	6.74	22.10
^{208}Pb	7.37	52.40
^{181}Ta	7.58	99.99
^{180}W	8.41	0.12
^{182}W	8.07	26.30
^{183}W	6.19	14.28
^{184}W	7.41	30.70
^{186}W	7.19	28.60

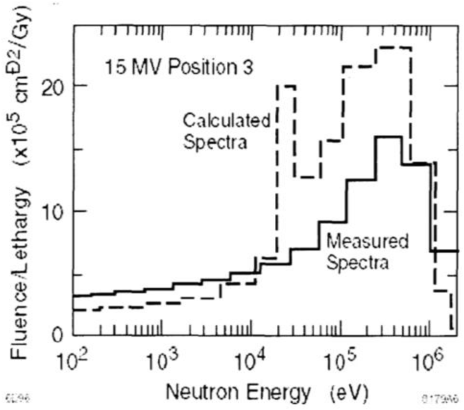
Neutron Yield for Low Energy Electron Beam at 1 Ampere Current

S. N0	Neutron Yield n/s in 4π solid angle for 1 Ampere Electron Current x 10^{15}						Neutron Yield n/s (x10^{15}) at 100 MeV for W/Ta for Equal Beam Power
	Electron Energy	Be	D_2O	LiD	CD_4 (liquid) /BeD_2	W/Ta	
1	8 MeV	2.1	4.4	7.5	11.5	-	-
2	10MeV	5.5	9.3	**12.5**	**15.0**	**1**	**20**
3	15MeV	10.2	14.0	**22.3**	**34.3**	**3.5**	**30**
4	20MeV	14.9	20.0	**28.6**	**44.8**	**20**	**40**

CD4 and/or BeD2 Targets can provide same no. of neutrons as from high Z targets at 100 MeV

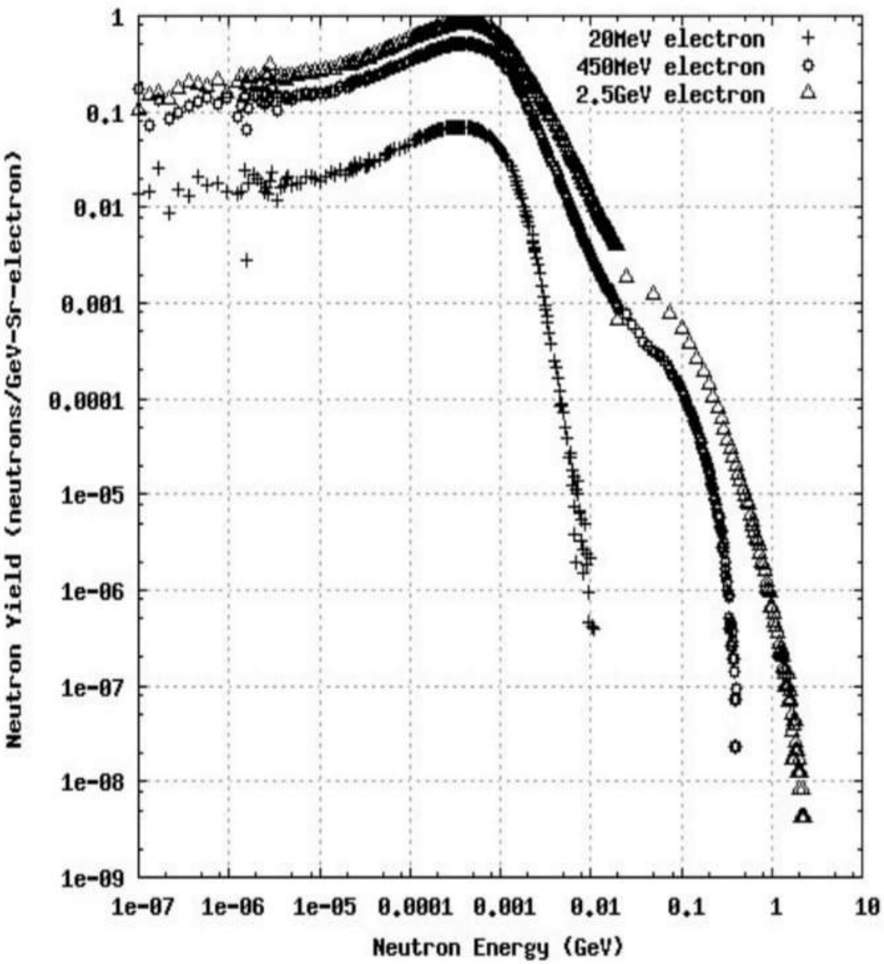
Neutron Energy Spectra for Electron Accelerators





5.Calculated and measured neutron energy spectra for 14.9 MeV electron beam at position 3.

Fig. 4 — Neutron fluence around the 4 mm W target on 2.5 GeV electron incidence



Neutron Energy at Max Intensity is 0.4 to 0.5 MeV

Neutron Energy Spectra for 10 MeV Electron Beam

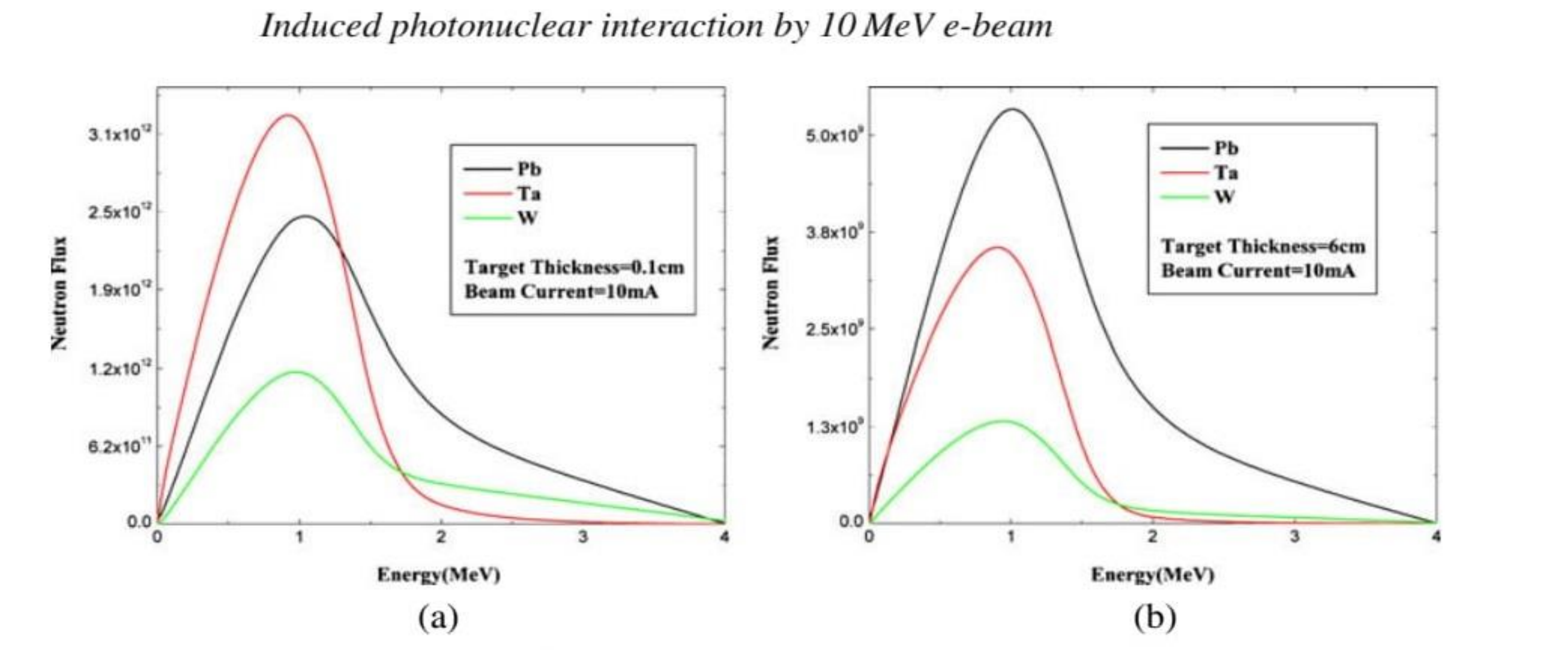


Figure 7. Energy distribution of photoneutrons in the targets. (**a**) The target with

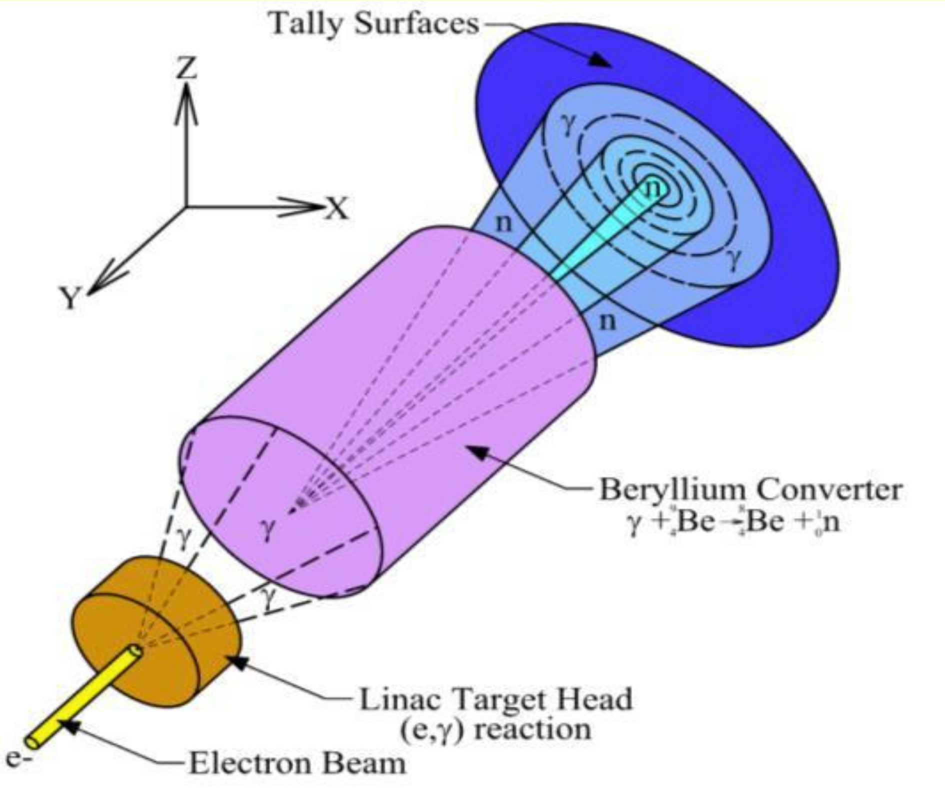
Neutron Energy Range 0 to 4 MeV with maximum at 1 MeV

RHODOTRON TT200 (IBA): 10 MeV, 10 mA, 100 kW beam

Neutrons can produce ~ 1012 n/s

Pramanna- J. Phy. 78, 257, 2012

Proof-of-Principal experiment for the generation of photo-neutrons



Beam Energy	W	Ta	Pb	Mo	Cu
6 MeV	1.4 MeV	1.4 MeV	1.5 MeV	1.2 MeV	1 MeV
9 MeV	2 MeV	2 MeV	2.1 MeV	1.7 MeV	1.5 MeV
12 MeV	2.5 MeV	2.5 MeV	2.6 MeV	2.25 MeV	2 MeV
15 MeV	3 MeV	3 MeV	3.2 MeV	2.75 MeV	2.5 MeV
18 MeV	3.5 MeV	3.5 MeV	3.6 MeV	3.1 MeV	3 MeV

Low threshold reactions

Nuclide	*Threshold(MeV)*	*Reaction*
^{2}D	2.225	$^{2}H(\gamma,n)^{1}H$
^{6}Li	3.697	$^{6}Li(\gamma,n+p)^{4}He$
^{6}Li	5.67	$^{6}Li(\gamma,n)^{5}Li$
^{7}Li	7.251	$^{7}Li(\gamma,n)^{6}Li$
^{9}Be	1.667	$^{9}Be(\gamma,n)^{8}Be$
^{13}C	4.9	$^{13}C(\gamma,n)^{12}C$

High threshold reactions

Nuclide	Threshold (MeV)	Isotope Abundance (%)
^{206}Pb	8.09	24.10
^{207}Pb	6.74	22.10
^{208}Pb	7.37	52.40
^{181}Ta	7.58	99.99
^{180}W	8.41	0.12
^{182}W	8.07	26.30
^{183}W	6.19	14.28
^{184}W	7.41	30.70
^{186}W	7.19	28.60

Thermal neutron yield was ~1.4×10^{7} n/s at ~0.3kW electron beam at 9 MeV

Energy Gain for Electron Driver

- Energy gain of the system in conventional reactor systems:

$$G = \frac{0.20\, k\, N_0}{\nu(1-k)Ep}$$

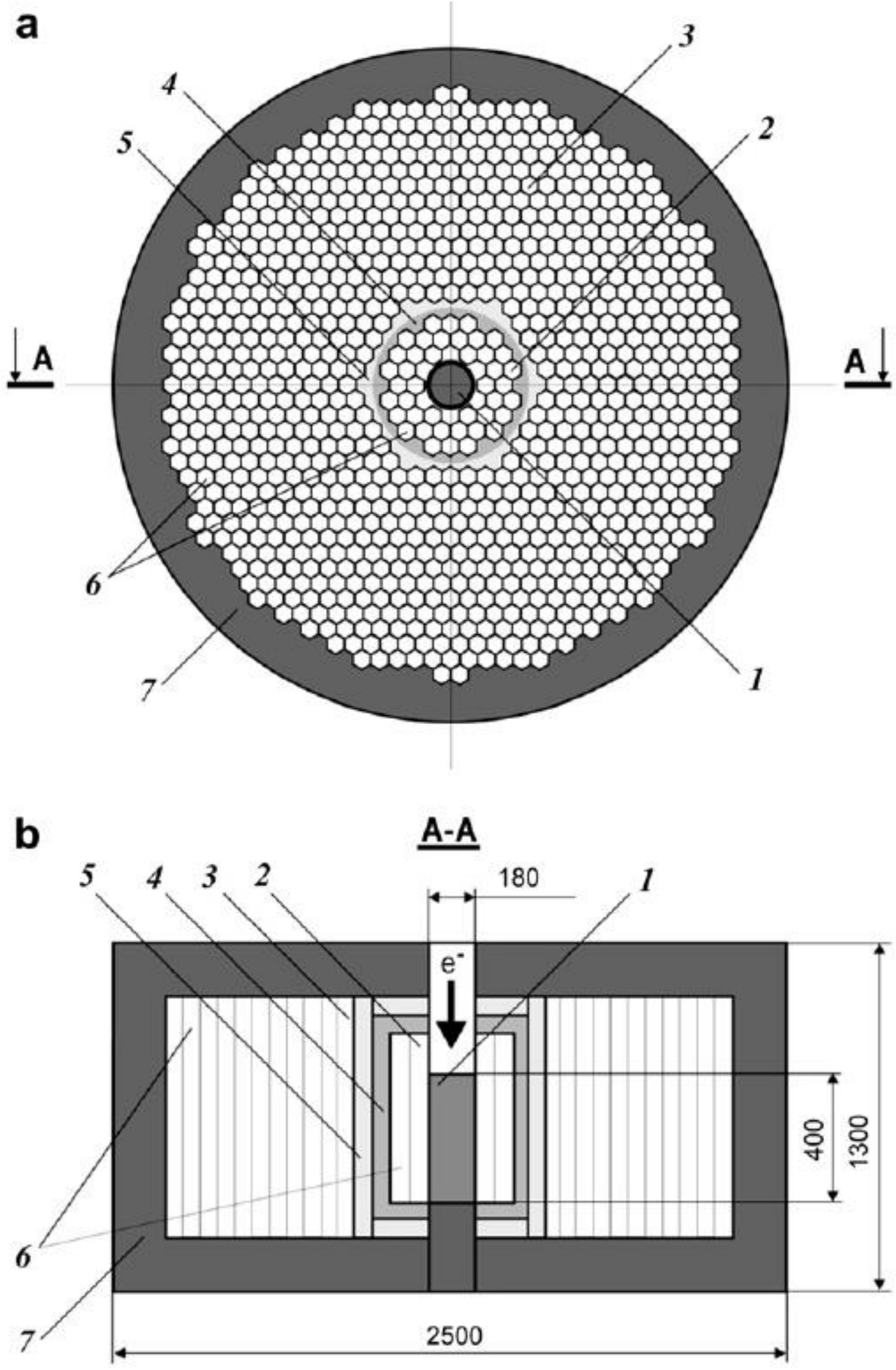
- E_p = beam energy of the incident particle.
- N_0 = no. of primary neutrons.
- **For 5 MW, 50 MeV e- beam,**
- Beam current will be ~ 0.1 A ~ 100 mA
- The no. of neutrons produced will be ~ 2.05×10^{16} n/sec.

- G = 1.42 for k = 0.97
- G = 2.15 for k = 0.98

Neutron-generating Target And Two-core Subcritical Blanket With Fast And Thermal Neutron Spectrum

Schematic Diagram Of The Design Of Subcritical Blanket:

1 - Target;
2 - Fast neutron zone;
3 - Thermal neutron zone;
4 - layer of B4C;
5 - layer of ZrH2;
6 - fuel assembly; and
7 - external reflector of neutrons.



Two-core Subcritical Blanket With Fast And Thermal Neutron Spectrum

- The subcritical two-core blanket consists of the internal zone with fast neutron spectrum and external zone with thermal spectrum.
- A special ‘‘neutron filter’’ from B4C-ZrH2 is installed between the external and internal zones, which decreases the effect of thermal neutrons on the fast zone, compared to the case when there is no material absorbing neutrons.
- The «neutron filter», as noted above, consists of a layer of boron carbide of 2.15 g/cm^3 density with the enrichment of 10B isotope of 50% at ~ 2.4 cm thickness and a stratum of zirconium hydride of 1.7 g/cm^3 density,~ 4.8 cm thick.

Two-core Subcritical Blanket With Fast And Thermal Neutron Spectrum (Cont..)

- filter reflects about 30% of neutrons from the fast zone side (93% of having energy over 0.1 MeV) and allows the penetration of about 42% of neutrons to the thermal zone
- The high enrichment uranium dioxide, UO2, is used as fuel in the fast zone, whereas fuel composition of zirconium hydride and uranium-zirconium is used in the thermal zone.
- From the exterior, the reactor is surrounded with reflector from Pb-Bi of 20 cm thick.
- with a considerable softening of spectrum (15% out of neutrons penetrating have energy below 4.6 eV). In the opposite direction, from the external zone, the portion of neutrons penetrating to the internal zone amounts to ~ 17%, there being ~ 0.3% neutrons with energy below 4.6 eV.

Calculation Characteristics Of Homogenous Targets

E_{elec} MeV	Pb—Bi	^{238}U	0.3 (Pb—Bi) + 0.63 ^{235}U + 0.07 ^{238}U[a]
50	$\gamma_n^{tot} = 1.347 \times 10^{-2}$ $(\gamma,xn) = 1.337 \times 10^{-2}$ $(n,xn) = 7.660 \times 10^{-5}$	$\gamma_n^{tot} = 3.199 \times 10^{-2}$ $(\gamma,xn) = 2.748 \times 10^{-2}$ $(n,xn) = 1.658 \times 10^{-4}$ $(n,f) = 4.336 \times 10^{-3}$	$\gamma_n^{tot} = 7.604 \times 10^{-2}$ $(\gamma,xn) = 2.610 \times 10^{-2}$ $(n,xn) = 3.835 \times 10^{-4}$ $(n,f) = 4.951 \times 10^{-2}$
100	$\gamma_n^{tot} = 2.823 \times 10^{-2}$ $(\gamma,xn) = 2.799 \times 10^{-2}$ $(n,xn) = 2.388 \times 10^{-4}$	$\gamma_n^{tot} = 6.607 \times 10^{-2}$ $(\gamma,xn) = 5.676 \times 10^{-2}$ $(n,xn) = 3.905 \times 10^{-4}$ $(n,f) = 8.889 \times 10^{-3}$	$\gamma_n^{tot} = 1.580 \times 10^{-1}$ $(\gamma,xn) = 5.417 \times 10^{-2}$ $(n,xn) = 7.661 \times 10^{-4}$ $(n,f) = 1.030 \times 10^{-1}$

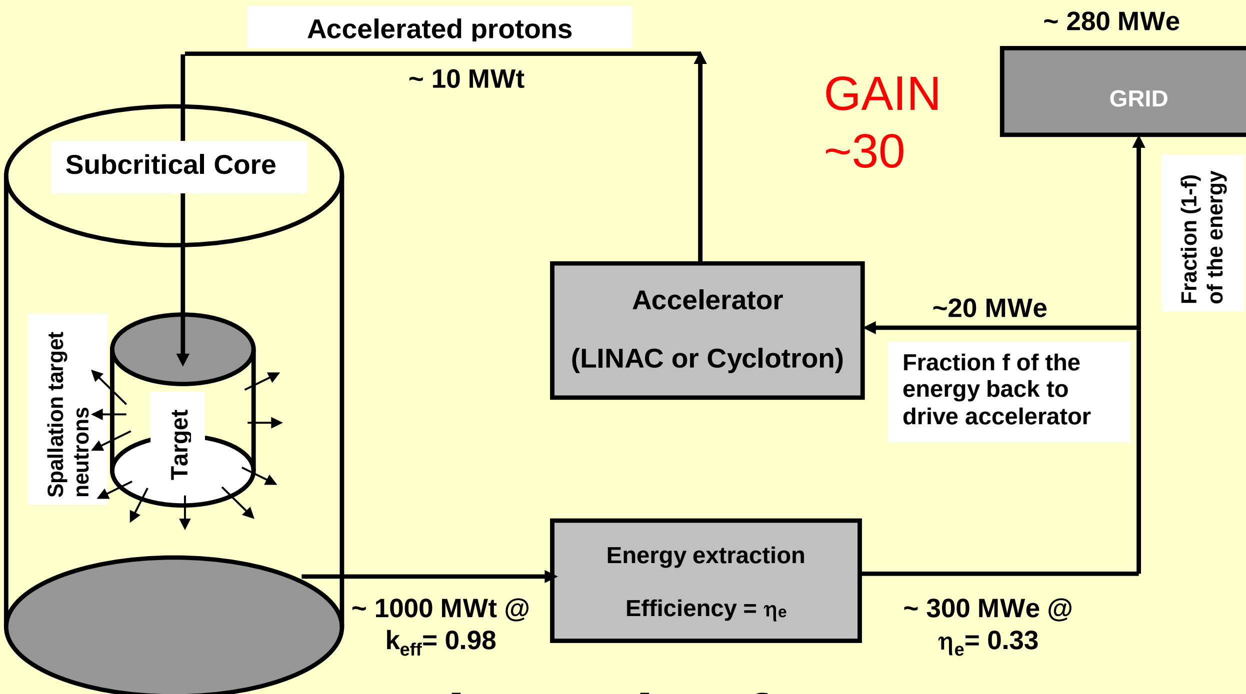
The total number of fissions in the system (*M = M1 + M2)* *normalized to one neutron from the external source (target) is 52, and* the neutron multiplication (*N = νM) is ~130.*

For example, the neutron increase is 50 in a single-zone subcritical blanket with multiplication coefficient 0.98 and 130 in this case. The neutron gain due to the cascade is approximately a factor of ~130/50 = 2.6.

For 4 MW Electron Beam ; gain G ~ 12.89
Power output will be ~ 12.89 x 4 = ~ 51 MW.

A dual-zone reactor increases the power by a factor of 12.
The power of the system with input electron beam power 4 MeV will be ~ 50 MW (27.6% is released in the fast zone and 72.4%in the thermal zone of the blanket). The average neutron flux density is $3.8 \cdot 10^{14}$ $sec^{-1} \cdot cm^{-2}$ in the fast zone and $6 \cdot 10^{13}$ $sec^{-1} \cdot cm^{-2}$ in the thermal zone.

Accelerator-Driven System for thorium fuel and waste transmutation



Schematic of ADSS

ADSS has exclusive niche in:

- **Thorium fueled reactor due to enhanced availability of non-fission neutrons of spallation target for faster breeding.**
  (This will enable early introduction and faster growth of thorium fuel-based power reactors in the country.)
- **Transmuting transuranic (TRU) elements in the spent fuel with enhanced safety with sub-critical operation, that is otherwise difficult in a conventional fast reactor.**
  (This will reduce/eliminate need for geologic repository to dispose spent fuel.)

Energy Multiplication of 100 and Accelerator Efficiency of 50% needs VALIDATION

Photo Neutrons at 100 MeV Electrons with Heavy Water for ADS Applications

(H. Feizi and A H Ranjbar 2016 JINST 11 P02004)

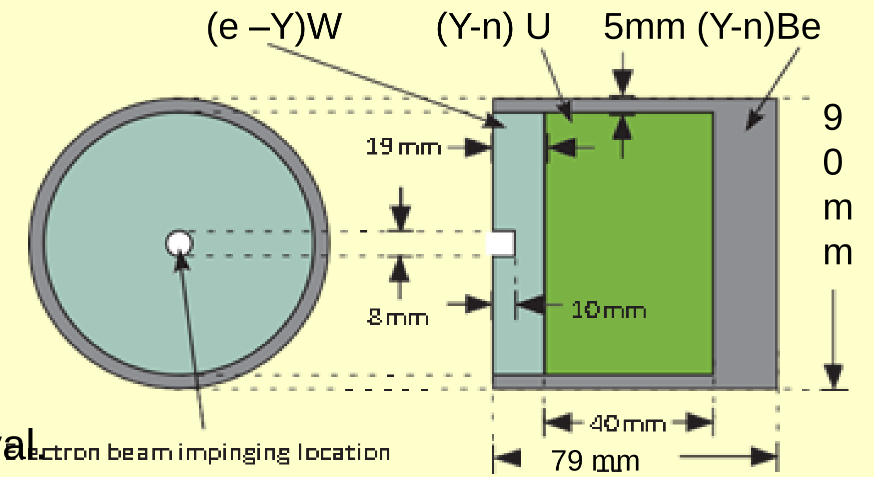
FLUKA CODE SMULATIONS:

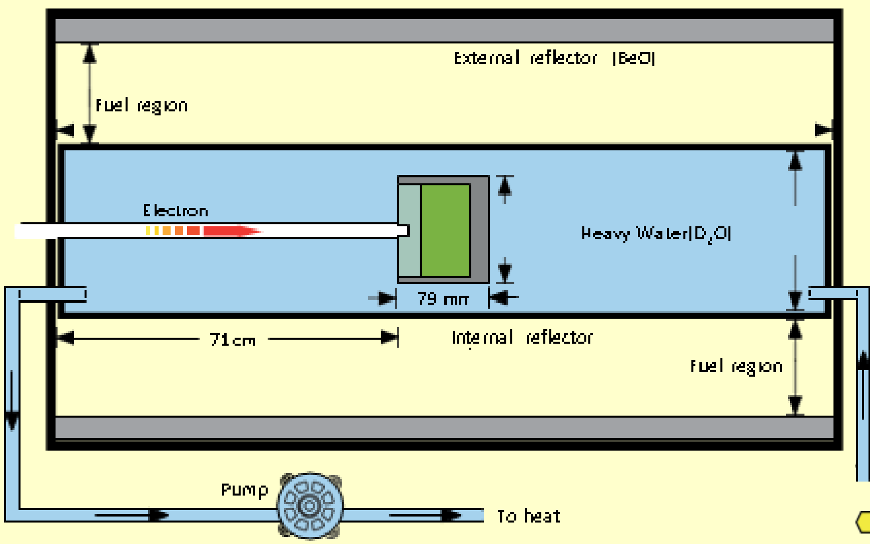
•For 100 MeV Electron Beam, W (9mm) e-Y convertor, U (40 mm) Y-n convertor and Be (20mm) as Y-n additional low energy convertor produced

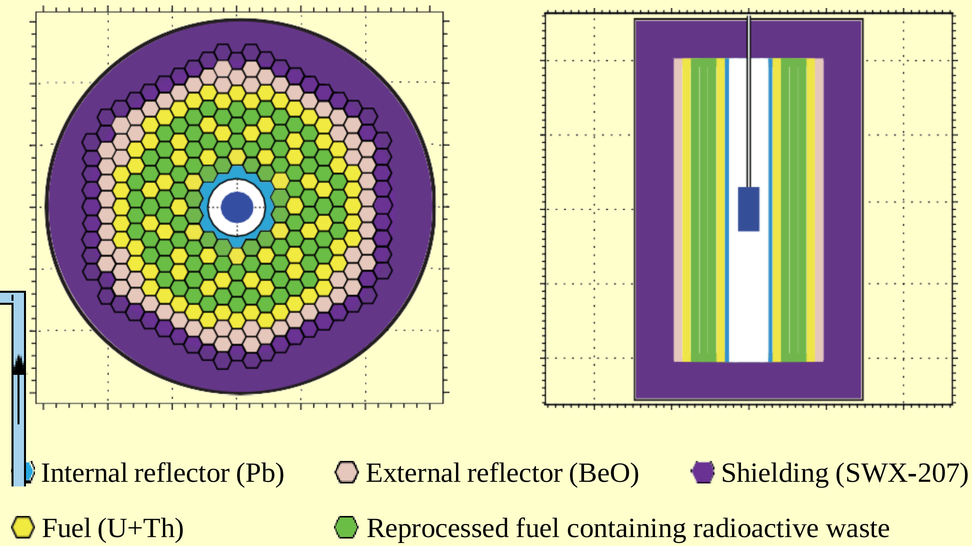
3.986 x 10^{14} n/s/mA

4 x 10^{16} n/s for 10 MW, 100 mA

•Heavy Water acted as Y-n convertor, neutron moderator and also for heat removal







Design Considerations for Low Energy High Intensity Electron Beam based Reactor

- X Ray Targets: (e – Y) Convertor
  - For 100 MeV, High Z (W, Ta, U, Pb-Bi) are used
  - For 10 MeV, High Z (W, Ta. U, Pb-Bi) are used as X Ray Converter and Low Z (Be, D20, LiD, CD4 (liquid), or BeD2) as Neutron Targets,

Typical X Ray Target Thickness for e – Ɣ Conversion

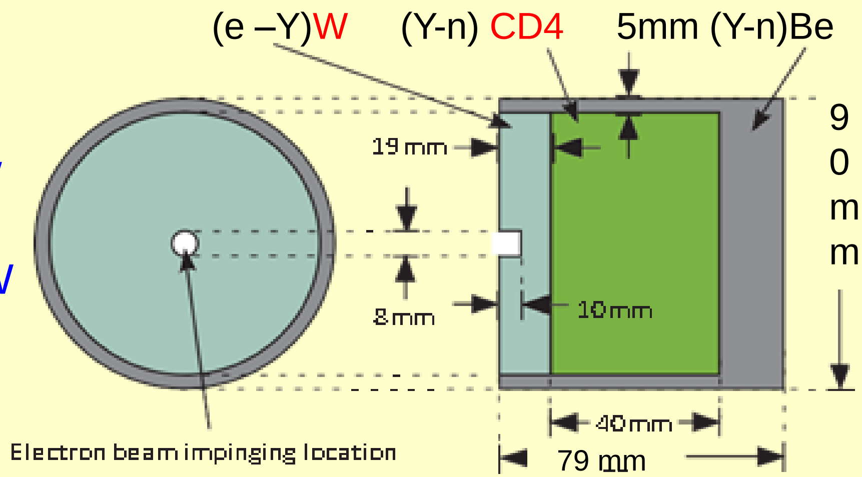
Electron Energy MeV	Electron Range R (g/cm^2)					**Optimum Target Thickness (40% of R)**				
	U 19.1 g/cm3	**Pb** 11.34 g/cm3	**Bi** 9.8 g/cm3	**W** 19.4 g/cm3	**Ta** 16.6 g/cm3	**U** **mm**	**Pb** **mm**	**Bi** **mm**	**W** **mm**	**Ta** **mm**
8	5.28	5.25	5.20	5.30	5.3	**1.10**	**1.85**	**2.12**	**1.09**	**1.28**
10	6.16	6.13	6.08	6.21	6.20	**1.29**	**2.16**	**2.48**	**1.28**	**1.49**
15	7.95	7.95	7.88	8.09	8.09	**1.66**	**2.80**	**3.24**	**1.67**	**1.95**
20	9.35	9.40	9.31	9.59	9.59	**1.96**	**3.30**	**3.80**	**1.98**	**2.31**
50	14.4	14.63	14.48	15.00	15.10	**3.01**	**5.16**	**5.91**	**3.09**	**3.64**
100	18.51	18.94	18.74	19.60	19.66	**3.88**	**6.68**	**7.65**	**4.04**	**4.74**

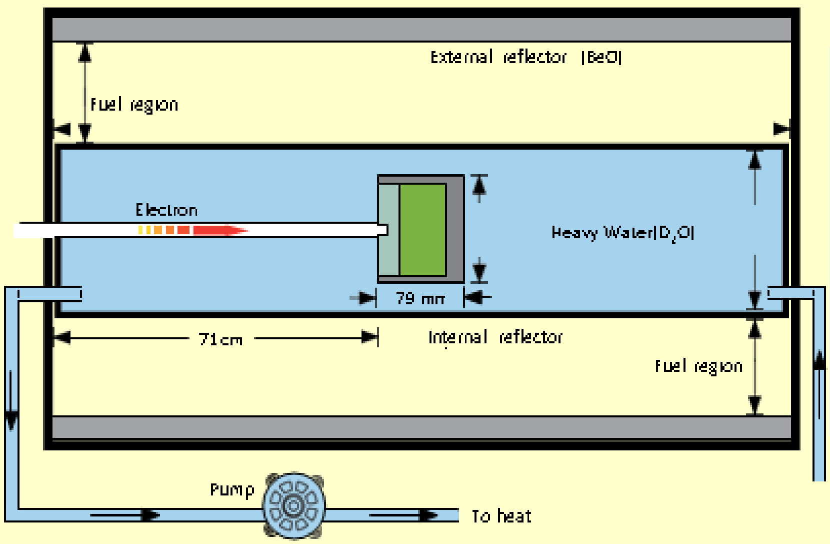
Design Considerations for Low Energy High Intensity Electron Beam based Reactor (Contd)

- Neutron Targets: (ϒ, n) Convertors
- Low Threshold Neutron Targets: Be, D20, LiD, CD4 (liq.), or BeD2
- Bremsstrahlung X Rays should be stopped by the (ϒ, n) target.
- Radiation Shielding data for 10 MeV beam requires 1 TVL (2 TVL) to stop 90% (99%) of X rays dose and hence used for Y-n reactions.
- For 10 MeV X Rays, 1 TVL for H2O is 49 cm. For CD4 (density: 1.19), 1 TVL is 41 cm. So CD4 thickness: 41 to 82 cm
- Liquid Targets should prefer for efficient heat extraction

Proposed Photo Neutron Target at 10 MeV Electrons with CD4 and D2O

- For 10 MeV, 1 A, 10 MW Electron Beam, W (1.3 mm) e-Y convertor, CD4, Y-n convertor and Be (20mm) as Y-n additional low energy convertor can produce
  1.5×10^{16} n/s for 10 MeV, 1 A. 10 MW
  In comparison with
  4×10^{16} n/s for 100 MeV, 0.1 A,10 MW
- Heavy Water will act as Y-n convertor, neutron moderator and also for heat removal. This might give additional neutrons





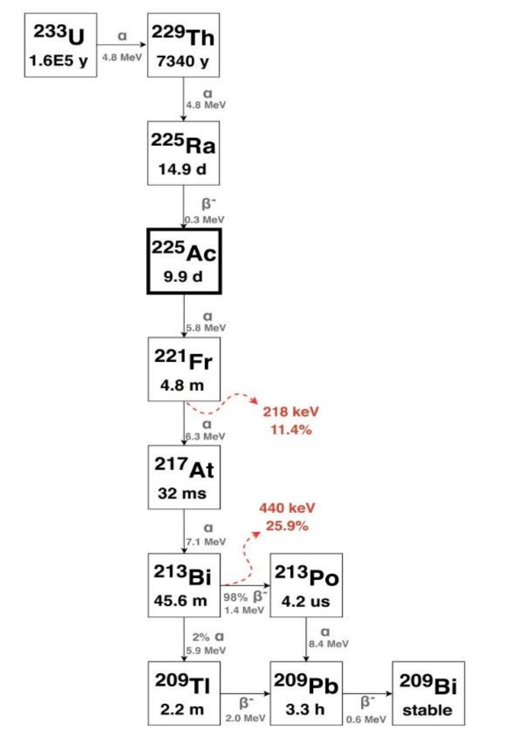
Beam Diameter: 20 mm
(e –Y) Convertor W: 1.3 mm
(Y-n) convertor CD4:41-82 cm
(Y-n) convertor Be: 2 cm

High Intensity Low Energy Micro Reactor

- 10 – 15 MeV, 1 to 3 A Electron Beam
- Bremsstrahlung Target: U, W, Ta, Pb/Bi
- Photonuclear Target:
- CD_4 (liquid)/ BeD_2, LiD_2/ D_2O
- **Target Heat Removal by liquid CD_4 and D_2O**
- Reactor Design similar to 100 MeV Beam
- A Gain of 12 to 15 can be anticipated.
- Then a Micro Reactor with ~20 MW can be feasible
- 20 MW Power Station suitable for a town

225Ac Production by Electron Beams

Actinium225 is used for malignant tumor treatment.
Ac225 emits Alpha particles for Targeted Alpha Therapy (TAT).
Its decay products Fr221, At217 and Bi213 are also Alpha emitters



- **X rays produced by electron beams can be employed to produce 225Ac by 226Ra (Ɣ, n) 225Ra followed by beta emission,**
- 18 MeV, 26 µA electrons produced X rays (from W Target) when exposed to 20 mg of 226Ra, produced 2.44 MBq (66 µCi) of 225Ac after one hr of exposure.
- This Scales to 48 GBq (1.3 Ci) of 225Ac per month for 1 g of 226Ra source.
- TRIUMF ARIEL (35 MeV, 10 mA) can produce 74 TBq (2000 Ci) of 225Ac per month from 1 gm of 226Ra
- Orsay ALTO (50 MeV, 10 µA) can produce 56 GBq(1.5 Ci) per month

Electron Linacs have good potential for 225Ac production for Cancer Treatment

Status of Electron Accelerator Technology

- 1 to 10 MeV, 100 kW Electron Beams are routinely employed for Industrial Radiation Processing
- Robust Technology
- Many suppliers available for 1 to 5 MeV, 100 kW Beams
- 10 MeV, 100 kW -500 kW Beams available (?) in industry
- INP Russia ILU (300 KW) and IBA Belgium Rhodotron (500 kW) Beams are available
- 10 MeV, 1 – 3 A SCRF Linac is possible at J. Lab. USA
- A Program to study neutron production on 10 MeV, ~1 MW is suggested. This can be scaled up to 10 MW Beam later
- 225Ac production for Cancer treatment is also proposed

UHF accelerator producers (100 - 200 MHz)

- INP - Institute of Nuclear Physic, Russia (ILU family);
- IBA - Ion Beam Application, Belgium (Rhodotron family);
- Denki Kogyo Co, Japan.

Accelerators type ILU (INP)

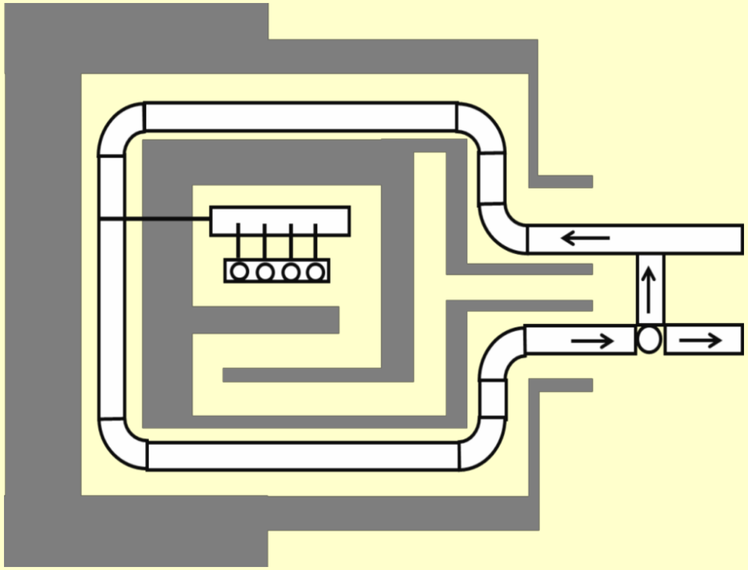
Parametrs	ILU-6	ILU-8*	ILU-10	**ILU-12****	**ILU-14****
Energy	0.5-2.5 MeV	0.8-1 MeV	4-5 MeV	**5 MeV**	**7.5 - 10 MeV**
Beam power	20 kW	20 kW	50 kW	**100/300 kW**	**100 kW**

***Local shield with weight 76t**

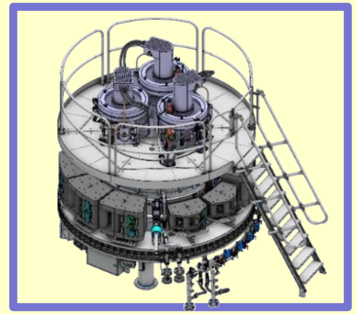
****Multi resonator system**

ILU 14 accelerator 10 MeV, 100 kW at sterilization facility

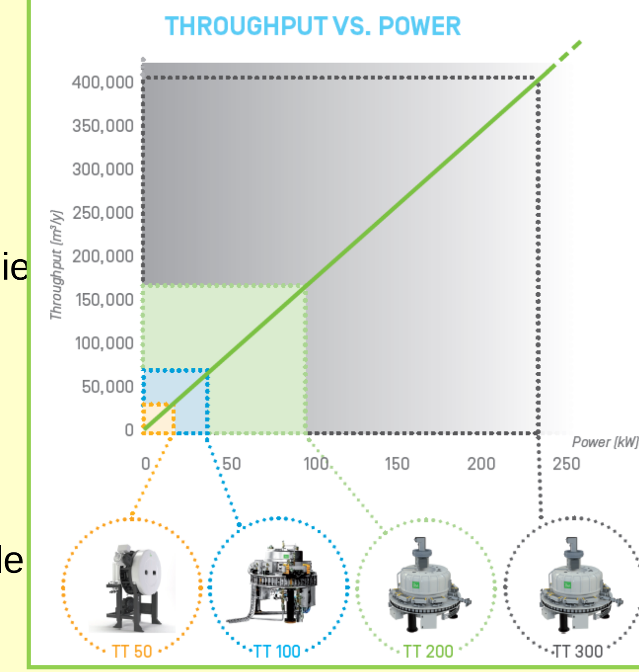
Energy, MeV	10	7.5
Accelerating structure efficiency, %	61	77
Total efficiency, %	26	32



To the 2nd Generation Rhodotron

New TT50	TT100	TT200/TT300	TT1000	High Energy
				
2.0 to 10MeV	2.5 to 10MeV	2 to 10MeV	2 to 7MeV	Up to 40MeV
10 passes	12 passes	10 passes	6 passes	12 passes
2mA	4mA	10mA/30mA	80/100mA*	3.1mA
20kW	**40kW**	**100kW/300kW**	**560kW**/**700kW***	**125kW**
352MHz – 1.3m ∅	215MHz – 1.6m ∅	107.MHz – 3.0m ∅	107.5MHz – 3.0m ∅	107.5MHz – 3.0m ∅
Pulsed	Continuous wave	**CW or pulsed**	**CW or Pulsed**	**Pulsed**
Efficiency ~20%	Efficiency ~20%	Efficiency **>25%**	Efficiency **>50%**	Efficiency ~30%
			***Design power**	

Evolution of the Rhodotron Portfolio:
Unique & Evolutive



Unique Rhodotron Features

- 1 to 10 or 40MeV, multiple energie
- **Compact** footprint
- Fast installation
- **Efficient** use of energy
- Precise energy & emittance = **transportability**
- **CW** or equivalent High Duty Cycle
- **Continuous and fast X & Y scanning**
- No need of **chiller**

TT50 **20 kW**

TT100 **40 kW**

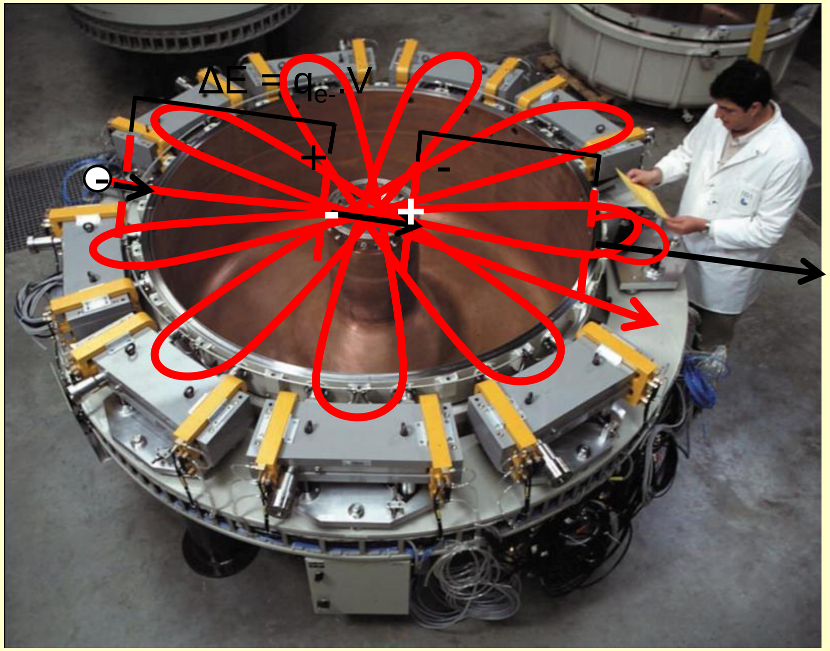
TT200 **100 kW**

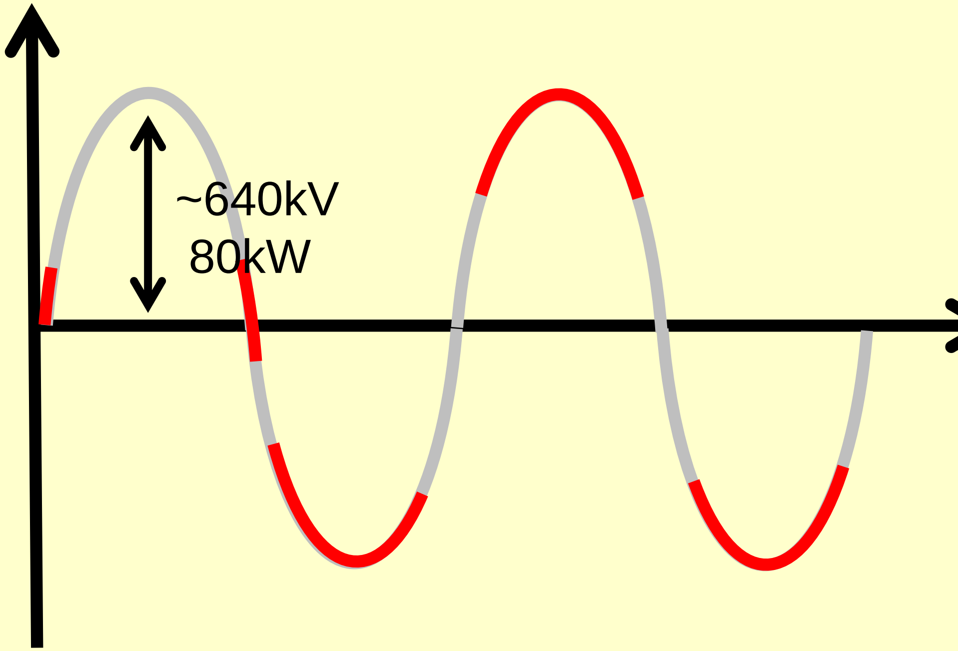
TT300 **190 kW** **300 kW with 2 RF chains**

TT1000 **560 kW** **700kW Design**

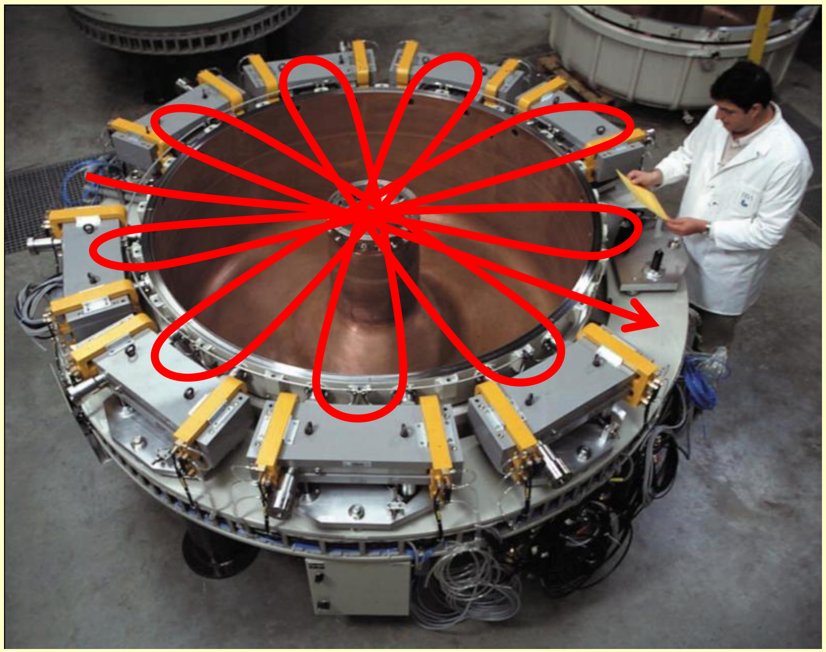
The TT300 Duo – E-Beam and X-Ray at 200kW+

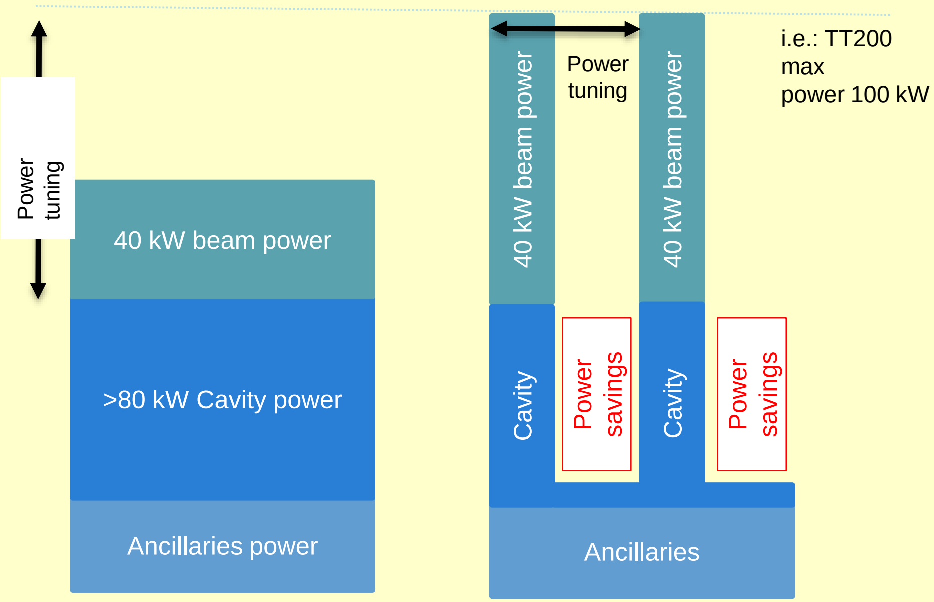
RF Pulsing **Principle & Advantages**





RF Pulsing **Principle & Advantages**

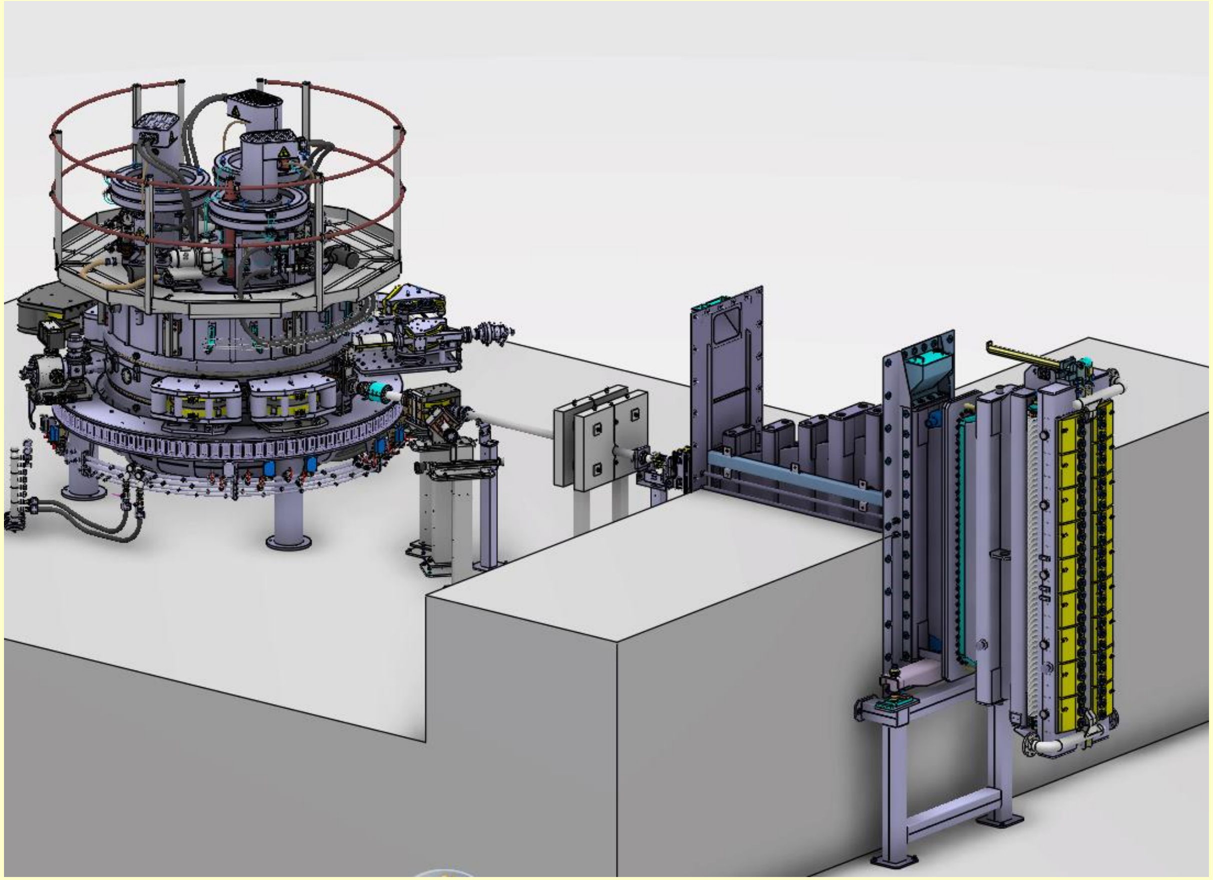




Continuous Wave mode

Eco mode 40 kW
~30 % less consumption

The New TT1000 configuration for RX on pallets



- 80mA at 5 or 7 MeV
- Designed for 100mA
- High efficiency X-Ray target
- 2400mm X-Y parallel scanning
- Automated energy measurement
- RF redundancy
- Solid State RF chain

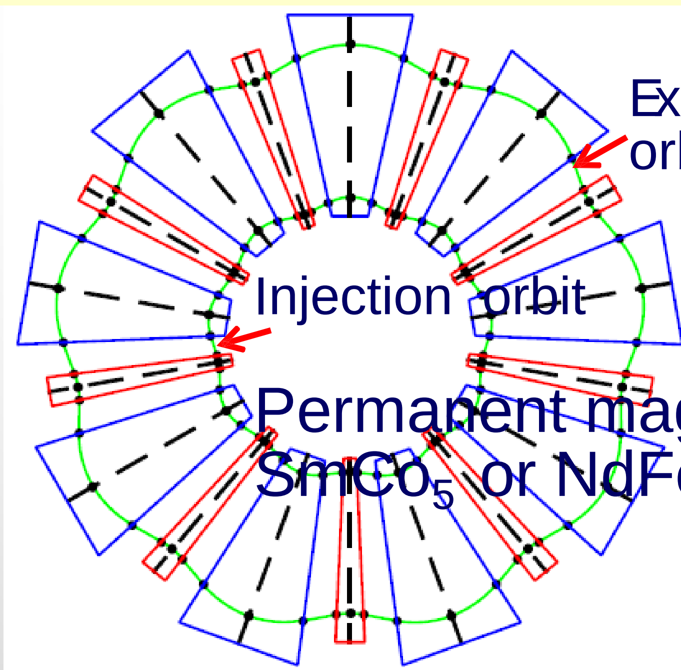
Conclusions and Next Steps

- 0.8 – 1.0 GeV, 1 -10 MW Proton Beams are considered for ADS (Gain ~30)
- 100 MeV, 5 -10 MW Electron Beams studied (Gain ~12 to 15)
- **10 -15 MeV, 10 MW Electron Beams proposed for ADS.**
- **Using CD4/BeD2 as Photo neutron targets, same number of neutrons can be produced as with 100 MeV Beam of equal power**
- **Detailed Design of Low Z Target with Thermal Analysis**
- **Design of Micro Reactor for Energy Multiplication**
- A Program to study neutron production on 10 MeV, ~1 MW is suggested. This can be scaled up to 10 MW Beam later
- 225Ac production for Cancer treatment is also proposed

Thank You

eFFAG – compact CW recirculating electron accelerator

(Fixed-Field Alternating Gradient)



FFAGs

-Fixed magnetic fields like cyclotron,

-Separated components,

-Synchrotron-like dynamics.

Permanent magnets based on ceramic ferrites: $SmCo_5$ or NdFeB could be used.

50 keV to 9 MeV compact ring with injection and extraction orbits. Outer radius <100 cm

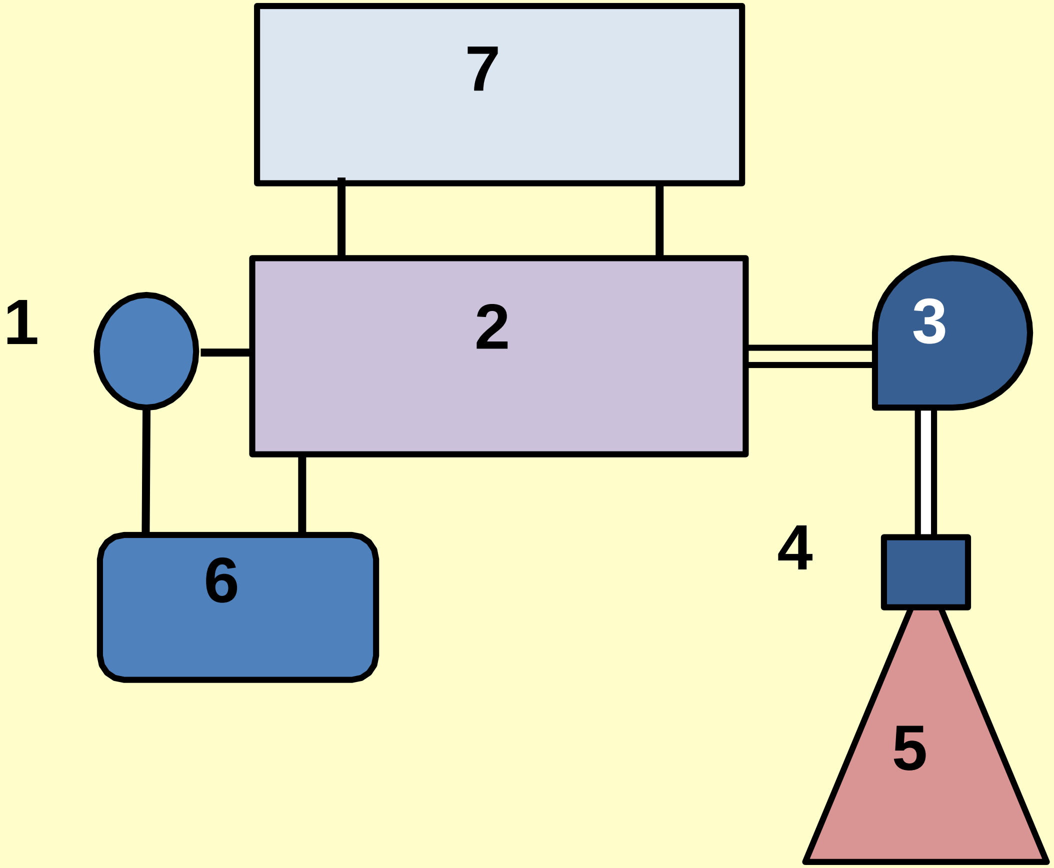
eFFAG – compact CW ecirculating electron accelerator

(**F**ixed**-F**ield **A**lternating **G**radient)

Market case for compact CW effags

- Compact (<1 m diameter, transportable),
- High current: 1 – 2 mA,
- No power supplies for magnets,
- Inexpensive components
- A single 100-200 keV cavity (as in cyclotron),
- 45-90 acceleration turns,
- Duty cycle: 1ns/10 ns ~10%,
- Space charge limited to ~10^9 electrons/RF bunch
- For 100 MHz cavity (10 ns bunch spacing),
- **Electron Energy: 9 MeV,**
- **Beam current: 1.6 mA,**
- **Average beam power: ~140 kW.**

Superconducting radio frequency compact, high power, electron linac 2-40 MeV, 100 kW



1. Electron gun
2. Superconducting electron linac
3. Bending magnet
4. Scanning magnet
5. Output chamber
6. Microwave power
7. Helium cryoplant

NIOWAVE Inc.

Superconducting radio frequency compact, high power, electron linac

❖ Electron Energy	0.5 – 40 MeV
❖ Beam power	1 – 100 kW
❖ Average beam current	up to 2,5 mA
❖ Frequency	350 MHz
❖ Electron bunch length	≈5 ps
❖ Electron gun voltage	100 kV

NIOWAVE Inc.