Electron Linacs as Possible ADS Drivers

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Industrial Applications of Electron Beam

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

Linear Electron Accelerators at BARC

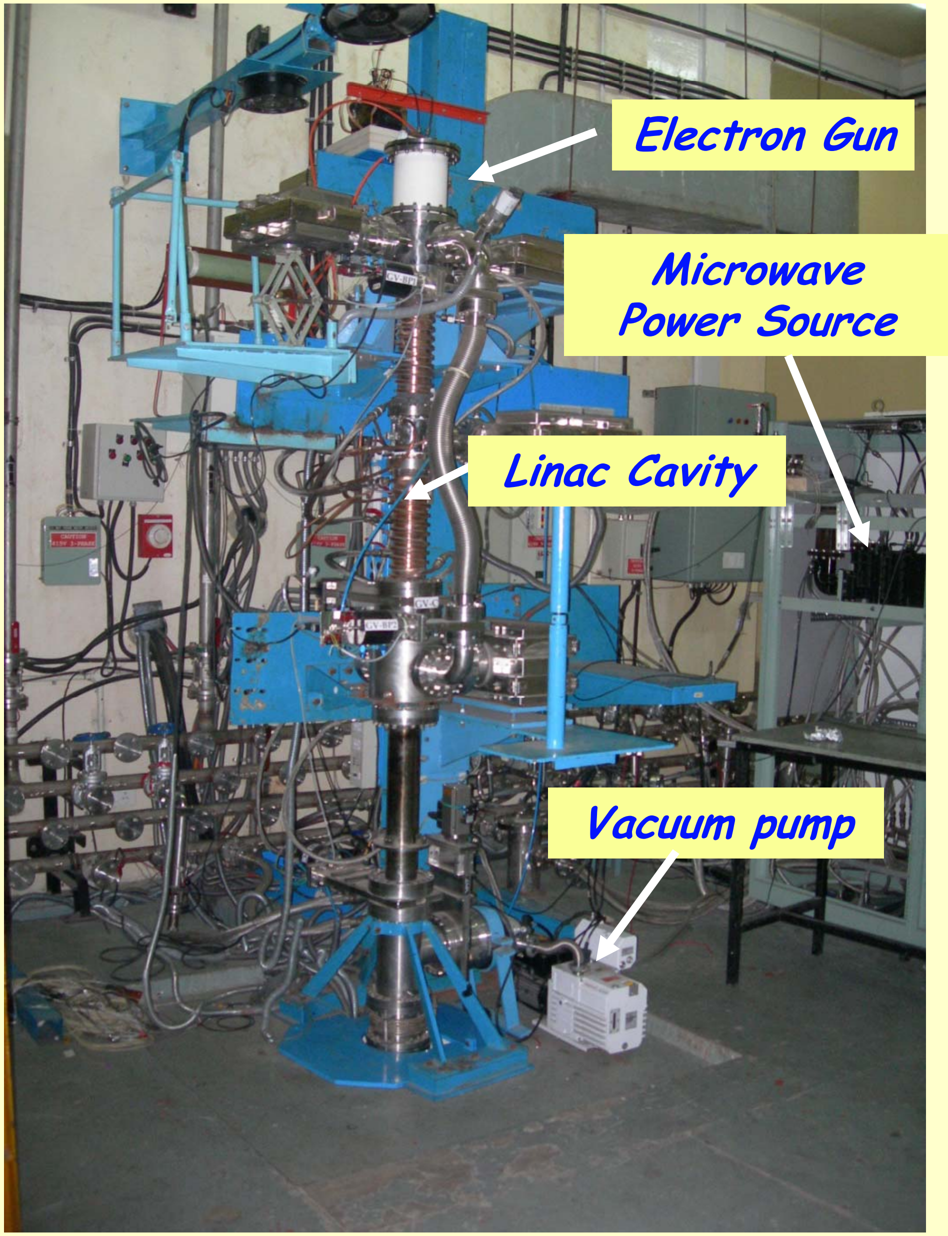
- **500 keV,10 kW DC LINAC at BRIT**
- **3 MeV, 30 kW DC LINAC at EBC**
- **10 MeV, 10 kW RF LINAC at EBC**
- **9MeV, ~1 kW RF LINAC at ECIL**
- **30 MeV RF LINAC at Vizag**
- 9 MeV ~400 W RF COMPACT LINAC
- 100MeV, 100 kW RF LINAC for neutrons (proposed)

500 keV Electron Accelerator Installation

VOLTAGE MULTIPLIER COLUMN of 3 MV ACCELERATOR

- 3 MV , 30 kW Parallel Coupled Column
- LaB6 Cathode based Electron Gun
- 120 kHz RF Oscillator and Power Transformer
- Beam Extracted in Air

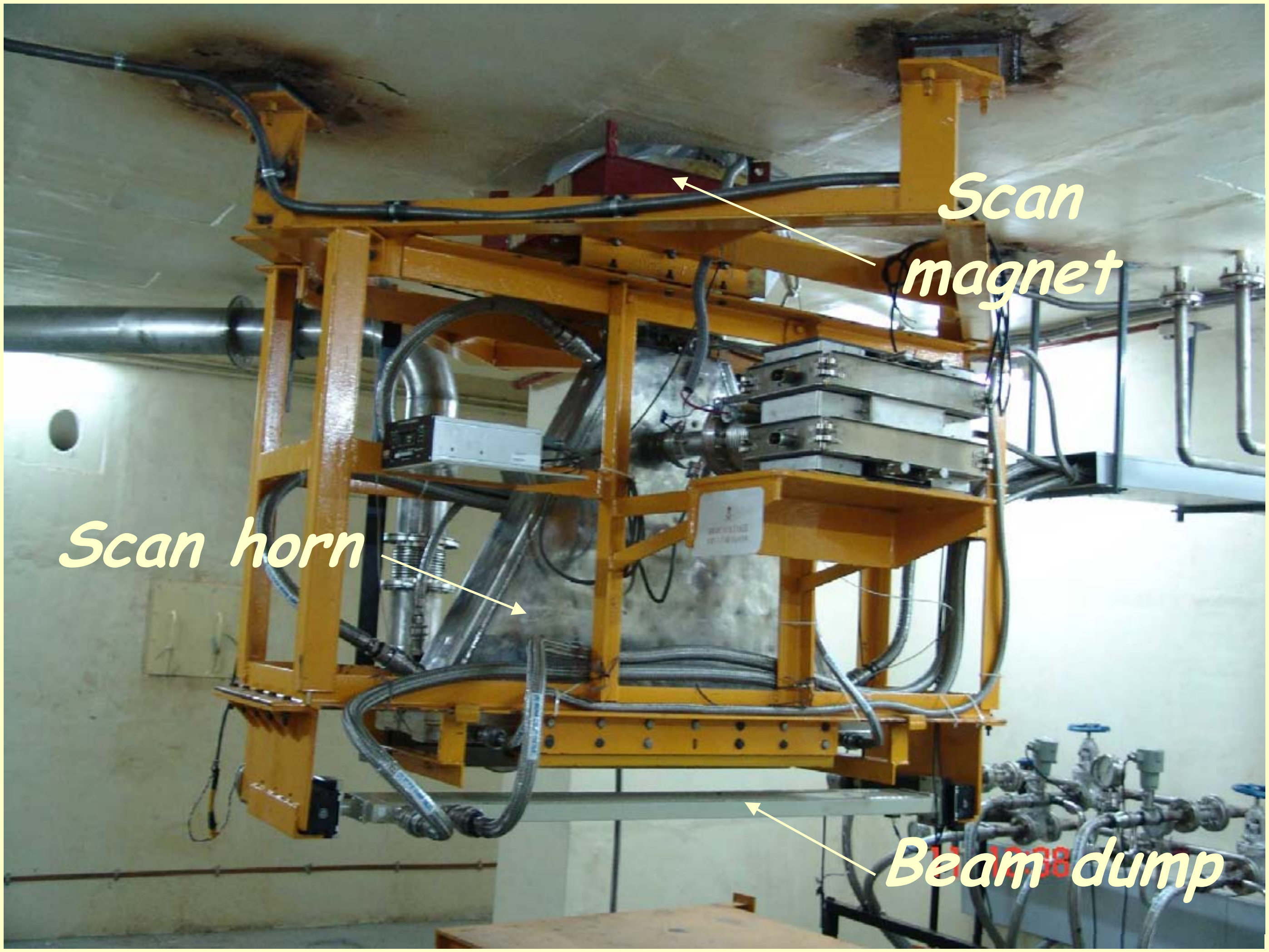
First Floor View of 10 MeV RF linac



Specifications

Energy: 10 MeV
Avg.beam current: 1 mA
Pk beam current: 250mA
Beam power : 10 kW
Pulse width : 10 μs
Rep.rate: 400 Hz
Length : 1 m

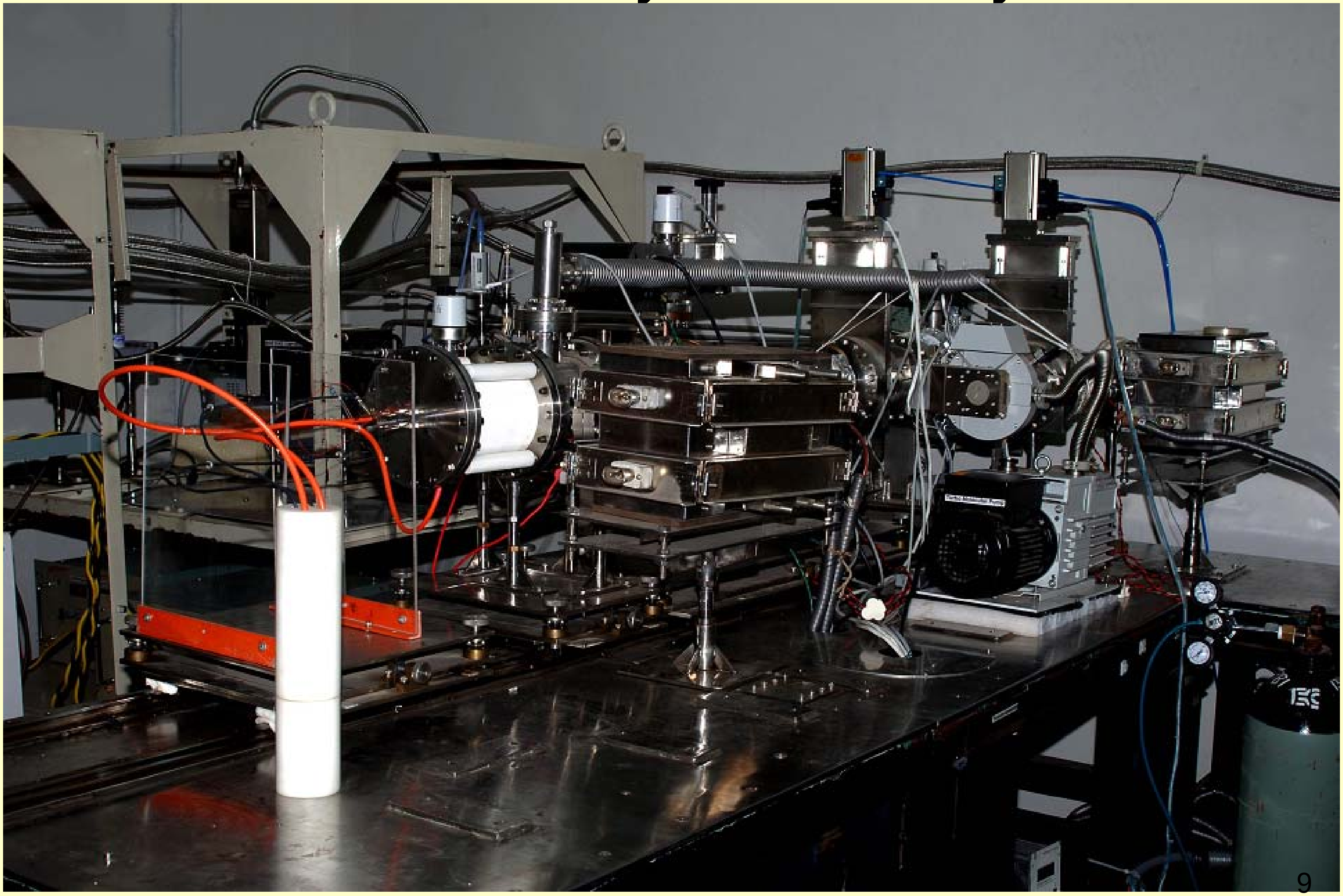
Ground Floor View of 10 MeV RF linac



9 MeV Cargo Scanning Linac

Beam Energy	9-10 MeV
Beam Current	0.2 mA
Beam Power	2 kW(max.)
X-rays beam dose rate	30 Gy/min/m
X-rays final beam focal spot size	2 mm
x-rays beam symmetry	± 5 % at 7.5 deg. off the central axis.
Leakage of Radiation	0.1 %
X-rays field size.	A standard 30 Deg. Cone
Computer Control & Instrumentation	A standard control system with programmable logic controller
EMI/EMC	The system should comply with EMI/EMC regulations.

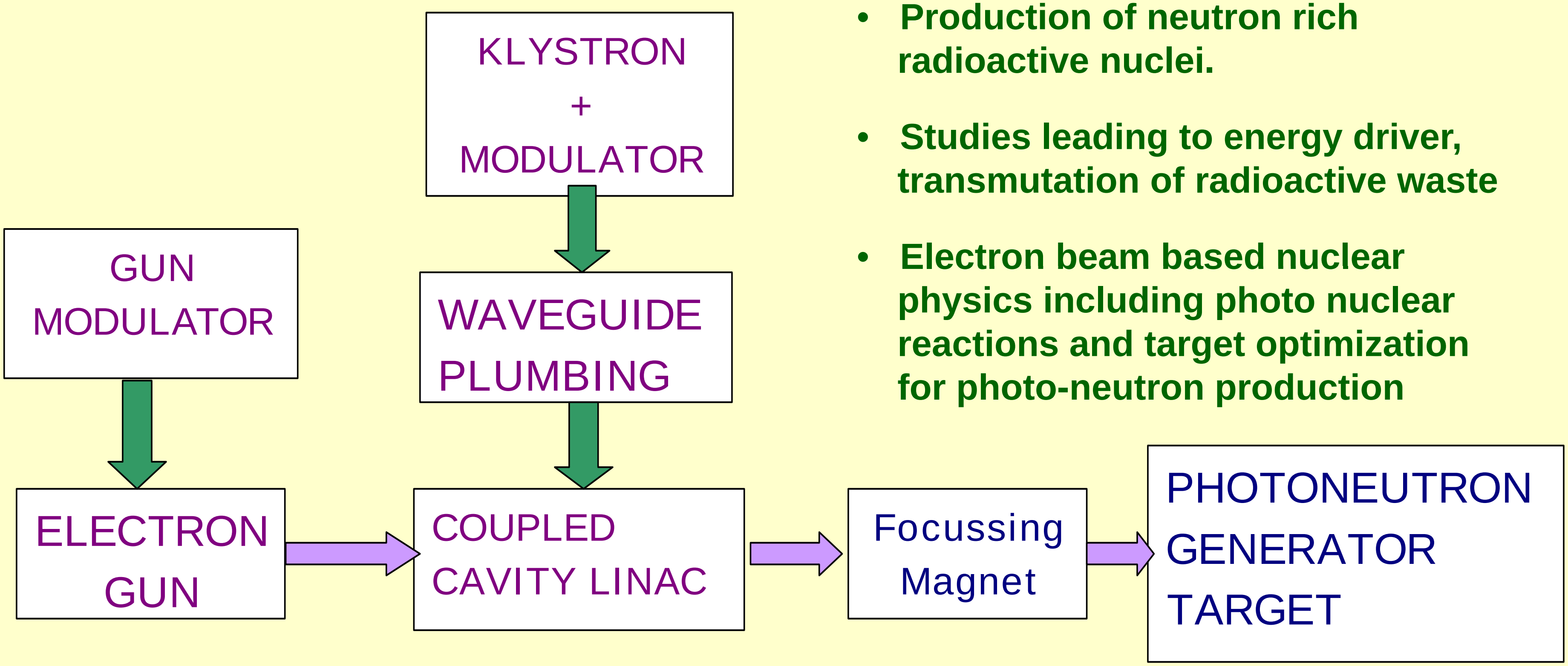
9 MeV Linac assembly at ECIL, Hyderabad



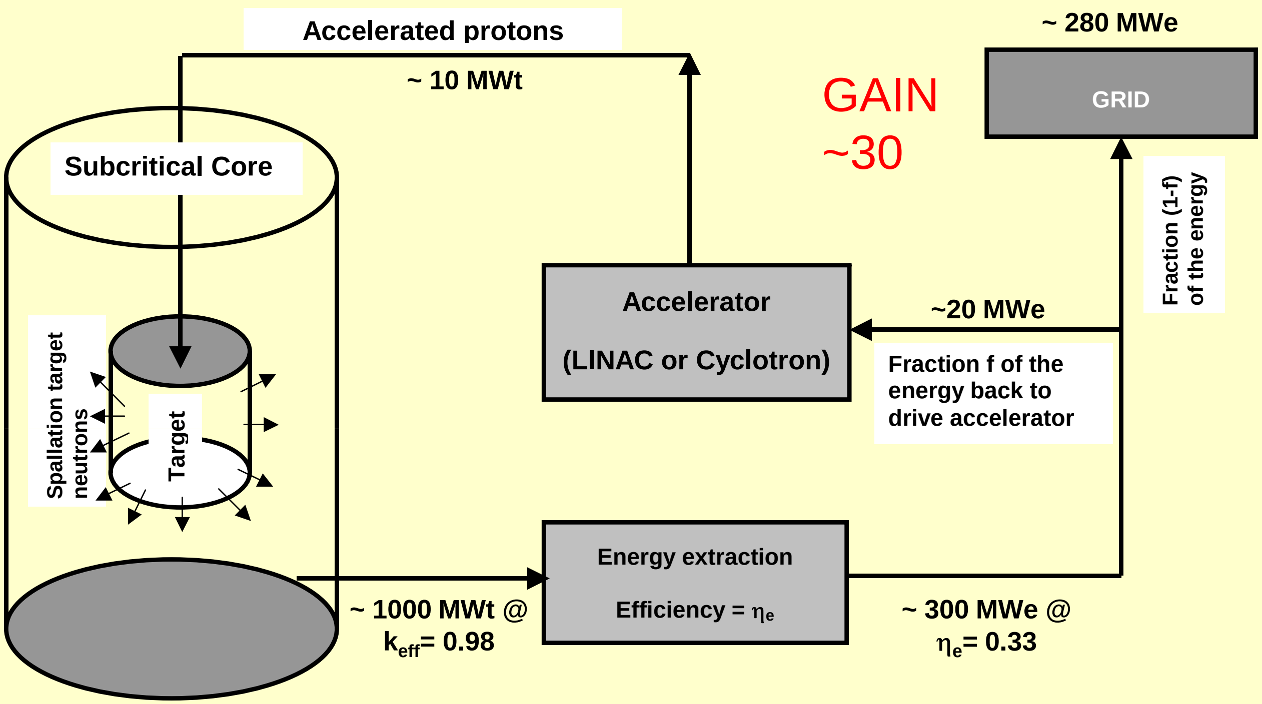
30 MeV, 3 kW RF Electron Linac

APPLICATIONS:

- **Medical radio-isotopes production,**
- **Neutron generator (10^{12} – 10^{13} n/s)**
- **Production of neutron rich radioactive nuclei.**
- **Studies leading to energy driver, transmutation of radioactive waste**
- **Electron beam based nuclear physics including photo nuclear reactions and target optimization for photo-neutron production**



Accelerator-Driven System for thorium fuel and waste transmutation



Schematic of ADSS

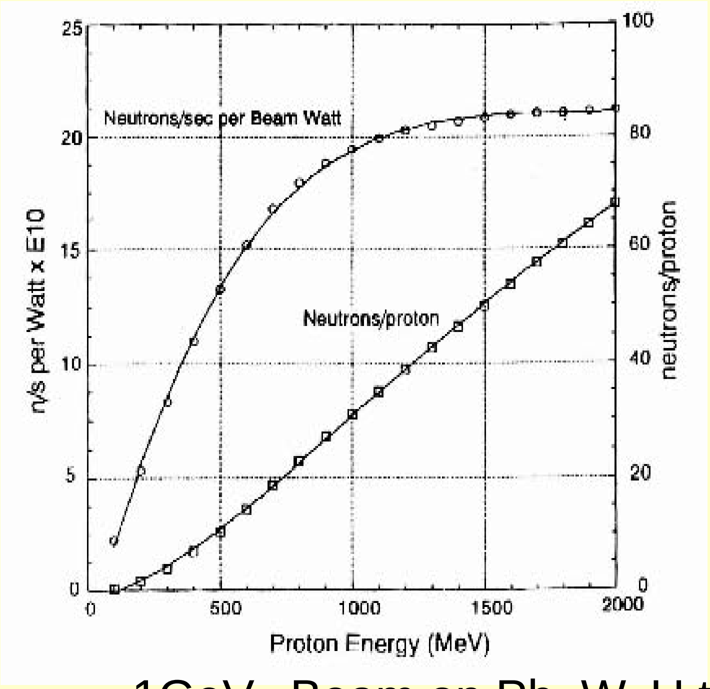
ADSS has exclusive niche in:

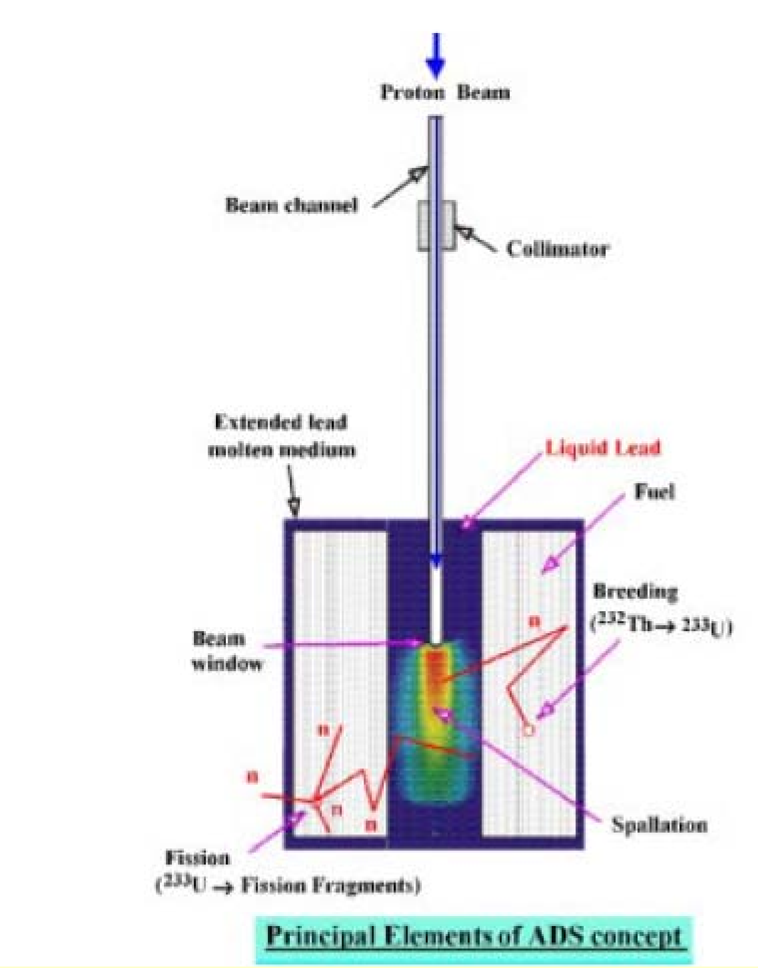
- **Thorium fueled reactor due to enhanced availability of non-fission neutrons of spallation target for faster breeding.**
  (This will enable early introduction and faster growth of thorium fuel-based power reactors in the country.)

- **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.**

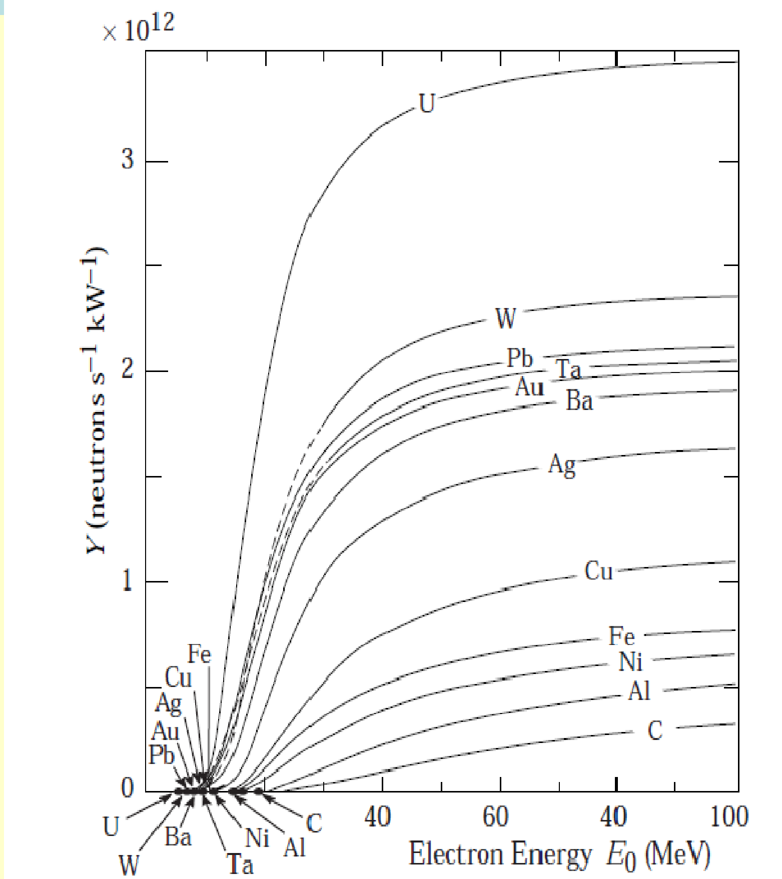




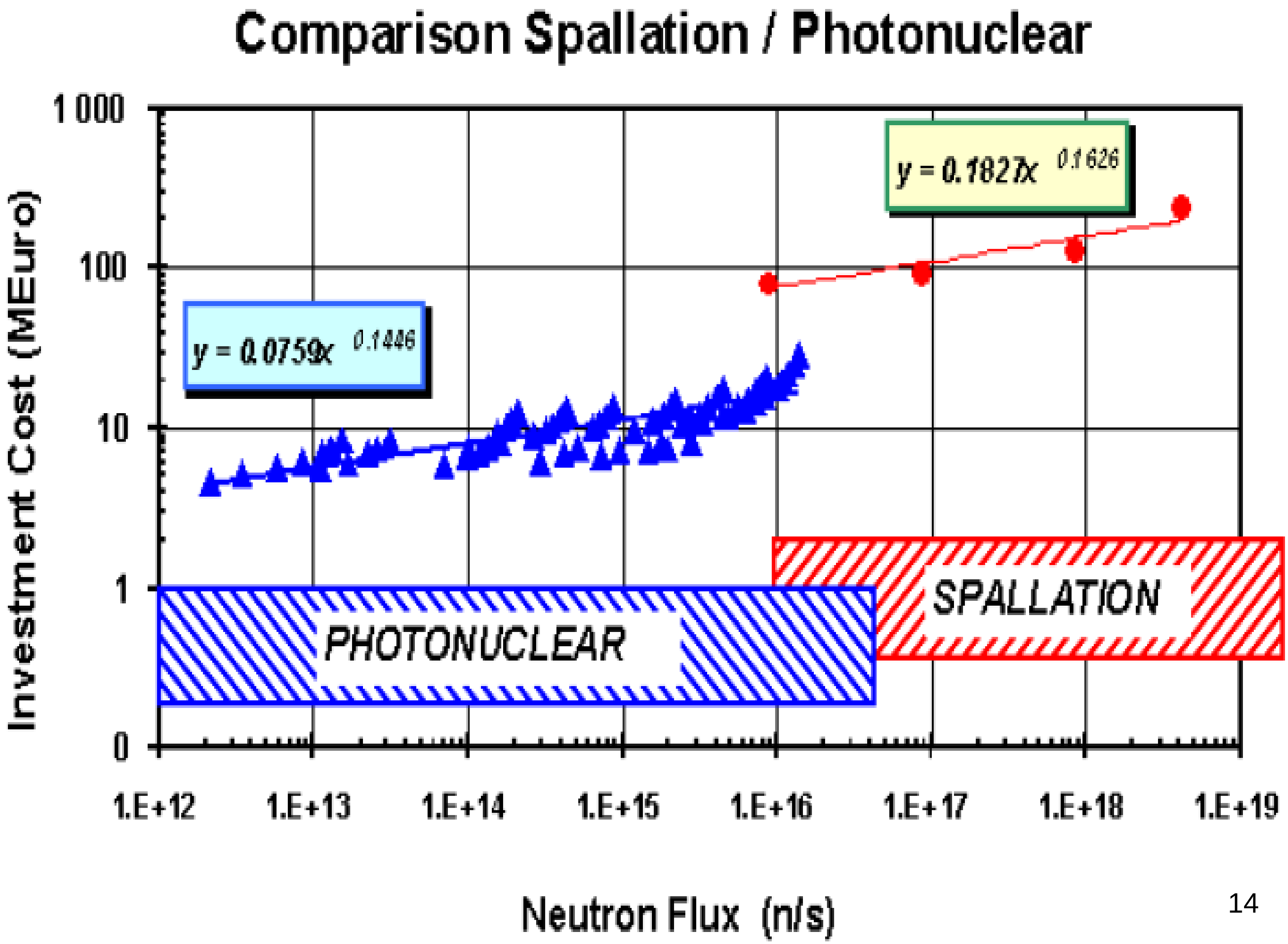
1GeV, Beam on Pb, W, U targets, produce ~ 2X10^{11} n/s/W.
1GeV, 10 mA, 10 MW Beam will produce ~ 2 X10^{18} n/s.

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	$0.955\text{-}1.91X10^{16}$


Comparison Spallation / Photonuclear
y = 0.1827x 0.1626
y = 0.0759x 0.1446
SPALLATION
PHOTONUCLEAR
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
1.E+19
Neutron Flux (n/s)

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.

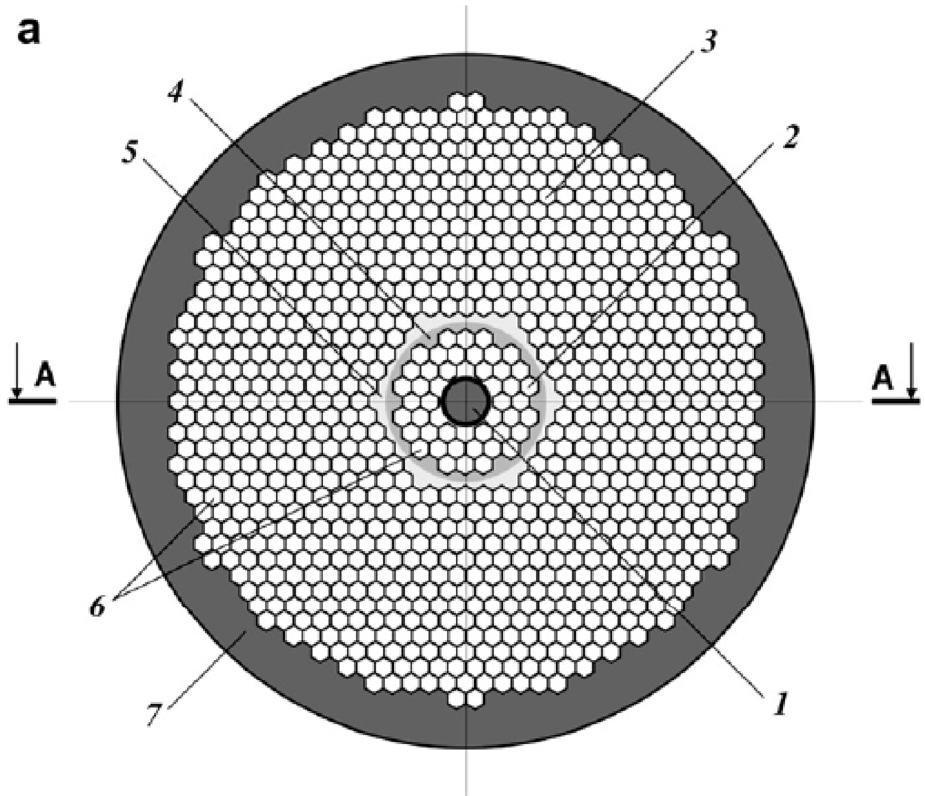
- **For 5 MW, 50 MeV e- beam,**
- Beam current will be ~ 0.1 A ~ 100 mA
- The no. of neutrons produced will be ~ 2.05×10^{16} n/sec.

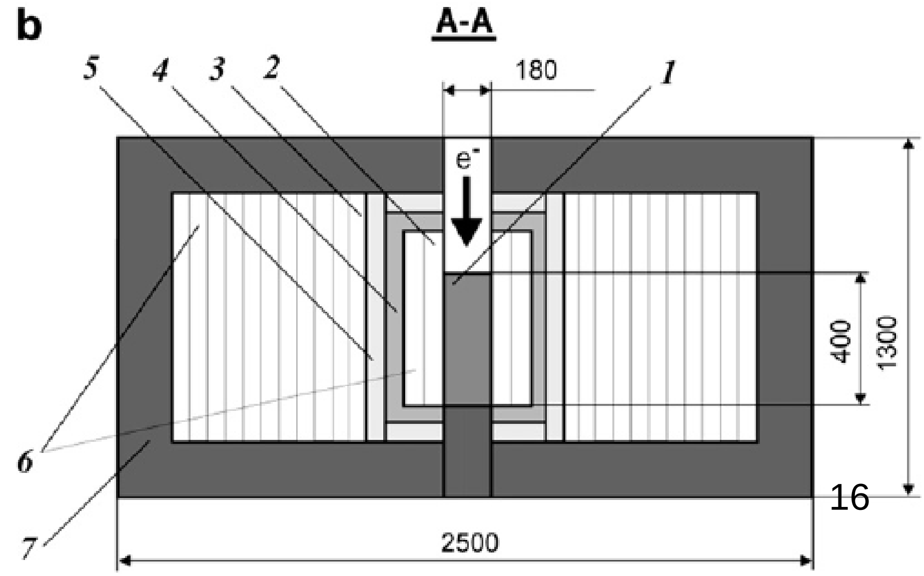
- G = 1.42 <u> for k = 0.97</u>
- G = 2.15 <u> for k = 0.98</u>

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

Target Material

E_{elec} MeV	Pb−Bi	^{238}U	0.3 (Pb−Bi) + 0.63 ^{235} + 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 = vM) 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 approximately 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.

RF Electron Linacs :

- Photonuclear and photofission neutrons
- Yield/beam power second only to proton spallation
- Robust technology
- Flexible output characteristics
- Inexpensive and “small,” transportable
- Evaporation neutron spectrum, similar to spallation source, but less high energy tail

Specifications of the electron driver accelerator :

- Electron driver is to induce more than 10**16 fissions/s in the uranium target (ignoring for the moment the issue of power density deposition in the target).
- This goal leads to beam specifications as follows:
- **Final beam energy: 50 to 70 MeV.**
- **Average beam current: 100 to 200 mA.**
- For 5- 10 MW electron beam, a high-power CW superconducting linac is suitable
- **100% of the RF power transmitted to the beam**
- **Cryogenics**
- **Compact Design**

ELECTRON INJECTORS

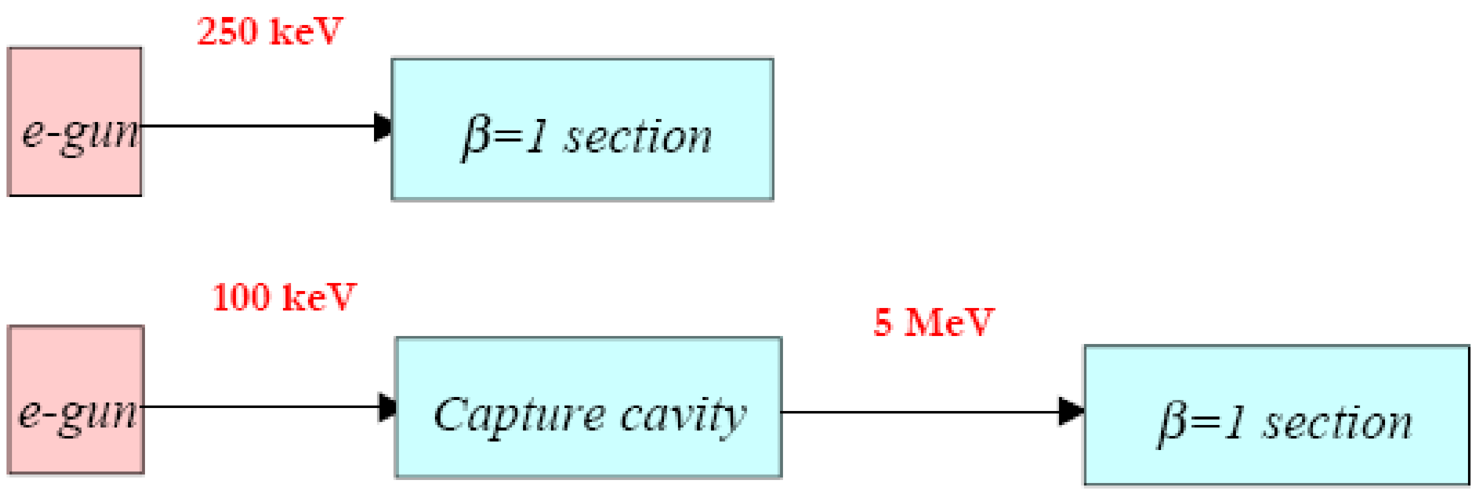


Fig. 2.3: Two alternative schemes for the injector section.

Table 2.1: Potential sources of RF Components.

Frequency	350 MHz	700 MHz	1.3 GHz
Electron gun	→ LIL thermionic guns *(current increase needed)*	*(Non-existent at present)*	→ TTF injector 1 40 kV gun + 300 kV electrostatic column, 1mA CW, 216.7 MHz *(current increase needed)*
SC cavities	→ LEP 4-cells β=1 cavity	→ big R&D effort going on for proton cavities. *(easily applicable to electron cav.)*	→ TTF 9-cells β=1 cavity
RF CW power couplers	→ LEP coupler: design power = 210 kW	→ AAA/APT coupler: design power = 210 kW, >500 kW on test stand at 70K	To be developed *(from TTF couplers 200 kW peak - 1.5 kW average ?)*
RF CW power supplies	→ LEP 1.1 & 1.3 MW klystrons	→ AAA/APT 1 MW klystrons → Thalès IOT 80 kW *(300 kW to be developed)*	Easy development from Thalès 10 MW peak – 250 kW average – klystrons

Table 2.2: ***Main parameters for a proposed EURISOL β=1 section at different frequencies (20 mA, 5–50 MeV*). The*** *total AC efficiency is obtained by assuming an AC-to-RF conversion factor of 60 %, and cryogenic efficiencies of 0.1 % at 2 K and 0.3 % at 4.5 K, respectively.*

Frequency	350 MHz	700 MHz	1.3 GHz
No. of cavities needed	8 (4-cells) in 2 LEP modules	4 (5-cells) in 1 module	4 (9-cells) in 1 module
Operating accelerating field	3.3 MV/m	10.5 MV/m	10.8 MV/m
Section length	25 m	7 m	7 m
Total RF power needed	0.9 MW	0.9 MW	0.9 MW
Operating Q_o	2.10^9	1.10^{10}	5.10^9
Total thermal load	760 W @ 4.5K	130 W @ 2K	140 W @ 2K
Total AC efficiency	51.3%	55.3%	54.8%

* Easily upgraded to 30 mA, 5–70 MeV, just by raising the input RF power.

Existing availability

	350 MHz	700 MHz	1.3 GHz
Electron gun	→ **LIL thermionic guns** *(current up-grade needed)*	?	→ **TTF injector I** 40 kV gun + 300 kV elect. column, 1mA CW, 216.7 MHz *(current up-grade needed)*
SC cavities	→ **LEP 4-cells β=1 cav.**	→ **big R&D effort going on for proton cav.** *(easily applicable to electron cav.)*	→ **TTF 9-cells β=1 cav.**
RF CW power couplers	→ **LEP coupler:** design power = 140 kW, 500 kW on cavity *(power up-grade needed?)*	→ **AAA/APT coupler:** design power = 210 kW, >500 kW on test stand @70K *(power up-grade needed?)*	**To be developed** (from TTF couplers 200kW peak-1.5kW average ?)
RF CW power supplies	→ **LEP 1.1 & 1.3MW klystrons**	→ **AAA-APT 1 MW klystrons** → **Thalès IOT 80 kW** (300 kW to be developed)	**Easy development** from Thalès 10MW peak -250 kW average- klystrons

Conclusion
about the electron driver option

10^{15} fissions/sec is ACHIEVABLE

with an electron driver for photofission

+ Many advantages :

→ a **very compact** driver : 20 meters long

→ a **very safe** driver : low activation of the structure

(compared to the 100MeV deuteron option)

→ **low price** : about 20 M€ investment

(compared to the 1 GeV proton driver)

THANK YOU