PERSPECTIVES OF TRANSMUTATION, CONTROLLED FISSION AND CHARACTERIZATION OF MATERIALS WITH HIGH-INTENSITY ELECTRON ACCELERATORS

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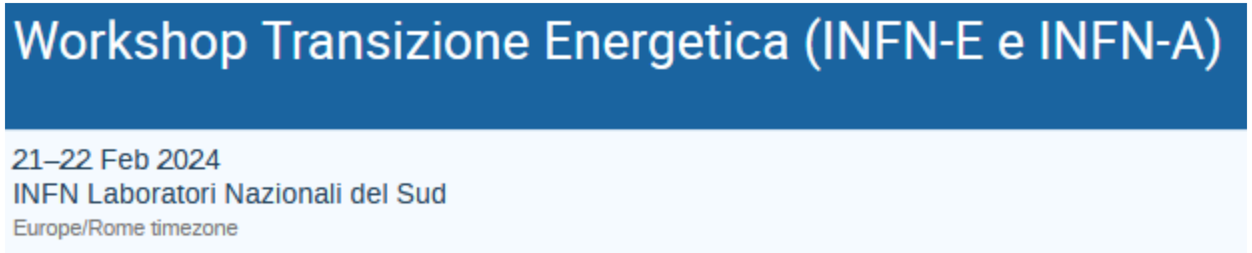

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OUTLINE

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2. **PROTON BASED SPALLATION SOURCES**

3. **ELECTRON BASED NEUTRON SOURCES**

    - *CHARACTERISTICS, PROPERTIES*
    - *OPTIMIZATION FOR NUCLEAR REACTORS*
    - *NEUTRON PROPERTIES: SPECTRUM, FLUX,…*
    - *APPLICATIONS*

4. **LINEAR ACCELERATOR AS A STUDY MACHINE**

5. **SYNCHROTRON BASED SOURCES, PERSPECTIVES AND SYNERGIES WITH FUTURE COLLIDERS**

6. **CONCLUSIONS**

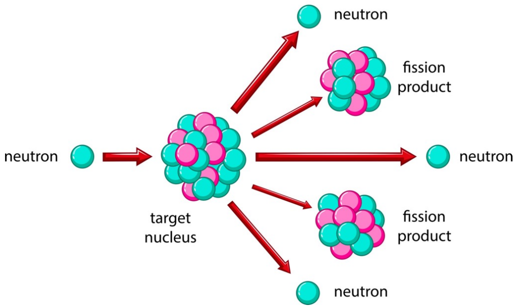
INTRODUCTION: NUCLEAR REACTIONS IN A THERMAL REACTOR

Most reactors use the ^{235}U as a fuel which, after having absorbed a neutron, can fission in many different ways typically producing a two nucleus, with mass numbers around 95 and 135. Some of the products are themselves unstable and carry out beta decay until you get two stable nuclei.

typical reaction

$$n + {}^{235}\mathrm{U} \longrightarrow {}^{236}\mathrm{U} + \gamma$$

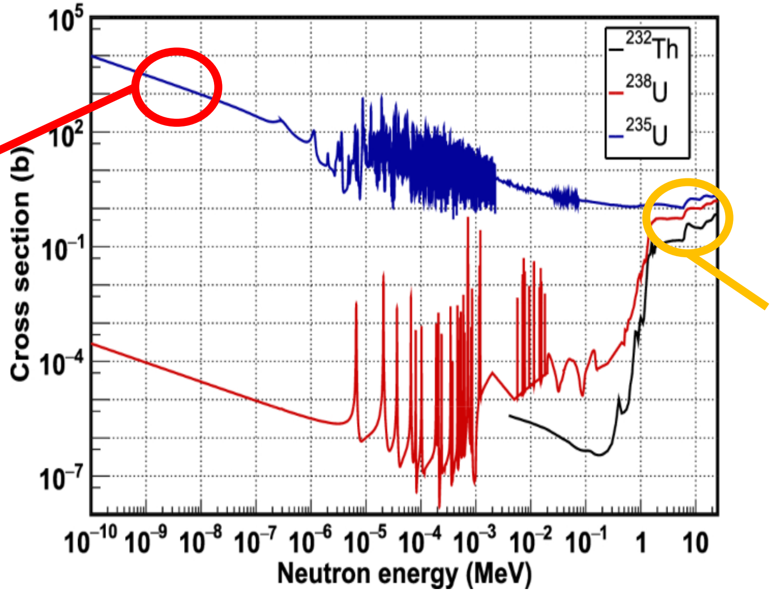
$${}^{236}\mathrm{U} \longrightarrow {}^{141}\mathrm{Ba} + {}^{92}\mathrm{Kr} + 3\,n$$



Energy released about **200 MeV**, (Pu 210 MeV) divided between the kinetic energy of the new nuclei, kinetic energy of neutrons and gamma rays.

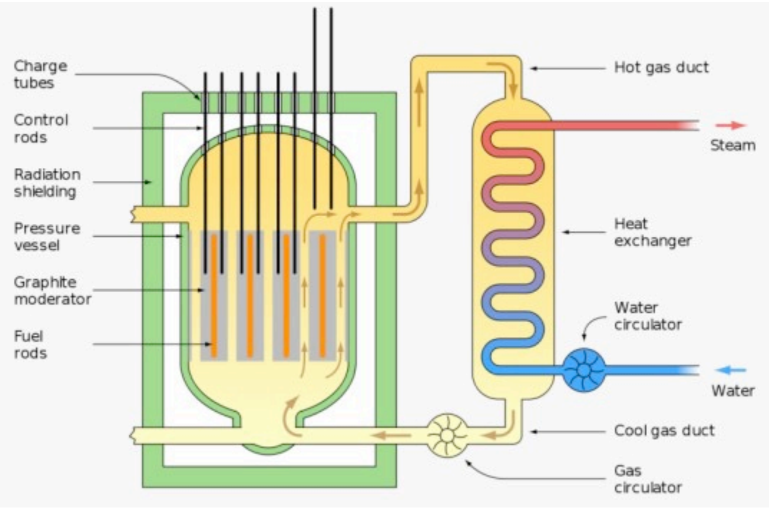
To have a **self sustained reaction** the excess neutrons produced in fission, have to have sufficiently high **probability to be absorbed by other nuclei.**

⇒ The **core of a reactor** is composed of alternating layers of fuel and moderators



Thermal neutrons (0.02 eV) for fissionable material

Fast neutrons (> 1MeV) for fission of fertile material



- ⇒ **U-235 constitutes only about 0.72 % of natural uranium**. At the very beginning of the nuclear energy development people try to research on the fast reactor and to fully make use of the U-238. U-238 constitutes about 99.2 % in natural uranium;
- ⇒ Nowadays **U-238 is transformed into Pu-239** and Pu-239 is mixed with uranium fuel to fabricate MOX fuel for thermal reactors
- ⇒ There are no commercial fast reactors operation in the world (safety,…)

$$n + {}^{238}\mathrm{U} \longrightarrow {}^{239}\mathrm{U} + \gamma$$

$${}^{239}\mathrm{U} \longrightarrow {}^{239}\mathrm{Np} + e^{-} + \bar{\nu}$$

$${}^{239}\mathrm{Np} \longrightarrow {}^{239}\mathrm{Pu} + e^{-} + \bar{\nu}$$

ACCELERATOR DRIVEN SUBCRITICAL REACTORS

ADS systems have been proposed for:

⇒ **transmutation** of specific isotopes present in spent nuclear fuel;

⇒ **generation of electricity**;

⇒ **production of fissile materials** through **fertile-to fissile** conversion.

Basically, an **ADS** has two basic components when used for controlled fission:

- a **neutron source**
- a **subcritical core** which could contain thorium, uranium, reprocessed fuel and radioactive waste.

To calculate the **energy gain we** consider that the number of secondary neutrons N_s produced from N_0 primary neutrons:

$$N_s = N_0 \frac{k_{eff}}{1 - k_{eff}}$$

where **k_{eff} is the neutron multiplication factor (k_{eff}<1 for subcritical reactors)**. The **Energy gain G** is the ratio of thermal energy produced relative to input beam energy supplied:

$$G = \frac{\Delta E_{th}}{\Delta E_{beam}} = \frac{\Delta E_f N_0}{N_b E_p \nu} \frac{k_{eff}}{1-k_{eff}} = G_0 \frac{k_{eff}}{1-k_{eff}} = \frac{P_{th}}{P_{beam}}$$

where N_b is the number of beam particles (N_0/N_b is the ratio between the primary neutron per beam particle) and E_p is their energy, ΔE_f is the energy liberated in each fission process and ν are the number of neutrons generated in each fission.

Advantages relative to critical reactors:

⇒ **Flexibility with respect to fuel composition** i.e. an ADS can burn fuels which would be problematic in critical reactor

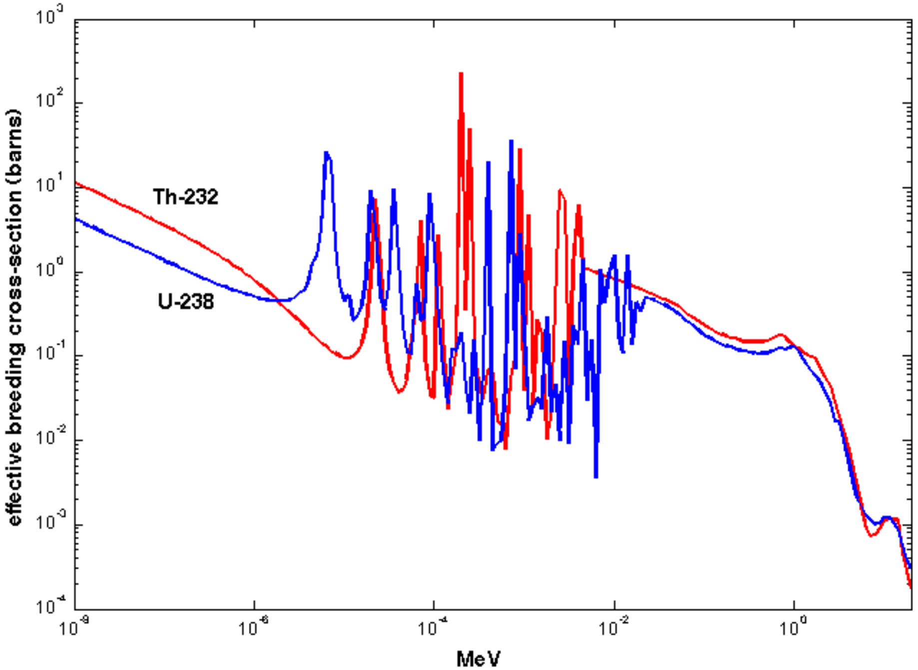
⇒ The second advantage is potentially enhanced **safety of subcritical reactor** systems relative to critical systems

⇒ ADSs have been proposed for power generation **using the Th233** (fertile material). The neutron source breeds the 233U (from Th) that is a fissile material. Such a system is capable of operating on a pure Th feed stream, and has much-reduced minor actinide production, which simplifies waste handling.

$$\mathrm{n} + {}^{232}\mathrm{Th} \longrightarrow {}^{233}\mathrm{Th} + \gamma$$

$${}^{233}\mathrm{Th} \longrightarrow {}^{233}\mathrm{Pa} + \mathrm{e}^- + \bar{\nu}$$

$${}^{233}\mathrm{Pa} \longrightarrow {}^{233}\mathrm{U} + \mathrm{e}^- + \bar{\nu}$$



NEUTRON SOURCES BASED ON PROTON SPALLATION SOURCES

⇒ **Spallation neutron sources** are the primary accelerator-driven source of intense neutrons. It is a complex, **multistep process** (incident high energy proton collides with a nucleus, exciting it and ejecting nucleons and particles that subsequently interact with other nuclei in a cascade)

⇒ They require:
  - **high power proton accelerators** in the GeV energy range
  - **heavy metal targets** for efficient neutron production

⇒ **Neutron production is quite efficient** approximately **20 neutrons** are produced per **1 GeV proton**.

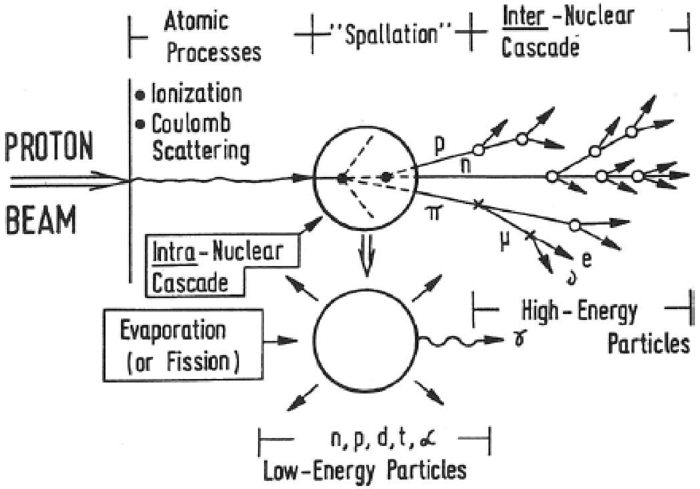
⇒ Several technical problems:
  - operation of **MW proton beam**
  - **Target**
  - **Cooling**
  - **windows**

⇒ **Moderators required** if we want to pilot thermal reactor

⇒ Good for **fast reactors** with many technical challenges.

⇒ Strong international effort

⇒ **High cost**



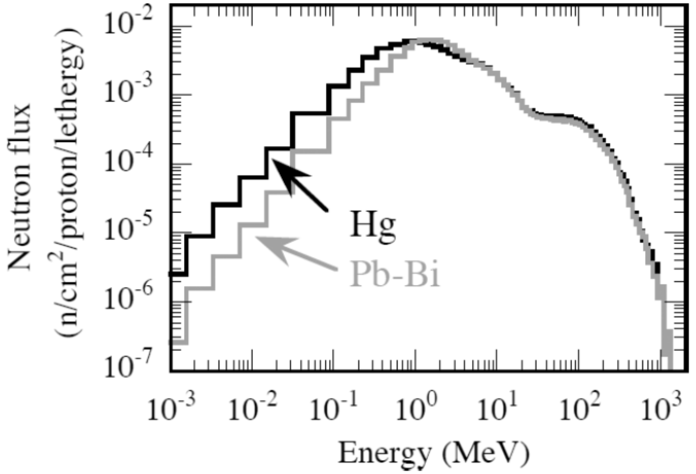


Fig. 2. Neutron spectrum for two spallation target materials, mercury and lead–bismuth eutectic, for 1.5 GeV incident protons. (Reprinted from Ref. 9.)

	ATW	XT-ADS	EFIT	MYRRHA	EA	JAEA	C-ADS
Date	1999	2007	2007	2007	1995	2007	2012
Reference	40	117	117	119	43	120	121
Technology	SC linac	SC linac	SC linac	SC linac	Cyclotron	SC linac	SC linac
Number of cores	4	1	1	1	1	1	1
Beam energy (GeV)	1.0	0.6	0.8	0.6	1.0	1.5	1.5
Beam power (MW)	45	1.5	16	2.4	15	30	15
Beam current (mA)	45	2.5	20	2.5–4.0	15	20	10
Target	LBE	LBE	LBE	LBE	Pb	LBE	LBE
k_{eff} (maximum)	0.97	0.95	0.97	0.95	0.98	0.97	
Thermal power (MW)	840	57	400	85	1500	800	>1000

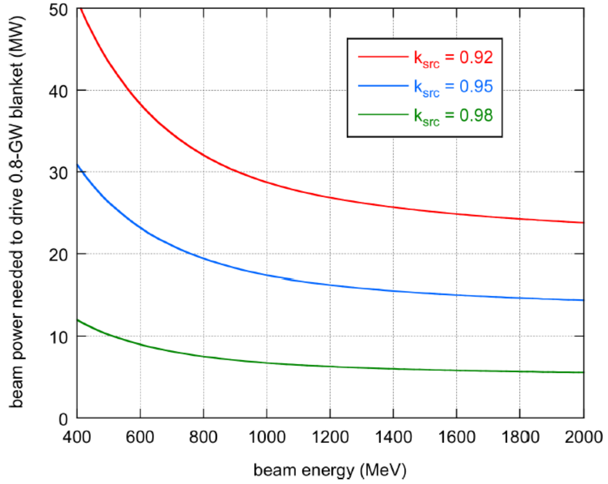


Fig. 8. Accelerator beam power required to drive a subcritical core at fixed thermal power for three different neutron multiplication factors.

S. D. Henderson, Spallation Neutron Sources and Accelerator-Driven Systems, Reviews of Accelerator Science and Technology Vol. 6 (2013) 59–83

ELECTRON BASED NEUTRON SOURCES

⇒ Electron based neutron sources **studied and implemented since many years** *[S.S. Abalin 1985]*

⇒ They are based on **photo-nuclear production**

⇒ **Limitations**: relatively **low neutron rate** per incident electron ~8%

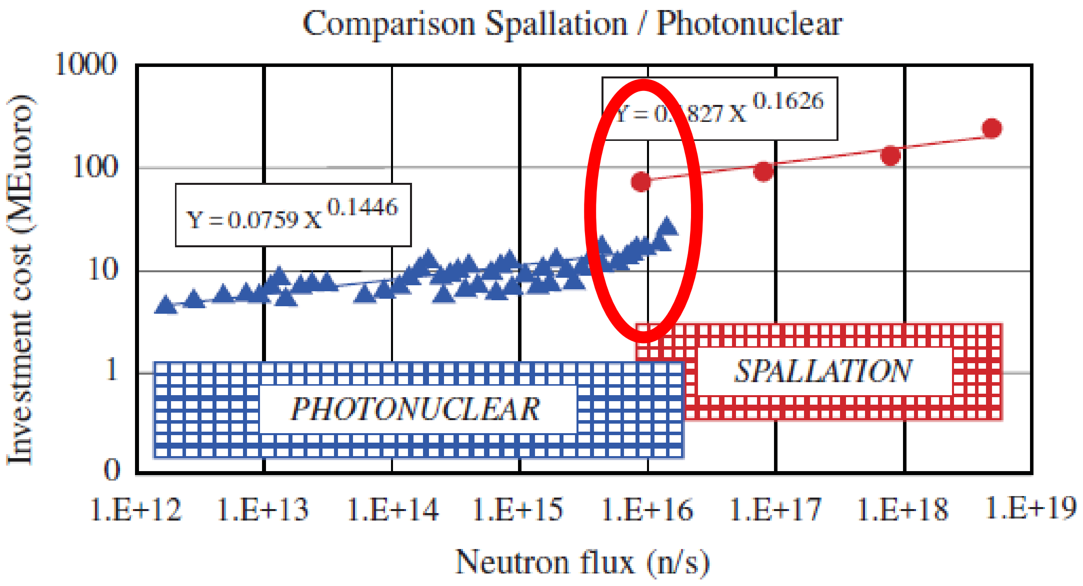
⇒ Possibility to use a **low energy (<100 MeV), high intensity (>10 mA) electron sources with a final rate >$4x10^{14}$ (n/s/mA)** *[H. Feizi and A.H. Ranjbar, 2016 JINST 11 P02004].*

⇒ **Small power reactors** especially if we can implement schemes with k_{eff}~0.99

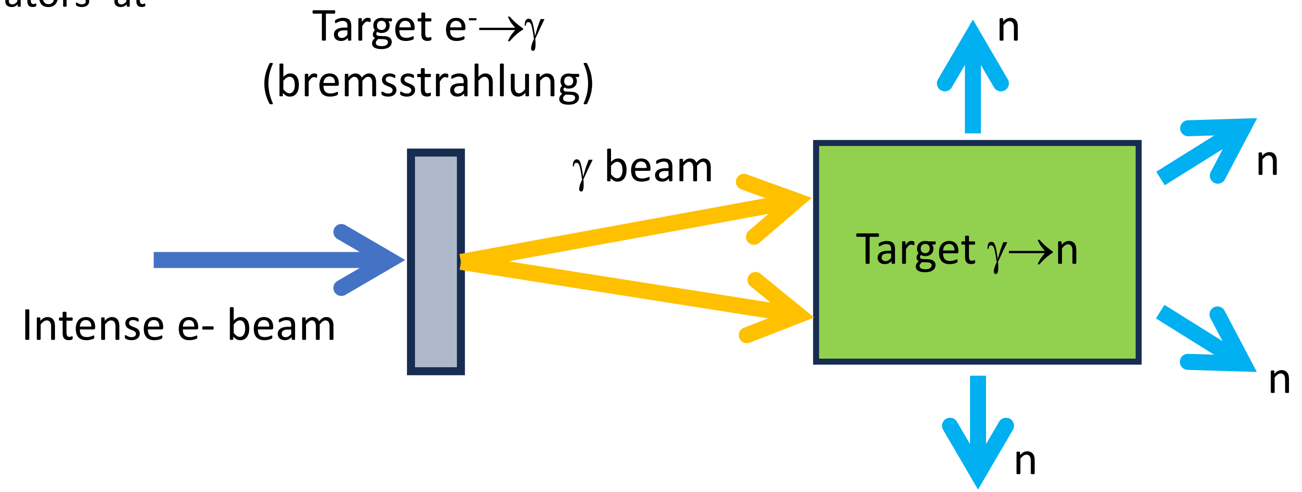
⇒ **Strongly reduced costs,** wide availability of electron accelerators at energies of 100-200 MeV

⇒ **low radiation damage to the target**

⇒ **Interesting perspectives as neutron sources** and applications



[D. Ridikas, et a., proc. *Int. Conf. PHYSOR 2002*, 2002.]



Target $e^- \rightarrow \gamma$
(bremsstrahlung)

γ beam

Target $\gamma \rightarrow n$

n

n

n

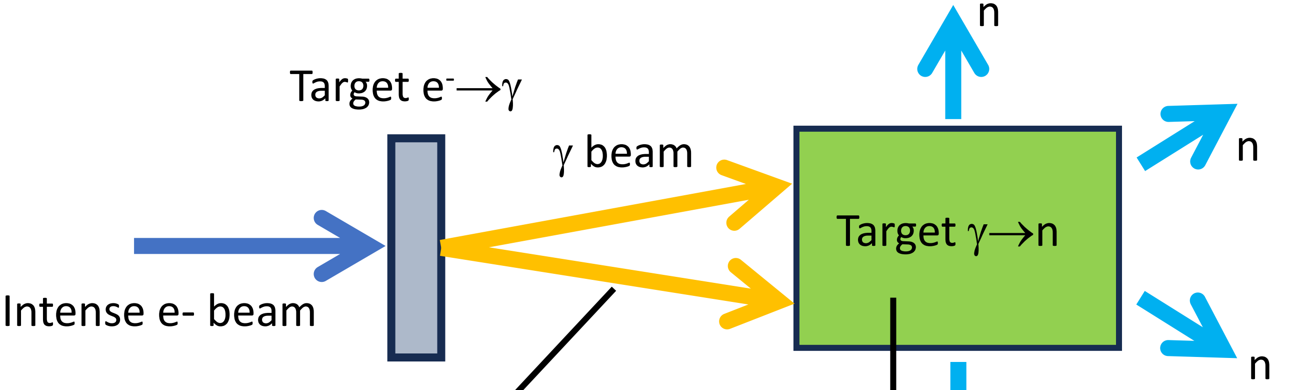
n

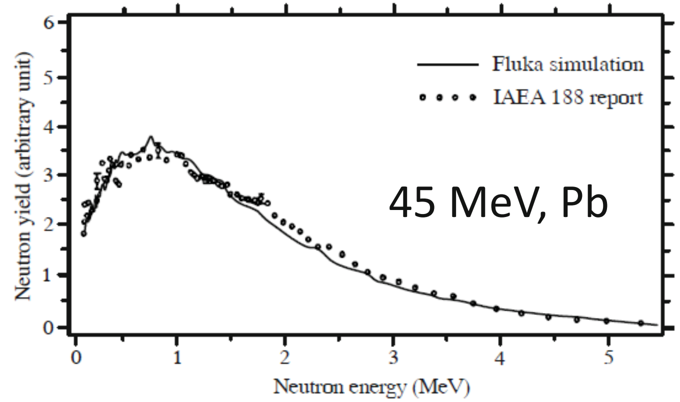
Intense e- beam

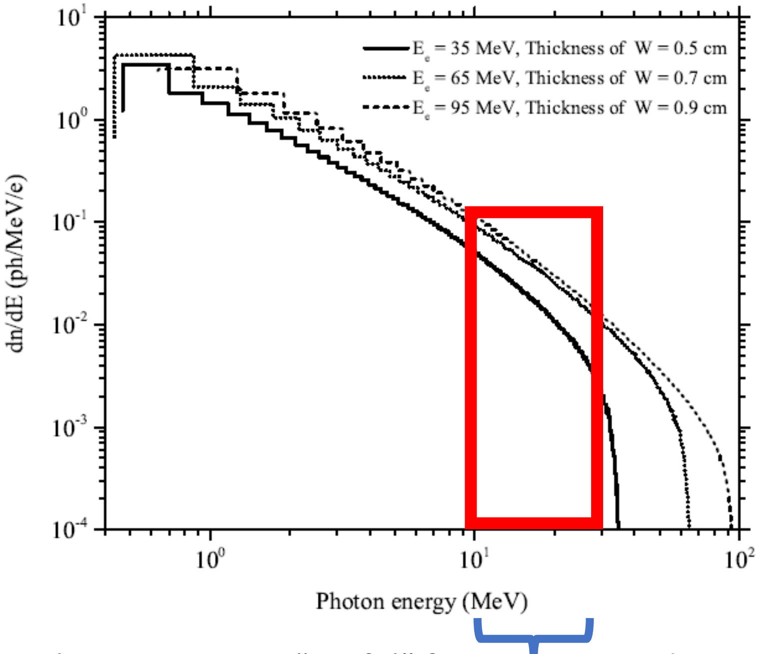
PHOTO-NEUTRON SOURCE: CHARACTERISTICS AND PROPERTIES

⇒ For gamma rays with energies between threshold (binding energy) to ~40MeV, **neutron production mainly occurs through giant dipole resonance** (excitation of a nucleus that decays by neutron emission). It takes place for photon energies in the range of 5-25MeV. Optimum photons energies ~**15MeV**.

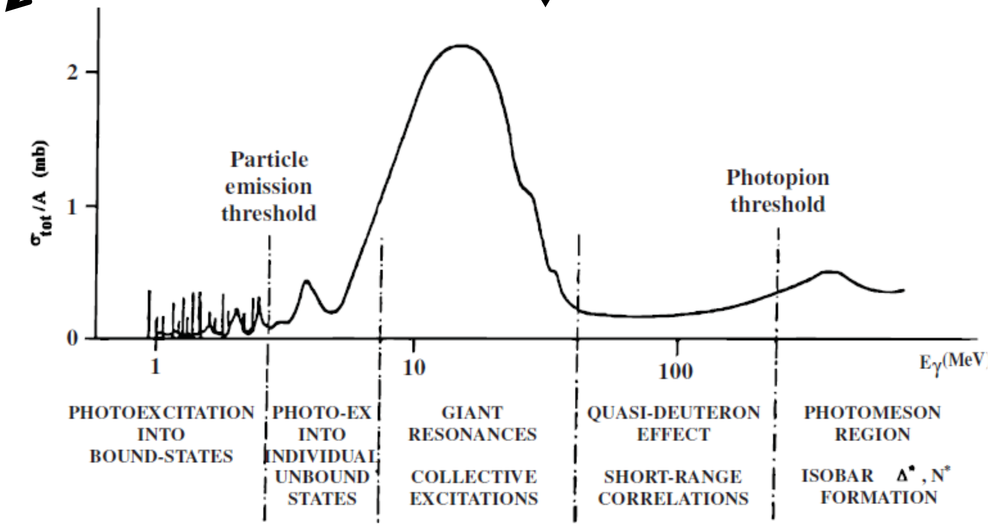
⇒ **Bremmstrahlung gamma spectrum** has a large bandwidth and **only a small portion is “useful” for neutron production**

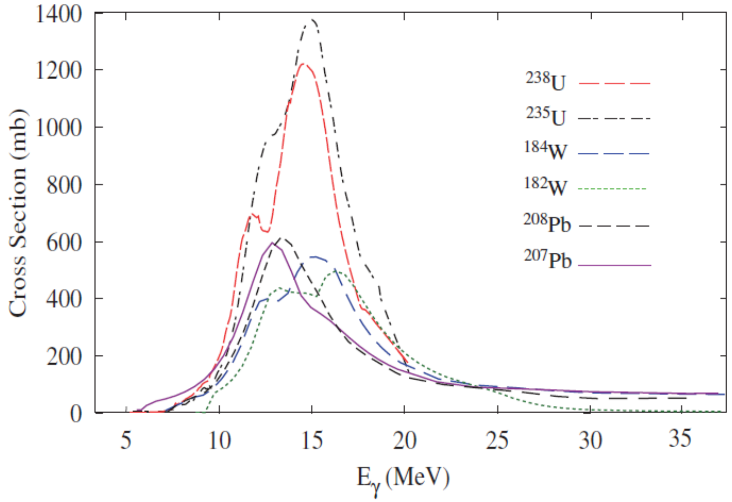






Photon energies “useful” for neutron production





[H. Feizi and A.H. Ranjbar, 2016 JINST 11 P02004].

PROPOSED SCHEME AND TARGET FOR A SMALL POWER NUCLEAR REACTOR

[H. Feizi and A.H. Ranjbar, 2016 JINST 11 P02004].

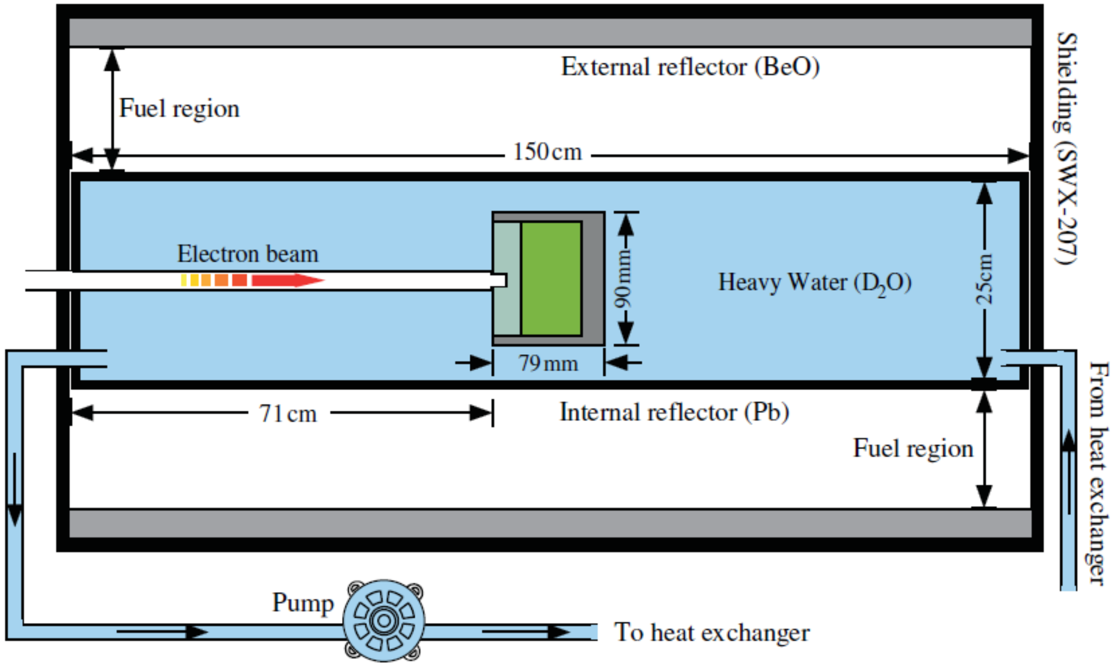
⇒ The target has a **e-γ converter in W** and a **γ-n converter in U**.

⇒ **Beryllium** is used as another converting layer since it has three peaks of photoneutron production below 3 MeV;

⇒ **Heavy water** could be used as a coolant and moderator

⇒ The fuel region that includes the radioactive waste has a **cylindrical shape**;

⇒ The **internal reflector** (Pb) provides the smoothness of photoneutron flux along the Z-axis and the **external reflector** (BeO) prevents the photoneutrons escaping from the core and backscatters them into the system.



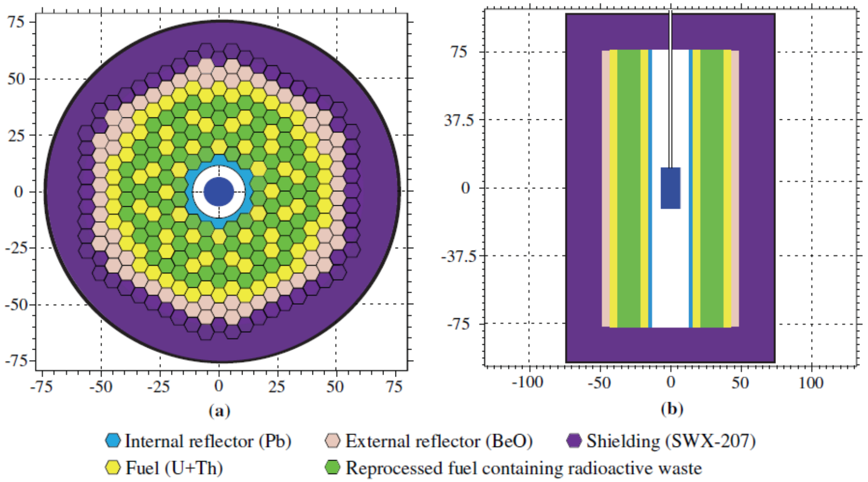
Numbers:

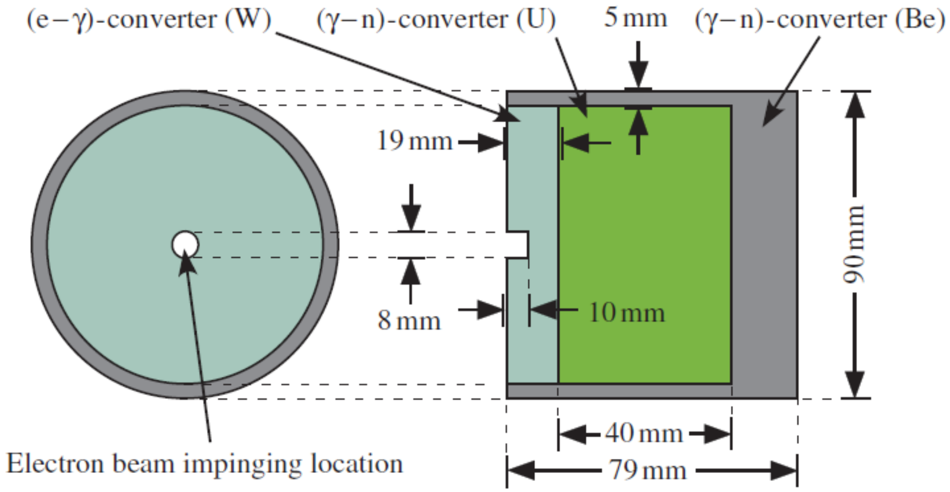
⇒ **20 mA@100 MeV** beam, **2 MW beam power**, 1.2x10^{17} e/s

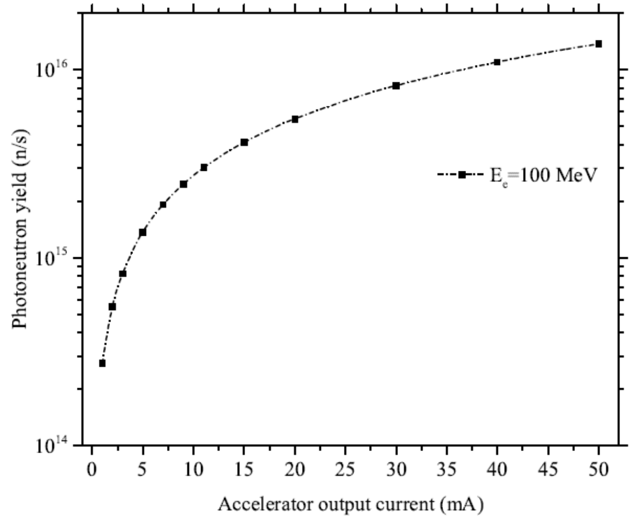
⇒ Bremsstrahlung radiation (full spectrum) is **830 kW**,

⇒ in the range **10-20 MeV** is photon power is **180 kW**, corresponding to 7.6x10^{16} ph/s;

⇒ Feizi et al. calculations gives **5-7x10^{15} n/s**

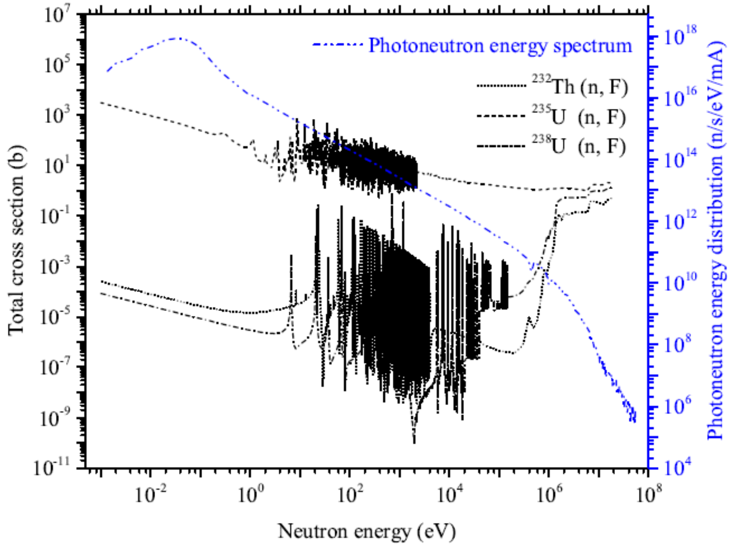




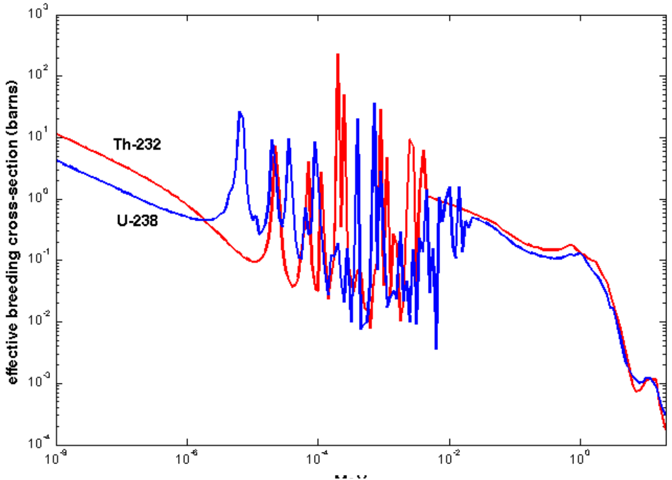


NEUTRON PROPERTIES: SPECTRUM FOR NUCLEAR POWER APPLICATIONS

- ⇒ **Large portion of neutrons are thermal neutrons** and can be directly used to fission of U-235 and Pu-239 in a thermal reactors. Advantage.
- ⇒ The **same energy spectrum is appropriate for breeding Th-232 or U238**
- ⇒ Preliminary works [*Bin Liu 2022]* on a design of a small subcritical reactor have been done but **complete works have to be done**.
- ⇒ Critical components of this scheme is the **target (W) power density**



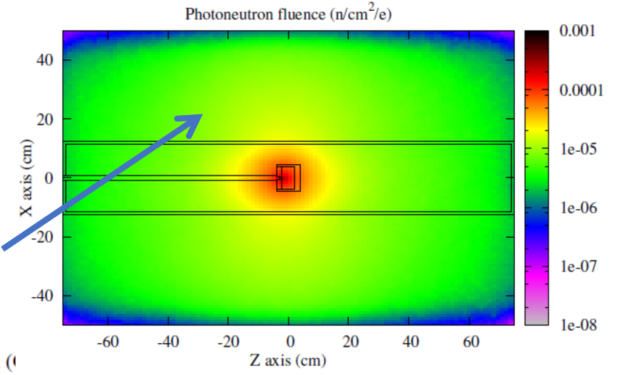
[H. Feizi and A.H. Ranjbar, 2016 JINST 11 P02004].

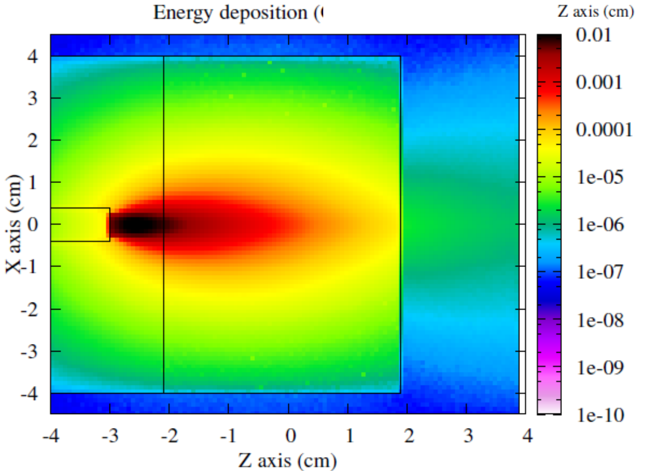


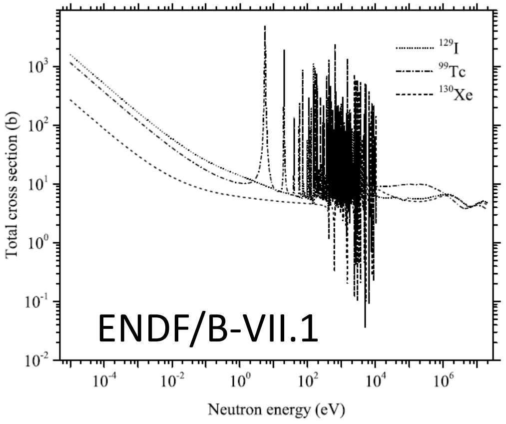
- ⇒ A **scaled accelerator with a 100-400 kW absolutely feasible** and **extremely interesting** to test the scheme and to deeply investigate the capabilities of **gamma-based reactors** (see next slides). 2-4 mA 60-100 MeV. keff limits etc…

Parameter	Value [React.]	Value [exp.]
Beam Energy (E_p)	100 MeV	60-100 MeV
Beam current (I_b)	20 mA	2-4 mA
Beam power (P_{beam})	2 MW	100-400 kW
Primary n flux (N_0)	5-7x10^{15} n/s	0.2-1.4x10^{15} n/s
G_0	0.033-0.047	0.033-0.047
k_{eff}	0.985	0.985
G	2.2-3.1	2.2-3.1
Thermal power (P_{th})	4.4-6.2 MW	0.3-1.2 MW
ν	2.4	2.4

1-2x10^{12}n/s/cm^2







LINEAR ACCELERATOR FOR A POSSIBLE IMPLEMENTATION

31st Int. Linear Accel. Conf., LINAC2022, Liverpool, UK

LIGHTHOUSE - A SUPERCONDUCTING LINAC FOR PRODUCING MEDICAL ISOTOPES

J. M. Krämer, G. Blokesch, M. Grewe, B. Keune, V. Kümper, M. Pekeler, C. Piel, P. v. Stein,
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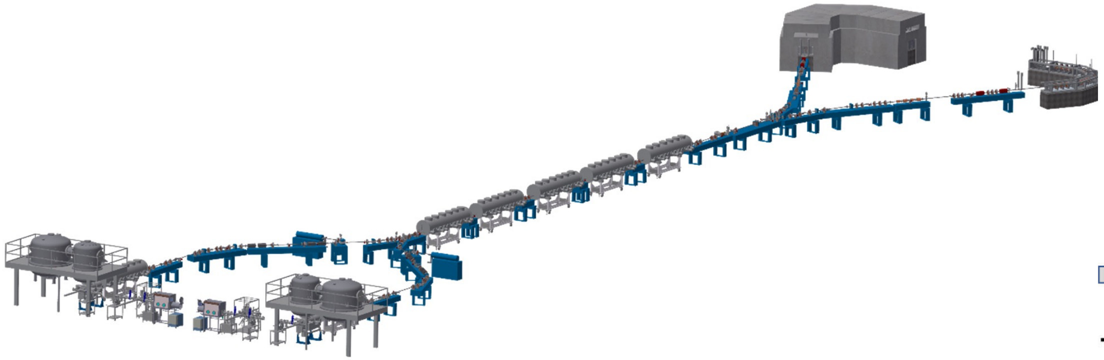
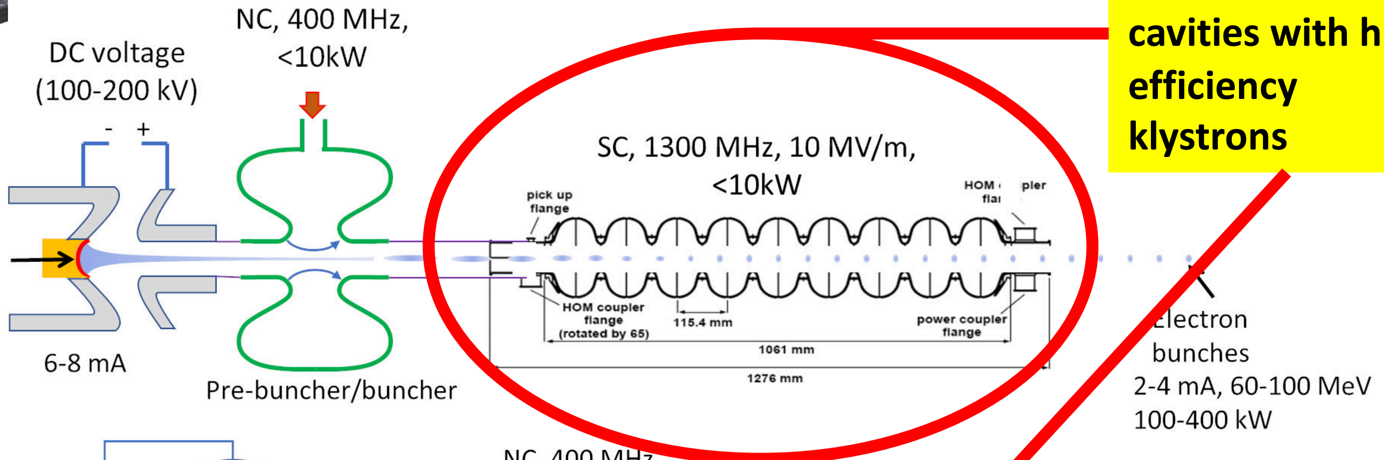
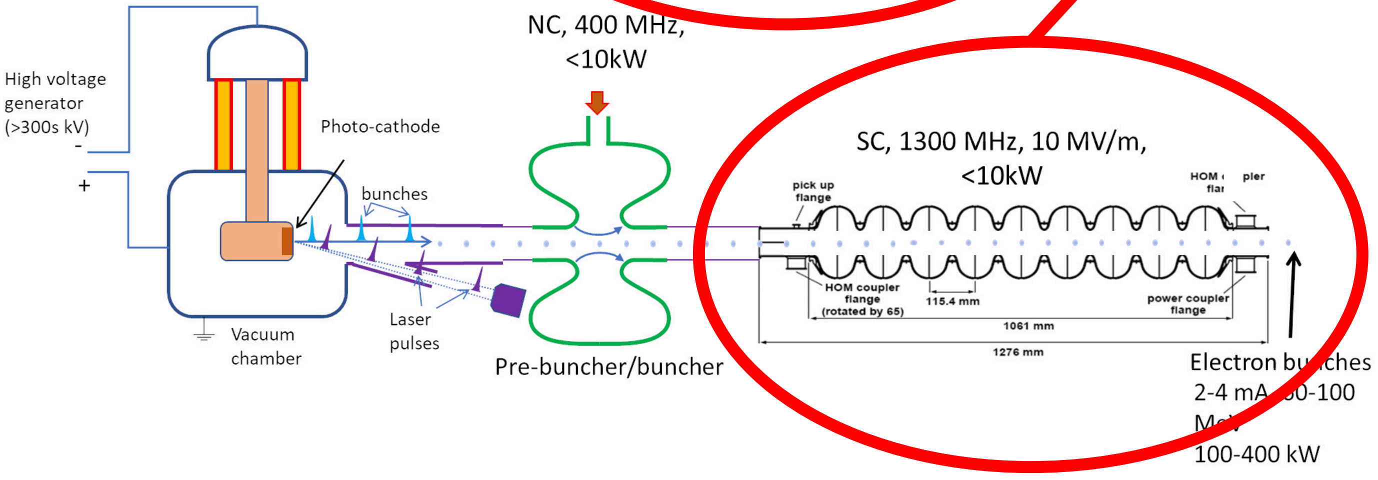


- ⇒ **Isotope ^{99}Mo** is used for diagnosing several 10 million patients every year.
- ⇒ Up to now, it is produced from highly enriched Uranium (HEU) using high-flux neutron reactors.
- ⇒ The Institute for Radio Elements (IRE), Belgium has projected the design of a high-power superconducting linac for producing 99Mo without use of nuclear fission as part of their SMART project.
- ⇒ The **LightHouse accelerator consists of a photo gun and seven superconducting radiofrequency (SRF) modules**, a beam splitter, and target illumination optics. It will deliver two electron beams of 75 MeV and 1.5 MW each.
- ⇒ The electrons are stopped in the 100Mo target, producing bremsstrahlung. A (γ, n) reaction will then knock out one neutron from the Mo-nucleus, yielding the radioisotope 99Mo.

- beam power: **3 MW**
- beam energy: **75 MeV**
- beam current: **40 mA at 1.3 GHz continuous wave (CW)**.
- **DC photo-gun operates at 350 keV**
- Gun and SRF module are based on the CBETA injector design by Cornell University
- **1.3 GHz TESLA-type cavities**

Possibility to use 400 MHz FCC-like cavities with high efficiency klystrons



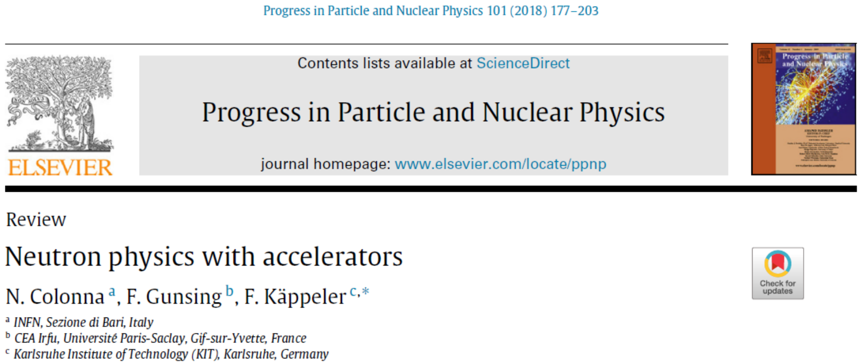


COMPARISON OF NEUTRON FLUX PROPERTIES WRT EXISTING FACILITIES

⇒ the proposed neutron source is a **CW source**

⇒ **beam power 1-2 orders of magnitude** larger than the electron based existing facilities

⇒ **neutrons per second are 1-3 order of magnitude larger** than the electron based existing facilities



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Review

Neutron physics with accelerators

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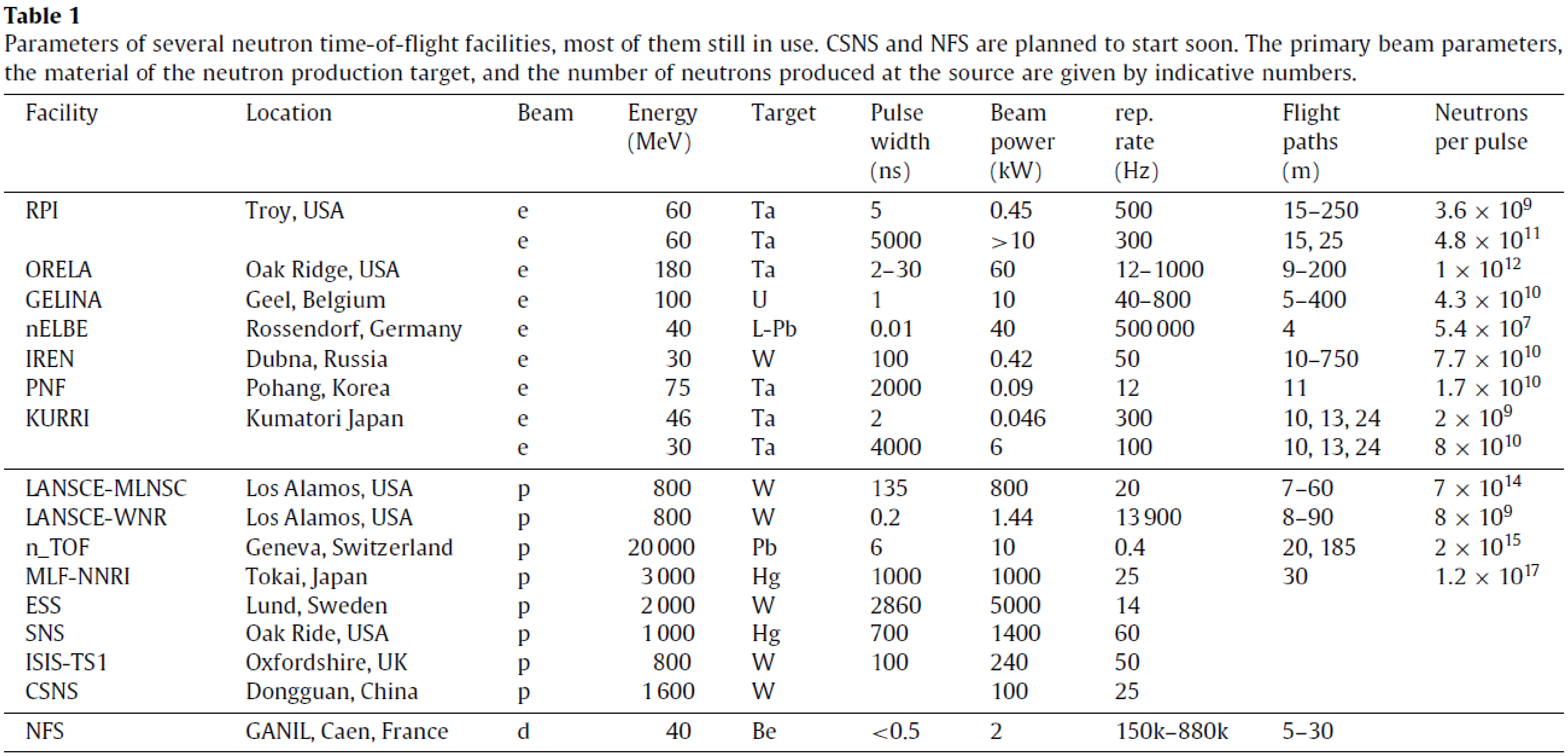


Table 1

Parameters of several neutron time-of-flight facilities, most of them still in use. CSNS and NFS are planned to start soon. The primary beam parameters, the material of the neutron production target, and the number of neutrons produced at the source are given by indicative numbers.

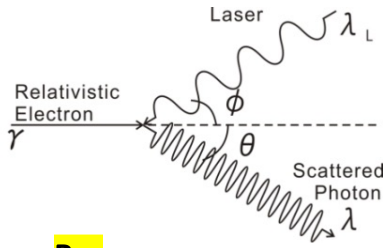
Facility	Location	Beam	Energy (MeV)	Target	Pulse width (ns)	Beam power (kW)	rep. rate (Hz)	Flight paths (m)	Neutrons per pulse
RPI	Troy, USA	e	60	Ta	5	0.45	500	15–250	3.6×10^{9}
		e	60	Ta	5000	>10	300	15, 25	4.8×10^{11}
ORELA	Oak Ridge, USA	e	180	Ta	2–30	60	12–1000	9–200	1×10^{12}
GELINA	Geel, Belgium	e	100	U	1	10	40–800	5–400	4.3×10^{10}
nELBE	Rossendorf, Germany	e	40	L-Pb	0.01	40	500 000	4	5.4×10^{7}
IREN	Dubna, Russia	e	30	W	100	0.42	50	10–750	7.7×10^{10}
PNF	Pohang, Korea	e	75	Ta	2000	0.09	12	11	1.7×10^{10}
KURRI	Kumatori Japan	e	46	Ta	2	0.046	300	10, 13, 24	2×10^{9}
		e	30	Ta	4000	6	100	10, 13, 24	8×10^{10}
LANSCE-MLNSC	Los Alamos, USA	p	800	W	135	800	20	7–60	7×10^{14}
LANSCE-WNR	Los Alamos, USA	p	800	W	0.2	1.44	13 900	8–90	8×10^{9}
n_TOF	Geneva, Switzerland	p	20 000	Pb	6	10	0.4	20, 185	2×10^{15}
MLF-NNRI	Tokai, Japan	p	3 000	Hg	1000	1000	25	30	1.2×10^{17}
ESS	Lund, Sweden	p	2 000	W	2860	5000	14		
SNS	Oak Ride, USA	p	1 000	Hg	700	1400	60		
ISIS-TS1	Oxfordshire, UK	p	800	W	100	240	50		
CSNS	Dongguan, China	p	1 600	W		100	25		
NFS	GANIL, Caen, France	d	40	Be	<0.5	2	150k–880k	5–30	

HIGH INTENSITES GAMMA SOURCES IN THE 15 MeV RANGE

⇒ The proposed scaled implementation setup allows to explore the possibility to implement a neutron source based on **gamma factories**;

⇒ There are basically two schemes:

COMPTON SOURCES



$$\lambda_T = \lambda_{laser}\frac{1+\gamma^2\theta^2}{4\gamma^2}$$

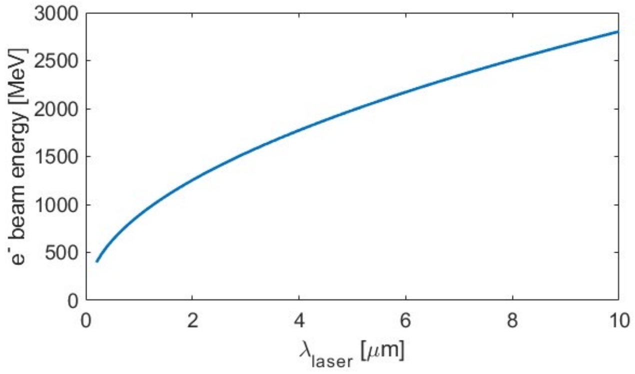
⇒ **Pro**:

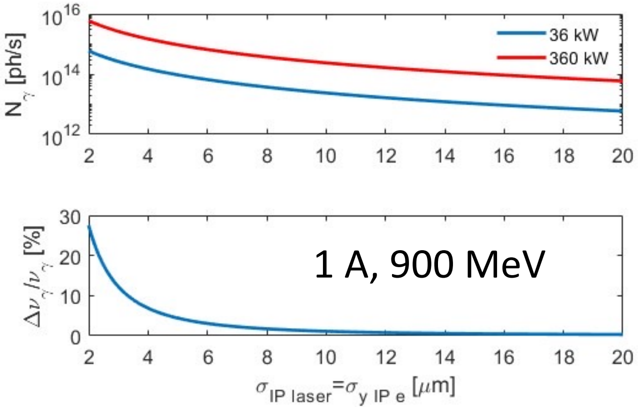
- **narrow band** energy spectrum of the gamma beam that can be “tuned” exactly at 15 MeV with collimators;
- **Relatively low electron beam energy** (< 1 GeV) to reach 15 MeV photons using λ_{laser}<1 um

⇒ **Cons**:

- the **main limitations** come from the relatively **low cross section of the Compton process** (0,67 barn), that requires extremely high intensity laser sources and beam currents to achieve photon fluxes at the level of 10^{17}ph/s
- **Single source** of photons, limited performances
- **Reliability** (experimental machine, collider)

⇒ Other schemes can be implemented, suffer from the same limitations





[D. Alesini et al., IEEE TRANS. ON NUCL. SC., VOL. 63, NO. 2, APRIL 2016]

SINCHROTRON RADIATION

⇒ **Large-scale facility**: high energy synchrotron with **superconducting dipoles**

⇒ **Pro**:

- **Stability** of a synchrotron source
- **State of the art** technology for SC magnets with possible upgrades to HTS HF magnets
- **Multiple sources** for a **large scale nuclear plant** with a **100s MW level thermal power** achievable
- P_{th}/P_{beam}~10
- Fully synergic with the effort on **R&D for future circular colliders** (HF magnets, high efficiency klystrons,…)

⇒ **Cons**:

- High energy required for the electron beam (**32 GeV**). BUT: the ring energy scale with sqrt(1/B field) in term of critical energy and the required beam power with 1/B field⇒ HF magnet technology can overcome the present limits;
- **High RF power** is required BUT a strong effort on high **efficiency klystrons and SC cavities is undergoing;**
- **Relatively wide spectrum** of the radiation emitted limit the overall efficiency P_{th}/P_{beam} to 10;

SINCHROTRON-BASED GAMMA SOURCES

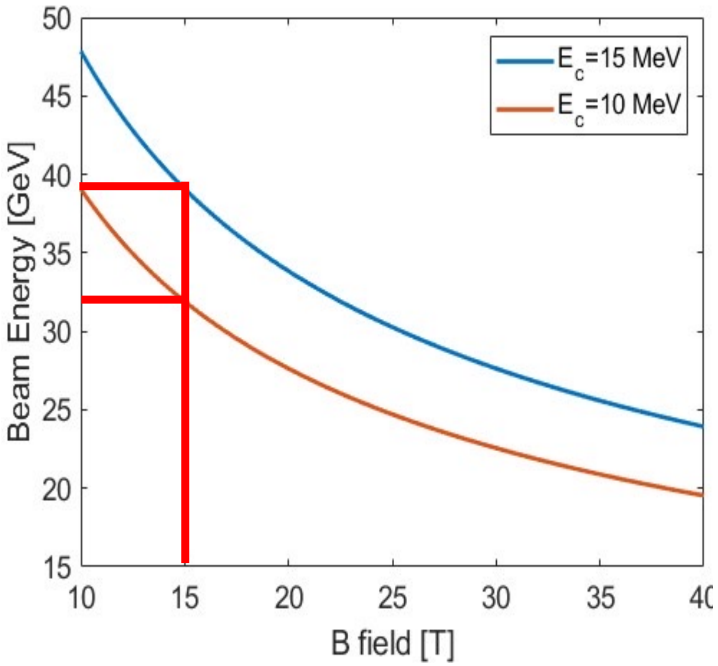
- ⇒ Assuming **state of the art magnet technology** ($NbSn_3$) at **15 T** is possible to calculate the beam energy (E_b) to have a **critical energy** of the photons from bending/wiggler (E_c) in the range **10-20 MeV**;
- ⇒ Is possible to compare the **photon spectrum** from a bending magnet with that of a 20mA/100MeV bremsstrahlung radiation.
- ⇒ Scaling the parameters we expect for a single magnets a total photon flux of **>10^{16} n/s**.
- ⇒ The **photon power is limited by the RF system capabilities in term of power and voltage**.

$$E_c[eV] = 655 \cdot E_b[GeV]^2 B_M \longrightarrow \text{10-20 MeV}$$

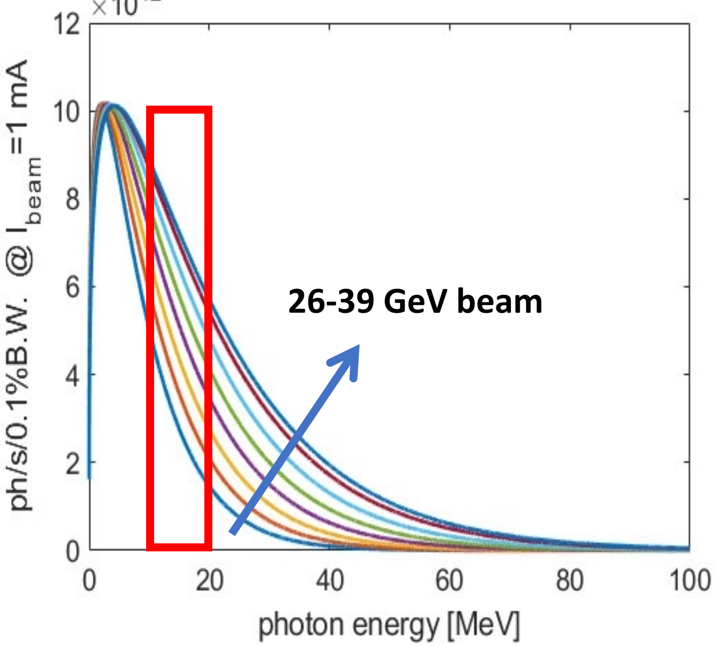
$$P_{rad}[kW] = 1.266 \cdot E_b[GeV]^2 B_M^2 \boxed{L_M I_b} \longrightarrow \text{300-900 kW}$$

$$V_{acc}[MV] = \frac{P_{rad}[kW]}{\boxed{I_b[mA]}} = 1.266 \cdot 10^{-3} \cdot E_b\,[GeV]^2 B_M^2 \boxed{L_M}$$

- ⇒ In principle, **to reduce the required V_{acc} is better to use lower B_M** and higher beam energies E_c;
- ⇒ For a given B_M and E_b is better to use **short magnets** (L_M);
- ⇒ On the other hand, ring dimensions are proportional to beam energy (E_b);
- ⇒ A **radiated power ≤400 kW allow to keep the required voltage per radiating device <40 MV** with a beam current <20 mA. This radiated power is also a reasonable number for the target



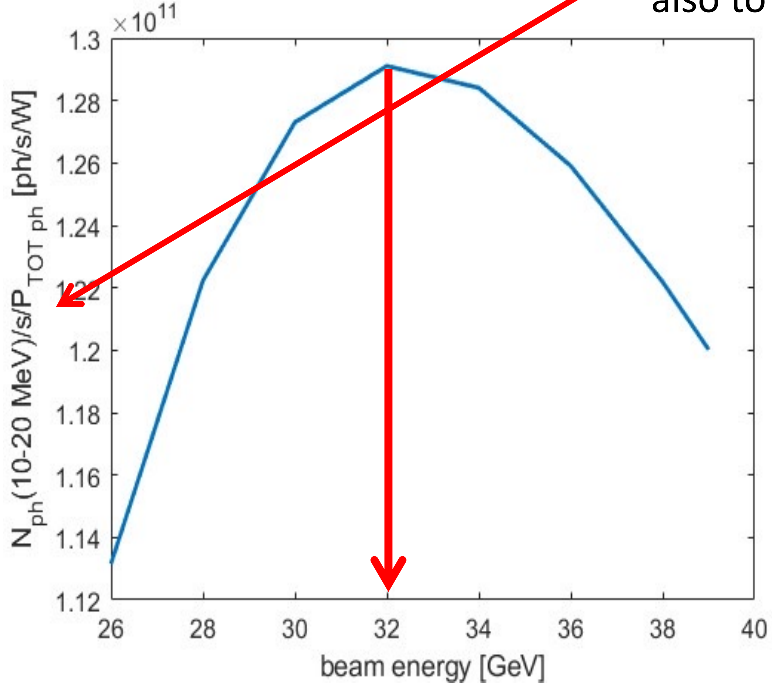
Dipole 15 T, 0.1 m



26-39 GeV beam

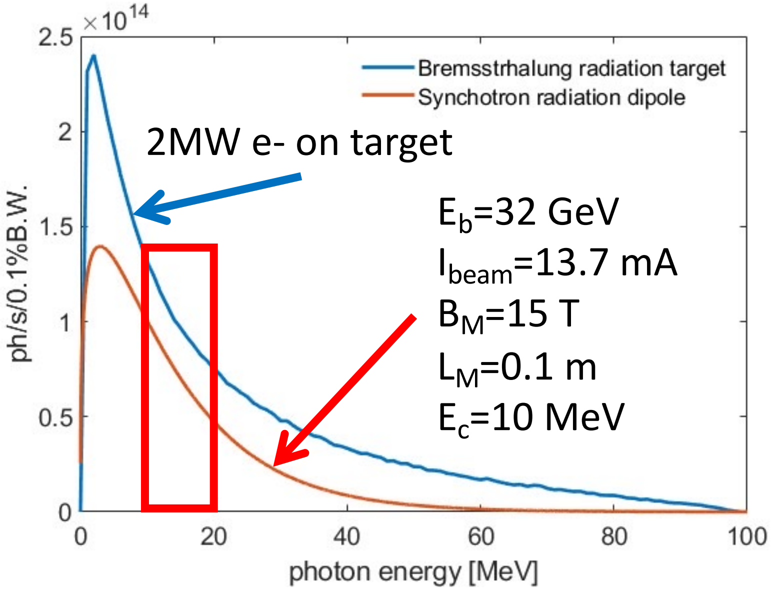
Dipole 15 T, 0.1 m

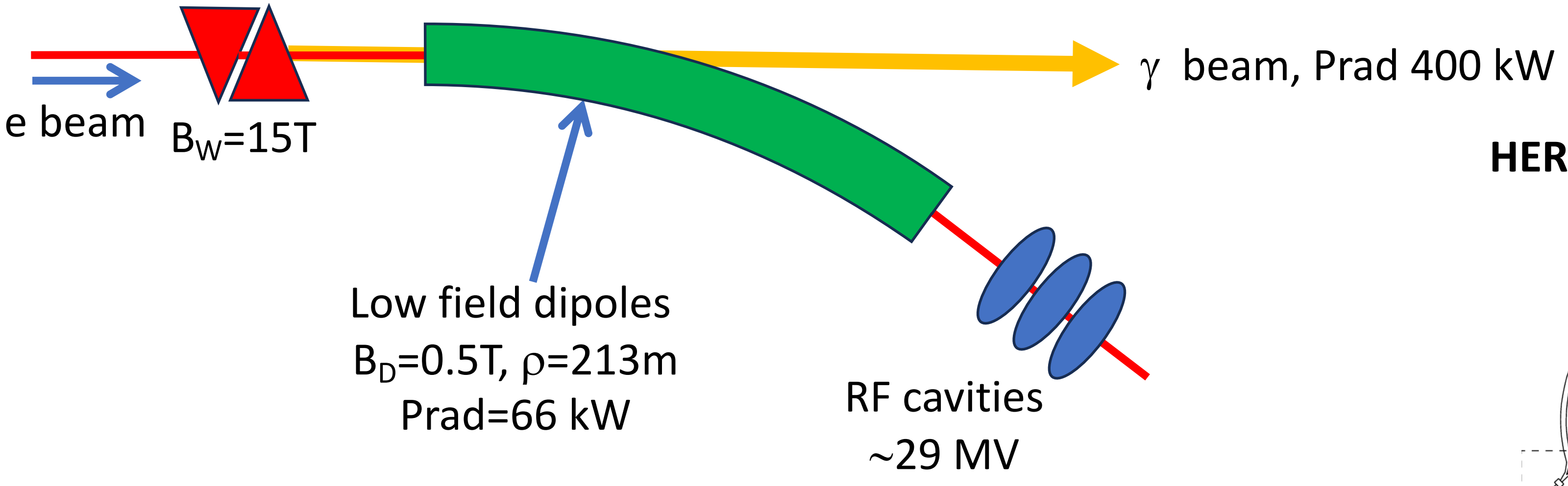
This correspond also to N_{ph}/V_{acc}



SYNCHROTRON-BASED GAMMA SOURCES CONFIGURATIN AND PARAMETERS

Parameter	Bremsstr.	Ring
Beam power (P_{beam})	2 MW (e^-)	400 kW (ph)
Ph. flux 10-20 MeV (N_{ph})	7.6×10^{16} ph/s	5.2×10^{16} ph/s
Neutron flux (N_0)	$5\text{-}7 \times 10^{15}$ n/s	$3.4\text{-}5.5 \times 10^{15}$ n/s
G_0	0.033-0.047	0.11-0.16
k_{eff}	0.985	0.985
G	2.2-3.1	7.4-10.5
Thermal power (P_{th})	4.4-6.2 MW	3-4.1 MW





TRISTAN (KEK) parameters

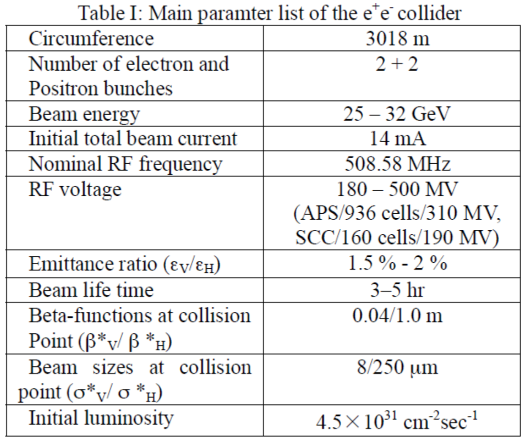
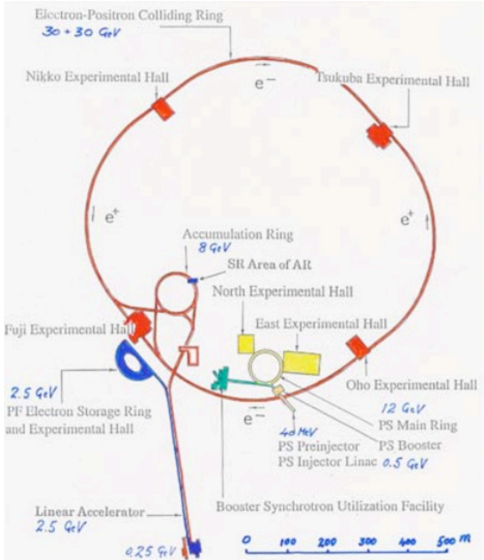


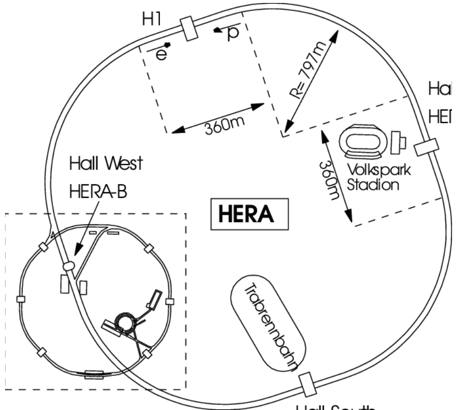
Table I: Main paramter list of the e^+e^- collider

Circumference	3018 m
Number of electron and Positron bunches	2 + 2
Beam energy	25 – 32 GeV
Initial total beam current	14 mA
Nominal RF frequency	508.58 MHz
RF voltage	180 – 500 MV (APS/936 cells/310 MV, SCC/160 cells/190 MV)
Emittance ratio ($\varepsilon_V/\varepsilon_H$)	1.5 % - 2 %
Beam life time	3–5 hr
Beta-functions at collision Point (β^*_V/β^*_H)	0.04/1.0 m
Beam sizes at collision point (σ^*_V/σ^*_H)	8/250 μm
Initial luminosity	4.5×10^{31} cm^{-2}sec^{-1}



HERA (DESY) parameters

27 GeV, 40 mA



RF CAVITIES VOLTAGE STATE OF THE ART AND R&D ONGOING

SRF system options for FCC-ee

FCC Week London, 7 June 2023

Franck Peauger, Olivier Brunner

12-May-23	Bare cavity in vertical test stand		Jacketed cavity with HOM couplers in vertical test stand		Cryomodule (with FPC) in horizontal test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
1-cell 400 MHz	6.9	3.3E+09	6.6	3.15E+09	6.3	3.0E+09	[illegible]	2.7E+09
2-cell 400 MHz	13.2	3.3E+09	12.6	3.15E+09	12	3.0E+09	10.8	2.7E+09
5-cell 800 MHz	24.5	3.8E+10	23.3	3.64E+10	22.2	3.5E+10	[illegible]	3.0E+10

12-May-23	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	[illegible]	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.72	6.23	10.61	20.01	10.61	20.76	10.61	20.12	20.10
# cell / cav	1	5	[illegible]	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	7.95	18.75	7.95	19.44	7.95	18.85	18.83
#cells	56	120	[illegible]	280	528	540	528	2440	3000
# cavities	56	24	132	56	264	108	264	488	600
# CM	14	6	33	14	66	27	66	122	150
+ #CM	14	6	33	8	0	13	0	122	123
- #CM	_	-	14	-	-	-	-	-	-
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	19	0.3	129	3	129	4	129	23	3
stat losses/cav * [W]	8	8	8	8	8	8	8	8	8
Qext	5.8E+04	3.1E+05	9.2E+05	7.6E+06	9.1E+05	1.6E+07	4.5E+06	4.2E+06	8.1E+07
Detuning [kHz]	9.885	4.385	[illegible]	0.140	0.106	0.012	0.009	0.056	0.002
Pcav [kW]	901	210	378	89	382	47	78	163	8
energy loss / turn ** [MV]	39.40	39.40	[illegible]	370.00	1890.00	1890.00	10100.00		10100.00
cos phi	0.33	0.28	0.35	0.35	0.90	0.90	0.98	0.86	0.89
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

* Heat loads from power coupler and HOM couplers not included

** Energy loss / turn from K. Oide table Jan. 19, 2023

one RF system per beam

common RF system for both beams

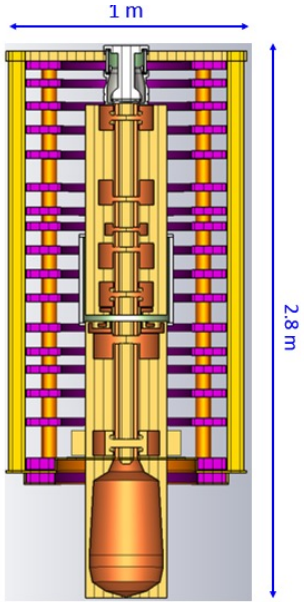
Total of 364 cryomodules, 1456 cavities, 25% with Nb/Cu, 75% with bulk niobium

Development progress on TS MBK for FCC^{ee}

Zaib Un Nisa (CERN)
Igor Syratchev (CERN), Jinchi Cai (UESTC), Graeme Burt (ULAN),
Anis Baig (ULAN, CERN)

Design Parameters for TS MBK for FCC^{ee}

Parameters	Design Target	KlyC	CST
Frequency (GHz)	0.4	0.4	0.4
Voltage (kV)	58	58	58
First stage (kV)	10-20	11.5	11.5
N beams	10	10	10
Total Current (A)	27	27	27
Output Power (MW)	1.2	1.28	1.2
Efficiency (%)	80	80.6	79
Tube length (m)	<3	--	2.8



31/05/2022

FCC Week 2022

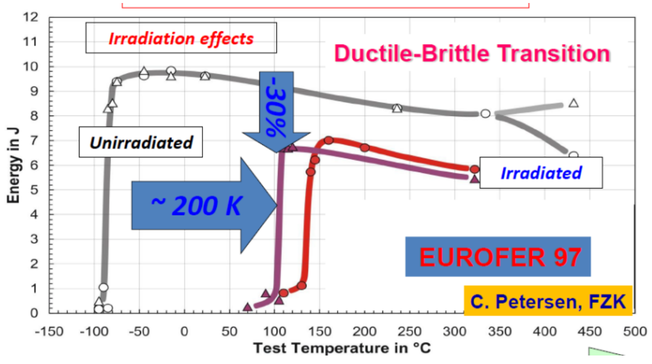
	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.120
W	80	135	1.05
H	120	26.7	2.1
ttb	182.5	5	11.3

100 MW of RF power in CW (50 MW per ring) to compensate losses by synchrotron radiation

OTHER USES OF INTENSE NEUTRON BEAMS (FROM ELECTRON ACCELERATORS)

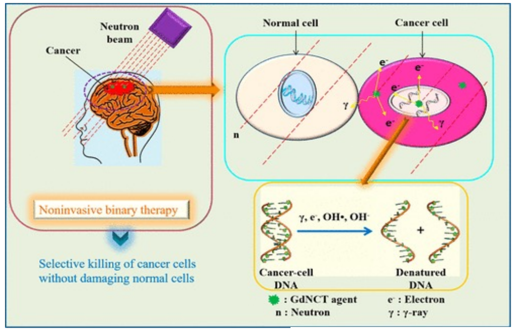
⇒ **Radiation damage on structural materials** for future fusion reactors

- gas production, due to (n,cp) reactions with threshold of a few MeV



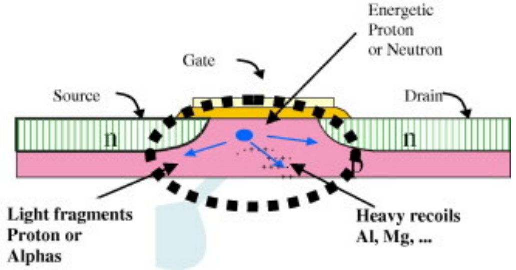
⇒ Study possible production routes of **innovative radioisotopes** for therapy and diagnostics (theranostics):

- ^{176}Y(n,g)^{177}Yb (b-decay $T_{1/2}$=2 h) -> ^{177}Lu
- ^{160}Gd(n,g)^{161}Gd (b-decay $T_{1/2}$=3 m)-> ^{161}Tb
- ^{47}Ti(n,p)^{47}Sc (to be used in combination with ^{44,43}Sc)

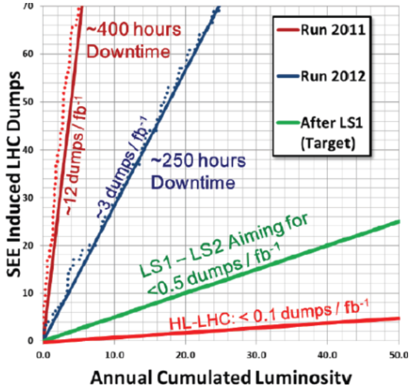


⇒ Study the **effect on electronics of atmospheric neutrons** (Singe Event Upset SEU or Single Event Error SEE) for various applications:

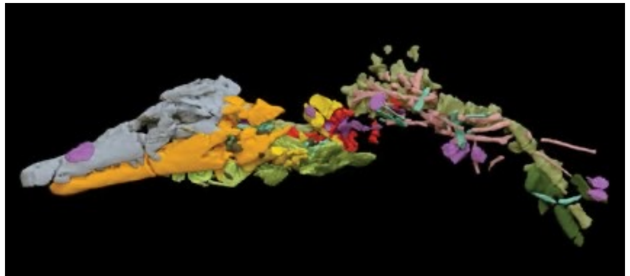
- aerospace, industrial automation, medical devices, automotive electronics, communication infrastructures, etc…



⇒ Study **neutron damage to electronics in the high neutron field environment** of particle accelerators (intermediate energy) and fusion reactor (such as ITER control and monitoring systems).



⇒ **Neutron imaging** (or radiography) for fossils and cultural heritage



CONCLUSIONS

⇒ **Perspectives and limits of electron based neutron sources** for nuclear applications have been illustrated

⇒ **A small scale experimental linear accelerator** (<100 MeV, 2-4 mA, CW, 100-400 kW) would allow to study, in scale, neutron properties, targets, gamma-based neutron sources with other possible applications (medical, irradiation, spectroscopy,…)

⇒ A **full study** of a small scale accelerator driven reactor has still to be done: beam+target+fuel

⇒ **Synchrotron based neutron sources** are large scale facilities that, in principle, allow to implement **multiple target stations** for a **large scale nuclear power plant and/or neutron facility**:

- Accelerator design, magnets, synchrotron light interaction with target are all topics to be studied
- Strong synergies with future linear collider developments; cavities, rf power sources,
- **It is a real, feasible, possible implementation with state of the art acceleratori and magnet technology**

THANK YOU FOR YOUR ATTENTION!