Applications IV

Comparison to other sources

Neutron sources

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DC Neutron Sources: Reactors

As of December 2018:
IAEA research reactor database showed:
226 operational research reactors (86 of them in developing countries),
9 under construction (four of these 100 MW or more),
13 planned (11 in developing countries),
26 temporarily or in extended shutdown,
56 permanently shutdown, and
510 decommissioned or undergoing decommissioning.

A majority of the operational and temporary shutdown research reactors are over 40 years old.
Highest neutron yield is the SM-3 100 MW reactor in Russia
at 5 x 10^{15} thermal and 2 x 10^{15} fast neutrons /cm^2 /s.

Power : **up to 100 MW**
Floorspace: **typ. 300x300 m**
Flux: **5 x 10^{15} n/cm^2/s (inside the core)**
Building costs: **600 - 2000 M$ (construction)**
Operating costs: **20 - 100 m$ per year**
Disassembly: **200 - 300 M$ (no storage of waste)**

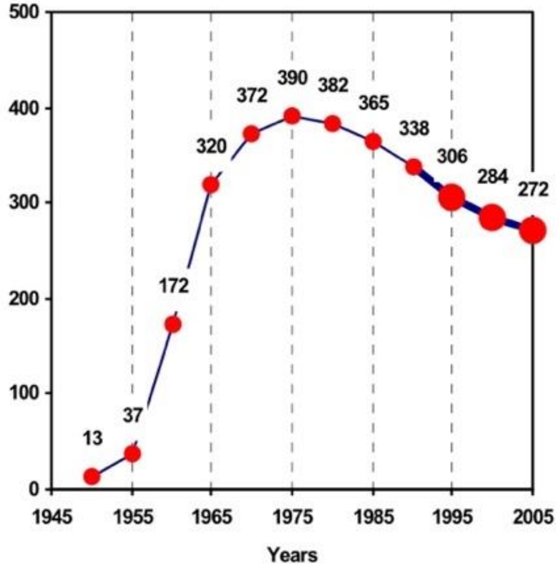
World Nuclear Association, Website I.T. Treiyakov, "Status of research reactor in Russia and prospects for their development"
Int. Symposium on the peaceful Application of nuclear technology in the GCC Countries, Jeddah 2008
P,V, Strugar, „Maximum Neutron Flux in Thermal Research Reactors", Journal of Optimization theory ans applications: Vol.5 No.4, 1970

Neutron sources

DC Neutron Sources: Reactors

There is a decline in numbers of active research reactors since its peak in the 1970's [ii].

CARR – China advanced research reactor (Fang Shan, China)
Newly build research reactor in China.
Becoming operational in 2010.
Includes a cold neutron hall of 30x60m
Power: 60 MW
Neutron yield: 8×10^{14} n/cm²/s



CMRR China Mianyang Research Reactor (Mianyang, China)
Started operation in 2013
Includes a cold neutron source.
Power: 20 MW
Neutron yield: Thermal: 2.4×10^{14} n/cm²/s
Cold: 10^9 n/cm²/s

Neutron sources

DC Neutron Sources: Reactors

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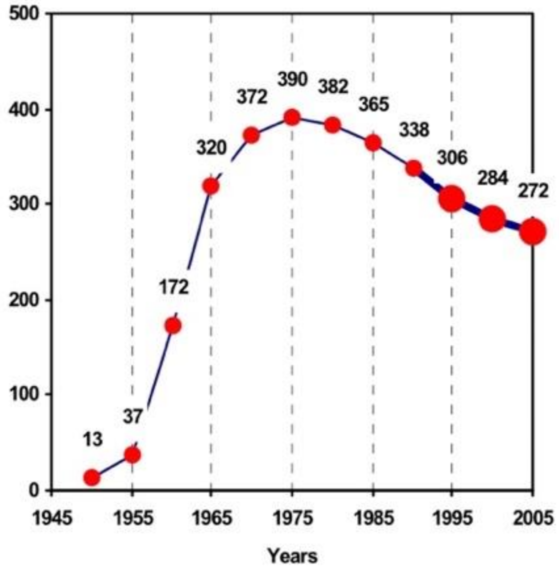

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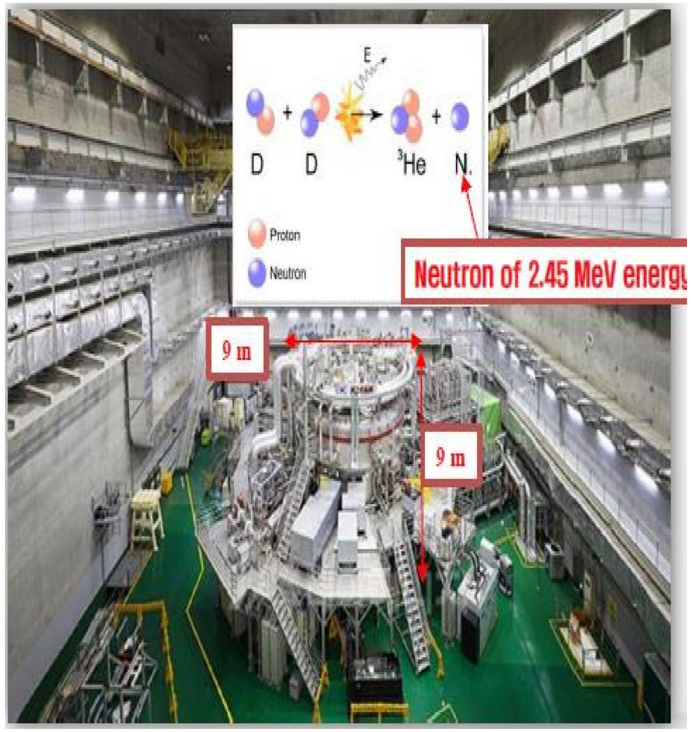
Fusion reactors

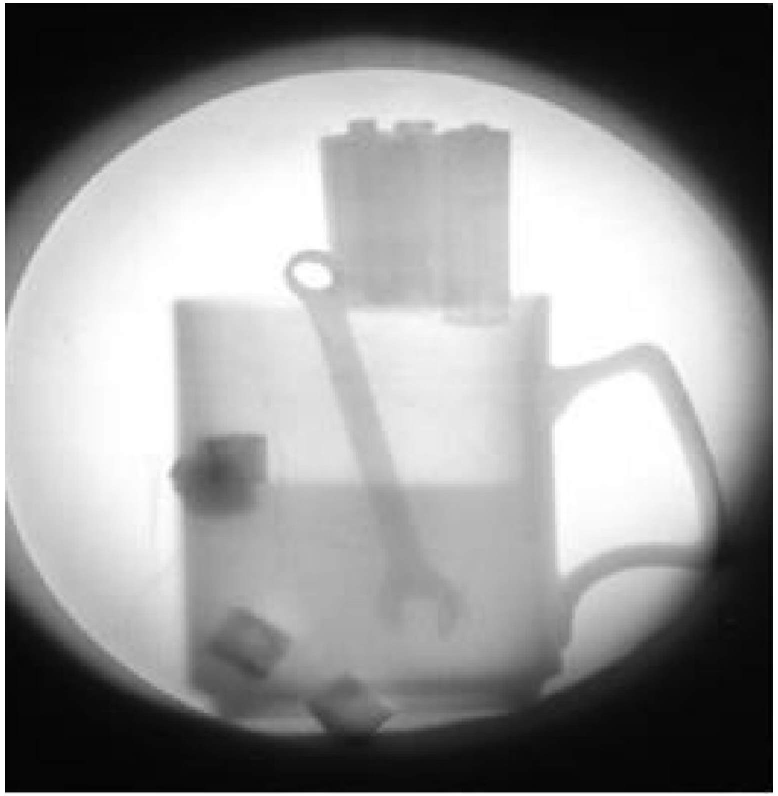
As long as no fusion reactor achieved gain the neutron numbers are limited.
The Stellarator and Tokamak schemes are among the main routes to MCF.
Using DD as a fuel results in 2.45 MeV neutrons, use of DT results in 14.1 MeV neutrons at higher yield.
Shortage of Tritium and legal obligations: most of the machines to run with DD



Fusion reactors

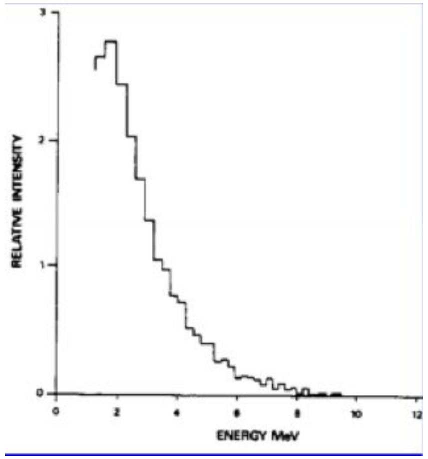
KSTAR Korean DD Fusion Tokamak

A neutron imaging beamline was added to the KSTAR fusion reactor facility. A collimator of 10 cm and a flight path of up to 4 m from the plasma surface was used for fast neutron imaging,



Picture was taken in a single shot of 8 s.
Magnetic confinement fusion reactor.
Operates up to 100 s / shot
Neutron yield per shot up to 10^{15}
Neutrons yield: 10^{13} n/s

Radioactive Isotopes ^{252}Cf sources



Spontaneous fission of isotope ^{252}Cf (2.56 y), ~neutrons per fission.
Californium-252 sources can contain Cf-250 (13.08 year half-life[iii]).

Production rate is $4.3x10^9$n per Ci of ^{252}Cf and the neutron energy distribution: continuous distribution with average energy of 1-3 MeV.

The fission occurs only 3% of the decays,
α-decay accounts for the rest.
^{252}Cf is usually produced in high-flux reactors.
The neutron spectrum resembles that of a fission reactor with an average neutron energy of 2 MeV.

Size: few cm^3;
with shielding few 10's cm^3
Flux: < 10^{10} n/s (for 10 mg ^{252}Cf)[i]
Specific activity: 532 Ci/g; 19.7 x 10^{12} Bq/g

[i] Frontier Technology Corporation, Ohio, US
[ii] Tentori, Alessandro, Dissertation, Polytechnica di Milano, 2018

Radioactive Sources

Alpha neutron sources

Combining an alpha emitter and ^{9}Be, there will be a constant rate of neutron production. The reaction is:

$$^{9}Be + \alpha \longrightarrow {}^{12}C + \text{neutron} + 4.44\,\text{MeV}\ \gamma$$

Emissions is isotropic,
most probable neutron energy is about 5 MeV
at about 10^{7} n for each Ci of ^{226}Ra.
Because of the high γ-emission of ^{226}Ra and its daughter, sometimes it is preferable to use ^{210}Po (138 d), ^{214}Am(458 y) or ^{238}Pu (86 y) that produces 3×10^{6}n for one Ci of α activity.

Radioactive Sources

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AmBe(“ambee”) sources are a mix of Am-241and Be-9.

- **Yield: ca. 2.0 to 2.4 x 10^6 neutrons/sec. per Ci ca. 5.4 to 6.5 x 10^4 neutrons/sec. per GBq**
- **Half-life: 432.2 years**
- **Av. neutron energy: 4.2 MeV (11 max)**
- **Neutron dose rate: 2.2-2.7 mrem/hr at 1 m/Ci**
  0.59-0.73 uSv/hr at 1m/GBq
- **Gamma dose rate: 2.5 mrem/hr at 1 m/Ci**
  0.68 uSv/hr at 1m/GBq

NRC.gov

[iii]**PuBe** (“pewbee”) sources are a mix of Pu-239 or Pu-238 and Be-9.

- **Yield: ca. 1.5 to 2.0 x 10^6 neutrons/second per Ci ca. 4 to 5.4 x 10^4 neutrons/second per GBq**
- **Half-life: 24,114 years**
- **Av. neutron energy: 4.2 – 5 MeV (11 max)**
- **Neutron dose rate: 1.3-2.7 mrem/hr at 1 m/Ci**
  0.35-0.73 uSv/hr at 1m/GBq
- **Gamma dose rate: 0.1 mrem/hr at 1 m/Ci**
  0.027 uSv/hr at 1 m/GBq

CW accelerators

CW Spallation Source:

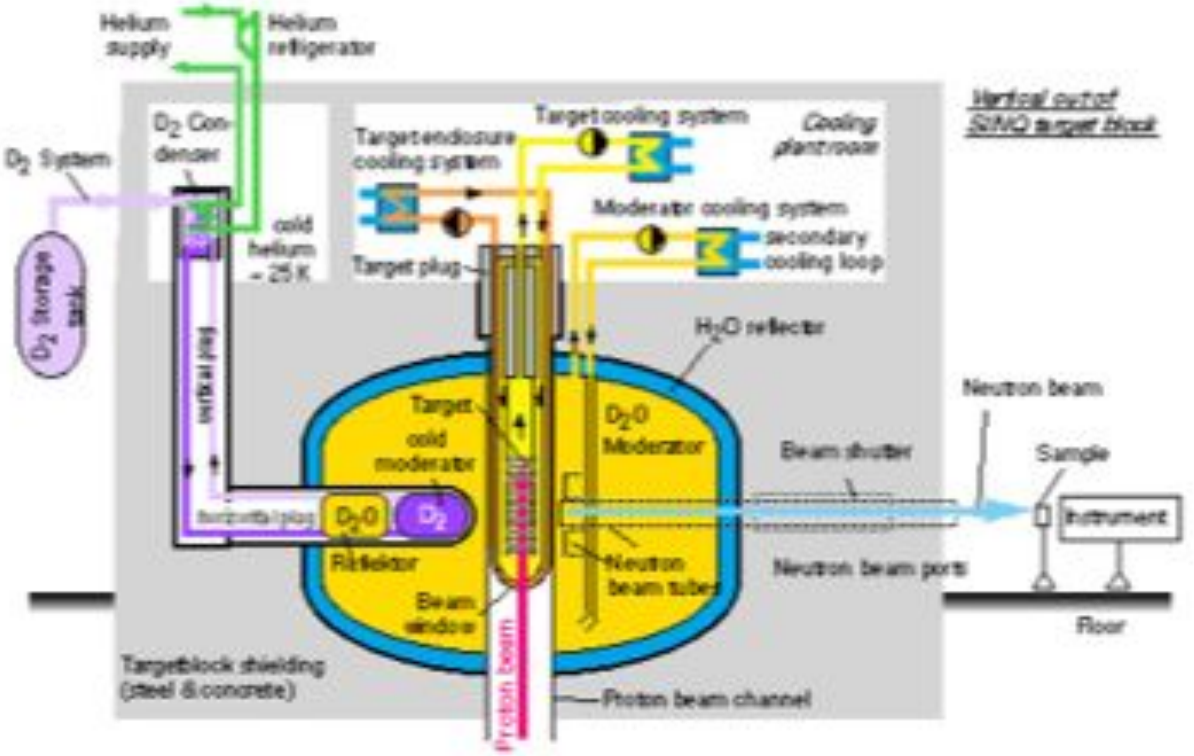
SINQ at Paul-Scherrer-Institute (PSI)

Ion beam: Protons beam, 2.2 mA,

590 MeV, 1.3 MW

Neutron yield: 2 x 10^{14} n/cm^2/s

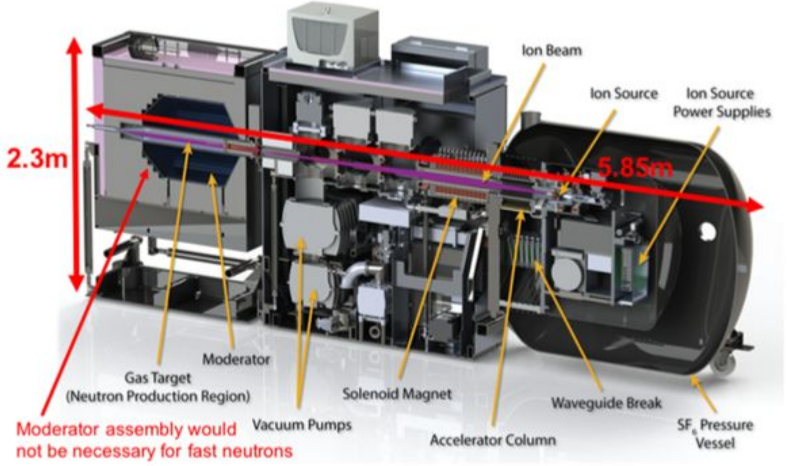
Advantages: High time-averaged flux, reactor-type instrumentation, politically acceptable, piggy-backing on existing accelerator technology



DC compact accelerators

DC compact accelerators
PHOENIX DD ion accelerator
Alectryon:

Ion beam: Microwave ion source and DC 300 kV ion acc. focused by a solenoid
Target: Gaseous Deuterium or potentially Tritium
Neutron Yield: 3 x 10^{11} n/s (DD) or potentially 5 x 10^{13} n/s (DT)
Lifetime: 1000's of hours
Size: a few m



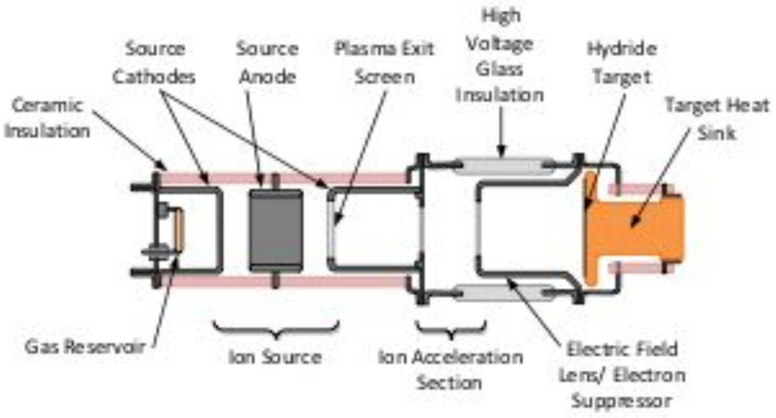
Thunderbird:

Ion beam: Microwave Ion source
and DC 300 kV ion accelerator focused by a solenoid
Target: Solid Titanium target loaded with Deuterium
Neutron Yield: 1 x 10^{9} to 1 x 10^{11} n/s (DD)
Lifetime: exceeding 10000 hours (target cleaning/replenishing procedure)
Size: a few m

Pulsed Sources

Sealed Tube Neutron Generator (STNG)

STNG's use DD or DT fusion reactions.
Deuterons from an ion source are accelerated towards a deuterated or tritiated target. The reactions are exothermic, thus MeV neutrons can be produced using voltages typically in the 50-150 keV range, suitable for compact tubes. DD tubes produce predominantly 2.45 MeV neutrons and DT tubes 14.1 MeV neutrons.



Thermo Scientific:

D711: neutron yield: 2 10^{11} n/s
working gas: DT
pulsing capability:no
lifetime: 1000 hrs @ 10^{10} and 500 hrs @ 2 10^{10} n/s
cost: 325 k$
head dimension: 24.5 cm diameter

P385: neutron yield: 3 10^8 n/s – 5 10^8 (max)
working gas: DT
pulsing capability:20-250 Hz, min. pulse width 5 µs
head dimension: 10 cm diameter x 70 cm length

Pulsed Sources

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Sealed Tube Neutron Generator (STNG)

All Russia Research Institute of Automatics, VNIIA

ING-07: neutron yield: 1 10^9 n/s
working gas: DT
pulsing capability: up to 10 kHz, min pulse width 20 µs
head dimensions: 19 cm diameter x 44 cm length

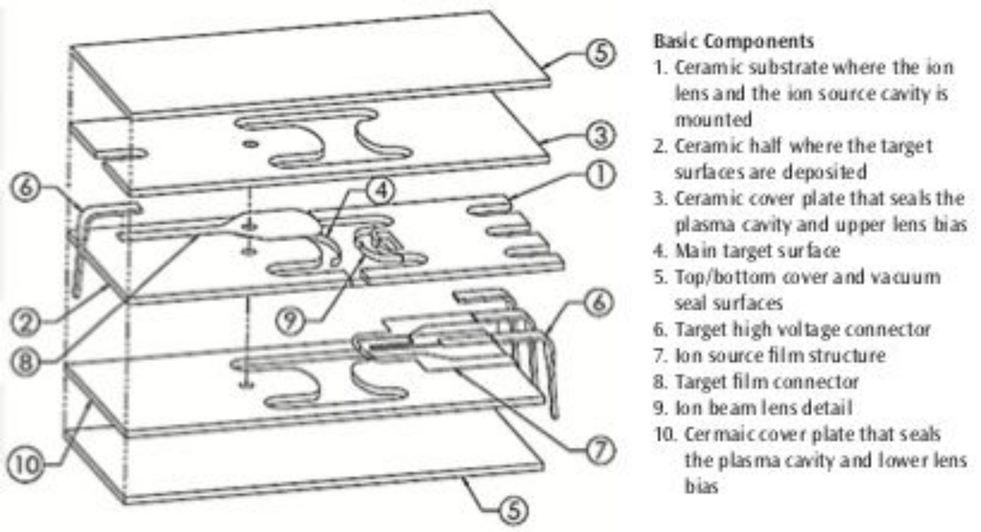
ING-03 neutron yield: 2 10^{10} n/s
working gas: DT
pulsing capability: 100 Hz, min pulse width < 1 µs
lifetime: 100 hrs @ 100 Hz
head dimensions: 13 cm diameter x 96 cm length
cost: 57 k$

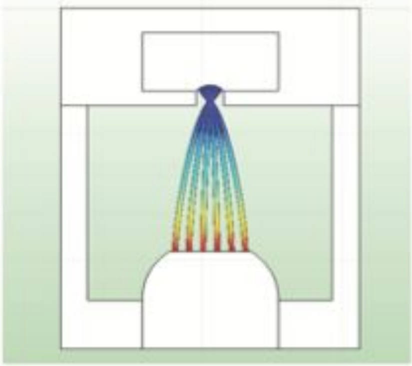
Some systems designed to deliver 10^9 n/s have been built. At this yield active cooling of the ion source and the target is required (incl. pumps, heat exchangers, control systems).
Some high yield actively cooled ENG's have reached 10^{13} n/s in a burst mode. For those generators release of some tritium into the environment cannot be excluded.

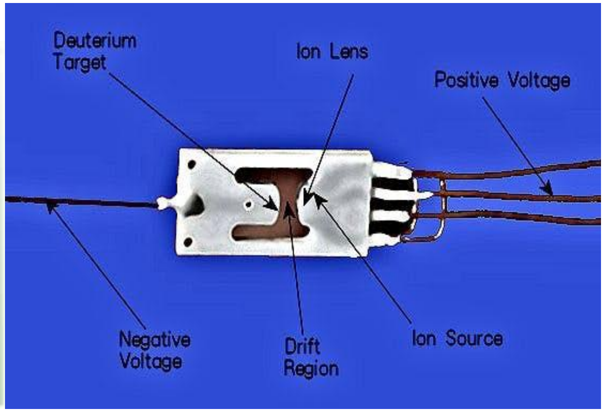
Neutristors

A Neutristor is a very compact, disposable, neutron generator for use in energy exploration and medical applications. It is much smaller than other neutron sources. It was developed by the Sandia National Laboratory

Neutron yield: 1000 n/pulse (not sure, some publ. claim 2000 n/pulse using DT)
Peak neutron yield: 2×10^8 n/s
Av. neutron yield: 16 n/s
Repetition rate: 1/minute
Lifetime: not clearly stated, available inform. indicate a few thousand shots
Pulse duration: 500 ns
Dimensions: 4 cm x 1.5 cm x 0.3 cm
Price: around 1200 USD (for 10-100 pieces)
around 250 USD (for larger quantities)







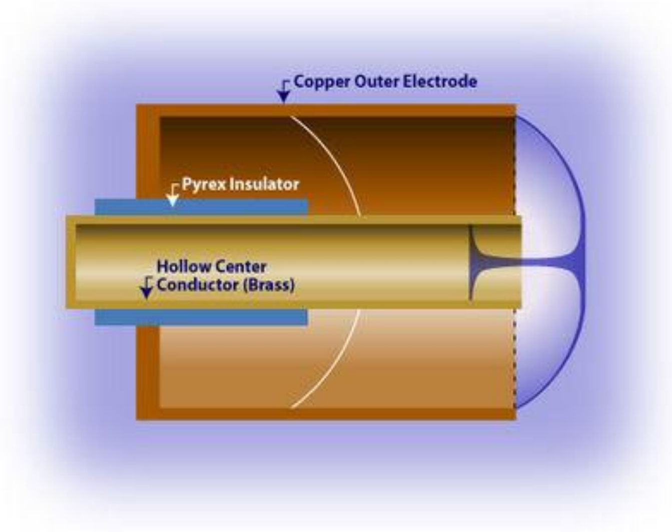
DPF (Dense Plasma Focus)

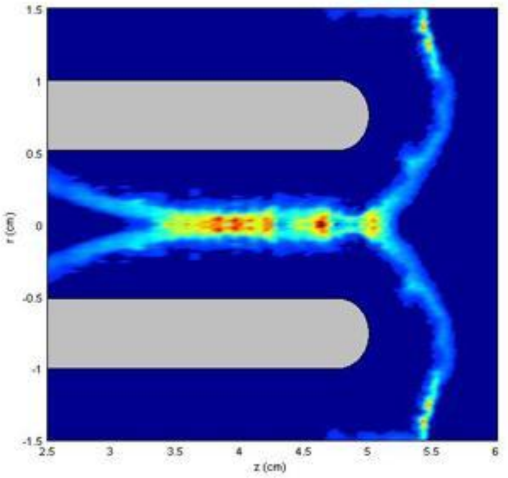
A dense plasma focus (Mater-Type) is a special form of a pinch plasma.

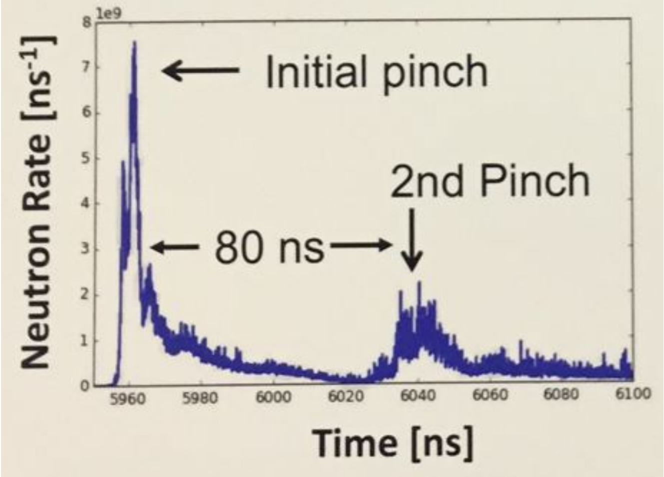
Small and compact DPF devices operate in the 10’s of kA peak current regime and larger devices have been built up a few MA peak current.

While compact kA-like systems are fairly reproducible the MA devices usually suffer from neutron production jitter of up to 100%.

Common to all DPF is the fact that they rely on an instability and thus the precise timing of the neutron production so far has not been achieved. Moreover, especially on larger devices more than one neutron burst per discharge can occur.





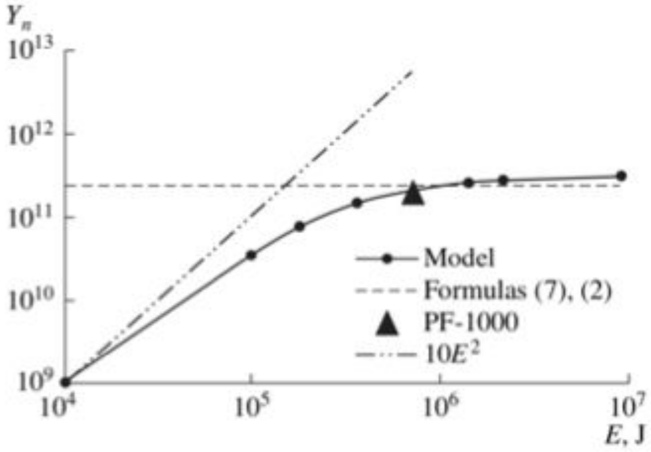


2 Simulation of the ion density of a deuterium DPF (LLNL)

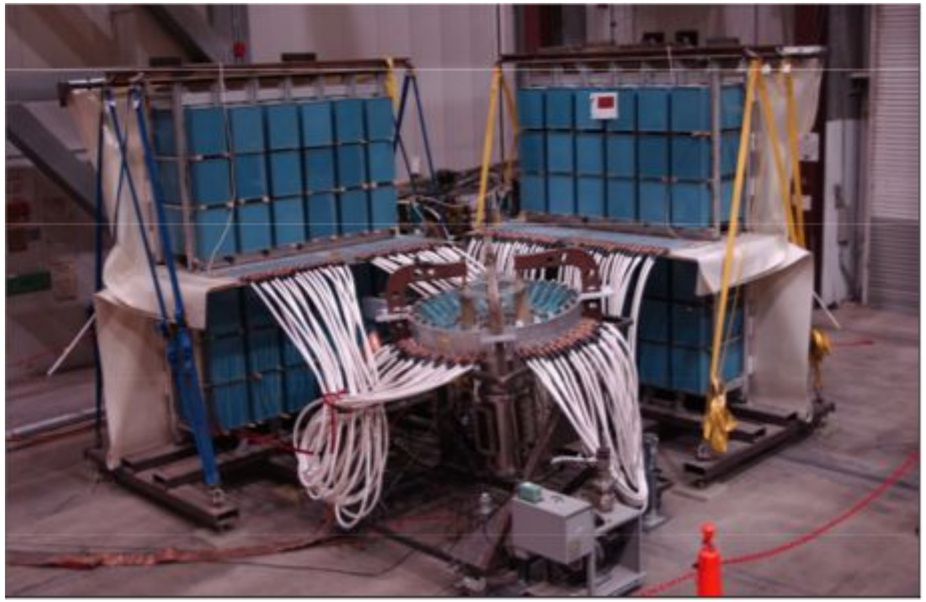
DPF (Dense Plasma Focus)

Neutron yield scales with bank energy with I^4 or I^5 scaling, but seems to saturate around 10^{11} per pulse.

ENEA 6 kJ DPF
Bank energy: 6 kJ
Neutron yield: 3 x 10^8 per shot
Pulse duration: approx. 100 ns
Repetition rate: 1 Hz



GEMINI (NSTeC)
Max Current: 3,25 MA @ 50 kV
Normal operation: 2,5 MA
Bank energy: 133 kJ
Neutron yield: 6 x 10^{11} per pulse
Pulse duration: approx. 10-100 ns
Repetition Rate: unknown, sub Hz



DPF (Dense Plasma Focus)

MJOLNIR (LLNL)
Max. current: 1,3 MA will be upgraded to 2.6 MA
Bank energy: MJ
Neutron yield: 3 x 10^{10} per pulse
Pulse duration: sub 100 ns
Repetition rate: unknown, 1/20 min

TAMU (LANL)

Max current: 1.5 MA
Bank energy: 480 kJ
Neutron yield: 2 x 10^{11} per pulse (DD)

DPF 6.5 (LANL)
Max current: 2.2 MA
Bank energy: unknown
Neutron yield: 2 x 10^{12} per pulse (DD)

Compact Ion Accelerators

To maintain a compact size and limited ion energy, conventional ion accelerators rely on low-energy nuclear reactions in light converter targets.
Due to the ratio of the dielectronic stopping compared to the nuclear stopping a significant amount of the incident energy is released as heat in the target.
As the range of the ions is short, this poses constrains in the allowed power deposition.

Low-energy (p,n) reactions, e.g.,

$$p + {}^{9}Be \longrightarrow n + 2\alpha + p \text{ and}$$
$$\longrightarrow n + {}^{9}B.$$

Compact Ion Accelerators

Compact accelerator driven neutron (CANS) sources have gained interest over the last decades.

Common to CANS is:

- Proton or deuteron source producing a particle beam at energies of the order of 100 keV with a peak intensity up to 100 mA
- RFQ stage to shape the continuous ion beam and accelerate to a few MeV.
- Additional accelerating stages to boost the energy up to requested energy (10’s of MeV)
- Transport line to the target
- Target to convert ion beam into neutrons
- Moderator and reflector to slow down the neutrons to the requested energies
- One or more neutron beamlines for users

“Compact neutron sources for neutron scattering, Report CEA, Version 06, 2018

Compact Ion Accelerators

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Once the deuteron energy exceeds 2.3 MeV in the accelerator, (d,n) stripping reactions on the copper components can lead to the activation of the accelerating structure, which forces severe constraints on the allowable losses for deuteron beams, way beyond those needed for proton beams.

An accelerator designed for deuterons does have an advantage in so far as the same structure can be used to accelerate protons, albeit at lower energy, whereas the reverse may not be true due to problems with activation.

The neutron source is typically only a few $10cm^3$ in size, the facility usually 10 to 30 m.
Costs estimated to around 60M$ with: 32 M$ Accelerator, 6 M$ target station, rest is building and shielding.

Commercial companies claim that they can provide accelerators with very high capabilities (Iav = 30mA, CW, Ep = 12MeV, P = 300kW). It is however unclear if they actually delivered any of these systems.

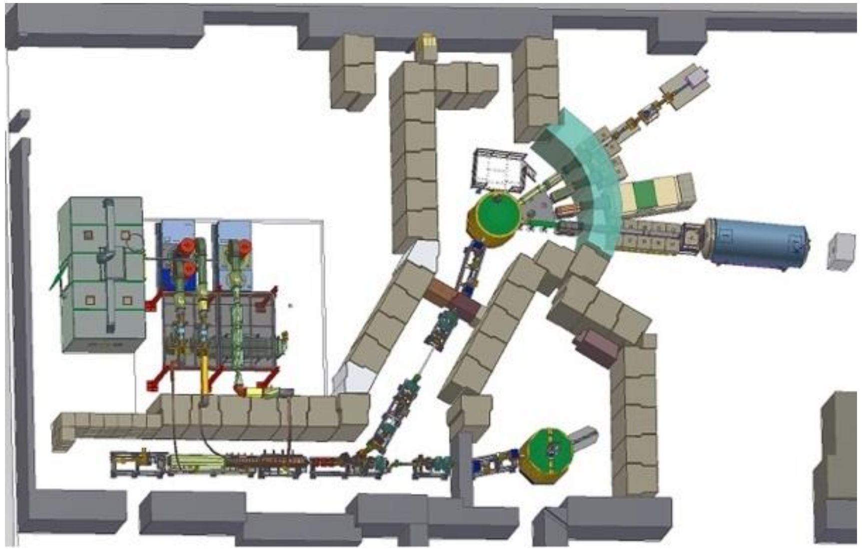
Properties of CANS[v]:

- Low energy protons to start with (10 MeV vs. 1 GeV)
- Lighter shielding (20 t instead of 6000 t)
- Instrument line starts at moderator
- Reduced size: 20 m vs. km
- A CANS is **not** a nuclear facility
- Flux limited by the peak current of around 100 mA

(IAEA-TECDOC-1439)

Compact Ion Accelerators

LENS[v] facility (Bloomington University, Indiana, US):
Ion beam: 13 MeV protons,
I_{peak} 20 mA 1% duty cycle
$I_{average}$=0.24 mA, 3kW
Yield: 5 10^{11} pulse @ 20 Hz
Pulse duration 600 μs, 10 μs
Size 10's of meters.
Cost: estimated 20 M$ (not including neutron instrum.)



RANS[v] facility (Riken, Japan)

Ion beam: 7 MeV Protons (LINAC: PL7 by AccSYS Corp.)
I_{peak} = 100 μA; normal = 70 μA
Repetition Rate: 20-180 Hz
Pulse Width: 10 μs – 180 μs (duty < 1.3%)
Neutron emission Target: Be
Neutron energy: keV – cold; Moderator: e.g. Polythylene;
Neutron yield: - 10^{12} n/s
Neutron Flux: - 10^4 n/cm^2/s (@5m)

Compact Ion Accelerators

LANSAR (AccSys Technology, Inc)

DL-2:

- Ion Beam: 2.1 MeV deuterons
- I_{peak} = 140 µA
- Rep. rate: 120 Hz
- Neutron yield: 1 10^{11} n/s
- Dimension: 2.5 m

DL-11:

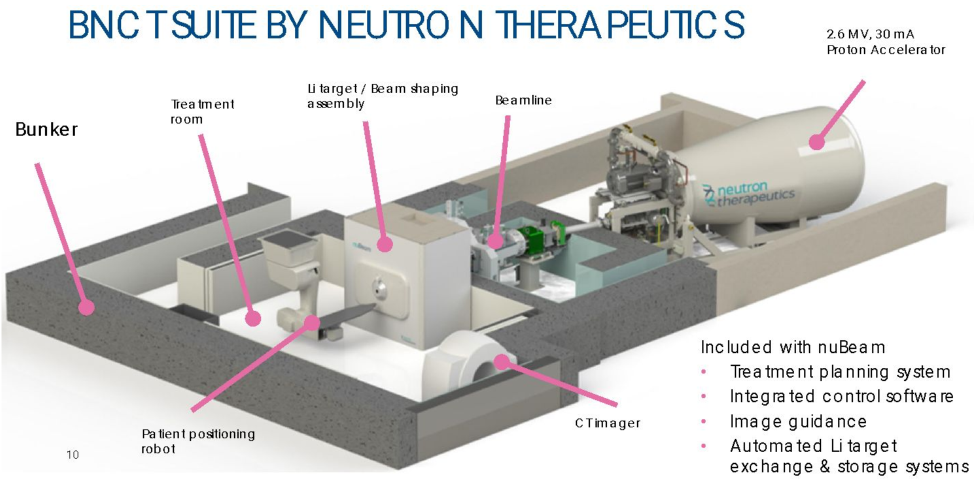
- Ion Beam: 11 MeV protons
- I_{peak} = 1000 µA
- Rep rate: 120 Hz, pulse width 30-215 µs
- Neutron yield: 3 10^{13} n/s
- Dimension: 6 m
- Cost: 4 M$

Compact Ion Accelerators

HUS BNCT neutron source, Helsinki, Finland (source: talk TM IAEA 2019)
Helsinki University Hospital has installed a 2.6 MeV, 30 mA proton accelerator
for cancer treatment using the BNCT (Boron Neutron Capture Therapy) approach.
This treatment is becoming more popular.

In the past BNCT had been restricted to reactor sources and with the fading research reactors this treatment was declining. With the new compact neutron sources, there is a revival in many countries for BNCT.

Electrostatic proton linac:
Energy: 2.6 MeV
Current: 30 mA
Target: rotating Li target in complex shielding incl. MgF moderator.
Neutron flux at treatment site: 1×10^{9} n/cm^{2}/s
Gamma background: smaller than 1×10^{13}



Compact electron accelerators

Electron Accelerators were among the first compact accelerator-driven neutron sources.

Cross sections for neutron production by electrons is inferior to ion-neutron generation

As electrons are easily accelerated to MeV over short distances the accelerator facilities can be quite reasonable in size.

The neutrons are produced by direct electron impact and by the generation of high-energy Bremsstrahlungs photons and the subsequent excitation of giant resonances in heavy nuclei, which results in neutron evaporation and residual heat in the target.

Bremsstrahlung photoproduction:

e^- on heavy target —> photons

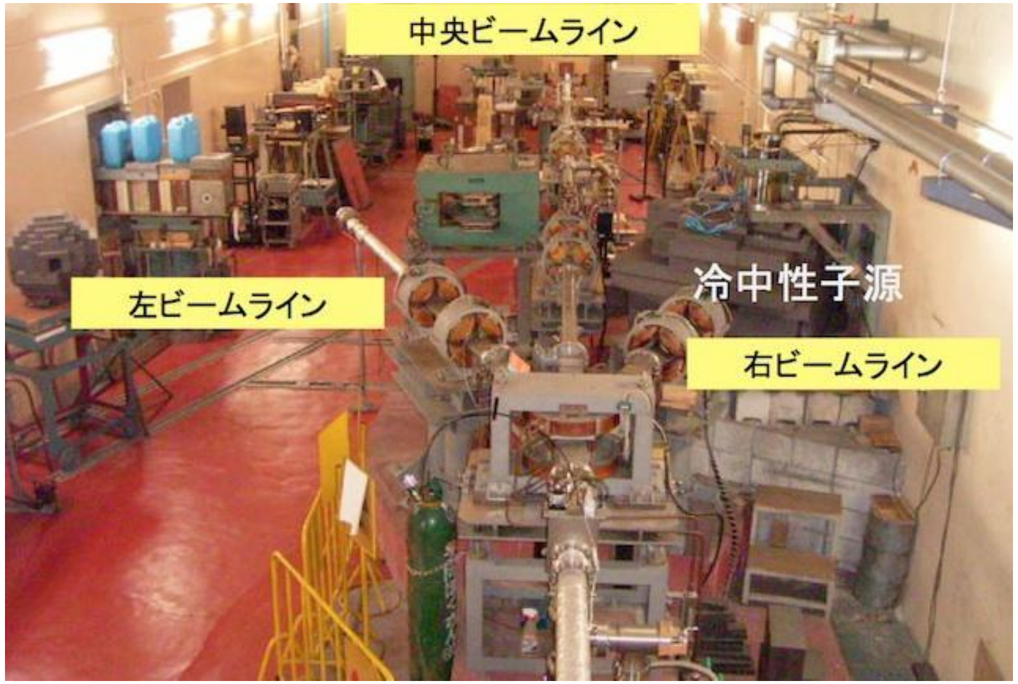
photons on heavy nucleus —> giant resonance

excited nucleus decay —> neutron

~ 3000 MeV/n (as heat)

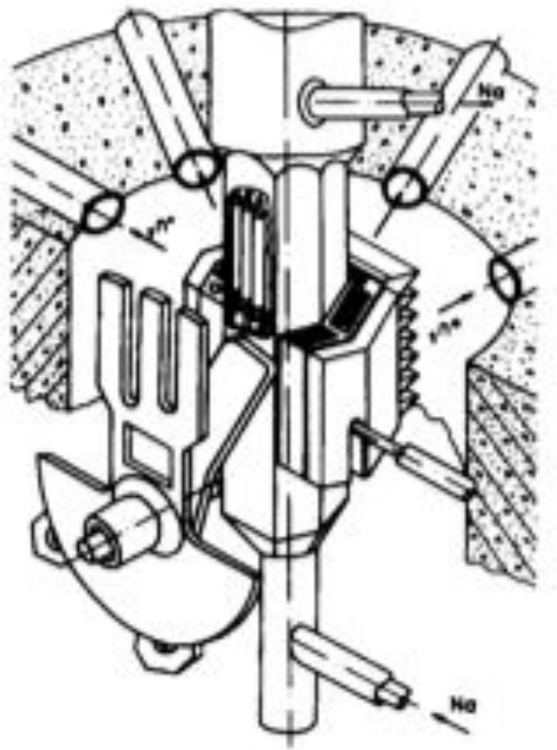
Compact electron accelerators

HUNS[v] facility (Hokkaido, Japan), 1973
Electron (s-band RF LINAC)
Electron beam: 35-45 MeV
Max. Current: 140 μA
Repetition: 1 – 200 Hz
Pulse width: 10 ns- 3 μs
Neutron Emission Target: Lead
Neutron Energy: ev-thermal-cold
Moderator: Solid Methane
Neutron Emission: 1.6×10^{12} n/s (E_e=35 MeV, 1 kW)
Cold neutron flux: 3.1×10^{3} n/cm^2/s @7m
P: 1 kW



Pulsed Reactors

Pulsed fission reactors can exceed the prompt neutron flux of DC research reactors by orders of magnitude.
A sub-critical reactor is brought to criticality usually by using a rotating reflector.
Although the peak neutron flux can exceed 10^{18} n/s the flux on a sample often does not exceed 10^{7} n/s, so about 11 orders of magnitude are lost due to shielding and transport limits.

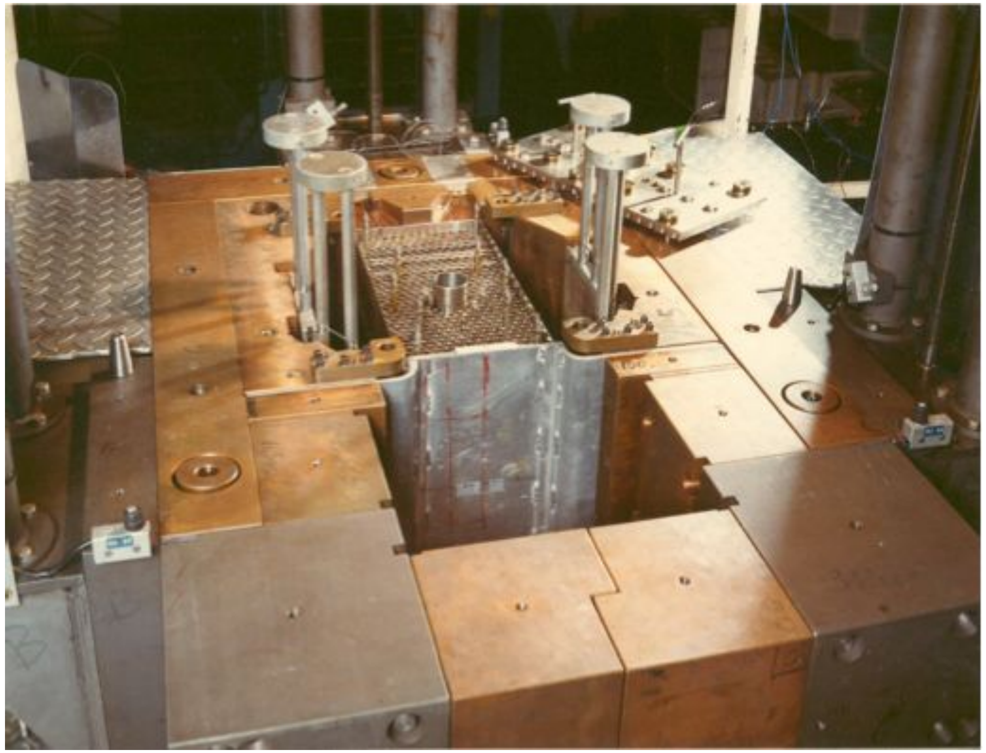


Example, **IBR-2 reactor** Joint Institute for Nuclear Research, in Russia (near Dubna, built in 1982)
Rotating reflector shield to pulse a 7 element PuO reactor core at 5-25 Hz.
The reactor is cooled by liquid sodium. At an average Power of 2 MW the reactor peaks at 1500 MW during the pulse of 215µs and slows down to 0.1 MW in between.
The neutron flux in the central channel of the reactor is **1.3×10^{17} n/s/cm^2 during burst and 1.5×10^{14} n/s/cm^2 average**

Alexandr V. Belushkin (1991) IBR-2 – the fast pulsed reactor at Dubna, Neutron News, 2:2, 14-18, DOI: 10.1080/10448639108218724

Pulsed Reactors

The **VIPER pulsed reactor** at AWE (1967) delivers short bursts of neutrons of up to 20 GW in a fraction of a millisecond.



- **Peak neutron flux 1×10^{18} or 1×10^{15} /cm^2/s**
- **γ Radiation Absorbed Dose up to 10 kGy. Equivalent** dose rates down to μSv/hr at steady state.
  Size: about 30 x 30 m

Pulsed Reactors

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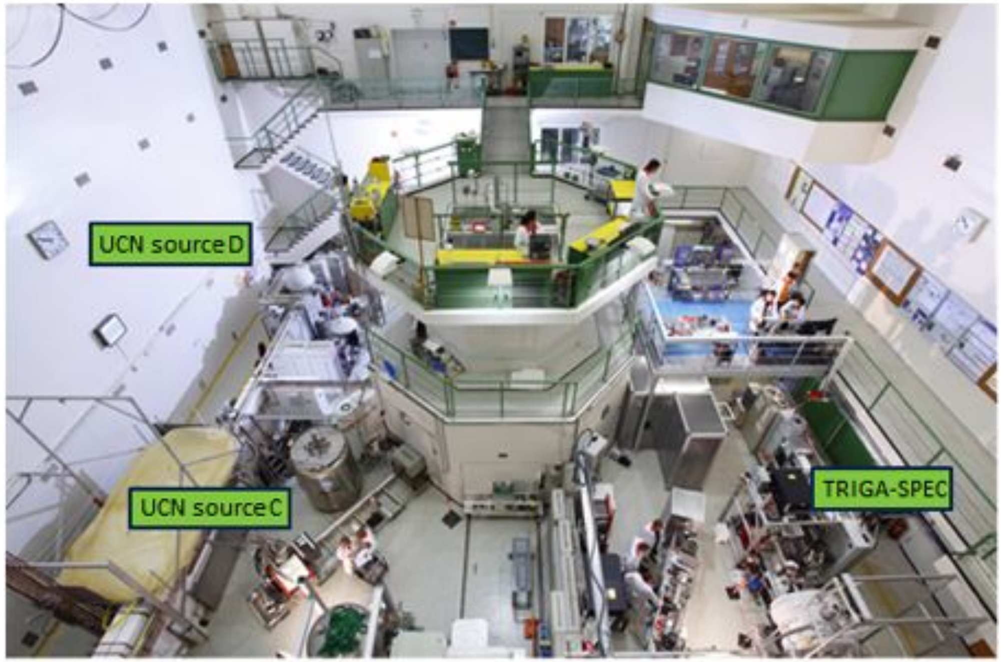
TRIGA reactors (Training, Research, Isotopes, General Atomics) use prompt criticality in an inherently safe, low average power reactor configuration.

The reactor is driven into criticality and the strong negative temperature coefficient of the reactivity pull the reactor back into sub-criticality.

Usually the reactor needs to cool down afterwards.

The reactor is operating using 20% enriched uranium.



Fast pulsing can be achieved by rapid insertion of positive (negative) criticality using fuel or poison respectively. The minimum pulse duration was proposed to be short as 17 µs. Size: few 10’s of meters.

- **Peak neutron flux 1 x 10^{16} n/cm^2/s @ 250 WM peak power**

Spallation Sources

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Spallation:

p + heavy nucleus = 20 ~ 30 n + fragments

1 GeV *e.g., W, Pb, U* *~ 30 MeV/n (as heat)*

ESS (LUND, Sweden)
2GeV Proton Beam on a tungsten wheel of 5t weight, 2.6 m diameter, rotating at 23.33 RPM
Neutron pulse: 2860 ns pulse duration, 14 Hz repetition rate
Power: 5 MW, 4% duty cycle
Neutron yield: 10^{18} n/s
Shielding (primary) 6000 t steel monolith
Size: $1 km^2$
Building costs (ESS): 2000 M$
Operating costs (ESS): 160 M$/a

Spallation Sources

ISIS
Accelerator: 200 µA, 800 MeV, 160 - 240 kW,
Neutron pulse: 100ns pulse duration, 50 Hz repetition rate, 2 x 10^{13} n/cm^2/s average
Building costs (ISIS): 1000 M$
Operating Costs (ISIS): 70 M$/a

N_TOF (CERN, Switzerland)
Accelerator: LHC, 27km synchrotron, 7 x10^{12} protons/pulse, 20 GeV, 7 ns pulse width, repetition rate 1/1.2 Hz
Target: massive lead target,
Moderator: surrounded by 1 cm cooling water and a 4 cm thick layer of borated water
Neutron pulse: 6 ns pulse duration, 0.4 Hz repetition rate, 2x 10^{15} n/pulse

N. Colonna et al., Progress in Particle and Nuclear Physics, 101, p.177-203 (2018)
S. Barros et al., Optimization of n_TOF EAR2 using FLUKA", Journal of Intrum. 10, P09003 (2015) doi:10.1088/1748-0221/10/09/P09003

Spallation Sources

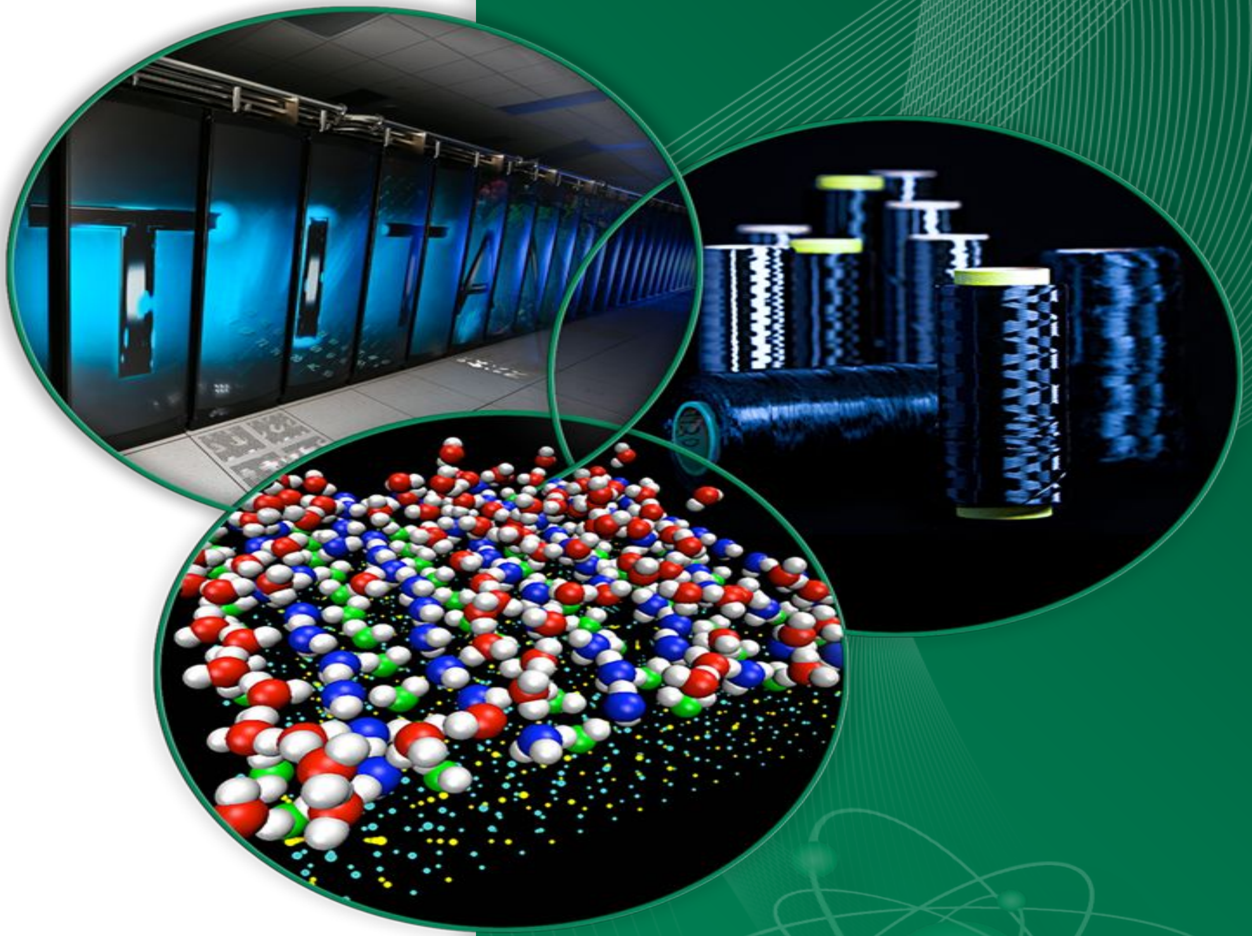
SNS
Accelerator: 1.4 mA, 1 GeV, 1.4 MW
Target:
Neutron pulse: 700 ns pulse duration, 60 Hz repetition rate[xviii], 2×10^{17} n/s
Thermal neutrons at beamline start: 2×10^{12} n/s, at sample: 2×10^{10} n/s

Peak n- flux: 8×10^{15} n/cm^2/s

Building costs: 1.4×10^9 USD

Operating costs: 1.7×10^8 USD

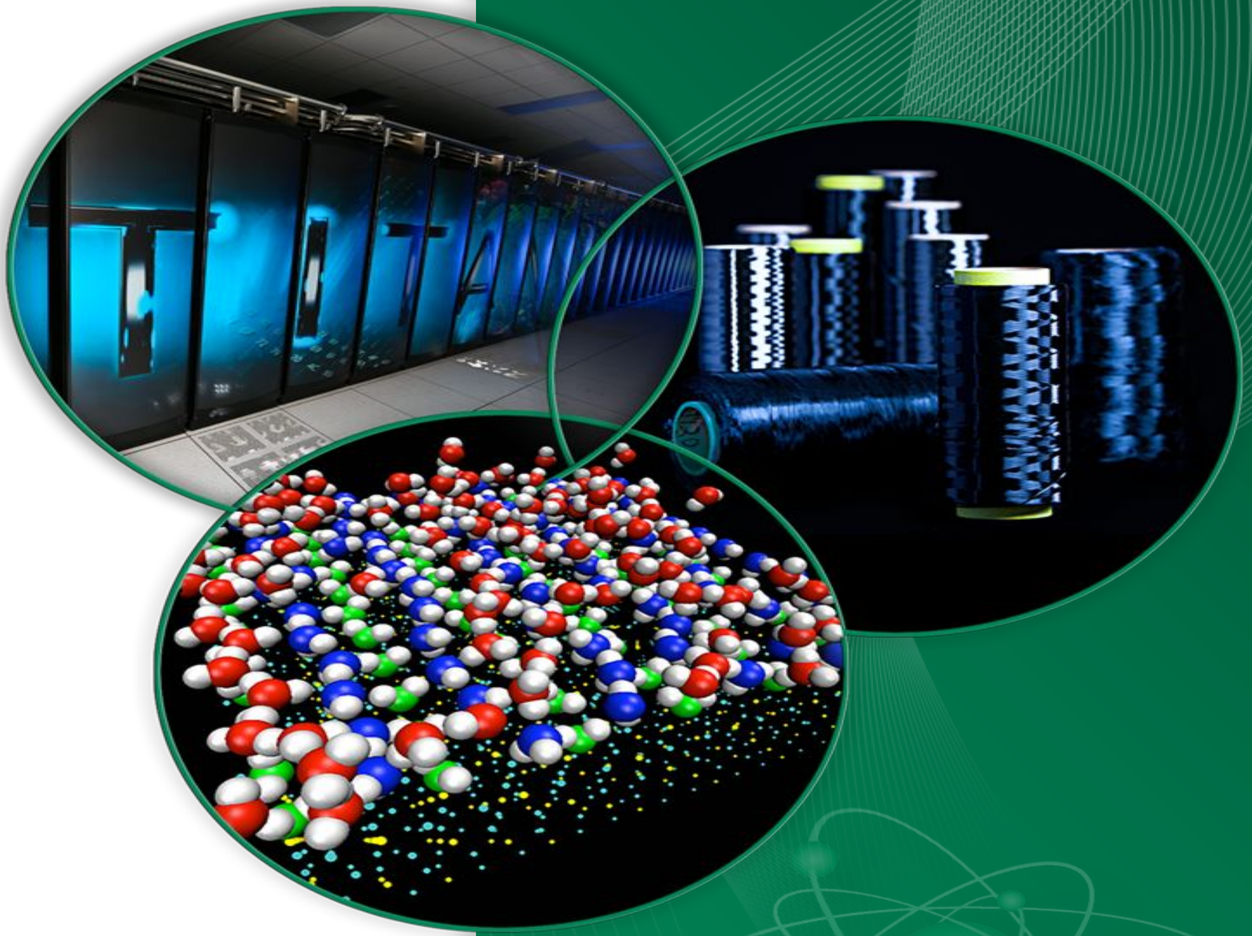
High Power Targets and Performance Optimization versus Costs or How much shall one pay for a useful neutron?



F. X. Gallmeier

5th High Power Targetry Workshop
May 20, 2014

Neutron Economy at SNS



1.4 MW SNS produces: 2×10^{17} n/s

Thermal neutrons at beamline start: 2×10^{12} n/s

Neutrons at sample position (white): 2×10^{11} n/s

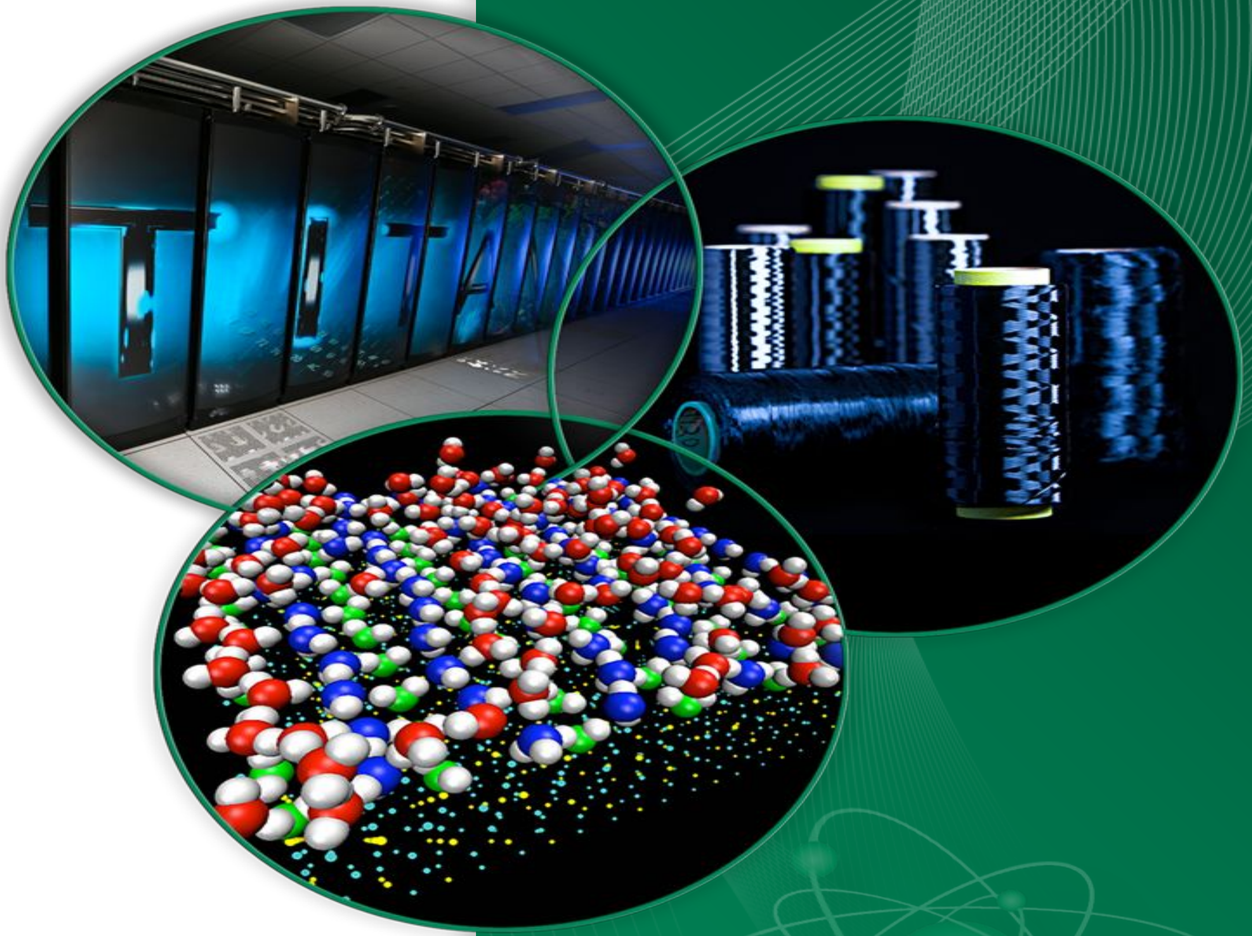
Neutrons at sample (chopped): 2×10^{10} n/s

Neutrons scattered: 2×10^{8} n/s

Neutrons counted: 5×10^{7} n/s

Neutron counted/Neutrons produced: 3×10^{-10}

Costs Analysis



SNS construction cost: $ 1.4×10^9

- Yearly SNS budget: $1.7×10^8

SNS expected life: 40 yrs

- Yearly hours of operations: 5000h

Yearly counted neutrons: 9×10^14 n/yr

- Neutrons per dollar: 4×10^6 n/$

Spallation Sources

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LANCSE, Los Alamos Neutron Science Center, NM, US

Accelerator: 800 m proton LINAC; 800 MeV

120 Hz repetition rate, pulse duration 800 µs,

micro bunch structure 60ps separated by 5 ns

Ions in a micro-bunch: 3 x 10^8 protons

Buncher: Proton Strorage Ring (PSR):

Accumulates the 800 MeV ions for 450µs

and releases the bunch in a single 250 ns bunch,

delivering 60 µA @ 20 Hz

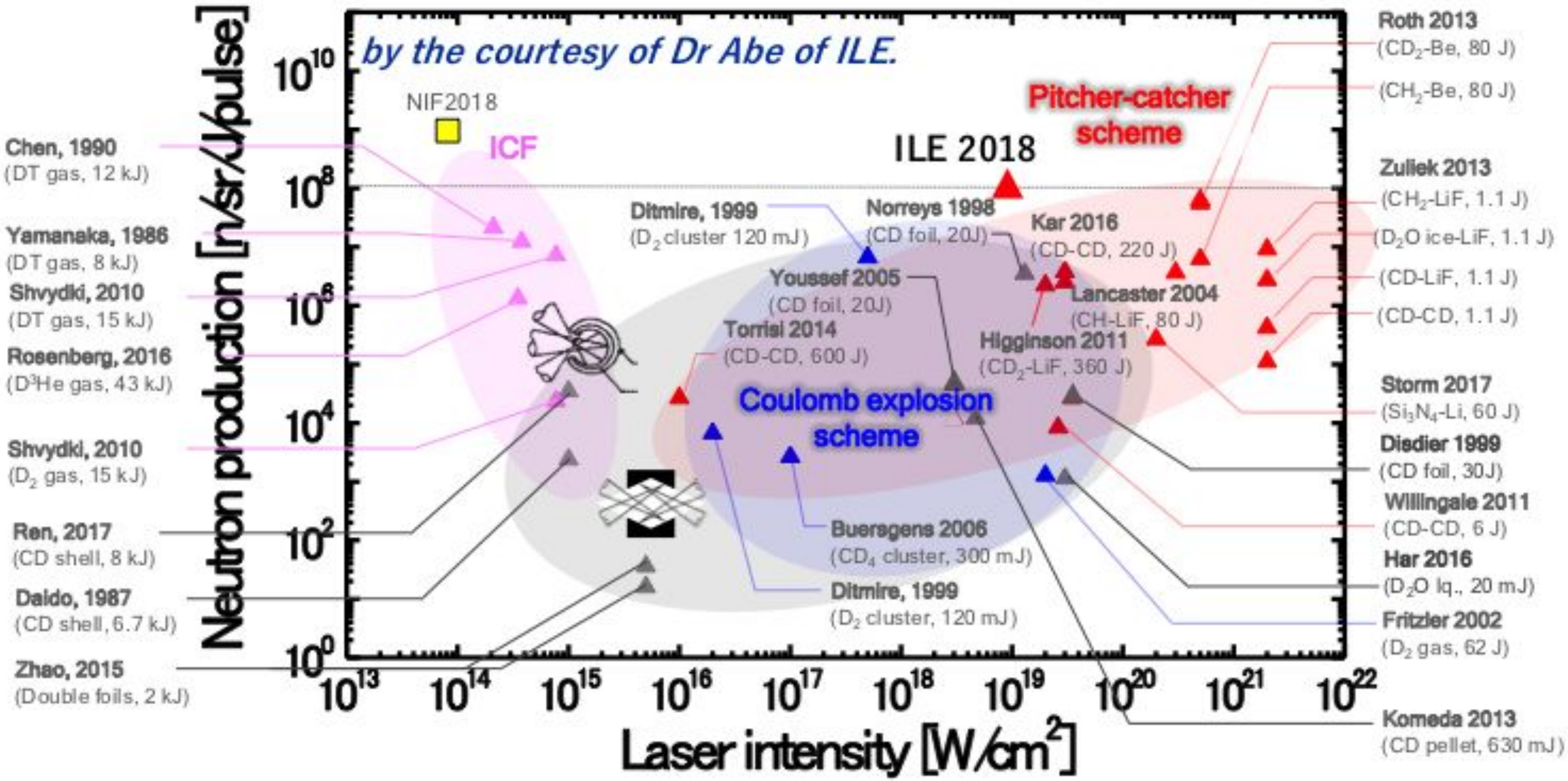
Target: Split target moderator reflector shield (TMRS)

Upper target (10 cm x 7.25 cm tungsten rod); lower target (10 cm x 27cm rod)

Neutron pulse: 0.2 ns pulse duration, 13900Hz repetition rate, 8 x 10^9 n/pulse

P.W. Lisowski et al., „The Los Alamos National Laboratory Spallation Neutron Sources“, Nucl. Sci. and Engineering **106**, 208-218 (1990)

Laser Drivers



Fusion Laser Sources

Driver: 192 Laser beams

Energy: 1.8 MJ/480 TW; 600 MJ input energy

Repetition rate: 1 shot per 2 hours/ 1 shot /day

Neutron yield: 2 x 10^{18} /shot

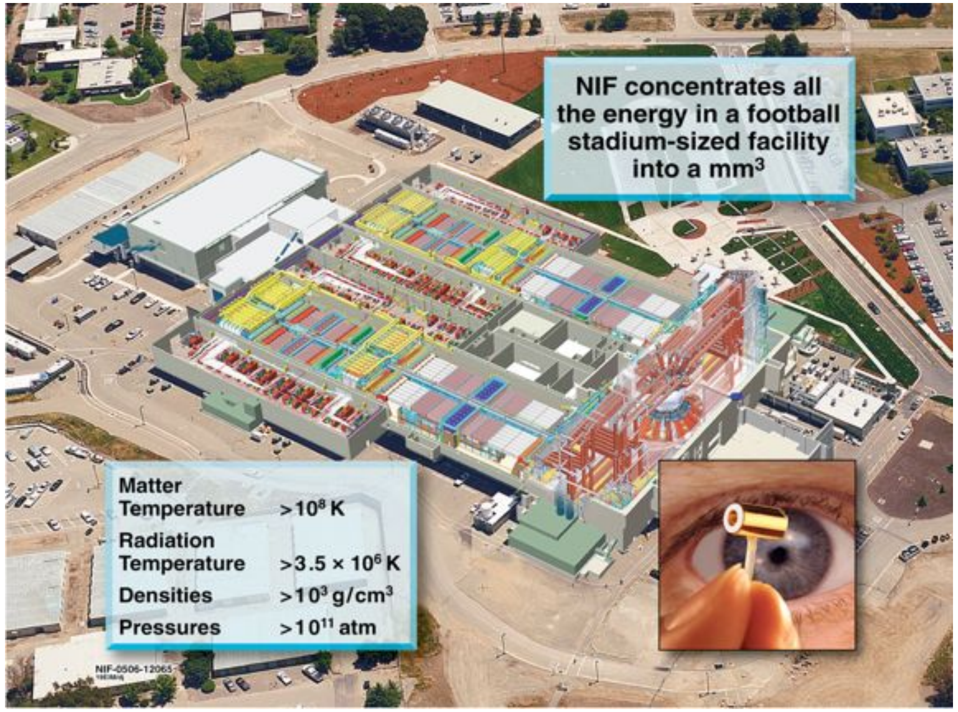
Pulse duration: 160 ± 30 ps

Neutron flux: pk: 1.1 x 10^{28} n/cm^2/s

av.: 2.4 x 10^{14} n/cm^2/s (@ 3mm from hot spot)

Size: 250 x 120 m

Cost: ~ 4 B$



Laser driven ion sources

PHELIX

Driver: 1 Laser beam

Energy: 250 J

Repetition Rate: 1 shot / 90 minutes

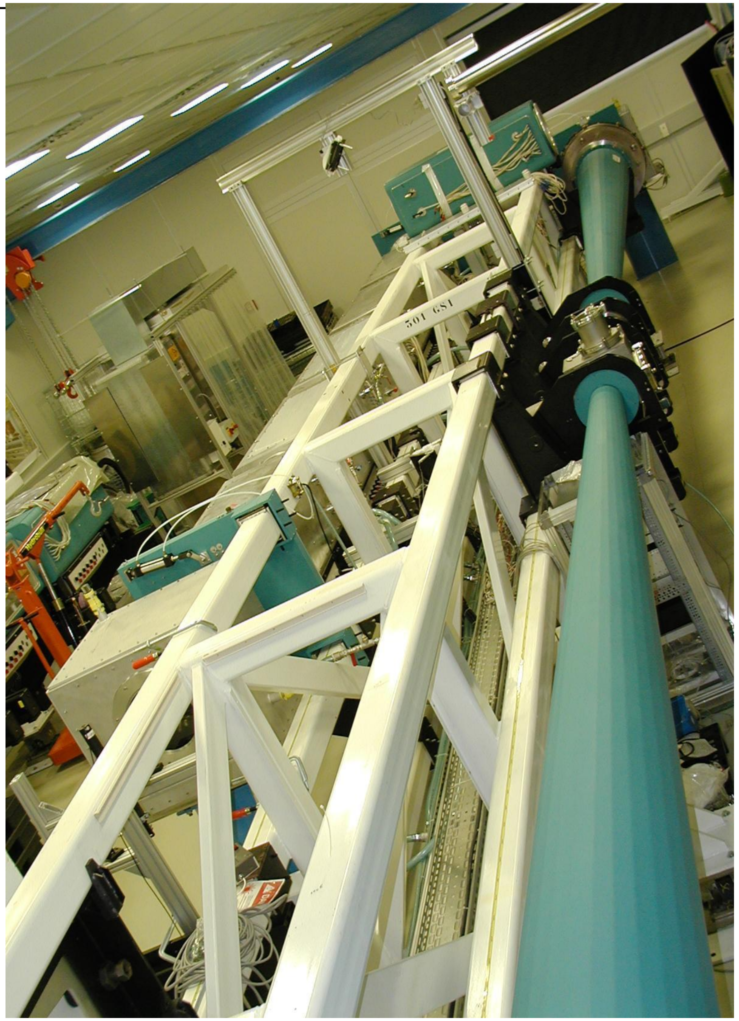
Neutron yield: 2.4×10^{11} / shot; 1.4×10^{10} /sr /shot

Pulse duration: of order of 100 ps

Neutron flux: peak: 1.4×10^{20} n/cm^2/s (@ 1cm from spot @ 100ps)

av: 2.5×10^{6} n/cm^2/s (@ 1cm from spot @ 100ps)

Size: 30 x 30 m



Laser driven ion sources

Hercules (Zeus):

Driver: 1 Laser Beam

Energy: 1.1 J (< 10J possible)

Repetition Rate: 0.1 Hz (5 Hz at smaller energy)

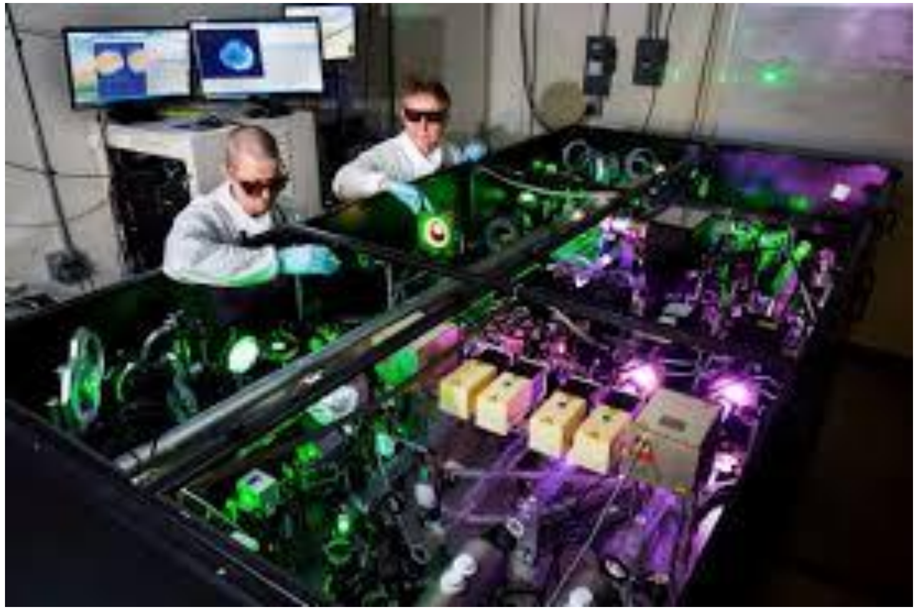
Neutron Yield: 1×10^{8} n/shot

Pulse duration: of order of 100 ps

Neutron flux: peak: 1×10^{17} n/cm^2/s (@ 1cm from spot @ 100 ps)

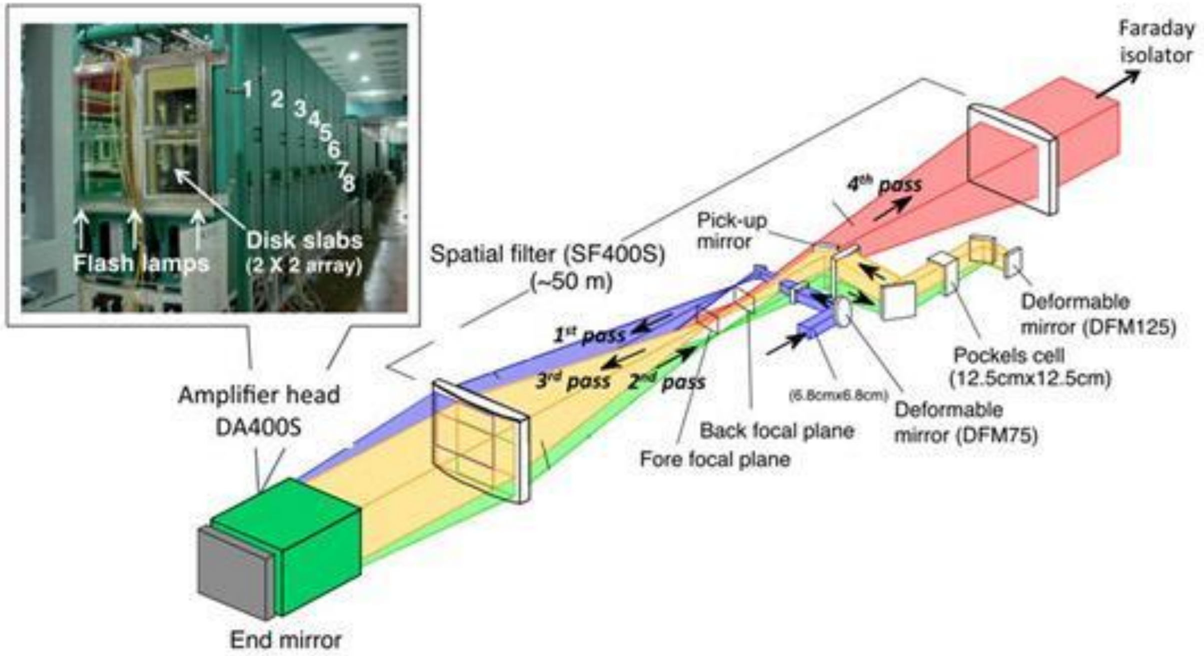
av: 1×10^{6} n/cm^2/s (@ 1cm from spot @ 100 ps)

Size: 30 x 10 m



Laser driven ion sources

LFEX (ILE, Osaka):



Driver: **4 Laser Beams**

Energy: **1000 J (250 J in a single beamline)**

Repetition Rate: **1/120 min**

Neutron Yield: **1 x 10^{11} n/sr shot**

Pulse duration: **of order of 100 ps**

Neutron flux: peak: 1 x 10^{20} n/cm^2/s (@ 1cm from spot @ 100 ps)

av: 1 x 10^{6} n/cm^2/s (@ 1cm from spot @ 100 ps)

Size: **60 x 40 m**

Prospects

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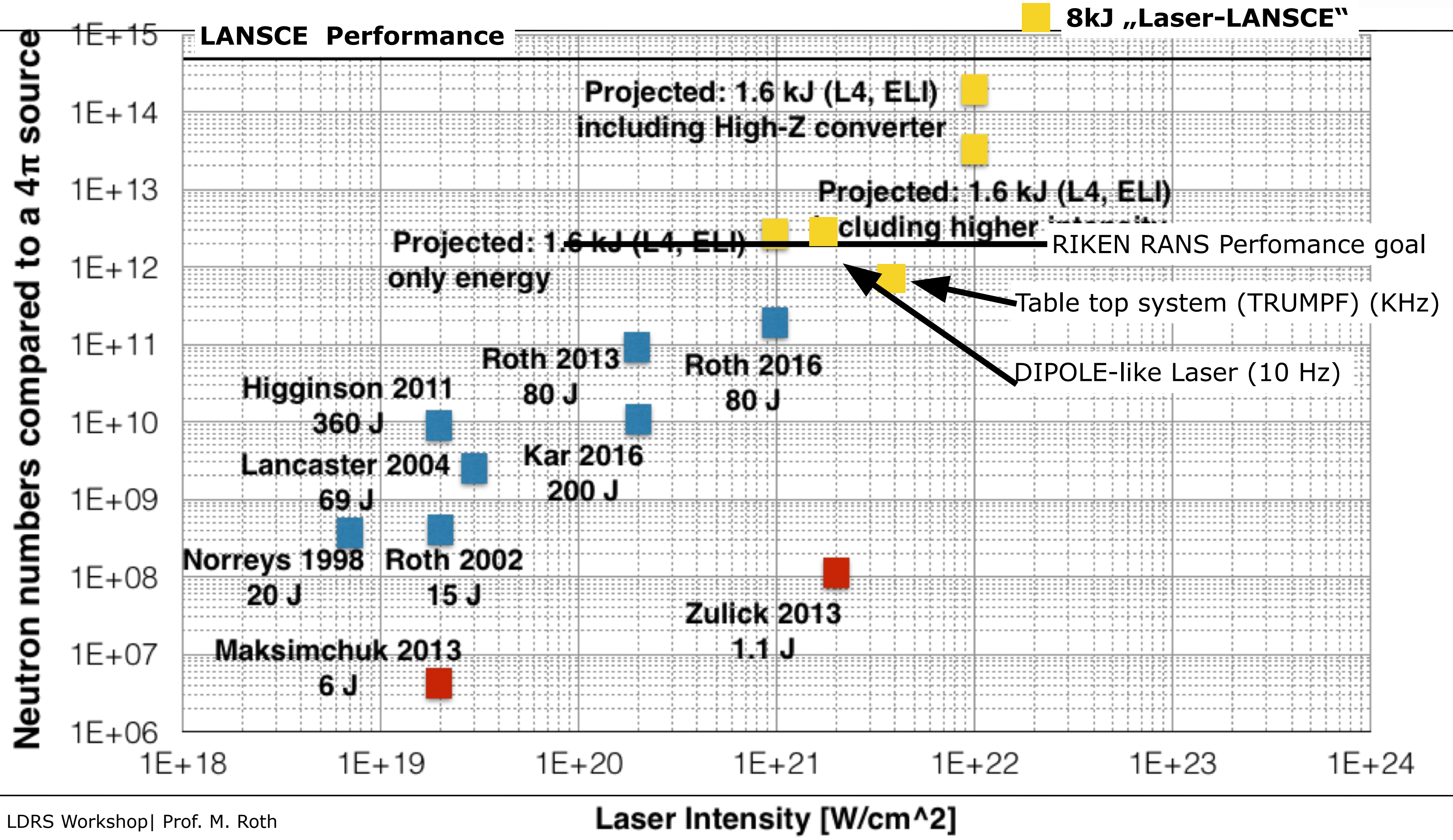

LASERS OFFER ULTRA-BRIGHT RADIATION SOURCES (neutrons)