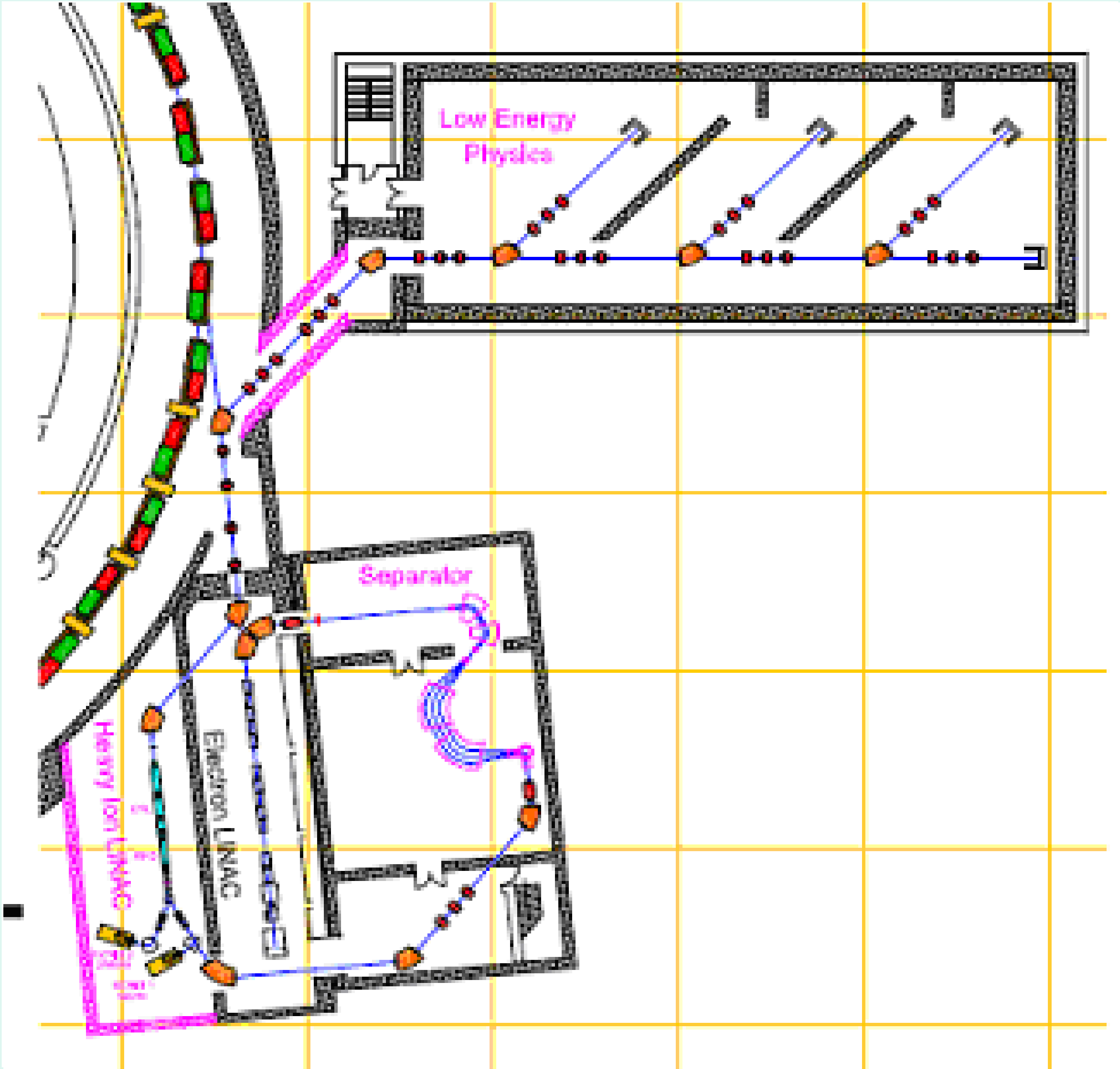
Electron Beam Driver

for

Radioactive Ion Beam Facility


Low Energy Physics
Separator
Electron LINAC
Heavy Ion LINAC

The requirements for a potentially successful upgrade:

1) Must fit on the limited real estate available either near or within the existing facility

2) Must provide a minimum of 10^{13} f/s in the production target without assuming major technical developments in targetry.

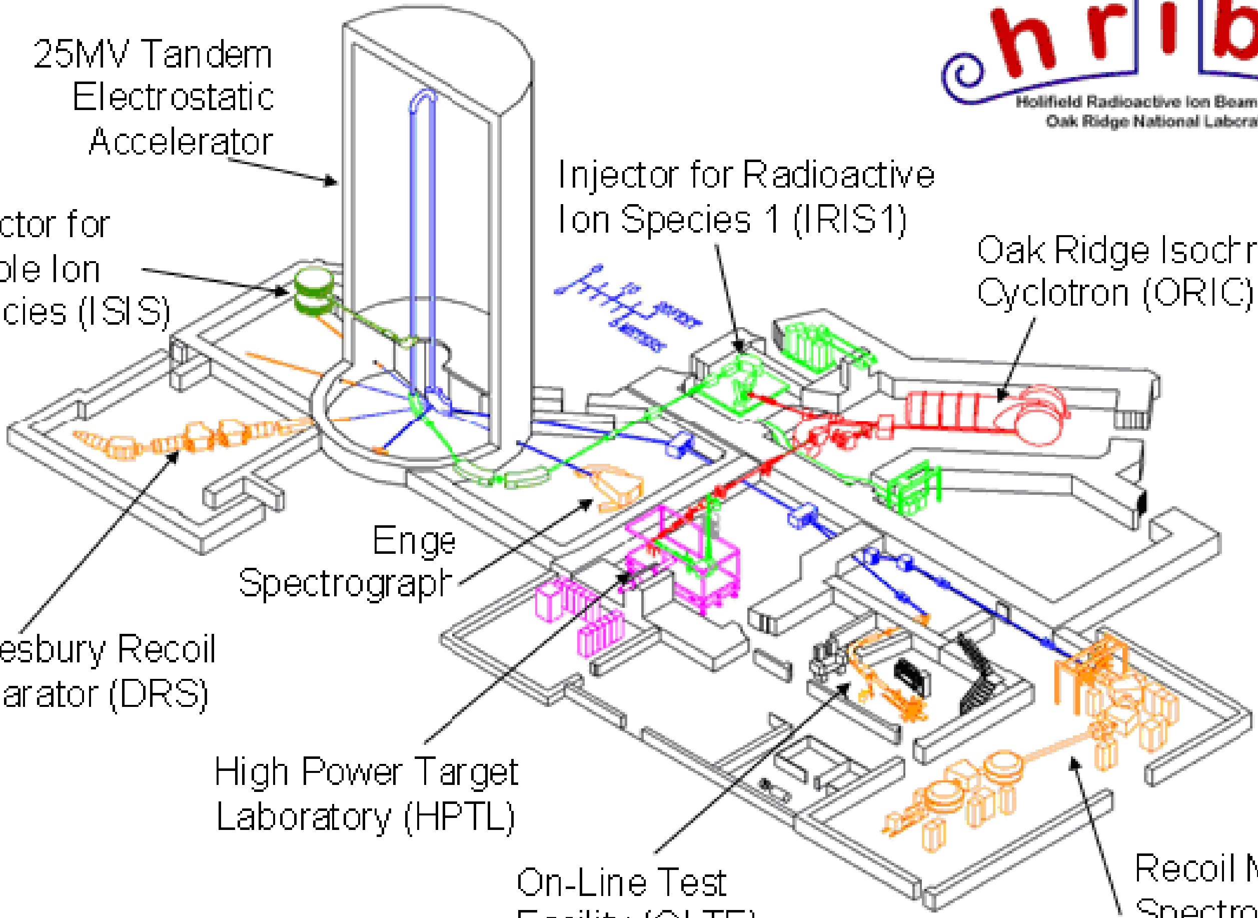
3) Must be cost effective (an upper limit in the $20M to $30M range; the accelerator cost must therefore be ~$10M or less).

4) Must require only a limited addition of staff for both operations and maintenance.

5) Should be completed in time to have significant impact on science before the next-generation facility is available.

hribf

Holifield Radioactive Ion Beam Facility
Oak Ridge National Laboratory



25MV Tandem Electrostatic Accelerator

Injector for Stable Ion Species (ISIS)

Injector for Radioactive Ion Species 1 (IRIS1)

Oak Ridge Isochronous Cyclotron (ORIC)

Enge Spectrograph

Daresbury Recoil Separator (DRS)

High Power Target Laboratory (HPTL)

On-Line Test Facility (OLTF)

Recoil Mass Spectrometer (RMS)

Photo-fission vs. Proton induced fission

HRIBF now produces:

- neutron-rich species by ^{238}U(p,f);
- proton energies of 40 to 50 MeV;
- the typical fission rate is ~4 x 10^{10} f/μC.

To date beam currents up to 10 μA:

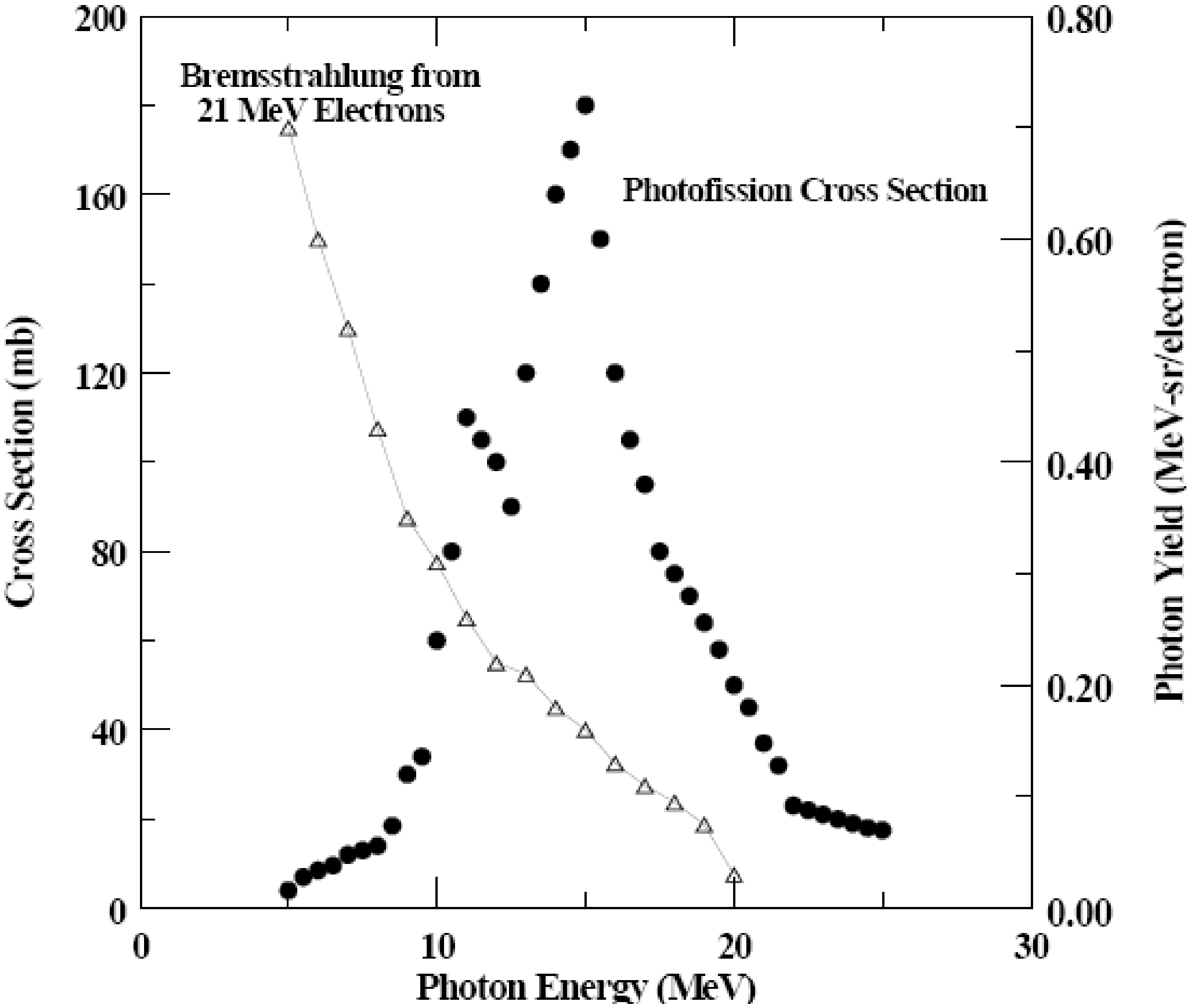
- targets of diameter ~1.4 cm;
- thickness ~3.9 g/cm^{2}, corresponding to

~6 g of ^{238}U in the form of uranium carbide plus graphite with a 4 to 1 C to U atomic ratio.

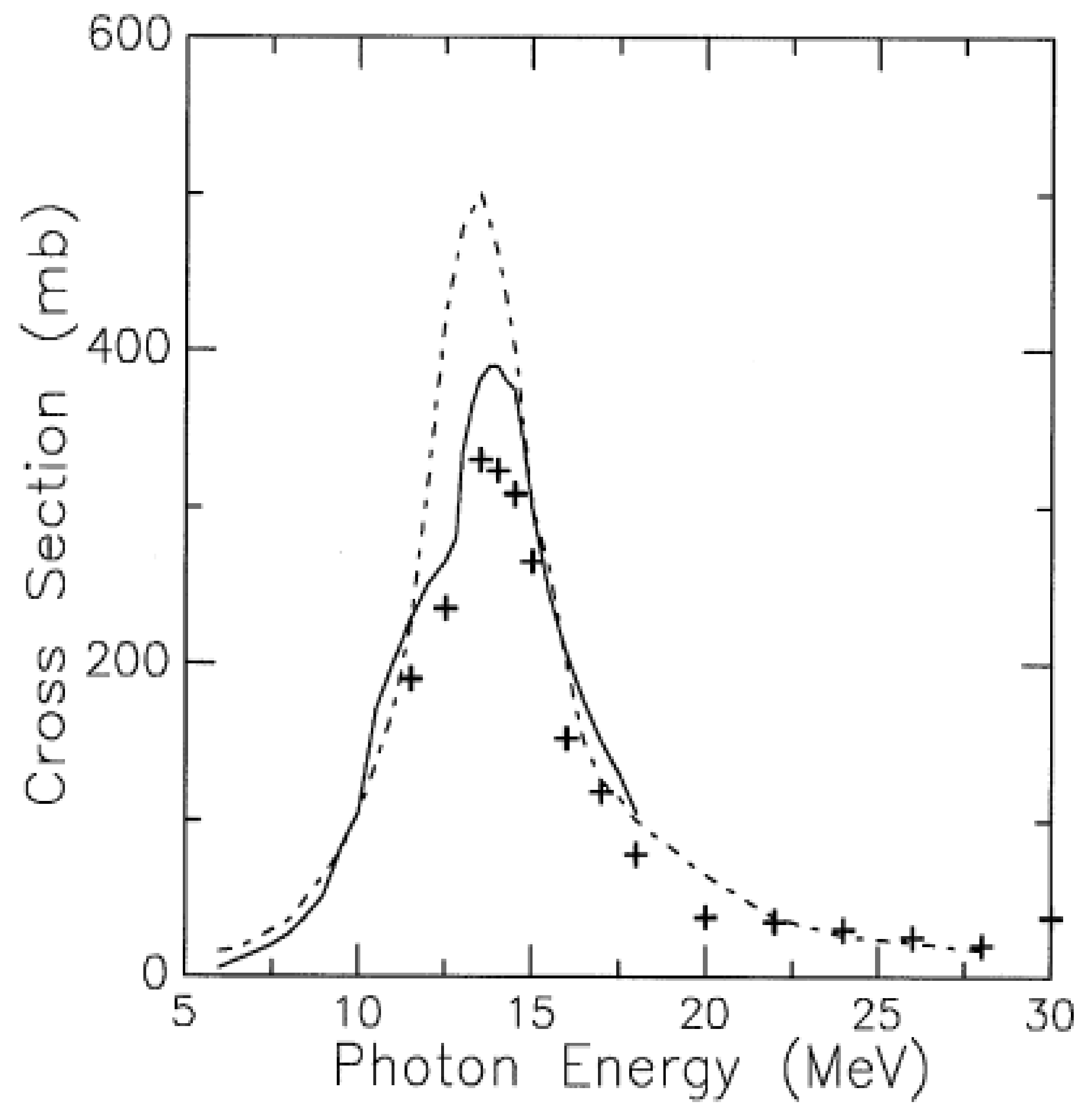
The electron beam driver concept was originally proposed as a low cost addition to a Tandem facility and has been adapted at other facilities. It was also seriously considered as an option for the SPIRAL II upgrade at GANIL in France.

GANIL chose to use the larger and more costly (~$170M total cost) option of a high-current super conducting linac to provide 5 mA of ~40 MeV deuterons to generate a secondary neutron beam by breakup on a carbon converter target and subsequently provide neutron-rich species from neutron-induced fission.

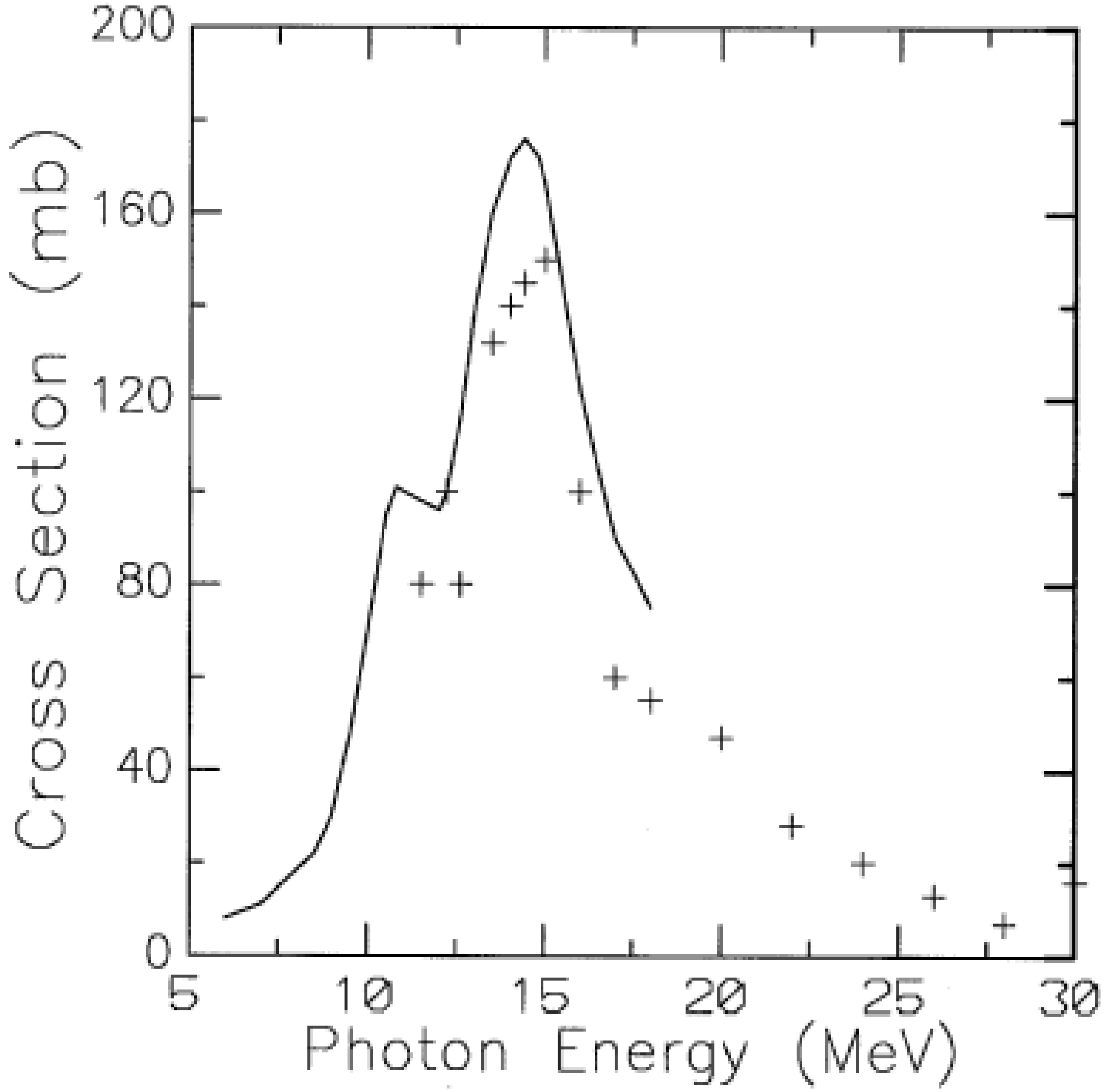
Photofission cross section and Bremsstrahlung yield from 20.9 MeV electrons on an intermediate thickness heavy converter target.

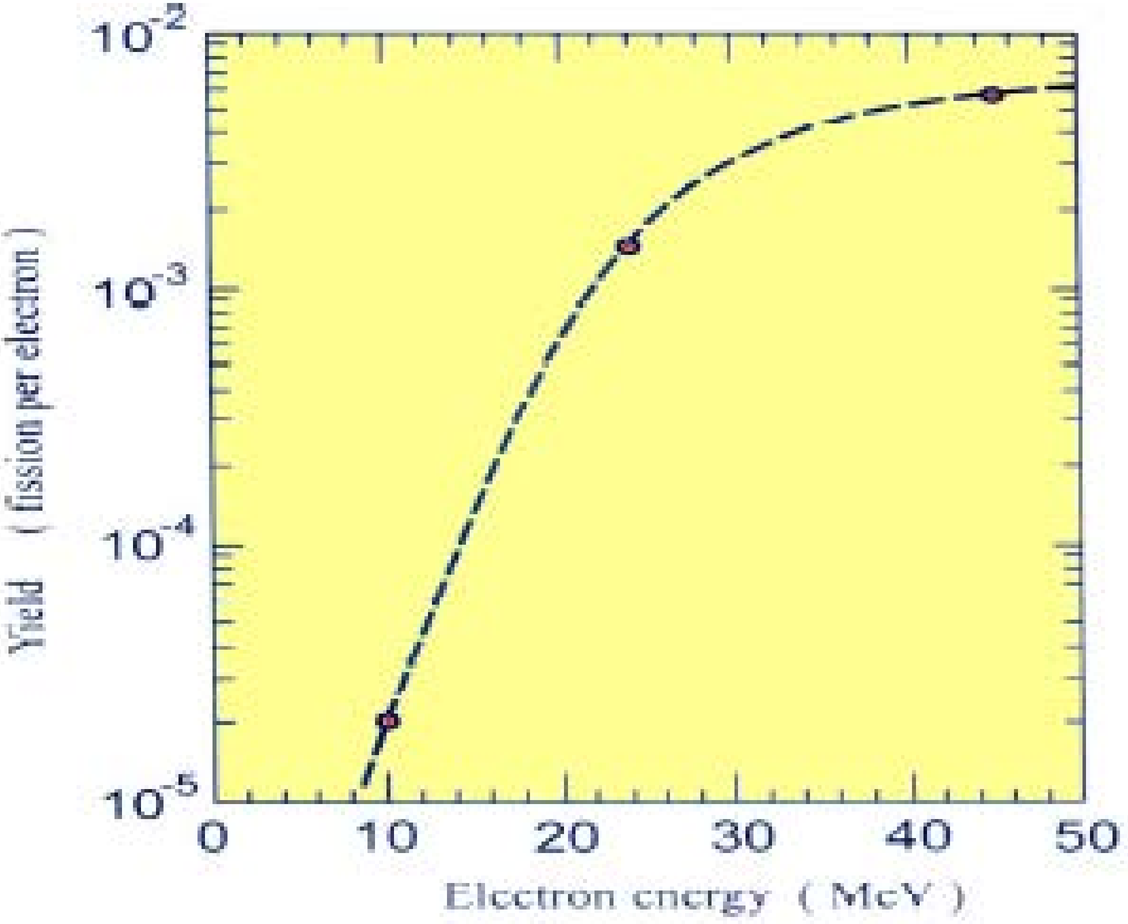

Bremsstrahlung from
21 MeV Electrons
Photofission Cross Section
Cross Section (mb)
Photon Yield (MeV-sr/electron)
Photon Energy (MeV)
0
40
80
120
160
200
0.00
0.20
0.40
0.60
0.80
0
10
20
30

Experimental cross sections for photofission of ^{235}U for photon energies to 30 MeV. The solid line is a smooth curve through Livermore data and the plus signs are data from the Institut Kernphysik. The dashed line is the (c,n) cross section for lead .


600
400
200
0
5
10
15
20
25
30
Cross Section (mb)
Photon Energy (MeV)

Experimental cross sections for photo"ssion of ^{238}U for photon energies to 30 MeV. The solid line is a smooth curve through Livermore data and the plus signs are data from the Institut Kernphysik.


Cross Section (mb)
0
40
80
120
160
200
5
10
15
20
25
30
Photon Energy (MeV)

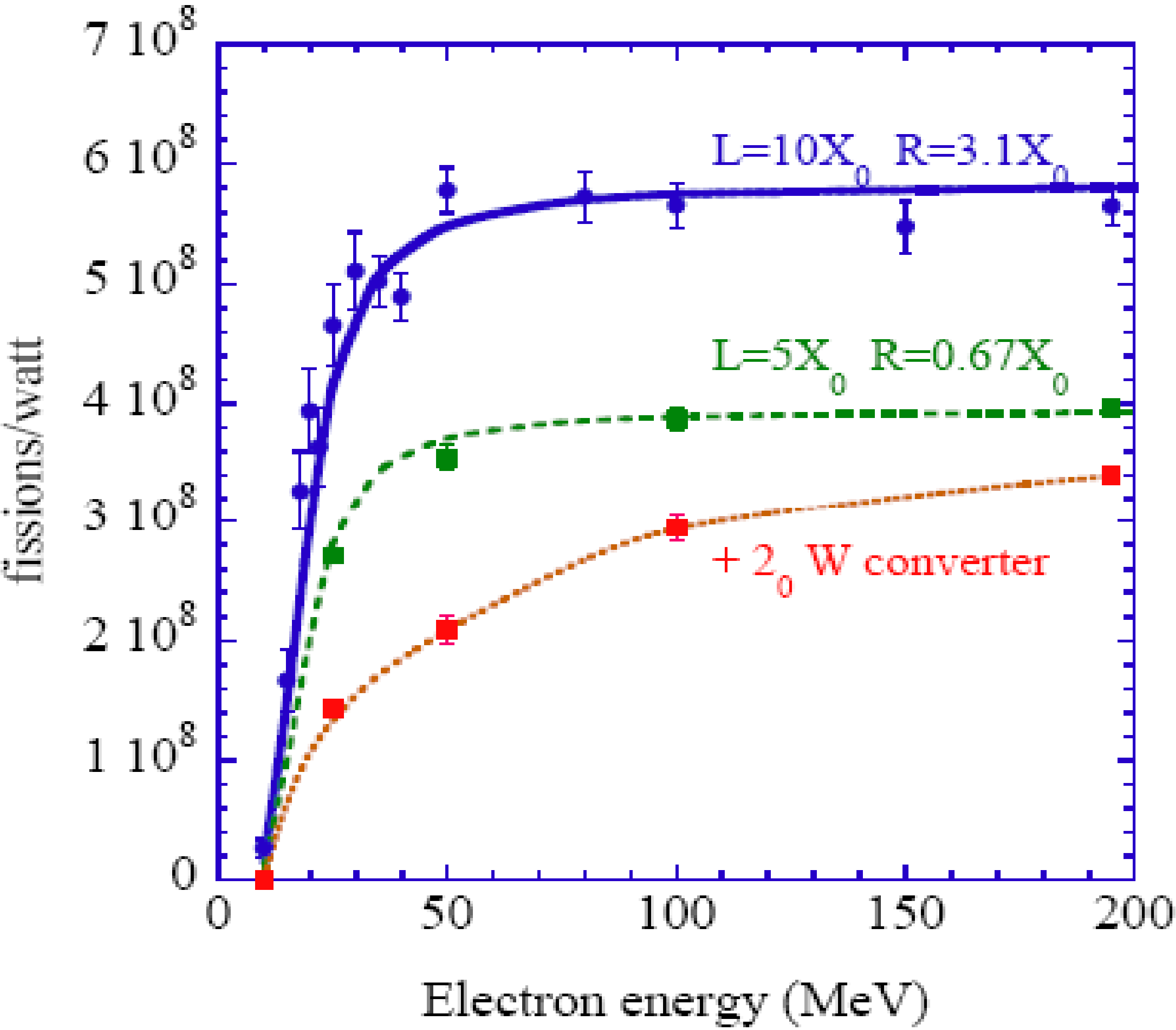

10^{-2}
10^{-3}
10^{-4}
10^{-5}
Yield (fission per electron)
0
10
20
30
40
50
Electron energy (MeV)

Fission rates for electron beam induced photo fission of ^{238}U for three different configurations.

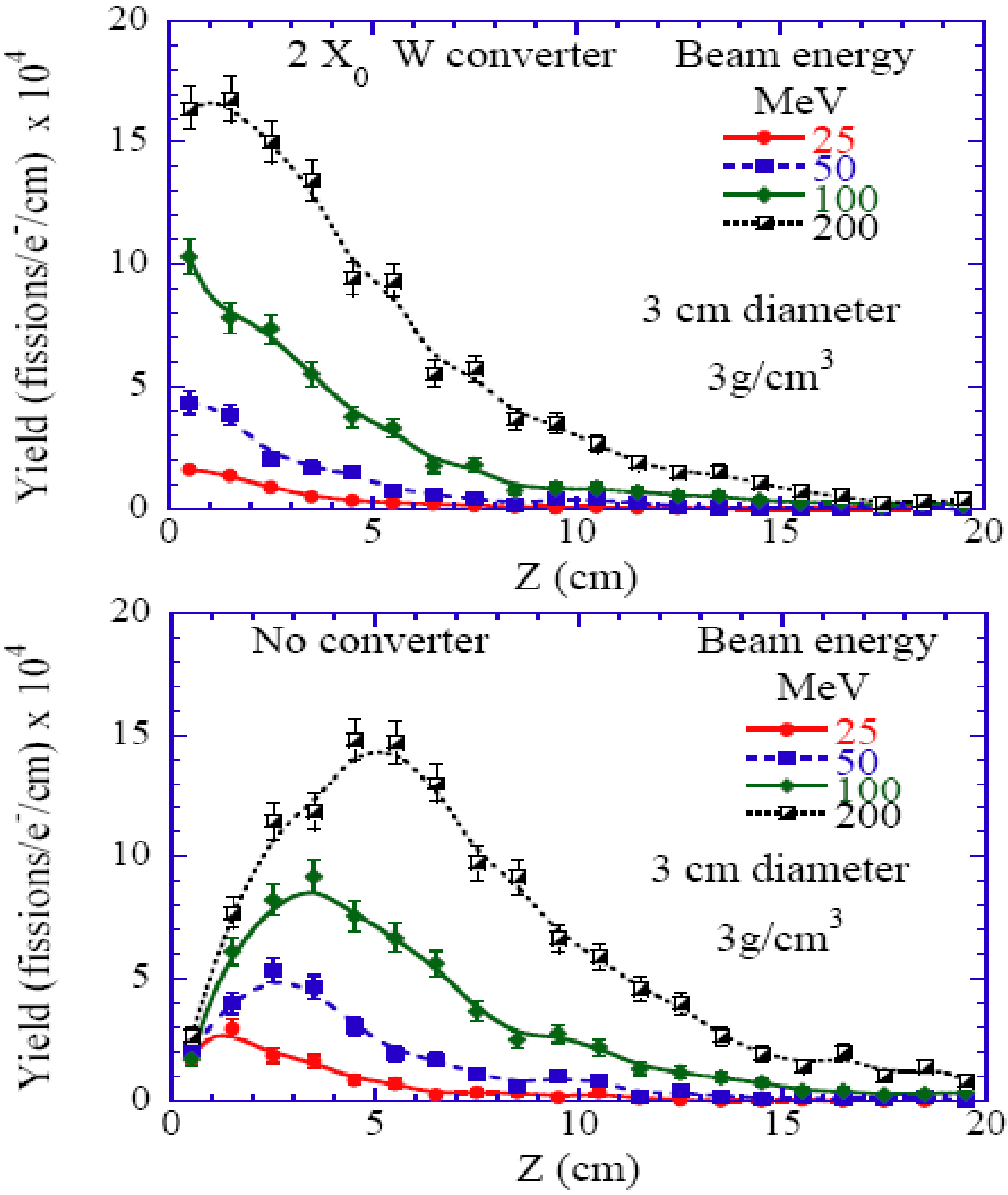
1. a cylindrical target 10 radiation lengths (X_0) long by 6.2 X_0 in diameter.

2. a cylindrical target $5X_0$ long by 1.34 X_0 in diameter.

3. same as 2 but with a $2X_0$ thick W disk positioned in front of the target, serving as a converter. X_0 for U is 6 g/cm^2, and for W is 6.8 g/cm^2.

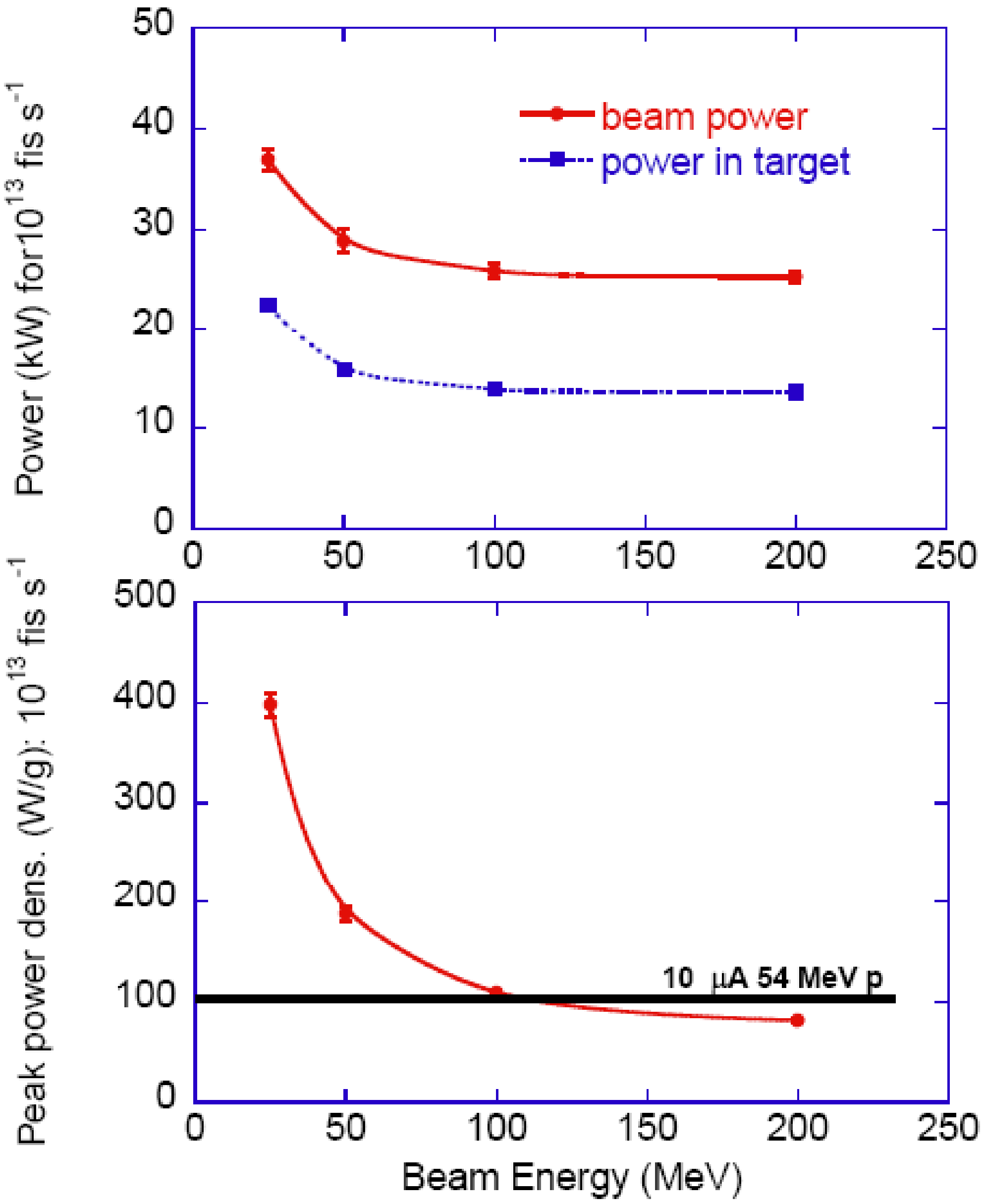

L=10X0 R=3.1X0
L=5X0 R=0.67X0
+ 2 0 W converter
fissions/watt
Electron energy (MeV)
7 10^8
6 10^8
5 10^8
4 10^8
3 10^8
2 10^8
1 10^8
0
0
50
100
150
200

Depth distribution of electron beam induced photo-fission events in a cylindrical target 3 cm in diameter and 20 cm long made of 3 g/cm^3 UC_4.

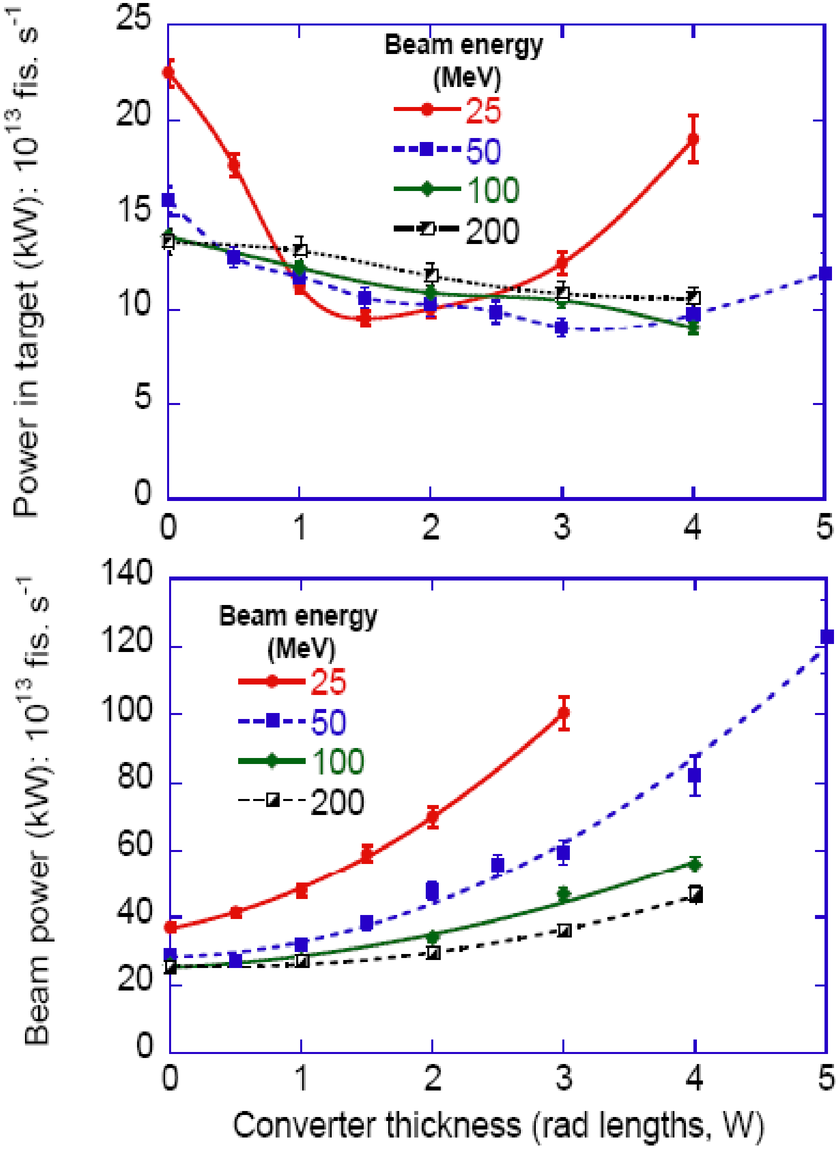

2 X$_0$ W converter
Beam energy MeV
25
50
100
200
3 cm diameter
3g/cm^3
Yield (fissions/e$^-$/cm) x 10^4
Z (cm)
0
5
10
15
20
No converter
Beam energy MeV
25
50
100
200
3 cm diameter
3g/cm^3
Yield (fissions/e$^-$/cm) x 10^4
Z (cm)
0
5
10
15
20

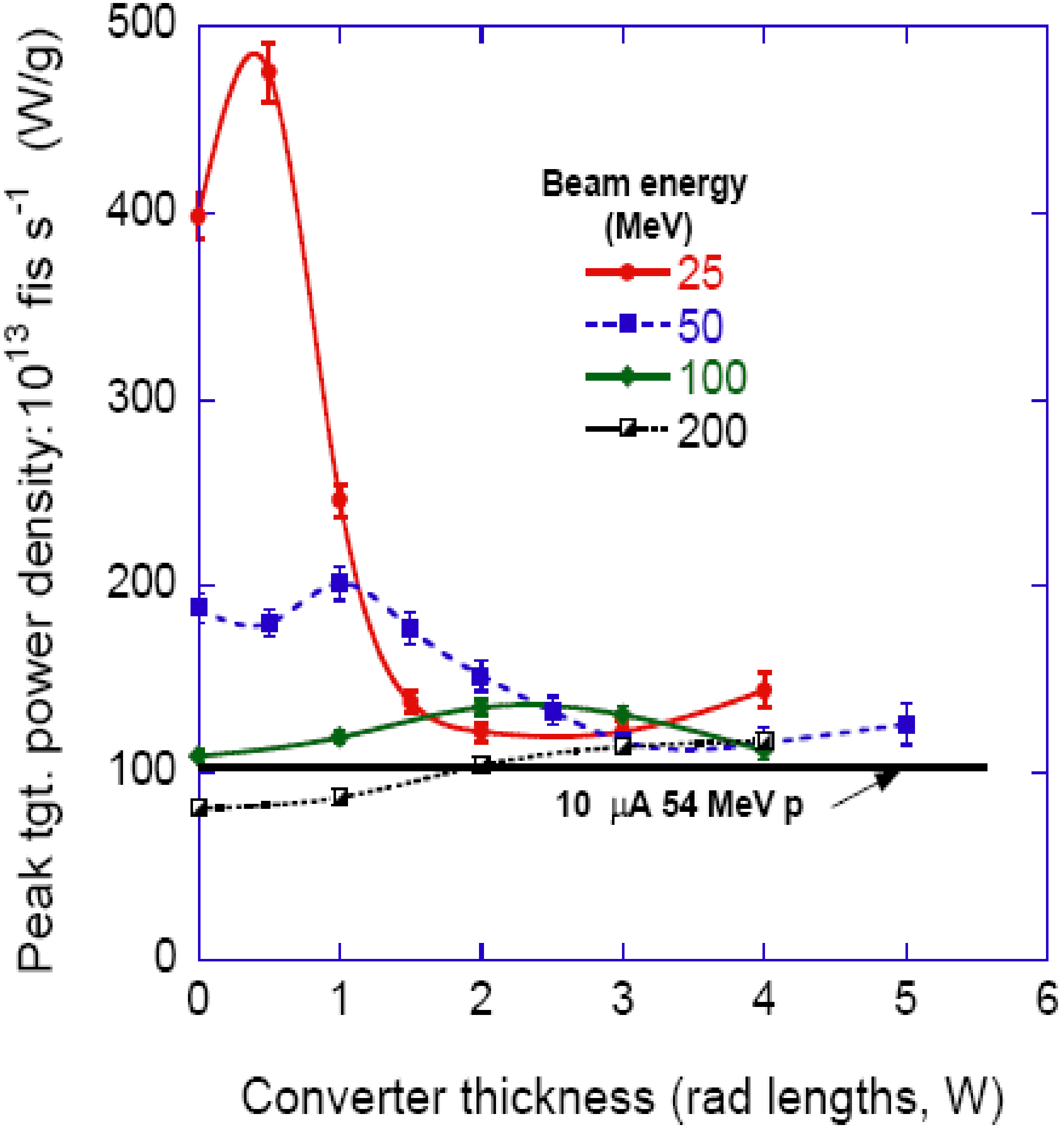
Beam power and target power deposition effects as a function of electron-beam energy. The electron beam intensity is adjusted to produce 10^{13} f/s.

The target is the standard 5 X_0 long by 1.34X_0 diameter 3 g/cm^3 UC_4.

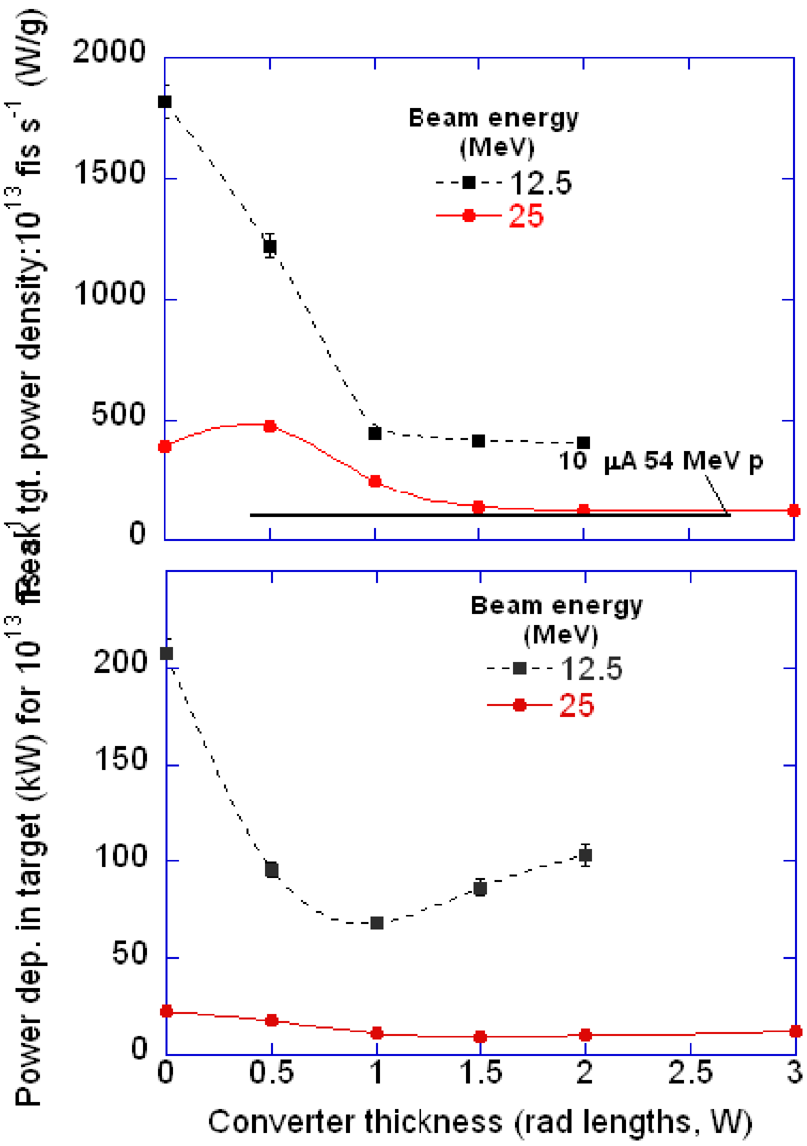

Power (kW) for10^{13} fis s^{-1}
beam power
power in target
50
40
30
20
10
0
0
50
100
150
200
250
Peak power dens. (W/g): 10^{13} fis s^{-1}
500
400
300
200
100
0
10 µA 54 MeV p
0
50
100
150
200
250
Beam Energy (MeV)

The effect of W converter material on beam power requirements and power deposition in targets. The target is the standard 5 X_0 long by 1.34 X_0 diameter 3 g/cm^3 UC_4.


Power in target (kW): 10^{13} fis. s^{-1}
Beam energy (MeV)
25
50
100
200
0
5
10
15
20
25
0
1
2
3
4
5
Beam power (kW): 10^{13} fis. s^{-1}
Beam energy (MeV)
25
50
100
200
0
20
40
60
80
100
120
140
0
1
2
3
4
5
Converter thickness (rad lengths, W)


Peak tgt. power density: 10^{13} fis s^{-1} (W/g)
500
400
300
200
100
0
0
1
2
3
4
5
6
Converter thickness (rad lengths, W)
Beam energy (MeV)
25
50
100
200
10 µA 54 MeV p

For the energies 25 MeV and higher, the power and maximum power density deposited in the target are roughly equal for a fixed fission rate. This is not true for 12.5 MeV. The power deposited to reach 10^{13} f/s remains a factor of 5 larger than for higher energy beams, even with an optimal converter.


Peak tgt. power density:10^13 fis s^-1 (W/g)
2000
1500
1000
500
0
Beam energy (MeV)
12.5
25
10 μA 54 MeV p
Power dep. in target (kW) for 10^13 fis s^-1
200
150
100
50
0
Beam energy (MeV)
12.5
25
0
0.5
1
1.5
2
2.5
3
Converter thickness (rad lengths, W)

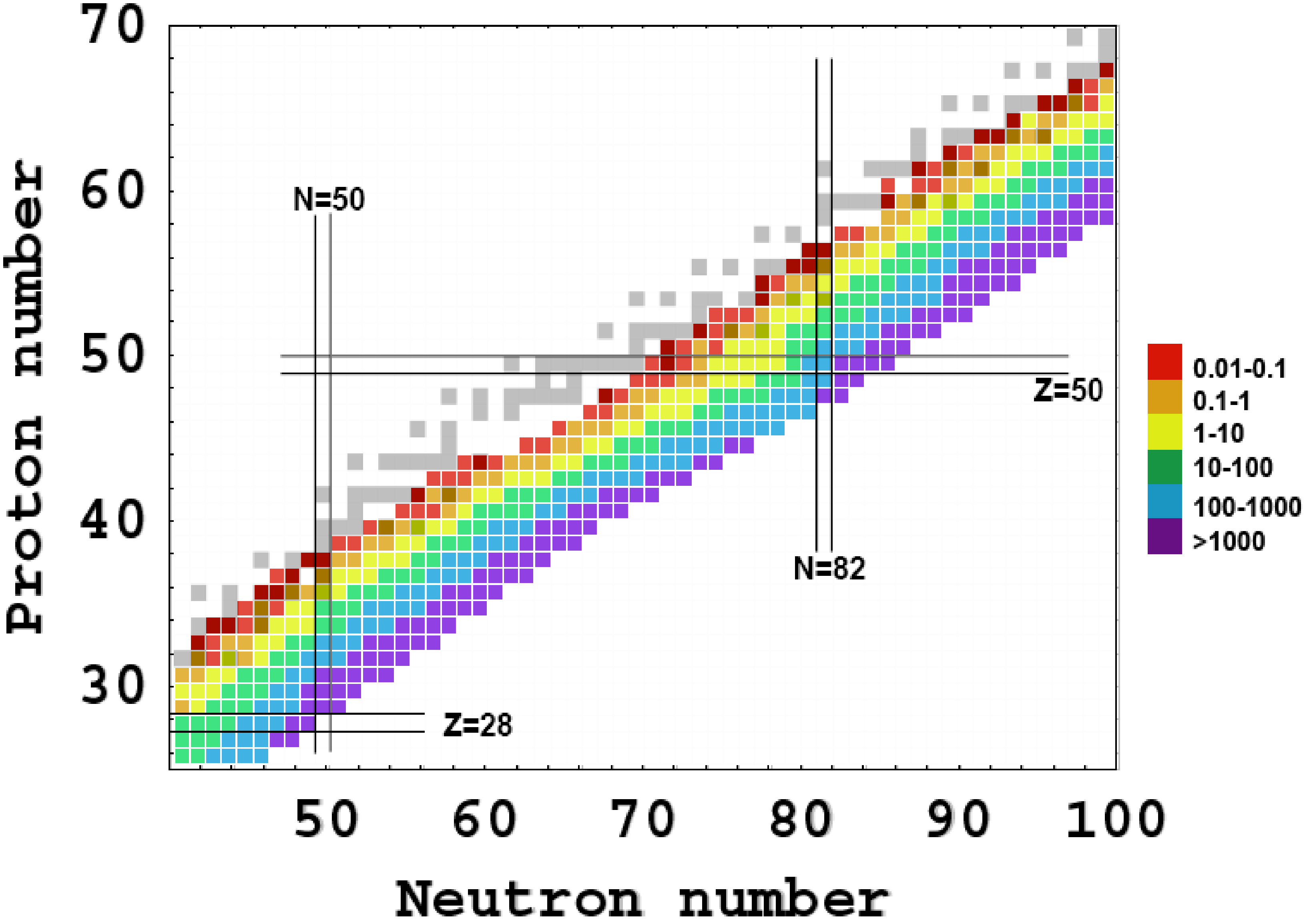
The Driver Accelerator

The photofission yield is given by the integral of the photofission cross section and the number of Bremsstrahlung photons of a given energy, over the total energy range of the photofission cross section or the Bremsstrahlung energies if they peak at below about 30 MeV. This results in saturation in the yield per kW of electron beam power of both photoneutrons and photofission for electron energies above about 50 MeV.

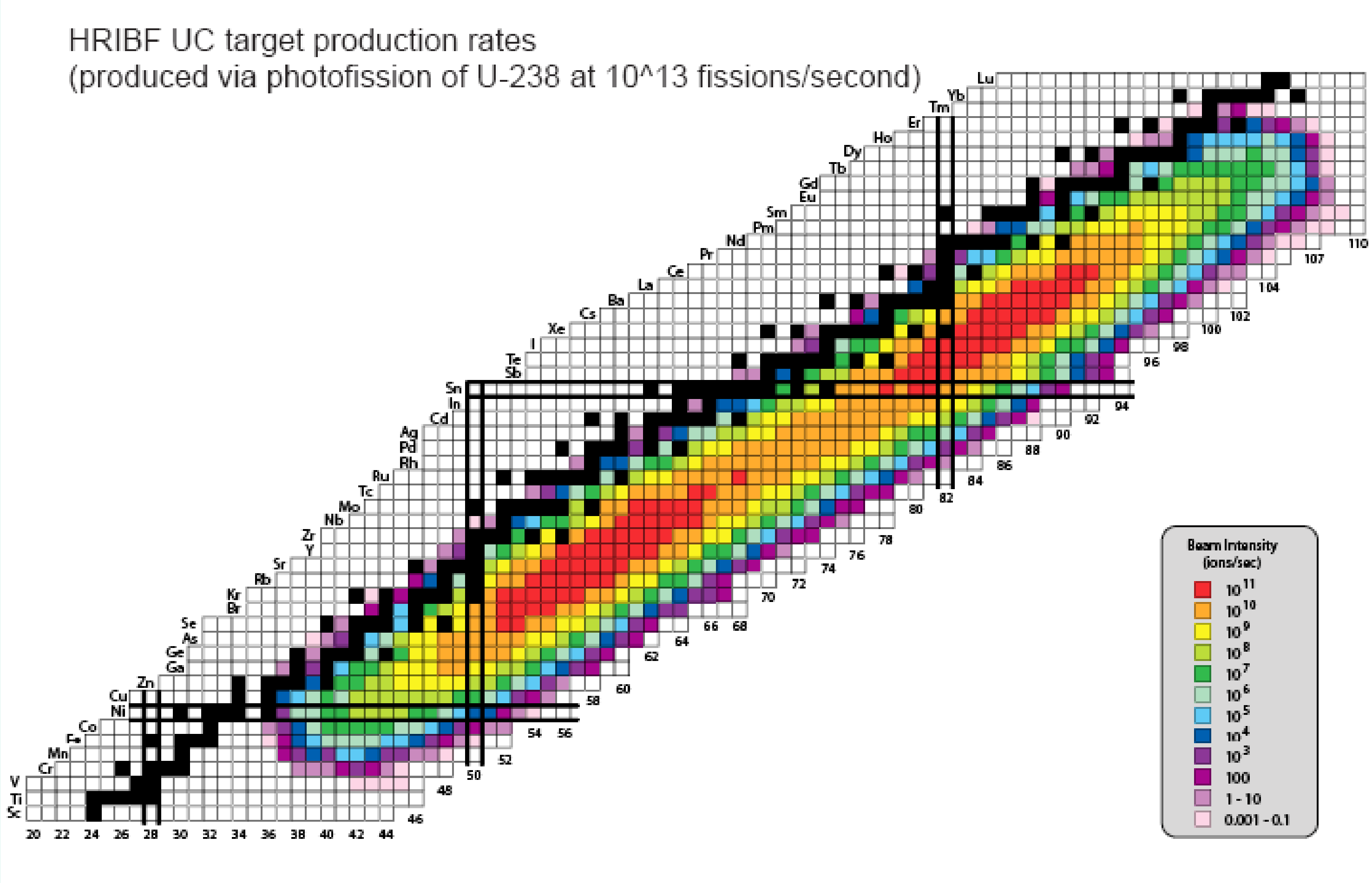
The saturation in yield for electron energies around 50 MeV. Because of this, a driver accelerator for the proposed upgrade can be any electron accelerator capable of at least 25 MeV electrons and beam powers of about 50 to 70 kW.

The ratio of the production rate of neutron rich species by thick target bremsstrahlung from 50 MeV electrons to that produced by 40 MeV proton bombardment. The isotopes are produced by fission of ^{238}U. For the electron-induced photo-fission, the beam power is adjusted to achieve 10^{13} f/s (~28 kW of 50 MeV e^- with no converter). The proton-induced fission rate is ~$5x10^{11}$, corresponding to 10 μA of 40 MeV p on ^{238}U.

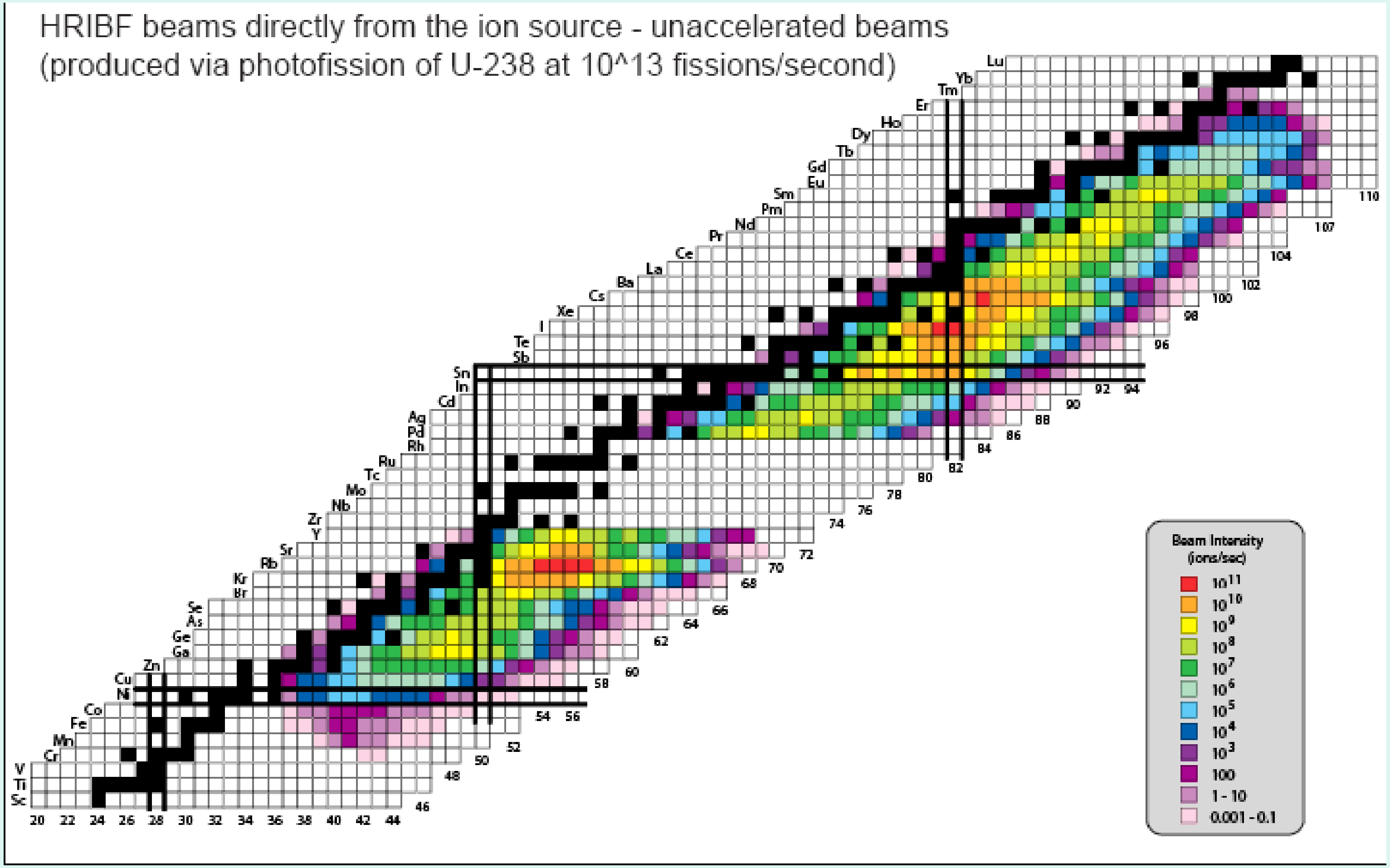
The increase in fission rate above present HRIBF practice is about a factor of 25. The corresponding increase in production of the most neutron-rich radioactive species is much more than a factor of 25. This is because photo fission is a much “cooler” process – i.e., occurs at lower excitation energy and consequently results in smaller number of neutrons being evaporated both from the compound system before fission and from the fission fragments.


70
60
50
40
30
Proton number
N=50
N=82
Z=50
Z=28
50
60
70
80
90
100
Neutron number
0.01-0.1
0.1-1
1-10
10-100
100-1000
>1000

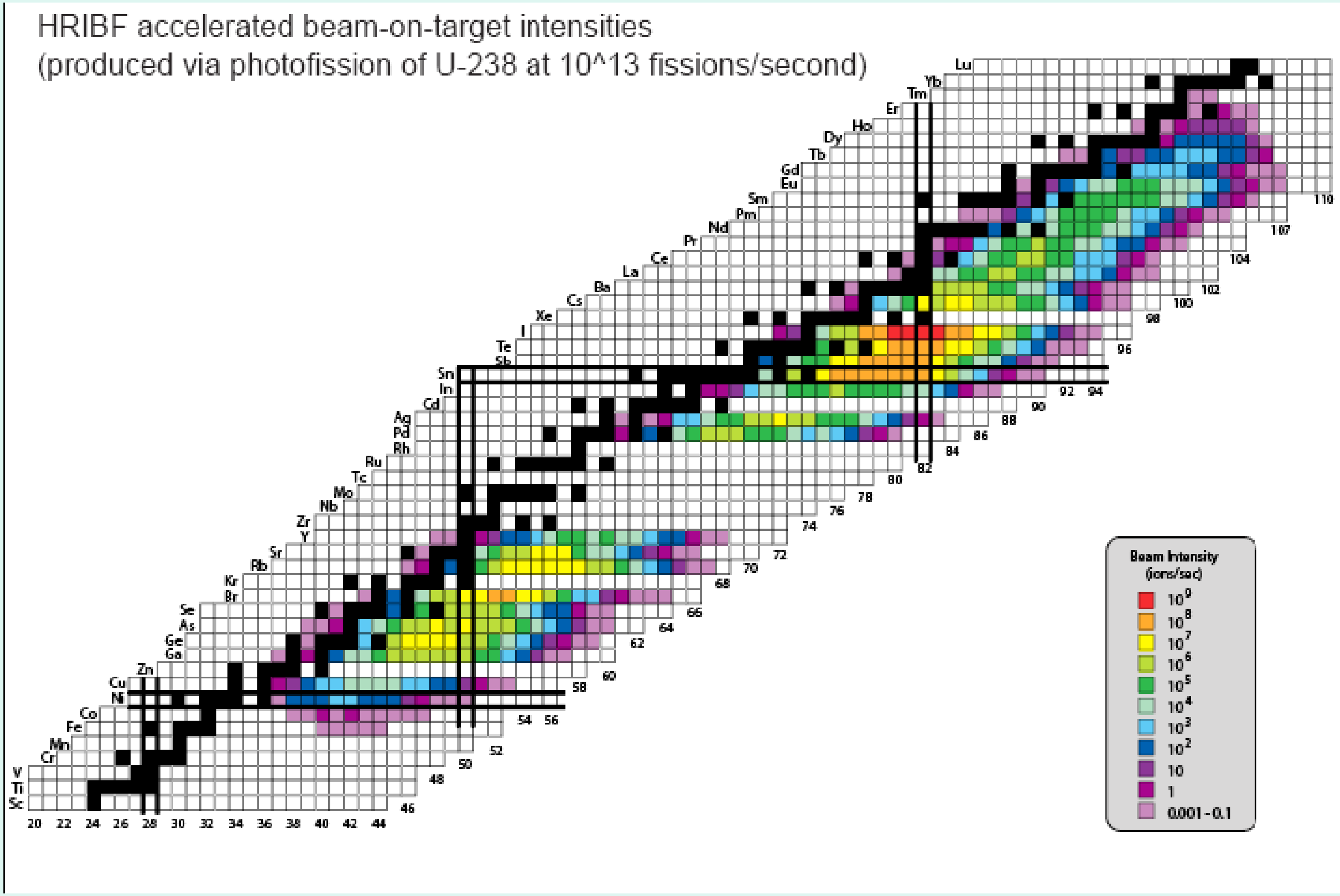
In-target production rates for a total photo-fission rate of 10^{13} /s.

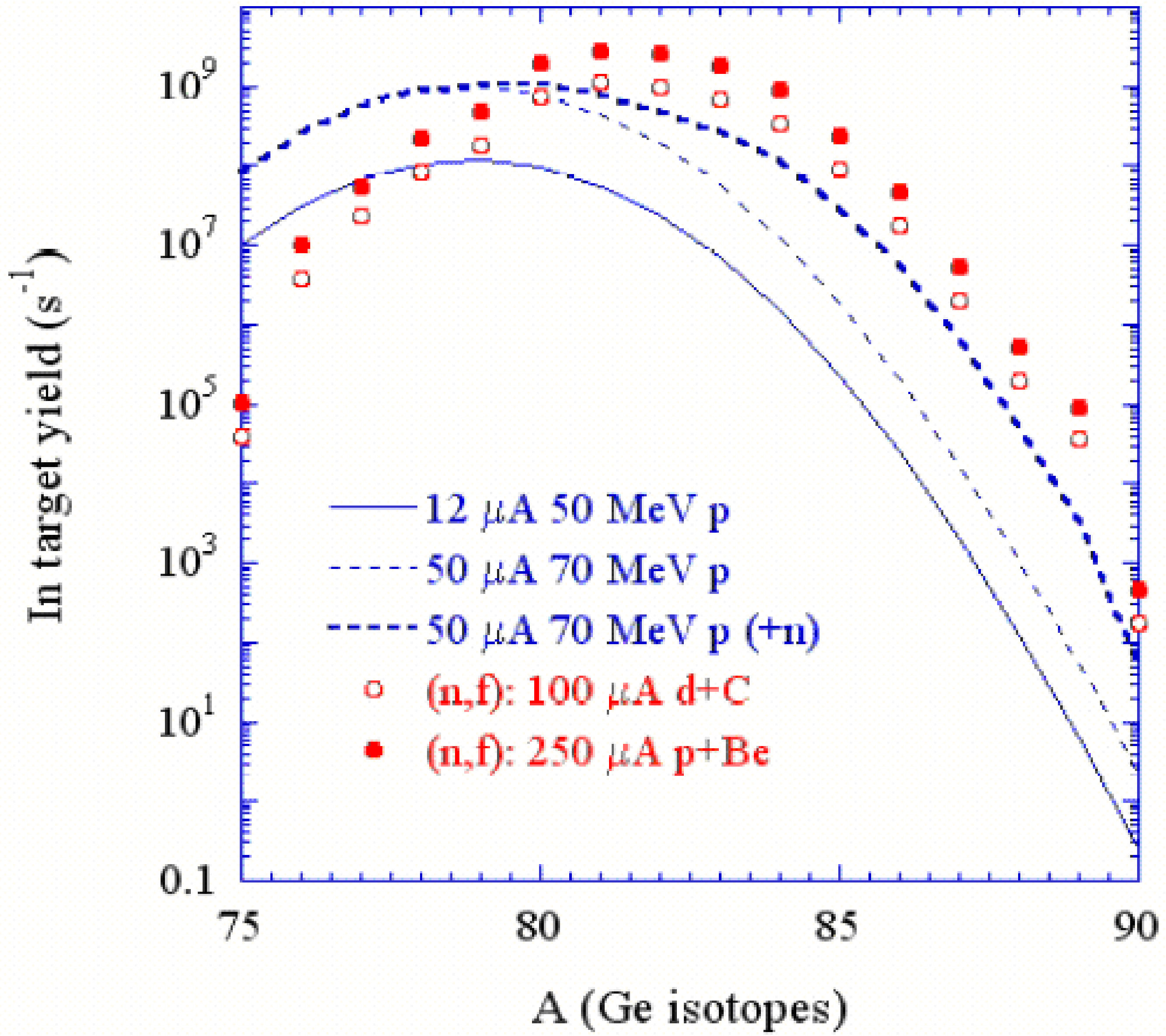


Estimated low energy RIB intensities from a photo-fission facility at 10^{13} f/s.

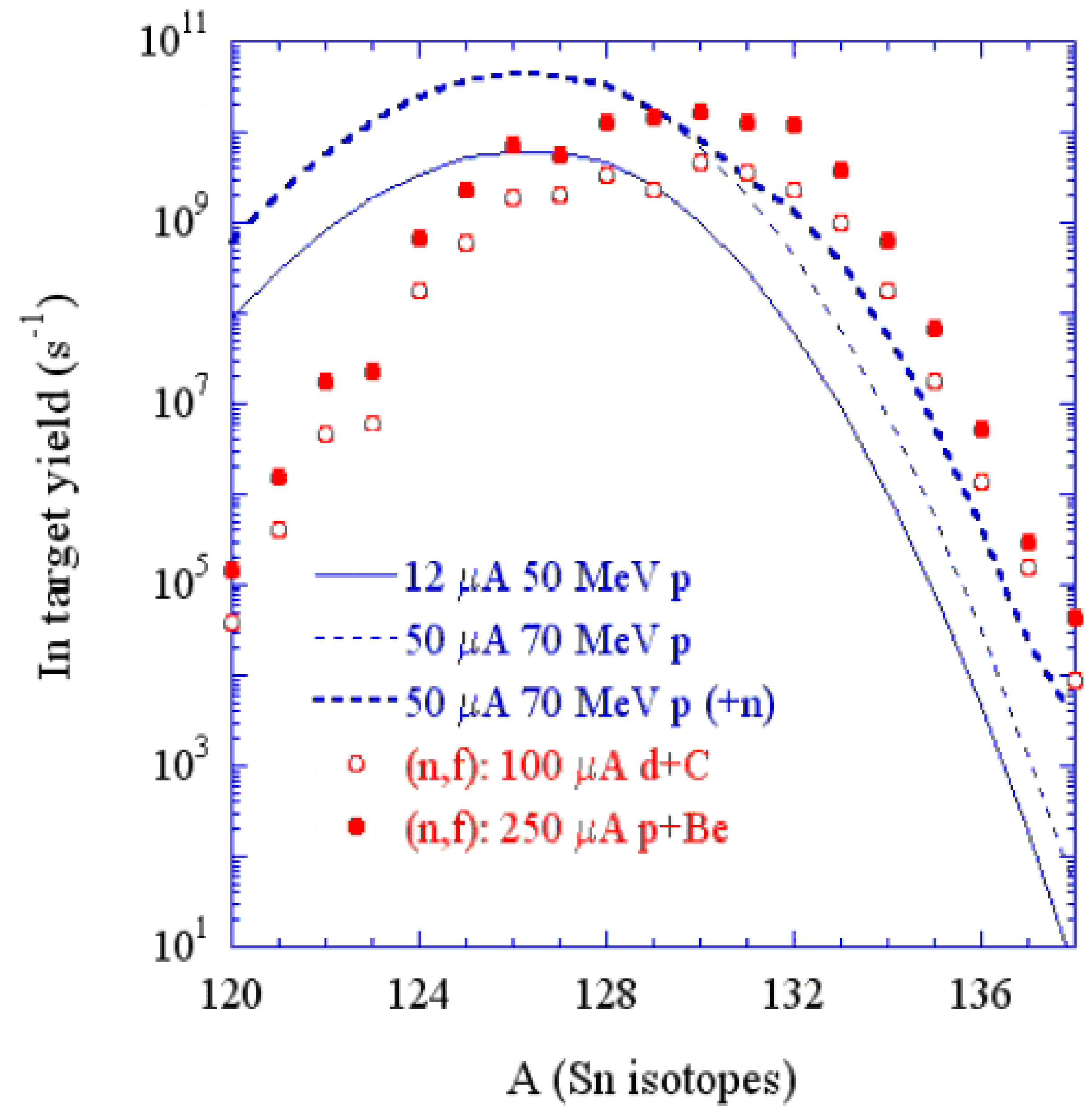


Post –accelerated beam-on-target yields from a photo-fission driver operating at 10^{13} f/s.





In target yield (s^{-1})
0.1
10^1
10^3
10^5
10^7
10^9
75
80
85
90
A (Ge isotopes)
12 µA 50 MeV p
50 µA 70 MeV p
50 µA 70 MeV p (+n)
○ (n,f): 100 µA d+C
● (n,f): 250 µA p+Be


10^11
10^9
10^7
10^5
10^3
10^1
In target yield (s^-1)
120
124
128
132
136
A (Sn isotopes)
12 µA 50 MeV p
50 µA 70 MeV p
50 µA 70 MeV p (+n)
(n,f): 100 µA d+C
(n,f): 250 µA p+Be

The basic conclusions are:

1) Photo-fission rates of 10^{13} f/s can be achieved with beam power ~50kW (Ee = 25-50 MeV), and without assuming significant improvements in target technology.

2) Photo fission rates of 10^{13} f/s correspond to improvements of very n-rich beam intensities in the range 10^{2}-10^{4} compared to present HRIBF performance.

3) Significant issues of the Target Ion Source (TIS) system design and radioactive materials handling remain to be addressed, but no technical breakthroughs are required to achieve the results listed here.

4) **High power (~100kW) electron beams of energy 25-50 MeV are the most cost effective path for making several order of magnitude improvements in intensities of very neutron-rich beams at HRIBF.**

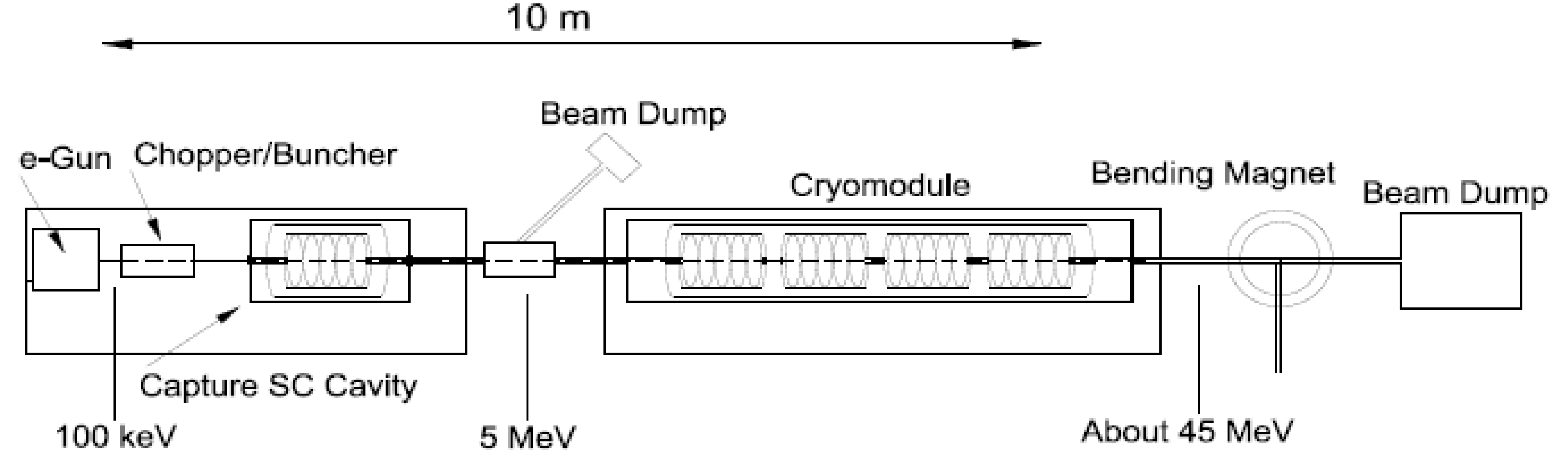
5) Shielding of the production area, and developing target installation and removal technology and protocols for a photo-fission based upgrade of HRIBF are a significant challenge and are addressed, at least conceptually, in the next sections.

6) Going significantly beyond the mid 10^{13} f/s scale is probably not practical with electron-driven facilities, but such rates can be achieved with facilities based on secondary neutron induced fission. Such facilities are very expensive compared to an electron-driven facility.

Electron Linacs

Non-superconducting options exist from commercial manufacturers such as Accel. Although they can provide a 50MeV, 200mA turnkey linac for around $5M, the beam is pulsed and less desirable than a CW machine which would reduce of thermal stresses in the RIB targets. Superconducting near-CW commercial linacs can also be obtained, but for a much higher price.

There have been several proposals from existing accelerator facilities for superconducting electron linacs that can reach between 40 and 50 MeV with the required beam power. The GANIL proposal for the electron beam option for SPIRAL II had done a conceptual design of a 45 MeV linac. The beam current required for 60 kW is less than 1.5 mA and should be readily obtained. The GANIL proposal estimated that this would cost about €6M plus the cost of the personnel to complete the development.


10 m
Beam Dump
e-Gun
Chopper/Buncher
Cryomodule
Bending Magnet
Beam Dump
Capture SC Cavity
100 keV
5 MeV
About 45 MeV

Superconducting: The superconducting cavity. is included in the main cryostat with the main accelerator cavities to both save length and cost. The electron gun is a laser-driven photocathode gun. This proposal is for a very high current design for a free electron laser. Thomas Jefferson Laboratories has produced a similar design aimed at a 50 MeV, 1.2 mA electron beam. The estimate of the cost of that linac was less than $7M, plus the cost of the cryogenics.

Compact 50 MeV superconducting electron linac proposed. It uses a capture section cavity as part of the cryogenic cavities, in the same cryostat as the main cavities and a photocathode electron gun. These changes would reduce the length and some associated costs such as building costs.

One of the important aspects of the proposed approach of using an electron accelerator as the new driver is that it is not a significant technical development to deliver the required electron-beam energy and power to produce 10^{13} f/s in a conversion target. The cost of any of the potential electron-driver accelerators is roughly the same (around $10 M). This is significantly lower than a cyclotron or deuteron linac that could produce comparable fission yields.

The preferred approach is to use the Rhodotron accelerators. They have already been designed for simplicity of operation in an industrial environment.The designs of the superconducting linac are proposed by researchers at laboratory with strong technical support in the technology.

Because of the preference for the Rhodotron accelerator, the layouts of the facility and the converter target and ion source have been developed around a Rhodotron driver. However, the 45 MeV linac proposed for the SPIRAL II project has also been tested in the proposed layout.

It has been demonstrated that a facility based on relatively high power (30 to 100 kW) electron beams in the energy range 25-50 MeV can be used to induce fission in a modest-sized UC4 target at a rate in excess of 1013 f/s.. The electron-induced fission option is almost certainly the most cost effective way to reach 1013 f/s using a sufficiently cold process to populate the most neutron-rich species effectively. This is largely because the required electron accelerators are comparatively cheap and small.

ISAC-II at TRIUMF will probably be capable of producing fission rates up to ~ 5 x 10^{13} f/s using direct bombardment with 100 µA beams of 500 MeV protons on of 30g/cm^3 thick UC4 targets. The 500 MeV proton beam at TRIUMF is capable of substantial production of low energy neutrons by spallation, and hence of “cold” two-step fission. Preliminary estimates suggest a maximum rate less than ~10^{13}.

The distribution of final fission products produced by photo-fission of ^{238}U is very favorable (i.e. shifted to greater neutron numbers) compared to proton-induced fission. The distribution is very similar to that produced by neutrons of energy ~15 MeV incident on ^{238}U. Lower energy neutrons (~ few MeV) produce a distribution of products shifted somewhat more toward neutron excess and with a stronger suppression of symmetric fission. The latter effect leads to a reduced yield of elements with atomic number in the range 43 to 49, as well as an order of magnitude suppression of elements with $Z > 60$ or $Z < 30$.

An accelerator capable of producing 5 mA beams of 40 MeV deuterons is planned for Spiral II at GANIL. This facility is designed to be capable of rates up to 10^{14} f/s. The target proposed for achieving 10^{14} f/s is made of a large number of normal density (11 g/cm^3) UC_2 disks, each ~1 mm thick and 14 mm diameter. These disks are stacked together to form a composite cylindrical target 8 cm long by 7.5 cm in diameter, with a total mass of 5.1 kg. GANIL design, ~500 µA (20 kW) is required to reach 10^{13} f/s, and 5000 µA (200 kW) required for 10^{14} f/s..

Another method of producing neutrons for inducing fission is by spallation in heavy targets (e.g. Hg) using beams of 1 GeV protons. For very large targets (60 cm x 16 cm) large neutron yields up to 30 neutrons per proton can be achieved.. The U target mass could range from 30 kg to more than 100 kg, depending upon the configuration. Such a system should achieve fission rates of ~ 10^{15} f/s using MW scale 1 GeV proton beams,