ADS prospects and requirements

A brief review of the present status and future possible developments for Accelerator Driven Reactors, of the requirements for the accelerator, and whether these can be met by a cyclotron or an FFA

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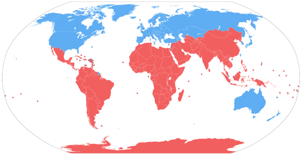
A Nuclear Future?

Good news: the need to stop using fossil fuels is now acknowledged politically. Lots of greenwash, but core argument accepted. Climate-change deniers are as extinct as flat-earthers.

But no sign of reduction in energy use, either in personal behaviour or politically. People want clean energy, not less energy. Clean fuels are needed to replace fossil fuels.

Developing world population aspire to developed world standard of living from 0.7 kW/person (India) to 8.4 kW/person (US). Clean fuels will have to provide many times current energy use

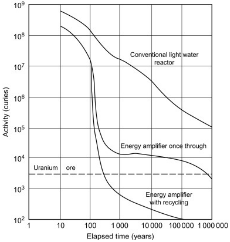


Renewables have a lot of scope for expansion - but very hard to see how this could fill the gap That means new nuclear power - and there are signs that this is beginning to happen

ADS in the nuclear future

Two possible roles

The Waste Issue



Radiotoxic for millennia due to Minor Actinides (MAs). Volumes small, but geological disposal tough politically. ADS fast neutrons cause MAs to fission (incineration). Fission products have shorter lifetimes. Envisage reactor parks of several PWRs whose spent fuel has its MAs incinerated in an ADS.

The Fuel Issue

If nuclear power does expand, current once-through system burning fissile $^{235}\mathrm{U}$ will not be efficient enough, and fertile $^{238}\mathrm{U}$ and $^{232}\mathrm{Th}$ will need to be brought into the cycle through fast breeder reactors

ADS can breed fertile to fissile fuel: $^{238}\mathrm{U} \rightarrow$ Pu or $^{232}\mathrm{Th} \rightarrow {}^{233}\mathrm{U}$. Fuel rods have useful lives of years rather than months.

Why ADS anyway?

"A reactor needs an accelerator like a fish needs a bicycle"

Safety - 'big red button'

But modern reactors can be switched off

Need extra neutrons for breeding

But the number of extra neutrons from spallation is small (2%-5%)

Need fast neutrons from spallation

But fission neutrons are fast.

Need high neutron flux to burn MAs

But high flux conventional reactors are possible

Why ADS anyway?

Continued

Lack of delayed neutrons

The fraction of delayed neutrons from MA fission is small, making control using rods harder as response times get too fast. This is (only) significant for systems with very high ($\sim 30\%$) MA content, perhaps like the proposed MA incinerator.

Neutron flux couples breeding and power

Breeding with intermediate $^{233}\mathrm{Pa}$ state gives time-lagged feedback in power, making reactor impossible to control.
(See R B, "Do thorium reactors need an accelerator", Proc. AccApp15 (2015))

Accelerator requirements for ADS

Assuming protons. Other options suggested but not much developed.

Energy $\sim$ 1 GeV

Low energies give few neutrons: at high energies the rate is linear

Current $\sim$ 10 mA

Assuming $k_{eff} \sim 0.95$ and power $\sim 1 GW_{th}$

High reliability

Short trips give temperature changes and weaken components
Long trips cause power outages and lose money (possibly lots of money)

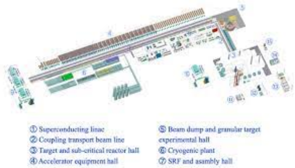
Cost not too high

Though there's no such thing as a cheap accelerator

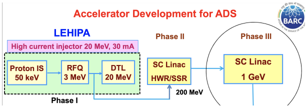
ADS projects

Belgium: MYRRHA @ SCK·CEN
600 MeV 4 mA linac, 400 m long
In progress: 100 MeV by 2026, 600 MeV by 2033, completed and commissioned 2036
€558 M of €1.6Bn cost committed

China: ADANES @Huizhou, Guangdong
500 MeV 5 mA in 2025,
then 1 GeV 15 mA by 2032
(as of 2019: Wenlong Zhan @ JPARC Symposium and Yuan He @ IPAC19)



India. BARC
In 2009: propose 250 MeV, 5 mA cyclotron
Now 1 GeV Linac. (PIP-II, 800 MeV, 2mA)
Plan to breed from thorium (they have lots)
(from P Singh, CERN workshop, 2017)



Linacs not cyclotrons

The ADS programme is moving forward (slowly) - and it's doing so with Linacs
LIkewise: SNS and ESS are using Linacs to make their spallation neutrons

Why? PSI's 590 MeV 2.2 mA is not far from 1 GeV 10 mA goal.
Do we say: just tweak the design parameters a bit and you're there, going further will be easy
Or: this is the best performance after many years of experience and going further will be hard.

Linacs can deliver the required current and energy.
Cyclotrons and FFAs can only do so on paper and the case needs to be convincingly made.

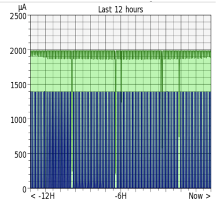
Reliability

How many trips would be acceptable?

Original statement, based on fast reactor experience: < 3/year
More recent studies: 25,000 short (< 1 sec), 2500 medium (1 - 10 sec) , 2500 long (10 sec - 5 min) per year

E Pitcher and S Henderson: Report from the DOE ADS White Paper Working Group

Much more than today's proton accelerators
PSI status nowadays visible on
`http://gfa-status.web.psi.ch/hipa-info.html`
Challenging but not impossible



Reliability is a science

Known techniques: Under-rating components. Parallelism. Graceful failure. Regular maintenance

Proton Accelerators today are built as new technology, and continuously modified. Reliability is not a top consideration. But it could be.

The Reliability Frontier

An accelerator is very complicated.
So is an aeroplane
Aeroplanes are reliable. Because they are made that way.

We have learnt a lot from honest analysis of real machines

- High voltages can lead to breakdown. RF trips are a problem
- High powers $\rightarrow$ overheating $\rightarrow$ distortions
- Ion sources are temperamental and need frequent renewal
- Radiation makes hoses and cables brittle and they need to be replaced
- Superconducting technology adds hours to repair times
- ...

More to go wrong in a LINAC – and more scope for recovery

Cost

LINACs are inevitably expensive: hundreds of metres long and every metre full of SC-RF, quadrupoles, and other expensive hardware.

Cyclotrons and FFAs have a much smaller footprint and will cost less than LINACs even though they also include the dipole magnet(s).

Synchrotrons should be cheaper again as the magnetic volume is much smaller.

But even a linac is not the main cost of an ADSR. The reactor, fuel handling, and power generation equipment will be more expensive.
Sizewell C cost £18Bn (2 reactors, 3.2 GW_e total)
ESS cost €1.8 Bn

Looking forward

If we phase out fossil fuels

  If nuclear power is part of the replacement

    If we can't bury the MA waste, or if thorium is needed as a fuel

    Then we're going to need a lot of ADS reactors

These will be built with linacs
unless we develop a cyclic accelerator with the required energy (~ 1 GeV) and current (~ 10 mA)
If we can do so - see François and Luciano's talks - it should be possible to make them cheaper and more reliable than a linac
The cost+complexity+reliability of the accelerator is not holding up the ADS program.

Conclusion

	1 GeV	$\sim$10 mA	Low cost
Cyclotron	No	Yes	Yes
Synchrotron	Yes	No	Yes
LINAC	Yes	Yes	No
FFA	Yes	Yes	Yes

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Conclusion

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LINAC	Yes	Yes	No	Yes
FFA	Yes	Yes	Yes	No

If we can build a 1 GeV 10 mA cyclic accelerator, that's not the breakthrough the ADS is waiting for - but if the ADS programme gets going, it will provide a market for such an accelerator.

"Ask not what you can do for the ADS, ask what the ADS can do for you"