# AUSTRON - a Spallation Neutron Source for Central and Eastern Europe

Presented by
H. Schönauer, CERN, CH-1211 Geneva 23

With contributions from
H. Aiginger, W.H. Breunlich, P.J. Bryant, K. Hübner,
W. Pirkl, M. Regler, G.H. Rees, K. Schindl, A.Wrulich

## Introduction

A medium-sized spallation neutron source was initially promoted by the "Central European Initiative" (CEI) as a promising venture for the central and eastern part of Europe. At a workshop held at CERN in fall 1991 potential users and accelerator specialists evaluated a machine configuration matching both the user requirements as formulated there and budget constraints. This machine, which could be located in the eastern part of Austria, has tentatively been dubbed the "AUSTRON". Amongst half a dozen scenarios compared, the combination of a 70 Mev $H^-$ Linac with a 1.6 GeV synchrotron yielding 100 kW average beam power in "stage 1" emerged as the most cost-effective solution. It delivers 4 kJ per pulse of $<1$ µs length of 1.6 GeV protons at 25 Hz repetition frequency. "Stage 2" foresees the addition of a second ring; this would be used either to double the beam power, or, operating as a storage ring, to double the energy per pulse at half the repetition rate or to modify the time structure of the proton beam.

A fairly modest additional investment will enable the AUSTRON to accelerate light ions (up to Ne) to some hundreds of MeV/nucleon for medical research. The proposed configuration and the options for stage 2 are presented, as well as the most recent evolution of the project after a meeting on AUSTRON held in Vienna in May 1993.

Recently, the Austrian Government has agreed to assure one third of the estimated construction cost (January 1992 prices) of ATS 3 Billions ($ 265 M) of the AUSTRON, if the remaining two thirds will be contributed by other European countries.

## User Requirements

Prior to the meeting at CERN a working group "Scientific Case" chaired by Prof. P. Povinec (Bratislava) had prepared the following priorities, which were reviewed and confirmed :

1. A pulsed spallation neutron source featuring
    - 100 - 200 kW average beam power on target
    - 25 Hz repetition rate
    - $<1$ µs pulse length

    The short pulse length combined with low repetition rate favours time-of-flight measurements, in addition the latter increases the peak neutron flux.

2. Neutrons in the few 100 keV range with a time structure of
    - a few 100 Hz pulse repetition rate
    - a r.m.s. pulse length ~2.5 ns .

3. Independently of the working group, a number of medical institutions expressed strong interest in a parasitic production of light ions with the requirements:

   - light ions up to neon
   - energy up to 400 Mev/nucleon
   - $10^9$ ions/s .

There was general agreement on the principle that the machine design should be conservative to favour a short construction time. This automatically excludes major R & D on novel accelerator concepts, as interesting as they might be, leaving R & D to the instrument designers. The users were well aware of the initiatives in the EC to build a neutron source in the 5 MW range, but it was felt that the rather long planning and construction time of this machine (estimated not to be operating before 2010) ruled out all arguments about competing projects.

## The Machine Configurations Considered

A total of six scenarios was evaluated, which are compiled with their characteristic features in Fig.1. The majority of them are scaled versions of existing machines or projects. So configuration #1 is derived from ISIS by halving the cycle frequency and doubling the energy, configuration #2 is the LAMPF + PSR concept, the FFAG (#5) has been studied at Jülich, Argonne and recently at the Hahn-Meitner Institute. Scenarios #3 and #4 are crossbreeds with elements from ISIS and TRIUMF KAON; the technique of #4 to store four pulses from the 50 Hz synchrotron stems from the CERN PS in its LHC injector role. Scenario #6 is derived from an original idea of C. Rubbia in the context of drivers for inertial fusion.

To tag a price to the different configurations, a rather coarse scaling from the costs of the "parent" machines and projects had to be done. Even so, since the results are quite divergent, some scenarios are ruled out by their cost. This is particularly true for scenario #2, which is the only one thas has an upgrading potential up into the MW beam power zone envisaged by the next machine generation.

As there is no existing FFAG machine, it was felt difficult to produce a cost estimate and to predict the duration of design and commissioning periods. This applies even more to the double-helix machine #6. For this reason both concepts have been excluded from the final choice.

The 5 GeV scenario #3, although competitive in cost, was finally discarded in favour of #1, which features more flexible upgrading options and which would not prohibit acceleration of light ions (as would do the coupled-cavity linac section in stage 2 of #3).

Configuration #4 would be a very desirable machine; unfortunately the price tag and the absence of a straightforward staging approach weigh against it.

## The Proposed Accelerator Complex

Consequently, the final choice was configuration #1, the 1.6 GeV, 25 Hz rapid cycling synchrotron with a circumference of about 200 m and a 70 MeV drift tube linac as injector. It produces a beam pulse consisting of two bunches of 50 ns length each at a distance of 350 ns, i.e. a total pulse length of about 420 ns. It is shown together with the light-ion add-on's in Fig. 2; note however, that the final ion energy should read 400 MeV/nucleon instead of the 250 MeV/nucleon initially proposed. A tentative set of machine parameters is compiled in the Table "AUSTRON Stage 1 Parameter List". The column "First Upgrade" refers to the recommendations of a recent meeting on AUSTRON of which the conclusions are appended to this article.

## Upgrading Options

Fig. 2 also shows three options proposed for a future Stage 2. They are

- **Option 1 :** A second, identical RCS (rapid cycling cyclotron). It would pulse and eject in synchronism with the first. Both mean and peak power are doubled with respect to Stage 1 to 200 kW and 8 kJ/pulse, respectively. The pulse frequency of 25 Hz remains unchanged.
- **Option 2 :** Adding a 1.6 GeV, same circumference storage ring (SR). It could be operated in two ways :
  (i) Every other pulse of the RCS is stored in the SR and ejected together with the following pulse from the RCS. This halves the repetition frequency to 12.5 Hz and doubles the proton energy per pulse. The mean beam power remains unchanged.
  (ii) Every pulse is stored in the SR, debunched and rebunched at a higher harmonic number (h=12 instead of h=2). After shortening the bunches to ~10 ns length, they would be extracted one by one at a rate of 300 Hz. (this operation requires a fixed-frequency RF system of about 17 MHz and a few hundred kV). In this way the time structure required for fast neutron physics can be realized.
- **Option 3 :** Adding a larger machine of 5 GeV, say, slowly cycling at 12.5 Hz and accelerating ~5 μA protons. This option does not improve the neutron spallation yield. However, the secondary beams generatied by 5 GeV protons may represent an attractive regional facility for nuclear physics and related research.

These options are by no means exhaustive. The basic configuration appears flexible and allows many extensions and upgrades. In the light of the recent improvements of ISIS, now producing 160 kW mean beam power in operation, one may even envisage to boost the Stage 1 performance from the beginning.

## Light Ions for Medical Research

The rather unusual option for a spallation neutron source to produce light ions would lead to a considerable enlargement of the users community. This may well balance the loss of the order of five percent of beam time for neutron physics (a typical operational mode would be 1-2 minutes of ion beam production every 30 minutes). The proposed ion species, up to ${}_{20}Ne^{10+}$, all feature a ratio of q/m = 1/2; the energy required is around 400 MeV/nucleon, corresponding to a penetration of $O^{8+}$ ions in water of ca. 20 cm.

The major items to be added to the bare proton accelerator would be (cf. also Fig.2) :

1. A second pre-injector in form of an Electron Cyclotron Resonance (ECR) source and an ion Radio-Frequency Quadrupole (RFQ). Note that the ion travelling speed in the drift tube linac in the "2 $\beta\lambda$" - mode is half of the one of the protons.
2. Upgrading the RF acceleration system of the RCS to a larger frequency swing (cf. Parameter List)
3. Switching magnets and a beam transport line to the medical facility of variable magnetic rigidity, possibly tracking the field cycle of the main accelerator magnets; this applies equally to the extraction kicker and septum.

The extra cost of <100 MATS (<9 M$) (accelerator only) estimated for the ion option is less than that of a dedicated facility; the real savings, however, occurs in operation costs, as they are a fraction (comparable to beam time share) of the operation costs of the neutron source.

## Acknowledgement

The continuous encouragement and support by Prof. M. Regler was of great help and a driving force of the project.

# AUSTRON PARAMETER LIST (Stage 1)

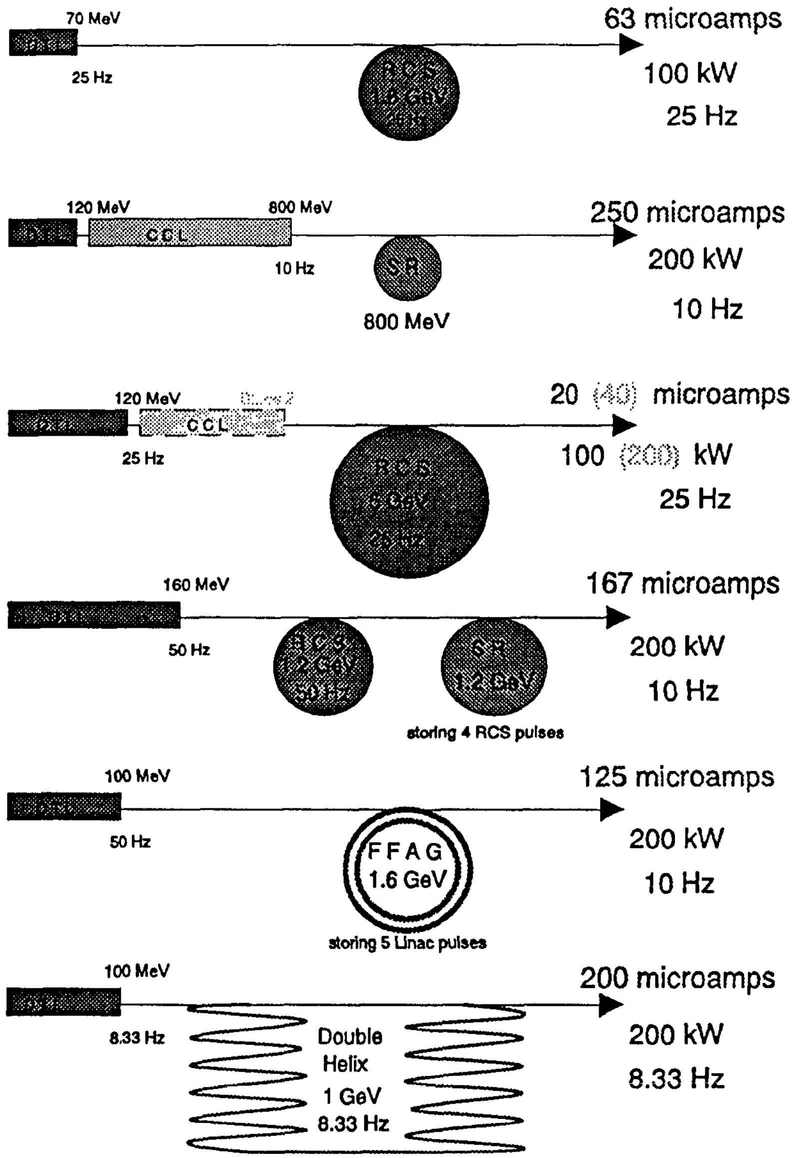
| **Synchrotron** | | | **First Upgrade** | |
|---|---|---|---|---|
| Output energy | 1.6 | GeV | | |
| average current | 63 | μA | 126 | μA |
| repetition rate | 25 | Hz | | |
| beam power | 100 | kW | 200 | kW |
| number of p per pulse | 1.6 $10^{13}$ | | 3.2 $10^{13}$ | p/p |
| transverse emittance (invariant, 86%) | 150 | π μm | 205 | π μm |
| pulse length (2 bunches of 50 ns each, 350 ns spacing) | 420 | ns | | |
| circumference | 200 | m | | |
| injection energy | 70 | MeV | | |
| RF frequency | 1.1 - 2.8 | MHz | 1.43 - 2.8 | MHz |
| peak RF voltage | 170 | kV | | |
| harmonic number | 2 | | | |
| bunch area | 0.5 | eVs | | |

**Injector** (H$^-$ source, R.F. Quadrupole, Drift Tube Linac)

| | | | | |
|---|---|---|---|---|
| Linac output energy | 70 | MeV | 130 | MeV |
| repetition rate | 25 | Hz | | |
| pulse length | ~100 | μs | ~130 | μs |
| beam current during pulse | 30 | mA | ~40 | mA |
| numb. of turns injected into RCS | ~60 | turns | ~90 | turns |

**Light Ions** (up to $_{20}$Ne$^{10+}$)

| | | | | |
|---|---|---|---|---|
| Electron Cyclotron Resonance Source | ~ 2 | keV/n | | |
| Radio-Frequency Quadrupole | 250 | keV/n | | |
| Linac output energy | 16.5 | MeV/n | | |
| pulse length | ~100 | μs | | |
| beam current during pulse | >10 | μAe | | |
| Synchrotron RF frequency range | 1.1 - 4.3 | MHz | 1.43 - 4.3 | MHz |
| harmonic number | 4 | | | |
| output energy | 400 | MeV/n | | |



| | Estimated Cost [M$] | + | - |
|---|---|---|---|
| 1) | 120 | **Fits cost limit**<br>No R&D (reminiscent of ISIS)<br>Broad upgrading potential<br>Light ion acceleration feasible | Only 100 kW in Stage 1 |
| 2) | 210 | Low repetition rate<br>200 kW beam power<br>No R&D required<br>(reminiscent of LAMPF-PSR) | *Too expensive*<br>No light ions |
| 3) | 125 (205) | **Stage 1 fits cost limit**<br>Upgrading to 200 kW<br>by adding a 400 MeV CCL | Only 100 kW in Stage 1<br>No light ions in Stage 2 |
| 4) | 175 | Low repetition rate<br>200 kW beam power<br>No R&D | *Too expensive*<br>No light ions |
| 5) | ? | Low repetition rate<br>200 kW beam power | Major R&D effort needed<br>(No reference machine)<br>*Cost not known* |
| 6) | ?? | Very low repetition rate<br>200 kW beam power<br>light ions (probably) feasible | Considerable R&D<br>*Cost uncertain* |

FIG. 1 AUSTRON: Accelerator configurations considered

Acronyms used:
DTL = Drift Tube Linac (Alvarez type)
CCL = Coupled Cavity Linac
RCS = Rapid Cycling Synchrotron
SR = Storage Ring (or Compressor Ring)
FFAG = Fixed Field Alternating Gradient Cyclotron/Synchrotron

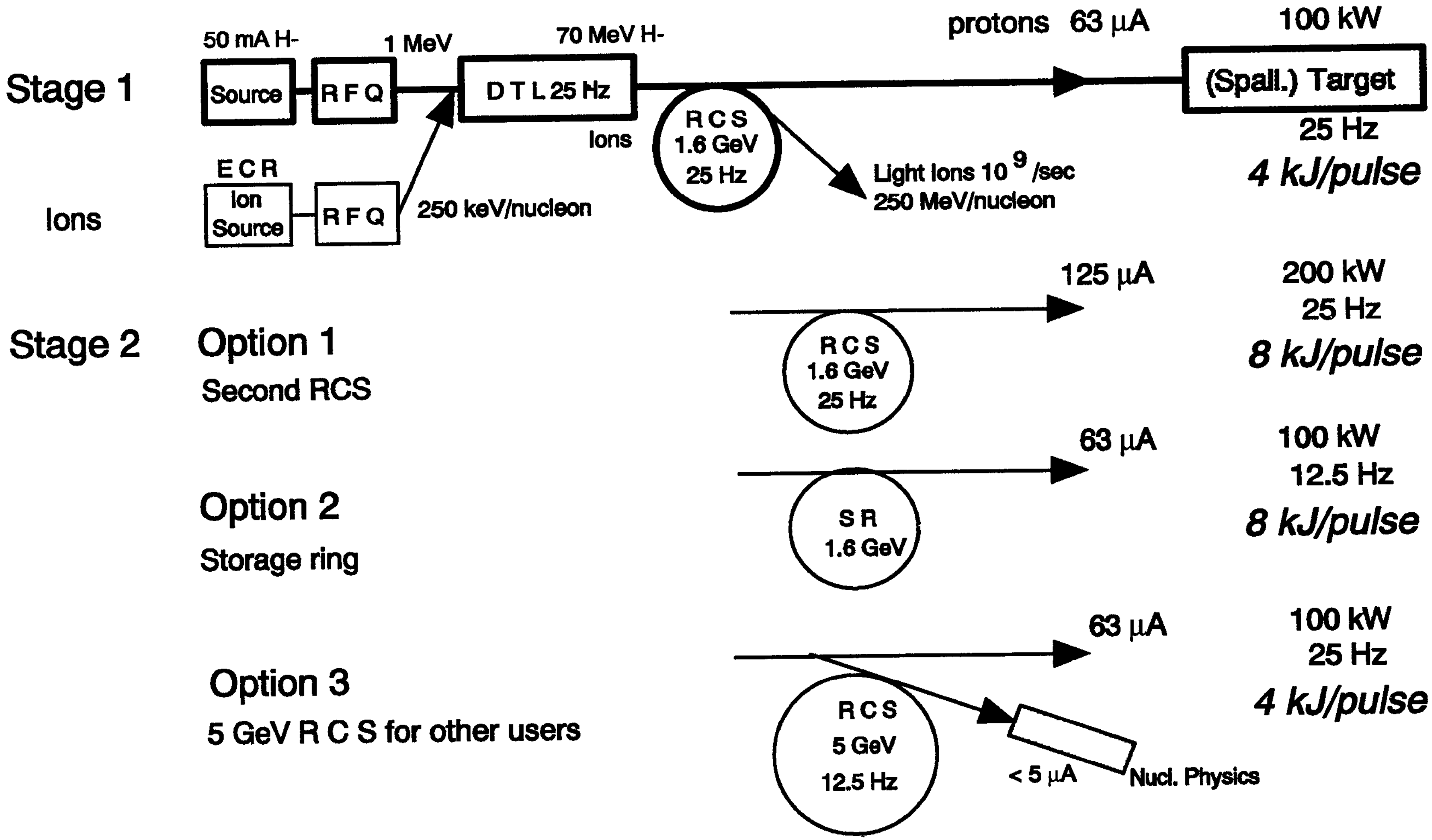


Fig 2: AUSTRON, preferred Stage 1 accelerator complex, with options for Stage 2

# Recent Evolution

## (Summary of a Meeting on AUSTRON held in Vienna on May 3-4, 1993 )

P.J. Bryant
CERN, CH-1211 Geneva 23

The AUSTRON was conceived primarily as an advanced neutron spallation source with a performance comparable to that of the ISIS machine at the Rutherford Appleton Laboratory. It was also planned that it should devote a small fraction of its time to producing light ions for medical research. The consensus of opinion at the meeting endorsed this basic concept with the following points that strengthen the justification for a spallation source:

- The competitive atmosphere in the ISIS user community indicates a strong demand.
- Industrial exploitation is still at an early stage of development.
- The progressive closure of nuclear reactors will restrict access to neutrons.

The meeting also showed great interest in the medical research that could be carried out with light-ions. This was seen as an essential step in the comparison of the different radiation therapies and their applications to various types of cancer. Only after such research, would it possible to plan dedicated facilities with full confidence that the best choices were being made.

While the basic concept and design parameters of the AUSTRON were well received, there was also a strong interest in the upgrade potential of the facility. The basic indicator for performance is the power delivered by the accelerator complex to the target, since this determines the neutron production. There are three ways of increasing this power:

- Increasing the beam energy (e.g. 1.6 to 3.2 GeV).
- Increasing the beam current (e.g. 63 to 126 μA).
- Increasing the repetition rate (e.g. 25 to 50 Hz).

The discussions during the meeting were of fundamental importance for arriving at a balanced judgement of the advantages and disadvantages of each method for increasing the delivered power and it was in this domain that the meeting had most influence on the accelerator design. The choice between increasing beam energy or intensity falls mainly on accelerator considerations, while the repetition rate is also influenced by physics requirements.

Increasing the beam energy is the surest way, from an accelerator point of view, of increasing the delivered power. Doubling the energy, rather than doubling the intensity, also eases the thermal problems in the target. Against these positive features, it was shown that raising the energy had a more detrimental effect on the installation and running costs. There is also more induced activity from a beam loss at 3.2 GeV than at 1.6 GeV. Thus machine access may be restricted. A higher beam energy implies a longer target, which has a negative implication for physics. Finally, it was mentioned that detailed target designs and moderator layouts did not exist at higher energies. The feelings were that there was no gain to be made above 5 GeV and in the range of 2-3 GeV it could not be guaranteed that doubling the energy would double the neutron yield.

As a corollary to the above, upgrading the beam current has the advantages of being cheaper both for the installation and running costs. It is also what could be described as the 'higher technology' method. It implies a better theoretical understanding of beam dynamics, higher precision in all aspects of operation, possible need of feedback systems, design of a low -impedance environment for the beam and so on. Space-charge limitations make it necessary to increase the injection energy from 70 MeV to about 130 MeV before the beam current can be doubled Since most of the beam losses occur during RF trapping, the increased injection energy will make loss management a little more difficult and will increase the induced activity per particle lost. However, the consensus from the meeting was that 150 MeV was a 'soft' threshold for this problem. It is also a problem that can be reduced by techniques such as chopping the beam and improving RF trapping and collimation techniques.

Since the basic design already foresees an increase in energy on the target from the 800 MeV of ISIS to 1.6 GeV and the above statements do not favour any further increase, it was felt that the upgrade programme should concentrate on doubling the beam current

With regard to the repetition rate, the time structure of the proton beam determines that of the neutron beam and thus the physics requirements play an important role in the choices to be made. Physics requirements for the neutrons fall into three broad categories:

- Sub-eV pulsed at about ten Hz with a pulse length (rms) < 1 µs.
- A few eV, pulsed at several tens of Hz with a pulse length (rms) ≤ 1 µs
- A few hundred keV, pulsed at several hundred Hz with a pulse length (rms) ≤ 2.5 ns.

Frequencies up to tens of Hz can be achieved by the whole accelerator complex, but the last user group requires several hundred Hz. This can only be satisfied by using a different radiofrequency system in a second ring and is therefore regarded as a 'far-future' upgrade because of its substantial cost. The second user group are more concerned with average power than the exact value of the repetition rate and would be satisfied by the ISIS value of 50 Hz. The first user group see a definite need for a low rate of the order of 10 Hz.. Thus, the 25 Hz chosen for the basic design can be understood as a solution that biased the repetition rate to a lower value in favour of the first group while using the cost advantage of the slower machine to help pay for a higher energy, so that the second group would not be disadvantaged by the reduced average power. Since it is better to use a sub-harmonic of the power distribution system, this optimisation fell on 25 Hz. While the second group of users is not disadvantaged, the first group is only partially satisfied. The beam current upgrade would automatically improve this situation by enabling operation at 12.5 Hz with the same neutron yield as the basic design without the need for any major installation (stretcher ring).

The maximum ion production rate of $10^9$ ion/s ($4 \times 10^7$ ion/pulse) was maintained. The basic design allows for a 'pulse per pixel' mode of treatment of a tumour that would irradiate 1500 pixels in a one-minute treatment. The energy will be controllable so that the tumour can be treated in slices of constant depth. The more sophisticated continuous scanning will only be possible with a slow spill from a storage ring and is therefore regarded as a 'far-future' upgrade. It became clear from early discussions that the original energy of 250 MeV/nucleon was not sufficient to support a full medical research programme. Fortunately, modifications with a very modest cost were possible to achieve 400 MeV/nucleon that corresponds to a penetration in water of 20 cm for oxygen ions.

The principle stages in the building of the AUSTRON accelerator complex with the estimated prices are tabulated below. Figures 1 and 2 shows the main parameters and schematic layouts.

The above conclusions imply that the target should be designed for 250 kW average power at 1.6 GeV with a 25 Hz repetition rate. This would take into account the first upgrade, which is likely to be implemented almost directly, and possible operational improvements over the first decade of operation. In the longer term, it is likely that an additional ring and a second target would be preferred to an upgrade of the first target station.

| BASIC DESIGN | MATS | MATS |
|---|---|---|
| Protons: power on target 100 kW (1.6 GeV, 63 μA, 25 Hz)<br>Ions: Up to neon, operation in 1-2 min. periods, $10^9$ ion/s (max),<br>1 pulse per pixel operation with controlled energy and intensity | 1450. | 1450. |
| Immediate improvement of ion operation from 250 MeV/nucleon to 400 MeV/nucleon | 5. | |
| Preparation for First Upgrade (must be included in basic design) | 47. | |
| | 52. | 1502. |
| **FIRST UPGRADE TO DOUBLE CURRENT** | | |
| Protons: injection energy increased from 70 to 130 MeV,<br>power on target 200 kW (1.6 GeV, 126 μA, 25 Hz) | 190. | |
| | 190. | 1692. |
| **FURTHER UPGRADES** | | |
| Storage/stretcher ring for 12.5 Hz/300 Hz and/or slow spill<br>Second target station etc.<br>These are major investments.for the far future. | --. | --. |

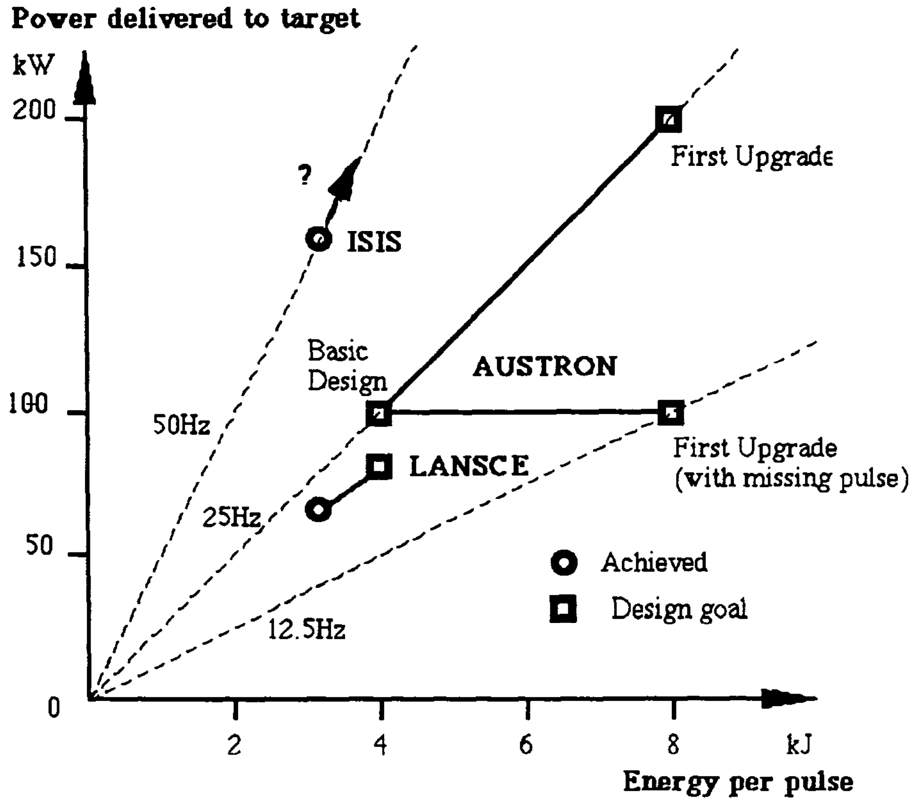


Figure 1 The AUSTRON and comparable neutron sources

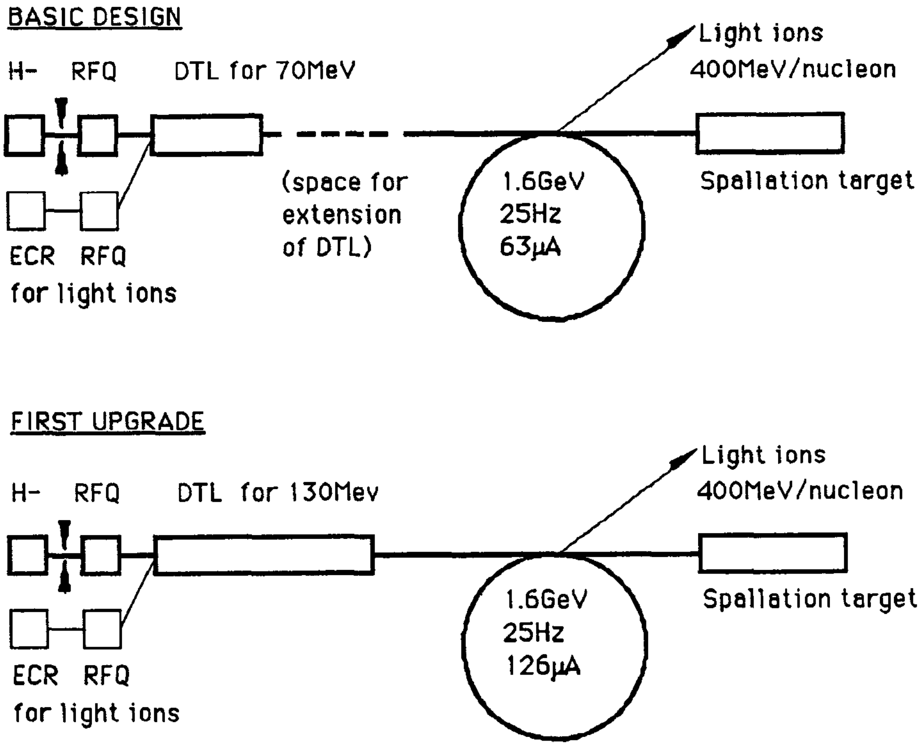


Figure 2 Schematic layout of Basic Design and First Upgrade

($H^-$ = negative ion hydrogen source, DTL = Drift tube linac, ECR = Electron cyclotron resonance source, RFQ = Radio-frequency quadrupole)

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