ADS Programme and Associated Developments in India-Roadmap and Status of Activities.

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Abstract. Large-scale utilization of thorium as nuclear fuel has been a long-term goal in the Indian nuclear power programme. The 3-stage programme for gradual switch over from uranium to plutonium-fuelled fast-breeders and finally to Th fuel system has been in place for this purpose. With external neutron source driven ADS, the self-sustainable thorium fuel cycle and growth of nuclear power generation capacity seem distinctly feasible. Accordingly, India has initiated a programme in 2003 to pursue a roadmap on physics studies & stage-wise technology development for ADS. Under this programme, activities related to reactor concepts & design, spallation target system and technology for high power proton accelerator have progressed. Reactor design studies were made on some representative schemes of sub-critical reactors to introduce and sustain thorium fuel utilization, development of indigenous reactor calculations codes, application of high-energy particle-matter interaction codes to estimate neutronics in spallation target and its coupling with surrounding reactor core. A reactor physics experimental programme is also underway to couple 14-MeV neutron generator (D-T reaction) with a sub-critical Nat. uranium-water core. In another reactor studies, a research reactor is being designed with feasibility for future conversion into a spallation neutron source-driven sub-critical ADS reactor. In the spallation target technology programme, thermal hydraulics analyses were made of liquid metal flows around beam window under various beam-induced heating conditions in target volume. A liquid metal LBE flow loop has been designed for experimental validation of CFD analyses through simulation of proton heating the beam window by using plasma torch and electron beam. This loop would also have corrosion test set up for samples of various materials. Energy efficient and reliable high power proton accelerator for ADS presents challenges in accelerating low-energy space-charge dominated proton beam, and at high-energy in utilizing superconducting (SC) RF cavities with cryogenics. Design and construction of 20-MeV cw proton linac at BARC and development of techniques to fabricate & characterize high-β SC RF cavities from niobium are progressing. The above spectrum of ADS-related activities is covered in this paper along with some thoughts on future directions.

1. Introduction

Indian assessment of the utilization of ADS and associated R&D programme on the relevant technologies were the subject of studies at BARC during the period 1999-2001. A roadmap of planned actions was brought out at the end of these studies [1]. At that time, the prime concern of planners of Indian nuclear power programme was to seek the excess neutron economy offered in the ADS sub-critical core for utilization of thorium as fuel, in somewhat similar way as proposed by Carlo Rubbia [2] in the Fast Energy Amplifier (F-EA). However, there are reasons other than the sustainability in terms of fissile material, which prompted us to an early introduction of thorium fuel cycle through ADS. The main among these is the negligible radiotoxicity of long-lived, transuranic (TRU) nuclear waste generated in the thorium fuel cycle for a given amount of delivered energy.

In recent times, India plans to supplement its nuclear power generation in a big way in the coming years by introducing new generation light water and fast breeder reactors. The anticipated nuclear power electricity generation capacity may grow to ~40-50 GWe in next few decades. This rapid expansion will necessarily require technological solution for disposal of spent nuclear fuel. With this in view, there is also appreciation of ADS characteristics as actinides burner for safe incineration of higher actinides and to fully close the uranium fuel cycle.

A part of the planning proposed in roadmap mentioned above was implemented in the 10^{th} and (now) ongoing 11^{th} (2007-12) five-year plans as projects on ADS sub-systems and preparations for an external source driven experimental sub-critical assembly at BARC. The focus of these activities, however, has remained on thorium fuel cycle.

The fuel cycle strategies of separation and partitioning to meet demands of specific reactor systems are already the part of three-stage nuclear power growth plan of the country [3]. The ADS supported nuclear power system would alleviate, or at least minimize the volume of long-term repository for radiotoxic waste from the first and second stages of Indian nuclear power programme.

A reference configuration of ADS has been adopted as one-way coupled fast-thermal sub-critical reactor [4] in which fast neutron booster zone will consist of mainly higher actinides rich fuel and the thermal zone having thorium-based fuel in heavy-water moderated, annular core with pressurized water channels. More analytical work on such a reactor design needs to be undertaken in future.

2. Modalities & Plans for R&D on ADS

Since 2003, the Indian efforts of ADS development are guided and coordinated by a Steering Committee on ADS Programme (SC-ADSP) under the Indian Department of Atomic Energy (DAE). The presently adopted roadmap on ADS envisaged following developmental deliverables over next 10-15 years of R&D:

(i). Development of reactor physics codes with spallation target, improvement in nuclear data base and preparations for conducting reactor physics experiments with external source (14 MeV) neutron driven sub-critical assembly at BARC.

(ii) Experimental facilities of lead-bismuth eutectic-based process system for R&D on **spallation target** sub-system at BARC.

(iii). An ongoing 20-MeV high-current proton linac project in BARC.

(iv). Development of high-current proton cyclotron technology in VECC, Kolkata.

(v) Design studies on and developing fabrication and processes for **superconducting RF cavities** from bulk niobium.

(vi) Design studies for enabling a proposed experimental reactor for future upgrade to external source neutron driven ADS demonstration facility at new BARC campus in Visakhapattanam.

3. Reactor Physics Studies Activities

For analysis of high-energy proton interactions in spallation region of the target, we use particle transport codes FLUKA and CASCADE. For the neutronics of low energy neutrons in blanket (reactor core) region, we have developed simulation codes McBurn and BURNTRAN **[5, 6]** carrying out fuel burn up simulations based on the Monte Carlo method and the multi-group transport theory method respectively. The codes were used in validation studies such as (*i*) study of the IAEA ADS benchmark (fast system) **[7]**; and also for (*ii*) cell level burn up of 19 rod U and Th cluster used in Indian 220 MW PHWRs that was previously studied by other codes and for (iii) molten salt reactor (MSR) benchmark problem in IAEA TECDOC-1319 **[8]** with good agreement. Interfacing of the high-energy code CASCADE with McBurn has been carried out.

The code package BURNTRAN consists of a burn up module BURN, developed by us, and the one and two-dimensional multi-group discrete ordinates codes DTF **[9]** and ATRAN **[10]**, and a 172-group WIMS neutron data library. A number of modifications were carried out in the transport theory modules. The core region of interest is divided into several burn up zones and the transport theory codes provide the necessary reaction rates. The burn-up module is based on Gear's method for integrating a system of stiff differential equations.

3.1. Theoretical Studies on Methods for Reactivity Measurement

At a theoretical level, we believe, that the principal difference between ADS and critical reactor noise is due to the accelerator characteristics. Some of the accelerators used for experimental purposes could actually be pulsed accelerators operating at pulse rates ranging from a few Hz to kilo-Hz. Apart from pulsing, the noise characteristics of the ADS source will be non-Poisson. As such, a fundamentally different theoretical approach for deriving mathematical expressions for the noise descriptors than that used for interpretation of various noise-based experimental measurement techniques is necessary.

We have developed a theoretical approach and have derived formulae **[11]** for interpreting some of the classical noise methods such as Rossi alpha, the variance to mean, auto (and cross) correlation functions and (auto & cross) power spectral density, as well as some recently proposed methods such as the cross power spectral density between the proton current and the neutron detector signals for systems driven by periodically pulsed non-Poisson sources having a large multiplicity. We have further elucidated the noise character of the ADS neutron source **[12]** by describing it as a doubly stochastic Poisson point process, in which the proton beam current is described as an exponentially correlated Gaussian process. The theory has been further generalized to include delayed neutron contributions **[13]**. This new theoretical approach has received general acceptance; e.g. see ref. **[14].**

We have also developed a new method for calculating alpha-modes in a reactor which are useful for locating detectors in a pulsed neutron equipments.**[15]**.

3.2. Experimental Reactor Physics Studies on ADS

A sub-critical assembly of natural-U fuel elements and light water was chosen for the purpose of basic reactor physics experiments. A 14-MeV neutron generator in existence in PURNIMA laboratory for several years for conducting fusion blanket neutronics studies consists of a 400 kV DC high-voltage accelerator, and neutrons are produced by the D-T fusion reaction resulting in a continuous neutron source of about $3x10^9$ n/s. Efforts are on to increase its source strength by replacing the dc accelerator system with a 400-keV RFQ, and to have pulsed beam mode of operation for conducting pulsed neutron source-based reactor physics experiments. Measurement of flux distribution, flux spectra, total fission power, source multiplication, and degree of sub-criticality will be carried out during experiments planned.

4. Target technology & LBE system development

The presently ongoing ADS programme activities emphasize R&D on technology of heavy liquid metal (HLM) process system for spallation target, and also as coolant for the next generation high-temperature reactor (HTR) and metallic-fueled fast breeder reactors (FBR). Under the ongoing R&D programme, liquid metal loops consisting of mercury, and LBE circulation systems are being set up, computational tools are being developed and corrosion studies including mitigation methods for process system materials have been initiated. The mercury circulation loop was operational for testing the liquid metal flow diagnostics instrumentation and measurement of void fraction in 2-phase systems.

The LBE liquid heavy-metal target development programme is being pursued mainly at BARC, it involves solutions related to the following issues:

- Thermal-hydraulics issues in high specific heating zone of target.
- Corrosion and erosion mitigation methods for structural material.
- Radiation damage of container materials (specifically, the beam window) by high-energy protons and neutrons.
- Effects of spallation products on corrosion and radio-toxicity.
- Safety issues related to target performance under abnormal conditions.

4.1. Beam target reaction Computational codes:

FLUKA & CASCADE.4 for **beam-target reactions** have been updated and made operational to estimate spallation neutron yields, residues, heat deposition and spatial and energy spectra. All these calculation data output are enabled for coupling with the reactor core in MC and transport neutronics codes to complete the design of ADSS.

CASCADE.4 code was applied for spallation reaction calculations for proton beam interactions with Tin (^{112}Sn to ^{124}Sn). This was with a view to possible use in future of Tin as target and/or fast reactor coolant so that residues are free from polonium radioactivity and alpha emitting rare earths. The results were compared with the experimental data for proton energy range of 0.66 to 8.1 GeV. Neutron yield from target at 1 GeV was 11.5 to 19 neutrons per proton **[16].**

IAEA and ICTP had organized an expert meeting on model codes for spallation reactions in Feb, 2008 and wherein an international benchmark model of spallation reactions was developed to validate selected experimental data. The specifications of the benchmark include the set of experimental data to be compared; e.g. Double Differential production cross-section for neutron, proton, deuteron, triton, helium-3, alpha, and pions at various energies and various targets were fixed. For this benchmark model, we have performed calculations with our code CASCADE.04 and the results will be presented and discussed in the Satellite Meeting on Nuclear Spallation Reactions in this topical meeting- AccApp'09 **[17]**.

4.2. Spallation target for reference ADS

Heat deposition calculations were made for molten LBE spallation target for a reference ADS design. For these calculations, uniform intensity proton beam of diameters 7 and 10 cm, and 0.9 mA average current ingress through bottom of target beam window of T91 material was used. The spallation neutron characteristics (neutron yield, angular and energy spectra, production of ^{210}Po, shielding) have been studied for 300 and 650 MeV proton beam using CASCADE.04 code. The target (fig.-1) is considered to be cylindrical (Length = 60 cm, radius = 7 cm) LBE with density 10.5g/cm^3. It is surrounded by the cylindrical (Length = 60 cm, radius = 27.5 cm) reactor core.

LBE circulation through the target was effected by means of gas-injection driven buoyancy system. Spatial heat deposition rate distribution obtained was used as input for a CFD code programme to generate thermal hydraulics parameters for the target system.

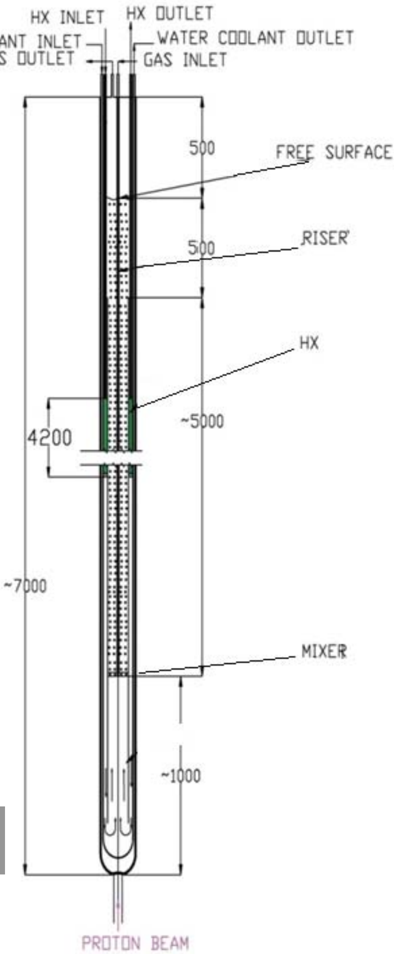


Fig.-1

4.3. Thermal-hydraulic simulations and experimental studies

Design and development of a LBE experimental loop facility has been completed and procurement of equipment are progressing. This loop, which to be located in common facility building under construction (CFB) in BARC would be enabled for experiments to validate thermal hydraulics codes under simulated HLM flows in beam window and windowless target module configurations and also conduct tests on corrosion rates of materials in liquid metal and at high temperatures.

Setting up this experimental LBE facility in BARC will generate experience in construction of special components like Heat-exchanger, Primary coolant systems etc.

The schematic of the proposed loop is shown in **Fig.-2.** The major components of the loop consists of target simulation region, mixer, riser, separator, mechanical pump, heat exchanger, Plasma torch and dump tank for LBE storage. The loop can be operated both by mechanical pump and by gas-injection. The mass flow rate (maximum of 120 kg/s by pump) and the geometry of the target flow region is ~ 1:1 scale of the actual target. The loop can operate up to 350^{0}C. A plasma torch, with special arrangement to spread the beam, has been developed to simulate window thermal loading **[18].** The primary coolant will be of Organic (Dyphyl-THT) fluid/Water. This facility is currently in the fabrication stage.

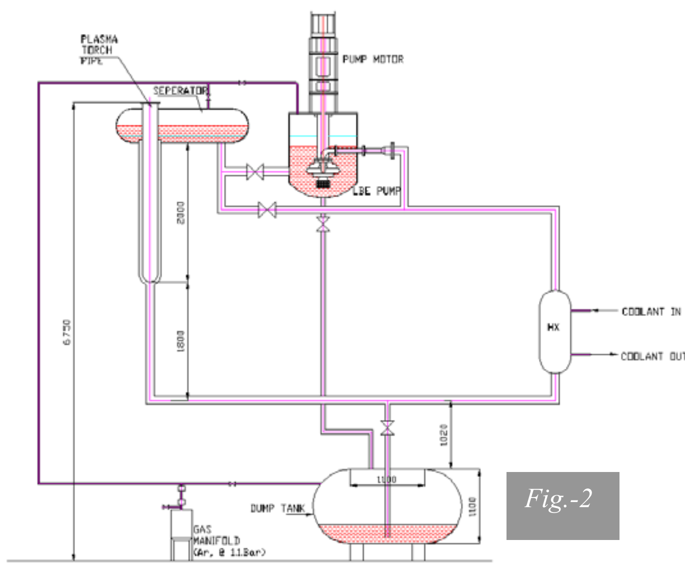
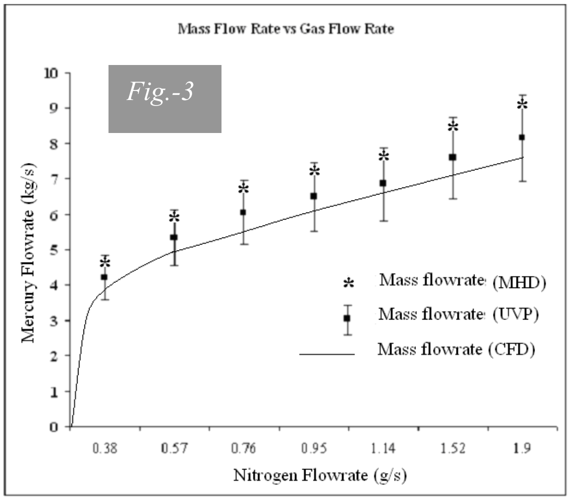


Fig.-2

4.4. Experimental Mercury Loop Facility

A mercury (Hg) loop has been setup to develop various special diagnostics, flow simulation studies and CFD code validations etc without heat simulation. The velocities simulated will be similar to that of actual target but geometry will be around one fifth of the actual one. The void fraction in the two-phase flow will be measured by high-energy gamma ray attenuation method. The Hg flow circulation in the loop is effected by nitrogen gas injection. Special diagnostics like Ultrasonic Velocity Profile Monitor has been used for velocity mapping. The

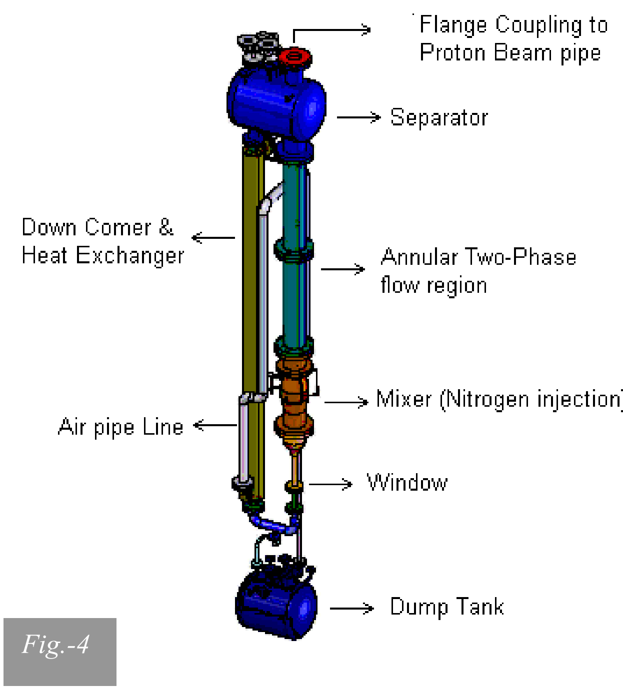


system has been commissioned and experiments are in progress. The measured mass flow rate of mercury as a function of nitrogen flow rate is shown in **Fig.-3.**

4.5. LBE irradiation facility with 30-MeV cyclotron.

A LBE loop (**fig.-4**) is being setup to study thermal and radiological issues related to irradiation of target by proton beam. For this purpose, a dedicated proton beamline of 30 MeV and current of 0.5 mA beam from cyclotron accelerator in Kolkata will be used. The studies include thermal-hydraulics, radioactive gas handling, remote dismantling of irradiated target module, material studies related to generation of helium and hydrogen, radiation effects on ductile to brittle transition temperature, and swelling and radioactive issues related to Polonium generation, etc. The height of LBE circulation loop in this facility is ~ 7 m, which would operate at ~220^{0}C with LBE flow rate of maximum ~25 kg/s that would be realized through nitrogen gas injection.

Using the scanning magnet, different beam diameters and current densities will be obtained and the performance of the window and heat extraction capabilities of the loop will be tested. In addition radiation damage studies will be carried out.



4.6. Corrosion studies in heavy liquid metal (HLM)

Studies have been carried out for SS316L, SS304 L samples in circulating LBE in which oxygen ingress was eliminated by means of Argon gas purging and temperatures maintained at 250^{0} and 350°C in cold and hot legs respectively. After exposure to LBE for 3600 hrs, results showed that 304L had not undergone any corrosion at either temperature. Tensile tests of the specimens exposed to LBE showed lowering of ductility and increase in tensile strength after exposure at 250°C compared to the annealed unexposed sample. EDAX analysis of the cross-section of the exposed specimens did not show any penetration of LBE into the grain boundaries of 304L or depletion of nickel at either temperature after 3600 hrs.

5. Accelerator Sub-systems

The proton linac is a more desirable driver accelerator for nuclear waste burner to meet higher beam current requirement toward extended end of cycle (EOC), and also for thorium breeder to maximize the non-fission neutron inventory. The cyclotron accelerator is considered to be limited in the beam current intensity up to about 5~10 mA. This type of driver accelerator is suitable for thorium fuel-cycle based energy production ADS with almost uniform beam power requirement from BOC to EOC.

Two main activities on developing high current proton accelerators are progressing in India as extended five-plan projects and likely to be operational by end of 2012:

(a). A low-energy high intensity proton (linac) accelerator- **LEHIPA** at BARC, Mumbai- as 20 MeV normal conducting linac .

(b). High current proton ion source injector for axial injection into a cyclotron as phase-1, and subsequently a 10-MeV compact cyclotron as phase-2 at VECC, Kolkata.

Additionally, there are a number of supporting activities in India to develop indigenous enabling technologies of accelerator sub-systems. All these activities do not necessarily come under the umbrella ADS programme, but these strengthen the development efforts on high current proton accelerator technologies.

5.1. Progress and status of LEHIPA

Design of this 100% duty cycle cw proton RF linac began in late 2003.The development modules (**fig.5**) for the LEHIPA project are- an ECR proton ion source enabled for pulse and dc operation, a 3-MeV RFQ and 3-20 MeV Drift-Tube Linac (DTL). The RF was chosen to be 352.21 MHz in view of commercially available 1.3 MW klystron for driving RFQ and DTL and other RF hardware. This frequency was also adequate for manageable transverse dimensions of RFQ and DTL features. So far, the major progress was made in realization of following tasks:

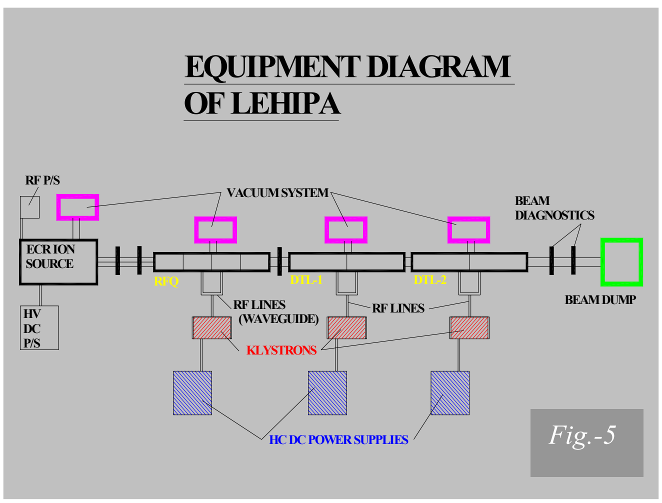


Fig.-5

a. **Beam dynamics** and physics design **[19]** for entire accelerator has been completed. The system-wise specifications for power supplies, accelerating structures (LEBT, RFQ & DTL), **building layout** and **shielding** requirements for safety are worked out on the basis of this design.

b. A prototype of **ECR proton ion source** has been integrated and tested with dummy plasma chamber, 3-electrode ion extraction, and power supplies including 50 kV high voltage system. During short-time test runs, plasma was ignited in the chamber and it yielded up to 42 mA unanalysed ion current.

c. The accelerator channel, RF power supplies and other utilities would be housed in a facility building that was designed with adequate shielding wall thickness. This part of common facility building has basement and ground floor areas. While construction of basement has been completed, structural work in high-bay area of ground floor would be finished and handed over by end of 2009.

d. **RF power supplies** system design, specifications of equipment and their procurement for first 1-MW modular power supply of RFQ have been completed. A prototype (60-kW) RF system based on TH571 B tetrode tubes of Thales was made & operated at lower power level, which would be tested with a prototype RFQ to accelerate deuterium beam to **400 keV**.

e. Design of power converter of 2.5 MW high-voltage DC (**HVDC**) was evolved on the basis of concurrent R& D at Institute for Plasma Research (IPR), Gandhinagar. This design is based on series and controlled addition of number of smaller stages of voltages, in a phase synchronized fashion from rectifier transformers with multiple secondaries, switched power units and a digital controller. The output is generated with addition of small stages of voltages. Procurement of hardware for first of the three required HVDCs is progressing with IPR, who would carry out its integration and power test at BARC by mid-2009.

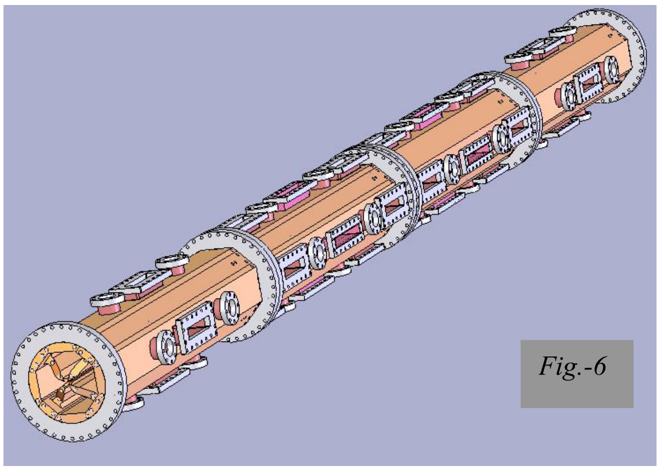


Fig.-6

f. Indigenous development of high precision machining & braze-fabrication techniques for accelerating structures of **RFQ and DTL** have been initiated, and satisfactory progress is reported in the R&D for RFQ (**fig.-6**) fabrication. First fabricated module from this work is expected by mid 2009 for testing with prototype, low-power RF system.

g. Engineering details for DTL were prepared including those of tanks-wall cooling water channels along its circumference and water-cooled drift tubes housing permanent magnet quadrupoles (PMQ). The details for sealing requirements for vacuum, water flow and RF contacts between tank and drift tube stem were included in the details. A RF physics tests model of DTL is under fabrication for conducting electrical tests to validate design calculations. Made of carbon steel with copper plated inner walls, 1.2 meter long tank with ports and dummy drift tubes

5.2. Progress and status of high current cyclotron

It is proposed to develop a 200/250 MeV, 5 mA Separated Sector Cyclotron (SCC) for accelerator-target-reactor coupling in a technology demonstration ADS. However, present activities are focused on the development of ECR ion source and a 10 MeV, 5-10 mA compact radial sector proton cyclotron, and to study and resolve various physics and technological problems associated with the production, bunching, acceleration, injection, extraction, etc. of the high intensity proton beams. Designs of buncher cavity and dipole magnet for cyclotron are complete.

A 2.45 GHz microwave ion source to produce ~30mA of proton beam at 100 keV, has been coupled through a three stubs tuning unit and ridged wave-guide with 1.2 kW magnetron. Two motor controlled movable magnetic coils with separate power supplies provide the desired magnetic field. The resonance zone can be adjusted by moving these coils online. After complete assembly of ECR ion source system, the HV deck was tested up to 90 kV, and ion current of 2 milli-Amp was realized. Current increased with raising RF power level, but tests were interrupted due to increased heating at ridged waveguide. Further investigations are being made to improve performance. The spiral inflector for proton beam injection into cyclotron orbit was also made and tested up to 20 kV voltage.

5.3. SC RF cavities development

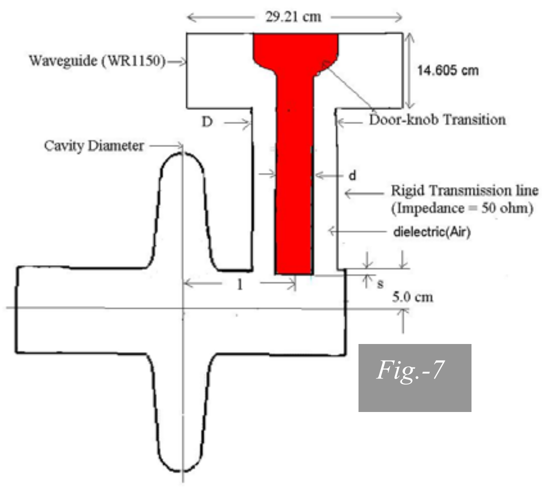


Fig.-7

SC RF cavities application in the high power proton linac has been planned in high-energy section of linac which could be starting with ~ 100 MeV. While studying linac's elliptical profile cavity cells at about 704 MHz, initial efforts were made on developing cavity for lowest β (ratio of proton velocity to that of EM wave) section (β~ 0.45).

The single-cell cavity design was optimised for the RF frequency of 700 MHz, β~0.42 and 1056 MHz, and β~0.49. The copper prototype of both the cavities was fabricated.

For 1.05 GHz (**fig.-7**), in designed (copper model) mode TM_{010} the calculated resonant frequency was 1.056 GHz and at 4.2K the Q_0 =4.2 4.248 x 10^8. On copper model measured frequency and Q_0 were 1051.17 MHz and 14982. A frequency shift of ~77.5 kHz is observed by passing copper bead from the center of the cavity **[20].**

For 700 MHz, in designed (copper model) mode TM_{010} at 4.2K the Q_0 =6.093 x 10^8 @ 4.2^0K. On copper model measured frequency and Q_0 were 694.8 MHz and ~10000. A frequency shift of ~77.5 kHz is observed by passing copper bead from the centre of the cavity.

The coaxial input couplers for these cavities were designed and their respective external Qs evaluated using Kroll-Yu method **[21].** The copper prototype of the coupler was fabricated. The measurement was carried out with the 700MHz cavity and the axial coupler where the beam pipe of 80 mm diameter acted as a outer conductor of the coaxial coupler and inner conductor was a copper cylinder of diameter 34.78 mm. The external Q was measured from the reflected power at the coupler port.

5.4. Spallation Neutron Source.

Technological developments on ADS, which have been initiated in RRCAT, Indore are oriented towards technological development programmes to develop a 1-GeV rapid cycling synchrotron (RCS) spallation neutron source (SNS) facility. This programme includes a 100-MeV normal conducting, high repetition rate, pulsed proton linac injector, and ongoing work so far center around RF hardware and design studies of proton linac modules- a RFQ, DTL, development of high power RF load and solid-state RF power amplifier. Technology infrastructure in the center is being upgraded for development and processing of superconducting RF cavities.

6. Summary

R&D activities under ADS programme in India have been initiated with emphasis on high power proton accelerator and heavy liquid metal target systems. Low-energy section of normal conducting proton accelerator and an experimental LBE circulation loop are under development in BARC as technology demonstration of ADS sub-systems. These are likely to become operational by end 2012. Design studies are also initiated on a baseline ADS demonstrator with 650 MeV proton beam accelerator coupled to LBE target in an upcoming thermal reactor. In a separate molten LBE loop being set up on 30 MeV proton beamline from cyclotron, the effects of beam irradiation will be studied. Superconducting cavities fabrication processes and RF testing are being learned with the help of geometrically similar cavities made of copper.

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