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Front End
Designs for the 7-GeV Advanced Photon Source

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ABSTRACT

The conceptual designs for the insertion device (ID) and bending magnet (BM) front ends have been completed for the 7-GeV Advanced Photon Source (APS) under construction at Argonne National Laboratory. These designs satisfy the generic front end functions. However, the high power and high heat fluxes imposed by the X-ray sources of the 7-GeV APS have presented various design engineering challenges for the front end. Consideration of such challenges and their solutions have led to novel and advanced features including modularized systems, enhanced heat transfer concepts in the fixed mask and the photon shutter designs, a radiation safety philosophy based on multiple photon shutters for a fail-safe operation, a sub-micron resolution beam position monitor for beam monitoring and ring feedback information, and minimal beam filtering concepts to deliver maximized beam power and spectra to the experimenters. The criteria and special features of the front end design are discussed in this paper.

Introduction

Traditional synchrotron sources were designed to produce bending magnet radiation and have proven to be an essential scientific tool. Currently, a new generation of synchrotron sources is being built that will be able to accommodate a large number of insertion device (ID) and high quality bending magnet (BM) sources. One example is the 7-GeV Advanced Photon Source (APS) now under construction at Argonne National Laboratory (ANL). The research and development effort at the APS is designed to fully develop the potential of this new generation of synchrotron sources [1].

Of the 40 straight sections in the APS storage ring, 34 will be available for IDs. The remaining six sections are reserved for the storage ring hardware and diagnostics. Although the ring incorporates 80 BMs, only 40 of them can be used to extract radiation. The accelerator hardware shadows five of these 40 bending magnets, so the maximum number of BM sources on the lattice is 35.

Generally speaking, a photon beamline consists of four functional sections. The first section is the ID or the BM, which provides the radiation source. The second section, which is immediately outside the storage ring but inside a concrete shielding tunnel, is the front end (FE), which is designed to control, define, and/or confine the x-ray beam from the source. In the case of the APS, the front ends are designed to *confine* the photon beam. The third section, just outside the concrete shielding tunnel and on the experiment floor, is the first optics enclosure (FOE), which contains optics to filter and monochromatize the photon beam. The fourth section of a beamline is a long string of beam transports, additional optics, and experiment stations to do the scientific investigations. This presentation describes only the front ends of the APS beamlines. An early conceptual study of the APS front-end design is given in [2].

By 1996, the APS will complete 32 front ends, 16 IDs composed largely of undulators and, to a lesser extent, wigglers and 16 BM sources.

A detailed physics study of the APS sources is provided in [3]. Table 1, based on reference [3], provides useful beam characteristics on the currently planned APS sources.

The APS Front End Design Philosophy

The APS front ends are standardized and modularized to achieve several purposes. As mentioned above, by 1996 we will have built 32 front ends. This is a large enough number to warrant standardization for the resulting reduction in cost. In addition, standardization results in reduced engineering and design effort, ease of manufacturing, quality control and quality assurance, ease in installation, and reliability in maintenance and operations. The large variation in the horizontal extent of the beam size between the BM and the ID devices is a hindrance to full standardization of certain of the front-end components. But, if the front end components are designed for the most critical wiggler size and for the highest heat flux levels of the APS undulators, full standardization will result for all ID front-end components. This is the current APS front-end design philosophy.

Needless to say, the standardized designs of the APS front ends also must satisfy the baseline requirements for any front-end design. That is, the front ends are configured via a complex design, control, and interlock system to

(i) provide biologically safe working conditions on the experiment floor,

(ii) trigger protective measures to isolate the front end from the ring under any vacuum failure scenario,

(iii) provide proper collimation so that the beam cannot strike unprotected and uncooled elements within the vacuum envelope even under steering errors,

(iv) provide shuttering and, hence, absorbance of the full power of the beam and/or Bremsstrahlung during injection and/or in case of a vacuum failure,

(v) monitor and control the position of the beam with precision,

(vi) operate within the phase-space parameters of the beam that the experimenters expect and for which they prepare their equipment.

The design of the APS front ends began with a ray tracing study [4] of the source to determine first the front end aperturing needed and next the component placement and sizing.

Front End Aperture Sizing

The standard design of the ID front ends is understandably much more complex than the BM front-end design and the ID front-end design will be detailed here. The ID front ends must satisfy the power requirements of Undulator A coupled with the horizontal beam size of Wiggler A (see Table 1). For a 100 mA ring current at 7-GeV positron beam energy, Wiggler A (for a K factor of 14) covers a photon energy range of 5 to 32.6 KeV. The source ID radiation fan width is taken to be ± 1.5 mrad. (For the BM front ends, the source fan width is ± 3.0 mrad.) An optical pass sketch resulting from the ray tracing studies for the ID front end is shown in Fig. 1. The vertical and horizontal beam confinements for the ID front ends are as follows:

<u>The Vertical Beam Confinement</u>:

Max. vertical beam missteering acceptance	1.4	mrad
Max. vertical pass-through	0.49	mrad
Design Vertical pass-through	0.28	mrad

<u>The Horizontal Beam Confinement:</u>

Max. horizontal beam missteering acceptance	3.7	mrad
Max. horizontal pass-through	3.0	mrad

Figure 2 is the elevation view of the conceptual design of the APS ID front end. In this conceptual design, the components on the ID front end are (in the order of their appearance in Fig. 2):

1. All metal ring isolation valve
2. Photon beam position monitor 1
3. Fixed mask 1
4. Photon shutter 1
5. Collimator
6. All metal slow valve
7. All metal fast valve
8. Photon beam position monitor 2
9. Fixed mask 2
10. Photon shutter 2
11. Filter assembly
12. Safety shutter
13. Collimator
14. Window

The aperture sizes for ID front-end components resulting from the ray tracing studies are presented in Table 2.

In Fig. 3, the conceptual design of the APS BM front-end elevation view is shown. The BM front-end components are (in the order of their appearance in Fig. 3):

1. All metal isolation valve
2. Photon beam position monitor 1
3. Fixed mask
4. Photon shutter
5. Slow valve
6. Fast Valve
7. Photon beam position monitor 2
8. Safety shutter
9. Collimator
10. Be window

The tunnel provides a controlled environment for the front-end components. The air temperature in the tunnel is controlled at 23 ± 1° C. The deionized cooling water for the components is maintained at 32 ± 1° C at the inlet. The shielding tunnel envelop is made of heavy concrete and fashioned as a "dog-leg" ratchet wall to provide the maximum aisle access to the front-end inside the tunnel. The usable length of the front end area of the tunnel is about 7.5 meters for both the IDs and the BMs and is necessarily congested by the components, particularly in the ID case. Figure 4 shows, schematically, a sliding door arrangement in the ratchet wall that is utilized to access each front end area for maintenance. A brief description is given below for the major components of the APS ID front end as well as the current state of the research activity associated with a particular component.

ID Front End Components

Manual Valve: This is an all metal valve and is UHV vacuum tight. It isolates the front end from the ring. Opening this valve is strictly controlled by the safety coordinator.

Fixed Mask Assembly (Fixed Aperture): This is the first front end element to interact with the beam. It can be exposed to the full beam or part of the beam and thus requires a careful design analysis. In the case of the APS, the first assembly is designed to *contain* the beam but not *define* it. A similar mask is located further downstream on the front end, and this second mask can be of a beam *defining* variety. An extensive generic cooling tube research and development program has been undertaken at the APS to find efficient tube configurations for enhanced cooling of the large heat loads that may be imposed on the mask walls.

Photon Beam Position Monitors (PBPM): This device is a cooled multi-blade system, in horizontal and vertical disposition, placed in the fringes of the beam to detect the position of the beam. A second PBPM is placed 4 m downstream. Together they yield precise beam slope information. When heated by the beam, the blades of the APS front end

PBPMs generate photoelectrons. This, in turn, causes a microamp level of photocurrent in each blade that can be measured and reduced to calibrate the deviation of the beam from its golden orbit. The beam position in the vertical plane can be measured to within one µm. The beam missteering is kept within ten percent both in position and divergence. When excessive deviations are detected, the output from the PBPMs is fed back into the ring correction (steering) magnets to adjust the beam's position and the angle at the ID center or in an extreme case of beam loss, the PBPM can trigger a beam dump. PBPM signals are fed back to the ring for proper beam steering. The current design and the research activity associated with the APS PBPMs are presented in a companion paper in this conference [5].

With the current state of the art, it is possible with two PBPMs spaced apart as described above to achieve a precision in position of ± 3.3 µm and ± 0.14 µrad in the angle of the particle beam.

Photon Shutter (Movable Mask): This component completely intercepts the x-ray photon beam via a fast-acting mechanism in order to isolate the downstream components from the source. Closing time may be as long as a few seconds (NSLS) or as short as 55 ms (ESRF). The photon shutter also acts as a safety device to protect the safety shutter from direct beam impingement. Therefore, it is interlocked to close before the closing of the safety shutters (two of which are required as per the APS Preliminary Safety Analysis Report, PSAR). The positions of both the photon shutter and the safety shutters are carefully indicated. That is, the photon shutter must be first closed and opened last and has redundant closed-position indication (fail-safe). The position of the safety shutter is redundantly indicated in both up (open) and down (closed) positions.

At the APS, the fixed mask and the photon shutters use a common and generic coolant tube with enhanced heat transfer capabilities [6]. The tube material is Glid-cop or a comparable material for high strength and fatigue resistance at elevated temperatures. The tube is filled with a copper foam (copper wool) brazed to the inside walls of the tube for good thermal contact. The heat transfer enhancement available from such tubes is shown in Fig. 5 (from the test data at the APS [7]). The presence of the copper wool (porous filler) in the flow tube, in addition to causing highly enhanced heat transfer, provides other benefits. At the expense of a somewhat increased pressure drop, the porous matrix in the tube makes these tubes very quiet, nearly jitter free. This is an important consideration for critical components such as PBPMs, masks, and, potentially, slits and first optics crystals where flow-induced jitter can become a serious concern. Additionally, these tubes require a relatively small amount of flow to achieve high convective heat transfer coefficients, an important consideration from an operational point of view. The APS ID front ends have many components requiring very robust cooling due to the high heat loads imposed on them from very powerful IDs. Conventional techniques for cooling would have resulted in an order of magnitude higher flow requirements in the front end. Research is continuing at the APS to optimize the tube geometry and the porosity.

The conceptual design of the APS ID front ends includes two fixed masks and two photon shutters. The fixed masks, in addition to confining the beam, serve to limit the length of the photon shutters placed immediately downstream.

The first photon shutter serves the traditional purposes of a shutter in the front end. While the second photon shutter, with two shutter blades, is used exclusively by the experimenters. This redundancy provides an added safety margin in the front-end operations and, also, psychological comfort to the users. Both shutters are fashioned similarly in a coiled "hockey-stick"-type blade through which the coolant deionized water flows. The hockey stick is hinged from both ends (Fig. 6), and the complete assembly can be removed intact from the flanged side for replacement or maintenance. The blade of the first photon shutter is set at a shallow 1.5° grazing angle to the beam.

The first photon shutter is designed to operate both in fast and slow closing modes, as desired. The slow closing takes about one second ("soft landing"), and the fast closing takes about 100 ms ("hard landing"). This duality is provided so that the APS has the possibiity of operating in a "no-beam-dump mode for non-threatening vacuum breach initiators" (which statistically constitute over 80% of the vacuum break signals in synchrotrons). Currently, the APS PSAR calls for a beam dump on all vacuum breach initiators. In this case, the "soft landing" will be adequate. If, in the future, the fast valve protection can be designed so that beam dump is not required for non-threatening vacuum breaches, the "hard-landing"-type first photon shutter will be needed. Two companion papers [8 and 9] in this conference discuss in further detail the thermo-structural and vibrational aspects of the conceptual mask and the shutter designs with particular emphasis on the first photon shutter. The analyses seem to prove that the very critical component, the first photon shutter of the ID front end, as conceptualized here, will satisfy the stringent thermal, structural, and vibrational requirements under operations with the 2.5-m Undulator A ID of the APS (which will be the initial source). The technical requirements for the future 5-m Unculator A, including a design safety factor, are very challenging, and the research and development effort is continuing into an engineering solution to the thermal problems of the photon shutter.

The second photon shutter is the one that experimenters usually shut down in the course of their beamline activities. This shutter has a dual pneumatic motion to close the upper and lower blades of the shutter, which are shorter than those of the first photon shutter and are set at a somewhat higher inclination to the beam (3°). The upper blade of this shutter has a manual option to reset the vertical opening to suit different IDs so that the beam can be better confined to protect the window frame. Both shutters are interlocked to the safety shutters downstream. This shutter normally closes in 1-2 seconds.

Collimators: These components are required to define the line of sight to the source point and allow a cone of the beam to pass through. Portions of the beam outside the predefined cone, any other scattered x-rays, and the Bremsstrahlung are absorbed by the collimator body.

Slow Valve: This is an all-metal, remotely actuated UHV valve that seals to isolate the ring from any vacuum breach in the downstream transport piping. The closing time of this valve is usually 1-2 seconds. However, it cannot accept the heat load from the photon beam and, therefore, must be interlocked to close only when the beam is NOT present or when the photon shutter is closed. Closing of this valve occurs after the closing of the fast valve (described below) and helps retard the vacuum conductance upstream on vacuum breach.

Fast Valve: The fast valve is positioned immediately downstream from the isolation valve. The modern all-metal-seal fast valves close in as little as 5 to 9 ms, thereby retarding the vacuum progression upstream. This valve, however, does not seal and cannot support even instantaneous exposure to a full photon beam without physical damage. Therefore, it is interlocked to the photon shutter during operation. On vacuum failure, the photon shutter is activated, which triggers immediate beam dump. Once the photon shutter is down, the fast valve closes, followed by the closing of the slow valve.

Safety Shutter: This shutter (two independently but simultaneously operated shutters are required per front end per APS PSAR) absorbs Bremsstrahlung radiation from scattering of the particle beam during injection of the beam into the storage ring. Therefore during each injection mode (maybe every 8-10 hrs of operations), these shutters are closed (down). The material for the shutter is Heavi-Met, steel-clad tungsten, or lead. This shutter is usually not cooled, but does absorb all the Bremsstrahlung radiation coming through the line. Because it is not cooled, it should not be exposed to the photon beam. Therefore, the upstream photon shutter 2 is interlocked and sequenced to close (down) before this shutter is down.

Be Window: The beryllium window is a vacuum separator and is positioned as needed between different vacuum transports and/or experimental stations. The front end beryllium window is located at the end of the front-end transport and separates the ring vacuum (front-end vacuum) from the experimental beamline vacuum. The APS window is a dual diaphragm assembly with a tag gas in between. Dual window diaphragms lend added assurance because, if one of the window diaphragms should fail, the other one can assure vacuum integrity until maintenance is affected. The traditional window material is beryllium, although the high heat loads expected from APS undulators may force us to seek alternate window materials such as diamond-coated beryllium or CVD-diamond wafers. Of the two windows, the first absorbs most of the heat from the low energy photons and reaches high temperatures. The downstream window is usually less affected by heat, however, it is the one subject to pressure shocks if a vacuum breach occurs in the experiment line.

The tag gas is traditionally helium, although other gases may also be considered. The purpose of the gas is to keep the wafer surfaces free from oxidation/carbonization and to indicate when a vacuum breach occurs. The gas space is interlocked for beam stoppage/dumping when a vacuum breach is sensed by the gas system. Management of the filters and the windows in APS front ends is a very important issue and the subject of considerable current research.

As a matter of philosophy, the APS believes that the beam filtering in the front end should be the minimum required to maintain the structural integrity of the window and, thereby, assure the vacuum safety in the front end. The filter assembly is designed so that only the unwanted portions of the beam energy are absorbed so the window is thermally (hence, structurally) protected. Otherwise, a user-selectable filter box is located on the beamline to satisfy different optical requirements by the experimenter. References [10-12], two of which are companion papers at this conference, present further details of the APS front-end filter/window management research.

The Front End Vacuum: The APS front end vacuum is a UHV system that is the same as the ring vacuum (10^{-11} Torr). Therefore, ultimate care is taken to maintain vacuum integrity and quality in the front end so as not to jeopardize the ring vacuum. In the space available, a 120 l/s ion pump is placed immediately after the isolation valve to make sure that the ring side of the front end does maintain ring quality vacuum. On the FOE side, the front-end vacuum is separated from the beamline vacuum via a double wafer window. A strict rule applies to all synchrotron vacuum systems: there should be no water/vacuum joints in the beam transport, and all such joints and connections are isolated from the UHV by venting directly to the atmosphere. The direct link between the front end and the ring also dictates an additional engineering rule: the front-end vacuum components should be durable, require little maintenance, and be highly reliable. Therefore, complex and unproven engineering practices are shunned. Materials are carefully chosen to function in a UHV environment. (This last aspect directly impacts the seals. All-metal seals are the usual choice in the front end.

The APS ID front-end vacuum pumping calculations show good pump-down characteristics (Fig. 7). Adequate ion pumps supplemented by titanium sublimation pumps have been provided in the front end. Although the APS ID front end is relatively short and there is no vacuum delay tank (VDT), calculations prove that the front end has good vacuum retardation due to carefully engineered inherent aperturing.

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Table 1.
Design Parameters of Various APS Insertion Devices for a Ring Energy of 7 GeV and 100 mA Stored Current

	Undulators				Wigglers		Bending Magnet
	A	B	C	D	A	B	
Period length [cm]	3.1	2.1	20.0	8.0	15.0	25.0	NA
Device length [m]	5.00	5.00	5.00	5.00	1.50	5.00	3.06
Number of periods	160	238	25	62	10	20	NA
Max. magnetic field B_0 [T]	0.80	0.40	0.15	1.00	1.00	0.30	0.6
Characteristic energy E_c [keV]	26.0	13.0	4.9	32.6	32.6	9.8	19.5
$1/\gamma$ [mrad]	0.073	0.073	0.073	0.073	0.073	0.073	0.073
Max. deflection parameter, K	2.51	1.03	2.81	8.76	13.96	7.00	NA
K/γ [mrad]	0.183	0.075	0.205	0.639	1.019	0.511	NA
Total power [kW]	10.0	2.5	0.35	15.5	4.6	1.4	0.52*
Peak power density [kW/mrad^2]	333	250	9.8	160	26.0	15.6	1.78
Peak flux @16 m [kW/mm^2]	1.3	0.98	0.04	0.63	0.10	0.06	0.007
Peak flux @20 m [kW/mm^2]	0.83	0.63	0.02	0.40	0.07	0.04	0.004
Peak flux @24 m [kW/mm^2]	0.58	0.43	0.02	0.28	0.05	0.03	0.003
Peak flux @30 m [kW/mm^2]	0.37	0.28	0.01	0.18	0.03	0.02	0.002
Peak flux @40 m [kW/mm^2]	0.21	0.16	0.01	0.10	0.02	0.01	0.001

*Assuming 6 mrad horizontal acceptance.

Table 2. Analysis from Ray Tracing in the ID Front End#

Component	Location m	Physical Aperture mm x mm	Ray Traced Beam Size mm x mm
BPM 1	16.3	24 x 70	6.0 x 37
Fixed Mask 1 exit	17.1	24 x 64 (12 x 52)	6.5 x 39
Photon Shutter 1	18.1	16 x 70	7.0 x 41
Fast Valve	19.4	18 x 70	8.0 x 43
Fixed Mask 2 exit	20.3	22 x 66 (10 x 66)	8.5 x 45
Photon Shutter 2	21.1	6 x 80 (4 mm closed V overlap)	8.9 x 47
Filter Assembly	22.1	12 x 72	9.3 x 48
Lead Collimator	23.7	20 x 72	10.0 x 51
Window	24.8	8.8 x 72	(3.5 x 10)*

Designed for Highest K Device (Wiggler A)

* Actual Beam Foot Print in the presence of Filters

Figure Captions

Fig. 1 APS ID Front End Optical Pass and Ray Tracing Results.

Fig. 2 Elevation View of the Conceptual Design of the APS ID Front End: (1) All metal ring isolation valve (2) Photon beam position monitor 1 (3) Fixed mask 1 (4) Photon shutter 1 (5) Collimator (6) All metal slow valve (7) All metal fast valve (8) Photon beam position monitor 2 (9) Fixed mask 2 (10) Photon shutter 2 (11) Filter assembly (12) Safety shutter (13) Collimator (14) Window

Fig. 3 Elevation View of the Conceptual Design of the APS BM Front End: (1) All metal isolation valve (2) Photon beam position monitor 1 (3) Fixed mask (4) Photon shutter (5) Slow valve (6) Fast Valve (7) Photon beam position monitor 2 (8) Safety shutter (9) Collimator (10) Be window

Fig. 4 Top View of the Conceptual Design of the APS ID Front End.

Fig. 5 Test Data of the APS Wool-Filled Enhanced Heat Transfer Tube.

Fig. 6 First Photon Shutter for the APS ID Front End: (1) hinging joint, (2) welded bellows, (3) "hockey-stick"-type water-cooled blade, (4) actuator, (5) vacuum chamber.

Fig. 7 Calculations for the APS ID Front End Vacuum System (APS Undulator A Source).

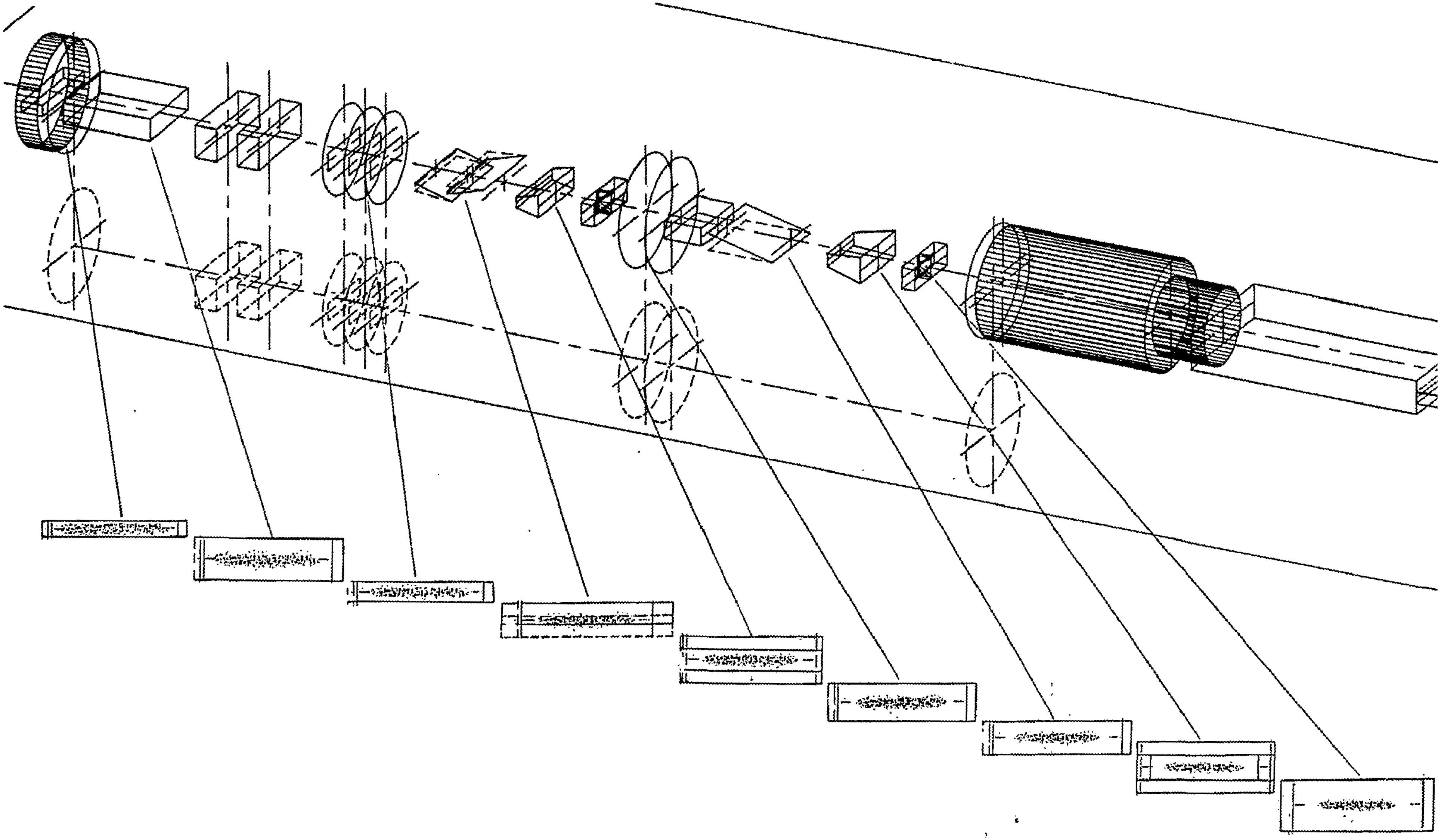
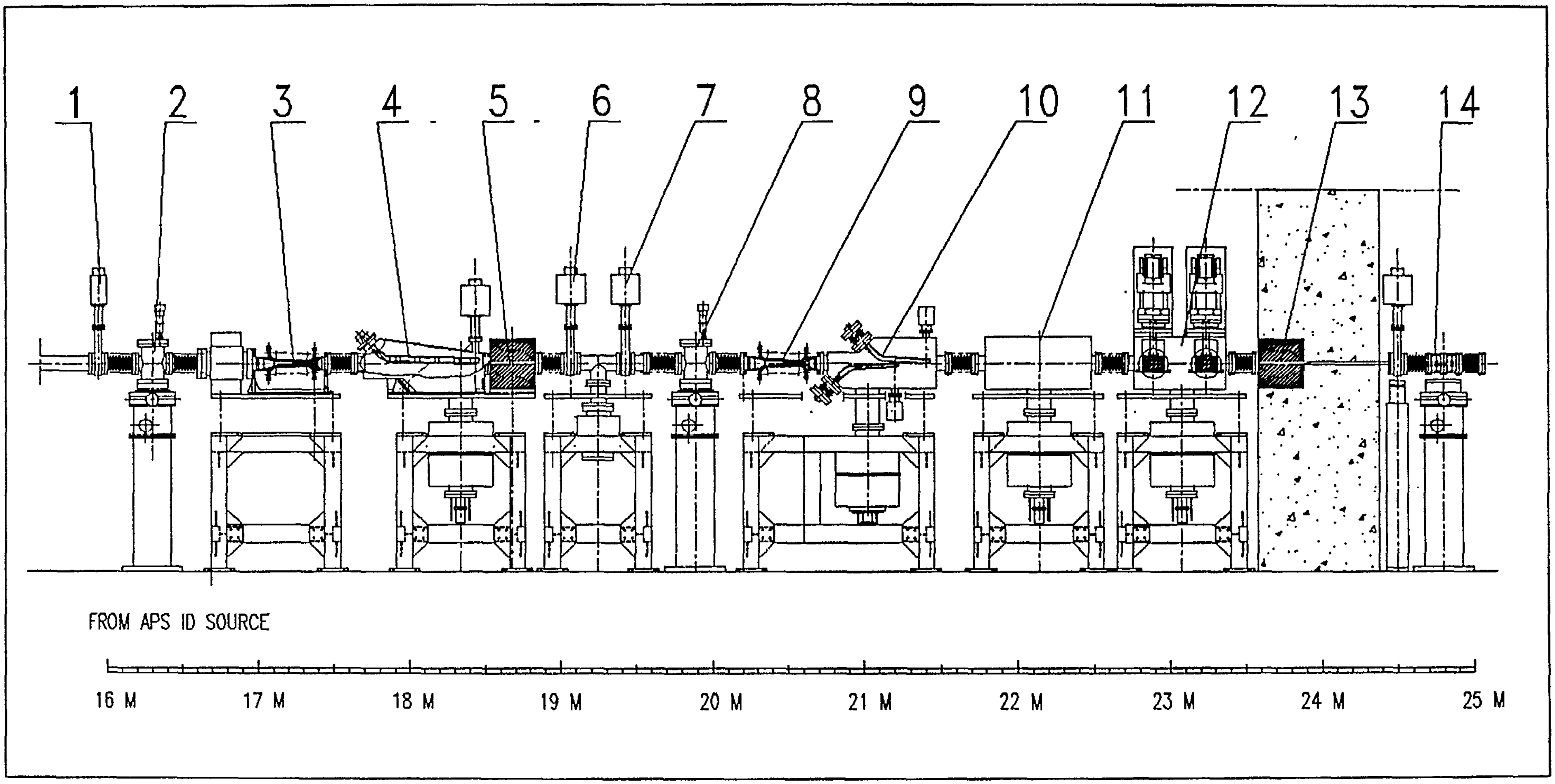
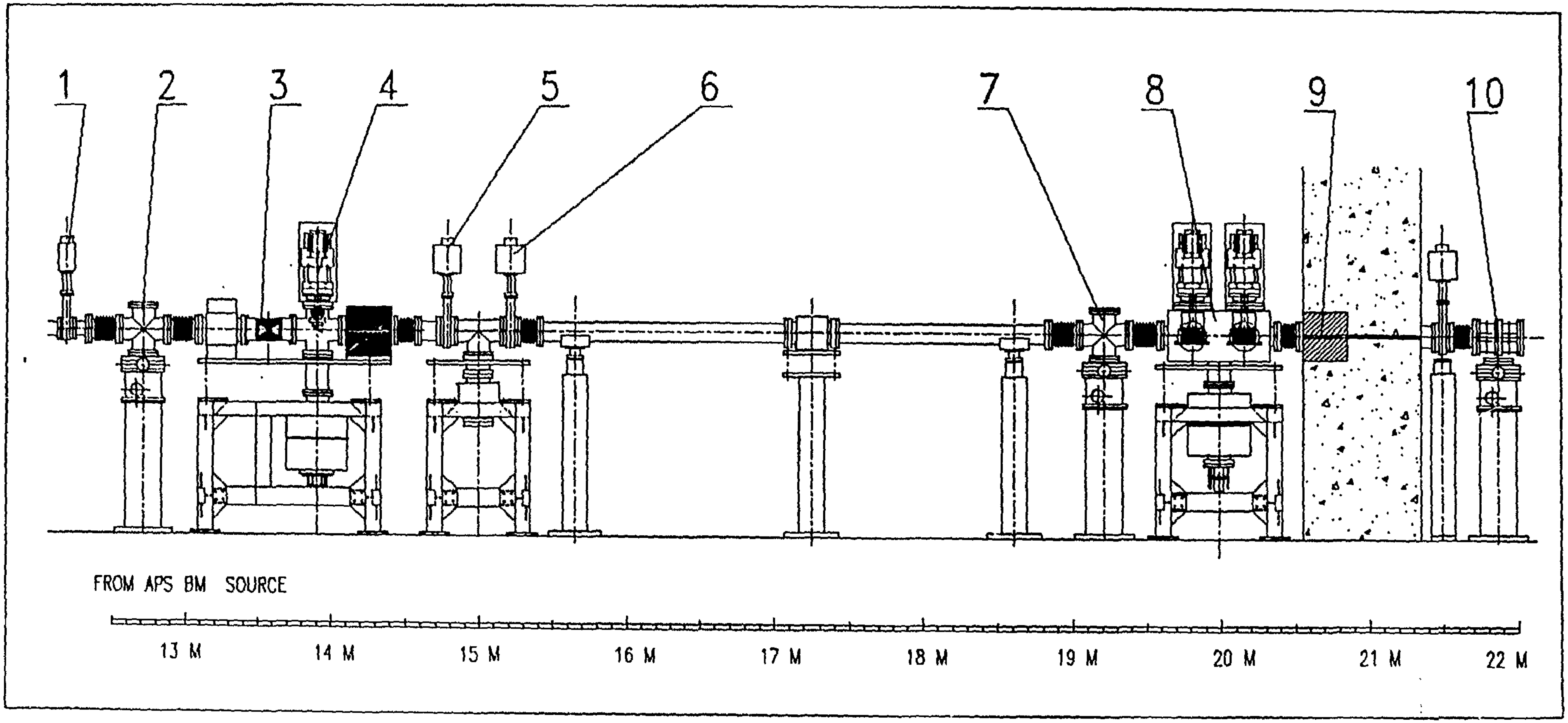


Fig. 2



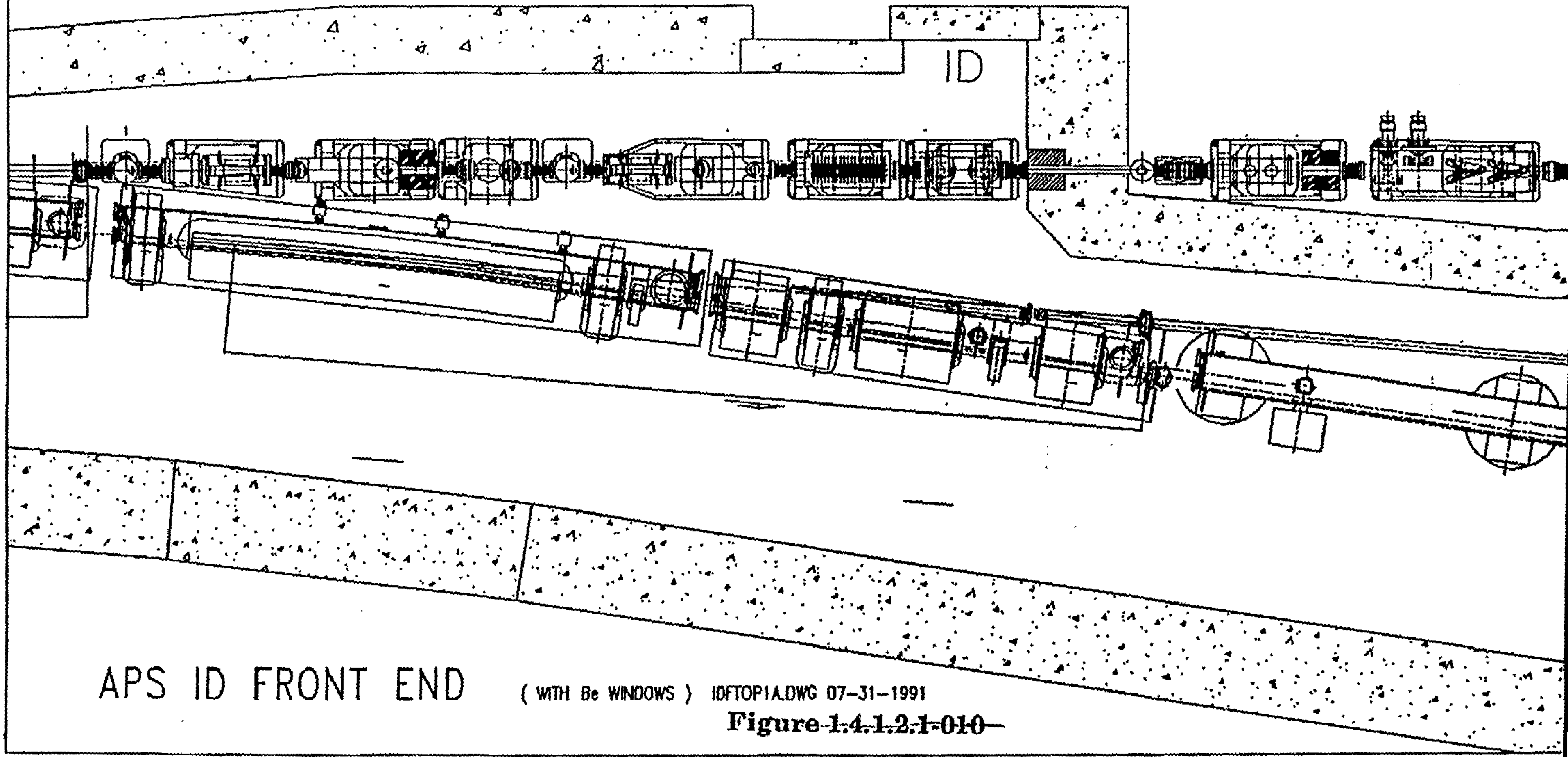
APS INSERTION DEVICE FRONT END

Fig. 3



APS BM FRONT END

Fig. 4



APS ID FRONT END (WITH Be WINDOWS) IDFTOP1A.DWG 07-31-1991

Figure ~~1.4.1.2.1-010~~

Fig. 5

FIG. 5

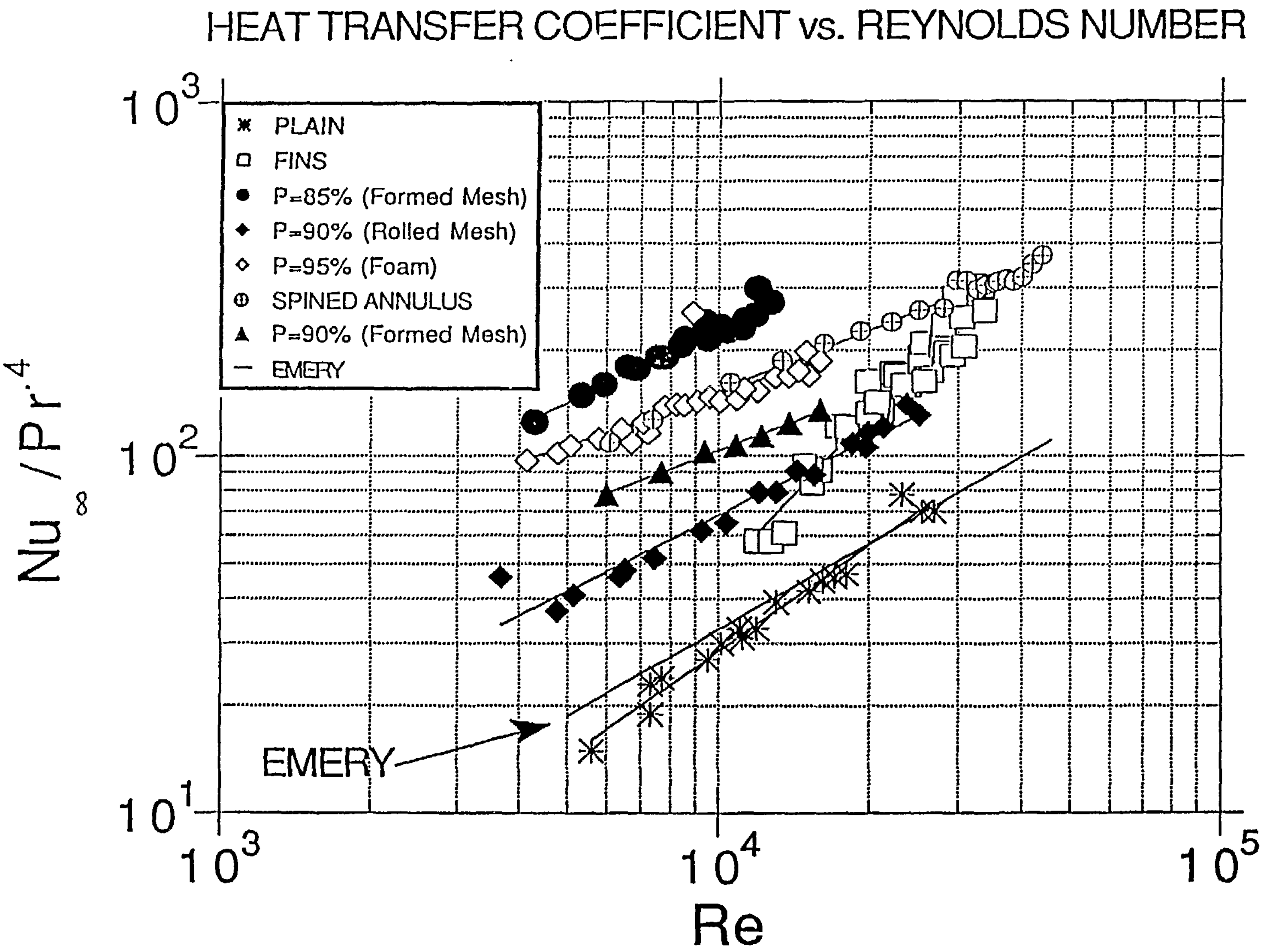

HEAT TRANSFER COEFFICIENT vs. REYNOLDS NUMBER
PLAIN
FINS
P=85% (Formed Mesh)
P=90% (Rolled Mesh)
P=95% (Foam)
SPINED ANNULUS
P=90% (Formed Mesh)
EMERY
EMERY
Nu 8 /Pr .4
10^3
10^2
10^1
10^3
10^4
10^5
Re

Fig. 6

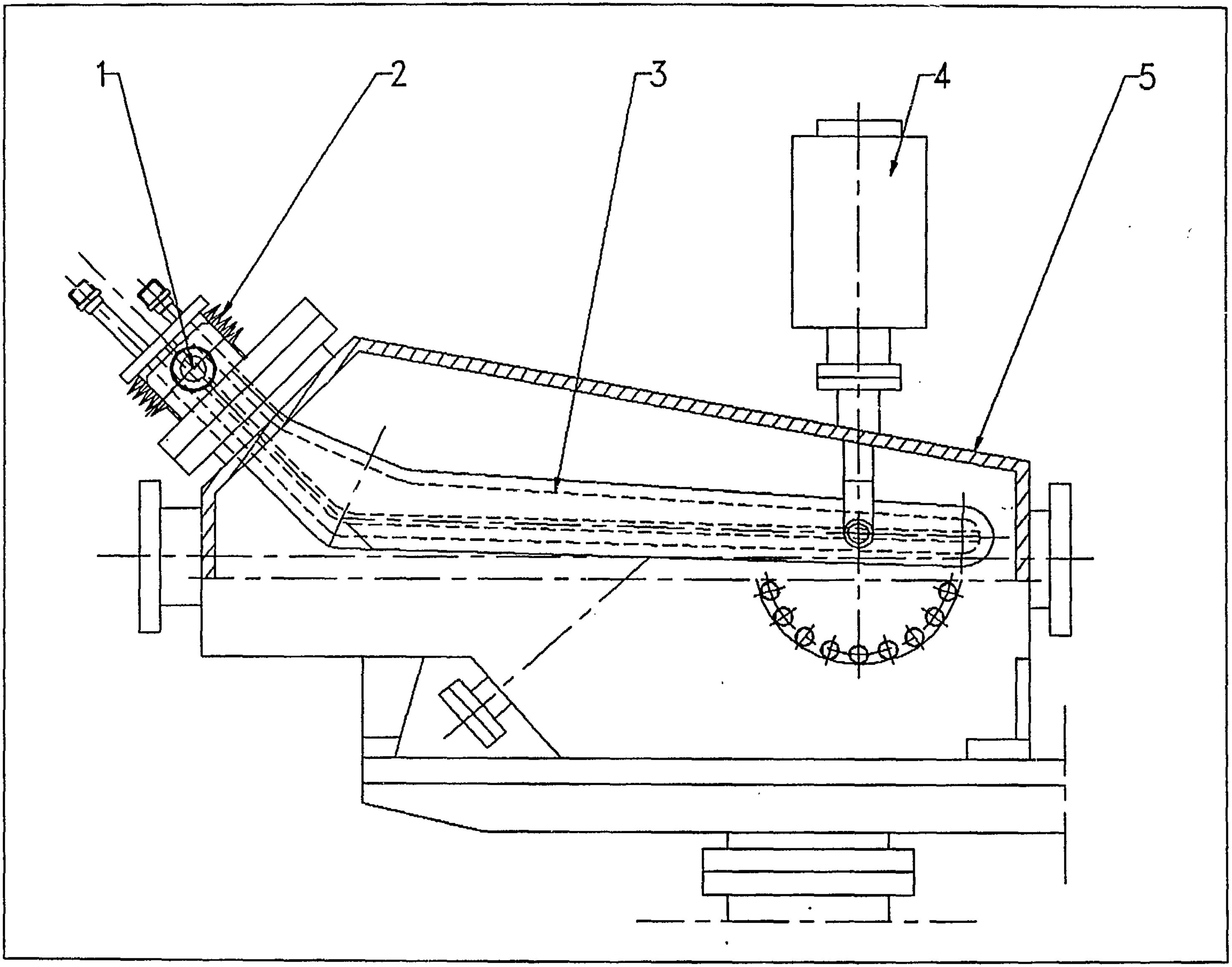


Fig. 7

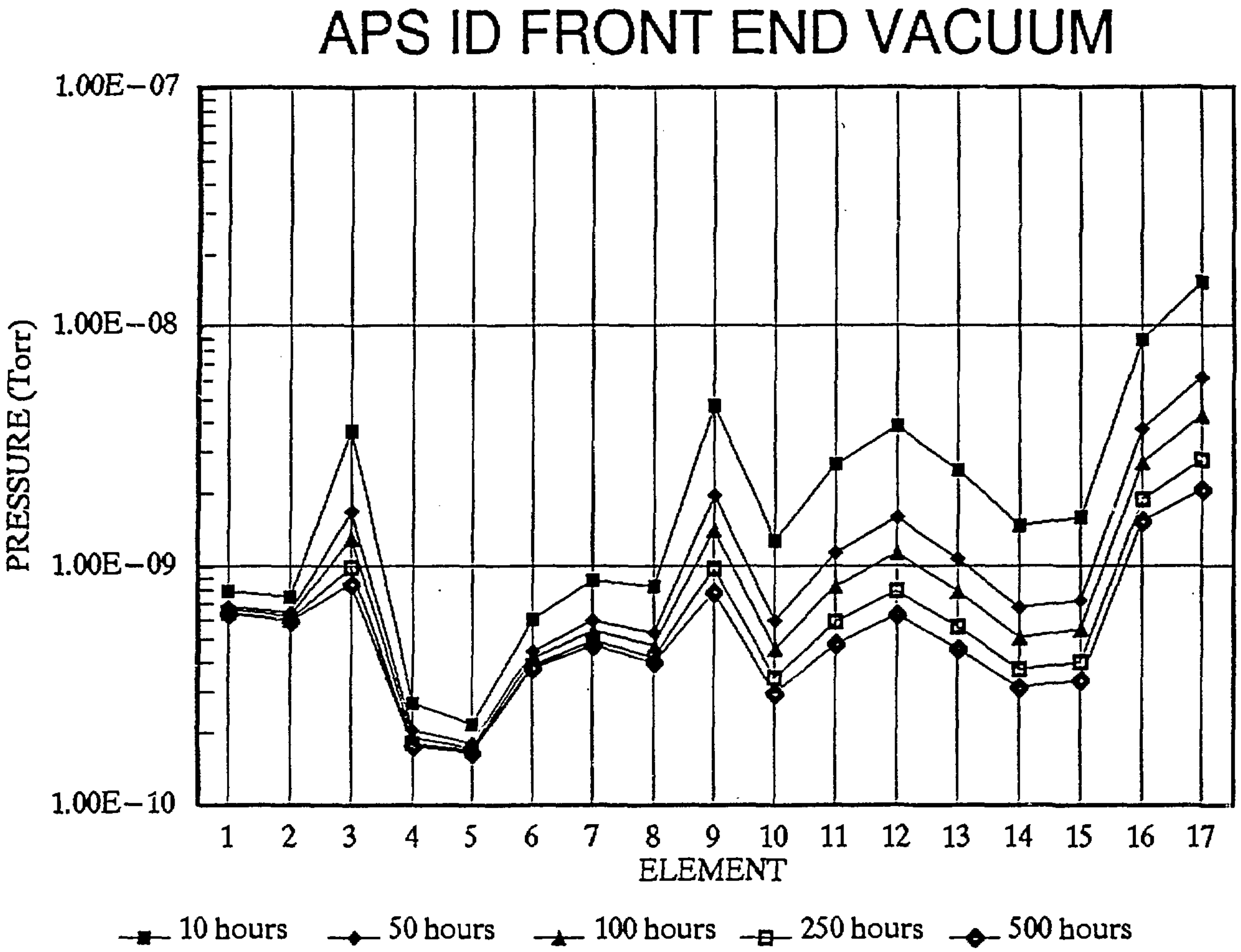

APS ID FRONT END VACUUM
PRESSURE (Torr)
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
ELEMENT
10 hours
50 hours
100 hours
250 hours
500 hours

Fig. 7