STATUS OF THE ESRF

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Abstract

The European Synchrotron Radiation Facility (ESRF) is now in its third year of construction of a storage ring complex, designed to deliver x-ray beams with a typical wavelength of 1Å and a brilliance of

$$B > 10^{18} \frac{\text{Photons}}{\text{sec mm}^2 \text{ mrad}^2 \text{ ‰ BW}}$$

The facility consists mainly of a low emittance 6 GeV storage ring with its insertion devices installed in 5 m straight sections, a 6 GeV injector synchrotron and a 200 MeV linear preaccelerator. A first stored beam is expected on schedule in 1992.

Introduction

The scientific case for the ESRF [1] identified a wide range of highly innovative experiments in solid state physics, chemistry and biology to be possible with high brilliance x-ray beams with a wavelength around 1 Å. The main user requirements and the resulting machine characteristics are given in Table 1. The schematic layout of the facility is given in Fig. 1. In the following the basic features and the actual status of the 200 MeV linac-preinjector, the 6 GeV injector synchrotron, the 6 GeV low emittance storage ring, the insertion devices and control system are described. Finally a short review of the time schedule is presented.

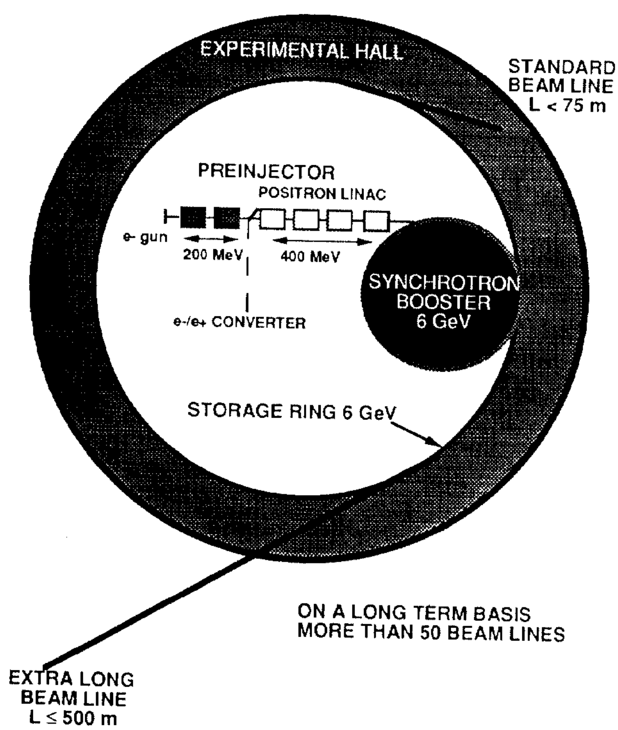


Fig 1 : Schematic Layout of ESRF Accelerator Complex

TABLE 1: USER REQUIREMENTS AND MACHINE CHARACTERISTICS

Wavelength of the fundamental line of an undulator	1 Å
Critical wavelength of synchrotron radiation from the bending magnets:	1 Å and 0.65 Å
Brilliance in the fundamental line of an undulator	$10^{18} \frac{\text{Photons}}{\text{sec mm}^2 \text{ mrad}^2 \text{ (‰ B.W.)}}$
Number of straight sections available for insertion decives	> 25
Useful straight section length	5 m
Beam stability	$\Delta x \leq 40$ µm $\Delta z \leq 9$ µm $\Delta x' \leq 1.5$ µrad $\Delta z' \leq 1$ µrad
Lifetime	$\tau \geq$ 8 hours
Operating energy	6 GeV
Design current	100mA (multibunch e-) 10mA (singlebunch)
Injection energy	6 GeV
Circumference	844.39m
Number of straight sections	32 (27 for I.D.s)
Emittance	$\varepsilon_x = 7 \cdot 10^{-9}$ m
Foreseen gap for undulators	20mm

Preinjector

A 200 MeV electron linac with an option to add an e^-/e^+ converter and a 400 MeV positron linac is foreseen as preinjector for the 6 GeV synchrotron. The commissioning of the ESRF will be done with e^- only. The e^+ option will be realized when it becomes apparent that ion effects prohibit the achievement of the planned coupling factor or the beam lifetime in the storage ring.

The design specifications for the e^- linac are given in Table 2. This e^- linac has been ordered from industry as a turn key machine. The two 35 MW klystrons, the two 6 m long accelerator sections, the buncher section, the gun and a large part of the control electronics are tested at the factory and ready for installation on the ESRF site.

TABLE 2: DESIGN SPECIFICATIONS FOR THE ELECTRON PART OF THE PREINJECTOR

	Multibunch e^-	Singlebunch e^-	Singlebunch e^+
Energy	200 MeV	200 MeV	200 MeV
Peak current	25 mA	0.25 A	2.5 A
Pulse duration	1 µs	2 ns	2 ns
Pulse rate	10 Hz	10 Hz	10 Hz
Energy spread	≤ 0.5%	≤ 0.5%	≤ 5%
Emittance $\varepsilon_{x,z}$ (2.5 σ)	$\leq 0.5\pi \cdot 10^{-6}$ rad m	$1\pi \cdot 10^{-6}$ rad m	$2\pi \cdot 10^{-6}$ rad m
Expected time for charging the storage ring for: for:	0.2 min 100 mA	0.9 min for 10 mA	20 min for 10 mA

The transferline from linac to the injector synchrotron contains an energy definition slit and an emittance measurement device which will be used for linac commissioning. It matches optically the maximum output aperture of the linac to the acceptance of the synchrotron. All components of the line are under fabrication and ready for delivery in autumn 1990.

Injector Synchrotron

The 6 GeV injector synchrotron is designed to allow:

- ◊ an emittance of the extracted beam fully governed by synchrotron radiation damping, therfore independent of the injected emittances of e^- or e^+ beams from the linac (Fig. 2);
- ◊ a large acceptance for eventual positron acceleration directly from the linac $\left(\hat{\varepsilon}_x \sim \hat{\varepsilon}_z \sim 12\,\pi \text{ mm rad}\right)$;
- ◊ fast cycling to allow operation with currents well below all eventual instability thresholds ($I \leq 5$ mA).

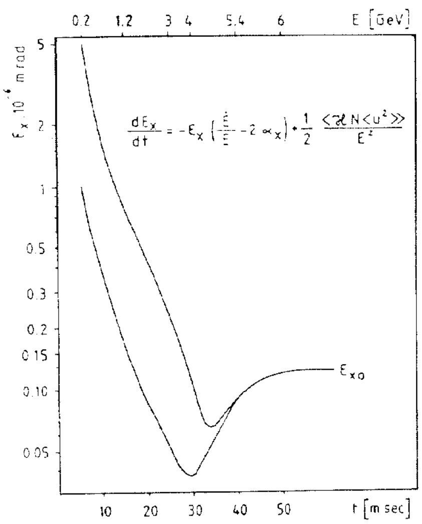


Fig. 2 : Dynamic behaviour of ε_x during acceleration in the Booster

To allow this in a cost effective way a separated function lattice damped in all three dimensions has been chosen, whose dipole, focusing quadrupole and defocusing quadrupole circuits are powered by individual pulse width modulated inverters (PWM) acting on classical white circuits (Fig. 3) which are amplitude and phase linked by a digital control unit.

The rigorous minimization of magnetic apertures (Dipole gap: 32 mm, quadrupole: inscribed radius 36 mm) allowed the single cell resonance circuits to be operated at a repetitive frequency of 10 Hz and at maximum voltages of 5.2 kV.

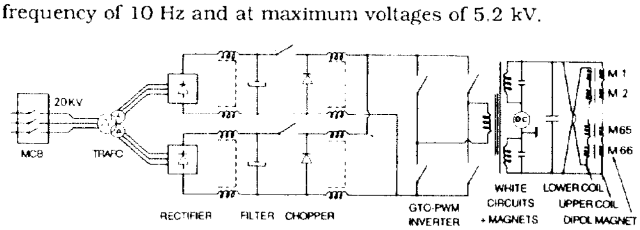
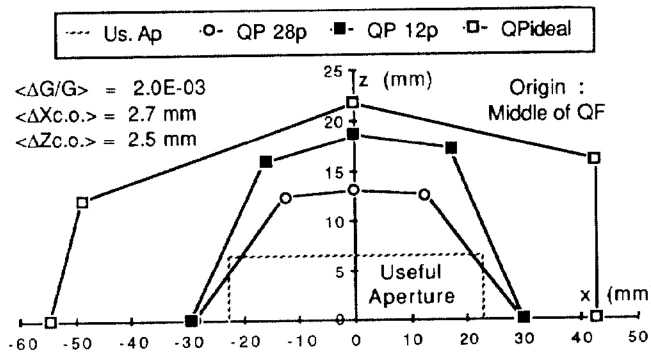


Fig. 3 · Dipole Booster Power Supply

The limit for the minimisation of the magnetic apertures is given by the reduction of the dynamic aperture due to the 28 poles of the quadrupoles which in turn reflect the limited width of the pole base of the quadrupole. Fig. 4 shows the dynamic aperture with and without the effect of the unavoidable 28 pole-component, taking into account the same closed orbit errors, the effect of the chromaticity correction sextupoles,and the statistical gradient error of the quadrupoles.



Effects of multipoles in the quadrupole on the dynamic aperture

Figure 4 : Booster dynamic aperture

The vacuum chamber is a all stainless steel vessel with 0.3 mm wall thickness reinforced by external ribs [2]. Fig. 5 shows a lattice module with dipole, quadrupole and sextupole magnets sharing a single vacuum chamber mounted on a common girder as they are planned to be preassembled before the installation as a unit in the synchrotron tunnel.

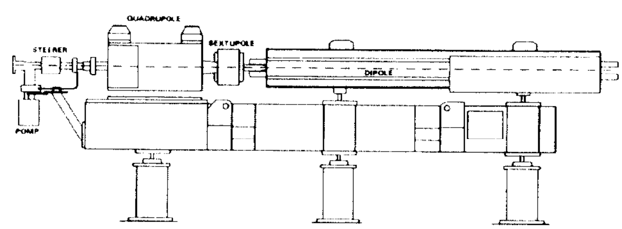


Fig. 5 Booster lattice module

The accelerating voltage is provided by two 5 cell cavities of the LEP type driven by a 1 MW 352 Hz transmitter. The main parameters of the synchrotron are summarized in Table 3.

TABLE 3: SYNCHROTRON PARAMETERS

Beam Energy	GeV	6
Nom. current (multibunch e^-)	mA	5
Nom. current (singlebunch e^-)	mA	0.1
Nom. current (singlebunch e^{+-})	mA	0.005
Lattice type		sep. function FODO
Repetition rate	Hz	10
Beam emittances	πmrad	$e_x=1.2 \cdot 10^{-7}$ (k=0)
	πmrad	$e_z=1 \cdot 10^{-8}$ (k=0.3)
Energy spread	σ_E ($\Delta E/E$)	$1 \cdot 1\ 10^{-3}$
Circumference	m	299.6
N° of cells/superperiods		39/3
Betatron tune	Q_x, Q_z	11.41/9.63
Momentum compactation	α_c	0.01
$\hat{\beta}_x / \hat{\beta}_z / \hat{D}_x$ (m)		13.2/13.5/0.81
Natural chromaticities	ξ_x / ξ_z	-14.9/-12.8
Bending radius	m	22.0
Harmonic number		h = 352
Revolution time	µsec	1
Damping times 6 GeV ($\tau_x/\tau_z/\tau_s$)	msec	2.3/2.3/1.15
Electrons/bunch multibunch mode		$8.9\ 10^7$
Electrons/bunch singlebunch mode		$6.2\ 10^8$
Min. inj. energy	MeV	200

After having magnetically measured and accepted the pre series dipole, quadrupole and sextupole magnets the series production of these magnets is under way. The power supplies, white circuits, vacuum chambers, cavities, girders, diagnostic elements and the transmitter are in various states of fabrication such as to allow start of installation of the injector synchrotron early in 1991 and start of commissioning in September 1991. The standard vacuum components like turbo pump stations, ion pumps, gauges are not yet ordered.

The 60 m transferline between synchrotron and storage ring is classical. The dipole magnets are identical and powered in series to the synchrotron dipole magnets. All elements besides quadrupole vacuum chambers and supports are under fabrication, ready for installation mid of 1991.

Storage ring

The specified high brilliance -cw- photon beams with a typical wavelength of λ ~1Å can presently only be generated by undulators working on low emittance e^- or e^+ beams of E > 5 GeV. As a compromise between minimizing the emittance on one side and the resulting increase in circumference of the storage ring and thereby the minimum distance between source point and experiment on the other side the storage ring parameters given in Table 4 have been chosen [3]. The lattice is an extended Chasman Green lattice [1]. The dynamic apertures for different operation conditions are given in Fig. 6. The two quadrupole triplets at the extremities of a lattice cell as well as the quadrupole quadruplet in the mid section of a cell are mounted on three girders together with the respective vacuum chambers, diagnostics and pumps in a preassembly area and then transported into the storage ring tunnel. All magnets are under fabrication; the dipole and sextupole preseries magnets have been magnetically measured.

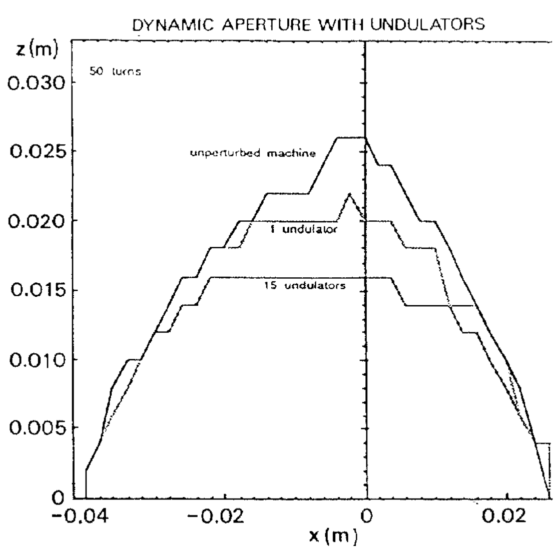


Fig. 6 : Dynamic Aperture of Storage Ring

Table 4: Storage ring parameters

LATTICE		
Energy	6.0	GeV
Beam current	100	mA
Circumference	844.39	m
Number of superperiods	16	
Horizontal betatron tune	36.2	
Vertical betatron tune	11.3	
Maximum horizontal beta	39	m
Maximum vertical beta	26	m
Maximum dispersion	0.46	m
Momentum compaction	2.8 x 10-4	
Natural rms energy spread	1 x 10-3	
Energy loss (bending magnets)	4.75	MeV / turn
Synchrotron damping time	3.6	ms
Horizontal betatron damping time	7.1	ms
Vertical betatron damping time	7.1	ms
Natural horizontal emittance	7 x 10-9	m.rad
Vertical emittance (10% coupling)	6.3 x 10-10	m.rad
Horizontal beam stay clear aperture	± 35	mm
Vertical beam stay clear aperture	± 15	mm
CHROMATICITY CORRECTION		
Number of sextupole families	6	
Horizontal uncorrected chromaticity	-115.0	
Vertical uncorrected chromaticity	-32.85	
Horizontal dynamic half aperture	-90, +60	
Vertical dynamic half aperture	-124, +124	
ORBIT CORRECTION		
Number of beam position monitors	224	
Number of horizontal correctors	96	
Number of vertical correctors	64	
Max. strength of horizontal correctors	0.9	m.rad
Max. strength of vertical correctors	0.6	m.rad
RADIO FREQUENCY		
Frequency	352.2	MHz
Harmonic number	992	
Number of klystrons	2	
Power / klystron	1	MW
Number of RF sections	2	
Number of cavities	4	
Number of cells per cavity	5	
Cavity shunt impedance	56.6	MΩ
Cavity power dissipation	125	kW
Peak voltage	10.64	MV
Total losses in the dipoles	4.75	MeV/turn
Losses in the insertion devices	1.5	MeV/turn
MULTIBUNCH MODE		
Nominal current	100	mA
Number of bunches	992	
Loss parameter	35.6	V/pC
Parasitic mode losses	10	keV
RF voltage	8.65	MV
Bunch length	6	mm
SINGLE BUNCH MODE *(computed under the assumption of bunch lengthening)*		
Nominal current	10	mA
Total loss parameter	10.5	V/pC
Parasitic mode losses	0.3	MeV
RF voltage (bucket acceptance ± 2%)	8.9	MeV
Bunch length	15	mm

These strong focusing lattices are very sensitive to positioning errors of the quadrupoles. An RMS positioning error of individual quadrupoles of 0.1mm creates RMS closed orbit errors of $\Delta x^{RMS}_{c.o.} = 10$ mm and $\Delta z^{RMS}_{c.o.} = 5$ mm at the undulator positions. The girder mounting reduces this error by a factor 3. But given the specification for the beam stability (see Table 1) and the soil characteristics of the ESRF site, a permanent control of the vertical settlement of all girders by a hydrostatic levelling system (HLS) [4] is envisaged using capacitive sensors and feedback to the remote controlled jacks of the girders. A long term laboratory test has shown, that the vertical position of a loaded girder could be kept constant with respect to a reference to within several microns over more than a month. All components of the HLS including remote controlled jacks are under fabrication. To correct for eventual vibrations of the girders, a feedback system is foreseen for position and angle of the e^- beam at the undulator locations using the position information from two x-ray position monitors in the synchrotron light beam lines. A first prototype with analog electronics has been tested [5]. A second version with digital electronics is under design.

The dipole vacuum chambers are made from stainless steel. The synchrotron radiation light leaves the beam pipe through a 9mm high slot on the outside of the chamber and enters into a side chamber, which is rf-wise screened by the slot and which contains the cooled copper absorber and the connection to the synchrotron light beam lines. The copper absorber is designed for the maximum possible power of 7 kW and power density of 600 Watt/mm^2, while the stainless steel slot bars must be protected from mis-steered photon beams by an active interlock sensing a threshold in closed orbit amplitude. The dipole chambes are under fabrication.

The straight section chambers are also stainless steel chambers with a brazed-in, indirectly cooled, bead-blasted copper absorber. These chambers are about to be ordered.

All openings in these chambers for pumps, diagnostics and the valves are rf-screened by waterjet produced stainless steel masks. The gaps between flanges have to be reduced to 0.1mm to ensure that the impedance of the total ring chamber is lower than 2 Ω.

All DC power supplies, the four 5-cell cavities of LEP-type, the two 1 MW 352 MHz RF-transmitters, the position monitor heads and the radiation safety system are under fabrication. Most of the standard vacuum equipment, the girders and supports and most of the diagnostic electronics are defined but not yet ordered. The present delivery schedule would allow start of installation of the storage ring early in 1991 and start of commissioning in February 1992.

Insertion devices

The insertion devices of the ESRF will be segmented in sections of 1.6m length. This allows an easier design of only a few standard mechanics, a simpler magnetic field measurement and a larger flexibility to reconcile thermal load and beam current and to group completely different insertion devices on one experimental set up. As a drawback one needs independently compensated ID's and phasing problems might occur below 1 keV. Table 5 gives preliminary characteristics of the first seven ID's, which are tailored to serve special classes of experiments. All of them are permanent magnet ID's. All are in the prototype phase. For the helical undulator (to produce circularly polarized x-rays) a concept has been developped to create the helical field by two plates of permanent magnets (Fig. 7) which would fit into the standard mechanics and would also allow a large horizontal aperture [6]. The created quadrupole and sextupole fields cancel out over the length of the undulator. Tracking studies have shown a similar acceptably small decrease in dynamic aperture as for the normal planar undulator.

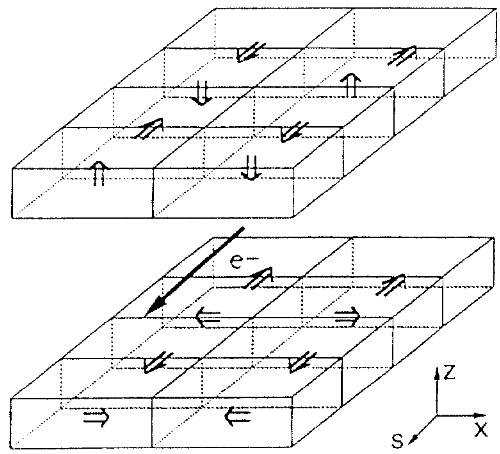


Fig. 7 : Helical undulator by two permanent magnet plates

TABLE 5: FIRST 7 ID'S (PRELIMINARY)

Segment length: 1.6m
Gap: 20mm
Permanent Magnet

Field of application	Type	λ geom	$B^{max}_{on\ axis}$
Microfocus	Tapered Und.	46mm	.48 T
High Flux	Tapered Und.	46 mm.	48 T
Diochroism	Lin./Hel. Und.	85 mm	.25/.15 T
Laue Diffraction	Tapered Und.	48 mm	0.51 T
Crystallography	Wiggler	125 mm	12 T
Surface Science	Undulator	44 mm	0.45 T
Machine Studies	Undulator	48 mm	0.51 T

Since the ESRF will need at full operation a total of 130 m of undulator length, it is essential to build the ID's most cost effective. Since the cost for permanent magnet material goes strongly up with tightened specification for uniformity of magnetization, a concept for fast and easy shimming undulators has been developped [7]. Fig. 8 shows the $\int B\,ds$ vs. the horizontal distance x from the undulator center with and without shimming

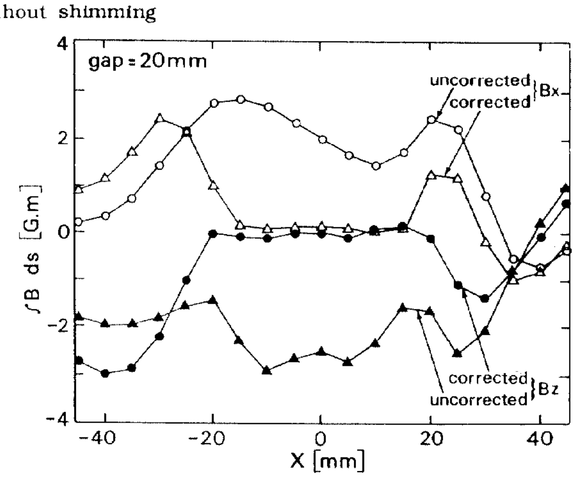


Fig. 8 : Effect of shimming a standard permanent magnet undulator

Control system

The ESRF control system [8] is structured into three levels: the console or process control level, the group level and the field level. The field level is made out of G64 card cages equipped with industrial interface boards for physical devices. Typically, 10 to 20 G64 crates are connected by means of a twisted pair multidrop field bus to a master, situated in a process level VME system.

The hardware and all network connections fom the console level down to the field level have been set up and tested successfully. Some hundreds VME field bus master- and G64 field bus slave boards are going into production. A remote procedure call tool, a technique for building distributed systems, has been completed. Basically, it allows a program on one machine to call a subroutine on another machine without knowing that it is remote. By this processing is distributed over the console / process and group level nodes.

System software for the control system is based on an object oriented client/server concept. Device servers to control hardware and general purpose servers to control physical beam variables are the method best suited to hide internal intricacies from the application level and to provide a user friendly programming interface. The concept leading to the design of these modules will strongly evolve whereas the interface towards application programmes has strictly to be kept stable. A set of device servers for the transferlines as well as for the booster synchrotron has been completed. The user's application programming interface has been tested by a control application for transferline setup.

To decouple applications from complex graphics programming, servers for virtual I/O devices based on the X-standard and on "Motif" are under investigation.

Buildings

The ESRF buildings consist mainly of a 850 m long circular hall, containing the storage ring tunnel and a 22.000m^2 experimental floor. In the inside of the experimental hall the preinjector and synchrotron buildings as well as the control room are located. The general utilities plant and the user- and staff-laboratories and offices are on the outside of the hall. Construction on site has started in January 1990. In March 1990 the fabrication of the storage ring tunnel slab and the cast in shielding wall, ratched shaped on the outside to shorten the traversal of photon beamlines has started (Fig. 9). All technical buildings and the first quadrant of the experimental hall will be handed over to ESRF for installation early in 1991, while beneficial occupancy of transformer areas and preinjector hall are already scheduled for autumn 1990. The ESRF main office building will be last in being ready in mid 1992.

Conclusion

The main components of the storage ring complex of the ESRF are under various states of fabrication, which will allow the start of installation in parallel with the completion of the building early in 1991. A first linac beam is expected mid 1991, a first beam of the injector synchrotron end of 1991 and a first beam stored in the storage ring in mid 1992. The total ESRF facility

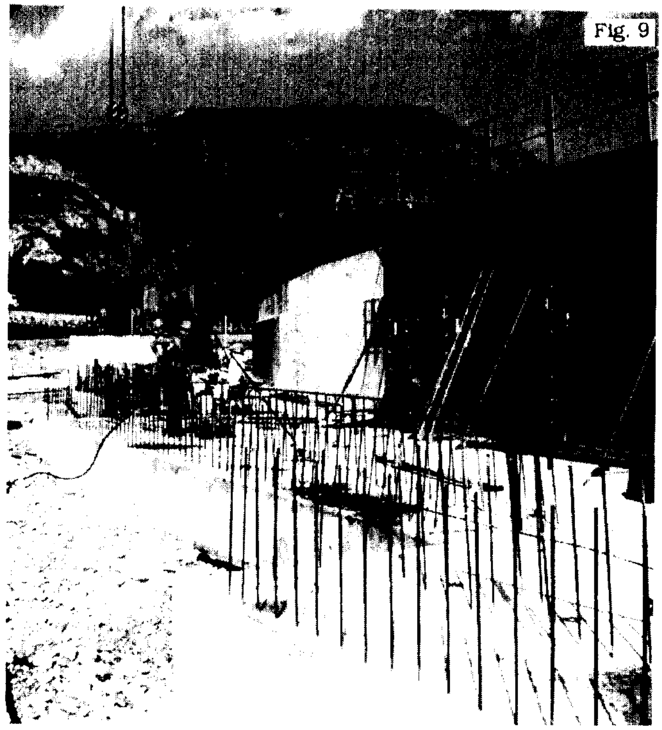


Fig. 9

which is a joint project of 11 European countries, is scheduled to resume regular user service with at least 7 fully operational beamlines at design brilliance mid of 1994. In addition several beam lines will be build up and financed by Collaborating Research Groups.

References

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[2] see e.g. J. Kouptsidis, R. Banthau, H. Hartwig, "A novel fabrication technique for this metallic vacuum chambers with low eddy current losses", 1985, Particle Accelerator Conference, Vancouver

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