The "Lillyput" - Mobile Electron Linear Accelerator for Radiography and its Use in Testing of Civil Engineering Objects

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Abstract

Purpose addressed design of 5 MeV mobile electron linear accelerator for nondestructing examination of civil engineering objects is presented. This project was executed in Italian - Polish collaboration. After construction and initial running - in at Świerk, the accelerator was completed at Aprilia and prepared for field - type utilization. Two modes of operation were provided: X-ray film radiography, and real - time radioscopy. Experimental work was carried in Italian Alps, where selected road - bridge was inspected. The obtained images were processed to get enhanced discernment of details.

1. Introduction

Nondestructive testing with high-energy X-ray radiography is one of the oldest and most popular applications of electron accelerators. Broad spectrum of various energy and various types machines were designed and built in a lot of laboratories and brought on the market by industrial companies.

When a new design appears, it is most frequently purpose oriented solution, with its technical features matched to a particular experimental programme.

The idea of LILLYPUT - linear accelerator, emerged in a collaboration of Italian industrial group IRVIN - Aprilia, and Polish Institute for Nuclear Studies - Świerk.

The principal aim, was to create a new, compact and mobile unit, able to be used in severe field - operation conditions, mostly for inspection and detection of damages in objects of civil engineering like bridges, viaducts, pipes, etc. In Italy, the country rich in mountains, there is a plenty of such objects, which should be examined at certain time intervals to avoid problems.

In the common project, the expected goal was to connect efforts and profit from experiences of both parts in accelerator physics and technology, appropriate instrumentation for data acquisition and processing, and practical application of accelerator - based systems.

The main features of the LILLYPUT accelerator should be emphasized: the machine's design with careful optimization of subsystems' solutions, subordinated to the requirements of field-operation, and computer-assisted procedures of image processing, which were prepared in ENEA-Frascati.

2. Formulation of Basic Requirements

As the accelerator has to work in open-air conditions, and radiation-head penetrate into important parts of examined object, a number of indications are imposed on the designing process:

- separation of the radiation source, and power-supplies and control system by a distance necessary to limit exposure at operators' position below prescribed level
- diminishing of dimensions and weight of radiation head, to enable its manoeuvring possibilities
- resistance to extremal weather conditions-broad range of environmental temperature and high humidity
- resistance to mechanical vibrations during transportation and manoeuvring on working place
- computer supported remote control and stabilizing systems for maintaining constant parameters in various conditions
- efficient interlock and protection circuits for ensuring of radiation safety

For matching of accelerator's parameters to its principal task in detection of defects in structures composed typically of steel and concrete, the list of technical requirements has been formulated as follows:

Energy of accelerated electrons	-	5 MeV
Dose-rate of X-rays, at 1m distance from source	-	500 rad/min
Tolerance of dose-rate	-	$\pm$ 5%
Focal spot on conversion target	-	2 mm max
Collimation cone angle	-	28^0
Radiation uniformity inside the cone	-	10% max
Time to reach nominal radiation- - intensity from switching "beam-on"	-	5 sec
Radiographic definition (in percentage of thickness for steel 50-250 mm at 1 m from source)		DR $\leq$ 1%
Leakage radiation (at 1m distance from radiation head outside collimator cone)	-	3% max of axial value
Working external temperature	-	0 - 50^0 C
Working relative humidity	-	100% max
Endurance for vibration	-	2 g 5 Hz-50 Hz
Endurance for shock	-	20 g for 18 msec

3. Description of design features

The adapted configuration of accelerator is composed of two subunits separated by the distance of 50 m, and interconnected by a bundle of cables and waterpipes.

The first unit - radiation head is located on a manoeuvring crane, and contains an accelerating structure with electron gun, beam transport and monitoring devices, X-ray source with collimator, and r.f. power supply system.

In an operators' van, all power supplies, switch-boards, electronics, automatic control and monitoring systems,as well as appropriate instrumentation for experimental programme are located.

Of main interest are:

- accelerating structure
- r.f. system with automatic frequency control
- conversion target and collimator
- cooling system with temperature stabilization
- computer assisted monitoring and control

Accelerating structure is of standing-wave, $\pi/2$ mode with axial coupling guide, working in S-band.

Attached electron-gun is of diode type, with Pierce optics and internal magnetic focusing.

Two versions of the structure were designed and constructed - first with axial beam generating X-rays, and second with either axial beam, or transversal beam after 90^0 deflection. It might be useful for inspection of some difficult accessible places in objects.

Computation of electromagnetic fields and beam dynamics was done at Świerk, where the structures were also executed using technological procedures elaborated in SINS.

Main parameters:

Resonant frequency	F_0 = 2997.85 MHz
Quality factor	Q_0 = 12 500
Shunt impedance	Z_0 = 71 M Ω/m
Stop band	Δ = 115 kHz
Coupling to the waveguide (without beam loading)	β = 1.48
Mechanical length	L = 530 mm
Beam energy	E_0 = 5 MeV
Injection energy from the gun	E_i = 40 keV
Working temperature	t_w = 40^0 C
Working pressure	p = 10^{-8} Tr

Designing approach was rather conservative, in order to get well established results and very reliable operation.

The electron-gun, waveguide vacuum-window and conversion target are detachable for easy replacement.

Accelerating field in the structure is excited by r.f. power generated in pulse - magnetron and transmitted through the rectangular waveguide filled with insulation gas, and incorporating ferrite isolator and circulator in its path.

Automatic Frequency Control system keeps magnetron at structure's resonance, and utilizes hybrid coupler bridge for phase comparison and generation of correction signal. For proper operation of AFC the coupling waveguide - structure should be always overcritical. Magnetron is powered by high - voltage line - type pulser, with pulse length 4 μsec, and repetition frequencies 50 - 300 Hz.

Electron beam during acceleration process is guided by axial magnetic field generated by solenoid. Additional correction coils allow for transversal shifting of the beam, and transporting it to the right spot on conversion target.

The generated X-ray beam is monitored by ionisation - chamber and equalized by flattening filter.

Of extreme importance is the temperature control in radiation - head. Almost all components located there are temperature sensitive, and so for proper working parameters' stability, the cooling system should be very effective and computer supervised. Having in mind 50 m distance between radiation - head and the equipment - van, where also the heat exchanger is located, changing temperature drop on long water pipes, should be properly compensated.

To minimize the influence of external temperature variations, humidity, and sun operation, the radiation - head is hermetically sealed, filled with insulation gas, and capsule's walls done from stainless - steel, highly polished - to reflect sun radiation.

The monitoring and control system adopted to specific functions of accelerator has two modes of operation:

- radiographic mode
- service and experimental mode

This computer assisted electronic control network, uses three - processor system and GESPAC logic - the solution checked previously in another accelerators.

4. Laboratory measurements

At Świerk, all components of radiation - head have been separately tested, and after completion the entire capsule undergone vibration and shock tests. Several detected mechanical resonances have been eliminated.

The running-in procedure was effectuated on specially prepared test-bench. Main parameters have been verified.

Max. energy of accelerated electrons reached	6.5 MeV
Max. X-ray dose-rate at 1 m distance was	900 rad/min
Focal spot was below	2 mm

At Aprilia, the whole accelerator has been assembled, with operator's van, long cable connections, and autonomous power supply. Complete system of temperature control has been operated and tested. During radiation experiments, a series of steel-concrete samples were inspected, and reference radiograms prepared.

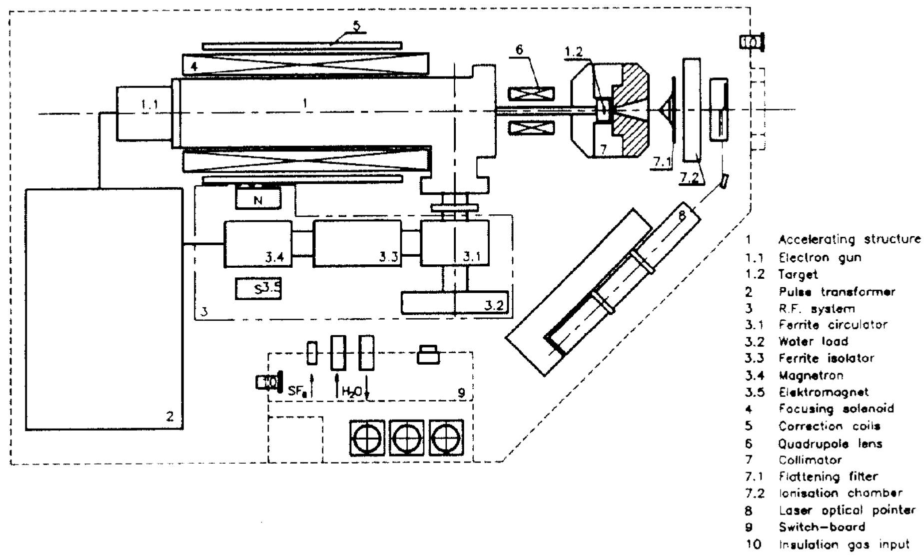
5. FIELD OPERATION

The road transportation of the accelerator had an itinerary: Aprilia - Pisa - Genova - Torino - Pardonecchia (Alps). Experimental area around the tested bridge was closed for penetration, and interlock chain for radiation safety was installed.

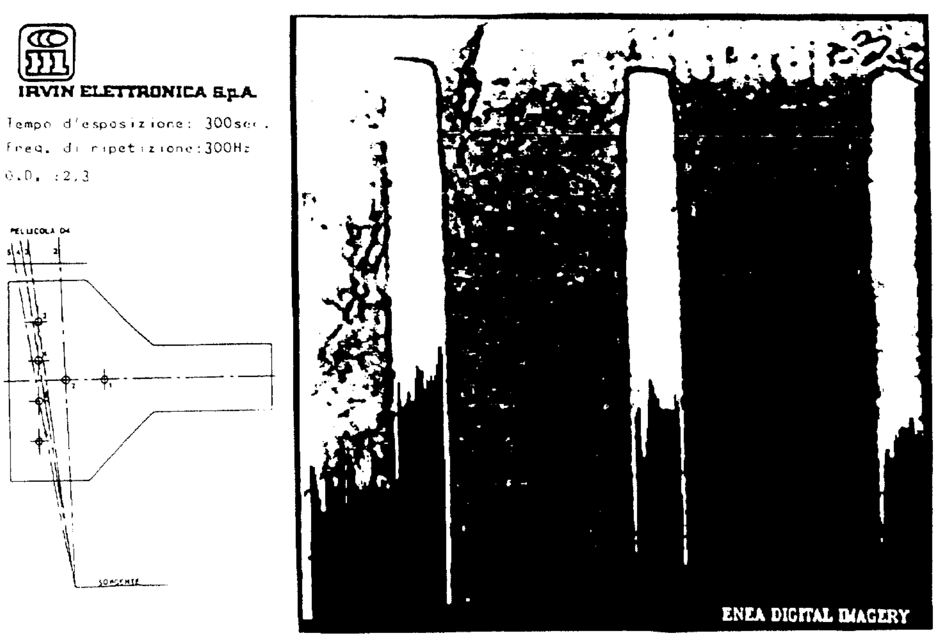
The vehicle with manoeuvring crane on which the accelerator head was attached, took position on the bridge, and crane's arm positioned the radiation head under bridge-span. Selected junctions of supporting girders were exposed to X-ray examination.

The resulting data were processed in ENEA - Frascati with help of digital imaging codes.

The whole experiment was considered as fully successful. After this field - exploitation, the accelerator was transported back to Aprilia, and was immediately operational.



BLOCK DIAGRAM OF "LILLYPUT" RADIATION HEAD



Reference radiogram of concrete - steel structure