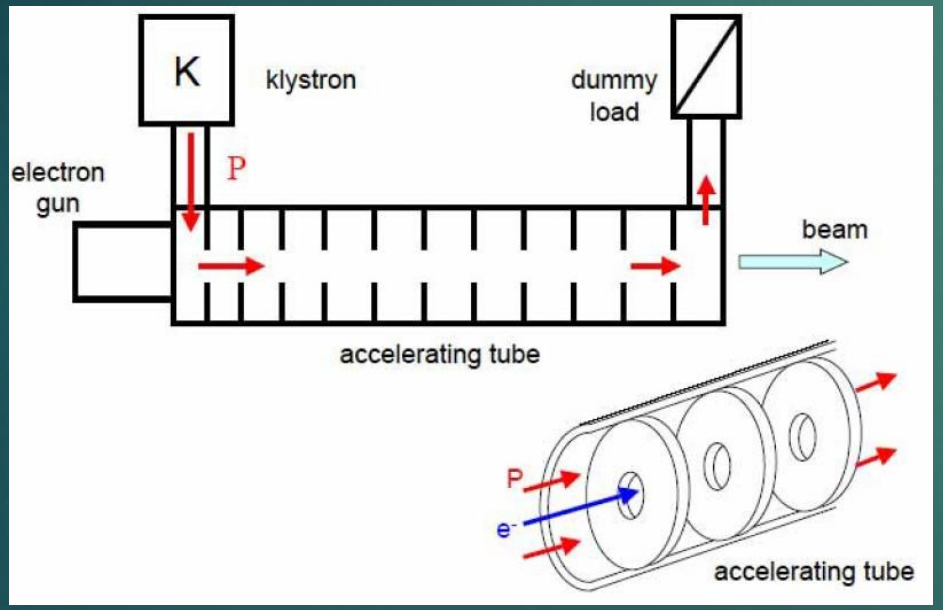
Linear electron accelerators for radiation processing

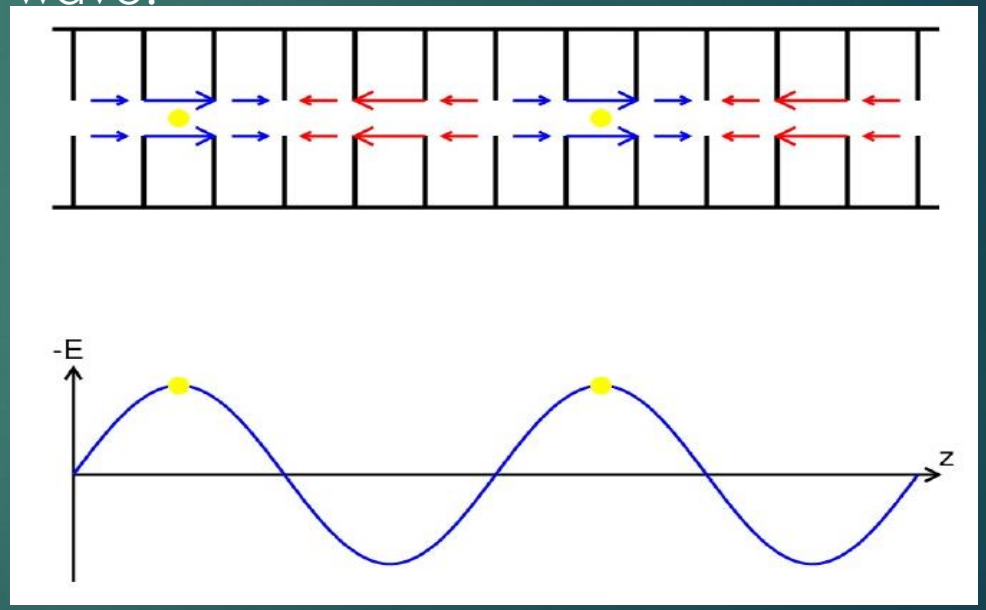
MIKHAIL DEMSKY, CORAD LTD, ST. PETERSBURG, RUSSIA (WWW.CORAD.PRO)

How linear electron accelerator (linac) accelerates electrons:

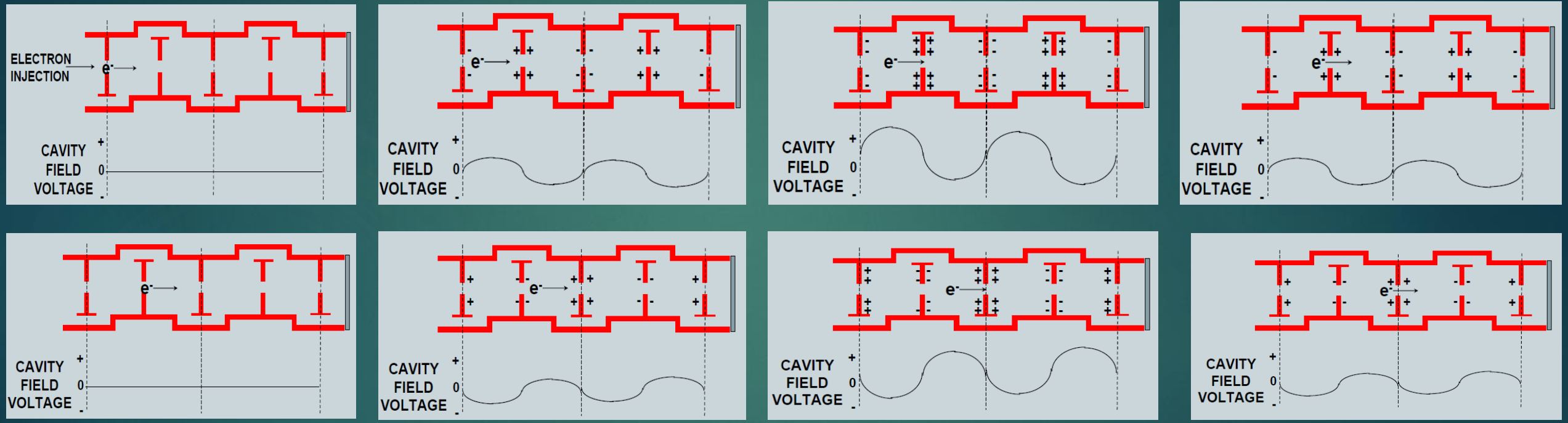
A scheme of a linac with a traveling wave accelerating structure:



Distribution of the electric field and electrons positions in $2\pi/3$ mode structure with traveling wave:



Electrons accelerating process in a standing wave side coupled structure:



Dr. Roland Schmidt, Siemens AG, Medical and industrial applications of linear electron accelerators, 27.04.2009

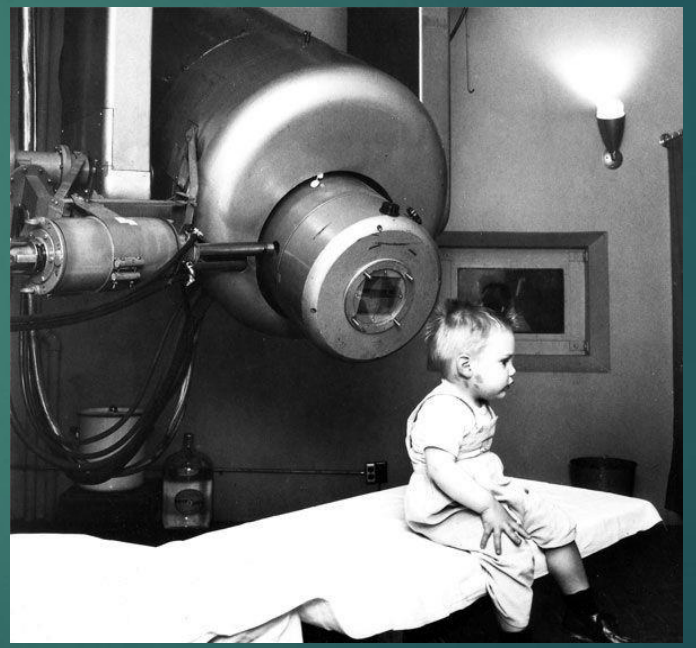
Main applications of linear electron accelerators (linacs) with energy of 5-10 MeV:

- Radiation therapy
- Non destructive testing
- Cargo inspections
- Radiation technology

About 5000 medical linacs for radiation therapy are operating worldwide

The first medical linear accelerator installed at Stanford Hospital in San Francisco in 1956:

The first patient to receive radiation therapy from the medical linear accelerator at Stanford was a 2-year-old boy:



Source: http://news.stanford.edu/news/2007/april18/med-accelerator-041807

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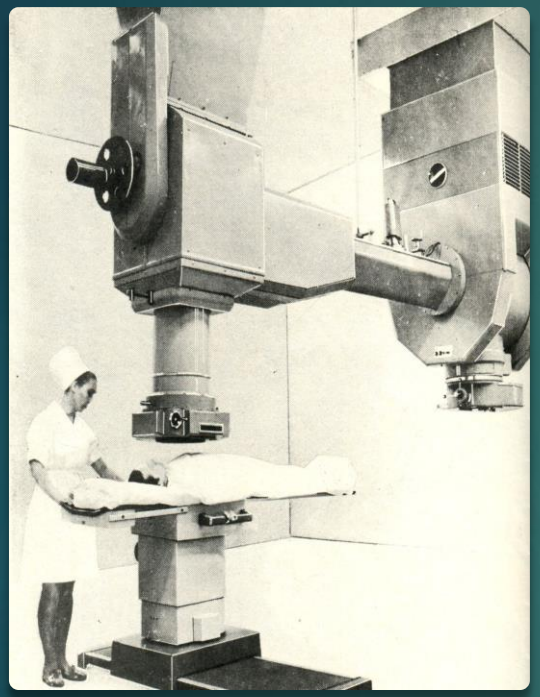
Medical linacs being made by the Efremov Institute (NIIEFA, Russia):



30 MeV

4 accelerators

In 1967 - 1972

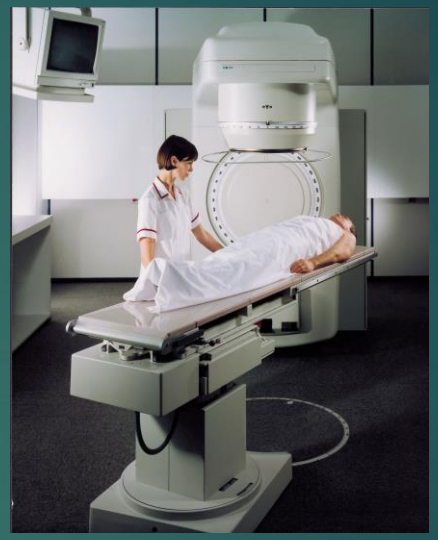
15 MeV

15 accelerators

20 МэВ

6 accelerators

1977-2004



6 MeV linac Elekta SL75-5 have been made together with NIIEFA

63 accelerators in 1996 - 2013

Source: Efremov Institute booklets of different years

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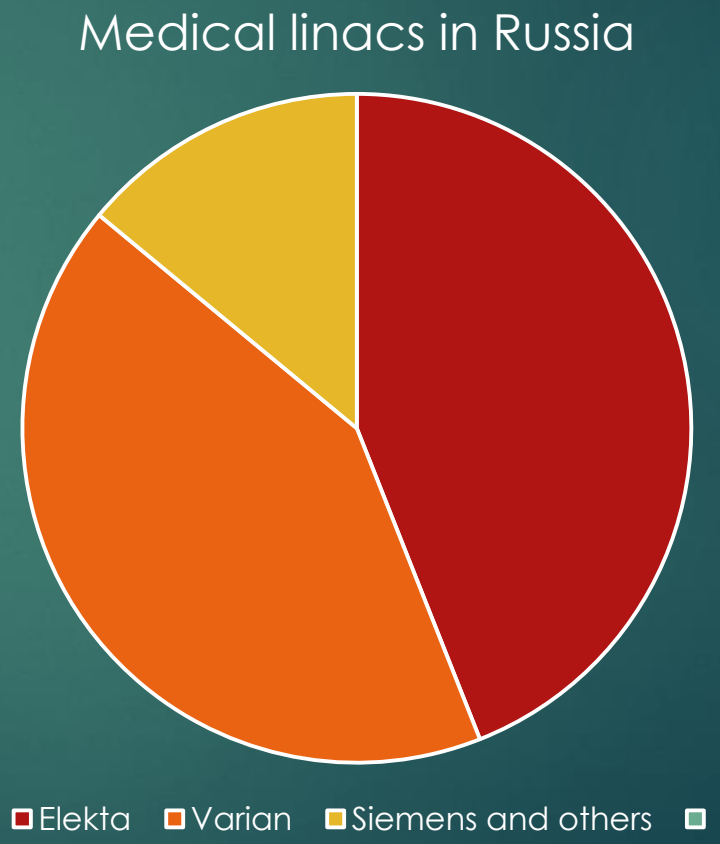
Now in Russia there are about 160 medical accelerators of the world's leading manufacturers:

~44% Elekta
~42% Varian
~14% Siemens and others



Linacs for Non Destructive Testing (NDT) and Custom Inspection

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Varian offers 5 linacs with different energy:

Type	Energy MeV	Steel thickness mm
M1	0,95	38-101
M3	3	38-203
M6	6	51-254
M9	9	76-381

X-ray Head and RF Unit

https://www.varian.com/ru/x-ray-imaging-components/products/security-industrial-imaging/linear-accelerators

Many companies makes linacs for NDT: Varian, Nuctech, Siemens, Efremov Institute and others

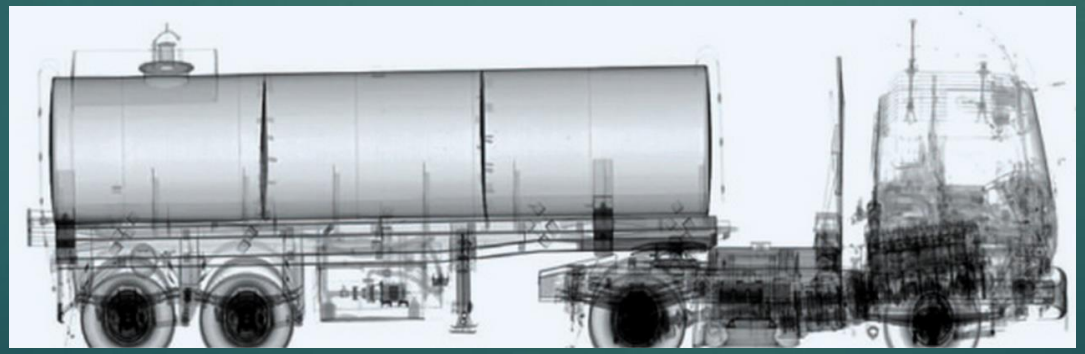
Linacs of Efremov Institute (Russia) for NDT with energy of 6 and 10 MeV:

http://www.niiefa.spb.su/

New linac made by SINP MSU & RPE TORIY (Russia) with energy adjusted in the range of 3-8 MeV

http://nuclphys.sinp.msu.ru/nseminar/28.05.13.pdf

Linacs for NDT are using in cargo inspection systems:



Dr. Roland Schmidt, Siemens AG, Medical and industrial applications of linear electron accelerators, 2009
& http://www.rapiscansystems.com/ru/products/cvi

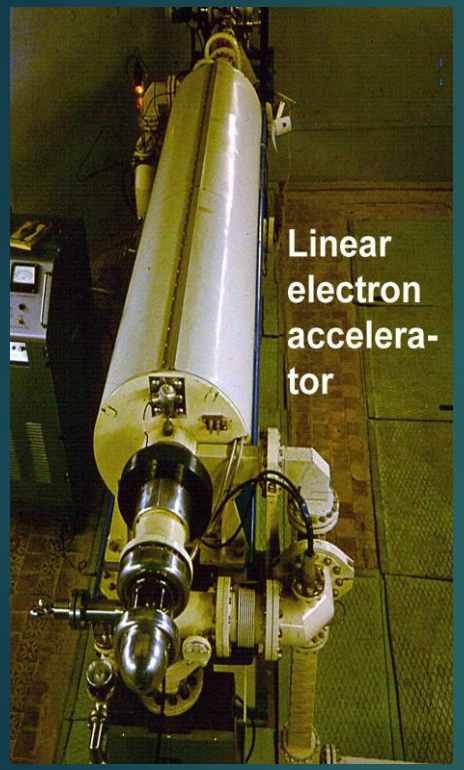
Linacs can compete with another accelerators in technologies where at least 5 MeV is needed and no more than 30 kW beam power:

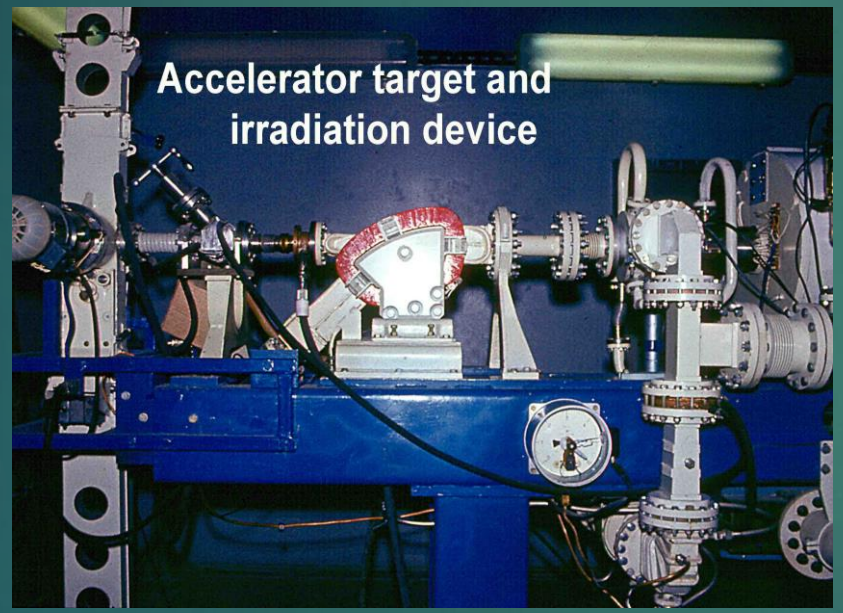
Technology	Dose range, kGy	Energy range, MeV
Sterilization of healthcare products	10-30	5-10
Food irradiation	1-10	10 in electron mode 5 & 7 in X-ray mode
Crosslinking of thick plastic items in order to increase temperature resistance, mechanical strength and producing heat shrinkable goods	50-150	5-10
Semiconductors irradiation	50-500	5-10
Gemstone irradiation	$5*10^4$ -10^5 Topazes	10-22
Activation analysis of gold in ores	1 - 3 X-ray	8

Manufacturers of high power linacs with energy of 5-10 MeV for industrial applications:

Company	Country	Quantity of 5-10 MeV linacs with power > 4 kW	Remarks
Linac Technologies	France	~15	before 2009
MEVEX	Canada	28	
SureBeam (now incorporated in L3 Communication)	USA	~20	before 2004 when it was bankrupt
TORIY	Russia	~100	before 1995 and now they are making a new linac together with SINP MSU
Efremov Institute (NIIEFA)	Russia	~18	~15 before 1982 and than else 3 linacs
CORAD	Russia	5	since 2005
Mitsubishi Heavy Industries	Japan	>4	
HI – WITS Technology Development Co., Ltd	China	at least 1	
HTA Co., Ltd (China)	China	at least 1	

8 MeV, 5 kW linac of the Efremov Institute is operating in Uzbekistan since 1976 already 39 years 16-24 hours per day





The physical concept of analytical process is the nuclear reaction of gold nuclei interaction with photon radiation induced by 8 MeV electron beam:

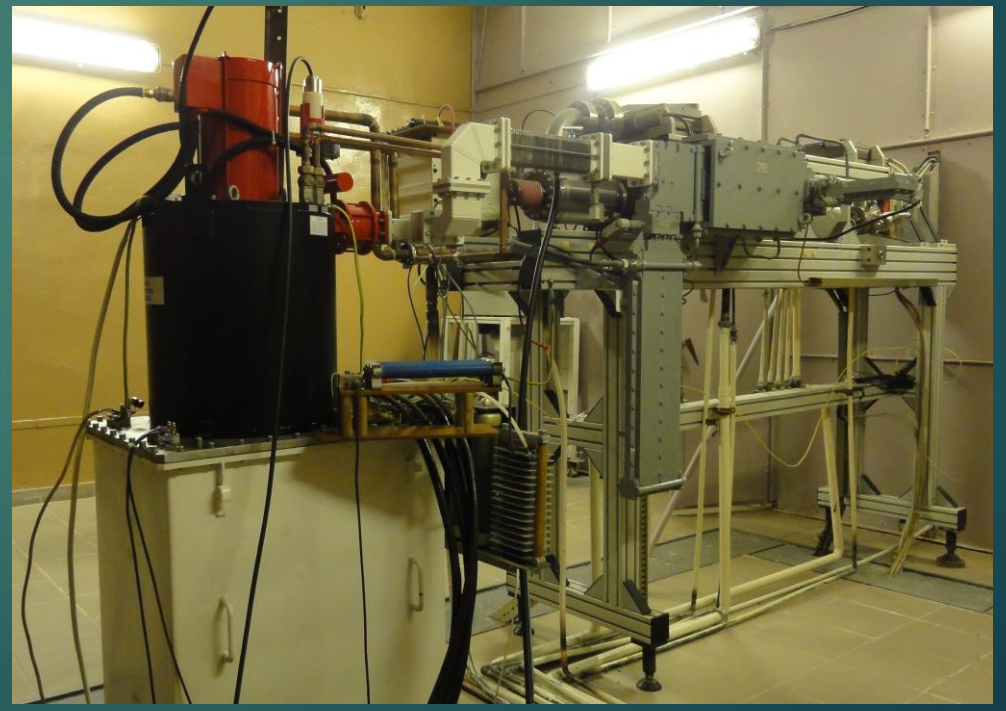
Au-197 + g = Au-197m

Isomeric state of Au-197m has a half-life period of 7,5 sec

Our company CORAD Ltd is making radiation facilities with linacs since 1992

CORAD Ltd is spin off of the Efremov institute. We used linacs made by Efremov institute (NIIEFA) on the basis of magnetrons at first.

Since 2005 we are making linacs ourselves on the basis of klystron TH2173F (Thales Electron Devices).



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EB systems designed and made by CORAD Ltd or in a collaboration with CORAD Ltd:

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Company	Location	Energy MeV	Power kW	Technology	Accelerator manufacturer	Year
POLICOR Ltd	St. Petersburg, Russia	8	5	Sterilization, crosslinking	NIIEFA	1992
LEIDI Radiation Technology Co.	Guanghan, Sichuan, China	8	5	Crosslinking, semiconductors irradiation	NIIEFA	1996
Electron Nord	Borre, France	6-10	5	Sterilization	NIIEFA & CORAD	2000
RAD Ltd	St. Petersburg, Russia	8 8	5 10	Sterilization, crosslinking of shrinkable items	NIIEFA CORAD	2004 2010
Karpov Institute	Obninsk, Russia	10	10	Crosslinking of shrinkable items	CORAD	2005
VINAGAMMA	Ho Chi Minh City, Vietnam	10	15	Food irradiation	CORAD	2011
Russian medical biophysical center	Moscow, Russia	10	10	Sterilization	CORAD	2012
Ural Federal University	Ekaterinburg, Russia	10	10	Sterilization	CORAD	2013

CORAD's linacs features:

- high efficiency due to using solid-state modulators for klystron and electron gun
- continuous control of electron energy, beam current and scanning length during electron beam processing
- beam extraction system allows irradiating opposite sides of boxes during one pass.

Klystron Modulator

Typical modulator on the basis of high power thyratron with efficiency of ~60%:

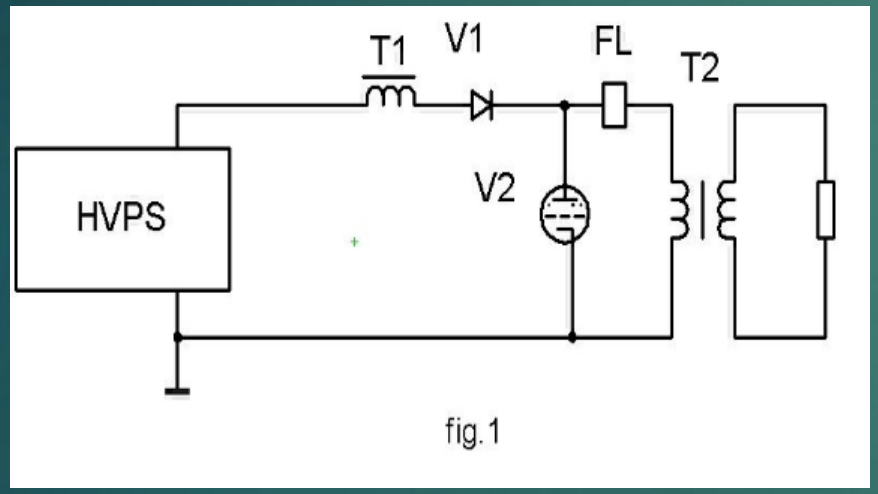


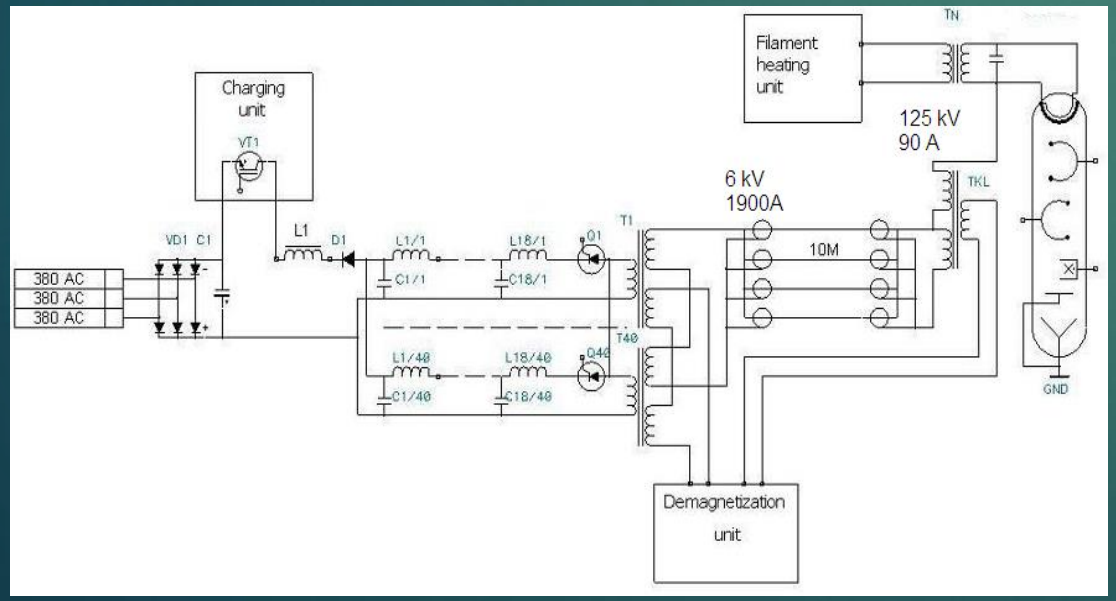
fig.1

Modulator of MEVEX linac with dimensions approximately 350x150x200 cm:

(www.mevex.com)

CORAD's solid-state modulator

The klystron modulator employs a well-known scheme with an inductive voltage adder configuration. Total output voltage up to 6 kV is a result of adding voltages of 58 cores, each being a load of a pulse forming line (PFL) switched by thyristors.

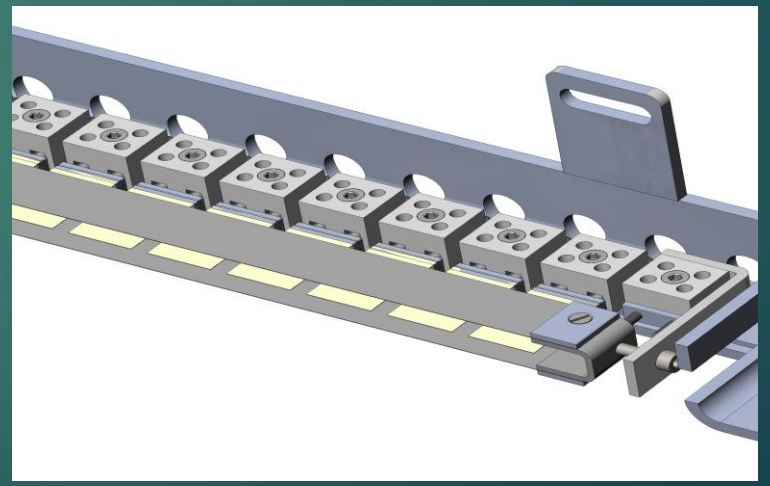


Efficiency ~85%

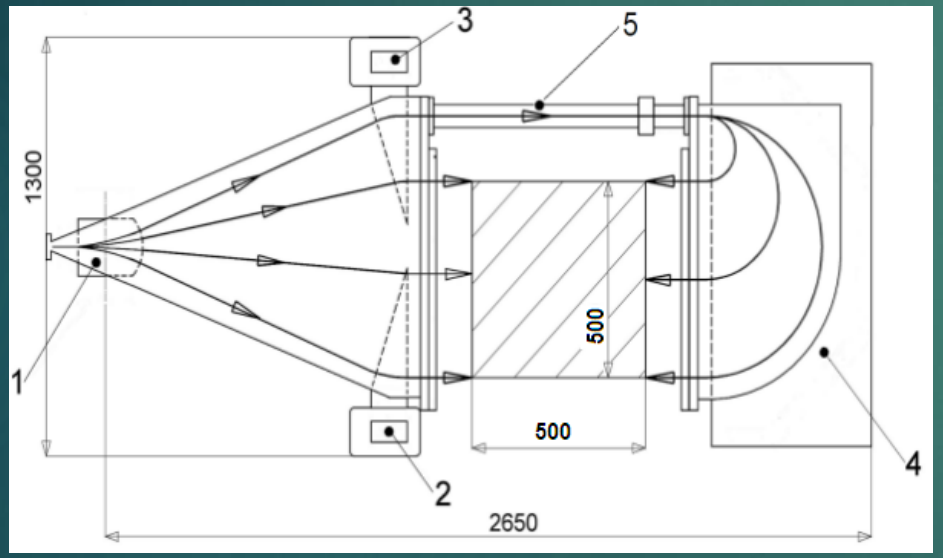
Dimensions 160x60x220 cm

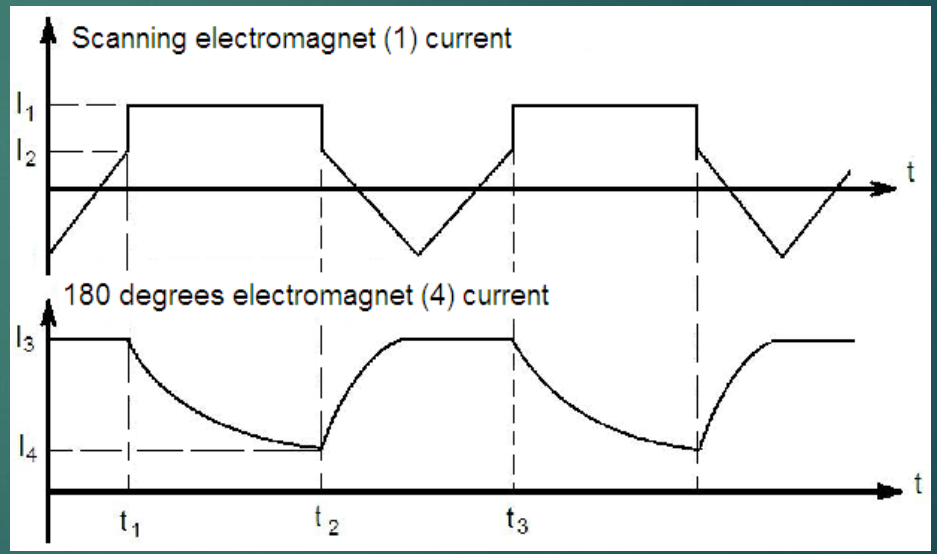
An air ionization chamber is used to control the scanning length and energy of electrons:

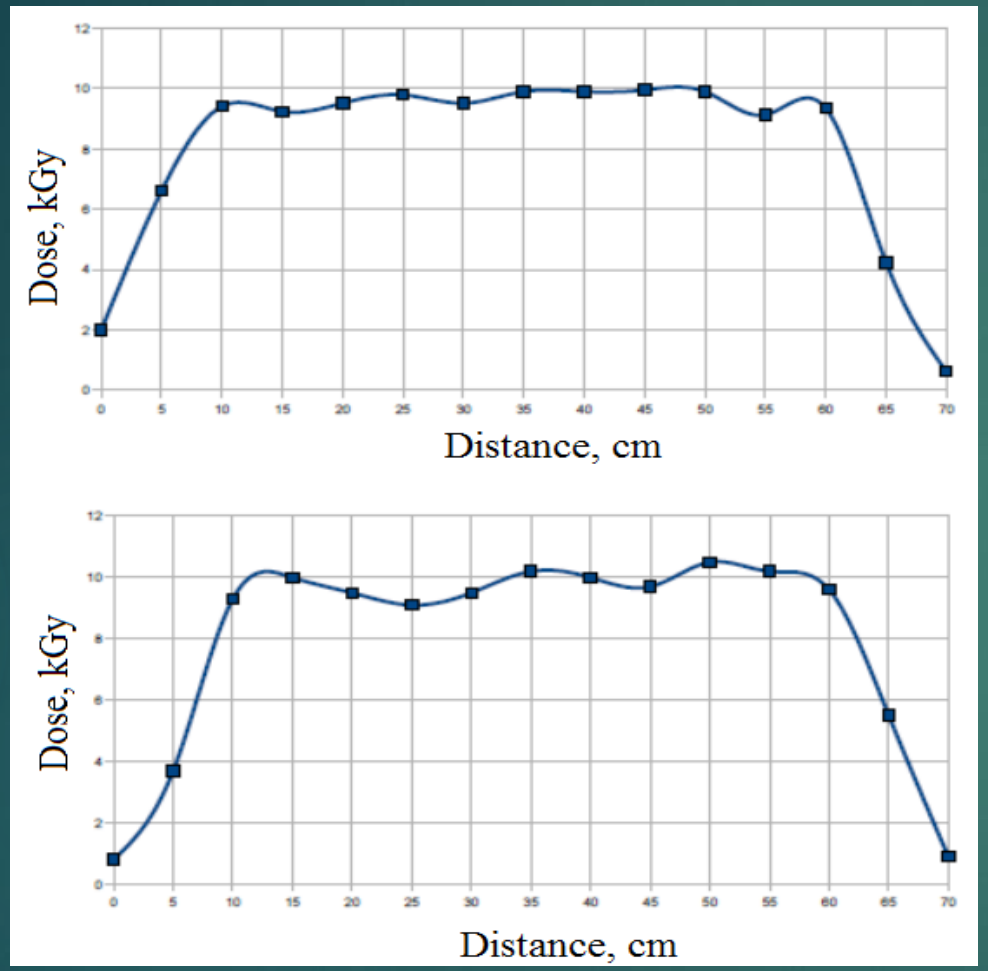
The distribution of the output signals from the thin foil strips is measured each time when the current of the scanning electromagnet achieves the maximum and minimum values. This measured distribution allows the scanning length and electrons energy determine during the irradiation process.



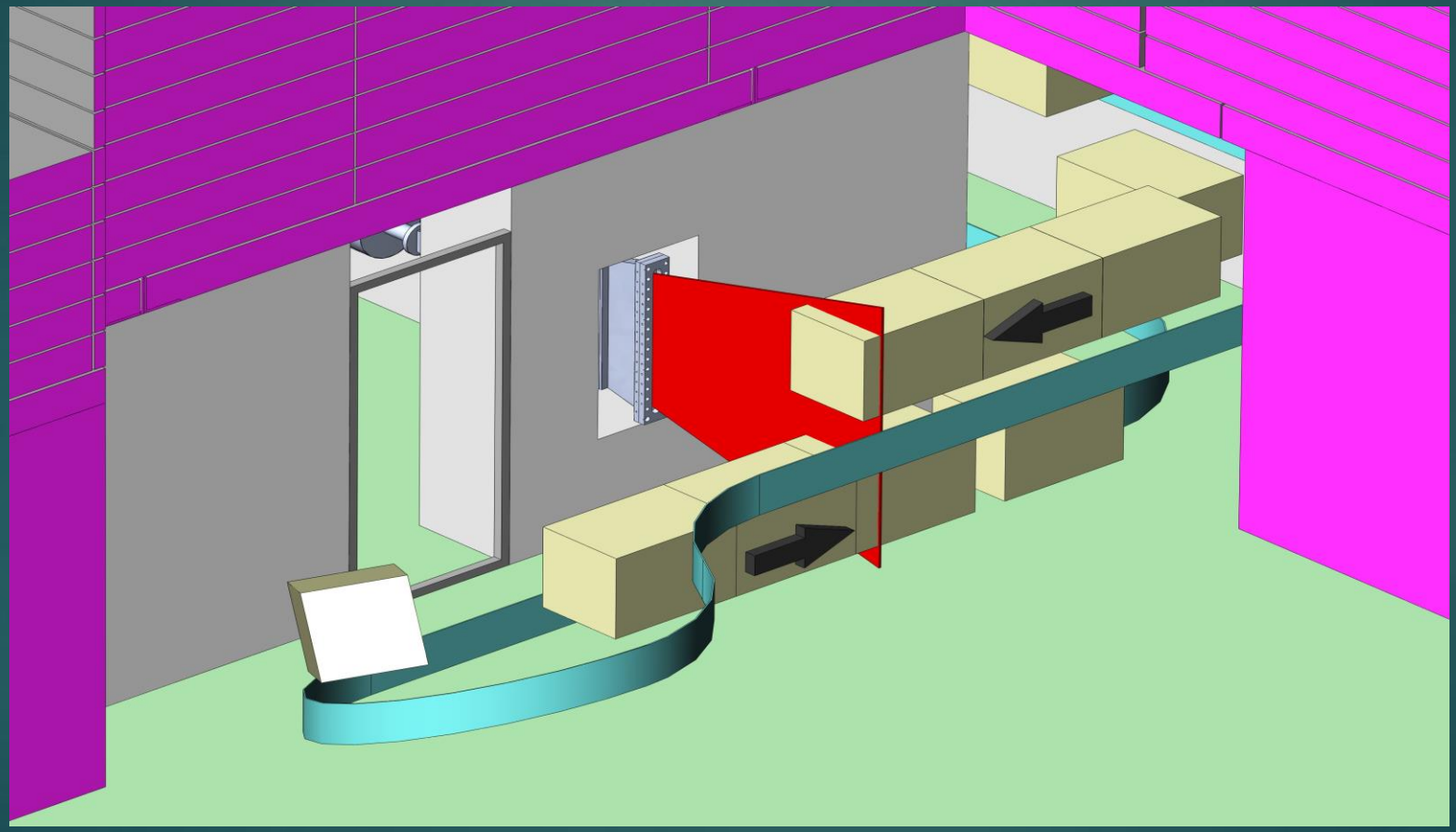
Irradiation of products from two opposite sides during one pass






Dose, kGy
Distance, cm
Dose, kGy
Distance, cm

CORAD offers now the new scheme of two sides irradiation:



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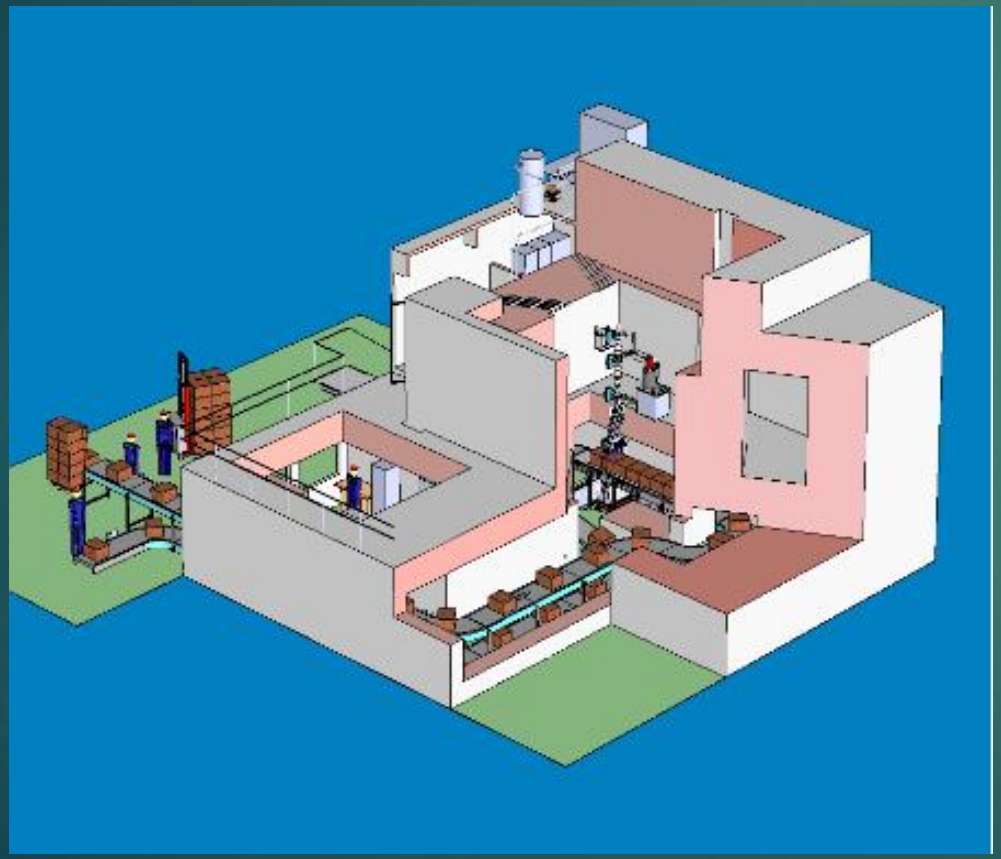
Equipment which was designed and made by CORAD Ltd.

VINAGAMMA (Ho Chi Minh City, Vietnam)



Russian medical biophysical center named after A.I. Burnazyan, Moscow, Russia

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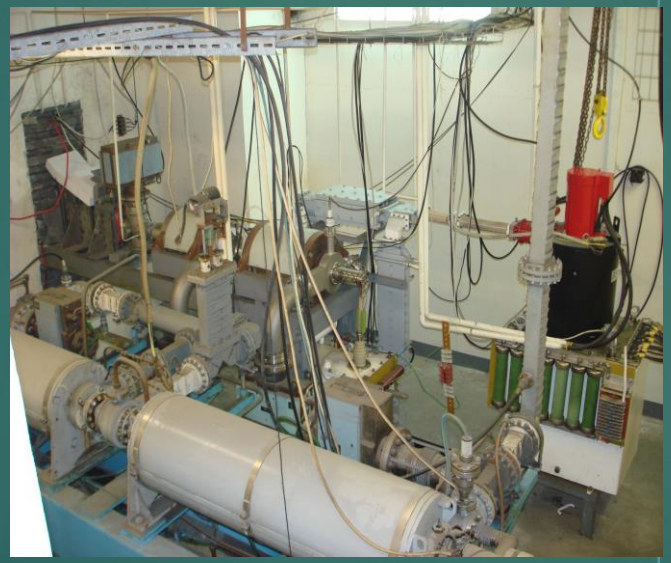
Physical and Chemical Karpov Institute, Obninsk, Russia

RAD Ltd, St. Petersburg, Russia



Ural Federal University named after B.N. Yeltsin, Ekaterinburg, Russia

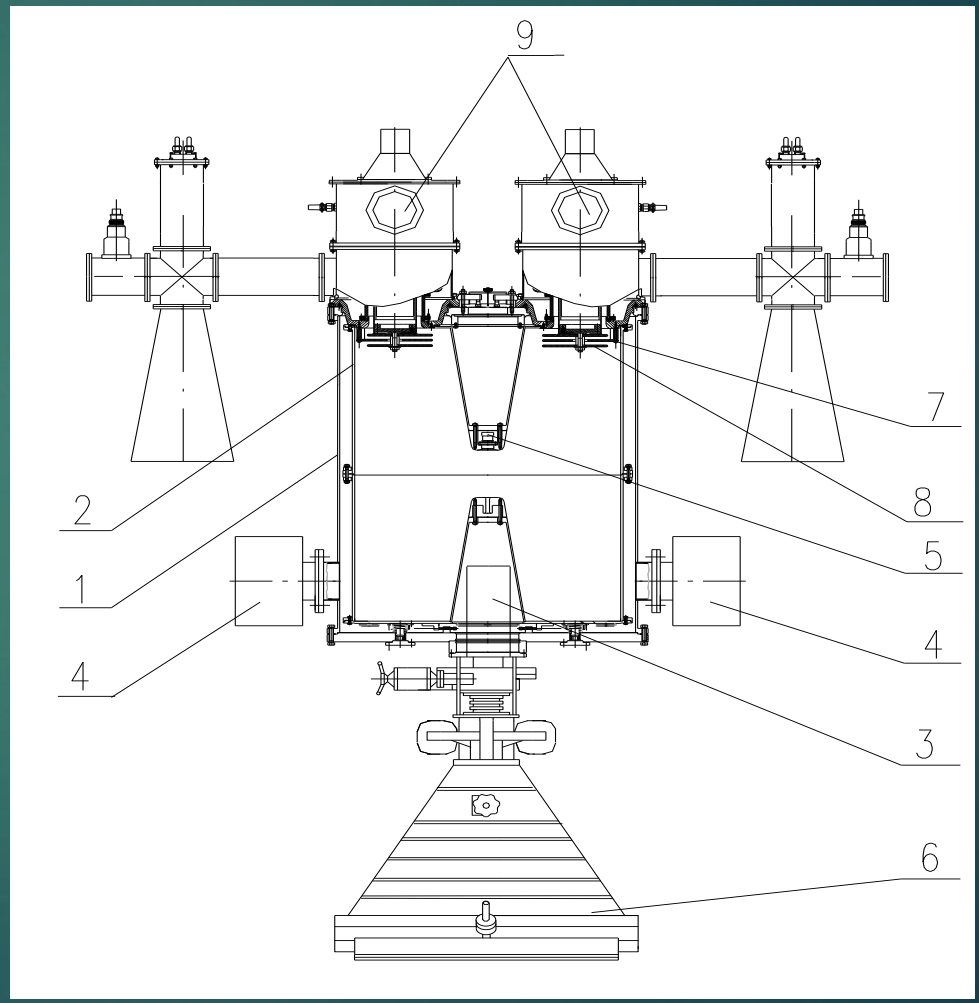
Linac for industrial applications of the Efremov Institute (NIIEFA)

The 10 MeV, 7 kW accelerator UELR-10-10S installed in the Chinese National Institute of Metrology, Beijing in 2011.

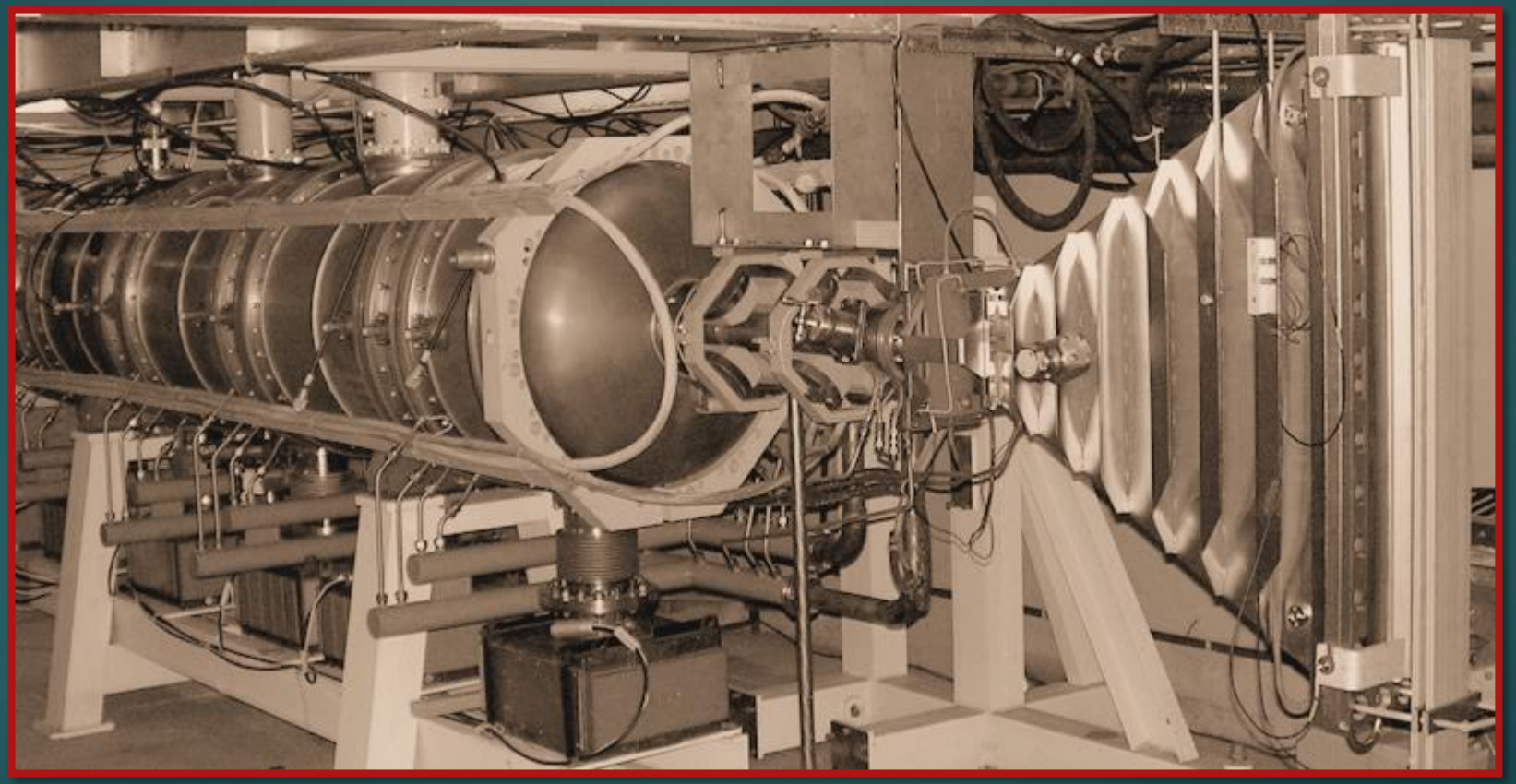
M. Vorogushin, NIIEFA Accelerators for Industry and Medicine, RuPAC 2012

Single cavity accelerator ILU-10 of Budker institute INP (Novosibirsk, Russia)

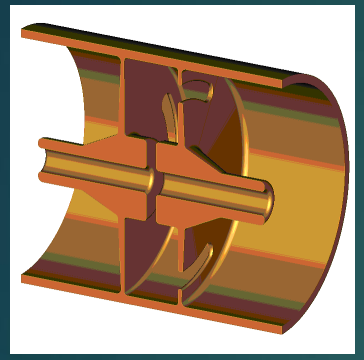
- Energy 4-5 MeV
- Av. Current 0-10 mA
- Pulse current 0-400 mA
- Pulse duration 500 mks
- Pulse repetition 1-50 Hz
- RF frequency 115 MHz
- Dim. D1280x1480 mm

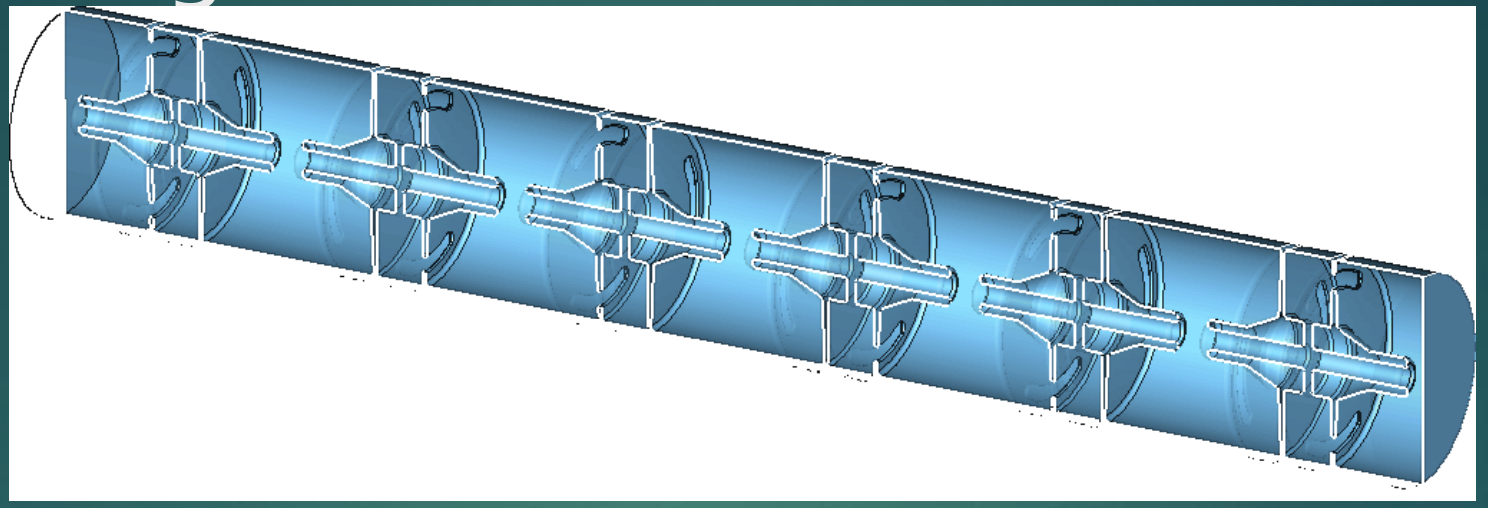


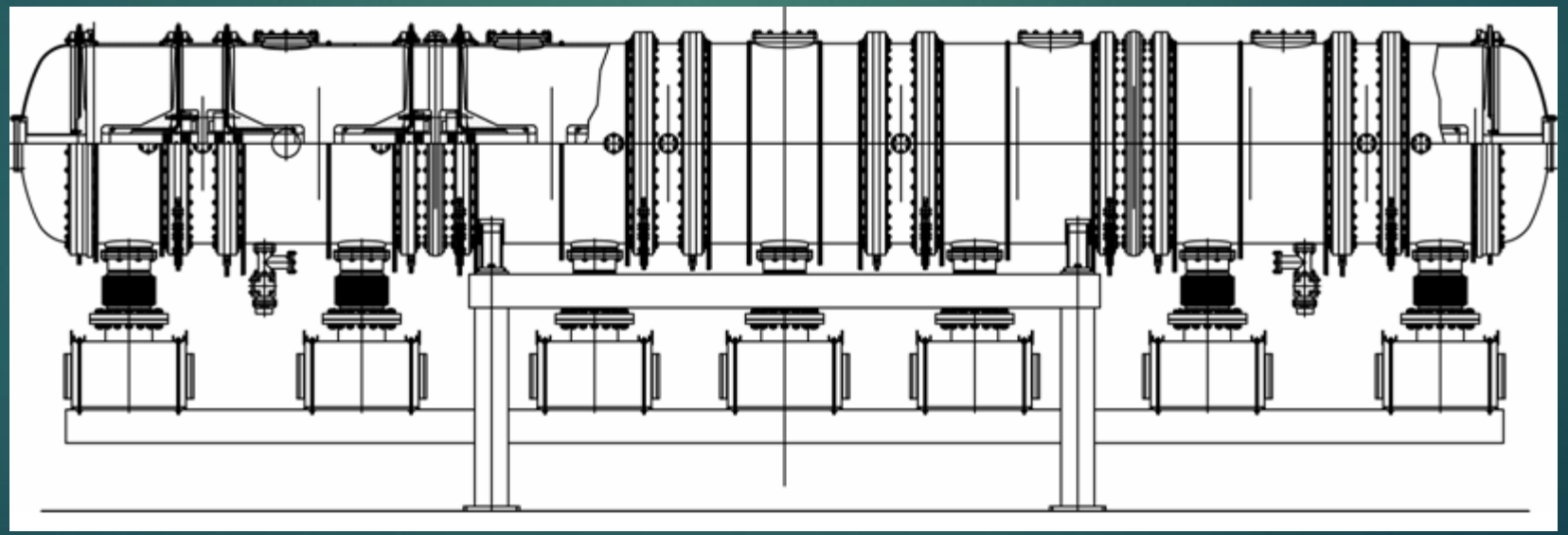
New linear accelerators of Budker INP
ILU-14 (7,5-10 MeV, 100 kW) and
ILU-12 (5-7,5 MeV, 60 kW)



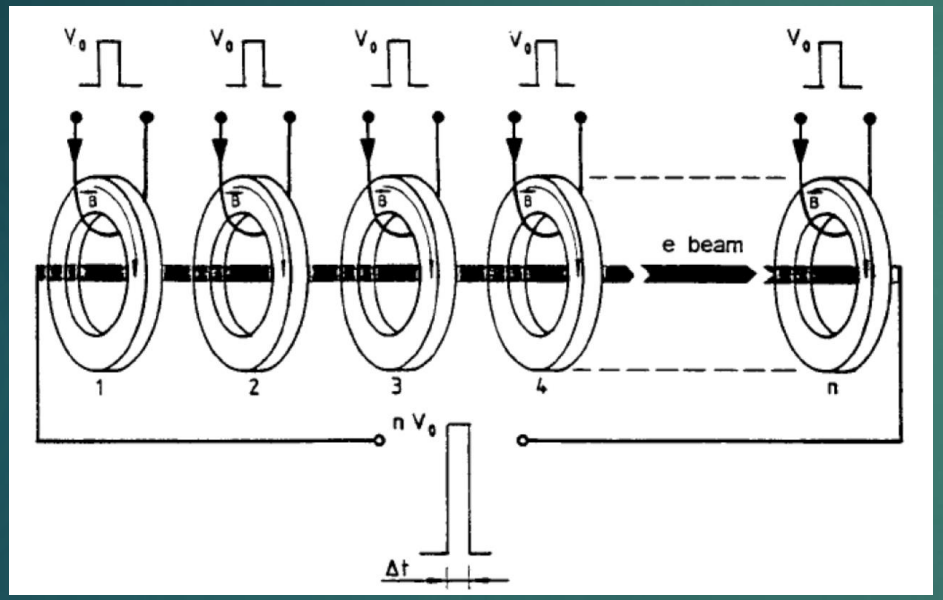
Accelerating structure

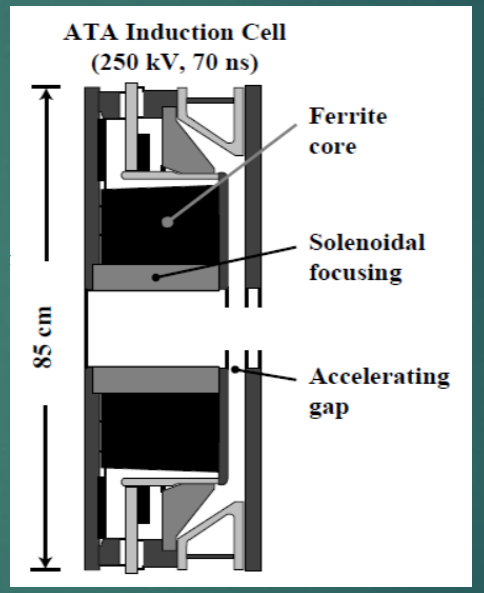


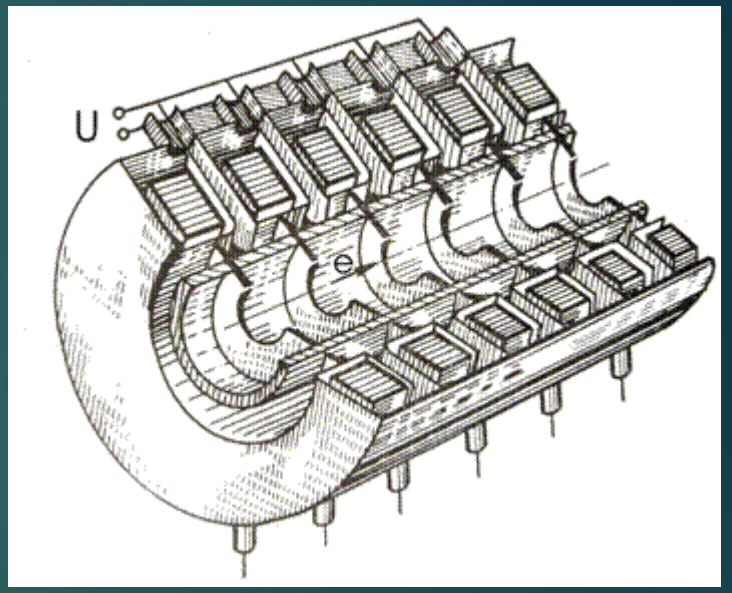




Linear induction accelerators







USA "core-type" induction accelerators

	Institute	Energy [MeV]	Current [A]	Pulse [ns]	Rep.-rate [Hz]	Operational years
Astron	LLNL	3.7	350	250	60 Burst 1.4 k (100)	1963–1967
Astron upgrade	LLNL	6	800	300	60 Burst 0.8 k (100)	1968–1975
ERA	LBNL	4	3 k	30	~1	~1970
NBS prototype	NBS	0.8[a]	1 k	2,000	< 1	~1975
ETA	LLNL	4.5	10 k	30	2 Burst 900 (5)	1977–1987
FXR	LLNL	17	3 k	60	0.3	1980–Present
ATA	LLNL	45	10 k	75	5 Burst 1 k (10)	1983–1995
HBTS	LLNL	3	2 k	50	~100 Burst 5 k	1984–1990
MBE-4	LBNL	1	0.04[b] Cs^+	500	< 1	1984–2000
ETA-II	LLNL	6.5	3 k	50	~1 Burst 2 k (50)	1989–Present
SNOMAD-II	MIT	0.5	500	50	~1 Burst 5 k	~1991
SLIA	PSI	5.5	10 k	~30	? Burst 10 M	~ 1996
CLIA	PI	0.75	10 k	100	100 (5 k) 1 k (5)	~1993
RTA	LBNL	1	1.2 k	250	4	1998–2001
Recirculator	LLNL	0.08[c]	0.002[b] K^+	4,000	0.1 Burst 100 k (100)	~1999
DARHT-I	LANL	19.8	2 k	60	< 1	1999–Present
DARHT-II	LANL	17	2.1 k	1,600	< 1	2003–Present

Abbreviations: LLNL – Lawrence Livermore National Laboratory (formerly LRL-Livermore), LBNL – Lawrence Berkeley National Laboratory (formerly LRL-Berkeley), NBS – National Bureau of Standards (presently NIST), MIT – Massachusetts Institute of Technology, PSI – Pulse Science Inc., San Leandro, CA, PI – Physics International Company, San Leandro, CA.

[a]Induction cells boosted injector voltage by 400 kV.

[b]Current of ion machines are distinguished by listing the ion and charge state with the current.

[c]Only one quarter turn installed. Energy boost by 5 induction cells was 500 V.

Former USSR "core-type" induction accelerators

	Institute	Energy [MeV]	Current [kA]	Pulse [ns]	Repetition-rate [Hz]	~Start year
LIA-3000	JINR	1.5	0.25	250	5	1967
SILUND	JINR	1.7	0.7	15	1	1973
SILUND-2	JINR	0.8	1.0	20	50	1978
SILUND-10	JINR	0.25	8	20	1	1980
SILUND-20	JINR	2	1	20	50	1982
LEUK-20	JINR	1.5	–	60	20	1985
LIA-30/250	JINR	30	0.25	500	50 Dual pulse	–
LIA-5/5000	ITEP	4	2	200	1 K design	1977
LIA-0.8/5000	MRTI	0.8	5	80	100	–
LIA-0.4/10000	NPI	0.4	10	100	10 Burst 50 (2 k)	–
LIA-0.5/5000	NPI	0.5	5	100	100 Burst 1 k (10)	–
LIA-4/2	NPI	4	2	80	100	–
SILUND-21	JINR	10(5)	1	60	–	1995

Abbreviations: JINP – Joint Institute for Nuclear Research, Dubna, NPI – Nuclear Physics Institute at Tomsk Pollytechnic University, Tomsk, MRTI – Moscow Radio Technical Institute, Moscow, ITEP – Institute for Theoretical and Experimental Physics, Moscow.

http://www.springer.com/978-3-642-13916-1
Induction Accelerators
(Eds.)K. Takayama; R.J. Briggs , 2011

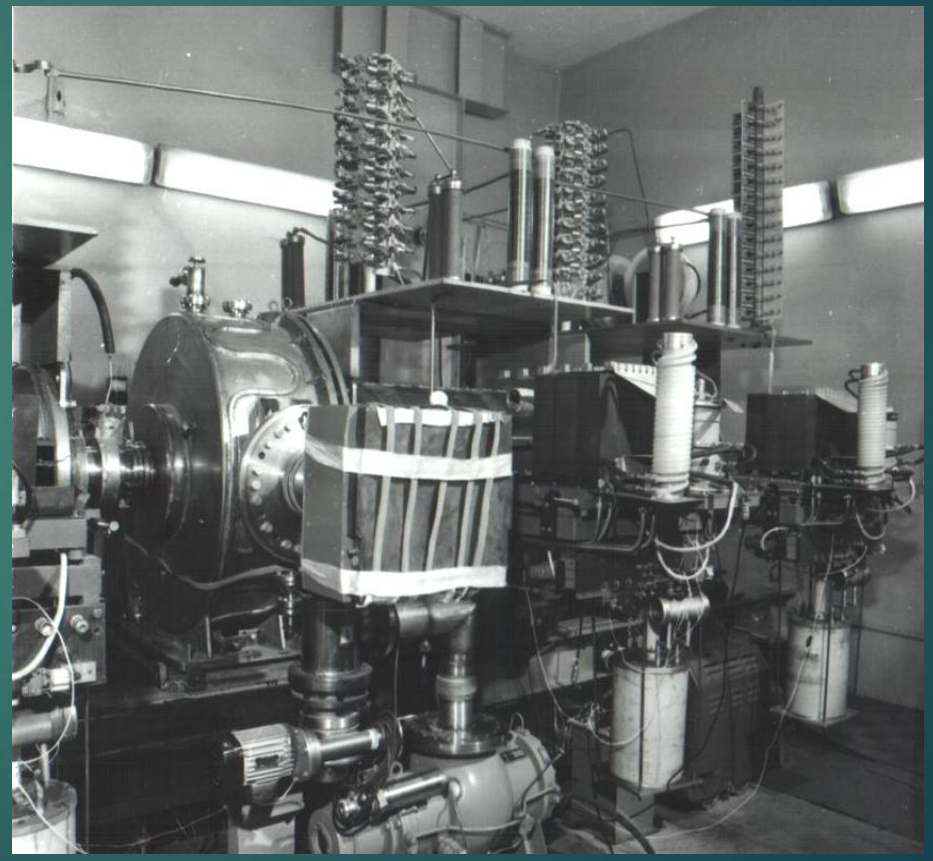
LIA for industrial application developed by Efremov institute in 1989-93

Energy – 600 keV

Beam current – 600 A

Pulse width – 250 ns

Pulse repetition rate – 400 Hz



M. Demsky, Yu. Vakrushin at others. Linear induction accelerators for industrial application. PAC 1993 and BEAMS' 90.

Project of LIA for flue gas treatment

1 – 8 electron guns with total beam current of 3000 A

2 – induction voltage adder for 750 kV

3 – oil filled coaxial line

4 – cannel with irradiated gas

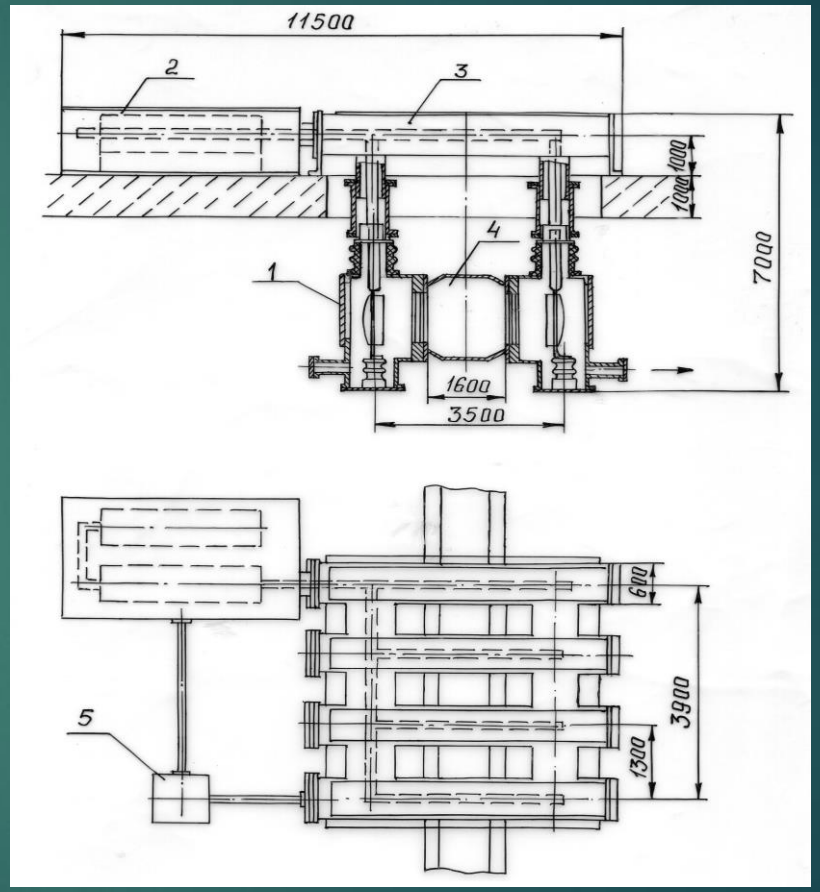
5 – cooling system

Pulse duration – 2 μs

Pulse repetition rate – 110 Hz

Average beam power – 500 kW

Total efficiency ~40%



Project of Linear Accelerator with 500 kW Average Power for Flue Gas Cleanup. Final Research Co-ordination Meeting on Radiation processing of Combustion Flue Gas. Poland - Zakopane, 24-28 May 1993, IAEA

THANK YOU FOR YOUR ATTENTION

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