CERN Accelerator School: Advanced Accelerator Physics
Warsaw, Poland, 27 September – 9 October 2015

Electron Accelerators Applications

Zbigniew ZIMEK
Centre for Radiation Research and Technology
Institute of Nuclear Chemistry and Technology

z.zimek@ichtj.waw.pl

Content

Accelerator technology for radiation processing

Up to 3.000 accelerators have been build for radiation processing (total number of accelerators applied in science, medicine and industry amounts approximately 30.000).

Accelerator technology development is based on new constructions and new components, what leads to progress in:

- Accelerator technology perfection (higher electrical efficiency, cost reduction);
- Reliability according to industrial standards;
- Accelerators for MW power beam level;
- Compact accelerator constructions;
- Very low energy, powerful accelerators.

Advantages of Radiation Processing

- Merits of (EB) radiation processing:
  simple, high speed process, with low energy consumption;
- Processing at room temperature:
  independence of radiation-induced reaction rate on temperature;
- Processing without additives (catalysts):
  clean process, pure products;
- Processing solid, liquid and gas phases:
  radiation penetrates materials in certain volume;
- Challenge:
  cost reduction, improvement of public acceptance.

Radiation Processing Applied in Industry

Technology	Energy [MeV]	Dose [kGy]
Crosslinking of PE	0.3-10	50-300
Thermo-shrinkable plastics	0.5-4	100-250
Curing of coating on wood	0.15-0.5	20-500
Degradation of polymers	2-10	500-1500
Graft polymerization	0.1-2.5	10-300
Vulcanization of rubber	0.5-1.5	20-500
Colors in Diamonds	2-10	few MGy
Sterilization	1-10	20-50
Dinisfestation of grain	1	0.5-1.0
Sprout inhibiting	5-10	0.1-0.2
Food preservation	5-10	5-10
Flue gases treatment	0.3-1.5	10-15
Sewage sludge treatment	0.5-5	0.5-1

RADIATION TECHNOLOGY APPLIED IN ENVIRONMENT PROTECTION

Phase	Object	Additives	Process
Gas	Flue gas	SO_2; NO_x	Removal, Useful by product
	VOC	Organic compounds	Degradation, removal
Liquid	Drinking water	Chemical pollutants	Degradation, removal
	Wastewater	Bacteria; viruses; parasites	Hygenizataion
	Industrial wastes	Organic and nonorganic compounds	Degradation, removal
Solid	Sewage sludge	Bacteria; viruses; parasites	Hygenizataion
	Solid materials	Agriculture wastes	Transformation, Useful by product

Electron Beam Wastewater Treatment

- Drinking water treatment,
- Contaminated groundwater treatment,
- Wastewater from papermill & pulp company,
- Wastewater from petrochemical company,
- Wastewater containing heavy metal,
- Reclamation for industrial supply,
- Communal wastewater.

Number of EB Processors in Japan (2007)

Application	Low 80 keV～ 300 keV	Medium 300 keV ～3MeV	High 3 MeV～ 10 MeV	Total	Growth in 10 yeas period
Wire/Cable	1	53	1	55	8 %
Foam	3	12	0	15	7 %
Srinkable	13	18	1	32	14 %
Tire	9	20	0	29	26 %
Curing/Grafting	69	2	0	71	61 %
Flue Gas	0	7	0	7	75 %
Sterilization	5	2	9	16	46 %
Service	4	10	9	23	44 %
R & D	144	2	1	147	28 %
Total	248	126	21	395	28 %

Application of electron accelerators

Application		Commercialized	
		In Korea	Worldwide
Polymer modification	Flame resistant cables	●	●
	Thermo-shrinkable products	●	●
	Curing of tire cord	●	●
	Foam sheets	●	●
	Artificial leather	○	●
	Films for coatings and packaging	◎	●
Sterilization/ Disinfection	Sterilization of medical products	●	●
	Preservation of spices, food	◎	●
	Disinfection of grains	◎	●
Environmental protection	Flue gas purification	◎	●
	Water/wastewater treatment	●	◎
	Sludge treatment	◎	○
Others	Curing/ coating of wood, paper etc.	●	●
	Semiconductors	●	●
	Ceramic composites	○	●
	Surface treatments of fabric	○	◎

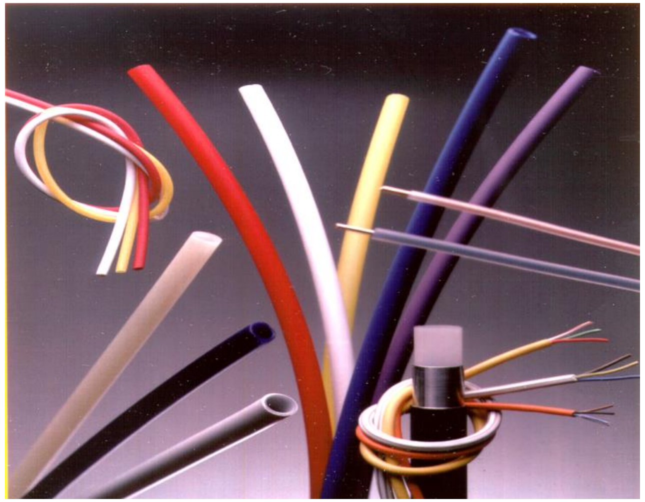
● Commercialized

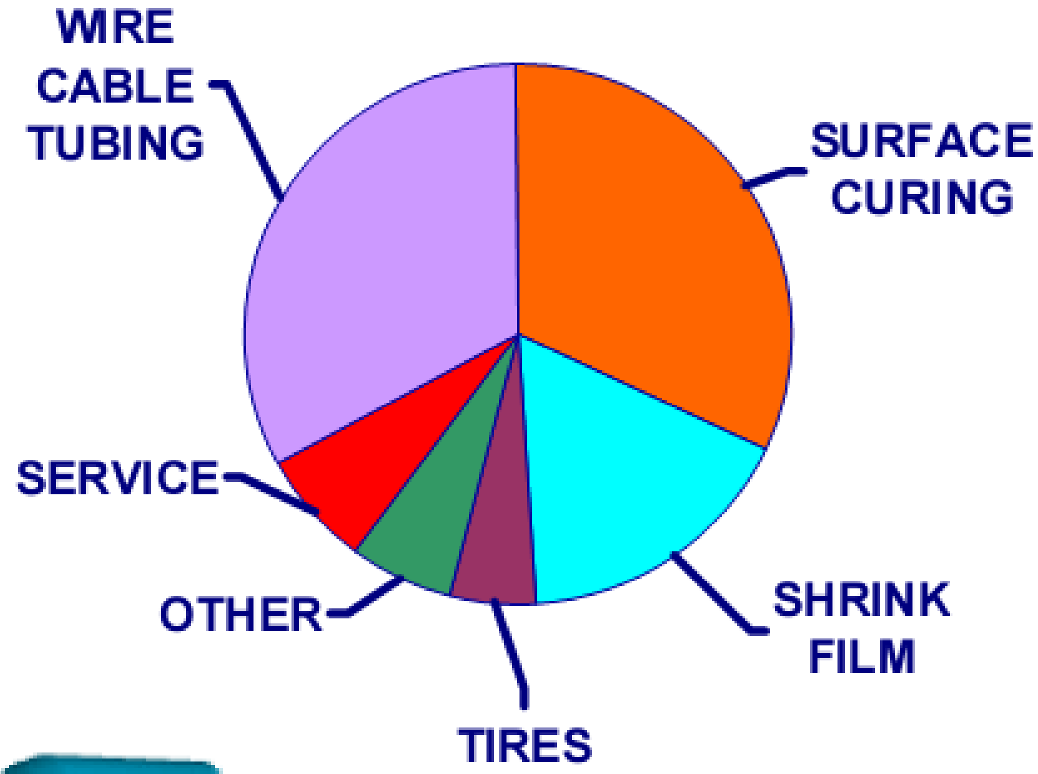
◎ Pilot plant

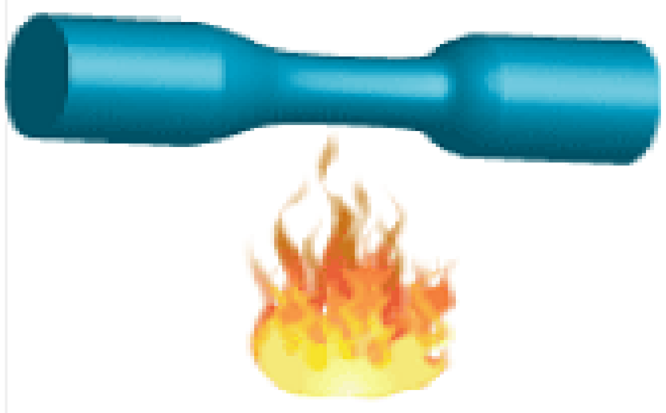
○ Lab. scale investigation

B. Han et al., 2011

Radiation modification of polymers

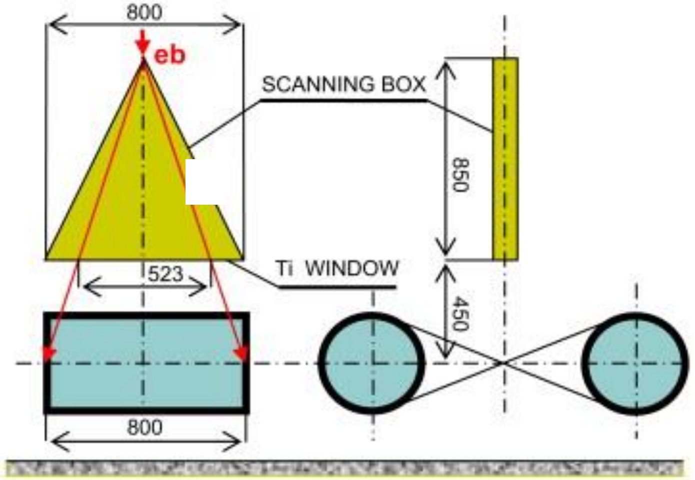


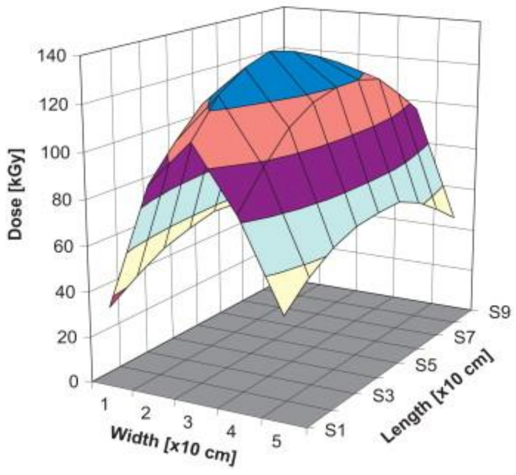


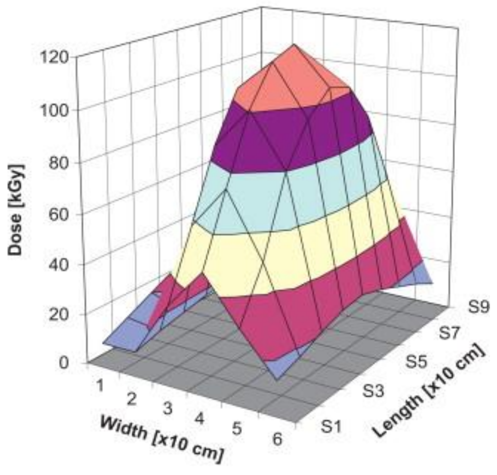


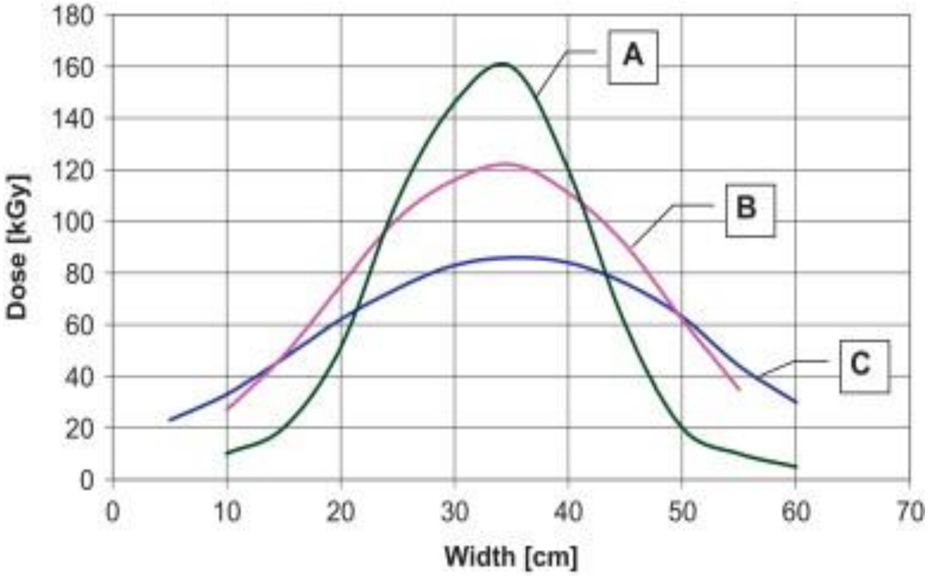
2003, A.I. Berejka,
IAEA-TECDOC-1386

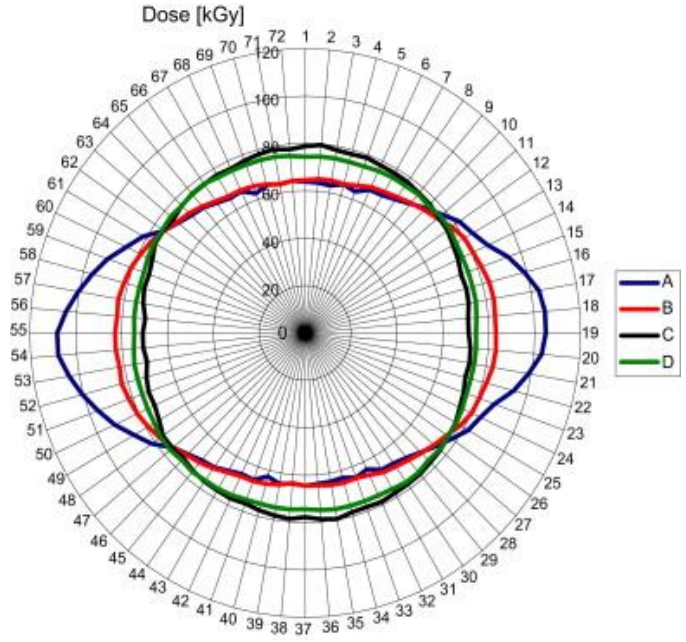
New generation of radiation crosslinked electrical cables











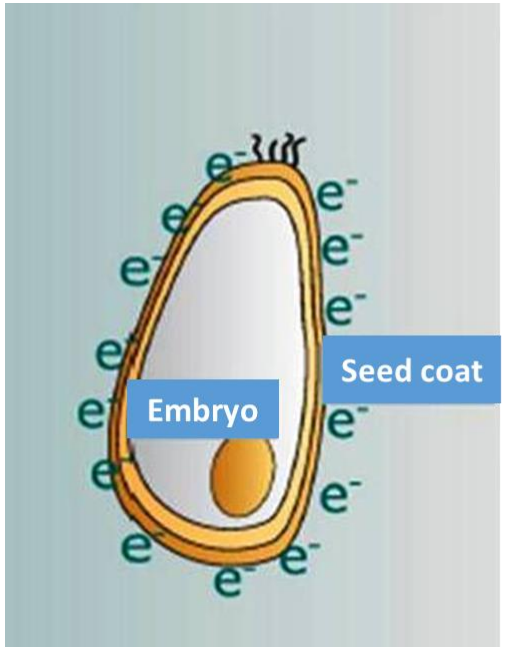
Dose distribution

Z. Zimek, G. Przybytniak, A. Nowicki, Optimization of electron beam crosslinking of wire and cable insulation,Rad. Phys. Chem. 81 (9), 2012,1398-1403
Z. Zimek , G.Przybytniak, A.Nowicki, K.Mirkowski,K.Roman, Optimizationofelectronbeamcrosslinkingforcables,Rad Phys. Chem, 84, 2013

Biocidal effects of eb treatment

- Sterilization of single use medical devices,
- Disinfestation (grain)
- Preservation (spices, food),
- Germ reduction,
- Surface sterilization,
- Surface disinfection.

Facility for grain disinfestations with productivity of 1000 t/hour equipped with ELV-8 transformer accelerator: 1-2.5 MeV, 100 kW



Seed eb surface treatment for killing pathogens and increase germination rate.

RADIATION PROCESS EFFECTIVENESS

Acceptable price of 1 W electron beam power	Type of radiation process	Product characteristics
100-250 $/W	Semiconductors modification	Low dose Small scale **High unit price**
100-50 $/W	Radiation sterilization	Medium dose **Large scale** **Medium unit price**
<2.5 $/W	Flue gas treatment	Low dose Very large scale **No commercial value**

Accelerator selection criteria

- Average beam power *(productivity),*
- Electron energy *(penetration),*
- Price *(investment cost),*
- Electrical efficiency *(cost of accelerator exploitation),*
- Size *(building geometry and size),*
- Reliability *(availability >95%).*

RELIABILITY:
PROBABILITY that a system can perform its intended function for a specified time interval under stated conditions.

High reliability is required when repair of sensitive sub-components are long or difficult.

Poor reliability may be acceptable, if each failure can be repaired in a very short time so the system has a high availability, and the maintenance costs are reasonable.

Equipment or system reliability can not be guaranteed.

AVAILABILITY:

Fraction of **TIME** during which a system meets its specification.

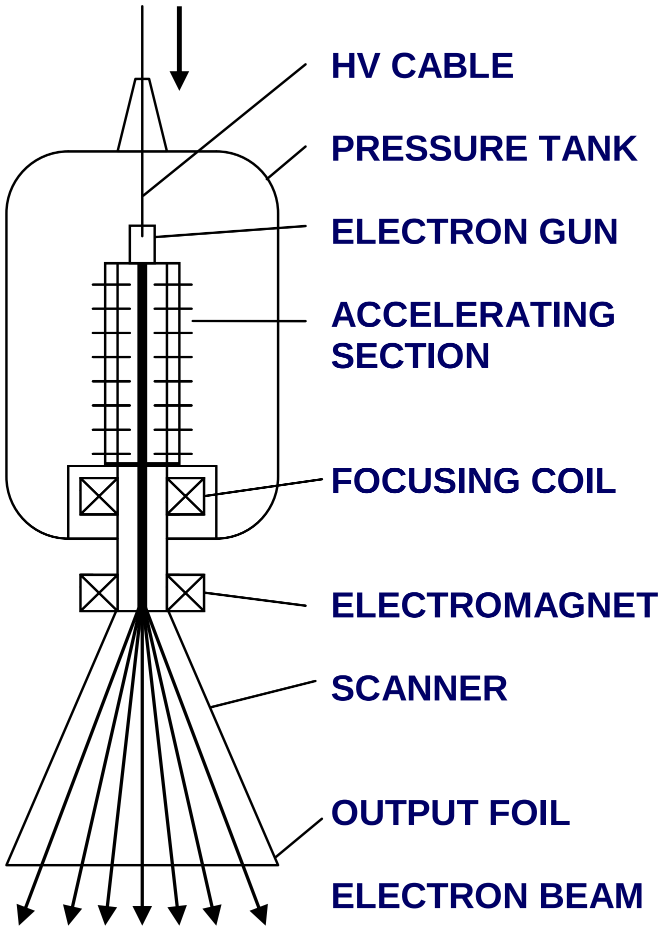
High availability is required if continuous service is the priority.

Equipment should not work at full capacity, and some margin must be allowed.

When weak point is established a suitable availability level can be achieved but it is a matter of finance, manpower and time.

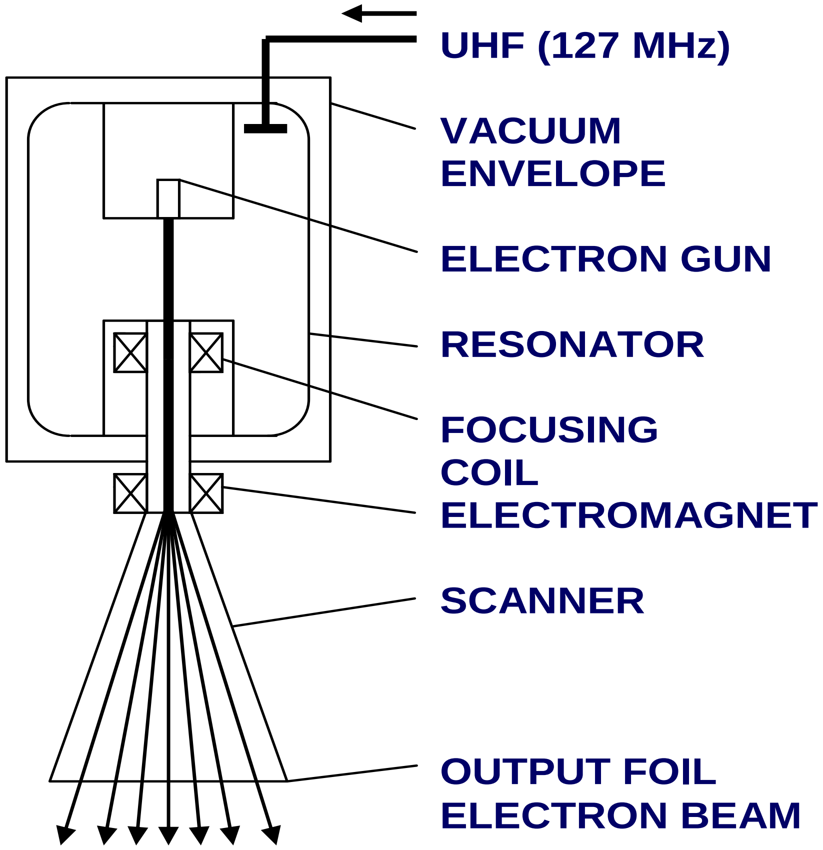
Reliability ≠ Availability

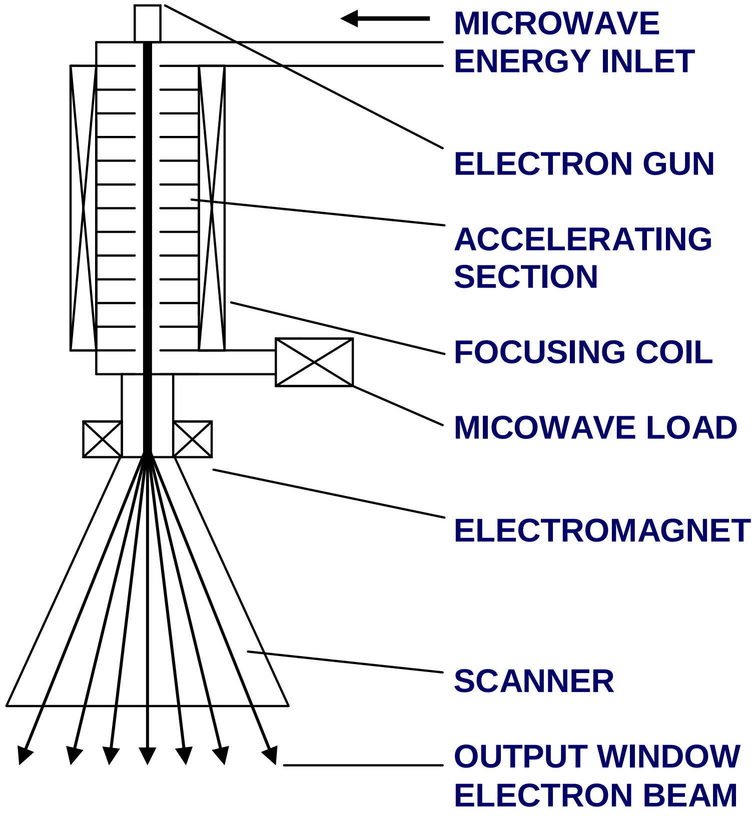
Electron accelerators for radiation processing



DIRECT DC (TRANSFORMER) ACCELERATORS

SINGLE CAVITY (RESONANCE) ACCELERATORS





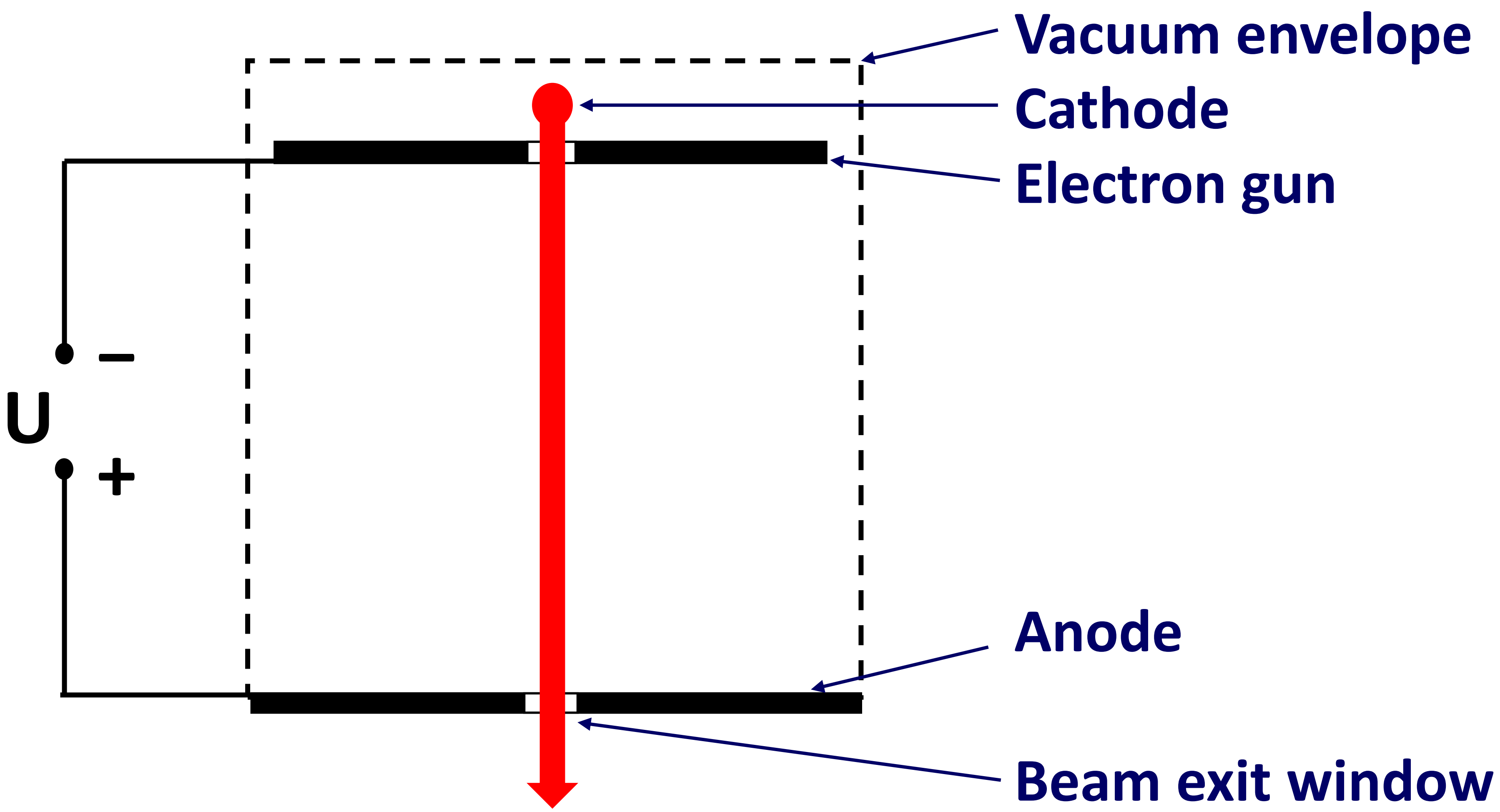
LINEAR (MICROWAVE) ACCELERATORS

Electron accelerators for radiation processing (achievements)

Accelerator type Parameter	Direct DC	UHF 100 - 200 MHz	Linear microwaves 1.3–9.3 GHz
Av. Beam current	<2 A	<100 mA	<30 mA
Energy range	0.05 – 5 MeV	0.3 – 10 MeV	2 – 10 MeV
Beam power	~500 kW	700 kW	150 kW
Electrical efficiency	60 – 80 %	20 – 50 %	10 – 20 %

DIRECT ACCELERATORS
(transformer type)

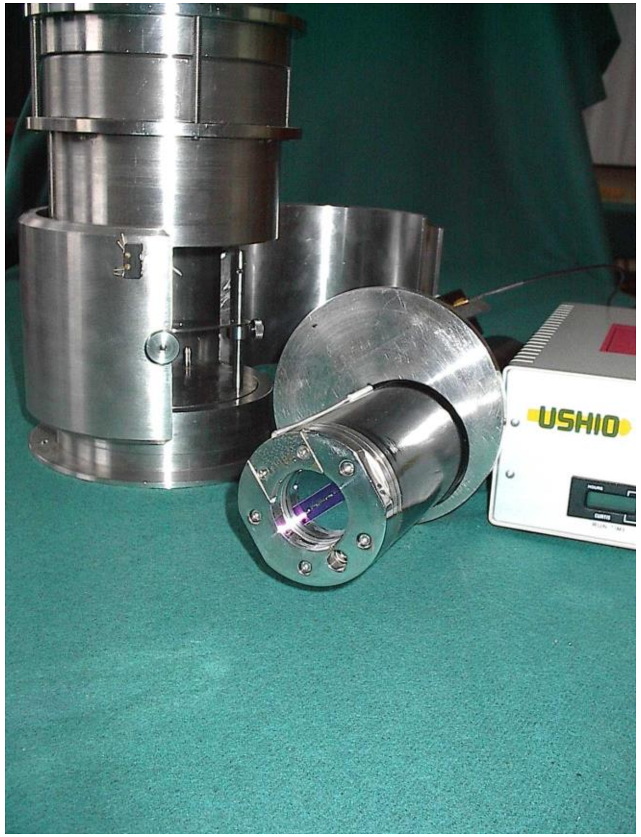
Direct accelerators: principle of operation

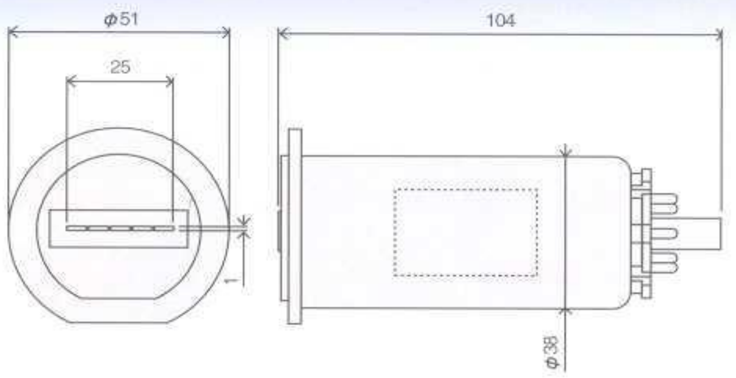


Capability of DC Power Supply (for transformer accelerators)

Accelerator	Power line transformer	Cockckroft-Walton	HF Transformer	Dynamitron
Ratings	150-1000kV 10-1000 mA	300-5000 kV 30-1000 mA	500-1000 kV 30 mA	500-5000 kV 1-70 mA
Frequency	50/60 Hz	1-3 kHz	20-50 kHz	50-100 kHz
Insulation	Oil/SF6	SF6	SF6	SF6
Efficiency	>90 %	70-80 %	85 %	30-60 %
Remarks	Low energy High power	High energy High power Large dimensions	High energy Low power Compact	High energy Low eff.

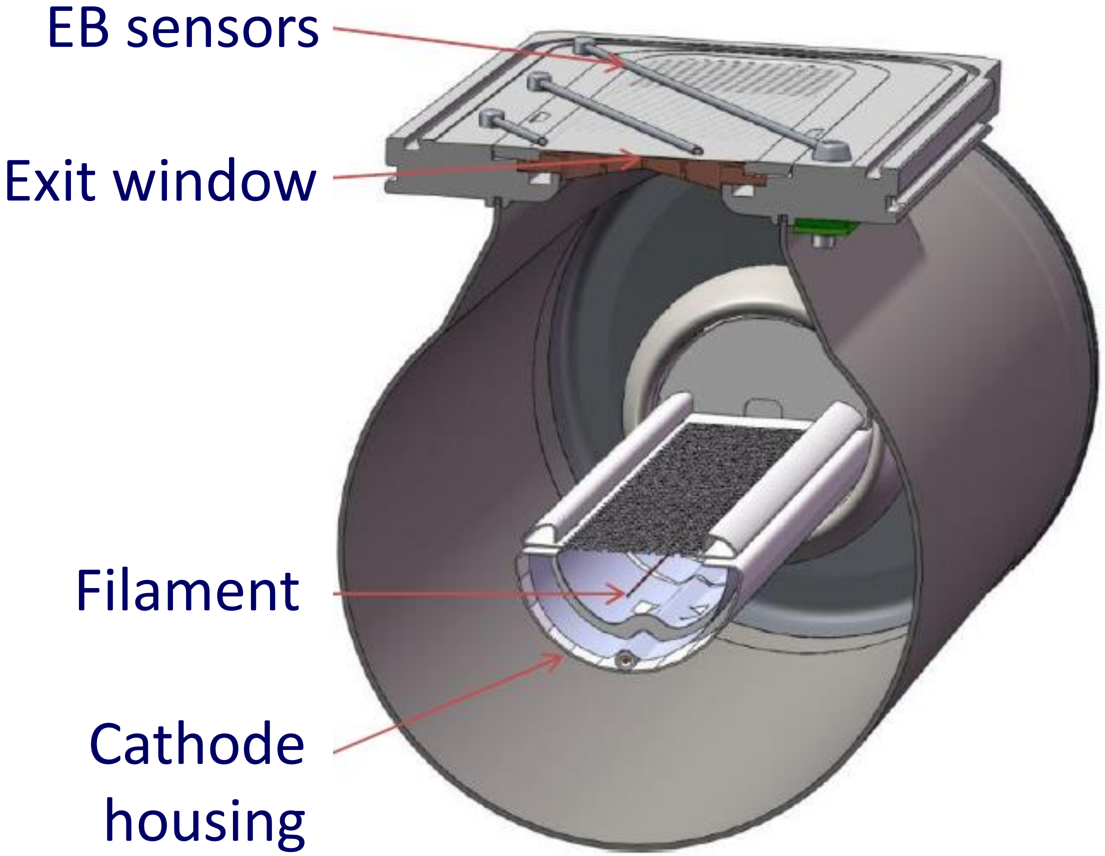
Miniature Electron Beam Tube
Min-EB





Voltage 50-75 kV
Beam power 8-50 W
USHIO / AIT

Permanent sealed, compact ebeam accelerators



Hermetically sealed by brazing and welding.
Can be refurbished by milling out frame with window foil and welding in new one

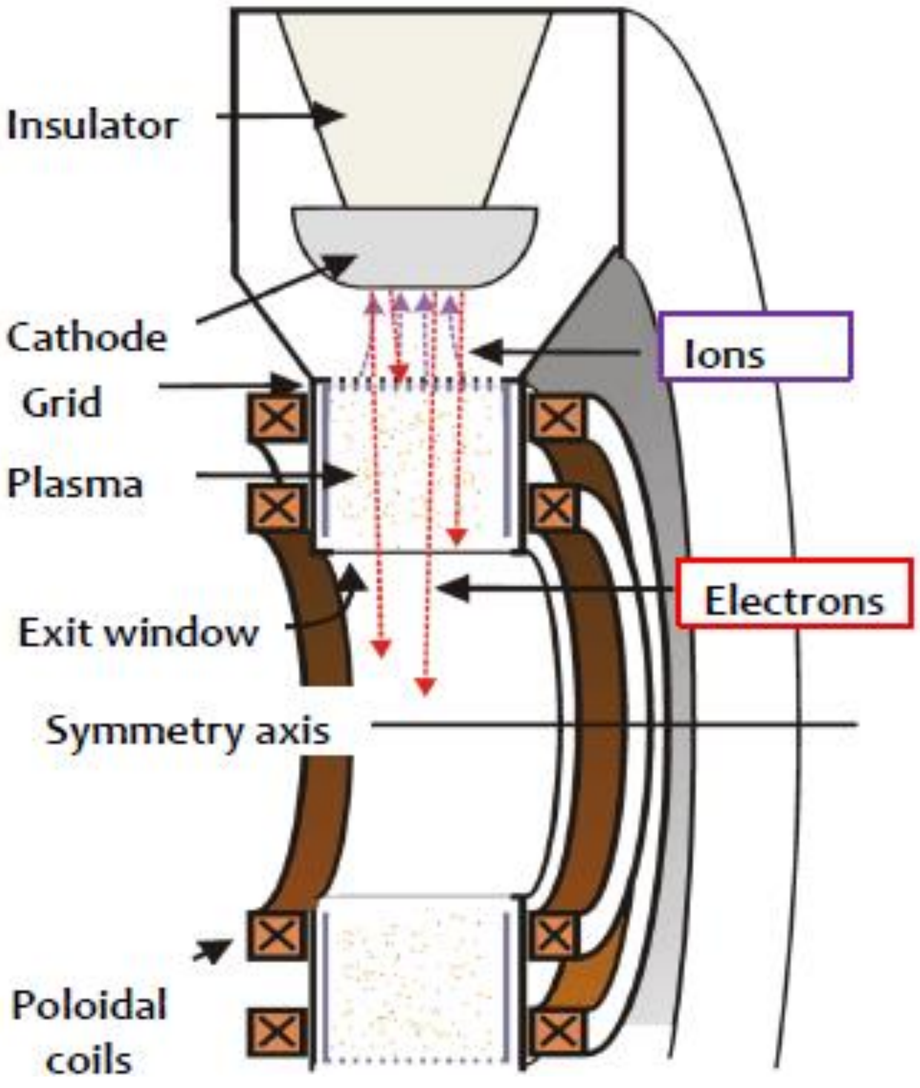
U.V. Laeuppi, 2015
Comet ebeam Technologies

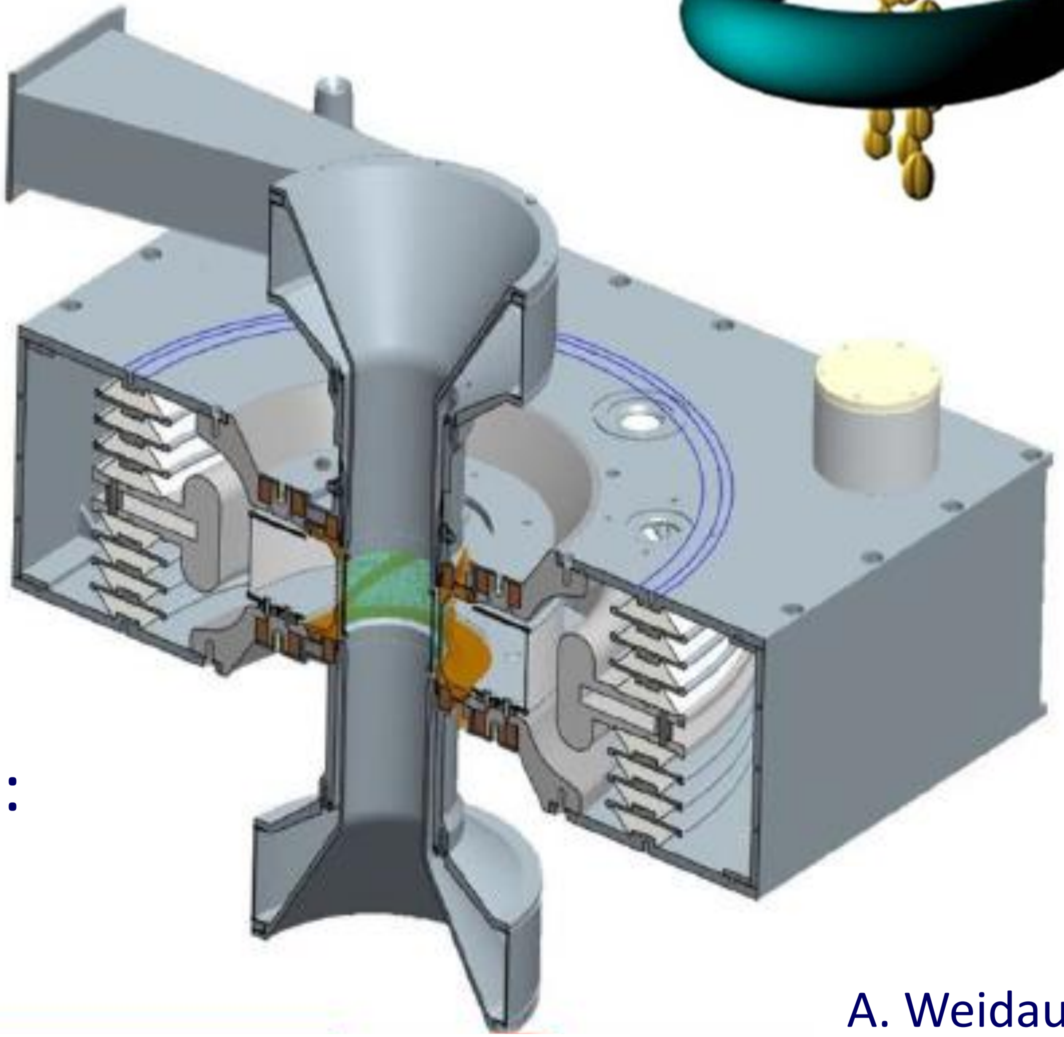
Permanent sealed, compact e-beam accelerators

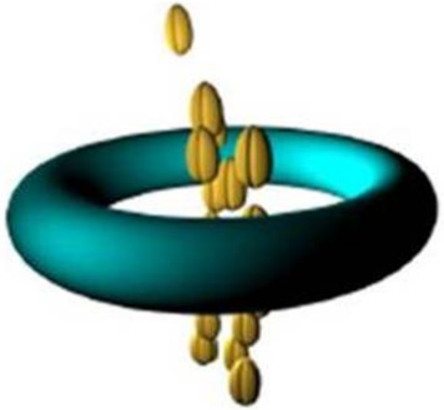
Guaranteed 8000 operating hours.
High voltage of 80 to 300 kVolt.
Actual beam intensity variation typically +/-5 % (specification +/- 10 %).

U.V. Laeuppi, 2015
Comet ebeam Technologies

Toroidal source of accelerated electrons
for seed surface disinfection



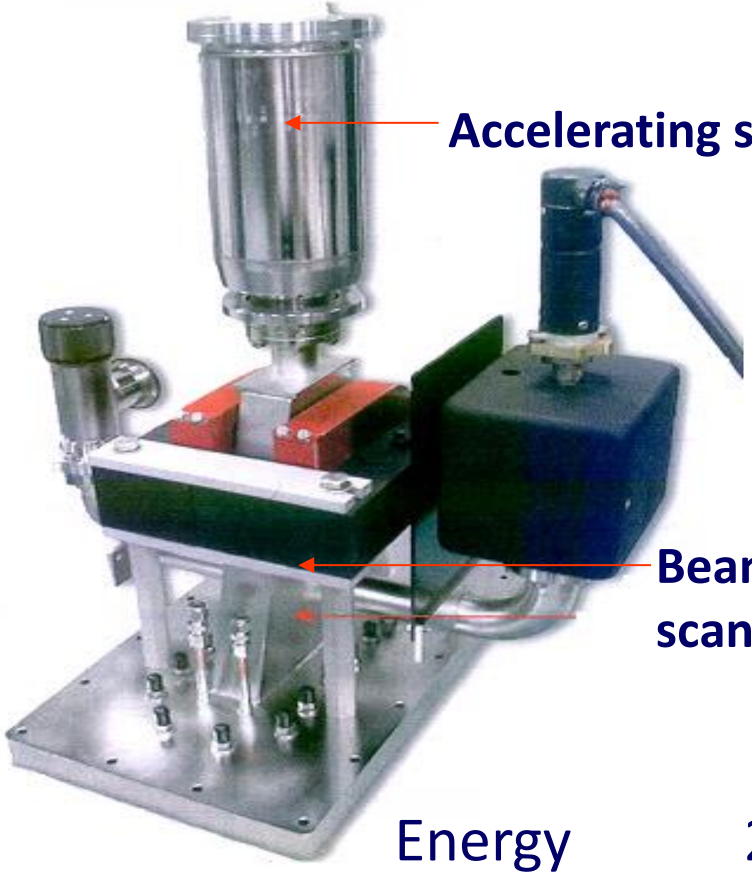




Operating parameters:
Ø 120 mm
U = 120 kV
P < 5 kW
J < 0.2 mA/cm^2

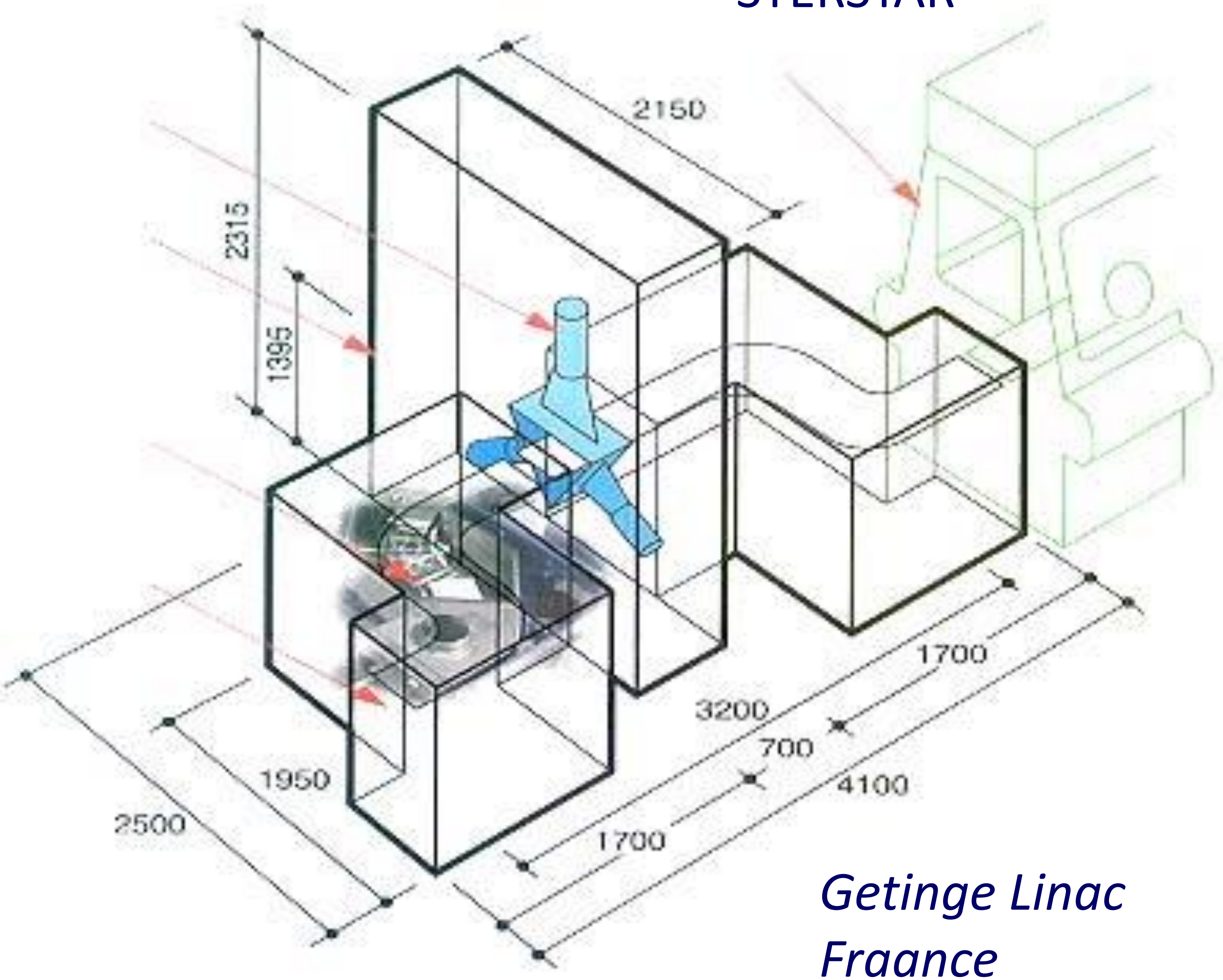
A. Weidauer,
Fraunhofer FEP, CERAVIS,
BayWa and Glatt Ingenieurtechnik

Low energy „in line" facility for surface sterilization



Energy 200 keV
Power 800 W
Current 4 mA
Scanning up to 20 cm
AC power 10 kVA
Size 40x40x80 cm

STERSTAR



Getinge Linac
Fraance

Energy Science Inc.

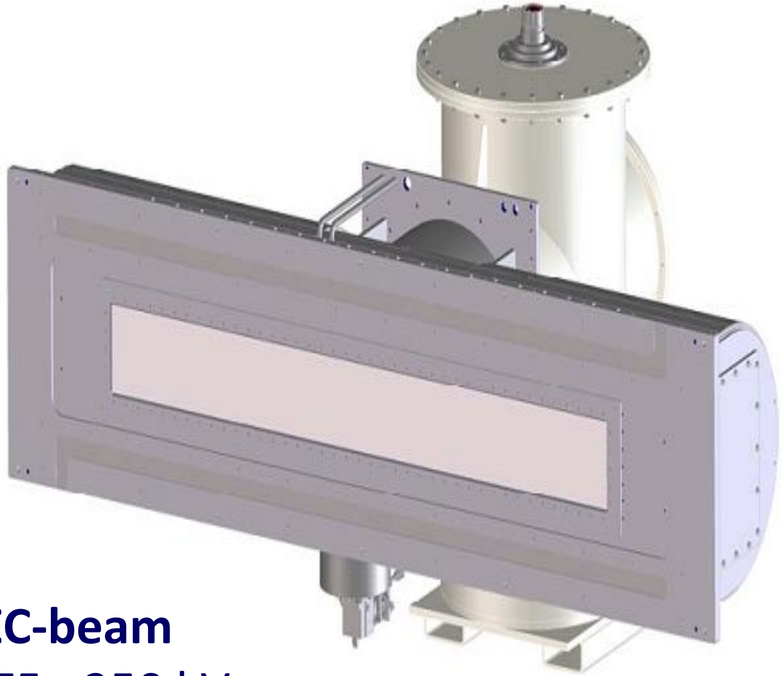
Low energy accelerators for surface treatment

PCT Engineered Systems

ELECTRON-BEAM ACCELERATORS FOR NEW APPLICATIONS

Parameters	Ratings
Web/Product width	30 – 330 cm
Accelerating voltage	70 – 300 kV
Throughput	Up to 15.000 kGy – mpm
Dose uniformity	Better than +/- 8 %
Line speeds	Up to 600 mpm
Beam orientation	Horizontal, vertical, or angled

CROSSLINKING AB



Operating characteristics EC-beam

- Acceleration voltage 75 - 250 kV
- Electron current 0 - 2000 mA
- Working width 400 - 3000 mm
- Throughput 14000 kGy m/min
- Distribution of dosage over working width < 10 %
- No gas cooling of the electron exit window necessary.

"Aurora-5" accelerator in the line producing foamed polyethylene (0.6 MeV; 30 kW)

- Gun life time – 3000 h
- Window foil life time – 3000-4500 h

"Electron10" accelerator in the line for production of heat-shrinkage anti-corrosion coatings (0.75 MeV; 45 kW)

- Gun life time – 3520 h
- (average for 5 years period);
- Window foil life time – 3230 h (average for 5 years period).

V.P. Maznev et al., RUPAC 2010

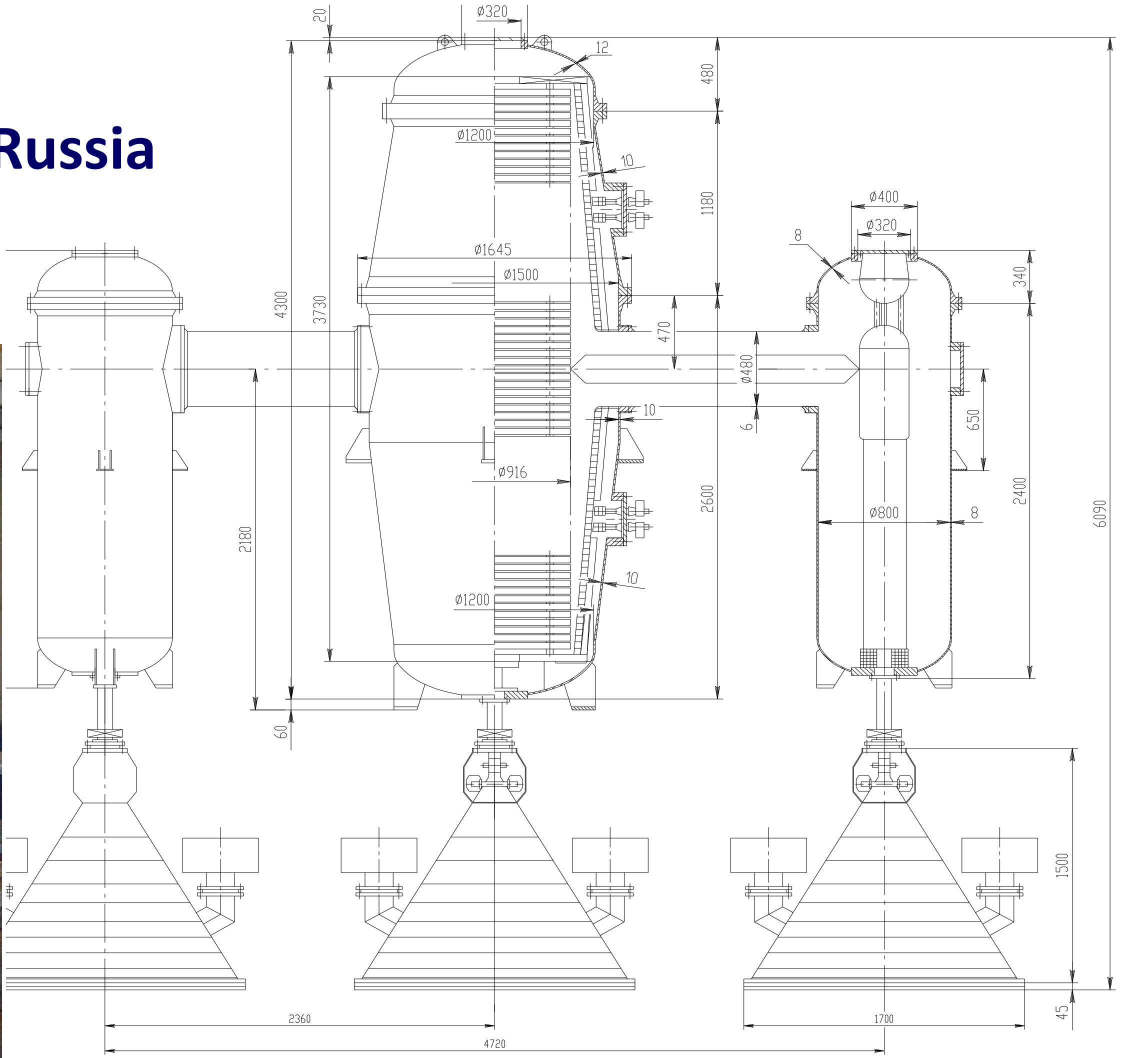
Cryovac Production Facility

State of the Art – 10 EB Units in a Row

ELV 12 coreless transformer accelerator

Electron energy 1 MeV
Beam power 400 kW
Frequency   1000 Hz
One power supply
Three scanners

BINP, Russia



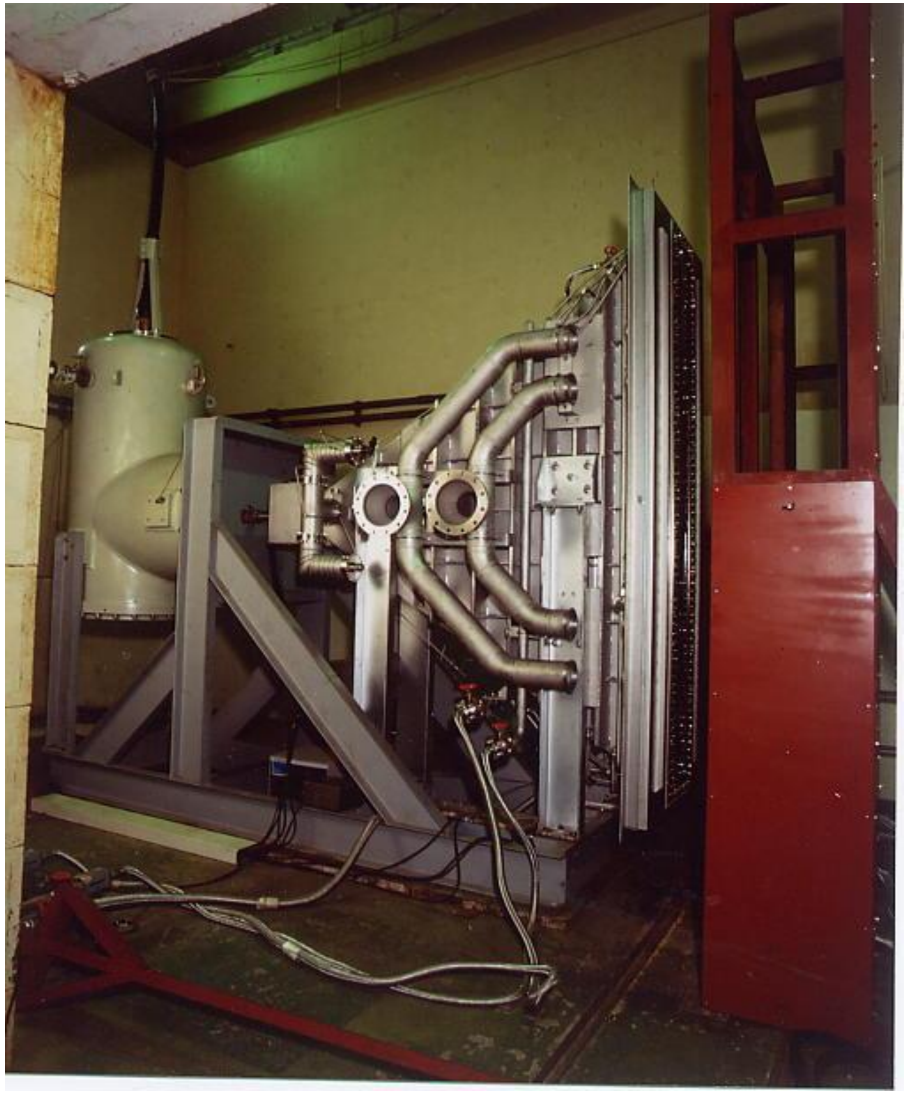
R.A. Salimov et al., 2000

ELV 12 coreless transformer Accelerator (1 MeV, 400 kW)

Facility for wastewater treatment
10 000 m^3/day

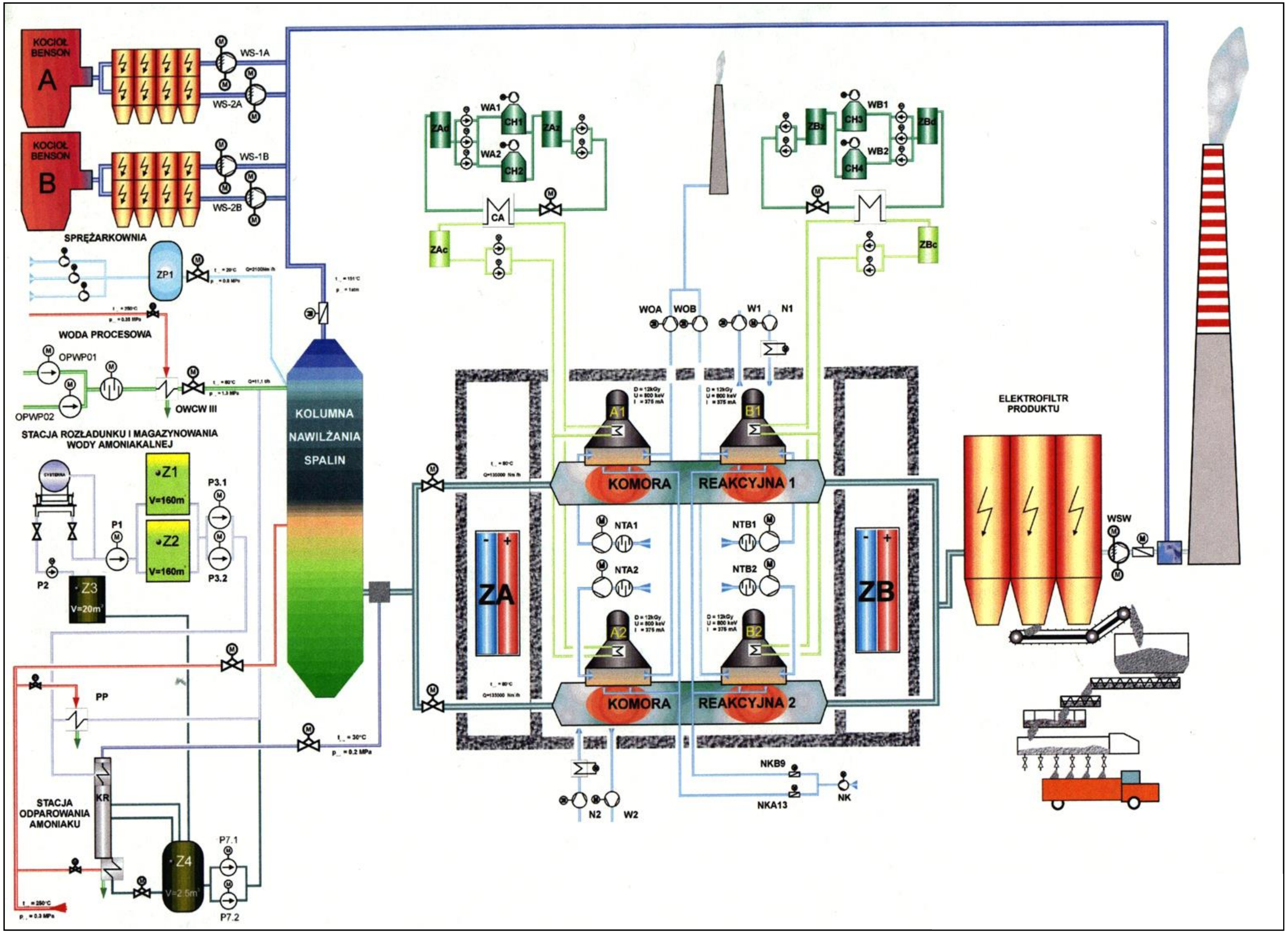
N.K. Kuksanov et al., RUPAC 2012

NHV transformer accelerator
800 keV; 300 kW

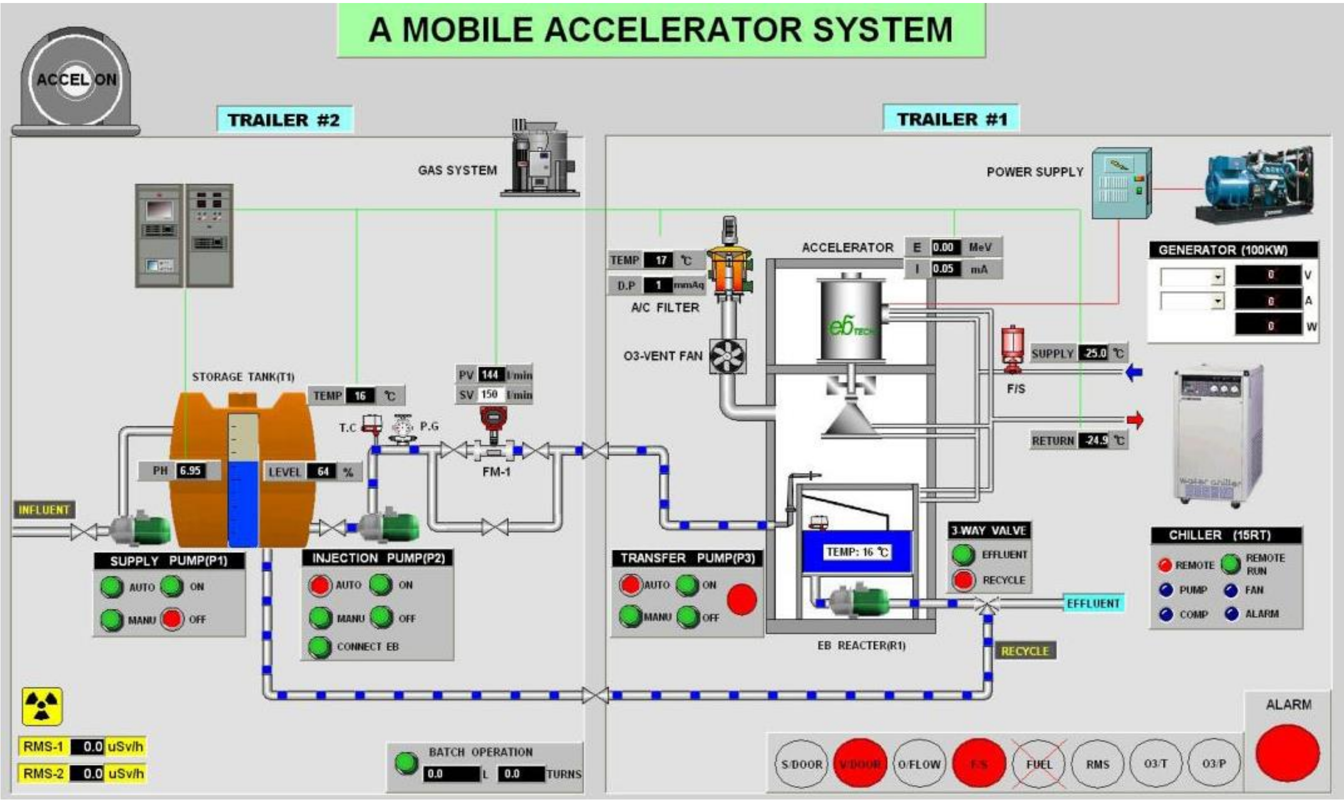


Pomorzany Power Station (Poland)

Radiation facility for flue gas treatment (SO_2 and NO_x removal)
270 000 Nm^3/h
0.8 MeV
4 x 300 kW
Total beam power 1200 kW

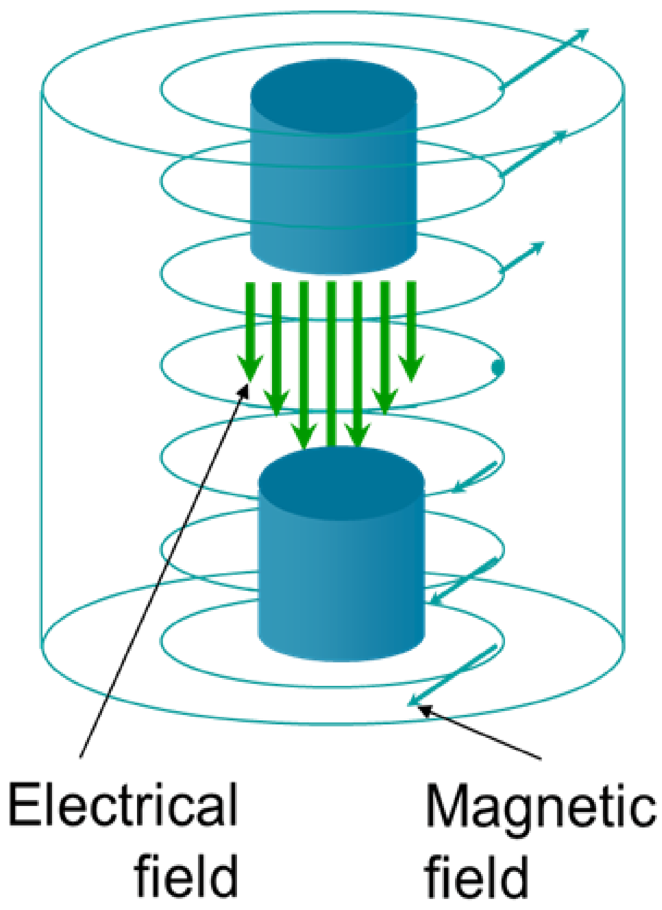


MOBILE ACCELERATOR SYSTEM

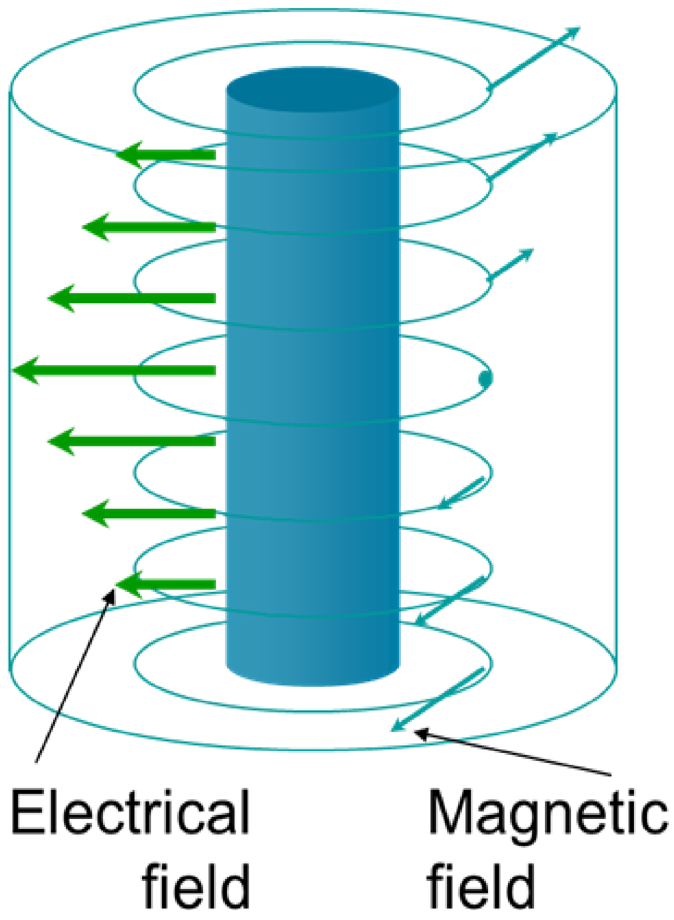


SINGLE CAVITY ACCELERATORS
single pass or multi-pass systems

Single cavity accelerators: principle of operation



„ILU” type family



„Rhodotron” type family

ILU type accelerators, INP, Russia

Ratings	ILU-6	ILU-8*	ILU-10	ILU-12**	ILU-14**
Electron Energy	0.5-2.5 MeV	0.8-1 MeV	4-5 MeV	5 MeV	7.5 – 10 MeV
Beam Power	20 kW	20 kW	50 kW	100/300 kW	100 kW

*Local shield weight 76t

**Multi cavity system

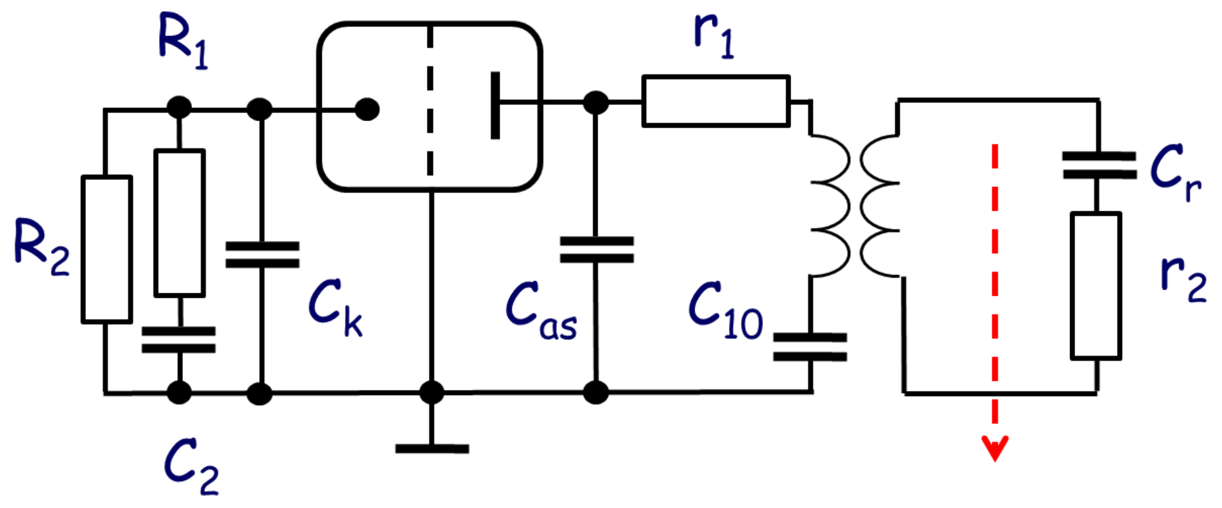
ILU 6 accelerator

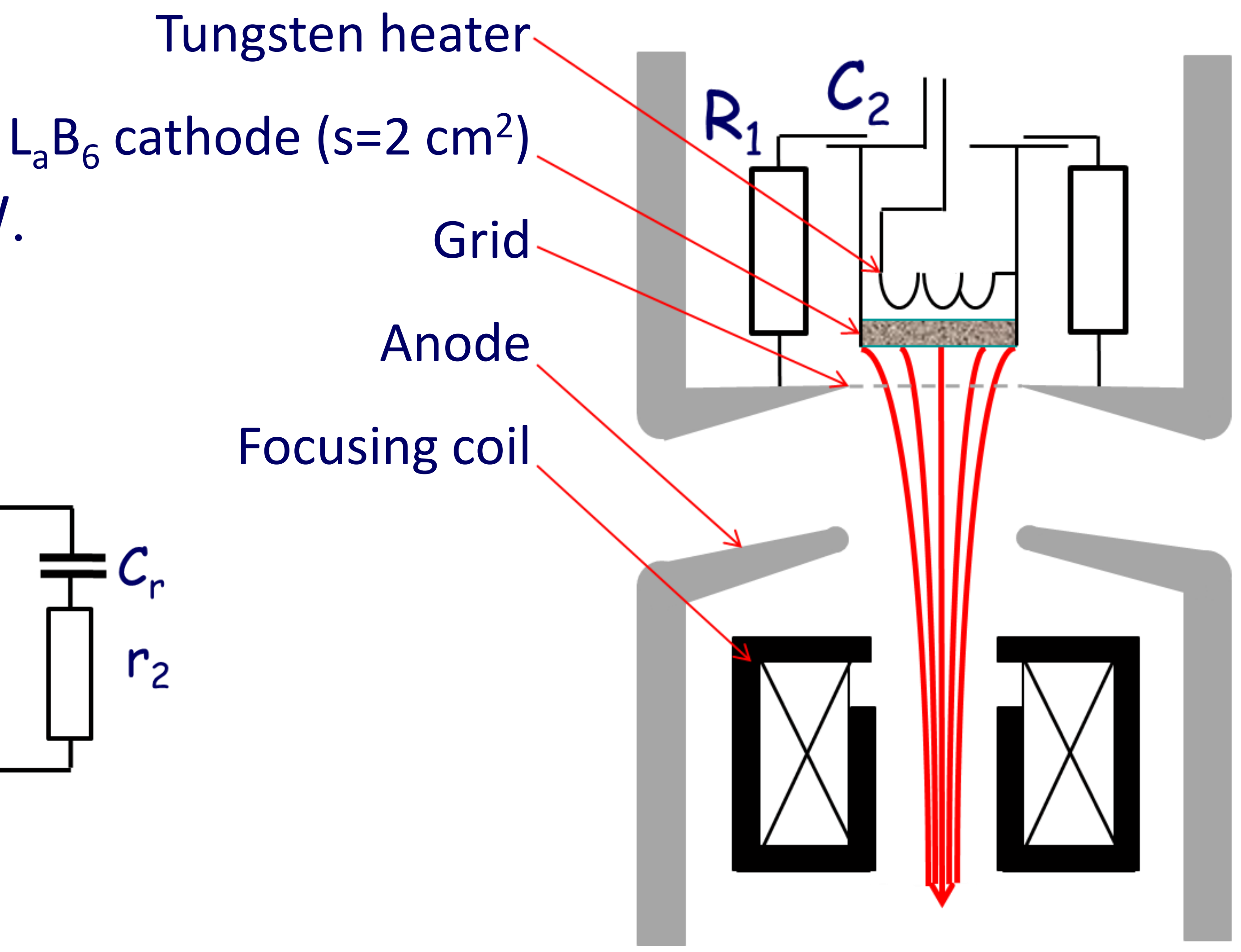
Grid – anode distance:

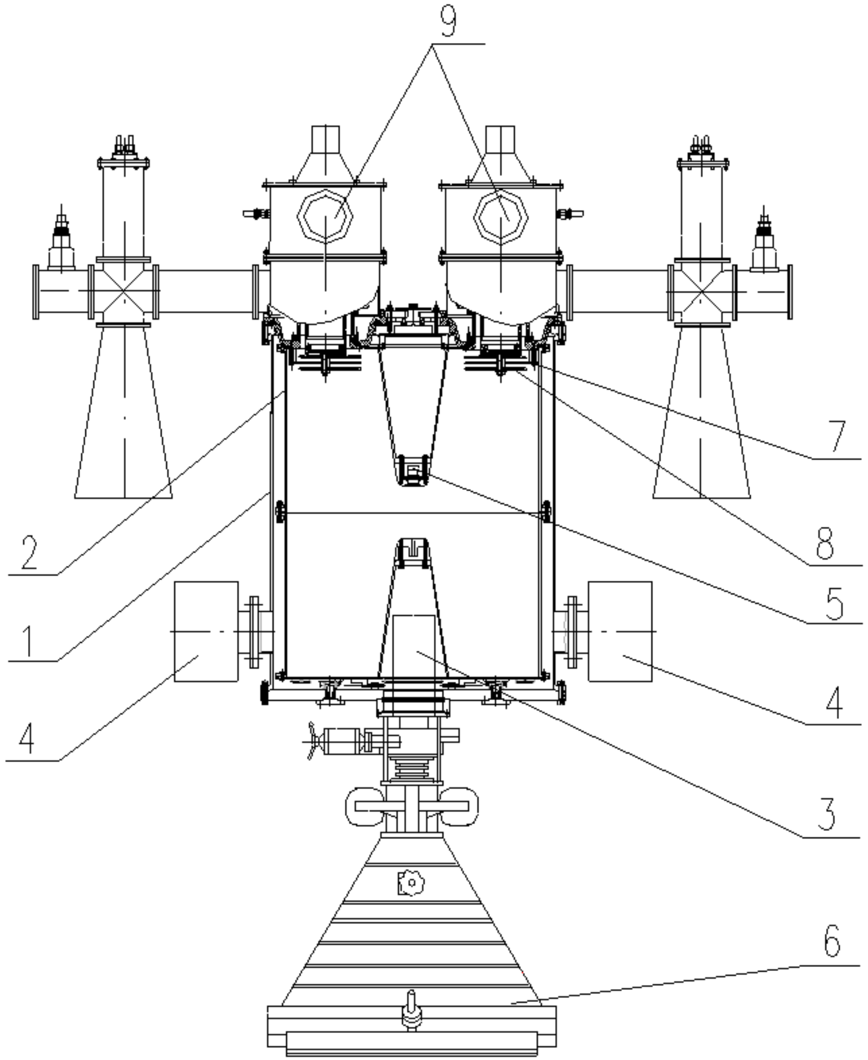
- for 105 MHz; 0,5-1 MeV 10 cm;
- for 115 MHz: 1-1,5 MeV 15 cm;
- for 127 MHz; 1,5-2 MeV 20 cm;

Q factor (measured): 20 000;

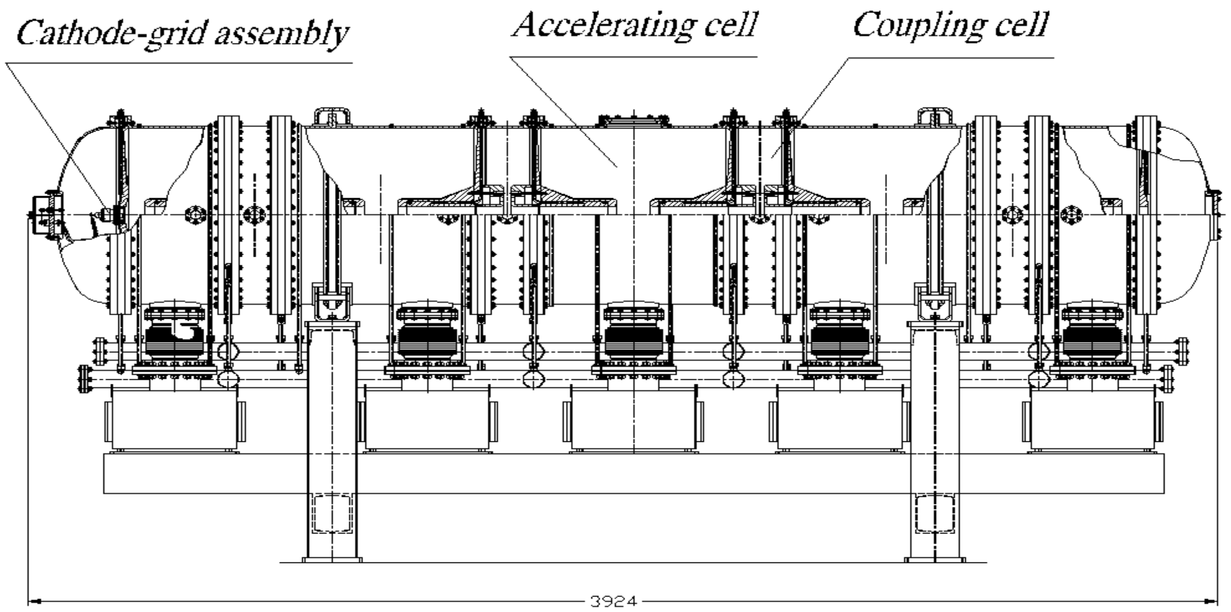
Thermal losses in resonator: 5,3 kW.





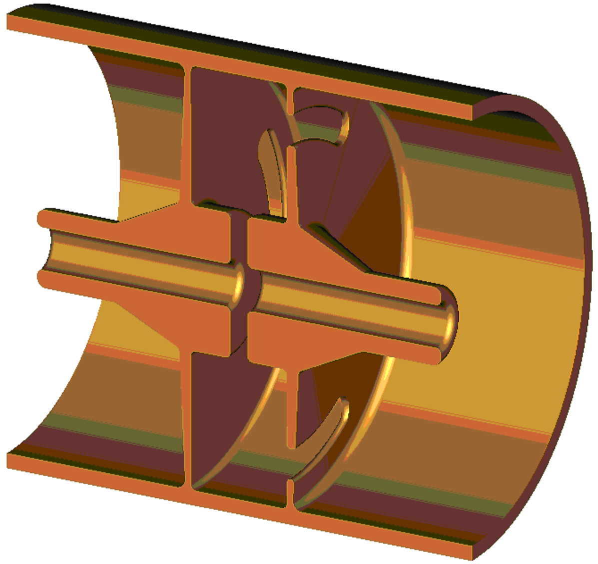


ILU 10



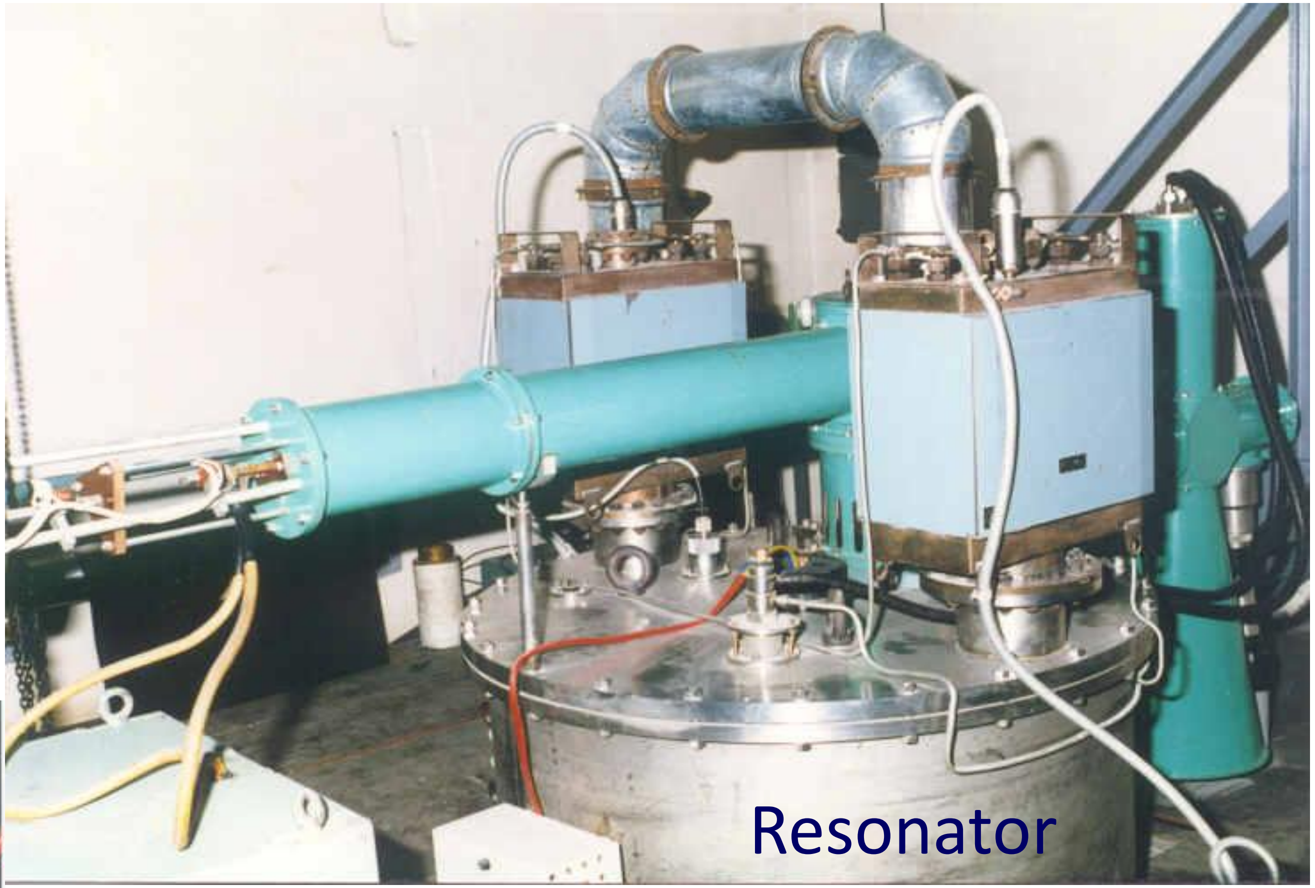
ILU 12

Coupling cell



1 – vacuum tank, 2 – copper toroidal cavity, 3 – magnetic lens, 4 – ion pumps, 5 – grid-cathode unit, 6 – outlet device, 7– coupling loop support, 8 – vacuum capacitor, 9 – RF generators.

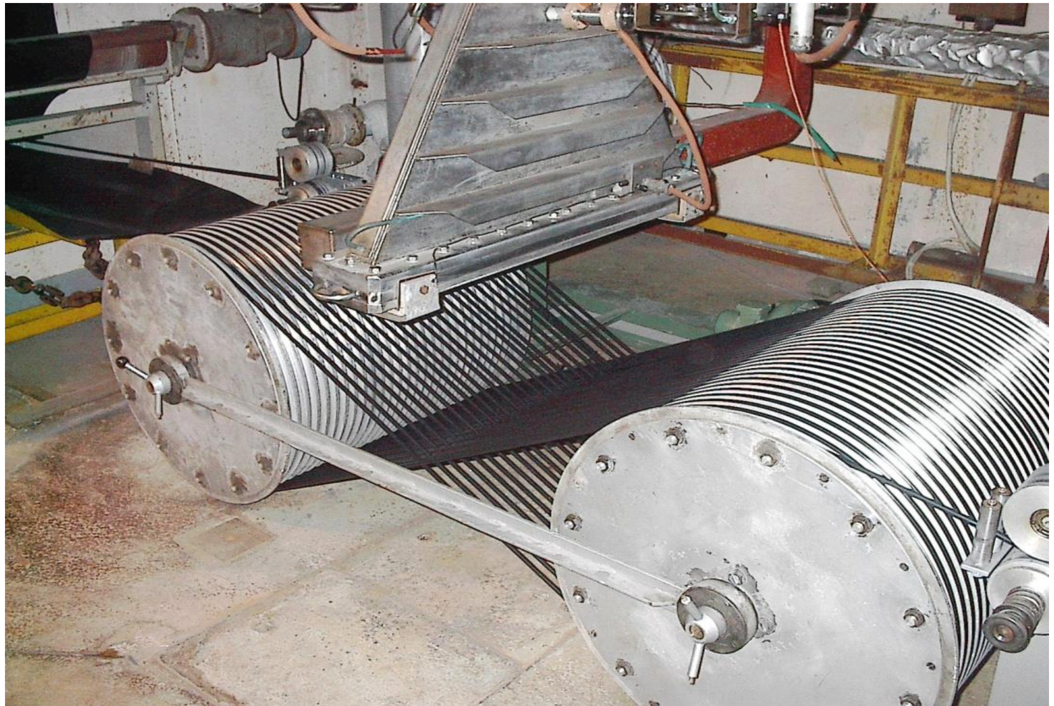
ILU 6 electron accelerator at pilot plant radiation facility INCT, Warsaw

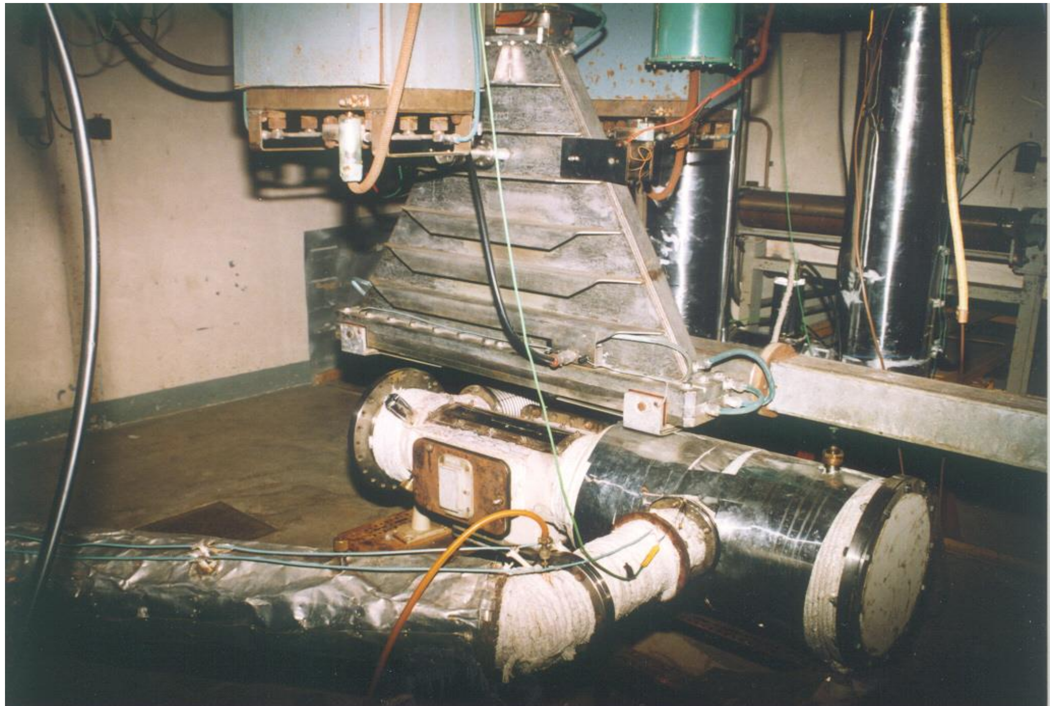


Scanner

Energy	0.3-2,5 MeV
Beam power	up to 25 kW
Pulse duration	0.4 ms
Repetition rate	up to 60 Hz
Scan width	980 mm
Frequency	127 MHz

ILU 6 Pilot Plant Facility, INCT, Warsaw

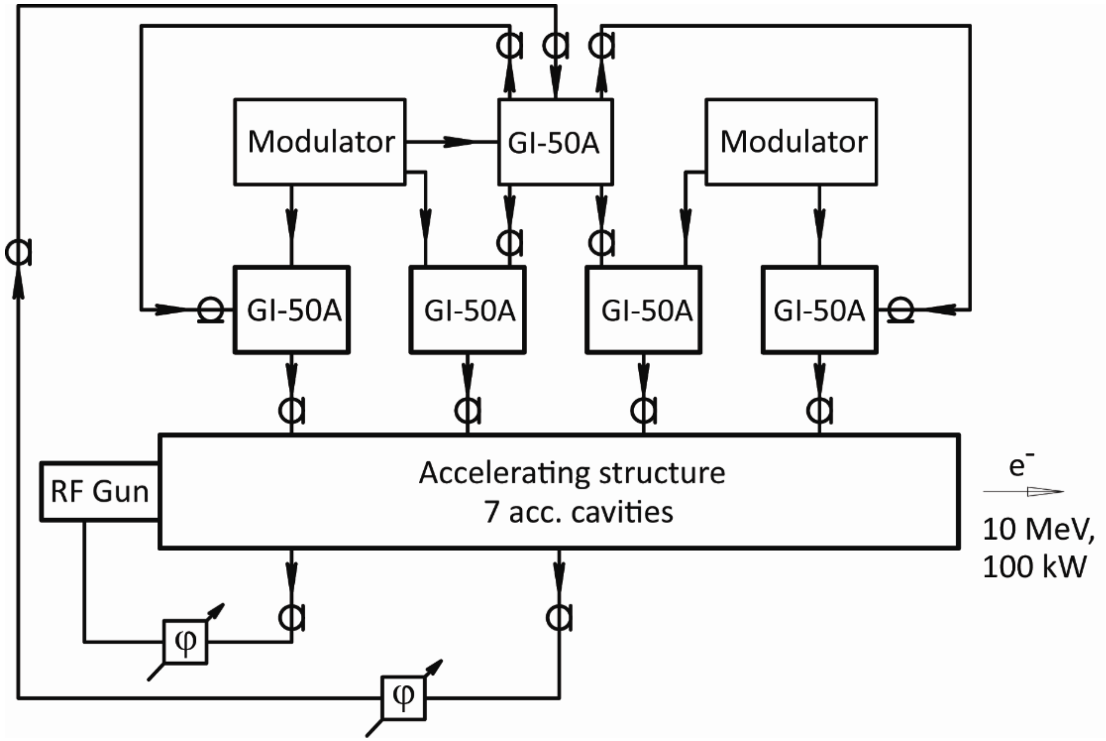


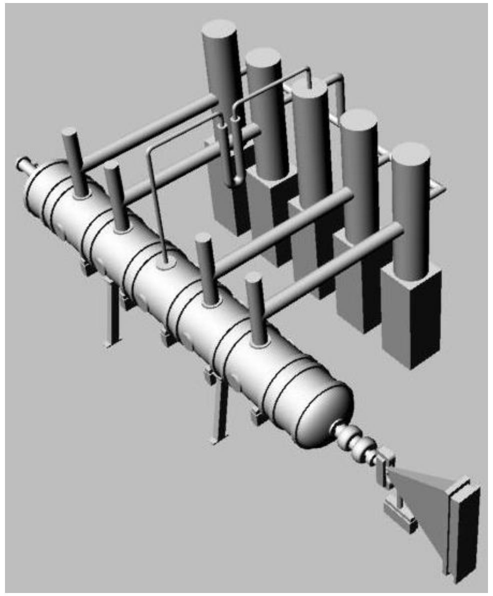


ILU-10 in RadPol SA, Poland, 2008

- Energy 5 MeV; beam power 50 kW;
- Treatment of polymer pipes (heat shrinkable tubes);
- Treatment of cables and wires;
- Movable accelerator between two technological lines.

ILU 14 accelerator
10 MeV, 100 kW

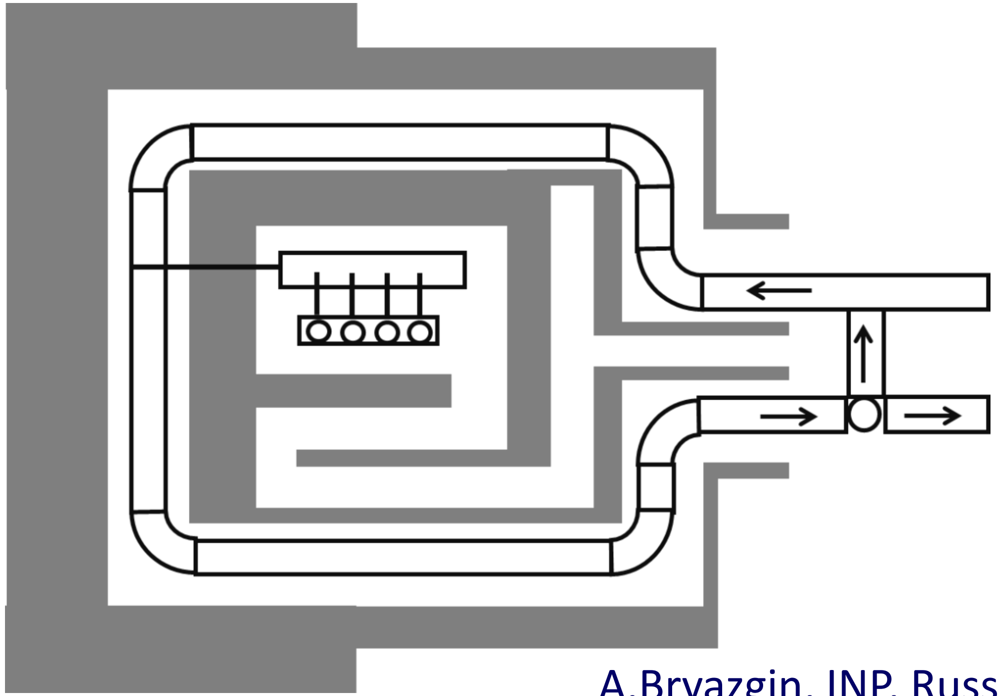




A.Bryazgin, INP, Russia

ILU 14 accelerator 10 MeV, 100 kW at sterilization facility, Russia

Energy, MeV	10	7.5
Accelerating structure efficiency, %	61	77
Total efficiency, %	26	32



A.Bryazgin, INP, Russia

Accelerators Rhodotron type, IBA, Belgium

Starting date: December 1991

TT100 Compact 10 MeV

40kW, 4mA

TT200 Standard 10 MeV

100kW, 10mA

Models available from 35 kW to 100 kW

TT300 High power 10 MeV

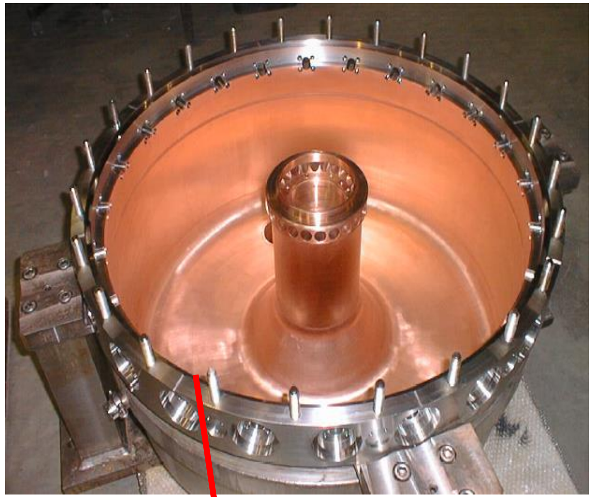
245kW, 35mA

Models available from 50 kW to 245 kW

TT1000 High power 7 MeV

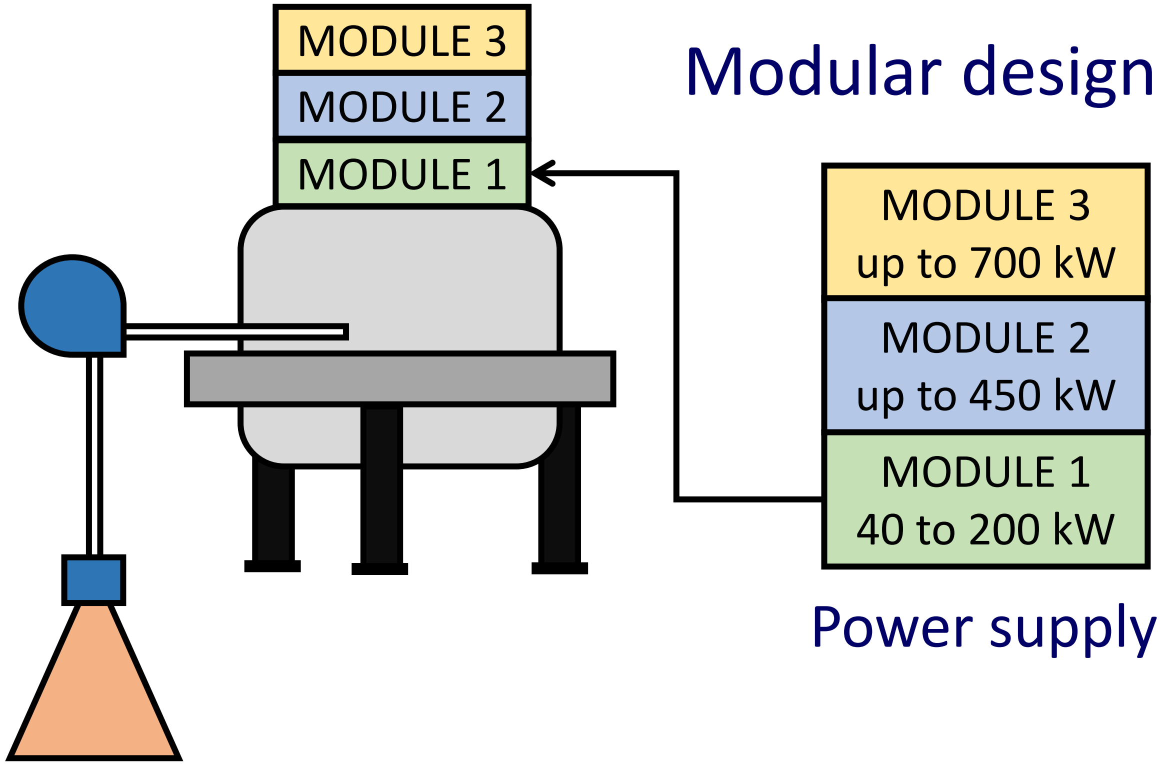
560kW, 80mA

Models available from 100 kW to 560 kW



Rhodotron: design and operation principles

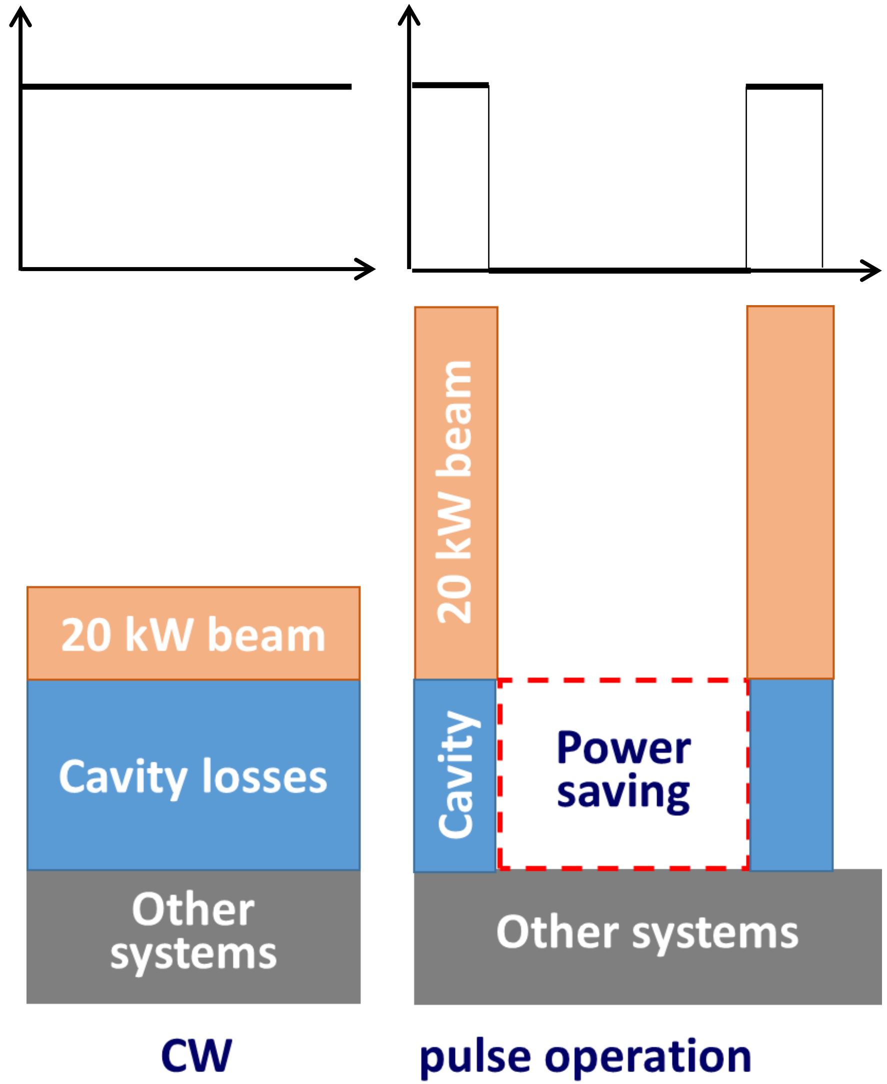
Modular design



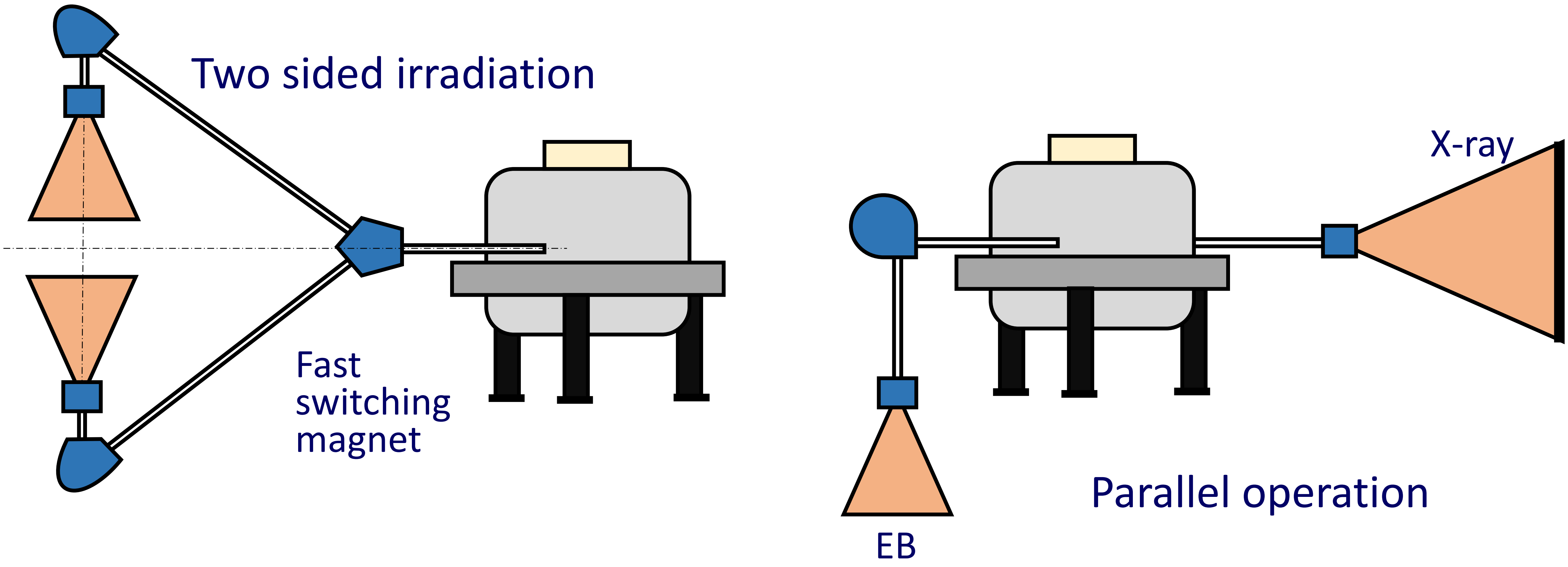
Power supply

M. Abs, J. Brison, P. Dethier, IBA

Reduced power consumption

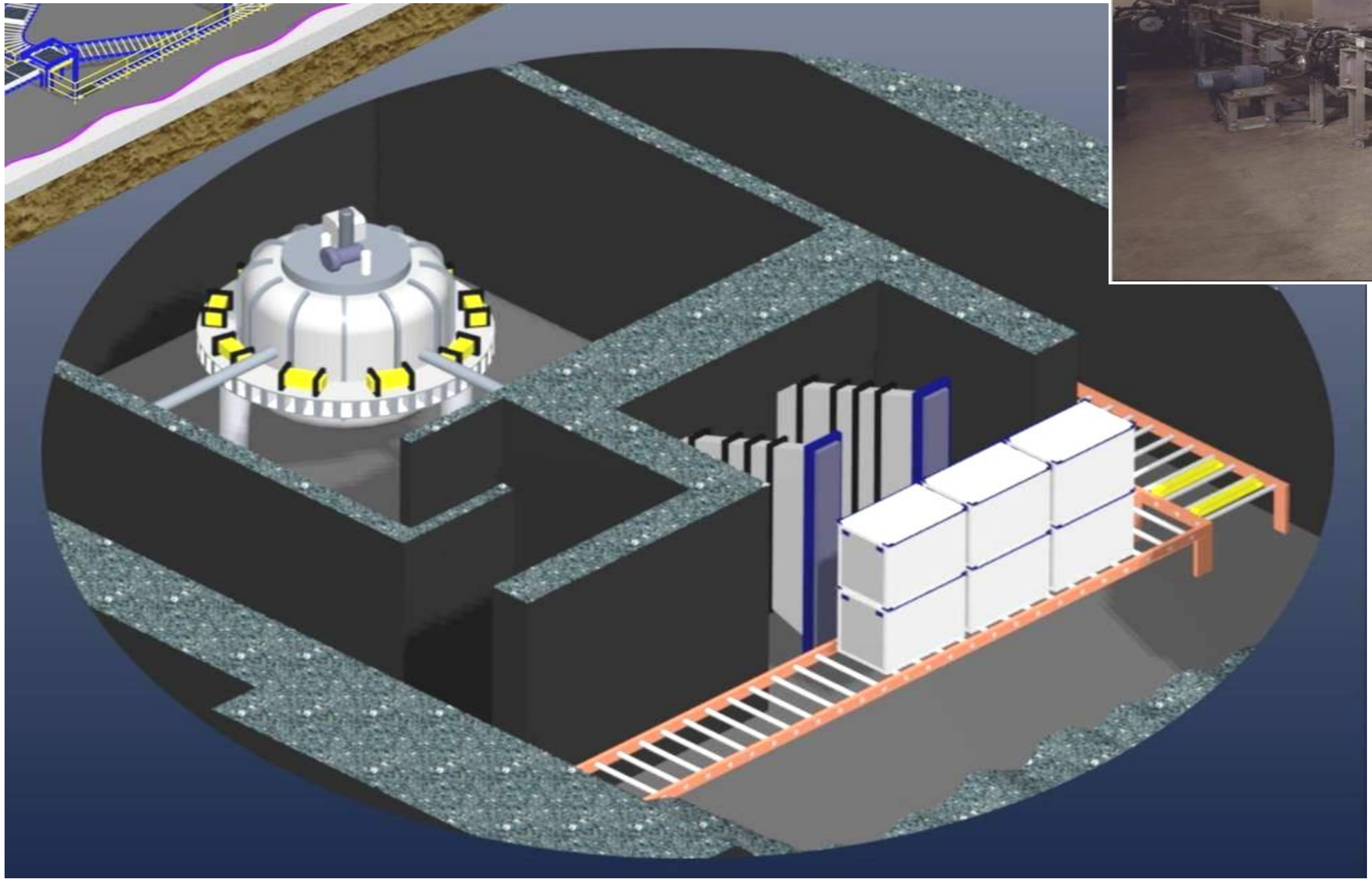


Rhodotron: design and operation principles



M. Abs, J. Brison, P. Dethier, IBA

RHODOTRON TT 300, IBA, USA



Electron energy:

5-7 MeV

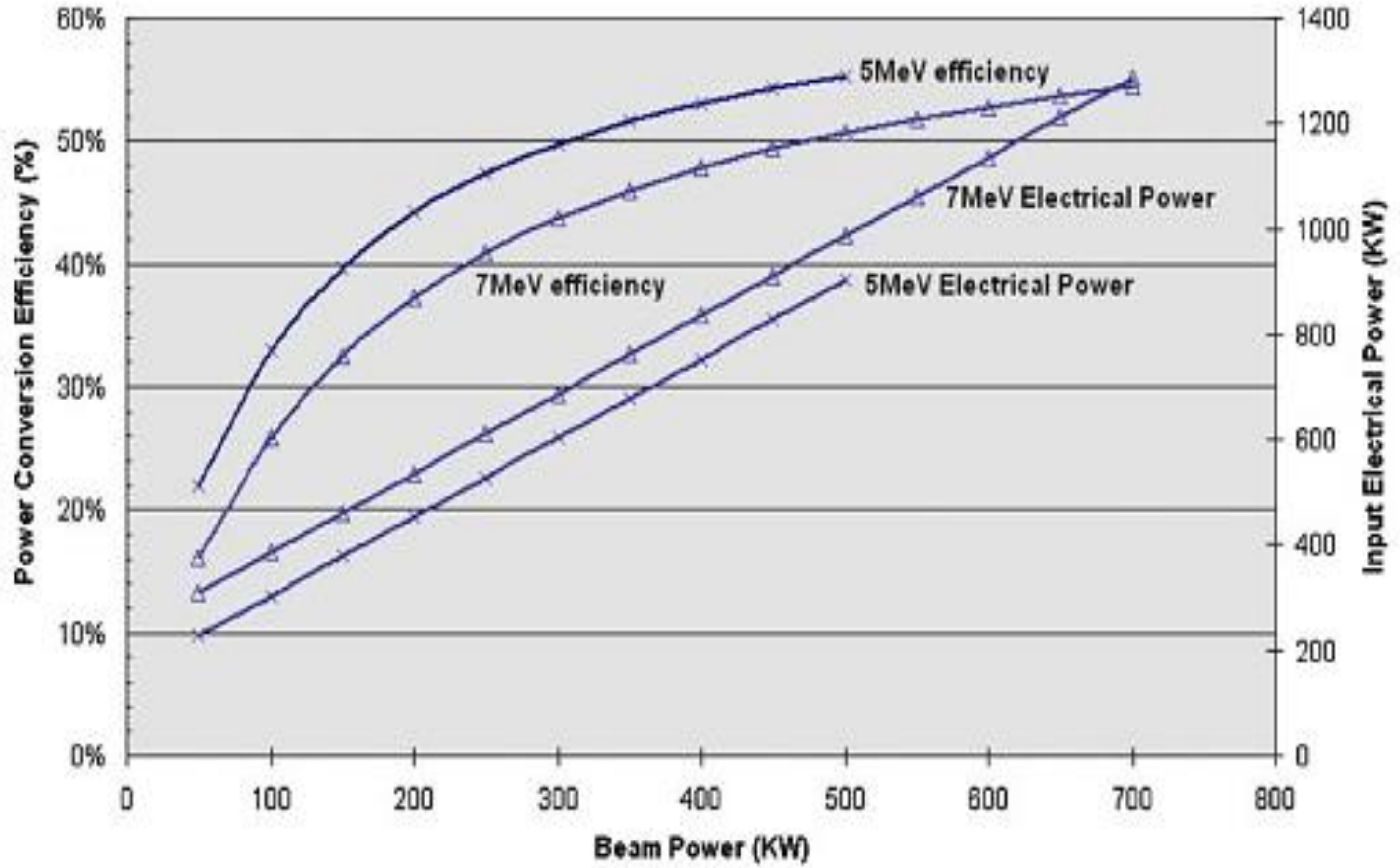
Beam power:

200 kW

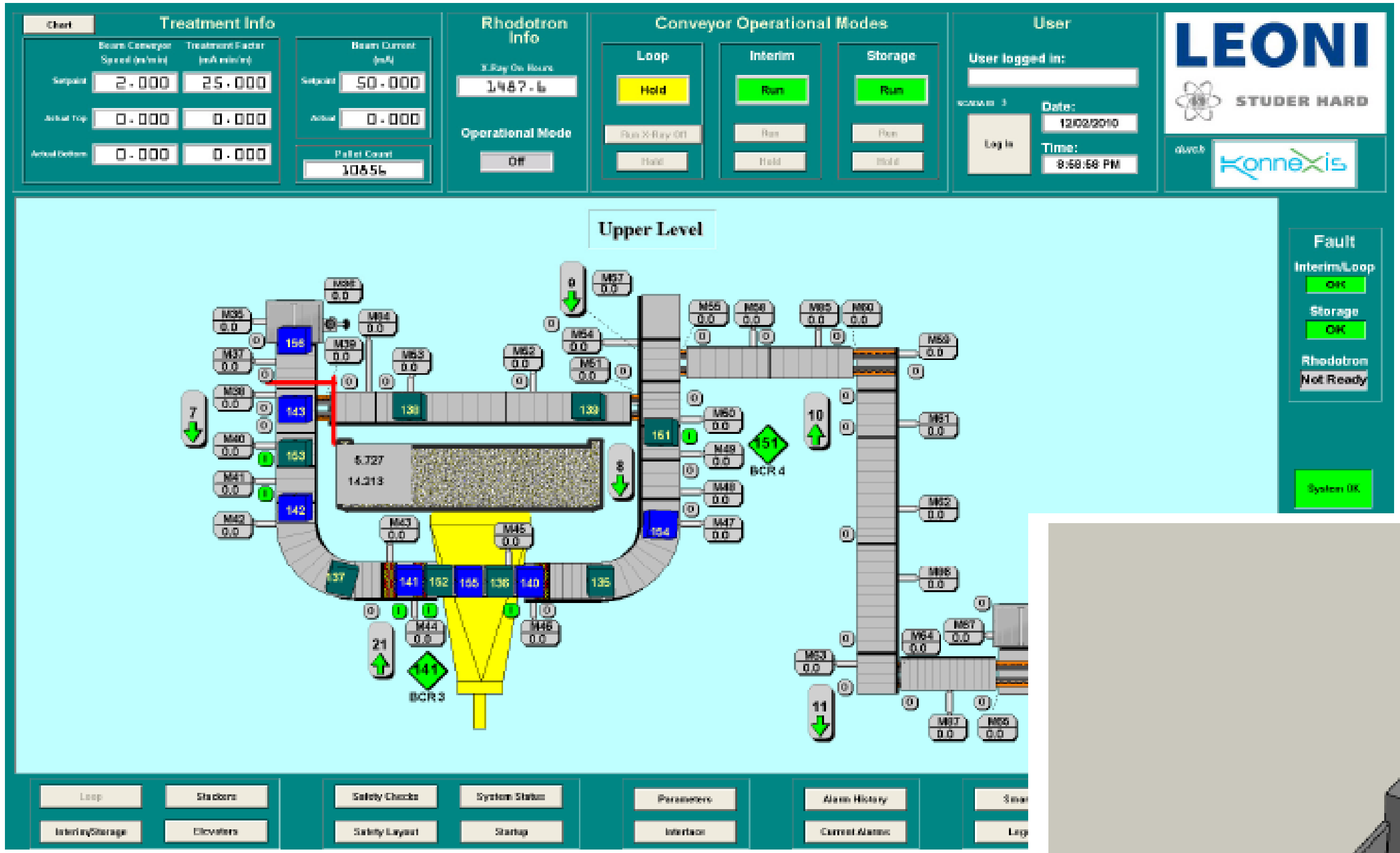
EB and X-ray options

The IBA Rhodotron TT1000: a very high power e-beam accelerator

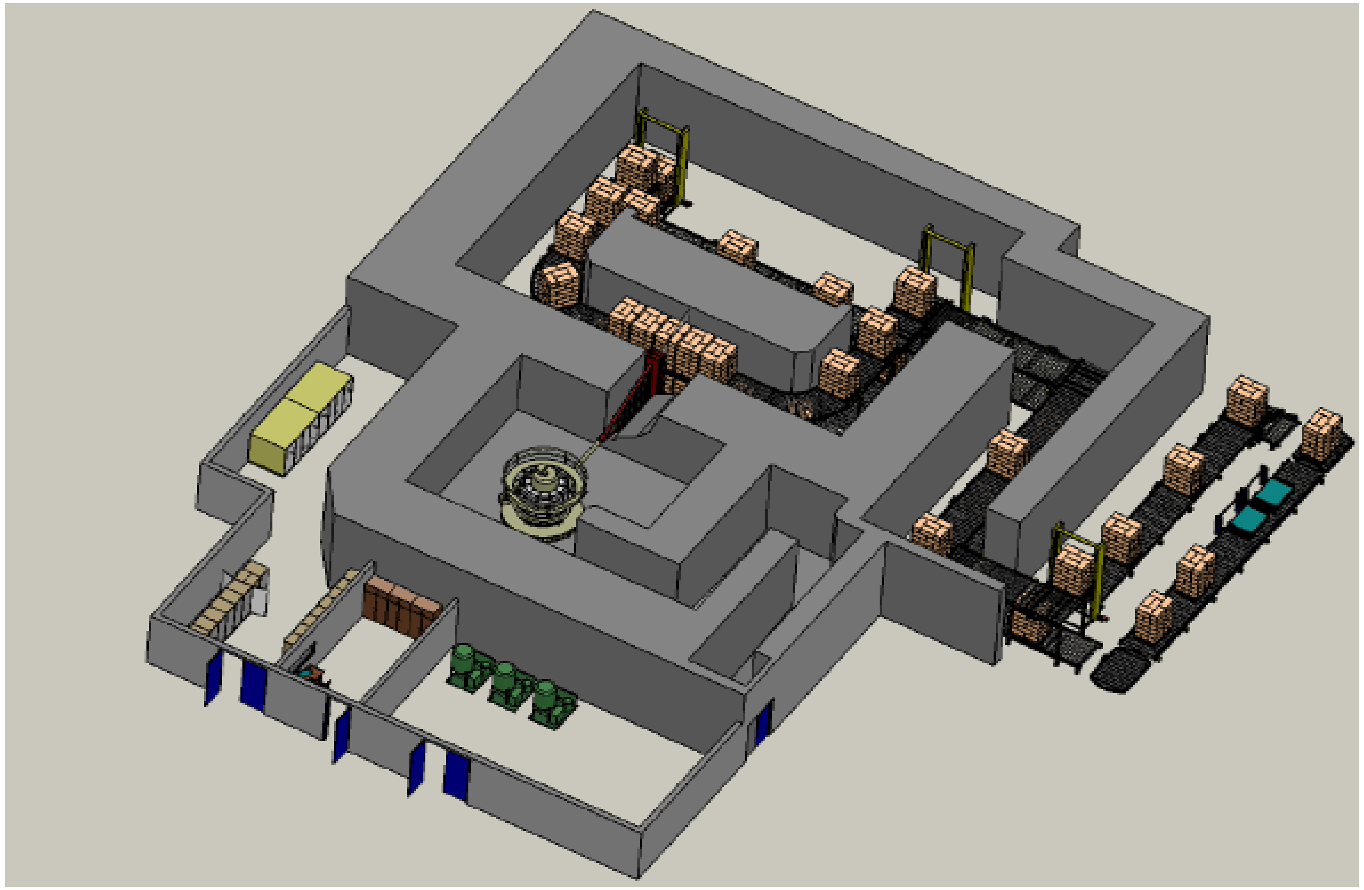
TT1000 Rhodotron aimed at delivering 5 and 7MeV electron beams with a current intensity of 100mA.
Continuous beam of 93mA at an energy of 7MeV in February 2003.



Radiation Physics and Chemistry
71 (2004) 285–288



RHODOTRON, TT1000, IBA
7 MeV, 560 kW
Switzerland

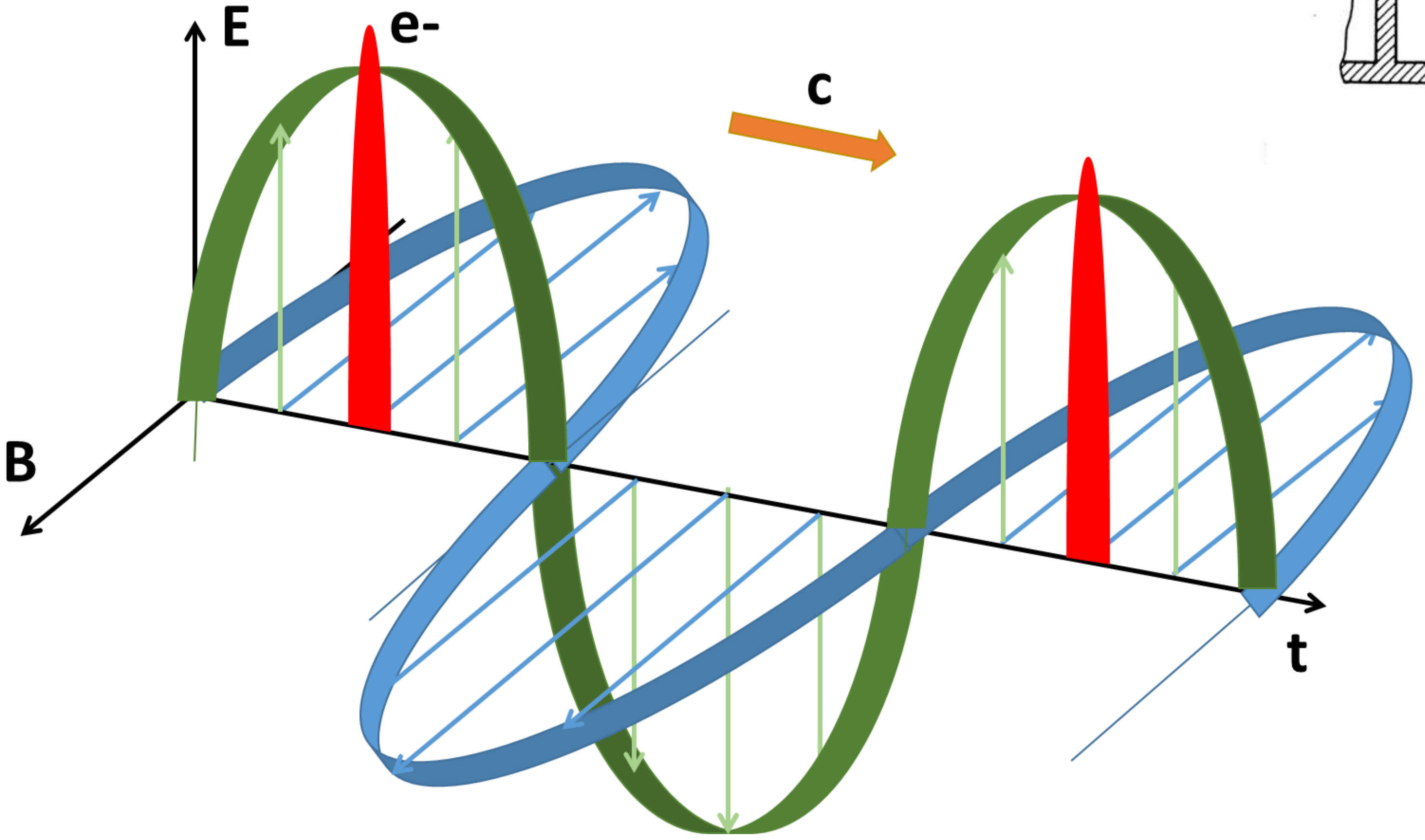


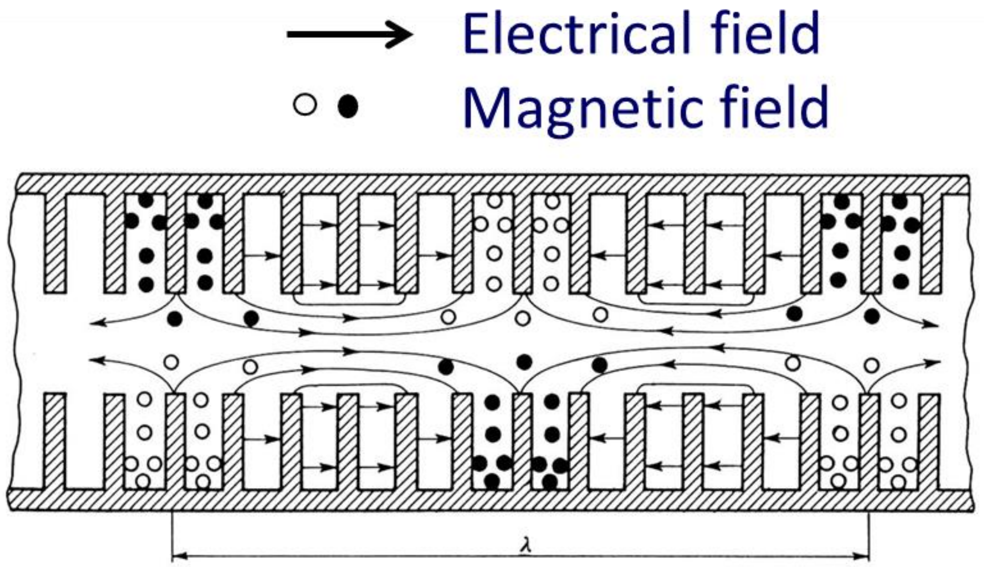
X-Ray (Dose 25 kGy)
product density 0.15 gr/cc,
Productivity 560 kW; 7 MeV, 15.5 m³/h,
8000/rok (9% for service) 124,000 m³.

Gamma equivalent
4.4 MCi gamma Co60.

LINEAR ELECTRON ACCELERATORS

Linear accelerator with traveling wave

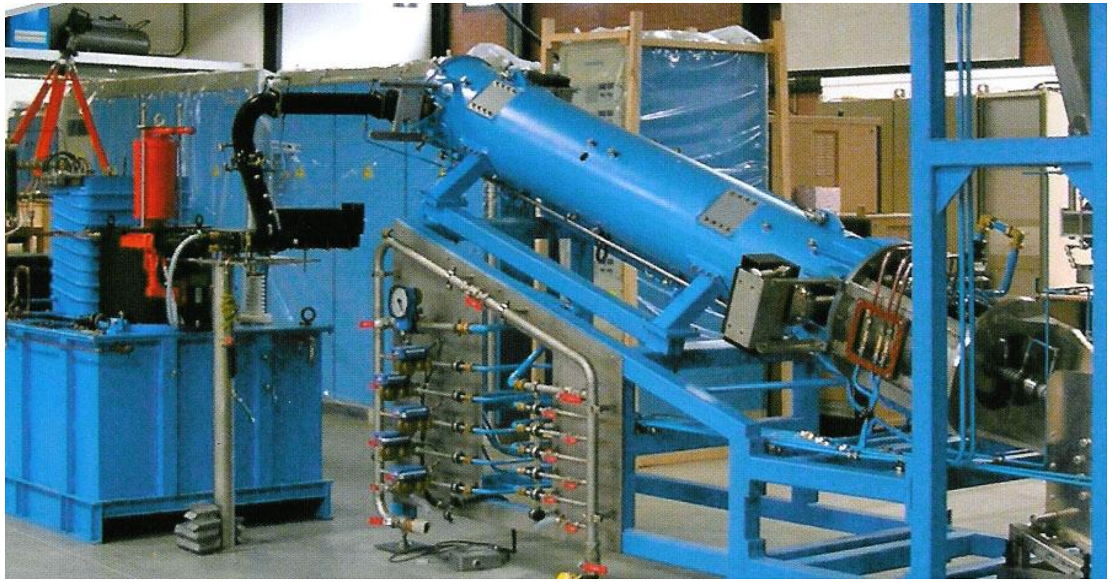




$$P_{eb} = E \times I_{av}$$

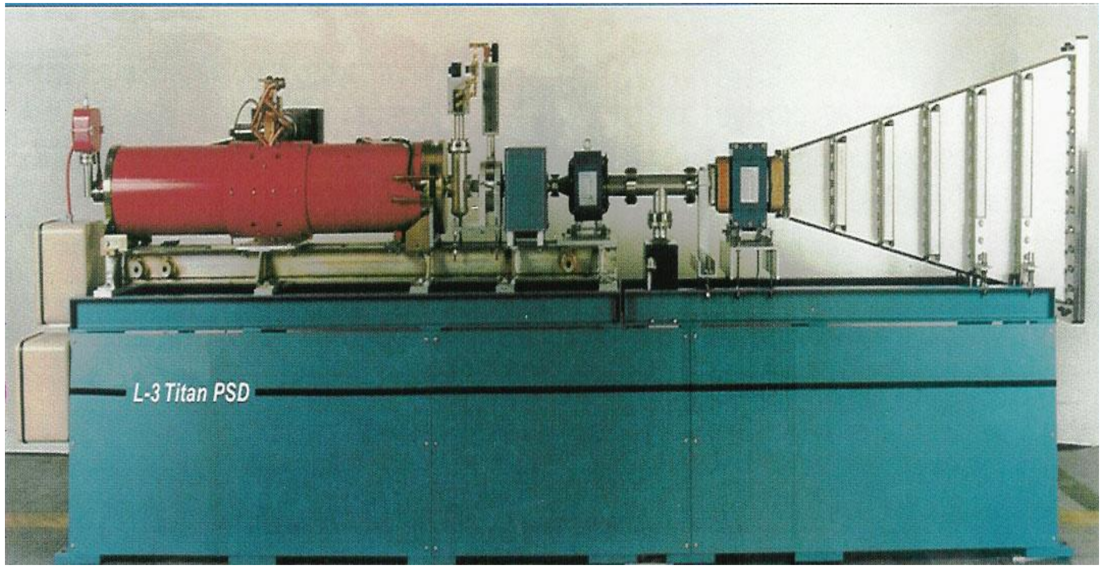
$$I_p \times \tau = I_{av} \times 1/F$$

P_{eb} – beam power
E – electron energy
I_{av} – average beam current
I_p – pulse beam current
F – repetition rate



Linear accelerator:
10 MeV, 10 kW
Getinge Linac Technologies
Orsay, France

Linear accelerator:
10 MeV, 15 kW
L3 Communications, USA



Linear accelerator UEL-10-10S:
10 MeV, 10 kW
NPK LUTS NIIEFA, Russia

10 MeV, 10 kW linac

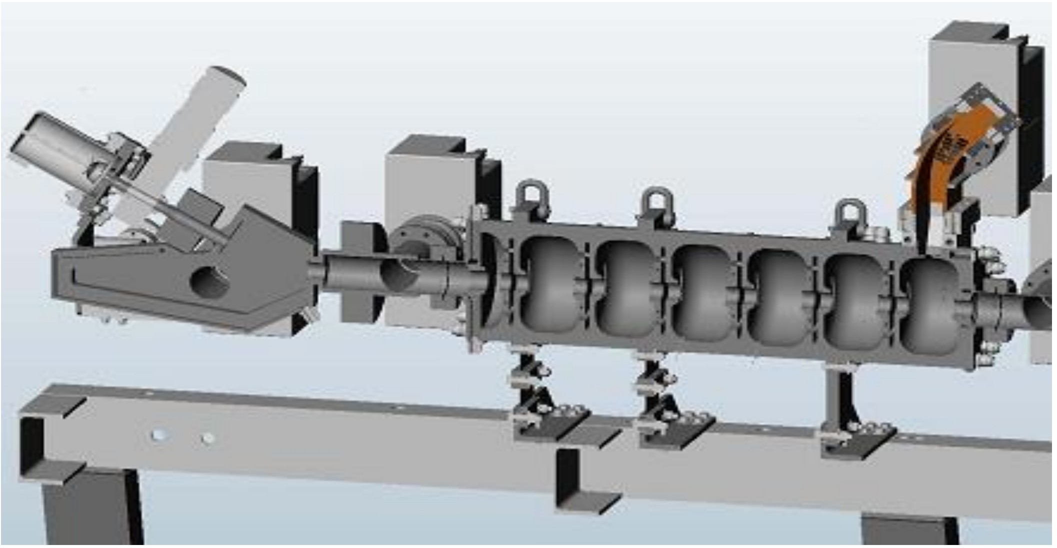
CoRAD, St Petersburg, Russia

The main features:

- Horizontally located accelerator, monorail conveyor,
- Two sides irradiation during one pass,
- Radiation shielding: concrete blocks (volume 360 m^3); facility spot: ~240 m^2,
- Solid-state modulators for klystron and electron gun, power line <75 kW,
- Control of electron energy, beam current and scan length,
- Throughput: 20-30 kGy; 55 boxes/h (40 x 40 x 60 cm^3, 19 kg).

Standing wave linear accelerators
L3 Communication (SureBeam), USA

Energy/beam power	Frequency	RF source	Energy source	Switch
5 MeV/15 kW	S	Klystron	PFN	Tyratron
10 MeV/18 kW	S	Klystron	PFN	Tyratron
5 MeV/150 kW	L	Klystron	Induct.	IGCT
10MeV/150kW	L	Klystron	Induct.	IGCT



GETINGE

LINAC

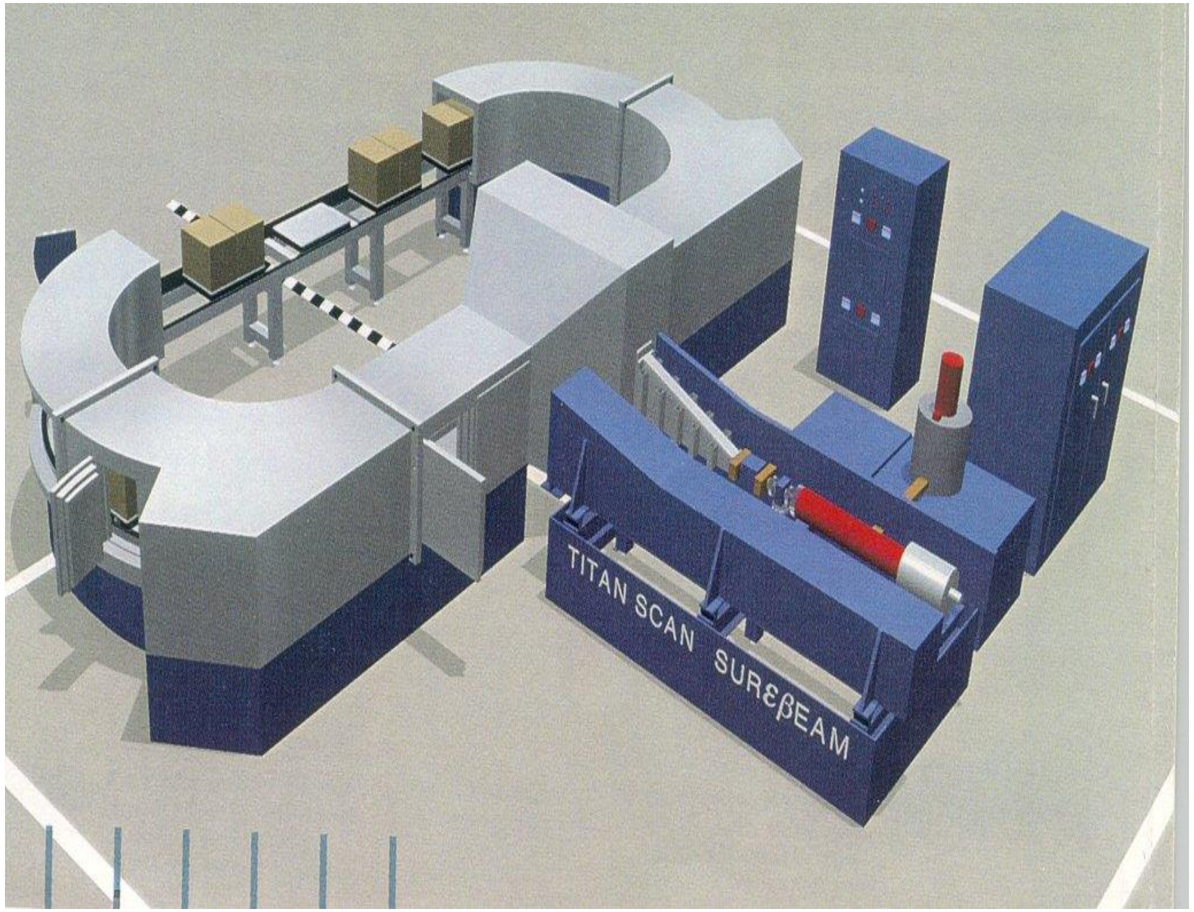
Energy 5 MeV

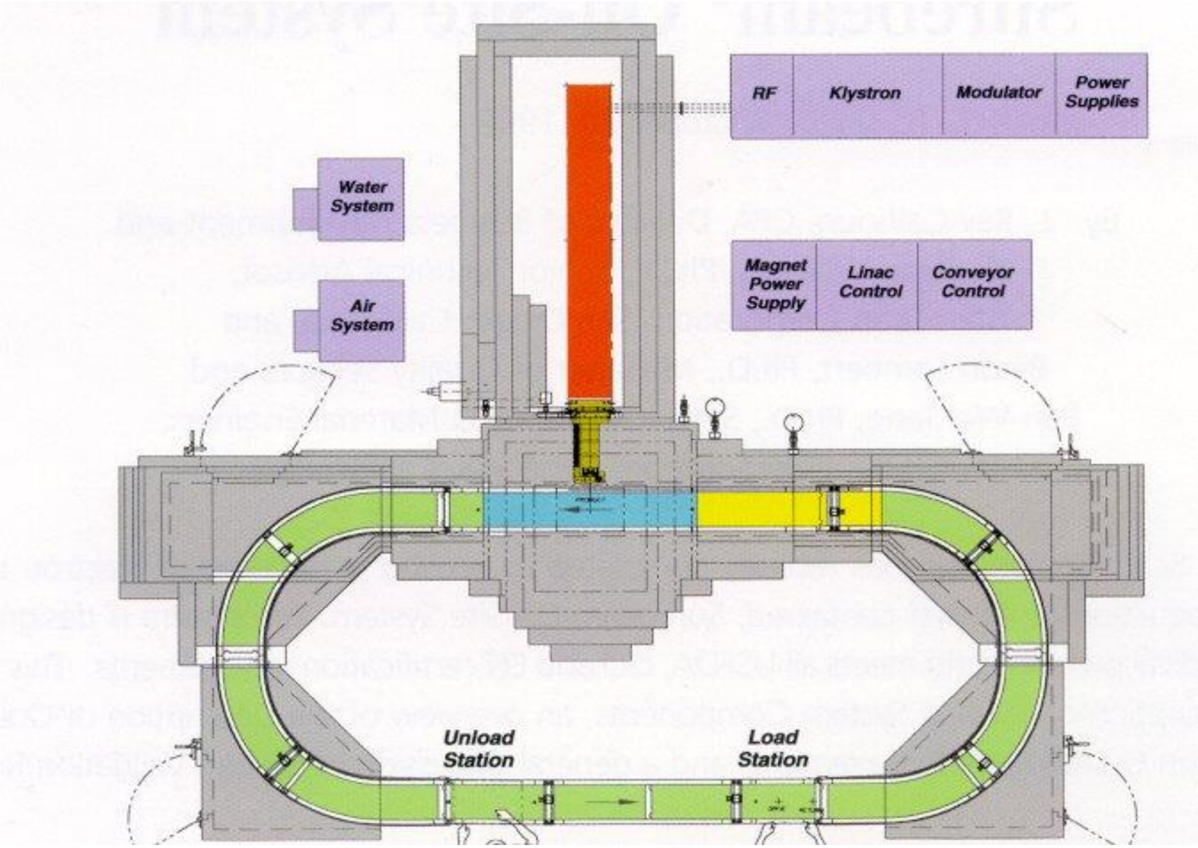
Beam power 5 kW

Scanning area 10x10 cm

10 MeV electron accelerator with local shield

K.G. Carlson et al., Radiat. Phys. Chem., 2000





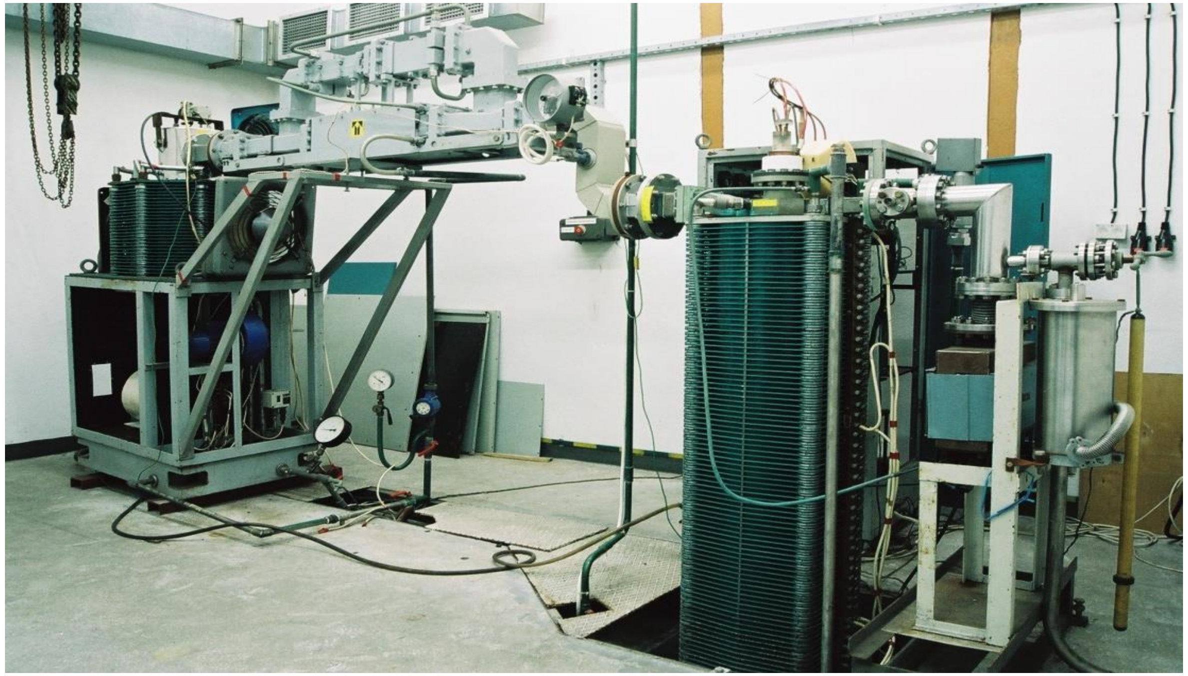
ELECTRON ENERGY 10 MeV
BEAM POWER 3-5 kW

DOSE 10-50 kGy
PRODUCTIVITY up to 50 000 m^3/rok

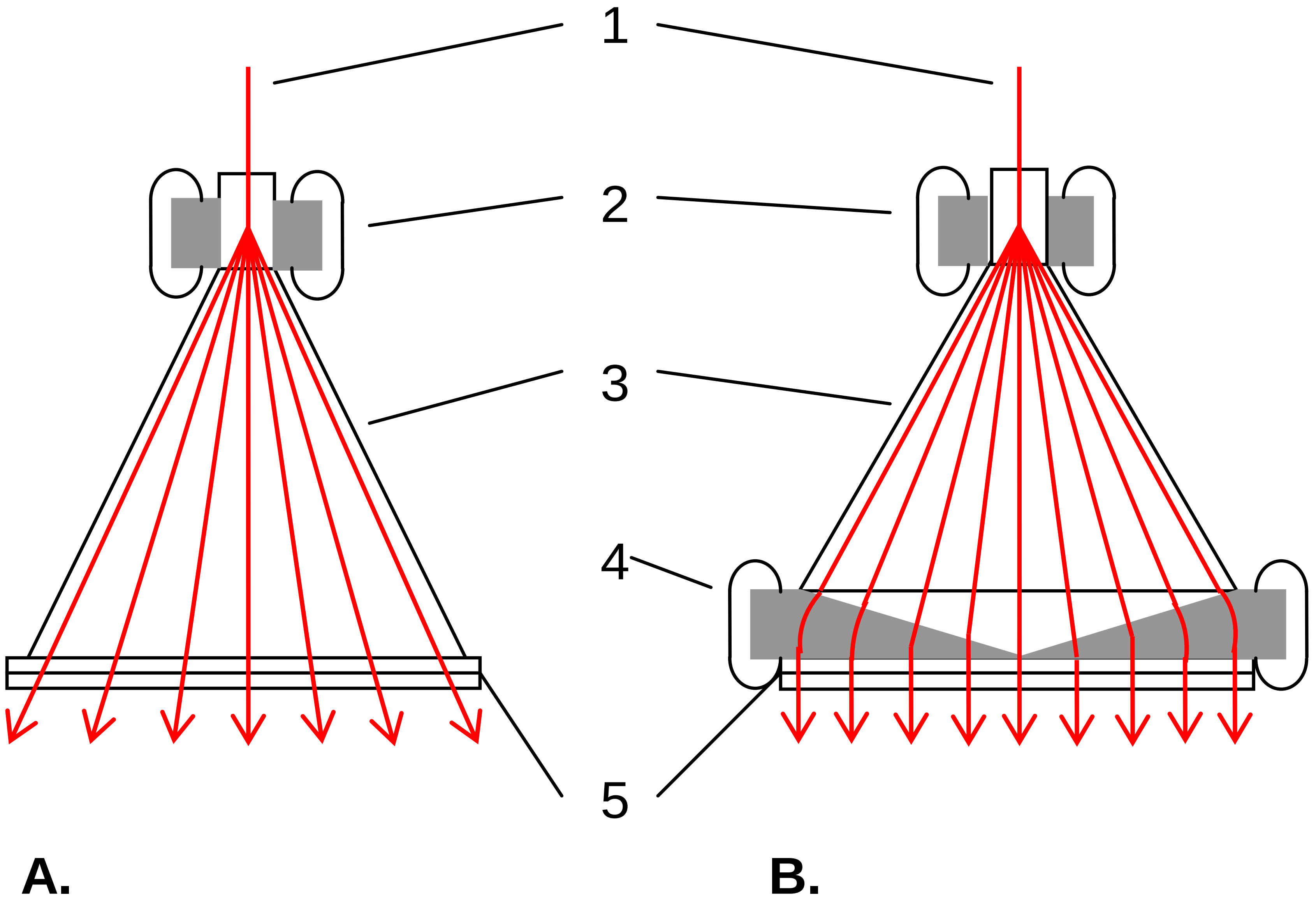


Radiation sterilization facility, 10 MeV, 15 kW, INCT





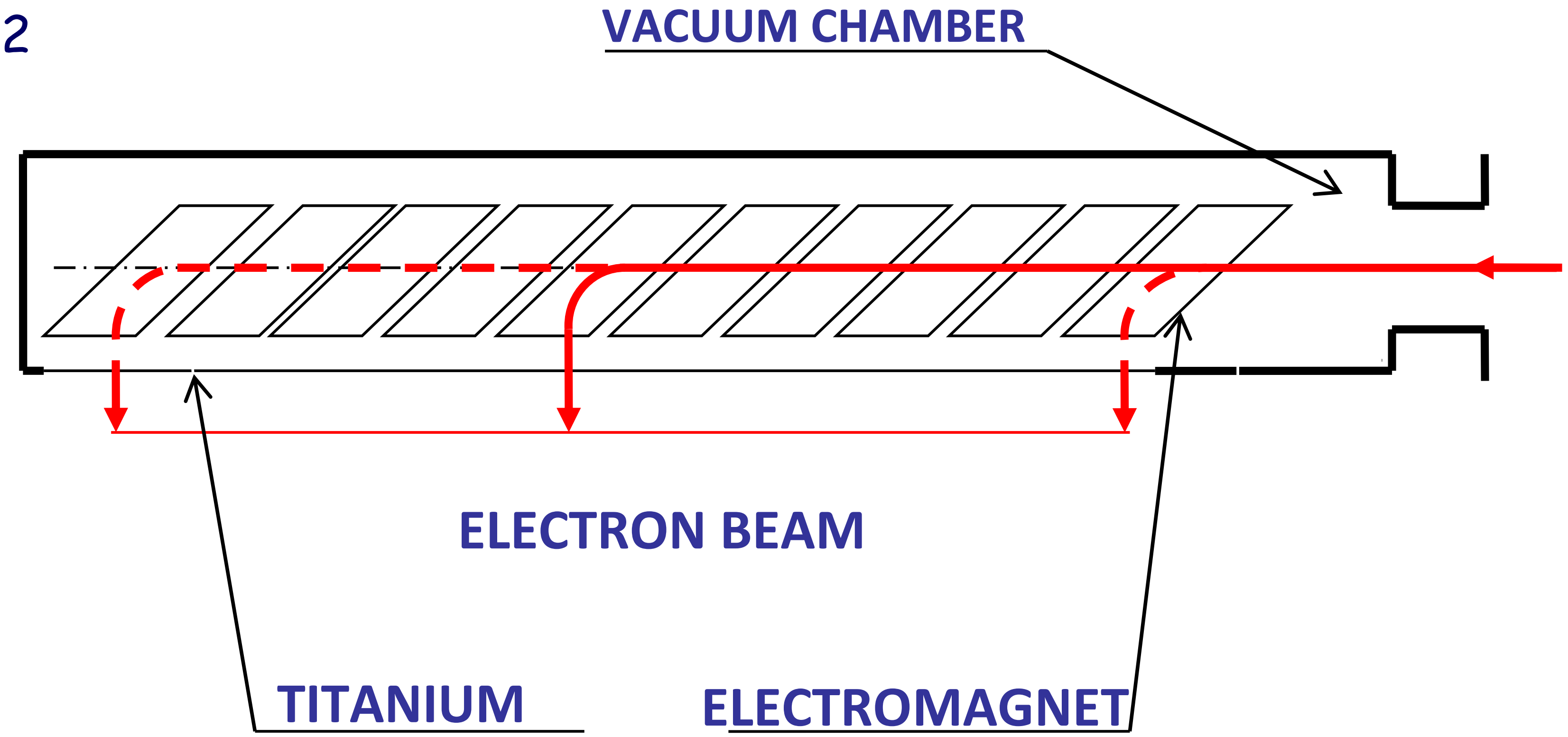
OUTPUT AND BEAM SCANNING DEVICES



Configurations of accelerator output device (A – triangular scanning, B – parallel beam): 1 – electron beam; 2 – scanning magnet, 3 – scanner; 4 – correction electromagnet; 5 – output foil

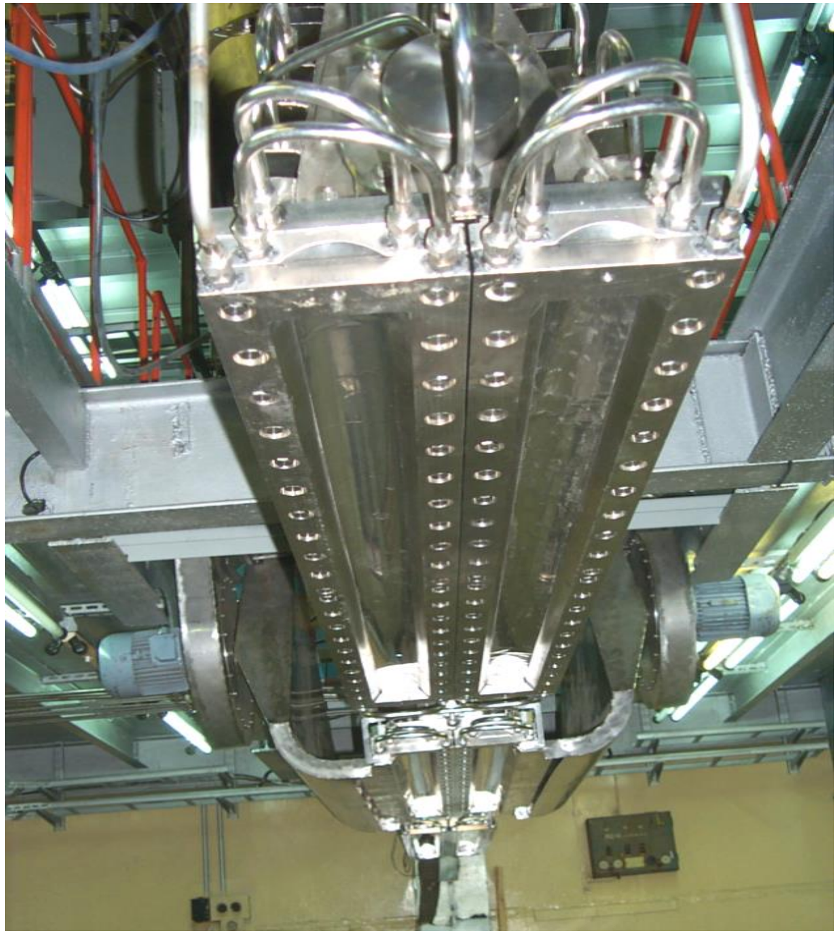
Linear scanning system

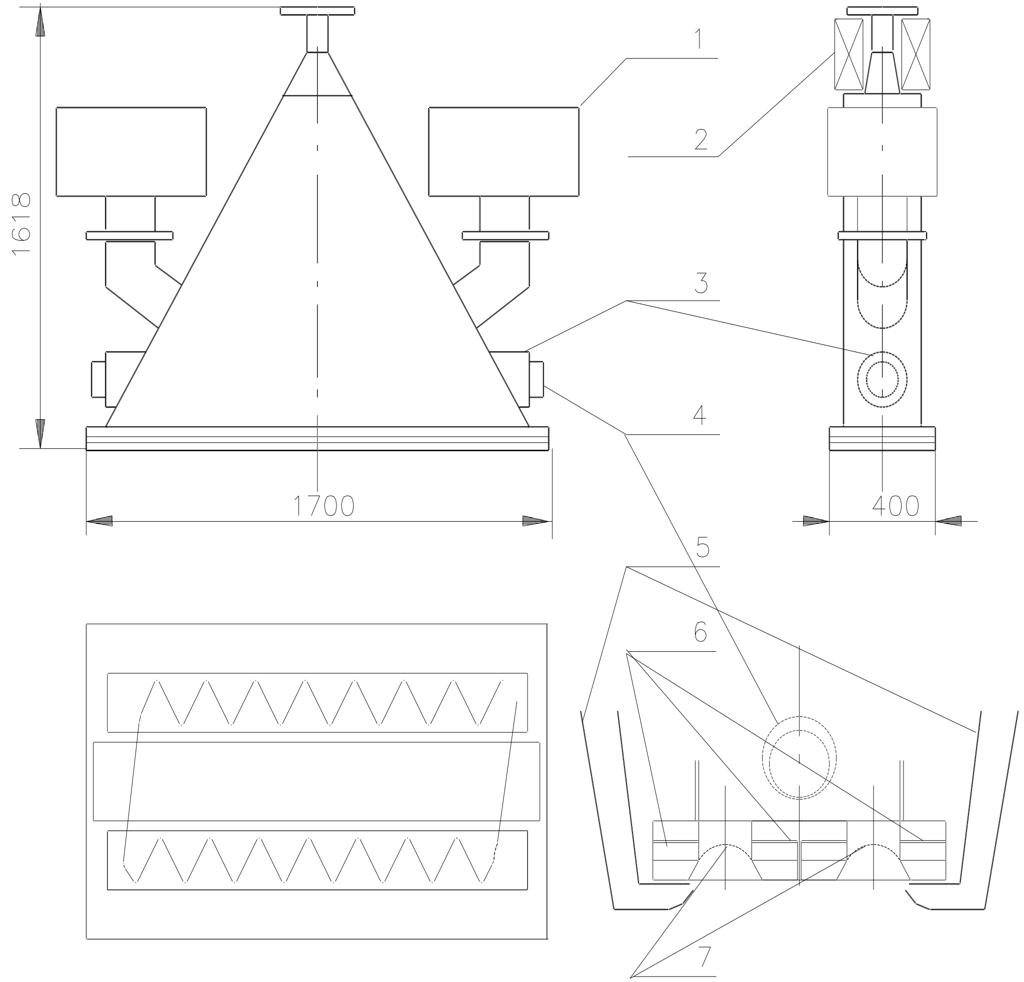
CAARI 2002
Denton, Texas
November 13, 2002



Double beam path scanning horn

N.K. Kuksanov et al., RuPAC 2012





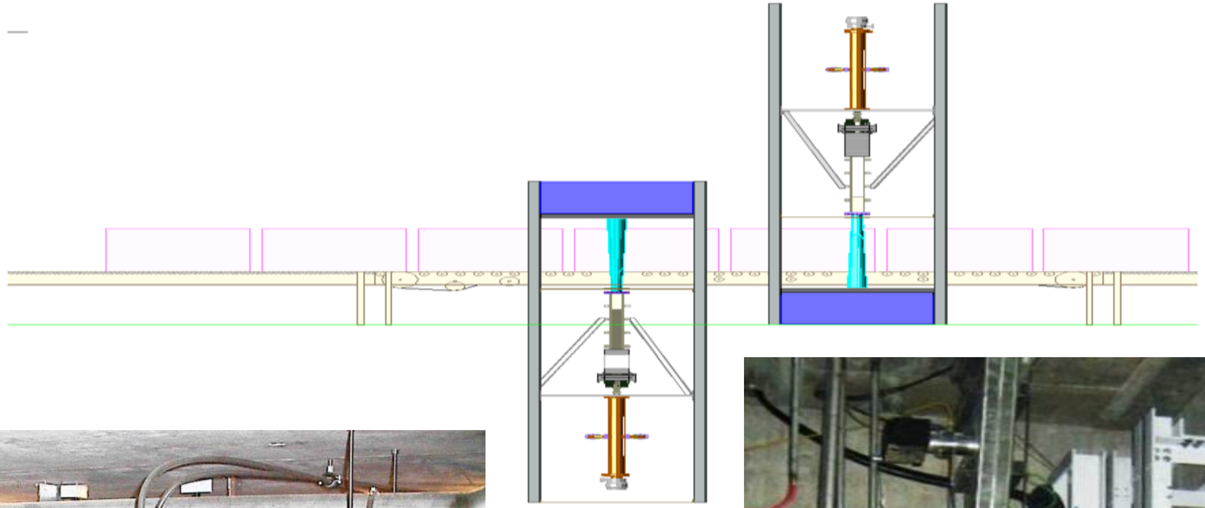
Two-windows extraction device:
1 – ion vacuum pumps, 2 - coils and cores of the beam scanning system, 3 - cylinder flange, 4 - foil blow, 5 - air jet cooling, 6 - frame for fixation of foil, 7 - extraction foils.

Long objects irradiation

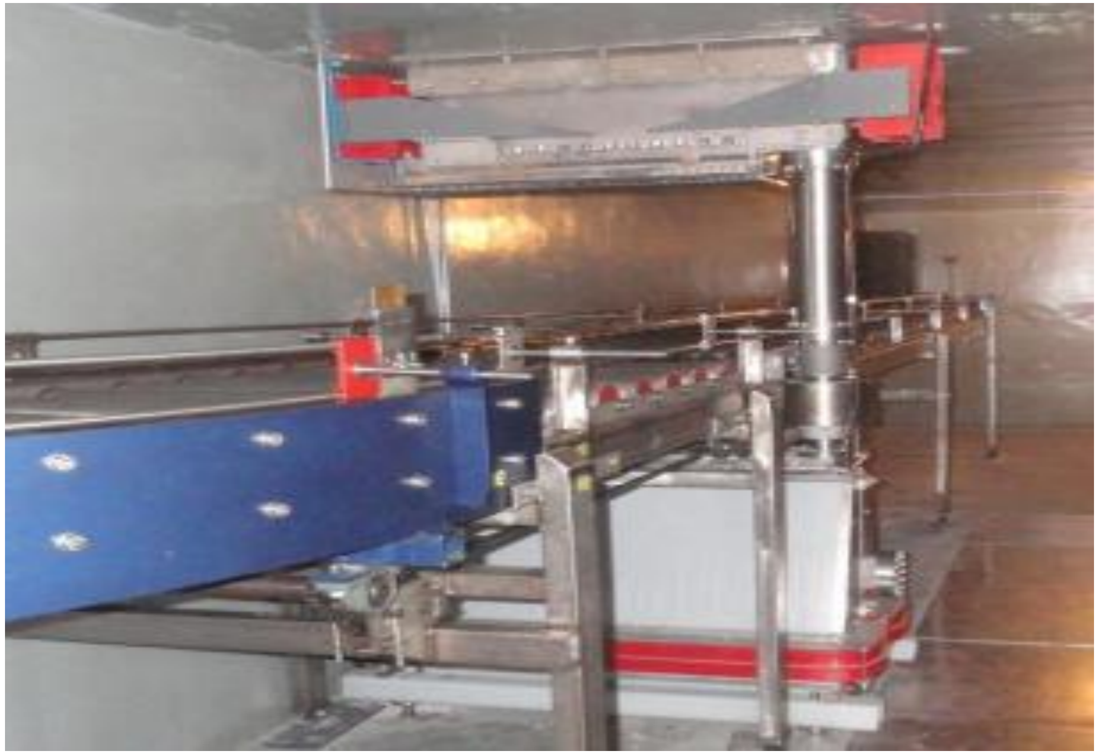
Double side irradiation auxiliary equipment

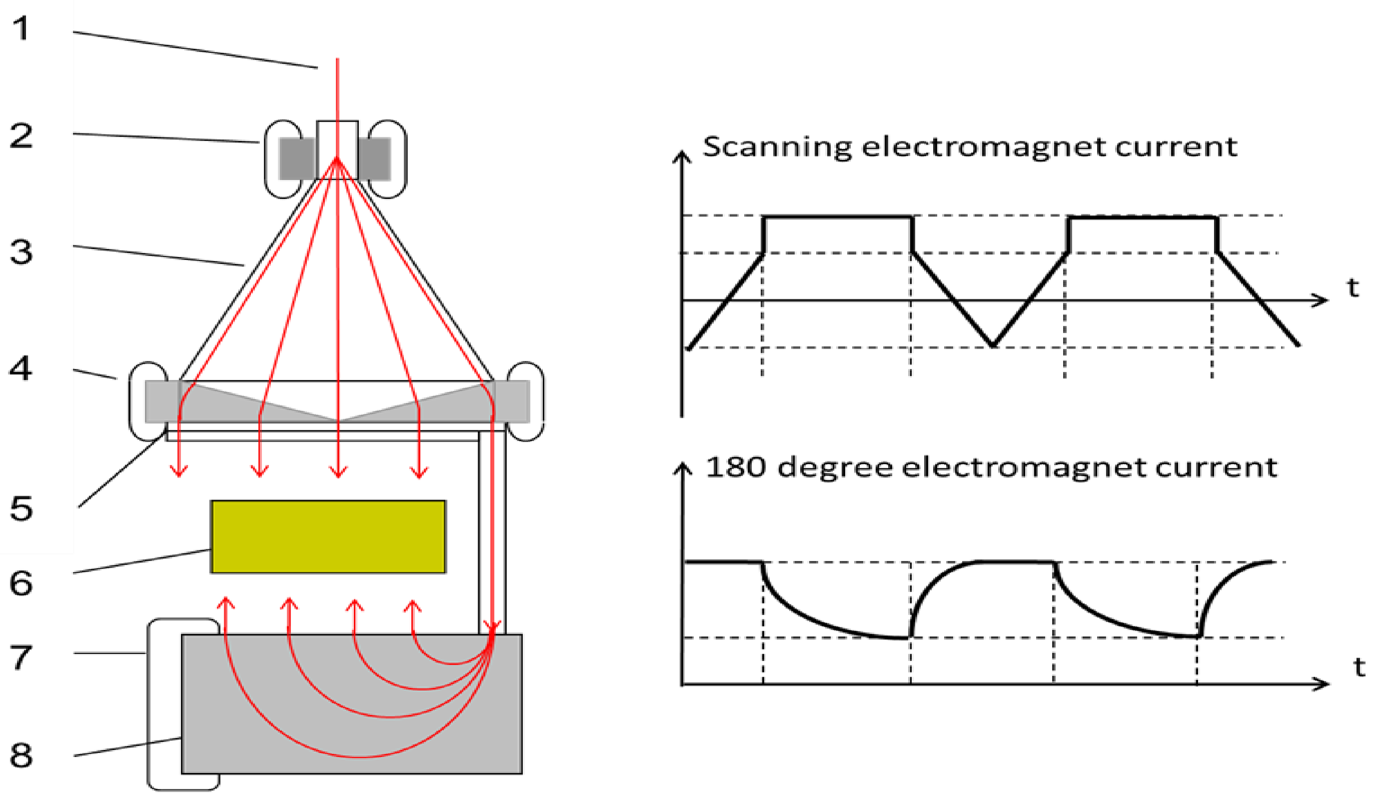
STUDER HARD

Two accelerators and double conveyor radiation facility layout



Configuration of accelerator output device for two sided irradiation

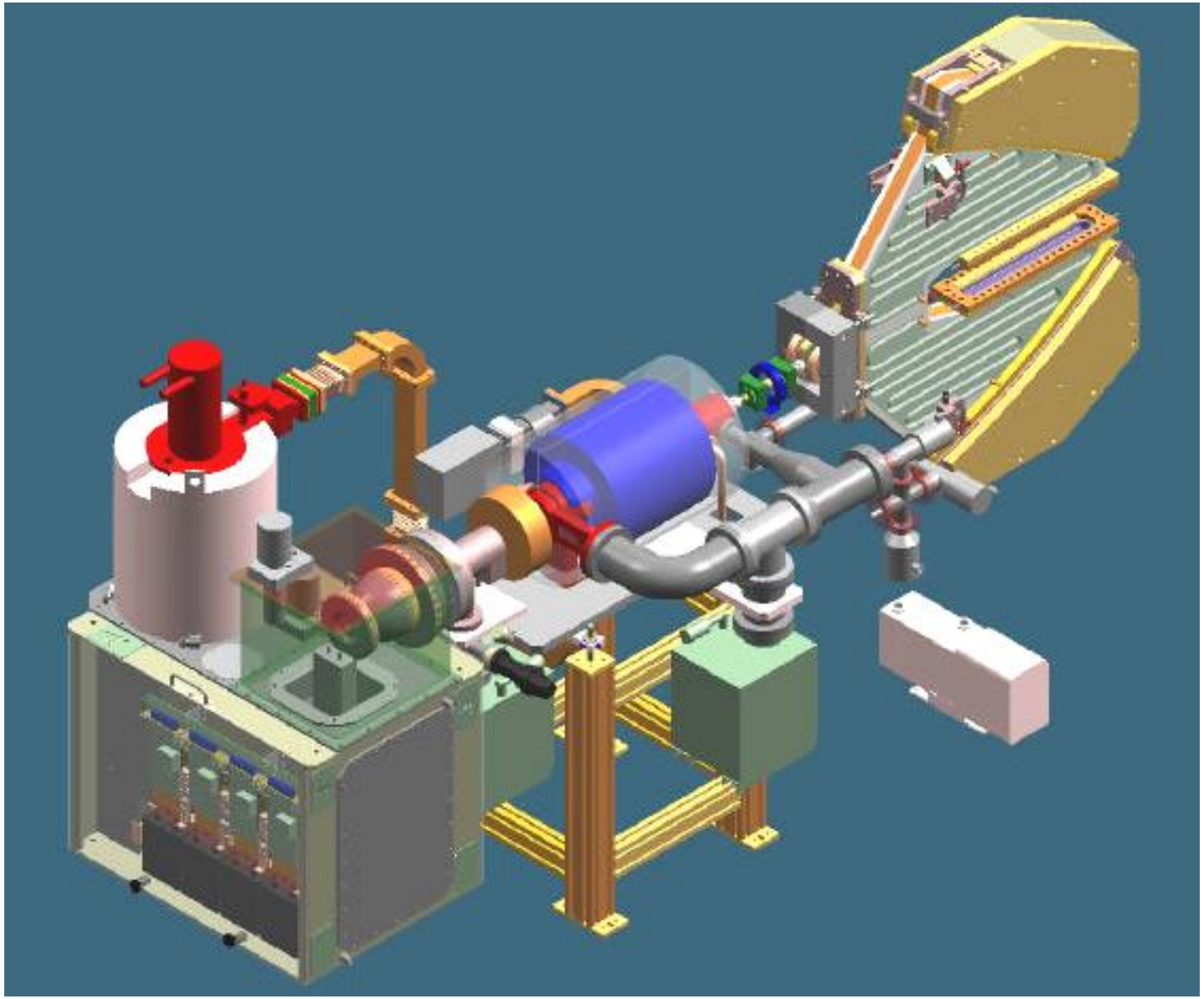




M.I. Demsky et al., RUPAC 2012

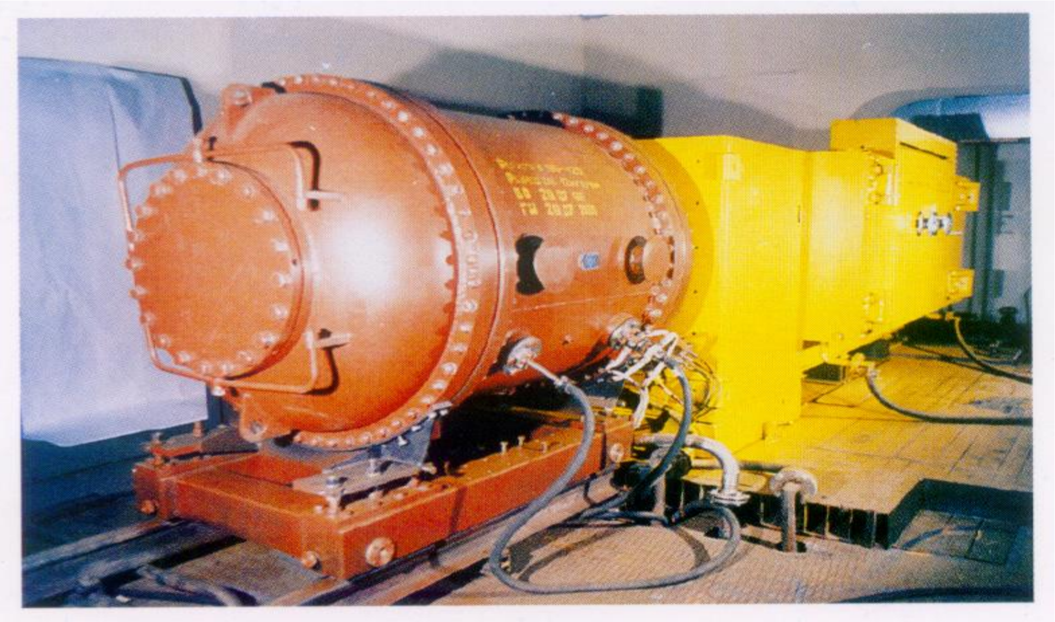
1 – electron beam; 2 – scanning electromagnet, 3 – scanner; 4 – correction electromagnet; 5 – output foil; 6 – irradiated box; 7 – electromagnet; 8 – vacuum chamber

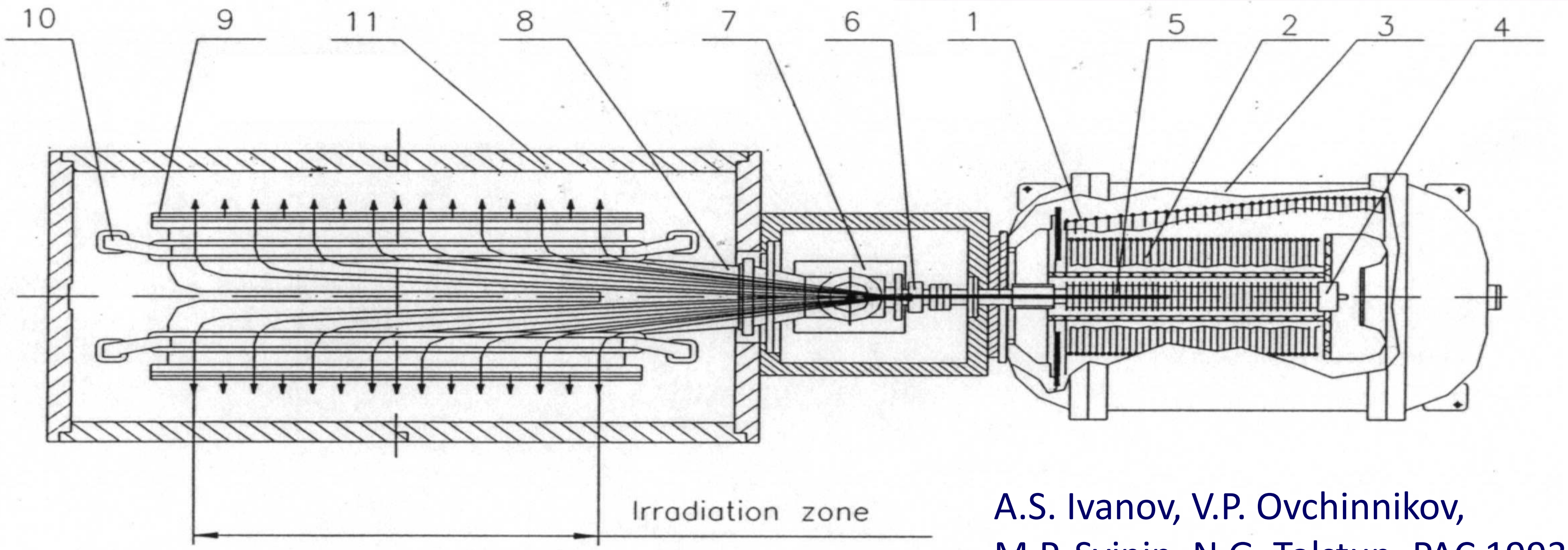
DOUBLE SIDE BEAM SCANNER (IBA)



ELECTRON-10
(0.5-0.75 MeV; 50 kW)

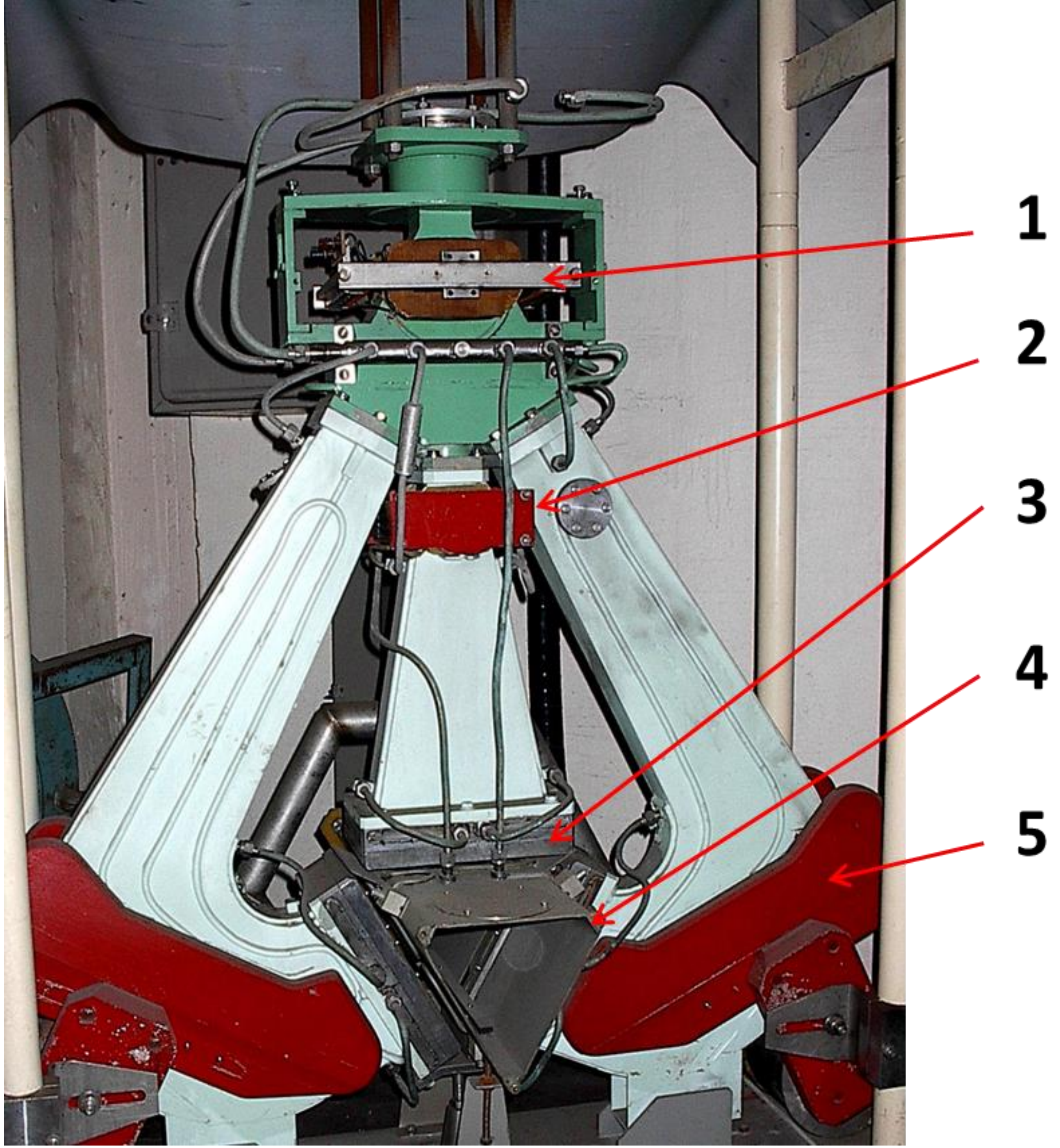
1 – Primary winding; 2 – Secondary winding; 3 – Pressure vessel; 4 – Electron source; 5 – Accelerating tube; 6 – Scanning device; 7 – Vacuum pump; 8 – Vacuum chamber; 9 – Outlet window;10 – Turning magnet; 11 – Radiation shielding.





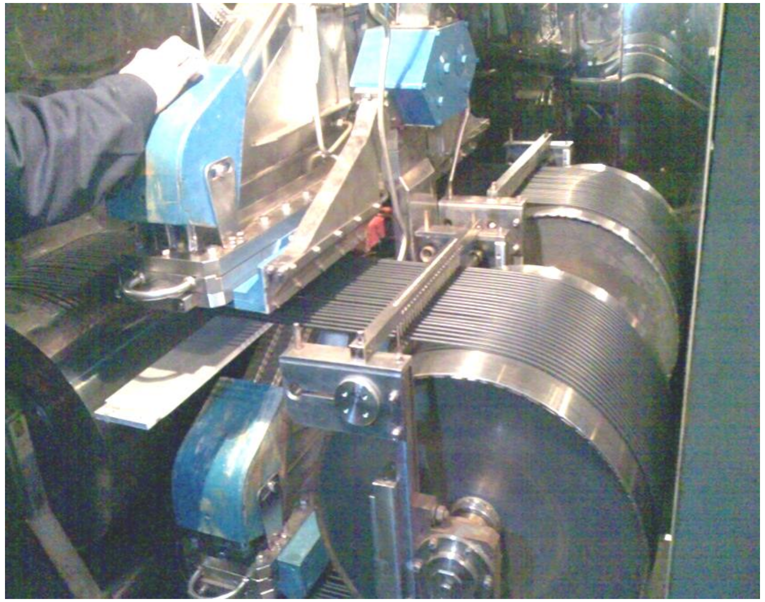
A.S. Ivanov, V.P. Ovchinnikov,
M.P. Svinin, N.G. Tolstun, PAC 1993

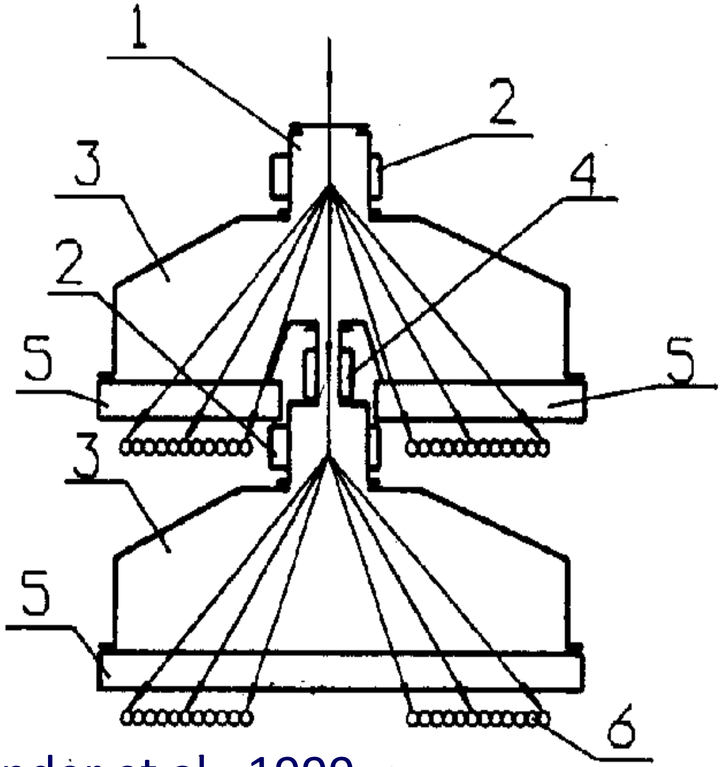
Three side irradiation of cylindrical objects



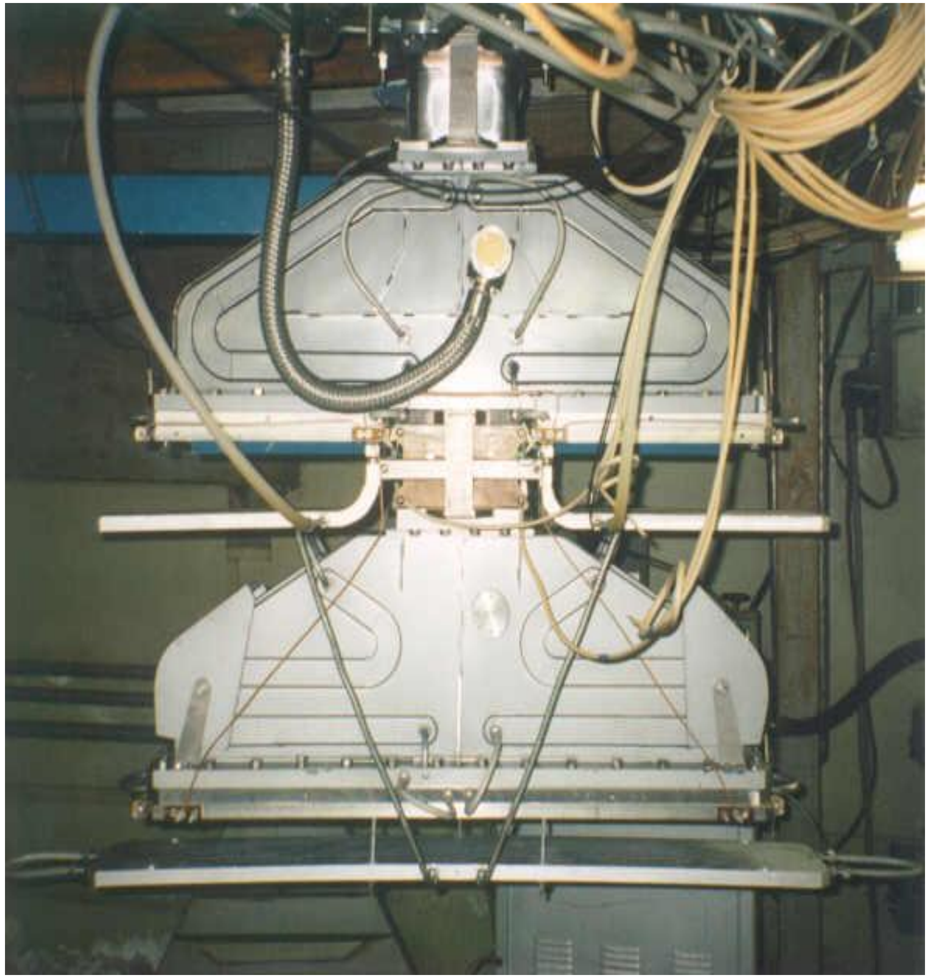
1 – switching magnet;
2, 5 – scanning magnets;
3 – output window;
4 – irradiation zone

Four pass scanning device (ILU 6)





V.L. Auslender et al., 1999



1, 3 – Vacuum system; 2, – Scanning and switching magnet; 4 – focusing coil; 5 – Exit window; 6 – Irradiated cables or wires

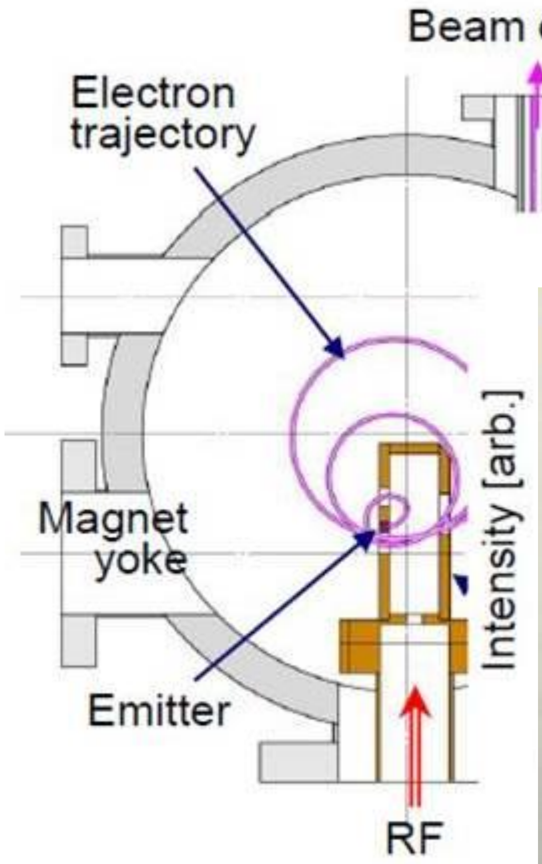
NEW ACCELERATOR DEVELOPMENTS FOR RADIATION PROCESSING

Compact CW linac for radiation technologies

Beam energy:	1 MeV
Beam current:	25 mA
Maximum beam power:	25 kW
Dimensions:	0.5x0.9x1.4 m
Gun/klystron HV:	15 kV
Power consumption:	~75 kW
Electrical efficiency:	~33%

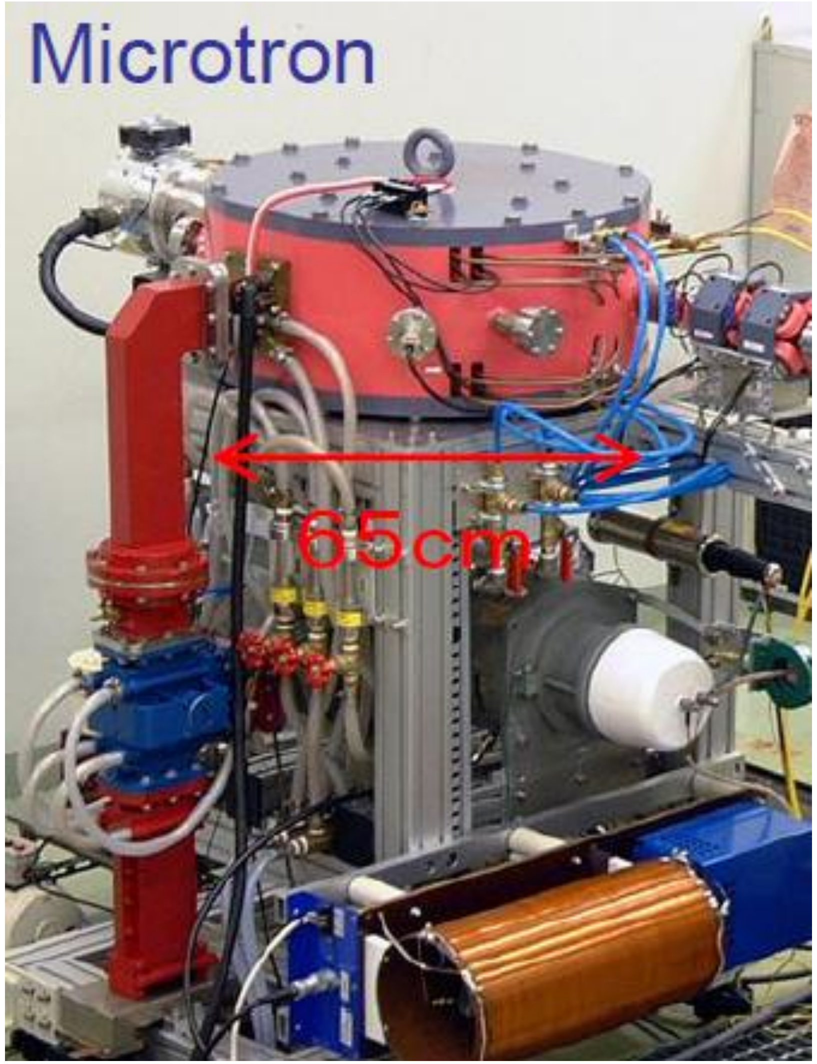
CW multi-beam klystron KU-399A

D.S. Yurov et al., RuPAC 2012

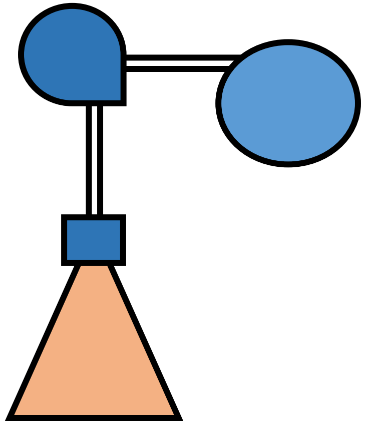


High power microtron for radiation processing

Compact construction
Small energy spread (1 %)



Electron energy	**8 – 10 MeV**
Pulse current	0.3 A
Pulse width	5 μ
Repetition rate	2000 Hz
Beam power	**30 kW**
Frequency	2856 MHz
Weight (main body)	800 kg
Body size	**40 x 60 cm**

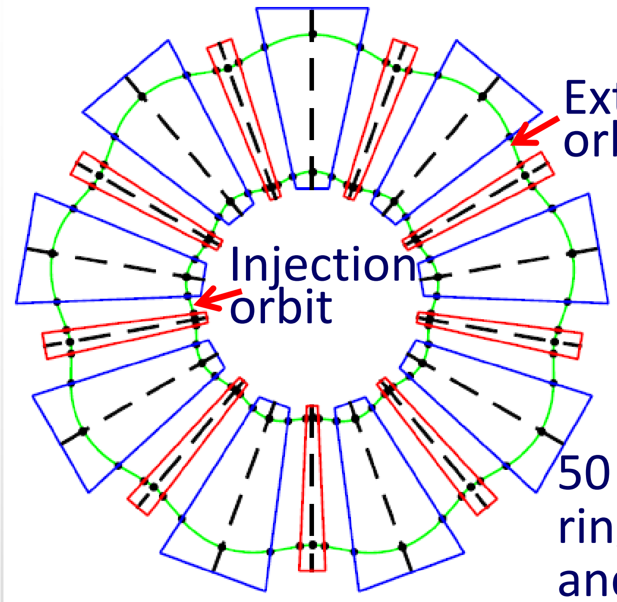


Hironari Yamada, 2015
Photon Production Lab. Co Ltd

eFFAG – compact CW recirculating electron accelerator
(Fixed-Field Alternating Gradient)

FFAGs

- Fixed magnetic fields like cyclotron,
- Separated components,
- Synchrotron-like dynamics.



50 keV to 9 MeV compact ring with injection and extraction orbits. Outer radius <50 cm

Permanent magnets based on ceramic ferrites: $SmCo_5$ or NdFeB could be used.

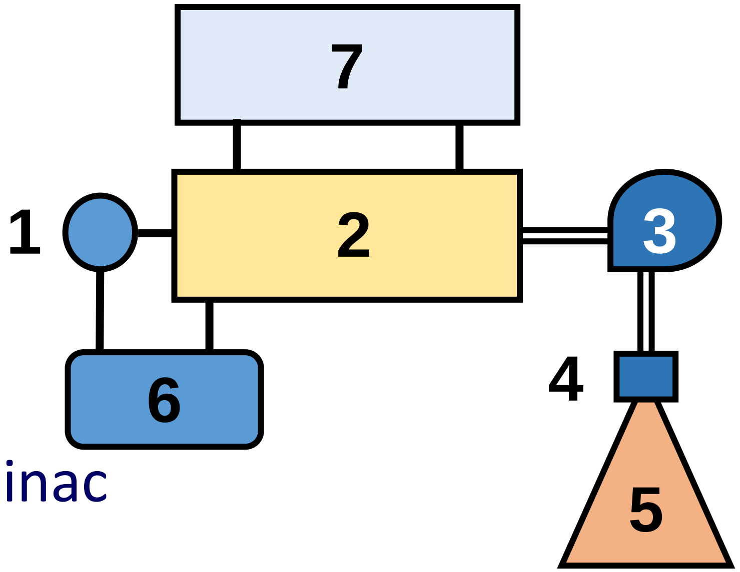
Market case for compact CW effags

- Compact, 1 m diameter, transportable,
- High current – 1-2 mA,
- No power supplies for magnets,
- Inexpensive components.

- A single 100-200 keV cavity (as in cyclotron),
- 45-90 acceleration turns,
- Duty cycle: 1ns/10 ns ~10%,
- Space charge limited to ~10^9 electrons/RF bunch
- For 100 MHz cavity (10 ns bunch spacing),
- Electron energy 9 MeV,
- Beam current 1.6 mA,
- Average beam power ~140 kW.

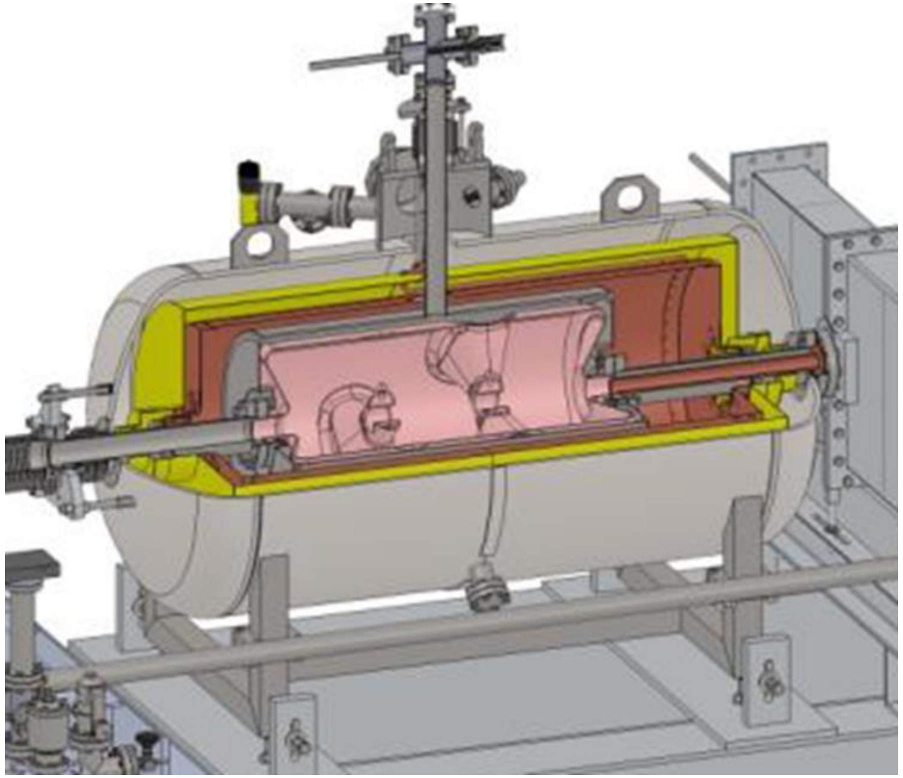
C. Johnstone, 2014

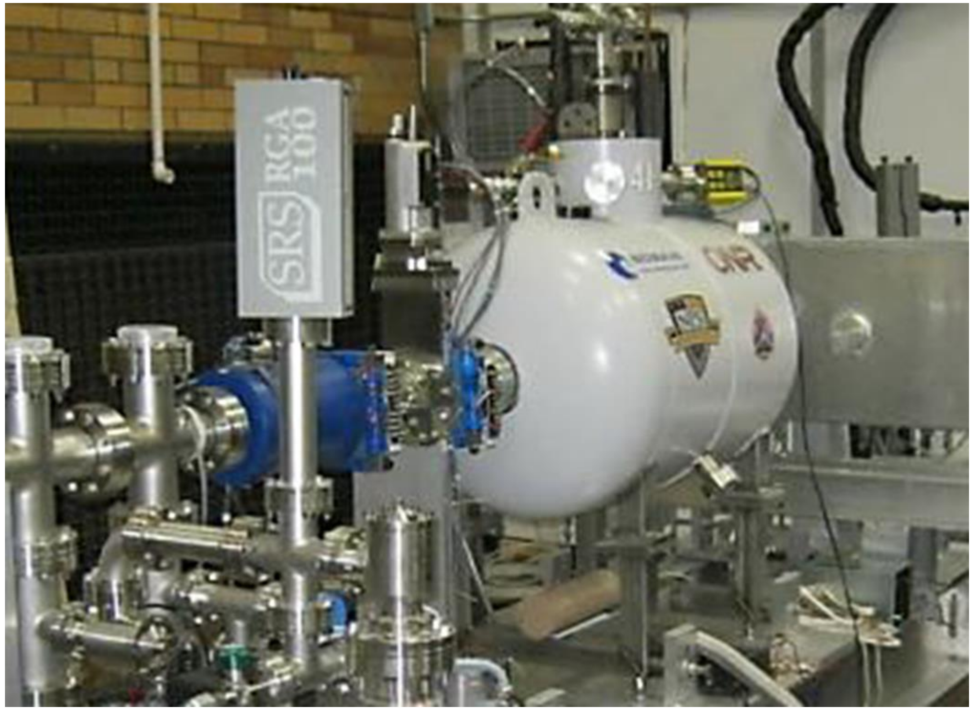
Superconducting radio frequency compact, high power, electron linac 2-40 MeV, 100 kW



350 MHz, 3 accelerating gaps
Electron bunch length ~5 ps

1. Electron gun
2. Superconducting electron linac
3. Bending magnet
4. Scanning magnet
5. Output chamber
6. Microwave power
7. Helium cryoplant





NIOWAVE Inc.

Prospects for Future Expansion

Many beneficial effects of radiation processing have been demonstrated:

- The development of polymeric materials with new properties by application different materials.
- Reduction of environmental pollution by degradation toxic compounds in air, water and soil.
- Cracking crude oil to increase the yield of lighter compounds which are the most valuable products.
- Increased sale of irradiated foods to reduce the use of toxic chemicals to control insects, and to reduce the risk of disease.
- Recovery of rare metals, such as scandium from effluents of hot spring by radiation grafted fiber absorbent (radiation grafted fibers for recovery of uranium from sea water)
- Radiation degradation of natural polymers, such as chitosan, starch and carrageenan to produce plant growth promoter and super water absorbent for improving agriculture.

Thank
you
for your
attention