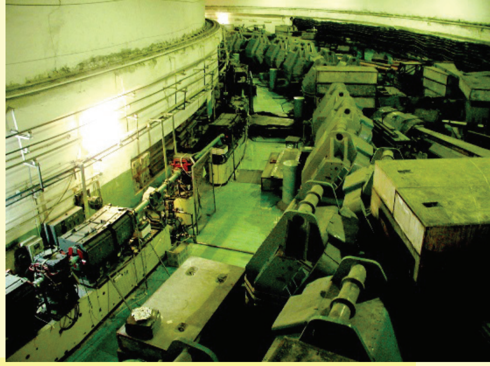
Development of MHF conception at ITEP

N.N.Alexeev, V.A.Andreev, M.M.Kats,
A.A.Kolomiets, V.I.Nikolaev, Yu.A.Satov,
A.V.Shumshurov, V.S.Stolbunov, A.B.Zarubin

Institute for Theoretical and Experimental Physics
Moscow, Russia

RuPAC 2016

Brief history of acceleators at ITEP



1958-1961 - construction and launch of U-7 – strong focusing proton synchrotron of 7 GeV with c electrostatic injector of 5 MeV

1967 - constructed new injector I-2 at the energy of 25 MeV
1973 - modified ring lattice and the beam energy increased up to 10 GeV, accelerator was renamed on U-10

1985 – start of the project of U-10 PS reconstruction to heavy ion synchrotron facility, project realization was stopped in 1989

1997-2002 - elaborated and realized the project of proton–heavy ion accelerator-accumulator complex ITEP-TWAC

2003-2011 – complex ITEP-TWAC was in operation

2012-2016 – complex ITEP-TWAC decommissioned, proton and ion linacs I-2, I-3, I-4 (RFQ) are in operation

Creation of new accelerators is always accompanied by the mastering of new ideas and technologies

The project of
<u>Multi-purpose Hadron Facility</u> (MHF)
has to be elaborated on a base of
world trends in accelerator
development

The creation of MHF would help to restore and significantly expand the accelerator technological base of ITEP and to bring the possibility of actual physical experiments and application works in usage of hadrons beams

Key trends in development of hadrons accelerators

Accelerators for HEP

- Colliders hh, ee, ep

Circular: HL-LHC, FCC-hh, CepC-SppC

Accelerators for HEP, Nuclear Science and Applications

- High Intensity Proton Accelerators

SNS, PSI, J-PARC, ISIS, LANSCE, ESS, Project X, …

- Heavy Ion Accelerators

RHIC, FAIR, RIKEN, FRIB, SPIRAL2, …

Accelerators for Applications

- Commercial use of accelerators

High Intensity Proton Accelerators (operating)

Facility	Power, kW	Energy, GeV	Time Structure	Accelerator Type
TRIUMF	100	0.52	CW, 23 MHz	cyclotron
LANSCE	80-120	0.8	120 Hz	linac
ISIS	200	0.8	40 Hz to TS1 10 Hz to TS2	70 MeV H^- linac+RCS
J-PARC MR	240	30	0.4 Hz x 5 μs	3 GeV RSC+MR
J-PARC RCS	300	3	25 Hz x 1 μs	181 MeV linac+RSC
FNAL MI	400	120	9.4 μs every 2.2 s	linac + RCS
CERN SPS	470	400	4.4 s cycle length	linac + 2 stage RCS
SNS	1300	0.94	60 Hz	linac + accumulator
PSI	1400	0.59	CW, 50 Hz	2 stage cyclotron

High Intensity Proton Accelerators (at design)

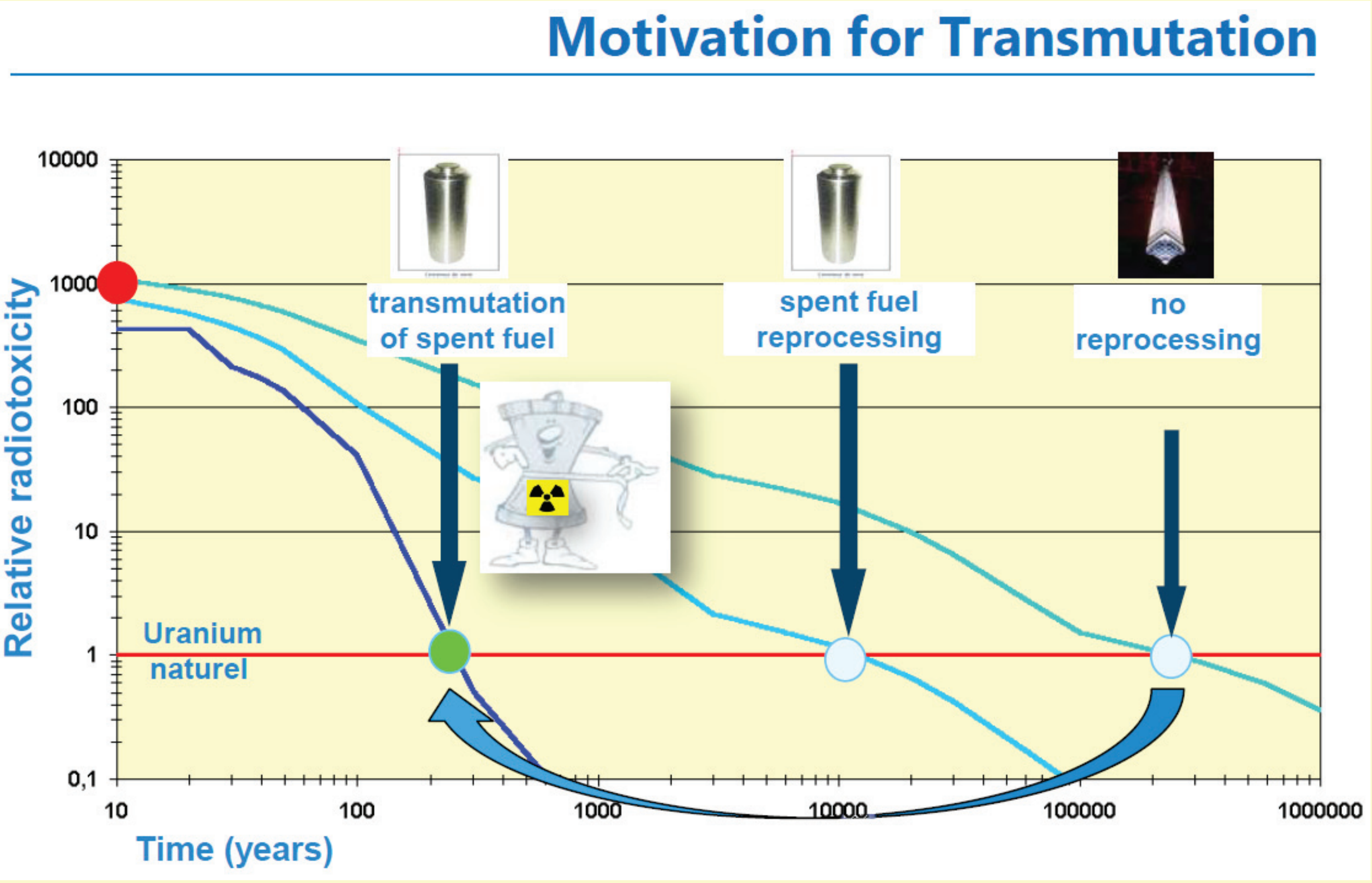
Facility	Power, MW	Energy, GeV	Time Structure	Accelerator Type
ESS	5	2	50 Hz x 2,5 ms	SRF linac + accumulator
CERN with SPL	4	5	50 Hz x 6 bunches	SRF linac + RSC
Project-X (stage 1+2)	3	3	CW linac /accumulator	CW SRF linac + accumulator
Project-X (stage 3)	2.3	6-120	10^{-5} duty factor	+ pulsed 8 GeV SRF linac + RCS
Daeδalus	3	0.8	60 Hz	2 stage cyclotron
MYRRHA	1.5-2.4	0.6	CW	CW RT+SRF linac
CADS	15-30	0.6	CW	CW RT+SRF linac

J. Galambos NA-PAC 2013 Pasadena CA Oct. 4, 2013

Accelerators for ADS

Accelerator Driven Systems are presently considered worldwide as potential for electric power generation and promising candidates for the industrial transmutation of very long living nuclear waste produced by conventional critical reactors into isotopes with much shorter life times.

The road towards the industrial transmuter still features many R&D steps.



A.Stankovskiy, 3rd Pillar of the European Strategy for P&T

<u>ADS technology development</u>:

MYRRHA – LN CW, 600 MeV, 2.4 MW

J-RARC – LN, 600 MeV, >1 MW

HYPER – 1 GeV, 16 mA

India ADS Program: 1 GeV, 30 mA

TAC (NSS+ADS): 1 GeV, 1 mA

C-ADS: LN CW, 600 MeV, 30 MW

… etc.

Key Technical Challenges

- **Increase gradients in SRF linacs**, development of high power coupler, high power RF sources, minimize cryogenic loads
- **Management of beam loss to very low fraction levels**
- Improvements in increased dynamic range for instrumentation to measure the 6-D phase space of beam
- Improvements in simulations to predict beam behavior to the level $<10^{-6}$ (*at present tuning for beam loss mitigation is largely an empirical exercise in high power facilities*)
- Improvement in charge exchange injection techniques of ring injection *(typically $\geq 10^{-4}$ of the beam is lost at injection; as the beam powers increase, this localized beam loss may become intolerable)*
- **For some applications (ADS) high reliability is a major consideration**.

Heavy Ion Accelerators

Project	Status	Beam	Accel. Type	f_{rep}, Hz	Beam duty	Energy, MeV/u	Ave. Power, kW
RIKEN	Achive Goal	d to U d to U	LN/CY LN/CY	CW CW	1 1	345-400 345-400	7-2 80 (U)
FRIB	Constru.	p to U	LN	CW	1	>200	400 (U)
FAIR	Constru.	p to U	LN/SR	0.2;0.5	<0.25	1000 30000	12 1
SPIRAL2	Constru.	p,d, A/z≤3	LN/CY	CW	1	33,20 14	200,200, 40
RAON	Constru.	p to U	LN	CW	1	600 200	400
IFMIF	Constru.	d	LN	CW	1	20	2x5
LIPAc	Constru.	d	LN	CW	1	4.5	1.1

Key Technical Challenges

- *High Intensity (CW) and High charge state Ion Source*
- *High Intensity Normal - and SC RFQ*
- *SC RF accelerating structures*
- *Management of beam loss to low level (Loss Detection, Collimation, Machine Protection)*
- *Rapid Cycling Synchrotron Technology (High Vacuum, RF, …)*
- *Charge Stripping and Accumulator Technology etc.*

Insights on Trends

- Visible technological gap between the best world and domestic samples and designs of hadron accelerator facilities
- Untapped technologies in the domestic accelerator field of activity are:
  - high current CW ion sources,
  - high current CW normal and SC accelerating structures,
  - heavy ion RSC,
  - other auxiliary technologies,
- Project MHF aims to reduce and eliminate technological gap

MHF: Conception

1. Strategic goal :

- *revival at ITEP technological base of accelerator science and technique for fundamental and applied nuclear research and innovative development of civil and defense purposes, using beams of protons and heavy ions of intermediate energies,*
- *integration of technological base with Engineering and University educational process*

MHF: Conception (cont.1)

2. Two phases of project implementation

- *The first phase includes the revival of ring accelerators in the existing infrastructure with upgraded injection facility to start physics experiments and applied works*

- *Phase two should advance MHF to the frontier of high intensity hadrons facilities providing a radical increase of the beam intensity and expansion of infrastructure for activation of a new actual scientific research and applications*

MHF: Conception (cont.2)

3. Objectives:

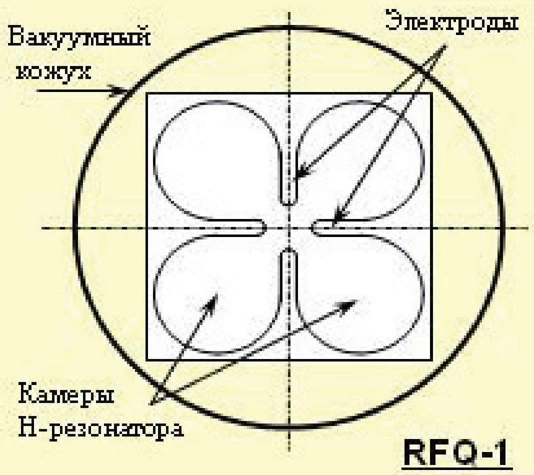
- *fundamental and applied research and technological development using relativistic proton and ion beams with energy to 10 GeV for protons and to 5 GeV/u for ions;*
- *applied research, technological development and industrial application using proton and ion beams with energy up to 1 GeV/u;*
- *fundamental research and technological development using high power pulsed nuclei beams with energy of <1 GeV/u;*
- *technological research and development in the field high intensity hadrons beams;*
- *expansion of scientific and educational activity in the areas of nuclear technologies*.

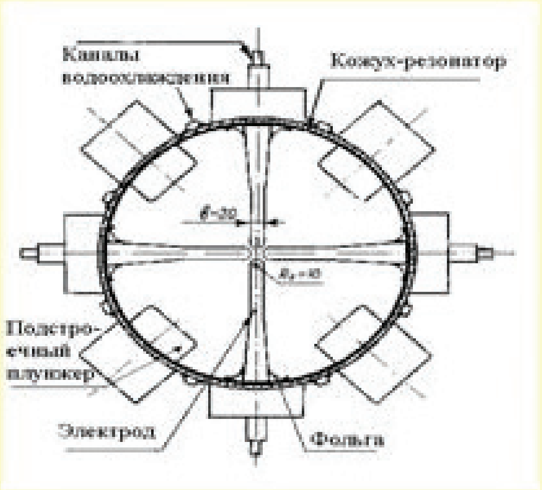
Core Capabilities available at ITEP

Core Capabilities	Areas of Expertise
Accelerator Science	Beam Dynamics, theory, simulation, beam experiments
Accelerator Technology	Ion sources, linacs, RF systems, kikers, ring lattice, beam lines, injection/extraction, correction systems, high vacuum
Accelerator Engineering	Design, construction, integration of electrical, RF, electronics, mechanical, cooling, vacuum systems, etc.
Particle Detectors	Advanced detector development, beam test pickups, devices, tools, instruments and facilities
Controls	Processor control, interlock & DAQ systems, machine adjustment, etc
Accelerator applications	Proton therapy, Implantation, Radiation effects on components and systems

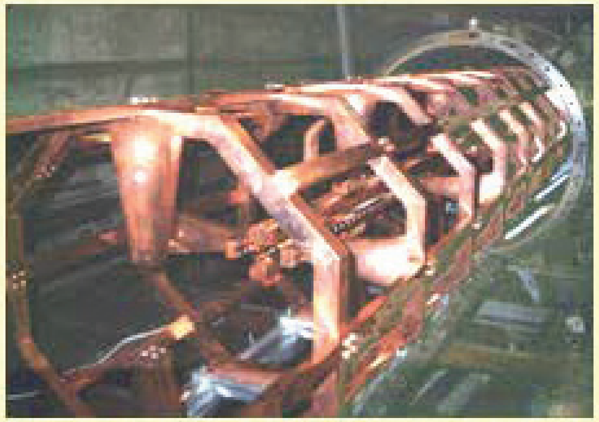
Proton and Ion RFQ sections

Cross sections of four vane RFQ



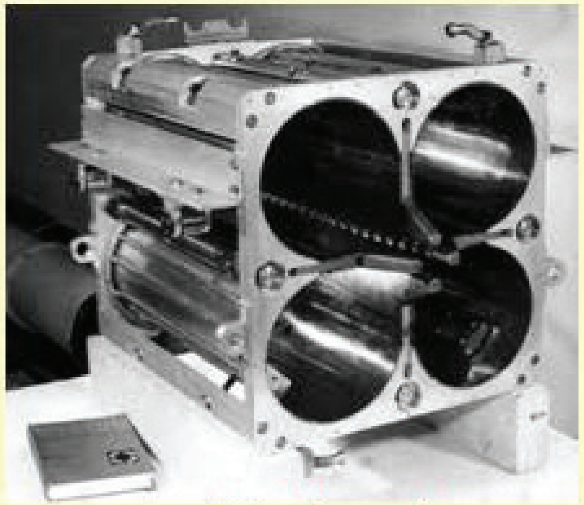


Ring-connected RFQ

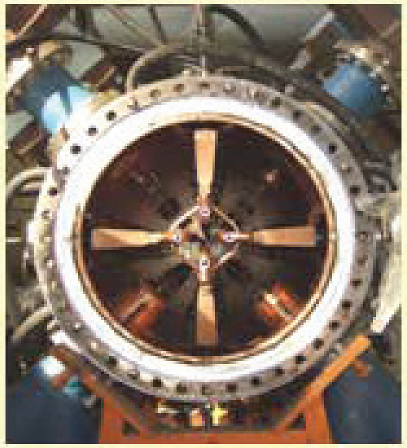


4-ladder SC RFQ

Four nave RFQ

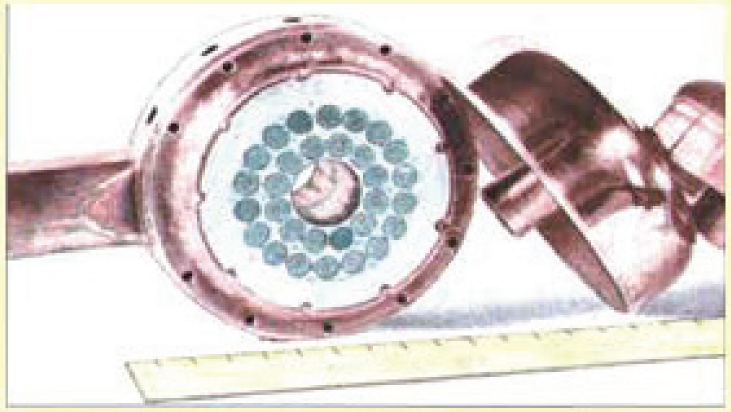


RFQ of ISTRA56

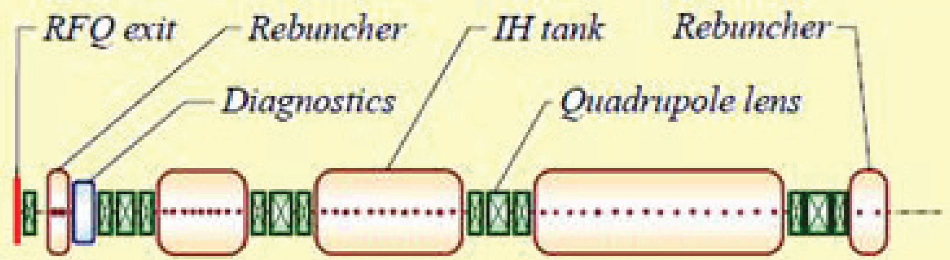


RFQ of I-4 Injector

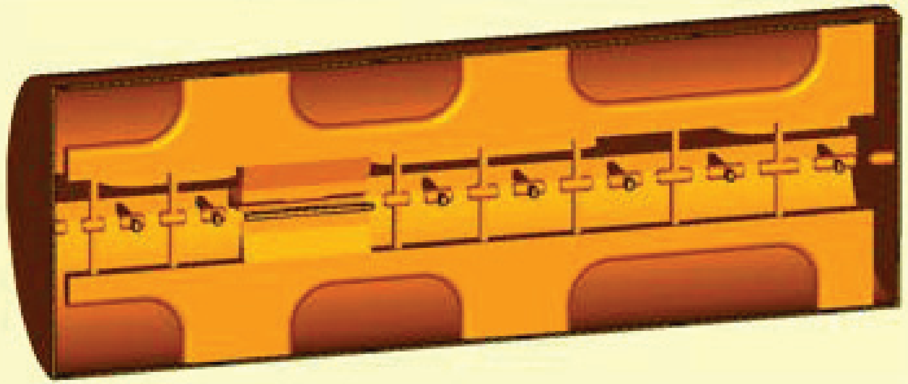
Drift tube with PMQ-lens



IH structure of I-4 Ion Injector



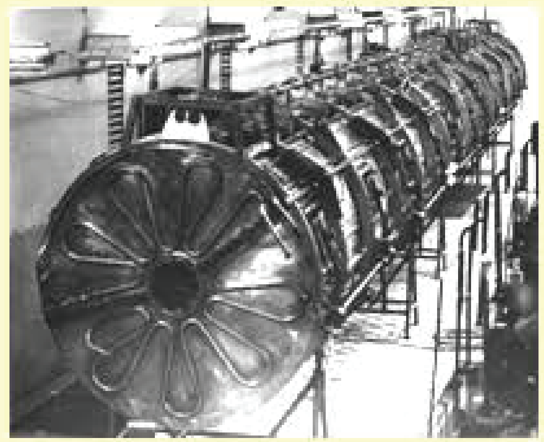
Hybrid RFQ section



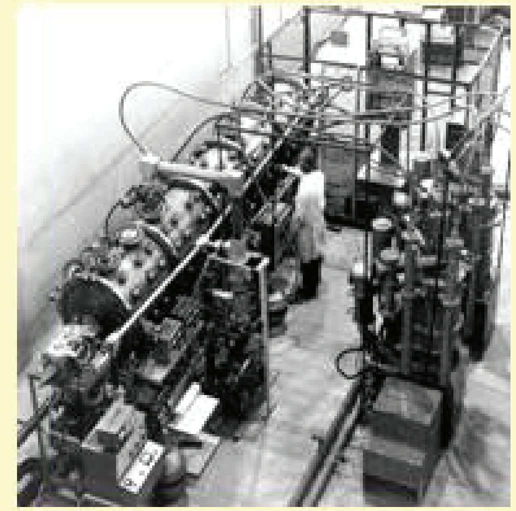
Construction of linacs

Proton linac I-2

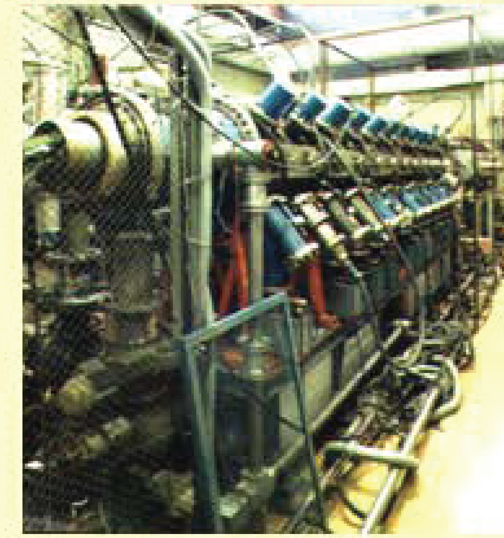
RF Resonator



Test stand of RFQ



RFQ for ISTRA-10

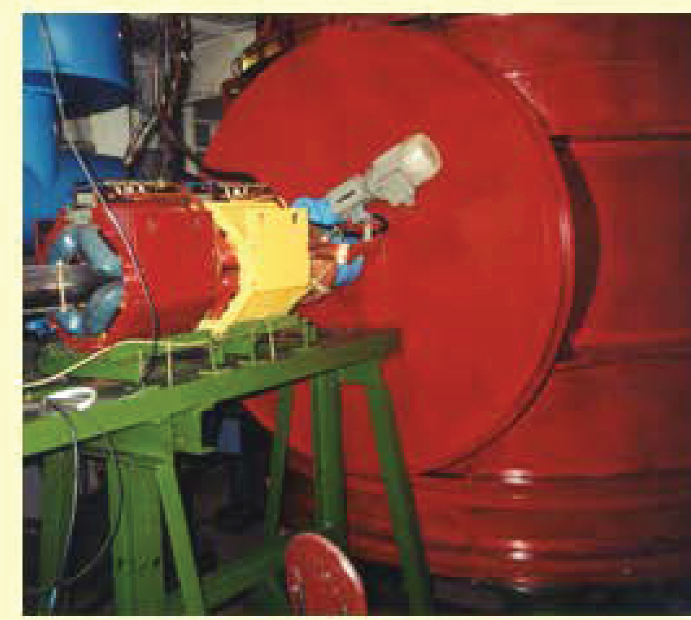


P-Linac ISTRA-10

Ion Linac I-4

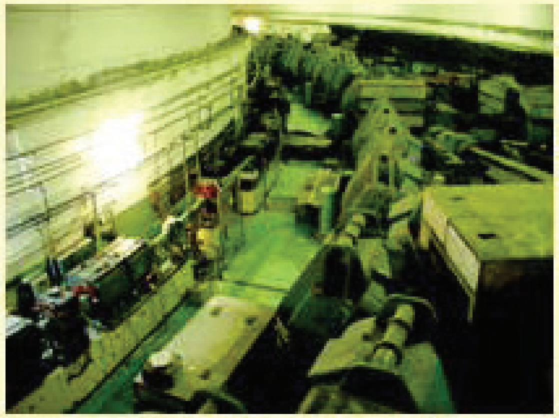
Ion Linac TIPr

Ion Linac I-3



Ring Accelerators

UK/U-10 Rings



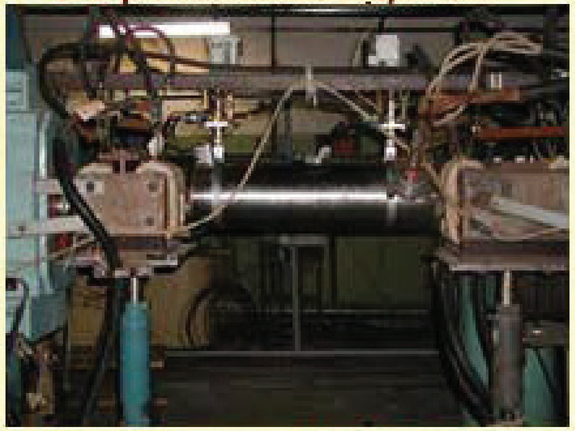
Beam injection and extraction lines

Magnetic pathway

Proton Therapy

Kicker modules

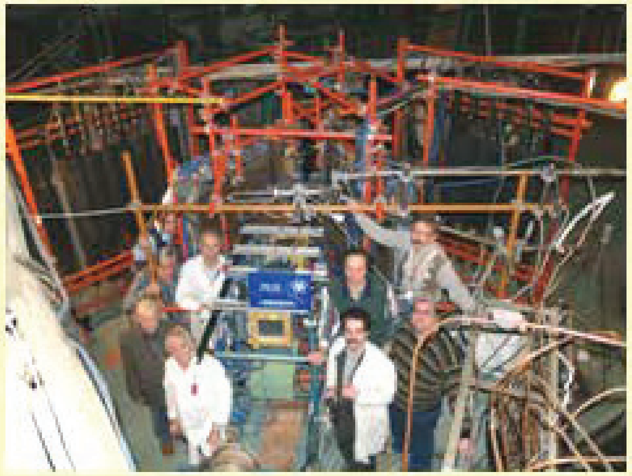
Septum magnet



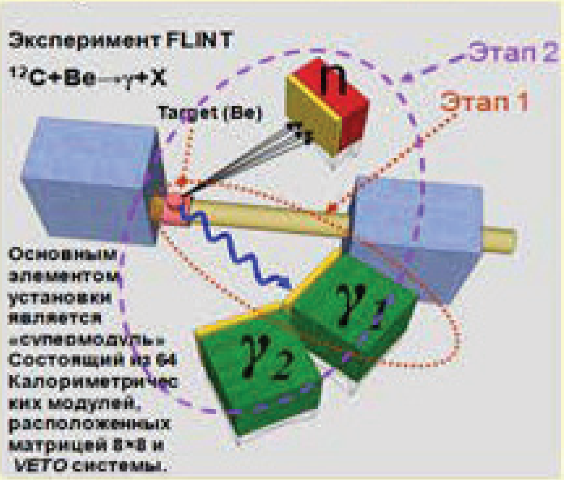
Cooling station

Target station

Experiment EPECUR

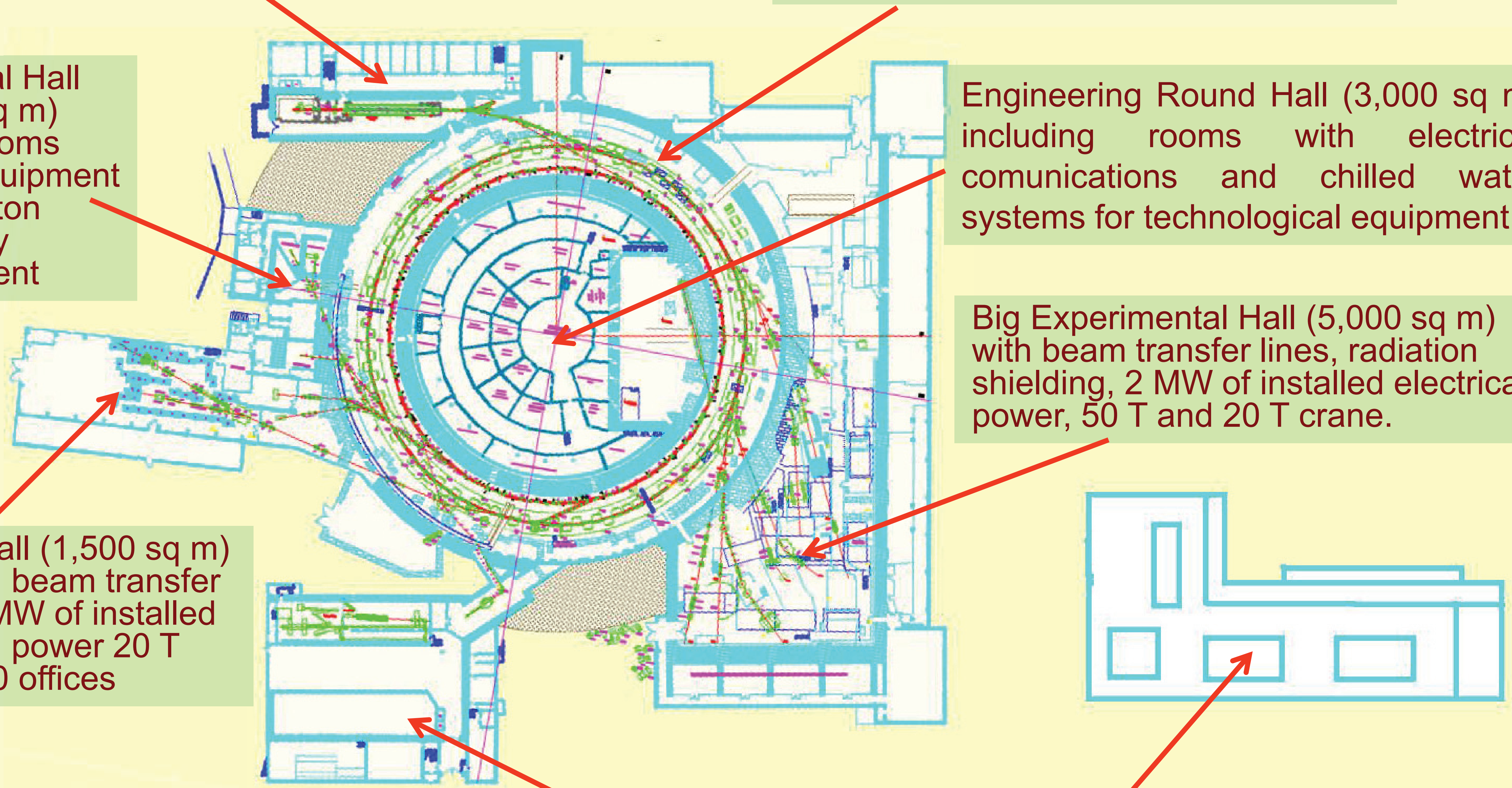


Experiment FLINT



Bench for R-test

MHF- Existing Infrastructure



MHF: Updates & New developments

- Upgrade of UK: *improvement of vacuum to 10^{-11} Torr, ramp to 4 T/s, injection of proton beam from I-2;*
- Upgrade of U-10: *improvement of vacuum to 10^{-11} Torr and upgrade of charge exchange injection system;*
- Upgrade of proton injector I-2: *increase intensity of proton beam to 1.2×10^{-14} s^{-1} (20 μA);*
- Upgrade of heavy ion injector I-3: *increase accelerating voltage to 12 MV;*
- Install new light ion injector I-4: *ions with $A/Z \leq 3$, energy 7 MeV/u, pulsed beam current up to 100 mA;*
- Upgrade of LIS: *increase laser beam power density on the target to ~10^{14} W/cm^2.*

MHF: Relativistic proton and ion beam in the energy range ≤ 10 GeV/u

Beam parameters:

particles – protons, any type of ions to U
energy - 1÷10 GeV for protons, 1÷5 GeV/u for ions
intensity - ~10^{12} s^{-1} for protons, (10^{9}÷ 10^{10}) s^{-1} for ions
secondary beams – e, π, μ, pbar, K

Fundamental, methodical and applied research:

Search for and study of cold dense baryonic matter (FLINT)
Baryon spectroscopy (EPICURUS)
Cumulative nuclear fragments (FRAGM)
Test of any type of detectors for HEP
Protonography

MHF: Proton and ion beams for applications in the energy range ≤ 1 GeV/u

Beam parameters:

particles – protons, any type of ions to U
energy– 10 MeV/u÷1 GeV/u
intensity - ~$2.5x10^{12}c^{-1}$ for protons, (10^{9}÷ 10^{11}) c^{-1} for ions

Applied research:

Proton and Ion Therapy for Cancer Treatment
Radiobiology, radiation genetics
Radiation effects on components and systems
Radiation-induced changes of material properties

Industrial application:

Ion Implantation for Semiconductors and Materials
Radioisotopes Production

Technological development :

High current cw proton and ion source
High current cw proton and ion accelerator structures
Specialized accelerators for applications
New technical means and technologies for beam therapy

MHF: High power pulsed nuclei beams in the energy range <1 GeV/u

<u>Beam parameters</u>:

particles – nuclei of C, Fe, Co, Ni
energy – 100÷1000 MeV/u
stacked intensity - (10^{11}÷ 10^{14})
pulsed beam power - >1 TW
compressed bunch – (50÷100) ns

<u>Fundamental research</u>:

High density energy in matter
Heavy ion fusion

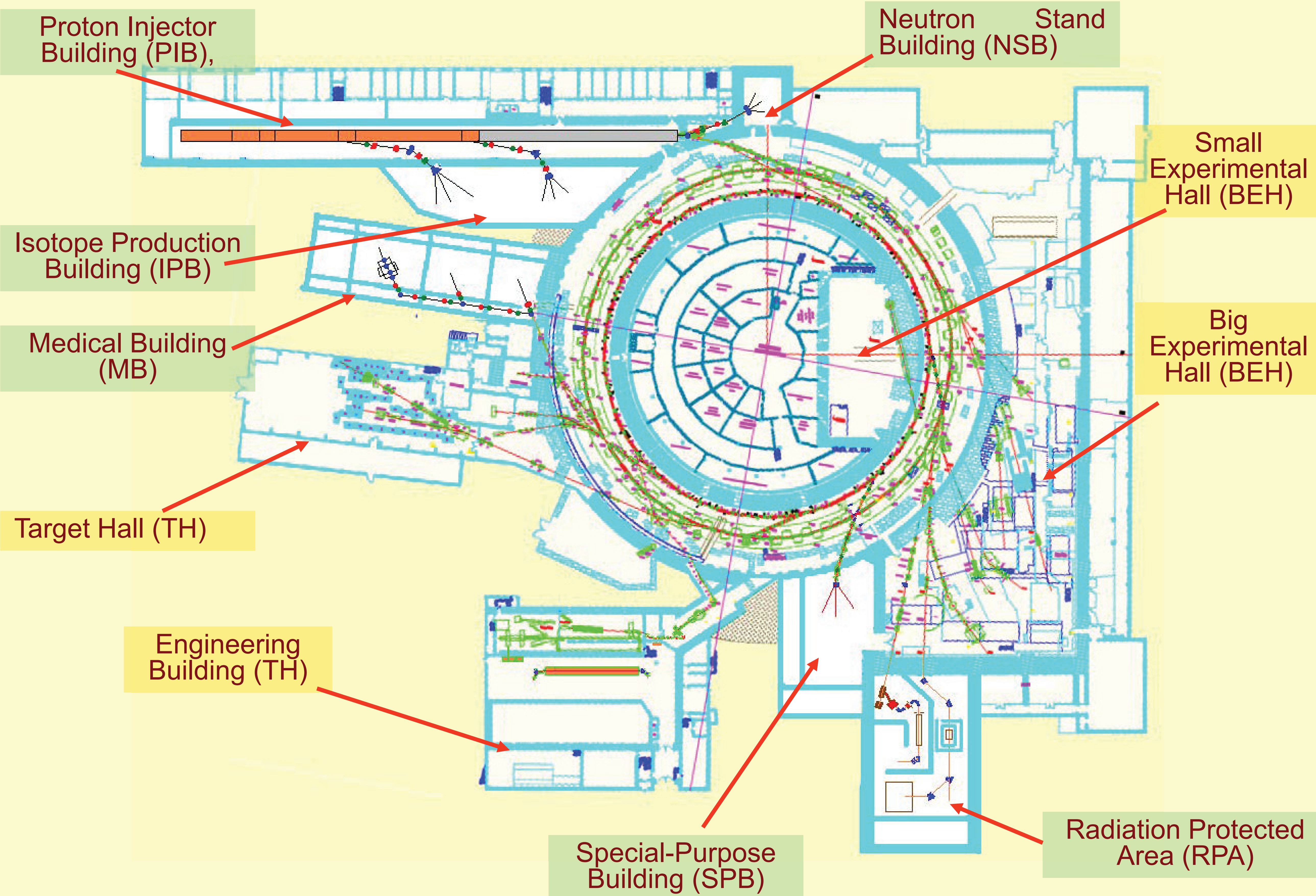
<u>Technological development</u> :

Multiple charge exchange injection
Stochastic cooling
Beam compression technique
Beam sharp and ring focusing
Barrier bucket technique

MHF: Perspectives-New proposal

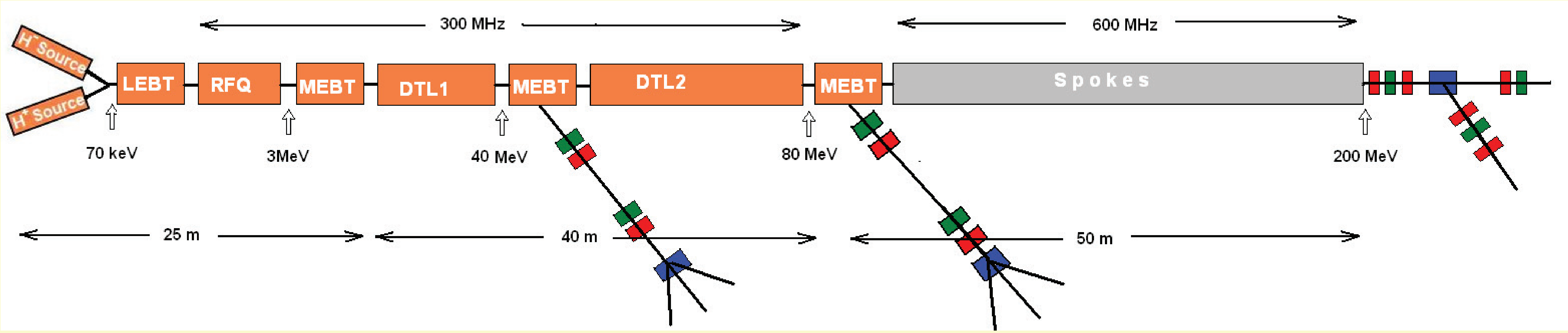
- Infrastructure expansion
- High current proton linac-injector, 200 MeV/200 kW:
  - High current proton RFQ
  - DTL proton Resonator
  - SC proton Resonator
- Rapid Cycling Synchrotron UKM, 1GeV/100 kW
- Auxiliary Ring Accelerator-Stretcher-Accumulator U-10
- Experiments and applications with intense beams:
  - Isotope production
  - Neutron experiments
  - Expanded Proton and C-Ion Therapy Facility
  - Rare Isotope experiments
  - Material science

MHF: Enhanced Infrastruture



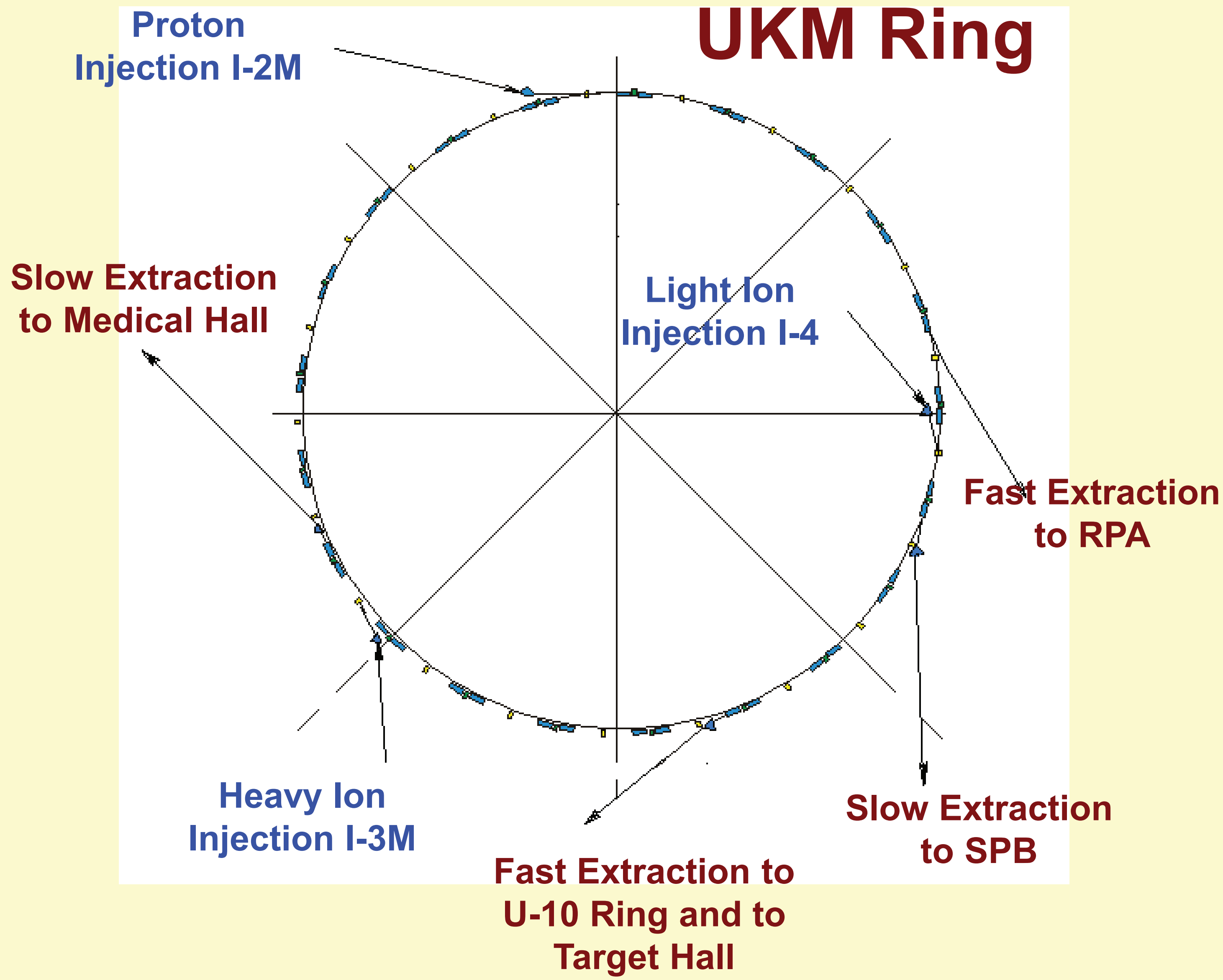
High current proton linac-injector

- Multicusp, volume-production, cesium enhanced, RF-driver, H^- ion CW source
- Duoplasmatron or ECR H^+ CW ion source
- Electrostatic LEBT
- 4-vane RFQ with π-mode stabilizers that accelerates the 70-keV beam from the ion source to 3 MeV
- Beam-chopping systems; and a beam-transport, rebunching, and matching section
- Five tanks of DTL accelerates the beam to 80 MeV
- Double-spoke superconducting cavities accelerates the beam to 200 MeV

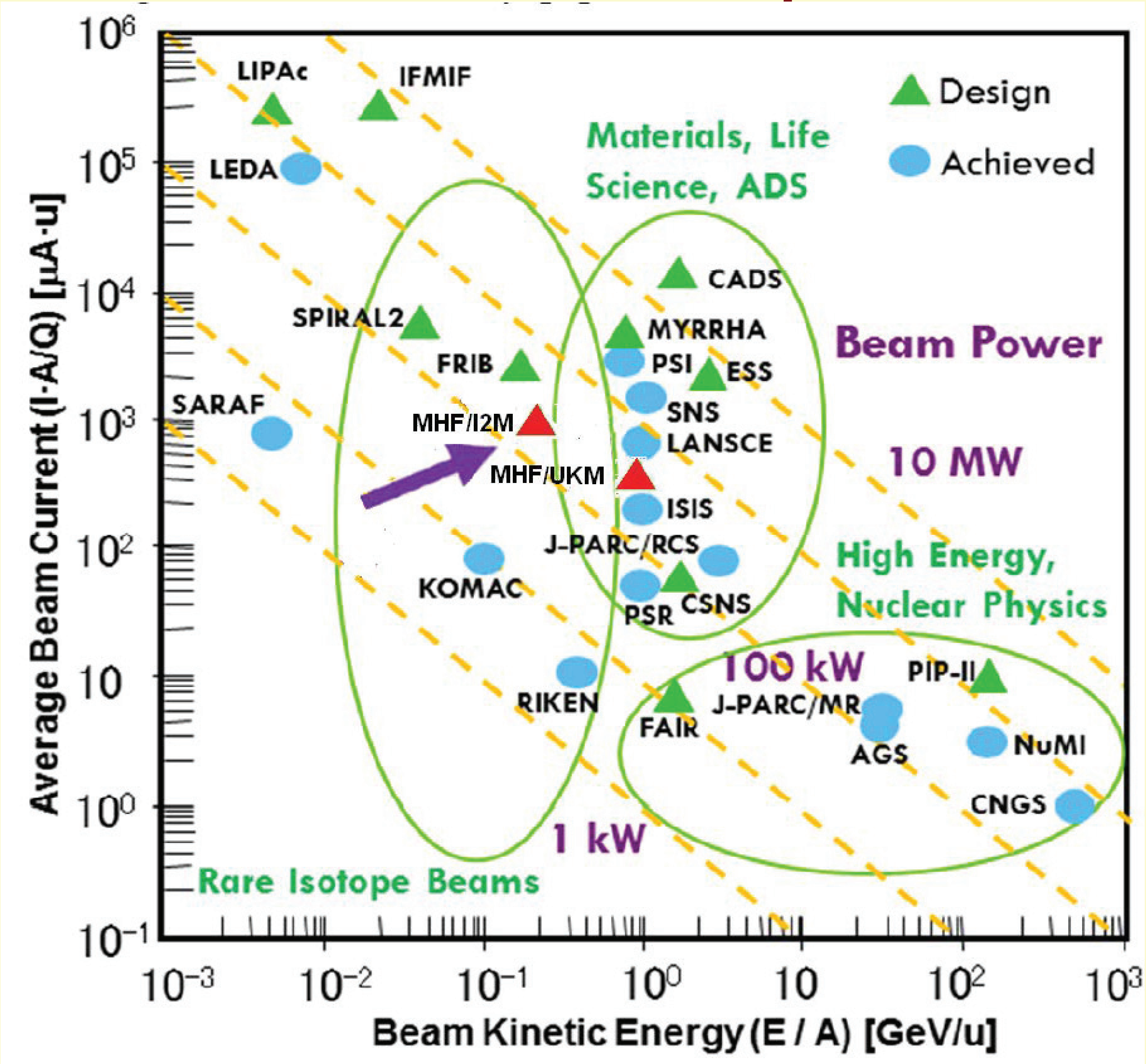


High current proton Rapid Cycling Synchrotron UKM

Circumference, m	222.768
Superperiods	21
Max. magnetic field, T	1.31
Max. B·ρ, T·m	12.89
Inj. proton energy, MeV	200
Inj. ion energy, MeV/u	12xZ/A (I-3) 7 (I-4)
Max. beam intensity for ions, p/p	$6x10^9$
Max. proton energy, GeV	3.04
Max. repetition rate, Hz	25
Max. intensity for protons, p/p	$2.5x10^{13}$
Beam power, kW	100
Tune shift $Q_{x,z}$	5.75
Hor. acceptance, π mm mrad	200
Ver. acceptance, , π mm mrad	120
Required vacuum pressure, Torr	$<10^{-11}$



Hadron accelerator power frontier

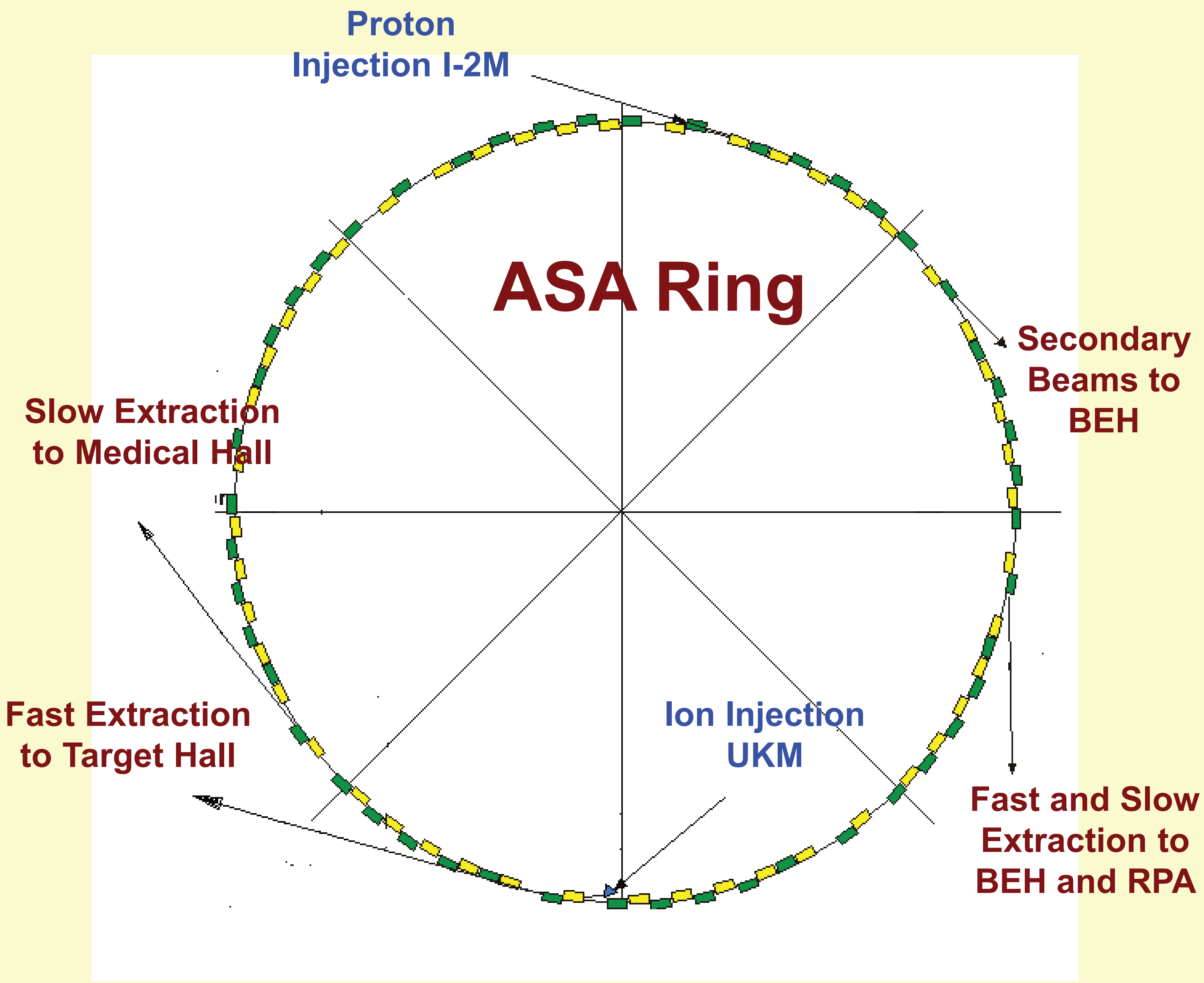


Jie.Wei, IPAC2014

Auxiliary Ring U-10

(Accelerator–Stretcher–Accumulator)

Circumference, m	251.15
Superperiods	8
Max. magnetic field, T	1.01
Max. B·ρ, T·m	34.1
Inj. proton energy, MeV	200
Inj. ion energy, MeV/u	50-1000
Max. proton energy, GeV	9.3
Max. repetition rate, Hz	0.5
Max. intensity for protons, p/p	1.5×10^{12}
Max. intensity for stacked nuclei beam	2.7×10^{13} (Co)
Max. power of nuclei beam, TW	2.4 (Co)
Tune shift $Q_{x,z}$	9.3
Hor. acceptance, π mm mrad	250
Ver. acceptance, , π mm mrad	120



MHF Capabilities

The priorities of MHF include all of the basic technological areas of high current hadron accelerators at intermediate energies, validating the use of accelerated beams for:

- physics research with kaon, muon, pion, and nucleon in precision experiments;
- experiments with high density energy in matter;
- experiments with rare isotope;
- radioisotope production;
- bio-research and proton & ion therapy for cancer treatment;
- material science and nuclear energy applications including critical input into design of future energy systems;
- testing of radiation effects on components and systems;
- technological and methodical research.

Conclusion

The main goal of the presented concept is to call attention to the absolute necessity of the forced development the accelerator-technological base in the country. Disengagement of Rosatom from the management of the accelerator area in science and industry was a serious mistake that destroyed the Foundation of nuclear energetic of the future, which is impossible without solution to global problems of nuclear safety, transmutation of nuclear waste and closed cycle. The purpose of MHF is to solve these and other problems of nuclear science, and realization of this project at ITEP is a strategically optimal for this time.

Thank you very much for your attention