12th INTERNATIONAL BEAM INSTRUMENTATION CONFERENCE

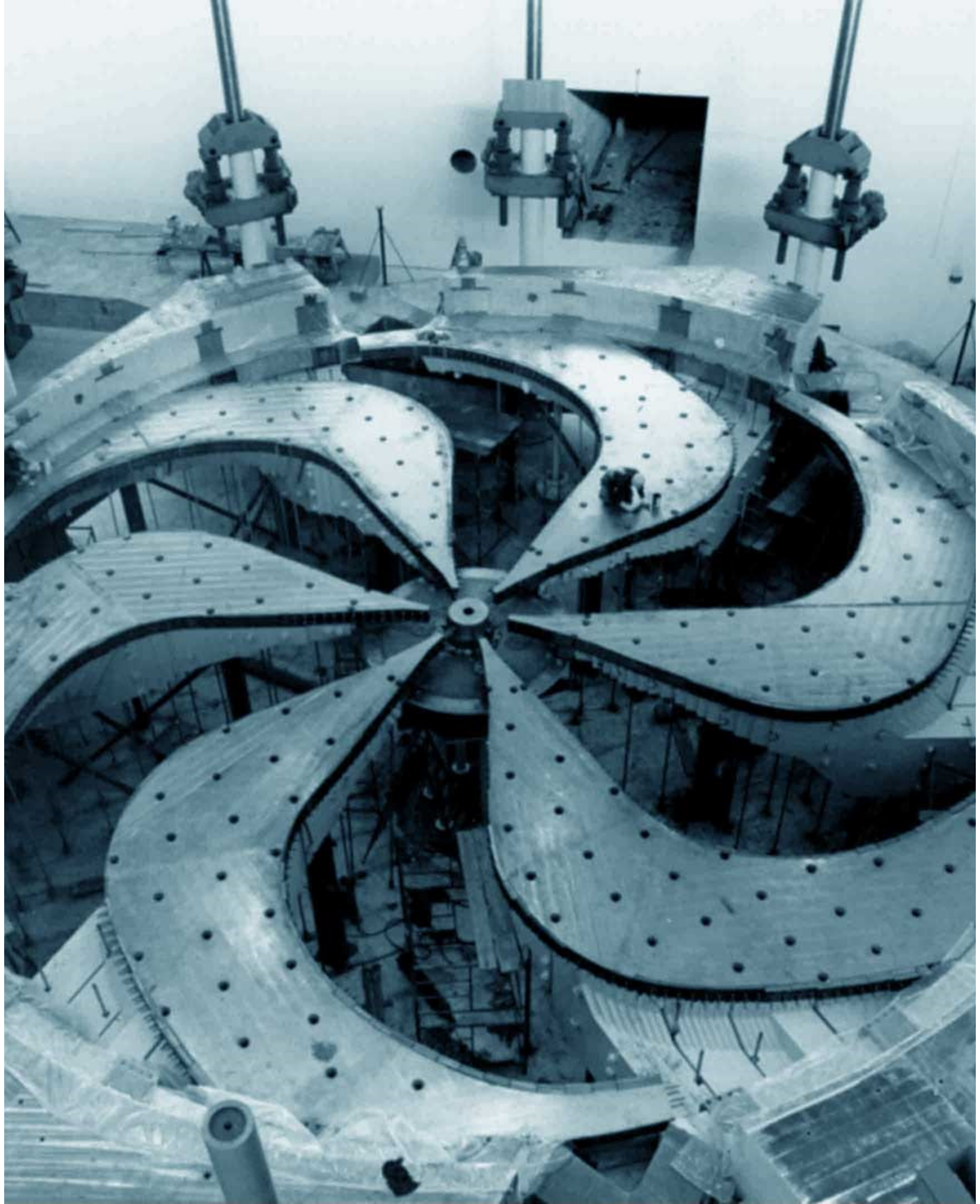
SASKATOON, CANADA

September 10-14, 2023

Canadian Light Source | Centre canadien de rayonnement synchrotron

IBIC2023

Overview of Accelerators in Canada



Bob Laxdal

Deputy Director, Accelerator Division, TRIUMF

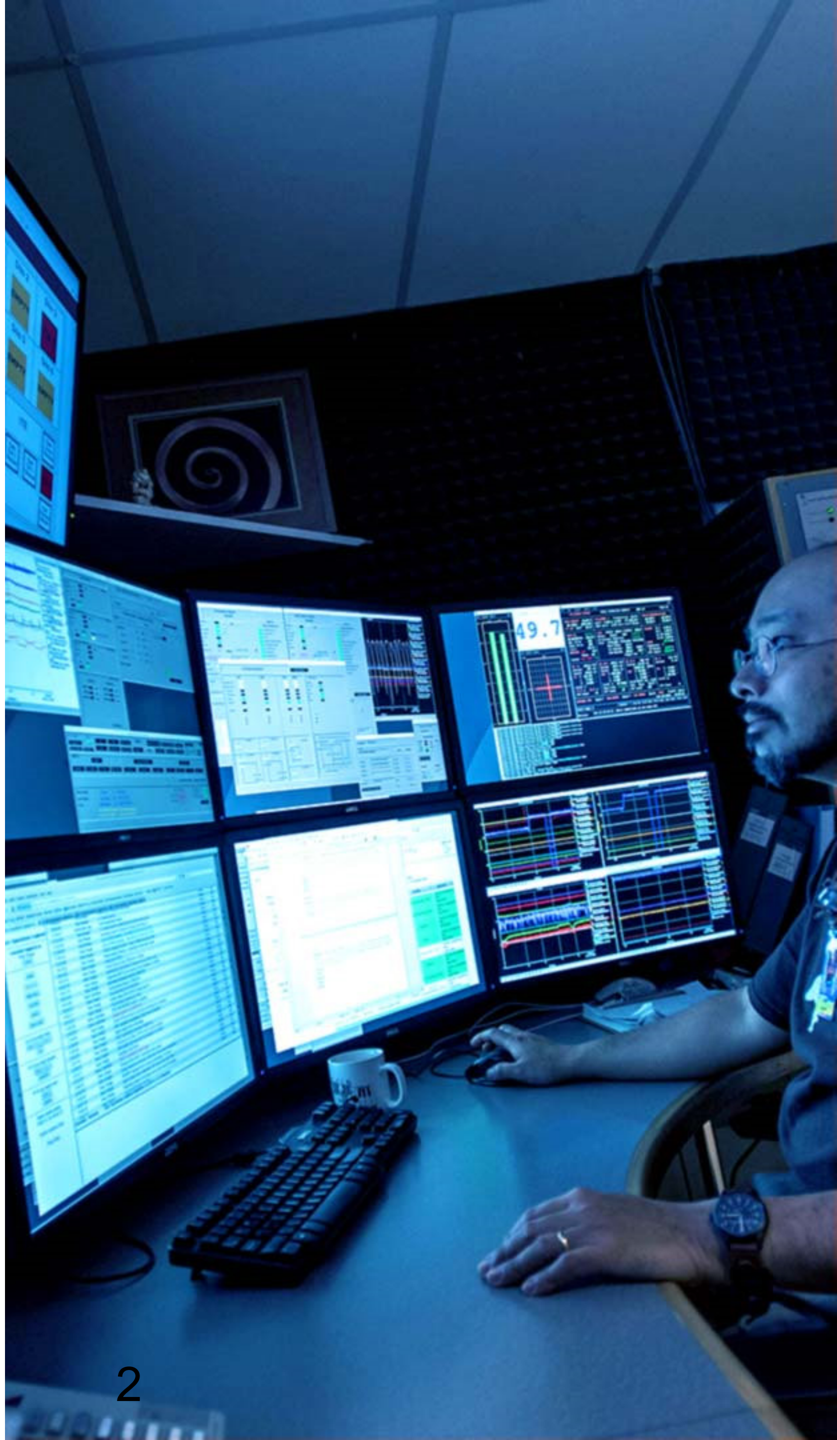
IBIC, Saskatoon

Sept. 11, 2023

Discovery, accelerated

Outline

- Early History of Accelerators in Canada
  - 1945-1955
  - 1955-1965
- Emergence of three centres
  - AECL, SAL, TRIUMF
- Present landscape
  - CLS
  - TRIUMF
  - Industrial accelerators
  - Accelerator applications
- Summary



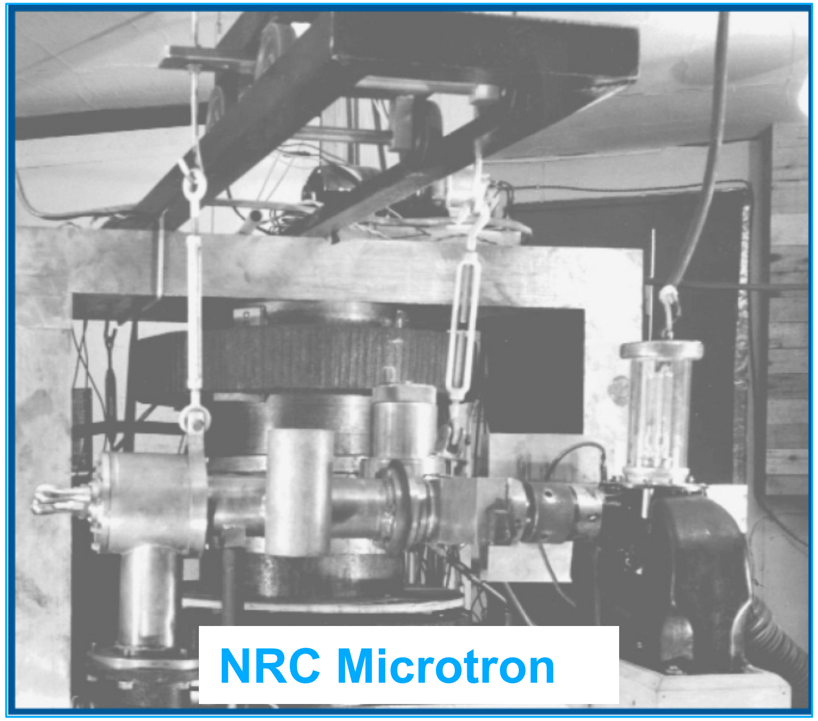
Early History

Historical Overview (1945-1955)

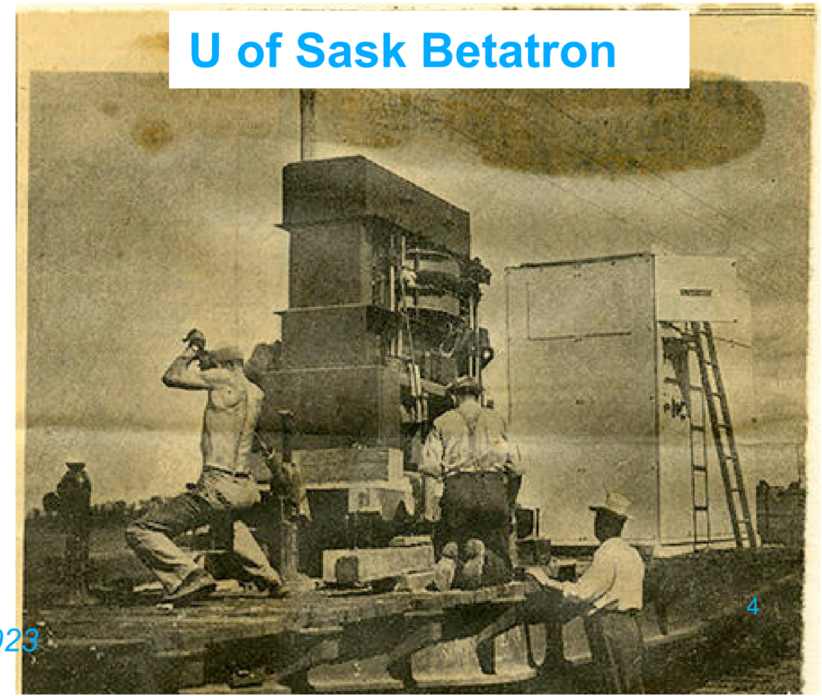
- Accelerator activities in Canada were slowed by World War II - technical advances in rf technology facilitated post-war development and the rise in prominence of nuclear energy increased available funding for sub-atomic physics

Highlights

- 1947 - The first MeV class rf accelerator in Canada was a 4.6MeV microtron – the world's first – National Research Council (NRC) in Ottawa - 8 turns, 3mA peak current
- 1948 - The University of Saskatchewan acquired a 22 MeV Allis Chalmers Betatron for nuclear physics and radiation therapy



NRC Microtron



U of Sask Betatron

Historical Overview (1945-1955)

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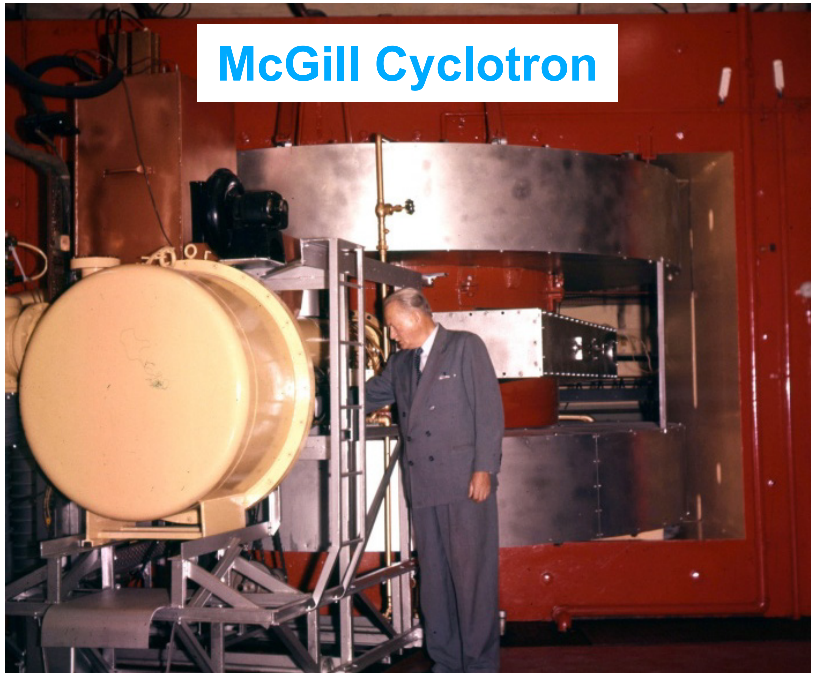
- 1948 - The University of Saskatchewan acquired a 22 MeV Allis Chalmers Betatron for nuclear physics and radiation therapy
- 1949 – 100 MeV proton cyclotron was built at McGill University, Montreal
- 1950 – 70MeV GE electron synchrotron – Queen's University
- 1951 – 3MV van de Graaff installed at UBC (Vancouver)
- 1952 – 3MV van de Graaff installed at Chalk River (NRC)

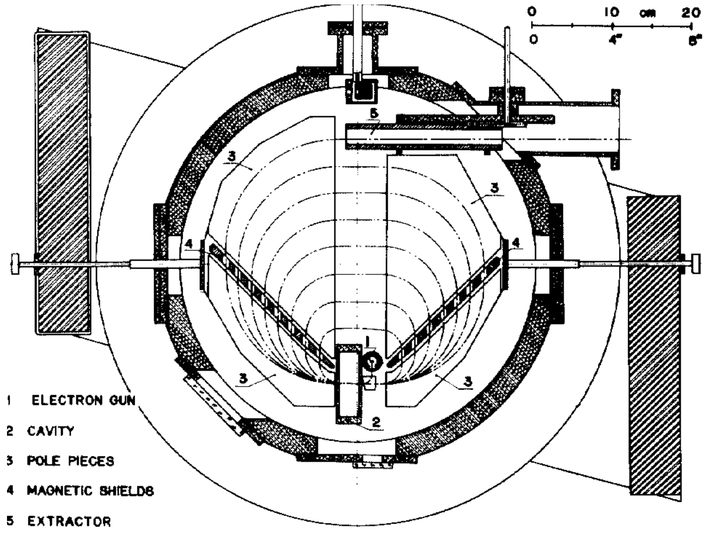


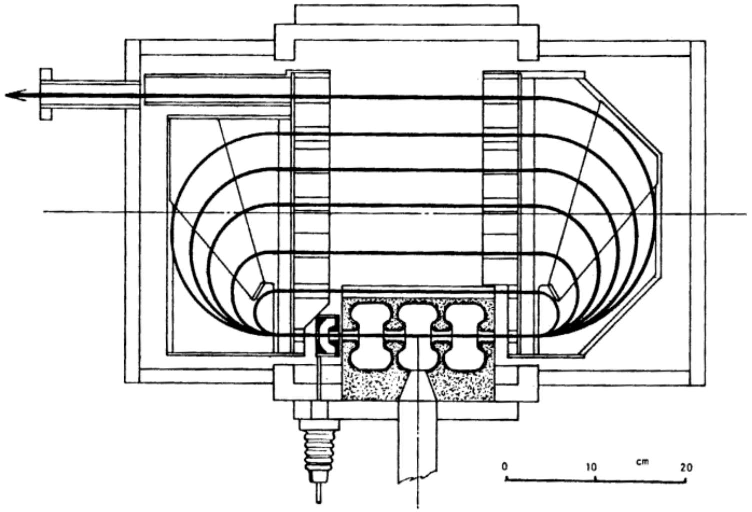
UBC van de Graaff

Historical Overview (1955-1965)

- 1961 - U of Western Ontario – installed a racetrack microtron (the world's first)
  - eight orbits were achieved and a 40-mA pulsed beam was extracted with maximum energy 6.3 MeV
  - A second therapy machine was built - 30-mA pulsed beam was achieved for final energies of 9–15-MeV (6 orbits)

6.3 MeV microtron





15 MeV microtron

Historical Overview (1955-1965)

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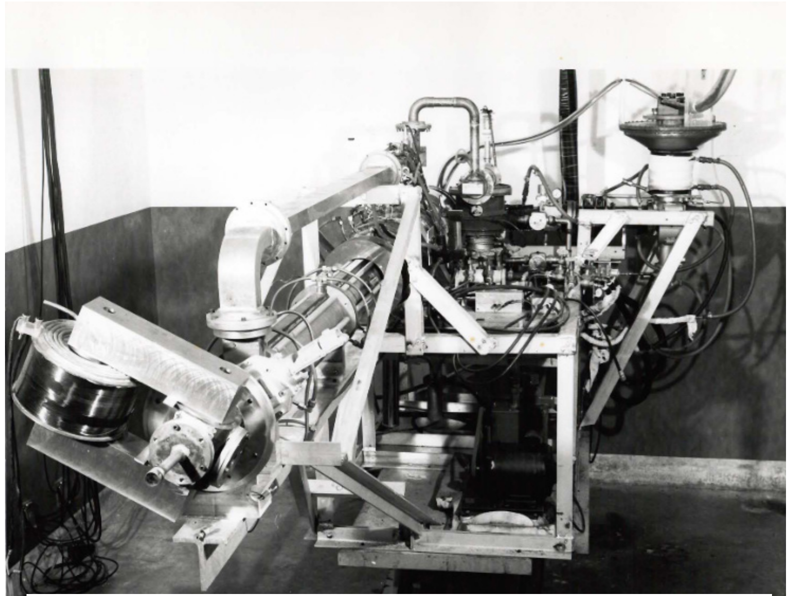
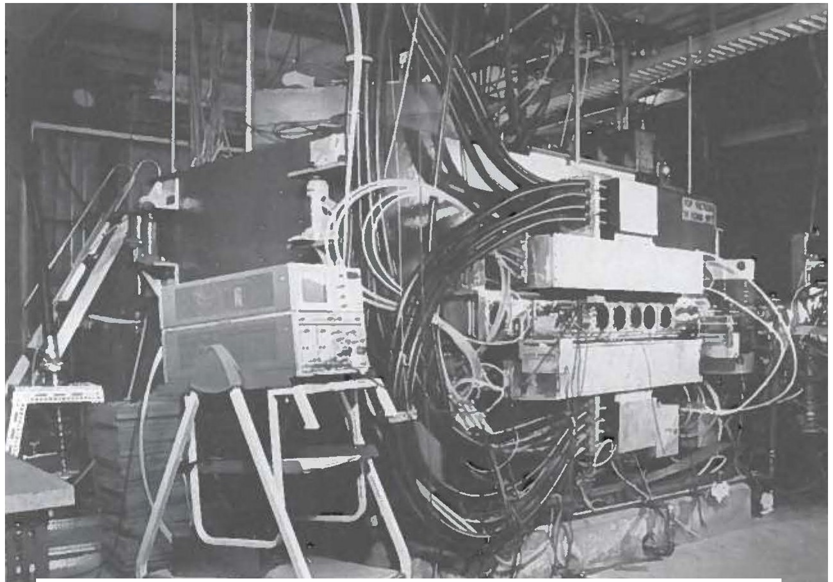
  - eight orbits were achieved and a 40-mA pulsed beam was extracted with maximum energy 6.3 MeV
  - A second therapy machine was built - 30-mA pulsed beam was achieved for final energies of 9–15-MeV (6 orbits)
- 1962 – McGill University designed and built a 8.5 MeV electron linac (200mA pulses) – first linac installed at a Canadian hospital – Royal Victorian hospital – Montreal
- 1965 – U. of Manitoba – 50MeV spiral sector H- cyclotron for nuclear physics – important advances in polarized sources and accelerator physics education – closed in 1989



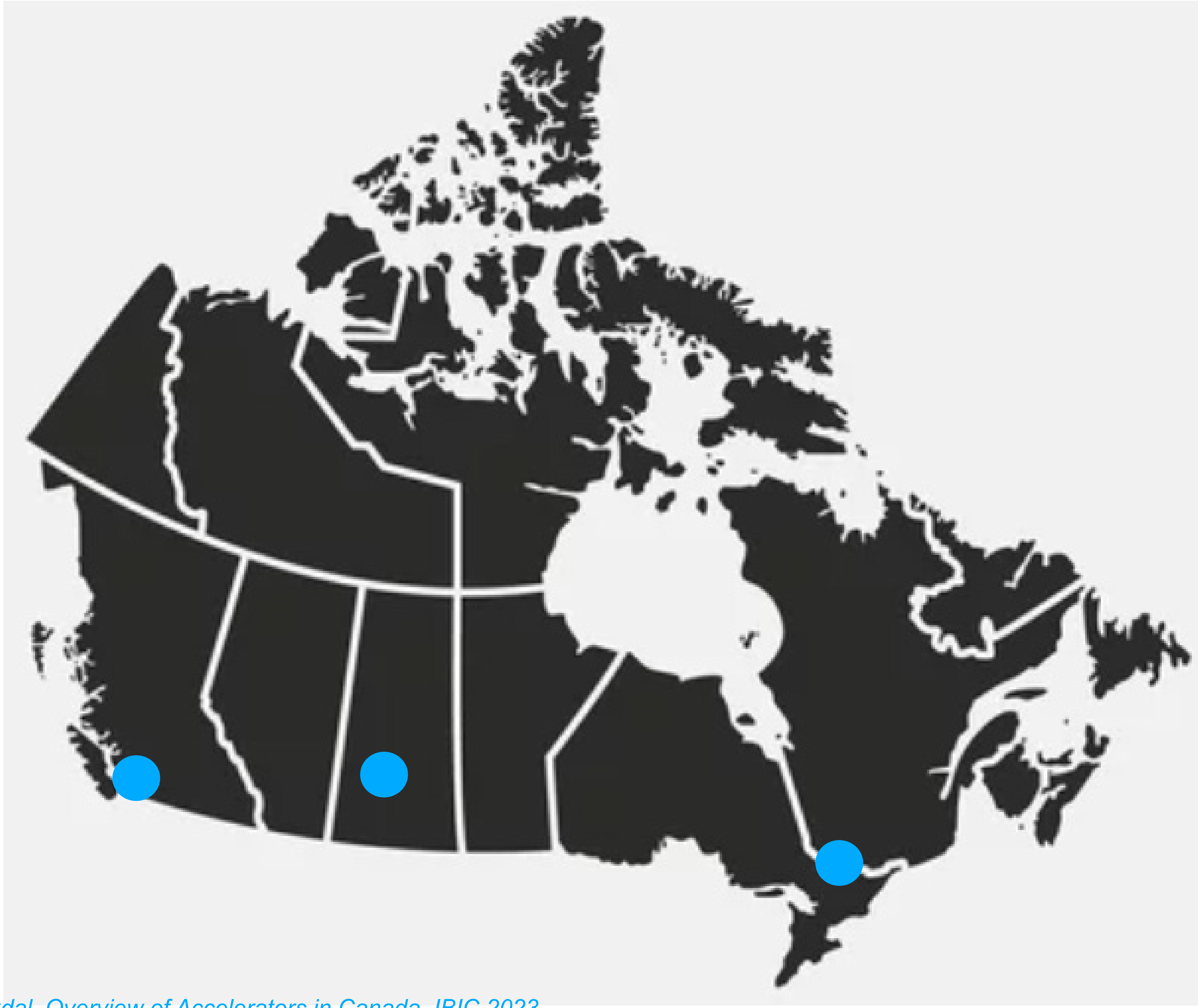
McGill 8.5MeV Linac



U. Manitoba Cyclotron

Rise of Major Facilities

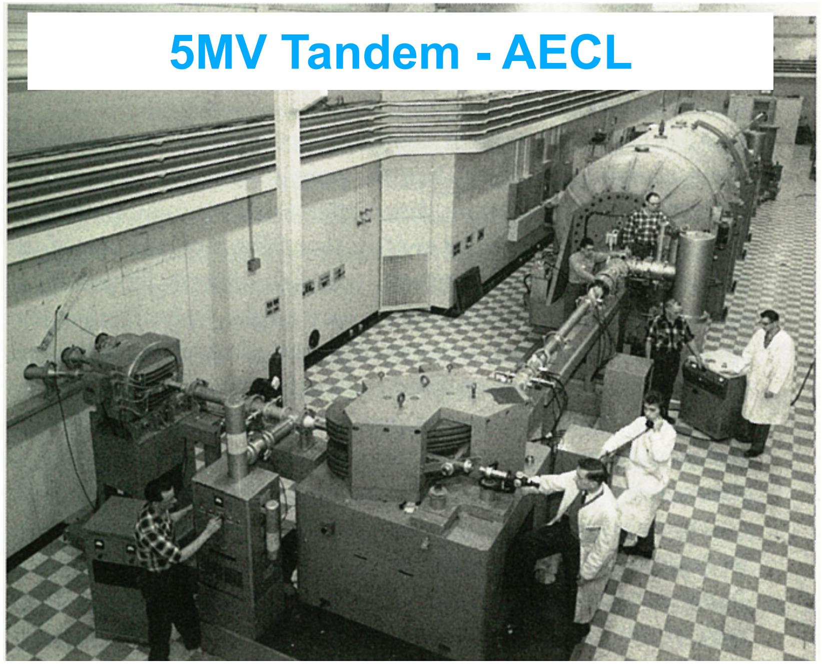
- Three accelerator centres emerge
  - AECL - Chalk River
  - SAL / CLS – Saskatoon
  - TRIUMF - Vancouver



AECL Chalk River

Atomic Energy of Canada Limited (AECL)

- In 1952, Atomic Energy of Canada Limited (AECL) was created to promote the peaceful use of nuclear energy.
  - Funding was available to expand the development of nuclear and accelerator technology
- 1952 – 3MV van de Graaff installed at Chalk River (NRC)
- 1959 - 5MV Tandem (HVEC) installed – world's first tandem



5MV Tandem - AECL

5MV Tandem - AECL

Tandem control room

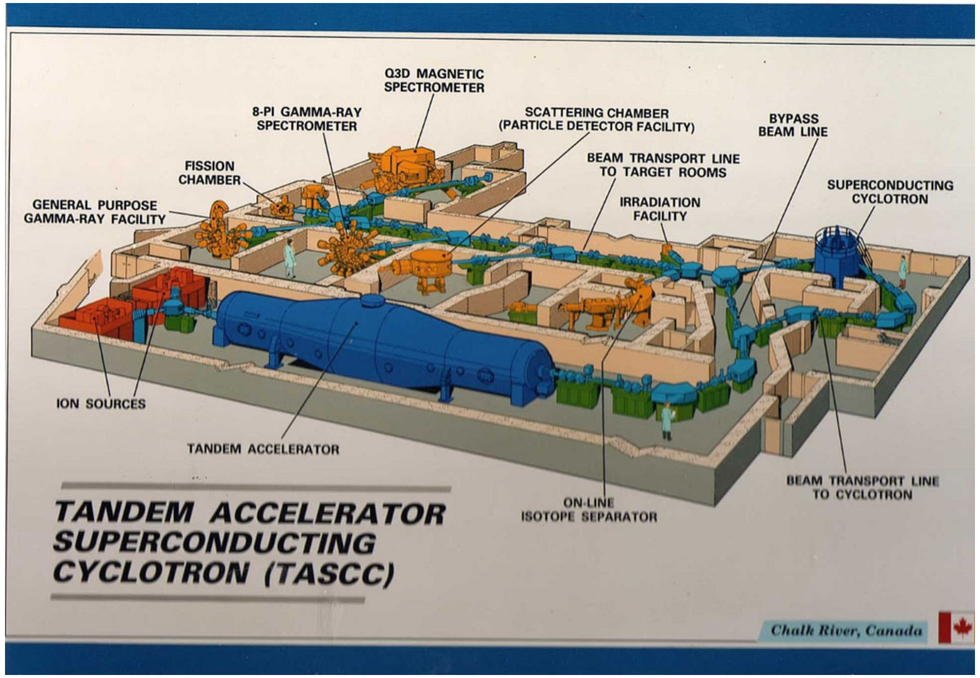
Ted Litherland, Al Bromley and Harry Gove. (Alan Bromley became US Presidential Science advisor)

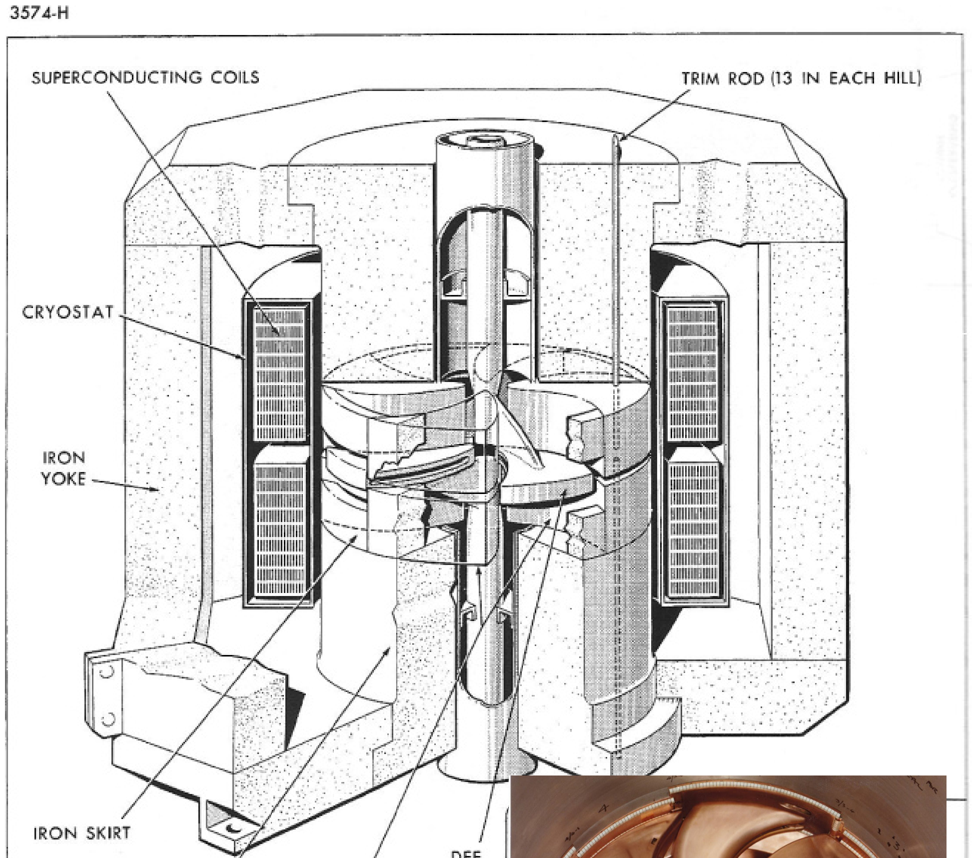
AECL Chalk River – accelerators for nuclear physics

AECL Chalk River – accelerators for nuclear physics

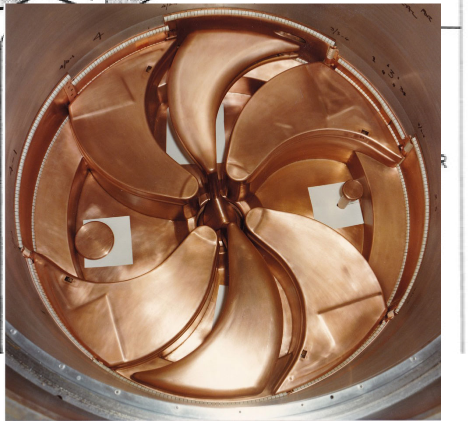
- 1966 – 13MV MP Tandem installed
- 1973 – AECL started to develop a superconducting cyclotron to boost the energy of the tandem - 4 sector – K500
- 1985 – TASCC Superconducting cyclotron operational – the first superconducting cyclotron to operate with a pre-accelerator
  - 50MeV/u Li and 10MeV/u U
  - operated until 1996

13MV MP Tandem





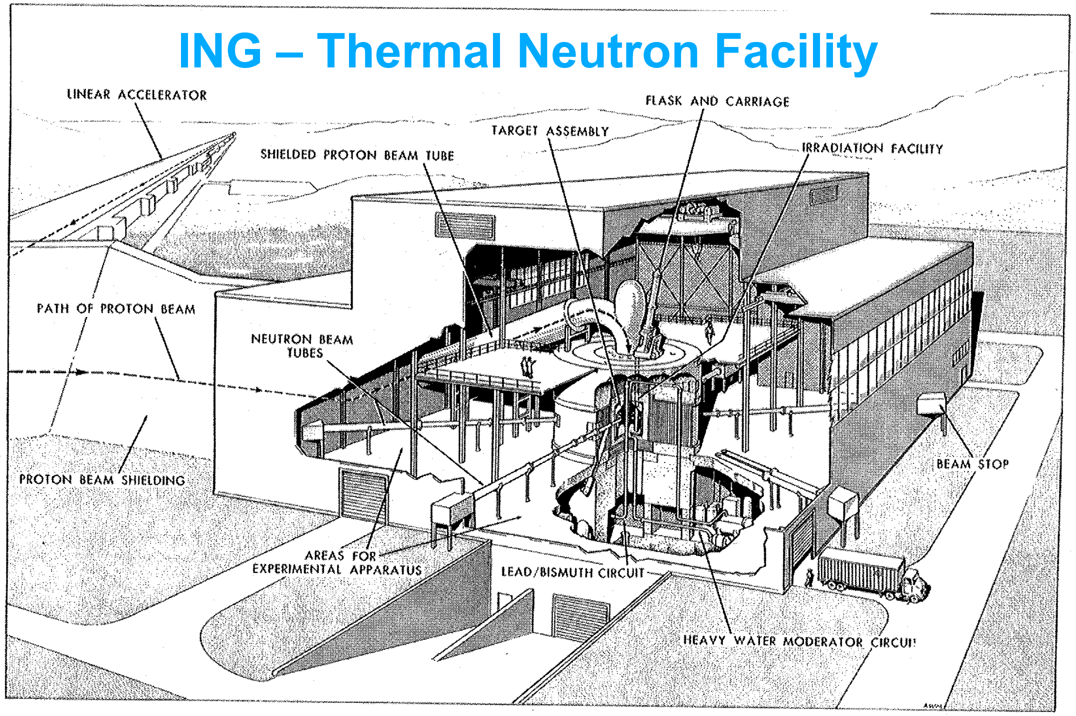
Superconducting Cyclotron

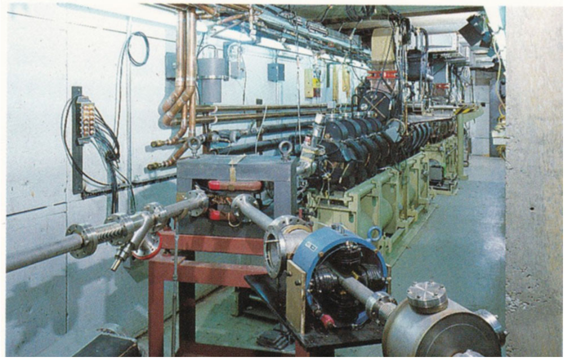


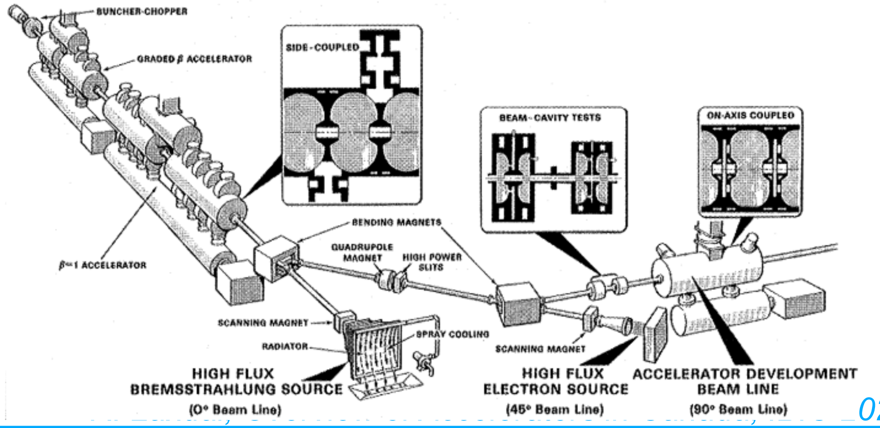
AECL – High intensity accelerators

- AECL had a strong interest in electronuclear breeding
- 1966 – Intense Neutron Generator - ING proposal
  - 1GeV proton linac beam with 65 mA average current
  - Liquid bismuth target surrounded by heavy water
  - Proposal rejected but the project spawned much development
- Prototype work
  - Duo-plasmatron source – 120mA
  - ETA (Electron test accelerator) - 20 mA, 4 MeV
  - HCTF (High Current test facility) – 3.3-MeV proton linac – achieved 5 mA in 1985
  - 1981-1990 – RFQ1 (with LANL) - 79-mA, 600keV cw proton beam achieved in 1990 – the highest of any RFQ at the time

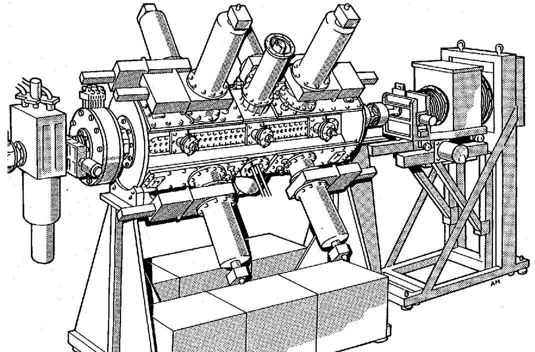
ING – Thermal Neutron Facility







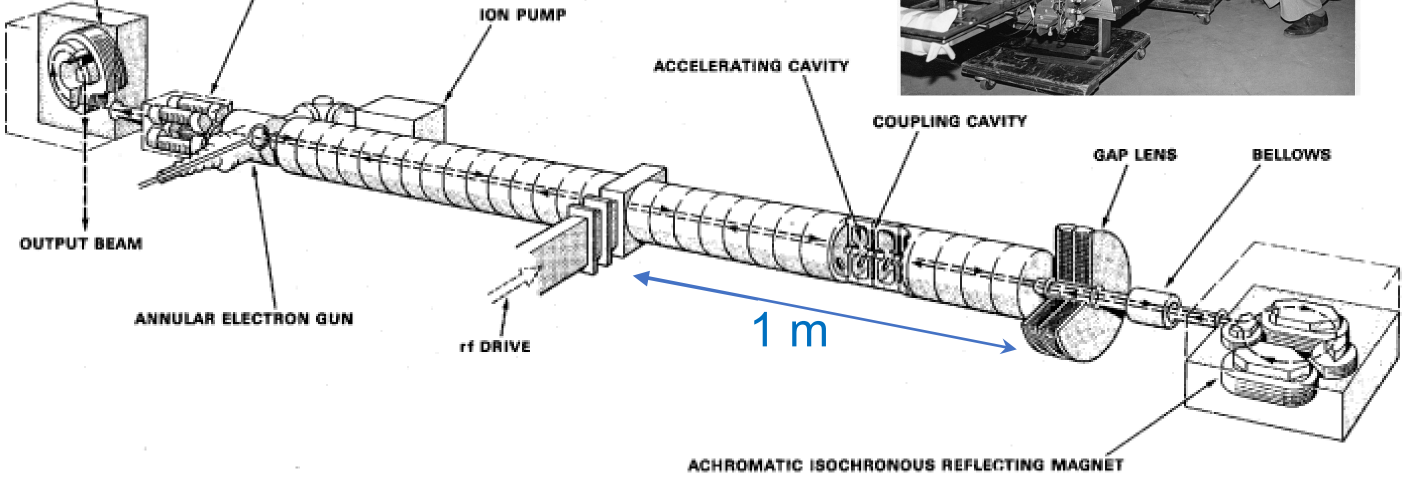
Electron Test Accelerator

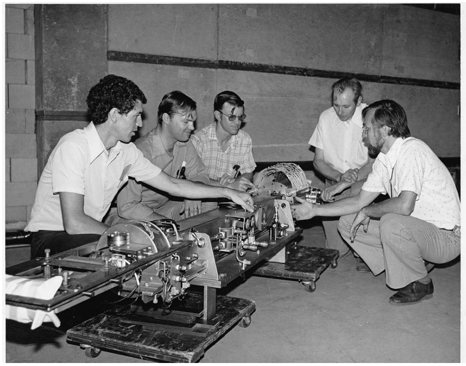


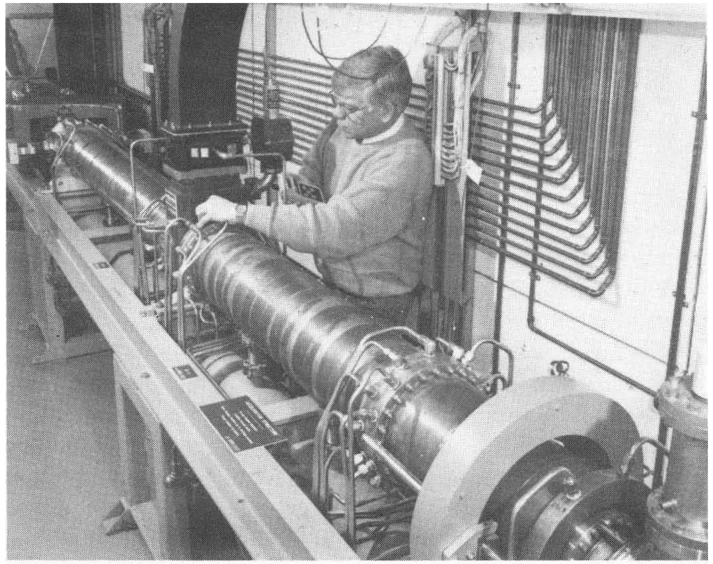
RFQ1

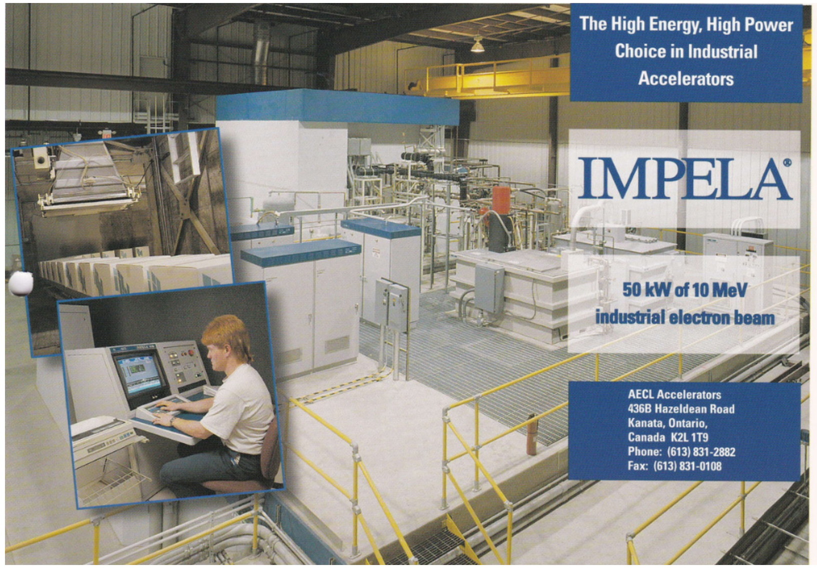
AECL Industrial and Medical Electron Linacs

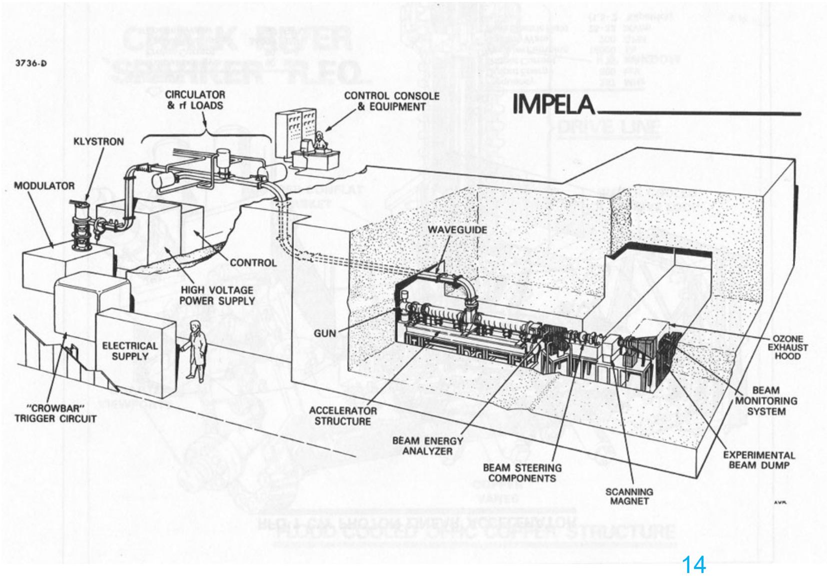
- Development of electron machines for industrial/medical application
- 1982 - Compact electron linacs – double pass therapy linac – 5-25MeV – Therac 25 (Reflexotron)
- 1984 – IMPELA – 10MeV 50kW for industrial materials processing







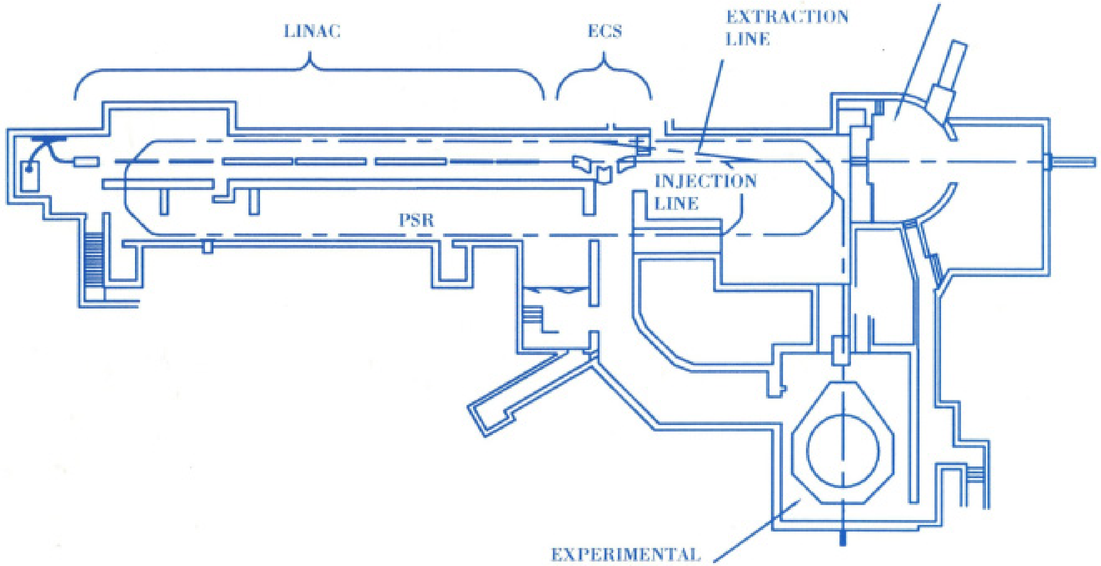


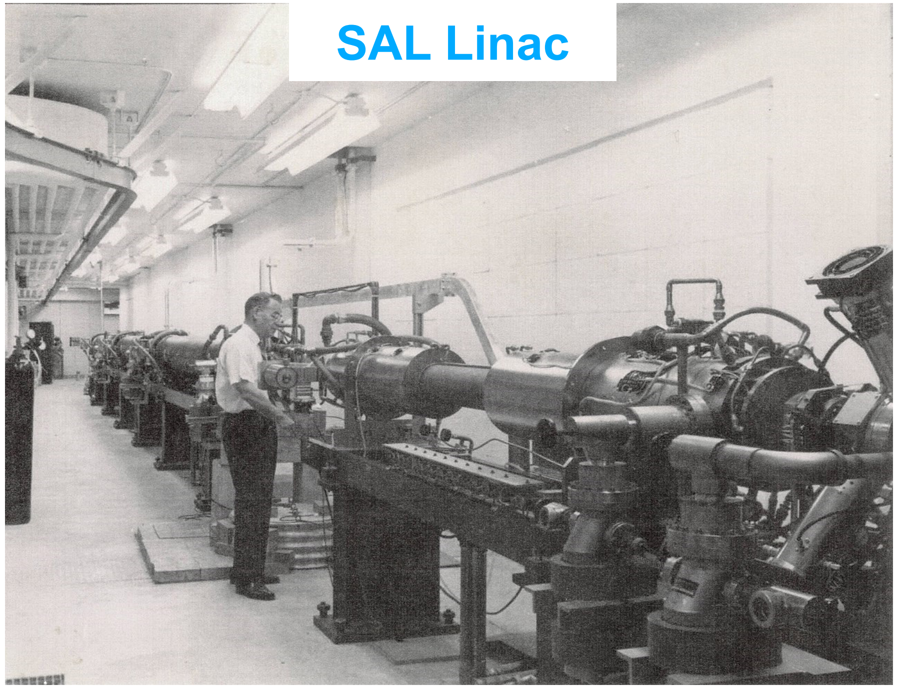


SAL / CLS Saskatoon

Saskatchewan Accelerator Laboratory (SAL)

- 1964 - Saskatchewan Accelerator Laboratory (SAL) opens - 140-MeV S-band Varian linac - upgraded to 220-MeV in 1975 and to 300 MeV in 1980.
- The EROS pulse stretcher ring was installed in 1986 – 100-300MeV with near 100% duty factor
    - The ring was a genius of prairie practicality. To reduce costs the new ring was squeezed into the existing building by hanging it from the ceiling above the linac
- The SAL/EROS physics program was terminated in 1999 to make way for CLS



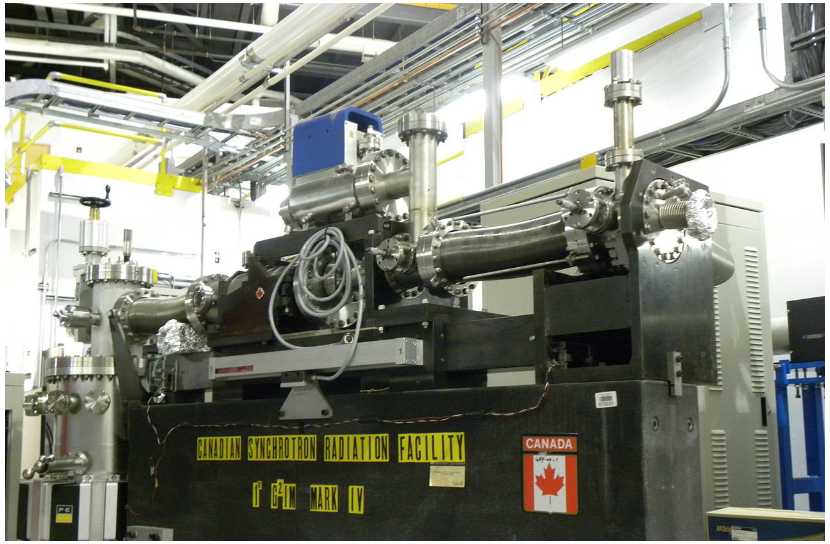

SAL Linac


EROS pulse stretcher ring

SAL -> CLS

SAL -> CLS

- 1978 – funding secured to add a Canadian beamline (CSRF) to the Synchrotron Radiation Center at the U. of Wisconsin- Madison
- 1990 – Canadian Institute for Synchrotron Radiation launched
- 1996 – proposal for a light source in Saskatoon – Canadian Light Source was accepted and funding was put in place (federal, provincial, municipal and university) to realize the project
- 2001 – building completed
- 2002 – SAL linac prepared as CLS injector at 250 MeV
- 2002 - Booster commissioned
- 2005 – First external user

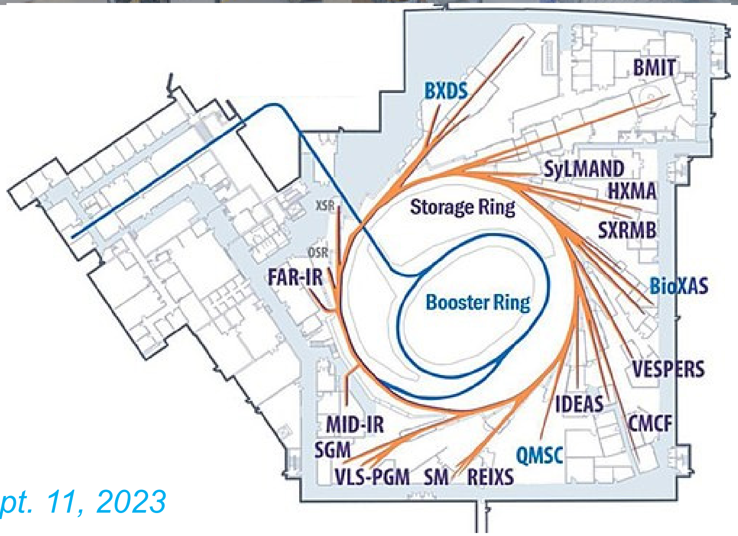


Monochrometer from CSRF beamline

Building in 2001

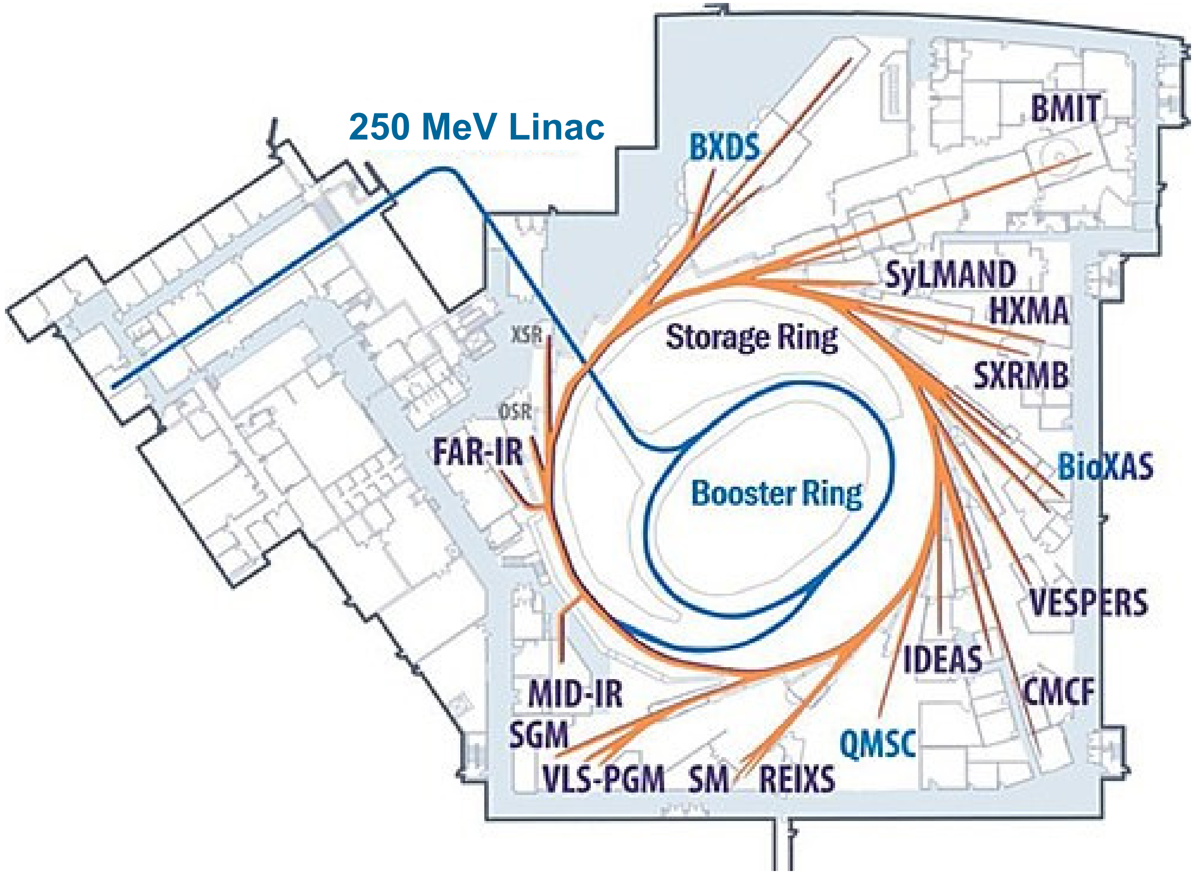
test

The Canadian Light Source Today



- Located on University of Saskatchewan campus
- 2.9 GeV ring, 220 mA
- 12 cell double bend achromat lattice
- 170.88 m circumference
- 22 beamlines

Canadian Light Source – Storage ring parameters



Storage Ring Parameters	
Lattice Type:	Double Bend Achromat
Beam Energy:	2.9 GeV
Periodicity:	12 cell
Circumference:	170.88 m
Beam current:	220 mA
Straight Length:	5.2 m
Cavity Frequency:	500 MHz
Cavity Voltage:	2.4 MV
Harmonic number:	285
Horizontal emittance	18.1 nm-radian
Energy spread (ΔE/E):	0.00111
Bunch Length:	10 mm

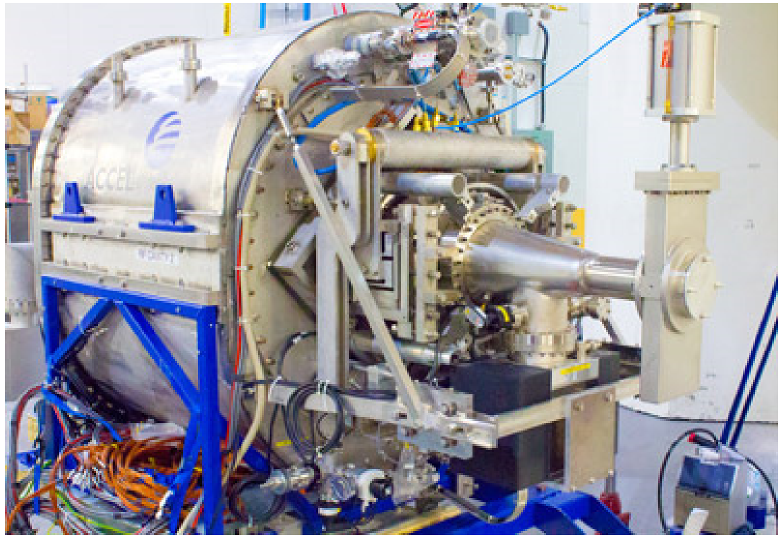
https://www.lightsource.ca/facilities/machine.php

Canadian Light Source Status and Commissioning Results L. Dallin, R. Berg, J. Bergstrom, M. de Jong, X. Shen, R.M. Silzer and J.M.Vogt, Proceedings of EPAC 2004, Lucerne, Switzerland
https://accelconf.web.cern.ch/e04/PAPERS/THPKF007.PDF

CLS Storage Ring RF Cavity

Canadian Light Source | Centre canadien de rayonnement synchrotron

- First light source to use SRF technology from the beginning of operation
- Utilize a 500MHz CESR-B cavity developed at Cornell University and built at Research Instrument, Germany
- Effective voltage 2.4MV
- CLS has an on-going project to add a second cavity to the ring for redundancy and improved performance



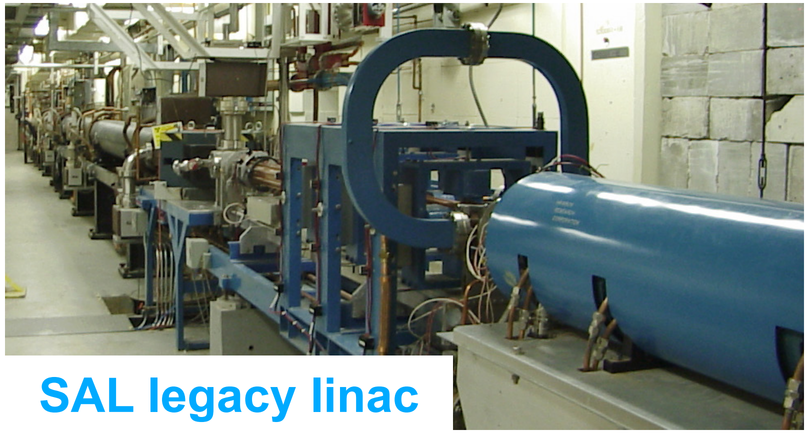
CLS Booster Synchrotron

- Accelerates from 250MeV -> 2.9GeV
- I > 10mA
- Two 500-MHz DORIS-type five-cell cavities driven by a single 75 kW klystron.
- Repetition rate of 1 Hz.

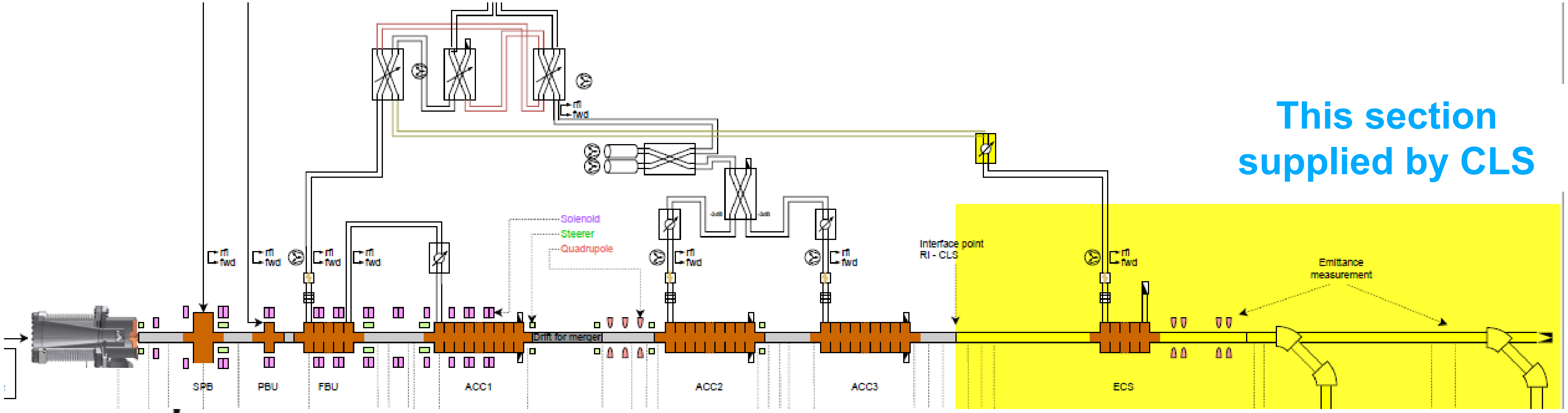
Booster Parameters	
Injection energy	250 MeV
Final Energy:	2.9 GeV
Extracted current	>10 mA
Circumference:	102.528 m
# of Dipoles	20
Rep rate	1 Hz
Cavity Frequency:	500 MHz
Cavity Voltage:	1.75 MV
Horizontal emittance @ 2.9GeV	523nm
Momentum spread (Δp/p@2.9GeV):	9.2e-4
Pulse Length @ 2.9GeV:	137 ns

CLS - Linac and Upgrade (2024)

- CLS will install a new injector from Research Instruments in spring 2024
  - 250 MeV, 3 GHz
  - Replacing 6 existing rf structures with 3 longer structures
  - Same final electron energy but with higher efficiency at the power plug and shorter RF pulses



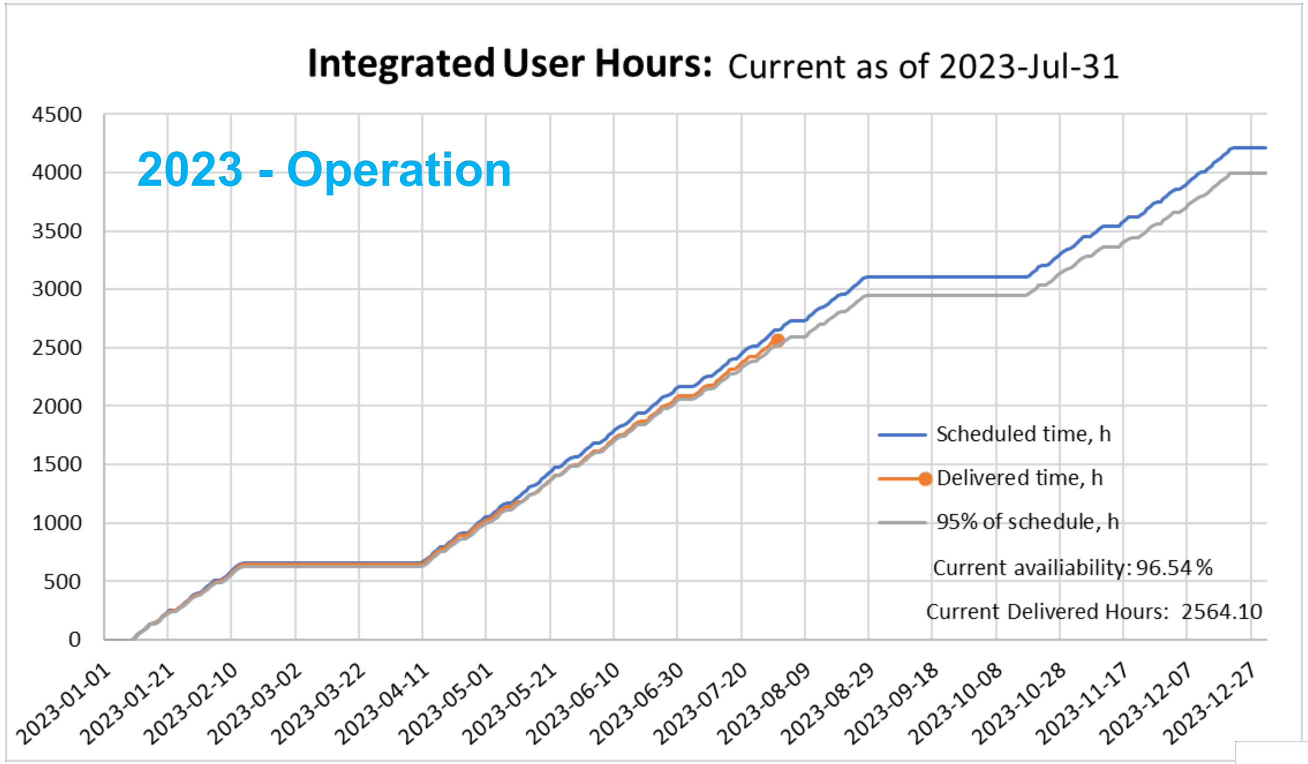
SAL legacy linac

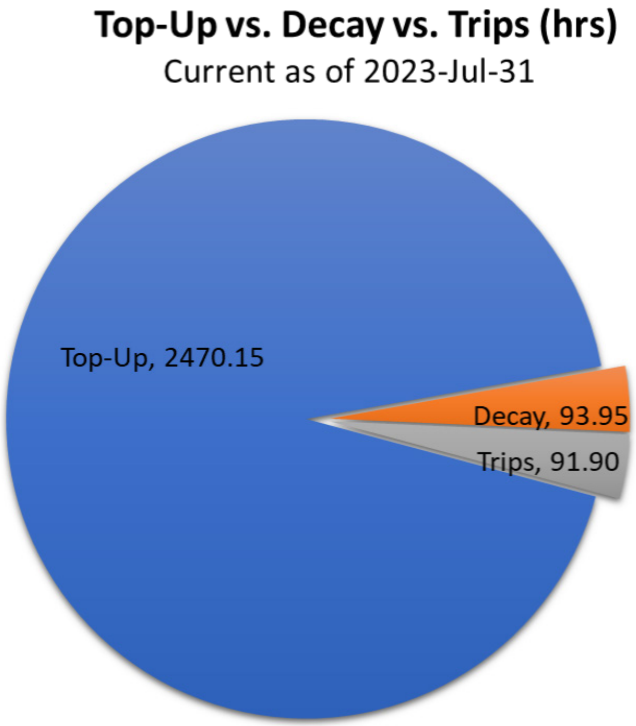


This section supplied by CLS

New linac from RI

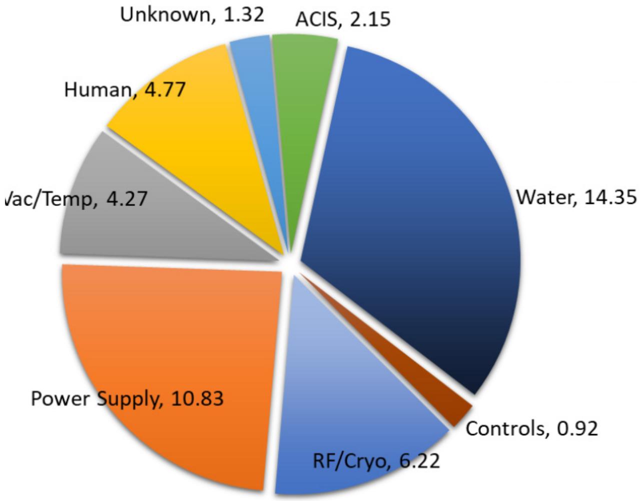
2023 - Operation of CLS

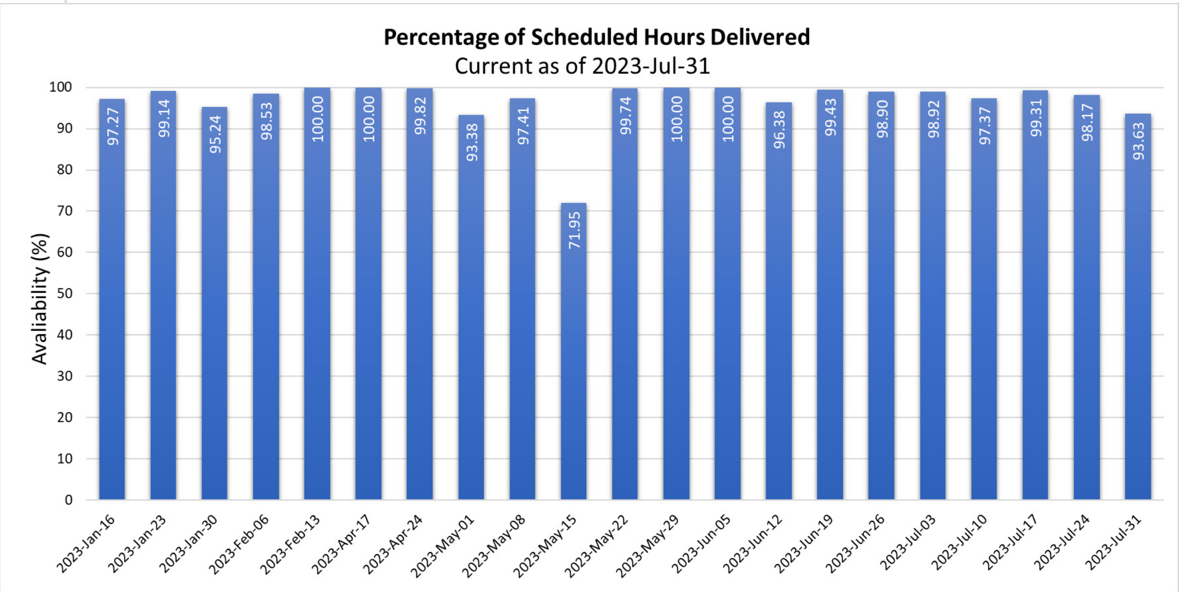




Time (hrs) Lost Due to Trips 2023

Current as of 2023-Jul-31

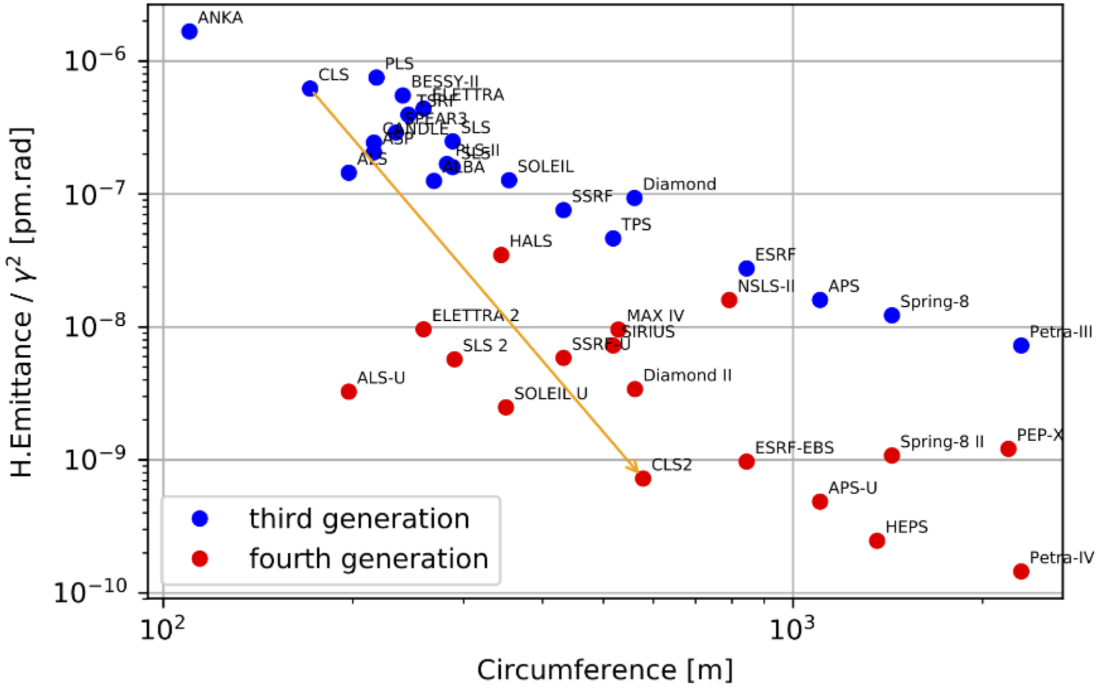


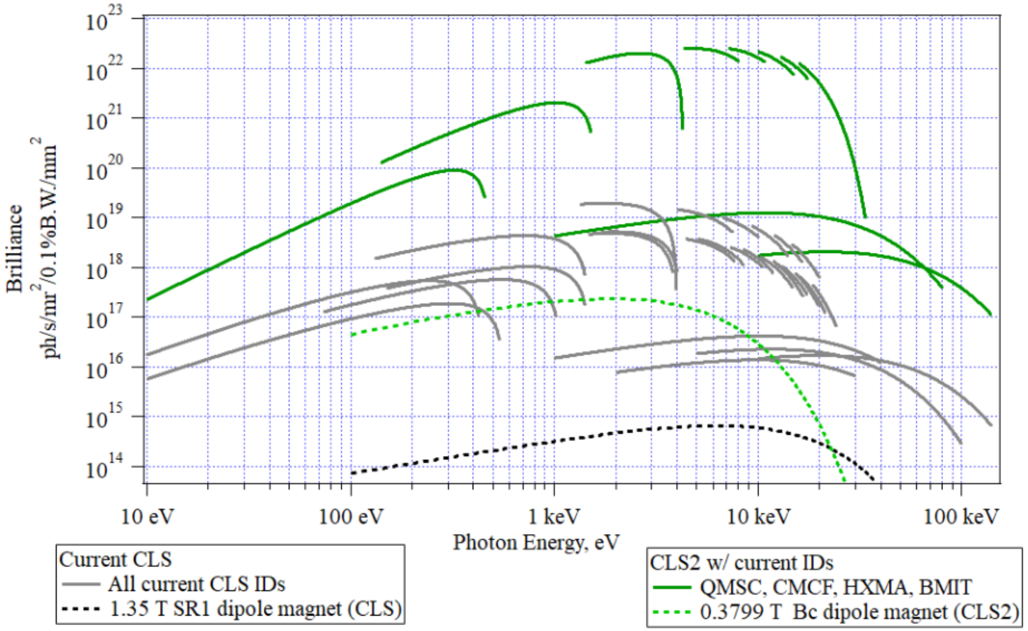


CLS2 Proposal *

* M. Boland, et al, Proceedings of IPAC21

- CLS staff have proposed a 4th generation light source CLS2 with conceptual parameters of a 3 GeV storage ring with circumference of 578 m
- Goal parameters are a storage ring current of 300mA and challenging horizontal emittance of 0.025nm-rad
- Design parameters would yield a gain of 1000 in brilliance over CLS

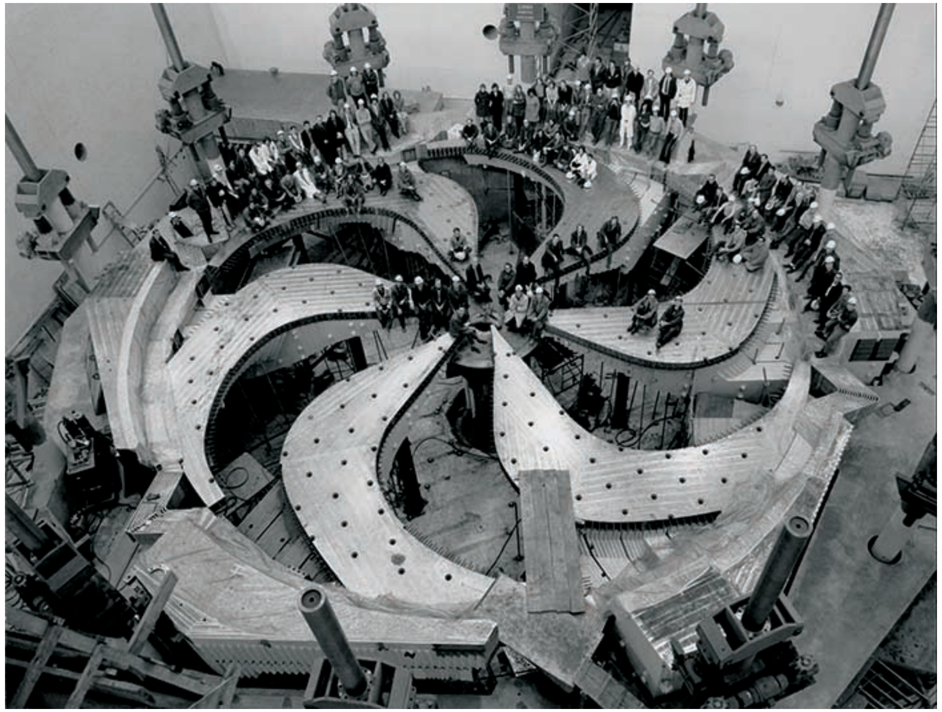




TRIUMF - Vancouver

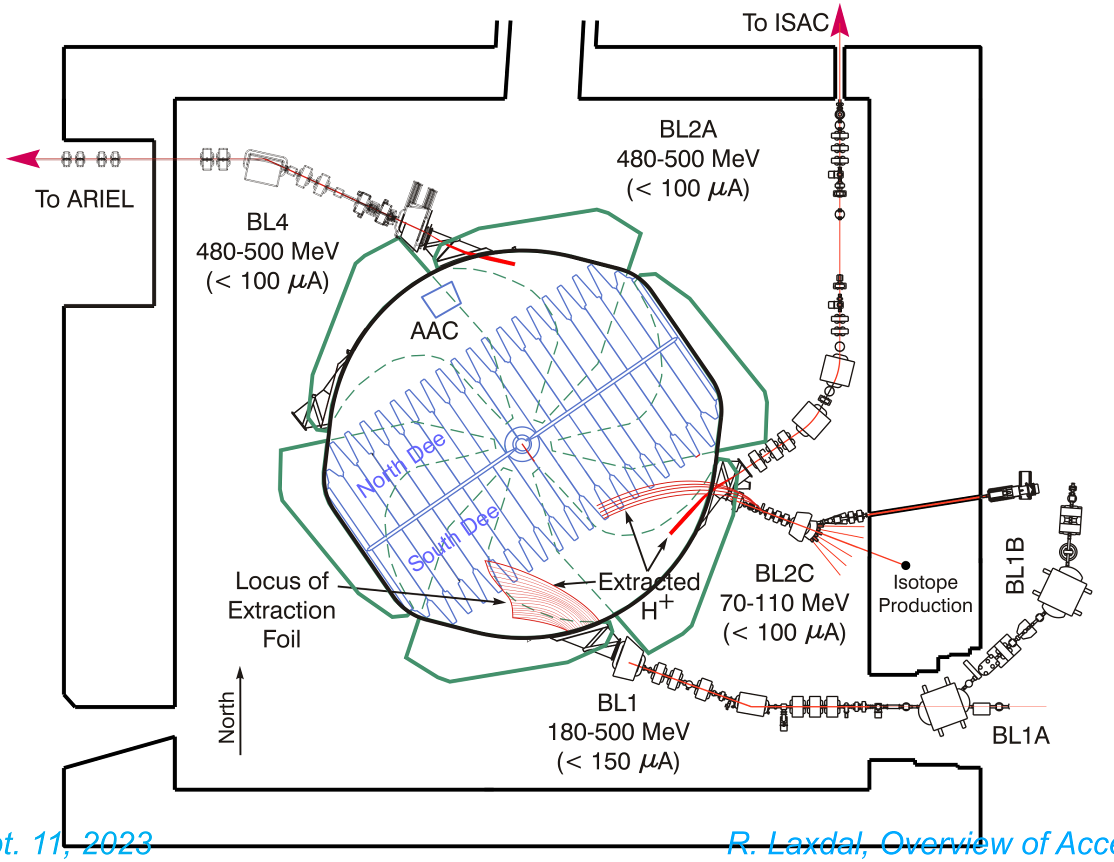
TRIUMF - Vancouver

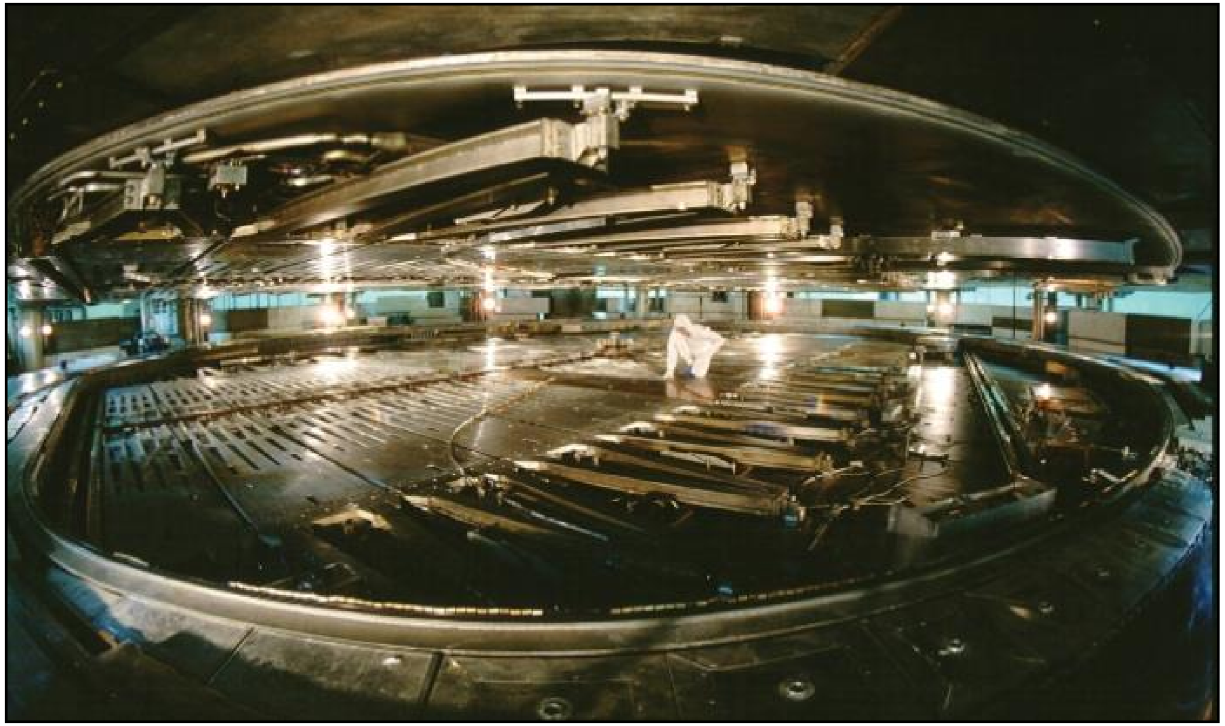
- Funded in 1968 with initially three universities backing the proposal
- TRIUMF was the third Meson Factory to be built in the world behind SIN (Villigen, Switzerland – now PSI) and LAMPF (Los Alamos, USA)
- The accelerator was much larger than any existing Canadian accelerator of the time it still boasts the largest extraction radius of any cyclotron at 7.8 meters.
  - 500 MeV H- cyclotron
  - 6 magnet sectors
- First beam was in 1974
  - … and the accelerator is still going strong nearly 50 years later now delivering 300 μA protons down multiple beamlines for radioactive ion beam production, isotope production, irradiation and neutron production

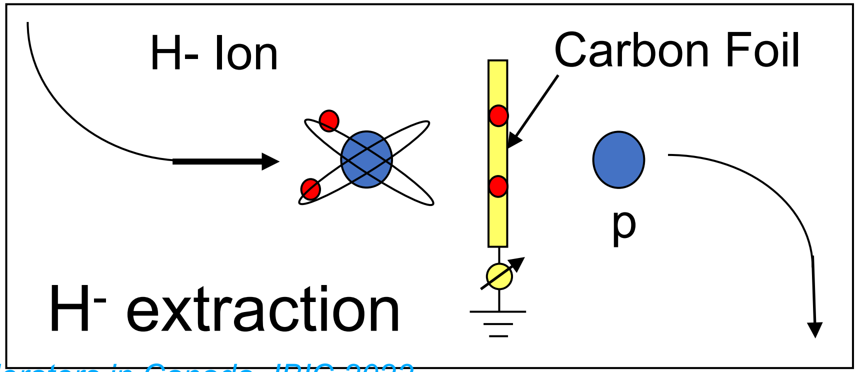


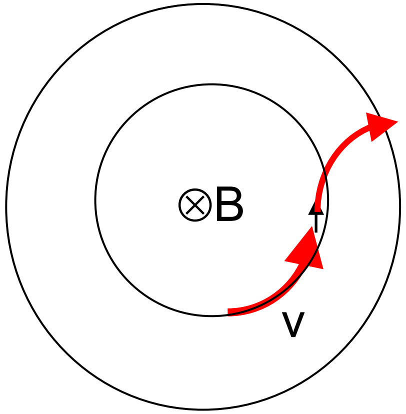
The 500 MeV Cyclotron

- H- extraction by foil stripping
  - Highly efficient, allows variable energy and simultaneous beam delivery – presently 3 beams extracted





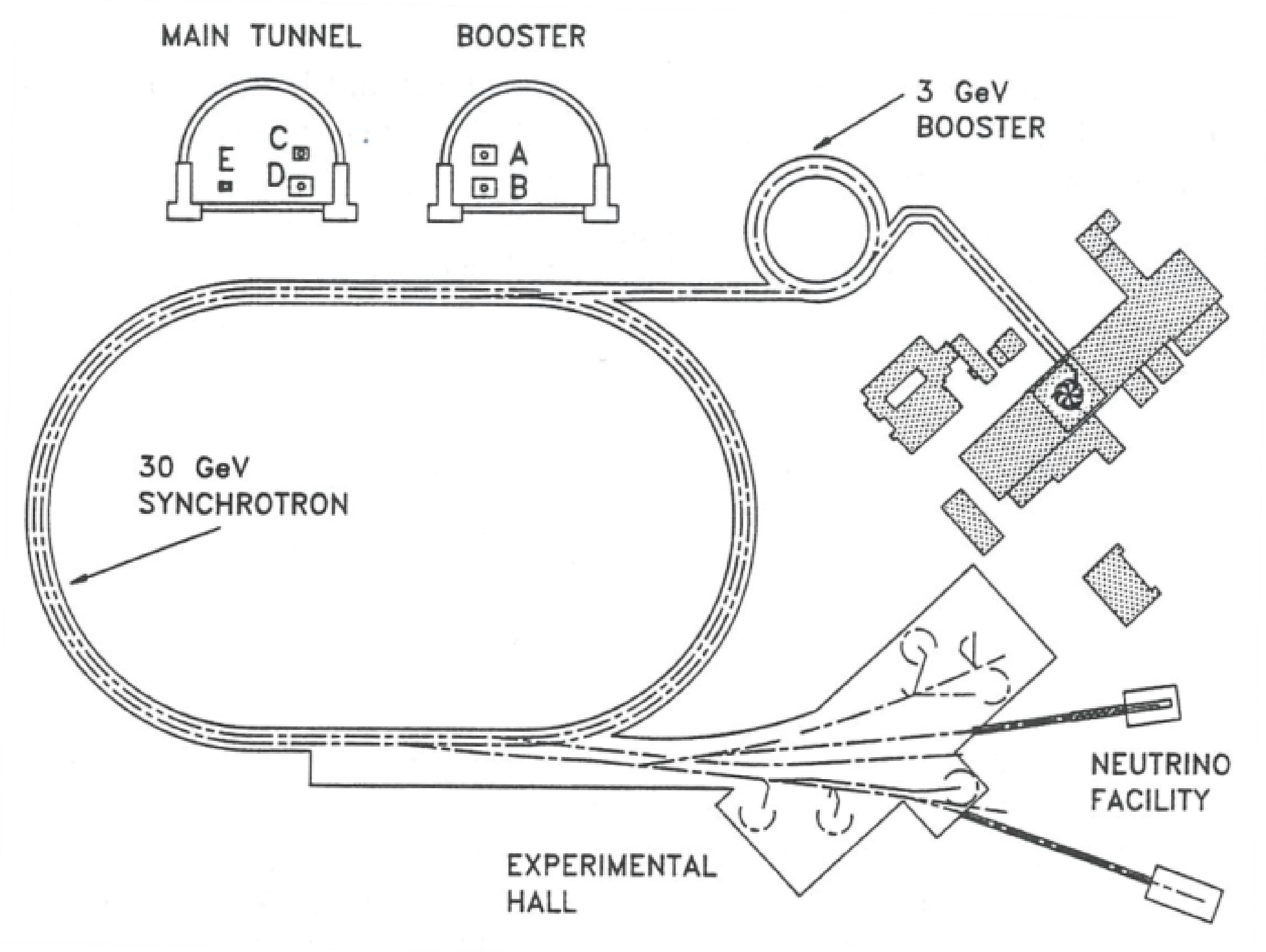




TRIUMF

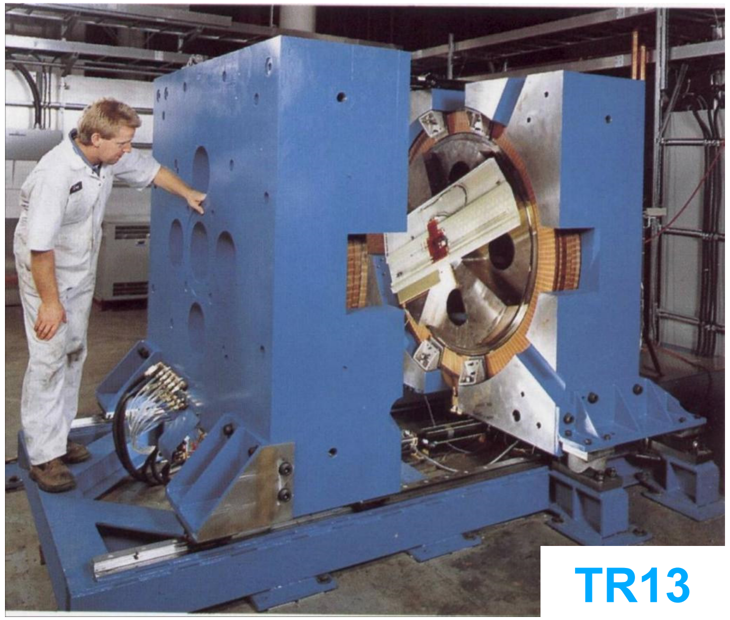
KAON Factory (1980-1994)

- TRIUMF developed a proposal for the KAON Factory –the TRIUMF cyclotron would inject into a set of rings to produce 100μA, 30 GeV protons
- Important for accelerator and beam physics development but ultimately the proposal was rejected in 1994
- Realized finally as J-Parc in Japan



Medical cyclotrons development (1988-1993)

- TRIUMF collaborated with EBCO (now ACSI) on the design of industrial cyclotrons for medical isotope production
- This led to the TR30 (30MeV H- cyclotron at 1mA) and the TR13/18 PET isotope machine – two TR30s and one TR13 are presently operated at TRIUMF for isotope production
- ACSI has gone on to develop other variants based on the original designs for the world market



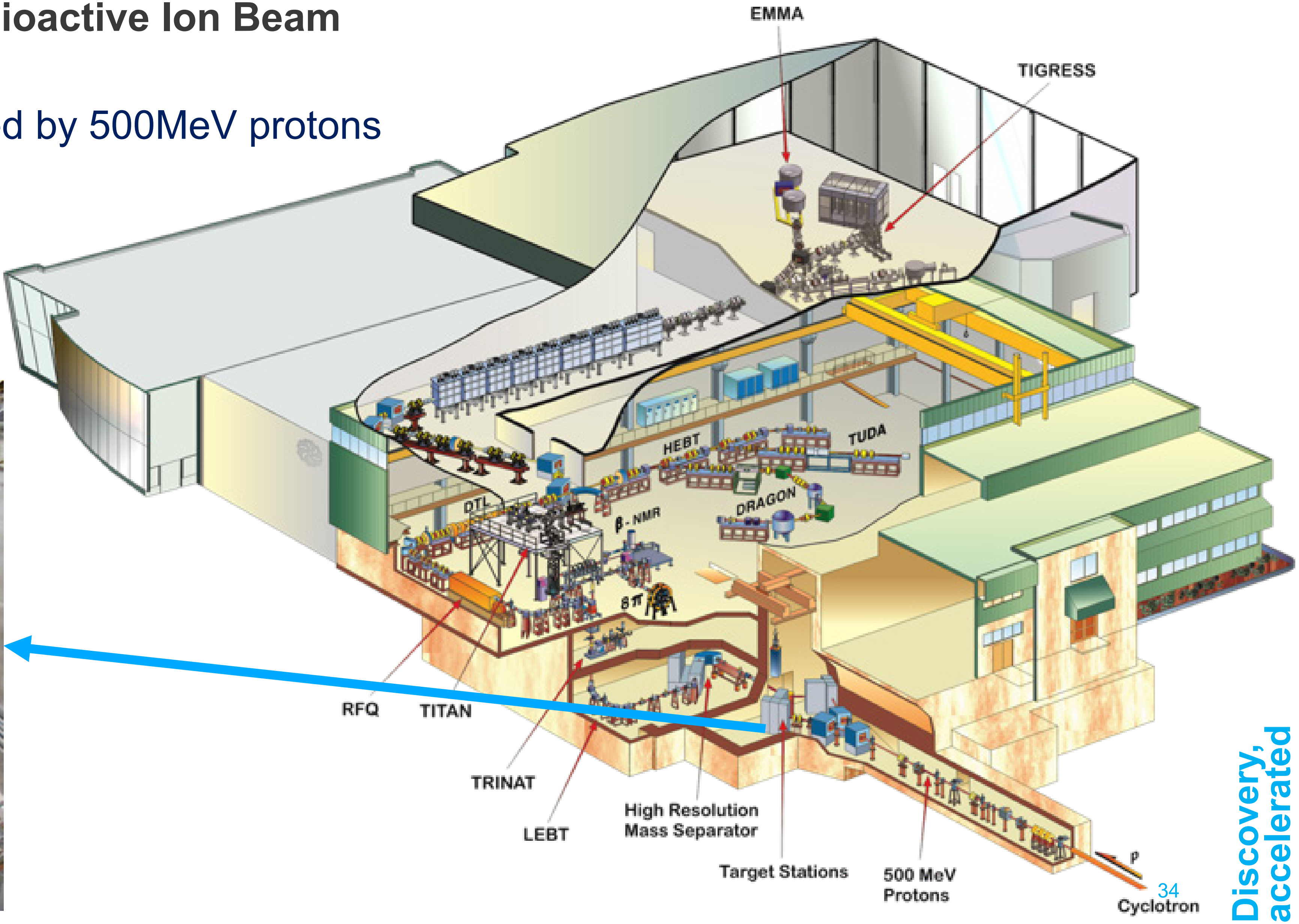
TR13

TR30 installed at TRIUMF

ISAC - The North American ISOL Facility (1996-   )

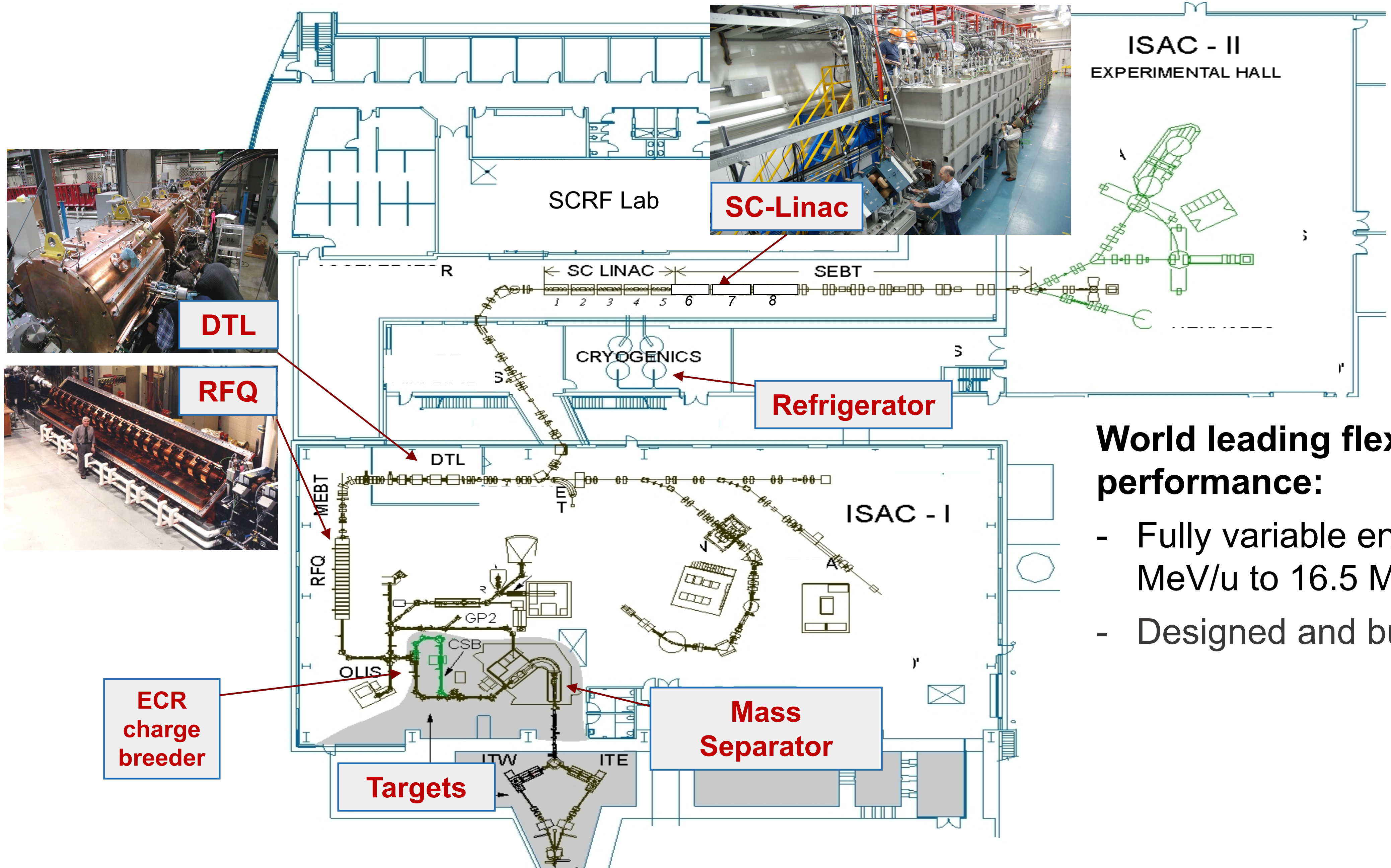
ISAC is at the forefront of Radioactive Ion Beam (RIB) science since 1996

- Two target stations bombarded by 500MeV protons (up to 50kW)
- > 3000 h of RIB beam/year



Discovery, accelerated

ISAC RIB – Post accelerators



World leading flexibility and performance:

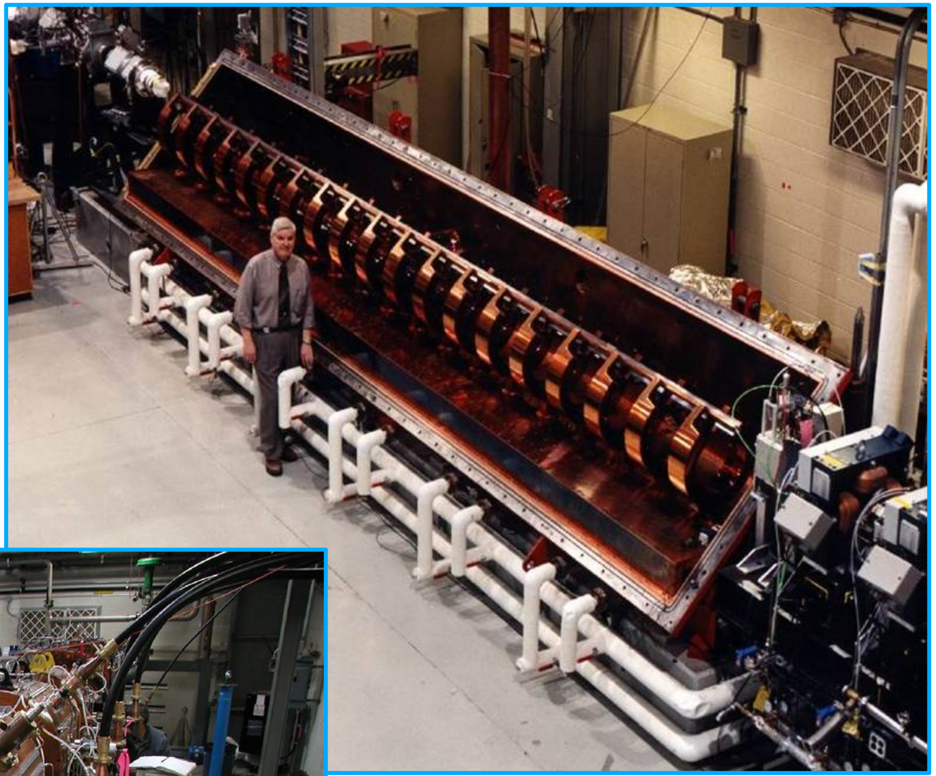
- Fully variable energy from 0.15 MeV/u to 16.5 MeV/u
- Designed and built in house

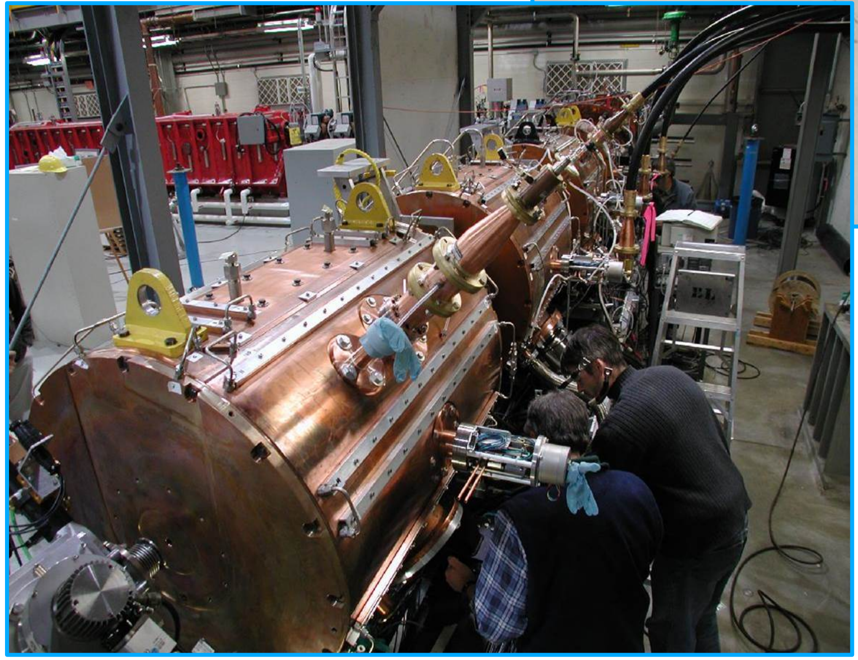
ISAC-I Post Accelerators (Commissioned in 2001)

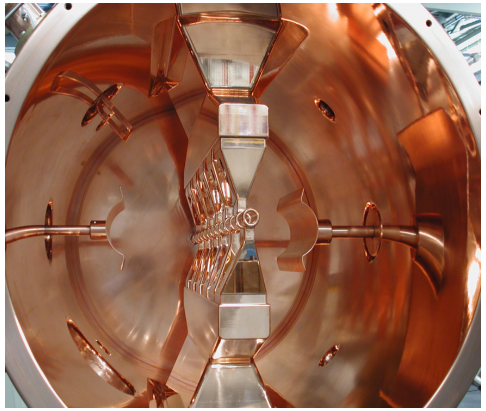
ISAC accelerators – room temperature cw RFQ and DTL

- Fully variable in energy from 0.15 to 1.8MeV/u with high beam quality
- **RFQ** 35 MHz (split-ring structure) -> A/q ≤ 30 → E=150 keV/u
- **DTL** 106MHz (IH structure) -> A/q ≤ 6 → 0.15 ≤ E ≤ 1.8 MeV/u

- **ECR** and EBIS (CANREB) charge breeders for accelerating A>30
- Diagnostics specialized for low intensity heavy ions (100 pps -> 10^8 pps)







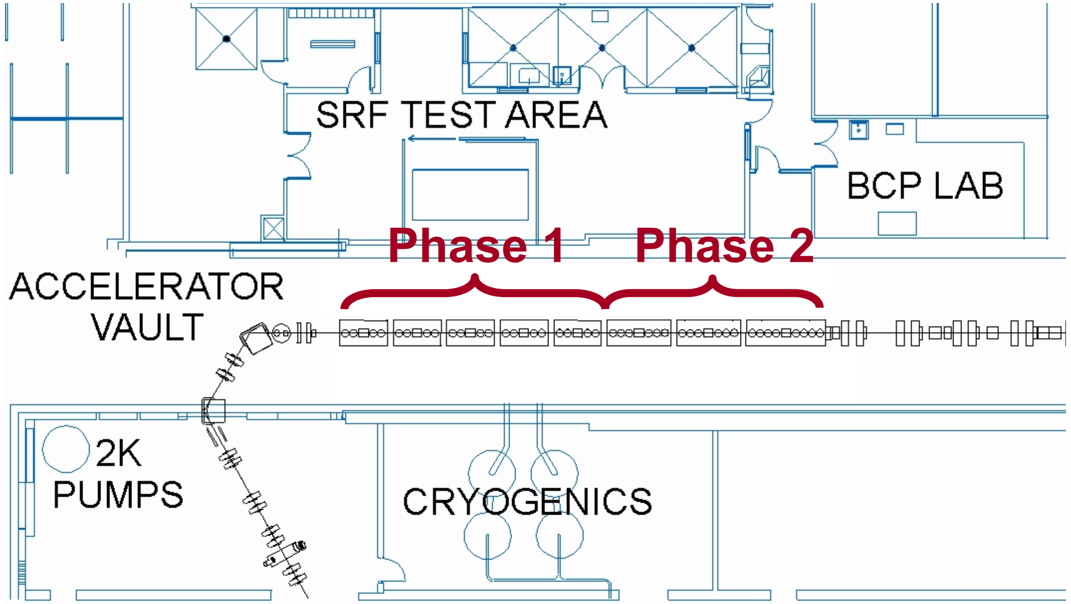
ISAC-II Post Accelerator (commissioned in 2006, 2010)

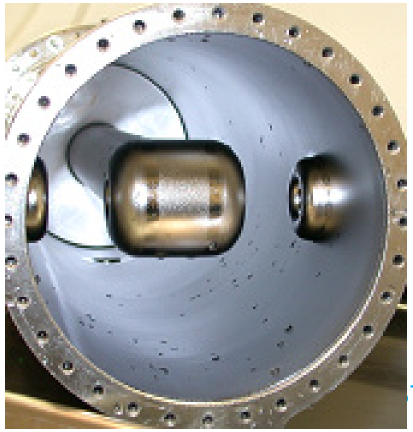
ISAC-II accelerator – superconducting cw quarter wave resonators linac

- Phase I – 20 MV added in 2006
- Phase 2 – 20 MV added in 2010
- Provides 0-40MV with high beam quality

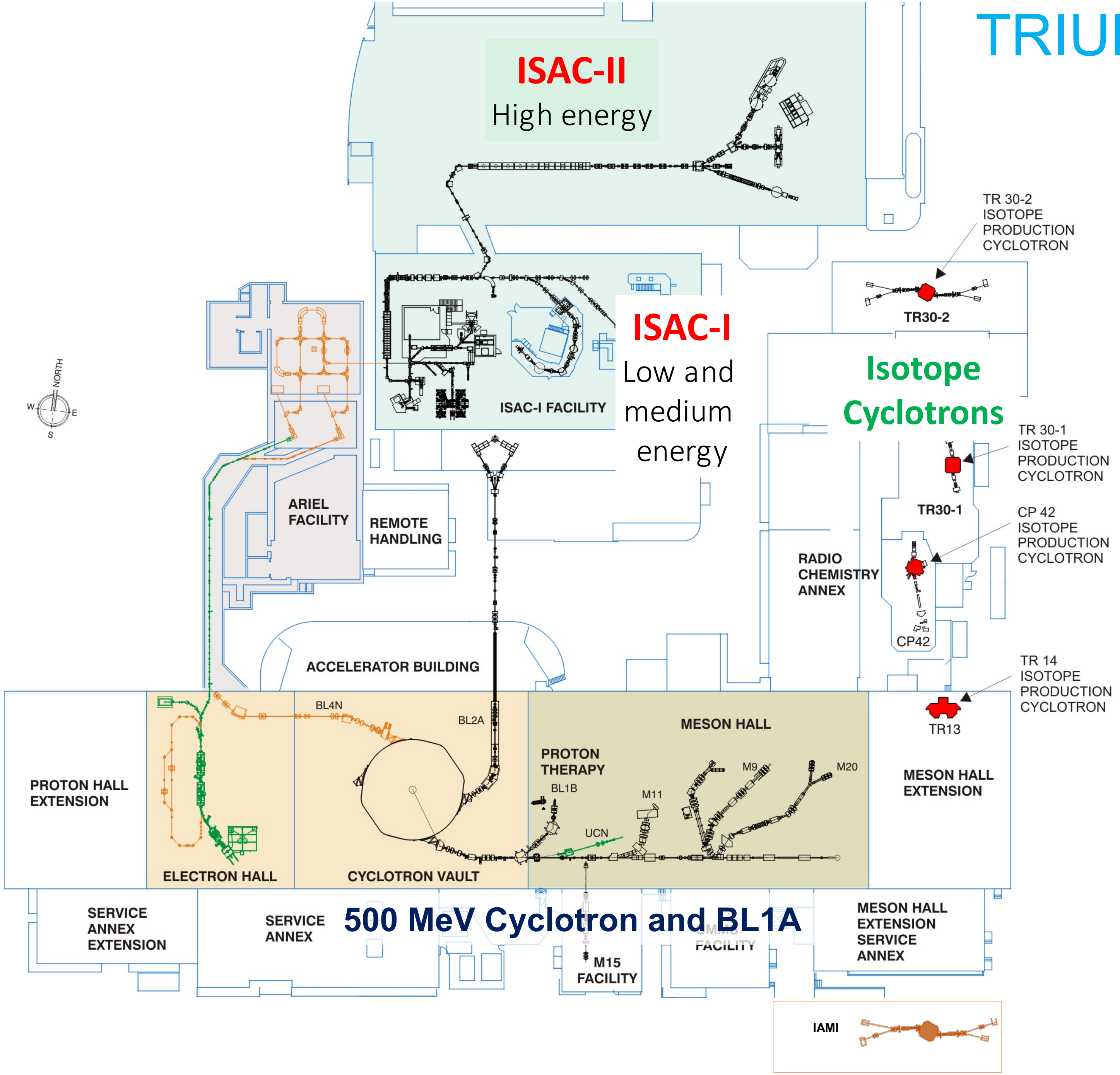
  $A/q=6 \rightarrow E \leq 6$ MeV/u

  $A/q=3 \rightarrow E \leq 15$ MeV/u



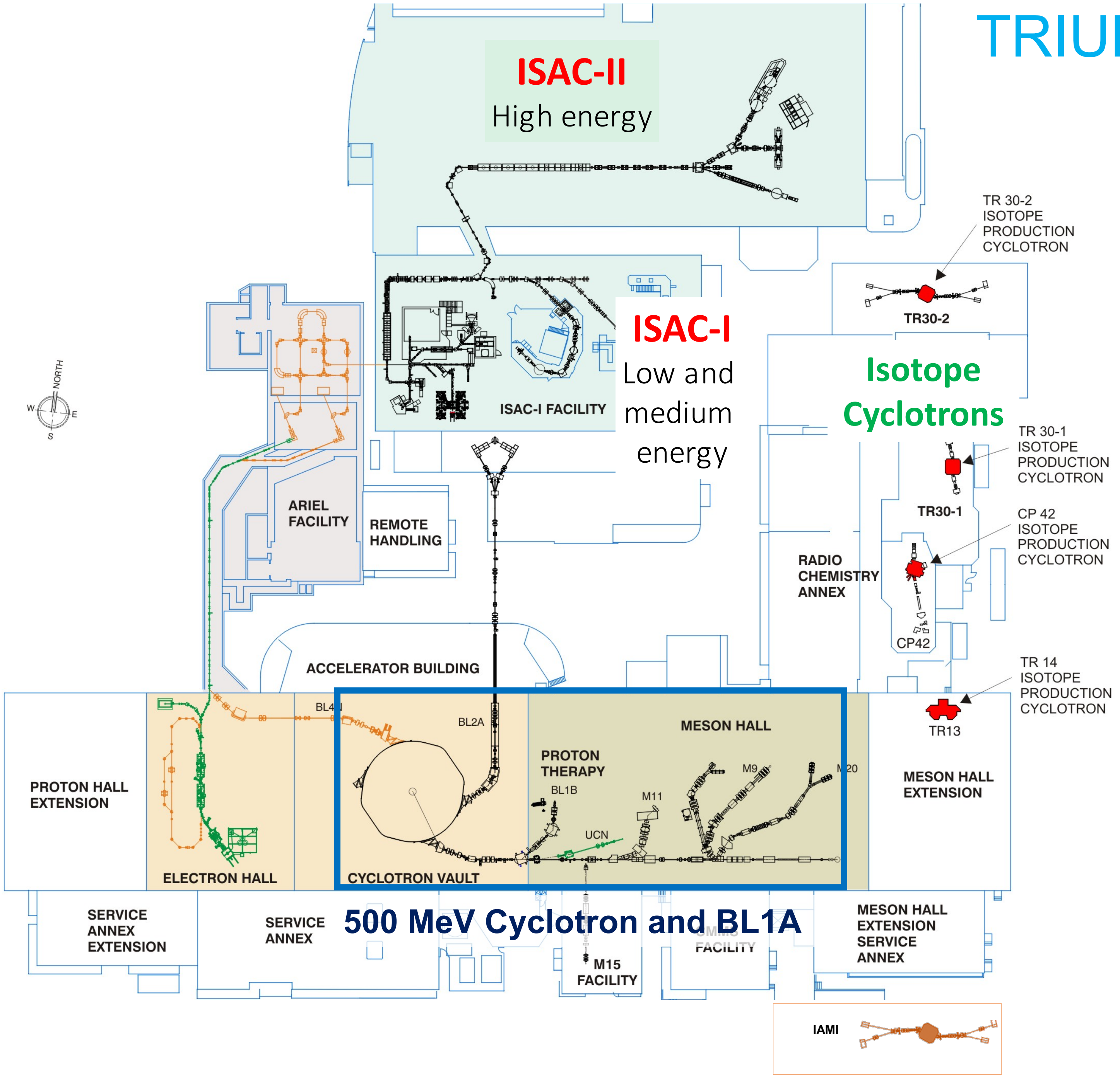


TRIUMF accelerator complex today



Discovery, accelerated

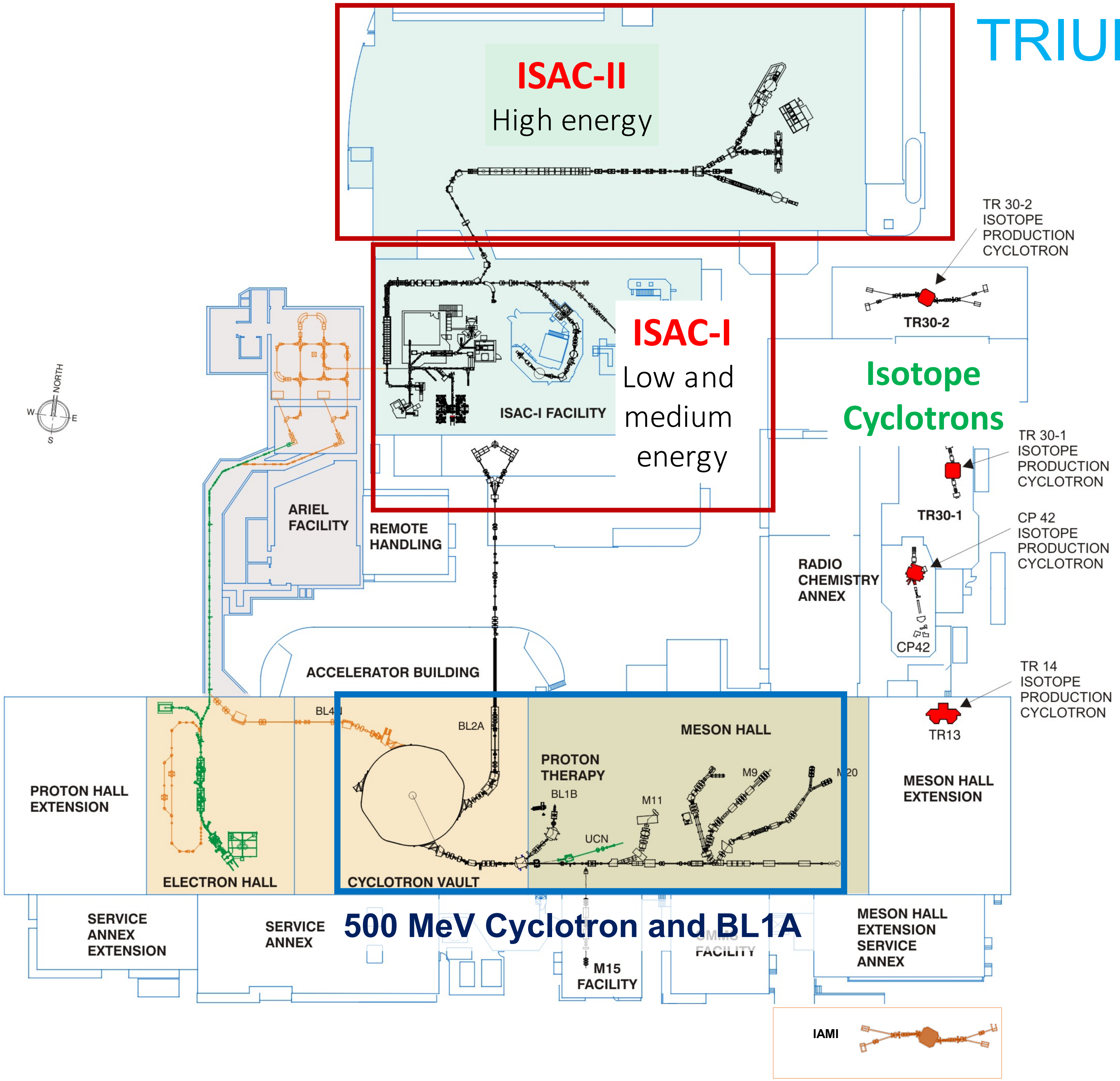
TRIUMF accelerator complex today



Primary beam driver (1974):

500 MeV Cyclotron, 300 μA, H^-
Produces rare isotopes, neutrons and muons

TRIUMF accelerator complex today



Primary beam driver (1974):

500 MeV Cyclotron, 300 μA, H^-

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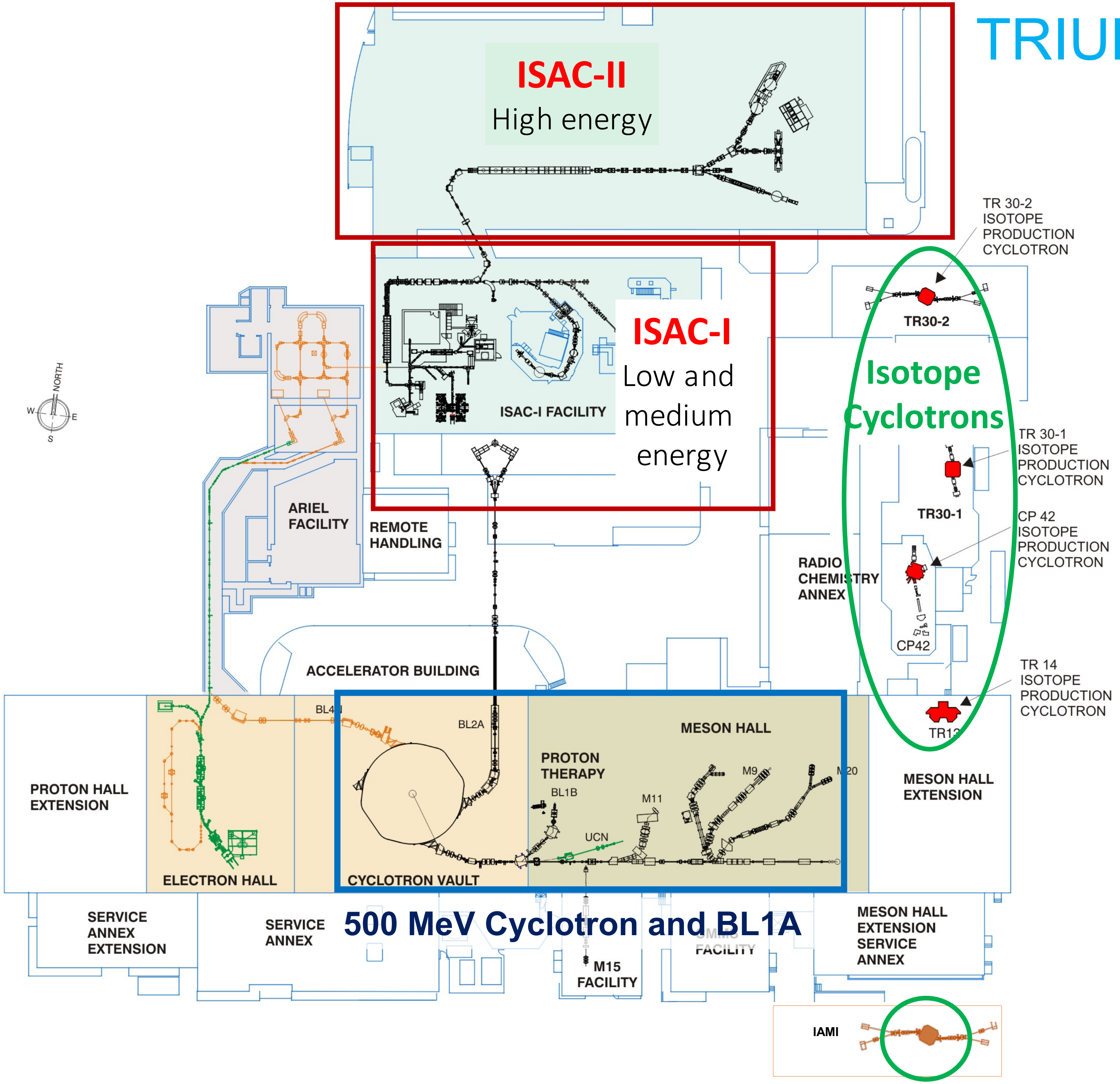
Isotope Separator and Accelerator facility – ISAC (1996)

- ISAC-I: Normal conducting-linac
  - 0.15-1.8 MeV/u (2000)
- ISAC-II: Superconducting-linac
  - 1.5-16.5 MeV/u (2006)

TRIUMF accelerator complex today



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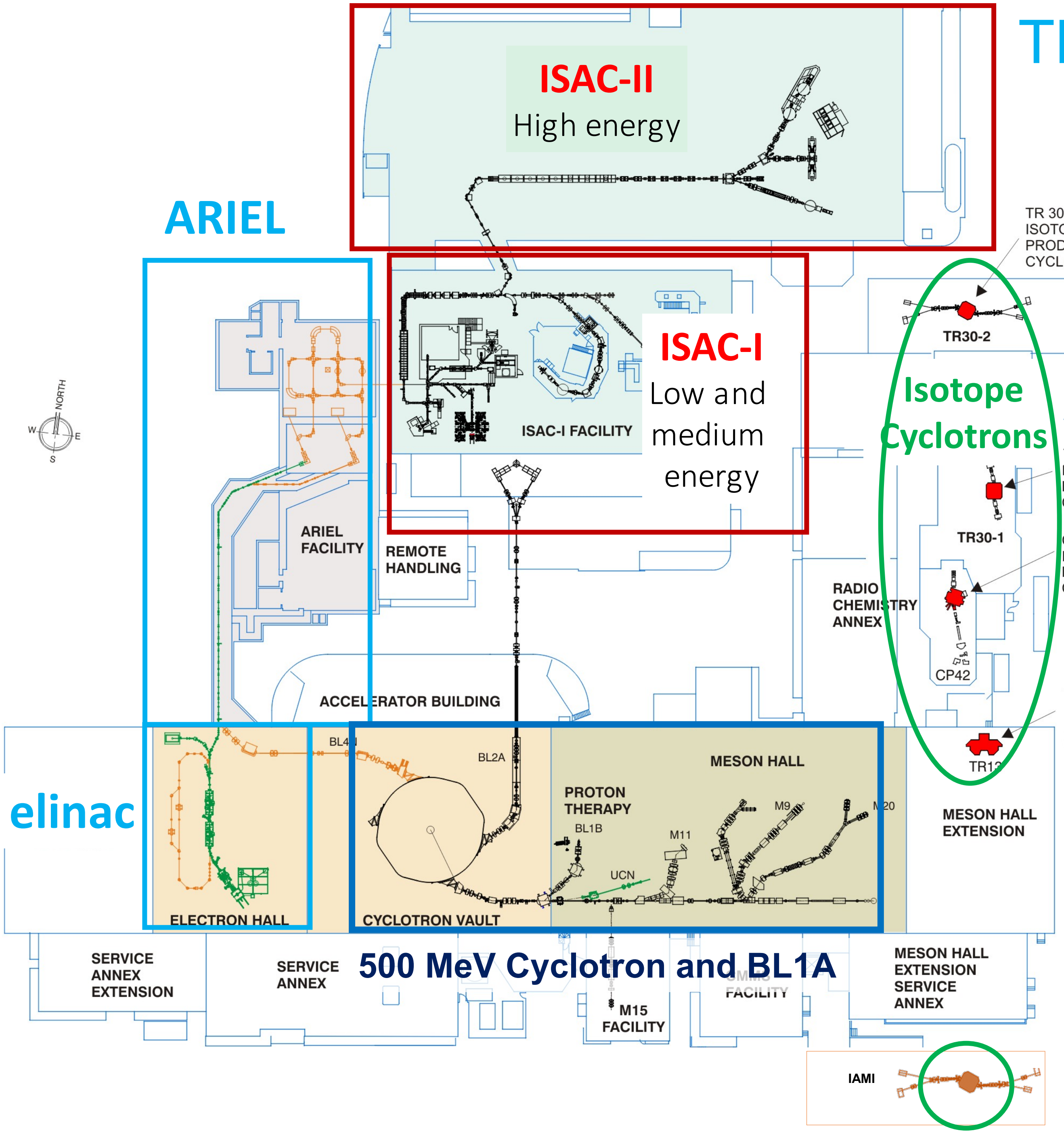
4 (+1) Cyclotrons for medical isotope production – TR30 and TR13 designed by TRIUMF (1990)

TRIUMF accelerator complex today



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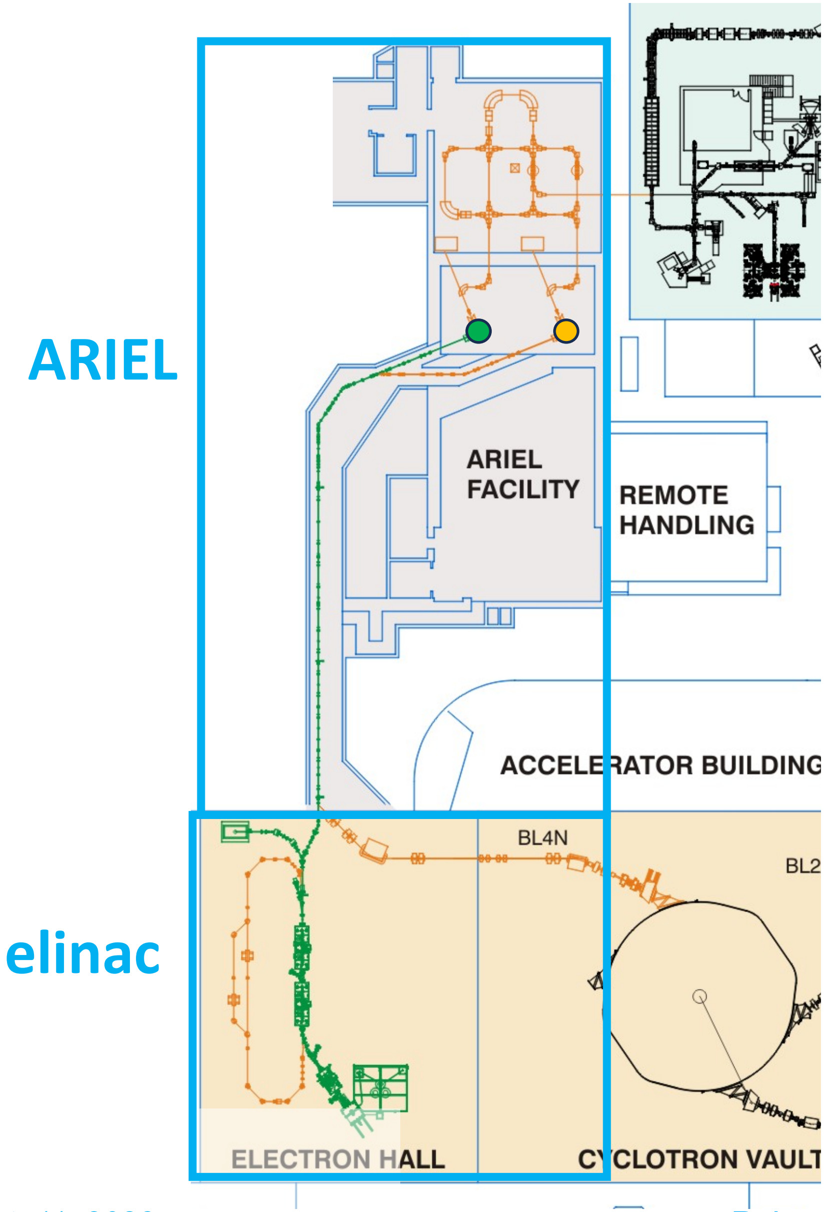
4 (+1) Cyclotrons for medical isotope production – TR30 and TR13 designed by TRIUMF (1990)

Advanced Rare Isotope Laboratory – ARIEL (in progress)

- Superconducting electron linac
  - 30 MeV, 10 mA, cw (2021)

Advanced Rare IsotopE Laboratory (2010-present)

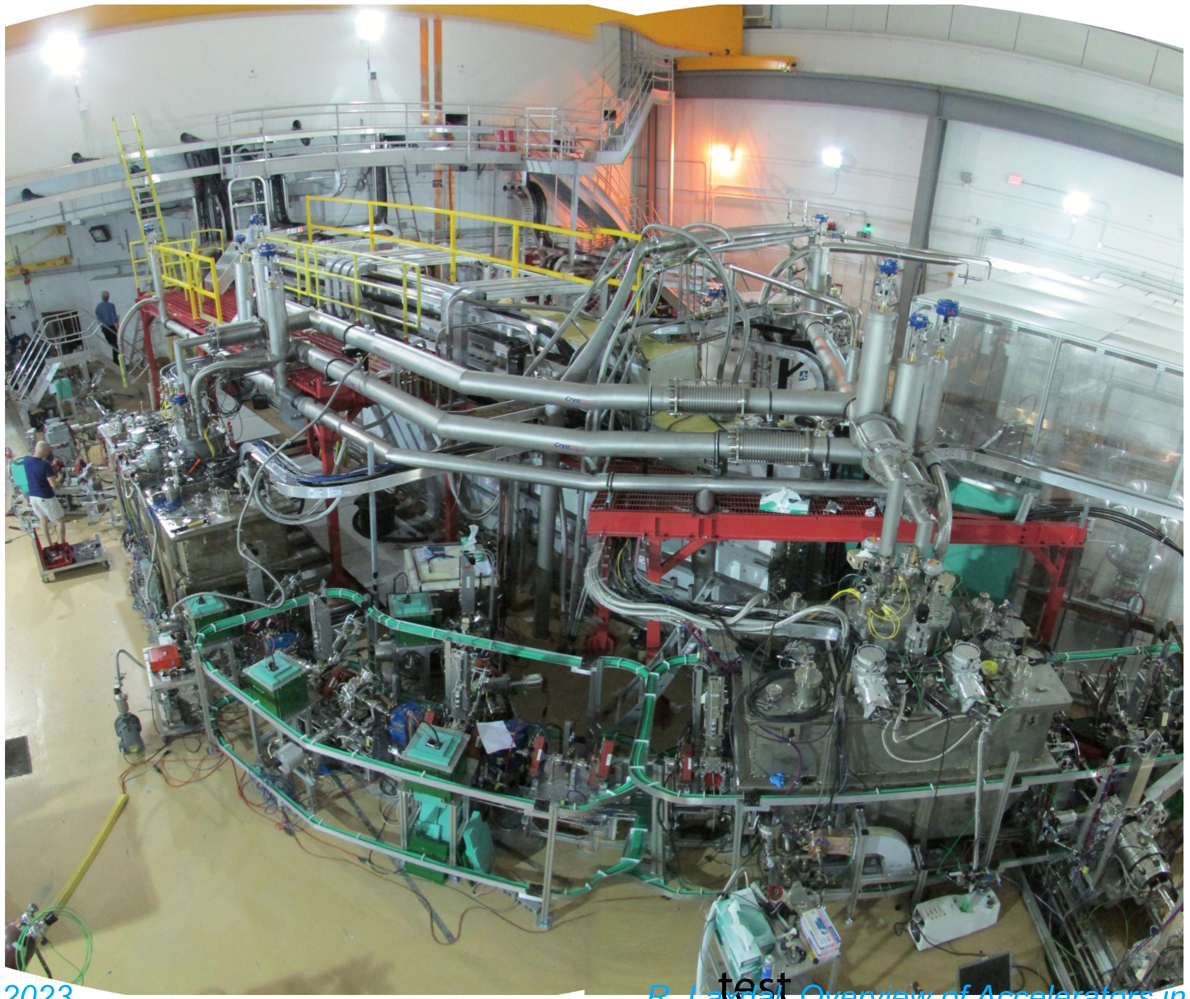


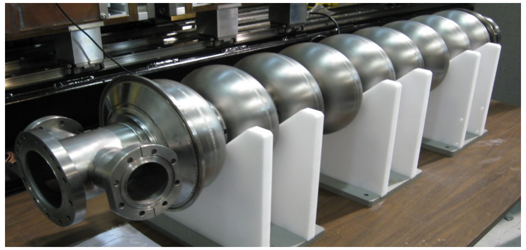
ARIEL objectives

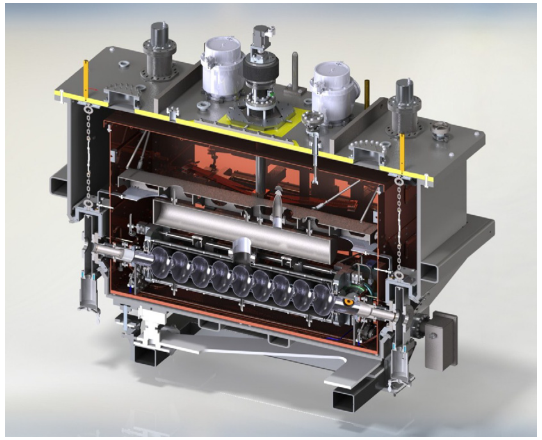
- **Two** new RIB production target stations,
  - **50 kW protons**
  - **100 kW electrons**
- Multi-user operation with up to **three** simultaneous isotope beams (**9000** RIB hours)
- Efficient/pure RIB acceleration: **EBIS** Charge State Breeder and **1/20,000 resolution HRS** (high-resolution mass separator).
- Production of **medical isotopes** in proton target station beam dump

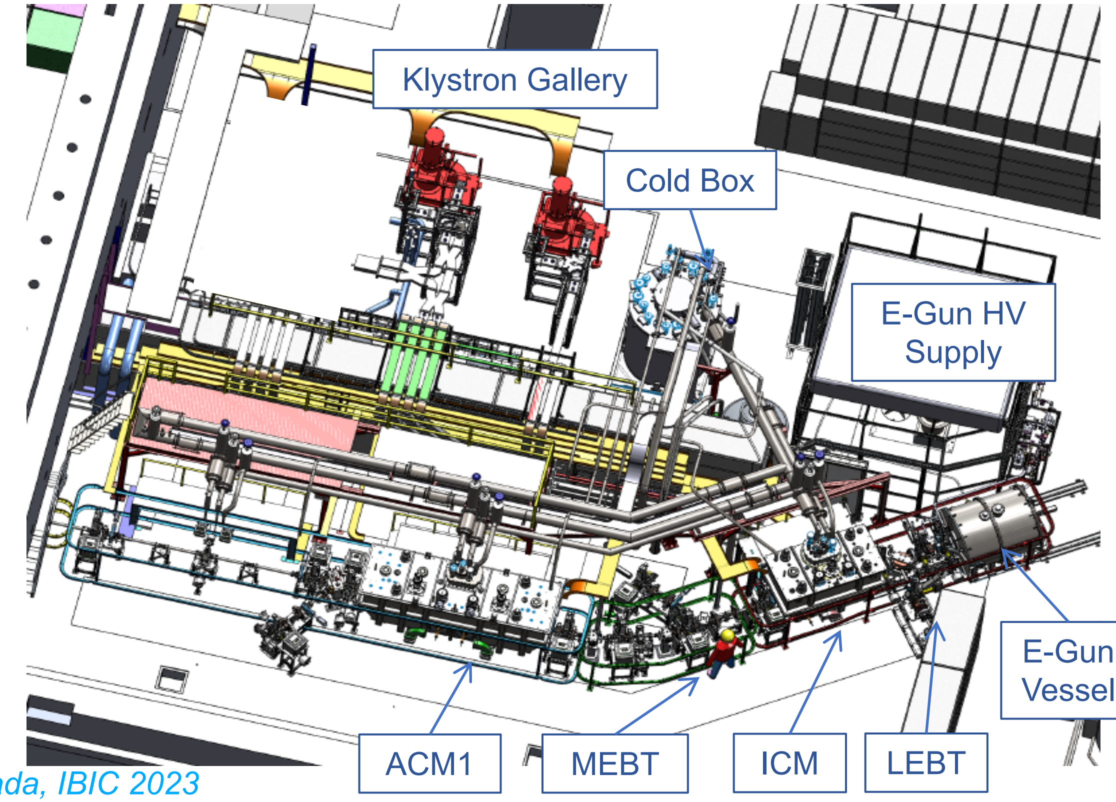
ARIEL superconducting electron linac

- Designed and built at TRIUMF
- 1.3GHz superconducting linac with three nine-cell SRF cavities
- 30 MeV and 300 μA (10kW) beam established in 2021





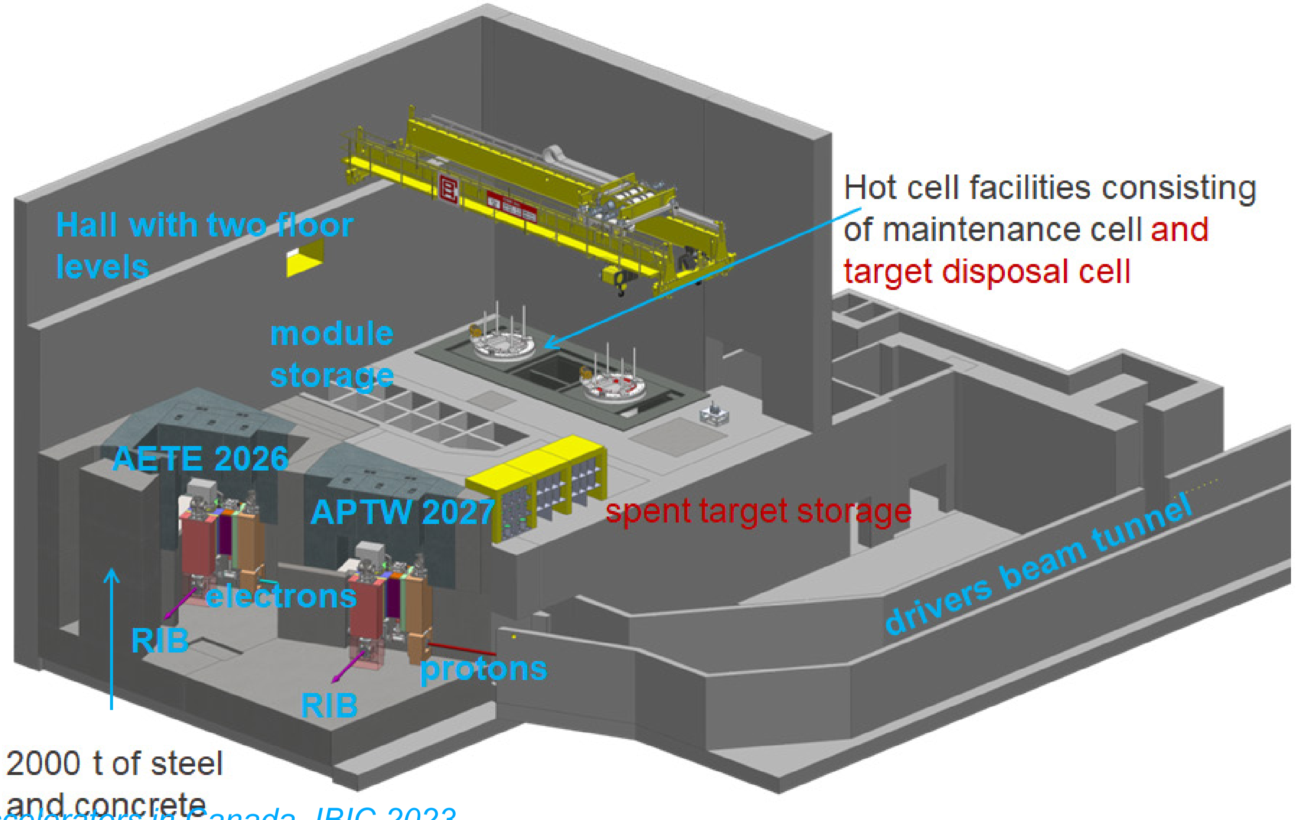




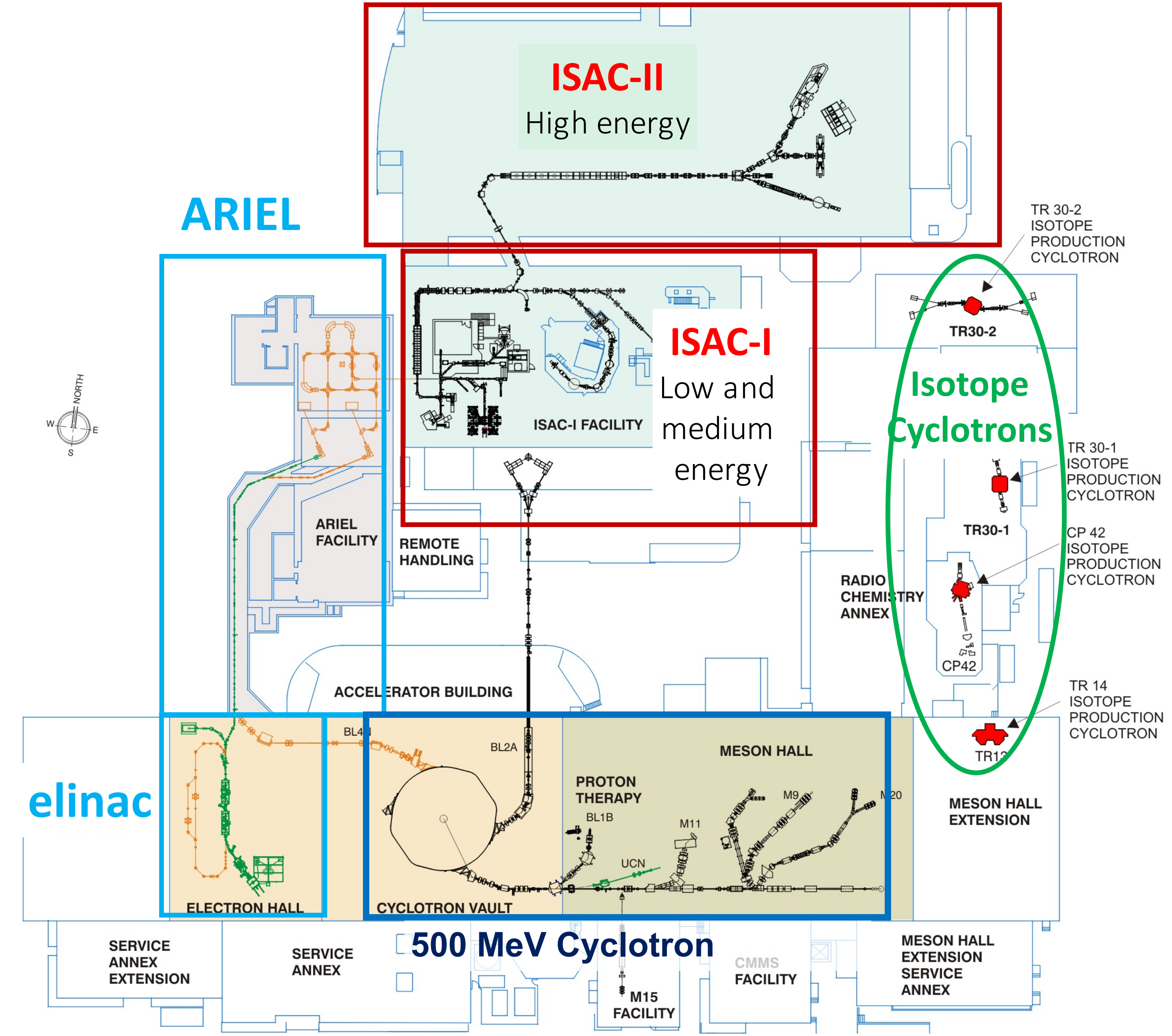
ARIEL completion status and timeline

ARIEL Objectives:

- ✓ ARIEL building complete
- ✓ ARIEL hot cell completed
- ✓ CANREB beamline and equipment installed – EBIS and HRS
- ✓ AETE prototype target module completed and tested
- ✓ BL4N beam extracted into vault
- ✓ E-Linac at 10kW (required day 1 power)
- RIB from AETE to ISAC in 2026
- RIB from APTW to ISAC in 2027
- Medical isotopes in 2028



TRIUMF



Wide variety of accelerator technologies.

- High intensity H- cyclotrons
- Room temperature cw heavy ion linacs
- Superconducting linacs for electrons and hadrons
- High power production targets
- Radioactive ion beam production and acceleration
- Remote handling
- Diagnostics for high intensity protons and electrons and low intensity heavy ions

Accelerator Companies and Users

Canadian accelerator suppliers

- There are also several Canadian companies devoted to either producing turn-key accelerators or parts for the accelerator community
  - ACSI (Vancouver, BC) – Offering high intensity proton cyclotrons from 12-33 MeV
  - Best Cyclotron (Vancouver BC) - six general energy domains for BCS cyclotron systems delivering protons at: 7.5, 9.5, 15, 25, 35 and 70 MeV.
  - Mevex (Stittsville, Ontario) – 5, 7, 10 MeV e-linacs - has built more than 100 accelerators for sterilization, medical applications and research institutes
  - D-Pace (Nelson BC) – supplies accelerator hardware including ion sources, diagnostics, beamlines, magnets, isotope target station

Accelerator applications in Canada

28 cyclotrons installed across Canada primarily for isotope production

- Fedoruk Centre, U. of Sask. Saskatoon
- BC Cancer Agency - Vancouver
- BWXT – Vancouver
- Cross Cancer Institute, Edmonton
- Health Sciences Centre, Winnipeg
- Regional Health Sciences Centre, Thunder Bay
- Hamilton Health Sciences, Hamilton
- Ottawa Heart Institute, Ottawa.
- Lawson Health Research Institute, London
- Toronto General Hospital - Toronto
- Centre for Addiction and Mental Health, Toronto.
- Montreal Neurological Institute, Montreal
- University of Sherbrooke Hospital, Sherbrooke
- Pharmalogic, Montreal

Image from Fedoruk Centre, Saskatoon

Linac based isotope production

- Canadian Isotope Innovations – Saskatoon – Cu-67, Mo-99/Tc-99m

Summary

- The 20th century post war years saw a rapid growth in accelerator installations across Canada primarily driven by the interest in nuclear physics and radiation therapy
- Significant ground-breaking work was done at AECL Chalk River
- Two centres presently exist for accelerator-based science – TRIUMF and CLS
- A host of smaller facilities dot the landscape primarily for medical and industrial applications supported by Canadian industry

References and Acknowledgements

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Thanks to Tonia Batten for slides from CLS!

TRIUMF

Thank you,
Merci

Discovery,
accelerated