TRIUMF

Canada's National Laboratory for
Particle and Nuclear Physics

Capabilities of ARIEL

Adam Garnsworthy
Principal Scientist for ARIEL,
Research Scientist, TRIUMF

July 18th 2018

ARIEL Science Workshop 2018
TRIUMF

TRIUMF Main cyclotron

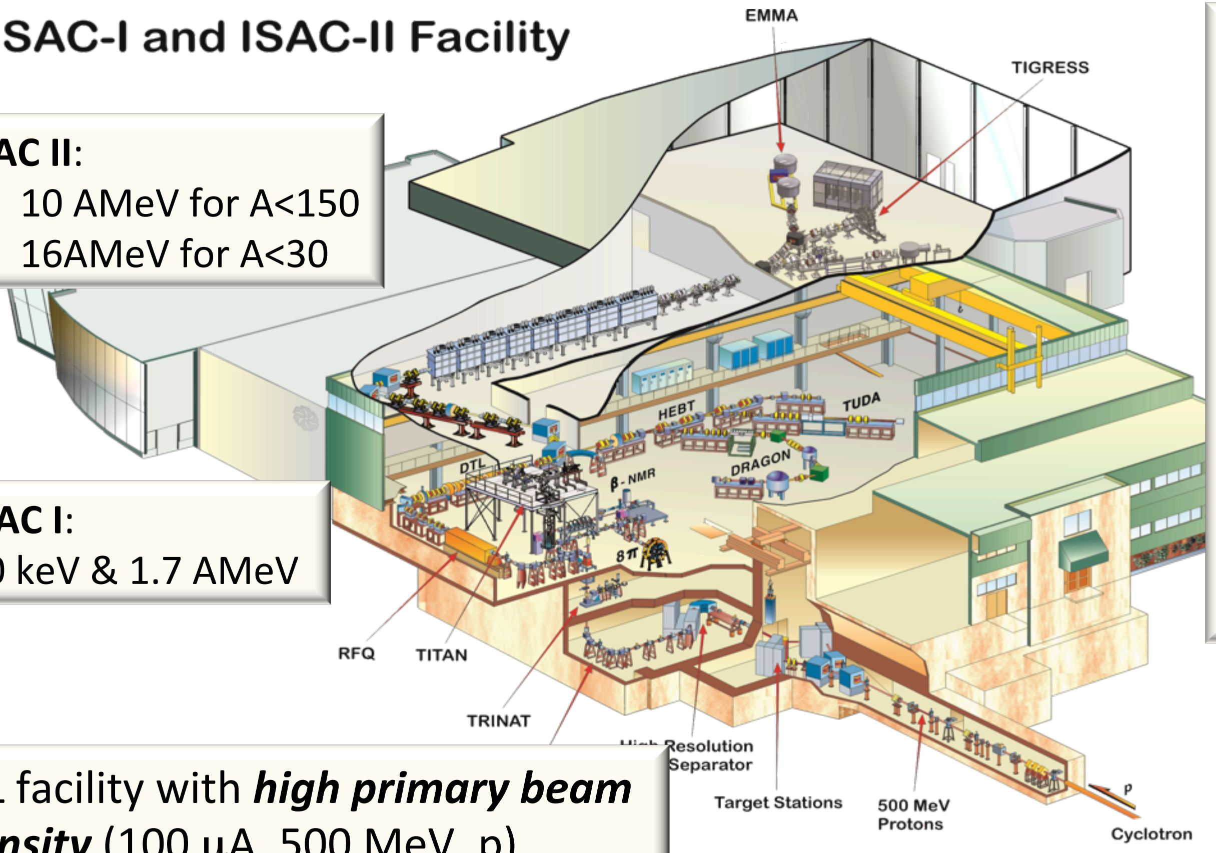
18m diameter cyclotron producing 520MeV proton beams to 4 beamlines.
First beam was extracted on 15th December 1974.

ISAC rare isotope facility

ISAC II:
- ➢ 10 AMeV for A<150
- ➢ 16AMeV for A<30

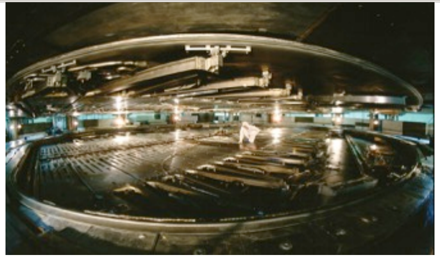
ISAC I:
60 keV & 1.7 AMeV

ISAC-I and ISAC-II Facility



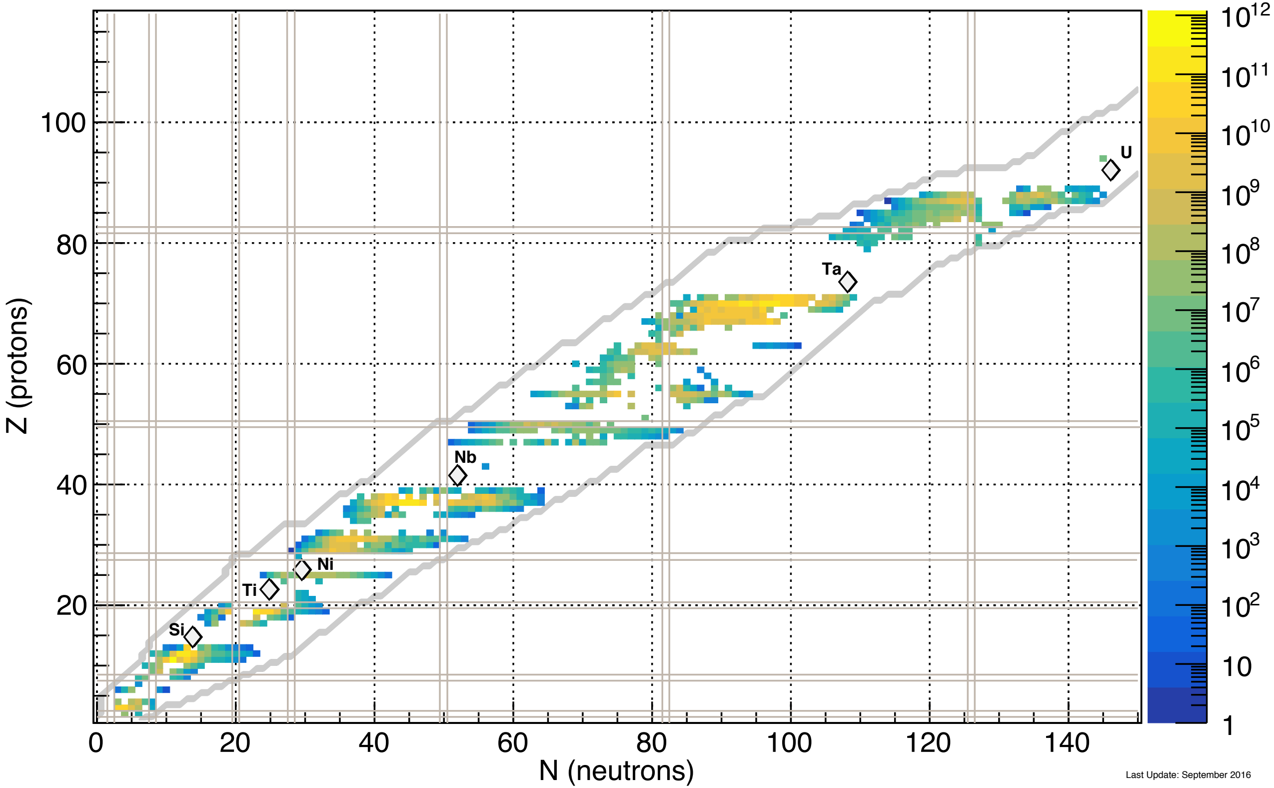
ISOL facility with ***high primary beam intensity*** (100 μA, 500 MeV, p)
Delivering RIBs since 1999.

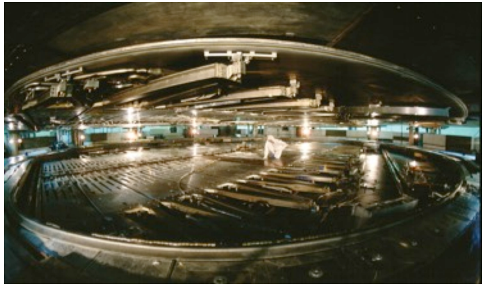
Programs in
- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science
- 18 permanent experiments



ISAC rare isotope facility

Isotopes delivered at ISAC (Updated Sept 2016)





Target materials:
SiC, TiC, NiO, Nb, ZrC, Ta, TaC, ThO, UC, UO

Ion sources:
Surface, TRILIS, FEBIAD, IG-LIS

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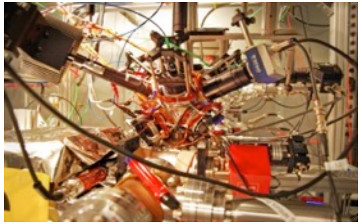
ISAC experimental areas

Low energy RIBs
< 60 keV

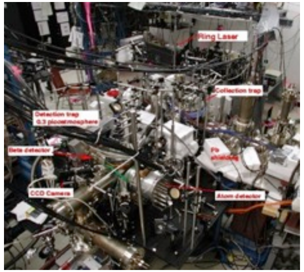
FRANCIUM MOT

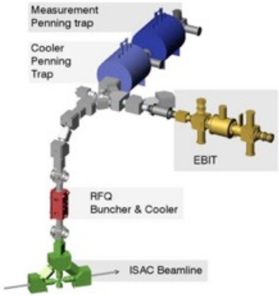
(PNC, anapole moment)



TRINAT

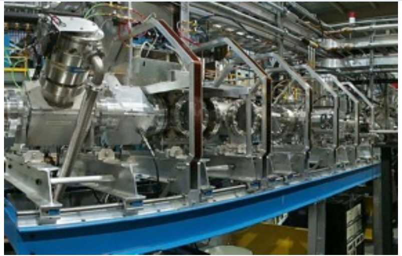
Neutral Atom Trap
(βν–neutrino correlations)





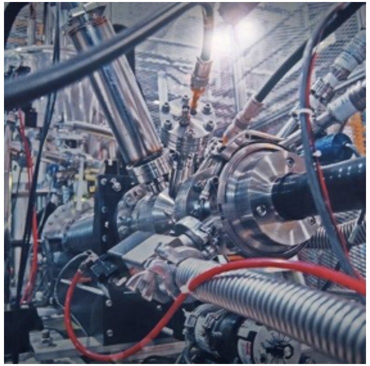
TITAN

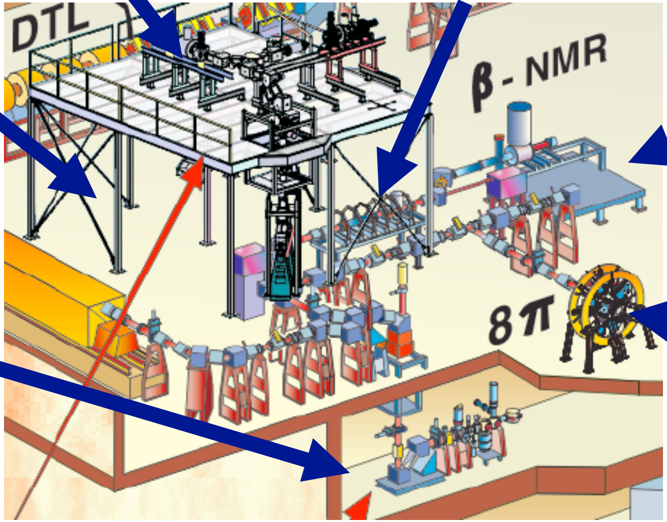
Penning Traps
(masses,
in–trap decay)



Polarizer beamline

Laser spectroscopy, MTV
CPT test, betaNMR



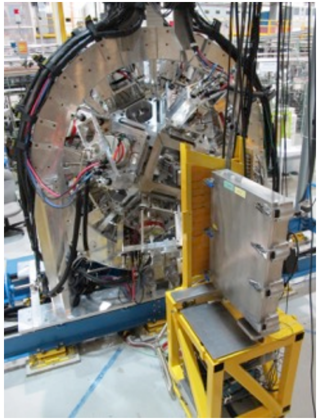


Beta–NMR

Material science

GRIFFIN

Gamma & Electron spectrometer
(decay spectroscopy, superallowed decays)

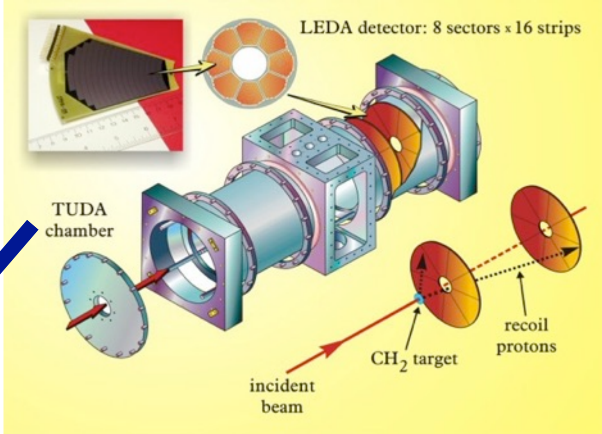


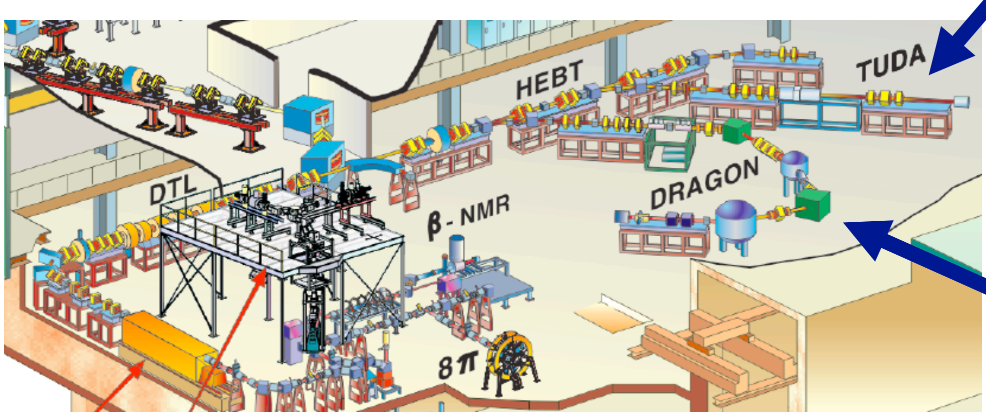
ISAC experimental areas

Medium energy RIBs
~ 0.15 -1.7 AMeV

TUDA

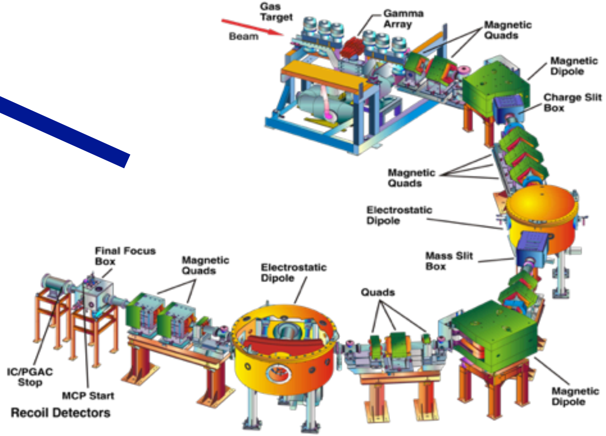
Astrophysical charged particle reactions





DRAGON

Astrophysical capture reactions

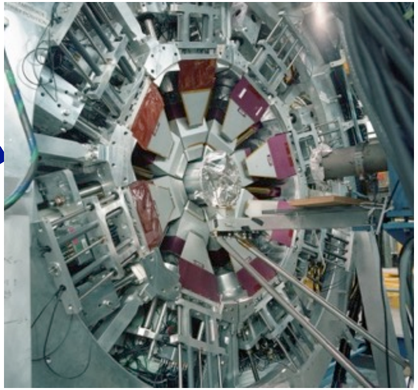


ISAC experimental areas

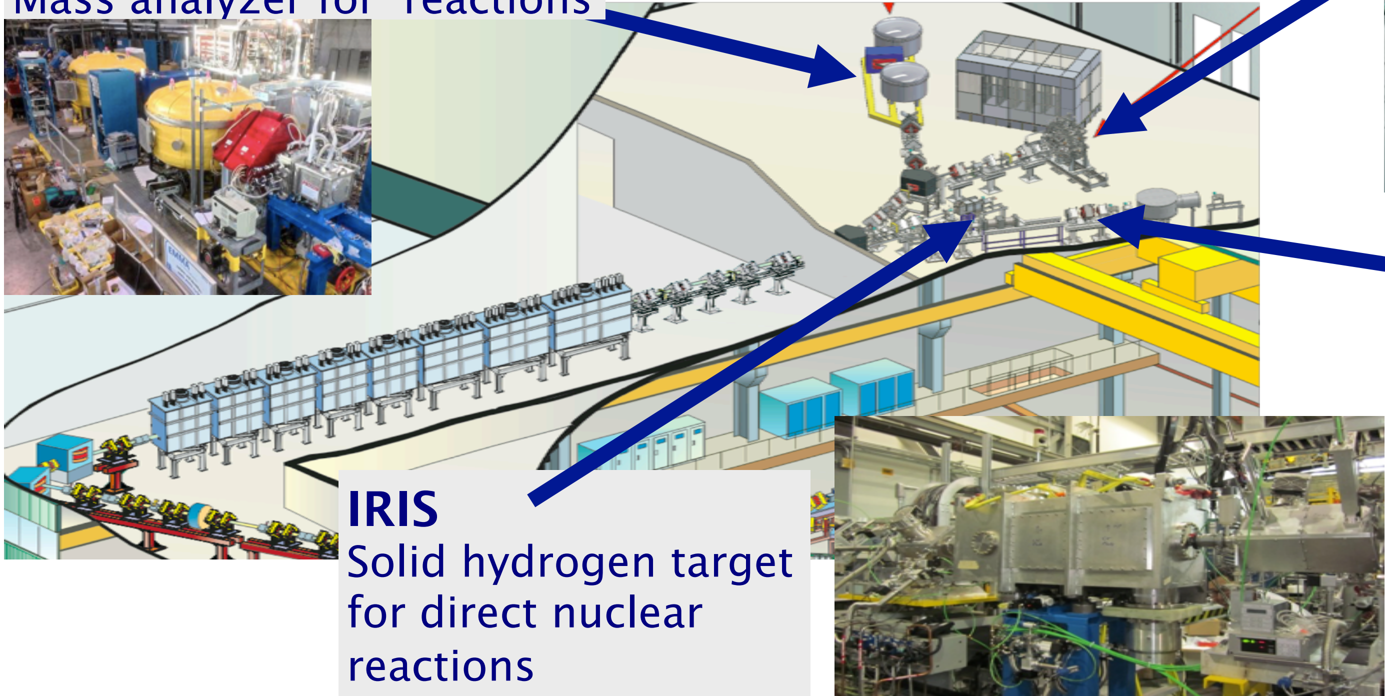
High-energy RIBs
> 6 AMeV

TIGRESS + auxiliary detectors

HPGe ɣ-ray spectrometer
in-beam spectroscopy of nuclear reactions

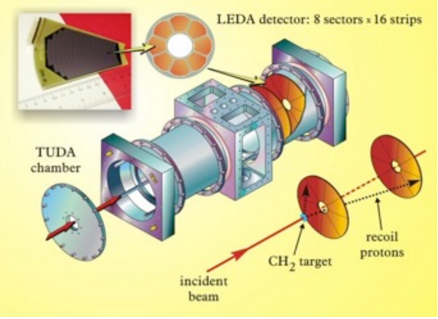


EMMA (2016)
Mass analyzer for reactions



IRIS
Solid hydrogen target for direct nuclear reactions

TUDA
Scattering array for direct reactions



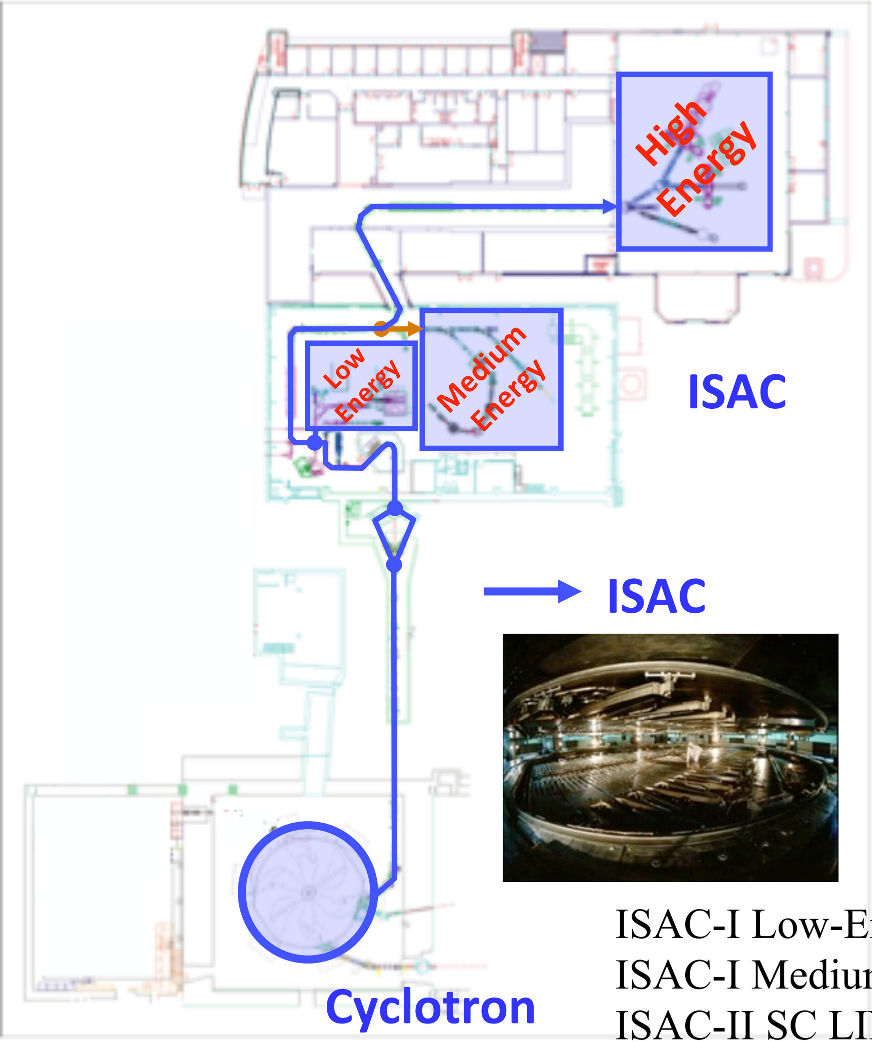
TRIUMF-ISAC

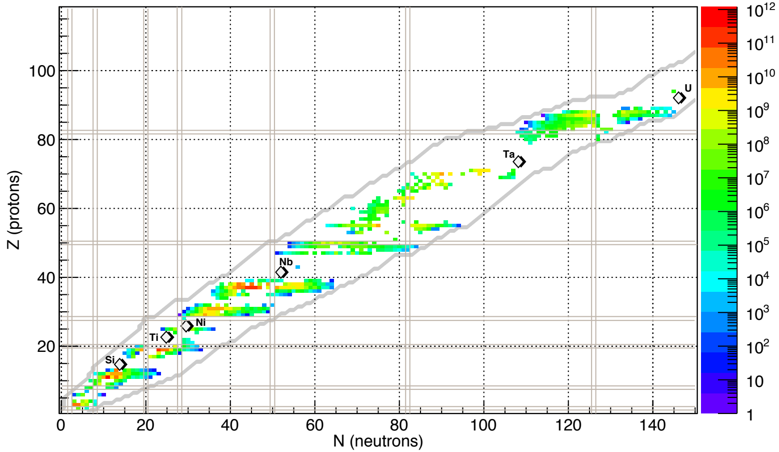
Isotope Separator and ACcelerator

1 RIB delivery to experiments

500MeV p^+ at 100μA on ISOL target

Targets: SiC, TiC, NiO, Nb, ZrC, Ta, TaC, ThO, UO, UCx
Ion sources: Surface, TRILIS, FEBIAD, IG-LIS





ISAC-I Low-Energy	<60keV	Ground state + decay, material science
ISAC-I Medium E	<1.5MeV/u	Astrophysics
ISAC-II SC LINAC	<10MeV/u	Nuclear reactions and structure

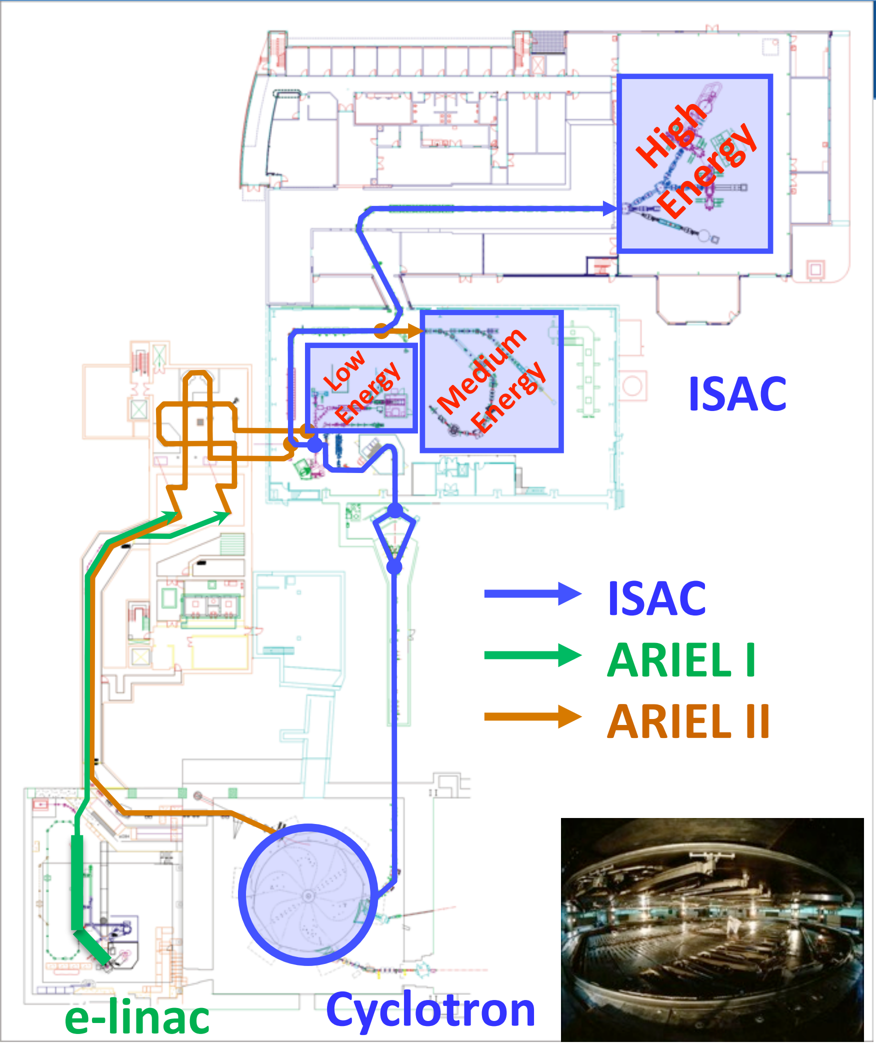
TRIUMF-ARIEL

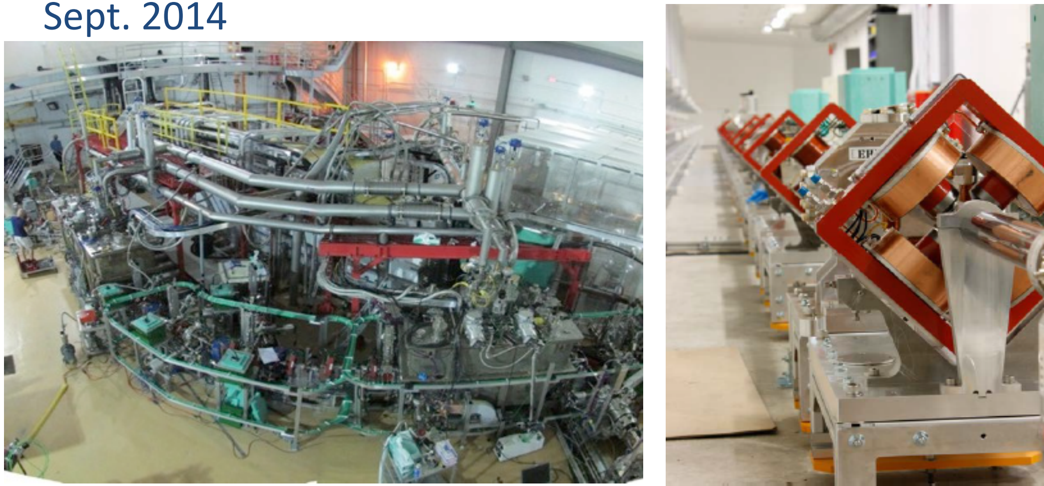
Advanced Rare-IsotopE Laboratory

1 RIB → 3 simultaneous RIBs

ARIEL Project:

- new electron linac driver for photo-fission
- new target stations and front end
- new proton beamline





E-linac and electron beamline
Sept. 2014

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ARIEL: The future of isotopes at TRIUMF

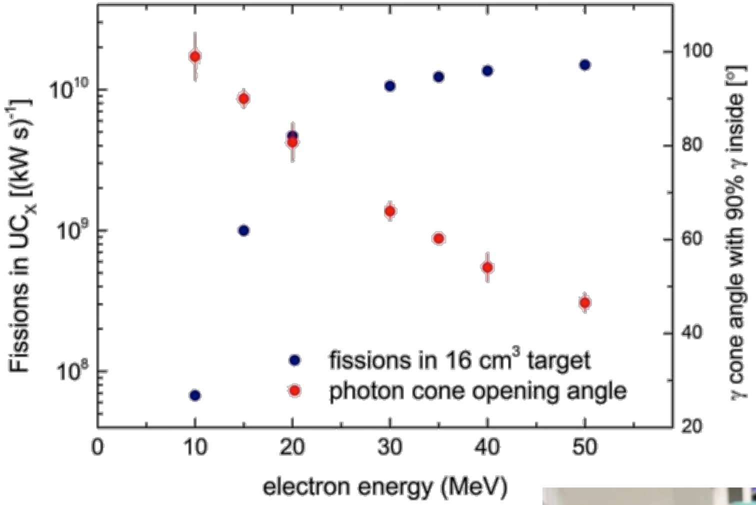
The **A**dvanced **R**are **I**sotop**E** **L**aboratory will triple TRIUMF’s isotope beam capacity

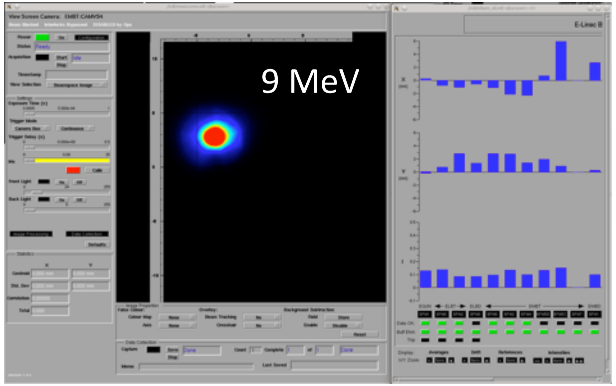
- Uses state-of-the-art, made-in-Canada super-conducting electron linear accelerator technology; targets are designed to allow medical isotopes to be extracted alongside the experimental program
- Represents ~$100 million investment by federal and provincial governments; supported by 19 university partners from across Canada
- Project to occur in two phases:
  - ARIEL-I completed in Fall 2014;
  - ARIEL-II funded by Canada Foundation of Innovation, funding now secured for 2017-2022.
- Will provide more and new isotopes

TRIUMF ARIEL

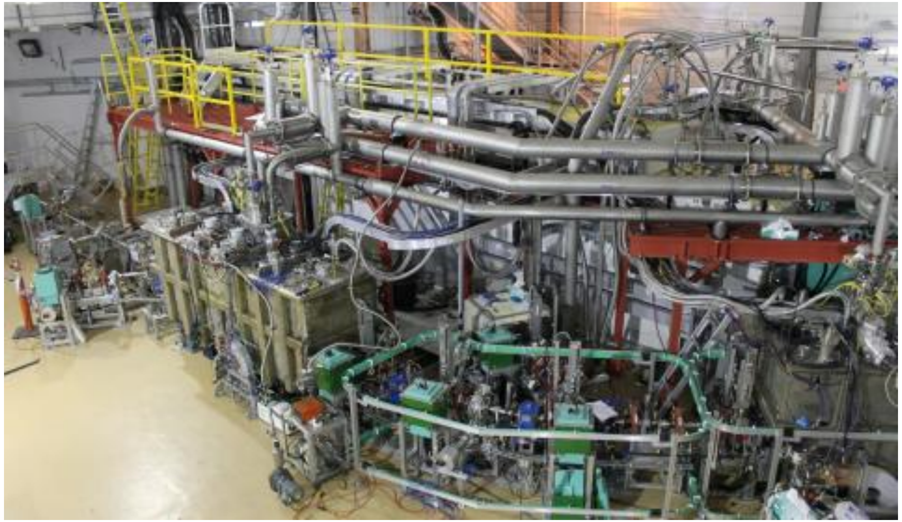
ADVANCED RARE ISOTOPE LABORATORY

New e-LINAC driver for RIB production



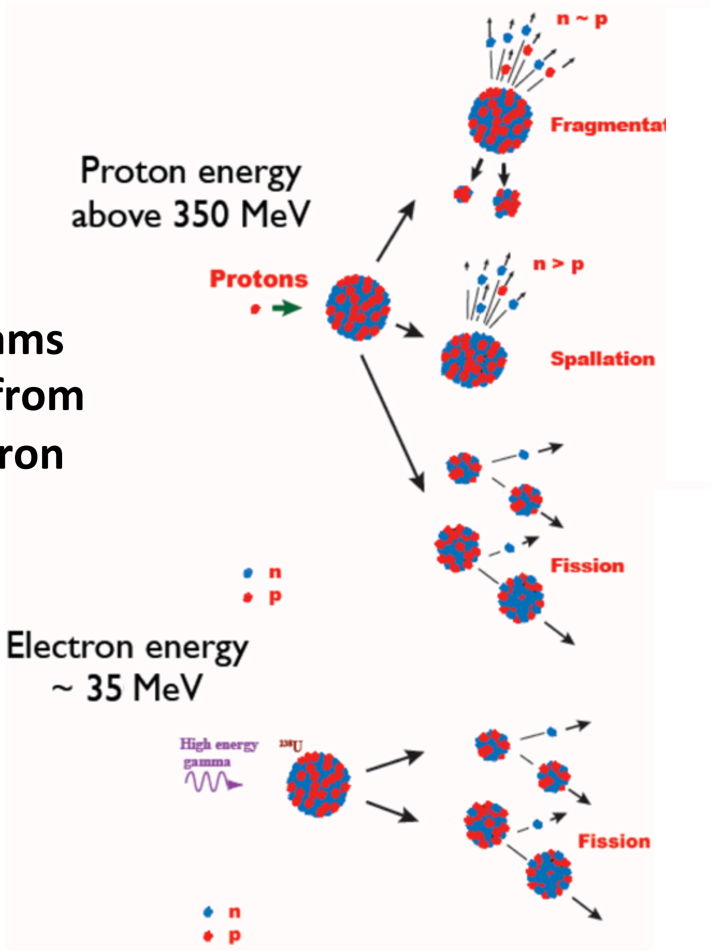


- 650 MHz, 300 keV, electron gun
- superconducting RF, 1.3 GHz, 2 K
- Electron energy ≥ 35 MeV
- Electron beam power ≥ 100 kW



ARIEL rare-isotope beam production

Rare-isotope beams will be produced from proton and electron driver beams.



500MeV Protons on UCx

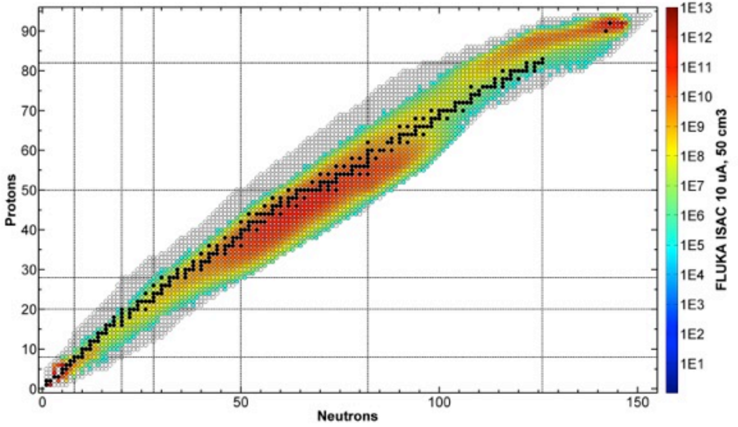
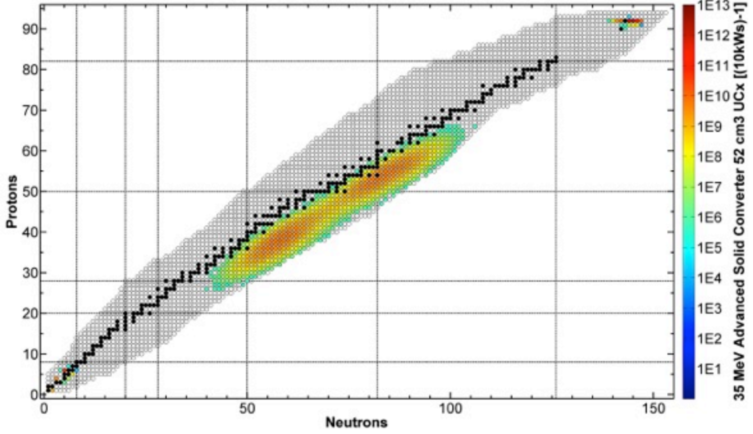
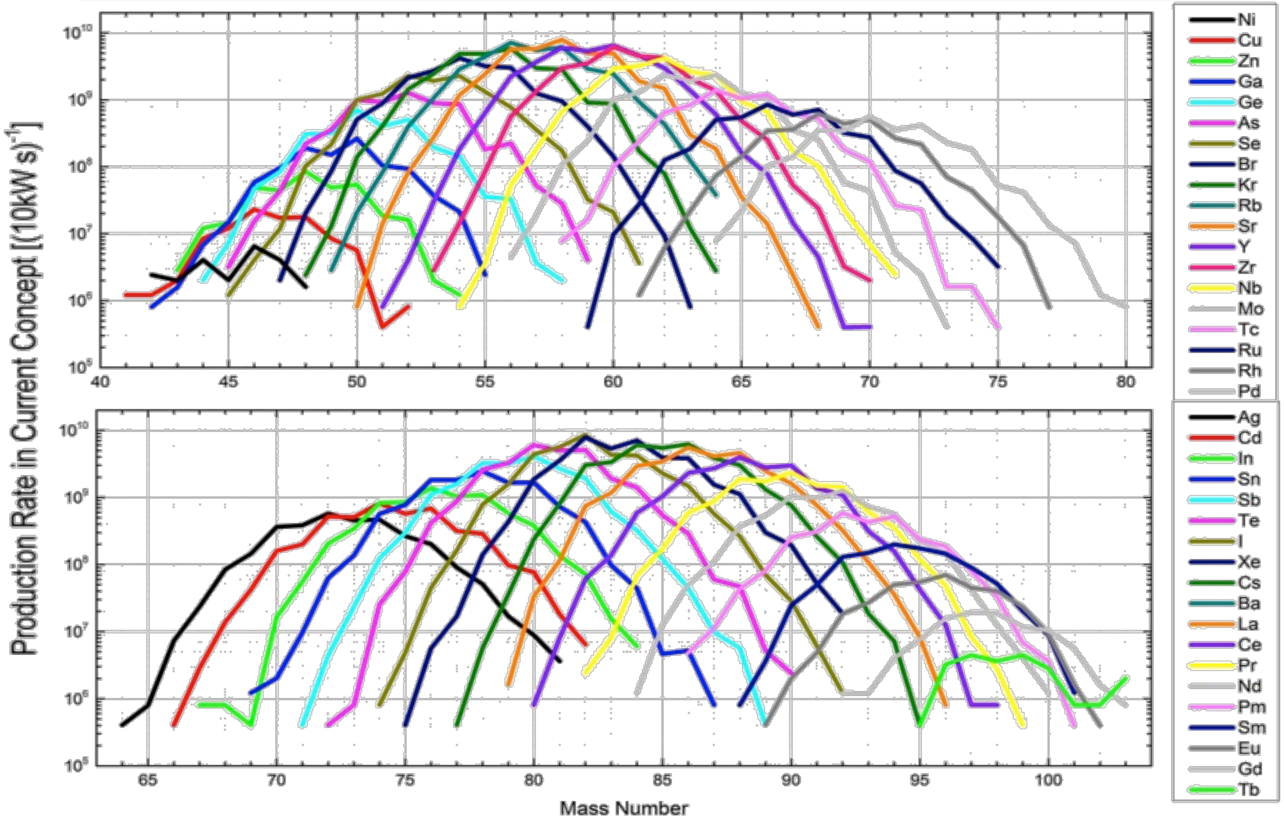


Photo-fission of UCx



FLUKA production map from 35 MeV Electrons

ARIEL Current Concept Design In-Target Production Yields [10 kW^{-1}·s^{-1}]



FLUKA: A. Gottberg (TRIUMF and results verified independently with GEANT4 (Marla Cervantes Smith, University of Victoria)

In-target production rates [10 kW^{-1} · s^{-1}]:

35MeV electrons→BeO:

^{8}Li: $5 \cdot 10^{10}$

	35MeV electrons→ UC$_x$	**500MeV protons→ UC$_x$:**
^{78}Ni:	$1 \cdot 10^{5}$	$2 \cdot 10^{6}$
^{98}Kr:	$8 \cdot 10^{7}$	$1 \cdot 10^{8}$
^{100}Rb:	$1 \cdot 10^{8}$	$9 \cdot 10^{7}$
^{98}Sr:	$5 \cdot 10^{9}$	$1 \cdot 10^{10}$
^{132}Sn:	$5 \cdot 10^{8}$	$5 \cdot 10^{9}$
^{146}Xe:	$2 \cdot 10^{7}$	$1 \cdot 10^{7}$
^{144}Ba:	$5 \cdot 10^{9}$	$2 \cdot 10^{10}$
^{150}Cs:	$4 \cdot 10^{5}$	$5 \cdot 10^{5}$

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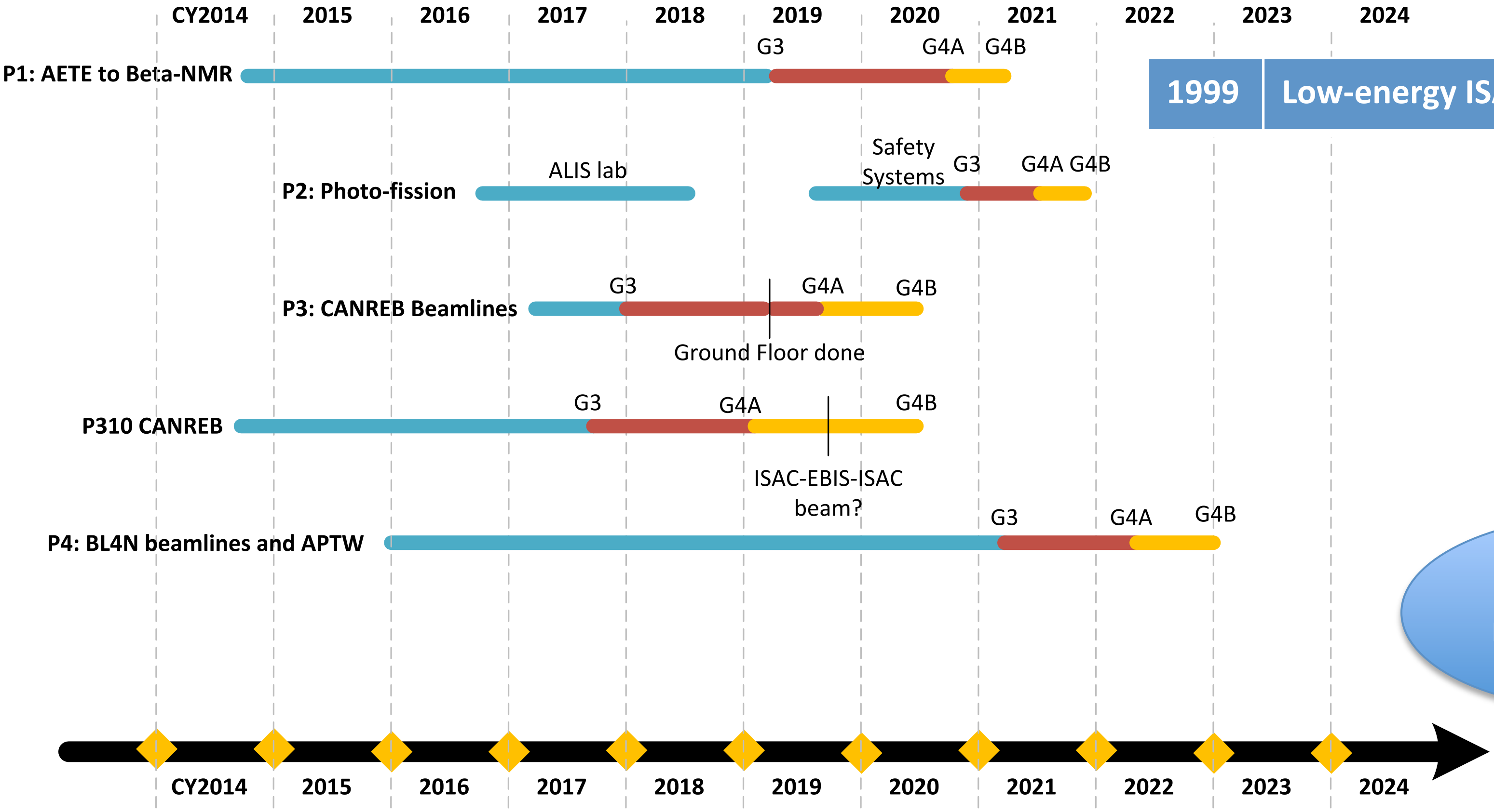
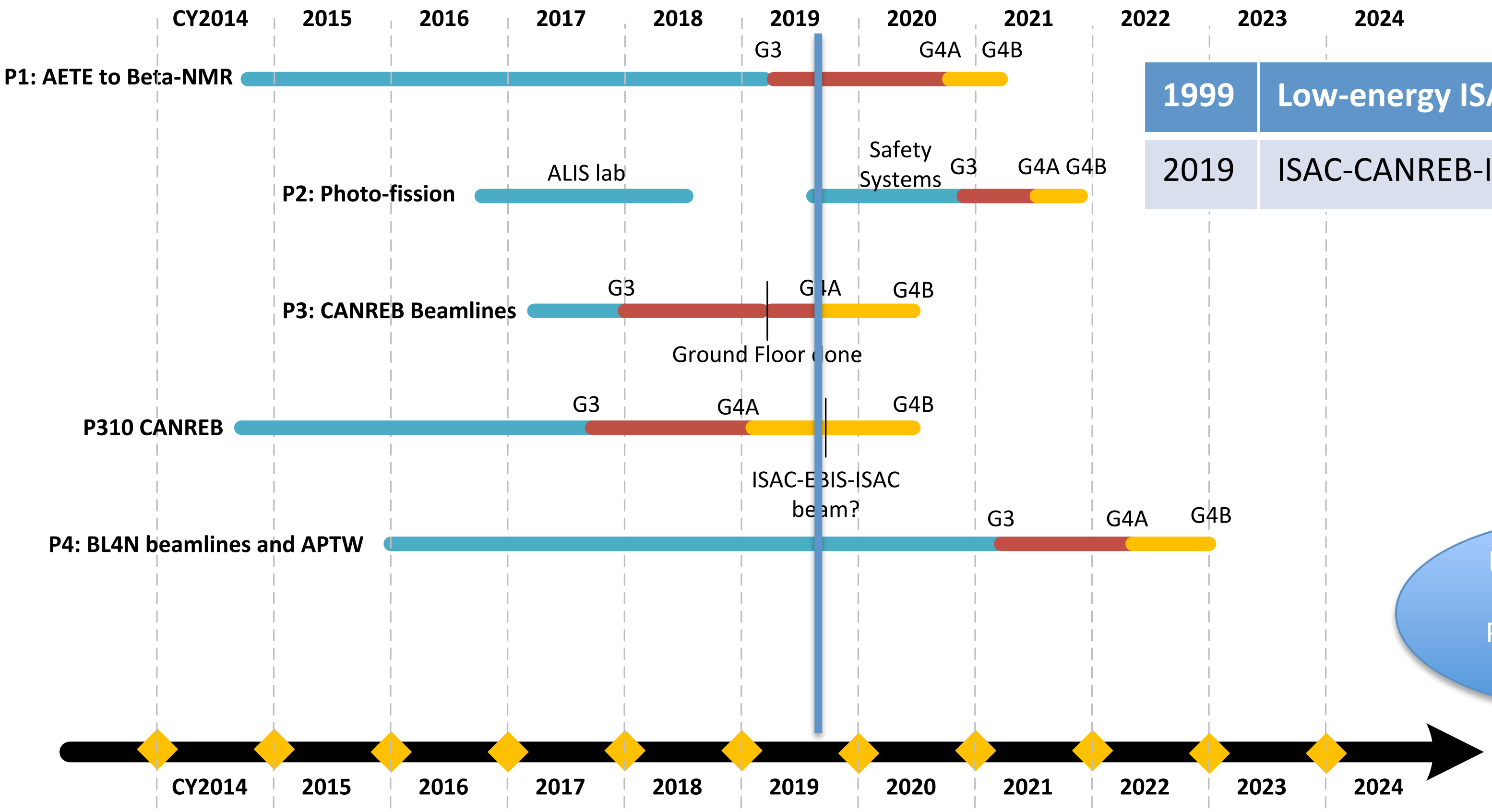
ARIEL Completion to Science



1999	Low-energy ISAC beams

Regular ARIEL user consultation Process with town-hall meetings

ARIEL Completion to Science

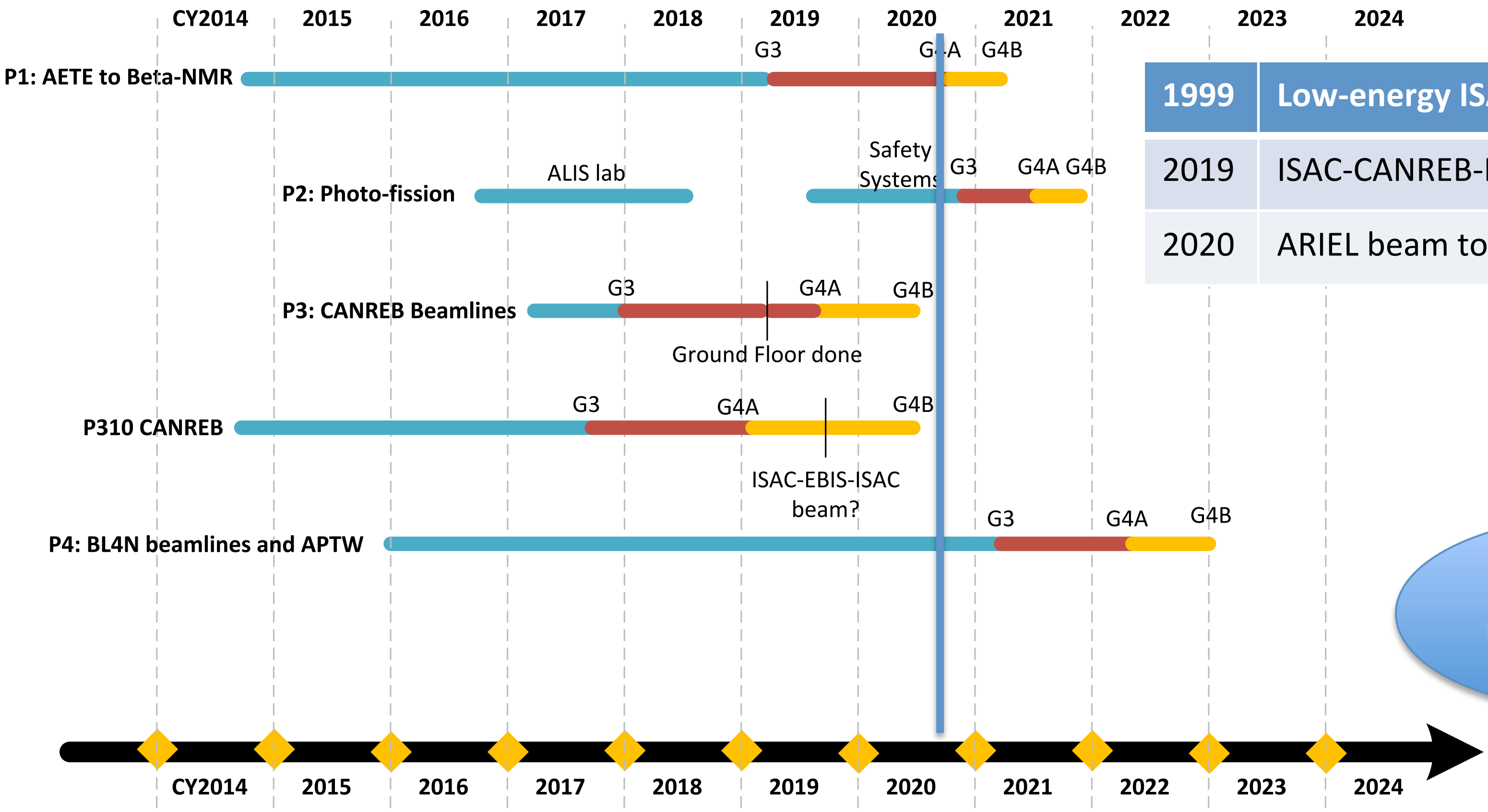


1999	**Low-energy ISAC beams**
2019	ISAC-CANREB-ISAC beams

Regular ARIEL user consultation Process with town-hall meetings

TRIUMF

ARIEL Completion to Science

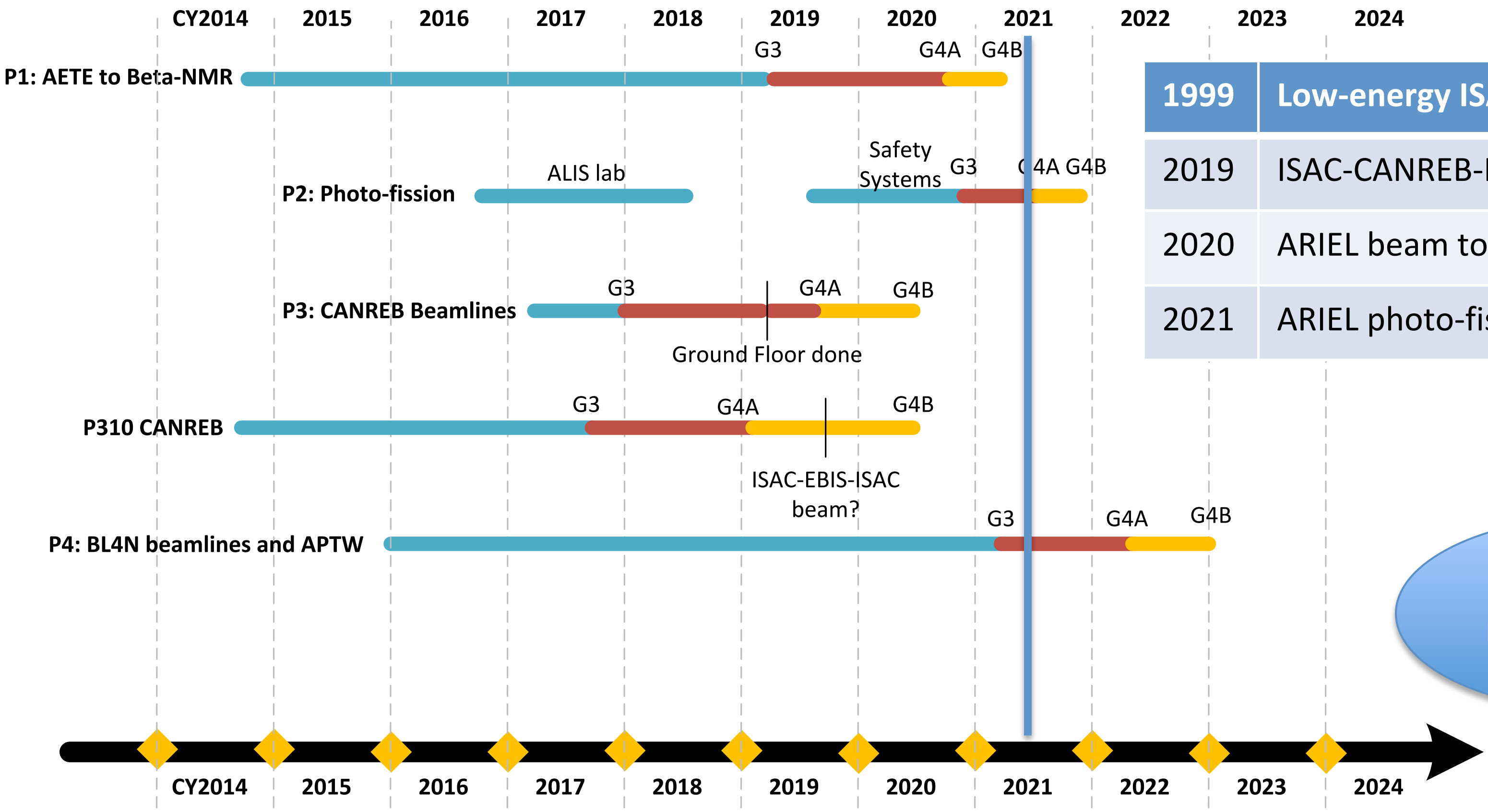


1999	Low-energy ISAC beams
2019	ISAC-CANREB-ISAC beams
2020	ARIEL beam to β-NMR

Regular ARIEL user consultation Process with town-hall meetings

TRIUMF

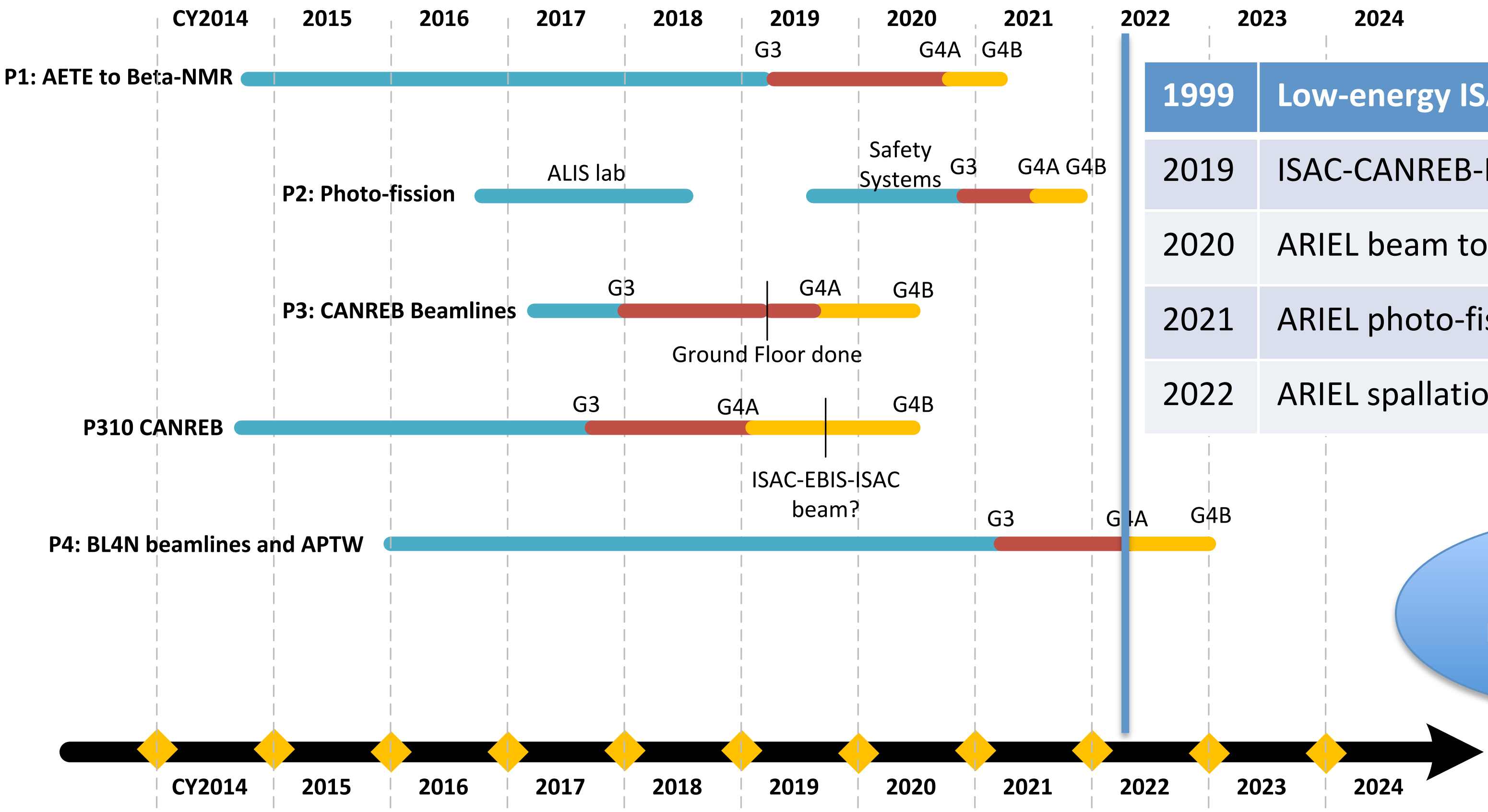
ARIEL Completion to Science



1999	**Low-energy ISAC beams**
2019	ISAC-CANREB-ISAC beams
2020	ARIEL beam to β-NMR
2021	ARIEL photo-fission beams to ISAC

Regular ARIEL user consultation Process with town-hall meetings

ARIEL Completion to Science

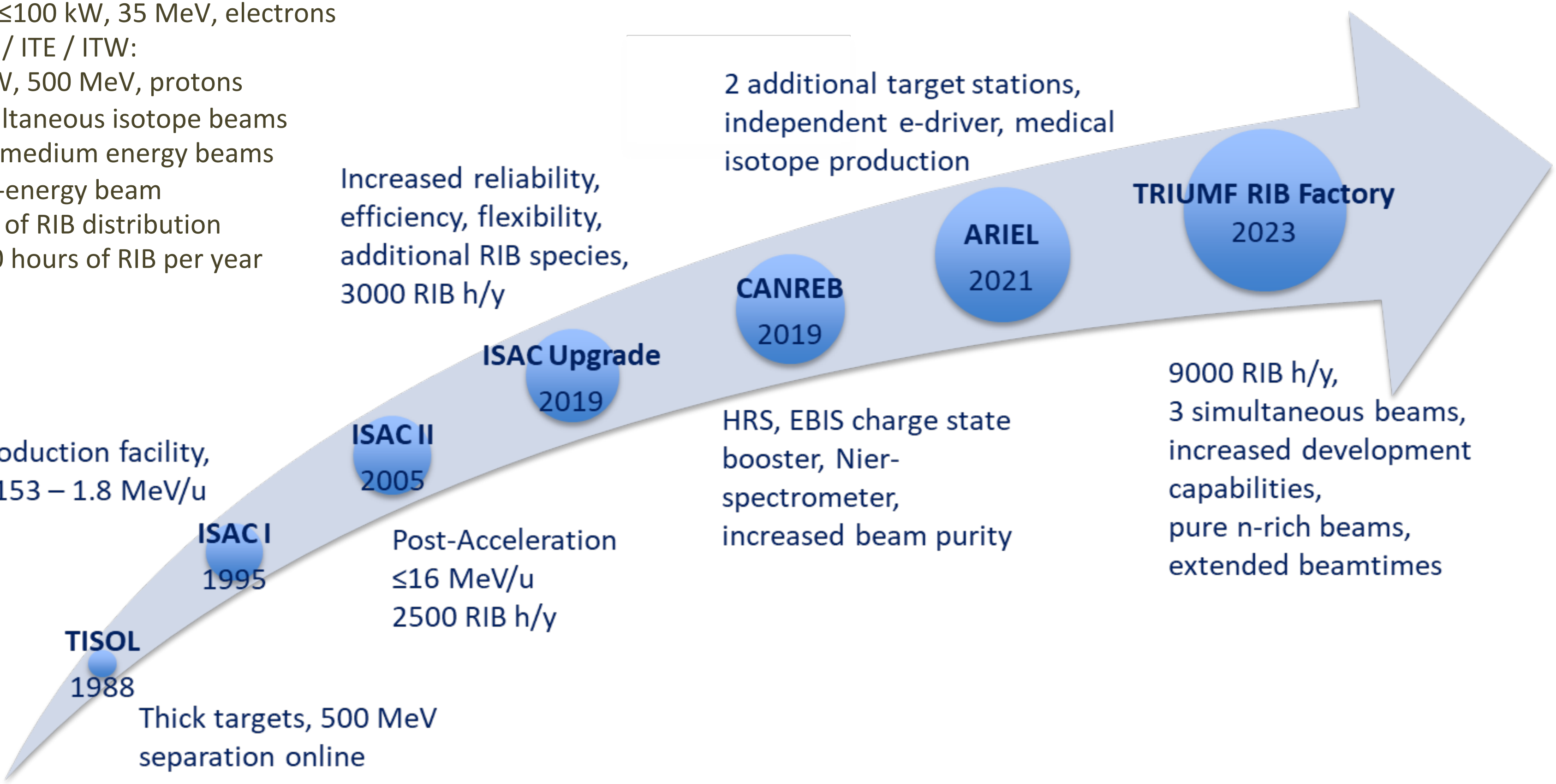


1999	**Low-energy ISAC beams**
2019	ISAC-CANREB-ISAC beams
2020	ARIEL beam to β-NMR
2021	ARIEL photo-fission beams to ISAC
2022	ARIEL spallation beams to ISAC

Regular ARIEL user consultation Process with town-hall meetings

ARIEL Baseline Parameters

- AETE: ≤100 kW, 35 MeV, electrons
- APTW / ITE / ITW:
  ≤50 kW, 500 MeV, protons
- 3 simultaneous isotope beams
- 2 low/medium energy beams
- 1 high-energy beam
- 250 m of RIB distribution
- > 9000 hours of RIB per year



TISOL
1988

Thick targets, 500 MeV
separation online

ISAC I
1995

Production facility,
0.153 – 1.8 MeV/u

ISAC II
2005

Post-Acceleration
≤16 MeV/u
2500 RIB h/y

ISAC Upgrade
2019

Increased reliability,
efficiency, flexibility,
additional RIB species,
3000 RIB h/y

CANREB
2019

HRS, EBIS charge state
booster, Nier-spectrometer,
increased beam purity

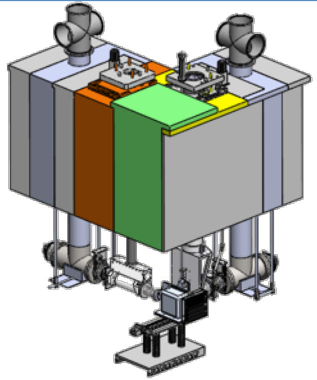
ARIEL
2021

2 additional target stations,
independent e-driver, medical
isotope production

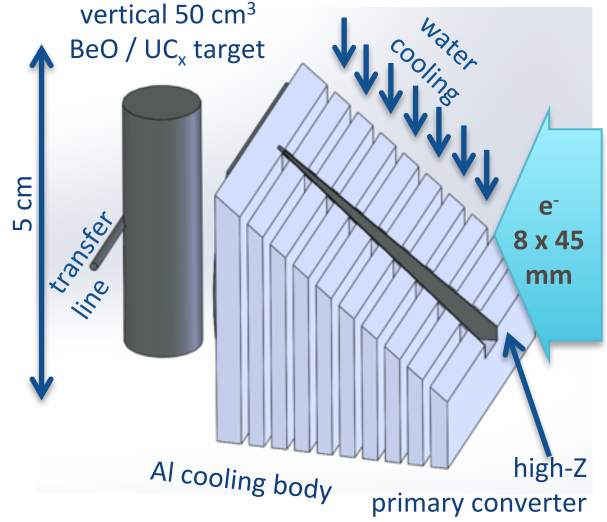
TRIUMF RIB Factory
2023

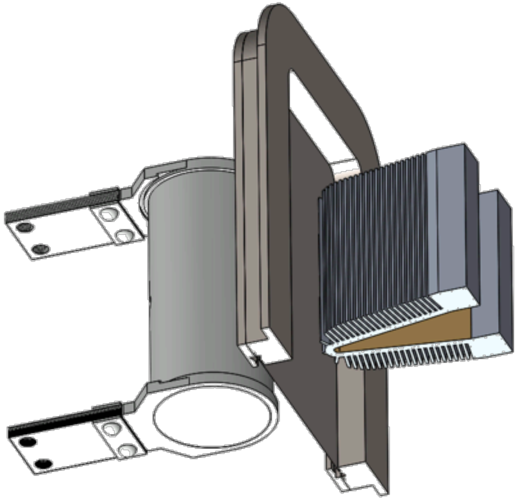
9000 RIB h/y,
3 simultaneous beams,
increased development
capabilities,
pure n-rich beams,
extended beamtimes

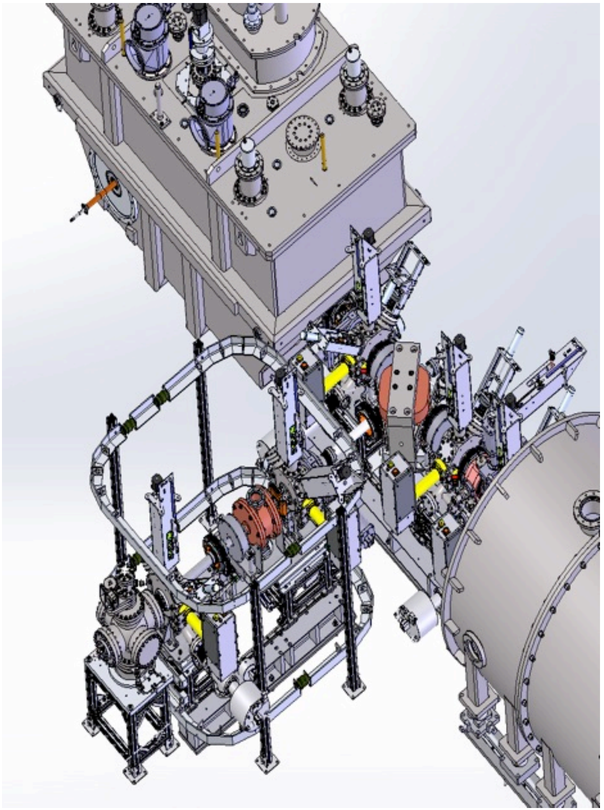
ARIEL-2: developments



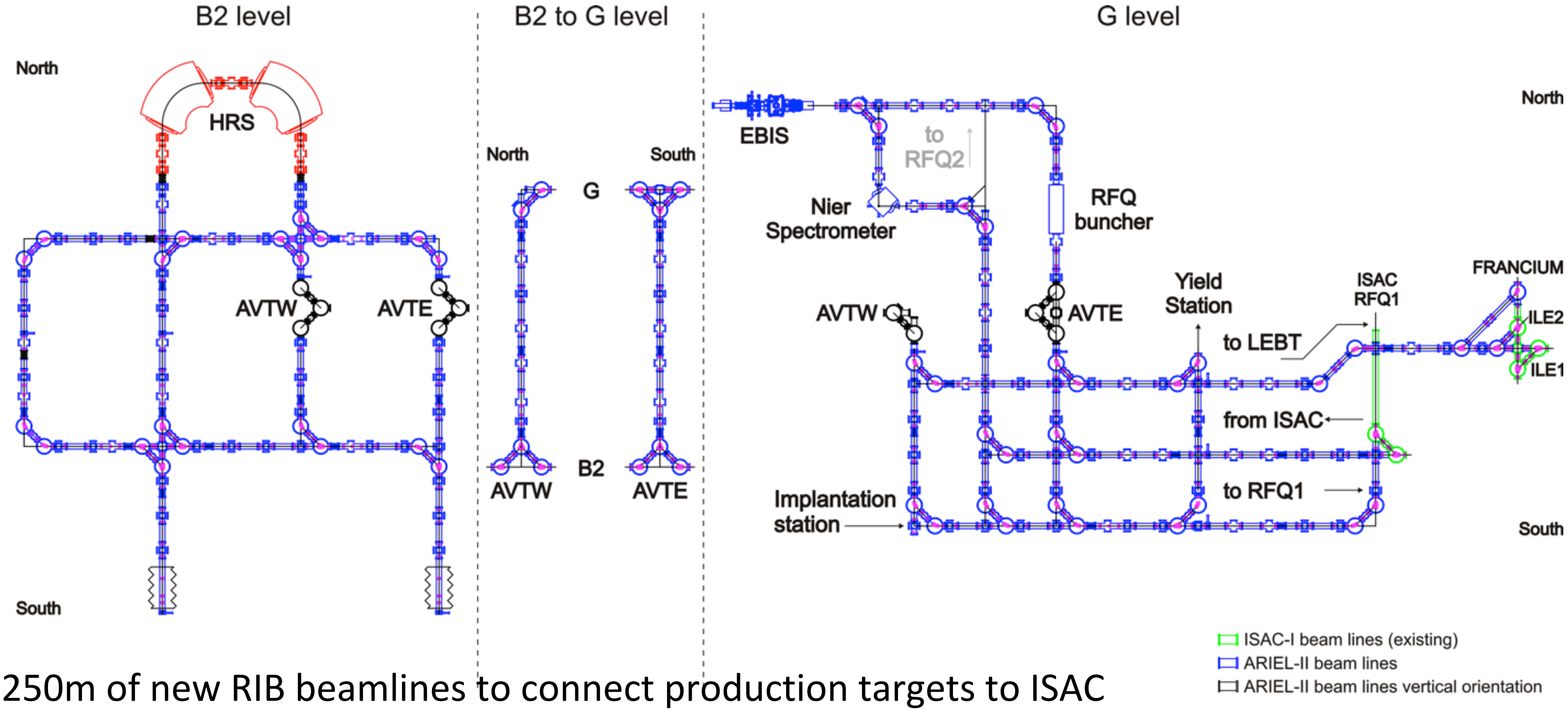
- Target developments for p- and γ-fission targets with $^{238}UC_x$ (100kW)
- New target removal and exchange concept
- Test stand for e-hall







RIB Beamlines



250m of new RIB beamlines to connect production targets to ISAC

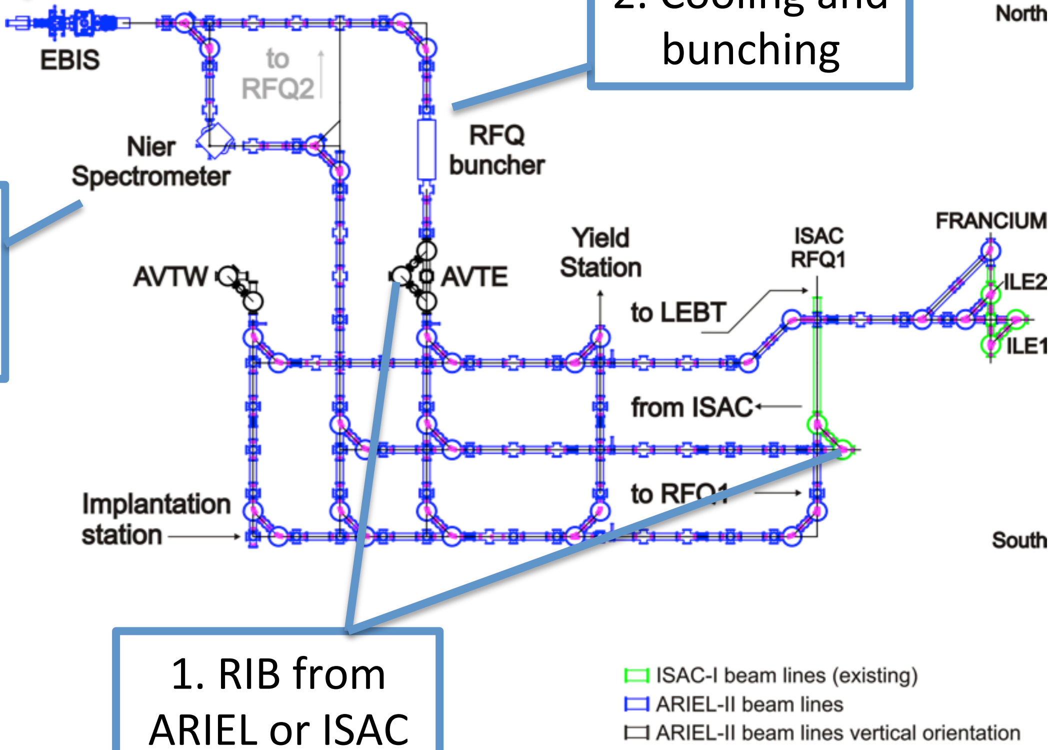
ARIEL ground-level equipment

3. Charge breeding

2. Cooling and bunching

4. Cleaning and deliver to ISAC accelerators

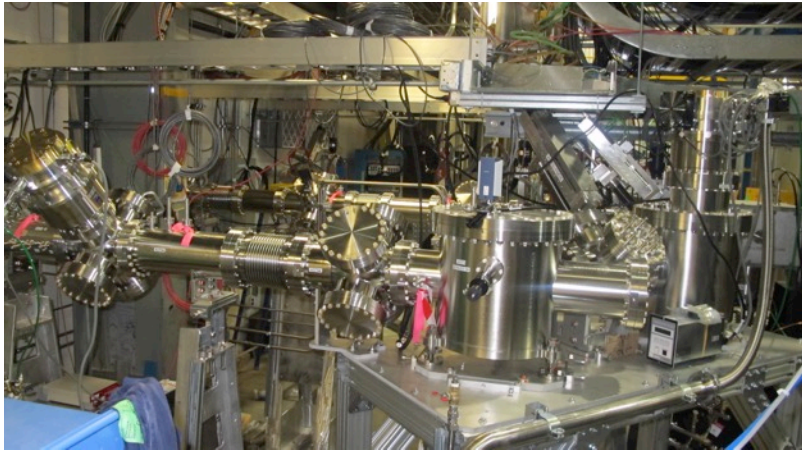
1. RIB from ARIEL or ISAC



Beamline installation well underway

ARIEL Building, ground floor

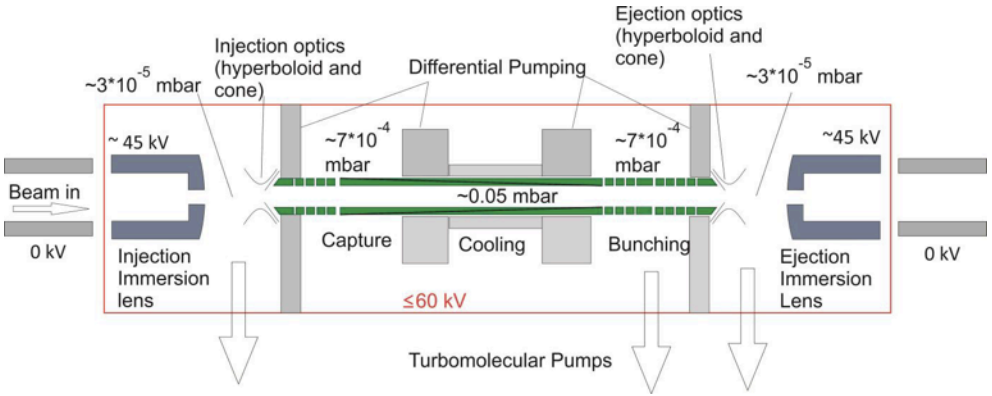
ISAC Building, ground floor

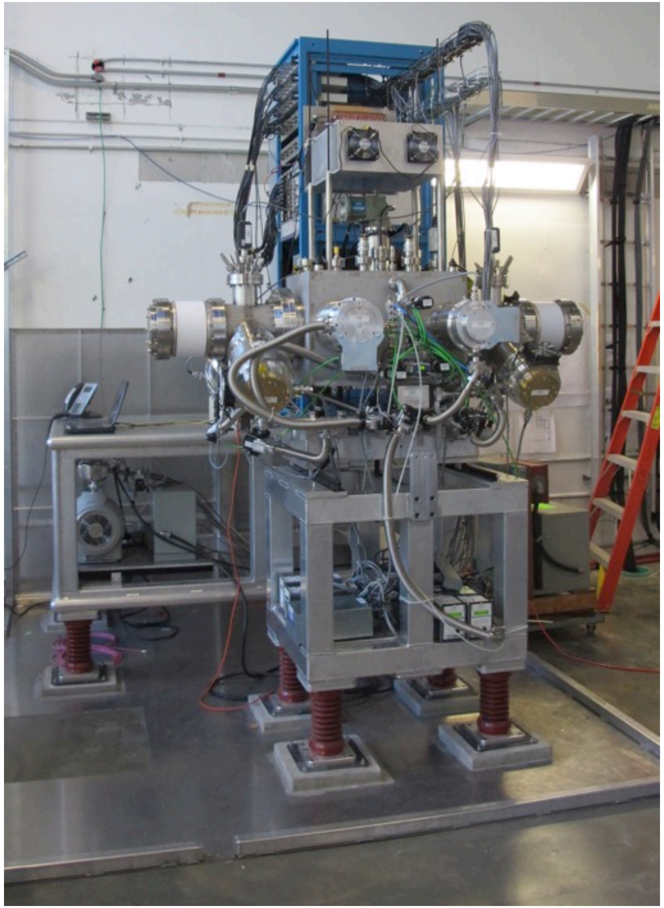


CANREB RFQ Buncher Installation

- RFQ Buncher, stand, HV cage floor, service platform, and electronics, have been installed in the ARIEL hall

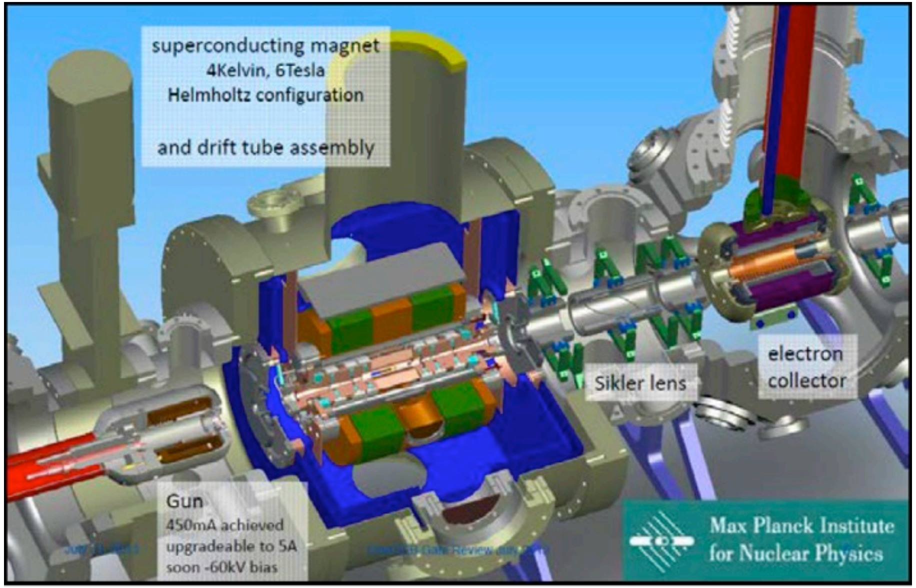
- Excellent performance demonstrated for 3 MHz RF circuit connected to RFQ load

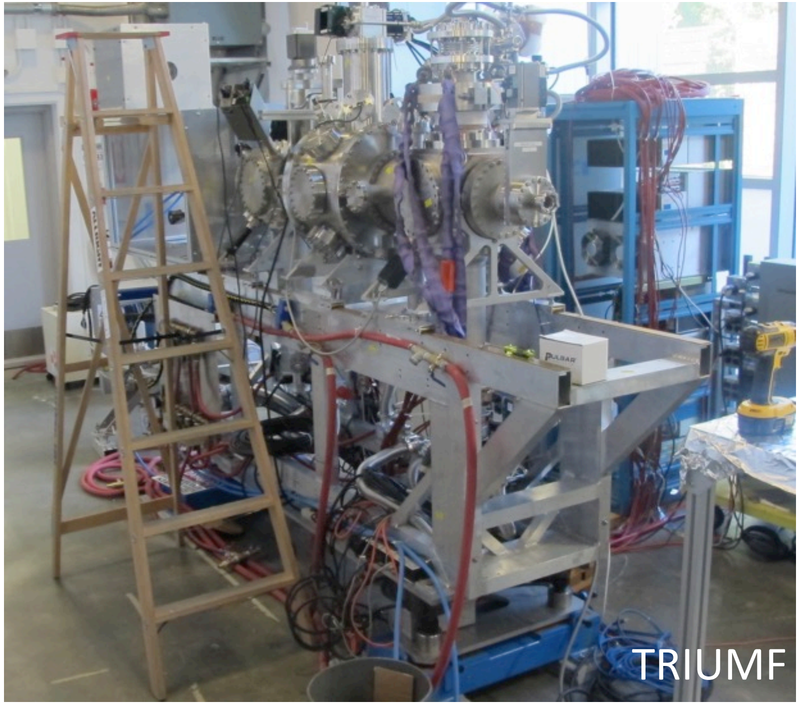




CANREB EBIS installation

- Designed and built at Max-Planck Institute, Heidelberg
- Delivered to TRIUMF in Jan 2018 and being installed at ARIEL.

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M. A. Blessenohl *et al.*, Review of Scientific Instruments 89, 052401 (2018).

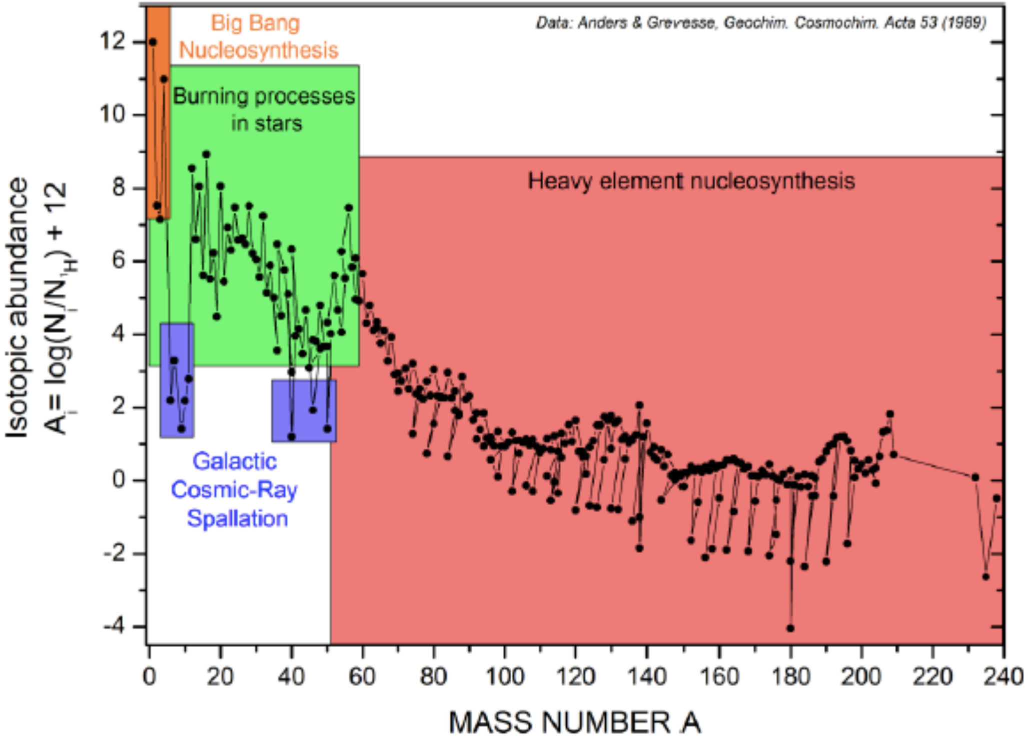
Origin of the elements

Nuclear astrophysics aims at understanding the origin of all stable isotopes as observed in the “solar abundance curve”

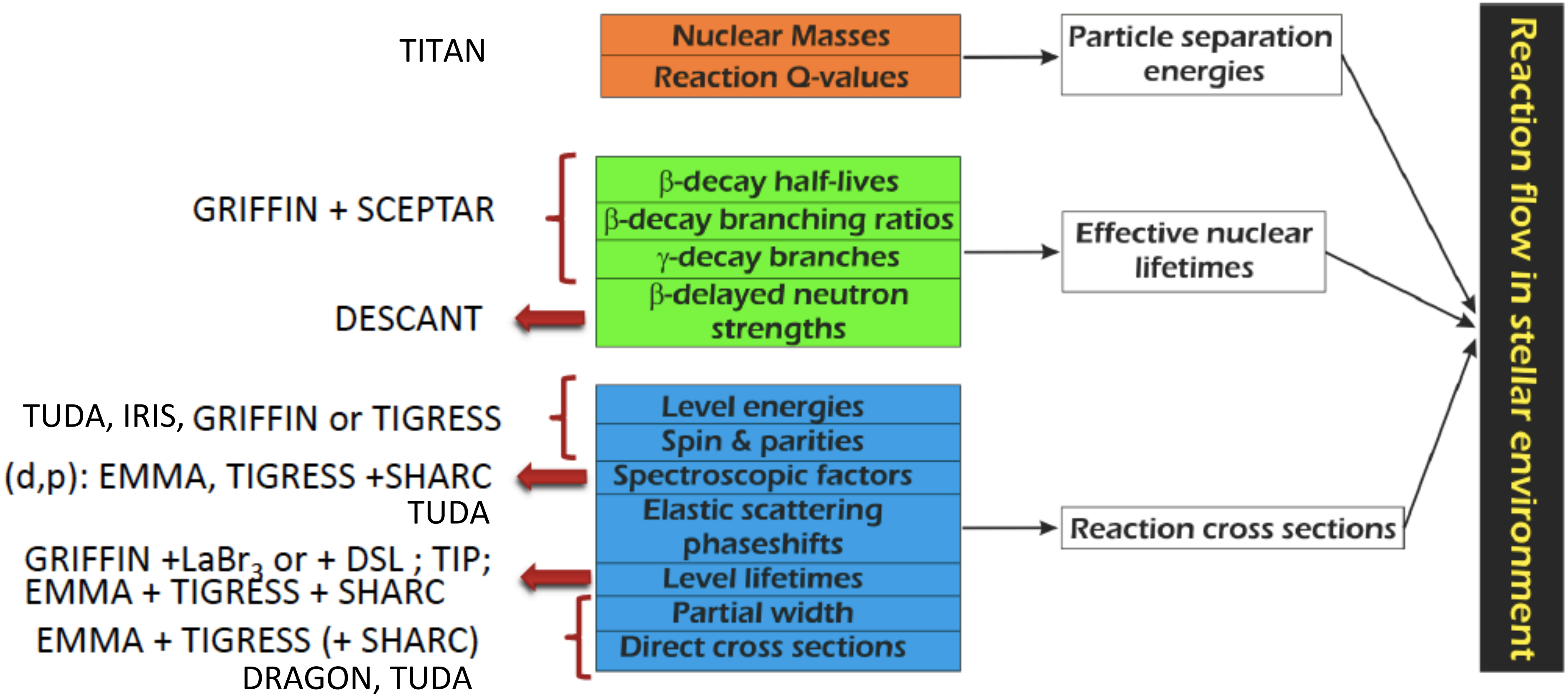
“Heavy element nucleosynthesis” summarizes several reaction mechanisms producing all elements heavier than Fe:

- “slow” neutron capture process
- “rapid” neutron capture process
- “intermediate” neutron capture process
- Production of proton-rich isotopes

$$N_{\odot} = N_s + N_r + N_i + N_p$$



Nuclear Physics Data from ISAC for Astrophysics



TITAN

Nuclear Masses

Reaction Q-values

Particle separation energies

GRIFFIN + SCEPTAR

β-decay half-lives

β-decay branching ratios

γ-decay branches

DESCANT

β-delayed neutron strengths

Effective nuclear lifetimes

TUDA, IRIS, GRIFFIN or TIGRESS

Level energies

Spin & parities

(d,p): EMMA, TIGRESS +SHARC

Spectroscopic factors

TUDA

Elastic scattering phaseshifts

GRIFFIN +$LaBr_3$ or + DSL ; TIP;
EMMA + TIGRESS + SHARC

Level lifetimes

EMMA + TIGRESS (+ SHARC)
DRAGON, TUDA

Partial width

Direct cross sections

Reaction cross sections

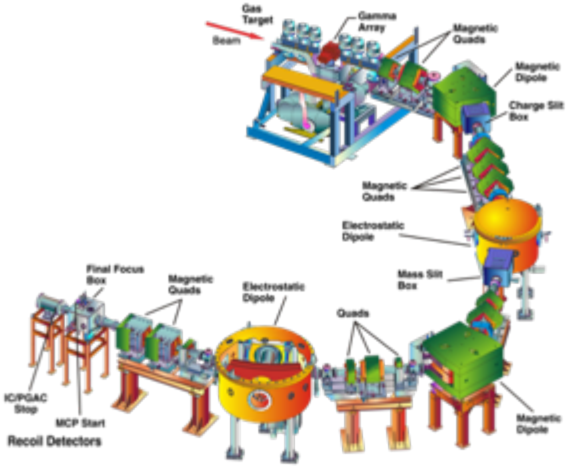
Reaction flow in stellar environment

Astrophysics at ARIEL

- DRAGON
  - Longer beamtimes for comprehensive direct measurements of reaction cross sections (on and off resonance)
- TUDA, IRIS, TIGRESS, SHARC, EMMA
  - CANREB intensity boost: Transfer reactions with spectroscopic precision
  - Capture reactions at higher-energy. Supernova, rp-process
  - (d,p) surrogate to obtain n-capture cross section

- GRIFFIN, DESCANT
  - Beta-decay half lives, Beta-delayed neutron branching ratios, level schemes and isomers
- TITAN
  - Masses/Q-values, isomers
- EMMA, TIGRESS, SHARC
  - (d,p) surrogate to obtain n-capture cross section

Direct Capture Cross Section measurements at DRAGON

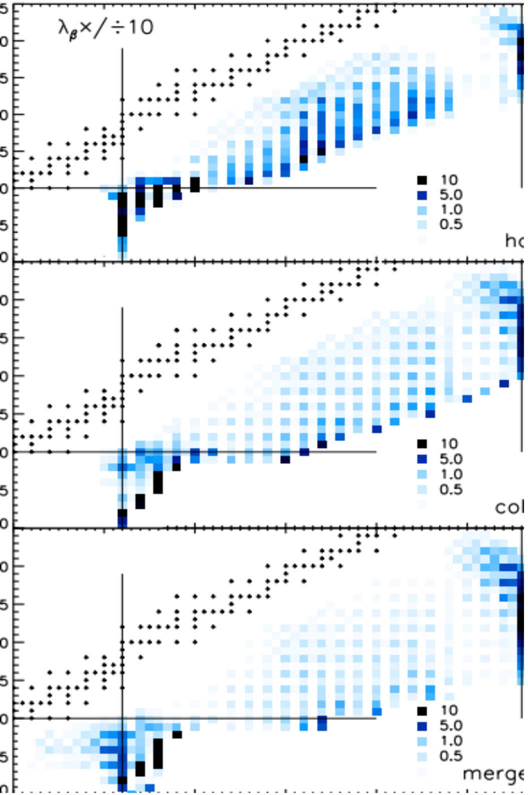


Reaction	Motivation	Intensity (s^{-1})	Purity (beam:cont.)
$^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}$	1.275 MeV line emission in ONe novae	5×10^{9}	100%
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$	Helium burning in red giants	6×10^{11}	
$^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	Nova contribution to galactic ^{26}Al	3×10^{9}	30,000:1
$^{12}\mathrm{C}(^{12}\mathrm{C},\gamma)^{24}\mathrm{Mg}$	Nuclear cluster models	3×10^{11}	
$^{40}\mathrm{Ca}(\alpha,\gamma)^{44}\mathrm{Ti}$	Production of ^{44}Ti in SNII	3×10^{11}	10,000:1 – 200:1
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$	1.275 MeV line emission in ONe novae	5×10^{7}	1:20 – 1:1,000
$^{17}\mathrm{O}(\alpha,\gamma)^{21}\mathrm{Ne}$	Neutron poison in massive stars	1×10^{12}	
$^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$	511 keV line emission in ONe novae	2×10^{6}	100:1
$^{33}\mathrm{S}(p,\gamma)^{34}\mathrm{Cl}$	S isotopic ratios in nova grains	1×10^{10}	
$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$	Stellar helium burning	1×10^{12}	
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$	Explosive hydrogen burning in novae	1×10^{12}	
$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$	Solar neutrino spectrum	5×10^{11}	
$^{58}\mathrm{Ni}(p,\gamma)^{59}\mathrm{Cu}$	High mass tests (p-process, XRB)	6×10^{9}	
$^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	SNII contribution to galactic ^{26}Al	2×10^{5}	1:10,000
$^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$	Ca/K/Ar production in novae	2×10^{7}	1:1
$^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$	^{19}F abundance in nova ejecta	2×10^{7}	1:1 to 4:1
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	NeNa cycle; explosive H burning in classical novae	2×10^{12}	

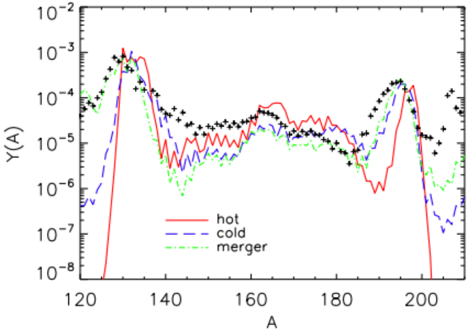
7 RIB

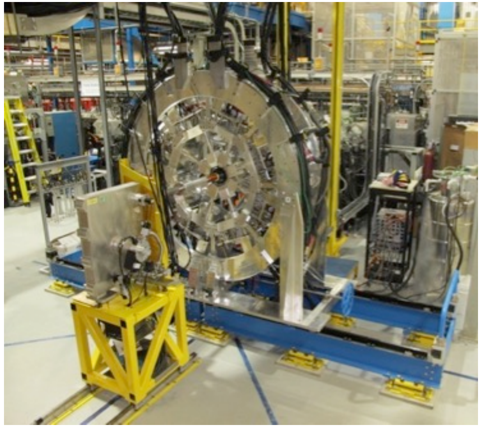
10 Stable beam

GRIFFIN – Detailed decay spectroscopy

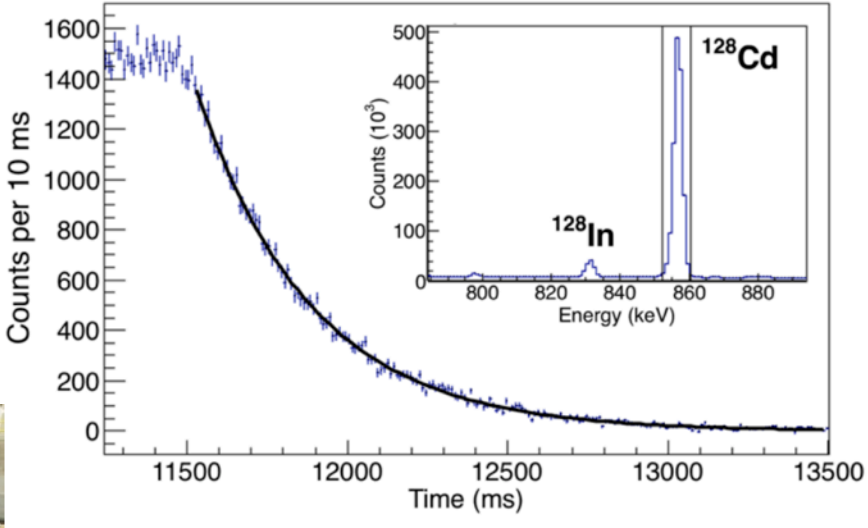


M. Mumpower *et al.*,
Prog.Part.Nucl.Phys. 86, 86 (2016)





R. Dunlop, et al., Phys. Rev. C 93, 062801(R) (2016).



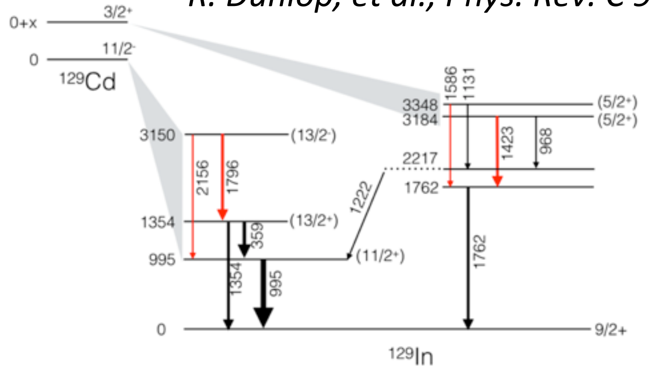
Activity curve gated on 857 keV γ ray photopeak

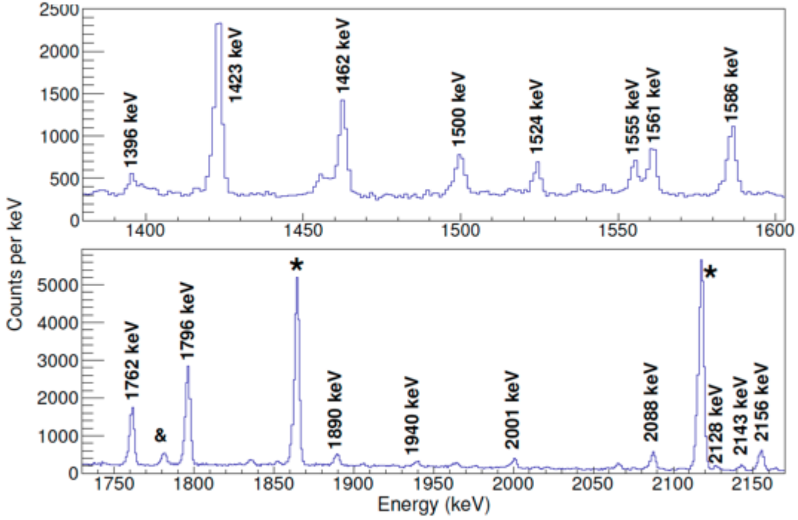
following ^{128}Cd decay: $T_{1/2}$ = 246.2(21) ms

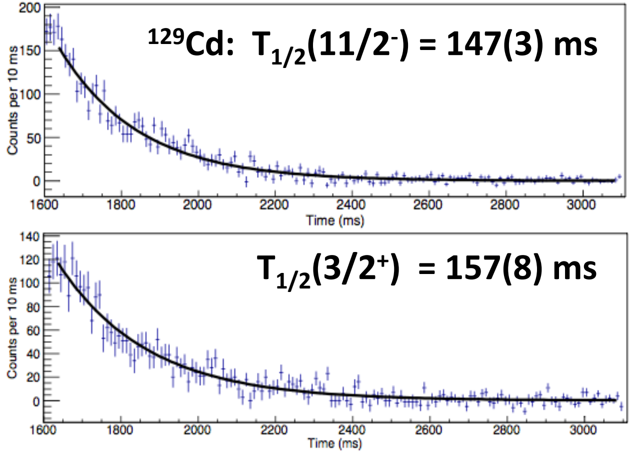
Previous 245(5) ms, from
G. Lorusso et al. PRL 114 192501 (2015)

Half-Lives of Neutron-Rich $^{128-130}$Cd

R. Dunlop, et al., Phys. Rev. C 93, 062801(R) (2016).

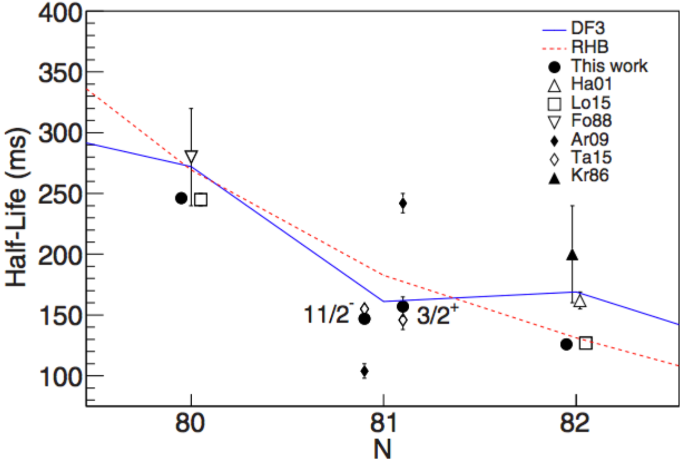






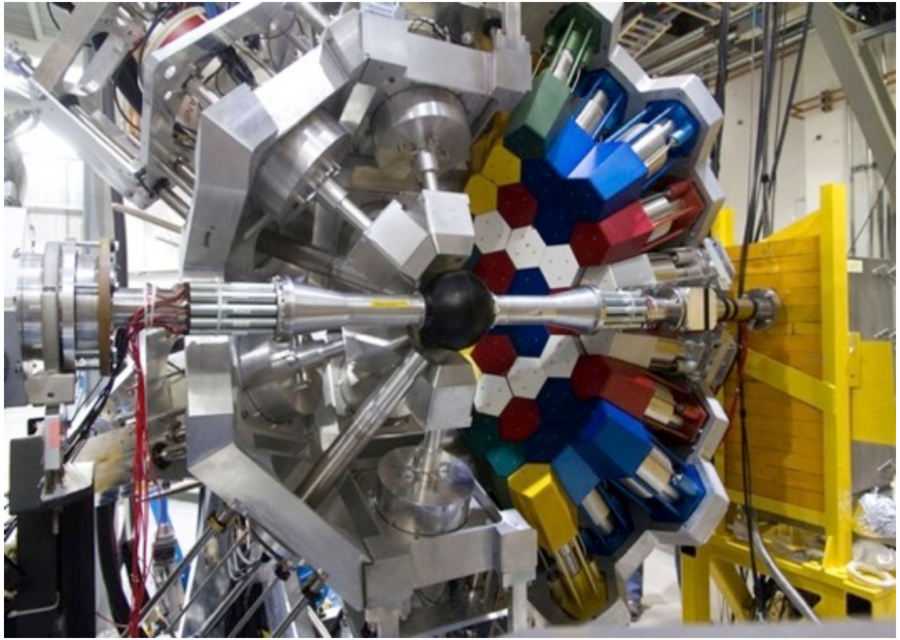
^{129}Cd: $T_{1/2}(11/2^-)$ = 147(3) ms

$T_{1/2}(3/2^+)$ = 157(8) ms

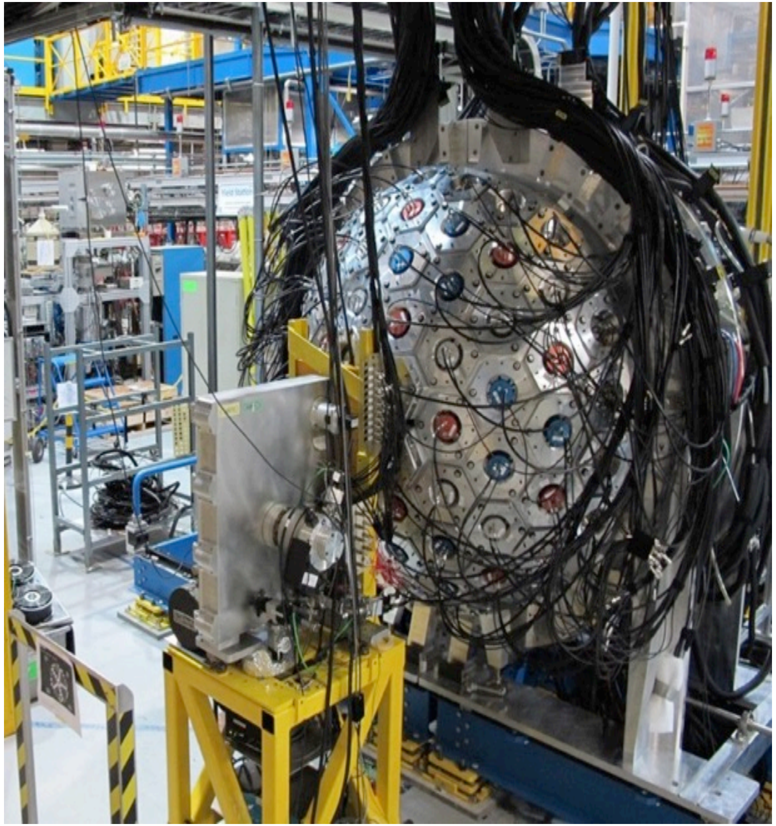


GRIFFIN+DESCANT

- 70 element array of deuterated scintillator for neutron detection
- Enables beta-gamma-ICE-neutron spectroscopy
- ~1π solid angle
- Neutron energy from time-of-flight (50cm flight path)
- Online neutron-gamma discrimination from pulse shape

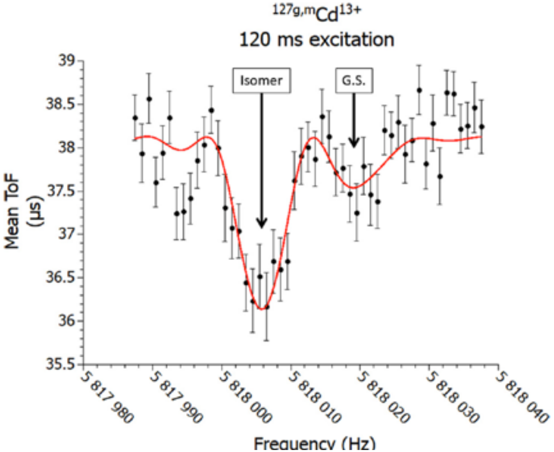


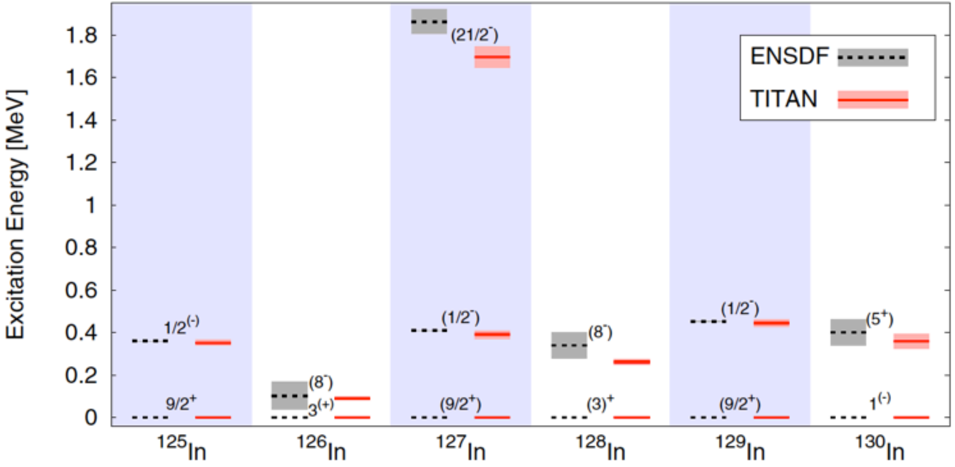
GRIFFIN + DESCANT, August 2016

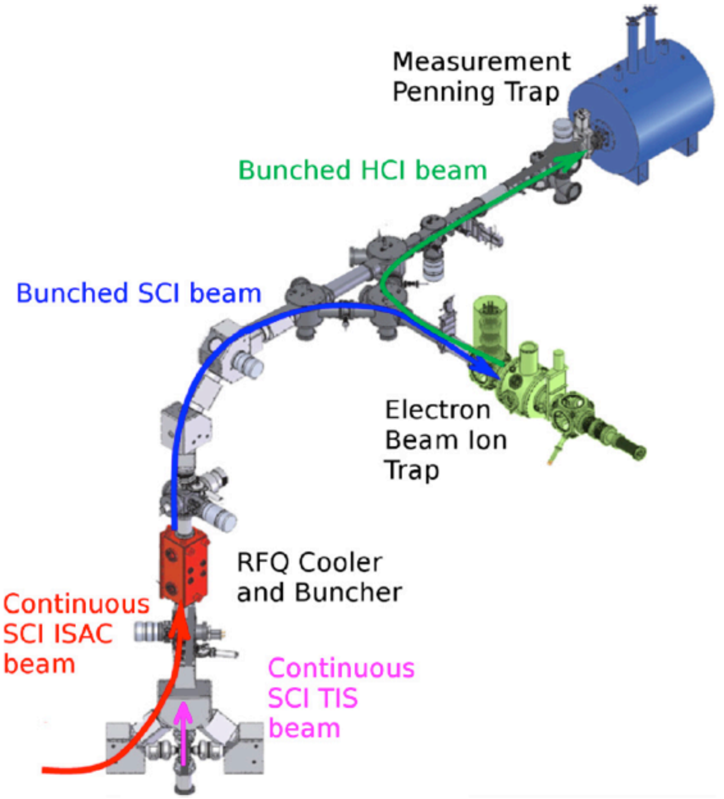


TITAN – Precision mass measurements

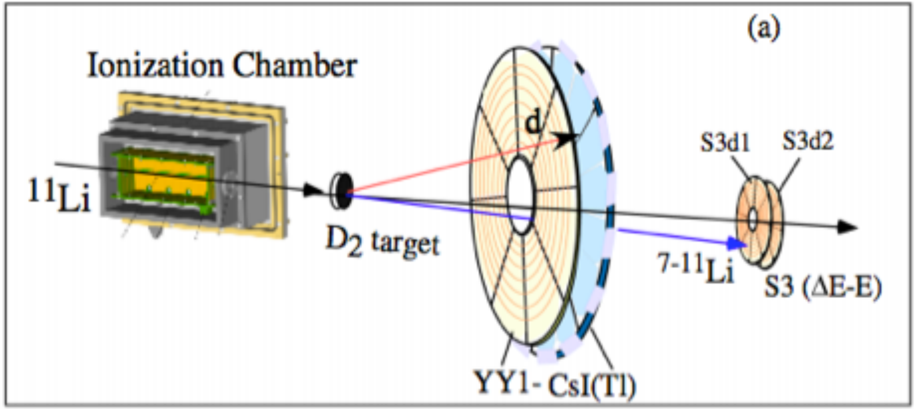
Separate isomer and ground states using precision available with highly-charged ions

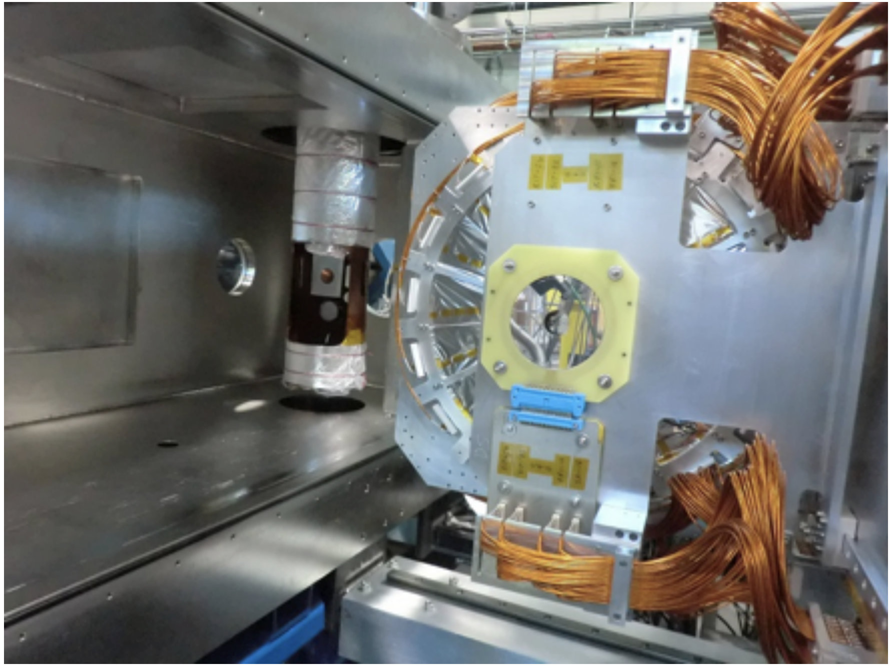






Cd: D. Lascar *et al.*, PRC 96, 044323 (2017).
In: C. Babcock *et al.*, PRC 97, 024312 (2018).





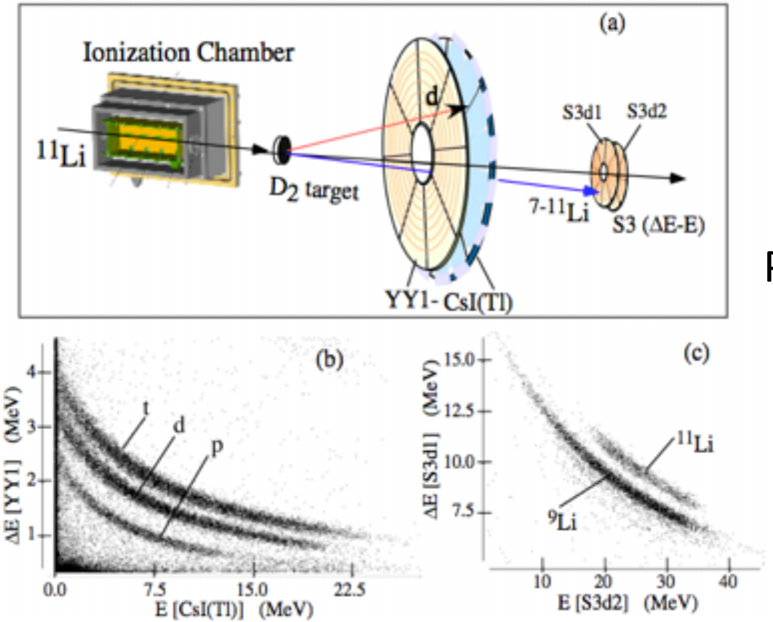
- Transmission ion chamber for beam identification
- Frozen gaseous target on thin Ag foil
- Si and CsI detectors for particle identification and angular distributions

IRIS: $d(^{11}Li,d')^{11}Li'$

PRL **114,** 192502 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

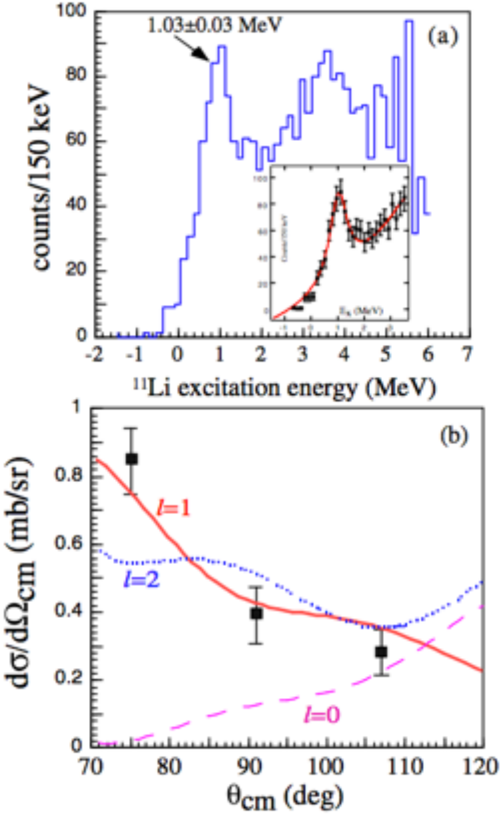
Evidence of Soft Dipole Resonance in ^{11}Li with Isoscalar Character

R. Kanungo, A. Sanetullaev *et al.*

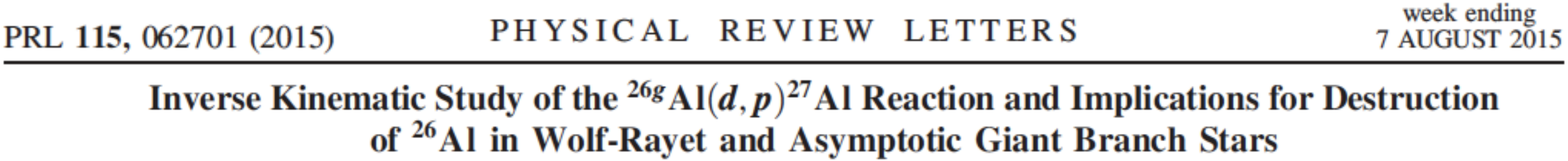


First evidence of a dipole resonance in ^{11}Li having an isoscaler character.

Provides stringent tests of *ab initio* theories and nuclear forces.

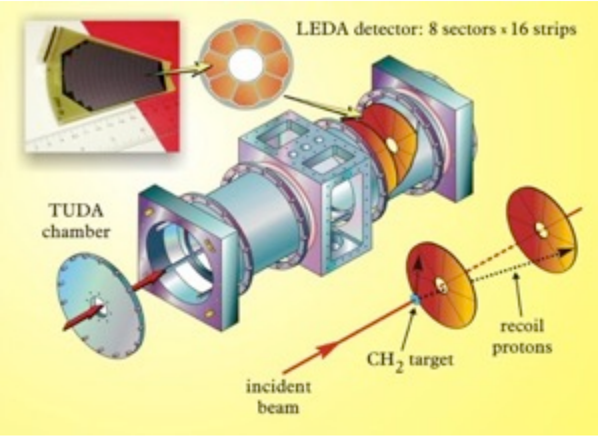


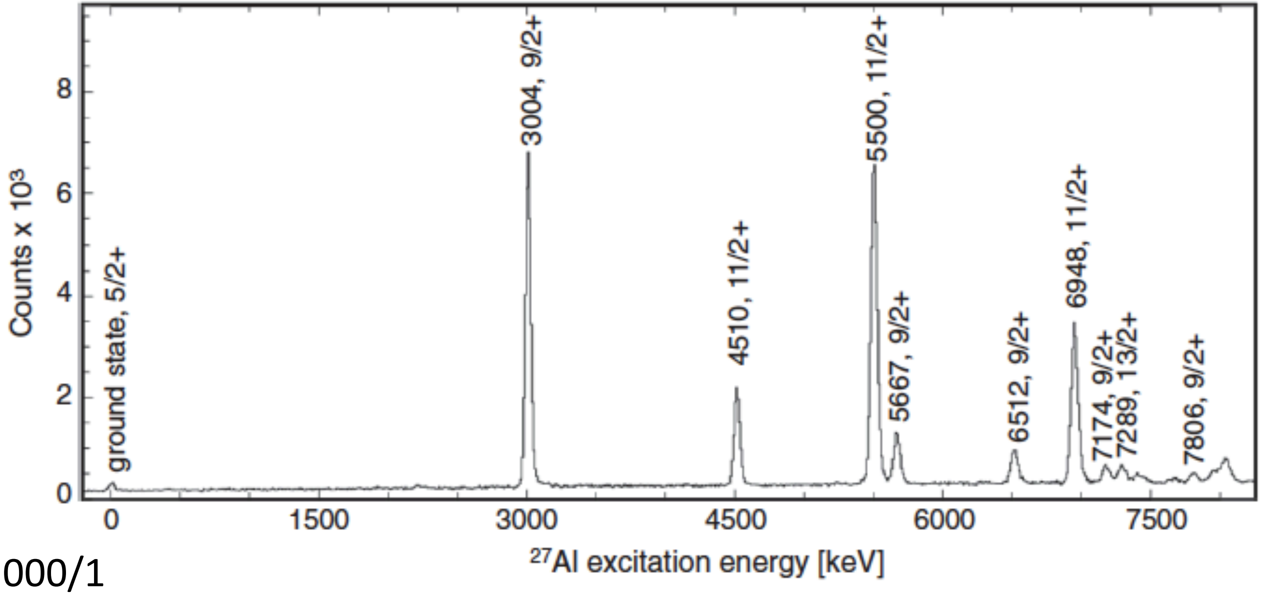
TUDA: ^{26g}Al(d,p)^{27}Al



PRL **115**, 062701 (2015) PHYSICAL REVIEW LETTERS week ending 7 AUGUST 2015

Inverse Kinematic Study of the ^{26g}Al$(d,p)^{27}$Al Reaction and Implications for Destruction of ^{26}Al in Wolf-Rayet and Asymptotic Giant Branch Stars





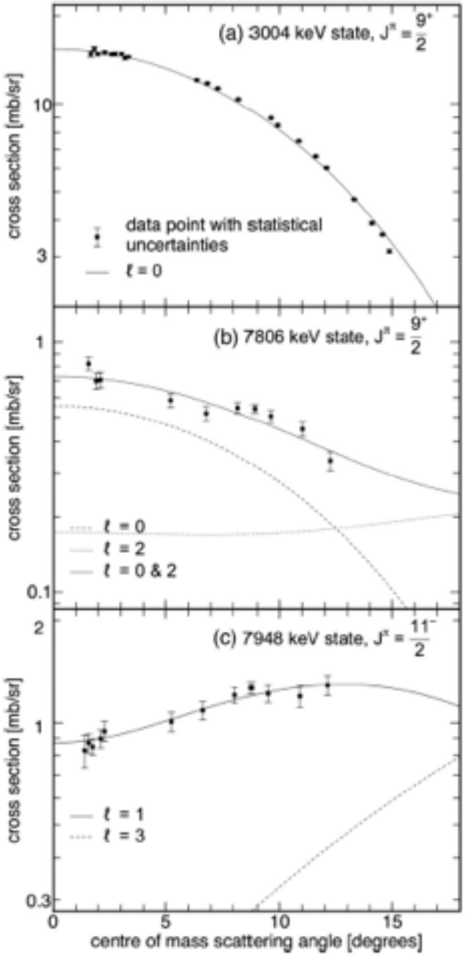
TUDA array

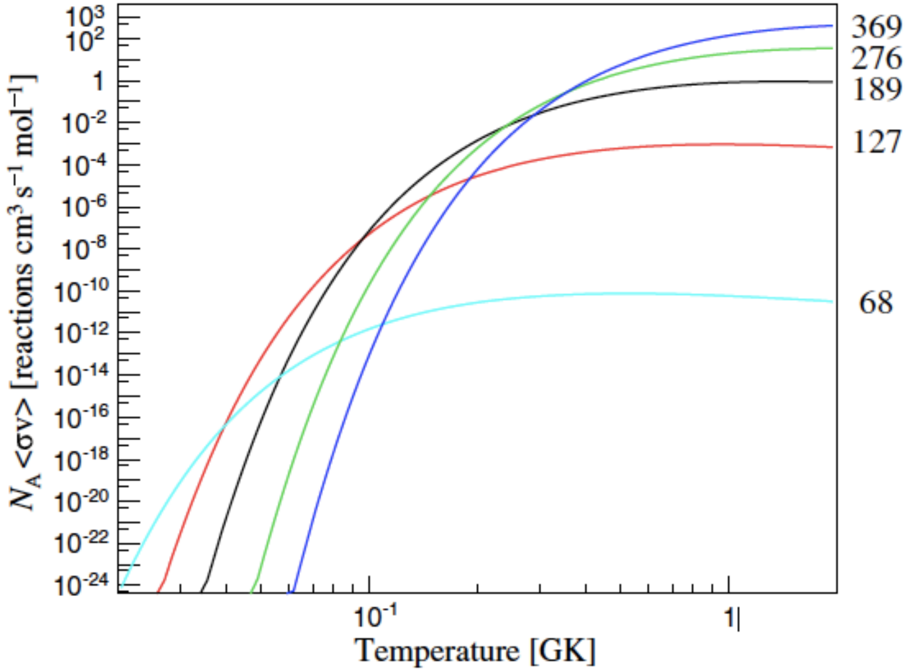
1pnA ^{26}Al at 6 AMeV with GS/IS=17,000/1

~50 µg=cm^2 thick CD$_2$ target

~40keV FWHM

TUDA: ^{26g}Al(d,p)^{27}Al



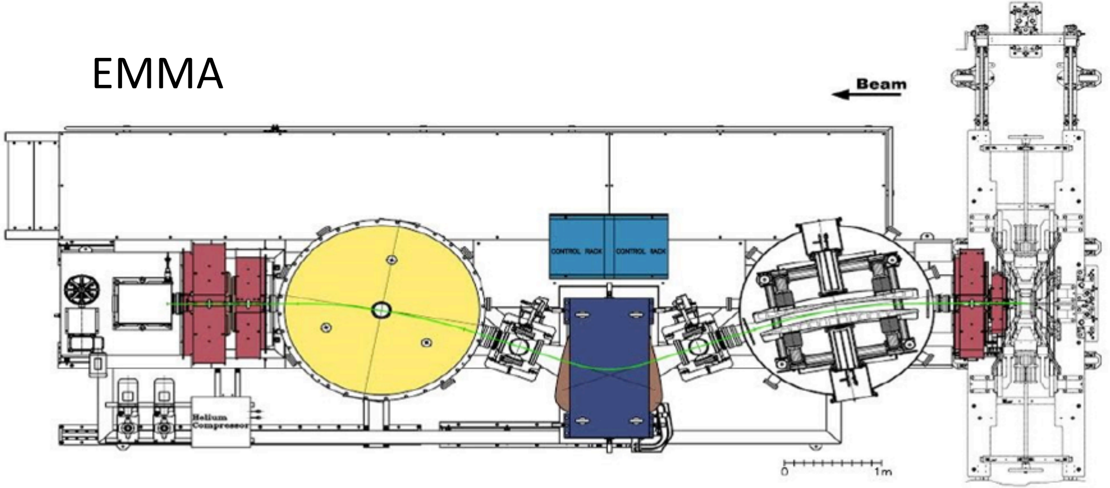


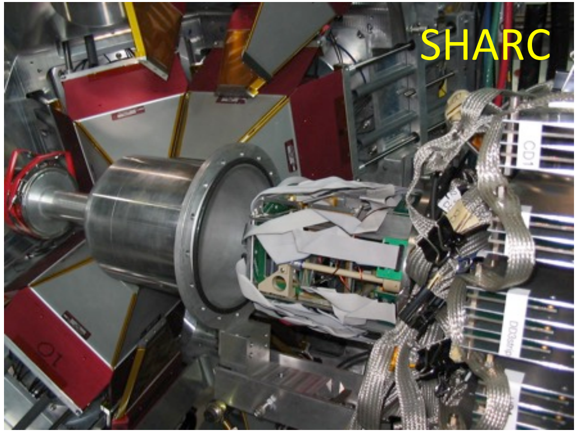
127 keV resonance in ^{27}Si determines the entire ^{26g}Al(p,γ)^{27}Si reaction rate over almost the complete temperature range of Wolf-Rayet stars and AGB stars.

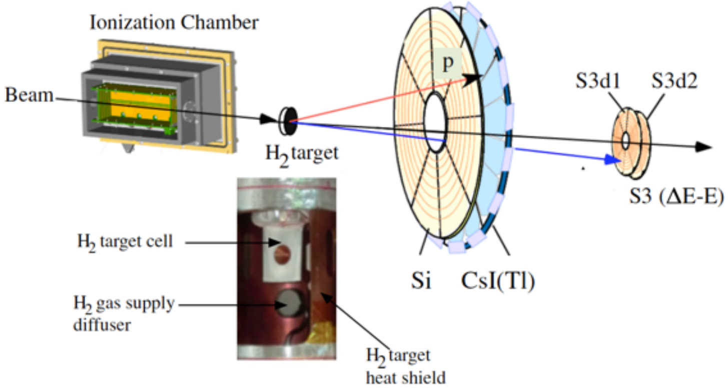
V. Margerin, G. Lotay *et al.*, PRL 115, 062701 (2015).

Nuclear Reactions: ISAC-II

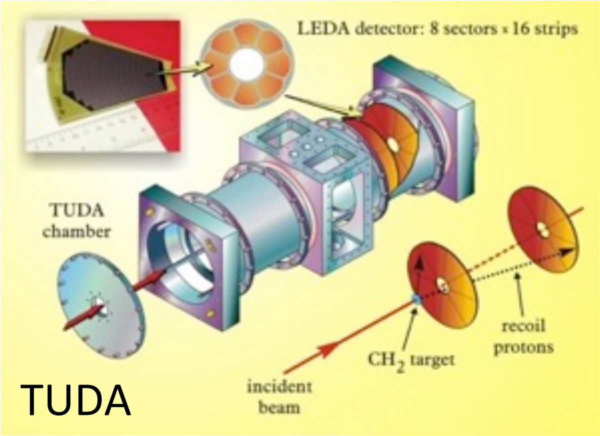
EMMA







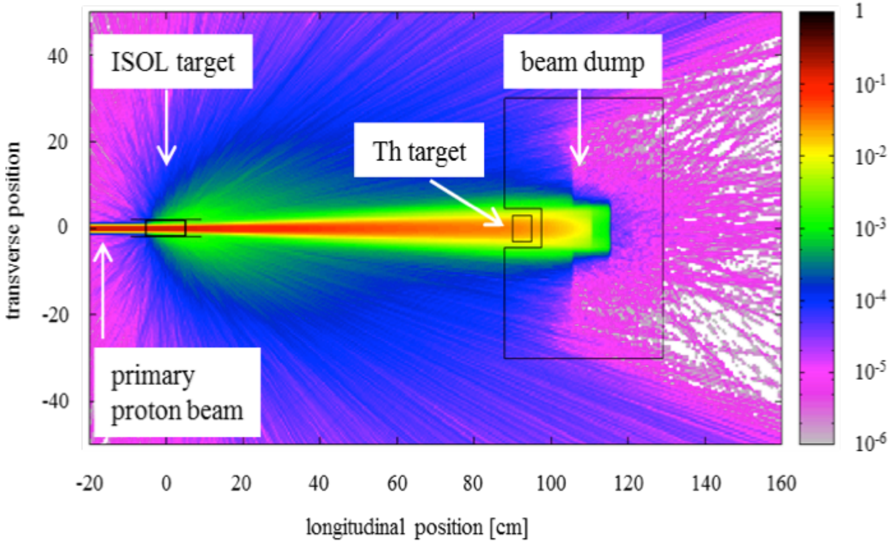
IRIS



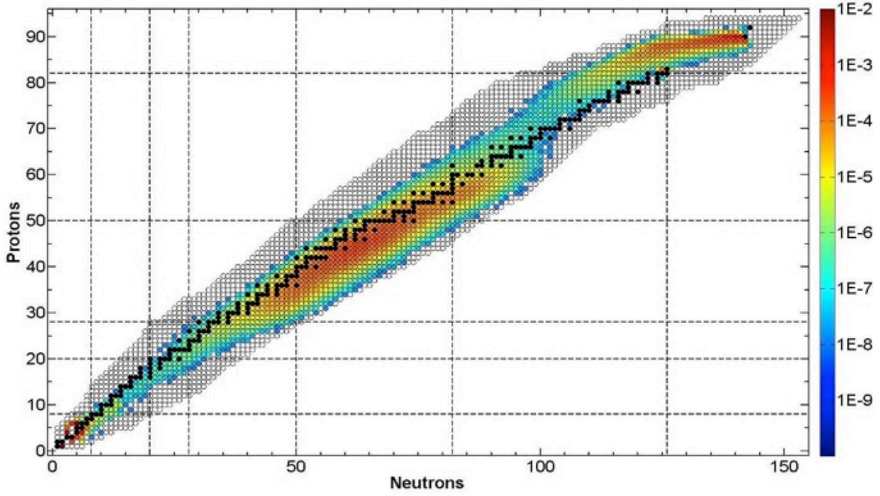
The Use of Waste Beam: Symbiotic Medical Targets

Generally at RIB facilities: <200 MeV stopped in target
for high-energy facilities → significant energy left → parasitic radioisotope production

Example: TRIUMF-ARIEL Proton Fluence [arb. units]



Hundreds of co-produced isotopes including;
^{225}Ra, ^{225}Ac, ^{224}Ra, ^{223}Ra, ^{213}Bi, ^{212}Pb, ^{212}Bi



Potential source of long-lived radio-isotopes of astrophysical interest.

Summary

ARIEL/ISAC will enable the delivery of three parallel radioactive beams to users:

- Two cyclotron-beams for proton-induced reactions, up to 100 kW
  - Heavy elements for test of symmetries in nature
  - p-rich beams for fundamental nuclear physics/astrophysics
  - Developments of isotopes for nuclear medicine
- One electron linac beam, up to 100 kW, 35 MeV
  - Photo-fission elements of n-rich beams, astrophysics, nuclear physics
  - Li-beams for material sciences

ARIEL will be a multi-user radioactive beam facility

- Up to three independent experiments
- More time for beam developments
- Harvesting of long-lived radio-isotopes

Many exciting opportunities for Nuclear Astrophysics

TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

Canada’s national laboratory for particle and nuclear physics

Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

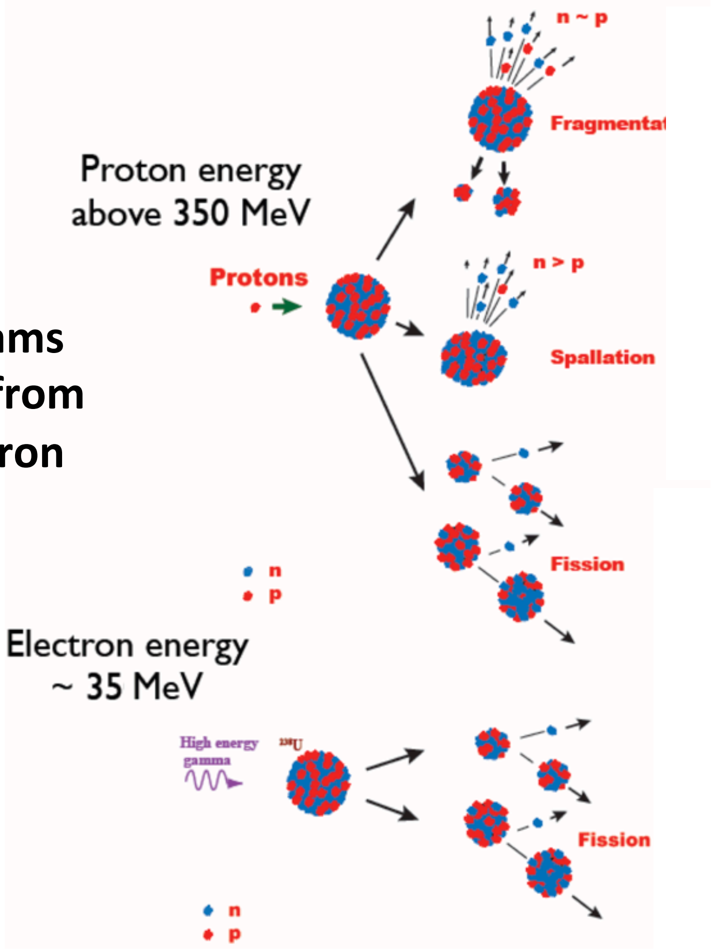
TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | McGill | Manitoba | McMaster | Montréal | Northern British Columbia | Queen’s | Regina | Saint Mary’s | Simon Fraser | Toronto | Victoria | Western | Winnipeg | York

Thank you!
Merci!

Follow us at TRIUMFLab

ARIEL rare-isotope beam production

Rare-isotope beams will be produced from proton and electron driver beams.



500MeV Protons on UCx

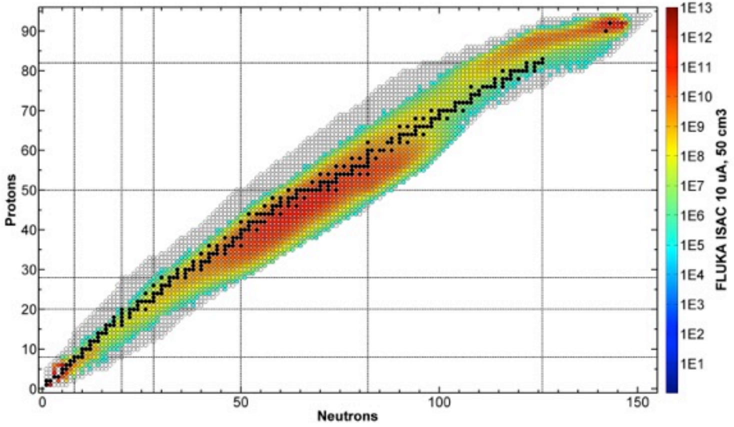
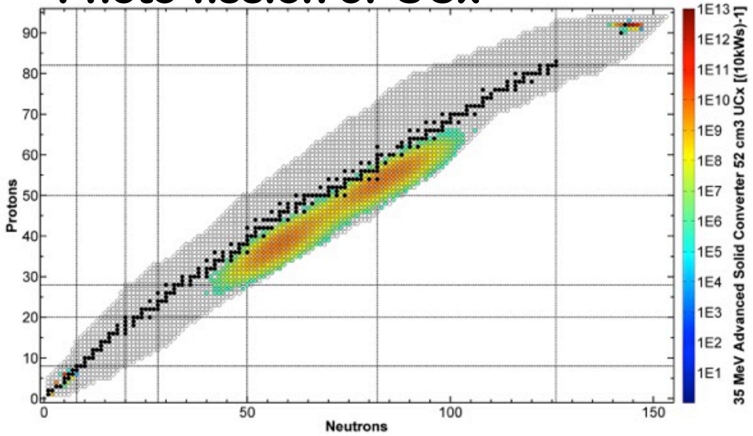
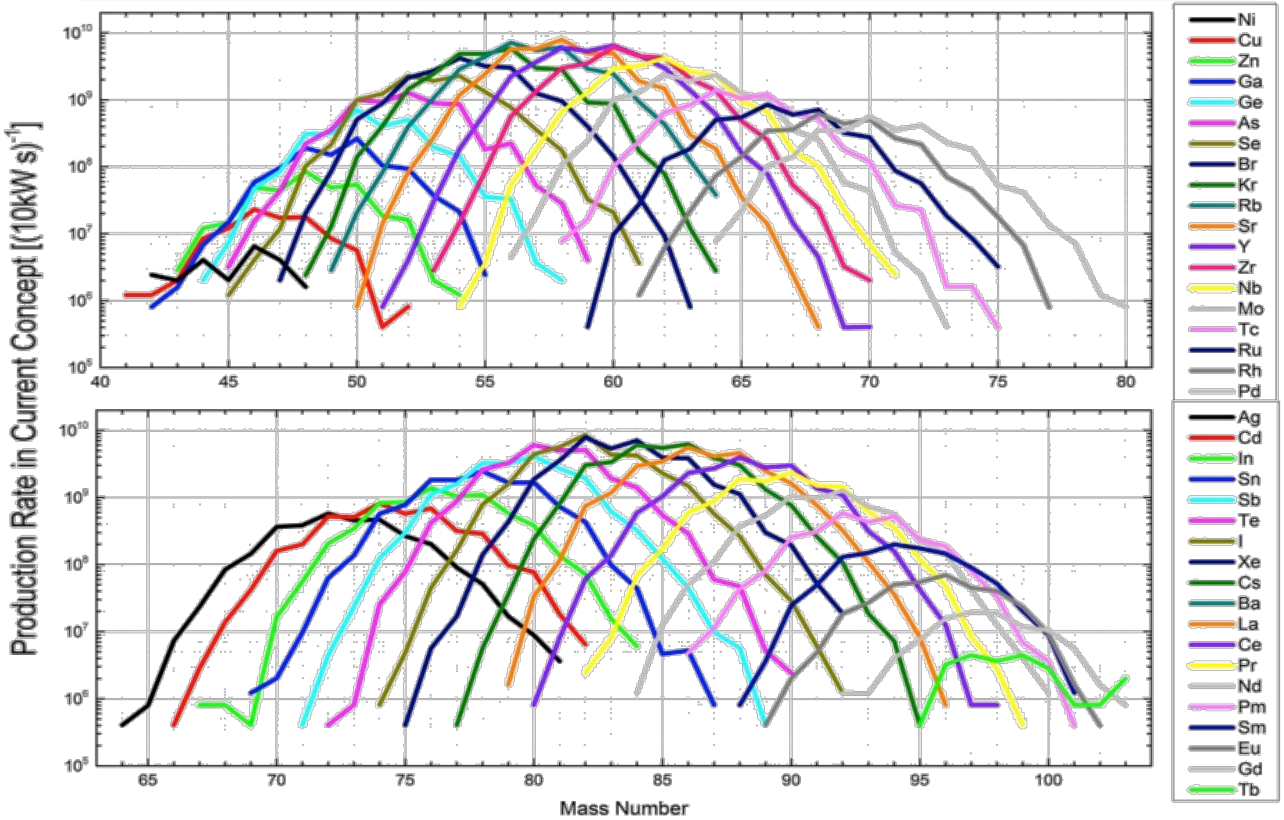


Photo-fission of UCx



FLUKA Production Map from 35 MeV Electrons

ARIEL Current Concept Design In-Target Production Yields [10 $kW^{-1} \cdot s^{-1}$]



In-target production rates [10 $kW^{-1} \cdot s^{-1}$]:

from BeO:

^{8}Li: $5 \cdot 10^{10}$

from UC$_x$:

^{78}Ni: $1 \cdot 10^{5}$

^{98}Kr: $8 \cdot 10^{7}$

^{100}Rb: $1 \cdot 10^{8}$

^{98}Sr: $5 \cdot 10^{9}$

^{132}Sn: $5 \cdot 10^{8}$

^{146}Xe: $2 \cdot 10^{7}$

^{144}Ba: $5 \cdot 10^{9}$

^{150}Cs: $4 \cdot 10^{5}$

500MeV Protons on UC$_x$:

^{78}Ni: $2 \cdot 10^{6}$

^{98}Kr: $1 \cdot 10^{8}$

^{100}Rb: $9 \cdot 10^{7}$

^{98}Sr: $1 \cdot 10^{10}$

^{132}Sn: $5 \cdot 10^{9}$

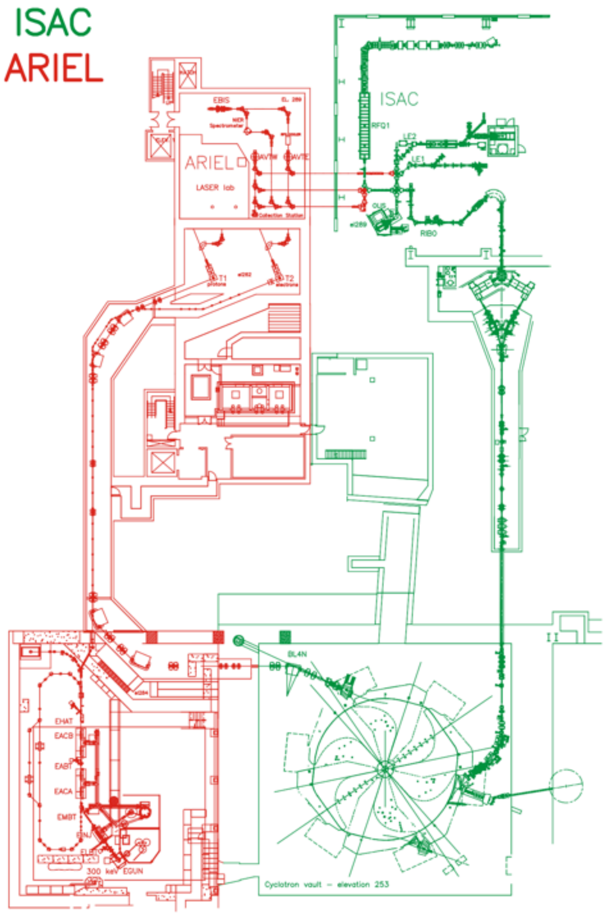
^{146}Xe: $1 \cdot 10^{7}$

^{144}Ba: $2 \cdot 10^{10}$

^{150}Cs: $5 \cdot 10^{5}$

FLUKA: A. Gottberg (TRIUMF and results verified independently with GEANT4 (Marla Cervantes Smith, University of Victoria)

ARIEL

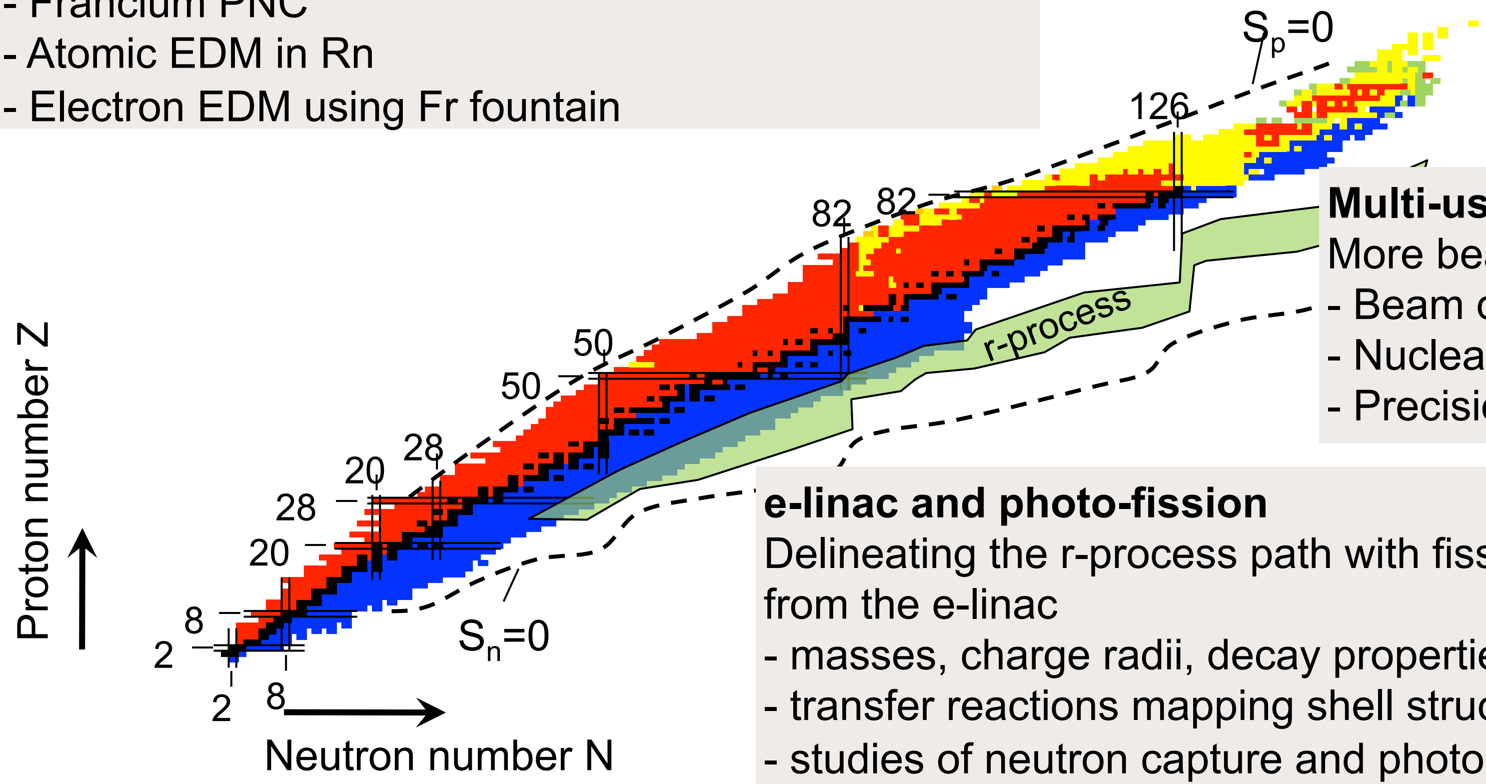


- 3 simultaneous RIB beams (1 ISAC + 2 ARIEL)
  - proton beam (ISAC east/west)
  - e-linac beam (ARIEL east)
  - proton beam (ARIEL west)
- Increased number of hours delivered per year
  - Ramp up to ~9000 RIB hrs/year
- New isotope species
  - Time for beam developments
  - Clean beam using HRS and new EBIS
- Enable long beam times
  - Nucl. astrophysics,
  - Fundamental sym. Tests

The Future: Science enabled by ARIEL

Actinide proton beam-line:
High intensity, clean beams for electroweak precision experiments using hundreds of days of beam per year
- Francium PNC
- Atomic EDM in Rn
- Electron EDM using Fr fountain

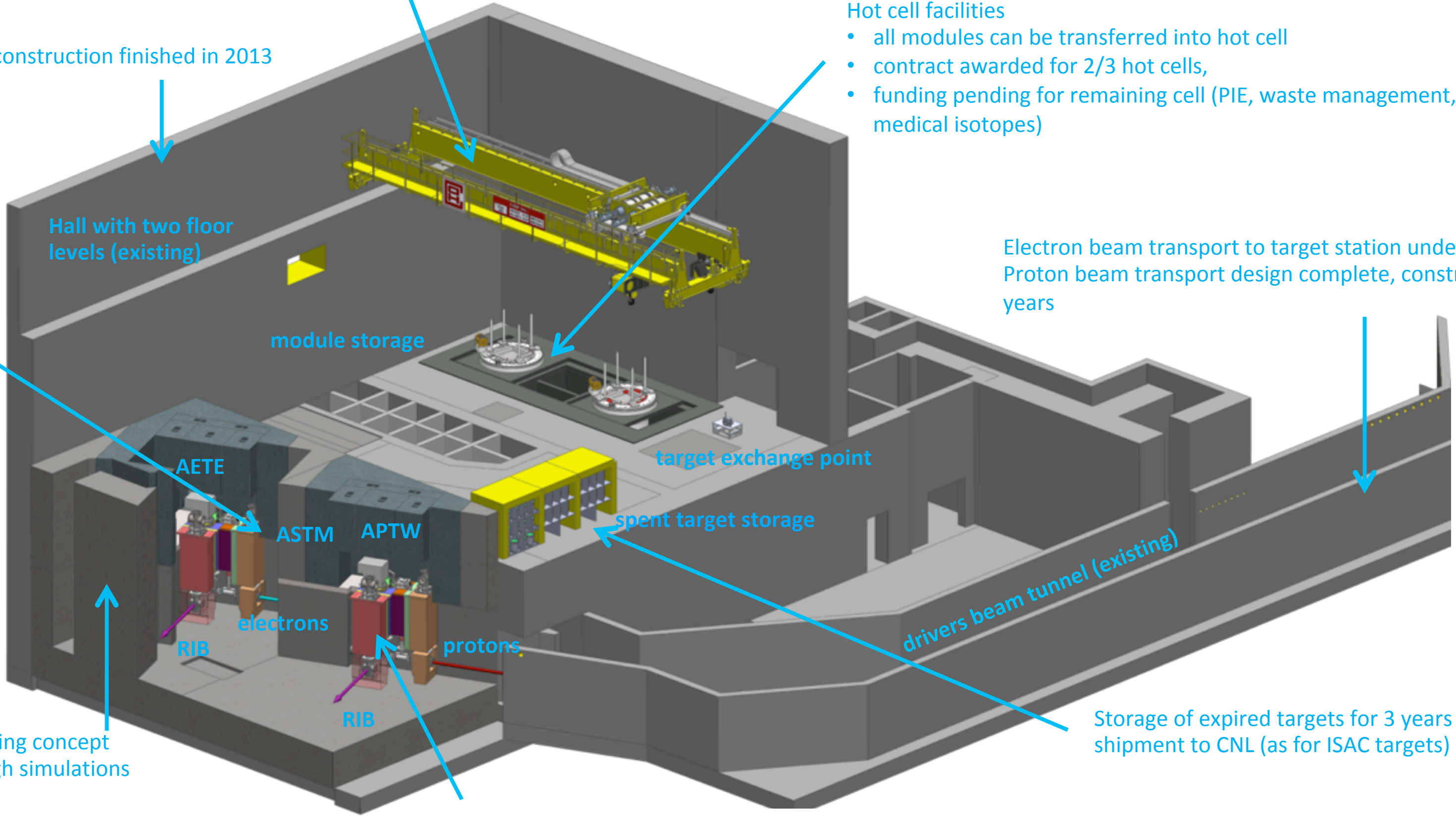
TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY



Multi-user operations:
More beam time for
- Beam development
- Nuclear astrophysics
- Precision experiments

e-linac and photo-fission
Delineating the r-process path with fission fragment beams from the e-linac
- masses, charge radii, decay properties
- transfer reactions mapping shell structure
- studies of neutron capture and photo dissociation rates

ARIEL Target Hall



Remote-controlled crane installed in 2014, following selected nuclear standards

- For most routine target hall processes
- Required for all shielding and module moves and initial installation

Hot cell facilities

- all modules can be transferred into hot cell
- contract awarded for 2/3 hot cells,
- funding pending for remaining cell (PIE, waste management, medical isotopes)

Target building construction finished in 2013

Symbiotic medical target in APTW beam dump

Electron beam transport to target station under construction
Proton beam transport design complete, construction in coming two years

Target pit shielding concept validated through simulations

Storage of expired targets for 3 years before shipment to CNL (as for ISAC targets)

All beam-critical components with life-time < 30 years are modular and serviceable in hot cell facility