

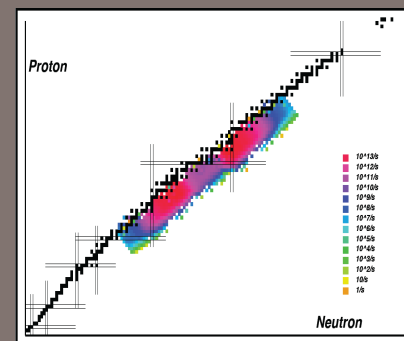
# The Advanced Rare Isotope Laboratory

## ARIEL

June 18, 2014

## Isotopes for Science and Medicine

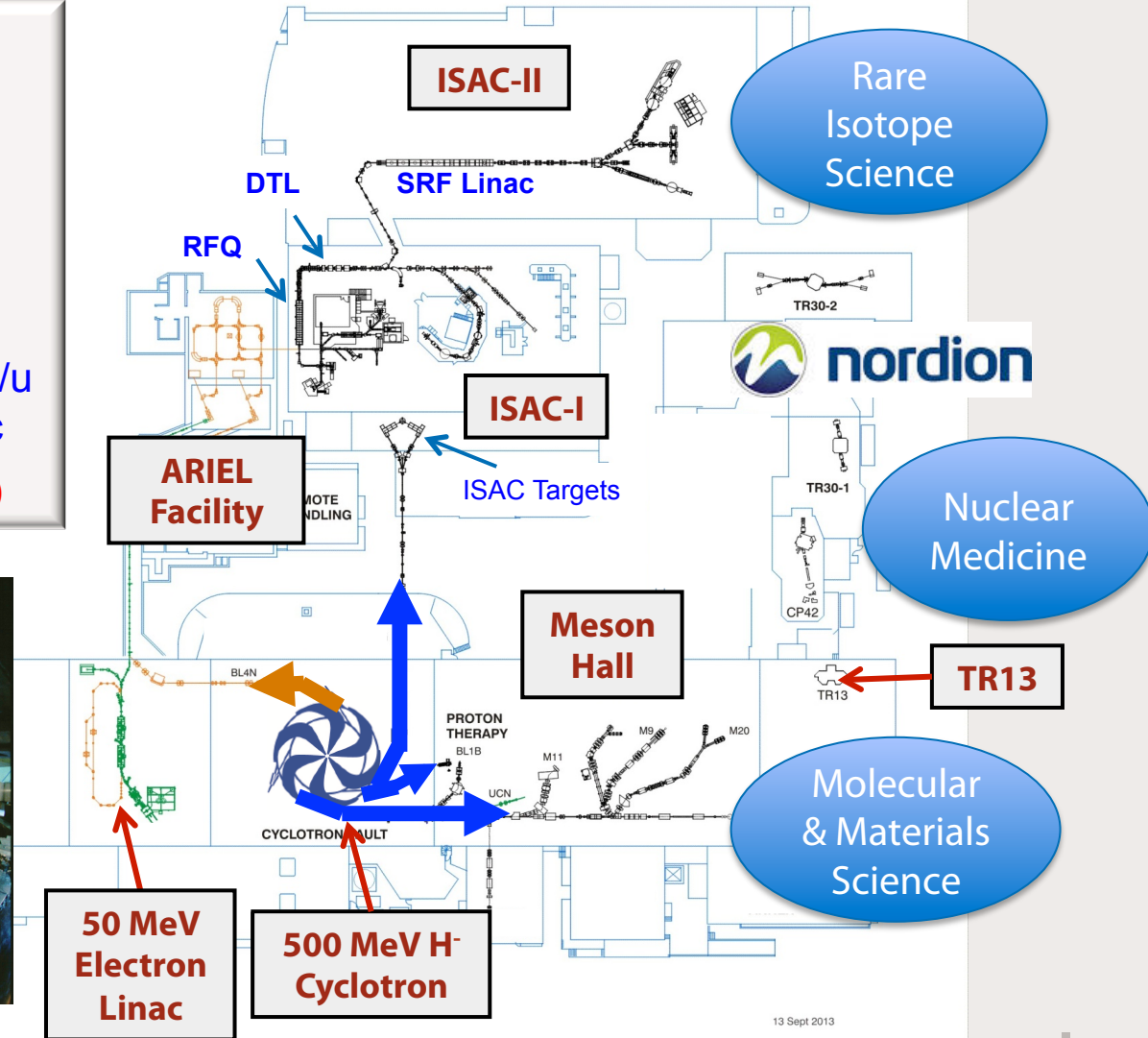
Reiner Kruecken | Science Division Head | TRIUMF  
Professor of Physics | University of British Columbia



# TRIUMF accelerator complex

## TRIUMF Accelerators:

- 500 MeV, 350 $\mu$ A, H<sup>-</sup> cyclotron
- 4 medical isotopes cyclotrons (TR13, CP42, TR30x2)
- ISAC 50kW ISOL facility
  - RFQ,  $3 \leq A/q < 30$
  - DTL,  $A/q \leq 7$ , 0.1-1.8 MeV/u
  - 40 MV Heavy Ion SC linac
- **ARIEL e-linac (10mA, 50 MeV)**



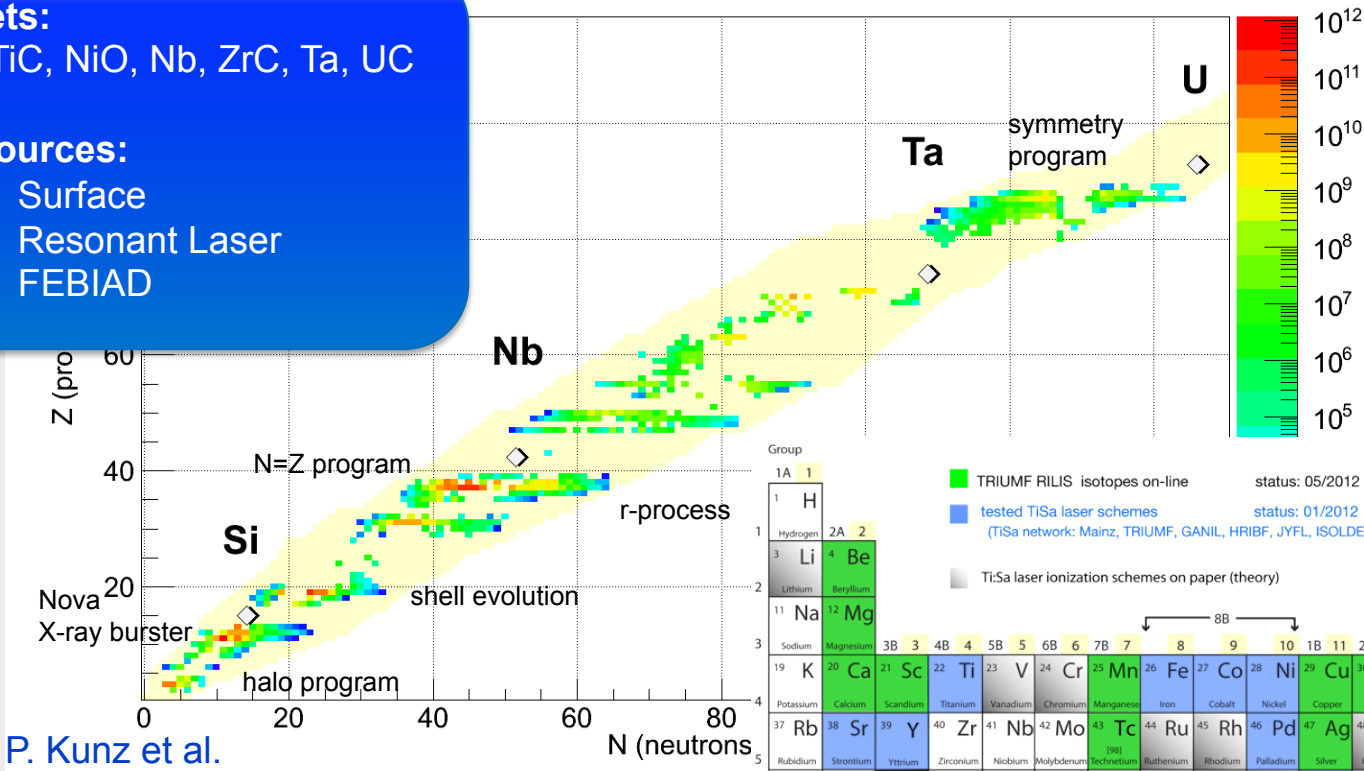


**Targets:**  
SiC, TiC, NiO, Nb, ZrC, Ta, UC

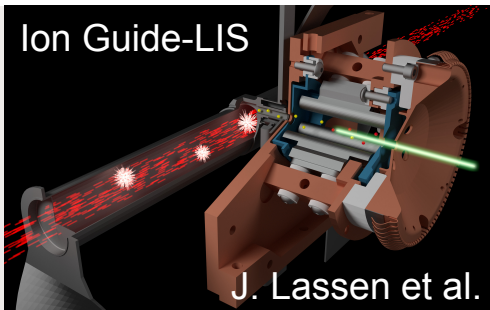
**Ion sources:**

- Surface
- Resonant Laser
- FEBIAD

Yield Chart of Nuclides



P. Kunz et al.



J. Lassen et al. - ARIEL - CAP 2014

■ TRIUMF RILIS isotopes on-line status: 05/2012  
■ tested TiSa laser schemes status: 01/2012 (TiSa network: Mainz, TRIUMF, GANIL, HRIBF, JYFL, ISOLDE)  
■ Ti:Sa laser ionization schemes on paper (theory)

J. Lassen et al.

1A 1	2A 2	3B 3	4B 4	5B 5	6B 6	7B 7	8	9	10	11B 11	12B 12	13A 13	14A 14	15A 15	16A 16	17A 17	18A 18																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
1 H	4 Be	11 Na	12 Mg	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112	113	114	115	116 Lv	117 Ts	118 Og	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000

# Isotopes for Science and Medicine

## Isotopes for developing a standard model for nuclear physics:

- probing ab-initio theory in light and medium-mass nuclei
- understanding the role of 3N forces in the shell evolution of nuclei

Nuclear Structure

## Isotopes as laboratories search for new forces in nature:

- Setting world-leading limits on physics beyond the standard model
- Developing leading EDM experiments for the atom (RnEDM) and electron (FrEDM)

Fundam. Symmetries

## Isotopes to determine the origin of the heavy elements in the universe:

- Understanding the nucleosynthesis in nova and x-ray bursters
- Delineating the r-process path and identifying its astrophysical origin

Nuclear Astrophysics

## Isotopes as probes of magnetism at interfaces and surfaces:

- Expanded user program in depth controlled  $\beta$ -NMR
- Understand magnetic and electronic properties of surfaces and interfaces
- Develop better battery materials

Materials Science

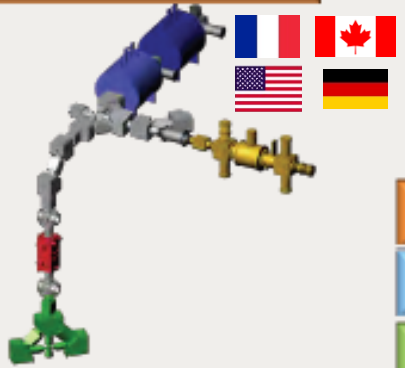
Nuclear Medicine

## Isotopes for molecular imaging of diseases and treatment of cancer:

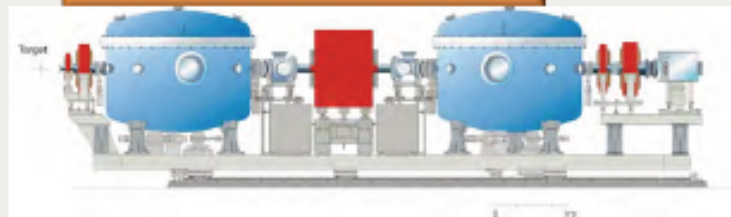
- Produce research quantities of alpha emitting isotopes for targeted alpha tumor therapy
- Develop new designer isotopes for diagnostics and treatment

# ISAC Experimental facilities and programs

TITAN Penning Trap facility



EMMA recoil mass analyzer

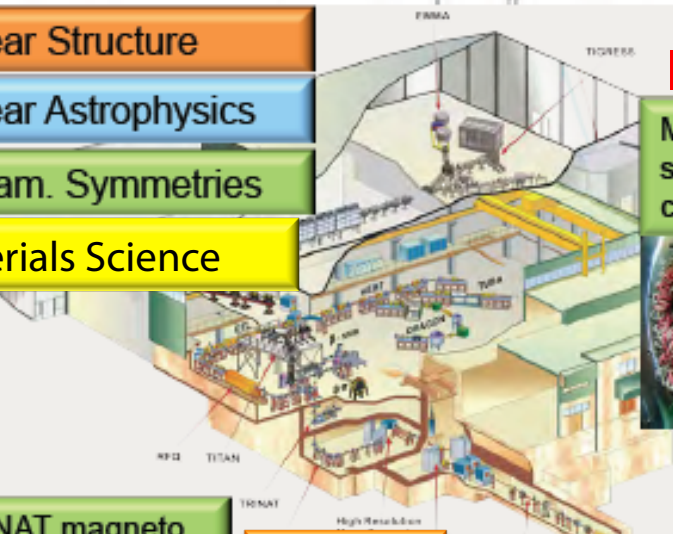


TIGRESS in-beam gamma-ray spectrometer

- Nuclear Structure
- Nuclear Astrophysics
- Fundam. Symmetries
- Materials Science



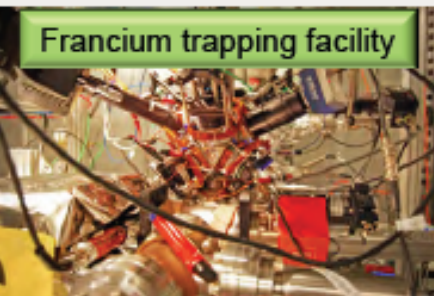
Laser polarizer line



MTV Mott scattering drift chamber



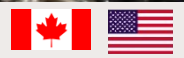
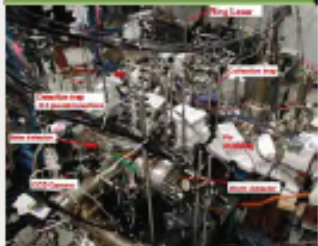
IRIS solid hydrogen reaction set-up



Francium trapping facility



TRINAT magneto optical trap



DESCANT



GRIFFIN



DRAGON recoil separator

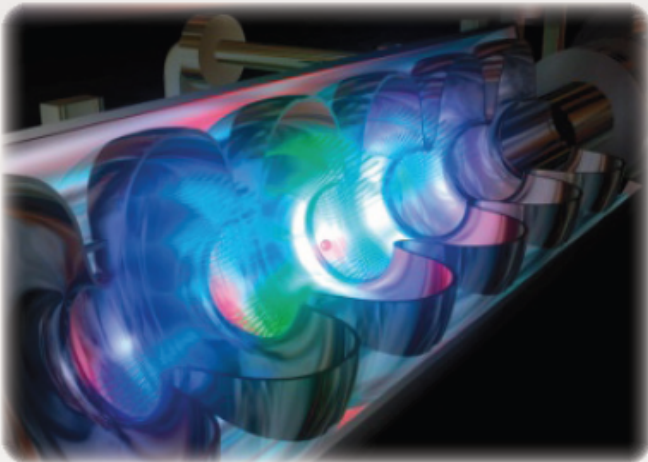


TUDA reaction setup



 **TRIUMF** **ARIEL**

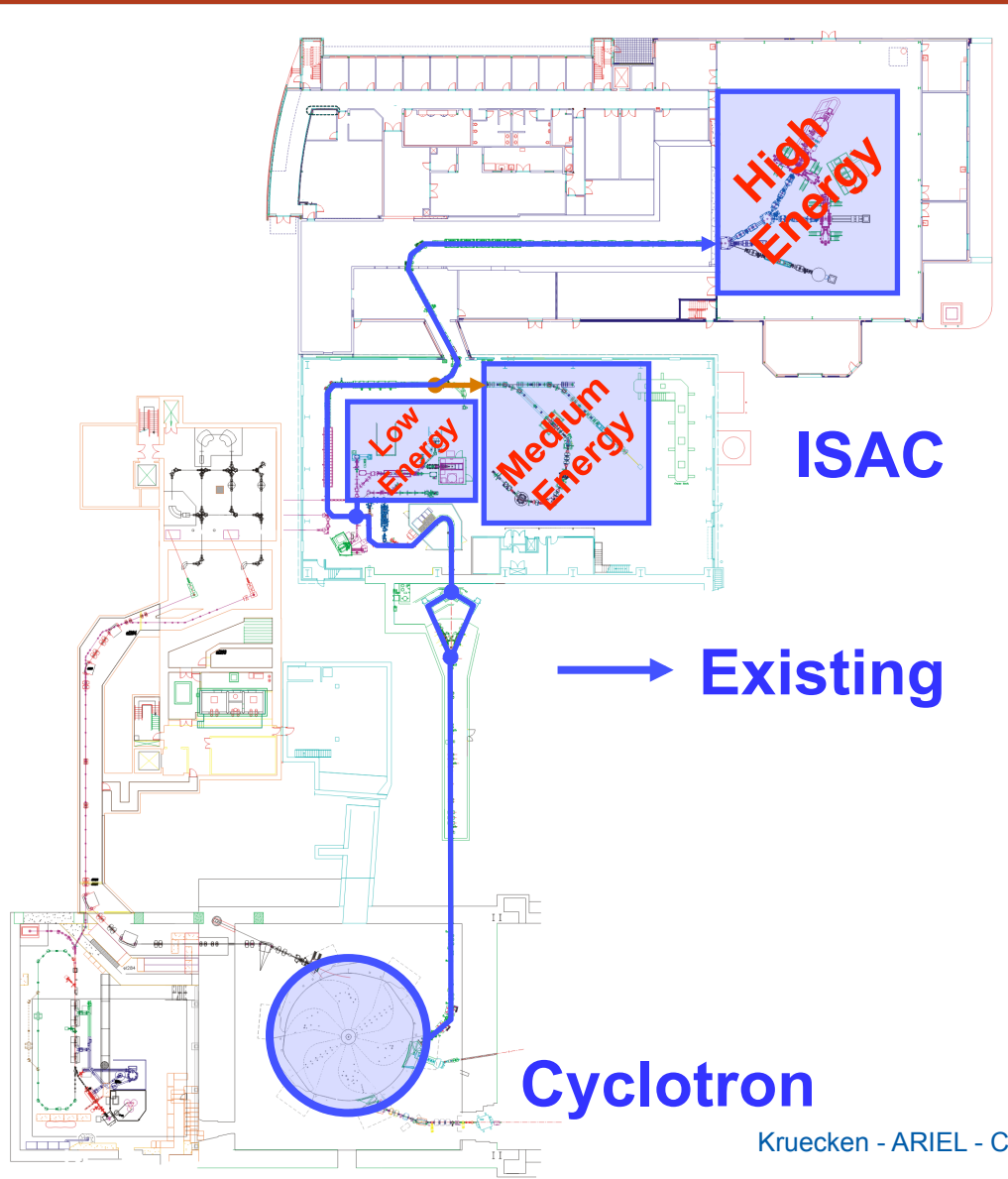
ADVANCED RARE ISOTOPE LABORATORY



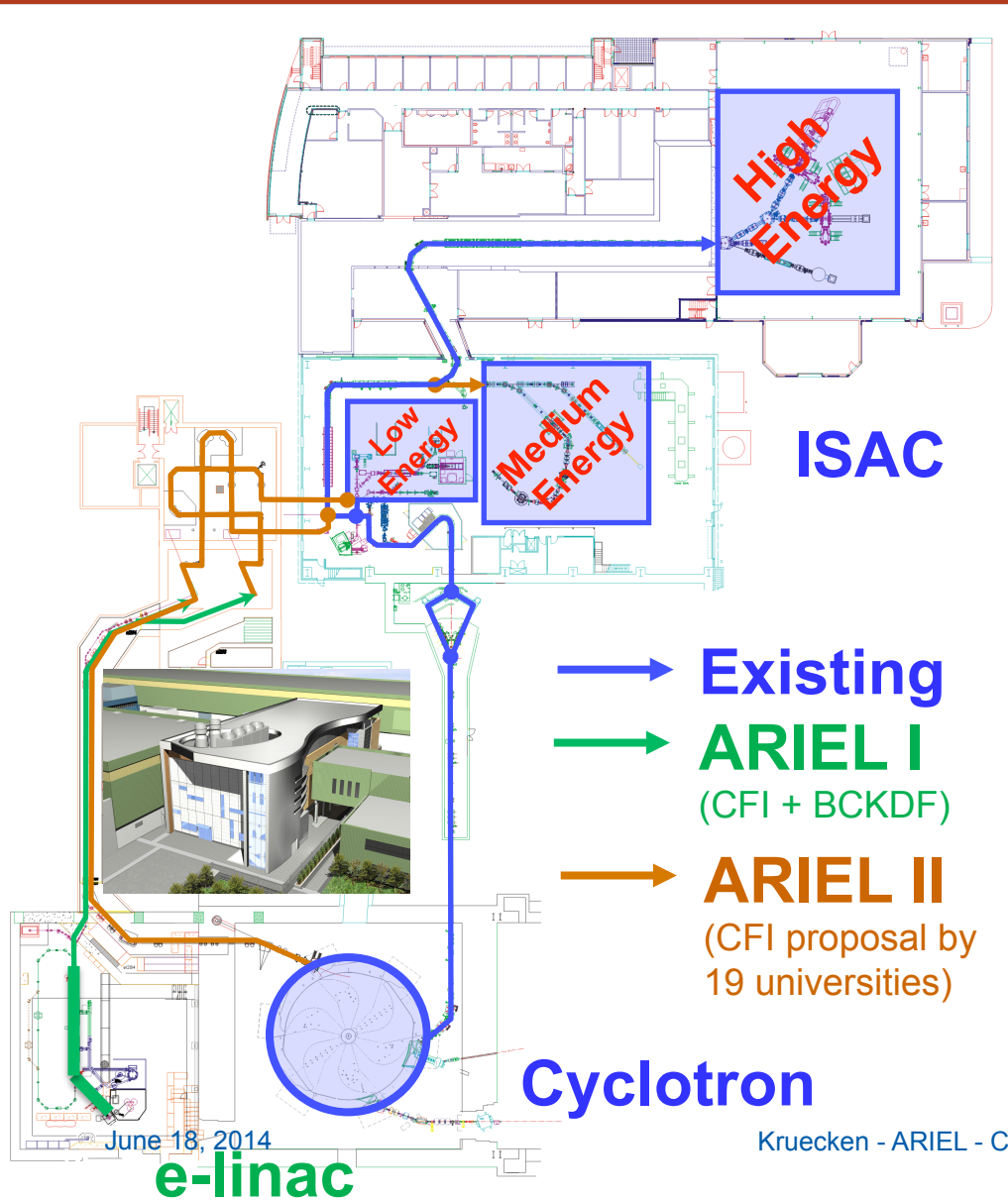
ARIEL will be TRIUMF's flagship Rare Isotope Beam facility for the production of isotopes for science and medicine. ARIEL uses proton-induced spallation and electron-driven photo-fission of ISOL targets for the production of short-lived, rare isotopes that are delivered to multiple experiments simultaneously at the ISAC facility.



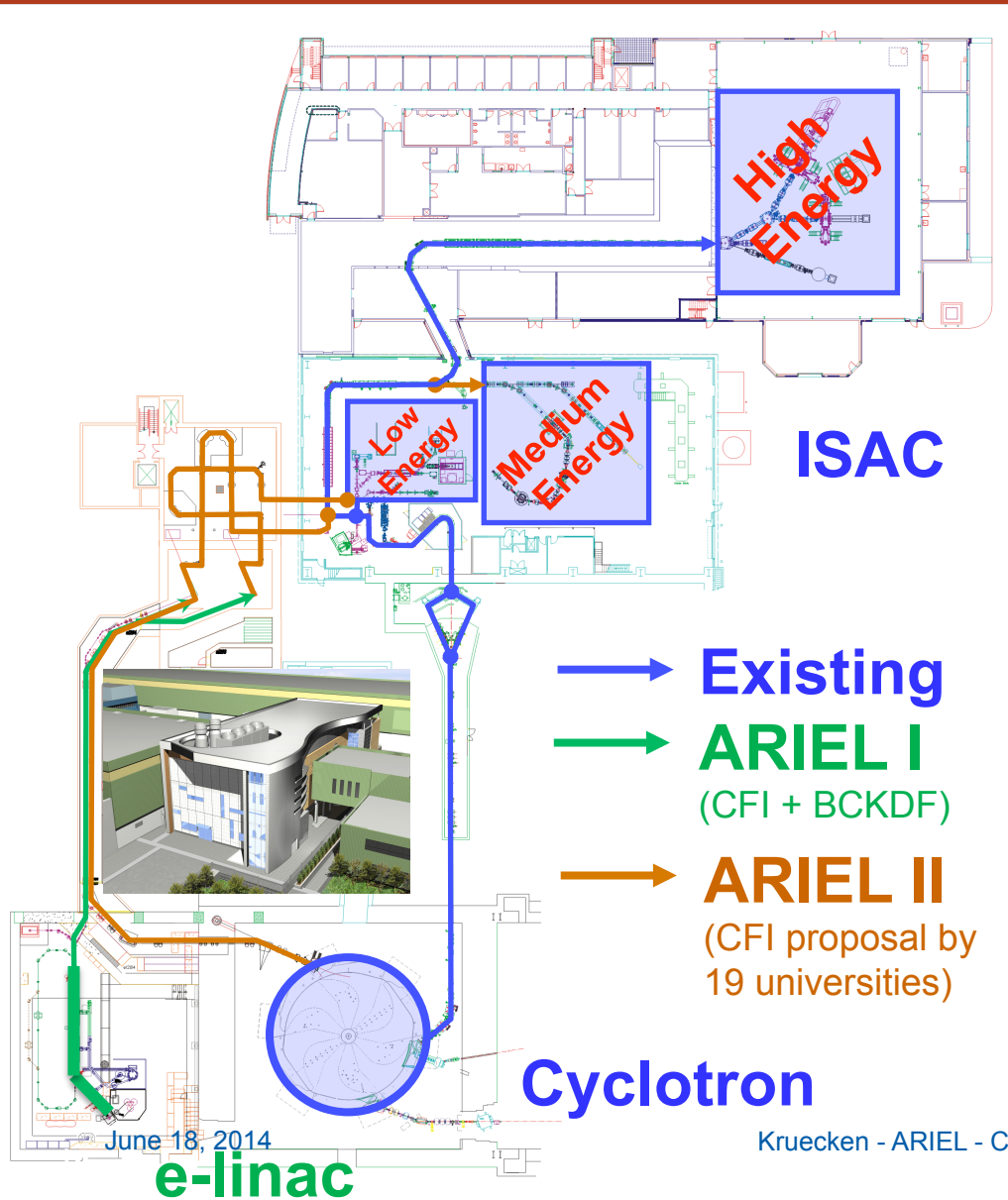
# Advanced Rare Isotope Laboratory



# Advanced Rare Isotope Laboratory



# Advanced Rare IsotopE Laboratory



Completing & operating ARIEL absolutely central to realizing laboratory vision:

**Global leadership for Canada in Isotopes for Science & Medicine**

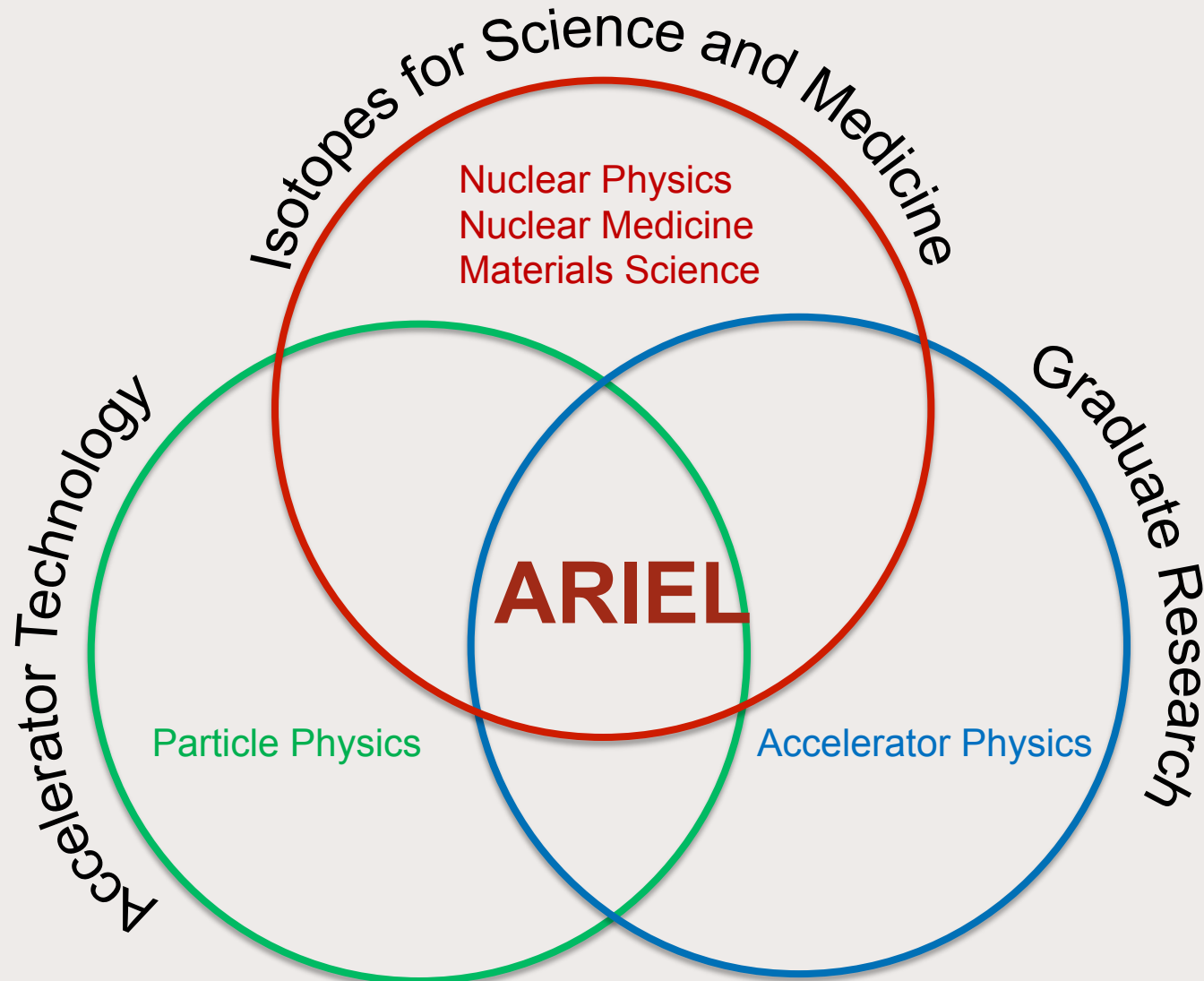
**Substantially expands capabilities:**

- Three simultaneous beams
- More and new isotopes
- Enables new experiments
- Expands national & international users
- International partnership w/ India
- World-leading capabilities
- Serves Canada and society

**Implementation:**

- Two new drivers: electron & proton
- Two new target stations and front end
- **Interleave science with construction**

# ARIEL: Synergies & Connections

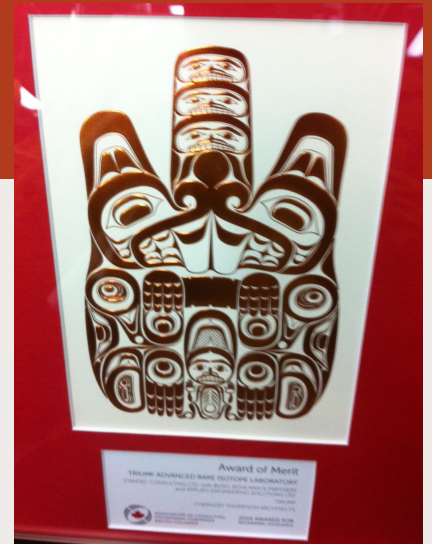




# ARIEL Buildings Occupancy



**ACEC-BC\*  
Award of  
Merit, 2014  
April 11**



- **Culmination of 3 years work**
- **Meets needs of entire ARIEL scope**

\*Association of Consulting Engineering Companies of BC.

# e-linac: MW-class Superconducting Electron Accelerator

Kinetic energy (MeV)	50
Average current (mA)	10
Duty Factor	100%
Beam Power (MW)	0.5

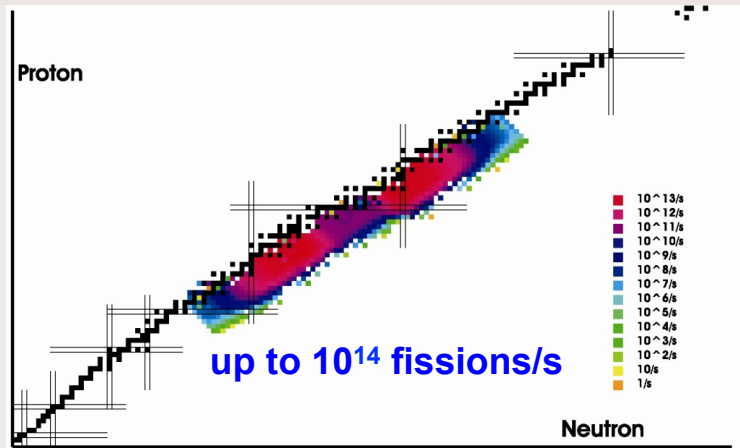
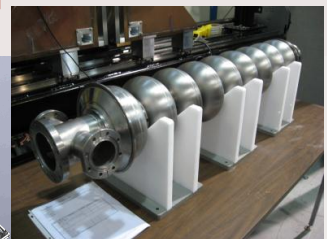
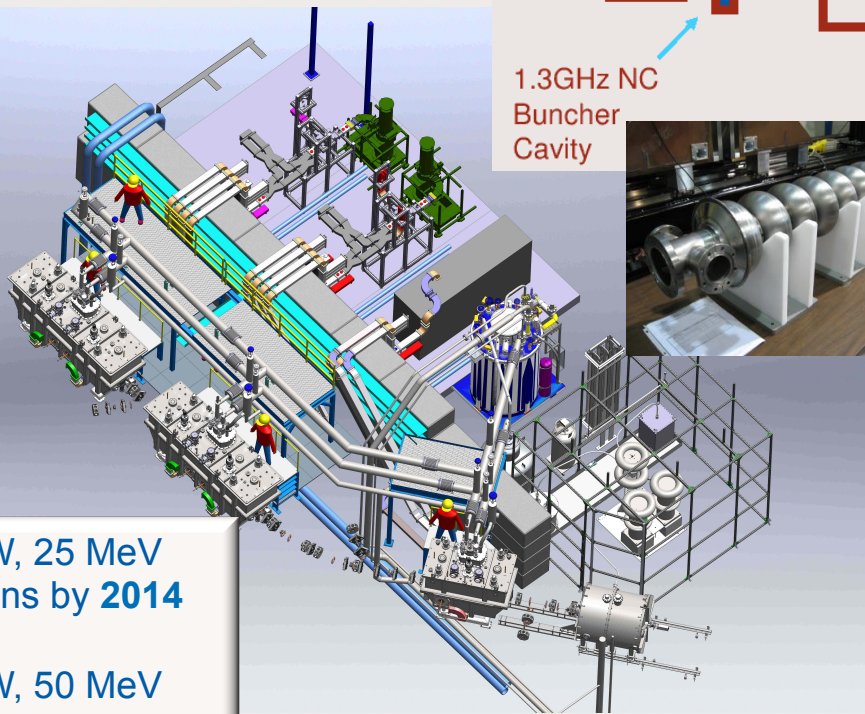
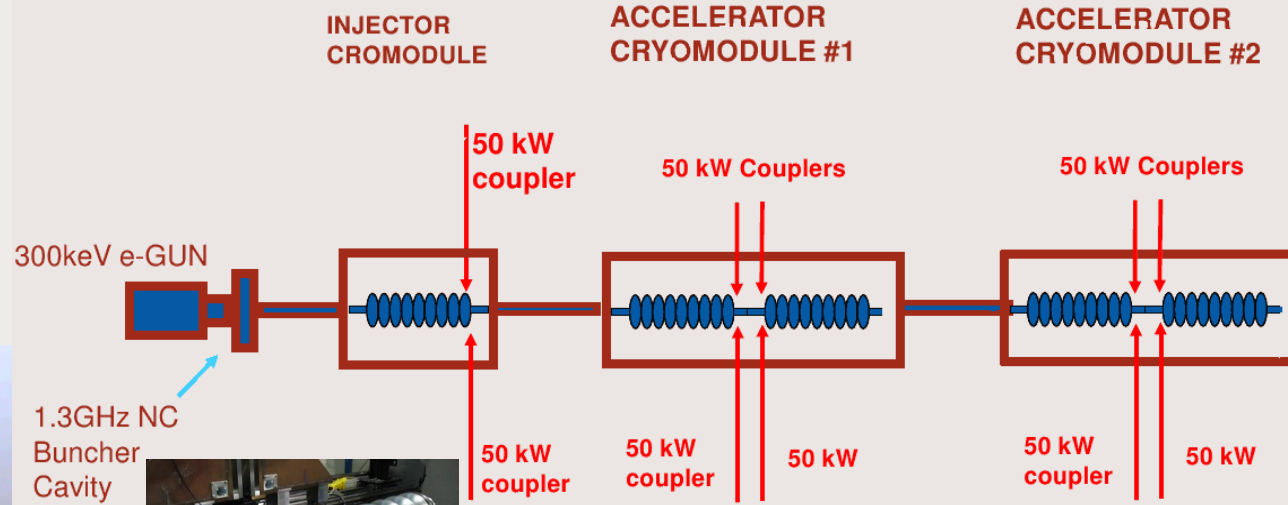


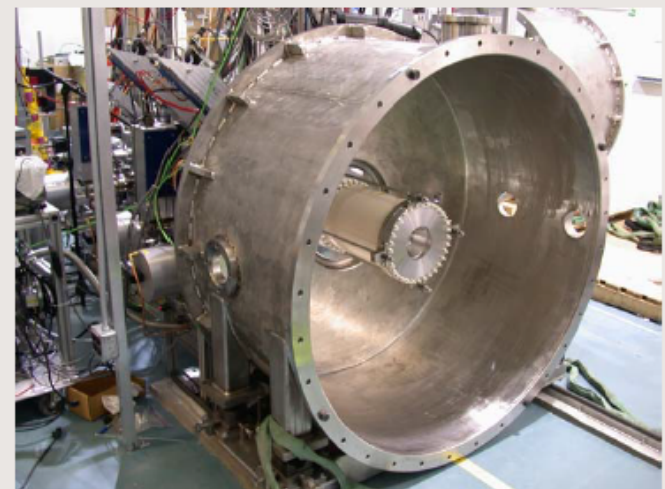
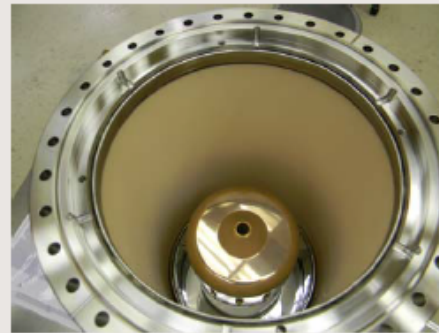
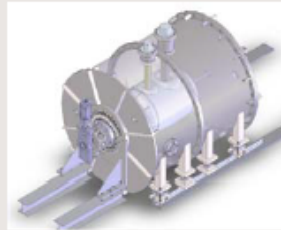
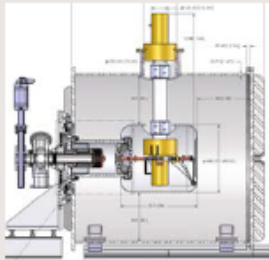
Photo-fission products using 50 MeV 10 mA electrons onto Hg convertor &  $UC_x$  target.

100 kW, 25 MeV electrons by **2014**  
 500 kW, 50 MeV electrons by **~2020**



# 300 kV electron gun

- 10 mA thermionic gridded gun, emittance  $5 \mu\text{m rms}$
- RF modulated grid at 650 MHz
- Use of dielectric waveguide to transmit modulation from ground potential to gun
- Gun commissioning June 2013



# “Made in Canada” Superconducting RF Cavities

## Multi-cell SRF cavity fabrication by PAVAC, Inc.

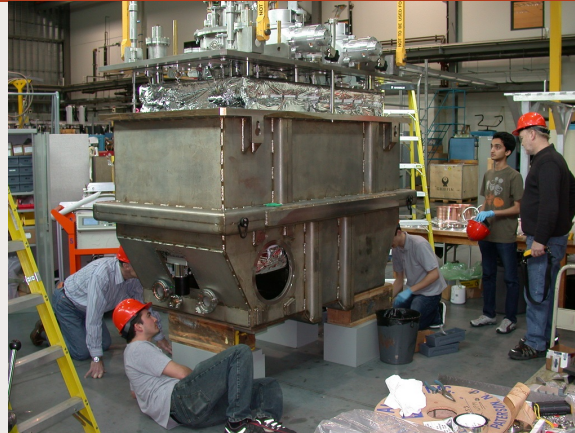
### Status:

- Three cavities delivered
- One more in fabrication

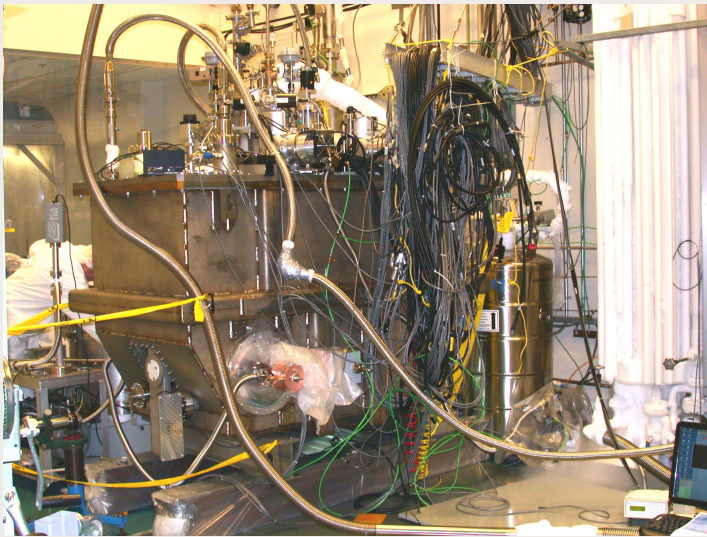




# Injector CM Final Assembly & Cold 2K Test



2014/04/07  
Cold mass  
in cryostat



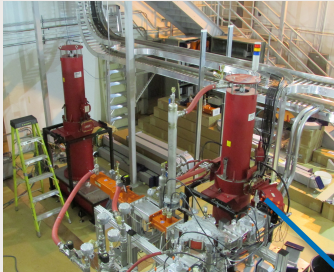
Cold test start 2014/04/17

2014/04/25 2K cold test complete.



# e-linac progress

Klystrons



Cryogenics infrastructure



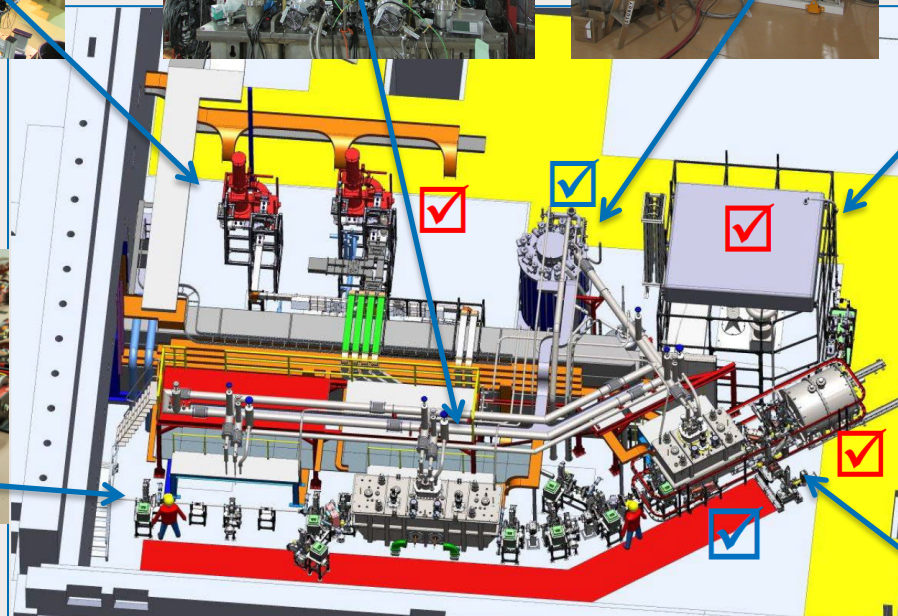
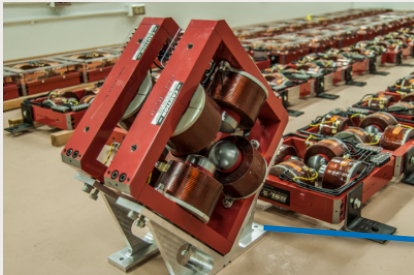
LHe cold box



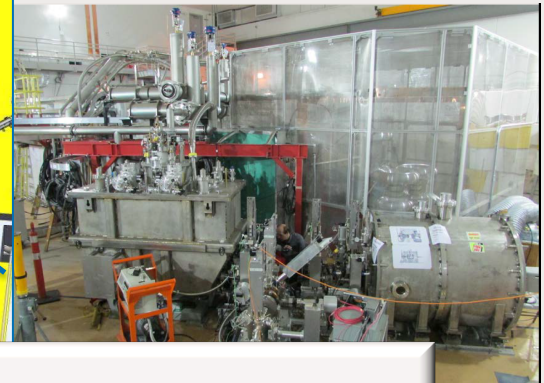
e-Gun HV power supply



Beamline magnets



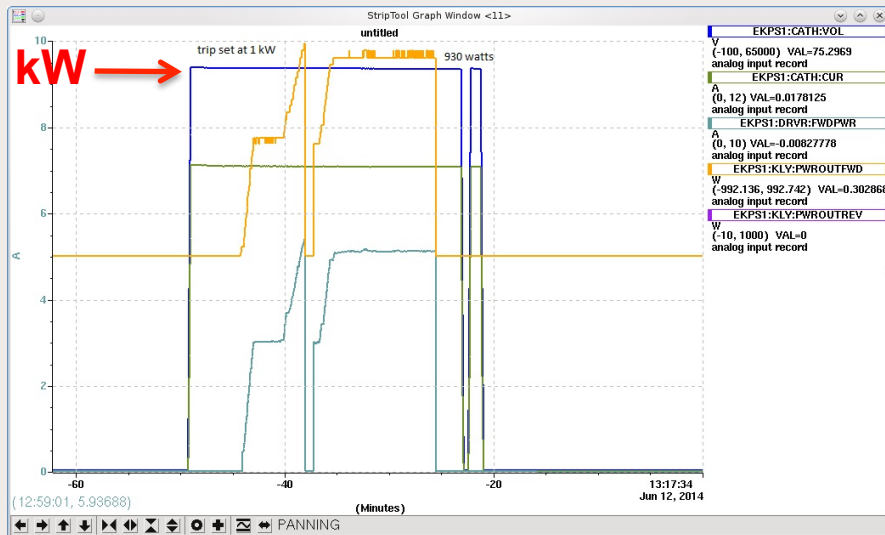
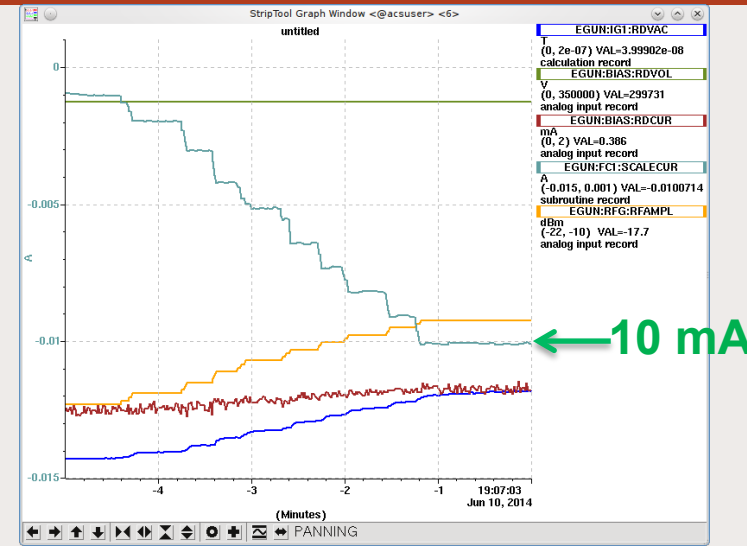
e-Gun and injector cryomodule



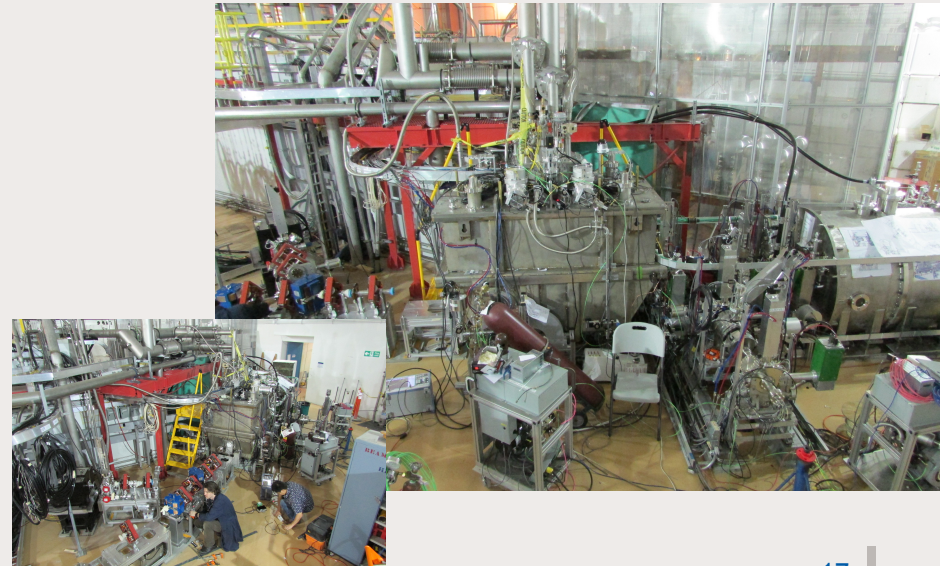
- E-gun and injector cryomodule installed in e-hall
- Commissioning started (CNSC license for 3kW, 10mA egun, 4K cooldown of ICM)
- On track for fall delivery of 25MeV, 100kW beam

# ARIEL e-Linac: Installation & Commissioning Status

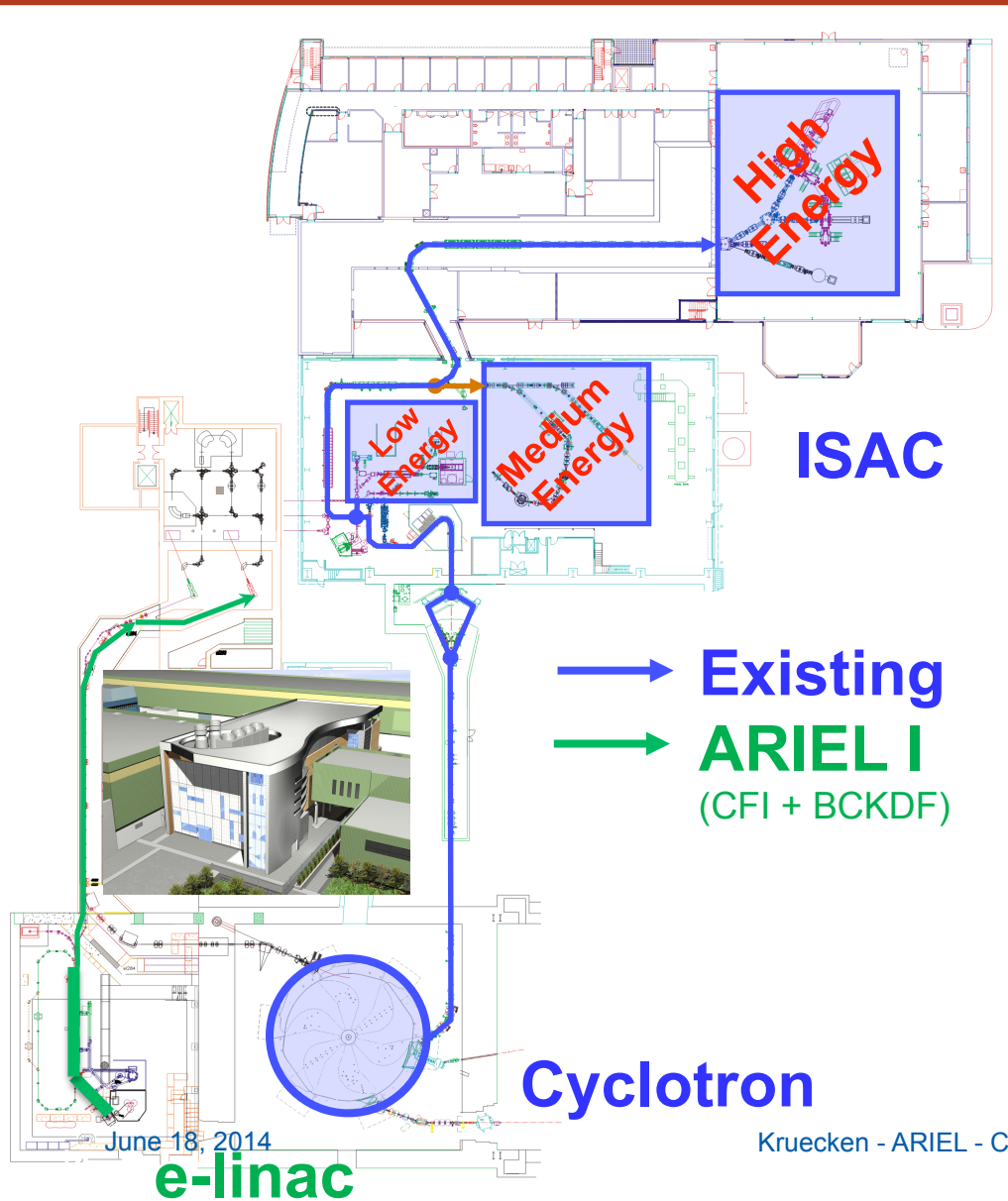
- Electron source operated at 300 kV, up to 10 mA peak current @ 1% duty factor
- Klystron integrated RF system test has been completed at 1kW level
- RF delivered to cavity on resonance at 4K
  - Cavity RF field sustained in self-excited loop in accelerating mode
- Next steps: lock the field in amplitude and phase, at 4 or 2K – increase gradient to 10MV/m



June 17, 2014



# Advanced Rare Isotope Laboratory



Completing & operating ARIEL absolutely central to realizing laboratory vision:

**Global leadership for Canada in Isotopes for Science & Medicine**

**Substantially expands capabilities:**

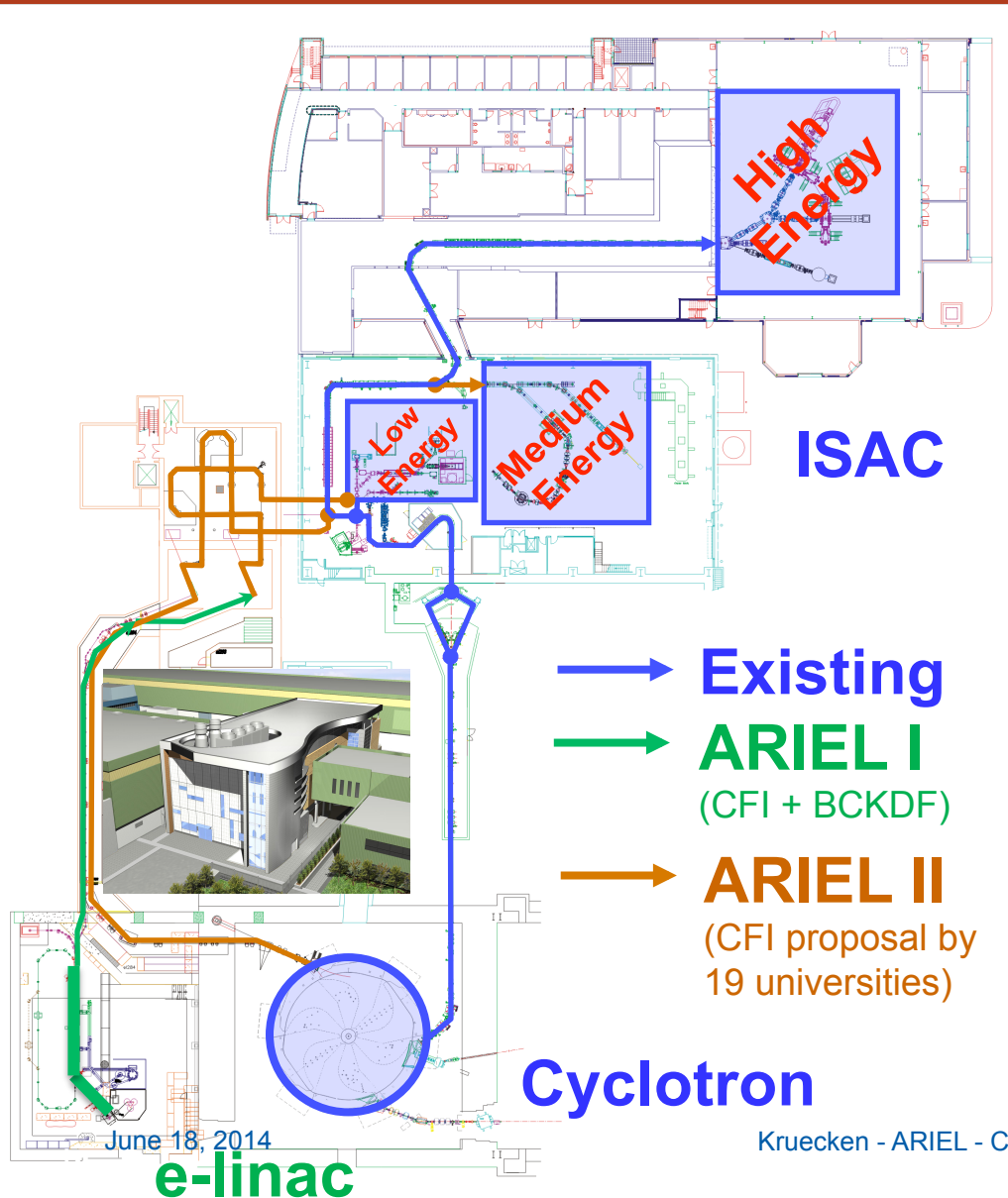
- Three simultaneous beams
- More and new isotopes
- Enables new experiments
- Expands national & international users
- International partnership w/ India
- World-leading capabilities
- Serves Canada and society

**Implementation:**

- Two new drivers: electron & proton
- Two new target stations and front end
- **Interleave science with construction**



# Advanced Rare IsotopE Laboratory



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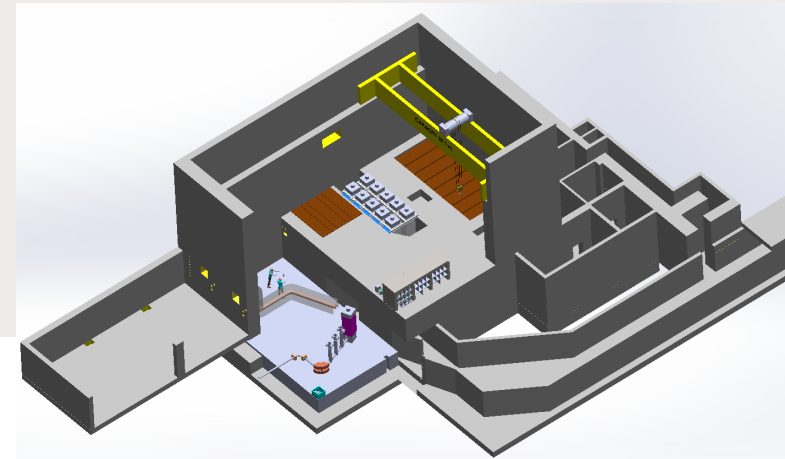
**Implementation:**

- Two new drivers: electron & proton
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# Phase 1: Li-8 for $\beta$ -NMR

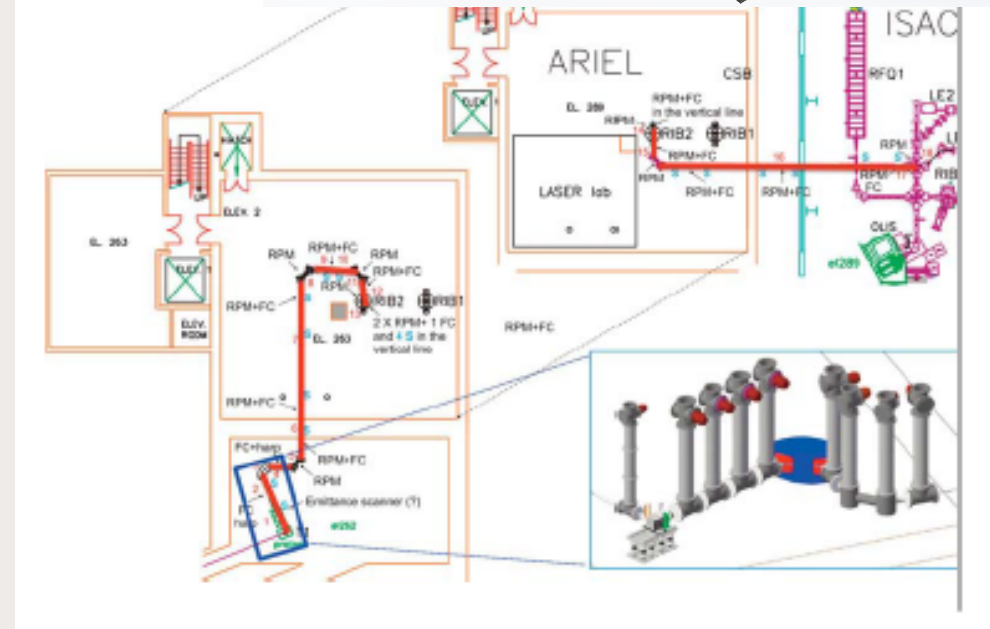
## Goals:

- Photo-production of Li-8 in a Be-9 target using bremsstrahlung photons produced by stopping 100 kW electron beam in a solid metal target, and delivered to  $\beta$ -NMR.



## Requires:

- ARIEL e-linac 30 MeV 100 kW
- Non-actinide target station with solid converter
- Pre-separator & beamline to  $\beta$ -NMR



# ARIEL II Phase 1: VECC MoU ADD-3

Phase 1 will be done in collaboration with VECC - Kolkata:

- In August 2013 MoU Add-3 was signed
- Scope includes two ARIEL target modules, tested in ARIEL, and front-end beamlines



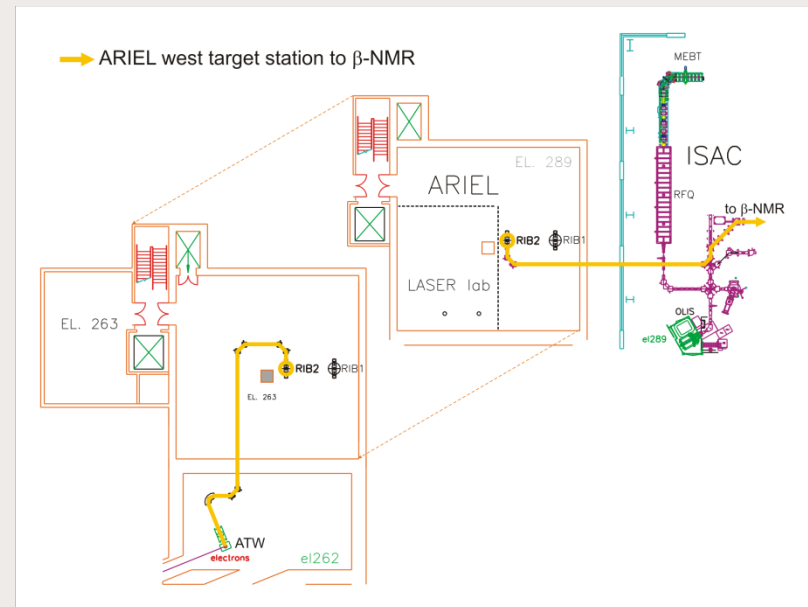
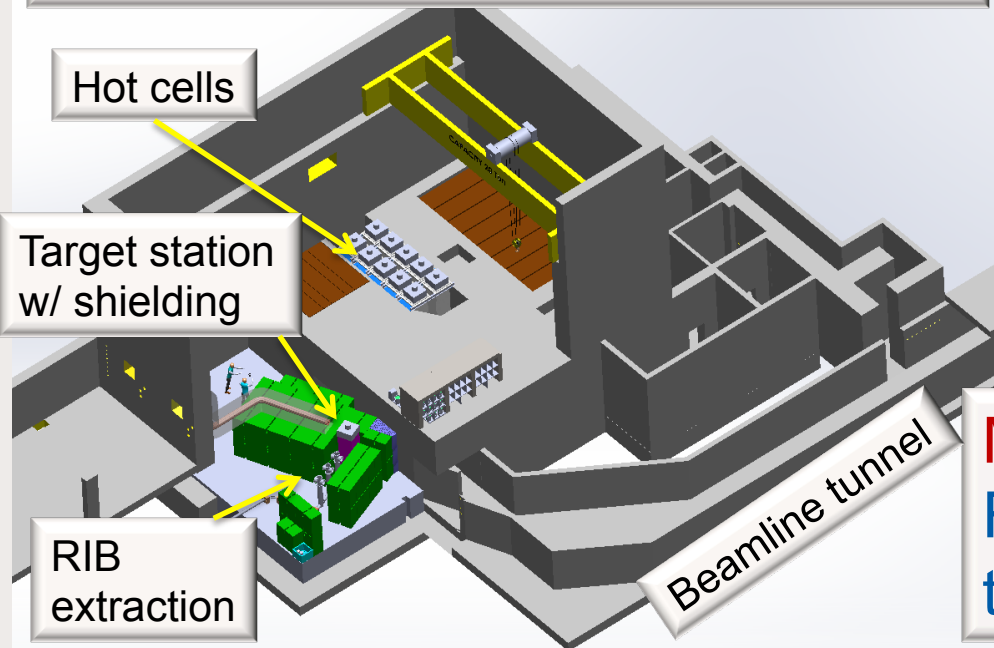
# Phase 2: Photo-fission for r-process studies

## Goals:

- Production and delivery of neutron-rich fission fragments by implementing actinide targets in conjunction with the solid photo-converter.

## Requires:

- east target station w/ actinides
- hotcell for work w/ actinides
- Medium Resolution Separator



## Milestones:

First photofission beams from the e-linac to ISAC

# Phase 3: Purified accelerated high mass RIBs

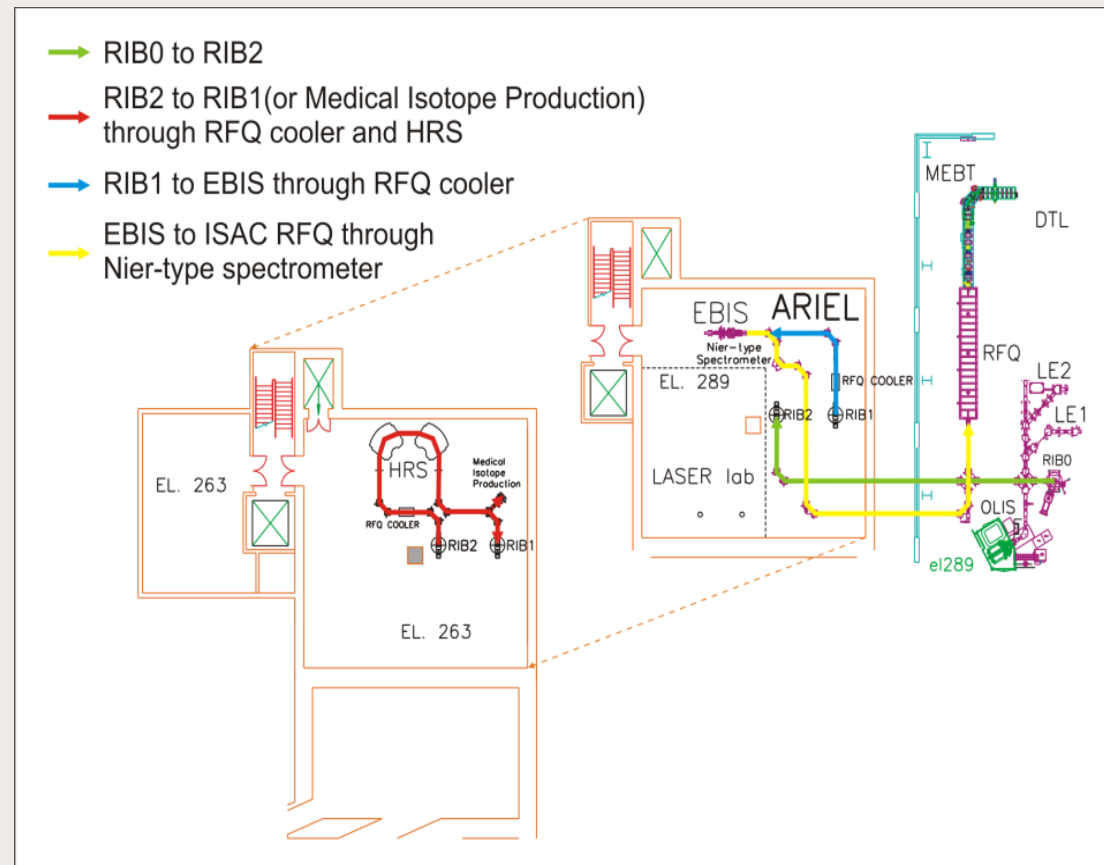
## Goals:

- Transport ISAC RIBs with  $A > 29$  to the ARIEL building for advanced purification & charge breeding and deliver them to the ISAC energy experimental areas.
- A collection station for medical isotopes will be implemented.

**CFI-funded CANREB project** provides the essential components required for the ARIEL front-end: EBIS, HRS, RFQ cooler.

**Requires (within ARIEL II):**

- 60 m LEBT beamlines





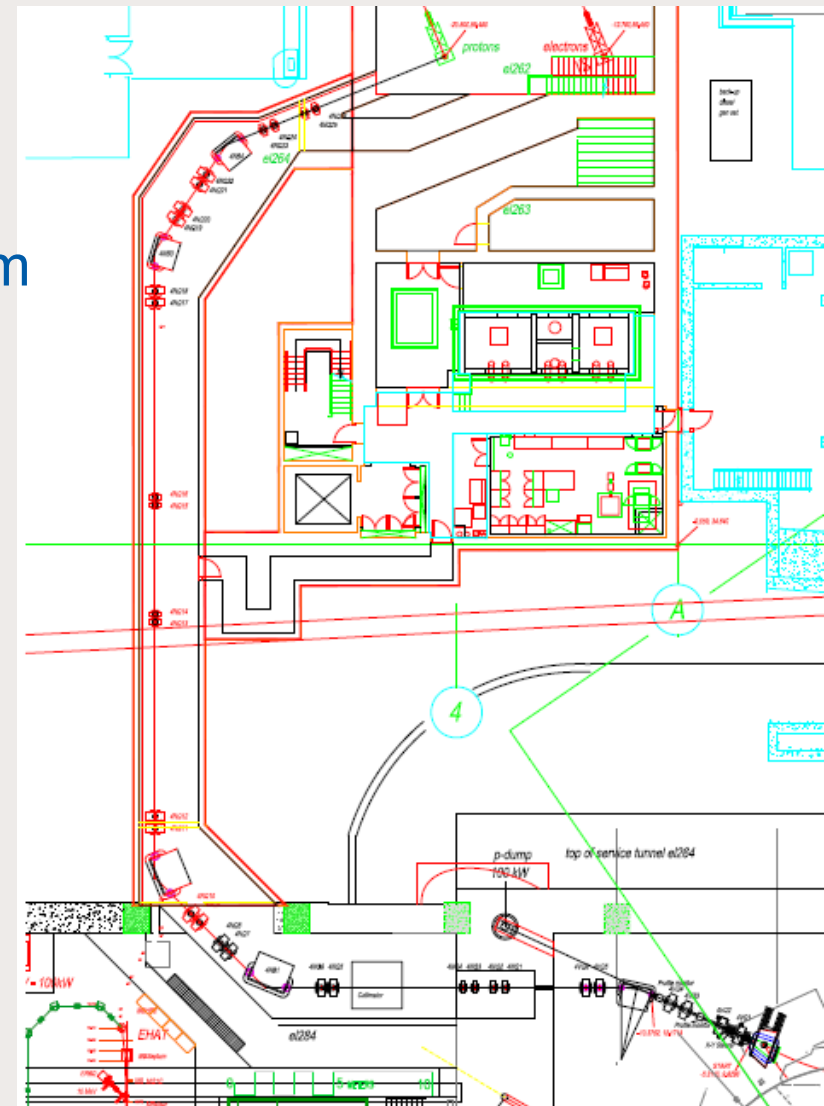
# Phase 4: Actinide Production for Fundamental Symmetry Tests

## Goals:

- Implement new proton beamline (BL4N) from cyclotron, delivering up to  $100\ \mu\text{A}$  at  $500\ \text{MeV}$  of proton beam to the West Target Station.

## Requires:

- Proton beamline BL4N



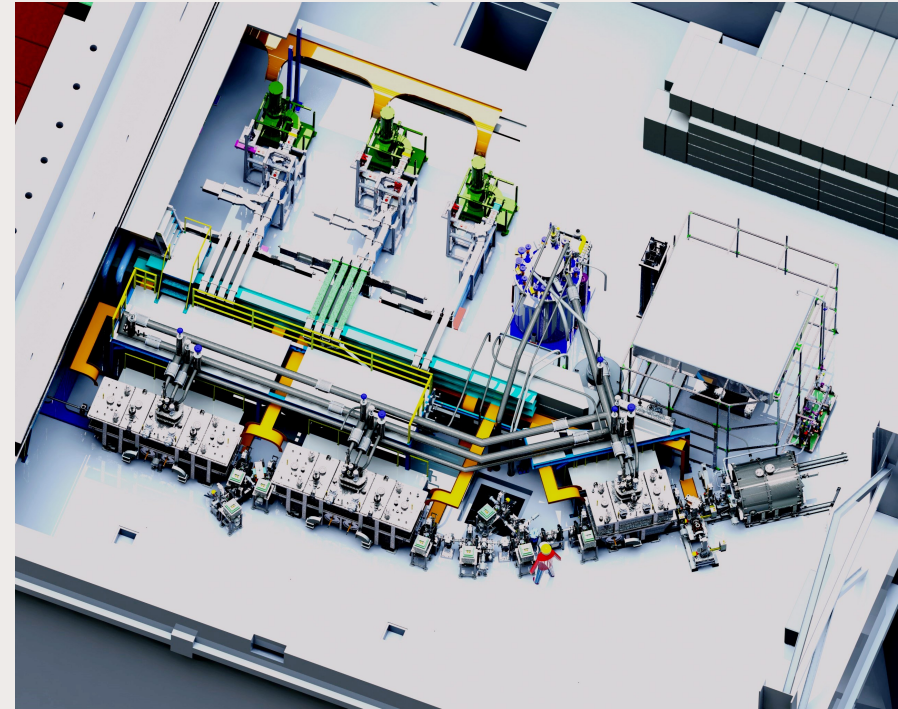
# Phase 5: Full power e-linac to reach most exotic neutron rich nuclei

## Goals:

- Increase the energy and power of the e- linac beam to full design specification **50 MeV, 500kW**, producing up to  $10^{14}$  fissions per second.

## Requires:

- additional Accelerator Crymodule w/ 2 cavities
- additional klystron



# ARIEL-II Science Drivers & Implementation Criteria

## Science Drivers

1. Increased beam time to  $\beta$ -NMR for full user program
2. Pure, heavy mass accelerated RIBs (from ISAC & ARIEL)
3. Reaching the r-process using photo-fission (w/ highest beam energy)
4. Enable long beam times for Fundamental Symmetries & Nuclear Astrophysics
5. Isotopes for Nuclear Medicine R&D

## Technical and other Objectives

- ❖ Delivery of three simultaneous RIBs to users
- ❖ High intensity photo-converter development (to enable 500 kW operation)
- ❖ Extend TRIUMF's core competencies in SRF and high power targets

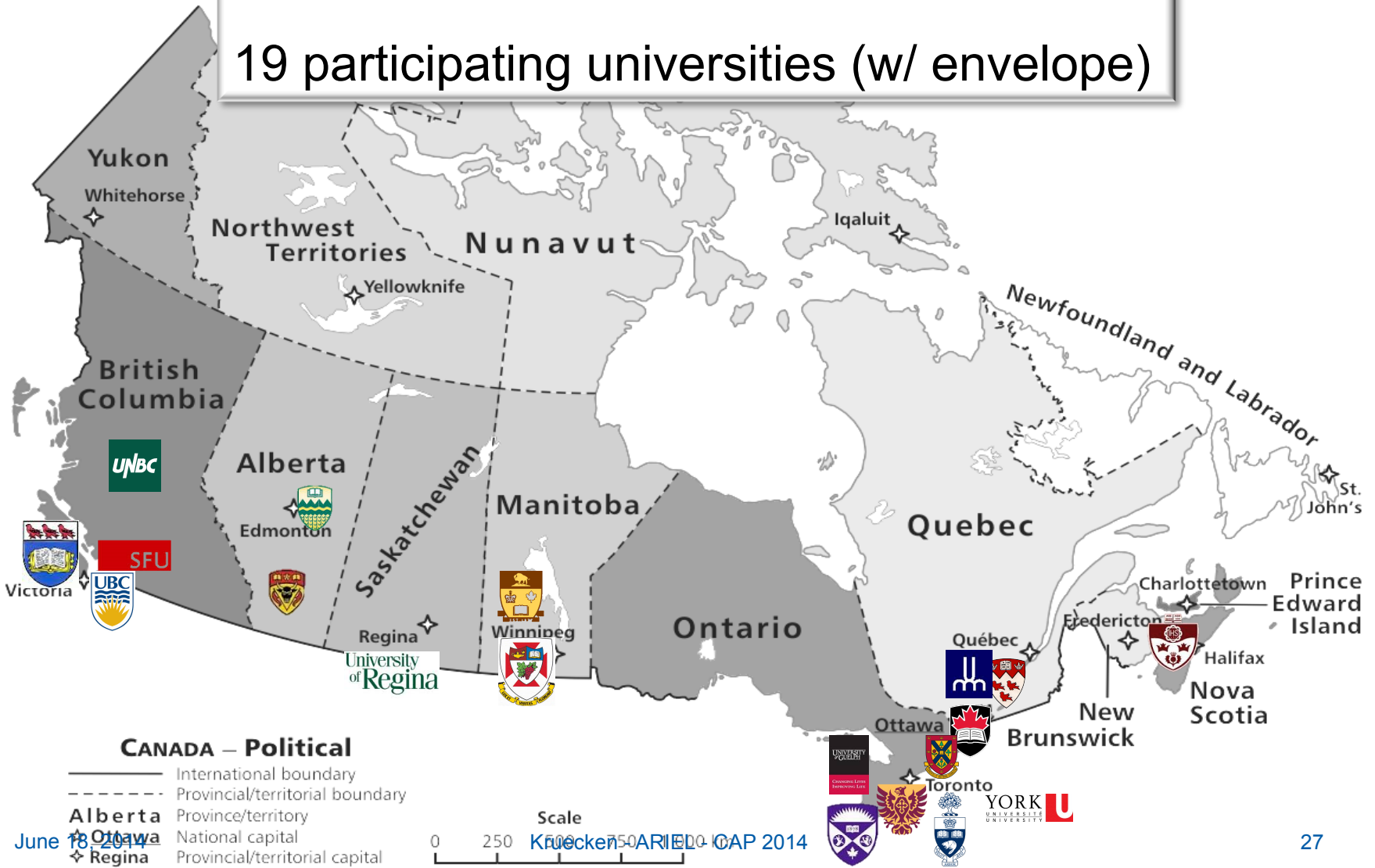
## Phased Implementation

- Phased construction enables continuous stream of scientific results from ARIEL.

# ARIEL-II: Completion to Science

\$32.4M CFI application

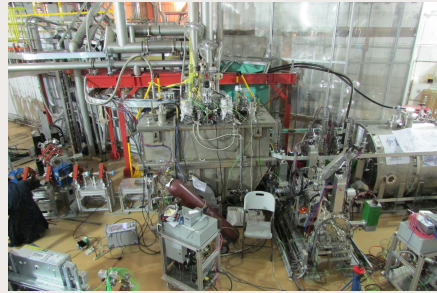
19 participating universities (w/ envelope)



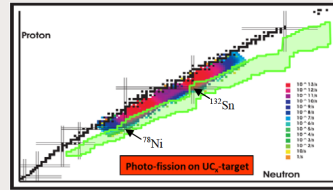
# ARIEL Timeline



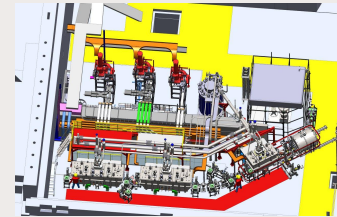
**August 2013**  
ARIEL Building complete



**September, 2014**  
e-linac Phase 1 Complete



**ARIEL-II Phase 2**  
Photofission → r-process



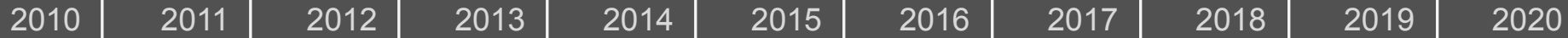
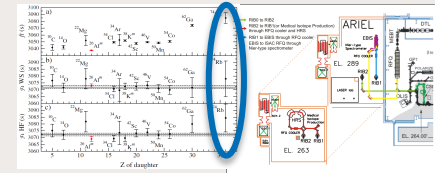
**ARIEL-II Phase 5**  
Extend r-process reach

**June 2010**  
ARIEL Project begins

**January 2013**  
CANREB CFI funding announcement

**March 2015**  
ARIEL-II CFI decision

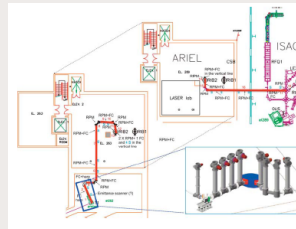
**ARIEL-II Phase 3 (CANREB)**  
Pure High Mass accel. RIBs  
Medical isotopes collection station



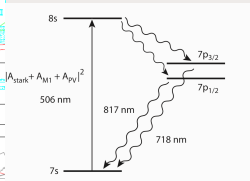
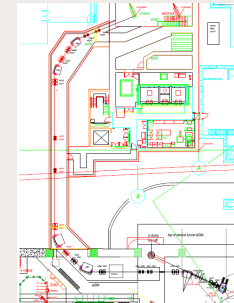
**August 2013**  
TRIUMF-VECC  
MOU Add-3 signed



**ARIEL-II Phase 1**  
Materials Science at  $\beta$ -NMR



**ARIEL-II Phase 4 (BL4N)**  
Fundamental Symmetries  
Two ARIEL beams

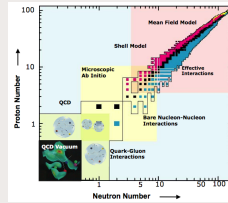




# Complete ARIEL and tap its unique capabilities for isotope production.

## Unified theory for all nuclei

- halo / dripline nuclei & ab-initio theory
  - high power proton beam
- shell evolution and 3N forces
  - high power electron beam



## Origin of the heavy elements

- H & He burning
  - High power proton beam
  - Beam development time
  - Long beam times
- r-process in neutron-rich nuclei
  - High power electron beam



## Fundamental Symmetries

- Francium and Radon EDMs and PNC
  - High power proton beam
  - Long beam times



→ Need high-power proton and electron production in full multi-user operation w/ 3 production targets

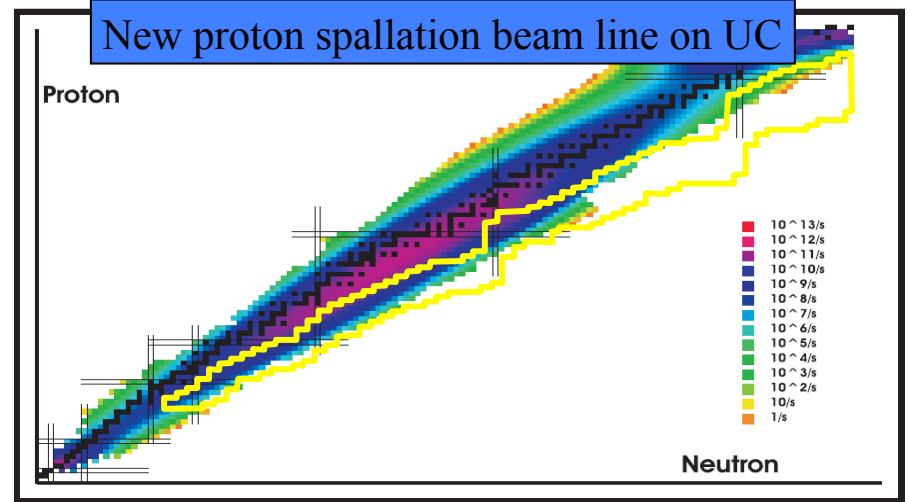


Figure 7: Production yield in target assuming a 10 μA proton beam onto a 25 g/cm<sup>2</sup> UC<sub>x</sub> target using FLUKA.

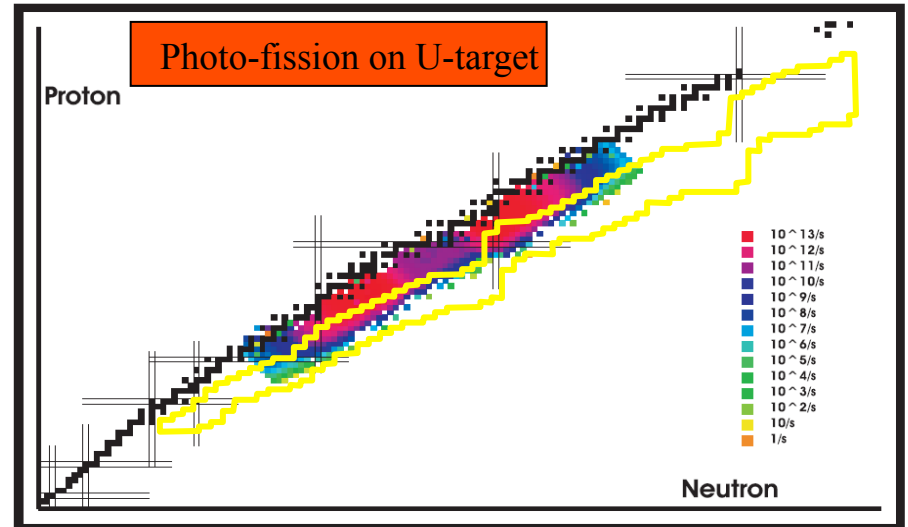


Figure 8: Production in target assuming  $4.6 \times 10^{13}$  photo-fission induced into a 15 g/cm<sup>2</sup> UC<sub>x</sub> target.

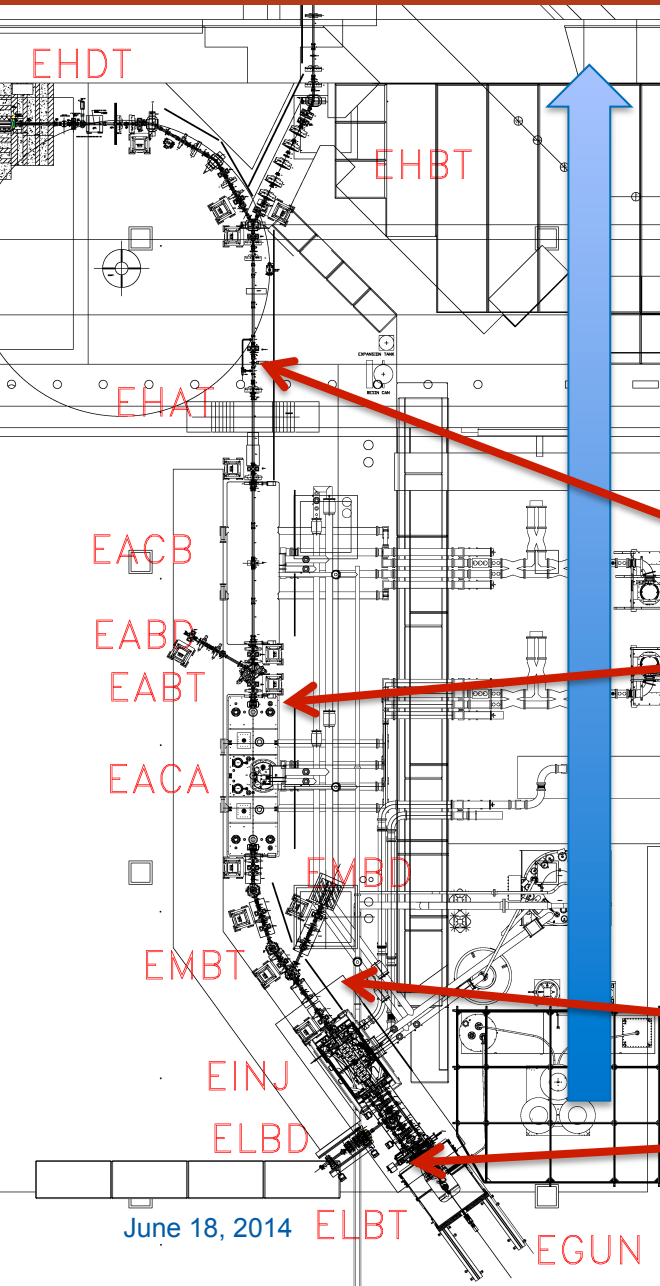
# Thank you!

# Merci!

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



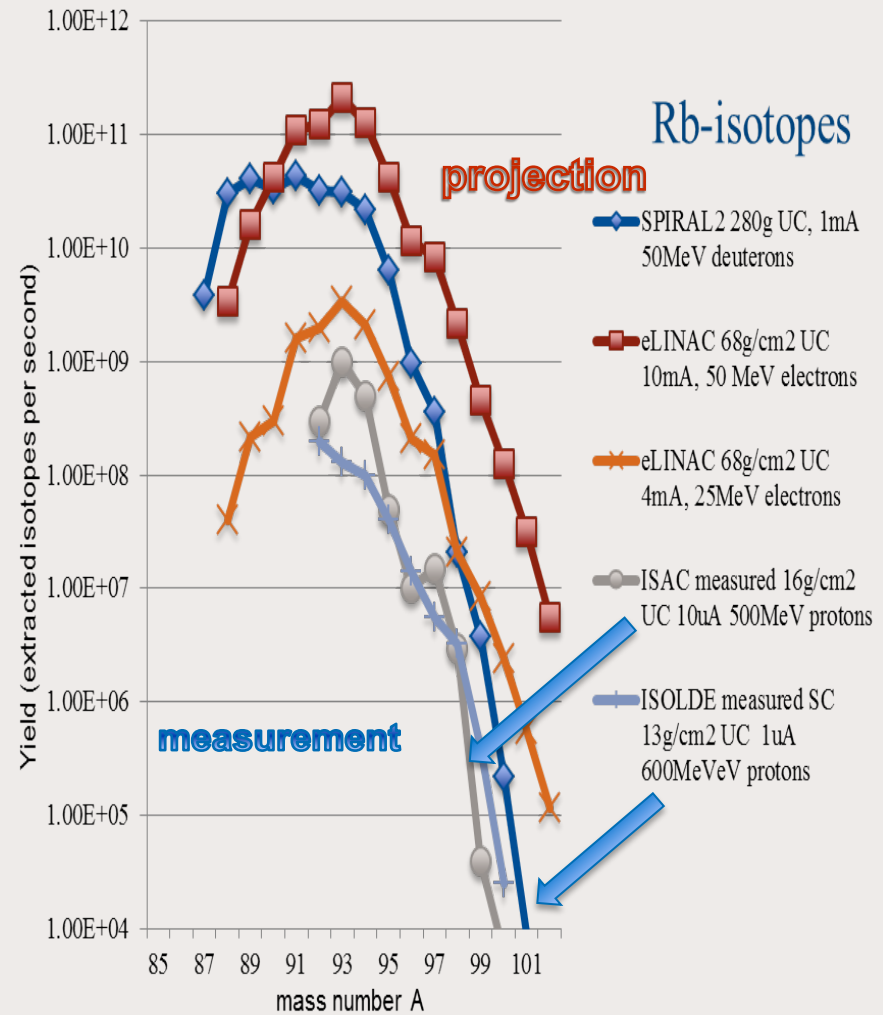
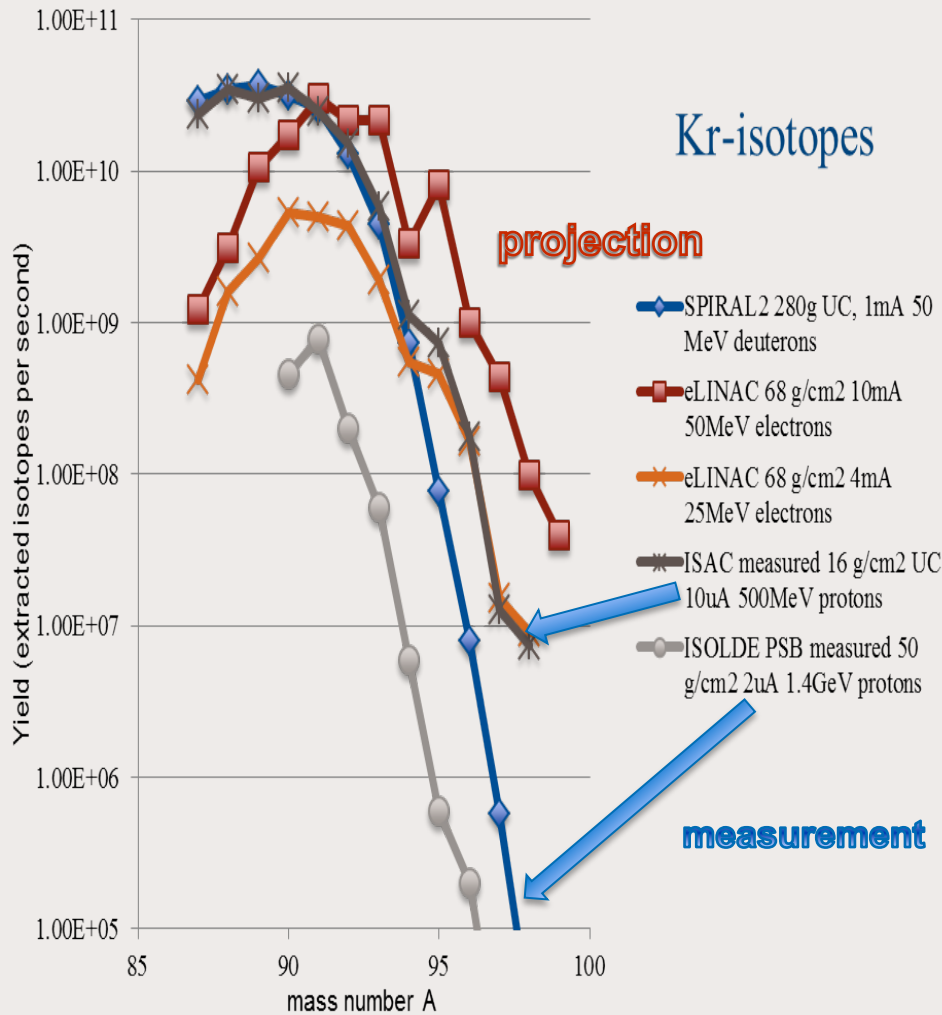
# Campaign staged: follows build out of equipment & increase of beam power



- **High Power Commissioning**, beam power up to 100kW.
- **Accelerator Commissioning**, beam energy up to 30 MeV
  - Part 4: beam average power progressively increased from 100W up to 30kW
  - Part 3: EACA second SRF cavity installed & commissioned; beam accelerated up to 30MeV at the EHD dump. Beam power limited to 100 W.
  - Part 2: EHAT and EHDT beamlines and EHD dump are added, and commissioned to 1kW beam power.
  - Part 1: EACA cryomodule (with a single SRF cavity), EABT and EABD are added; EACA equipment commissioned; beam accelerated to 20MeV at EABD dump.
- **Injector Commissioning**, beam energy up to 10 MeV
  - Part 3: beam average power progressively increased to 1kW at EMBD dump
  - Part 2: EINJ cryomodule, EMBT to EMBD are added; EINJ equipment commissioned; beam power < 100W, 10MeV.
  - Part 1: GUN, ELBT and ELBD commissioned to 300keV

June 18, 2014

# Reaching the r-process path in the laboratory: competitive isotopes



Projection ARIEL: FLUKA, using the converter-target geometry and experimental diffusion times, and extraction and ionization efficiencies from ISOLDE, overlaid with the isotope specific half-life. Uncertainty in projection: factor ~10. (TRIUMF 5YP page 422), SPIRAL: GANIL web site.



