TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

ACCELERATION ABOVE THE COULOMB BARRIER – COMPLETION OF THE ISAC-II PROJECT AT TRIUMF

Bob Laxdal, Sept. 8, 2010, CYCLOTRON 10

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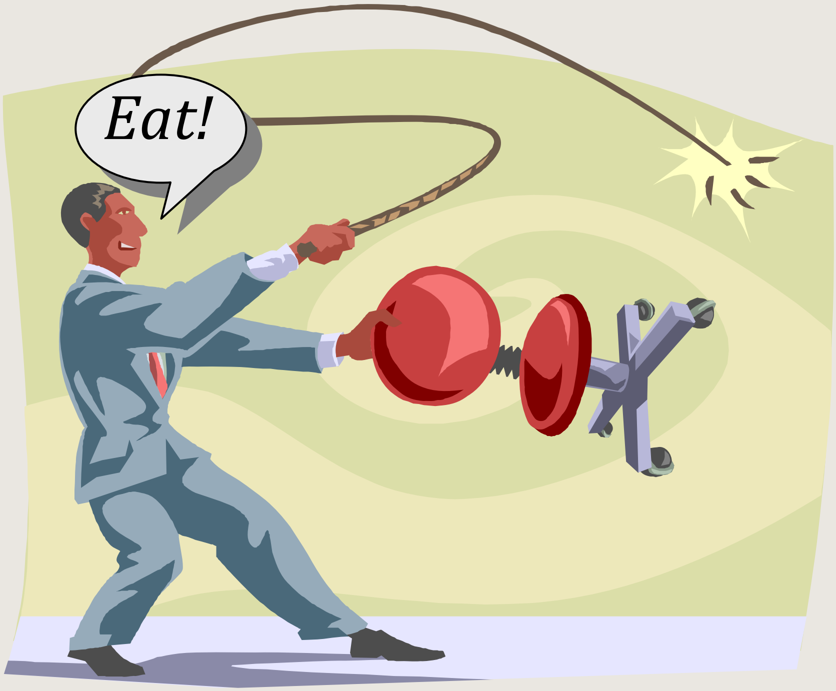
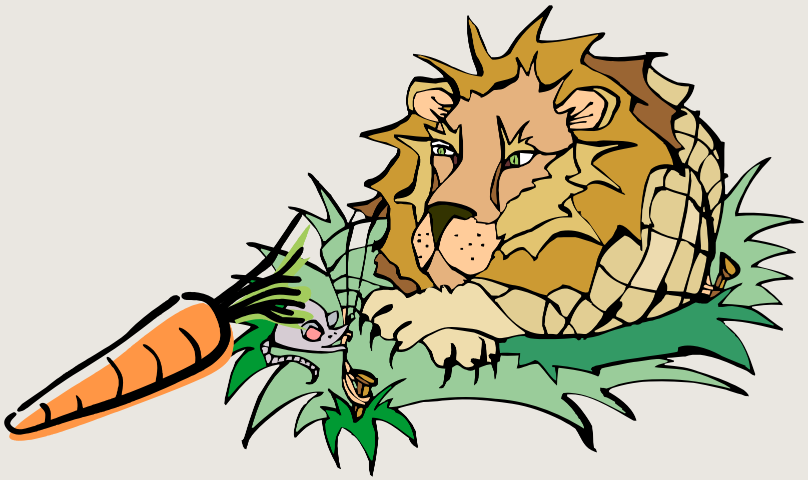
Preamble

Linacs at Cyclotron 10?

•May seem like a hard sell; but lots of examples of linear accelerators in cyclotron community

- •RFQ/DTL as injectors for ion cyclotrons
- •Post-accelerators at RIB facilities





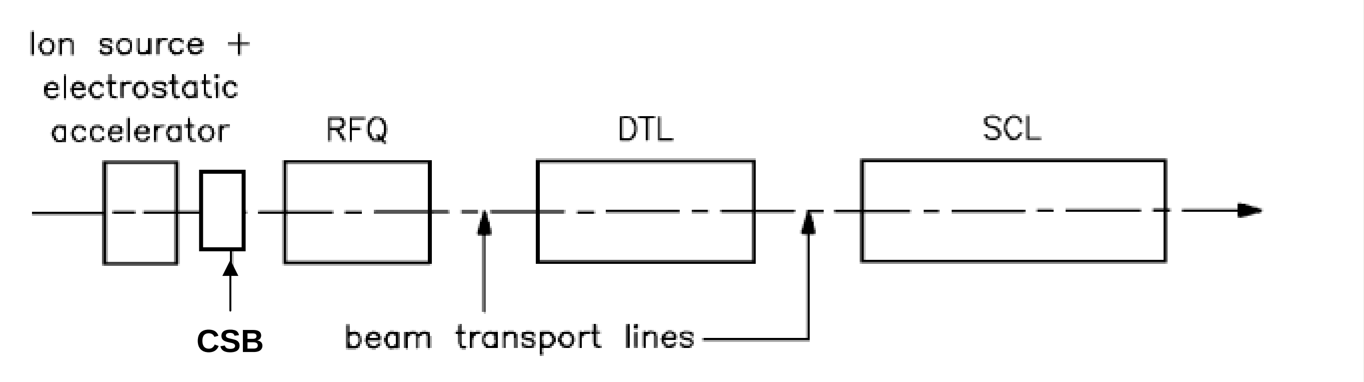
Linac vs Cyclotron: General

- Cyclotrons
  - Features
    - Compact, efficient use of rf, cw operation
  - Challenges
    - Complicated injection and extraction (except H-)
    - Transmission, activation
    - Energy variability (excluding H-), resonances, precise magnetic field

- Linear accelerators
  - Features
    - Easy energy variability, injection, extraction
    - good beam quality
      - $\varepsilon_{x,y}$ source emittance, ε_z ~1keV/u-ns
  - Challenges
    - Space, extended rf structures, costs, wall plug efficiency (SC helps), cw operation (SC helps)

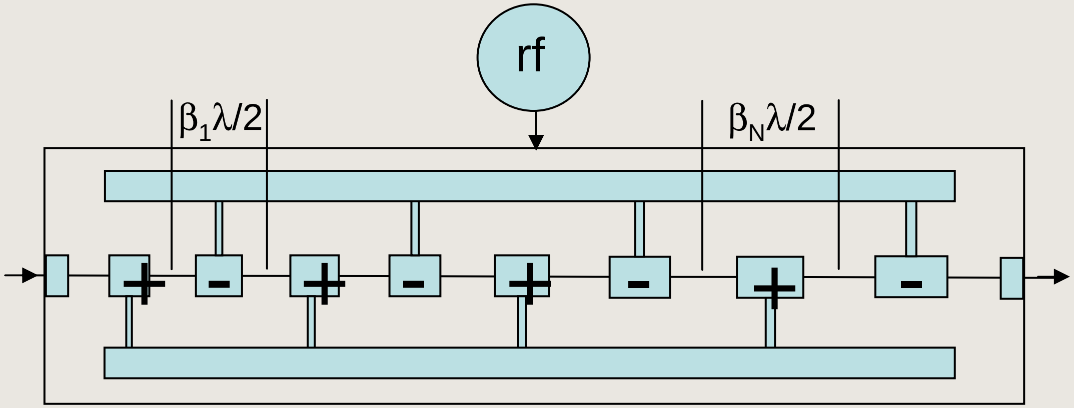
Building blocks

- Modern Light and heavy ion linear accelerators have some basic pieces
  - Source to create the ions at some potential to ~100kV to get the ions going with some velocity
  - A low velocity accelerator most typically an RFQ to provide strong focusing of the `slow' beam as it is gently bunched and accelerated
  - A room temperature Drift Tube Linac to accelerate the bunched beam to a `hand-off' energy to superconducting regime
  - Superconducting linac with short independently driven cavities for flexible yet efficient acceleration due to low surface resistance (low rf cavity power)

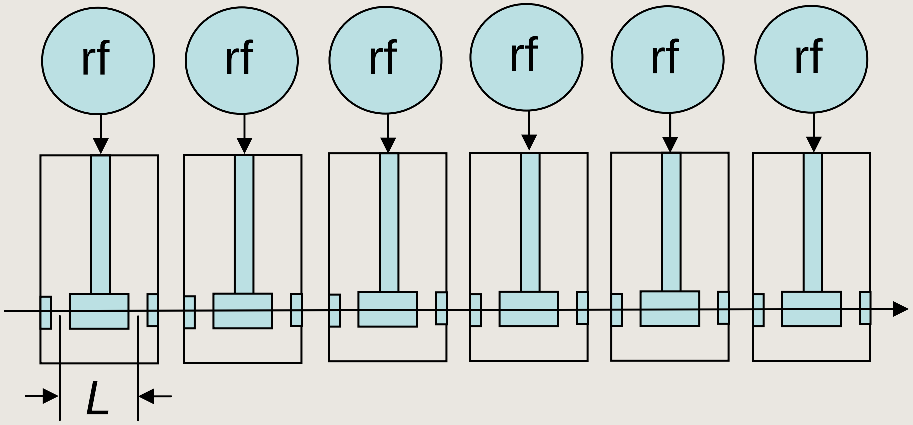


Short vs long `tanks’

- Long multi-gap tanks are efficient
  - reduce number of rf systems
  - require precise geometry with gap to gap distance that increases with velocity
  - Cyclotron analog

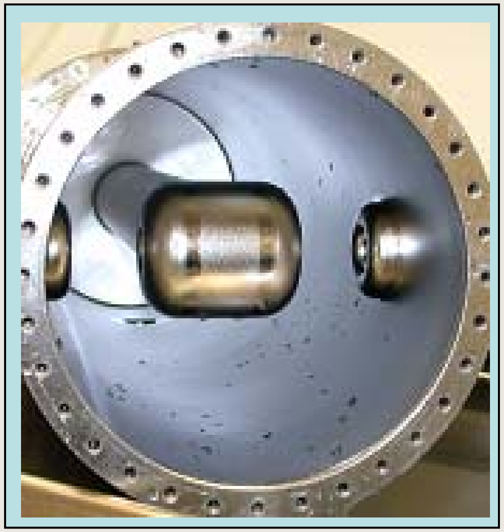


- Short independently driven identical cavities an alternative for SC technology
  - the cavity phases and amplitudes can be set independently
  - the cavities can accelerate a wide range of velocities
  - Higher voltages mean higher velocities



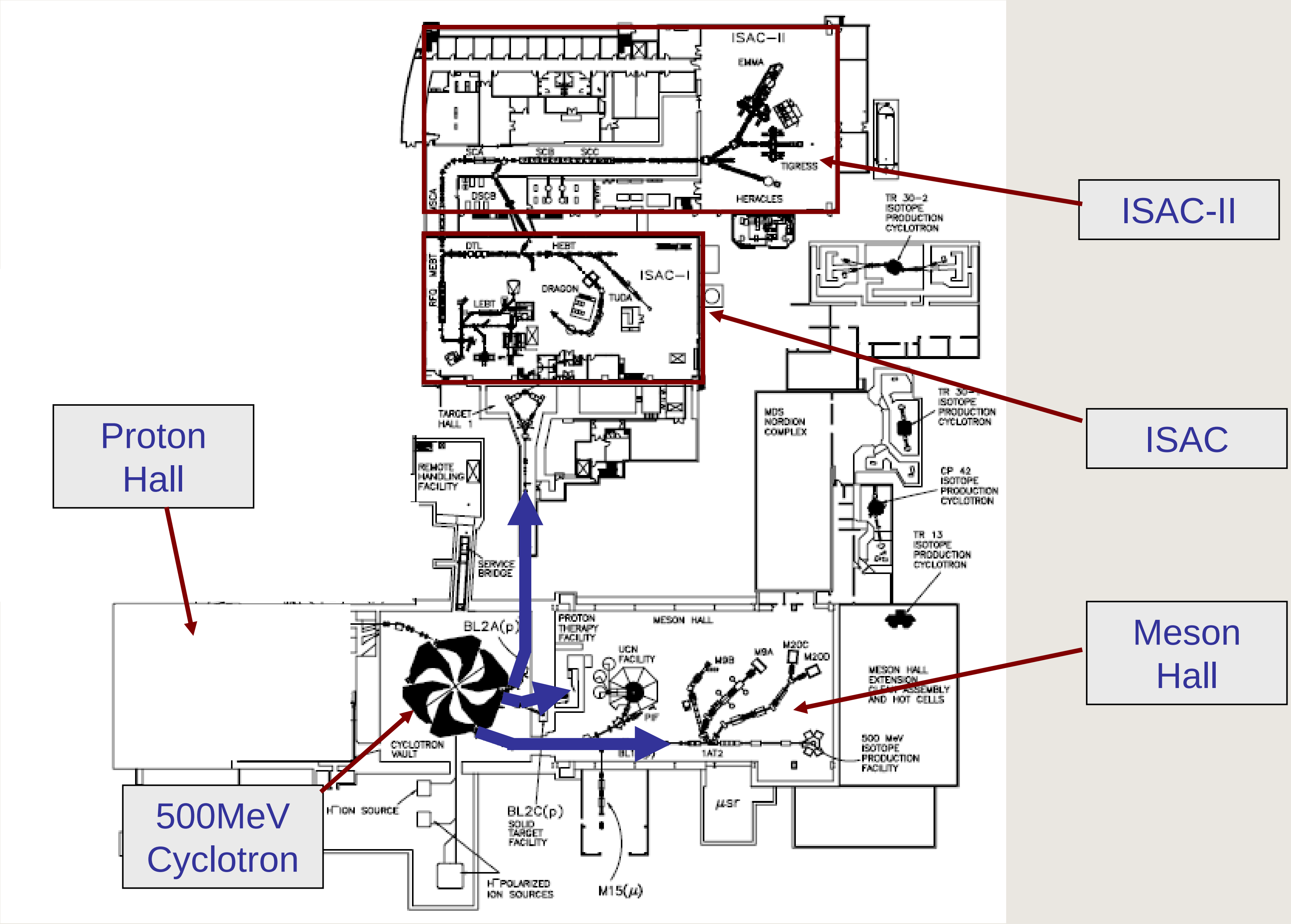
Outline

- Introduction
  - ISAC facility
  - ISAC Accelerators
- ISAC-II project
  - Motivation
  - Phase I Summary
- ISAC-II Phase II upgrade
  - development
  - Manufacture
  - Installation and commissioning
- Conclusions



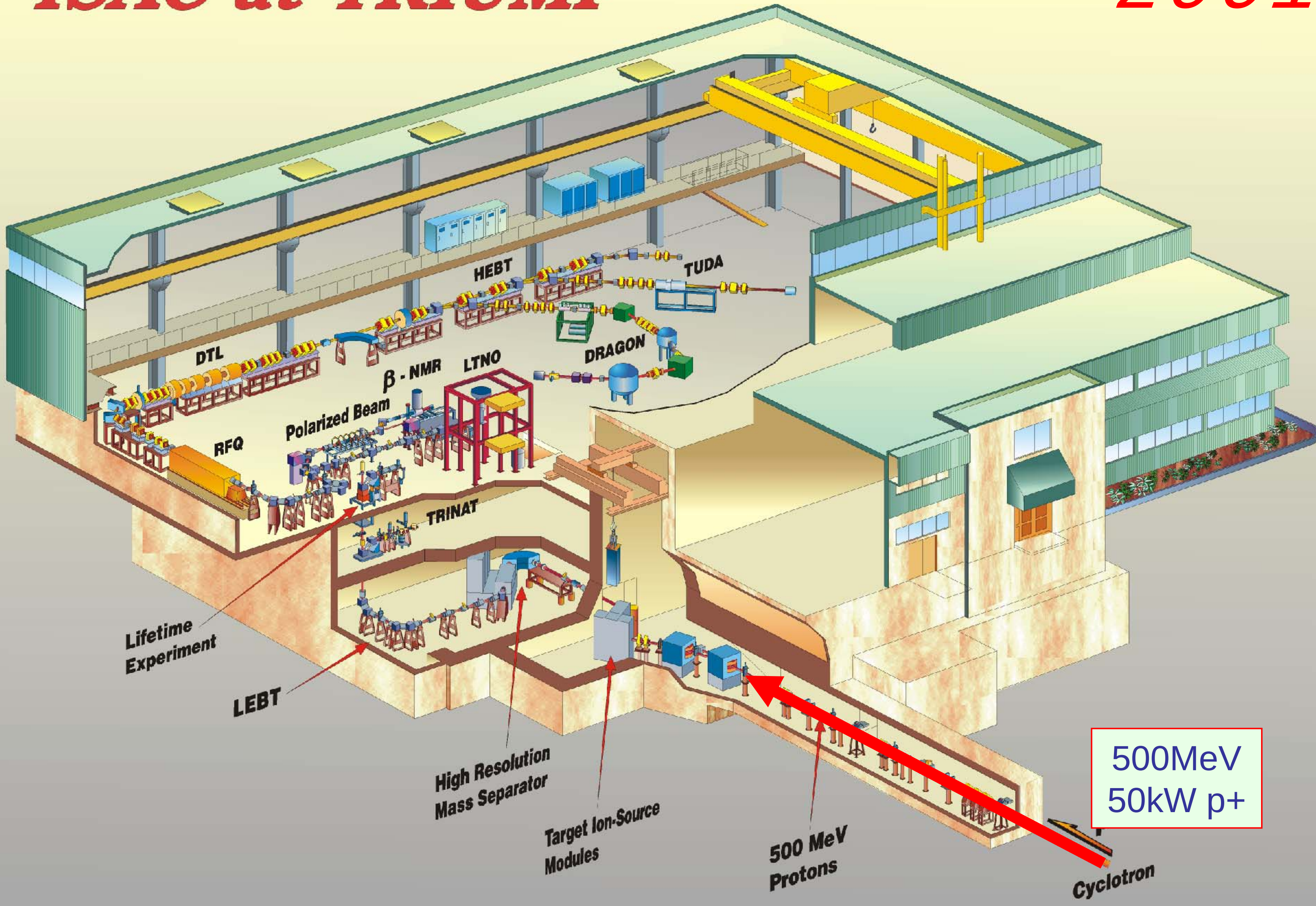
ISAC Facility

TRIUMF Facility

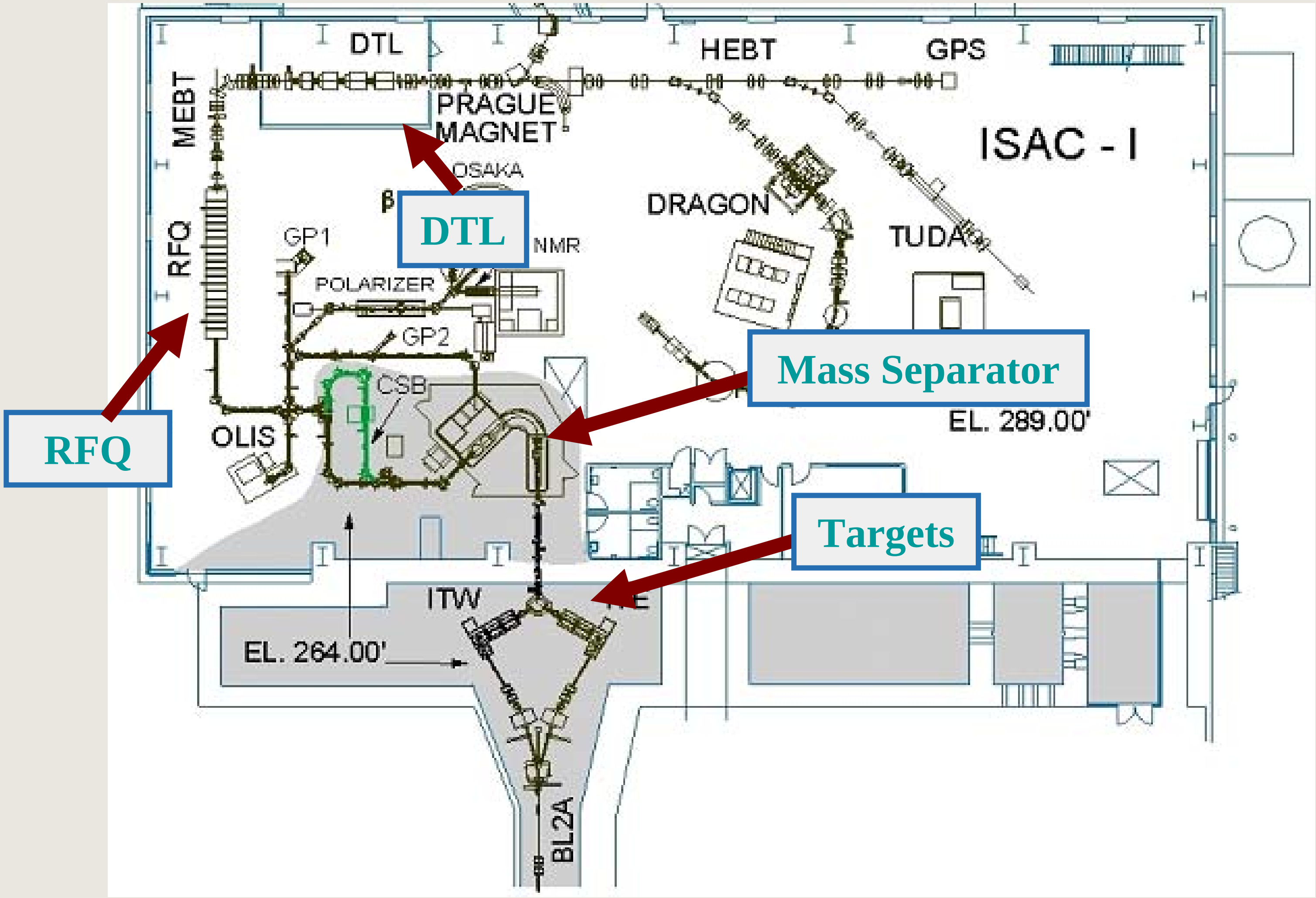


ISAC at TRIUMF

2001



ISAC RIB Facility - 2001



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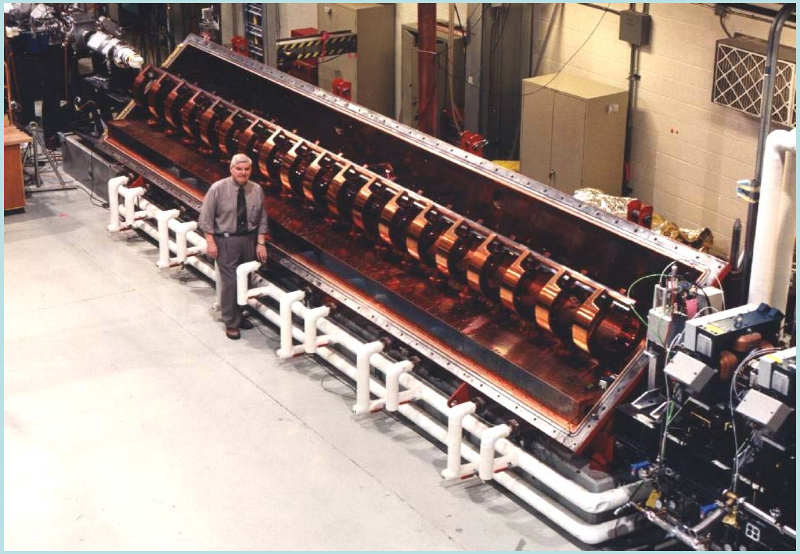
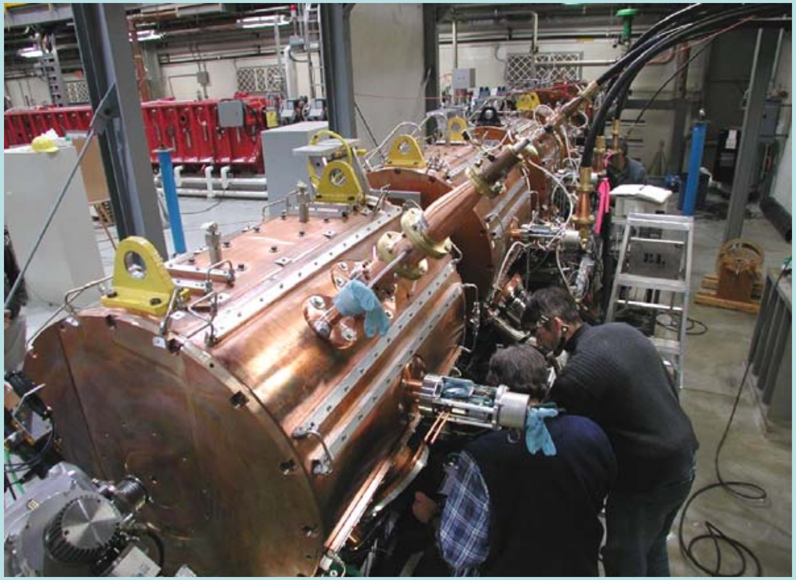
Room Temperature Linacs





ISAC 35MHz RF quadrupole

- accelerates ions with 3 ≤ A/q ≤ 30 from 2keV/u to 150keV/u

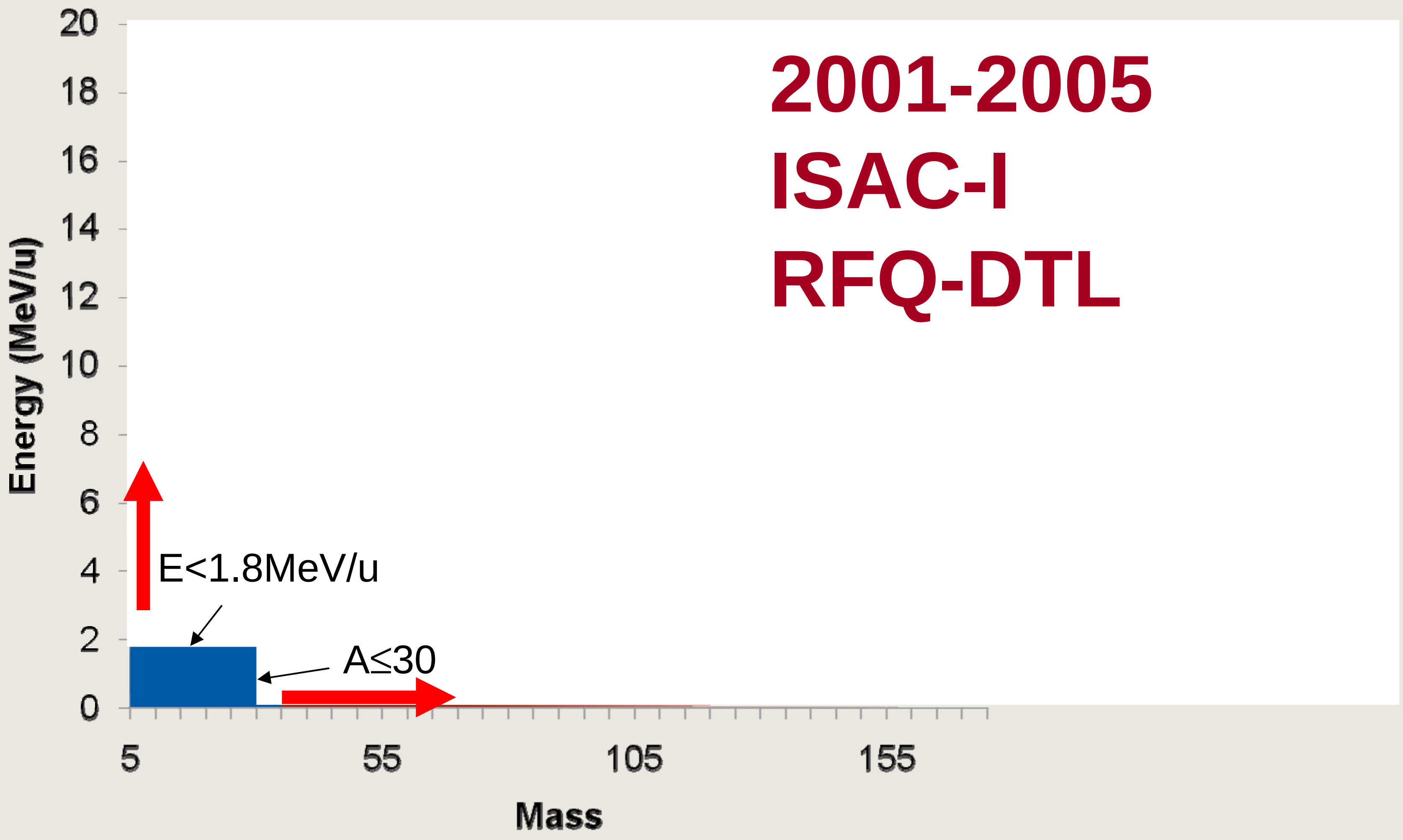
ISAC 106MHz Separated Function DTL

- accelerates ions with 2 ≤ A/q ≤ 6 to final energies fully variable from 0.15<E<1.8MeV/u

Summary

- ISAC-I Accelerators have been delivering high quality beams to experimenters since 2001
- Both accelerators designed and built in house with parts fabricated in the Vancouver area

Accelerated RIB at ISAC – 2001

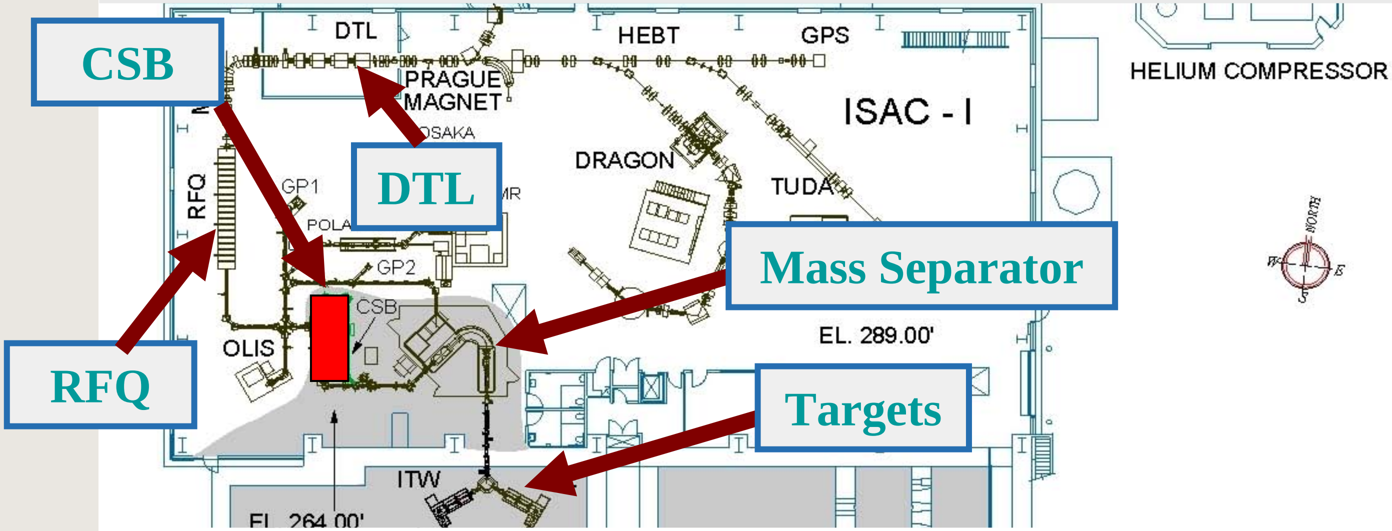


ISAC-II Project

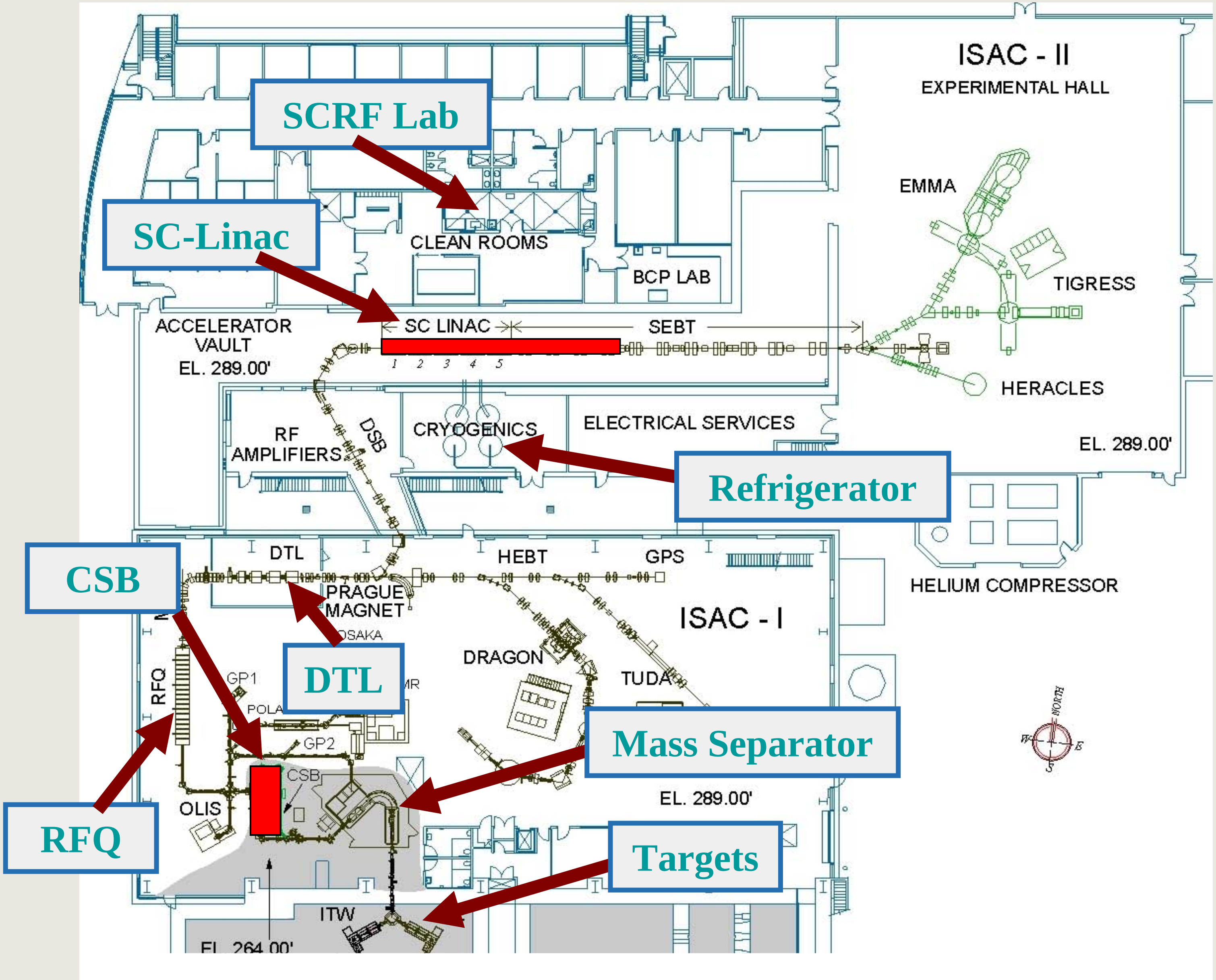
ISAC-II

- The idea ~1999
  - To expand ISAC capabilities
    - needed higher energies to support Nuclear Physics studies at and above the Coulomb barrier
      - Goal energy E≥6.5MeV/u for A/q=6 with full energy variability
      - The decision was to develop a superconducting heavy ion linac of 40MV
    - Needed broader mass range to A<150
      - Add ECR charge state booster (CSB)

ISAC-II The concept



ISAC-II The concept



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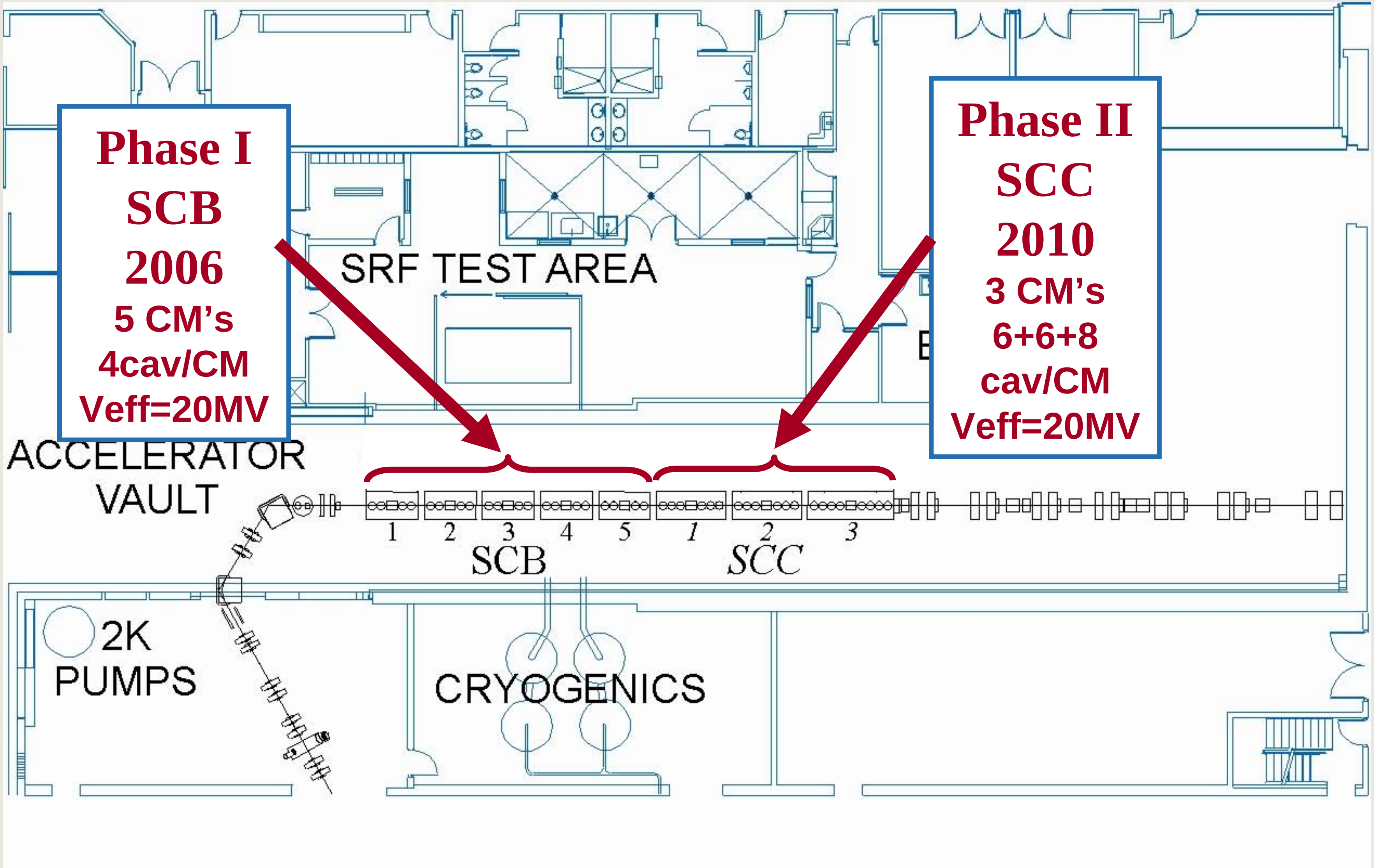
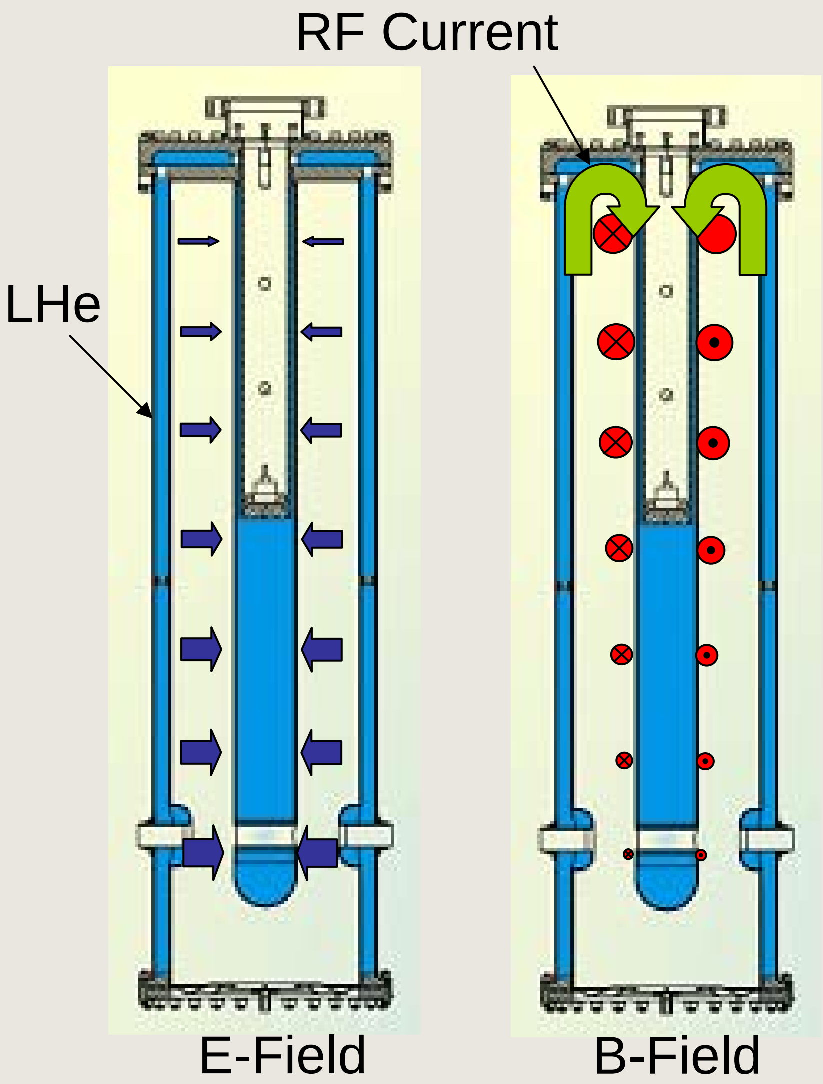
ISAC-II Superconducting Linac

ISACII SC-Linac



Quarter Wave Resonators (QWR)

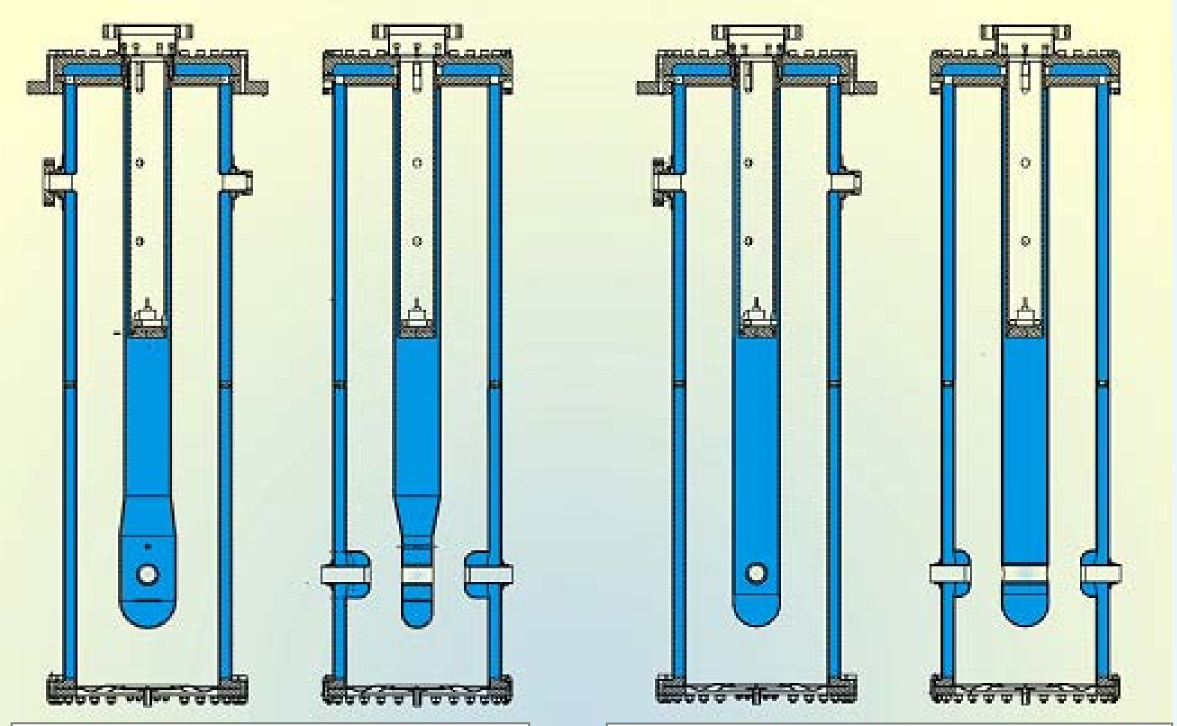


- Inner conductor forms two gaps with effective length of $\sim\beta_0\lambda$ and gap to gap length of $\beta_0\lambda/2$
- Hollow inner conductor and double wall jacket contains LHe

- ISAC-II design values
  - V_{eff}=1.1MV,
  - *Pcav=7W*
  - E_p=30MV/m, H_p=60mT,
  - *F=106, 141MHz*

ISAC-II QWR Cavities

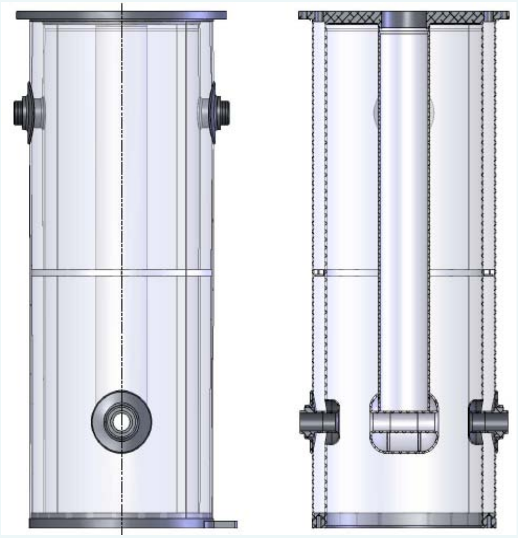
Phase I



106.1 MHz β=5.7%
SCB(1-8)

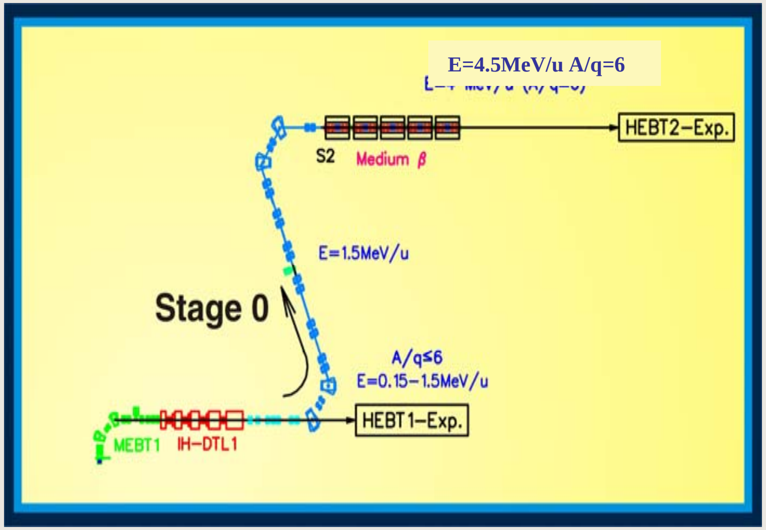
106.1 MHz β=7.1%
SCB(9-20)

Phase II

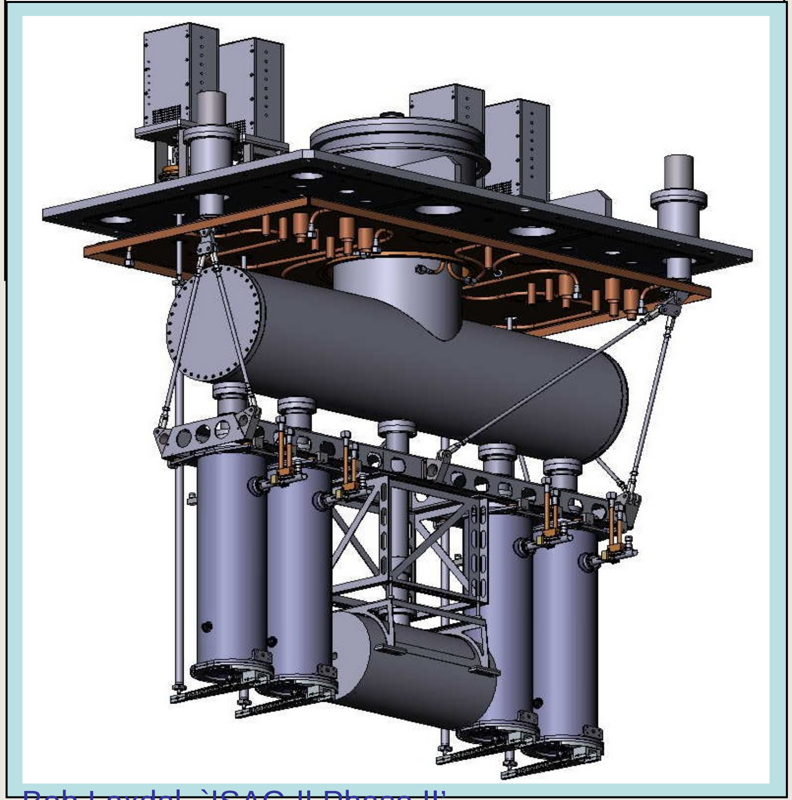


141.4 MHz β=11%
SCC

ISAC-II SC-Linac Phase I (2006)

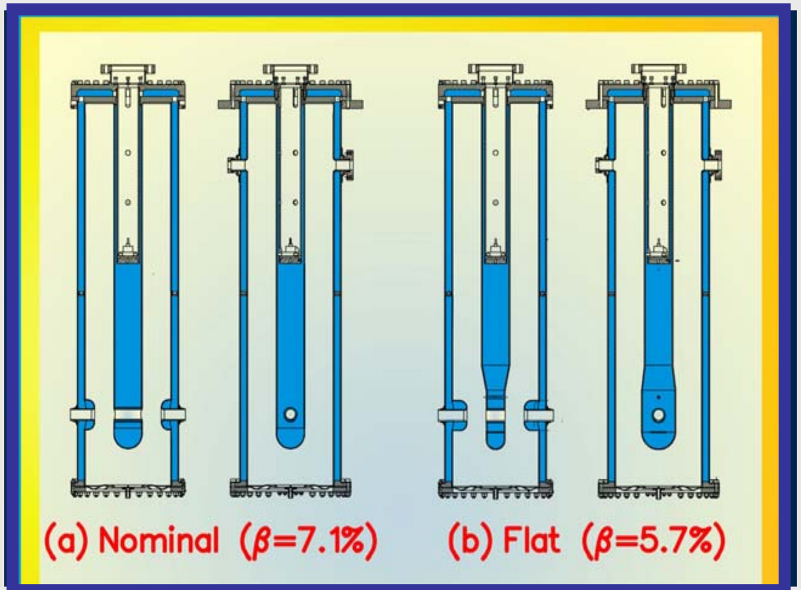


- ❑Twenty bulk niobium quarter wave cavities housed in five cryomodules
- ❑Boosts ion energy by 20MV with low mass RIBs above the Coulomb barrier



ISAC-II Phase I Cavities

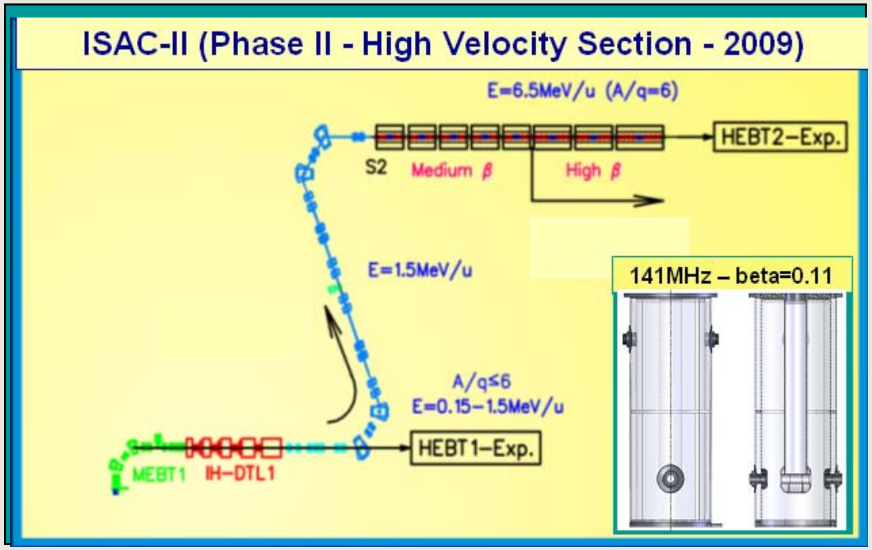
- Cavities designed in collaboration with INFN Legnaro
  - Removable tuning plate allows access for surface processing
  - Mechanical damper in inner conductor to reduce rf detuning from microphonics
- Cavities fabricated in Italy
- Installed cavities have exceeded specification by 10% with 33MV/m peak surface field averaged over four years
  - a significant increase over other operating heavy ion facilities

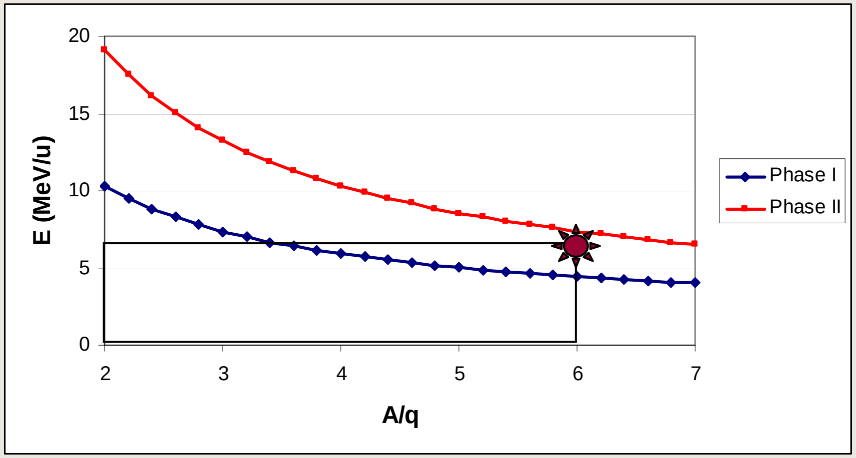


Prototype Cavity

ISAC-II Phase II SC-Linac Upgrade

- ISAC-II goal is to boost the energy of the heavy ions above the Coulomb barrier for all masses
  - E≥6.5MeV/u for A/q=6
- Phase II upgrade - adds 20MV of additional voltage gain for a total of 40MV in ISAC-II – add 20 QWR's at β=0.11





ISAC-II Superconducting Linac

Phase II Upgrade

- Main unique feature was the development of PAVAC Industries as a Canadian supplier of bulk niobium SRF resonators
  - Initiated in 2005 with first discussions with PAVAC
- 7.5M$ project
  - 2.7M$ - cryogenics – refrigerator and distribution
  - 1.4M$ - cavities
  - 2.4M$ - cryomodules
  - 1M$ infrastructure – rf amplifiers, power supplies, installation

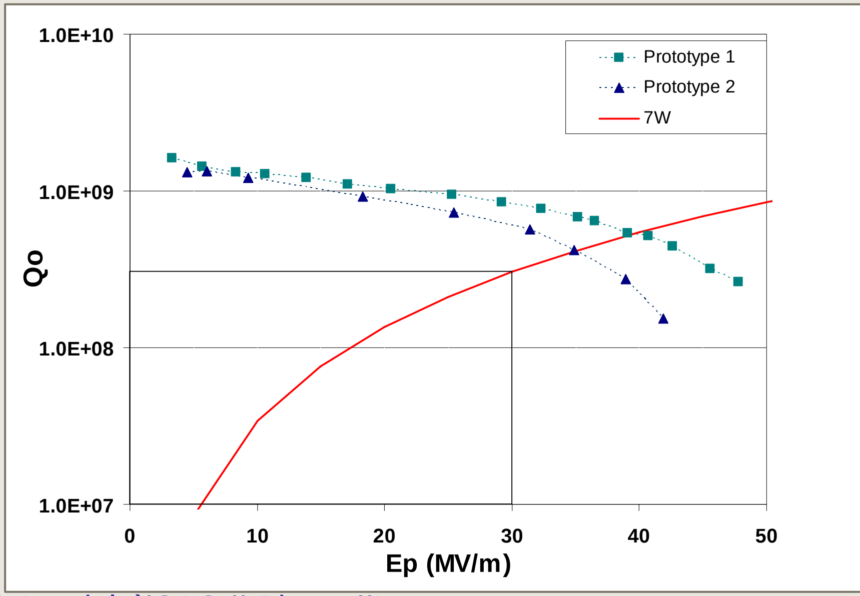
Schedule

- Project mandated completion date March 31, 2010
  - Coincided with end of the TRIUMF Five year plan, end of project budget
  - Politically `desirable’ to end on time; lab negotiating for next five year plan

		2005-1	2005-2	2006-1	2006-2	2007-1	2007-2	2008-1	2008-2	2009-1	2009-2	2010-1
Cavities												
	R+D		develop	develop								
	Cu proto				design	fabricate						
	Nb proto					design	fabricate	fabricate				
	production							design	fabricate	fabricate	fabricate	
Cryogenics												
	refirigerator				design	fabricate	fabricate	install				
	cold dist					design	design	fabricate	fabricate		install	
	LN2						design	design	fabricate	fabricate	install	
RF ancill												
	Amplifiers					design	fabricate	fabricate	fabricate	install	install	
	tuners				design	develop	fabricate	fabricate				
	coupler					design	develop	fabricate	fabricate			
Cryomodules												
	design				design	design	design					
	fabrication						fabricate	fabricate	fabricate			
	dirty assembly							dirty	dirty	dirty		
	clean assembly								clean	clean	clean	
	installation									install	install	install
Infrastructure												
	PS room						design	fabricate	assemble	install		
	Vault									design	install	install
	BCP lab							design	install			

ISAC-II Cavity Fabrication

- Development of PAVAC Industries of Richmond BC
  - First prototype made in copper 2007
  - Two niobium prototype cavities tested OK - 2008
  - Twenty production cavities ordered – March 2008
  - First bulk niobium cavity fabrication in Canada

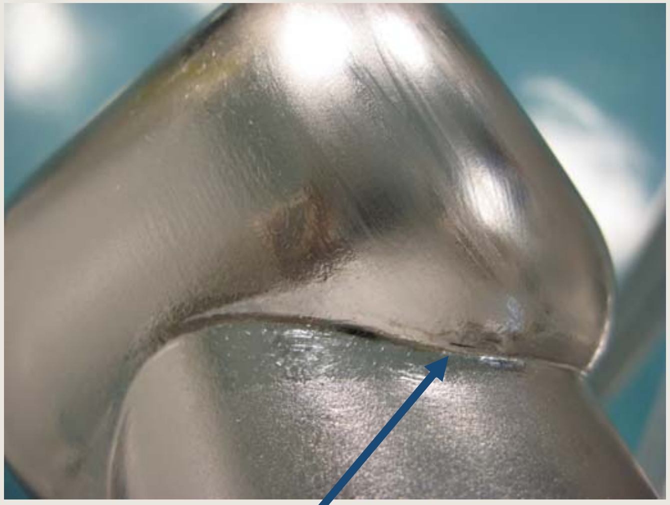


Challenges

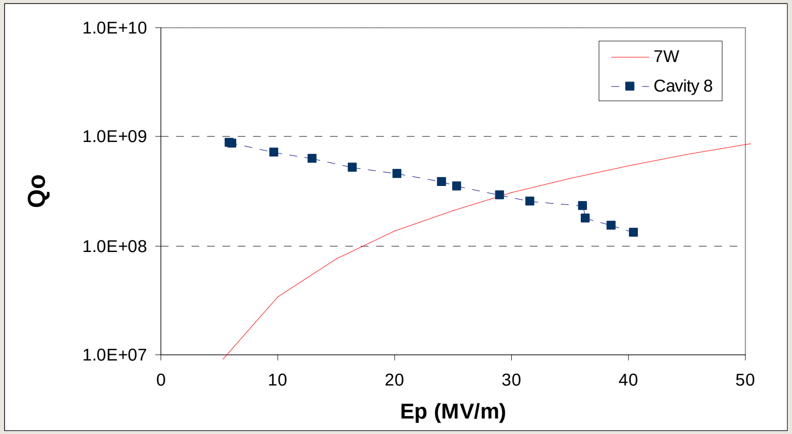
- Production/development
  - Four cavities developed vacuum leaks after etching at TRIUMF
  - New procedure for cavity tuning using etching developed
  - Engineer a responsive mechanical tuner – narrow bandwidth ±15Hz (±2μm on tuning plate)
- Mundane
  - Rf amplifier company goes bankrupt after delivery of 11 units
  - Competition with planning for next five year plan – initiated 1.3GHz program

Cavity Challenges

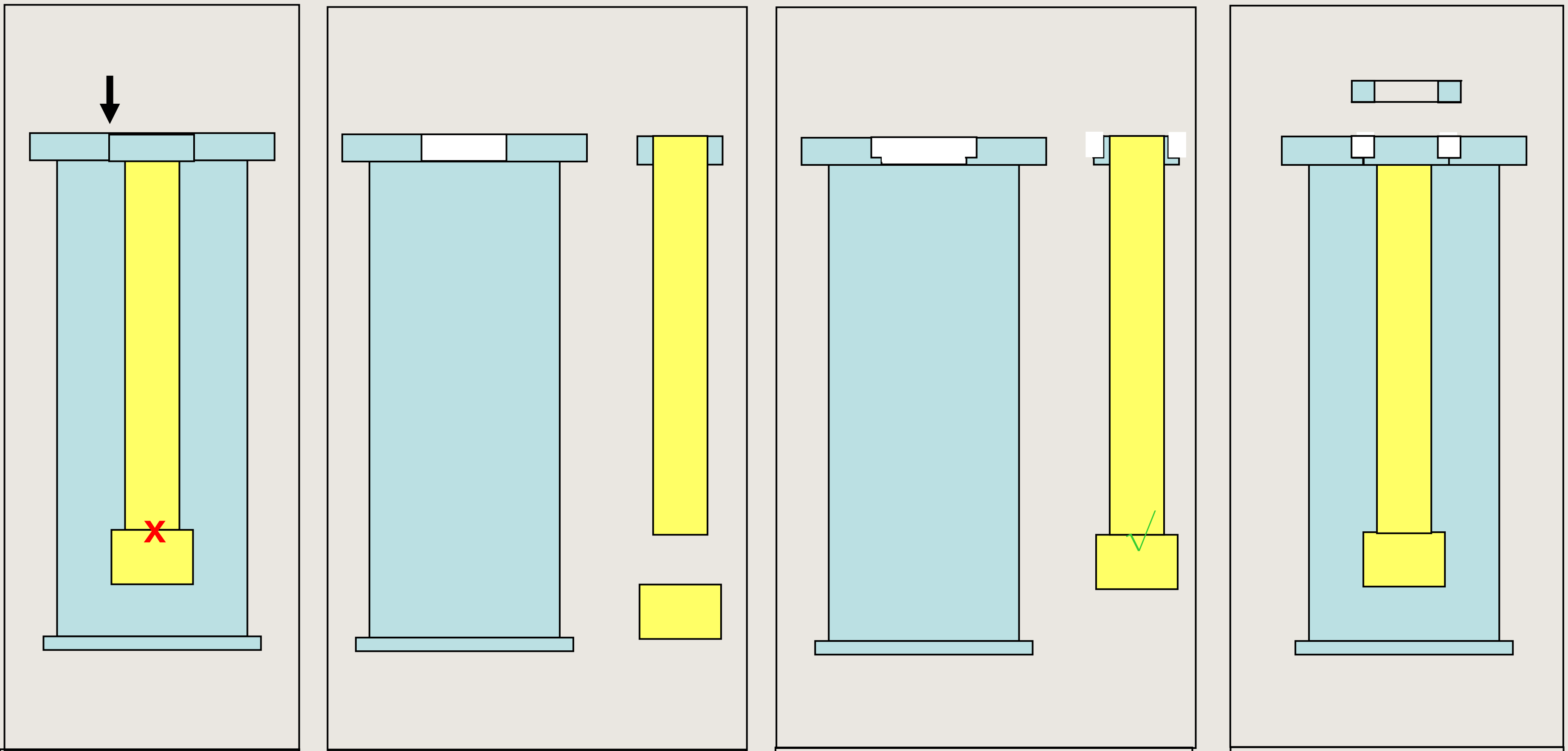
- Twenty cavities received
  - Sixteen cavities OK
  - four cavities developed vacuum leaks after BCP etching of 100microns
    - leak in the saddle weld from inner conductor to beam tube
    - PAVAC developed fix to recover cavities



Vacuum leak appears in weld region after BCP etching



Leak Repair (Pavac)



1. Cut out inner conductor

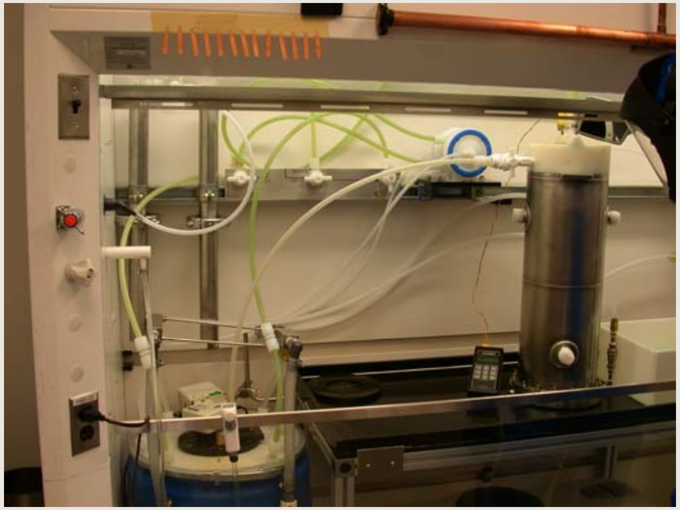
2. Remove beam tube and repair leaky weld

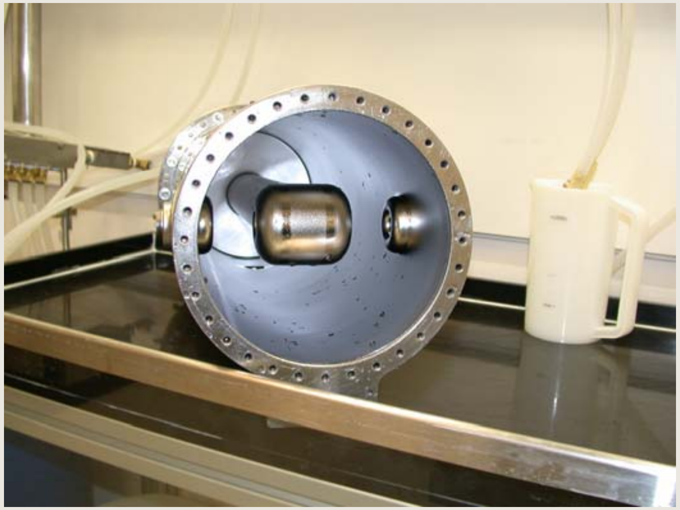
3. Machine weld prep on cavity flange and inner conductor

4. Weld inner conductor to cavity and add reinforcing ring

Chemical Processing

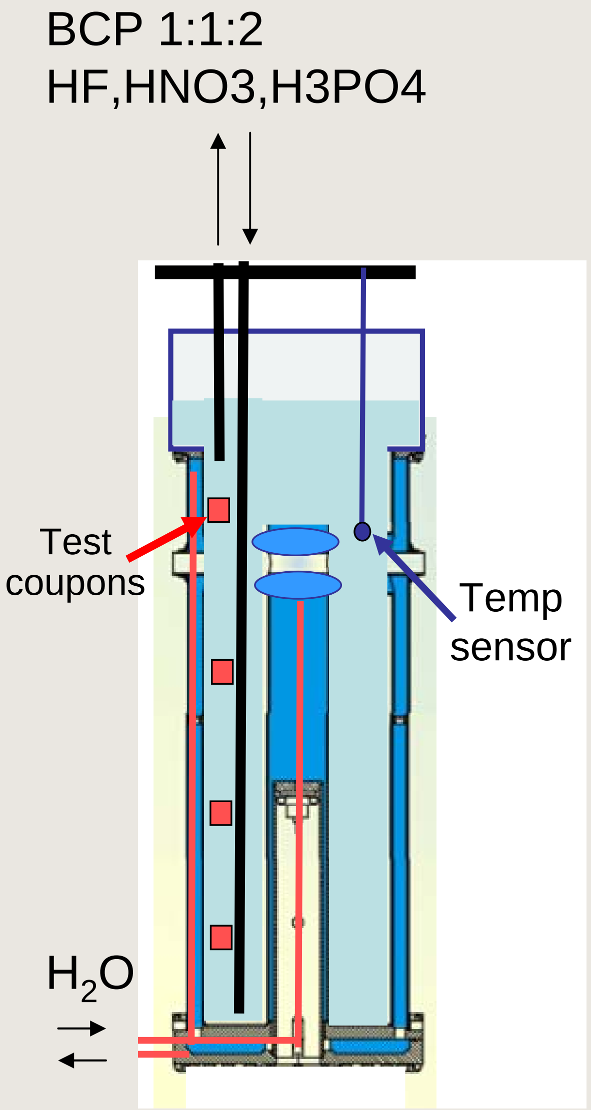
- Need to remove ~100micron damaged layer
- production cavities processed plus parts etched prior to welding for production series
- Custom etching gives predictable frequency shift





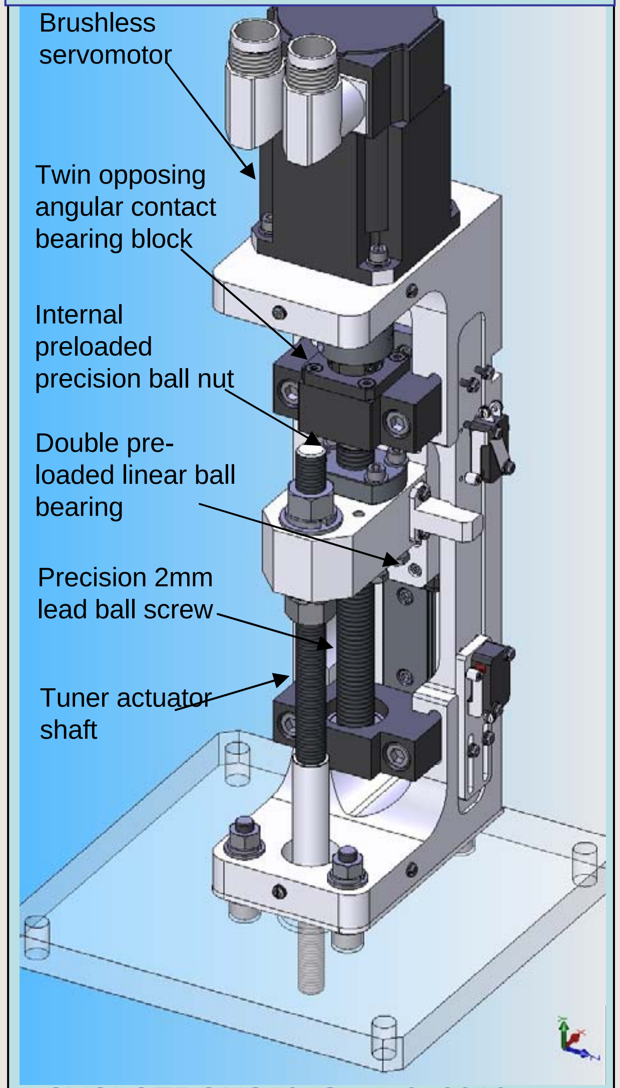
Custom Etching

- Uniform etching of the cavity will result in a ~neutral frequency change
  - Etching from the `root end' results in a -2kHz/micron frequency swing
- We aim +20kHz high in manufacture and use custom etching to establish an exact operating frequency
  - Fill the cavity 50% full for a prescribed time then fill 100% and complete the etch



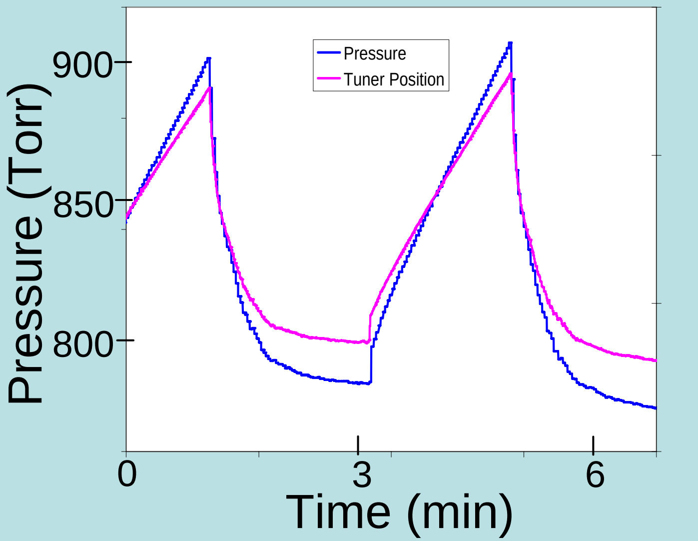
ISAC-II Mechanical tuner

New Tuner Motor Developed



- precision brushless servo-motor and ball screw on top of cryomodule
- Tuner Position resolution 0.04 Hz/step; corresponds to 5nm/step

- Force helium pressure fluctuations to test tuner
- ΔP=137 T, Δf=330Hz; corresponds to 50μm; cavity bandwidth is ±15Hz from overcoupling
- compensation is $\Delta f/\Delta t$ =13Hz/sec.
- No increase in phase noise during test.

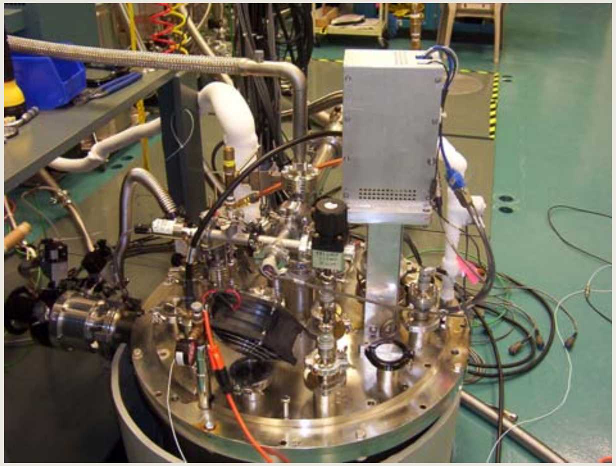


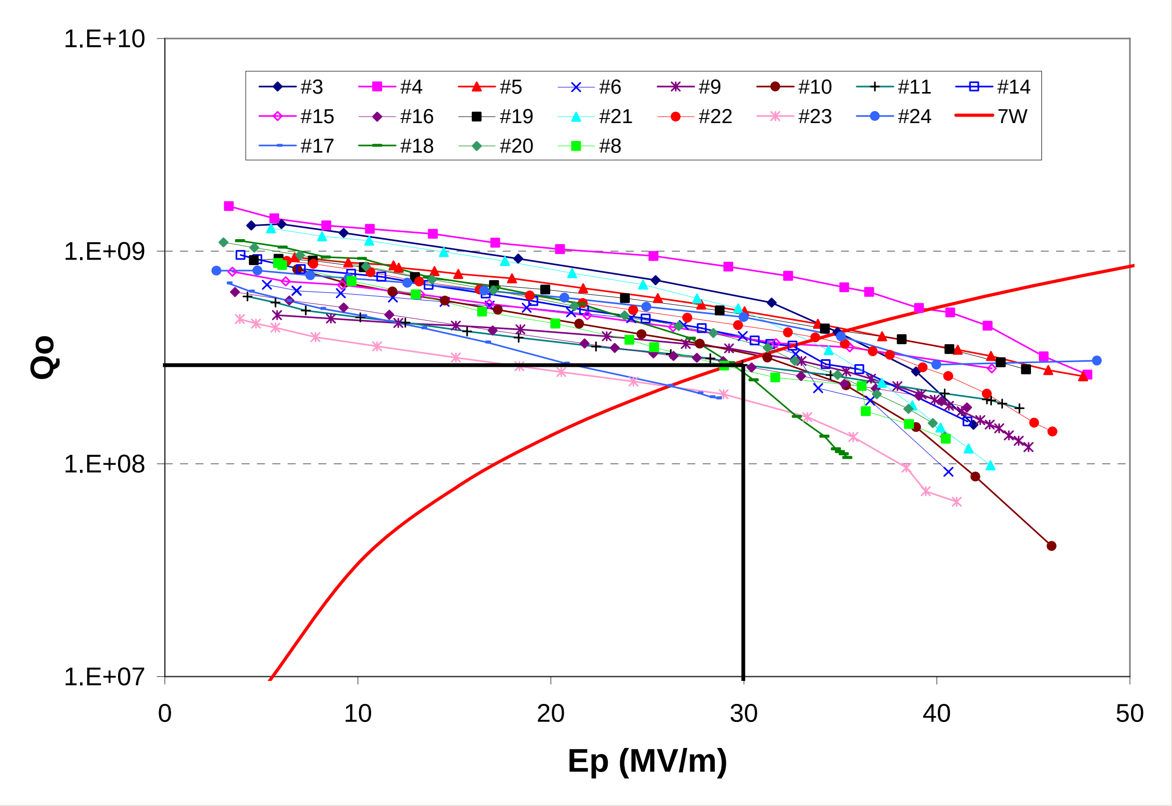
Linac Preparation

Cavity Characterization

Preparation: cavities are degreased, chemically etched, rinsed with high pressure water, dried and then assembled on test frame

•Single cavity tests are done to establish cavity performance prior to installation in the cryomodules





Cryomodule Assembly

- Each cryomodule top assembly unit is first assembled in a standard lab area (`dirty assembly') then completely disassembled, cleaned and re-assembled in clean room
- Establish cavity/solenoid alignment

Clean room cold test

•Cryomodule cold tests

- •Each cryomodule undergoes a cold test prior to delivery to the vault
- •Establish warm off-sets for cold alignment using WPM and optical targets
- •Check cavities and rf systems
- •Measured cryogenic static load
- •Establish vacuum integrity
- •Check of solenoid

Vault Tests

- Cryomodules were installed sequentially into vault as they became ready
- Allowed full systems check; rf, vacuum, cryogenics, controls well in advance of final cooldown

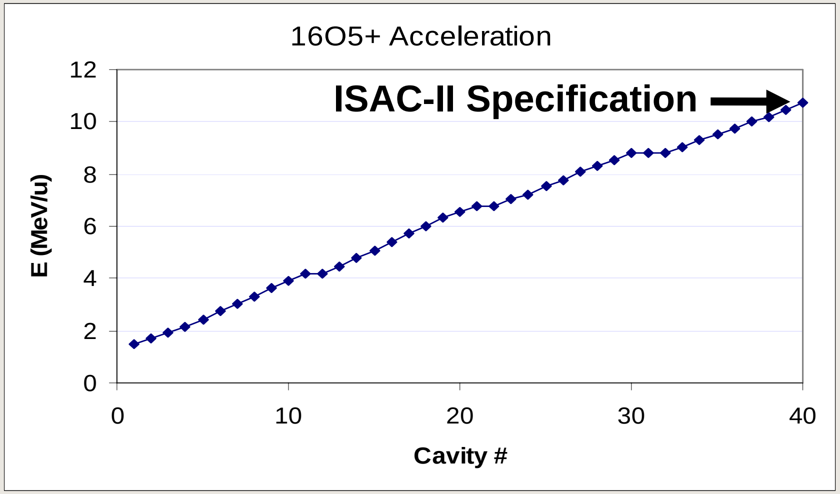
Installation/Commissioning

Installation Chronology

- Vault installation began Sept. 2009
    - Beamline removed
    - Cryogenic distribution installed
- Goal was full installation by March 31 – the end of the five year plan

Milestone	SCC1	SCC2	SCC3
Assembled	June-09	Nov-09	Mar 7
Off-line test	July Sept-09	Dec-09	Mar 15
Install in vault	Oct-09	Jan-10	Mar 24
Vault Cool	Nov-09	Feb-10	Apr 7

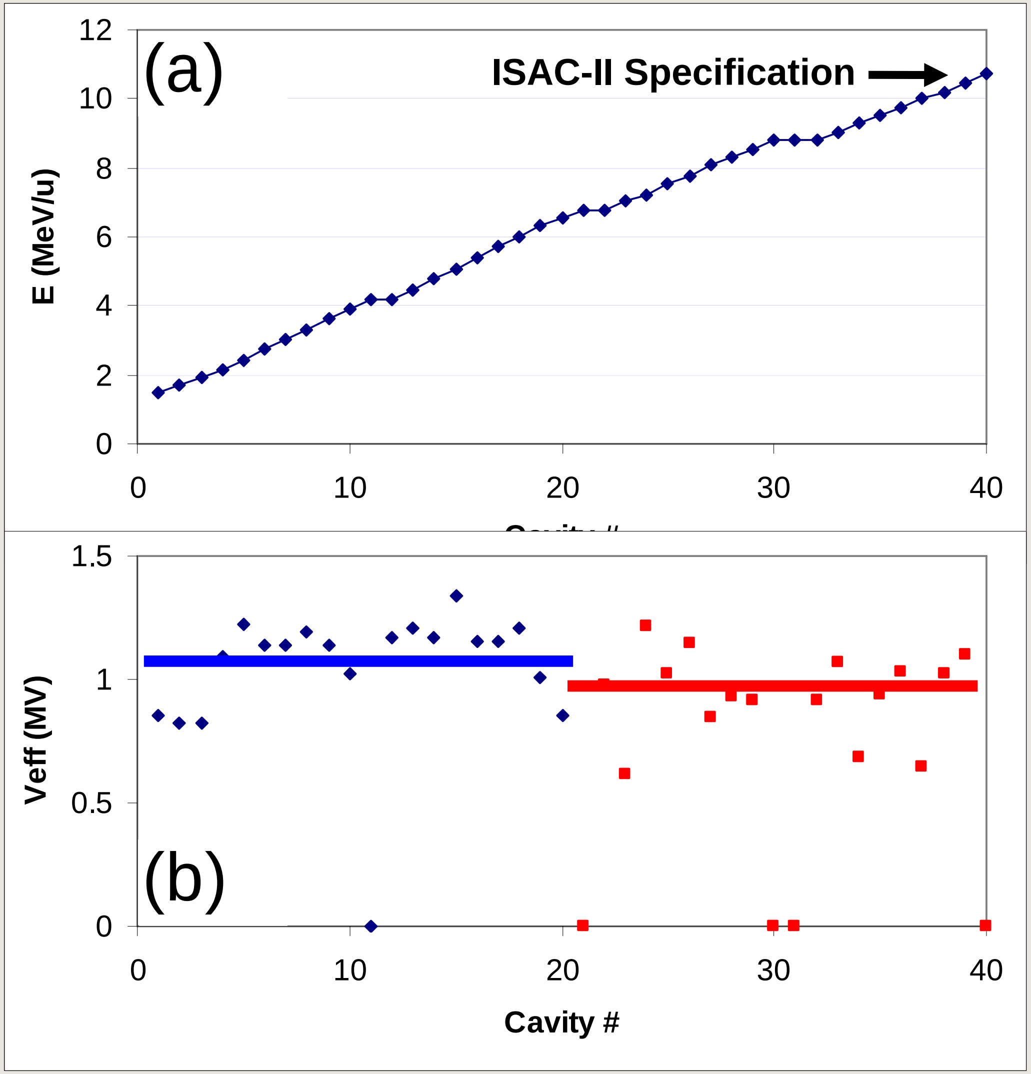
ISAC-II Phase II Status



- Final cryomodule installed March 21
- First beam was accelerated to ISAC-II specification April 24
- 16O5+ accelerated to 10.8MeV/u equivalent to 6.5MeV/u for A/q=6 (meets ISAC-II original specification on first acceleration)
- First stable beam delivered to experiment April 25
- First RIB's accelerated May 3
- Commissioning proceeds as the beam schedule allows

Performance from Acceleration

- First acceleration of 16O5+ used to measure cavity performance
- SCB's set to average Ep=30.3MV/m, SCC's set to average Ep=27MV/m
- One cavity unavailable in SCB and Four cavities unavailable in SCC – rf cable problems



Status

Beam Delivery

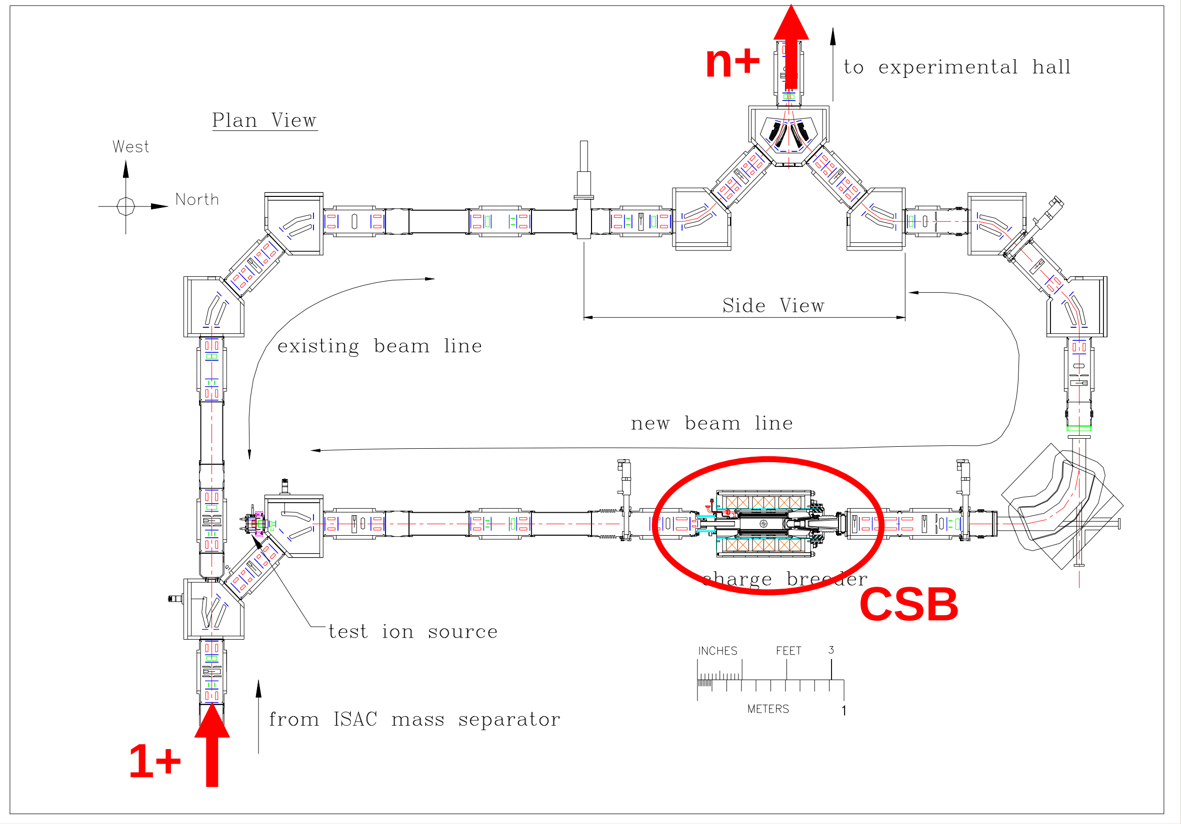
Accelerator immediately in heavy use.

The following beams have been accelerated in ISAC II since April 2010.

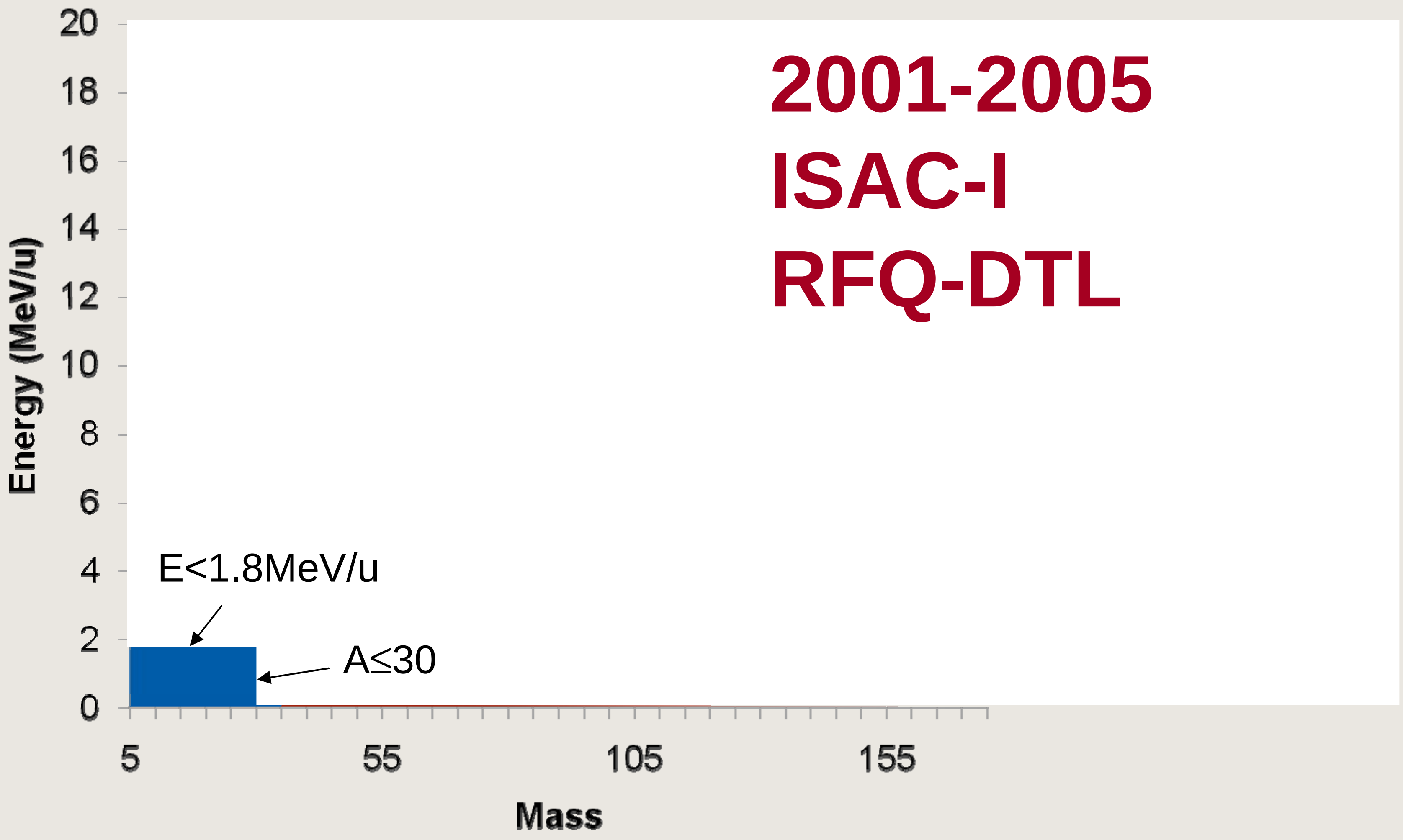
- Stable beams
  - 16O5+, 4He2+, 16O8+, 15N4+, 20Ne5+,
- Radioactive beams with stable pilot
  - 26Na, 26Al6+, 26Mg6+
  - CSB 78Br14+
  - 6He1+, 12C2+
  - 24Na5+, 24Mg5+
  - 11Li2+, 22Ne4+

Charge State Booster

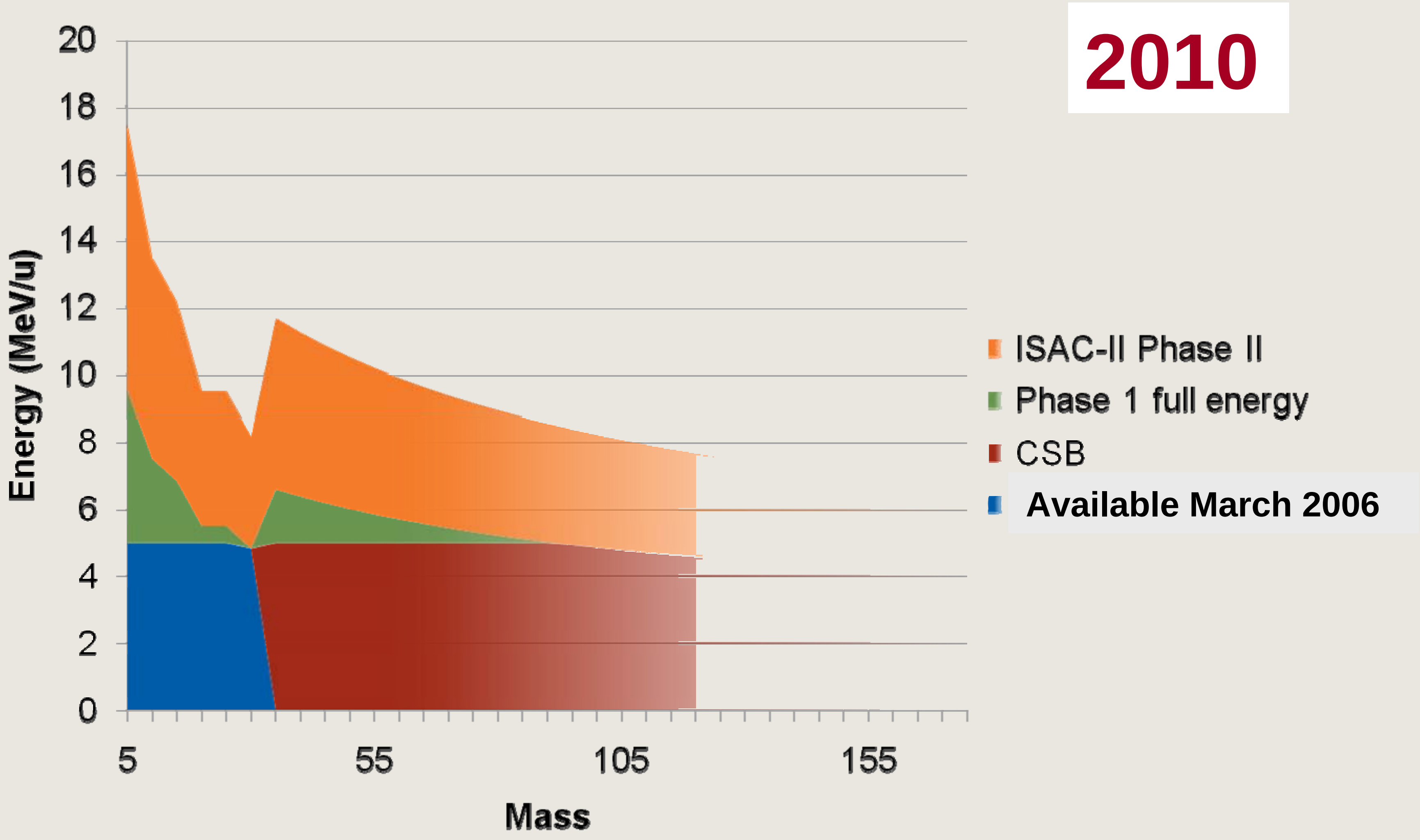
- •14GHz Phoenix ECR source from Pantechnik
- •Converts cw 1+ to n+ with 2-5% in the most probable charge state
- •Commissioned with stable beam 85Rb14+ and radioactive 78Br14+
- •All RIBs come with a quantity of stable impurities from the background gas
- •Need to purify the beam in flight – dev't in progress



Accelerated RIB at ISAC – 2001



Accelerated RIB at ISAC – 2010



Summary

- ISAC-II Phase II project
  - A 7.5 M$ project with R+D stretching over five years
  - Completed on time and on budget
- New SRF core competence and infrastructure
  - Allows collaborations, research and rich student program
  - Supports new accelerator initiatives in house – e-Linac
- Technical transfer of bulk niobium cavity manufacture to local vendor
  - PAVAC delivers two prototypes and twenty cavities
  - First Made in Canada superconducting linac
- ISAC-II now at full energy
  - ISAC-II now can boost heavy ions above the Coulomb Barrier – unique ISOL facility

Acknowledgements

- TRIUMF management
  - Strong support throughout
  - Paul Schmor, Gerardo Dutto
- ISAC-II Technical Team
  - Embraced the challenge and succeeded

Thank You!

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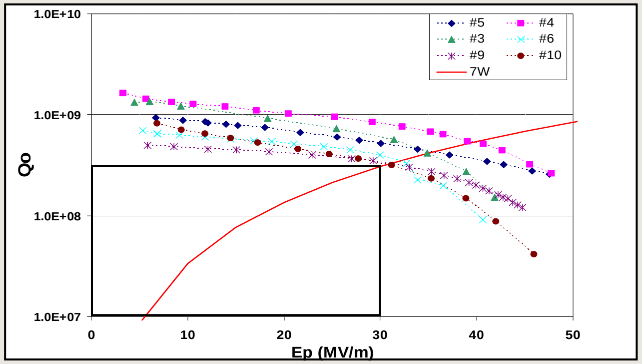
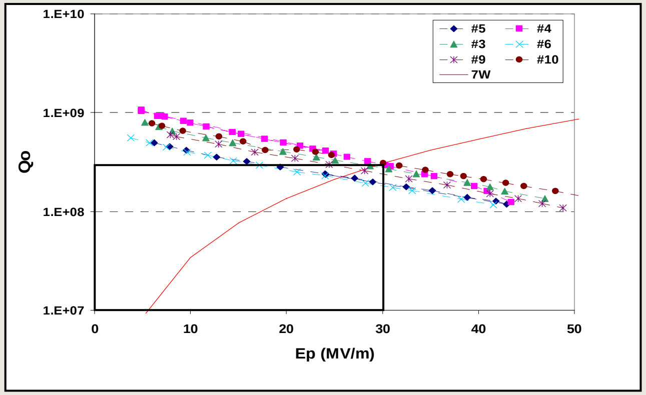
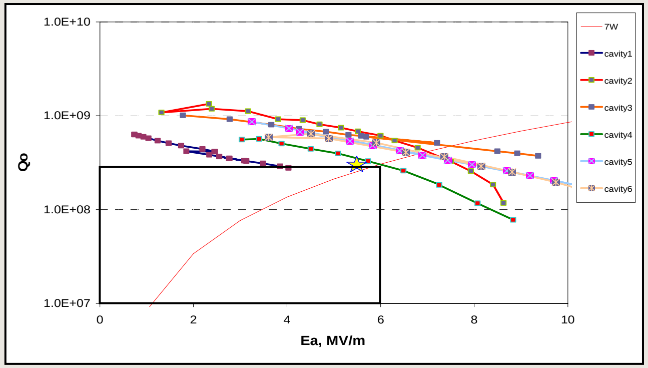
SCC1 Cavity Performance



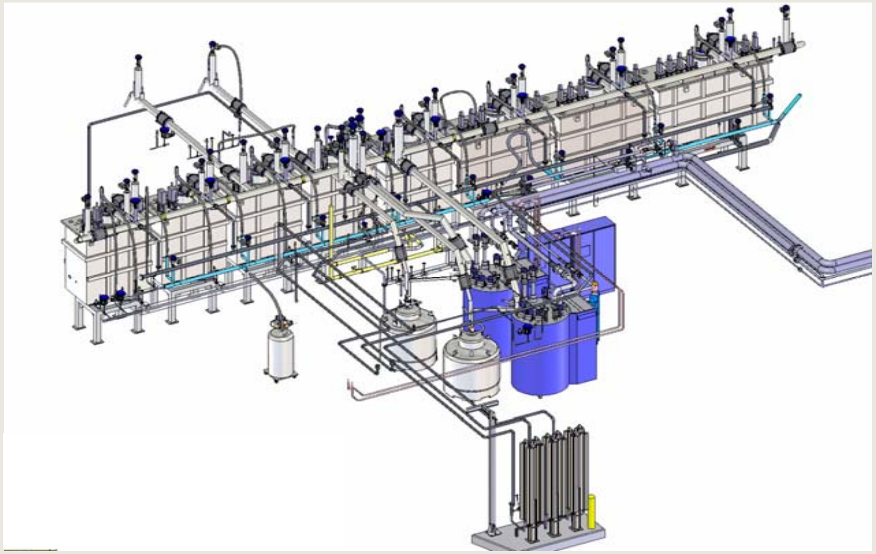


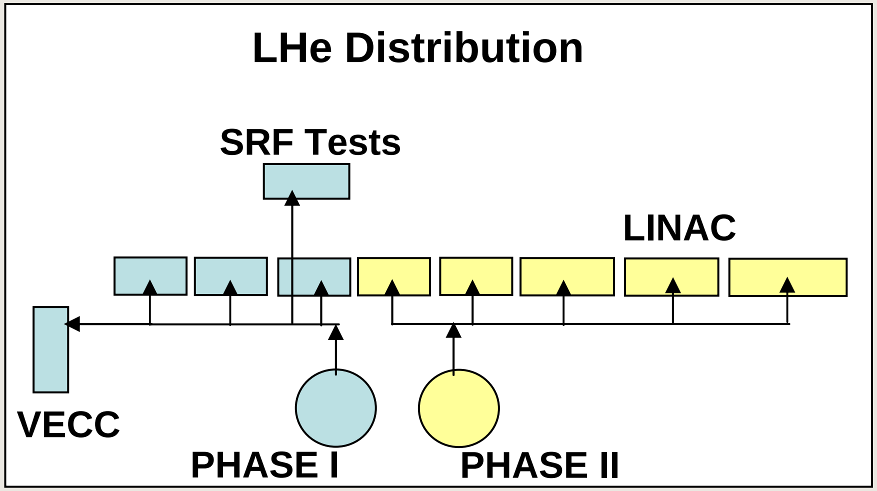


- Single cavity tests have an average performance of Ep=35MV/m at Pcav=7W
- Cavity performance in the cryomodule on the initial cooldown is significantly below – Ep=28MV/m
  - Q-disease suspected
  - Magnet shielding checked ok
  - Water tested ok
- Performance on-line with fast cooldown shows performance is recovered - one cavity shows signs of pollution; will try to recover with conditioning

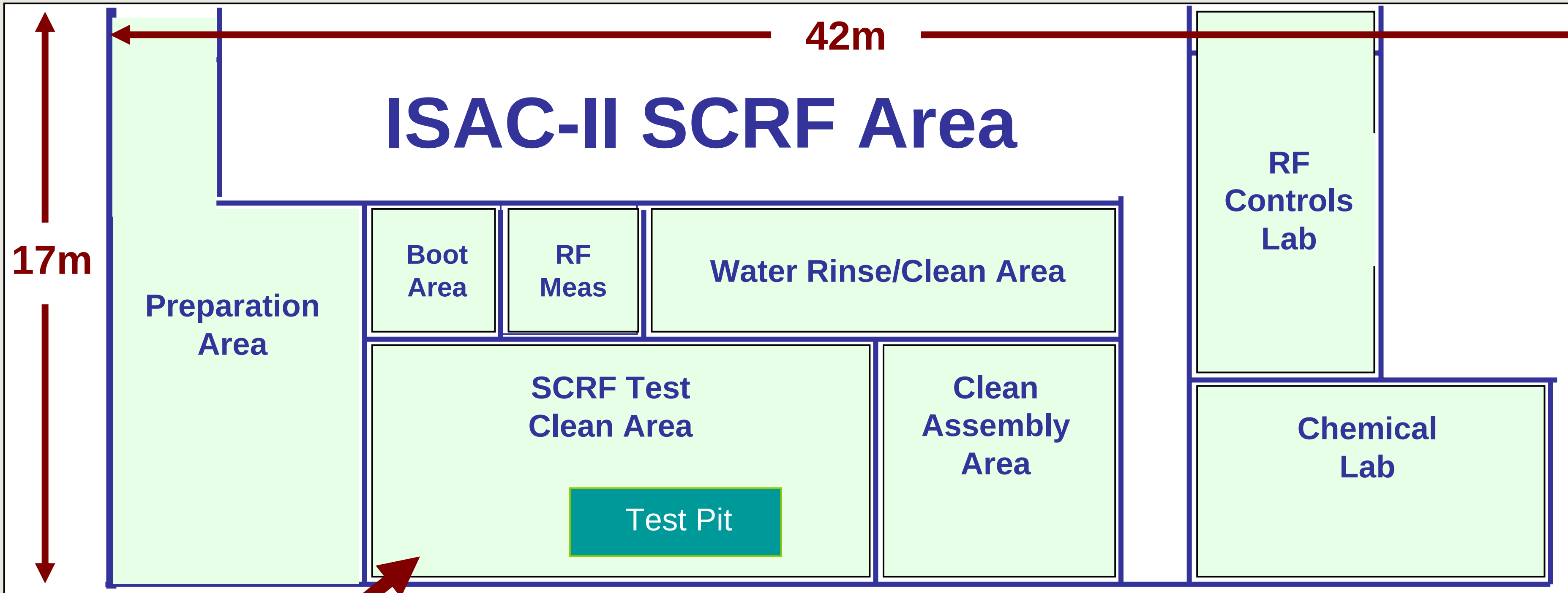
Cryogenic system

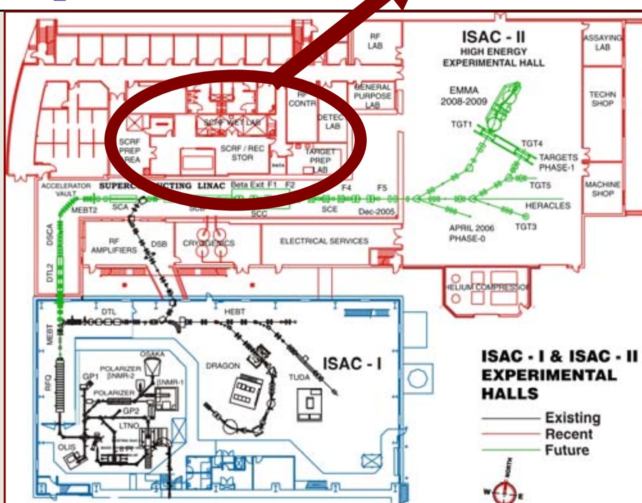
- A second Linde TC50 (600W) refrigerator doubles the refrigeration power and acts independently from Phase I
- Cold distribution piping keeps the two helium systems independent during normal operation:
  - Phase I delivers LHe to first three cryomodules as well as to two development areas,
  - Phase II delivers LHe to last five cryomodules
  - Valves exist to allow cooling entire linac from one plant





ISAC SRF Infrastructure





- The ISAC-II building houses the SCRF test and assembly areas
  - 500m^2 of floor space, overhead crane
  - Ultrasound cleaning tanks, High Pressure Water Rinse area, shielded rf test area, cryomodule assembly area, chemical etching lab
  - Over 100 single cavity tests performed and eight cryomodules assembled since 2004

TRIUMF

DTL Energy Variability

- Variable energy design
    - Short accelerating tanks provide discrete energy jumps
    - Detune V and φ in last operating tank
- Transmission>95%
- Beam quality good over full energy range