COMMISSIONING AND EARLY EXPERIMENTS WITH ISAC-II

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For the ISAC-II Linac Team

June 28, 2007

Outline

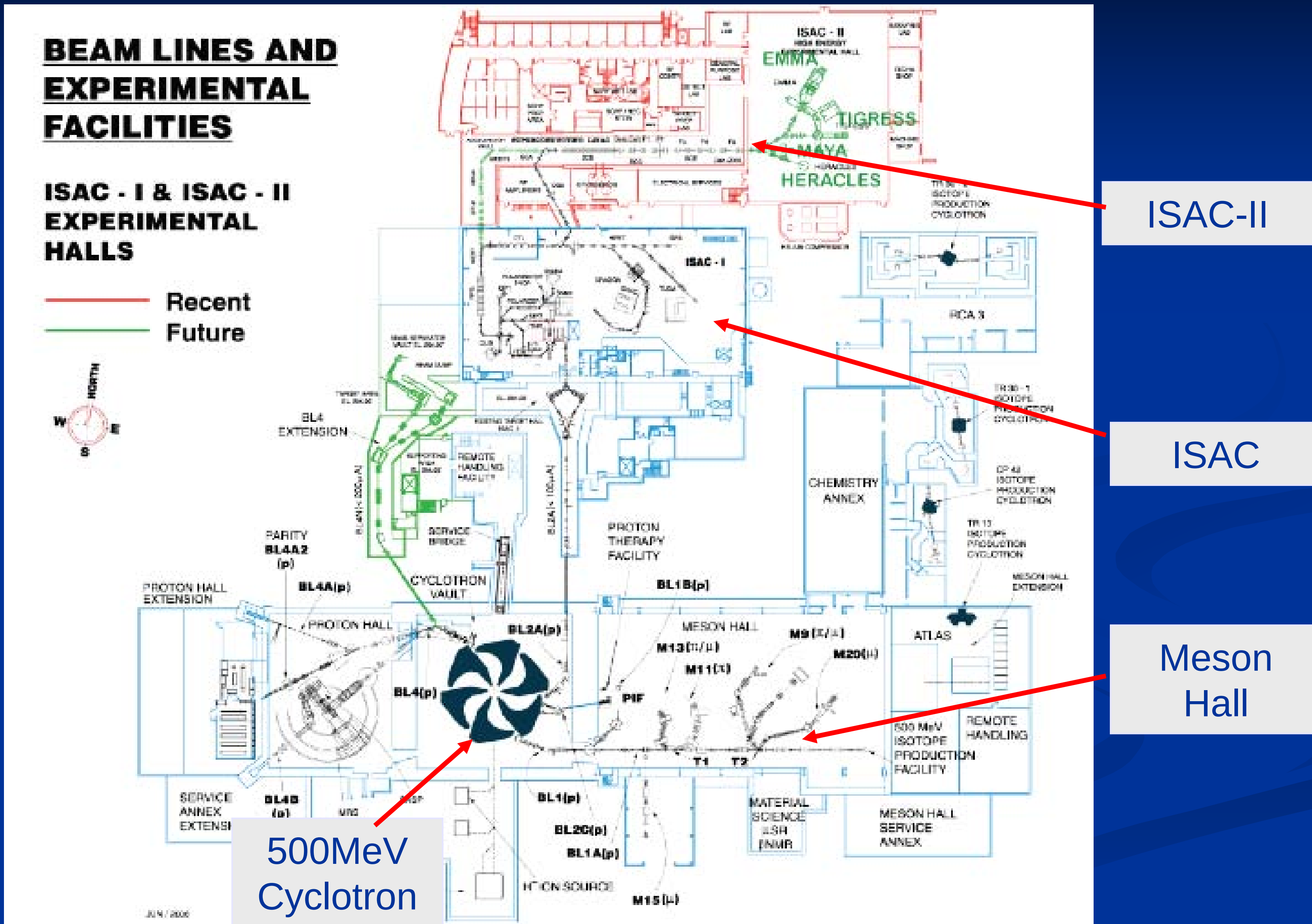
Outline:

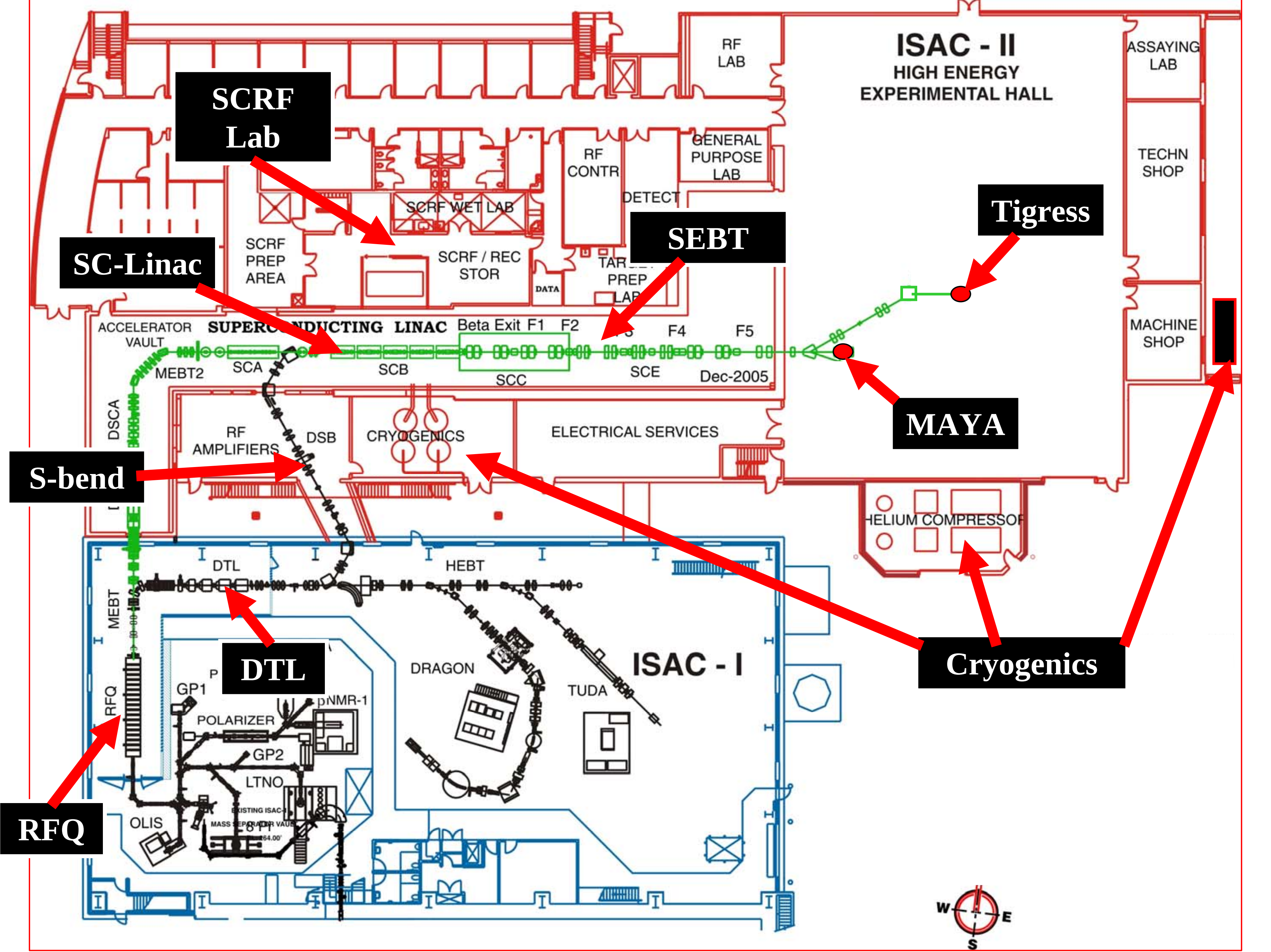
- ❑ ISAC Overview
- ❑ CW Heavy ion linacs
  - ▪Existing gradients worldwide; ISAC-II design goals
- ❑ ISAC-II hardware
  - ▪ towards higher gradient
- ❑ Installation and Commissioning
- ❑ Operating experience – Radioactive Ion Beam (RIB) delivery

ISAC Overview

TRIUMF

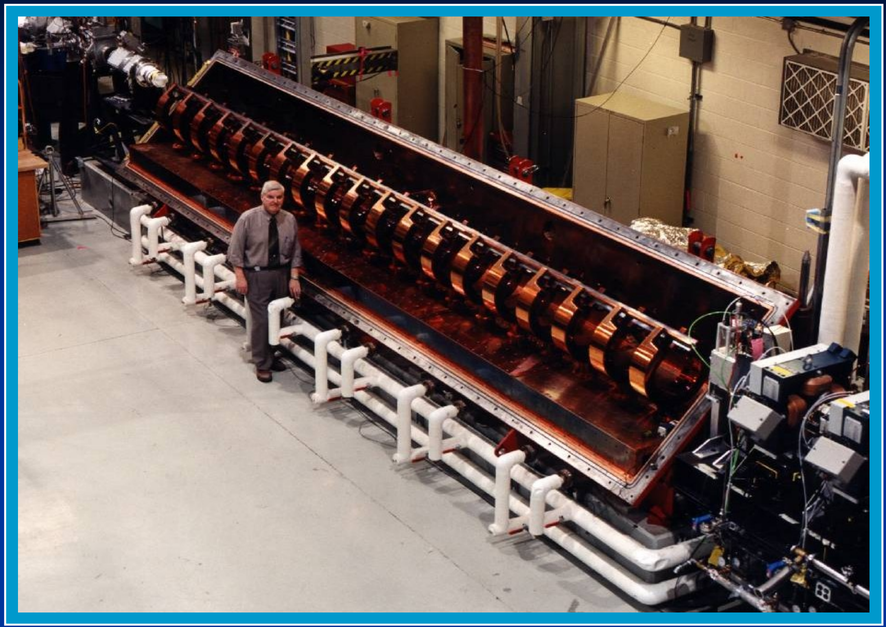
Canada's National Laboratory for Particle and Nuclear Physics





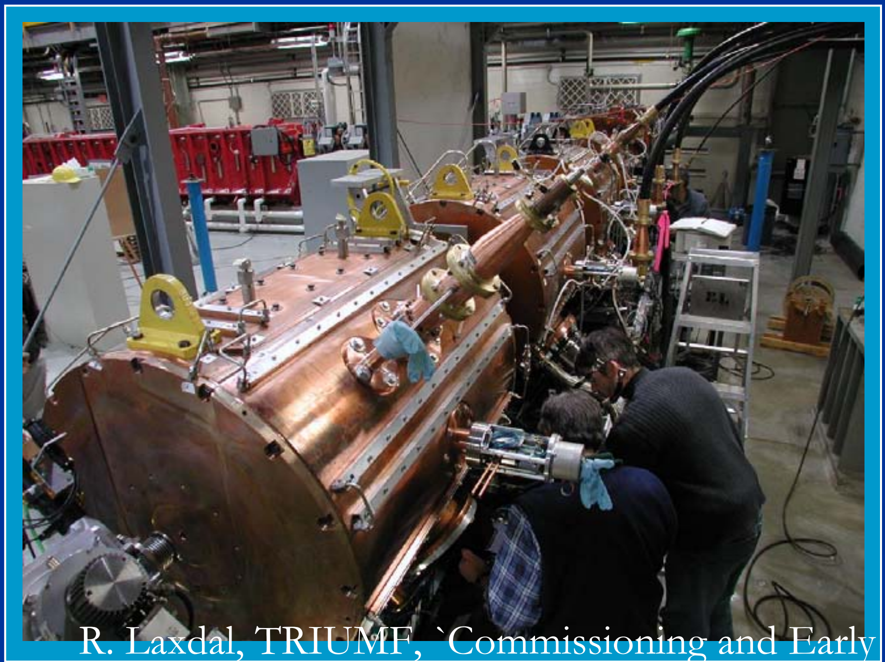
ISAC - II
HIGH ENERGY
EXPERIMENTAL HALL
RF LAB
ASSAYING LAB
TECHN SHOP
MACHINE SHOP
GENERAL PURPOSE LAB
RF CONTR
DETECT
SCRF WET LAB
SCRF PREP AREA
SCRF / REC STOR
DATA
PREP LAB
ACCELERATOR VAULT
SUPERCONDUCTING LINAC
Beta Exit F1 F2 F4 F5
MEBT2
SCA
SCB
SCC
SCE
Dec-2005
DSCA
RF AMPLIFIERS
DSB
CRYOGENICS
ELECTRICAL SERVICES
HELIUM COMPRESSOR
DTL
HEBT
MEBT
RFQ
GP1
POLARIZER
GP2
LTNO
OLIS
pNMR-1
DRAGON
TUDA
ISAC - I
SCRF Lab
SC-Linac
SEBT
Tigress
MAYA
S-bend
Cryogenics
DTL
RFQ
W
E
S

TRIUMF ISAC Facility



ISAC 35MHz Split-ring RFQ

- accelerates ions with A/q<=30 from 2keV/u to 150keV/u

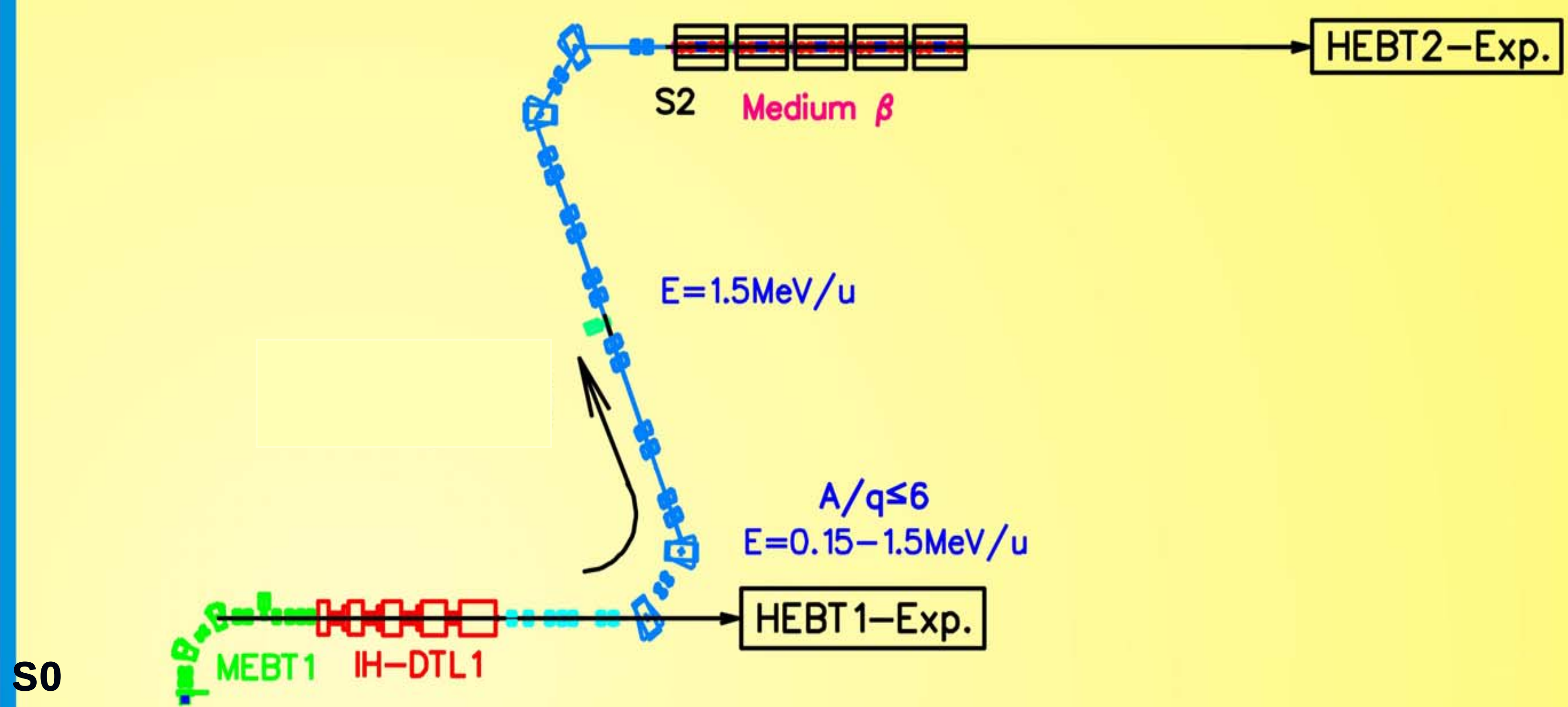


ISAC 106MHz Separated Function DTL

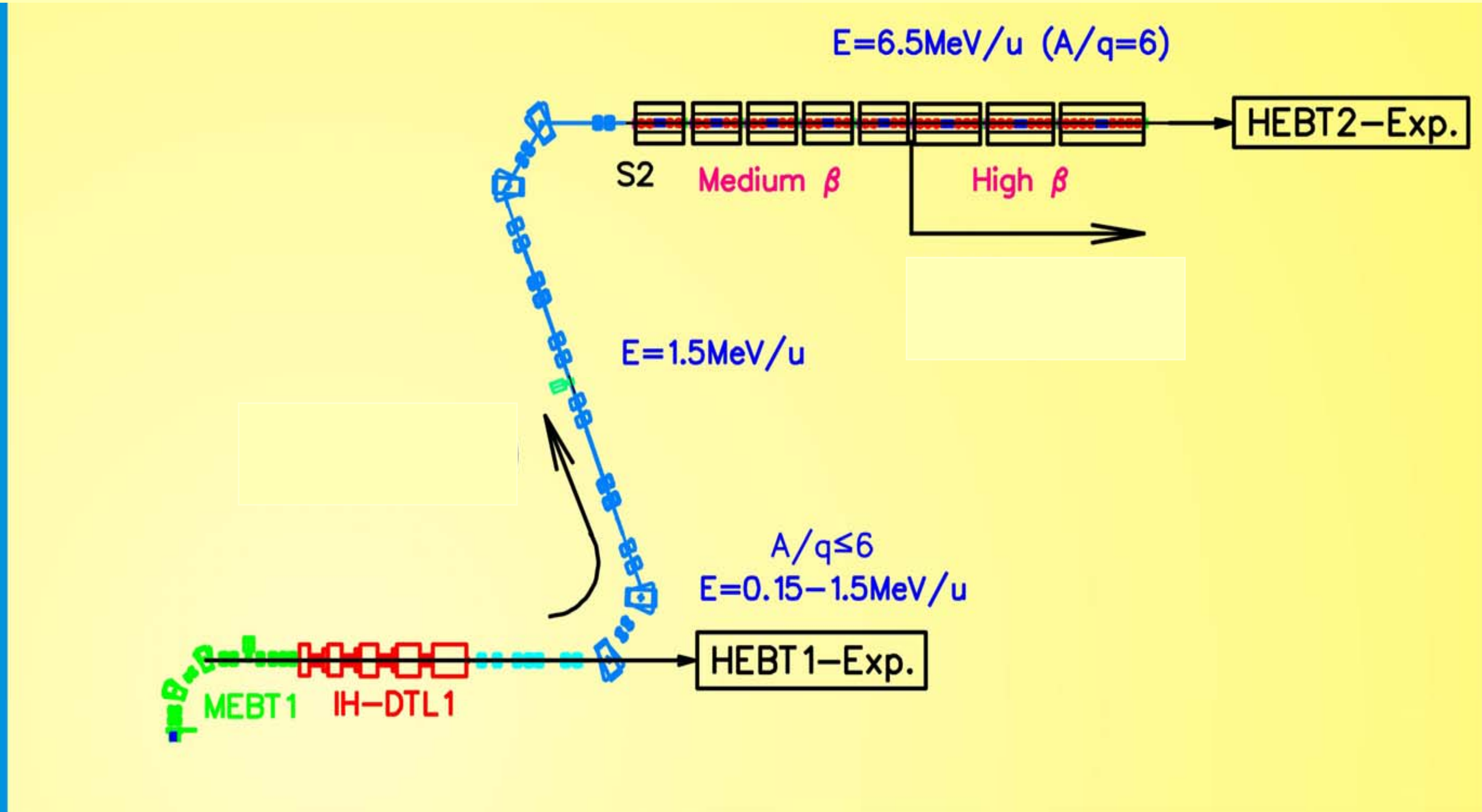
- accelerates ions with A/q<=6 to final energies fully variable from 0.15<E<1.5MeV/u

ISAC-II (Phase I - Medium Beta Section)

E=4.5MeV/u A/q=6



ISAC-II (Phase II - High Beta Section - 2009)



ISAC-II Specifications

Why Superconducting for RIB post accelerator?

- High gradient for cw operation
- Large apertures and longitudinal phase space
  - High transmission, easy to tune
  - Multi-charge acceleration possible
- Flexible machine
  - Suitable for a broad experimental program
  - Energy fully variable from no acceleration to full acceleration
  - Easy to manipulate longitudinal phase space
  - Can operate with one or more cavities inoperable
  - Can operate in fixed voltage (maximum energy) mode or fixed velocity (fixed phase) mode when changing ions

Projects and Proposals at Low Velocity

- ISAC-II TRIUMF – post-accelerator
- RIA – Driver and Post-accelerator
- Spiral-II – Driver
- EURISOL – Driver and Post-accelerator
- Soreq/SARAF – Driver
- REX-ISOLDE – post-accelerator

Heavy Ion Gradients – general comments

- Drivers – conservative gradient required
  - longer machines typically – large velocity swing – several cavity regimes
  - Treat as almost fixed gradient machine
- Post-accelerators –
  - Shorter machines typically – broad velocity acceptance
  - Utilize maximum gradient to improve performance and/or reduce cost

Low beta (0.1) vs High beta (1) performance

- E_{peak} at design P_{cav} gives a physical parameter that can be useful in comparing cavity performance
  - E_a depends on definition of length
  - Typically E_{peak}/E_a=4-5 for low beta QWR's while E_{peak}/E_a~2 for elliptical cavities.)
- For CW machines performance limited by LHe consumption - P_{cav} (Q at operating point) and not maximum achievable gradient (Cornell Ea~15-20MV/m for elliptical cavities or Ep~30-40MV/m)
- TRIUMF's goal for ISAC-II linac is to operate at Ep≥30MV/m

ISAC-II Linac Gradients

CW heavy ion SC-linacs with Nb technology

- ATLAS
  - Bulk niobium – Ep~15-20MV/m
- INFN-Legnaro
  - Sputtered Nb on Cu - Ep~20MV/m
  - Bulk niobium cavities – higher gradients demonstrated but little on-line experience
- JAERI
  - Explosively bonded Nb on Cu – Ep~23MV/m

Bulk Niobium Cavities at LNL

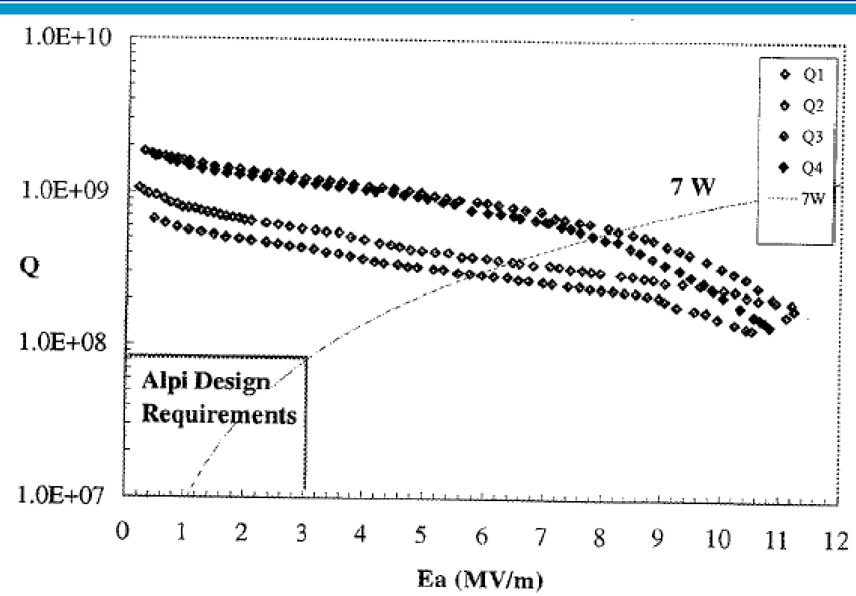


FIGURE 8. On-line performance of the bulk niobium resonators installed in cryostat n. 6.

A. Facco, Heavy Ion Acc. Tech. Argonne 1998

- Performance over 6MV/m (Ep=30MV/m) demonstrated
- Difficult to lock
  - unstable Alpi cryogenic system produces helium pressure fluctuations - tuner can't cope
  - Rf auxiliaries (coupling loops, amplifiers, cables) undersized to provide sufficient bandwidth
  - Alpi optics designed for 3MV/m - not compatible with high gradient

ISAC-II Linac Gradients

General Considerations

- Higher stored energy, U_o
  - Overcoupling used to broaden natural bandwidth
  - Requires $P_{forward}=\pi\ U_o \Delta f_{1/2}$
    - Increase amplifier, cables and coupling loop rating
  - Eigenfrequency excursions, Δf, from microphonics (fast) and helium pressure fluctuations (slow)
    - Adopt accurate constant-tracking tuner
- Higher peak surface field
  - Clean surfaces to reduce field emission, raise Q
  - Clean assembly techniques
- Higher rf defocussing fields (at φ_s=-25deg)
  - Adopt strong focussing lattice

ISAC-II

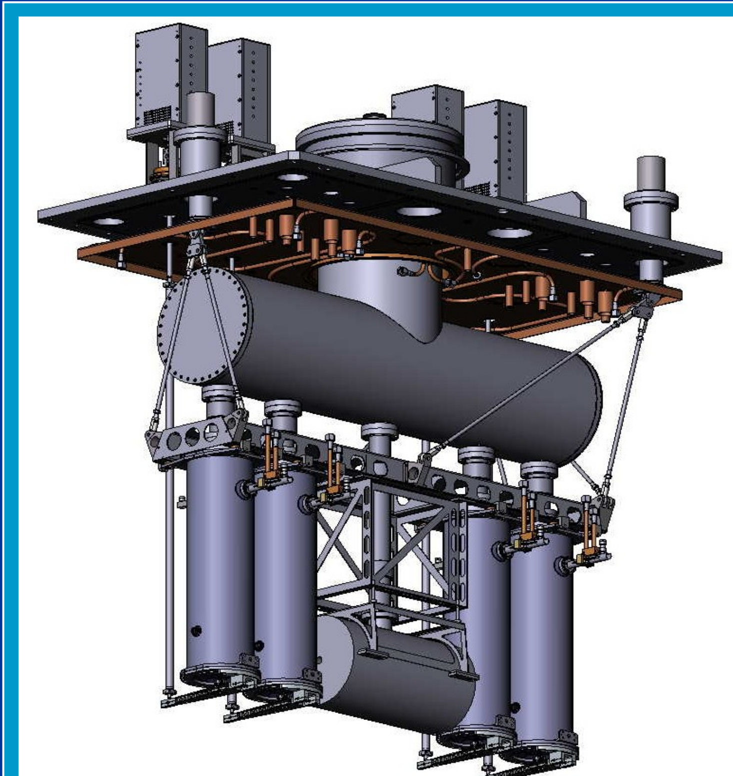
- Choose Ep=30MV/m
  - dV=1.1MV/cavity, Ea=6MV/m
  - Uo=3.2 Joules
  - $P_{forward}$=200W gives $\Delta f = \pm 20$Hz
    - ☑ Amplifier and cables compatible with 800W
    - ☑ Loop compatible with $P_{forward}$=250W
  - ☑ New fast tuner developed
- ☑ Clean room assembly
  - Single vacuum space for insulating vacuum and beam
- ☑ 9T solenoid in each cryomodule
  - Solenoid complete with `bucking' coil to reduce fringe field in cavity region.

ISAC-II SC-Linac Hardware

ISAC-II Linac: Cryomodule

- 2x2x1m stainless steel box vacuum vessel
- LN2 cooled copper sheet used as thermal shield
- Mu metal between vacuum tank and LN2 shield
- Cold mass suspended from lid on three adjustable support pillars

- Four cavities Ep=30MV/m
- One SC solenoid @ 9T
- V_{eff}=4.3MV
- Single vacuum for thermal insulation and rf

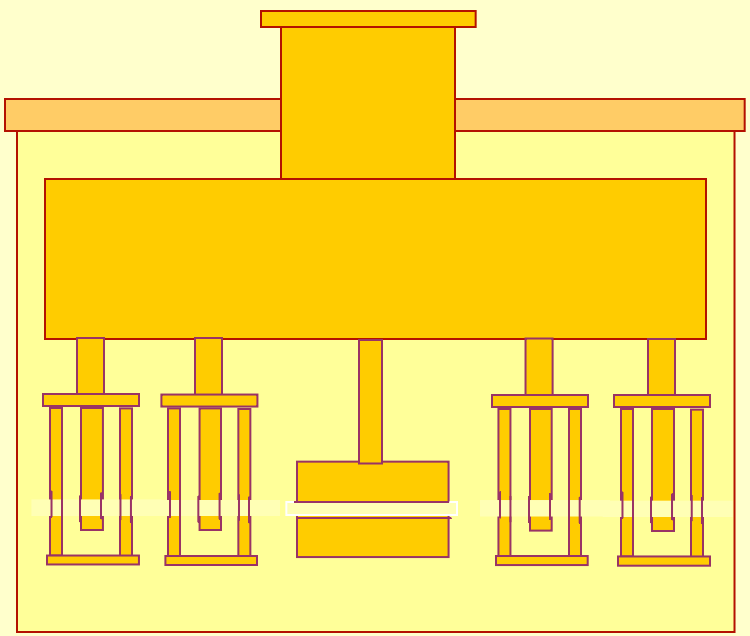


Lid Assembly in Assembly Frame

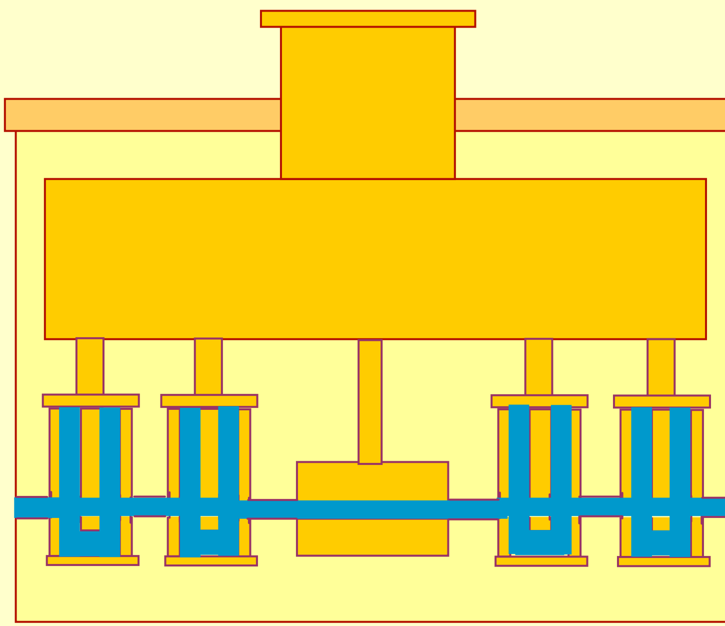
ISAC-II Linac: Cryomodule Vacuum

Single Vacuum vs Double Vacuum

- Cavity vacuum and thermal isolation vacuum share the same space
- Engineering easier but thermal vacuum must be done carefully (particulate control)
- ISAC-II, ATLAS, Legnaro, JAERI

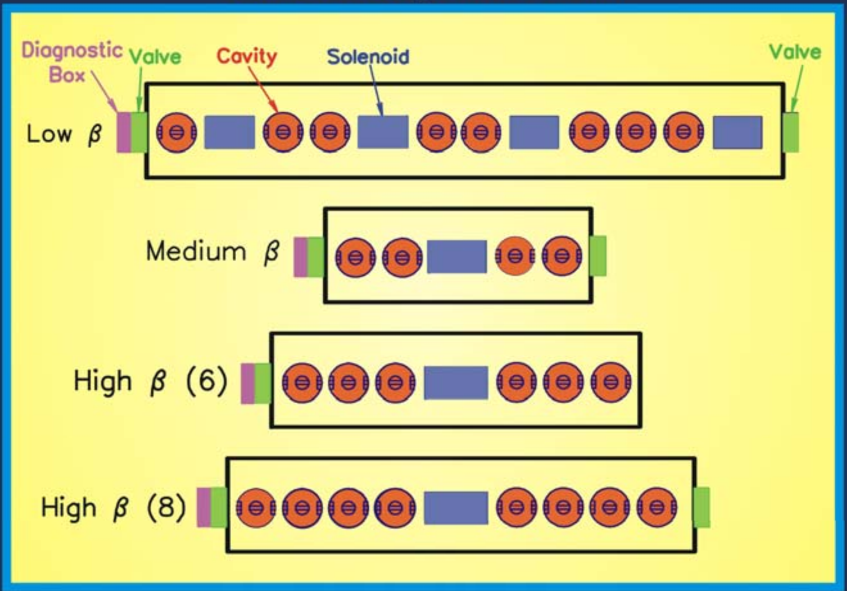


- Cavity vacuum connected through beam pipe and isolated from thermal vacuum
- Engineering more complex but eases cleanliness requirements in thermal vacuum space
- RIA, SPIRAL-II, SOREQ



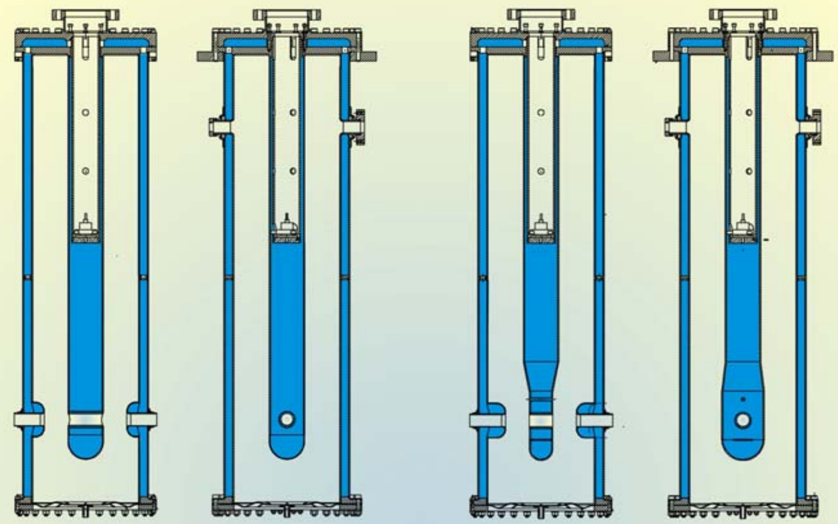
ISAC-II Linac: Medium β cavities

ISAC-II Cryomodules



Prototype Cavity

Medium Beta Cavities



(a) Nominal (β=7.1%) (b) Flat (β=5.7%)

freq=106.08MHz

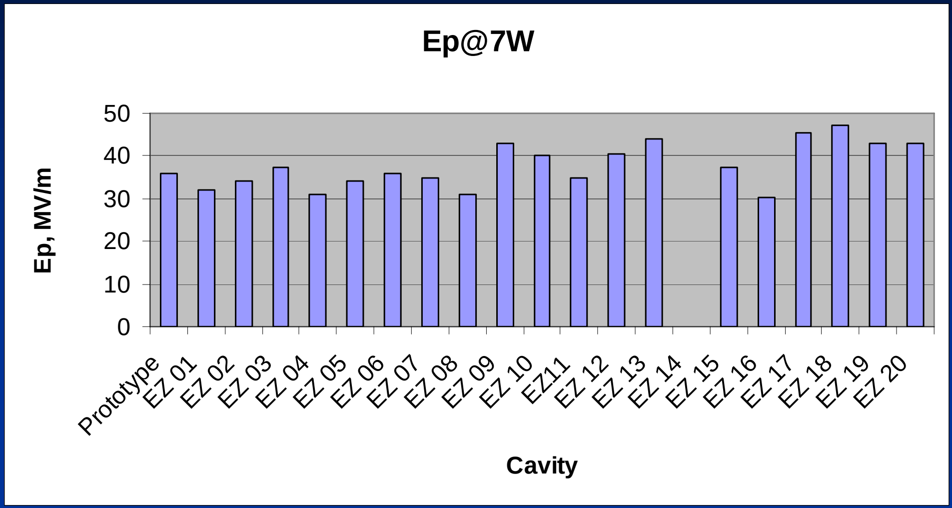
$E_p/E_a \simeq 5$

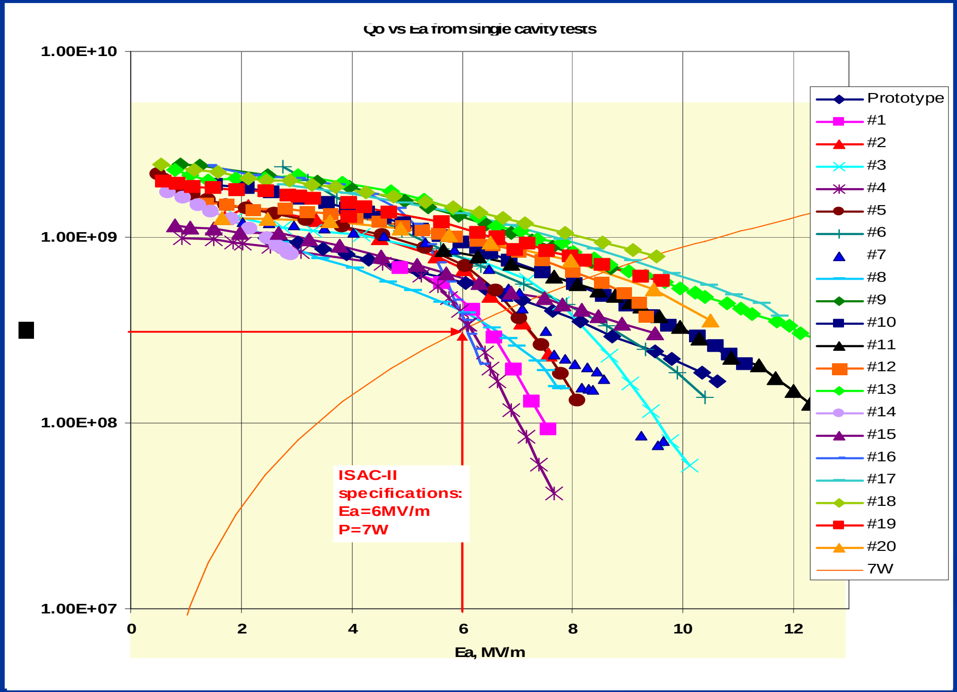
$H_p/E_a \simeq 100$ G/(MV/m)

$U/E_a \simeq 0.09 J/(MV/m)^2$

$\Gamma \simeq 19\Omega$

ISAC-II Linac: Single Cavity Performance



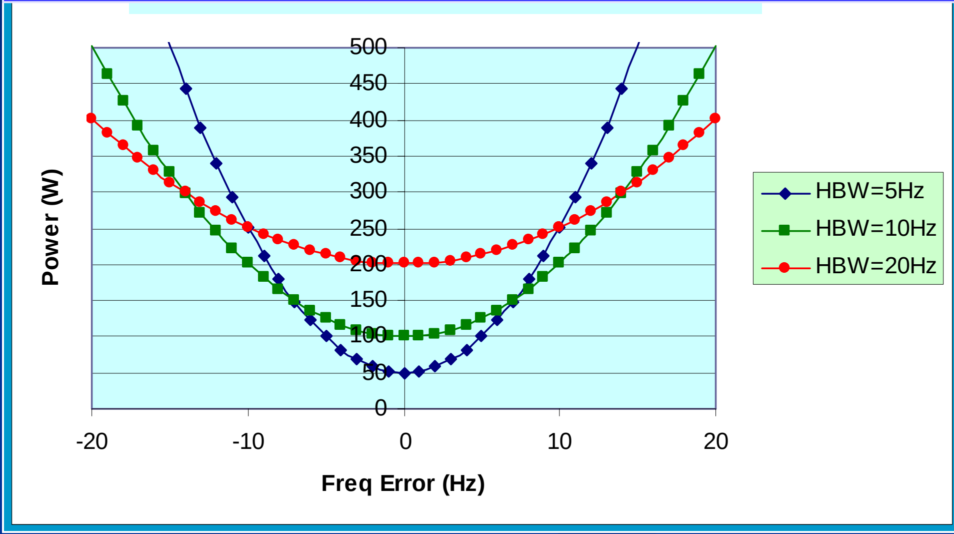


- Cavities tested initially in single cavity cryostat
- Four cavities retested with fast cooldown to reduce effects of Q-disease
- Average peak surface field at operating power of 7W is now Ep=38MV/m corresponding to a voltage gain of 1.4MV/cavity and a magnetic field of Bp=75mT and a gradient Ea=7.5MV/m.
- All cavities have been tuned to the ISAC-II frequency
- One cavity (spare) quenches at Ep=15MV/m

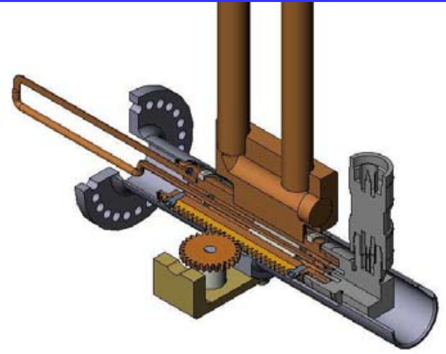
ISAC-II Linac: RF Systems

- RF power
  - Provide useable bandwidth by overcoupling
  - Require P_f=200W at cavity for $f_{1/2}$=20Hz at E_a=6MV/m, β=200
- Coupling loop
  - Developed LN2 cooled loop
  - <0.5W to LHe for P_f=250W
- Mechanical tuner
  - Precise (0.3~Hz), fast (>50Hz/sec) tuner with dynamic range of 8kHz and coarse range of 32kHz
- Tuning plate
  - Spun, slotted, \`oil-can' tuning plate to improve tuning range

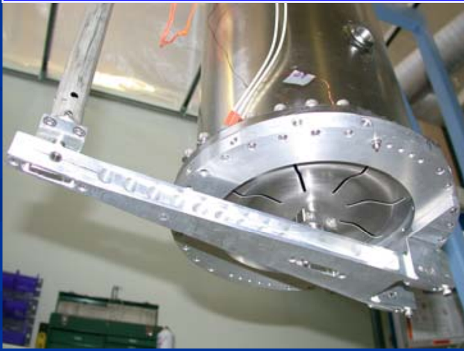
Forward power required for Ea=6MV/m and given bandwidth



Coupling Loop

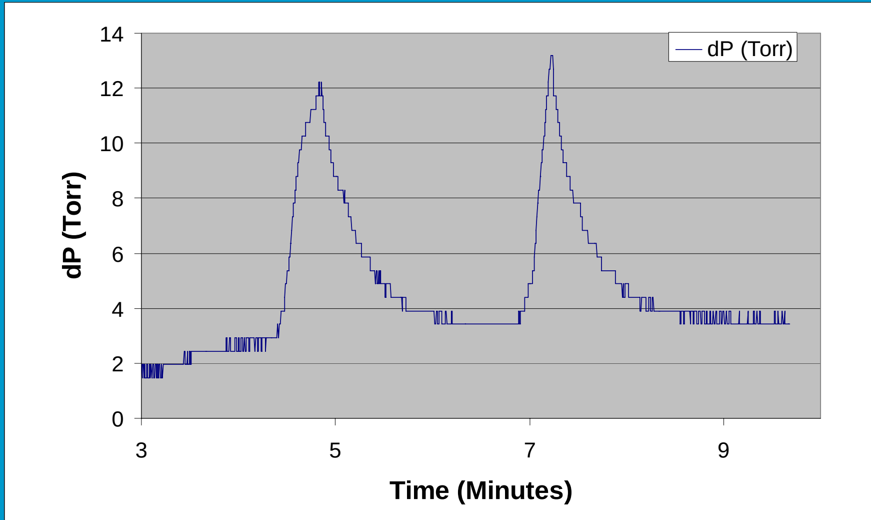


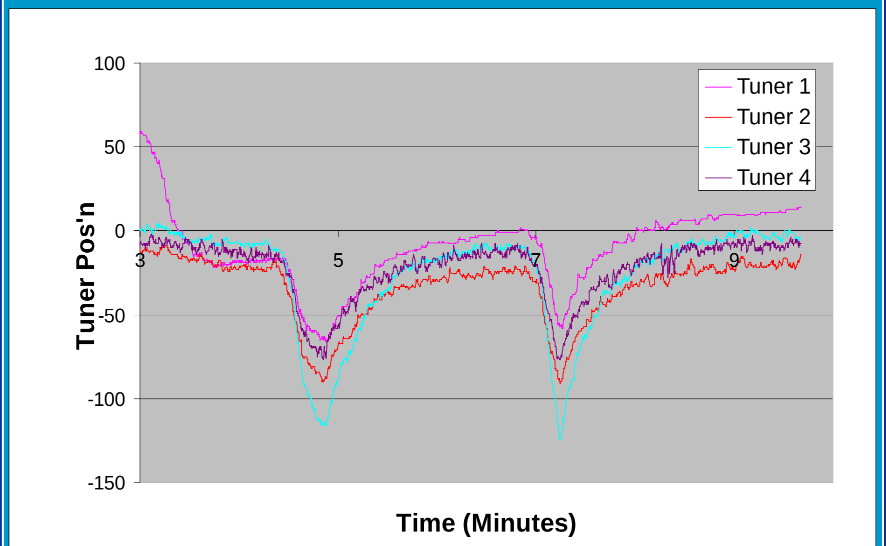
Mechanical Tuner

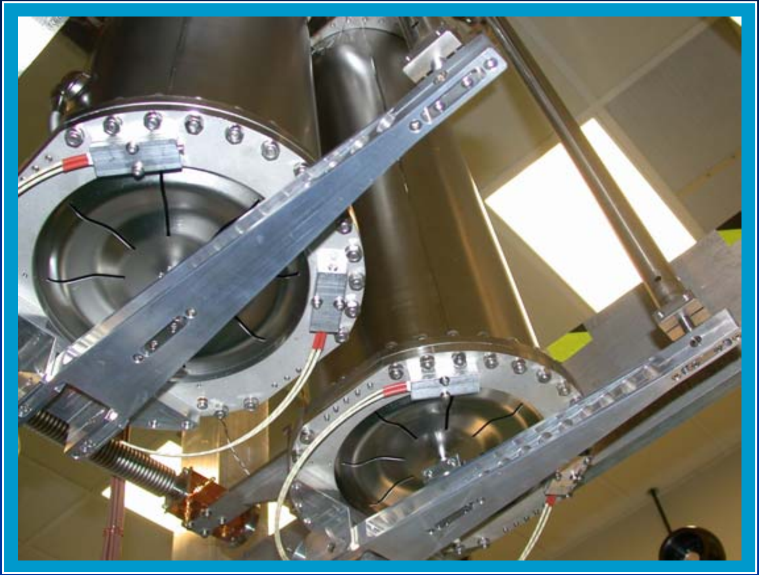


ISAC-II Linac: RF Tuner

Tuner Response with Four Cavities





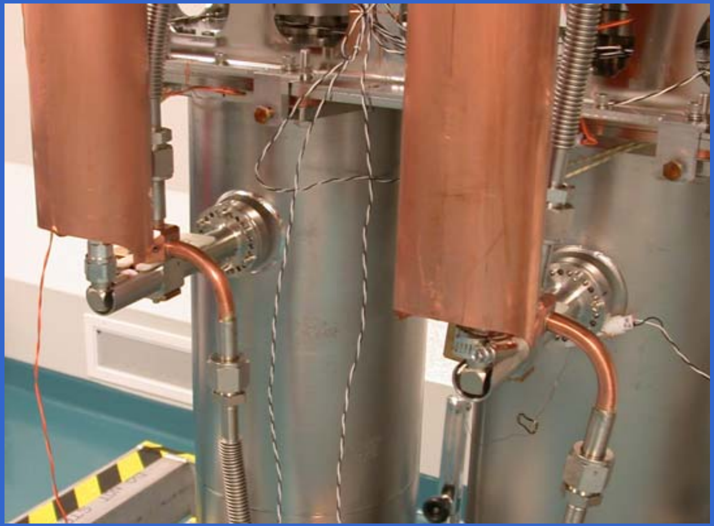


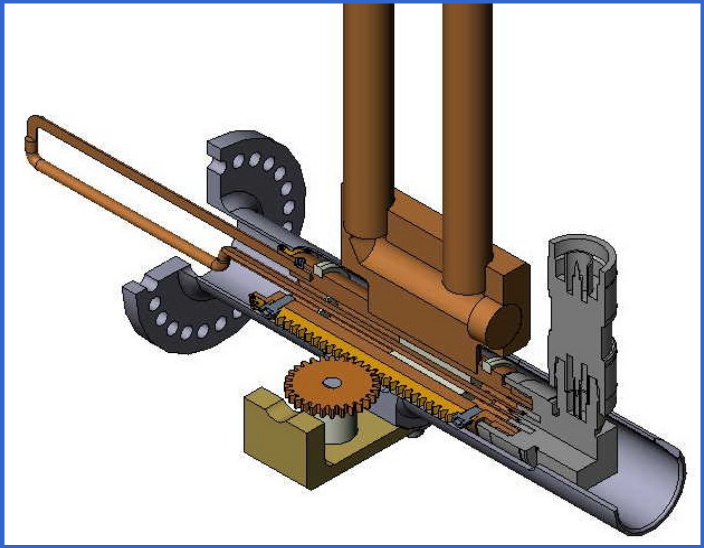
- **Lever mechanism with zero backlash hinges and stiff rod connected to precision linear motor (Kollmorgan) in air**
- **All four cavities locked to ISAC-II Specifications**
  - **Ea=6MV/m (Ep=30MV/m) and 106.08MHz**
  - **P_{cav}~6W, P_{for}~250W, β~170**
- **Helium exhaust valved off to force pressure fluctuation**

ISAC-II Linac: RF Coupling Loop

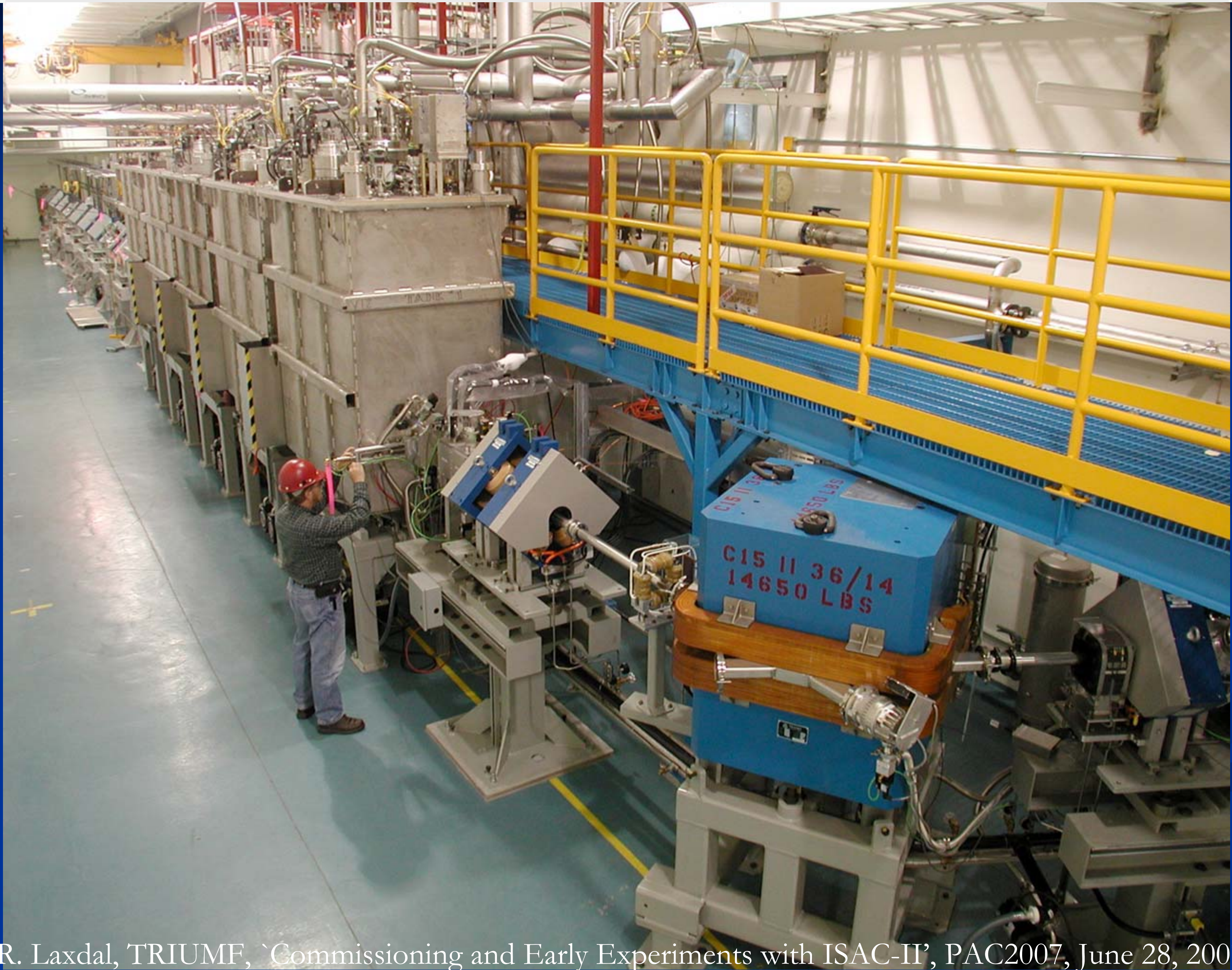
- ❑Developed from INFN Legnaro adjustable coupling loop
- ❑Modifications
  - ✓Stainless steel body for thermal isolation
  - ✓Copper outer conductor thermally anchored to copper LN2 cooled heat exchange block
  - ✓Aluminum Nitride dielectric inserts thermally anchor the inner conductor to the outer conductor
  - ✓Removed fingerstock to control microdust

✓Achieved <0.5W helium heating with Pf=250W





ISAC-II Linac: Accelerator Vault

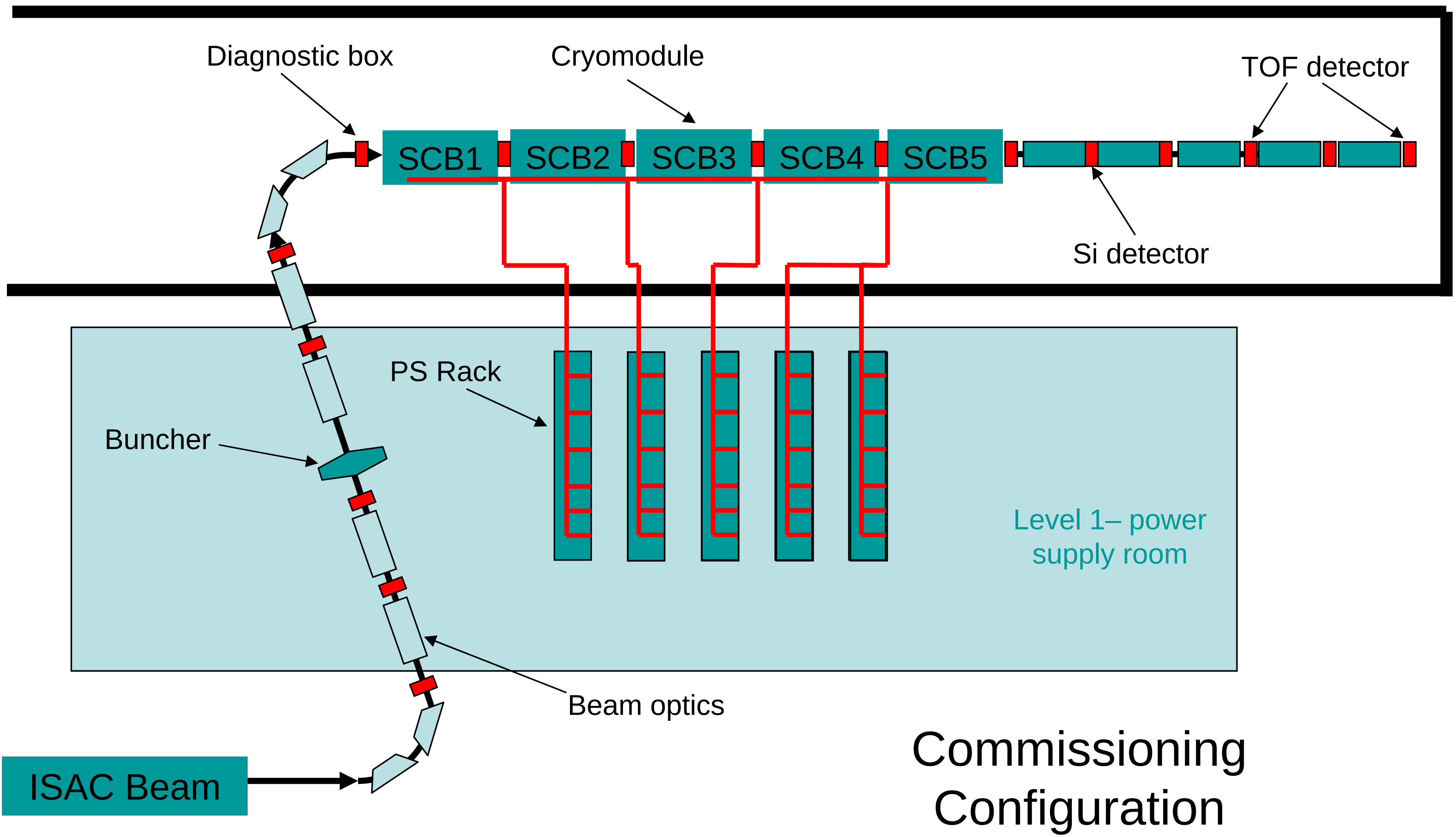


ISAC-II Linac: Milestones

- First acceleration – April 8, 2006
- Commissioning – April – Dec 2006
  - Beam-time allocated between ISAC-I experimental shifts
- First Radioactive Ion beam (RIB) to experiment – Jan. 5, 2007
  - First beam time - Jan. 6-19, 2007 (two weeks)
- Shutdown – warm-up
  - Jan. 19 – April 2 , 2007
- Second RIB campaign
  - May 4 – June 9, 2007 (five weeks)

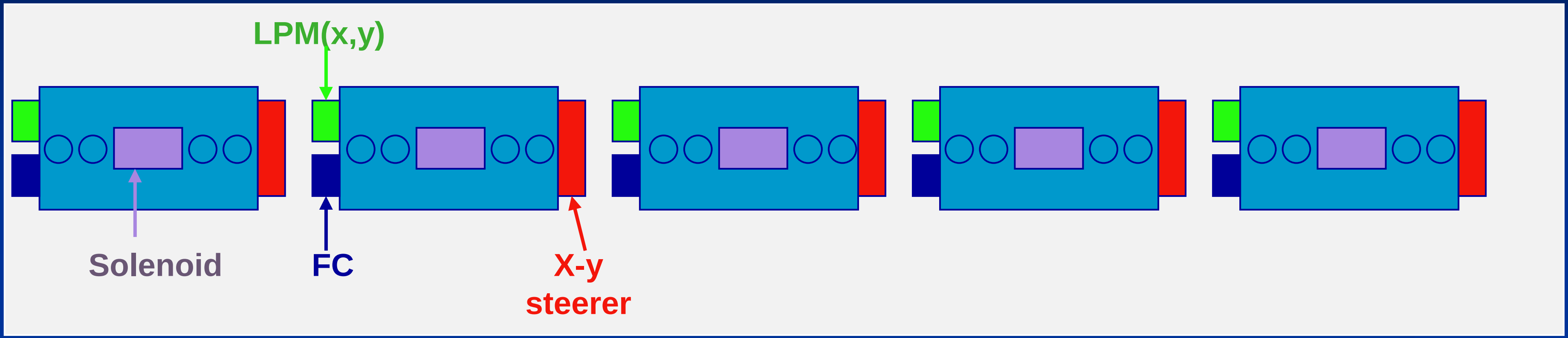
Commissioning

LINAC Commissioning Floor Layout

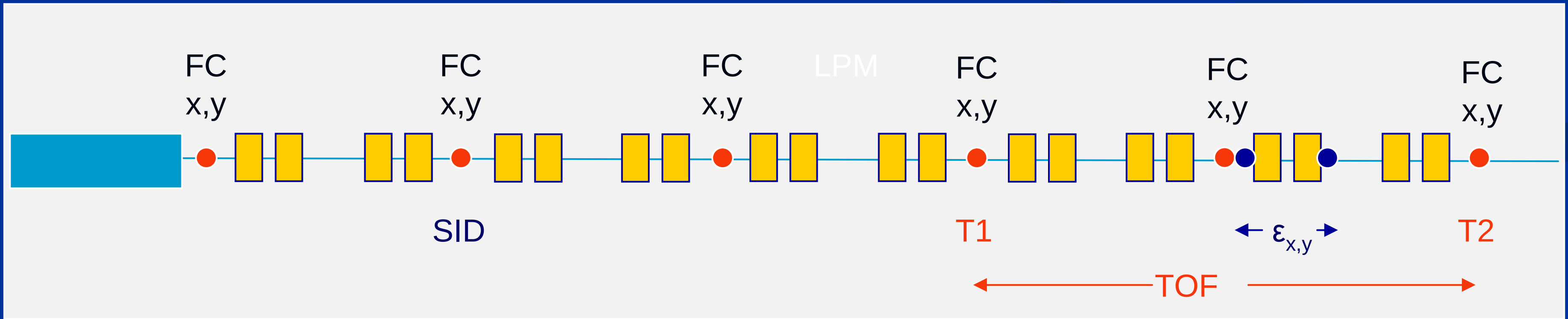


ISAC-II Linac: Diagnostics

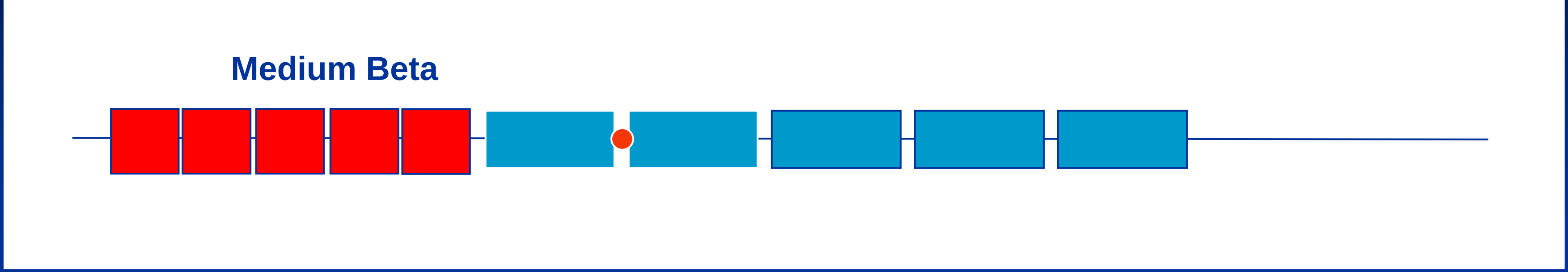
Linac

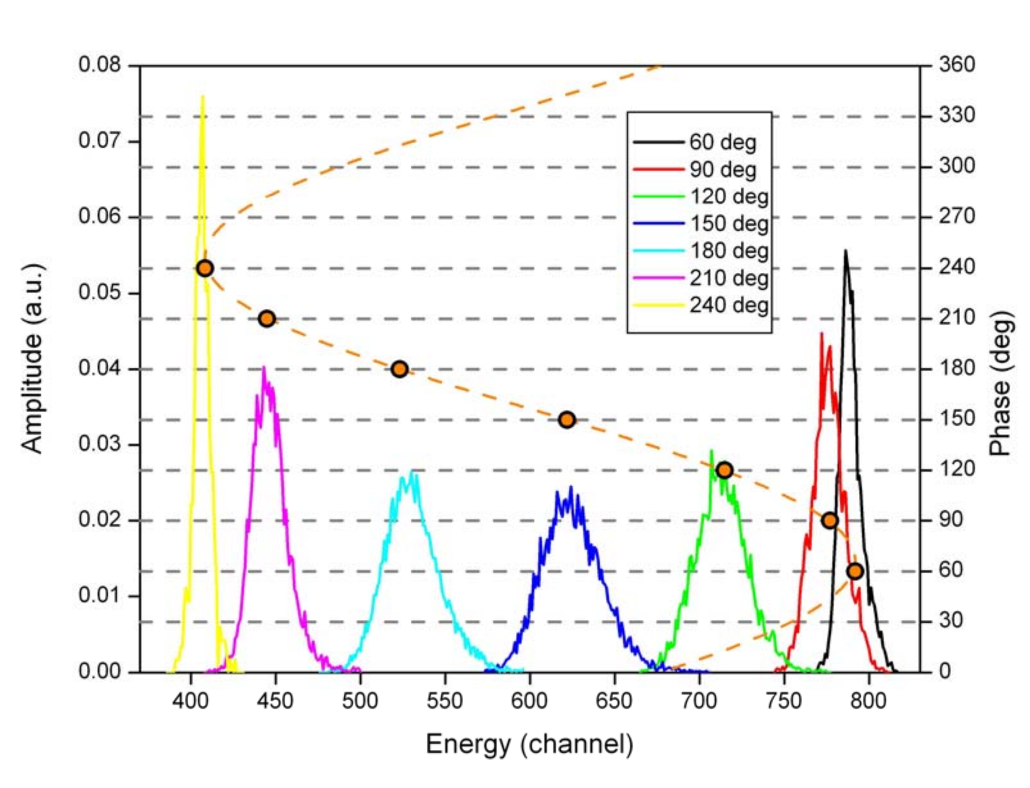


Beamline



ISAC-II Linac: Cavity Phasing

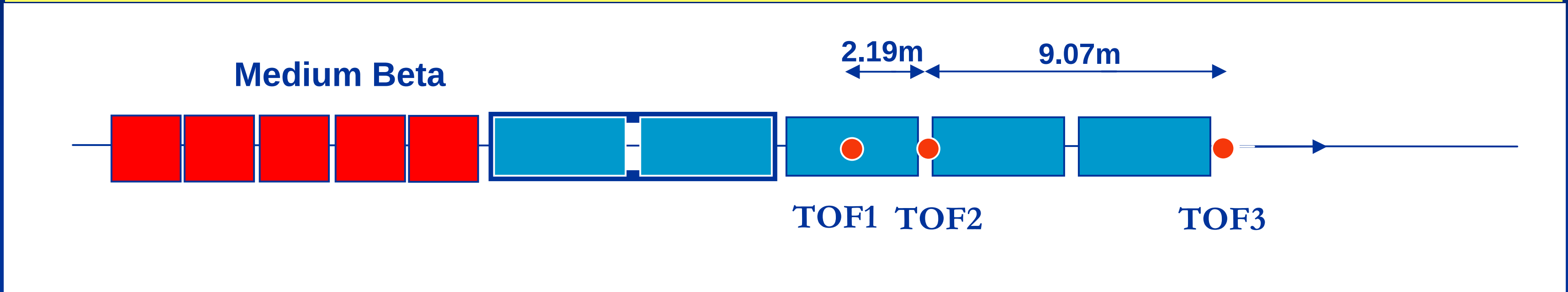


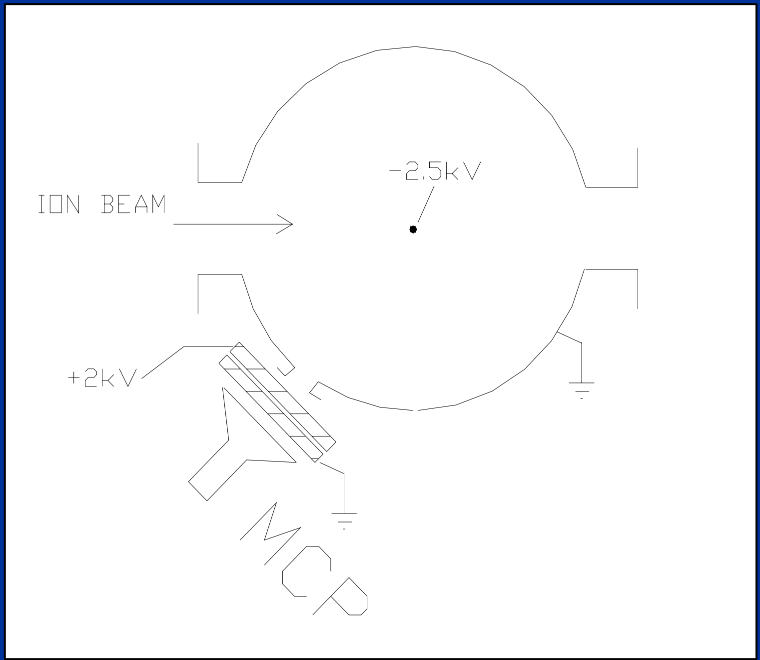


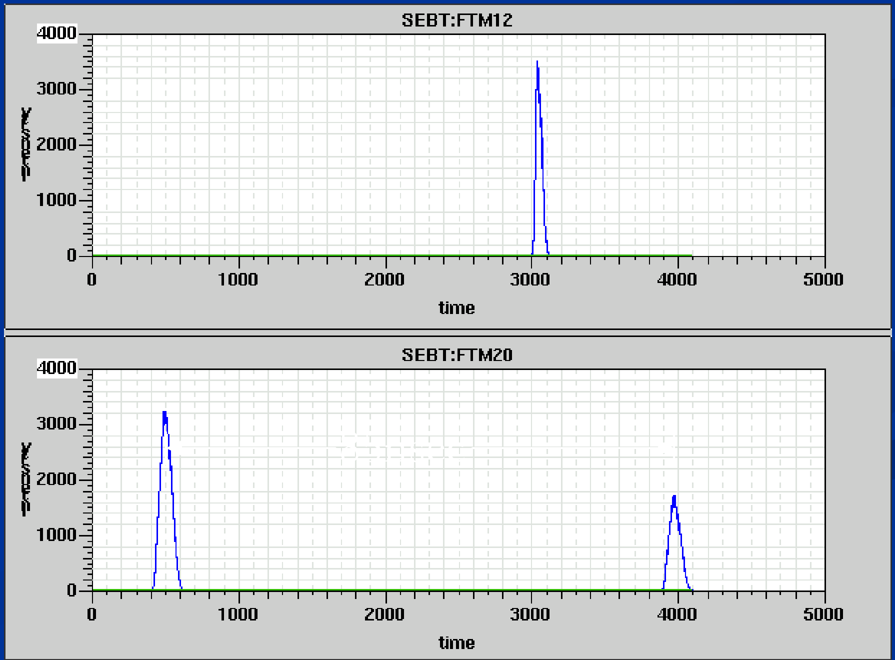
- •Si detector in downstream detector measures energy of particles scattered from a Gold foil
- •Ion Energy is measured for different cavity phases
- •φ = 0 deg determined from cosine fit to energy data
- •Cavity set to φ =-25deg for acceleration

ISAC-II Linac: Energy Measurement

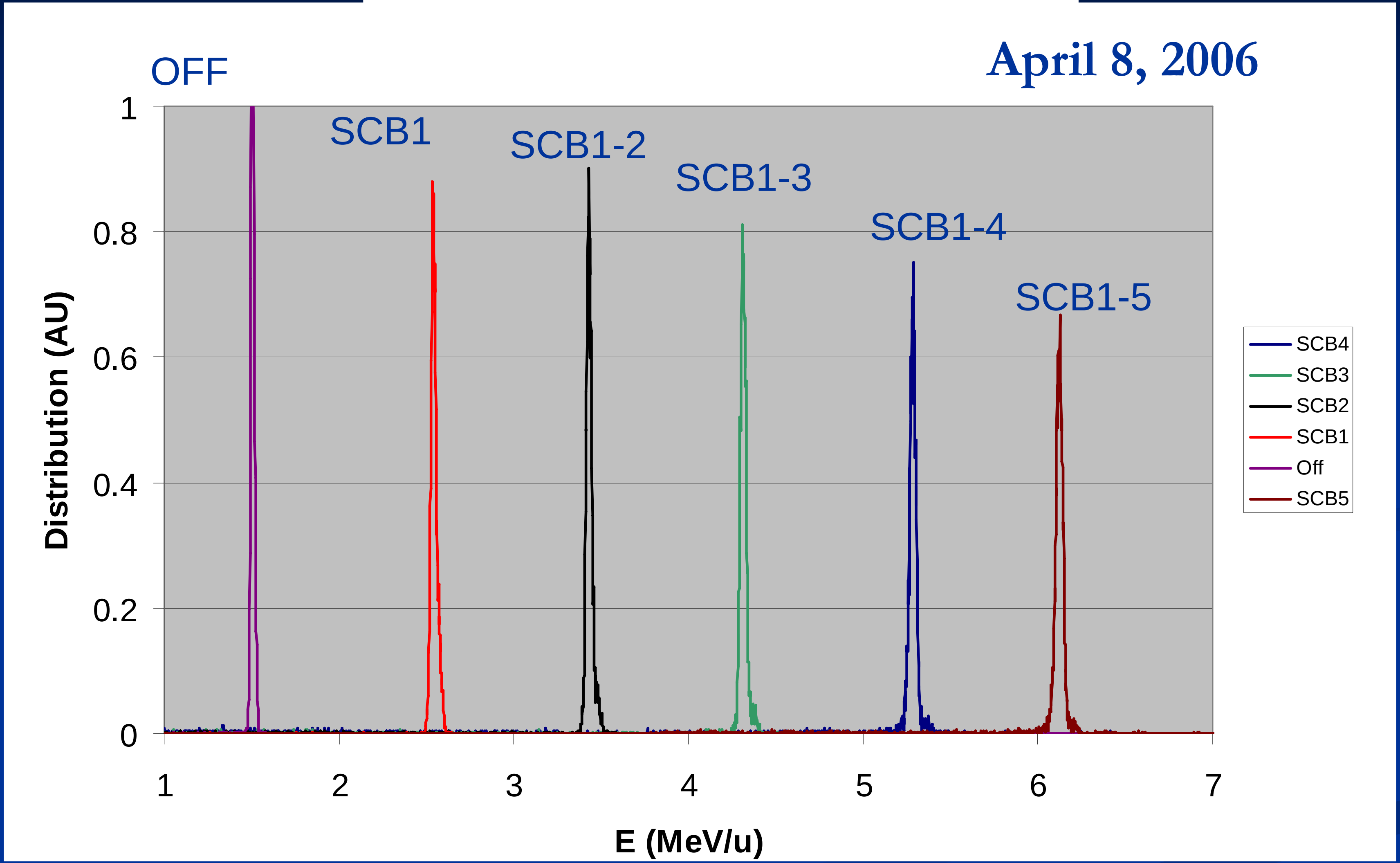
Three monitor system giving three TOF measurements. The quoted energy is derived from the weighted average of the three calculated energies.





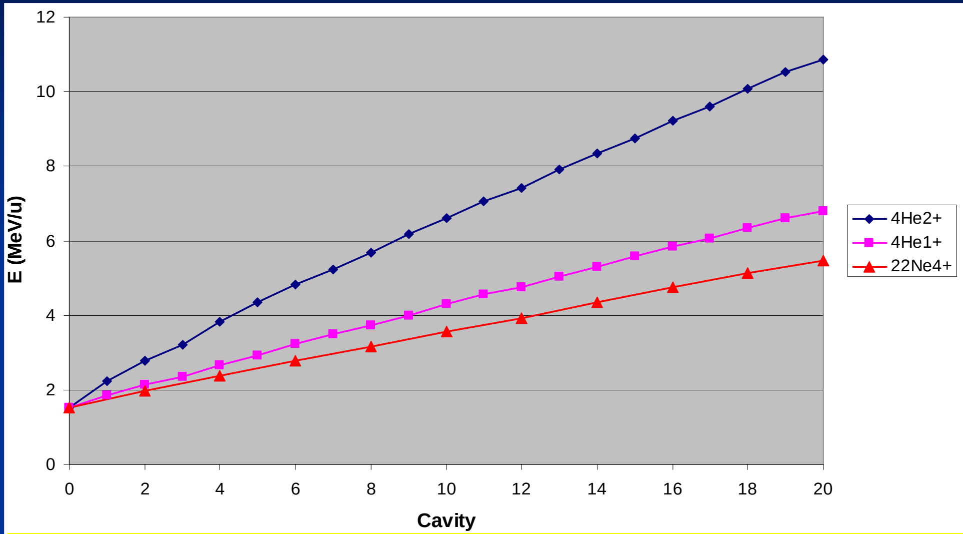


ISAC-II Linac: First acceleration

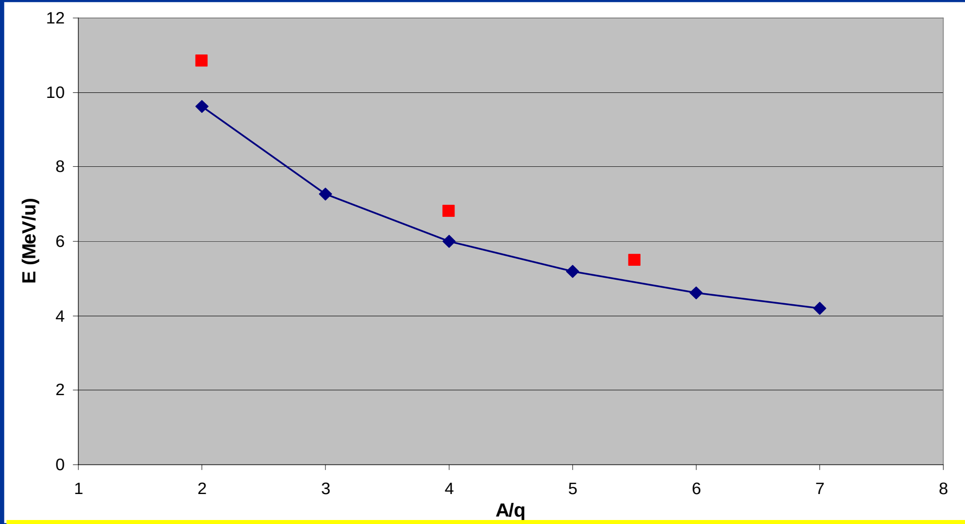


Energy after each cryomodule for C12(3+) with an injection energy of 1.5Mev/U.

ISAC-II Linac: Commissioning



Energy history during acceleration.



Expected E_{final} for 6MV/m and actual E_{final}

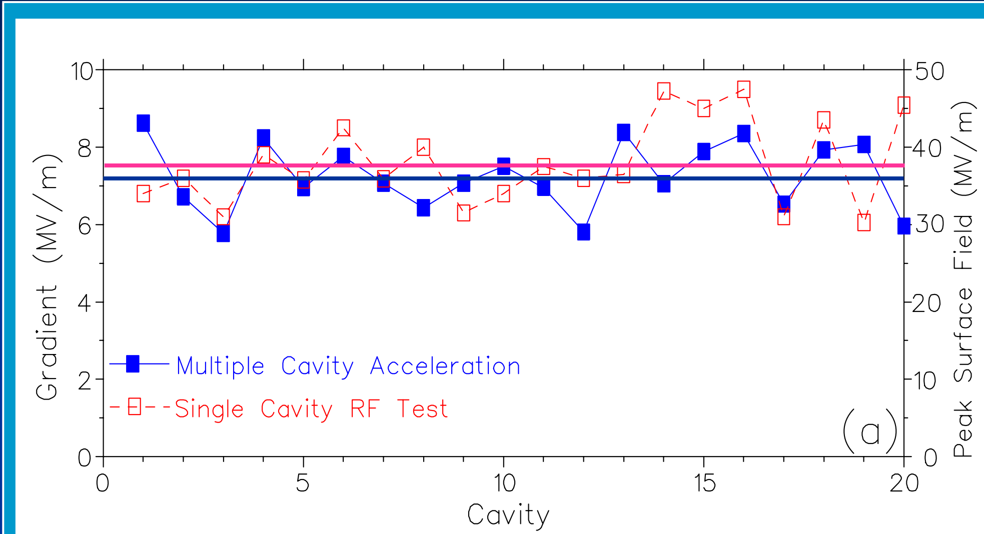
Commissioning beams

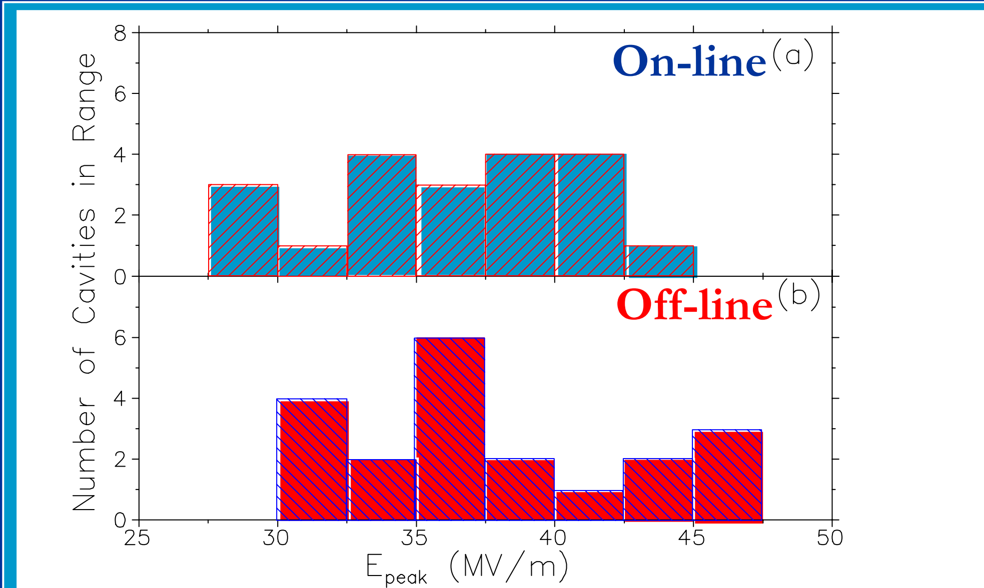
- A/q=5.5 (22Ne4+)
- A/q=4 (40Ca10+, 20Ne5+, 12C3+, 4He1+)
- A/q=2 (4He2+)

Performance

- Power @ 7W/cavity
- Design gradient is 6MV/m
- Average gradient is 7.2MV/m
- Final energy is 10.8, 6.8 and 5.5MeV/u for A/q=2, 4, 5.5 respectively
- Transmission >90%

Cavities: On-line vs. Off-line Performance

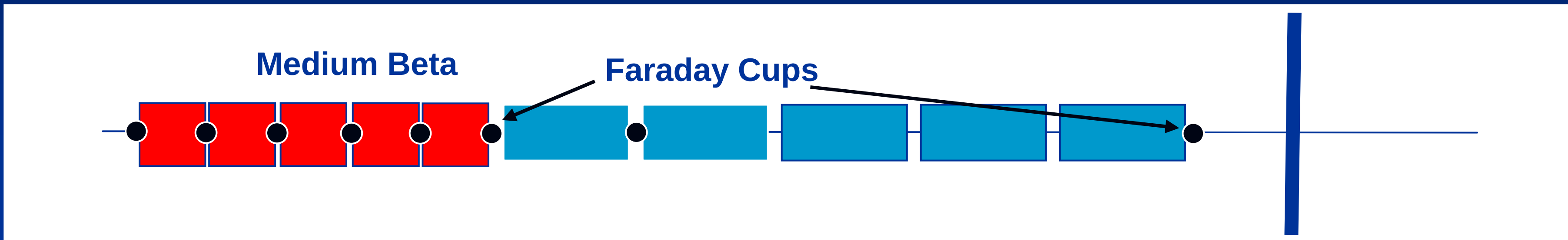


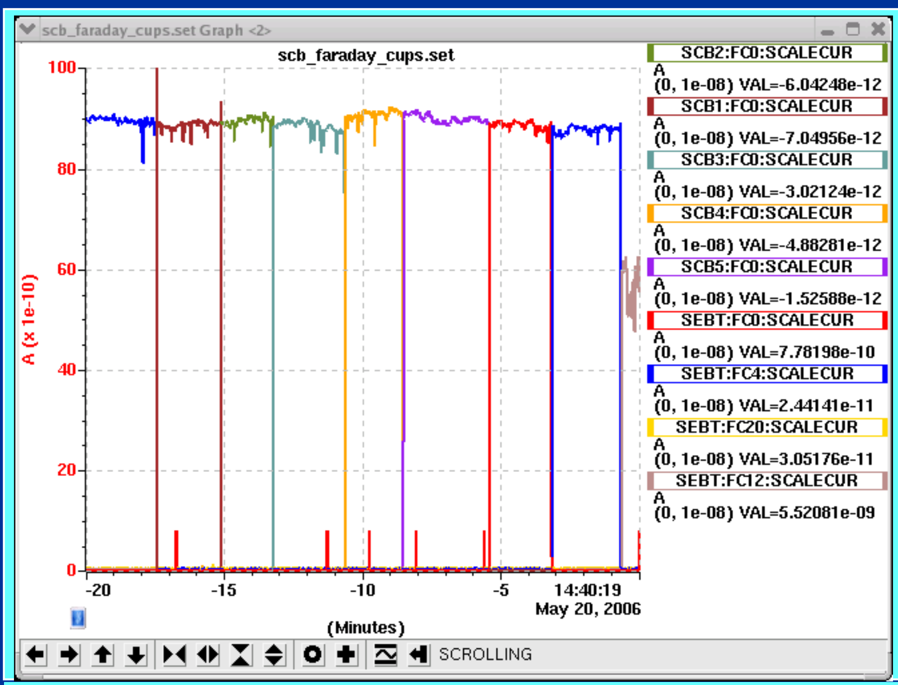


- On-line gradients calculated from beam acceleration at 7W/cavity averaged over three different ions. The average gradient for the on-line cavities is 7.25MV/m corresponding to a peak surface field of 36MV/m
- Off-line results give an average gradient at 7W/cavity of 7.6MV/m corresponding to Ep=38MV/m
- Some contamination evident in a few cavities but on-line performance down by only 5% from off-line tests

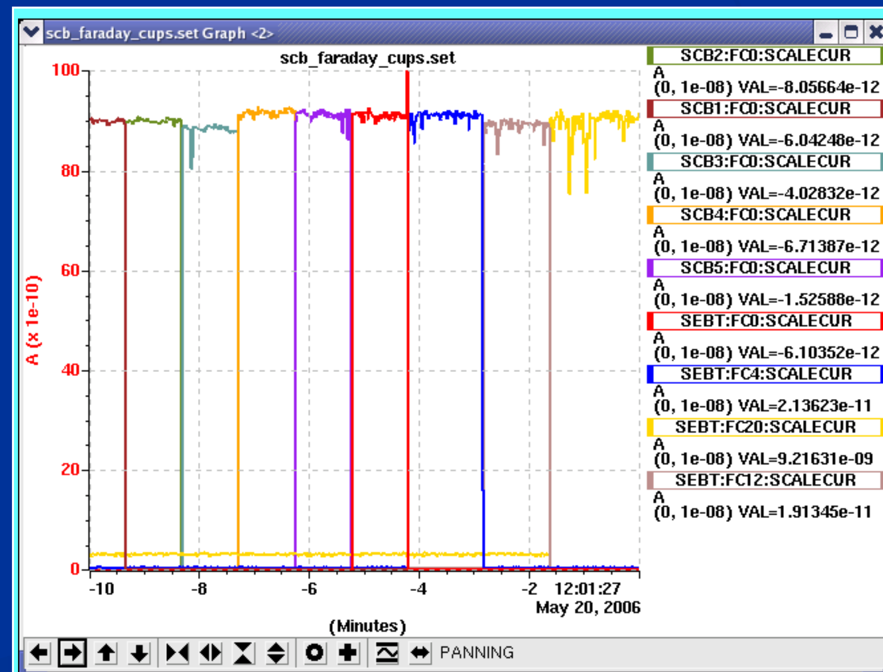
ISAC-II Linac: Transmission

Faraday cup readings throughout LINAC and SEBT sections show ~100% transmission for both coasting and accelerated beams for He1+.





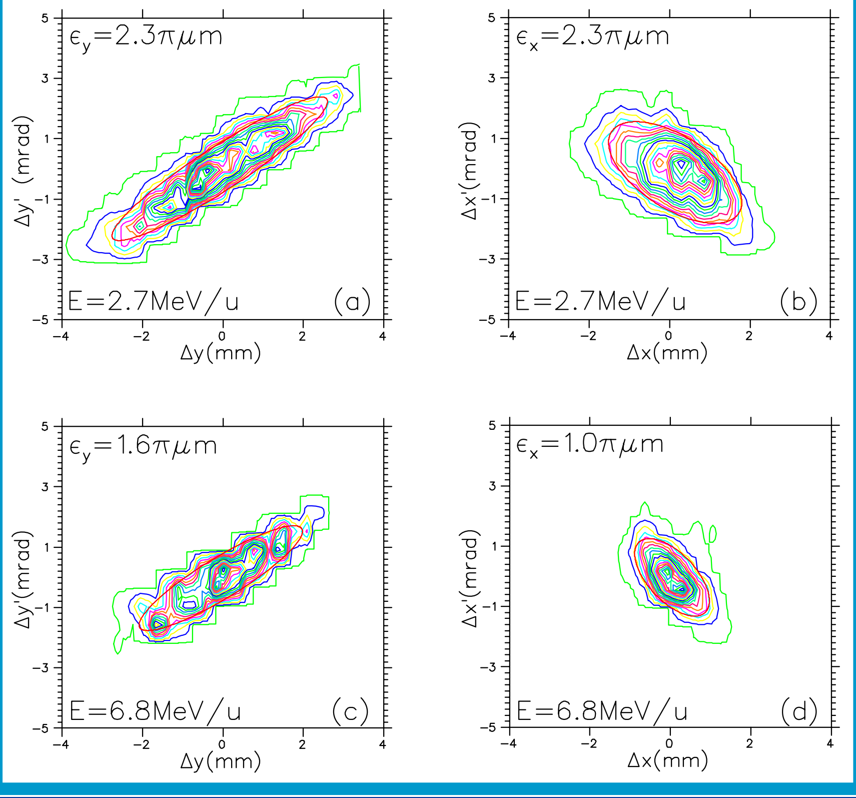
Coasting Beam (1.5MeV/u)

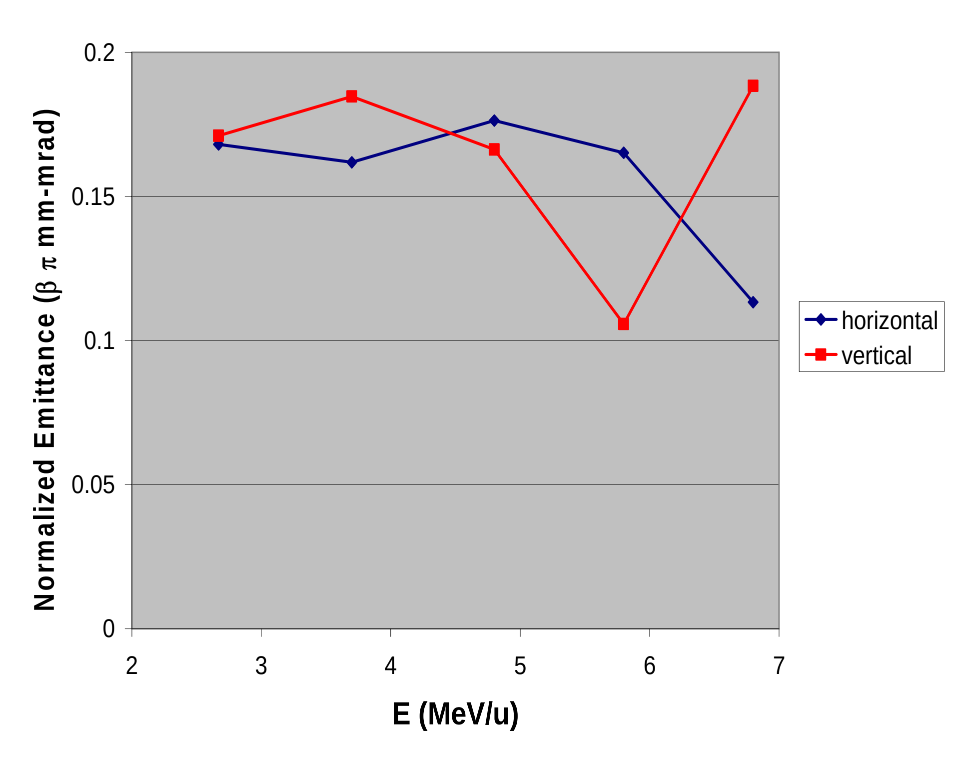


Accelerated Beam (6.8MeV/u)

ISAC-II Linac: Transverse Emittance

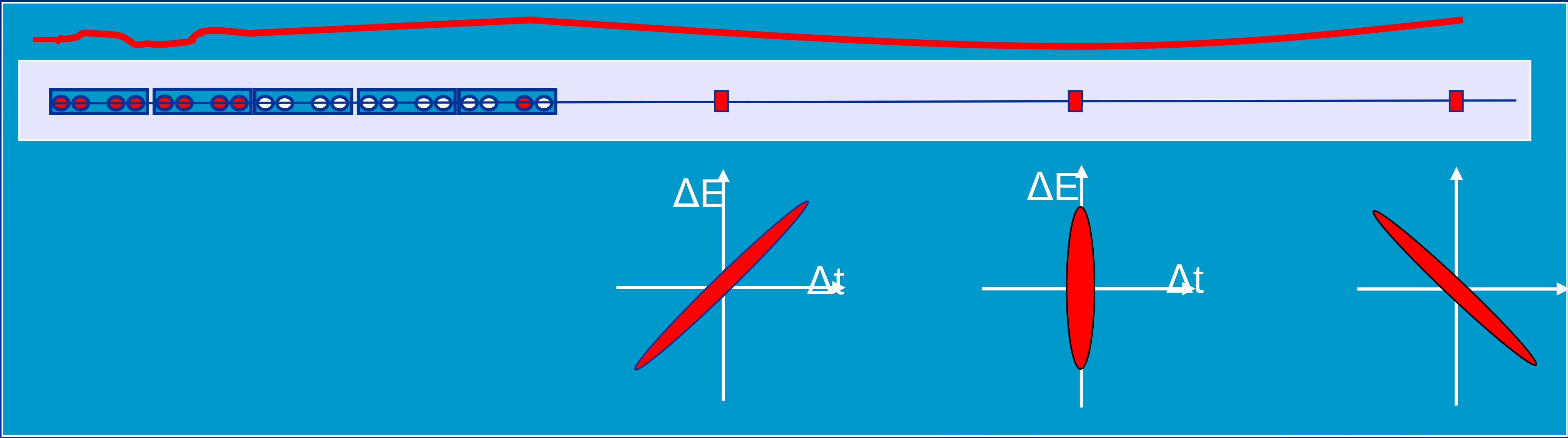
- The transverse emittance is measured with a standard slit and harp device located in the downstream SEBT beamline
- Measurements shown below are for 4He1+ taken after each cryomodule is fully on
- Measurements consistent with no transverse emittance growth





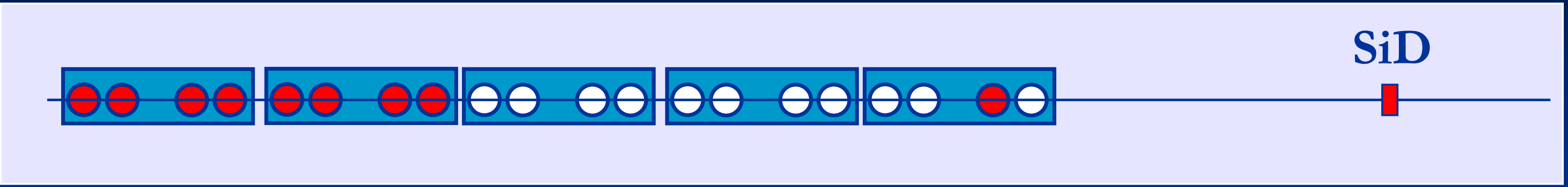
ISAC-II Linac: Longitudinal Emittance

Three Monitor Longitudinal Emittance Measurement



- Longitudinal emittance measured at 1π keV/u-ns
- Typical time widths are ±0.3ns with energy spreads of <±0.1%

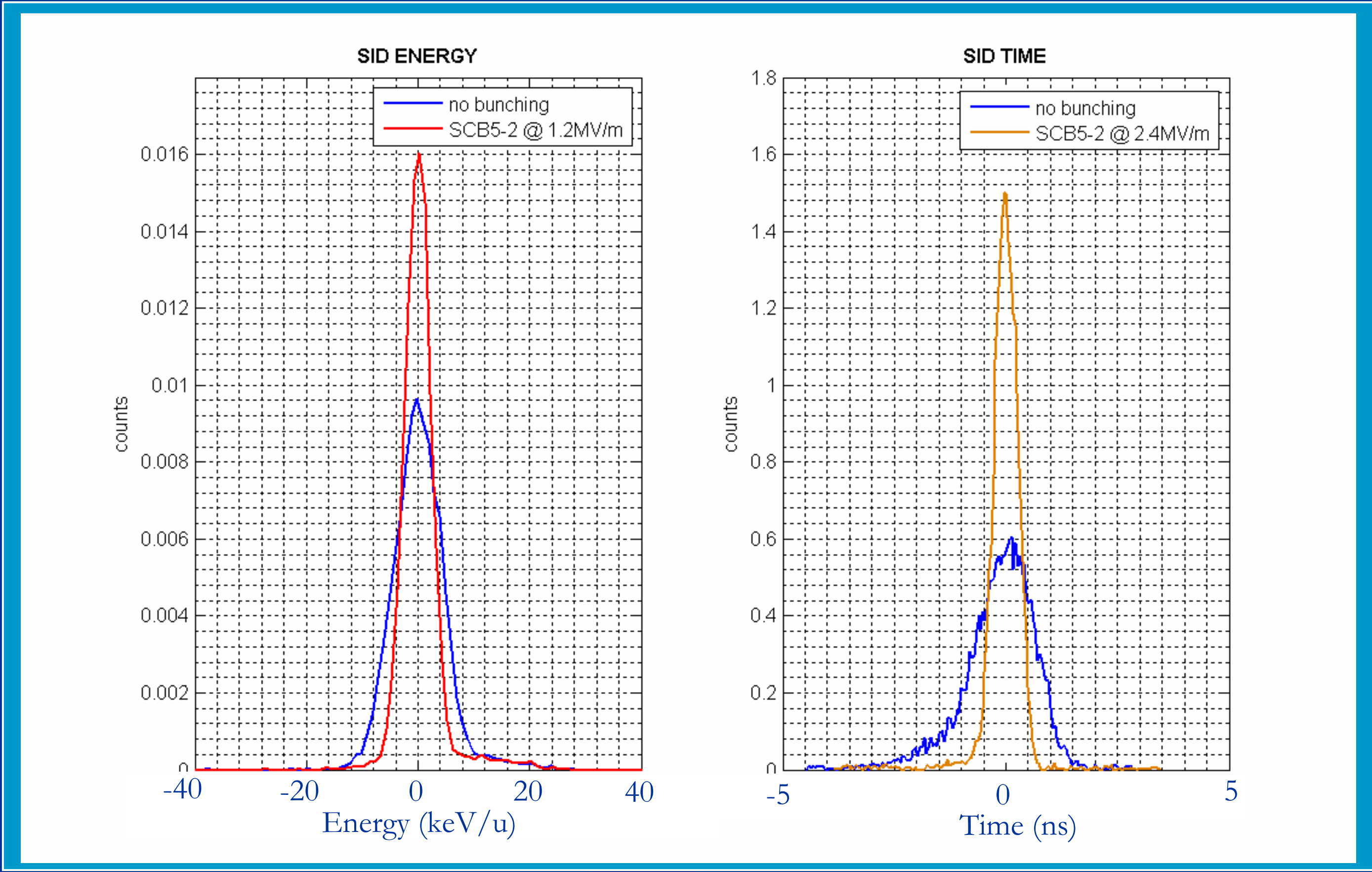
ISAC-II Linac: Longitudinal Manipulation



Use downstream cavities to improve time and energy spread of accelerated beam.

•Shows flexibility of SC machine

•E=3.7MeV/u 4He1+

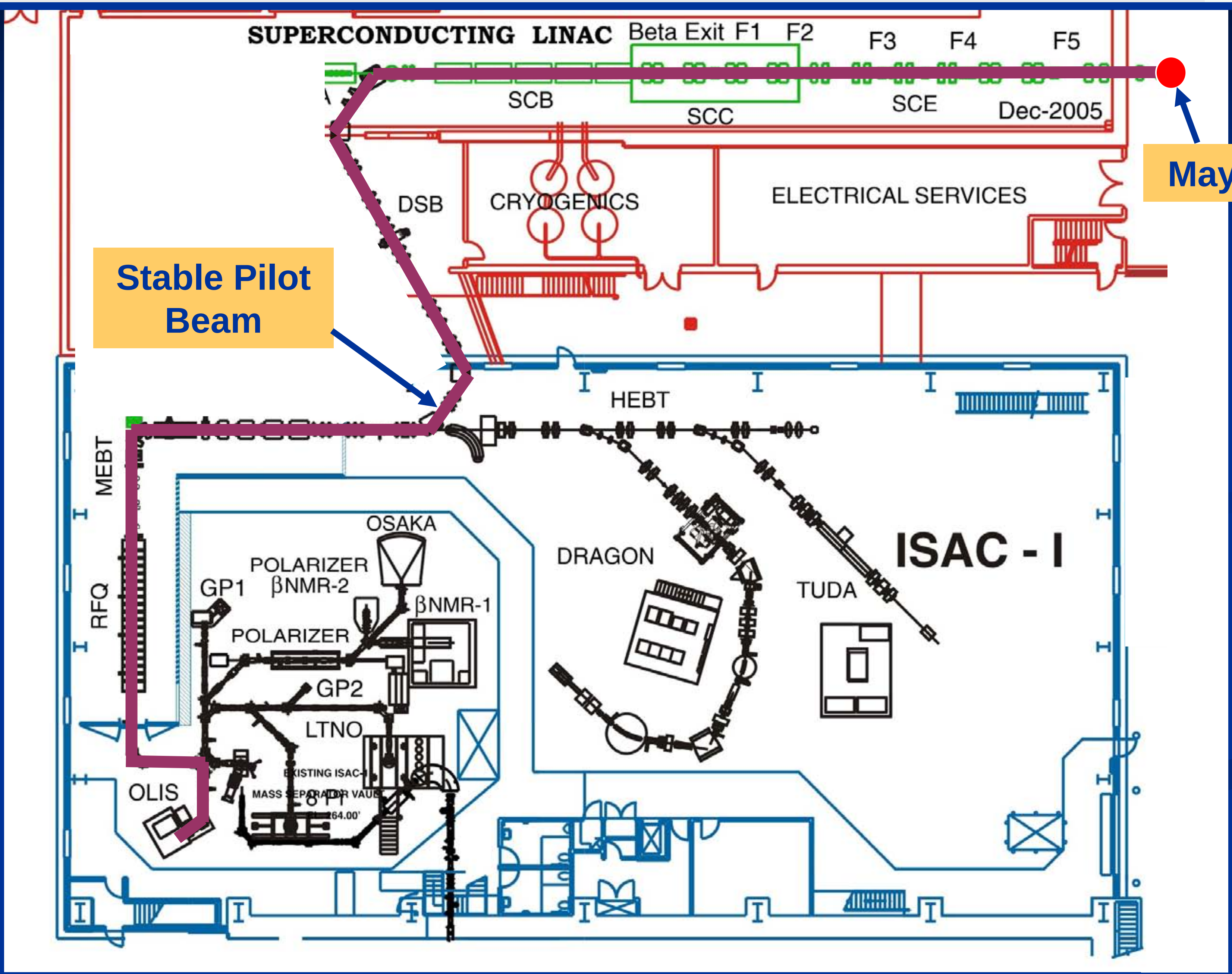


Operation

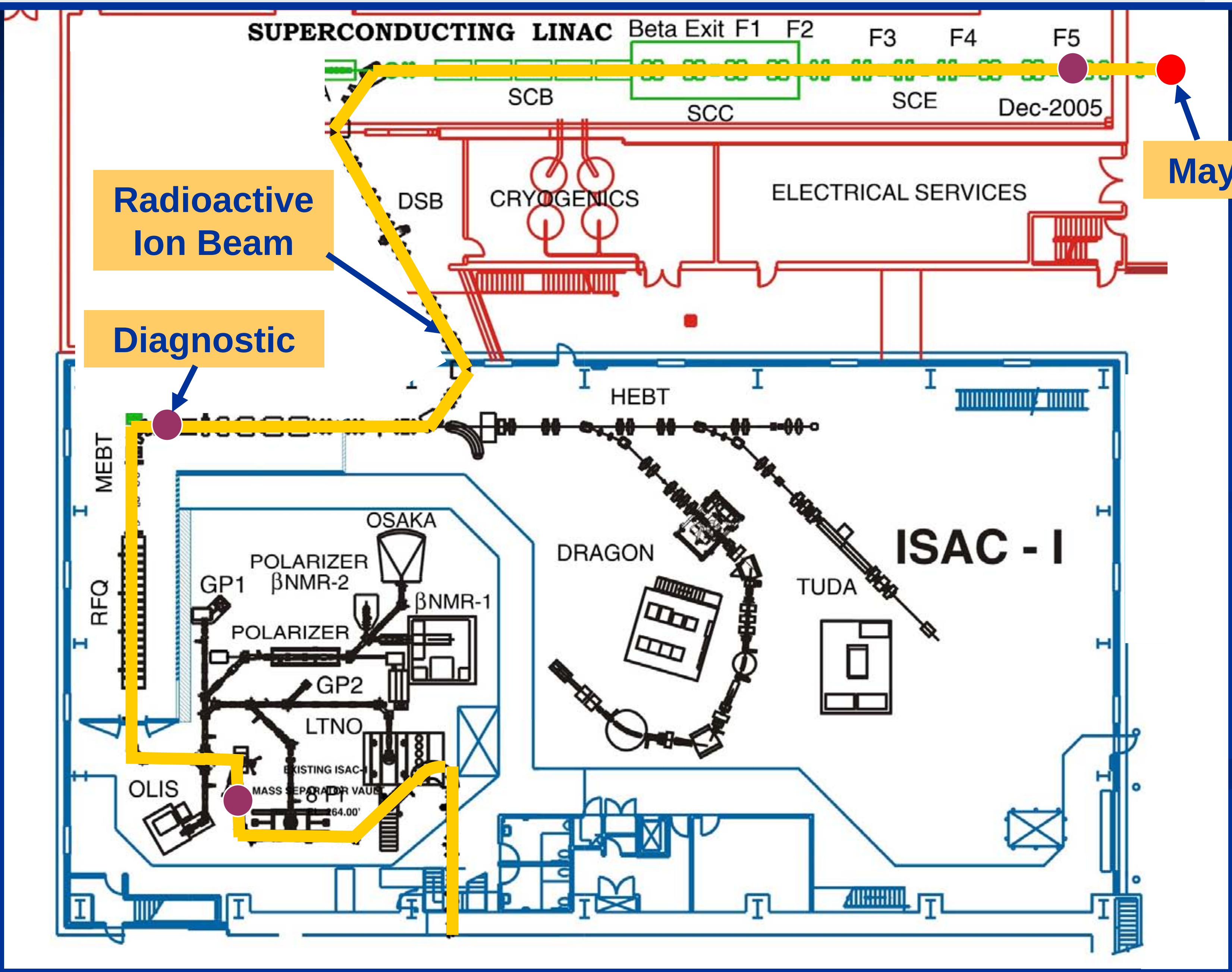
ISAC-II Linac: First Experiments

- First experiment runs for seven weeks
  - Jan. 5 – Jan. 19
  - May 4 – June 9
- Maya experiment
  - Radioactive ion beam
    - 11Li1+, 9Li1+ (both at 3.6MeV/u and 5MeV/u)
      - ~3000 pps, ~9000 pps
  - Pilot beam
    - 22Ne2+, 18O2+
      - High intensity – 3enA
      - Low intensity – attenuators and RFQ slits – 2000 counts

ISAC-II Linac: First Experiments



ISAC-II Linac: First Experiments

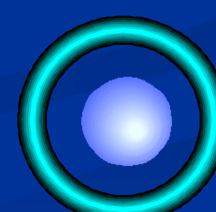


ISAC-II Linac: First Experiments

Why 11Li?

- The first nucleus observed to have a neutron halo.
  - Very weakly bound system.
  - Extend beyond the classical limit.

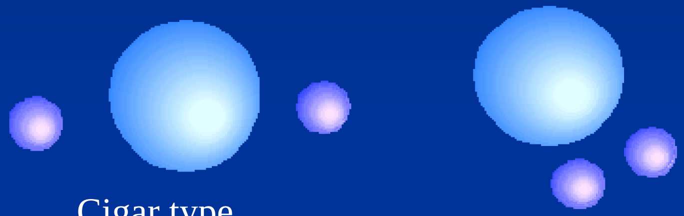
- The best two-neutron halo nucleus
  - Looks like ^{9}Li + n + n.
    - ^{9}Li+n nor n+n make a bound state.
  - Two different orbitals ($p_{1/2}$ and $s_{1/2}$) are mixed half and half in halo neutrons.
- TRIUMF has the highest-intensity low-energy beam of ^{11}Li in the world now.



ISAC-II Linac: First experiments

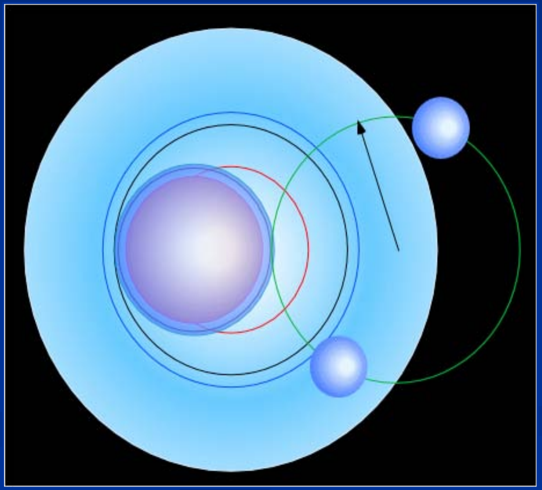
Fundamental questions:

- How are two halo neutrons correlated?



Cigar type   Di-neutron type

  - Paring correlation
  - Tensor correlation
  - Short range correlation

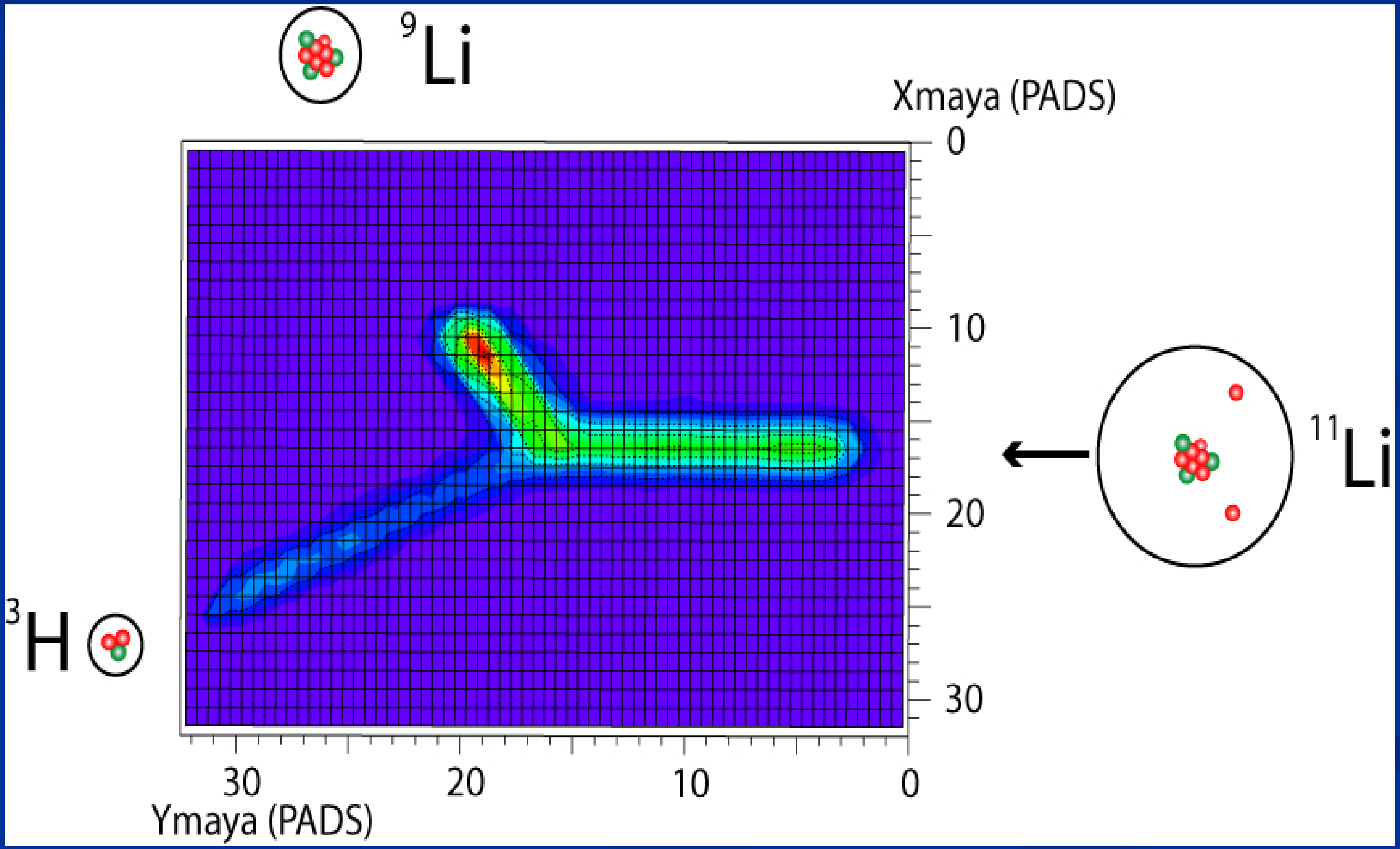


^{11}Li from radii measurements

- What is the structure of subsystem ^{10}Li?
  - Understanding how ^{9}Li+n+n make bound state.

ISAC-II Linac: First Experiments

$^{11}Li(p,t)\,^{9}Li$ first event ! (Jan. 5, 2007)

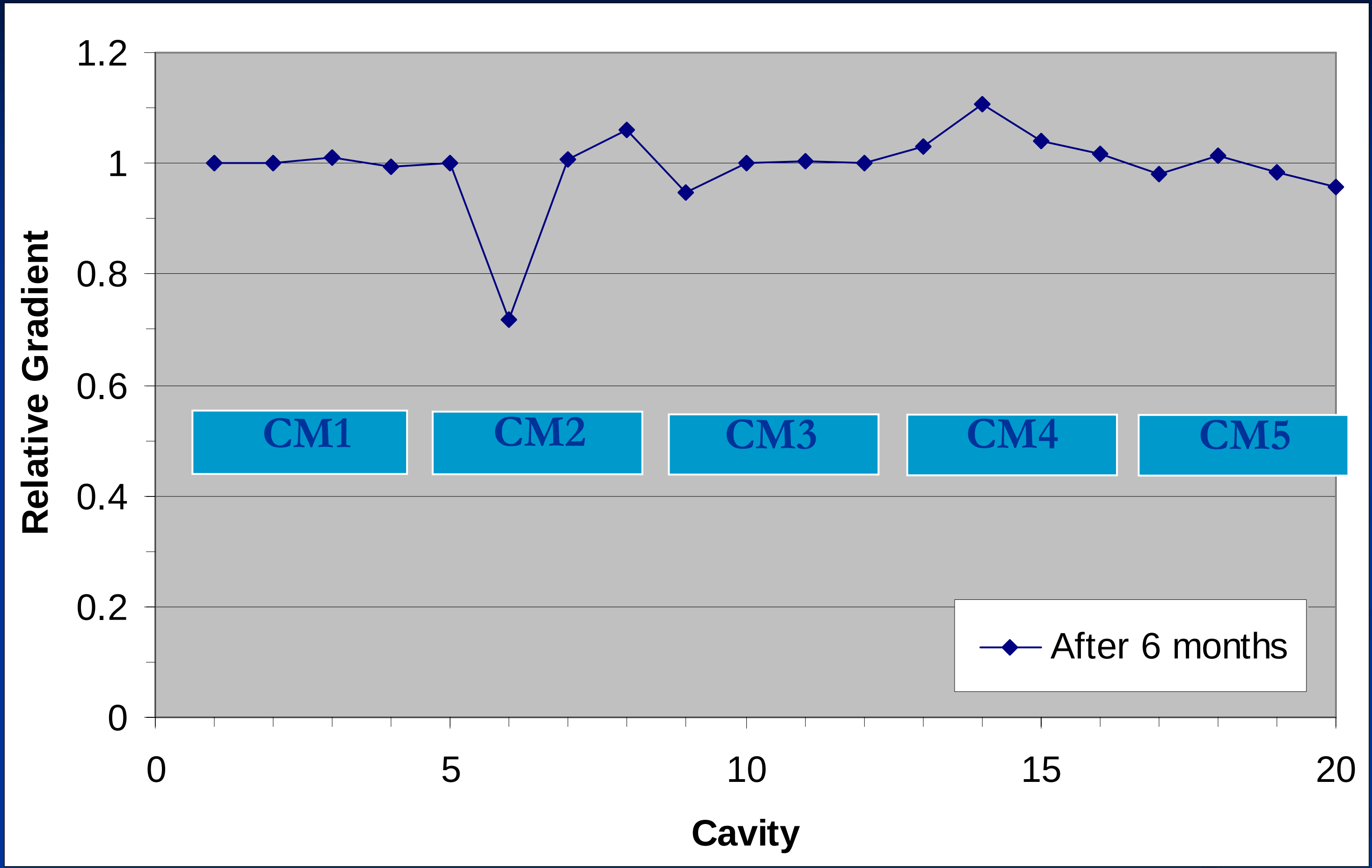


Maya Beam Delivery

- Seven weeks of beam time
  - 1100 hours scheduled
  - 825 delivered (75% availability)
    - Includes availability of driver, target, linear accelerators and procedures
  - ISAC-II Linac downtime – 36 hours (3%)
    - 16 hours cryogenics
    - 20 hours – rf amplfiers
      - Five amplifier tubes required replacement

Long term performance

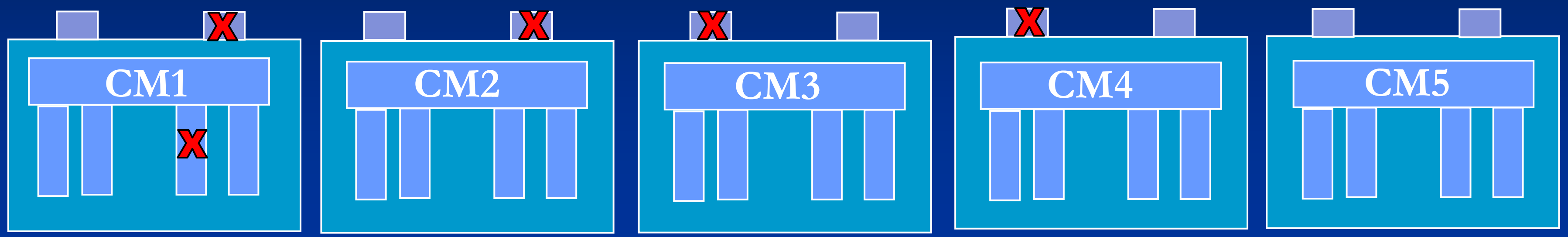
ISAC-II Linac: Relative Gradient



Average gradient down by only 1% in the first six months compared to initial gradients.

- **Cavity CM2:CAV2 has modest reduction in performance due to Q-disease**

ISAC-II Linac: Shutdown Work



•The linac was warmed up Jan. 19, 2007 during the cyclotron annual shutdown. Job list included:

- •Remove CM1 to the clean room for repair of the coupling loop drive and replacement of a turbo-pump
- •Replace three other turbopumps *in situ* using `clean' procedure (no explanation to date for high failure rate)
  - •Vent with filtered dry nitrogen, construct plastic barrier, …
  - •Results were a surprise

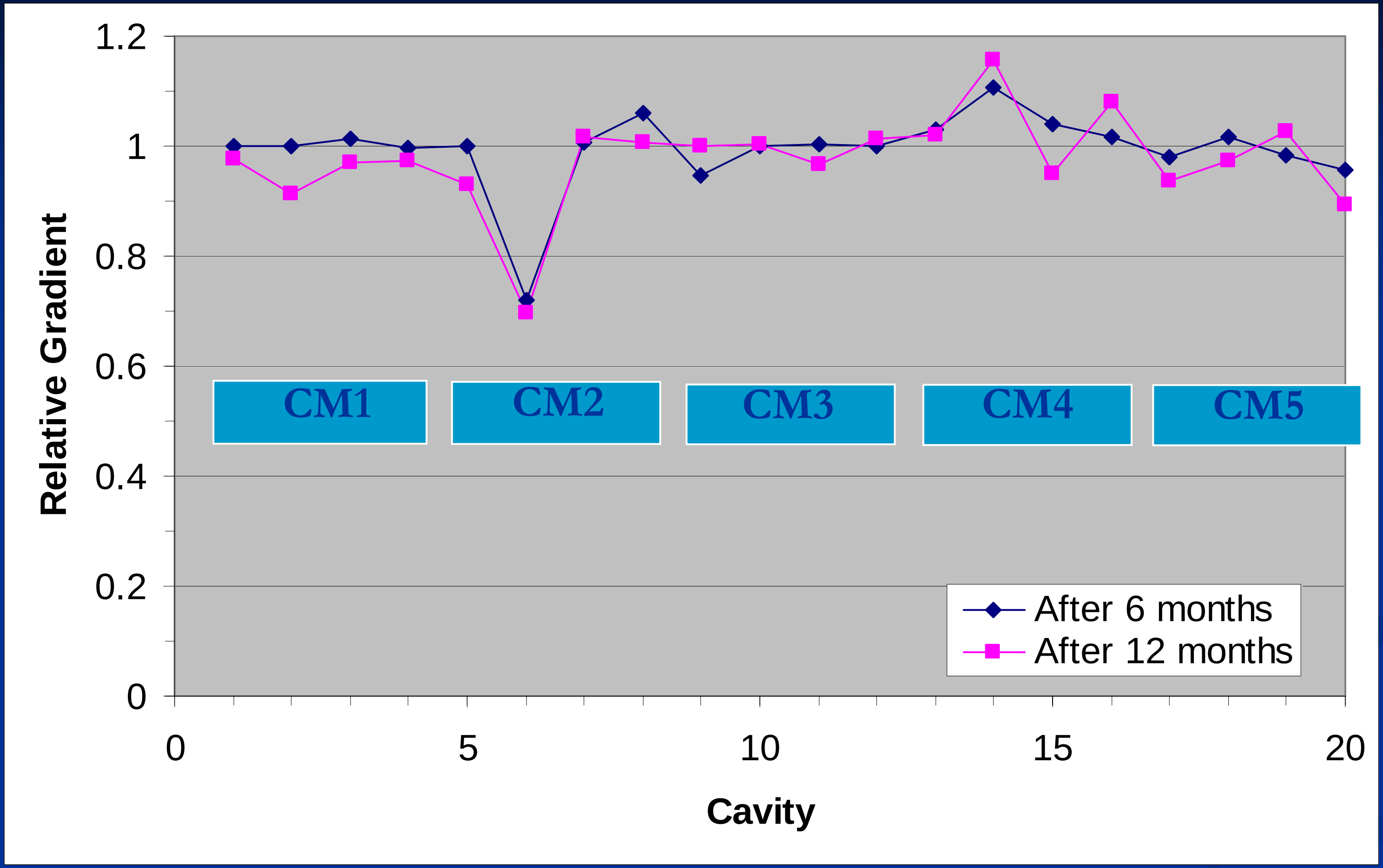
ISAC-II Linac: Shutdown Work

Varian 550 turbo-pump on CM4 suffered catastrophic failure!

There was no time for taking the cryomodule off-line for cleaning so we removed the fragments that we could reach, vacuumed the LN2 shield, pumped down and crossed our fingers.

- Remember that cavity vacuum shares isolation vacuum

ISAC-II Linac: Relative Gradient



•Average gradient within 98% of gradients measured during first commissioning.

•No deterioration due to shutdown activities

ISAC-II Linac: Performance

CW heavy ion SC-linacs with Nb technology

- ATLAS
  - Bulk niobium – Ep~15-20MV/m
- INFN-Legnaro
  - Sputtered Nb on Cu - Ep~20MV/m
  - Bulk niobium cavities – higher gradients demonstrated but little on-line experience
- JAERI
  - Explosively bonded Nb on Cu – Ep~23MV/m
- ISAC-II
  - Bulk niobium cavities – Ep=35MV/m

ISAC-II Linac: Conclusion

- ISAC-II is now accelerating radioactive and stable beams for experimental studies beyond the Coulomb barrier
- ISAC-II now operates cw at gradients corresponding to peak surface field of 35MV/m, the highest of any operating heavy ion facility
  - Gradients 20% above design specification and only 5% below single cavity test gradients
  - Little or no degradation over the first year of operation including first full warm-up
  - A single vacuum system does not preclude high performance operation in the cw regime (not strongly dominated by field emission)
- Tuning predictable and straightforward with good transmission
- Transverse and longitudinal emittance as expected and compatible with little or no emittance growth
- Machine flexible and scalable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