Beam Phase Detection with a Superconducting Resonator

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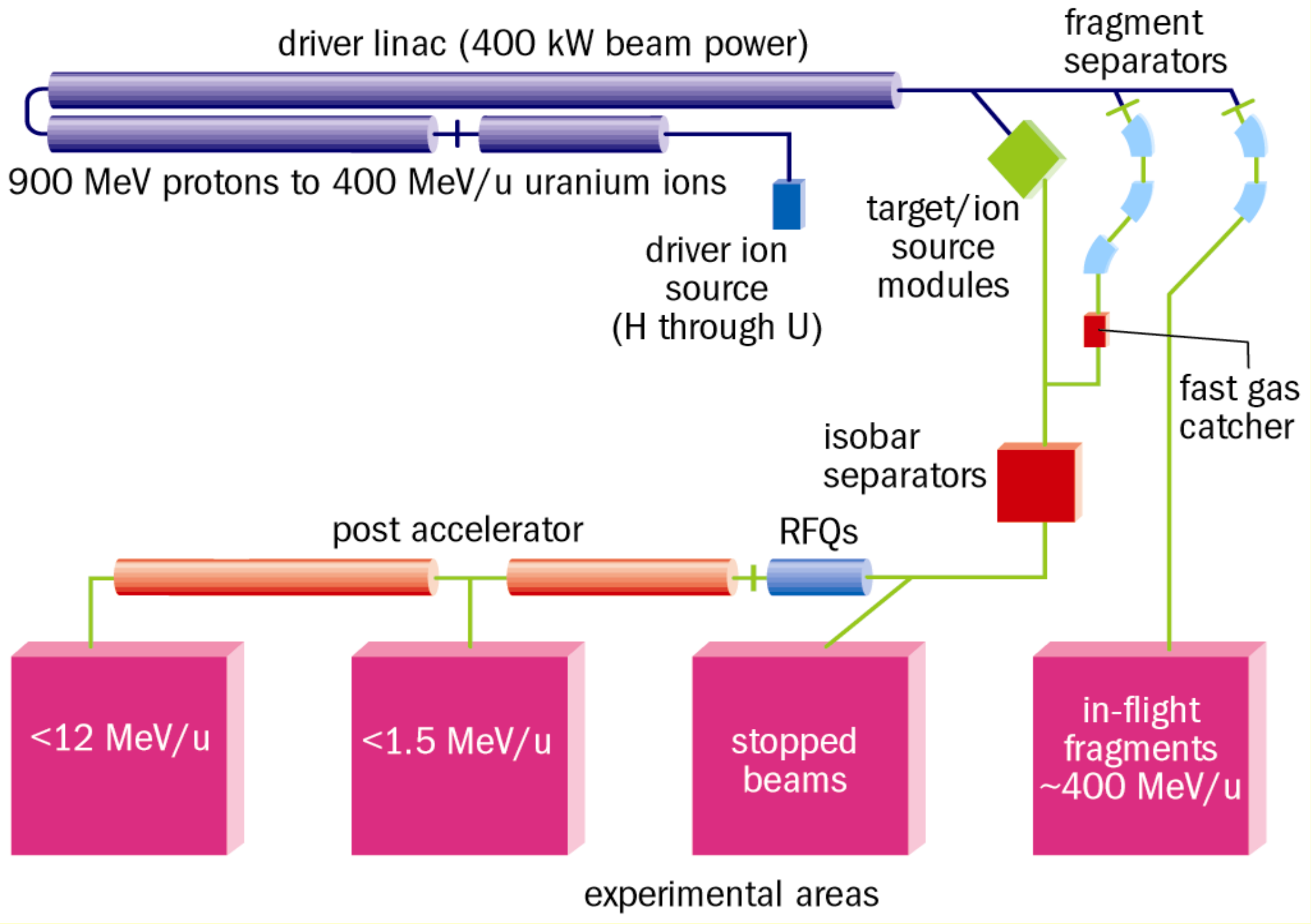
The Rare Isotope Accelerator



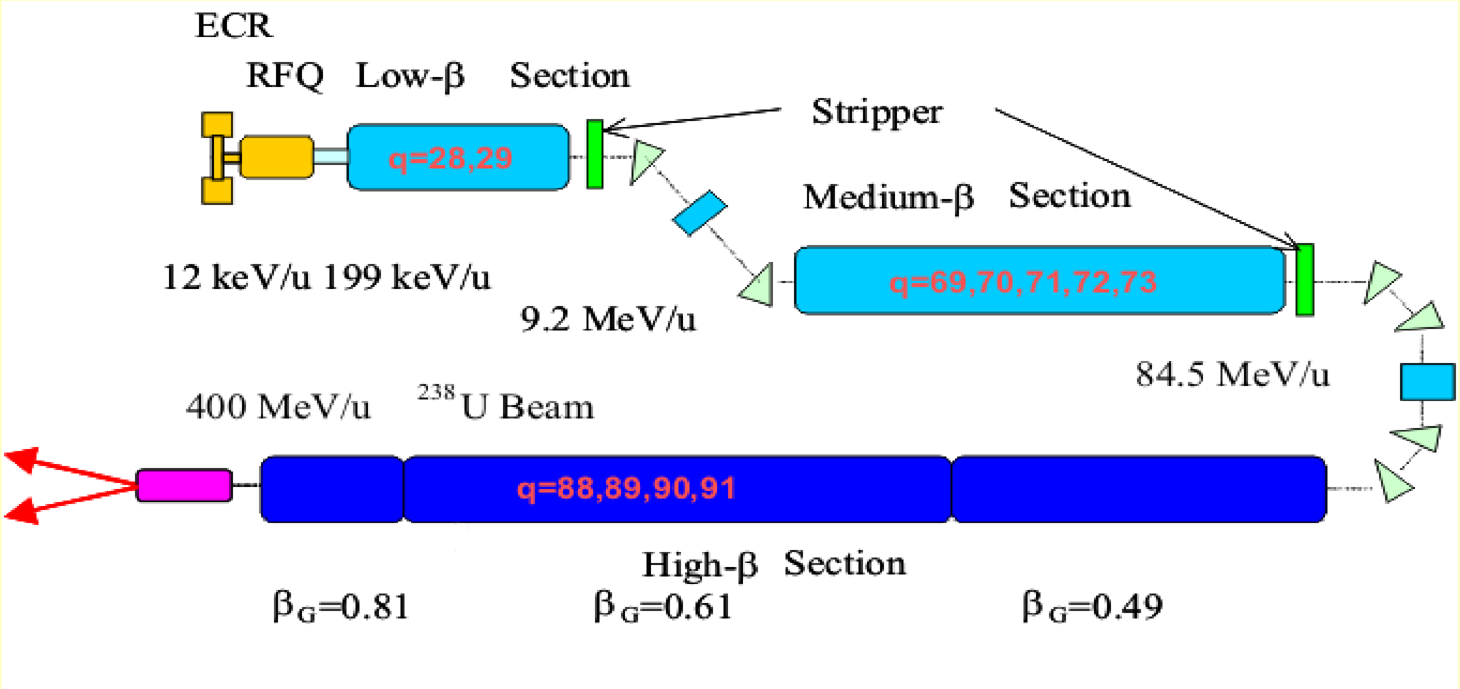
The Rare Isotope Accelerator

At this time RIA diagnostics are only partially understood.

Driver Diagnostics requirements include:

- Beam position measurements to 0.1 mm
- Beam phase determination to ~1^{o}
- Small emittance growth of multiple-charge-state beams
  - ✓ Strong focusing and a very compact geometry
  - ✓ Little space is available for diagnostics

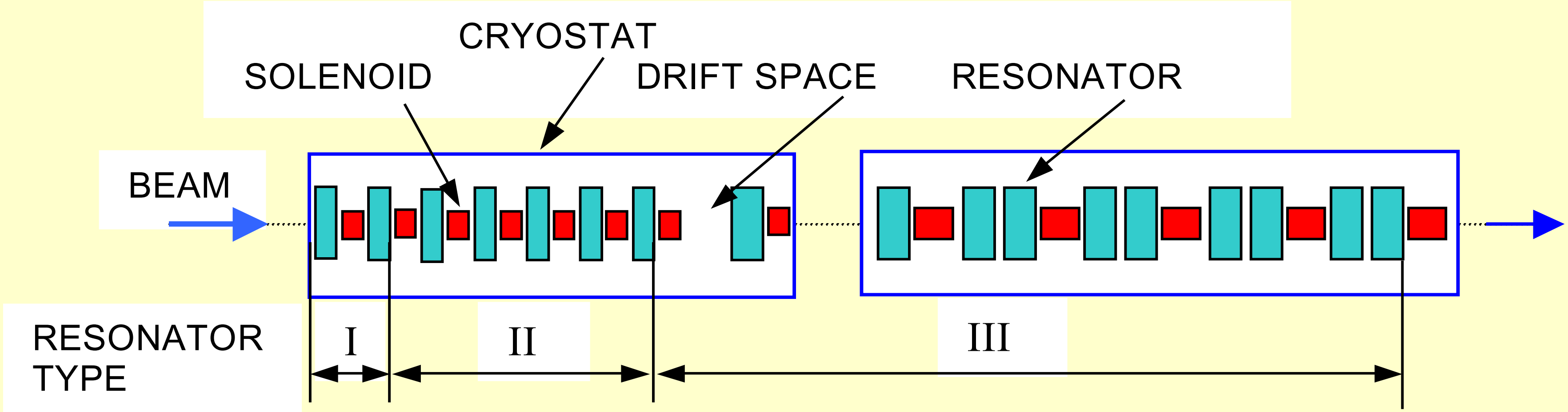
RIA DRIVER LINAC



- Heavy-Ion Accelerator for any ion
  - –Protons through uranium

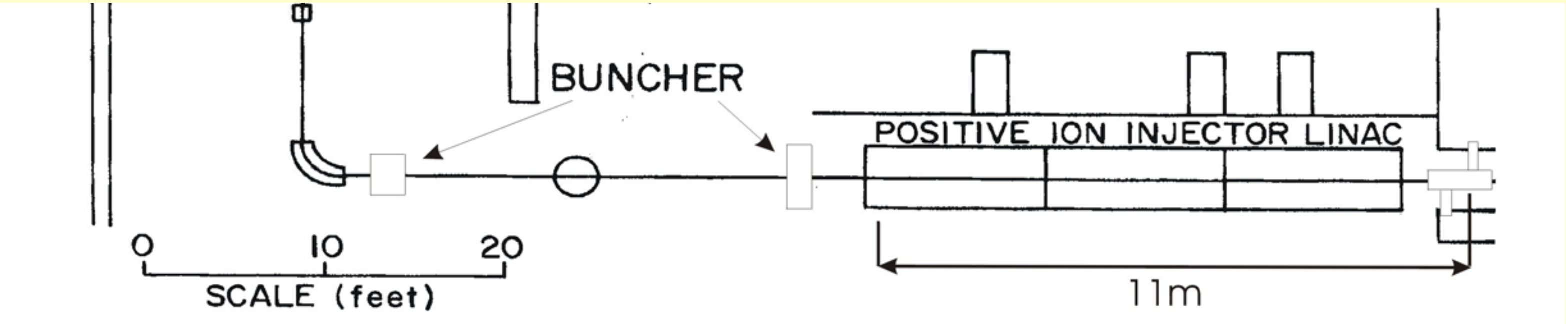
- Independently-phased resonator-based LINAC
  - –Starts at 199 keV/u

RIA DRIVER LINAC



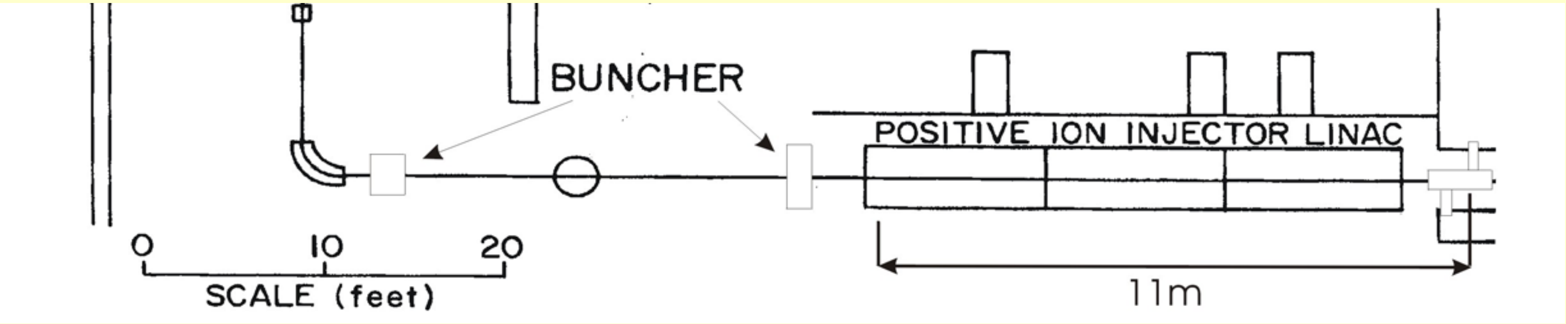
- Heavy-ion LINACs need a range of velocity profiles
  - Optimum acceleration over a wide q/m range.
    - ATLAS q/m range is 0.1 to 0.5.
    - RIA Driver q/m range is 0.12 to 1.0.
- Little room for diagnostics
  - Close spacing in low-energy section required
    - Low beam losses
    - Low emittance growth

Present ATLAS Phase Tuning Method



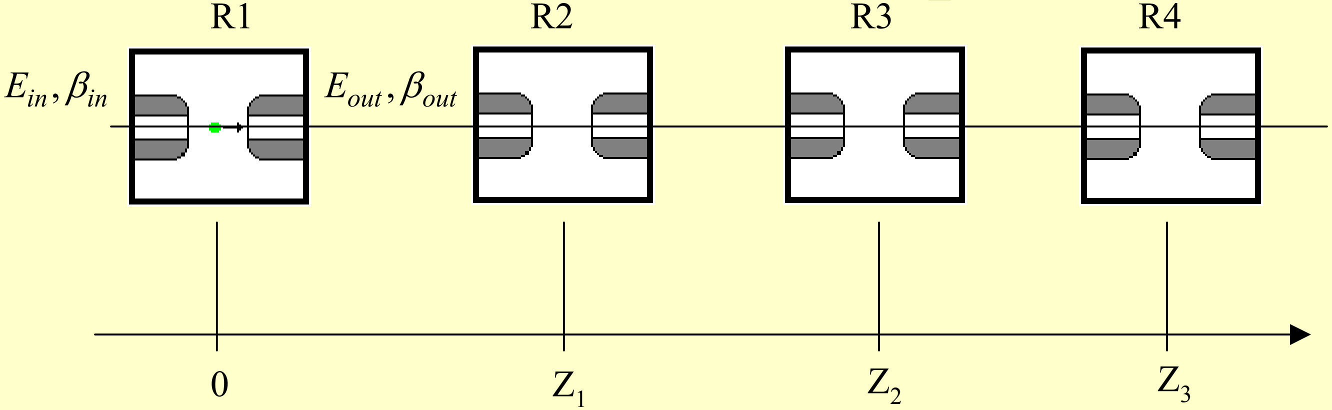
- Solid state detector at end of PII Linac
  - Beam scatters from gold foil at far forward angle
- Provides absolute measure of beam energy
- Gives direct timing information
- Identifies parasitic beam components

Present ATLAS Phase Tuning Method



- Difficult to accurately measure beam properties in first few resonators due to:
  - Phase and amplitude-dependent beam steering
  - Rapid energy change requires beam optics retunes
  - Poor beam tune can give erroneous data
  - Poor S/N ratio for energy under 5-10 MeV
  - Detector easily damaged

Resonant Beam Pickup Method



Single Beam Phase Monitor

- set phase

RF off $$\varphi_i^{off} = \frac{t_i}{T_{rf}} = 2\pi \frac{Z_i}{\beta_{in}\lambda}$$

RF on $$\varphi_i^{on} = 2\pi \frac{Z_i}{\beta_{out}(A_{rf}, \phi_{rf})\lambda}$$

$$\Delta\varphi_i = \varphi_i^{on} - \varphi_i^{off} = 2\pi \frac{Z_i}{\lambda}\left(\frac{1}{\beta_{out}(A_{rf}, \phi_{rf})} - \frac{1}{\beta_{in}}\right)$$

Pair of Beam Phase Monitors

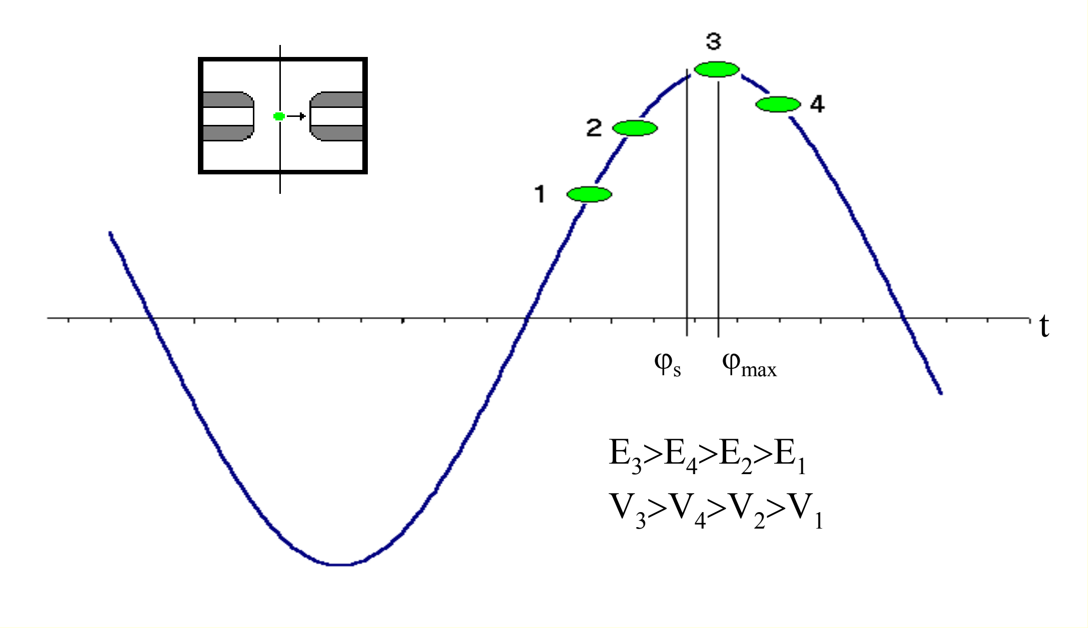
$$\varphi_i^{off} = \frac{t_i}{T_{rf}} = 2\pi \frac{\Delta Z_i}{\beta_{in}\lambda} \qquad \varphi_i^{on} = 2\pi \frac{\Delta Z_i}{\beta_{out}(A_{rf}, \phi_{rf})\lambda}$$

-set phase

-measure absolute energy

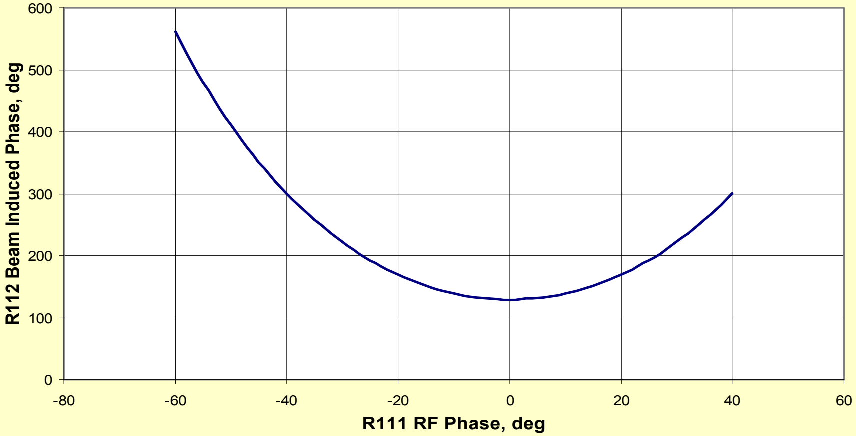
$$\Delta\varphi_i = \varphi_i^{on} - \varphi_i^{off} = 2\pi \frac{\Delta Z_i}{\lambda}\left(\frac{1}{\beta_{out}(A_{rf}, \phi_{rf})} - \frac{1}{\beta_{in}}\right)$$

Resonant Beam Pickup Method



$$\beta_{out}(A_{rf},\phi_{rf}) = k\sqrt{U_{in} + A_{rf}\cos\phi_{rf}} \qquad k = \sqrt{2\frac{q}{A}\frac{e}{m_0 c^2}}$$

$$\Delta\varphi_i(A_{rf},\phi_{rf}) = 2\pi\frac{Z_i}{\lambda k}\left(\frac{1}{\sqrt{U_{in} + A_{rf}\cos\phi_{rf}}} - \frac{1}{\sqrt{U_{in}}}\right)$$

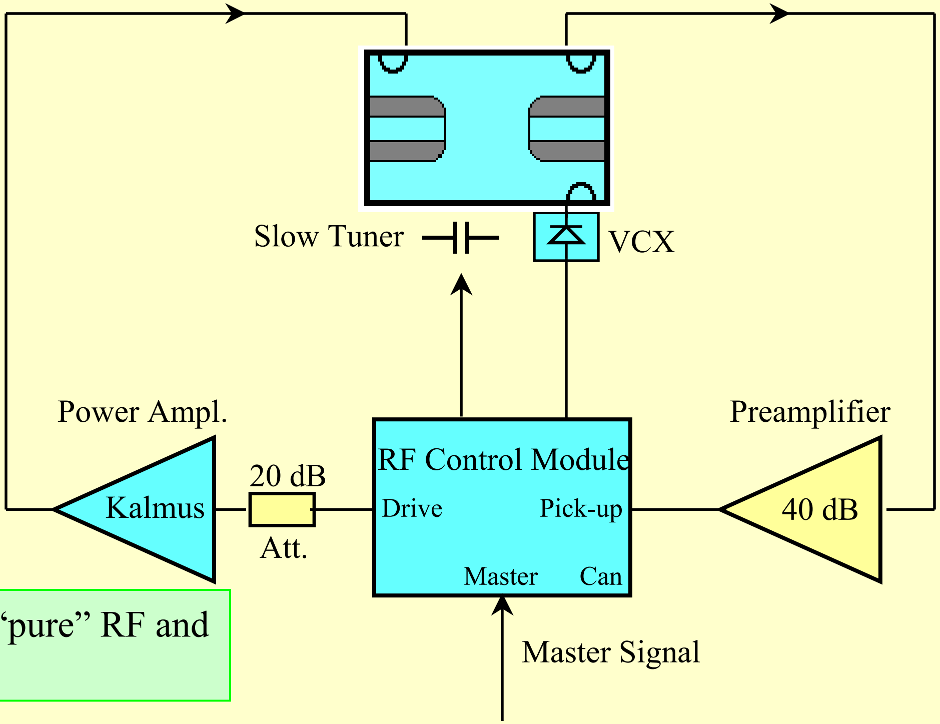


Resonant Beam Pickup Method

Uses a Superconducting Resonator Detector

Very High Q (~1.5X10^7)

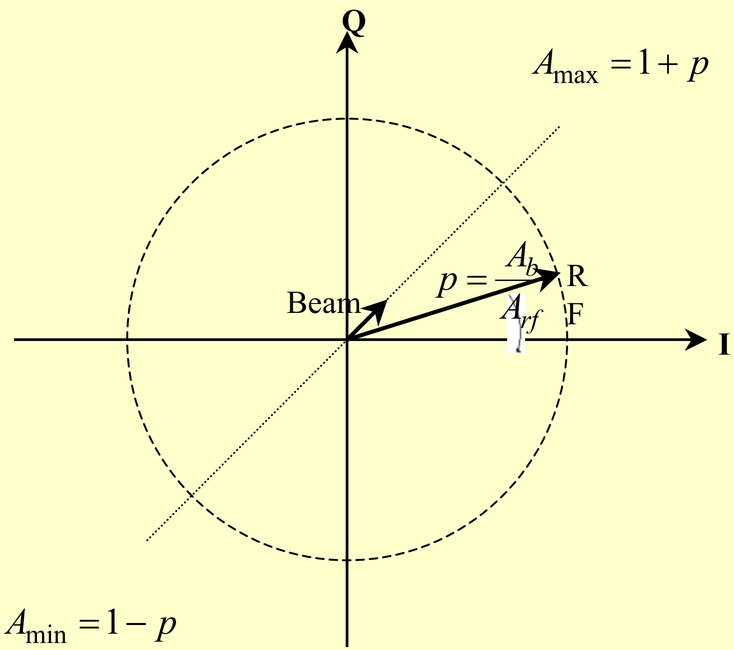
- Induced RF Field from beam:
  - ✓ 4-5 kV/m per µA
- Resonator must operate in order to match beam frequency
- All feedback loops (amplitude, phase and frequency) must be locked ∴ some RF is required
- Level of RF must be low



Resonator RF field is a superposition of "pure" RF and beam-induced signal

Beam Induced Signal & RF Superposition

Continuous RF Rotation



$$\phi_{rf}(t) = 2\pi t$$

$$A_{\Sigma}(t)\exp(i\phi_{\Sigma}(t)) = A_{rf}\exp(i\phi_{rf}(t)) + A_b\exp(i\phi_b)$$

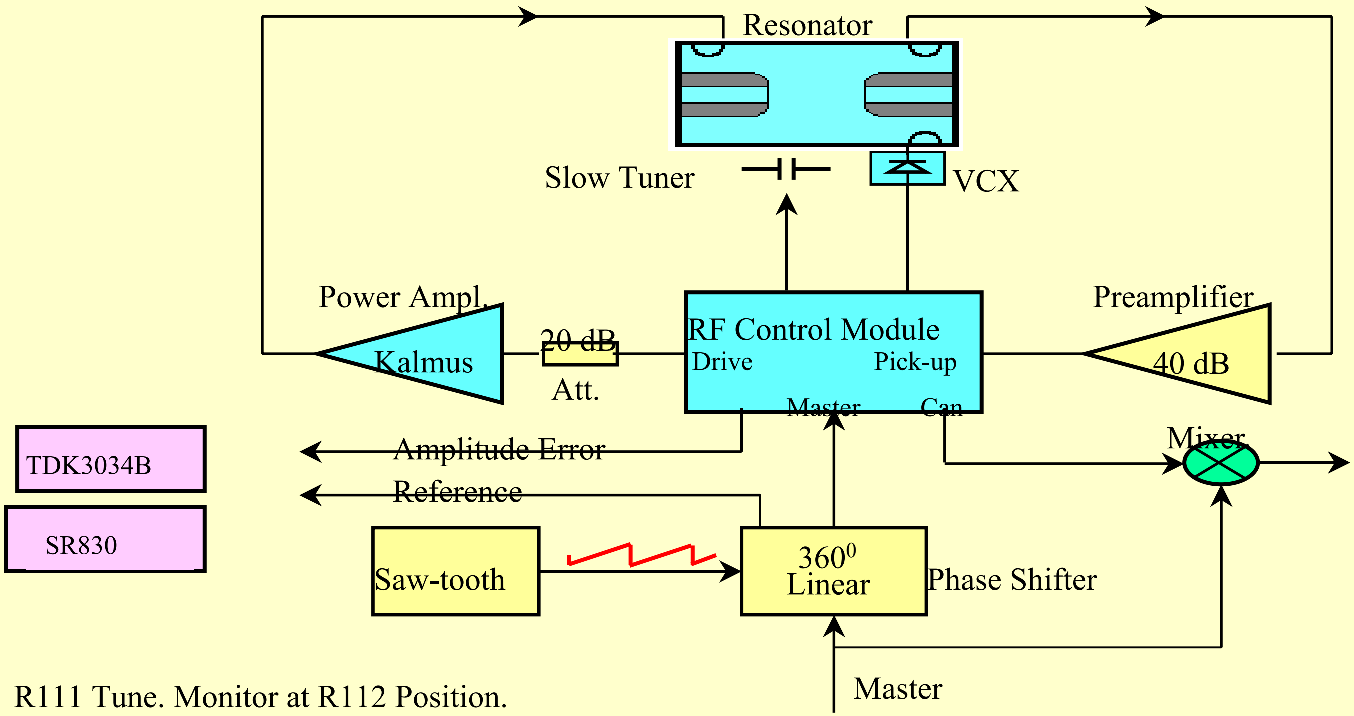
$$A_{\Sigma}(t) = A_{rf}\sqrt{1 + p^2 + 2p\cos(\phi_{rf} - \phi_b)}$$

$$\phi_{\Sigma}(t) = \arctan\frac{\sin\phi_{rf} + p\sin\phi_b}{\cos\phi_{rf} + p\cos\phi_b}$$

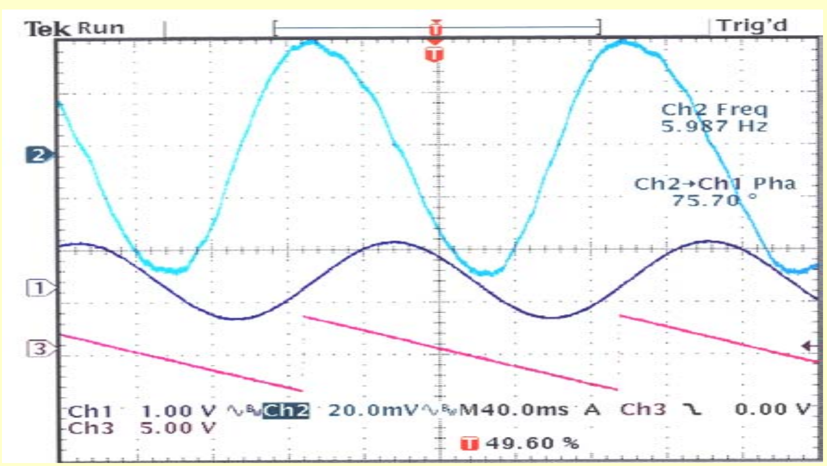
For low p: $A_{\Sigma}(t) \approx A_{rf}(1 + p\cos(\phi_{rf} - \phi_b))$

Modulation:	$A_{rf}\, p\cos(\phi_{rf} - \phi_b)$
Reference signal:	$A_{rf}\cos\phi_{rf}$

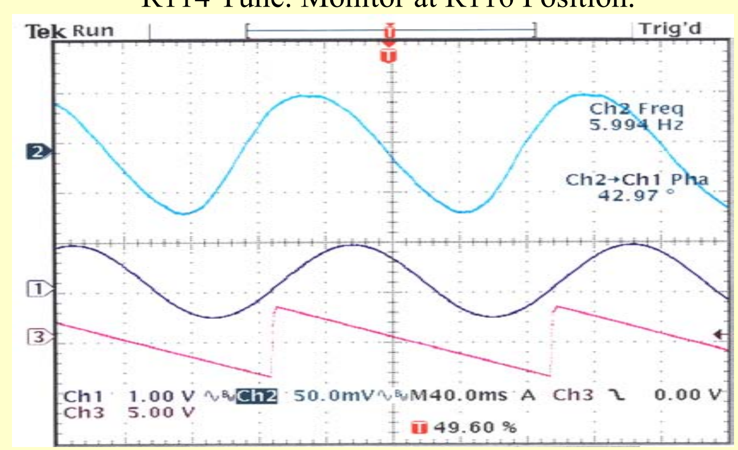
Electronics Block Diagram



R111 Tune. Monitor at R112 Position.



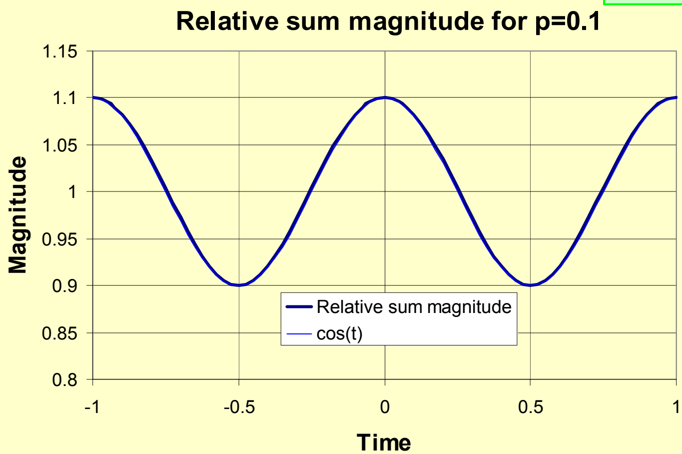
R114 Tune. Monitor at R116 Position.



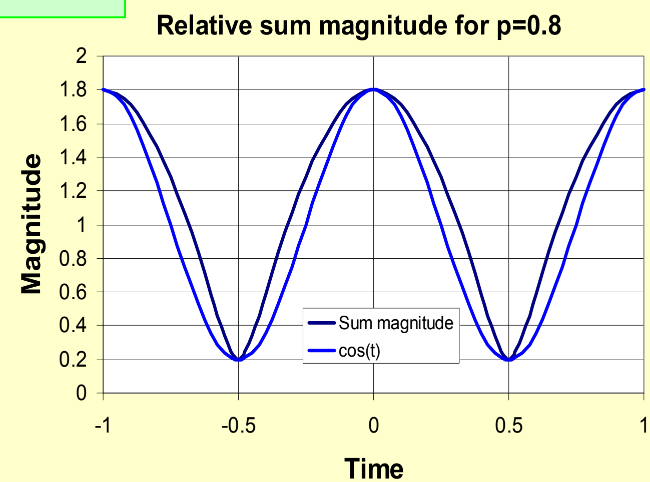
Beam Induced Signal & RF Superposition

Modulation: $A_{rf}\, p \cos(\phi_{rf} - \phi_b)$

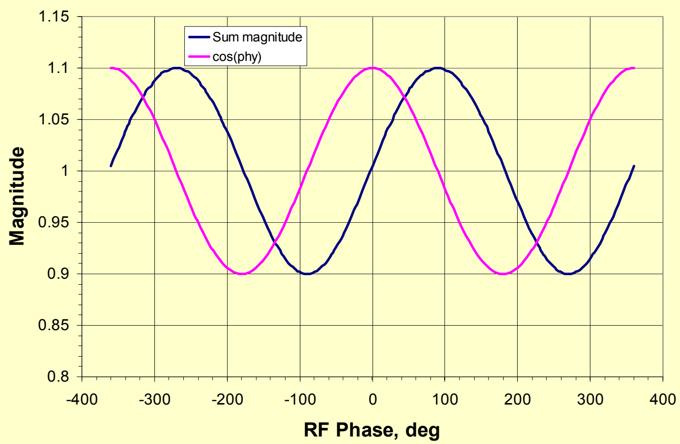
Reference signal: $A_{rf} \cos \phi_{rf}$



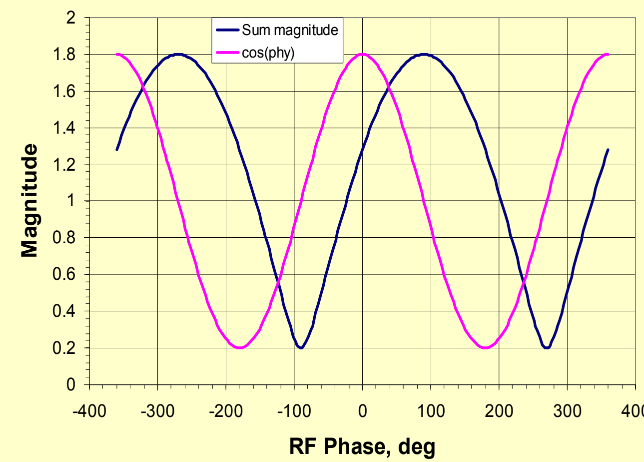
$\phi_b = 0$



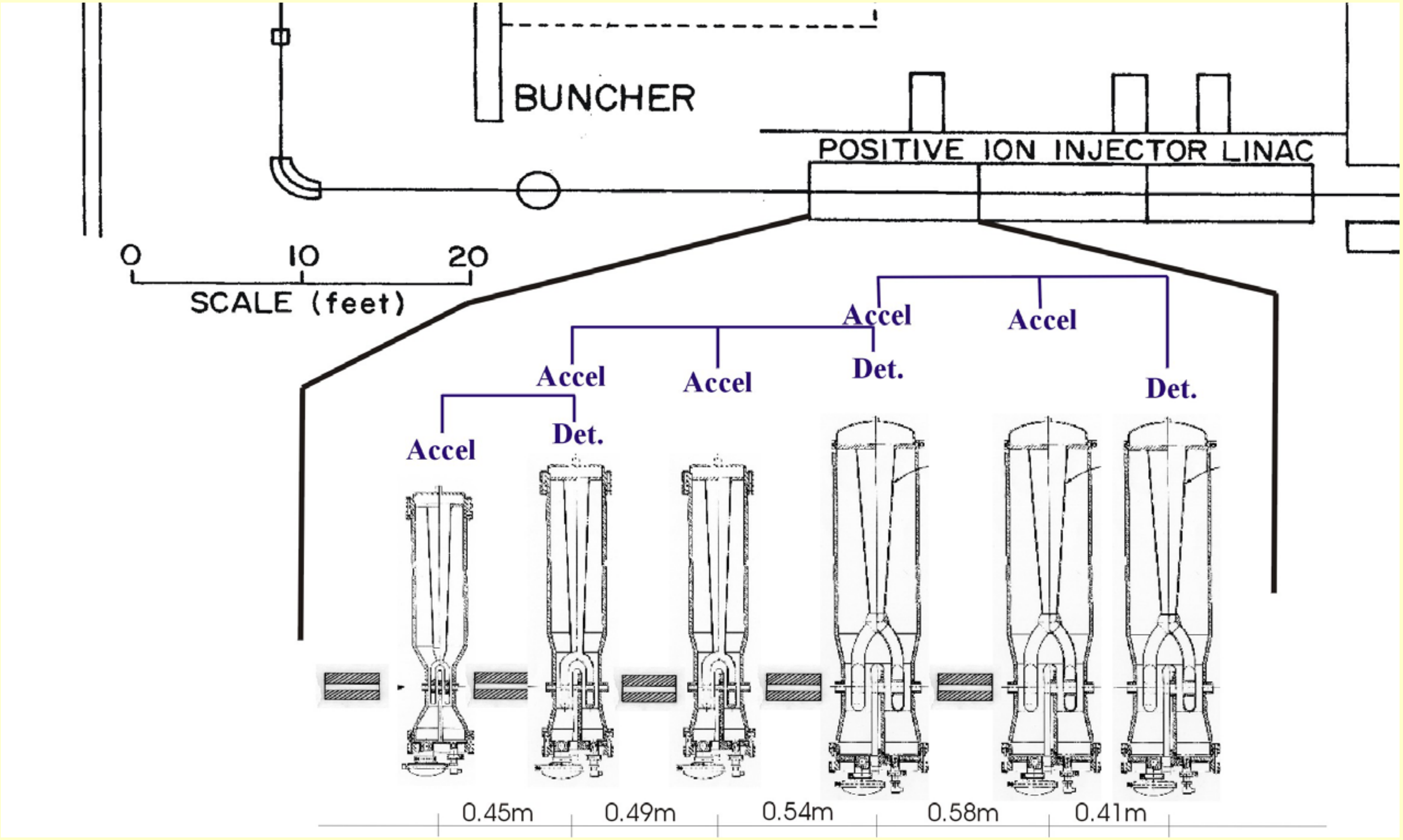
$\phi_{rf}(t) = 2\pi t$



$\phi_b = 90^0$



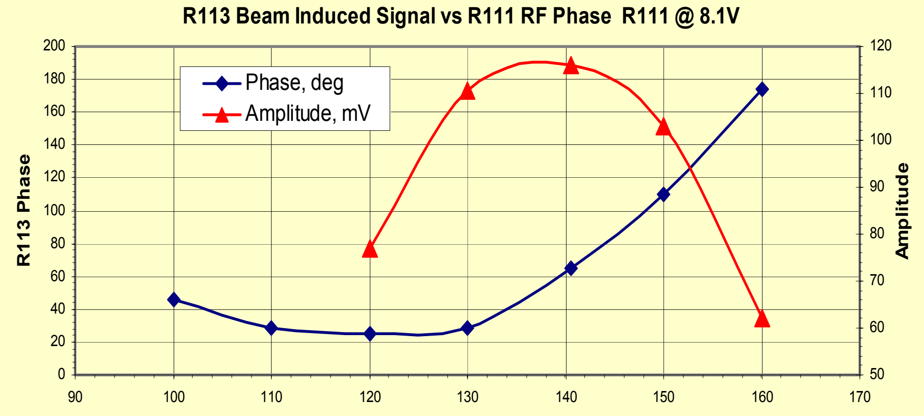
Resonant Beam Pickup Method

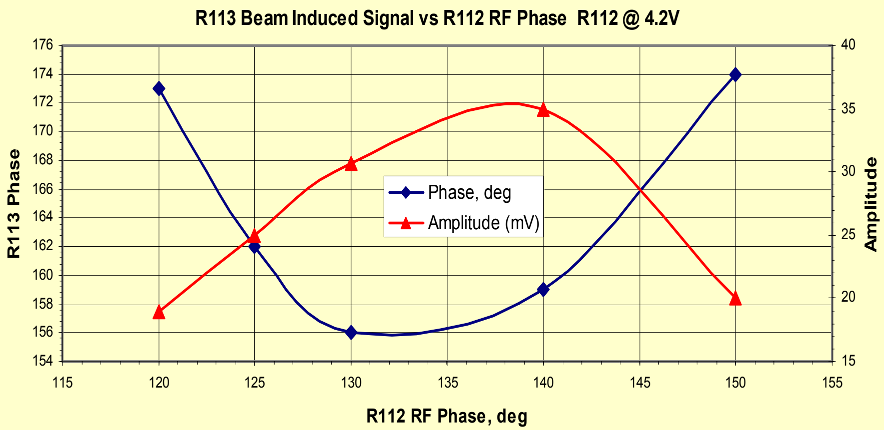


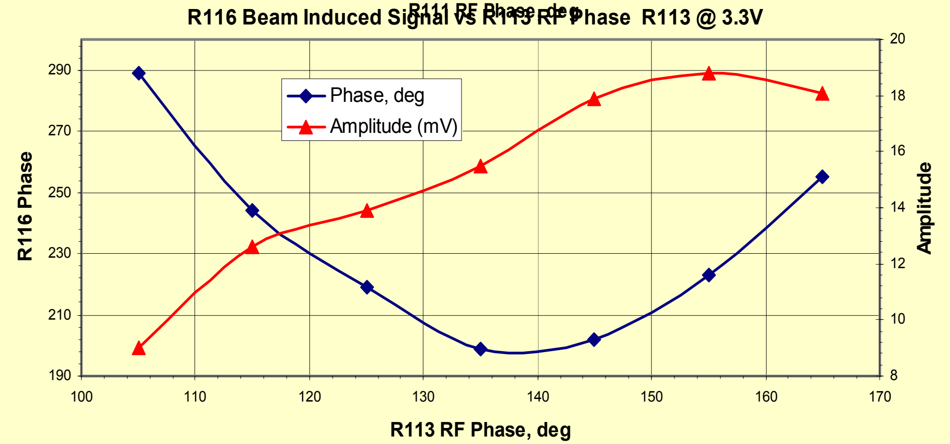
Uses nearby downstream SC resonator

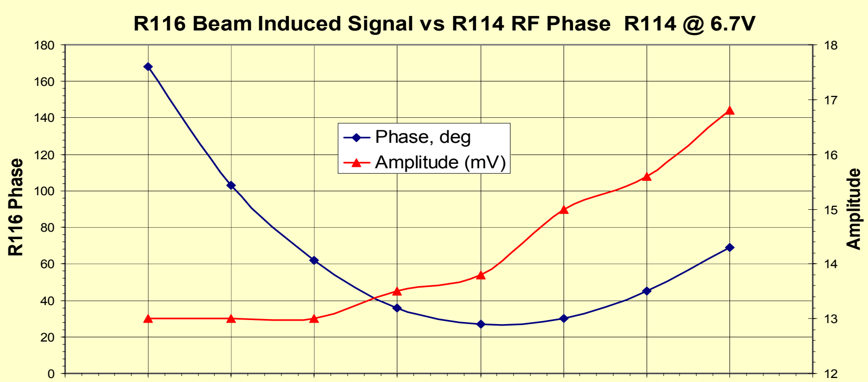
Resonant Beam Pickup Method

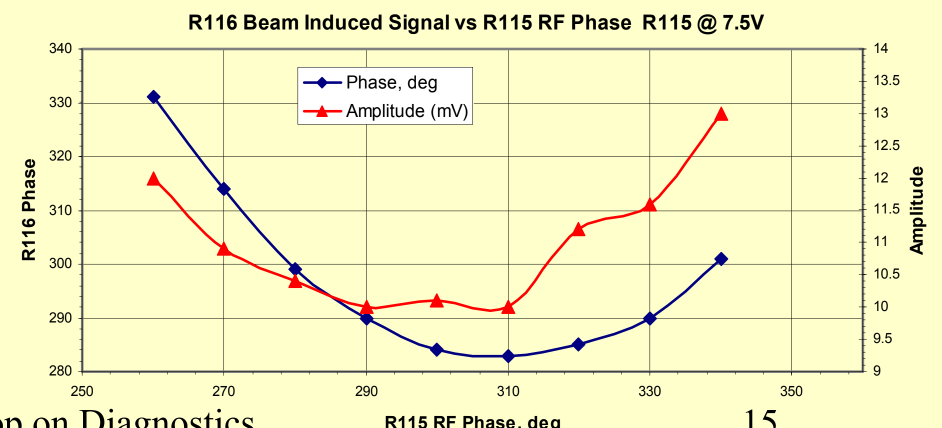
$^{40}Ar^{+7}$, q/A=0.175, I_b=1uA











Resonant Beam Pickup Method

- Features of the Resonant Pickup
  - Less sensitive to beam steering
  - Less sensitive to beam defocusing with energy change
  - Good centroid time accuracy: ≤ 1 degree
  - Energy measurement from phase shift possible
  - Phase width information from normalized amplitude (in principle)

Resonant Beam Pickup Method

- Limitations
  - Beam velocity desired to be close to synchronous phase of resonator.
  - Detection system must move from resonator to resonator as tuning progresses.
  - Is sensitive to scattered beam.
    - ✓Transverse tune through resonators must be good.

Resonant Beam Pickup Method

Results of Tuning

The resonant beam phase detection method,
Combined with a new bunching and chopping system

- Over 70% capture and acceleration of DC beam
- Improved speed in ‘from-scratch’ tuning of PII

Resonant Beam Pickup Method

Determining Energy Gain per Resonator

By accurately measuring the total phase shift seen by the detecting resonator, it should be possible to measure the energy gain from the last accelerating resonator.

The observed phase shift was used to calculate the energy gain of three of the resonators in alpha cryostat.

Resonant Beam Pickup Method

Calculate observed phase shift by adjusting output energy
Correct input energy into resonator with measured SBD value

Res. Pair	Distance (m)	Total Phase Shift (deg)	Energy In (MeV)	Energy Out (MeV)	SBD Measured Energy (MeV)
R113/ R114	.540	221	5.54	7.2	7.7
R114/ R116	.991	616	7.7	12.6	12.7
R115/ R116	.406	104	12.7	16.2	16.5

Resonant Beam Pickup Method

Summary

The Resonant Beam Pickup Method has been developed at the ATLAS accelerator using resonators similar to those planned for the low-velocity section of the RIA Project.

The technique is being implemented for the low-velocity resonators in ATLAS.

Data acquisition will be fully automated.