Efficiency and Intensity Upgrade of the ATLAS Facility

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- Short description of ATLAS
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  - CARIBU
- ATLAS Efficiency and Intensity Upgrade, Phase I
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- CW Radio Frequency Quadrupole (RFQ) development
- New Low-beta Cryomodule Development
- Charge Breeder for CARIBU based on Electron Beam Ion Source
- ATLAS Efficiency and Intensity Upgrade, Phase II Proposal
Argonne Tandem Linac Accelerator System (ATLAS)
### Beams in FY09

#### ATLAS Beams for FY2009

<table>
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<tr>
<th>Ion</th>
<th>Energy Range Provided (MeV)</th>
<th>Maximum Beam Current Used (pnA)</th>
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Californium Radioactive Ion Breeder Upgrade (CARIBU)

- Radioactive beam intensity up to $10^7$ ions/sec ($^{104}$Zr, $^{143}$Ba, $^{145}$Ba, $^{130}$Sn, $^{132}$Sn, $^{110}$Mo, $^{111}$Mo, …)
ATLAS Energy Upgrade

- 7 quarter wave SC resonators
- Innovative features
  - Advanced EM and Mech. design
  - Steering corrected drift-tubes
  - State-of-the-art surface processing and clean assembly
  - Separate cavity & cryostat vacuum
- ATLAS energy increase 30-40%
  - Highest real-estate gradient
- Limitation
  - VCX
  - Technology of QWR
  - B_{peak}=88 mT
- Commissioned – July 2010
Efficiency and Intensity Limitations of the current ATLAS

- Previous generation ECR
- ECR charge breeder: low efficiency, long breeding time
- Low Energy Beam Transport: emittance growth, beam losses
- Multi-Harmonic Buncher
  - Low voltage, strong space charge effects
  - As a result not efficient for high current beams (>10 \( \mu \)A)
- Low transverse acceptance of the first PII cryostat
  - The aperture diameter of the first cavity is 15 mm, the second cavity – 19 mm
  - The transverse acceptance is \(~0.6 \pi\) mm-mrad, normalized
- Longitudinal emittance
  - Strong transverse-longitudinal coupling in the first cavities at high field
  - Non-adiabatic motion in the phase space, low acceptance, emittance growth for high-intensity beams and beam losses
- Beam steering in the split-ring cavities, especially for light ions
- No space to install in-flight separator
- RF system, Cryogenics, Radiation Shielding, Control system, Beam diagnostics
Scope of the ATLAS Efficiency and Intensity Upgrade projects
Phase I (Funded) and Phase II (Proposal)

- Deliver $\geq 7$ MeV/u high-intensity ($\sim 10 \, \mu\text{A}$) ion beams for experiments
- The maximum beam energy of medium intensity beams ($\sim 1 \, \mu\text{A}$) will be increased to $\sim 11$ MeV/u for $A/q=7$ without any additional stripping and to over 20 MeV/u for beams with $A/q<3$ (such as $^{40}\text{Ar}^{14+}$).
- Increase the efficiency of CARIBU charge breeding by using an EBIS.
- Increase the overall transmission of any ion beam, including CARIBU radioactive beams, to 80% of the intensity of DC beams from the source/breeder.
- Replace the ATLAS ECR-II ion source with a ‘third generation’ superconducting ECR source.
- Add new in-flight separator to produce high-intensity in-flight secondary beams
- Upgrade ATLAS technical systems (RF, Beam Instrumentation, Controls, ARIS) and radiation shielding to handle higher intensity beams
ATLAS Efficiency and Intensity Upgrade projects (Phase I)

- New 60.625 MHz CW RFQ, ARRA – $4.55M
- New cryomodule and LHe distribution system upgrade, ARRA – $5.31M
- EBIS Charge Breeder (AIP) - $2.4M (FY10 - $0.88M) - off-line constr. & testing
- ATLAS Utilities Upgrade (AIP) – $0.88M (FY10- $0.422M)
RFQ 101

\[ a \quad - \quad \text{Aperture} \]

\[ ma \quad - \quad \text{Maximum distance from axis to electrodes} \]

\[ k = \frac{2\pi}{\beta\lambda} \quad - \quad \text{Wave number} \]

\[ R_0 = \frac{2a}{m+1} \quad - \quad \text{Average distance from axis to electrodes} \]

\[ L_c = \frac{\beta\lambda}{2} \quad - \quad \text{Length of accelerating cell} \]
RFQ studies, recent developments

- **HINS (Project X) RFQ for FNAL**
  - 325 MHz RFQ for protons and H-minus

- **Design features**
  - Produce axially-symmetric beam
  - Small longitudinal emittance
  - No emittance growth
  - Strong transverse focusing ($\sigma_0 \approx 43^\circ$)
  - Limiting current 140 mA
  - Acceleration efficiency is 96% for 45 mA
  - Short, 3 meters

44 nsec time delay over 1 m corresponds to 2.5 MeV protons

January 13, 2010
ARRA RFQ Project

- CW regime of operation
- Any ions in the $\frac{1}{7} \leq \frac{q}{A} \leq 1$ range
- Injection energy = 30 keV/u
- Extraction energy = 295 keV/u
- 60.625 MHz, 5th harmonic, 3.9-meter length
- 83 % efficiency of beam capture for acceleration
- Voltage 70 kV, $R_0=7.2$ mm
- OFE copper, high-temperature furnace brazing
- 50 kW RF power
- New features
  - Forms axially-symmetric beam
  - Very low longitudinal emittance
  - Increased efficiency of acceleration
Electrodynamics design, MWS model

- Highly 3D structure, resonance frequency \( f_0 \) is critical to geometry
- Verification of the simulated and measured \( f_0 \) of the RIA prototype RFQ
- Simulations: \( f_0 \) strongly depends from mesh number
- Copper Model measured frequency: \( f_0 = 55.852 \text{ MHz} \)
- Copper Model calculated frequency: \( f_0 = 55.7257 \text{ MHz with 3M mesh points} \)
Six-segment RFQ structure, strongly coupled

- Frequency of operating mode 57.5 MHz
- Frequency of the first nearest mode 68.4 MHz
- Frequency of the second nearest mode 93.5 MHz
Frequency of the 5-segment RFQ, MWS model with modulated vanes

Target frequency = 60.4 MHz
Operational frequency = 60.625 MHz
Tuning range

A=11.785”
Potential distribution in the aperture

- Electrostatic approximation

\[ U(r, \vartheta, z) = \frac{U_i}{2} \left[ F_0(r, \theta) + \sum_{n=1}^{\infty} F_{2n}(r, \vartheta) \cdot \cos 2nkz + \sum_{n=1}^{\infty} F_{2n-1}(r, \theta) \cdot \cos(2n-1)kz \right] \]

\[ F_0(r, \theta) = \sum_{m=0}^{\infty} A_{0,2m+1} \left( \frac{r}{R_0} \right)^{2(2m+1)} \cdot \cos 2(2m+1)\theta \]

\[ F_{2n}(r, \theta) = \sum_{m=0}^{\infty} A_{2n,2m+1} \cdot I_{2(2m+1)}(2nkr) \cdot \cos 2(2m+1)\theta \]

\[ F_{2n-1}(r, \theta) = \sum_{m=0}^{\infty} A_{2n-1,2m} \cdot I_{4m}[(2n-1)kr] \cdot \cos 4m\vartheta \]

\[ T = \frac{\pi}{4} \cdot A_{10} \quad - \quad \text{Accelerating efficiency} \]

\[ K^2 = \frac{eU_i}{4m_0c^2} \cdot \left( \frac{\lambda}{R_0} \right)^2 A_{01} \quad - \quad \text{Focusing efficiency} \]
ATLAS RFQ, Beam Dynamics design

- Very low longitudinal emittance
- Beam current up to 1 mA, CW
- For the first time for the RFQs, the full 3D model of the RFQ was created in CST Particle Studio
- Found exact same dynamics in the TRACK code and CST

Accelerating field from CST MWS

First MWS simulations of the modulated vanes in an RFQ resonator

RFQ section with 3D electric field map
Comparing TRACK 8-term potential to Full 3D RFQ Model (Fields)

✓ Field comparison along Z at $R_0/4$
  - TRACK 8-term potential (red)
  - Full 3D EM-Studio model (green)

✓ The longitudinal field component agree to better than 1%.

✓ The transverse components differ by 1-2%.

✓ For a complete independent check: A full 3D MW-Studio model with particle tracking produced the same energy gain as TRACK for the same input phase.
Increased efficiency of the RFQ accelerating field

- Conventional approach
- ANL approach
  Based on design developed at IHEP, Protvino (Russia)
Accelerating field in the RFQ

- Increased effective accelerating field due to the higher transit time factor
  - ATLAS RFQ: energy increase from 250 keV/u to 295 keV/u
  - Equivalent voltage gain in the modified section is 400 kV
  - The same RF power
Input & Output radial matchers

- Input beam matching – from static to dynamic acceptance
- Output beam matching – to the following beam linac
New Type of Output Radial Matcher

Geometry and its Parameters:

✓ First straight section of length $L_0$ at the average radius $R_0$
✓ End straight section of length $L_1$ at a radius $R_1$ to be determined
✓ Curved middle section of length $L_C$ linking the first and last straight sections

✓ The only defined parameters are the average radius $R_0$ and the total length of the matcher $L_T=L_0+L_1+L_C$ due to the fixed RFQ length.
✓ Using a fit where $L_0$, $L_1$ and $R_1$ are varied we were able to get a symmetric beam out of the RFQ for a total output matcher length as short as 7 cm.
✓ This more flexible output matcher relaxes the total length constraint we had with the more standard output matcher obtained by mirroring the input matcher.
Temperature Results

Scaled to inter-vane voltage of 70 kV
Load on segment 10.65 kW at temperature
Temp dependent heat loads
Vane inlet Temp 21.1°C
Quad inlet Temp 25.9°C
**Displacement Results**

Scaled to inter-vane voltage of 70 kV
Load on segment 10.65 kW at temperature
Temp dependent heat loads
Vane inlet Temp 21.1°C
Quad inlet Temp 25.9°C

Ambient Pressure and coolant pressure (70 psi) loads - no gravity
High power tests of the RIA driver linac RFQ

Study of the vane tips displacement

92 kV = 2×Kilpatrick

Power loss and stored energy

X-ray spectrum end point

Power in the cavity (kW)

Inter-vane voltage (kV)

Horizontal displacement

Intensity (a.u.)

BAA Seminar
RFQ Beam Dynamics

- A/q=4
- 10 μA, 295 keV/u
- 80.5 % Capture & Acceleration efficiency
- ~ 0.8 ns×keV/u normalized longitudinal rms emittance
- Symmetric output beam for direct injection to PII
New Cryomodule

7 QWRs, four 9-Tesla SC solenoids, total design voltage is 17.5 MV, best performance ~25 MV
5.12-meter long, Separate vacuum, Improved AEU design
Major components of the cryomodule

- Magnetic shield

- Thermal shield
Electromagnetic design

- 60.625 MHz or 72.75 MHz
- Reduce $B_{\text{PEAK}}/E_{\text{ACC}}$, $E_{\text{PEAK}}/E_{\text{ACC}}$
- Beam steering correction provided by the 2.5° tilt of the drift tube face
- Keep $R/Q_0$ high, Stored energy low
- Reduce the cavity height – reduce microphonics
- Simplify cavity fabrication and RF surface processing
Final Resonator Dimensions

\[ \Phi = 3 \text{ cm} \]

\[ \Phi = 14 \text{ cm} \]

\[ 40 \text{ cm} \]

\[ 30 \text{ cm} \]

\[ 20 \text{ cm} \]

\[ 10 \text{ cm} \]

\[ 40 \text{ cm} \]

\[ 30 \text{ cm} \]

\[ 75.6 \text{ cm} \]

\[ 115.6 \text{ cm} \]
Results of the EM optimization

- Outer conductor: form cylinder to conical shape
- Drift tubes are highly optimized to reduce \( E_{\text{PEAK}} \)
- 2.5 deg drift tube face tilt to compensate beam steering problem

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<td>( U_0 ) at 1 MV/m</td>
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<td>( \beta \lambda /2 )</td>
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<td>3.2</td>
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<td>( B_{\text{PEAK}} ) at 1 MV/m</td>
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<td>( R_{\text{sh}}/Q )</td>
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<td>575</td>
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Development of low-beta SC cavities

- 109 MHz cavities
  - Demonstrated 15 MV/m in 2 cavities
  - Average cryomodule performance is 12.1 MV/m
  - Quench $B_{\text{PEAK}} = 88 \text{ mT}$
- Voltage controlled impedance (VCX) tuner limits to 8.1 MV/m
- VCX will be replace with piezoelectric fast tuner (PZT)
- Highly EM optimization – reduce peak fields
- New RF coupler (up to 4 kW)
  - Compensates beam loading up to 1 kW, 250 $\mu$A, 4 MV per cavity
  - Additional power to control microphonics
  - Adjustable (operation, ~15-20% higher gradients)
- Both PZT and RF coupler are suitable for any other applications in low-beta cavities
- Diagnostics of quench locations in QWRs
  - Complicated geometry compared to elliptical cavities
Electropolishing

- High quality electropolishing should result to higher intrinsic $Q_0$, lower cryogenics load. For new cavities we expect at least $Q_0=1\times10^9$ at operational field (4.5K)
- Electropolishing of entire cavity after all welding done reduces risk of cavity contamination and possibly increases quenching peak fields
- Therefore essential part of the project R&D is high-quality electropolishing similar to ILC technique
- Physics Division SRF group is a major contributor to ILC program
New capacitive RF power coupler

- 4 kW forward power, RF losses = 1.75 W total, most of which is dumped in LN

Antenna
Bellows (up to 2” stroke)
Cold window
Thermal transition
Warm window

Beam current is 100 mA, synch. phase is 25 deg

Available tuning window (Hz)

Generator power (kW)

0 2 4 6 8 10

0 5 10 15 20 25 30 35 40 45 50

2.5 MV
4.0 MV
Fast piezoelectric tuner, first iteration

- Keep cavity internal volume clean; do not use slug tuners
- Reduce overall mass coupled to the PZT $\rightarrow$ increase $\omega \sim 1/\sqrt{m}$
  - Weld a Nb ring to the cavity to hold PZT
- First iteration was disappointing

50 microns through gap element

Radial displacement inches

$df/ds = -0.18 \text{ Hz/micron}$
Fast piezoelectric tuner, final design

\[ \text{df} / \text{ds} = -2.3 \text{ Hz/micron} \]

Tuner load 42 lbs

- A Nb ring added on opposite side to reduce \( \text{df/dp} = -1.19 \text{ kHz/atm} \)

Radial displacement inches

Flat surface

Efficiency and Intensity Upgrade of the ATLAS Facility

BAA Seminar
Cavity subsystems

- 4 kW capacitive coupler
  - Adjustable
  - 1 cold and 1 warm windows
- Pneumatic slow tuner

- Piezoelectric tuner (PZT)
  - ~90 Hz window
  - 35 μm displacement
Cold Test of the PZT and coupler in TC3

- Improved magnetic and thermal shielding, MLI
- Rapid clean assembly
- Suitable to accommodate any SC cavity built to date worldwide
- Successfully commissioned and operated both 4K and 2K continuously
- Recently has been used for test of single cell ILC cavity
- New RF coupler and PZT are being assembled together with HWR
Structural analysis

- Minimize frequency sensitivity to He pressure fluctuation: \[ \left| \frac{df}{dp} \right| \leq 1 \frac{kHz}{atm} \]
- Evaluate pendulum mode of center conductor and increase Eigenmode frequencies
- Stresses in the Nb and SS vessel are acceptable up to 40 psi (MAWP) of He pressure
- Optimize location of the fast tuner, provide ~100 Hz tuning window
- Avoid interference between slow and fast tuners
- Define required load for the slow tuner for frequency range ~30 kHz

Results after several iterations using MWS and ANSYS

- The cavity He vessel will be built in compliance with the ASME pressure vessel code
- Frequency sensitivity to He pressure fluctuation is low ( ~ 1 kHz/atm)
- Slow tuner range -30 kHz at 4500 pound force
- Fast tuning window = 90 Hz
Design and Fabrication

- Niobium for the prototype cavity has been shipped to the vendor
- Forming of Nb components for the prototype cavity is in progress
- Helium SS vessels for all 7 cavities are being procured
- One 4 kW amplifier for the prototype cavity test is being built
  - We will decide later what power we need for all cavities (2 kW or 4 kW)
- Design of the cryostat vessel is nearly complete – will go for the bids in ~1-2 weeks
- Design of the electropolishing apparatus is well advanced – will be built by October 1, 2010
- R&D components – 4 kW coupler, Piezoelectric tuner, modification of the existing Half Wave Resonator (HWR) for testing
- New test cryostat TC3 has been commissioned
- One 9-Tesla SC solenoid will be delivered this month, solenoid cryostat is being built at Meyer Tool
- **Next 2 milestones are**
  - Complete fabrication of the prototype cavity, RF measurements (warm) – 09/10
  - Cold test of the prototype cavity - 12/10
q/A=1/7 Ion Beam Envelopes, Beam Loss (<0.05%) distribution

Beam Line →
Transverse
RMS & Max.
Beam Size →

Lost particles →

\[
\frac{N_{\text{lost}}}{N_{\text{in}}} (\times 10^{-6}) \quad \text{vs} \quad \text{Length (m)}
\]
ATLAS beam Intensities after Phase I completed

- Beam intensity is limited by the ECR performance
ECR charge breeder, efficiency ~10%
Charge Breeder for CARIBU based on Electron Beam Ion Source

- **EBIS CB vs ECR CB**
  - Breeding efficiency – factor of 2-3 higher, CERN-ISOLDE has demonstrated 35% breeding efficiency for some ion species (\(^{65}\)Cu)
  - Breeding time - < 30 msec, an order of magnitude better
  - Emittance of the high Q+ ions – low
  - Improved isotope beam purity
  - Short pulses of very low intensity beams result to good signal/noise ratio for the experiments
  - Much more relaxed voltage matching between CARIBU and EBIS-CB HV decks

- Key component of the ATLAS charge breeding set-up is a high-efficiency (~90%) cooler-buncher upstream of the EBIS. This combination is perfectly suitable for relatively low intensity RIBs (below \(10^7\) ions/sec) produced by CARIBU. The state-of-the art cooler-buncher technology is available in the Physics Division.

- Traditional fast (~10 µsec) pulsed injection-extraction of ion beams will be used, pulse repetition rate is 30 Hz

- Large acceptance for ion beams, the diameter of the e-beam is ~ 600 µm

- Coupled to the post-accelerator capable to accelerate \(q/A \geq 1/7\), requires shorter breeding time as compared to the ion beams with \(q/A \geq 1/4\) (CERN REXEBIS)

- We propose to develop two electron guns 2 A and 0.2 A, both with very high density ~600-700 A/cm\(^2\) (factor of 5 higher than at CERN REXEBIS)

- EBIS-CB will be similar to BNL EBIS which has demonstrated the best performance
EBIS Charge Breeder for CARIBU, layout

Efficiency and Intensity Upgrade of the ATLAS Facility

EBIS Charge Breeder for CARIBU, layout

Q/A > 1/7

- Electron Gun
- Superconducting Solenoid
- Drift Tubes
- Electron Collector
- Ion Extractor
- To ATLAS
- Post-Accelerator
- RFQ-CB
- Q=12-25+
- RFQ Cooler-Buncher Efficiency is ~90%
- From CARIBU Mass-Separator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam current</td>
<td>Up to 2 A DC</td>
</tr>
<tr>
<td>Electron beam energy</td>
<td>Up to 10 kV</td>
</tr>
<tr>
<td>Electron beam current density</td>
<td>Up to 600 A/cm²</td>
</tr>
<tr>
<td>Breeding time</td>
<td>30-40 ms</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt; 20%</td>
</tr>
</tbody>
</table>

The state-of-the-art BNL Test EBIS is the best choice as a prototype of the EBIS-CB
Charge State Evolution of $^{131}$Xe (CBSIM code)

- Lower electron beam energies provide higher abundances of ions
- Lower rep-rates are beneficial for higher abundances of ions

Red line – $\log(J \cdot \tau) = 1.18$
($J = 500 \text{ A/cm}^2$, $\tau = 30 \text{ ms}$)
Breeding efficiency measurements at BNL T-EBIS

- Injected ions - $^{133}\text{Cs}^+$ ↔ extracted ions - $^{133}\text{Cs}^{22-25+}$
  - pulse duration – about 10 µs
  - current – 0.1-1 µA
  - number of ions per pulse – $10^7-10^8$
  - 4 rms normalized emittance is $\sim0.02 \pi \text{mm}\cdot\text{mrad}$

- Charge breeding efficiency
  - electron beam size (by adjusting the ratio of solenoid and e-gun magnetic fields)
  - electron beam current (by adjusting cathode-anode voltage)
  - electron beam energy (by adjusting drift structure electrodes potentials)

- Optimization of breeding efficiency on ion beam injection parameters (energy, size, angle)

- Comparison of experimental results with results of numerical simulations
ATLAS Efficiency and Intensity Upgrade - Phase II

- New accelerator technology (including SRF) offers
  - Factor of 3-4 higher accelerating gradients – creates real estate available for experimental equipment
  - Reduces number of RF resonators – increased operational reliability
  - Newer resonators – increased operational reliability
  - Eliminates beam halo formation and losses thanks to larger aperture and automatic beam steering correction
  - New SC resonators are capable to accelerate ~1 mA ion beams

- Superconducting ECR is required to generate higher intensity beams

- Higher efficiency EBIS charge breeder is required for CARIBU beams

- Available space can be used to install high-intensity target and in-flight separator
ATLAS Layout after Phase II upgrade

- Add one more cryomodule, $\beta_G = 0.077$
- Relocate SRF test Facility
- EBIS: complete installation and commissioning
- ATLAS infrastructure improvement
- Tandem decommissioning
- In-flight beam separator, high-intensity targets
- New CARIBU source transfer Facility
- High-intensity ECR
In-Flight Separator

- Angular acceptance of \( \pm 50 \) mrad in both x and y, a momentum acceptance of \( \pm 5\% \) and a maximum rigidity of 1.5 Tm
- The RF sweeper adds time-of-flight selection to the achromatic momentum selection, effectively providing a coarse mass selection for the recoils
- The SC debuncher reduces the energy spread of the recoil beam
- 2 orders of magnitude gain in intensity for the in-flight produced secondary beams
  - Improve the collection efficiency of the recoils by a factor of at least 10 over the existing system
  - new high-power target station will allow a factor of 10 higher beam intensity on target.
Conclusion

- Appreciable funds have been assigned for the ATLAS Upgrade
- ATLAS future is considered as the National User Facility for Intense Stable Ion Beams