ISLA: An Isochronous Spectrometer with Large Acceptances for the re-accelerated radioactive beams of FRIB

D. Bazin

NSCL/FRIB/MSU
NSCL and FRIB re-accelerated beams
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- NSCL-driven re-accelerated radioactive beams
NSCL and FRIB re-accelerated beams

- NSCL-driven re-accelerated radioactive beams
- FRIB-driven re-accelerated radioactive beams
Key concepts
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- ReA12 re-accelerated radioactive beams

  - Energies from 0.3 MeV/u to 12-20 MeV/u (depending on Q/A)
  - Small emittances ( < 6 mm beam spot, ~ 1 ns / 1 keV)
  - Intensities ranging from 1 to $10^8$ pps
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• **Requirements for a large acceptance spectrometer**
  - Collect reaction products in large kinematic space
  - Transmit several charge states for high efficiency
  - Identify reaction products with good elemental and mass resolutions
  - Reject unreacted beam
  - Accommodate auxiliary detector array around target
  - Possibly rotate beam around target
Some experiments in need of a spectrometer
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- Changes in shell structure
  - Deep-inelastic reactions using neutron-rich beams
  - Fusion-evaporation reactions for spectroscopic studies
  - in-beam $\gamma$-ray spectroscopy of high-spin states
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- Heavy and super-heavy elements
  - Fusion reactions with neutron-rich beams
  - Study of fission barriers
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- Radioactive beams intensities are (relatively) small
  - Inelastic studies of the radioactive species contained in the beam
    - Example: Coulomb excitation at or below Coulomb barrier
  - Experiments using reactions driven by luminosity rather than intensity
  - Higher cross sections mean less background from beam and other channels
    - Deep-inelastic reaction using neutron-rich beams
    - Fusion-evaporation reactions to produce $^{100}$Sn from $^{56}$Ni+$^{52}$Cr instead of $^{58}$Ni+$^{52}$Cr ($\alpha$+6n channel) versus ($\alpha$+4n channel)
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- Existing spectrometers
  - Well adapted to high intensity beams
  - Have either large acceptances or high rejection
Existing spectrometers
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- High intensity stable beams
  - Need very good rejection of primary beam ($\sim 10^{-12}$) ☹
  - Small acceptances ☹, small aberrations ☺, small focal plane ☺
  - Example: FMA, Wien filters
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  - Example: VAMOS
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- **Gas-filled spectrometers**
  - Large charge state acceptance ☻, poor resolution ☻
The best of both worlds?
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- **Time-of-flight spectrometer**
  - Most spectrometers map separation to position in focal plane
  - Isochronous spectrometer maps separation to TOF
  - Focal plane remains small even with large acceptances
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- **ISLA concept**
  - Isochronous spectrometer with filtering based on $B\rho$ selection from dipole field
  - Large-gap iron-free dipoles for large acceptances
  - Quadrupole-free design to reduce aberrations
  - Isochronous/dispersive focal plane at mid-point
  - $M/Q$ resolution depends on TOF resolution and quality of optics
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- TOFI spectrometer at LANL
  - Designed to measure masses of exotic nuclei
  - Small acceptances (2.8 msr, ± 2% ΔP/P)
  - Resolution in M/Q = 1/2000
  - J. M. Wouters et al., NIM A240 (1985) 77
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- ISLA concept
  - Large acceptances (32 msr, ± 5% ΔP/P)
  - Use iron-free magnets
  - Track particles at dispersive & focal planes
  - Allow rotation of incoming beam

D. Bazin, Heavy Ion Discussion, ANL Oct. 30, 2009
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  - large transverse momentum space
  - many charge states can be transmitted
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  - Point-to-point imaging
  - Direct measure of momentum at dispersive focal plane
  - Direct measure of scattering angle at final focal plane

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- **Isochronous design**
  - Superior M/Q resolution of spectrometer (only depends on TOF resolution)
  - No M/Q range limitation other than $\Delta P/P$ acceptance
Isochronous condition
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- **Time-of-flight of particles**
  - Should be independent of longitudinal and transversal momenta (velocity and angle)
  - First order derivation of isochronous condition:
    - Time = Length / Velocity = $L \times V^{-1}$
    - $\Delta T = \Delta L \times V^{-1} - \Delta V \times L \times V^{-2} = 0$ therefore $\Delta L = L \times \Delta V / V = L \times \Delta P / P$
    - Length dispersion coefficient ($L/d$) = R(5,6) = $\Delta L / (\Delta P / P) = L$ (-L in TRANSPORT and COSY?)
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- COSY vs TRANSPORT units
  - COSY: \( r_5 \) is defined as \(- (t - t_0) \times v_0 \times \gamma / (\gamma + 1) \) but not conserved with energy (?)!
  - TRANSPORT: \( R(5,6) \) conserved but program cannot fit to variable parameter
  - Use “Dynamical TRANSPORT” program…

D. Bazin, Heavy Ion Discussion, ANL Oct. 30, 2009
ISLA design parameters

- **Important considerations**
  - Minimize aberrations using highly symmetric configuration
  - Spectrometer composed of 4 identical Drift-Dipole-Drift cells
  - Horizontal focussing realized with entrance and exit pole angles

- **3 fitting parameters**
  - Drift length, dipole bending angle, entrance (= exit) pole angle

- **5 fitting conditions**
  - Isochronous, x & y focussing, doubly achromatic image (position and angle) at final focal plane
  - Possible thanks to the symmetry of the design
  - Demo…
ISLA first order optics

- First order fitting results

  - Input emittance: ± 100 mrad Horizontal, ± 80 mrad Vertical, ± 5 % \( \Delta P/P \)
  
  - Dipoles: radius = 1.1 m, gap = 40 cm, bend = 78.7°, poles = 25.3°
  
  - Drift: 1.24 m
  
  - Total length: 16 m
  
  - Results depend on fringe field shape
  
  - Correction coils needed to fine tune optics and correct aberrations
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Geometrical aberrations

- COSY calculation to 3\textsuperscript{rd} order
  - Same input emittance: ± 100 mrad Horizontal, ± 80 mrad Vertical, ± 5 % ΔP/P
  - Dispersive focal plane: (x/aa)=-2.7 cm, (x/bb)=-1.7 cm, (y/ab)=-4.2 cm, (y/bbb)=-2.5 cm
  - Final focal plane: (x/xyy)=-1 cm, (y/bbb)=4.9 cm, (y/aab)=-1.3 cm
  - Small detectors can be used at final focal plane
Time-of-flight aberrations

- **Dispersive focal plane**
  - Vertical are the largest: \( (L/bb)=0.26 \text{ cm} \), \( (L/bbd)=-0.17 \text{ cm} \)

- **Final focal plane**
  - Vertical also largest and cumulative: \( (L/bb)=0.52 \text{ cm} \), \( (L/bbd)=0.36 \text{ cm} \)

- **M/Q resolution from aberrations**
  - Total length of 16 meters
  - Acceptances fully filled (± 100 mrad Horizontal, ± 80 mrad Vertical, ± 5 % \( \Delta P/P \))
  - \((L/bb)\) aberration corresponds to M/Q resolution of 1/3000
  - \((L/bbd)\) aberration corresponds to M/Q resolution of 1/4400
TOF measurement & M/Q resolution (1)

- TOF ranges from ~ 300 ns to 2 µs
- Using RF signal from accelerator
  - RF bunches of ReA12: 80 MHz, 1 ns FWHM, possible to reduce using bunching
  - Corresponding M/Q resolution ranging from 1/300 to 1/2000
  - Requires “bunch tagging” to determine which bunch made the transmitted nucleus
  - Automatically provided if high efficiency γ-ray array around target
  - Otherwise, close geometry fast scintillators can be used
  - Only need moderate time resolution (12.5 ns) to resolve bunches
  - Other thoughts: macro bunching from extraction of charge breeder, followed by bunch compression (under investigation)
TOF measurement & M/Q resolution (2)

- Using SED detector in dispersive focal plane as start
  - ISLA is isochronous between dispersive and final focal planes
  - SED (Secondary Electron Detector) timing resolution of 300 ps
  - Flight path of 8 m: M/Q resolution ranging from 1/500 to 1/3300 from timing
  - \((L/a) = R(5, 2) = -5.14 \text{ mm/mrad} \) at dispersive focal plane
  - Requires dispersive angle measurement at final focal plane
  - 1 mrad resolution corresponds to M/Q resolution of 1/1500
  - Possible losses due to charge state changes from foil
  - SED detector used in VAMOS for very low energy reaction products
Secondary Electron Detector (SED)

- 45° tilted, 250 µg/cm² aluminized mylar foil emits electrons
- Electrons are guided towards a gaseous electron detector via electric and magnetic fields
- Position-sensitive electron detector records (x,y) position and time
- Large area (10 x 40 cm²), 1.4 mm position resolution, 300 ps time resolution
- Efficiency: 100% for Z>30, 75% for 12C
- A. Drouart et al., NIM A 579 (2007) 1090
Focal plane detectors

- Timing and position detectors for TOF and tracking
  - MCP and/or PPAC about 1 m apart for good angular resolution (1 mm / 1 mrad)

- Energy loss detector for elemental identification
  - Segmented ion chamber

- Residual energy detector
  - Silicon or CsI(Na) crystal

- Small sizes
  - Thanks to spectrometer design, all detector sizes are 5 x 5 cm\(^2\) maximum
Particle identification

- Without $B_\rho$ measurement from SED at dispersive plane
  - $M/Q$ directly obtained from TOF
  - $\Delta E-E$ spectra gated on $M/Q$ peaks can resolve isobars with the same charge state

- With $B_\rho$ measurement from SED at dispersive plane
  - Correct $B_\rho$ measurement from aberrations using angles at focal plane
  - Correct $E$ and $\Delta E$ measurements from corrected $B_\rho$
  - Full PID including charge state $Q$
Example of simulation

- **Fusion-evaporation reaction to produce $^{100}\text{Sn}$**
  - 3.7 MeV/u $^{56}\text{Ni}$ radioactive beam at $10^8$ pps on 0.5 mg/cm$^2$ $^{50}\text{Cr}$ target ($\alpha$+2n evaporation channel)
  - Cross section = $1.1 \times 10^{-2}$ mb (LisFus model v.4), $^{100}\text{Sn}$ energy = 0.9 MeV/u
  - Spectrometer set on most abundant charge state of $^{100}\text{Sn}$: 24+ (M/Q = 4.17)
  - 9 charge states transmitted through the spectrometer
  - Total transmission: ~ 40%
  - Time-of-flight: 1200 ns, M/Q resolution is 1/1200 with 1 ns wide bunch from ReA12
  - Expected rate: $2.7 \times 10^{-3}$ pps (10 per hour)
  - Total rate at focal plane: ~ 63 pps
  - Implantation/decay experiment possible in DSSD
- Charge state and momentum transmissions
- ΔP/P acceptance: 10%
- Angular acceptance transmission: ~ 75%
- Other reactions channels
  - Several other reaction products can be studied simultaneously (cocktail beam)
  - In average 8 to 9 charge states for each isotope
- **M/Q spectrum**

  - Each M/Q peak contains contaminants that can be resolved from $\Delta E$-E measurements
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**M/Q spectrum**

- Each M/Q peak contains contaminants that can be resolved from ∆E-E measurements.
- ΔE-E spectrum for products in M/Q = 4.17 peak
  - All charge states cumulated because LISE++ does not calculate separate Q (yet!)
- Isobar separation from energy loss and TKE
- $\Delta E-E$ spectrum for products in $M/Q = 4$ peak
- Contaminant $^{104}\text{Sb}$ is much weaker than $^{100}\text{Sn}$
- $M/Q$ gated spectrum would separate charge states
ΔE-E spectrum for products in M/Q = 4 peak with $B_\rho$ corrections

$B_\rho$ resolution assumed: 0.5%
Transmission with SED inserted at dispersive focal plane

- Mylar foil thickness: 250 $\mu g/cm^2$, thinner is possible (down to $< 100 \mu g/cm^2$)
- $^{100}$Sn transmission reduced by $\sim 4$ (11% compared to 40%), due to charge state changes in foil
- Possible improvements using thicknesses below equilibrium
Magnet design

- Iron-free superconducting dipoles
  - Preliminary calculation of 40 cm gap dipole
  - Study of fringe fields: fit by “modified Enge function” to take into account negative field outside of magnet

Coefficient values ± one standard deviation:

- $w_0 = 0.034203 \pm 0.0105$
- $w_1 = 2.684 \pm 0.0433$
- $w_2 = 0.90437 \pm 0.0329$
- $w_3 = 0.16963 \pm 0.00891$
- $w_4 = 0 \pm 0$
- $w_5 = 0 \pm 0$
- $w_6 = -1.0314 \pm 0.0238$
- $w_7 = -2.2195 \pm 0.00793$
- $w_8 = 10.901 \pm 18.9$
- $w_9 = 114.29 \pm 68.3$
COSY & ray-tracing calculations

- Aberration evaluation
  - No significant change using realistic Enge function for fringe fields
  - Final parameters (bend, pole rotation) to achieve optics depend on field shape
Other magnet design

- **Double-helix solenoids**
  - Can create virtually any field configuration
  - Multipoles components can be realized as well
  - Main issues: curved magnet, large gap
ISLA collaboration (present)

- **NSCL/MSU**
  - D. Bazin, W. Mittig, B. Sherrill, A. Stolz

- **Florida State University**
  - I. Wiedenhöver

- **ANL**
  - J. Nolen, S. Manikonda

- **LBNL**
  - P. Fallon

- **LNS, Italy**
  - F. Cappuzzello, A. Cunsolo, M. Cavallaro
ISLA web site

- https://groups.frib.msu.edu/group/isla

Purpose

- Allow interested parties to join collaboration
- Facilitate information flow towards members of collaborations and future users
- Get feedback on various ideas and options
- Follow progress on various sub projects
ISLA sub projects

- Optics studies (aberrations, corrections)
- Magnet design and studies (technology, simulation)
- Detector design (specifications, performance)
- Beam swinger (options, range)
- Infrastructure (space allocation, auxiliary detectors)