Cyclotrons for Nuclear Physics: Past, Present, Future

Daniel Winklehner, MIT
Preface

• Me: Daniel Winklehner, Postdoc at LNS in the Neutrino and Dark Matter Group. Email: winklehn@mit.edu

• Goal of this lecture:

A relaxed hour-and-a-half about the history and future of an iconic particle accelerator.
No homework, no quiz. :)

• Additional Information:

  – John Livingood: Principles of Cyclic Particle Accelerators
  – Joint Accelerator Conferences Website: http://www.jacow.org/

These slides contain material from a variety of sources. I tried to put references on the slides as much as possible. Apologies for unquoted original material.
Outline

• **Prelude:** Basic particle accelerator principles and figures of merit

• **Act I:** The ghost of cyclotrons past, or: “Who is Ernest Orlando Lawrence?”

• **Intermezzo:** Cyclotron concepts, types of cyclotrons, uses, and limitations

• **Act II:** The ghost of cyclotrons present, or: “Why are cyclotrons still important?”
  – Current state-of-the-art cyclotrons and their applications

• **Act III:** The ghost of cyclotrons yet-to-come, or: “It’s nice, but does it cure cancer?” (spoiler: yes, sometimes.)
  – Ironless cyclotron, cyclotron gas stopper, cyclotrons for neutrino physics, Accelerator Driven Systems (ADS) …

From Lawrence’s 1934 patent
Source: wikipedia.org
The cyclotron as seen by... …the inventor

By David L. Judd and Ron MacKenzie
The cyclotron as seen by the accelerator theorist

By David L. Judd and Ron MacKenzie

\[ r = r_0 \left[ 1 + \left( \frac{fr_0}{c} \right) \cos (3\theta + \delta_0 + \delta_1 r) + \right. \\
\left. \left( \frac{fr_0}{c} \right)^2 \cos (5\theta + \delta_2 - \delta_3 r^2) + \right. \\
\left. \left( \frac{fr_0}{c} \right)^3 \cos (7\theta + \delta_4 - \frac{1}{4} r^3) \right] \times \left\{ \frac{\frac{3}{2} r^3 \ln Z}{1 + \left( \frac{r}{r_0} \right)^3} \right\} \]

\[ \frac{d\phi}{dt} = \left[ \sin (\omega t - \phi) \cdot \sinh \theta - \frac{3}{2} \sin f_{\phi} t \right] \frac{eV}{2\pi \omega} \]

...the accelerator theorist
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie

…the electrical engineer
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie

…the mechanical engineer
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie

…the experimentalist
The cyclotron as seen by...

By David L. Judd and Ron MacKenzie

...the operator
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie

…the health physicist
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie

…the laboratory director
The cyclotron as seen by...

By David L. Judd and Ron MacKenzie

...the funding agency
The cyclotron as seen by...

By David L. Judd and Ron MacKenzie

...the visitor
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie

…the student
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie

…you, after today
Quick Recap: Beam Parameters

A beam is...”an ensemble of particles that travel mostly in the same direction” (let’s use $z$)

- Typically: $v_z \gg v_x, v_y$

- Can be comprised of multiple ion species:
  
  $$q_i = Q_i \cdot e, \quad m_i = A_i \cdot amu \ (931.5 \text{ MeV/c}^2)$$

- Since we are dealing with moving charge, there is a current
  
  $$J_i \cdots \text{species current density, } I_i \cdots \text{ species total current (A)}$$

- Beam can be DC, cw, or pulsed/bunched
Longitudinal Beam Properties

Bunch Currents

\[ I \sim n e \langle v_x \rangle \]

Duty factor \[ = \frac{\sum \tau_{\text{pulse}}}{T} \]

\[ I_{\text{peak}} = \frac{Q}{\tau_{\text{pulse}}} \]

\[ I_{\text{ave}} = \frac{Q_{\text{tot}}}{T} \]

From: W. Barletta
Distributions in 6D Phase Space (+t)

- Particle number density:
  \[ n(x, y, z, p_x, p_y, p_z, t) \]
  or \[ n(x, y, z, v_x, v_y, v_z, t) \]
- Charge density: \( \rho = q \cdot n \)
- Simplification: \( n(x, x', y, y', z, \Delta p/p) \) (“Trace Space”)
  \[ x' = \frac{dx}{dz} = \frac{v_x}{v_z}, \quad y' = \frac{dy}{dz} = \frac{v_y}{v_z} \]
If there is no coupling between longitudinal motion and transversal motion the transversal Trace Space density is

\[ n(x, x', y, y') \]

Maybe we are even only interested in 2D projections

\[ n(x, x') = \int \int dydy' n(x, x', y, y') \]

Or slices (interesting in diagnostics and simulations)

\[ n(r, r') = n(x, x', y = 0, y' = 0) \]

Because these can tell us something about our beam line transport…
Kapchinsky-Vladimirsky Distribution

- The K-V distribution is a uniformly distributed hollow ellipsoid in Trace space:

\[
f(x, y, x', y') = f_0 \cdot \delta \left( \frac{x_b^2 x'^2 + \sqrt{x_b^2 x_b^2 - \epsilon_x^2 xx'} + x_b^2 x^2}{\epsilon_x^2} + \frac{y_b^2 y'^2 + \sqrt{y_b^2 y_b^2 - \epsilon_y^2 yy'} + y_b^2 y^2}{\epsilon_y^2} - 1 \right)
\]

with \(x_b, y_b\) the maximum beam extent (\(b\) for ’beam’) in x and y directions, \(x'_b, y'_b\) the maximum angles, and \(\epsilon_x, \epsilon_y\) the (full) beam emittances.

- All projections in 2D subspaces are uniformly filled ellipses.
Trace Space Example

K-V Beam – Projections are uniform ellipses
Liouville’s Theorem

- States that for non-interacting particles in a system that can be described by a Hamiltonian, the phase space density is conserved.

\[ \frac{dn}{dt} = 0, \text{ or } n = n_0 = \text{const}. \]

- In terms of mechanical momentum:

\[ \iint d^3 q_i d^3 P_i = \text{const}. \]

- (also true for linear space-charge)

- Trace space area: \[ A_x = \frac{1}{P} \iint dx dP_x = \frac{1}{\gamma \beta mc} \iint dx dP_x \]
Trace Space Example

K-V Beam – Projections are uniform ellipses
Phase Space Evolution - Drift
Geometric Emittance

- Definition from Area

\[ \epsilon_x = \frac{A_x}{\pi} \text{ [}\pi\text{-mm-mm rad}\text{]} \]

\[ A_x = \frac{1}{P} \iiint dxdP_x = \frac{1}{\gamma\beta m_c} \iiint dxdP_x \]

\[ A_x = \frac{1}{\gamma\beta} \iiint dxdx' \]

- Normalized Emittance:

\[ \epsilon_{x,\text{norm.}} = \gamma\beta \epsilon_x \]

- Const. even under acceleration
Emittance vs. beam dynamics

- Courant-Snyder form of envelope equation:

\[ x''_m + \kappa x_m - \frac{\epsilon^2}{x_m^3} = 0 \]

- Emittance works against focusing...
Why preserve (reduce?) emittance?

• Kind of a no-brainer ;)

• Emittance determines the size of the final focus at a certain focal length from the focusing device.

• Emittance determines the distance beam transport elements have to have.

• Emittance determines the distance beam transport elements have to have.

• Emittance…the smaller the better…

• And we have a good definition…right?
Phase Space Evolution - Aberration

- Simple envelope equation solver with spherical aberration...
- Filamentation of the trace space
Phase Space Evolution - Aberration

• Simple envelope equation solver with spherical aberration…

• Filamentation of the trace space

• Ellipse surrounding the beam is growing.

• Actual phase space volume is conserved (still Hamiltonian system)
Other beam Cross-Sections

Gaussian beam

Beam with halo

From: W. Barletta
RMS Emittance

- Second moments of a distribution $f(x, y, x', y')$:

$$
\langle x^2 \rangle = \frac{\iiint x^2 f(x, y, x', y') \, dx \, dy \, dx' \, dy'}{\iiint f(x, y, x', y') \, dx \, dy \, dx' \, dy'}
$$

$$
\langle x'^2 \rangle = \frac{\iiint x'^2 f(x, y, x', y') \, dx \, dy \, dx' \, dy'}{\iiint f(x, y, x', y') \, dx \, dy \, dx' \, dy'}
$$

$$
\langle xx' \rangle = \frac{\iiint xx' f(x, y, x', y') \, dx \, dy \, dx' \, dy'}{\iiint f(x, y, x', y') \, dx \, dy \, dx' \, dy'}
$$

- Emittance:

$$
\epsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \quad [mm\text{-}mrad]
$$
How does this compare to full emittance?

- Well, that depends... on the actual distribution.
- K-V Distribution: $\epsilon_x = 4\epsilon_{x,rms}$
- Waterbag Distribution: $\epsilon_x = 6\epsilon_{x,rms}$
- (Bi-)Gaussian Distribution: $\epsilon_x = n^2\epsilon_{x,rms}$ if truncated at $n \cdot \sigma$

Graph by T. Kalvas

7/22/2016
Brightness

• The brightness is commonly defined as current density per unit solid angle:

\[ B = \frac{J}{d\Omega} = \frac{dI}{dS \, d\Omega} \]

• Or in terms of the transversal projections:

\[ \bar{B} = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y} \left[ \frac{A}{m^2 \cdot \text{rad}^2} \right] \]

• Normalized:

\[ B_n = \frac{B}{\beta^2 \gamma^2} \]
Act I

A BRIEF HISTORY OF CYCLOTRONS

From Lawrence’s 1934 patent, Source: wikipedia.org
The Invention

• 1929: Ernest Orlando Lawrence has the idea for the cyclotron after reading about Widerøe’s linear accelerator.

• The first cyclotron: Brass, wire, and sealing wax. Cost ~25$, 4” diameter.

• 1931: 11” cyclotron was built by M. Stanley Livingston (Lawrence’s grad student) – acceleration of protons to >1 MeV

• 1933: 27” cyclotron... trend to go bigger and bigger (largest: 184”)

• 1934: Lawrence patents the cyclotron
Livingston, Lawrence, and 27” cyclotron

Image Source: https://www.physics.rutgers.edu/cyclotron/cyc_history.shtml
The Basic Principle

The Heyday

• Until the 1950’s, cyclotrons were the accelerator of choice to do nuclear physics experiments.

• Many were built at major universities in the US (Berkeley, Princeton, MIT, Cornell, Yale, Harvard,…), and around the world.

• Many discoveries were made (new elements, isotopes, …)

• Increase in size to reach higher energies worked for a while, then relativistic effects prohibited larger cyclotrons.

• Remedies were synchrocyclotrons and isochronous machines (see later section of this lecture),

• After 1960, cyclotrons were soon surpassed by synchrotrons to reach higher energies.
Achievements

• 1939: Lawrence wins Nobel Prize for the invention of the cyclotron.

• 1951: Edwin McMillan, Glenn Seaborg win Nobel Prize in chemistry for their discoveries in the chemistry of the transuranium elements.

• Commissioned in 1989, the NSCL K1200 cyclotron is the highest-energy continuous beam (cw) accelerator in the world! (Info valid until 2006)

• PSI Ring Cyclotron can accelerate 2.2 mA cw beams
Intermezzo

CYCLOTRON CONCEPTS
The “Classic” Cyclotron

• Weak focusing dipole magnet (cf. Lecture on accelerators by Elke Aschenauer)

• Governing equations:

\[ F_C = \frac{mv^2}{r} \quad F_B = qvB \rightarrow \frac{mv}{q} = \frac{p}{q} = rB \quad \omega = 2\pi f = \frac{qB}{m} \]

• Problem: relativistic mass increase with higher velocity leads to desynchronization.

\[ r = \frac{\gamma\beta m_0 c}{qB} \quad \omega = 2\pi f = \frac{qB}{\gamma m_0} \]

• Mitigate by:
  
  – Changing frequency during acceleration → Synchrocyclotron
  
  – Changing B-field with radius (increase with radius, opposite of weak focusing) → Isochronous (or AVF) machine
Synchrocyclotrons

- 184” Berkeley cyclotron by Lawrence was first synchrocyclotron
- Weak focusing, but no longer cw operated!
- Change frequency during acceleration of essentially one bunch at a time

Figures from: IBA S2C2 Synchrocyclotron Report
Isochronous Cyclotrons

- AVF (Azimuthally Varying Field) → Hills/Valleys
- Edge focusing
- Either compact (single coil) or ring type
- Double gap cavities
- Higher harmonic modes
Cyclotrons 101
$V_{\text{Dee}} = 100 \text{ kV}$

$V_{\text{dee}} (t) = \text{const.}$
Cyclotrons 101

\[ V_{\text{Dee}} = 70 \text{ kV} \]

\[ V_{\text{dee}}(t) = \]

\[ V_{\text{Dee}} = 70 \text{ kV} \]
Cyclotrons 101

\[ V_{\text{Dee}} = -70 \text{ kV} \]

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Cyclotrons 101

$V_{\text{Dee}} = 70 \text{ kV}$

$V_{\text{dee}}(t) =$
Phase Stability

• What if particle comes in slightly off-phase (B-field errors, relativistic kinematics, bunch length, energy spread)?

\[ V_{\text{dee}}(t) = \]

![Graph showing phase stability](image)
Phase Stability

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\[ V_{\text{dee}}(t) = \]

![Diagram showing voltage over time with a particle slightly off-phase](image)
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- Run at shifted phase \( \Phi_s \sim 60^\circ \) (synchronous phase)

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Phase Stability

• What if particle comes in slightly off-phase (B-field errors, relativistic kinematics, bunch length, energy spread)?

• Run at shifted phase $\Phi_S \sim 60^\circ$ (synchronous phase)

• Phase Stability: particles near the synchronous particle in $\Phi_S & E$ stay near the synchronous particle in $\Phi_S & E$. 

$V_{\text{dee}}(t) =$
• Synchronous particle is on equilibrium orbit. Other particles (slightly offset) oscillate around this orbit. → Radially and Vertically

• (cf. Lecture on accelerators by Elke Aschenauer)

• Example: Synchrocyclotron →
Resonances - Synchrocyclotron
Beam injection

• Simplest way: Don’t inject. (Internal sources, H+, H-, deuterons, He-3, He-4)

• Radial injection (almost exclusively separated sector machines, ring cyclotrons)

• Axial Injection:
  – Spiral Inflector
    • Mirror Inflector

Figure: D. Winklehner

Figure: W. Kleeven

Ground Electrode

HV Electrode

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Beam extraction

- Simplest way: Don’t extract. (internal target) – Earliest cyclotrons
- Still, need to increase turn separation at the end:
  - Increase Dee voltage
  - Excite resonance (typically precessional or regenerative, both \( \nu = 1 \), but…)
- Extract once turn separation is large enough:
  - Septum (electrostatic, RF pulsed)
  - Self extracting
- Once orbit is right, need extraction channel
- Or stripping extraction (H2+, H-)!
IBA compact self-extracting cyclotron

Figure: W. Kleeven
Vortex Motion for High Space Charge

The combination of non-linear space charge forces (outwards) and alternating gradient focusing (inwards) curls beam up into a almost perfect circle (horizontal plane)

Simulation of PSI Injector 2: JJ. Yang

Simulation of proposed IsoDAR cyclotron: JJ. Yang
Short break (building RIKEN SRC)
Act II

CURRENT MACHINES

PSI 590 MeV Ring Cyclotron, Source: www.psi.ch
Cyclotron advantages

- Clearly, cyclotrons are not at the high energy frontier (anymore). However, they have certain attractive qualities:
  - Well-understood
  - Comparably cheap
  - Can be very compact
  - Can deliver fairly high cw beam currents (PSI: 2.2 mA protons)

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• Still used very successfully for:
  – Medical isotope production (PET)
  – Cancer therapy (Bragg-peak, p, carbon)
  – Nuclear physics
  – Education
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A selection of facilities using cyclotrons

• Mostly for Rare/Radioactive Isotope Experiments
  – ISOL
  – Fragmentation/In-flight separation
• Also: n, μ production
• All need driver beams
• Examples:
  – PSI
  – RIKEN
  – TRIUMF
  – NSCL
Overview PSI Facility

PSI

Injector II Cyclotron 72 MeV
isotope production
\( I_b < 100 \mu A \)

Ring Cyclotron 590 MeV
2.2 mA /1.3 MW
target M (d = 5mm)
target E (d = 4cm)

proton therapie center
[250 MeV sc. cyclotron]

Cockcroft Walton
870 keV transfer channel
72 MeV transfer channel
\( \mu/\pi \) secondary beamlines

1.5 mA /0.9 MW
CW operation

SINQ
spallation source

SINQ transfer channel

SINQ experiments

[Markus Lüthy]
Paul Scherrer Institut (PSI) - Machines

CW Acceleration using a Sector Cyclotron

590 MeV Ring Cyclotron
(magnets) in operation for 30+ years

- 8 Sector Magnets
- Magnet weight
- 4 Accelerator Cavities 850kV (1.2MV)
- Accelerator frequency
- harmonic number
- beam energy
- beam current max.
- extraction orbit radius
- relative Losses @ 2mA
- transmitted power

1 T
~250 tons
72 → 590MeV
50.63 MHz
6
72 → 590MeV
2.2 mA
4.5m
~1.2·10⁻⁴
0.26-0.39 MW/Res.

Pro: Con:
- CW operation is inherently stable - inj./extr. difficult, interruptions, losses!
- efficient power transfer with only 4 resonators - large and heavy magnets (therm. equilibrium!)
- cost effective, compact - energy limited ~1GeV
- no pulsed stress in target [- no pulsed structure for neutrons]

Paul Scherrer Institut (PSI) - Science

- Science:
  - Neutron production (SINQ) for n scattering and imaging of molecules and atoms
  - Muon production (SμS): Muon Spin Rotation, Relaxation or Resonance: A research tool using muons as sensitive local magnetic probes in matter.

Research at the LMU focuses mainly on magnetic properties of materials and on positive muons or muonium (bound state of a positive muon and an electron) as light protons or hydrogen substitutes in matter.
RIKEN - Machines

- RIBF at the Nishina Center
- 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions.

Image credit: nishina.riken.jp
• RIPS is an in-flight type radioactive isotope (RI) separator to produce intense RI beams via the projectile fragmentation of stable ions or the in-flight fission of uranium ions.

• Map out isotope chart, discover new elements and isotopes.

• 2004: Element 113 discovery.

• 2009: at RIBF, polarized deuteron beams are accelerated up to 440A MeV in the AVF-RRC-SRC acceleration mode.

• Three Nucleon Force Study via Few Nucleon Systems

• BigRIPS – large acceptance in-flight RI separator
TRIUMF - Machines

- 500 MeV proton cyclotron (accelerate H-, extract by stripping)
- Bombard suitable target, extract rare isotopes and re-accelerate
• Isotope Separation and Acceleration (ISAC) → linear accelerator post-accelerates separated isotopes

• Science:
  – Nuclear structure
  – Nuclear astrophysics
  – Fundamental symmetries
NSCL - Machines

• 2000: Coupled Cyclotron Facility starts producing beam (before only separately)

• Beam is created in ECR ion sources (SuSI and Artemis)

• K-500/K-1200: compact superconducting isochronous cyclotrons
NSCL - Science

- Fragmentation of heavy ions impinging on a thin beryllium foil
- A1900 mass spectrometer separates rare isotopes for use in experiments.
- Science:
  - Study of nuclei with extreme neutron excess
  - Quark-Gluon Plasma
  - Nuclear Astrophysics (low energy area)
  - Fundamental Symmetries

- Outlook: Construction of FRIB underway (replace cycl. with linac)
FUTURE CONCEPTS

Proposed design of a 6-sector cyclotron for the DAEδALUS experiment. Source: The DAEδALUS collaboration
Cyclotron Advantages

• Clearly, cyclotrons are not at the high energy frontier (anymore). However, they have certain attractive qualities:
  – Well-understood
  – Comparably cheap
  – Can be very compact
  – Can deliver fairly high cw beam currents (PSI: 2.2 mA protons)

• New developments:
  – Push intensity limits!
  – Lighter, more compact…Ironless?
  – Decelerator.
Cyclotron Advantages

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• New developments:
  – Push intensity limits!
  – Lighter, more compact…Ironless?
  – Decelerator.
Why push intensity?

- Many experiments benefit from higher statistics. Higher current: Run shorter time with more particles, get better results earlier 😊

- Other processes can only be sustained with a certain influx of particles (e.g. accelerator driven subcritical reactors - ADS)

- Efficiency: More particles from one accelerator → more isotope production for medical purposes (run several targets off one accelerator)

- PSI Ring has demonstrated > 2.2 mA cw proton beams.

- Neutrino and Dark Matter group here at MIT is proposing an experiment to measure CP violation (see Neutrino talk next week), calls for 10 mA of protons… possible? See next slides…
**DAEδALUS Neutrino Production**

- Use Pion/Muon decay-at-rest induced by 800 MeV protons for neutrino production, virtually free of $\bar{\nu}_e$
- Use inverse beta decay (IBD) to measure $\bar{\nu}_e$ appearance
- Need detector with large number of protons (free hydrogen): Scintillator or Gd doped water Cherenkov detector

![Diagram of neutrino interactions]

**Graph:***
- $\nu_e$ and $\nu_\mu$ fluxes as a function of energy [MeV].
- $\nu_e$ and $\nu_\mu$ peaks at different energies. 

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DAEδALUS – Three Accelerator Concept

- Constrains Initial flux
- Constrains rise of probability wave
- Osc. maximum at ~40 MeV

Near-site Accelerator Module, up to 1.5km, 0.8 MW
Mid-site Accelerator Module, 8km, 1.6 MW
Far-site Accelerator Module, 20km, 4.8 MW

Underground detector: Gd-doped water Or Liquid scintillator
How to provide the 800 MeV protons?

DAEδALUS

DSRC

Ion Source

LEBT

DIC

Target

800 MeV/amu

60 MeV/amu

not to scale
The 4 Phases of DAEδALUS

<table>
<thead>
<tr>
<th>Phase</th>
<th>Producers and Activities</th>
<th>Location/Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Produce 50 mA H$_2^+$ source, inflect, capture 5 mA and accelerate</td>
<td>BCS Inc. Teststand, Experiment at INFN-LNS Catania</td>
</tr>
<tr>
<td>II</td>
<td>Design and build DIC, extract, produce antinu flux via $^8$Li</td>
<td>WATCHMAN, KamLAND, JUNO</td>
</tr>
<tr>
<td>III</td>
<td>Build first DSRC, Run as a “near accel.” at existing large detector</td>
<td>NOvA, LENA, Super K</td>
</tr>
<tr>
<td>IV</td>
<td>Build the high power DSRC, Construct DAEδALUS</td>
<td>JUNO HyperK, LENA</td>
</tr>
</tbody>
</table>

We are here

Accelerator Science
SBL $\bar{\nu}_e$ physics
SBL $\bar{\nu}_\mu$ physics
Can we use the injector cyclotron alone?

**DAEδALUS**

- **DSRC**
- **Ion Source**
- **LEBT**
- **DIC**

- **Target**
- **800 MeV/amu**
- **60 MeV/amu**

Not to scale
Can we use the injector cyclotron alone?

DAEδALUS

DSRC

Target

800 MeV/amu

IsoDAR

Ion Source

LEBT

DIC

60 MeV/amu

not to scale
IsoDAR Production

- Use beta-decay-at-rest induced by 60 MeV protons to produce very pure $\bar{\nu}_e$ beam

  Proton beam $\rightarrow ^9\text{Be} \rightarrow n \rightarrow \text{captures on } ^7\text{Li} \rightarrow ^8\text{Li} \rightarrow \bar{\nu}_e$

- Measure $\bar{\nu}_e$ disappearance through inverse beta decay.

- Low energy, very short baseline.
IsoDAR: Measure $\bar{\nu}_e$ Disappearance

Search for oscillations at short distances and low energy.

1 kton detector

(3+1) Model with $\Delta m^2 = 1.0 \text{ eV}^2$ and $\sin^2 2\theta = 0.1$

Proton beam

$^7\text{Li} (99.99\%)$ sleeve

$^9\text{Be}$ target surrounded by $\text{D}_2\text{O}$

16.5 m
• Acts defocusing on the beam
Space Charge Potential

• Space charge potential of a uniform and round beam with beam radius $r_b$ in a grounded beam pipe $r_p$:

$$
\phi(r) = \begin{cases} 
\Delta \phi \left( 1 + 2 \ln \frac{r_p}{r_b} - \frac{r^2}{r_b^2} \right) & \text{for } r \leq r_b \\
\Delta \phi \cdot 2 \ln \frac{r_p}{r} & \text{for } r_b \leq r \leq r_p 
\end{cases}
$$

$$
\Delta \phi = \frac{I}{4\pi \varepsilon_0 v_b}
$$

![Graph showing potential and electric field vs. radius](image-url)
Spiral Inflector

- Takes the beam from axial direction to horizontal plane
- No SCC
- Complicated Boundary Conditions
Other Problem: Extraction

- “Classical“ with Septum
- Requires extreme beam stability
- Very good turn separation
- Need to play with resonance to increase turn separation
- PSI (2.2 mA) has 99.98% efficiency, still loses 200 W of beam on septum
- Upper limit for hands-on maintenance (activation)
- No good for 10 mA beam
Accelerate $\text{H}_2^+$

- 2 protons for each charge state
- Reduces Space Charge in LEBT and Spiral Inflector
- Can do stripping extraction in Superconducting Ring Cyclotron for DAEδALUS

Challenges:
- Ion Source? Microwave or Multicusp
- Vibrational States
Why Ironless?

• It is very important to be able to select the particle energy to determine the depth of the Bragg peak

• This is usually done with degraders. Wedges that are inserted in the beam path. Messy.

• The connection of the gantry to the main beam line has to be rotatable, what if we can put the cyclotron on the gantry and move it together? But: Iron is heavy.

• Ironless Cyclotrons would be energy scalable!

• Much lighter!

• Ongoing research at MIT – Plasma Science and Fusion Center
Synchrocyclotron Coils

- Main Field Coils + Shaping Coils + Compensation Coils
Extraction, The $v_r = 2/2$ resonance

- Dee voltage in a synchrocyclotron is typically 2-5 kV. That means acceleration is slow and turn separation is tiny.

- How do we get the beam out?

- If things go in circles… Resonances! Usually something we would like to avoid, but in this case we can use it.

- Use second order resonance $v_r = 2/2$ by introducing a field bump that increases linearly radially outwards.

- How? Coils. No iron, no permanent magnets because it needs to be scalable with final particle energy (70 – 230 MeV)
Harmonic Oscillation around $r_0$ with $v_r < 1$, $r_0 = 45$ cm
Task is to bring $v_r = 1$ and excite oscillation amplitude.
Latest Coil Model - Top View
Main Field (230 MeV Field) – Option ab7a
Magnetic Septum (230 MeV Field)
Tracking and Extraction 230 MeV
Possible Cryostat and Support Design
The NSCL Cyclotron Gas Stopper

Why, What, Status & Low-energy transport

Cyclotron-Stopper

Carpets

Conveyor

NSCL

Slide Credit: Stefan Schwarz, NSCL
Why slow down beams at the NSCL?

NSCL: User facility, RIB production by projectile fragmentation and fission, **fast beams**

- LEBIT facility for Penning trap mass spectrometry of projectile fragments
- BECOLA: laser spectroscopy coming online

**Re-accelerator ReA**, new science opportunities with rare isotopes from projectile fragmentation
- Nuclear astrophysics: key reactions at near-stellar energies
- Nuclear structure via Coulomb excitation or transfer reactions

**FRIB**: fast, **stopped and reaccelerated beams**

> 1000 RIBs made
> 80% RIBs used in experiments
From fast to not-so-fast

‘Stopped beam’ area:
60 keV, 1+

LEBIT

EBIT: 1+ → n+, 12 keV/u

ReA3
3 MeV/u and more

'Stopped beam' area:

120 MeV/u Fully stripped

Beam stopping vault

A1900

LINAC

Slide Credit: Stefan Schwarz, NSCL
Complementary stopper options:

- **Solid stopper**: Future option for special elements and very high beam rates
  Example: $^{15}$O, $I > 10^{10}$/s

**Linear gas stopper (v2/v3)**
- Low-pressure with RF carpets / wires
- ANL gas cell / Cryogenic gas cell

**Cyclotron stopper**
- Cyclotron-type magnet
- Low-pressure + RF ion guiding
  → *Light ions*

Slide Credit: Stefan Schwarz, NSCL
Cyclotron stopper – the idea

1 Confine:
- Magnetic field, <2.6 T
  - ‘wind up’ trajectory in central chamber
    → confinement in radial direction
- Cyclotron-type sector field:
  → axial focusing

2 Thermalize:
- Low-pressure gas in cryogenic chamber
  ions lose energy, spiral towards center

3 Extract:
- Use HF/RF ion guiding techniques
  to move thermalized ions to center and out
  within a few 10 ms

Origins:
- Proposal to stop lighter ions: I. Katayama et al., HI 115 (1998) 165

NSCL-Cyc-stopper:
- Bollen et al. NIM A550 (2005) 27, NIM B266 (2008) 4442,

Path length for ions into 100mbar of He (B₀ =1.6 Tm)
- Energized to nominal field at 180A / 2.6T max
- Measured profiles agree with expectations
  → Important for efficient stopping!
Fast ion extraction

**Ion transport to center:**
- Large **RF ion carpet**, ~1m diameter
- 6-fold segmented (C, size limitations)
- ‘Surfing’ technique

**Ion extraction through axial hole on fixed side:**
- RFQ ion guide + B-field = bad
  ➔ Use **ion conveyor**
‘Surfing’ RF carpet:
- Push field → move ions to carpet
- Electrode stripes with RF → keep ions above carpet
- **Low-frequency electric wave** moves ions along carpet

Effective potential with moving buckets

Trajectory:

References:
G. Bollen, IJMS 299 (2011),131
S. Schwarz, IJMS 299 (2011),71
M. Brodeur et al., IJMS 336 (2013) 53
A. Gehring, PhD thesis 2013

*Slide Credit: Stefan Schwarz, NSCL*
**Carpets:**
- 6 segments, pitch ~0.47 mm, Kapton backed, radius: 42 cm.
- 6 ‘vacuum-compatible’ RF resonant circuits
- 3 pockets fit in pole valleys, → RF circuits accessible, but hidden from high-energy beam
- HF: a few 10 kHz, a few V
- RF load: 4 nF each
- RF/HF cabling: Kapton isolated
- Support structure: PEEK
- Push field: segmented plate on lid

**RF tests:**
- Two carpets set up: 7.5 / 8.4 MHz
- At ~60 Vpp, need about 16-20 W per carpet.

**Ion tests:**
- Use degrader drive to move ion source across carpet
- To start ... after this workshop
Status

Magnet:
- tested to full field

Stopped-ion transport:
- stopping chamber in place,
  initial pressure tests at RT passed
- 90° prototype RF carpets tested
- 60° RF carpets: Electronics working
- Conveyor: Offline tests promising

Next:
- Install carpet + conveyor
- Test ion transport with magnetic field
- Cool chamber with LN

Move to dedicated vault: 2018?

G. Bollen, M. Brodeur, M. Gehring, K. Lund, N. S. Joshi, C. Magsig, D. J. Morrissey,
J. Ottarson, SCS, S. Chouhan, J. DeKamp, J. Ottarson, A. Zeller … and many more!

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Conclusion – Take Home Message

• Cyclotrons brought us a long way in the early days by overcoming the limitations of linear electrostatic accelerators.

• They are ultimately limited by relativistic mass increase, even though to a certain extent this can be mitigated by ramping the RF frequency or radially changing the B-field.

• Main usage nowadays is in medical isotope production and cancer therapy, but

• There are a number of facilities world-wide using cyclotrons for nuclear physics (rare/radioactive isotope facilities)

• There are interesting ideas for future cyclotron development/usage that go beyond the state-of-the-art (neutrino physics, ADS, ironless cyclotrons, cyclotron gas stopper)
Thank you for your attention!

QUESTIONS?