Outline

- Accelerator frontiers and power-frontier accelerators
- Applications of high-power accelerators
- Main parameters of circular high-power accelerators
- Design philosophy of high-power accelerators
- Performance limiting topics of high power circular accelerators
- Major systems of high power circular accelerators
- Examples of high-power circular accelerators
- Summary

- Homework
Accelerator frontiers and Power-frontier accelerators
Accelerator Frontiers

- Energy/luminosity frontier
  - Ring based:
    » Large Hadron Collider (LHC); Relativistic Heavy Ion Collider (RHIC) …
  - Linac based
    » Stanford Linear Collider (SLC); International Linear Collider (ILC) …

- Brightness/coherence frontier

- Power/intensity frontier
Colliders
• Higher center-of-mass energy can be achieved than with fixed target accelerators)

Hadron versus electron colliders
• Hadrons are “complex” but they reach higher energy
  » E.g. LHC, RHIC, TEVATRON …
• Electrons are “cleaner” but due to synchrotron radiation they cannot reach too high energy)
  » E.g. CESR, LEP, BEPC, KEK-B …

Circular versus linear colliders
• Circular accelerators are more efficient to accelerate, but at very high energy there is synchrotron radiation
  » E.g. all electron/positron rings and hadron rings like LHC and FCC
• Electrons in particular prefer linear accelerator to reach high energy
  » E.g. ILC

Combination of ring/linac; hadron/lepton
 » e-RHIC, linac-ring and ring-ring proposals
Accelerators for Discovery Science [1]
Large Hadron Collider (LHC, CERN)

- Circumference 27 km; energy 2 \times 7 \text{ TeV}; cost \sim \text{\(€6B \) Euro}
Inside Large Hadron Collider: Accelerator

- Tunnel ~ 175 m underground; 1,232 dipoles running at 1.9 K for 8.3 T
Inside Large hadron Collider: Detector

- Massive and complex detectors to probe Higgs Particle
Accelerators for Discovery Science [2]
Relativistic Heavy Ion Collider (RHIC, BNL)

- 3.8 km circumference; Au^{79+} 100 GeV/u; cost ~ $1B
Accelerator Frontiers

- **Energy/luminosity frontier**
  - Ring based:
    » Large Hadron Collider (LHC); Relativistic Heavy Ion Collider (RHIC) …
  - Linac based
    » Stanford Linear Collider (SLC); International Linear Collider (ILC) …

- **Brightness/coherence frontier**
  - Ring based:
    » National Synchrotron Light Source (NSLS-II)
  - Linac based:
    » Linear Coherent Light Source (LCLS-II)

- **Power/intensity frontier**
  - Ring based:
    » Spallation Neutron Source (SNS); Japan Particle Accelerator Research Center (J-PARC)
  - Linac based
    » Facility for Rare Isotope Beams (FRIB)
Power and Intensity Frontier Accelerators
Example of High-power Accelerator Pioneer
ISIS Neutron Source (with DIAMOND Light Source)

- Complementing spallation neutron source and synchrotron light source
ISIS Neutron Source Target Station

- W target station; serving 700 experiments and 1700 users annually
Fixed target accelerators

Cyclotron and linac based: continuous wave beam
- Cyclotrons have fixed output energies; cost efficient for modest energy
  » E.g. NSCL, PSI, TRIUMF …
- Linacs are more flexible; easier to extend to higher energy
  » E.g. LANSCE, FRIB, ESS …

Linac and ring based: pulsed beam upon “compression” by ring
- Partial-energy linac plus synchrotron: easier to extend to higher energy
  » E.g. ISIS, J-PARC, CSNS …
- Full-energy linac plus accumulator: easier to control beam loss
  » E.g. PSR, SNS …

Electron, proton, and heavy ion accelerators
- Usually accelerator complexity increases with heavier particles
Applications of high-power accelerators
Areas of Accelerator Applications

- Accelerators for discovery science
- Accelerators based platforms for scientific and industrial users
- Accelerators for environment and energy
- Accelerators for medicine
- Accelerators for security and defense
- Accelerators for industry
Accelerator Power and Intensity Frontier

- **High energy, nuclear physics** ($\nu$, K factories)
  - 1 ~ 400 GeV proton
  - Linac + Synchrotron

- **Material, life science, (SNS)** accelerator-driven subcritical systems (ADS)
  - 0.5 ~ 3 GeV proton
  - Cyclotron, linac, rapid cycling synchrotron, accumulator

- **Rare isotope beams (RIB)**
  - 0.01 ~ 1 GeV/u heavy ion
  - Linac, cyclotron, synchrotron

- **Material irradiation; isotope**
  - ~0.02 GeV/u deuteron; linac
Accelerators for Discovery Science
J-PARC Main Ring (KEK/JAEA)

- 400 MeV linac; 3 GeV rapid cycling synchrotron; 30 GeV synchrotron main ring
- 1 MW proton beam
Accelerators-based Platforms for Users: Spallation Neutron Source (ORNL)

- 1 GeV linac; accumulator ring; liquid Hg target; 1 MW proton power
Accelerators for Environment and Energy
China Initiative Accelerator Driven Subcritical Project (CAS)

- **Waste burner**: accelerated protons produce neutrons (spallation process), which converts long-lifetime nuclear waste to short lifetime ones (transmutation process)

- **Energy amplifier**: accelerated protons produce neutrons, which burns thorium to generate electricity (instead of burning uranium in reactors)

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China Initiative Accelerator Driven Subcritical Project

![Diagram of the project phases](Attached Diagram)

- **1st Phase (2022)**: Theory proof (250 MeV, 10 mA, 10 MWt)
- **2nd Phase (2030)**: (1.0 GeV, 10 mA, 500 MWt)
- **3rd Phase (2040)**: (1.5~2.0 GeV, 10~25 mA, 1000 MWt)
Accelerators for Medicine
Heavy Ion Medical Accelerator in Chiba (HIMAC)

- Use carbon beam (450 MeV/u) to treat cancer minimizing side effects
Accelerators for Security and Defense
Commercial Cargo Inspection Accelerator

- Truck-based electron linear accelerator for X-ray imaging
Accelerators for Industry
Electron Beam Welder

J. Wei, 2018 PHY862, MSU
Main parameters of circular high-power accelerators
Main Parameters

- Beam power
- Ion species
- Kinetic energy
- Type of accelerators
- Time structure
- Repetition rate
- Intensity and bunching factor
- Bunch length
- Emittance
- Parameter evolution
### Example: Primary SNS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam power on target</td>
<td>1.4 MW</td>
</tr>
<tr>
<td>Proton beam kinetic energy on target</td>
<td>1.0 GeV</td>
</tr>
<tr>
<td>Average beam current on target</td>
<td>1.4 mA</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Protons per pulse on target</td>
<td>$1.5 \times 10^{14}$ protons</td>
</tr>
<tr>
<td>Charge per pulse on target</td>
<td>24 µC</td>
</tr>
<tr>
<td>Energy per pulse on target</td>
<td>24 kJ</td>
</tr>
<tr>
<td>Proton pulse length on target</td>
<td>695 ns</td>
</tr>
<tr>
<td>Ion type (Front end, Linac, HEBT)</td>
<td>H minus</td>
</tr>
<tr>
<td>Average linac macropulse H- current</td>
<td>26 mA</td>
</tr>
<tr>
<td>Linac beam macropulse duty factor</td>
<td>6 %</td>
</tr>
<tr>
<td>Front end length</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Linac length</td>
<td>331 m</td>
</tr>
<tr>
<td>HEBT length</td>
<td>170 m</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>248 m</td>
</tr>
<tr>
<td>RTBT length</td>
<td>150 m</td>
</tr>
<tr>
<td>Ion type (Ring, RTBT, Target)</td>
<td>proton</td>
</tr>
<tr>
<td>Ring filling time</td>
<td>1.0 ms</td>
</tr>
<tr>
<td>Ring revolution frequency</td>
<td>1.058 MHz</td>
</tr>
<tr>
<td>Number of injected turns</td>
<td>1060</td>
</tr>
<tr>
<td>Ring filling fraction</td>
<td>68 %</td>
</tr>
<tr>
<td>Ring extraction beam gap</td>
<td>250 ns</td>
</tr>
<tr>
<td>Maximum uncontrolled beam loss</td>
<td>1 W/m</td>
</tr>
<tr>
<td>Target material</td>
<td>Hg</td>
</tr>
<tr>
<td>Number of ambient / cold moderators</td>
<td>1/3</td>
</tr>
<tr>
<td>Number of neutron beam shutters</td>
<td>18</td>
</tr>
<tr>
<td>Initial number of instruments</td>
<td>5</td>
</tr>
</tbody>
</table>

J. Wei, 2018 PHY862, MSU27
Beam Power

- User demands secondary beams: photons, neutrons, rare isotopes, ...
- Productivity of secondary beams is typically proportional to the primary beam power

\[
\langle P \rangle = E_k \langle I \rangle
\]

- kinetic energy
- average current

\[
\langle I \rangle = f_N N_p e
\]

- Repetition rate
- Number of particles per pulse

- For high power:
  - Raise energy
  - Raise repetition rate,
  - Raise pulse intensity

---

Cylindrical Tungsten Target (10 cm diam by 200 cm long) Bombarded on Axis by a Point Source of Protons

![Diagram showing neutron production vs. proton energy](image.png)

Figure 8. Production of low-energy (o) and high-energy (\(\bullet\)) neutrons for a cylindrical tungsten target (10-cm diam by 200-cm length). The length of 200 cm was arbitrarily chosen and was long enough to range out 2000-MeV protons.
Ion species are also dictated by facility mission goals

- **Scientific user demands**
  - Neutron sources prefer protons for high yield of spallation process
  - FRIB prefer heavy ions for rare isotope production via fragment separations
  - RHIC’s focus on heavy ions for nuclear physics discoveries

- **Industrial user demands**
  - Isotope harvesting needs to use specific primary beams as drivers
  - Irradiation facilities can use either heavy ion (higher impact factor) or proton

Many high power facilities use proton beams striking targets

- **Powerful ion source**
- **Relatively straightforward to reach high energy**
  - Typically negligible synchrotron radiation (except cases like LHC)

Circular proton facilities often start with H⁻ beam from the ion source to facilitate multi-turn charge-exchange injection into the ring
Kinetic Energy

- Range largely determined by applications & experiments
  - E.g. 0.5 – 5 GeV for neutron spallation

- Within a given range, a higher output energy implies
  - a higher output beam power, relatively “cheap” to achieve for a RCS (linearly proportional)
  - alleviated heating on target due to longer stopping length
  - higher magnet field, higher ramping power, more difficult field quality control

- A higher injection energy implies
  - reduced space-charge effects due to electro-magnetic force cancellation
  - more probably magnetic stripping demanding lower field, longer magnet, more injection space
  - higher cost of the injector accelerator
Types of Accelerators
Continuous Wave versus Pulsed Beams

- (a) and (b): Coasting beam; (c) and (d): pulsed beam
- Macro-pulse: time structure that users care about
- Mini-pulse: time structure that matches circular accelerator circumference
- Micro-pulse: time structure determined by the injection linac accelerating system
Repetition Rate

- Requirements from the user / target: 10 – 60 Hz
  - Time resolution & power per pulse needs -> lower rate
  - Total beam power -> higher rate

- Rapid-cycling synchrotrons: sensitive to repetition rate
  - Demands a strong power supply
  - Demands a high radio-frequency (RF) voltage
  - Demands RF shielding to avoid heating on vacuum chamber while allowing image charge to circulate (impedance control)
  - Demands lamination to avoid heating in magnets

- Accumulator rings: less sensitive comparing with RCS
  - More demanding on the pre-injector (ion source output, linac klystron power …)
  - Higher injection energy, lower extraction energy
  - Higher ring intensity (instabilities) and beam loading
Pulse Intensity; Bunching Factor

- Proportional to output beam power – as high as possible
- Usually limited by space charge constraints, instability threshold, instability growth
- Ring average current
  \[ \bar{I} = Nef_s \]
- Ring peak current
  - Parabolic: \[ \hat{I} = \frac{3\pi}{2\phi} \bar{I} \]
  - Gaussian: \[ \hat{I} = \frac{1}{\sqrt{2\pi}\sigma}\bar{I} \]
- Bunching factor
  \[ B = \frac{\bar{I}}{\hat{I}} \leq 1 \]
  - Parabolic: \[ B = \frac{C - L_{gap}}{C} \]
  - Gaussian: \[ B \approx \frac{\sqrt{2\pi}}{6} \approx 0.42 \]
  Empirically: \(~0.5\) (accumulator); \(~0.35\) (RCS)
Bunch Length

- Range largely determined by applications & experiments
  - E.g. ~ 1 ns for neutrino factory proton drivers
  - Spallation neutron: not sensitive to bunch length as long as there is adequate spacing between pulses

- Choice of Radio Frequency accelerating system
  - Hardware availability considering wide RF frequency sweep
  - Consideration of possible coupled-bunch instability
  - Needs for a clean beam gap for extraction
    » For low harmonic: control bunch area/bucket area ratio
    » For high harmonic: missing bunches
Emittances

- **Transverse emittance**
  
  constant of acceleration: \( \int x dp_x \) \( p_x \sim \beta \gamma x' \)

  - Preservation of normalized emittance often needed for downstream applications; damping is not practical
  - Controlled emittance enlargement is usually used to alleviate space-charge effects
  - Constraints from magnet aperture and power supply

- **Longitudinal emittance**

  constant of acceleration: \( \int \phi dW \)

  \( W \equiv \frac{\Delta E}{h \omega_s} ; \quad \frac{\Delta E}{E} = \beta^2 \frac{\Delta p}{p} \)

  - Often limited by the available momentum acceptance
  - Controlled emittance enlargement is usually used to alleviate collective instabilities
  - Constraints from aperture at dispersive bending region
### Example: SNS Beam Evolution Parameters

<table>
<thead>
<tr>
<th></th>
<th>Front End</th>
<th>Linac</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>IS/LEBT</td>
<td>RFQ</td>
<td>MEBT</td>
</tr>
<tr>
<td>Relativistic factor β</td>
<td>0.0118</td>
<td>0.0728</td>
<td>0.0728</td>
</tr>
<tr>
<td>Relativistic factor γ</td>
<td>1.00007</td>
<td>1.0027</td>
<td>1.0027</td>
</tr>
<tr>
<td>Peak current</td>
<td>47</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Minimum horizontal acceptance</td>
<td>250</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td>Output H emittance (unnorm., rms)</td>
<td>17</td>
<td>2.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Minimum vertical acceptance</td>
<td>51</td>
<td>42</td>
<td>18</td>
</tr>
<tr>
<td>Output V emittance (unnorm., rms)</td>
<td>17</td>
<td>2.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Minimum longitudinal acceptance</td>
<td>4.7E-05</td>
<td>2.4E-05</td>
<td>7.4E-05</td>
</tr>
<tr>
<td>Output longitudinal rms emittance</td>
<td>7.6E-07</td>
<td>1.0E-06</td>
<td>1.2E-06</td>
</tr>
<tr>
<td>Controlled beam loss; expected</td>
<td>0.05</td>
<td>N/A</td>
<td>0.2²</td>
</tr>
<tr>
<td>uncontrolled beam loss; expected</td>
<td>70</td>
<td>100²</td>
<td>2</td>
</tr>
<tr>
<td>Output H emittance (norm., rms)</td>
<td>0.2</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>Output V emittance (norm., rms)</td>
<td>0.2</td>
<td>0.21</td>
<td>0.27</td>
</tr>
</tbody>
</table>

**Note**
- a) corresponding to 27% chopped beam
- b) corresponding to 5% chopped beam
- c) beam loss on the transverse and momentum collimators
- d) including total 4% of beam escaping foil and 0.2% beam loss on collimators
- e) including 4% beam scattered on the target window
Design philosophy of high-power accelerators
Significance of Exposure to Radiation

- US occupational limit: 50 mSv per year
- DOE laboratory guideline: 12.5 mSv per year
- Hands-on maintenance:
  - 1 mSv/hour
  - 50 hours of work per year

(1 Sv = 100 Rem)

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 Sv</td>
<td>50% chance of survival</td>
</tr>
<tr>
<td>&gt; Sv</td>
<td>Serious to lethal</td>
</tr>
<tr>
<td>&gt; 50 mSv</td>
<td>Requiring medical checks</td>
</tr>
<tr>
<td>50 mSv.y⁻¹</td>
<td>Occupational dose limit</td>
</tr>
<tr>
<td>15 – 50 mSv.y⁻¹</td>
<td>Strict dose control necessary</td>
</tr>
<tr>
<td>5 - 15 mSv.y⁻¹</td>
<td>Professional exposure</td>
</tr>
<tr>
<td>&lt; 5 mSv.y⁻¹</td>
<td>Minimum control necessary</td>
</tr>
<tr>
<td>1 mSv.y⁻¹</td>
<td>Natural background</td>
</tr>
<tr>
<td>10 μSv.y⁻¹</td>
<td>Insignificant</td>
</tr>
</tbody>
</table>
Accelerator design that minimized uncontrolled beam losses

- Avoid high space-charge tune shift (0.25 or larger) at injection resulting (for resonance crossing)
- Allow adequate physical and momentum acceptance
- Avoid premature \( \text{H}^- \) and \( \text{H}^0 \) stripping and injection foil scattering
- Avoid large magnet field errors, misalignments and dipole-quadrupole matching errors during ramping
- Avoid instabilities (e.g. head-tail instability, coupled bunch instability, negative mass and microwave instability, electron cloud instability)
- Minimize accidental beam loss (ion source and linac malfunction, extraction kicker mis-fire etc.)

Beam collimation to reduce uncontrolled beam losses

- "Scarifies" shielded collimation area to reduce uncontrolled beam loss

Robustness in accelerator operations

- Operational flexibility and robustness
  - Tune adjustment; injection option; ramp-dependent correction; adjustable collimation; foil inter-change; spare interchange
- Engineering reliability and availability
  - Heat and radiation resistance; foil interchange mechanism; quick-disconnect flanges, crane
Performance limiting topics of high power circular accelerators
Performance Limiting Examples

- Beam Loss Control
- Space Charge
- Coupling Impedance
- Instabilities
- Multiple Charge State Acceleration
- Electron Cloud
Radio-activation & Beam Loss

- Hands-on maintenance: no more than 1 mSv/hour residual activation (4 h cool down, 30 cm from surface)
- ~ 1 Watt/m uncontrolled beam loss
- ~ $10^{-6}$ beam loss per tunnel meter at 1 MW operation
- < $10^{-4}$ beam loss in a 200 m accumulator; ~ $10^{-3}$ in a 200 m rapid cycling synchrotron
Space Charge
Performance Limiting for Low-energy Linac and Rings

- Linac: halo generated through core-halo parametric resonance; resonances between transverse longitudinal motion
- Ring: resonances & halo excited by lattice nonlinearity in the presence of space charge induced tune spread

Tune footprint along the four IFMIF cryomodules superimposed to the Hofmann chart
Courtesy P.A.P. Nghiem et al

Vertical emittance growth due to space charge in SNS ring. Courtesy A. Fedotov et al
### Table V. Estimated beam coupling impedance of the SNS accumulator ring at frequency below 10 MHz. The beam revolution frequency is 1.058 MHz. The leading impedance source contributing to possible instability is the extraction kicker modules located inside the beam vacuum pipe (Sec. IV.C.2).

| Device/Mechanism                  | $Z_{||}/n$ (Ω) | $Z_{\perp}$ (kΩ/m) | Comment                                      |
|----------------------------------|----------------|--------------------|----------------------------------------------|
| Space charge                     | $-j196$        | $j(-5.8+0.45)\times10^3$ | incoherent and coherent part                 |
| Extraction kicker                | $0.6n+j50$     | $33+j125$          | 25 Ω termination at PFN pipe coated; lowest tune at 200 Hz |
| Injection kicker & pipe          | $0.5/n$        | $17.5$             | MAFIA modeling to be damped                   |
| Injection foil assembly          | $j0.05$        | $j4.5$             |                                              |
| rf cavity                        | $0.9$ (resonance peak) | $18$              |                                              |
| Resistive wall                   | $(j+1)0.71$ at $\omega_0$ | $(j+1)8.5$ at $\omega_0$ |                                              |
| Broadband beam position monitor  | $j4$           | $j18$              | unscreened                                   |
| Broadband bellows                | $j1.1$         | $j7$               | tapered 1-to-3 ratio                         |
| Broadband steps                  | $j1.9$         | $j16$              | screened                                      |
| Broadband ports                  | $j0.49$        | $j4.4$             | unscreened                                    |
| Broadband valves                 | $j0.15$        | $j1.4$             |                                              |
| Broadband collimator             | $j0.22$        | $j2.0$             |                                              |
e-cloud: beam-induced multipacting

Long proton bunch (~170m)

Captured electron

Head of proton bunch: captures electrons

Tail of proton bunch: repels electrons

Repelled electron

Secondary electrons

Tertiary electrons....

Lost proton

e-

proton-electron yield

electron-electron yield

Vacuum Chamber Wall

(Wang, Blaskiewicz, Furman, Pivi, …)
Electron Cloud Performance Limiting for PSR But Not Yet for the SNS Ring

- Preventive measures are effective in the SNS ring suppressing electron generation and enhancing Landau damping.

BPM $\Delta V$ signal

CM42 (4.2 $\mu$C) (Circulating Beam Current)

SNS ring extraction kicker with patterned TiN coating

Courtesy: SNS / BNL
Major systems of high power circular accelerators
Major Systems

- Lattice and functional layout
- Magnet, power supply, vacuum
- Radio-frequency acceleration
- Injection and charge stripping
- Extraction
- Collimation system
- Loss detection and machine protection
- Personnel protection
- Transport lines
- Target and beam dump
Layout (Frozen Since Aug. 2000)
Accumulator Ring Layout
SNS AR Example

- No energy ramping
- Long straight-section, large aperture
  - Injection flexibility
  - Collimation efficiency
- Four straight-sections for four functions
  - Injection;
  - RF;
  - Collimation;
  - Extraction
  - (Diagnostics all-around)
- Dispersion-free straight sections
  - Decoupled H, V, L
Rapid Cycling Synchrotron Layout
J-PARC RCS Example

- Large amount of RF for acceleration
- Long straight-section, large aperture
- Collimation downstream of injection to catch lost beam
- Dispersion-free straight sections
  - Decoupled H, V, L
First find the strengths of the two arc quadrupole families to get an horizontal phase advance of $2\pi$ and using the vertical phase advance as a parameter.

Then match the straight section with arc by using the two doublet quadrupole families and the matching quad at the end of the arc in order to get the correct tune without exceeding the maximum beta function constraints.

Retune arc quads to get correct tunes.

Always keep beta, dispersion within acceptance range and quadrupole strength below design values.

![Graph showing the working point (6.40, 6.30) with beta functions $\beta_x$ and $\beta_y$.](image)
Example: Ring Lattice Magnets

- **FODO/Doublet (hybrid) lattice**
- **32 dipoles, 52 quadrupoles**
- **Chromatic correction with 20 arc sextupoles**
- **Orbit/coupling correction with correctors in the arcs**
- **Resonance correction in arc and straights**

Four-fold symmetry
Arc: four FODO cells
S.S.: doublets

FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

J. Wei, 2018 PHY862, MSU, Slide 54
Accumulator Ring Magnets
SNS AR Dipole and Corrector Examples

- Large beam chamber aperture for large beam admittance
- High field uniformity and low field errors \(10^{-4}\)
- Nonlinear magnetic corrections
- Solid core (no cycling)

SNS accumulator arc half cell under installation
Courtesy ORNL / SNS / BNL

Ring arc half cells installed in tunnel
Accumulator Ring Magnets
Quadrupole Magnet Examples

- Figure-of-eight narrow magnet for clearance at congested area
- Mineral insulated conductor for radiation resistant conditions near the neutron target
- Solid core (no cycling)
J-PARC Dipole Magnet Example

- Laminated steel, magnet end “cuts”, and special braided aluminum conductor to suppress eddy current due to rapid cycling
- Accurate dipole-quadrupole magnet power supply tracking
Vacuum

Example: J-PARC RCS Ceramic Chamber with RF Shields

- High repetition rate (eddy current)
- Large aperture
- Beam coupling impedance (RF shielding of beam image current)
- Electron cloud suppression (surface coating of TiN)
Radiofrequency Acceleration

- Wide frequency sweep range
- High repetition rate
  - High voltage, long space
  - Ferrite ~ 10 kV/m; magnetic alloy ~ 20 kV/m
- High-intensity beam loading
  - Feed-forward, dynamic tuning, feedback
Multi-turn Charge-exchange Injection

- Transverse and longitudinal painting
  - Chicane bump and painting bump
  - Large beam aperture, challenging power supply
- Tight space
  - Many elements in limited drift space
  - Magnet fringe field
- $H^-$ and $H^0$ stripping loss
  - Choice of magnetic field
- Stripping foil & shielding
3D Phase-space Painting

FIG. 26. (Color in online edition) Beam transverse profile of correlated bump painting used in charge-exchange injection into the SNS ring (Sec. III.C.4).

FIG. 28. (Color in online edition) Energy distribution at the injection foil, using either an energy spreader or a conventional debuncher. An energy spreader significantly suppresses the beam tail (Sec. III.C.4).
Extraction Kicker and Septum
Rise-time Minimization and Impedance Reduction

- Ferrite kicker inside vacuum pipe
- Optimize saturable inductor to effectively “shorten” rise time (200ns)
- Improved flat-top flatness (1%)
- PFN termination: lower impedance
- Increase magnet height to halve coupling impedance (same drive)
- Shield the terminating resistance, reducing cable reflection

Kicker waveform

Time (200 ns per box)
Beam Collimation
Halo & Beam Loss Control; Charge Selection

- Multi-step beam gap cleaning
  - LEBT chopping (25 ns)
  - MEBT chopping (10 ns)
  - Ring beam-in-gap cleaning

- Multi-step scraping & collimation
  - MEBT, HEBT, Ring, RTBT

- Phase space collimation in transport line

- Two-stage collimation in ring
Scraping in Beam Transport

- Normalized phase space

\[
X \equiv \frac{x}{\sqrt{\beta_x}} \quad X' \equiv \frac{dX}{d\mu} = \frac{\alpha_x x + \beta_x x'}{\sqrt{\beta_x}}
\]

- Two pairs of scrapers at \( \pi/2 \) betatron phase advance
  - Escaping radius at \( \sqrt{2} \) times scraper radius
  - Channel aperture needs to be larger than the escaping radius

\[
\mu(s) = \int_s^s \frac{ds'}{\beta(s')}
\]
Ring Multiple-stage Collimation

- Secondary back-off distance $H$ determined by a balanced consideration
  - Chamber aperture
  - Scraper adjustment range
  - Primary scattering performance

- Phase advance optimized to minimize escaping secondary

\[
\mu_1 = \cos^{-1}\left( \frac{A}{A+H} \right)
\]

\[
\mu_2 = \pi - \mu_1
\]
Secondary Collector Design

- Length enough to stop primary protons (~ 1 m for 1 GeV beam)
- Layered structure (stainless steel particle bed in borated water, stainless steel blocks) to shield the secondary (neutron, g)
- Fixed, enclosing elliptical-shaped wall for operational reliability
- Double-wall Inconel filled with He gas for leak detection
Loss Detection and Machine Protection
Multi-time Scale Mitigation Necessary

- Low-energy ions have low detection sensitivity & high impact
- Must mitigate both acute & chronic beam loss (by beam inhibition)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time</th>
<th>Detection</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPS</td>
<td>~ 35 μs</td>
<td>LLRF controller; Dipole current monitor; Differential BCM; Ion chamber monitor; Halo monitor ring; Fast neutron detector; Differential BPM</td>
<td>LEBT bend electrostatic deflector</td>
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<tr>
<td>RPS (1)</td>
<td>~ 100 ms</td>
<td>Vacuum status; Cryomodule status; Non-dipole PS; Quench signal</td>
<td>As above; ECR source HV</td>
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<tr>
<td>RPS (2)</td>
<td>&gt; 1 s</td>
<td>Thermo-sensor; Cryo. heater power</td>
<td>As above</td>
</tr>
</tbody>
</table>

- Halo monitor rings in development
- Differential BCM used
- Thermo-sensors considered
ACCUMULATOR RING

WS: 2
QMM: 2
BCM: 1
WCM: 1
Tune: 2
E-Det: 5
Damper kicker: 2
BIG: 1
IPM: 2
BPM:
  21cm: 28
  26cm: 8
  30cm: 8
BLM: 75
FBLM: 12
Foil Video: 2

Ring Diagnostics

Tune Kickers:
(1) QMM kicker (.75m, 20°), (1) Tune kicker (1.5m, 60°),
(2) Damper kickers (.5m, 60°)
Target
Stationary, Rotating and Liquid Targets

- Target is often the bottleneck to high power applications
  - Neutron production targets: absorbs most beam power to an enlarged area
  - RIB target (FRIB): ~25% power onto 1 mm
  - High energy targets: < 5% power absorbed
- Non-stationary targets more often used
  - Liquid:
    - SNS, J-PARC: Hg
    - SARAF, IFMIF: Li
    - MYRRHA: PbBe
  - Rotating
    - FRIB ...

FRIB rotating multi-slice graphite target
30 cm diameter, 5000 rpm
60 MW/cm³ if stationary
Radiation-resistant Magnets, Handling

- High radiation area near the target, collimator, beam dump require special attention

SNS RTBT mineral insulated radiation hardened magnets
Courtesy SNS / BNL

Remote water fitting
Courtesy SNS / BNL

Remote vacuum clamps
Courtesy SNS / BNL

High Temperature Superconducting warm iron quadruple for use behind FRiB production target.
Courtesy FRiB / BNL
Examples of high-power circular accelerators
Example 1: Spallation Neutron Source (SNS)
Example 1: Spallation Neutron Source (SNS)
SNS: A US$1.4B Construction Project

- Goal: single purpose, world’s most powerful spallation neutron source
- Multiple national laboratories competed for the project; six-laboratory (ANL, BNL, Jlab, LBNL, LANL, ORNL) partnership hosted by ORNL
- Major technical decisions during the construction
  - Changing from all room temperature to mostly superconducting RF linac
  - Keeping accumulator design after comparing with rapid cycling synchrotron
  - Keeping liquid mercury target design after pitting issue was discovered
- Operations start in 2006; it took 5 years to reach 1 MW and 8 years to reach 1.4 MW beam power (design capacity)
- Expanding users
## SNS Budget (2004)

<table>
<thead>
<tr>
<th>WBS</th>
<th>May 2004 Review EAC ($M)</th>
<th>Nov 2004 Review EAC ($M)</th>
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<tr>
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<td>75.1</td>
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<td>1.04 Linac Systems</td>
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<td>1.06 Target Systems</td>
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</tbody>
</table>

* Based on EAC and actual costs and awards through September 30, 2004
Example 2: Japan Proton Accelerator Research Complex (J-PARC)

January, 2005

(Courtesy J-PARC)
• Goal: Multi-purpose proton facility for both research and application
• KEK and JAEA merged their respective interests for a joint project
• Major technical decisions for the construction
  • Choosing rapid cycling synchrotron for staged acceleration to 3 & 50 GeV
  • Choosing magnetic alloy over ferrite loaded RF cavities
  • Choosing braided aluminum over copper conductor for magnets
• Operations start in 2007 (RCS) – 2008 (Main Ring)
  • Experienced earth quack
  • Recovered linac energy to 400 MeV (from initial 186 MeV)
• Designed for 1 MW beam power (3 GeV neutron target); presently operating at lower power mainly due to target issues
• Impressive industrial user engagement
- Phase 1 + Phase 2 = 1,890 Oku Yen (= $1.89 billions if $1 = 100 Yen).
- Phase 1 = 1,527 Oku Yen (= $1.5 billions) for 7 years.
- JAERI: 860 Oku Yen (56%), KEK: 667 Oku Yen (44%).
Summary
• High power frontier accelerators are flourishing for both scientific discovery and applications

• Circular accelerators are used either to reach very high peak power or very high energy

• High power accelerators are challenging both in beam dynamics design and in engineering technology; yet both are within reach
Class References

- Handbook of Accelerator Physics and Engineering, A.W. Chao & M. Tigner
Homework
Problem 1

- Two identical, vertically stacked rapid-cycling synchrotrons are housed in the same tunnel. The circumference is 300 m. The proton beams are injected at 400 MeV, and extracted at 2 GeV. The repetition rate is 30 Hz for each ring. The pulse in each ring contains $10^{14}$ particles. The RF system operates at harmonic $h=2$, and that the pulse contains two bunches.

• What is the total output beam power? What is the total average current of the facility?
• What is the tolerable fractional uncontrolled beam loss in each ring?
• What is the range of RF frequency swing?
• The beam gap reserved for extraction kicker rise is a minimum 200 ns. Assuming that the bunch density distribution is parabolic. What is the maximum bunching factor? What is the average and peak current in the ring?
Problem 2

- Let \( E \) be the total energy, \( E_k \) be the kinetic energy, and \( p \) be the momentum. Assume that the deviation in kinetic energy is much smaller than the kinetic energy. Prove that

\[
\frac{\Delta E}{E} \approx \beta^2 \frac{\Delta p}{p} \\
\frac{\Delta p}{p} \approx \frac{\gamma}{1 + \gamma} \frac{\Delta E_k}{E_k}
\]

where \( \beta \) and \( \gamma \) are the relativistic factors. For a proton beam of 1 GeV kinetic energy with a +/-1% spread in \( \Delta p/p \), how accurate are these relations?
Problem 3

- Prove that in terms of variable \( X = \frac{x}{\sqrt{\beta_x}} \), the normalized displacement \( \mu(s) = \int_{s}^{s'} \frac{ds'}{\beta(s')} \) obeys simply harmonic motion.

- With two-stage betatron betatron collimation consisting of a scraper and two collectors, prove that when the conditions

\[
\mu_1 = \cos^{-1}\left( \frac{A}{A + H} \right) \quad \mu_2 = \pi - \mu_1
\]

are satisfied, minimum number of secondary particles escape the collimation process. Here, the scraper radius \( A \) and the collector radius \( A + H \) are both defined in terms of the normalized variables.

- Express the above phase-advance conditions in terms of the physical apertures.
Problem 4

Consider beam density distribution in the normalized phase space during multi-turn injection. Define \( \rho^2 \equiv X^2 + X'^2 \) and the quantity \( \lambda(\rho)\rho d\rho \) is the number of particle populated within the phase-space circle of radius \( \rho \) and width \( d\rho \).

• What is the closed-orbit function with time to realize a uniform distribution in phase space with a constant density \( \lambda(\rho) \) within a radius \( R \) during a total injection time of \( t_{\text{max}} \)?

• Prove that the closed-orbit function to realize a Gaussian distribution

\[
\lambda(\rho) = \frac{2N_0}{\sigma^2} \exp\left(-\frac{\rho^2}{2\sigma^2}\right)
\]

is approximately

\[
X_C(t) = \sqrt{2\sigma} \sqrt{-\ln\left(1-\frac{t}{t_{\text{max}}}\right)}
\]

where the injection is performed during a time \( 0 < t < t_{\text{max}} \).
Thank you!