the Cyclotron Facilities at PSI

an overview

Werner Joho, PSI
original Cyclotrons

the cyclotron as seen by the inventor

the first classical cyclotrons
(the RF-system squeezed into the magnet gap)
The first Cyclotron 1931

invented by E.O.Lawrence,
constructed by M.S.Livingston
Berkeley, California

4 inch diameter
1 kV on the Dee
80 keV Protons
43 years later (1974)

Ring Cyclotron
590 MeV Protons
15 m Diameter

Hans Willax,
Jean Pierre Blaser,
Villigen, Switzerland
History of the Cyclotron

1929 Idea by E.O.Lawrence in Berkeley
(inspired by R.Wideroe!)
1931 4 inch cyclotron 80 keV p
1932 10 inch cyclotron 1.2 MeV p
1934 26 inch cyclotron 7 MeV p
1939 60 inch cyclotron 16 MeV d
1946 184 inch synchrocyclotron 200 MeV d
                        400 MeV α

1938 Idea for sectored cyclotron (AVF) by Thomas
1962 88 inch sector cyclotron K=160 MeV ion
1974 SIN/PSI Ringcyclotron 590 MeV p
1982 supercond.cyclotron MSU K=500 MeV ion

2008: ca. 90 indiv. cyclotrons, ca. 200(?) commercial cyclotrons
the Livingston Plot

Energy Records for Particle Accelerators

exponential increase of maximum energy

Cyclotrons are the early leaders!
In homogeneous magnetic field the circular orbits are vertically unstable. **Vertical stability** with radially decreasing field $B(r)$.

Definition of field index $n$ with "logarithmic derivative":

$$\left(\frac{dB_0}{B_0}\right) \equiv -n \left(\frac{dr}{r}\right)$$

Focusing frequencies:
- Stable for $0 < n < 1$
- $Q_r = \sqrt{1-n}$, $Q_y = \sqrt{n}$
- $Q_r^2 + Q_y^2 = 1$

=> weak focusing, horizontally and vertically.
Larmor Frequency

Revolution frequency $\omega_0$ in homogeneous magnetic field:

$$\omega_0 = \frac{q}{m} B$$

($= \text{Larmor frequency}$)

$\omega_0$ is independent of radius $R$ and energy $E$!

$\Rightarrow$ Basis for classical Cyclotron (non rel.)

relativistic formula for all energies, with $E_{\text{tot}} = \gamma mc^2$ and $\omega_0 = 2\pi v_0$

$$v_0 = \left(\frac{q}{2\pi m}\right) \frac{B}{\gamma}$$

$$\frac{q}{2\pi m} = 15.25 \text{ MHz/T} \quad \text{for protons}$$

$$\frac{q}{2\pi m} = 28 \text{ GHz/T} \quad \text{for electrons}$$
Isochronism

Acceleration of a particle with RF frequency $\nu_{\text{RF}}$ on harmonic $h$:

$$\nu_{\text{RF}} = h \nu_0$$

If this RF frequency stays constant during acceleration, we talk about an isochronous cyclotron. The condition for this is an average field which increases proportional to $\gamma$:

$$\Rightarrow B_0(R) \sim \gamma(R)$$

For an azimuthally symmetric field this leads to vertical instability. The way out is:

1) **magnetic sectors** give vertical focusing $\Rightarrow B(r,\phi)$, Thomas 1938

   $$\Rightarrow B_0(R) = \text{field averaged over the whole orbit}$$

2) **synchro-cyclotron** with $\nu_{\text{RF}}(t)$ $\Rightarrow$ pulsed beam, reduced intensity
Cyclotrons

- Classical Cyclotron
  - Single pole
  - Classical Cyclotron

- Synchrocyclotron
  - Single pole (dying out!)
  - FFAG with sectors

- Isochronous Cyclotron
  - Single pole with sectors
  - Isochronous Cyclotron

- Ring Cyclotron
  - CW-beam
  - Pulsed beam

- ASTOR concept
  - CW-beam
  - Pulsed beam

Non relativistic energy limit
Thomas Cyclotron (1938)

Sectors on the pole plates of an H-magnet

=>$ \text{vertical edge focusing}$

between Hill (H) and Valley (V)

$\Delta B = B(\text{Hill}) - B(\text{Valley})$

focal length $f_y$ through edge angle $\Psi$:

$$\frac{1}{f_y} = \frac{\Delta B}{(B\rho)} \tan \varphi, \quad (f_x = -f_y)$$
horizontally:
the deflection of a particle with parallel
displacement $x$ is delayed by the path length
$ds = x \tan \Psi \Rightarrow x' = \frac{ds}{R}$
the effect is the same as a
defocusing quadrupole
with strength: $\frac{1}{f_x} = -(1/R) \tan \Psi$

vertically:
focusing with $f_y = -f_x$
Comet Cyclotron, Spiral Sectors

250 MeV Protons for Therapy (ACCEL/ PSI)

superconducting Magnet with 4 Sectors

The spiral structure is responsible for the vertical beam focusing

---

0.5 m
Advantages of Ring Cyclotrons
(Hans Willax 1963)

- Magnetic field and RF system are decoupled
- Many high voltage cavities
- Fast crossing of resonances, good turn separation
- Monoenergetic beam, single turn extraction
- Flattop cavity
- Strong vertical focusing
- Small magnet gap, low power consumption
- Straight sections
- Easy construction of extraction and injection elements (no kickers!)
- Lots of space for diagnostic and correction elements
- Low extraction losses
- => High intensity

Requires injector!
PSI has 3 Top-class Accelerators!

- **Ring-Cyclotron**, 590 MeV Protons
  
  => Neutrons, muons

- **Storage Ring**, 2.4 GeV Electrons
  
  => X-rays

- **compact-Cyclotron**, 250 MeV Protons
  
  => Cancer Therapy
Ring Cyclotron
590 MeV Protons

1.4 MW average Beam Power
(World Record!)

most intensive
Muon Beams
5·10^8 μ^+ /s, 10^8 μ^- /s

Spallation-Neutron-Source
10^{14} n/s

equivalent to
medium Flux Reactor
(but without Uranium!)
Swiss Light Source (SLS) 2.4 GeV Electron Storage Ring

- constant beam current (400-402 mA)
  due to top-up injection every 2.5 min.

- extreme stable Photon Beams
  due to „fast orbit feedback“ (< 0.5 μm)
supraconducting Cyclotron
250 MeV Protons for
Beam Therapy

Eye Tumours

2 rotating Gantries
3D-Spot Scanning
INJECTOR I
1973-2011
- Light Ions
  $E/A = (Z/A)^2 \times K$
  $K = 120 \text{MeV}$
- Protons 72 MeV
- 200 $\mu$A (11 $\mu$A polar.)
- Eye tumour therapy

INJECTOR II
1984-
- Protons 72 MeV
- 2.7 mA (200 kW)

Ringcyclotron
1974-
- Protons 590 MeV
  2.4 mA (1.4 MW)
  (10 $\mu$A polar.)

COMET s.c.
2007-
- Protons 250 MeV
  Tumour therapy

Tumour therapy (pions), protons
up to 2006

W.Joho 2013
The PROSCAN Facility

Cyclotron COMET

(Future Gantry III)

Material Research

Optis

Gantry I

Gantry II

Medical Pavillon
Comet Cyclotron

Radiation Therapy with 250 MeV Protons

superconducting Cyclotron:
Magnet, 3m Ø
Collaboration: ACCEL & PSI
Irradiation with Protons by Spot-Scanning (E. Pedroni, PSI)
Proton Therapy

Irradiation of Tumour from different Directions with Gantry

⇒ minimal Dose at Surface
OPTIS, Eye Tumour Therapy with Protons

1984-2012
> 5'500 Patients

Tumour Control:
> 98%

(Collaboration with Hospital Lausanne)
Irradiation on 4 Days
Injector I  Cyclotron

Philipps (1973-2011)
72 MeV Protons:
100-200 $\mu$A
polarized: 10 $\mu$A

Ions, Energy/Nucleon:
$E/A=(Z/A)^2$ 120 MeV
e.g. Deuterons, $\alpha$:
30 MeV/Nucleon
Cockcroft-Walton Pre-accelerator

Voltage: 810 kV

Acceleration Tube

Proton Source inside Faraday Cage on 60 kV
Injection of 870 keV Protons into Injector II
Injector II

- Injection Line
  - 870 keV

- Extraction Line
  - 72 MeV Protons (after 100 turns)

- Resonator
  - 50 MHz
Layout Injector II

- Sector magnet 1
- 72 MeV protons
- Extraction magnets
- 860 keV protons
- RF cavity 50 MHz
- Flattop Cavity

W. Joho 2013
Recipe for high Intensity

- continuos beam (cw)
- very low extraction losses

=> separated turns with large turn separation dR at extraction

=> high energy gain per turn, powerful RF-system with high voltage cavities

dR \sim \text{Radius } R

=> \text{large machine radius} !!

the last 5 turns in the Injector II
Ringcyclotron
4 new cavities 2008

590 MeV Protons
1.4 MW Beam Power
(World Record!)
8 Magnets à 250 t
4 Cavities à 900 kV
Extraction 99.99%
The PSI Ring-Cyclotron

8 Sektormagnets

4 Acceleration Cavities
1:10 Model of Ringcyclotron
RF Cavity

Ring Cyclotron
590 MeV, 50.7 MHz

original version:
aluminum, V=720 kV
300 kW power loss
216 turns

new cavity:
copper, limit=1 MV
at V = 850 kV: 250 kW power loss
185 turns
New Copper Cavity (5.6m long)

50 MHz, CW
Voltage limit 1 MV
(old cavity 0.72 MV)

at 850 kV and 2.4 mA:
250 kW loss in cavity
350 kW goes to the beam

Beam limit 3 mA?
Phase Compression / Phase Expansion due to Variation in Cavity Voltage

The radial variation of the cavity voltage produces a phase dependent magnetic field. This effects the revolution time and thus the phase of a particle.

\[ E_G(R) \Delta \sin \Phi(R) = \text{const.} \]

\( E_G \) = peak energy gain/turn
\( \Phi \) = phase of particle

W.Joho, Particle Accelerators 1974, Vol.6, pp. 41-52
Flattop Voltage gives minimum energy spread
6 Orbits plotted at equidistant energies: 75, 177, 279, 381, 483, 585 MeV 
\[(R \sim \beta)\]
Ring Cyclotron magnetic field

Contour lines of the magnetic field

scaling of average field:
\[ B_0(R) \sim \gamma \]
increases 55%
from 72-590 MeV
Ring Cyclotron (1980) turns 26-315, 100-590 MeV
In the Ring Cyclotron the coupling resonance $\nu_r=2\nu_z$ is crossed twice before extraction.

In the Injector I the resonance $\nu_r=1$ is used to enhance the extraction efficiency.
A large horizontal oscillation is transformed into a large vertical one at the coupling resonance \( n_r = 2n_z \).

This can lead to beam losses.
Due to the strong vertical focusing in a sector cyclotron the current limit due to the space charge tune shift is a few mA in Injector II. Resonances can be crossed very fast with high RF voltages.
In an isochronous cyclotron: $\omega_0 = \text{const.}$

$$R = \frac{v}{\omega_0} \sim \beta, \quad (\beta = \frac{v}{c})$$

absolute radius limit at $v=c$: $R_{\infty} = \frac{c}{\omega_0}$

$$R = \beta R_{\infty}$$

$$R_{\infty}[m] = h \left(\frac{47.7 \text{ MHz}}{\nu_{RF}}\right)$$

Example: protons at PSI: $\nu_{RF} = 50.7 \text{ MHz}$, $R_{\infty} = h \cdot 0.94m$

<table>
<thead>
<tr>
<th></th>
<th>$E[\text{MeV}]$</th>
<th>$\beta_{\text{max}}$</th>
<th>$h$</th>
<th>$R_{\infty}[m]$</th>
<th>$R_{\text{max}}[m]$</th>
<th>$B_0[\text{T}]$ (center)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injektor I</td>
<td>72</td>
<td>0.37</td>
<td>3</td>
<td>2.83</td>
<td>1.05</td>
<td>1.1</td>
</tr>
<tr>
<td>Injektor II</td>
<td>72</td>
<td>0.37</td>
<td>10</td>
<td>9.40</td>
<td>3.5</td>
<td>0.33</td>
</tr>
<tr>
<td>Ring</td>
<td>590</td>
<td>0.79</td>
<td>6</td>
<td>5.65</td>
<td>4.5</td>
<td>0.55</td>
</tr>
</tbody>
</table>
The intensity limit of a Cyclotron is given by the beam losses. Important is the radial distance \( \frac{dR}{dn} \) between the last two turns before extraction.

\[ E = \frac{1}{2} m v^2 = \frac{1}{2} m \omega^2 R^2 \sim R^2 \]  
(non relativistic)

\[ E \approx n q \bar{V} \sim n \] (turn number),

\[ \bar{V} = \text{average RF voltage per turn} \]

\[ \Rightarrow R \sim \sqrt{n}, \quad \frac{dR}{dn} = \frac{R}{2n} \]

relativistic:

\[ \frac{dR}{dn} = \frac{\gamma}{\gamma + 1} \frac{R \bar{V}}{Q_{r}^2} \left( \frac{E}{e} \right) f^2 \]

\[ f \approx 1.1 - 1.2 \text{ for ring cyclotrons} \]

\[ \Rightarrow \text{large turn separation with:} \]

- high RF voltage (intensity limit \( \sim V^3 \) !)
- large machine radius \( R \) !

\[ \Rightarrow \text{compact cyclotrons (supercond. !)} \]

have limited intensity

\[ \Rightarrow \text{large turn separation with:} \]

- high RF voltage (intensity limit \( \sim V^3 \) !)
- large machine radius \( R \) !

\[ \Rightarrow \text{compact cyclotrons (supercond. !)} \]

have limited intensity
Longitudinal space charge forces increase the energy spread
=> higher extraction losses
=> limit on beam current

Remedy:
higher voltage $V$ on the RF cavities
=> lower turn number $n$ ($V \cdot n = \text{const.}$)

There are 3 effects, each giving a factor $V(\sim 1/n)$:
1) beam charge density $\sim n$
2) total path length in the cyclotron $\sim n$
3) turn separation $\sim V$

W.Joho, 9th Int. Cyclotron conference CAEN (1981)
History of the Peak current in the 590 MeV Ring Cyclotron

- 4 upgraded RF amplifiers
- new cavities 1-4
- new targets
- design goal 0.1 mA
- Injector II

Year timeline from 1974 to 2009.
Particle at position A:

- => gains additional energy from space charge forces
- => moves to higher radius due to isochronous condition
- => rotation of the bunch
- => nonlinearities produce spiral shaped halos
- => production of a rotating sphere („spaghetti effect“)
Longitudinal Space Charge in Cyclotron

Simulation of a 1mA beam, circulating in Injector II at 3 MeV for 40 turns without acceleration.

The core stabilizes faster than the halos; rotating sphere produces phase mixing (calculations by S.Adam)
Aristocracy ↔ Democracy

Synchrotrons
Linacs
democratic:
a particle oscillates between head and tail
(phase focusing)

Cyclotrons

aristocratic:
a particle „born ahead“ stays ahead!
(isochronism)

but at high intensity
a cyclotron becomes democratic !!
(space charge mixes phases)
RF efficiency in Ring Cyclotron

beam current needs
0.806 MW/mA

beam power
=0.59 MW/mA

=> RF efficiency=73%
(M.Seidel)
Graphite Target Wheel

1.3 MW Proton Beam creates Pions and Muons
„slow“ Neutrons for Material Research

- Production of fast Neutrons
- Slowing down in Moderator

1. **Fission** of Uranium (U$^{235}$) in a Reactor

2. **Spallation** of heavy Nuclei (e.g. lead) by Bombardment with Protons from an Accelerator

=> safe and fast turning off!
Spallation Neutrons

for beam energy > 1GeV
=> production of neutrons
prop. to beam power

Figure 1. Calculated neutron multiplicity on lead as a function of proton energy; the insert shows a calculated energy-normalised yield.
SINQ
Neutron Spallation Source

Shielding
7 m Concrete

Guide for cold Neutrons
cold Neutrons

Proton (590 MeV) => Lead Nucleus => ca. 10 Neutrons
=> Moderation to < 0.025 eV => Diffraction on Material Probes
Radiography with Neutrons

=> the interior of big objects becomes visible
Strategy for Cyclotrons

**High Energy**

- $E/A = (q/A)^2 K_B$, $K_B \sim B^2 R^2$
- High $q/A$
- ECR-source
- Stripping at high energy
- External injection
- 2nd stage
- "Jumbo"-coil

**High Intensity**

- Low losses at extraction
- High RF-voltage
- Extraction by stripping e.g. $H^- \rightarrow p$
- Big radius
- "Jumbo"-magnet
- Ring cyclotron with injector
- High $K_B$
- High magnetic field $B$
- Supercond. magnet
why is the PSI Ring Cyclotron such an efficient accelerator?

**general property of cyclotrons**
- isochronous magnetic field
  - continuos beam (CW)
    => high average current

**specialty of Ring Cyclotron**
- magnetic and RF-System are **decoupled**
  => economic magnets
  => economic RF-cavities

- high RF voltage + flattop cavity
  => single turns with good turn separation
  => very low losses

- efficient use of RF power
- multiple beam traversal of RF-cavity
- high Beam Power
Model of the last turns in the 590 MeV Ring Cyclotron

• the turn separation is proportional to the orbit radius $R$
  and the cavity voltage $V$

  =>$ \text{concept of a large ring cyclotron}
  \text{with many high voltage cavities}$

• Flattop cavity gives mono-energetic beam

  =>$ \text{leads to single turn extraction}$

  =>$ \text{an eccentrically injected beam is still eccentric at extraction.}$

  =>$ \text{This can be used to increase the radial separation}$
  =>$ \text{between the last two turns.}$

• In our simple model we assume an average turn separation
  of 6mm at extraction (energy gain 3 MeV/turn)
the last turns in the Ring Cyclotron, model with real tune $Q_r$

Intensity

<table>
<thead>
<tr>
<th>turn 1</th>
<th>turn 2</th>
<th>turn 3</th>
<th>turn 4</th>
<th>turn 5</th>
<th>turn 6</th>
<th>turn 7</th>
<th>turn 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>181</td>
<td>182</td>
<td>183</td>
<td>184</td>
<td>185</td>
<td>186</td>
<td>187</td>
</tr>
</tbody>
</table>

Radius

6 mm

Centered beam

Intensity

1.77       1.77       1.77       1.76      1.74        1.70      1.65       1.58     real tunes $Q_r$

$x^*$

beam 6 mm eccentric

$x$

1.77 1.77 1.77 1.76 1.74 1.70 1.65 1.58

Septum

188
590 MeV Ring Cyclotron
last 9 of 188 turns for a 2 mA beam

Simulation with OPAL
(A.Adelman, Y.J.Bi et al)

Measurement

loss at septum gives current limit

factor 1000 in intensity
Success Factors for PSI Ring Cyclotron

1. Magnets and RF-System are decoupled

2. 4 high voltage cavities → \( I_{\text{max}} \sim V^3 \)

3. large Radius \( R \) → high turn separation \( \frac{dR}{dn} \sim R \cdot V \)
   - fast acceleration into fringe field,
   - where \( Q_r \) drops: \( \frac{dR}{dn} \sim \frac{1}{Q_r^2} \)

4. excellent beam from Injector → separated turns

5. Flattop Cavity → high phase acceptance \( \Delta \Phi \)

6. eccentric Injection → \( Q_r \) at extraction 1.75 => 1.5
   - wins factor 3 in \( \frac{dR}{dn} \): 6 => 17mm

7. straight electrostatic Septum with 0.1mm strips → Losses at extraction \( \approx 10^{-4} \)

8. Continuous Beam (CW) → **1.4 MW Beam Power**
## Reduction of Extraction losses

<table>
<thead>
<tr>
<th>Cavity Voltage [kV]</th>
<th>Beam</th>
<th>Flattop Cavity</th>
<th>Losses [%]</th>
<th>Losses [µA]</th>
<th>Imax [µA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>Orig. Design</td>
<td>no</td>
<td>5</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>450</td>
<td>centered</td>
<td>no</td>
<td>1.2</td>
<td>0.5</td>
<td>40</td>
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<tr>
<td>450</td>
<td>eccentric</td>
<td>no</td>
<td>0.25</td>
<td>0.5</td>
<td>200</td>
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<tr>
<td>450</td>
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<td>yes</td>
<td>0.1</td>
<td>0.5</td>
<td>500</td>
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<tr>
<td>850</td>
<td>eccentric</td>
<td>no</td>
<td>0.06</td>
<td>0.5</td>
<td>800</td>
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<td>850</td>
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<td>yes</td>
<td>0.02</td>
<td>0.5</td>
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</table>

<table>
<thead>
<tr>
<th>Improvement by</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Quality</td>
<td>~ 3</td>
</tr>
<tr>
<td>eccentric Injection</td>
<td>~ 5</td>
</tr>
<tr>
<td>Flattop Cavity</td>
<td>~ 3</td>
</tr>
<tr>
<td>Cavity Voltage</td>
<td>~ 5</td>
</tr>
<tr>
<td>total</td>
<td>240</td>
</tr>
</tbody>
</table>
Properties of Cyclotrons

- versatile
- CW-Beams
- excellent Beam Quality

- all Ions from p to U
- Energies:
  - p: up to 600 MeV
  - => limit ≈ 10 GeV ?
- Ions: up to 500 MeV/n

=> high Intensity (few mA)
=> polarized Ions (few μA)

Coincidence Experiments with high Event Rates

Continuos Beam allows easy Tuning of Accelerator

in all 6 Dimensions
transv.: π 1 mm mrad (norm.)
ΔE/E ≈ 10⁻³
Δt ≈ 0.3 ns
Pulse Selection at low Energy gives flexible microscopic Time Structure for Time of Flight Experiments
Cyclotrons are still attractive!

- Commercial Cyclotrons for Radiation Therapy and Isotope Production
- Acceleration of Radioactive Beams
- Injectors for Ion Storage Rings
- Intense Neutron Sources, replacing Reactors
- Energy Amplifier Concept (Carlo Rubbia)
- Transmutation of Nuclear Waste
example: 600 MeV PSI Cyclotron in future with 3 mA => **1.8 MW**

=> production of neutrons in subcritical reactor (e.g. \( k = 0.97 \))

=> **110 MW_{th}** => **40 MW_{el}**

=> power plant with 1 GW_{el} needs 35 mA protons at 1 GeV => s.c. Linac

- **inherently safe**
- **use of Thorium (big reserves)**
- **no production of Plutonium for weapons**
reduction of lifetime of nuclear waste!

chem. separation of long lived actinides

high intensity protonen beam
≈ 40 MW (30*PSI), ca. 2050?

production of neutrons

transmutation of aktinides

Reduction from 1 Mill. years to 400 years

European Roadmap for Accelerator Driven Systems ... ENEA Italien 2001
some personal References

W.Joho, Particle Accelerators 1974, Vol.6, pp. 41-52


W.Joho, M.Olivo, Th.Stammbach, H.Willax "The SIN Accelerators, ..."


More information on the PSI Accelerator Facilities can be found in: www.psi.ch
More talks by the author are found in www.google.ch with “Werner Joho PSI” or directly in http://gfa.web.psi.ch/publications/presentations/WernerJoho/

History of SIN: Geschichte des SIN, Andreas Pritzker, Munda Verlag 2013
professional career of Werner Joho

1958 – 1962  physics student at ETH Zurich

1962 – 1990  Cyclotron group ETH => PSI , leader Beam Dynamics

1990 – 2003  Synchrotron Light Source (SLS) , Project leader Booster

after 2003  Consulting (PSI, Barcelona, Taiwan, Beijing, Vancouver)

external stays:

1963  CERN , Geneva, computer codes for cyclotron orbits

1964  Michigan State University, graduate studies

1971 – 1973  TRIUMF Vancouver , Canada, Injection Line

lectures on thermodynamics at University UBC

1990  Berkeley, California, Light Source ALS
Confidence in success!