high intensity and high power aspects of cyclotrons

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high intensity cyclotrons - Outline

• classical cyclotron – and its general suitability for high intensity beams
  – advantages of cyclotron concept, classification of circular accelerators

• beam dynamics - with emphasize on high intensity
  – isochronicity and related scalings, classical extraction: pattern/stepwidth, transv./long. space charge, ion induced vacuum desorption, tracking codes

• cyclotron subsystems - with relevance for high intensity
  – extraction schemes, RF systems/power efficiency, vacuum issues, collimation issues

• examples of high intensity cyclotrons
  – TRIUMF, RIKEN SRC, ARRONAX, PSI Ring

• discussion
  – Pro’s and Con’s of cyclotrons
Classical Cyclotron

first cyclotron: 1931, Berkeley
1kV gap-voltage
80kV Protons

powerful concept:

- simplicity, compactness
- continuous injection/extraction
- multiple usage of accelerating voltage

Lawrence & Livingston, 27inch Zyklotron

two capacitive electrodes „Dees“, two gaps per turn
internal ion source
homogenous B field
constant revolution time
(for low energy, $\gamma \sim 1$)
classification of circular accelerators

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<th>bending radius</th>
<th>bending field vs. time</th>
<th>bending field vs. radius</th>
<th>RF frequency vs. time</th>
<th>operation mode (pulsed/CW)</th>
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<td>varying $h$</td>
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<td>classical cyclotron</td>
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<td>simple, but limited $E_k$</td>
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<td>isochronous cyclotron</td>
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<td>suited for high power!</td>
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<td>synchrocyclotron</td>
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<td>higher $E_k$, but low $P$</td>
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<td>FFAG</td>
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<td>strong focusing!</td>
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<td>a.g. synchrotron</td>
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<td>high $E_k$, strong focus</td>
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basic thoughts on the theme of this talk

• Why is the cyclotron suitable for high intensity beams?
  – CW operation is naturally possible
  – efficient and cost effective multi-turn (resonant) concept
  – cyclotrons are simple and compact

• Which aspects are critical?
  – most important: clean extraction! → activation
  – ions: vacuum induced losses; desorption; foil related issues
  – intensity limitations from space charge
  – technical difficulties: wide vacuum chamber; resonators and high power throughput; technical and personnel safety; complex tuning
• next: **beam dynamics**
  – isochronicity and related scalings
  – classical extraction: pattern/stepwidth
  – transv./long. space charge
  – ion induced vacuum desorption
  – tracking codes
isochronicity and scalings

magnetic rigidity:

\[ BR = \frac{p}{e} = \beta \gamma \frac{m_0 c^2}{e} \]

orbit radius from isochronicity:

\[ R = \frac{c}{\omega_0} \beta = R_\infty \beta \]

\[ = \frac{c}{\omega_0} \sqrt{1 - \gamma^{-2}} \]

deduced scaling of \( B \):

\[ R \propto \beta; \quad BR \propto \beta \gamma \rightarrow B \propto \gamma \]

field index:

\[ \frac{R \, dB}{B \, dR} = k \]

\[ = \frac{\beta}{\gamma} \frac{d\gamma}{d\beta} = \gamma^2 - 1 \]

radius increment per turn decreases with increasing energy because the revolution time must stay constant → extraction becomes more and more difficult at higher energies

\[ R_\infty = \frac{R}{\beta} \]
derivation of stepwidth / turn separation

\[ BR = \frac{\sqrt{\gamma^2 - 1} \, m_0 c}{e} \]

\[ \frac{dB}{B} + \frac{dR}{R} = \frac{\gamma \, d\gamma}{\gamma^2 - 1} \]

starting point: bending strength
→ compute total log.differential
→ use field index \( k = R/B \cdot dB/dR \)

radius change per turn
\[ \frac{dR}{dn_t} = \frac{dR}{d\gamma} \frac{d\gamma}{dn_t} \]
\[ \frac{d\gamma}{dn_t} = \frac{U_t}{m_0 c^2} \]

\[ \frac{dR}{dn_t} = \frac{U_t}{m_0 c^2} \frac{\gamma R}{(\gamma^2 - 1)(1 + k)} \]
\[ \frac{dR}{dn_t} = \frac{U_t}{m_0 c^2} \frac{\gamma R}{(\gamma^2 - 1) \nu_r^2} \]
\[ \frac{dR}{dn_t} = \frac{U_t}{m_0 c^2} \frac{R}{(\gamma^2 - 1) \gamma} \]

isochronicity not conserved (just few outer turns)
isochronicity conserved (general scaling)
**stepwidth - discussion**

for clean extraction a large stepwidth (turn separation) is of utmost importance; in the PSI Ring most efforts were directed towards maximizing the turn separation

**general scaling** for isochronous cyclotron:

$$\Delta R(R_{extr}) = \frac{U_t}{m_0 c^2} \frac{R_{extr}}{(\gamma^2 - 1)\gamma}$$

**non-relativistic approx., scaling during acceleration:**

$$\frac{dR}{dn_t} \approx \frac{U_t}{m_0 c^2} \frac{R}{\beta^2} \Rightarrow \Delta R(R) \propto \frac{1}{R}$$

**illustration:**

- **stepwidth vs. radius** in cyclotrons of different sizes; 100MeV → 800MeV

**desirable:**
- limited energy (< 1GeV)
- large radius $R_{extr}$
- high energy gain $U_t$
extraction with off-center orbits

betatron oscillations around the “closed orbit” can be used to increase the radial stepwidth by a factor 3!

radial tune vs. energy (PSI Ring)
typically $v_r \approx \gamma$ during acceleration; but decrease in outer fringe field

without orbit oscillations: stepwidth from $E_k$-gain (PSI: 6mm)

with orbit oscillations: extraction gap; up to 3 x stepwidth possible for $v_r=1.5\pi$ (phase advance)

particle density

beam to extract

phase vector of orbit oscillations ($r,r'$)
PSI Ring Cyclotron – tune diagram

coupling resonance – pass quickly!

$Q_r$ decreases towards extraction
– enhance turn separation

**comments:**
- special care has to be taken with fine-tuning the bending field in the extraction region
- running on the coupling resonance would transfer the large radial betatron amplitude into vertical oscillations, which must be avoided
extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement

dynamic range: factor 2.000 in particle density

turn numbers

position of extraction septum
\( d = 50\mu m \)

[Y.Bi et al]
longitudinal space charge

sector model (W.Joho, 1981):
aim: compute **total energy spread** after acceleration process generated by longitudinal electric field
• consider rotating sectors of charge
• uniform charge distribution (overlapping turns)
• test particle “sees” only fraction of sector due to shielding of vacuum chamber with gap height $2w$

$$E_\theta \approx \frac{\rho \cdot \frac{a \ln \left(4 \frac{w}{a}\right)}{\pi}}{\varepsilon_0 Q}$$

$$\rho = \frac{\Delta R \cdot 2\pi R \cdot D_f \cdot 2a}{I_p}$$

$$= \frac{\beta c \cdot \Delta R \cdot 2a}{2 \cdot 2\pi eR E_\theta}$$

$$\frac{dU_{sc}}{dn} = 2 \cdot 2\pi eRE_\theta$$
longitudinal space charge (cont.)

relation turn number / radius:

\[ E_k \propto n_t \propto v^2 \propto R^2 \]

\[ R(n_t) = \sqrt{\frac{n_t}{n_{\text{max}}}} R_{\text{max}} \]

\[ \frac{\Delta R}{\Delta n_t} = \frac{R_{\text{max}}}{2\sqrt{n_t n_{\text{max}}}} \]

non-relativistic!

next: integration over turns

\[ \Delta U_{sc} = 2 \cdot \int_{n_t=0}^{n_{\text{max}}} \frac{dU_{sc}}{dn} dn_t \]

\[ = \frac{4e R_{\infty} I_p Z_0 \ln \left(4 \frac{w}{a}\right) \sqrt{n_{\text{max}}}}{R_{\text{max}}} \int_{n_t=0}^{n_{\text{max}}} \sqrt{n_t} dn_t \]

\[ \approx \frac{8}{3} e I_p Z_0 \ln \left(4 \frac{w}{a}\right) \cdot \frac{n_{\text{max}}^2}{\beta_{\text{max}}} \]

\[ \approx 2.800 \Omega \cdot e I_p \cdot \frac{n_{\text{max}}^2}{\beta_{\text{max}}} \]

front vs. trailing particle

for \( w/a = 4 \)

in addition: turn separation at extraction element scales with \( n_{\text{max}}^{-1} \)

thus attainable current at constant losses scales as \( n_{\text{max}}^{-3} \)
longitudinal space charge; evidence for third power law

• at PSI the maximum attainable current indeed scales with the third power of the turn number
• maximum energy gain per turn is of utmost importance in this type of high intensity cyclotron

→ thus with constant losses at the extraction electrode the maximum attainable current scales as: $I_{\text{max}} \propto n_t^{-3}$

historical development of current and turn numbers in PSI Ring Cyclotron
different regime for very short bunches: formation of circular bunch

**in theory**
strong space charge within a bending field leads to rapid cycloidal motion around bunch center [Chasman & Baltz (1984)]
→ bound motion; circular equilibrium beam distribution
→ see Ch. Baumgarten, Friday 13:30 on coupling theory

**in practice**
time structure measurement in injector II cyclotron → circular bunch shape observed

blowup in ~20m drift
transverse space charge

with overlapping turns use current sheet model!

vertical force from space charge: 
\[ F_y = \frac{n_v e^2}{\epsilon_0 \gamma^2} \cdot y, \quad n_v = \frac{N}{(2\pi)^{\frac{3}{2}} \sigma_y D_f R \Delta R} \]

[constant charge density, \( D_f = \frac{I_{\text{avg}}}{I_{\text{peak}}} \)]

focusing force:
\[ F_y = -\gamma m_0 \omega_c^2 v_{y0}^2 \cdot y \]

thus, eqn. of motion:
\[ \ddot{y} + \left( \omega_c^2 v_{y0}^2 - \frac{n_v e^2}{\epsilon_0 m_0 \gamma^3} \right) y = 0 \]

→ equating space charge and focusing force delivers an intensity limit for loss of focusing!

tune shift from forces:
\[ \Delta \nu_y \approx -\sqrt{2\pi} \frac{r_p R}{e \beta c v_{y0} \sigma_z} \frac{m_0 c^2}{U_t} I_{\text{avg}} \]
intense ion beams in cyclotrons

• ions in cyclotrons: e.g. GANIL, RIKEN, AGOR... but also synchrotrons: RHIC/BNL, FAIR/GSI, LHC chain/CERN...

• issues:
  – unwanted change of charge state
    (gas scattering, electro-magnetic stripping)
  – ion induced gas desorption
  – high energy density when stopped in material
heavy ion acceleration

- neglect energy dependences
  \[ I_{out} = I_{in} \exp(-P/P_c) \]
  \[ P = P_0 + Q_d (I_{in} - I_{out})/S_p \]
  - \( Q_d \): desorped molecules per lost ion
  - \( P_c \): measure for charge exchange cross section
  - \( S_p \): pumping speed (3000 l/s)

- \( Q_d \approx 10^5; P_c \approx 2 \times 10^{-6} \) mbar
  - measurements GSI, KVI etc.

- \( Q_d/S_p \) dominating factor for transmission

\[ \begin{align*}
P_0 &= 10^{-7} \text{ mbar} \\
Q_d &= 10^4 \\
Q_d &= 10^5 \\
Q_d &= 10^6
\end{align*} \]

compare electron rings:
- \( Q_d(\text{CO}) \approx 10^{-4}/\text{photon} \)
- \( n_\gamma \approx 1/\text{meter/electron} \)

[S.Brandenbourg, KVI]
heavy ion acceleration

measurements at KVI, S.Brandenburg

- transmission of $^{40}$Ar$^{5+}$ 8 MeV per nucleon
- base vacuum $3 \times 10^{-7}$ mbar
- injected intensity up to $6 \times 10^{12}$ pps
- beampower (for $T = 1$) 320 W
Beam dynamics modeling for high intensity beams in cyclotrons – general comments

**Multiscale / Multiresolution**
- Maxwell's equations in 3D or reduced set combined with particles; large and complex structures (field computations)
- many particles problem, \( n \sim 10^9 \) per bunch in case of PSI
- Spatial scales: \( 10^{-4} \) ... \( 10^4 \)m \( \rightarrow \) O(1E5) integration steps; advanced numerical methods; parallel computing
- neighboring bunches (Cyclotrons & FFAG)

**Multiphysics**
- particle matter interaction, simulation of scattering
- field emission in resonators
- secondary particles

at PSI development of **OPAL** code with many extensions in recent years see: amas.web.psi.ch

[A.Adelmann]
parallel computing - scalability

scaling test:
- grid 1024x1024x1024
- particles 1E9

- full 3D tracking run
- no parallel I/O considered in timing
- smallest number of cores = 1024 to run this problem

real case:
- 5E6 32 cores, 108 turns 64x128x64 + I/O $\rightarrow$ 19 hours (modern cluster)

[A. Adelmann]
examples of OPAL simulations in PSI Ring

distribution with varying initial length after 100 turns → short bunch stays compact, no tails!

tracking with 0, 6, 8 neighboring bunches;
considered bunch shows slight compression when taking neighbours into account [J.Yang, A.Adelmann]
next: **cyclotron subsystems**
- with emphasize on high intensity
  - extraction schemes
  - RF systems/power efficiency
  - comments on vacuum
  - collimation issues
injection/extraction schemes

- deflecting element should affect just one turn, not neighboured turn → critical, cause of losses
- often used: electrostatic deflectors with thin electrodes
- alternative: charge exchange, stripping foil; accelerate H\(^-\) or H\(_2^+\) to extract protons (problem: significant probability for unwanted loss of electron; Lorentz dissociation: B-field low, scattering: vacuum 10\(^{-8}\)mbar)

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<td>H(^-)</td>
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<tr>
<td>0.75eV</td>
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- extraction electrode placed between turns
- extraction by charge exchange in foil
  eg.: H\(^-\) → H\(^+\)
  H\(_2^+\) → 2H\(^+\)
injection/extraction with electrostatic elements

principle of extraction channel

electrostatic rigidity:

\[
E \rho = \frac{\gamma + 1}{\gamma} \frac{E_k}{q}
\]

\[
\theta = \frac{qlE}{E_k \gamma + 1}
\]

parameters
extraction chan.:  
\(E_k = 590\text{MeV}\)
\(E = 8.8\ \text{MV/m}\)
\(\theta = 8.2\ \text{mrad}\)
\(\rho = 115\ \text{m}\)
\(U = 144\ \text{kV}\)

major loss mechanism is scattering in 50\(\mu\text{m}\) electrode!

tungsten stripes (3mm x 0.05mm) | gap 16mm
extraction foil

- thin foil, for example carbon, removes the electron(s) with high probability
- new charge state of ion brings it on a new trajectory → separation from circulating beam
- lifetime of foil is critical due to heating, fatigue effects, radiation damage
- conversion efficiencies, e.g. generation of neutrals, must be considered carefully

electrons removed from the ions spiral in the magnetic field and may deposit energy in the foil

How much power is carried by the electrons?
→ velocity and thus $\gamma$ are equal for $p$ and $e$

$$E_k = (\gamma - 1) E_0$$

$$E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

Bending radius of electrons?

$$\rho^e = \frac{E_0^e}{E_0^p} \rho^p$$

→ typically mm
example: multiple H⁻ stripping extraction at TRIUMF

[R.Baartman]
example: $\text{H}_2^+$ stripping extraction in planned Daedalus cyclotron

purpose: pulsed high power beam for neutrino production
- 800MeV
- 5MW

see talks in ECPM program!

[L.Calabretta, A.Calanna et al]
components: cyclotron resonators

cyclotron resonators are basically box resonators
resonant frequency:

\[ f_r = \frac{c}{2} \sqrt{\frac{1}{a^2} + \frac{1}{l^2}} \]

beam passes in center plane;
accelerating voltage varies as \(\sin(r)\)
cross sections of PSI resonators

original Al-Resonator
Oper. freq. = 51 MHz
Max. gap voltage = 760 kV
Power dissipation = 320 kW
Q0 = 32,000 (meas. value)

new Cu-Resonator
Oper. freq. = 51 MHz
Max. gap voltage > 1MV
Power dissipation = 500 kW
Q0 ≈ 48,000

beam(s)

hydraulic tuning

old

new

loop coupler @ 50MHz
copper resonator in operation at PSI’s Ring cyclotron

- $f = 50.6\text{MHz}$; $Q_0 = 4.8 \cdot 10^4$; $U_{\text{max}} = 1.2\text{MV}$ (presently $0.85\text{MV}$)
- Transfer of up to 400kW power to the beam per cavity
50 MHz 1 MW amplifier chain for Ring cyclotron

Wall Plug to Beam Efficiency (RF Systems): 32%
[AC/DC: 90%, DC/RF: 64%, RF/Beam: 55%]

[Reference: L.Stingelin et al]
cyclootron vacuum system

- vacuum chamber with large radial width $\rightarrow$ difficult to achieve precisely matching sealing surfaces $\rightarrow$ noticeable leak rates must be accepted
- use cryo pumps with high pumping speed and capacity
- $\approx 10^{-6}\text{mbar}$ for p, $\approx 10^{-8}\text{mbar}$ for ions
- design criterion is easy access and fast mountability (activation)

example: inflatable seals installed between resonators; length: 3.5m
collimator for high intensity beam (sitting in beam transport line at PSI)

**aspects:**
- high power deposition; cooling at limit
- high radiation dose; estimated 20-40dpA; measured dose rate on axis: 500Sv/h (!)
- material properties and rad.damage? ($\lambda$, $\sigma_{0.2}$)
- activation in water circuits ($^3H$, $^7Be$)
- instrumentation ($T$, $I_{\text{loss}}$)
- long term reliability

[D.Kiselev, Y.Lee et al]
next: high intensity cyclotron examples

- IBA C70-Arronax, TRIUMF, RIKEN SRC, PSI-HIPA
parameters of some cyclotrons

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<th>TRIUMF</th>
<th>RIKEN SRC (supercond.)</th>
<th>PSI Ring</th>
<th>IBA C70 ARRONAX</th>
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<tr>
<td>particles</td>
<td>H⁻ → p</td>
<td>ions</td>
<td>p</td>
<td>H⁻ → p, ions</td>
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<tr>
<td>K [MeV]</td>
<td>520</td>
<td>2600</td>
<td>592</td>
<td>70</td>
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<tr>
<td>magnets (poles)</td>
<td>(6)</td>
<td>6</td>
<td>8</td>
<td>(4)</td>
</tr>
<tr>
<td>peak field strength</td>
<td>0.6</td>
<td>3.8</td>
<td>2.1</td>
<td>1.6</td>
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<td>[T]</td>
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<tr>
<td>R_{inj}/R_{extr} [m]</td>
<td>0.25/3.8...7.9</td>
<td>3.6/5.4</td>
<td>2.4/4.5</td>
<td>0.03/1.16</td>
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<tr>
<td>P_{max} [kW]</td>
<td>110</td>
<td>6.2 (¹⁸O)</td>
<td>1400</td>
<td>52</td>
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<tr>
<td>extraction efficiency</td>
<td>0.9995 (0.70)</td>
<td>(0.63)</td>
<td>0.9998</td>
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<tr>
<td>(tot. transmission)</td>
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<tr>
<td>extraction method</td>
<td>stripping foil</td>
<td>electrostatic deflector</td>
<td>electrostatic deflector</td>
<td>stripping foil</td>
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<tr>
<td>comment</td>
<td>variable energy</td>
<td>ions, flexible</td>
<td>high intensity</td>
<td>compact, flexible</td>
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IBA C70 ARRONAX

multi-purpose, compact cyclotron with 50kW beam power
  • H⁻ for high intensity, 70MeV variable energy
  • multiple ion species; two independent extraction systems
  • application: isotope production, nuclear medicine in Nantes, France
cyclotron examples: TRIUMF

- p, 520MeV, up to 110kW beam power
- diameter: 18m (largest n.c. cyclotron worldwide)
- extraction by stripping H\(^-\) → variable energy; multiple extraction points possible

photo: iron poles with spiral shape ($\delta_{\text{max}}$=70deg)
example: RIKEN (Jp) superconducting cyclotron

\[ K = 2,600 \text{ MeV} \]
Max. Field: 3.8T (235 MJ)
RF frequency: 18-38 MHz
Weight: 8,300 tons
Diameter: 19m
Height: 8m

superconducting
Sector Magnets :6
RF Resonator :4
Injection elements.
Extraction elements.

*utilization: broad spectrum of ions up to Uranium*
RIKEN SRC in the vault
Ring Cyclotron 590 MeV
2.2mA / 1.3MW
diameter: 15m

SINQ spallation source

meson production targets

proton therapie center
[250MeV sc. cyclotron]

dimensions:
120 x 220m²

examples: PSI High Intensity Proton Accelerator
losses and resulting activation in PSI Ring

- maximum intensity is limited by losses (typ. 200-400nA) and activation
- losses at extraction dominate the activation
- thus efforts at optimizing performance are concentrated on the extraction
  → largest possible turn separation; design of electrostatic septum

activation level allows for necessary service/repair work
- personnel dose for typical repair mission 50-300µSv
- optimization by adapted local shielding measures; shielded service boxes for exchange of activated components
- detailed planning of shutdown work

example (2010):
personnel dose for 3 month shutdown:
47mSv, 186 persons
max per person: 2.9mSv

map interpolated from ~30 measured locations
finally: **discussion**

- pro- and con`s of cyclotrons for high intensity beam acceleration
pro and contra cyclotron

pro:  
• compact and simple design  
• efficient power transfer  
• only few resonators and amplifiers needed  
• naturally CW operation

con:  
• injection/extraction critical  
• energy limited to 1GeV  
• complicated bending magnets  
• elaborate tuning required

alternative: sc. linac  
• no energy limit  
• small losses  
• but high cost and low efficiency
some literature w.r.t. high intensity cyclotrons

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<tr>
<th>Topic</th>
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<td><a href="http://www.springerlink.com/content/k61mg262vng17411/fulltext.pdf">http://www.springerlink.com/content/k61mg262vng17411/fulltext.pdf</a></td>
</tr>
<tr>
<td>space charge effects and scalings</td>
<td>W. Joho, High Intensity Problems in Cyclotrons, Proc. 5th int'l. Conf. on Cyclotrons and their Applications, Caen, 337-347 (1981)</td>
</tr>
<tr>
<td>long. space charge; comp. to analytical result</td>
<td>E. Pozdeyev, A fast code for simulation of the longitudinal space charge effect in isochronous cyclotrons, cyclotrons (2001)</td>
</tr>
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<td>$H_2^+$ concept for high power</td>
<td>L. Calabretta et al, A multi megawatt cyclotron complex to search for cp violation in the neutrino sector, cyclotrons (2010); upcoming NIM paper!</td>
</tr>
<tr>
<td>Ion induced desorption</td>
<td>E. Mahner et al, Experimental Investigation of Impact-Induced Molecular Desorption by 4.2 MeV/u Pb ions, PAC 2001, 2165</td>
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<td><a href="http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/WPAH036.PDF">http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/WPAH036.PDF</a></td>
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thank you for your attention!