Current Limits of (PSI’s) High Power Cyclotrons: Theory and Practice

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Outline

- PSI’s High Intensity Proton Accelerator (HIPA) Facility
- The Injector II Cyclotron
- The Vortex Effect
- The Ring Cyclotron
- Practical Limits of Predicting Practical Limits
- Basic Design Decisions for High Power Cyclotrons
- Summary
HIPA Facility at the Paul Scherrer Institute

Cockcroft–Walton

870 keV

72 MeV

Beamdump

Target E

Target M

INJECTOR 2

RING–Cyclotron

590 MeV

UCN

Experimental Hall

SINQ

HIPA Facility at the Paul Scherrer Institute

PSI High Intensity Proton Acc. (HIPA)
Cockcroft-Walton and Injector 2

- Compact microwave ECR ion source $E = 60\,\text{keV}$, $\varepsilon_{nrm} = 0.045\,\pi\,\text{mm}\,\text{mrad}$ ($\varepsilon_{1\sigma} = 4\,\pi\,\text{mm}\,\text{mrad}$).
- CW-Accelerator $V = 810\,\text{keV}$ then proton energy $E = 870\,\text{keV}$
- 10 mA of DC beam, axial injection after bunching with 50 MHz.
- 4 separate sectors (high flutter, enough space for resonators, probes and extractor).
- High accelerating voltages ($\approx 1\,\text{MV/turn}$), high (10th) harmonic number.
- Residual 2.2 mA after collimation in central region.
- Vortex ("Spaghetti") effect forms compact “round” bunches [1, 2, 3, 4].
- Bunch formation accompanied by filamentation and emittance increase: Expected from ECR-source $\varepsilon_{1\sigma} = 0.113\,\pi\,\text{mm}\,\text{mrad}$, fitted after Injector II $\varepsilon_{1\sigma} = 1.138\,\pi\,\text{mm}\,\text{mrad}$ (increase by factor 10).
- $\Rightarrow$ round bunches, no flat-top cavity required.
- Max extracted current so far $I \leq 2.7\,\text{mA}$.
The Vortex Effect in Injector 2

- Bunching (first and third harm. buncher) of DC beam.
- Strict isochronism, almost constant phase (opt. by trim coils).
- Optimal acceleration (phase ≈ 0).
- Well-centered beam: No Precessional enhanced turn sep. @ extraction.
- Low field, large radius: Injector II has high turn separation.
- Smooth tunes $\nu_{x,z} \approx 1.3 \ldots 1.7$.
- ⇒ very conservative design (expensive, but high quality).
Theoretical Limits (Vortex Effect)

Baartman 2013 (values at extraction) [5]:

\[ I_{\text{max}} = \frac{h}{2 g_r \zeta^3 \beta^3 \gamma \nu_x^A} \frac{V_{rf}^3}{V_m^2 Z_0} \]

where \( V_m = m_p c^2 / e \) and “formfactor” \( g_r \approx 1. \)

- Assumptions: zero emittance + spherical bunch.
- \( I_{\text{max}} \propto V_{rf}^3 \) (Joho’s \( N^3 \)-Law [6]).
- Assumed turn separation = \( \zeta \sqrt{5} \sigma = 2.7 \sqrt{5} \sigma \approx 6 \sigma. \)
- For Injector II: \( I_{\text{max}} \approx 2.2 \) mA [5].
- Measured Injector II: \( I_{\text{max}} \approx 2.7 \) mA (on beamdump, without Ring Cycl.)
- Note: horizontal tune with 4th power in denominator!
- However: \( I_{\text{max}} \propto \zeta^{-3} \) but \( \zeta \) depends on unknown halo...
- ...and specifically on limits of activation.
Vortex Effect is “Metastable”

Use of linear (!) Hamiltonian theory [8] allows to identify possible distortions of the Vortex Effect. Performed dedicated OPAL ([9, 10]) simulations to confirm the effect of linear distortions:

- Poor isochronism [8, 12].
- Too asymmetric emittances [12].
- Wrong rf phase ("bunching") [13].
- Too strong voltage gradient at low energy [13].
- Poor adiabaticity: $\frac{\Delta E}{E}$ too large [13].

None of these distortions considered in $I_{\text{max}}$-formula.
Example: Isochronous Machine with Field Bump

*From Contrib. to Cycl. Conf (2013, Vancouver)* [12]:

### Matched beam, blue phase:

- Phase $\phi(\text{deg})$
- Dashed: $d^2\phi/dE^2$
- All Emittances: $\frac{\pi}{2}$ mm mrad
- $\epsilon_x(E)$: Matched 2.2 mA, isochr.
- $\epsilon_y(E)$: Unmatched 2.2 mA, isochr.
- $\epsilon_x$, $\epsilon_y$: Matched 2.2 mA, bump up
- $\epsilon_x$, $\epsilon_y$: Unmatched 2.2 mA, isochr.

### E (MeV)

$\begin{align*}
\epsilon_x(E) & = 10^{-6} \\
\epsilon_y(E) & = 10^{-6} \\
\end{align*}$
Injection with $E = 72 \text{ MeV}$ of 50 MHz CW beam.

- High accelerating voltages ($\approx 3\text{ MV/turn}$), 6th harmonic
- Flat-Top cavity (3rd Harm., 150 MHz) to minimize energy spread.
- Precessional enhanced turn separation (Factor $\approx 3$).
- Maximal extracted current so far $I \leq 2.4 \text{ mA}$.
- Typical Beam Power (2 mA) is 1.2 MW, max 1.4 MW.
- No Vortex effect used and unclear if feasible.
- With new flat-top cavity 3 mA possible.
Theoretical Limits (Flat-Top Machines like Ring)

Derived from W. Joho (1981) [6]:

\[ I_{\text{max}} = \varepsilon \frac{3N_h}{g_{1c}16Z_0} \frac{\Delta \phi}{360^\circ} \frac{\Delta E}{e} \beta_{\text{max}} N^{-3}. \]

- \( \varepsilon = \frac{\Delta U_{sc}}{V_{rf}} \approx 1. \)
- With \( g_{1c} = 1.4, \ Z_0 = 377 \Omega, \ N_h = 6, \ \beta_{\text{max}} = 0.789, \)
  \( \Delta E/e = 520 \text{ MV}, \ N = 183 \) and \( \Delta \phi = 6^\circ: \ I_{\text{max}} = 2.38 \text{ mA}. \)
- Max. measured current (so far) \( I_{\text{max}} = 2.4 \text{ mA}. \)
- Again we have very good agreement.
- However: \( \varepsilon \) should probably be much smaller than one.
- Precessional enhancement of turn-separation ignored.
- Formula contains no parameter describing beam halo formation.
- \( \Rightarrow \) this is a good rule of thumb, tweaked for good agreement.
- \( \exists \) reasonable rules of thumb, \( \nexists \) accurate predictions.
The mentioned formulas for $I_{\text{max}}$ are valuable, however:

- **Theoretical (technical)** $I_{\text{max}} \neq \text{practical (legal)} I_{\text{max}}$.
- “Technical” limits for PSI machines are unknown and irrelevant.
- Extracting technical $I_{\text{max}}$ requires a beam dump able to take $I \geq I_{\text{max}}$.
- Extracting $I > I_{\text{max}}$, legal is risky for the machine and leads to further activation.
- ⇒ no save and legal way to determine PSI’s *technical* limit.
- The *legal authorities* define the acceptable activation in the cyclotron vault.

- **Max. activation** ⇒ maximal loss current at given energy. (Typically less than a few (ten) nA loss per location can be accepted.)
- ⇒ The higher the beam current, the lower the allowed *relative* losses!
- ⇒ Turn sep. $\zeta$ must be the larger the higher the current.
- Therefore $\zeta = \zeta(I, \lambda)$ and $\Delta \Phi = \Delta \Phi(I, \lambda)$ where $\lambda$ can be any parameter relevant to halo formation.
Choice of Ion Species & Extraction Method

Stripping Extraction ($H^-$ or $H_2^+$):

- Turn separation irrelevant, extraction by stripping: No limit on beam current (?)
- $H^-$: Weak binding, limited in energy and field due to Lorentz stripping.
- $H_2^+$: Double field strength needed. Lorentz stripping of rotationally excited states?

However there are hard physical limits:

- Rest gas stripping: Geometry determines max. pumping speed.
- Lorentz stripping: determined by magnetic field and energy.

Beam loss + activation not localized: Creates “ambient” activation.

Electrostatic Extractor ($H^+$):

- Beam loss at extraction septa is localized and depends on turn separation and halo.
- No stripping effects limit the maximal current.
- $\exists$ technical means to reduce losses: higher rf-voltage or prec. enhanced turn sep.
- Local losses, at extraction elements, allow for local shielding.
Single Stage vs. Multi Stage Design

Single stage design ("SSD", proposed by Mandrillon [7]):

- SSD is more compact and (of course) less expensive.
- SSD could make use of "vortex effect" up to final energy.
- But: SSD allows for limited number of sectors (AIMA: 6 sectors for ADS [7]).
- Therefore: SSD requires very high power/cavity.

Multi Stage Design "MSD", (pre-acc.+ ) injector + booster:

- MSD requires higher number of components: more expensive, more potential sources for failure.
- Feasibility of vortex effect in booster – after bunch elongation in transfer line – not demonstrated yet.
- MSD commissioning requires ≥ one beam dump / stage.
- MSD allows for different sector numbers of injector + booster.
- MSD allows for a modular design and hence modular upgrades.
- MSD allows for use of intermediate energy beam (72 MeV-beam for IP @HIPA).
Real World Issues of High Power Cyclotrons (1)

- Availability of commercial RF power amplifiers?
- Availability of high power RF tuners and transmission lines.
- Practical Power Limit of RF cavities: $P_{\text{max}} \approx O(1 \text{ MW})$.
  \[ \Rightarrow \approx 10 \text{ cavities and amplifier chains to achieve } P_{\text{beam}} = 10 \text{ MW}. \]
  \[ \Rightarrow \geq 10 \text{ sectors to place the cavities to achieve } P_{\text{beam}} = 10 \text{ MW}. \]
- High number of sectors $\Rightarrow$ injector-cyclotron required.
- High beam power: Interlock-system with large number of loss monitors required.
- High beam power: Huge dynamic range for diagnostic components!
Real World Issues for High Power Cyclotrons (2)

- Required dynamic range (and accuracy) of beam diagnostics $\approx 10^4$.
- Required precision of “realistic” simulations $\approx 10^4$ ($\geq 10^7$ particles/run).
- Even if high computing power is available: How accurate is the knowledge of (fringe-) fields and other variables? (Recall: $< 10^{-4}$ of overall accuracy required!)
- How to do beam development with high power beams? (Risk of damage, interlocks).
- Possible (but expensive) solution: RF kicker system to reduce number of bunches for beam development!
- Still: A high intensity machine in the Mega-Watt range requires to reduce losses down to $< 10^{-4}$.

$\Rightarrow$ Need for a considerable amount of fine-tuning.
The (technical, short term) $I_{\text{max}}$ and the (legal, 24h cont.) $I_{\text{max}}$ can be quite different.

The maximum **continuous** current of high intensity cyclotrons is determined by the losses.

Either losses are caused by beam halo at extraction...

... or by (Lorentz- and Restgas-) stripping during acceleration.

There are possibly means to reduce losses due to halo formation...

... but stripping losses are mostly **fixed by physical laws**.

24h-operation at full beam current requires extremely low losses $< 10^{-4} I_{\text{beam}}$.

Which maximum is most relevant depends on the intended use of machine.

The huge ratio between $I_{\text{beam}}$ and $I_{\text{loss}}$ is challenging:

Difficult to accurately cover huge dynamic range and accurately measure beam-current, -loss and -halo.
Thank You.

Matched Beam in Ideal Ring Cyclotron

From Contrib. to Cycl. Conf (2013, Vancouver) [12]:

Matched beam, flat phase (black):

All Emittances: $\pi/2$ mm mrad

$\phi(E)$

$\epsilon_x(E)$

$\epsilon_y(E)$

$E$ (MeV)
From Contrib. to Cycl. Conf (2013, Vancouver) [12]:

Matched beam, red phase:
From Contrib. to Cycl. Conf (2019, Capetown) [13]:

OPAL results for a matched coasting beam at 1 MeV in Injector II.
From Contrib. to Cycl. Conf (2019, Capetown) [13]: Using OPAL simulations to test the simplified linear model:
Fast vs. slow acceleration at low energy:

\[
V = 100\% \\
V = 50\% \\
V = 25\% 
\]
From Contrib. to Cycl. Conf (2019, Capetown) [13]:

- Top: Positive $V' > 0$: Bunch deforms quickly.
- Bottom: Negative $V' < 0$: Bunch size increases continuously.
From Contrib. to Cycl. Conf (2019, Capetown) [13]:

- RF-phase $\phi = -90^\circ$: No acceleration, “bunching” phase.
- RF-phase $\phi = 90^\circ$: No acceleration, “debunching” phase.

$V = 10\%$, $\phi = -90^\circ$, bunching

$V = 10\%$, $\phi = 90^\circ$, debunching

![Graphs showing bunching and debunching effects with various runs and turns.](image-url)