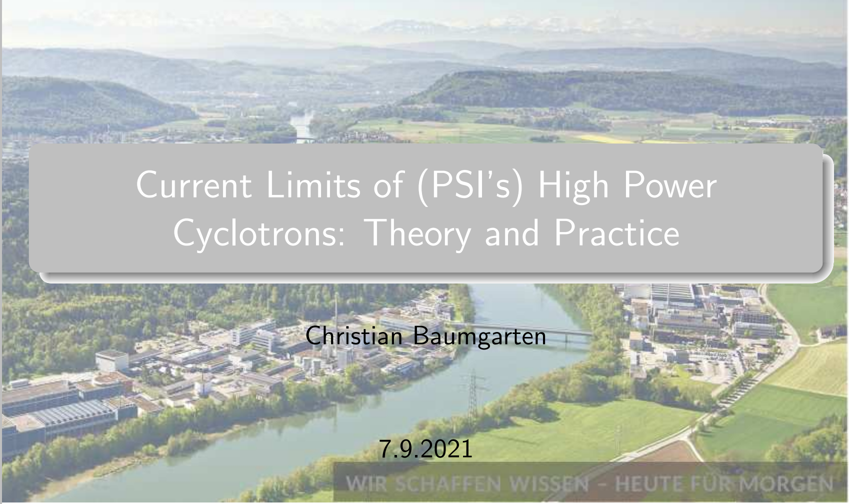

Current Limits of (PSI's) High Power Cyclotrons: Theory and Practice

Christian Baumgarten

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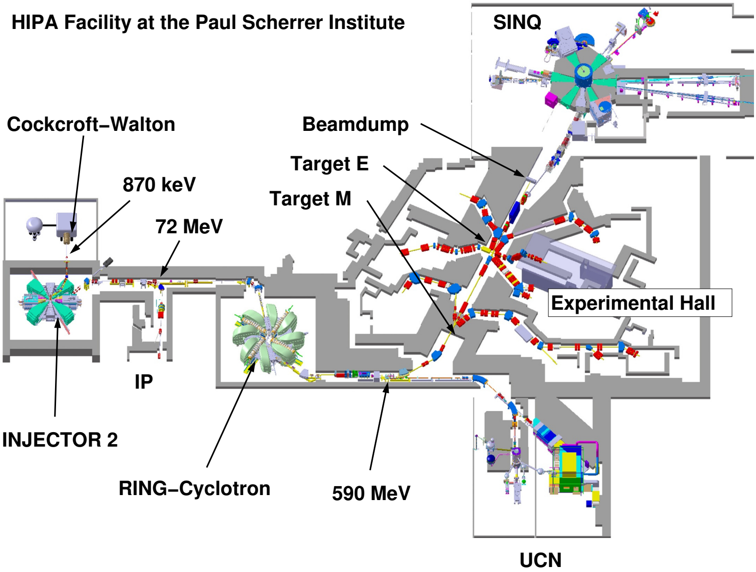
Outline

PSI High Intensity Proton Acc. (HIPA)

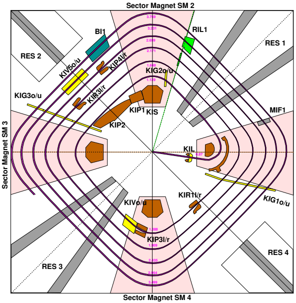


Cockcroft-Walton and Injector 2

- Compact microwave ECR ion source $E = 60\,\mathrm{keV}$, $\varepsilon_{nrm} = 0.045\,\pi\,\mathrm{mm\,mrad}$ ($\varepsilon_{1\sigma} = 4\,\pi\,\mathrm{mm\,mrad}$).
- CW-Accelerator $V = 810\,\mathrm{keV}$ then proton energy $E = 870\,\mathrm{keV}$
- $10\,\mathrm{mA}$ of DC beam, axial injection after bunching with $50\,\mathrm{MHz}$.
- 4 separate sectors (high flutter, enough space for resonators, probes and extractor).
- High accelerating voltages ($\approx 1\mathrm{MV/turn}$), high (10th) harmonic number.
- Residual $2.2\,\mathrm{mA}$ 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 $\varepsilon_{1\sigma} = 0.113\,\pi\,\mathrm{mm\,mrad}$, fitted after Injector II $\varepsilon_{1\sigma} = 1.138\,\pi\,\mathrm{mm\,mrad}$ (increase by factor 10).
- $\Rightarrow$ round bunches, no flat-top cavity required.
- Max extracted current so far $I \leq 2.7\,\mathrm{mA}$.

The Vortex Effect in Injector 2

- Bunching (first and third harm. buncher) of DC beam.
- Many collimators (horz. + vert.) below Coulomb threshold for removal of halo [11].
- 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 $\nu_{x,z} \approx 1.3 \ldots 1.7$.
- $\Rightarrow$ very conservative design (expensive, but high quality).



Theoretical Limits (Vortex Effect)

Baartman 2013 (values at extraction) [5]:

$$I_{\max} = \frac{h}{2\, g_r\, \zeta^3\, \beta^3\, \gamma\, \nu_x^4}\, \frac{V_{\rm rf}^3}{V_m^2\, Z_0}$$

where $V_m = m_p\, c^2/e$ and "formfactor" $g_r \approx 1$.

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

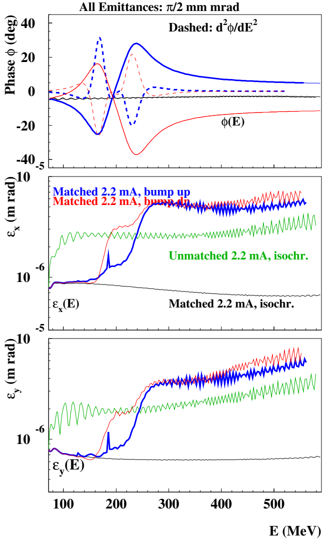
Vortex Effect is "Metastable"

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:

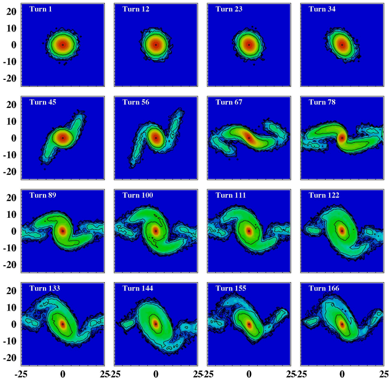
- Poor isochronism [8, 12].
- Too asymmetric emittances [12].
- Wrong rf phase ("bunching") [13].
- Too strong voltage gradient at low energy [13].
- Poor adiabaticity: $\frac{\Delta E}{E}$ too large [13].
- None of these distortions considered in I_{max}-formula.

Example: Isochronous Machine with Field Bump

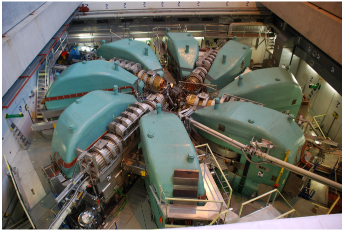
From Contrib. to Cycl. Conf (2013, Vancouver) [12]:



Matched beam, blue phase:



Ring Cyclotron



- Injection with $E = 72\,\mathrm{MeV}$ of $50\,\mathrm{MHz}$ CW beam.
- High accelerating voltages ($\approx 3\mathrm{MV/turn}$), 6th harmonic
- Flat-Top cavity (3rd Harm., 150 MHz) to minimize energy spread.
- Precessional enhanced turn separation (Factor ≈ 3).
- Maximal extracted current so far $I \leq 2.4\,\mathrm{mA}$.
- Typical Beam Power ($2\,\mathrm{mA}$) is $1.2\,\mathrm{MW}$, max $1.4\,\mathrm{MW}$.
- No Vortex effect used and unclear if feasible.
- With new flat-top cavity $3\,\mathrm{mA}$ possible.

Theoretical Limits (Flat-Top Machines like Ring)

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

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

- $\varepsilon = \frac{\Delta U_{\rm sc}}{V_{\rm rf}} \approx 1$.
- With $g_{1c} = 1.4$, $Z0 = 377\,\Omega$, $N_h = 6$, $\beta_{\max} = 0.789$, $\Delta E/e = 520\,\mathrm{MV}$, $N = 183$ and $\Delta\phi = 6^\circ$: $I_{\max} = 2.38\,\mathrm{mA}$.
- Max. measured current (so far) $I_{\max} = 2.4\,\mathrm{mA}$.
- Again we have very good agreement.
- However: ε 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.

Practical Limits of Predicting Practical Limits

The mentioned formulas for I_{max} are valuable, however:

- **Theoretical (technical)** $I_{\mathrm{max}} \neq$ **practical (legal)** I_{max}.
- "Technical" limits for PSI machines are *unknown and irrelevant*.
- Extracting technical I_{max} requires a beam dump able to take $I \geq I_{\mathrm{max}}$.
- Extracting $I > I_{\mathrm{max,legal}}$ is risky for the machine and leads to further activation.
- $\Rightarrow$ no save and legal way to determine PSI's *technical* limit.
- The *legal authorities* define the acceptable **activation** in the cyclotron vault.
- **Max. activation** $\Rightarrow$ maximal loss current at given energy. (Typically less than a few (ten) nA loss per location can be accepted.)
- $\Rightarrow$ The higher the beam current, the lower the allowed *relative* losses!
- $\Rightarrow$ Turn sep. ζ must be the larger the higher the current.
- Therefore $\zeta = \zeta(I, \lambda)$ and $\Delta\Phi = \Delta\Phi(I, \lambda)$ where λ 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.
- ∃ 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 $\geq$ 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?
- Availibility of high power RF tuners and transmission lines.
- Practical Power Limit of RF cavities: $P_{\rm max} \approx \mathcal{O}(1\,{\rm MW})$.
- $\Rightarrow \approx 10$ cavities and amplifier chains to achieve $P_{\rm beam} = 10\,{\rm MW}$.
- $\Rightarrow \geq 10$ sectors to place the cavities to achieve $P_{\rm beam} = 10\,{\rm MW}$.
- 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.

Summary and Conclusions

- The (technical, short term) $I_{\max}$ and the (legal, 24h cont.) $I_{\max}$ 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 $< 10^{-4}\, I_{\mathrm{beam}}$.
- Which maximum is most relevant depends on the intended use of machine.
- The huge ratio between I_{beam} and I_{loss} is challenging:
- Difficult to accurately cover huge dynamic range and accurately measure beam-current, -loss and -halo.

References

Thank You.

[1] C. Chasman and A. J. Baltz "Space Charge Effects in a Heavy Ion Cyclotron"; NIM **219** (1984), pp. 279-283.

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[3] R. Koscielniak and S. Adam "Simulation of Space-Charge Dominated Beam Dynamics in an Isochronous AVF Cyclotron", Proc. PAC 1992, pp. 3639-3641.

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[6] W. Joho, High Intensity Problems in Cyclotrons, Proc. 5th intl. Conf. on Cycl. Appl., Caen 1981.

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[9] J. J. Yang, A. Adelmann, M. Humbel, M. Seidel, and T. J. Zhang, Phys. Rev. ST Accel. Beams 13, 064201 (2010).

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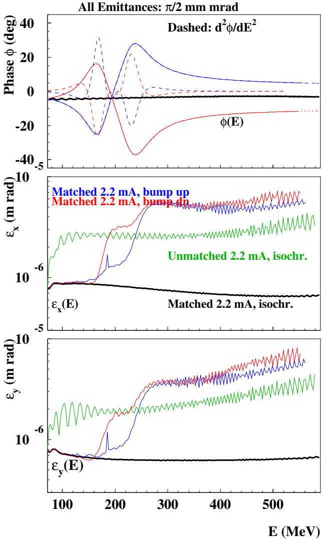
[11] A.Kolano *et al* "Intensity limits of the PSI Injector II cyclotron"; NIM A **885** (2018), 54–59.

[12] C. Baumgarten "Transverse-Longitudinal Coupling by Space Charge in Cyclotrons"; Proc. Cycl. Appl. 2013, pp. 316-319.

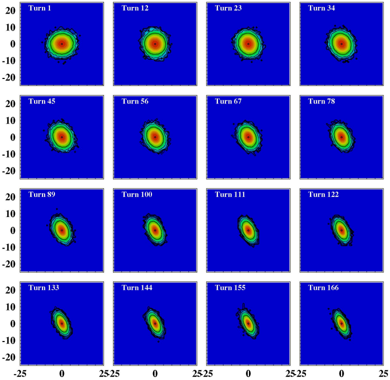
[13] C. Baumgarten "Factors Influencing The Vortex Effect In High-Intensity Cyclotrons"; Proc. Cycl. Appl. 2019, pp. 270-274.

Matched Beam in Ideal Ring Cyclotron

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

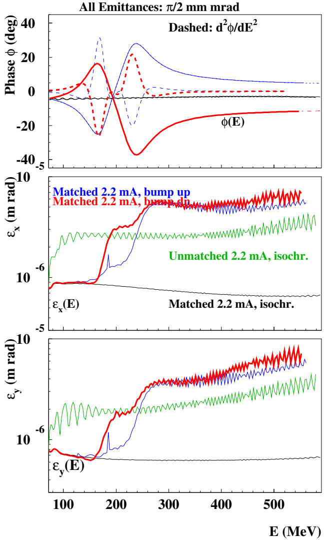


Matched beam, flat phase (black):

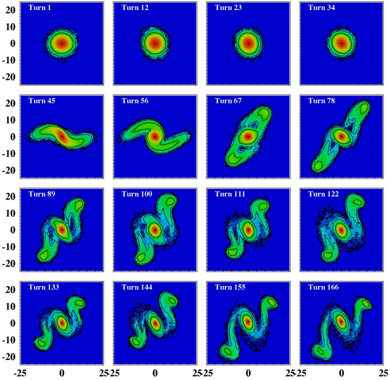


Matched Beam with Bump "U" (Ring)

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

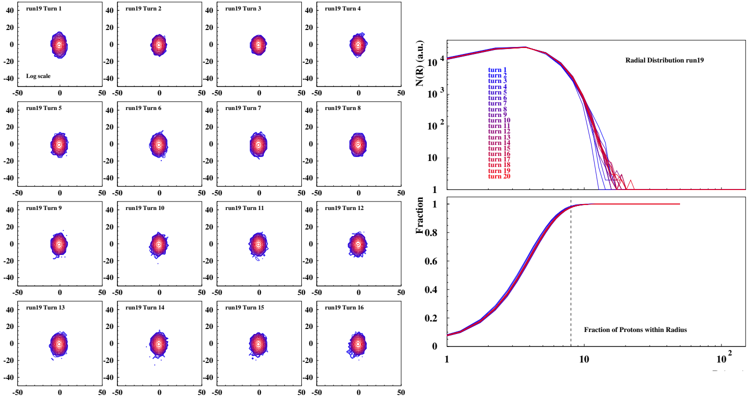


Matched beam, red phase:



Coasting Beam in PSI Injector II

From Contrib. to Cycl. Conf (2019, Capetown) [13]:

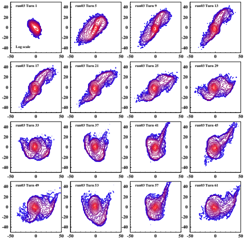


OPAL results for a matched coasting beam at 1 MeV in Injector II.

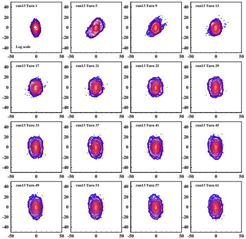
Adiabatic Approximation I (Inj. II)

From Contrib. to Cycl. Conf (2019, Capetown) [13]: Using OPAL simulations to test the simplified linear model:
Fast vs. slow acceleration at low energy:

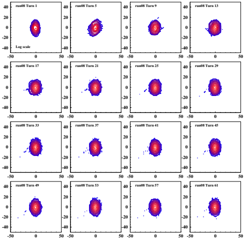
$V = 100\,\%$



$V = 50\,\%$

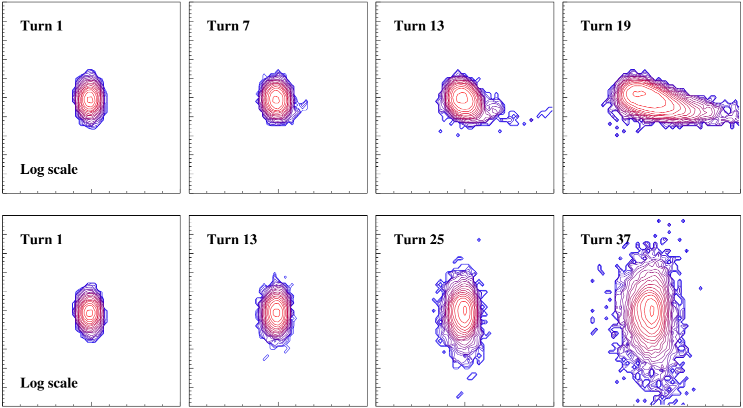


$V = 25\,\%$



Strong RF Voltage Gradients (Inj. II)

From Contrib. to Cycl. Conf (2019, Capetown) [13]:



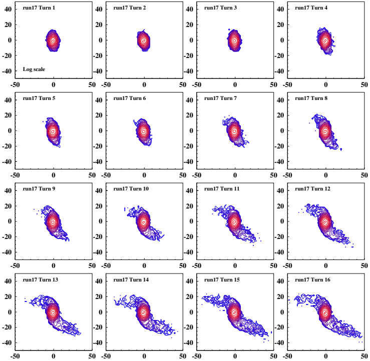
- Top: Positive $V' > 0$: Bunch deforms quickly.
- Bottom: Negative $V' < 0$: Bunch size increases continuously.

(De-)Bunching by RF Voltage (Inj. II)

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