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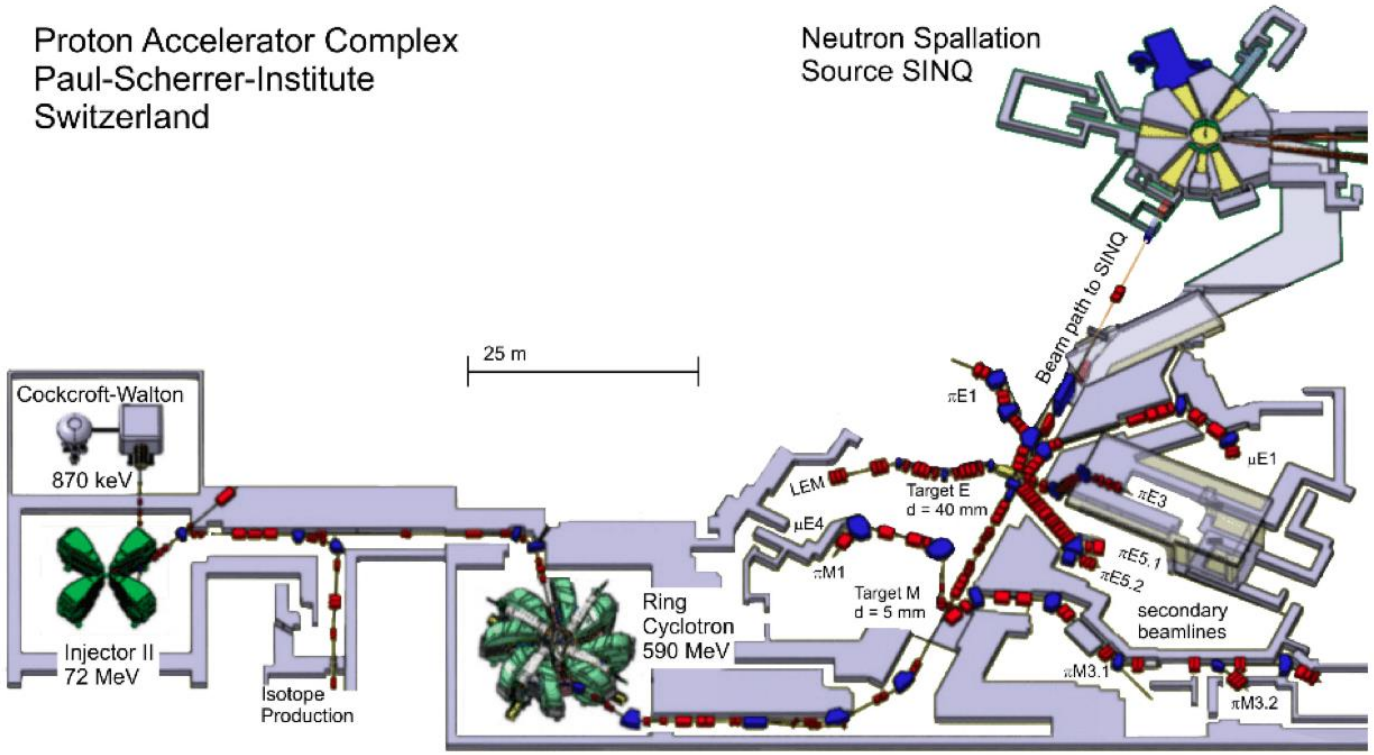
for Accelerator Applications

A Precise 3D Beam Dynamics Model of the PSI Injector II

12th September 2016

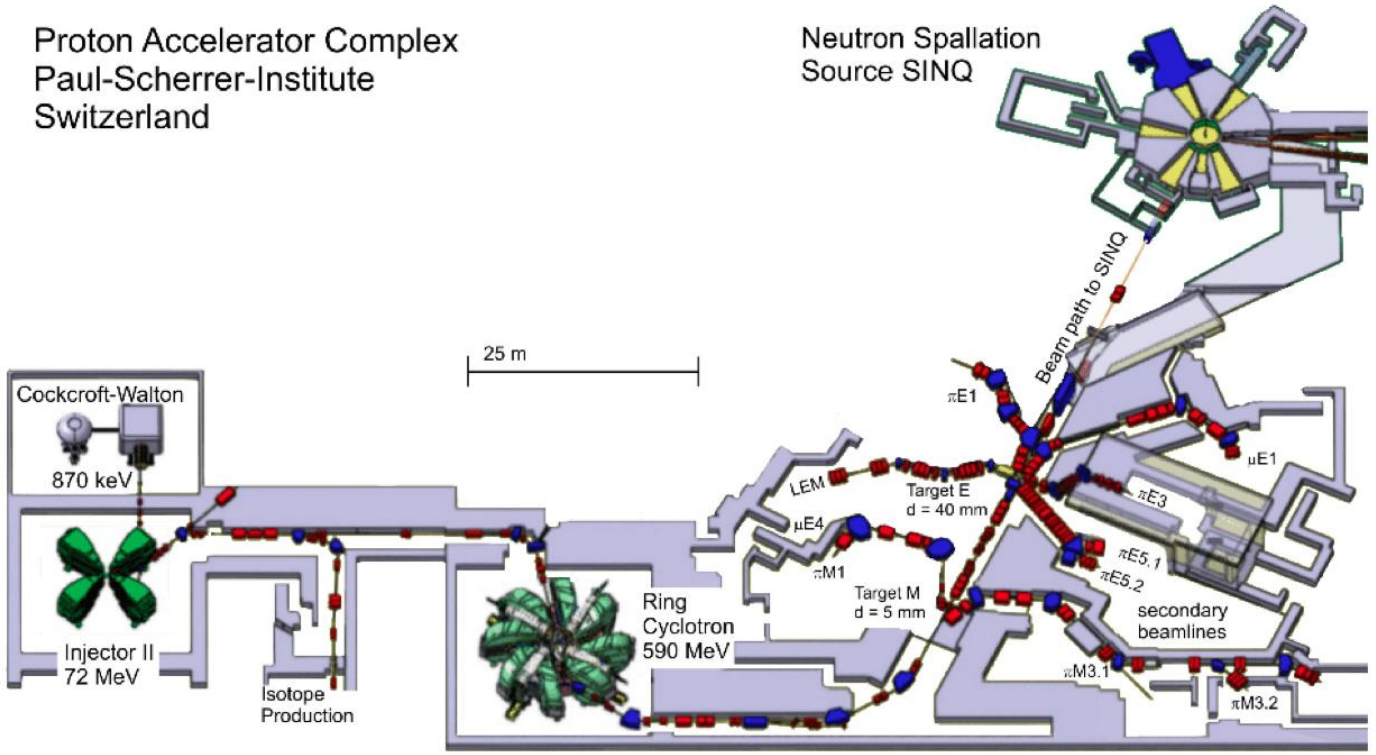
Anna M. Kolano

In this talk …



- Delivers **2.4 mA CW 1.416 MW** proton beam
- Chain of accelerators: 870 keV → 72 MeV → **590 MeV**
- **Planned upgrade to 3 mA** will involve both accelerators

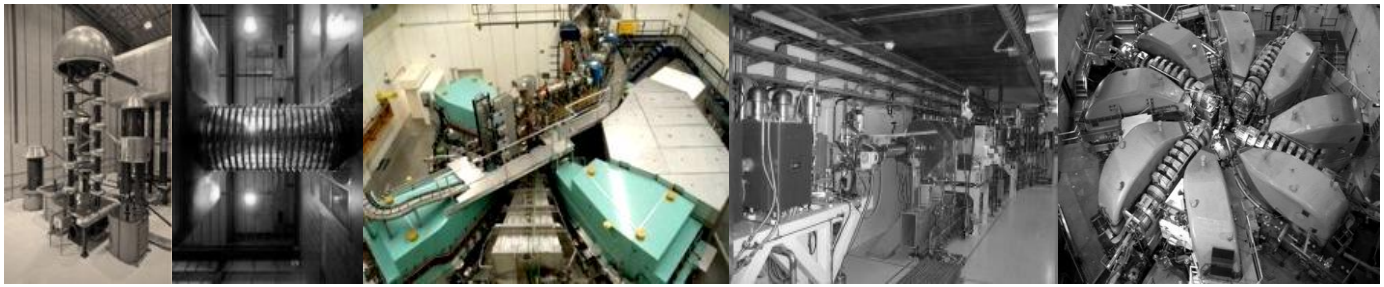
In this talk …



The big picture

3D beam dynamics model of Injector II with space charge

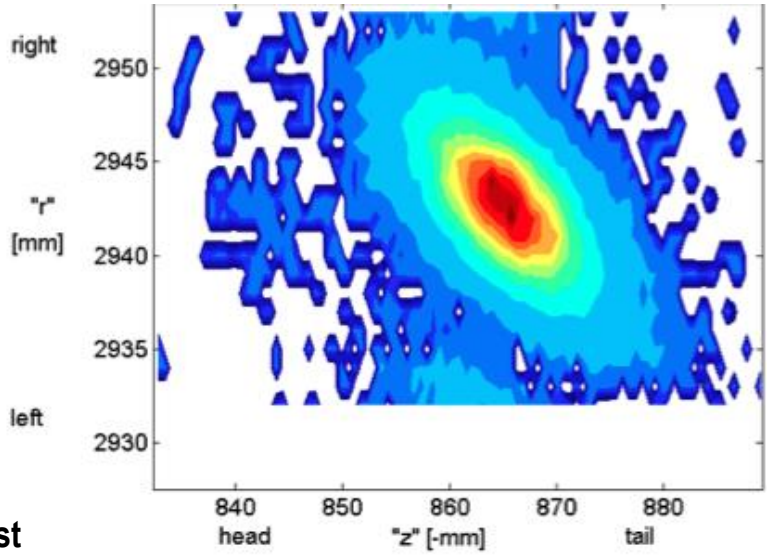
- What are the true intensity limits of Injector II?
- To understand the machine after the upgrade
- Can an Injector II-type machine be used for future projects ?



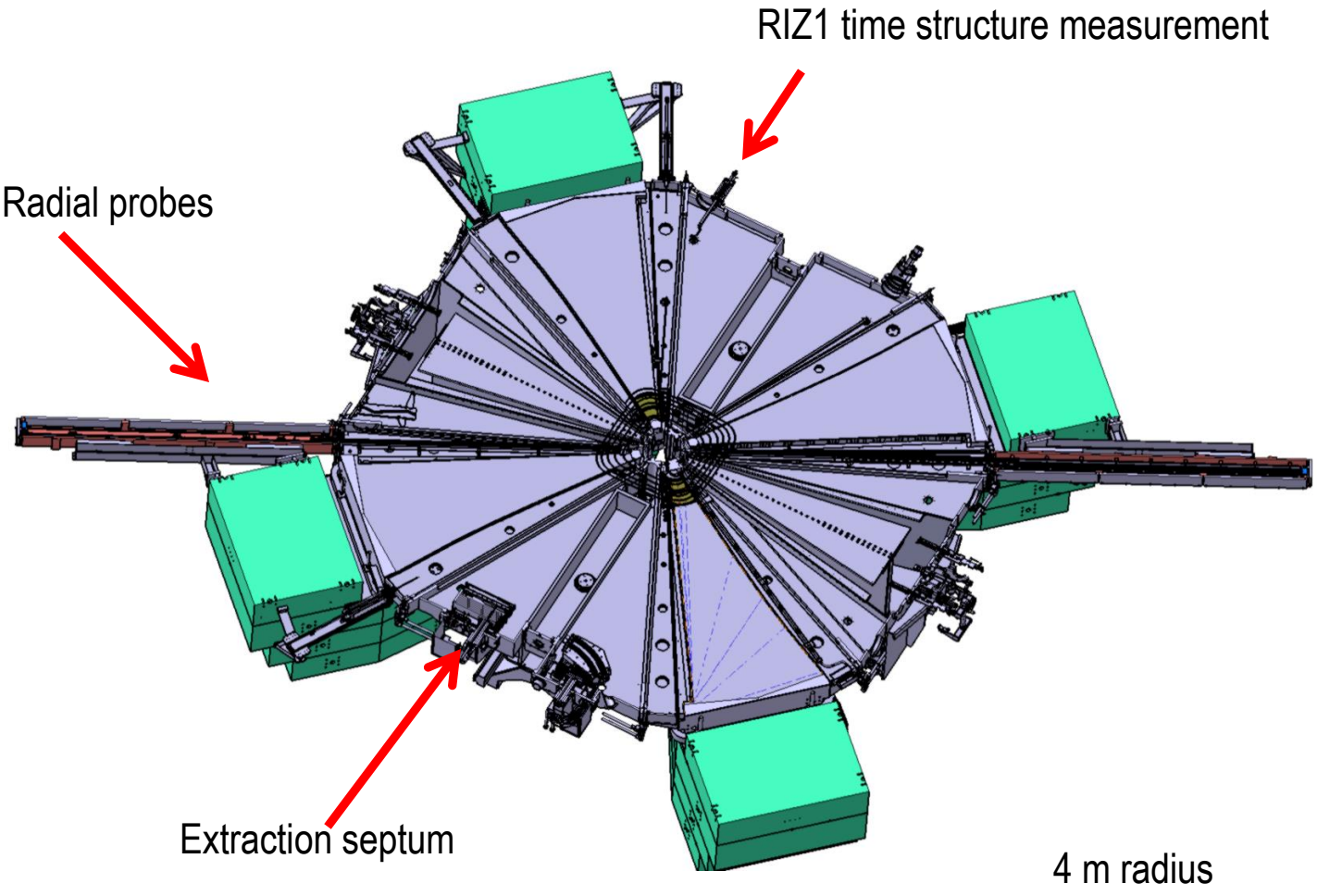
Injector II

- 4 separate sector isochronous cyclotron
- Hill field of 2 T
- 72 MeV in 83 turns in the production mode
- Injected beam current ~ **11 mA** DC→**2.2 mA** CW
- Accelerator Frequency 50.63 MHz
- **Quasi-stationary distribution formed over first several turns due to space charge forces combined with strong radial-longitudinal coupling**

RIZ1

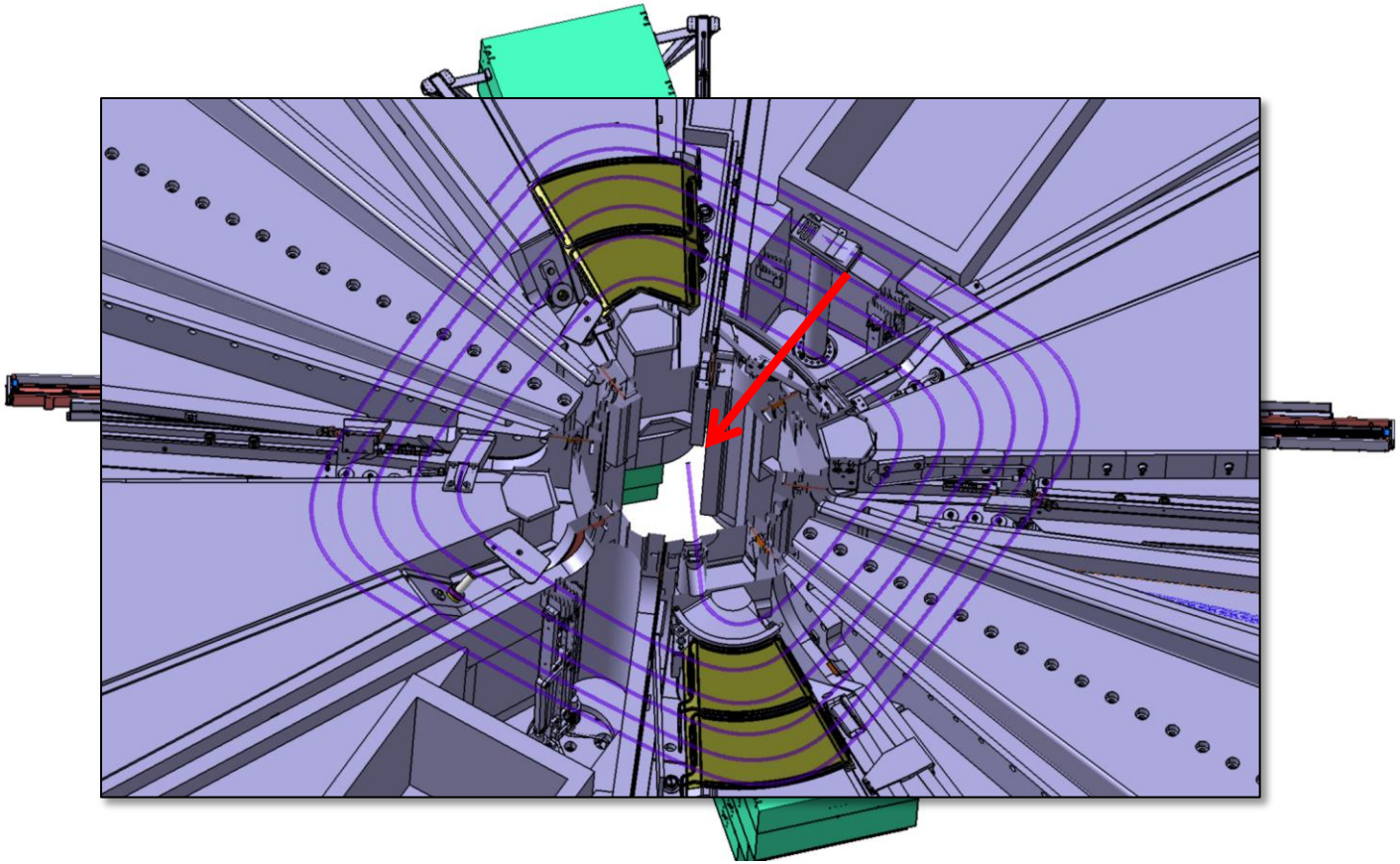


Injector II



Courtesy: Richard Kan, PSI

Injector II



- Injected uncoupled **11 mA** DC beam
- Cleaned with 14 collimators (8 in the model)

Courtesy: Richard Kan, PSI

How do we do it?

The Goal: minimize halo at the extraction →minimise losses in HIPA

OPAL
(Object Oriented Particle Accelerator Library)
- C++ framework for general particle accelerator simulations
- Open source
- **3D Space charge**
- **Massively parallel**
- Particle-matter interaction
- **Multi-objective optimisation.**

- OPAL
- Initial conditions (matched distribution* linear space-charge model)
- Accelerated bunch for 0.5 – 10 mA (non-linear model)
- We consider 2 configurations: Production and Upgraded

*C. Baumgarten, "A Symplectic Method to Generate Multi-variate Normal Distributions", arXiv:1205.3601v.

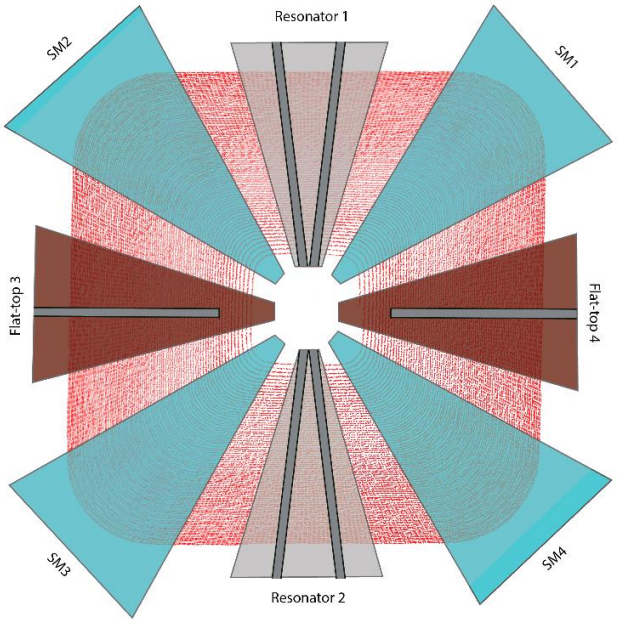
** C. Baumgarten,"Transverse-Longitudinal coupling by Space charge in Cyclotrons", Phys. Rev. ST Accel. Beams 14, 114201, 2011.

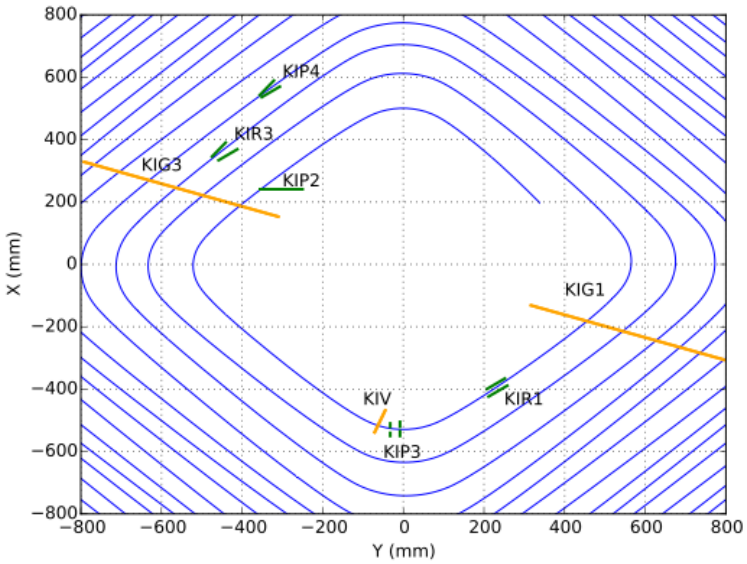
Models of collimation

- 3 models* under 2 configurations: **Production** and Upgraded
  - *Continuous 4 sigma cut*
  - *6-turn 4 sigma cut*
  - *Physical Collimator*

*A.M. Kolano. *A precise 3D beam dynamics model of the PSI Injector II*. PhD Thesis,The University of Huddersfield, 2016.

- Radial data comparable accross all models





2 mA beam in 83 turns

Models of collimation

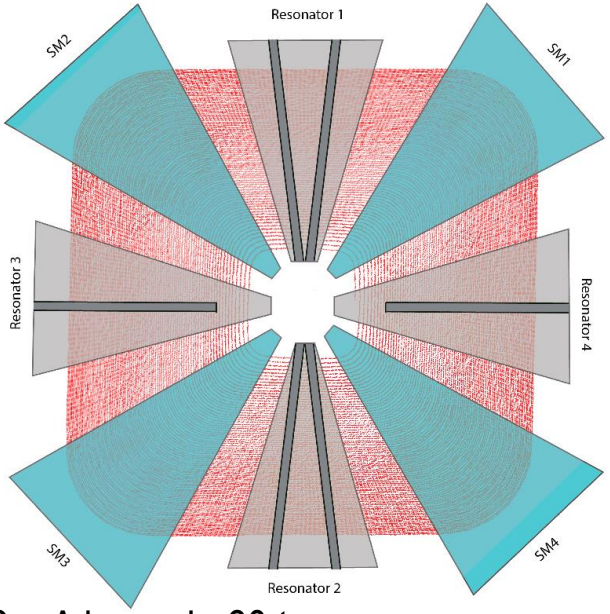
- 3 models under 2 configurations: Production and **Upgraded**

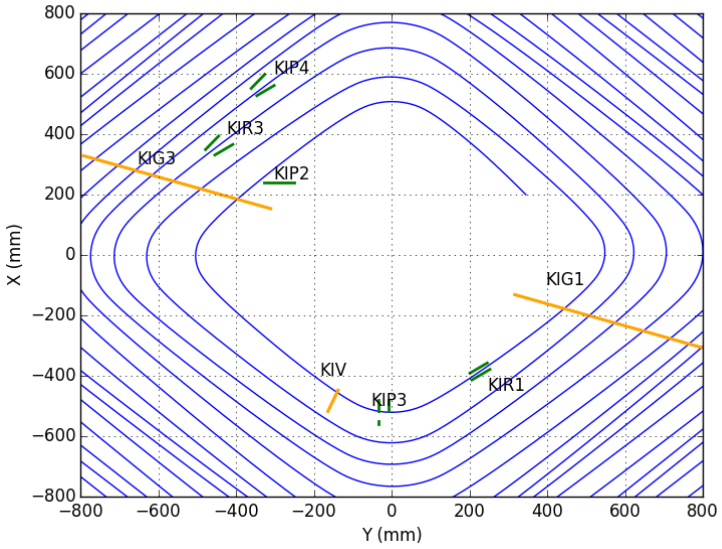
- Continuous 4 sigma cut

- 6-turn 4 sigma cut

- Physical Collimator

- Radial data comparable accross all models

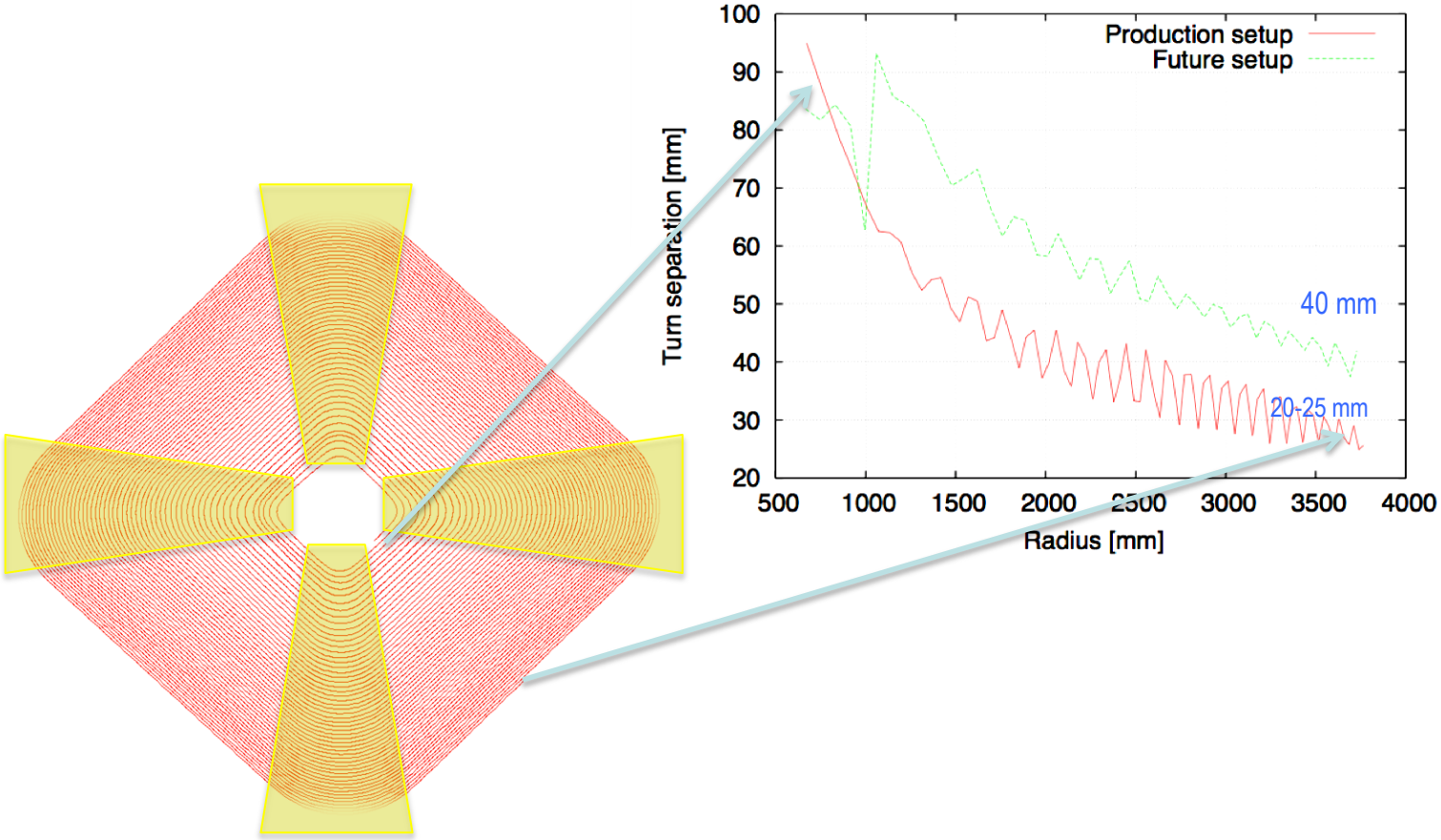




3 mA beam in 60 turns

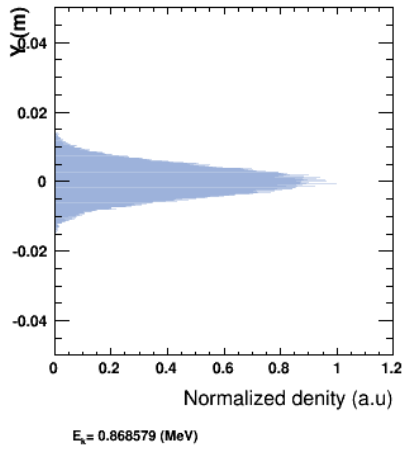
The same central/extraction region

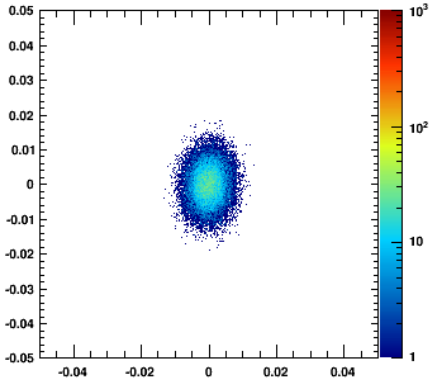
Configurations of Injector II

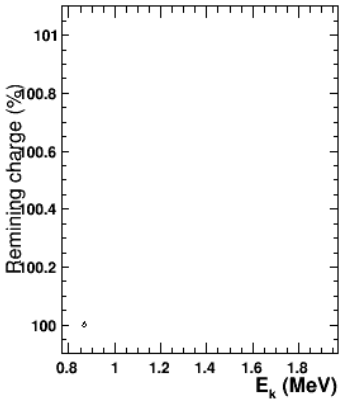


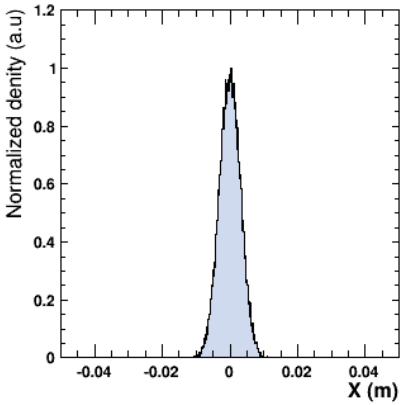
Production set-up with collimators

Space charge simulation with collimators over the first 9 turns
9.5 mA → 2 mA



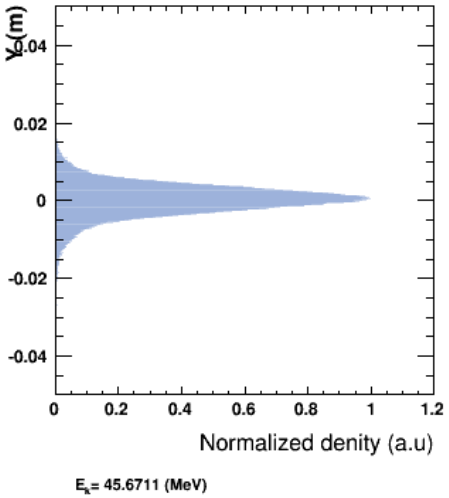


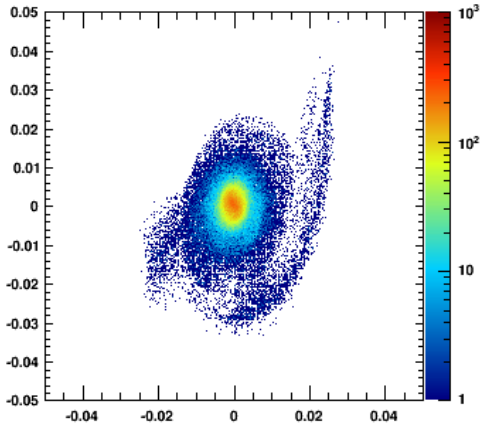


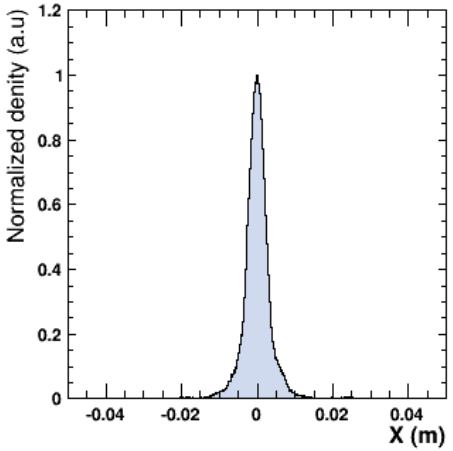


Space charge is not all that bad!

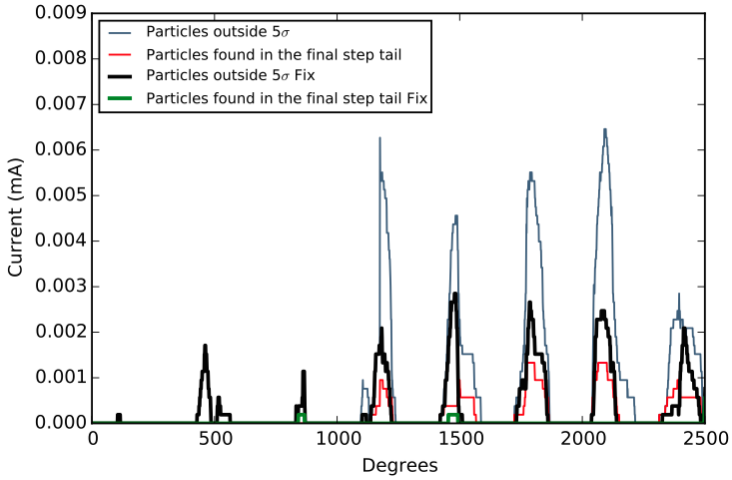
Last turns

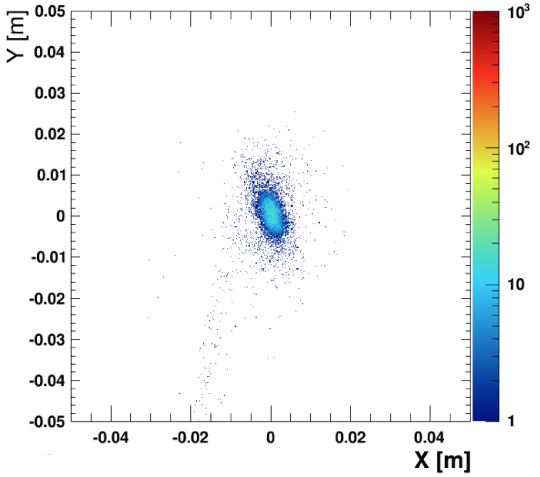




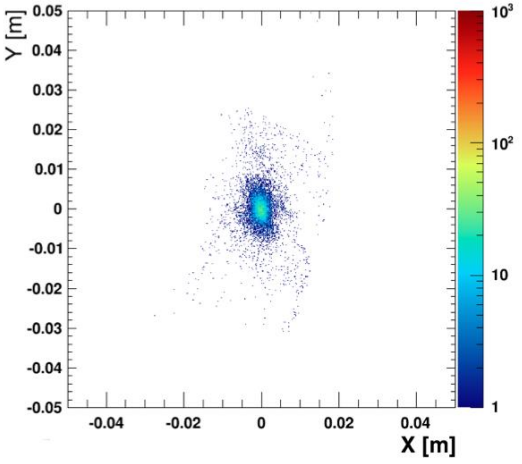


Halo and tail cleaning with KIP4 collimator





- Long longitudinal tail due to mismatch and/or misplaced collimators
- Eventually couples to the radial plane
- We can tag last step halo and track it back to its origins
- Successfully removed with KIP4 collimator

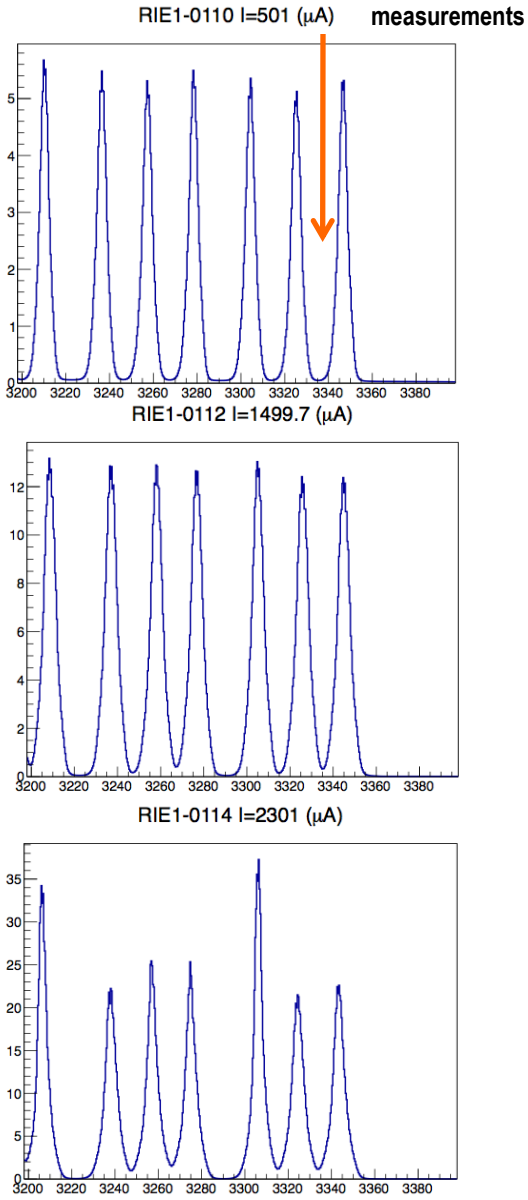


Measurements: radial profile

- Orbit pattern changes with intensity in Injector II
- KIP2 collimator cuts away large parts of the beam changing the betatron oscillations
- **Trim coils** are also used to force pattern that keeps the last valley in the same place
- Off-centered injection
- ν_r is kept at 1.3 over the last few turns

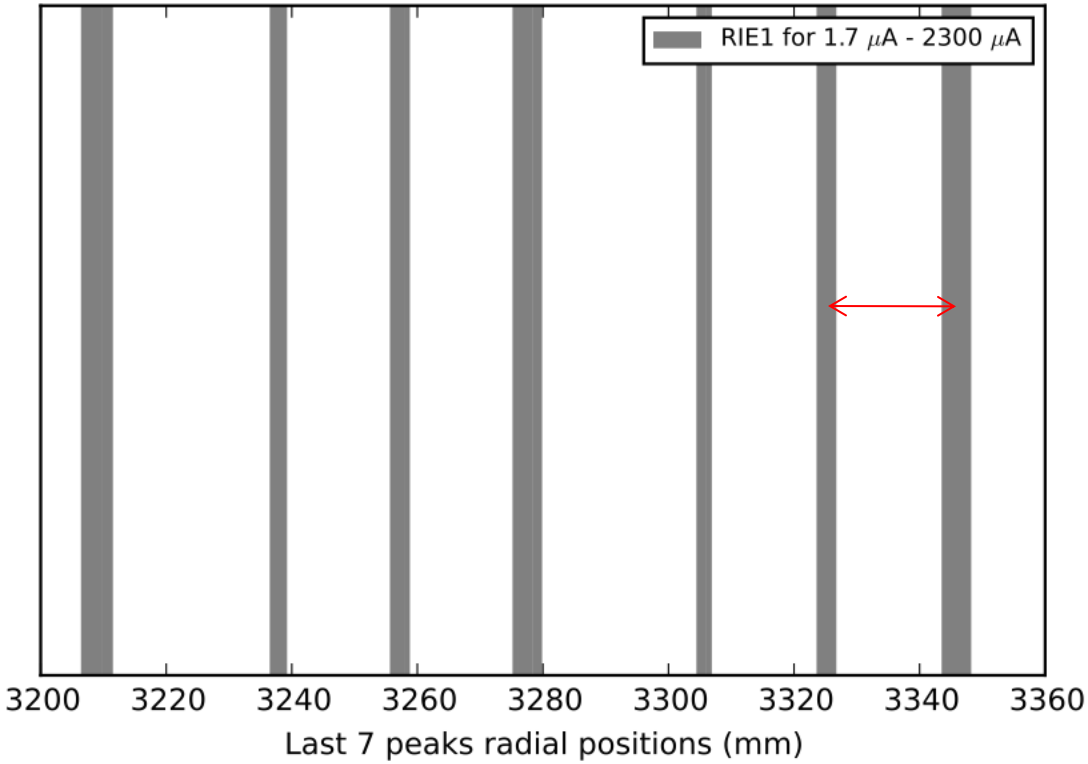
Optimizing python script to reproduce in simulations:

Parameters	
Objectives	**Design Variables**
Fixed peak position at extraction	Voltage offset
Min Δ peaks	Radius
~2	**~2**



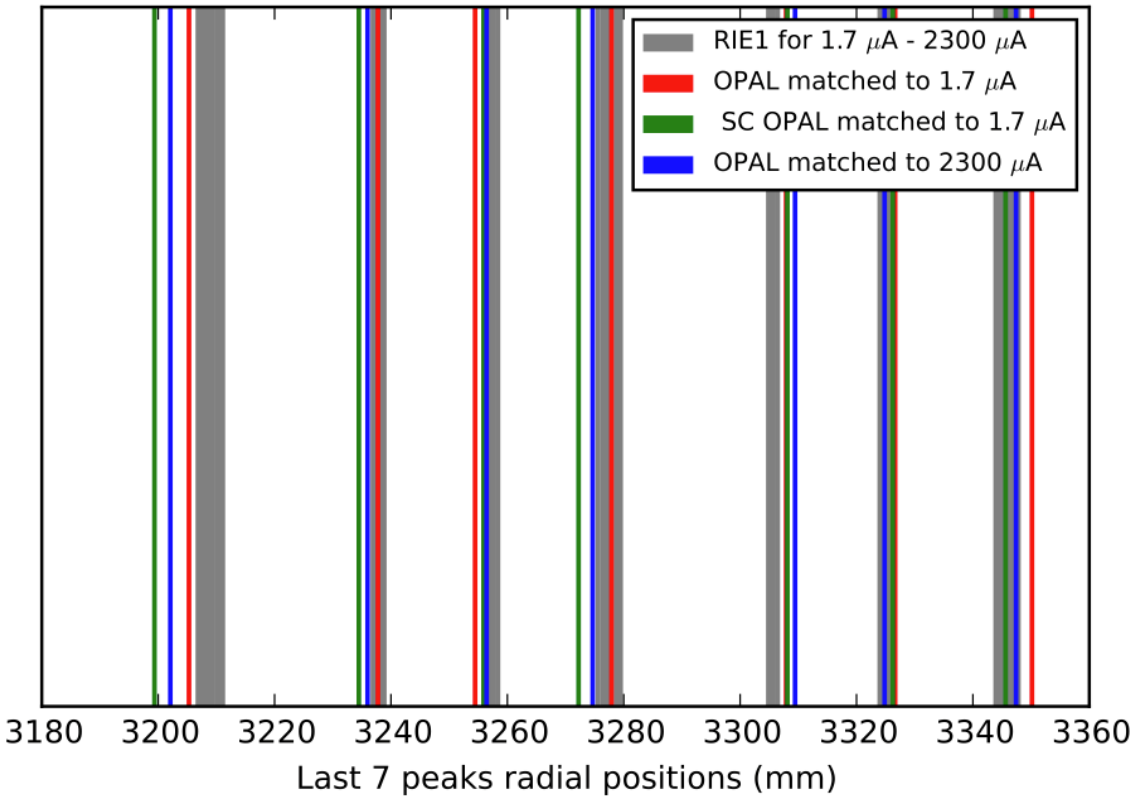
Radial peak positions

Injector II radial intensity peak **ranges**



Radial peak positions

Run the same initial conditions with full space charge

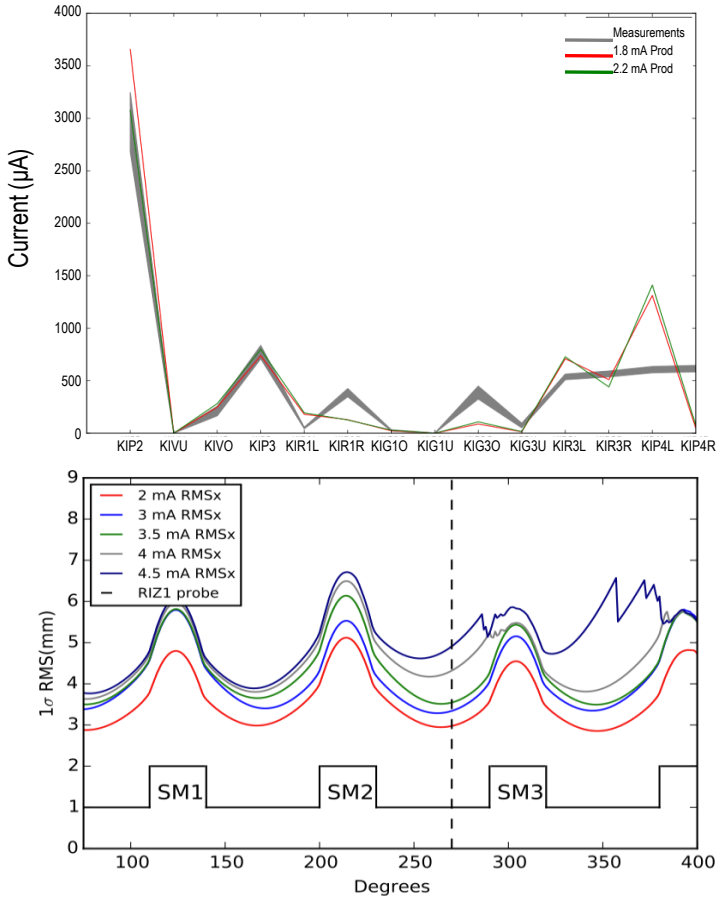


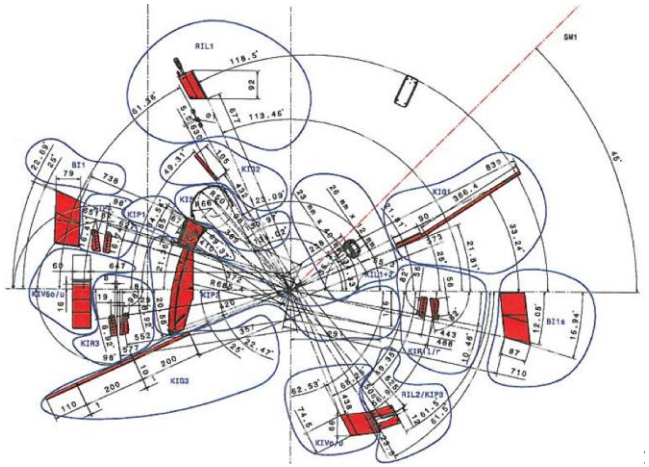
Validation

➢ Optimisation of initial conditions (r, pr, azimuth etc) using GA based *optPilot*

➢ Ensure correct Injector II parameters : turn number , energy, injection/extraction radius, radial turn pattern, current on collimators and their positions, cyclotron and RF frequency

➢ Benchmark with probe measurements: extracted current, RIE1 probe for radial intensity pattern, RIZ1 beamsize

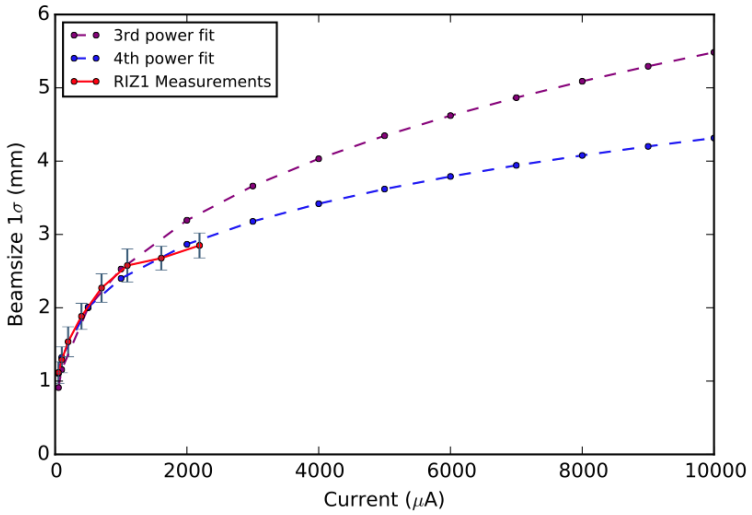


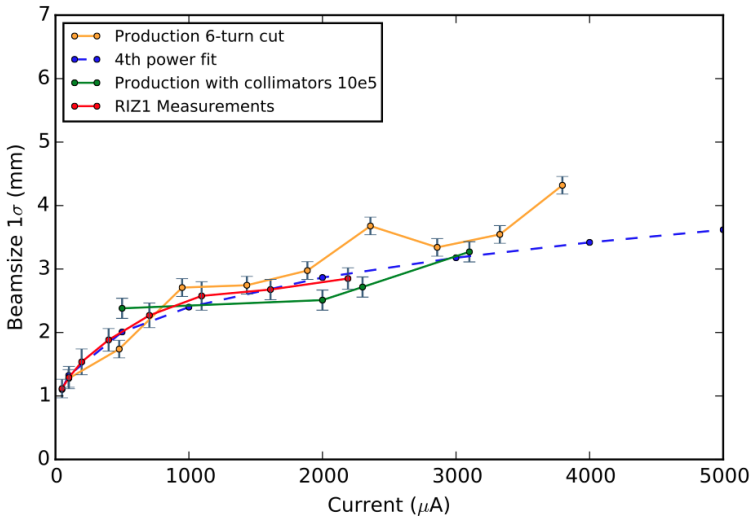


Central region collimators at energies between 0.87 and 2.5 MeV

Intensity limits of Injector II

➢ Following up on Joho`s scaling law** $I_{max} \propto V^3$ also for beamsize, with slightly better fit at power of 4, that is particularly good at higher intensities





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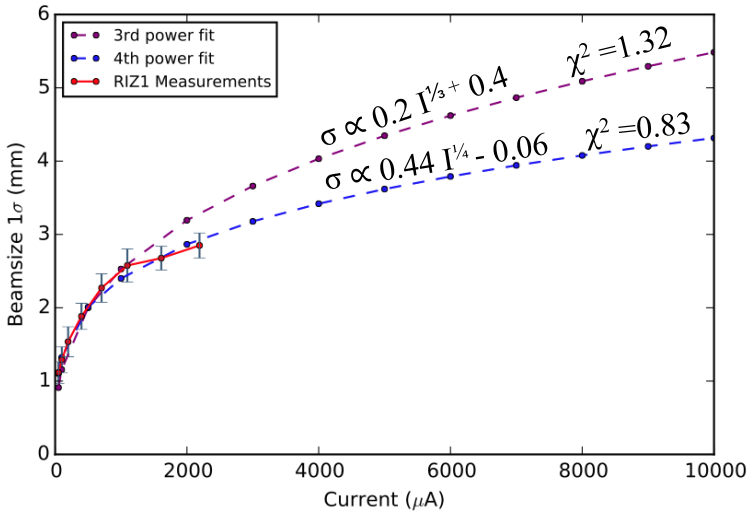
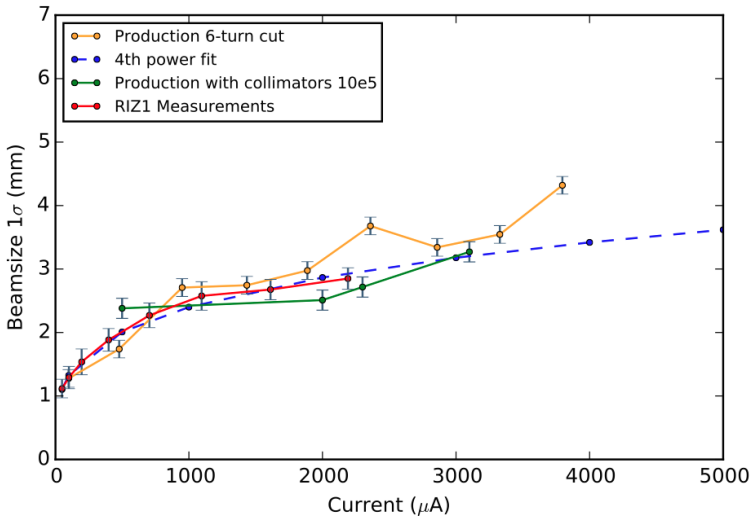
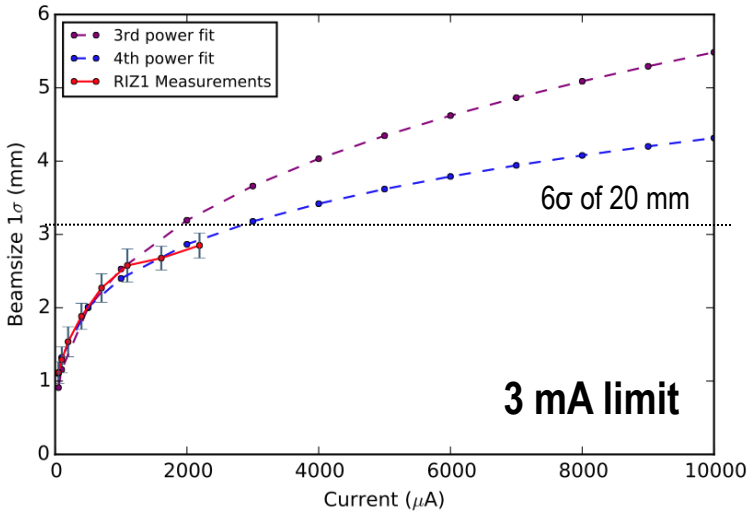
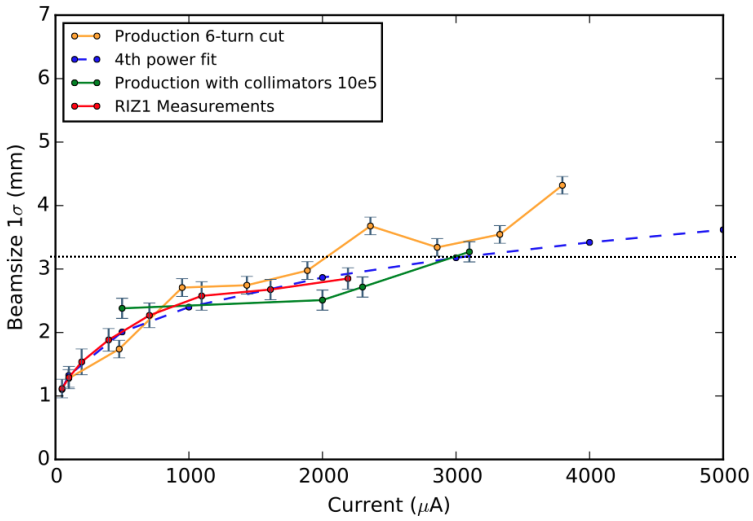




Intensity limits of Injector II

- Following up on Joho`s scaling law** $I_{max} \propto V^3$ also for beamsize, with slightly better fit at power of 4, that is particularly good at higher intensities
- Simplified models say **approx 2.2 mA*** (we already know **2.7 mA** was extracted) → strong transverse-longitudinal coupling combined with space charge sets higher limits
- Our models/fits predict **new 3mA limit** with existing configuration
- After the upgrade even up to 5mA could be possible





*R. Baartman. Space charge limit in separated turn cyclotrons. In *Proc. 21st Int. Conf. on Cyclotrons and their Applications*, Vancouver, Canada, 2013
**W. Joho, in *Proc. 9th Int. Conf. on Cyclotrons and their Applications* ,Caen, 1981, p. 337.

Summary

University of HUDDERSFIELD
International Institute for Accelerator Applications

NGA CDT

EPSRC
Engineering and Physical Sciences Research Council

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- Currents higher than 2.7 mA should be achievable
- Thanks to space charge and tuning of collimator positions
- New RF cavities will set the limits even higher

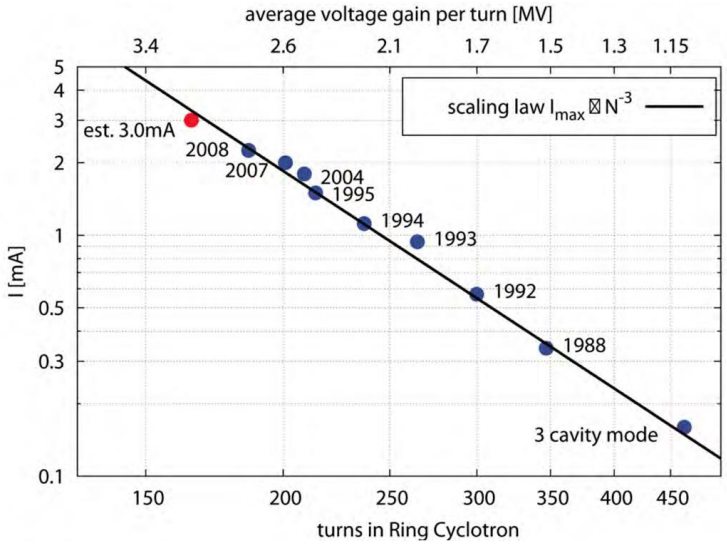
I would like to express my sincere gratitude to Prof Roger Barlow (IIAA), Dr Andreas Adelmann (PSI), Dr Christian Baumgarten (PSI) and colleagues from PSI and the University of Huddersfield for their support, guidance and expertise during this research

Joho's scaling law

- Is the motivation of improving the RF to get higher intensities
- 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
- with constant losses at the extraction electrode the maximum attainable current scales as:

$$I_{max} \propto turn\#^{-3}$$

$$Loss \propto turn\#^{3}$$



Ref: W. Joho, in Proc. 9th Int. Conf. on Cyclotrons and their Applications (Caen, 1981), p. 337.