PAUL SCHERRER INSTITUT PSI

University of HUDDERSFIELD
International Institute for Accelerator Applications

Studies of the PSI Injector II high current cyclotron

2nd September 2016

Anna M. Kolano

Prof Roger Barlow (University of Huddersfield)
Dr Andreas Adelmann (PSI)
Dr Christian Baumgarten (PSI)

In this talk …

The big picture

Injector II

Approach

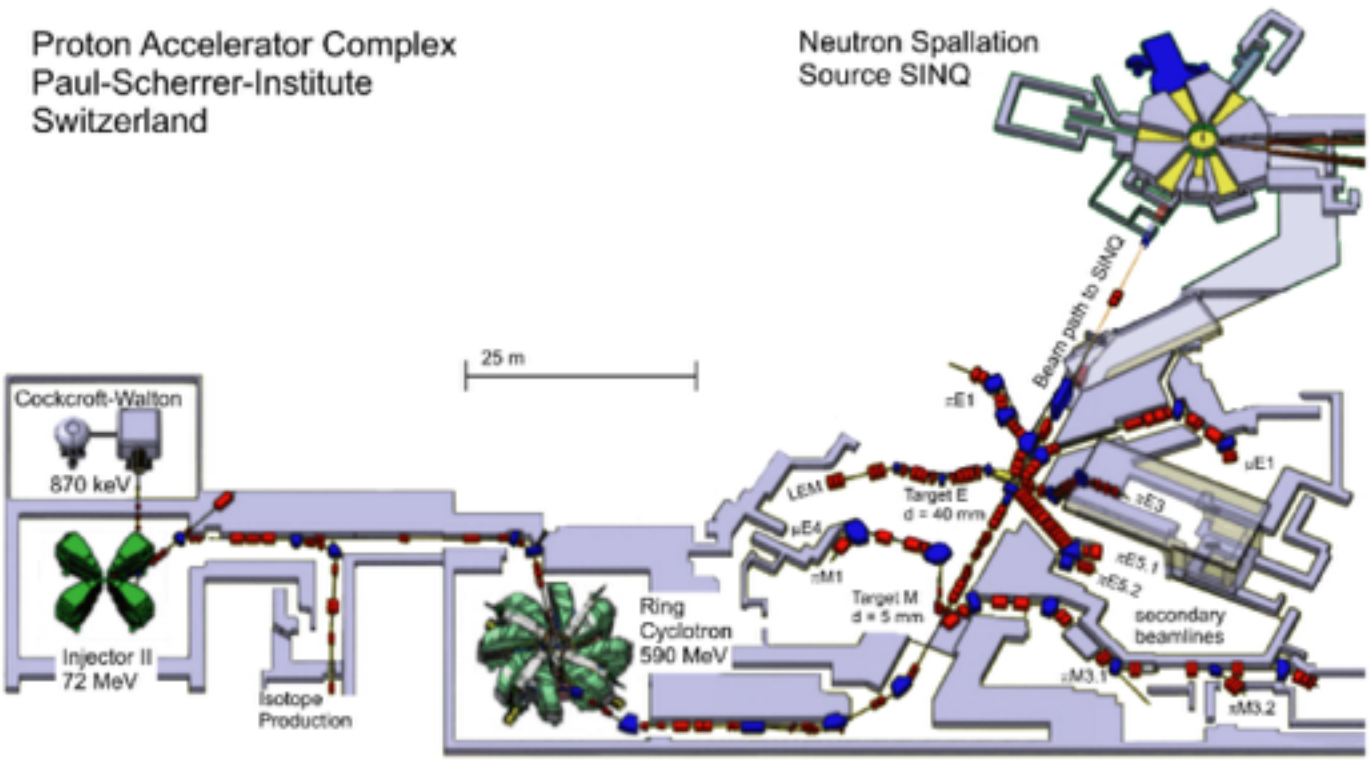
Models

Physical collimator model

Validation

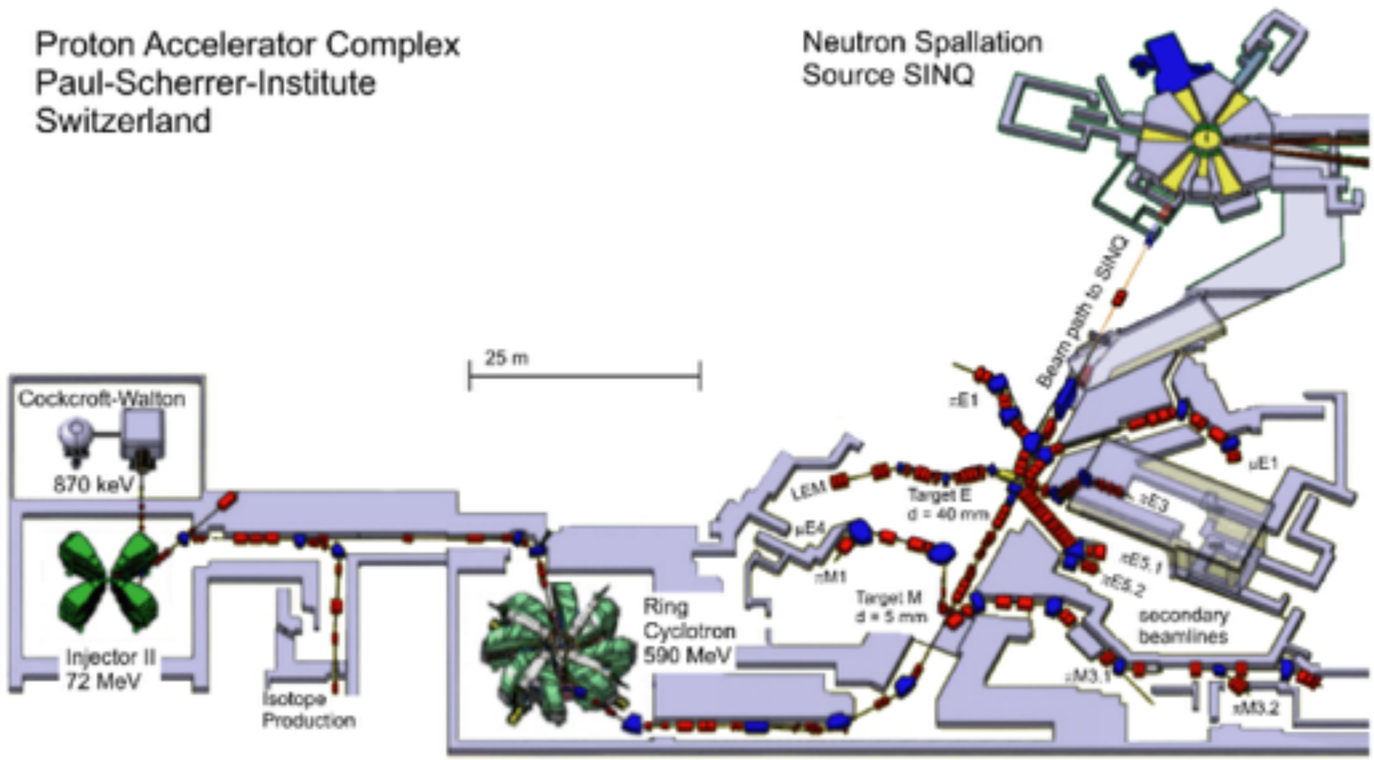
Intensity limits

Summary



- ➢ Delivers **2 mA CW 1.3 MW** proton beam
- ➢ Chain of accelerators: 870 keV → 72 MeV → **590 MeV**
- ➢ **Planned upgrade to 3 mA** will involve both accelerators

In this talk …


Proton Accelerator Complex
Paul-Scherrer-Institute
Switzerland
Neutron Spallation
Source SINQ
Beam path to SINQ
25 m
Cockcroft-Walton
870 keV
Injector II
72 MeV
Isotope
Production
Ring
Cyclotron
590 MeV
LEM
Target E
d = 40 mm
Target M
d = 5 mm
secondary
beamlines
πE1
μE1
μE4
πE3
πE5.1
πE5.2
πM1
πM3.1
πM3.2

The big picture

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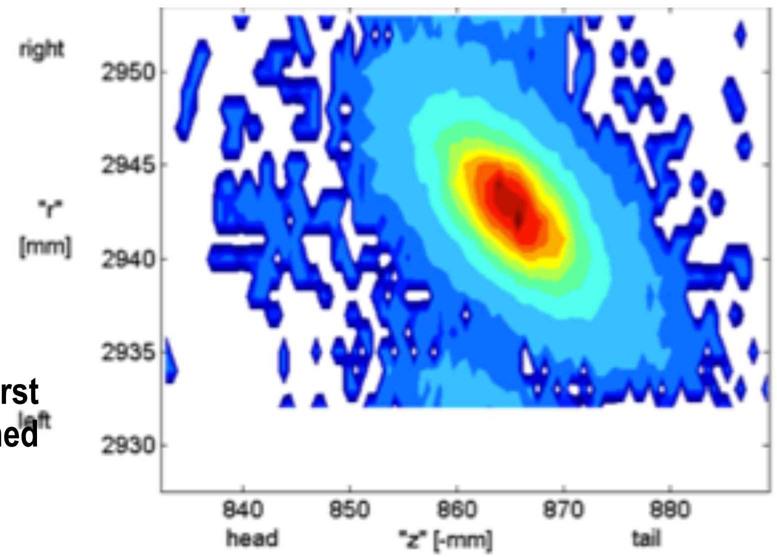
3D beam dynamics model of Injector II with space charge

- ➢ 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 ?

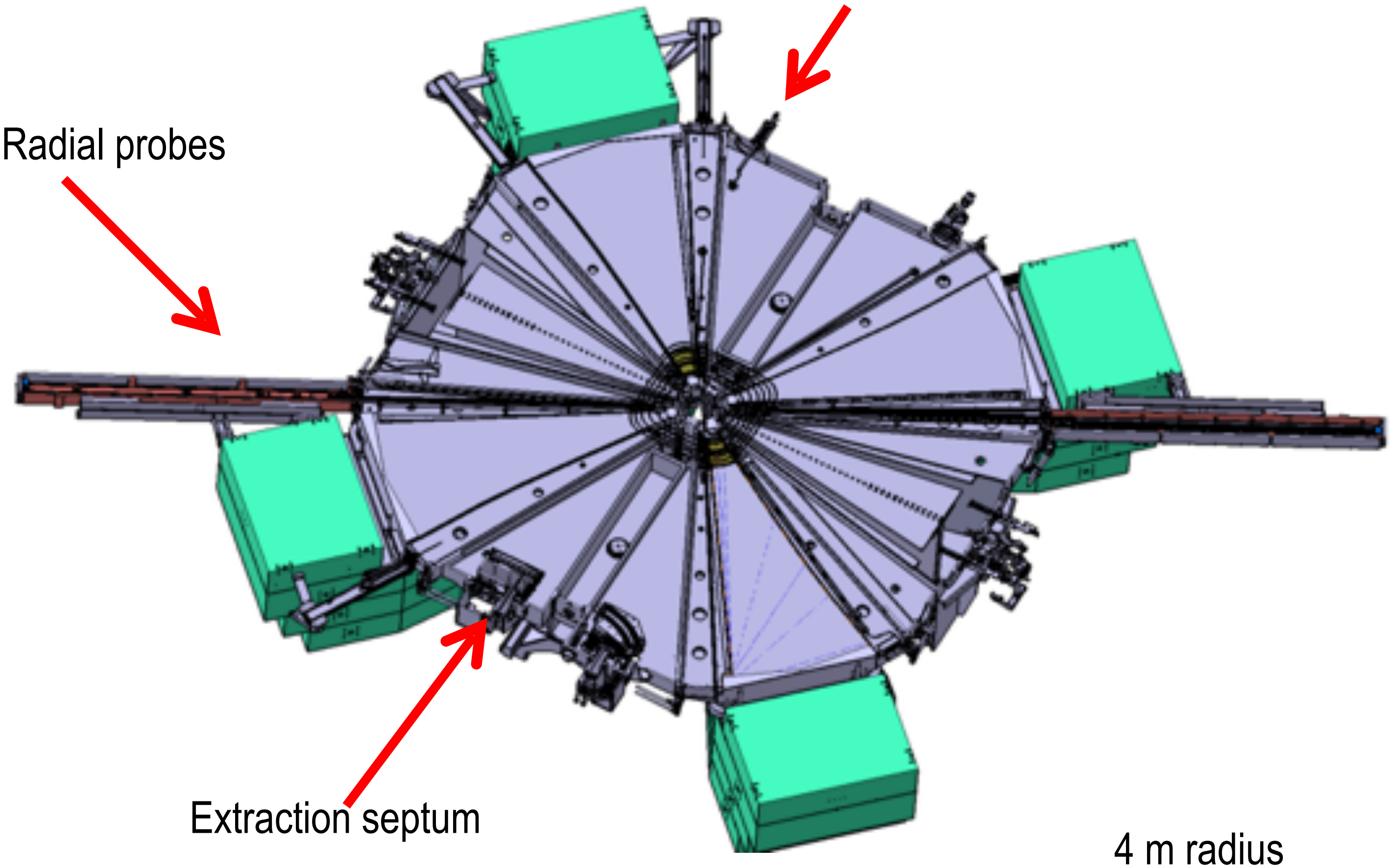
Injector II

- 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

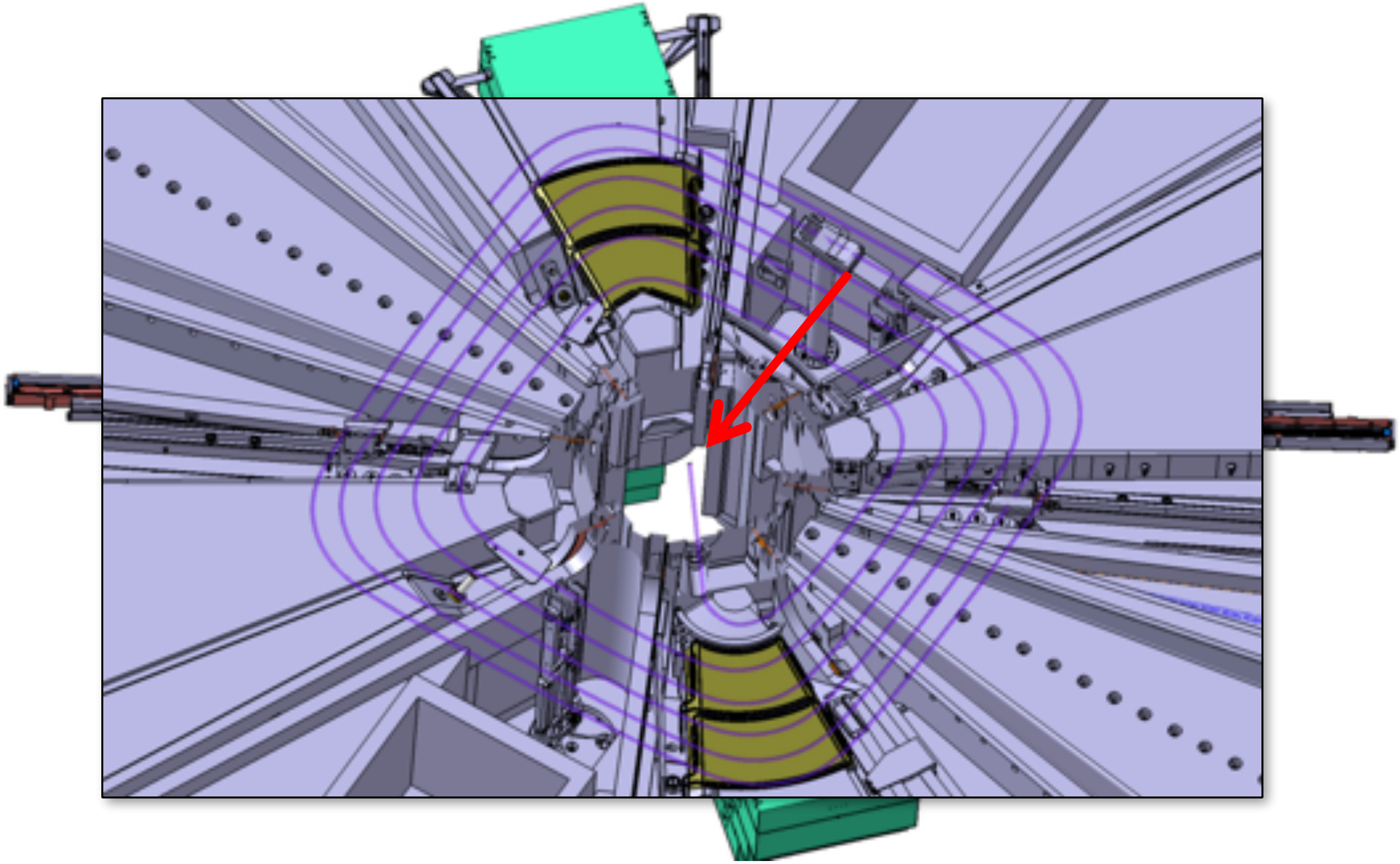


Injector II



Courtesy: Richard Kan, PSI

Injector II



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

Courtesy: Richard Kan, PSI

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How do we do it?

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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.

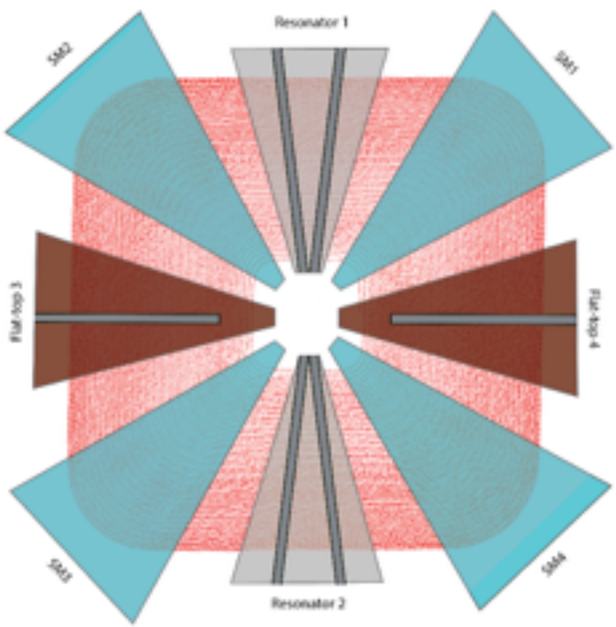
** C. Baumgarten,“Transverse-Longitudinal coupling by Space charge in Cyclotrons”, Phys. Rev. ST Accel. Beams 14, 114201, 2011.

Models of collimation

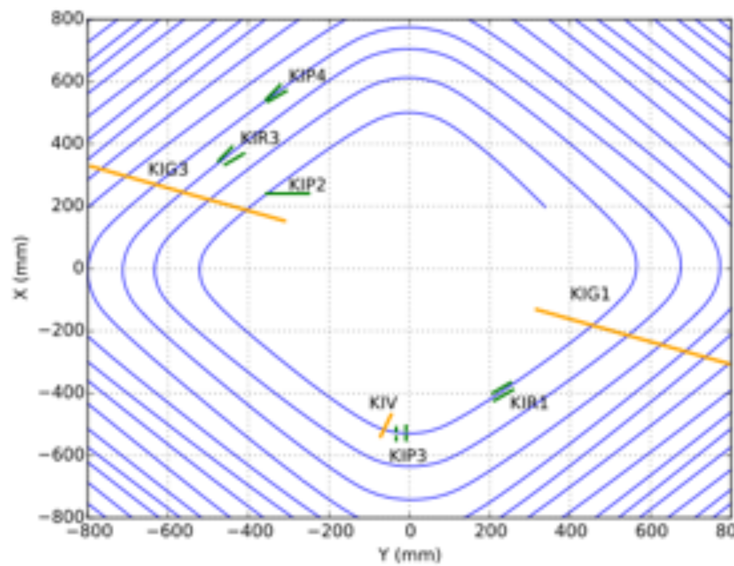
➢ 3 models under 2 configurations: **Production** and Upgraded

- *Continuous 4 sigma cut*
- *6-turn 4 sigma cut*
- *Physical Collimator*

➢ Radial data comparable accross all models



2 mA beam in 83 turns



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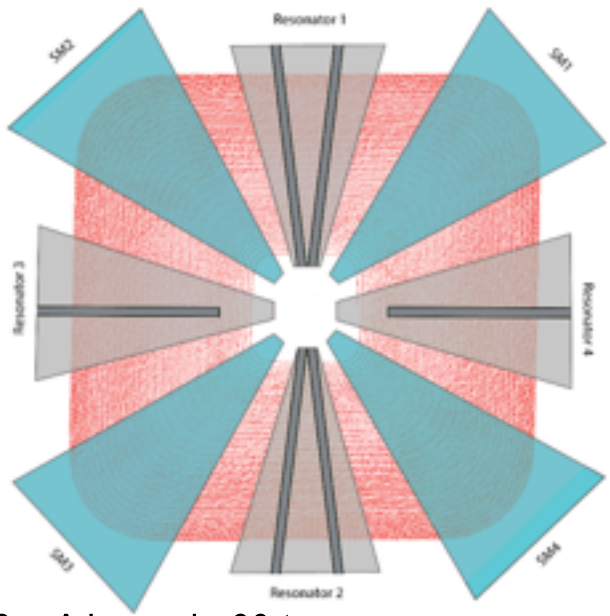
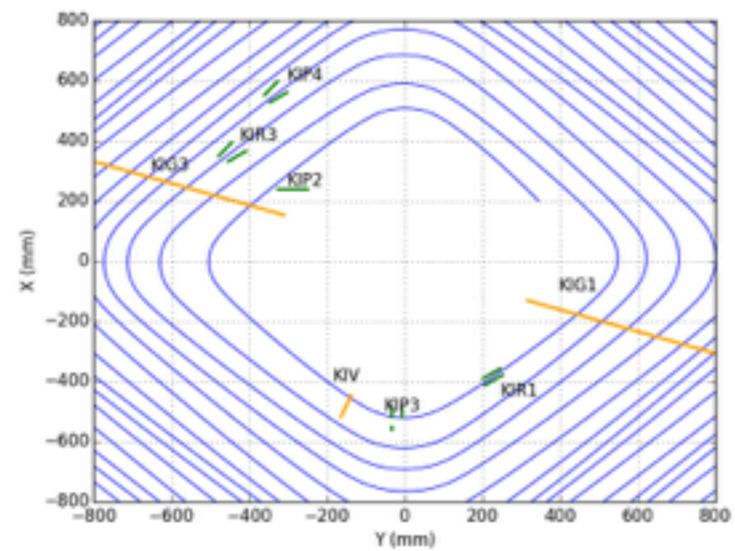
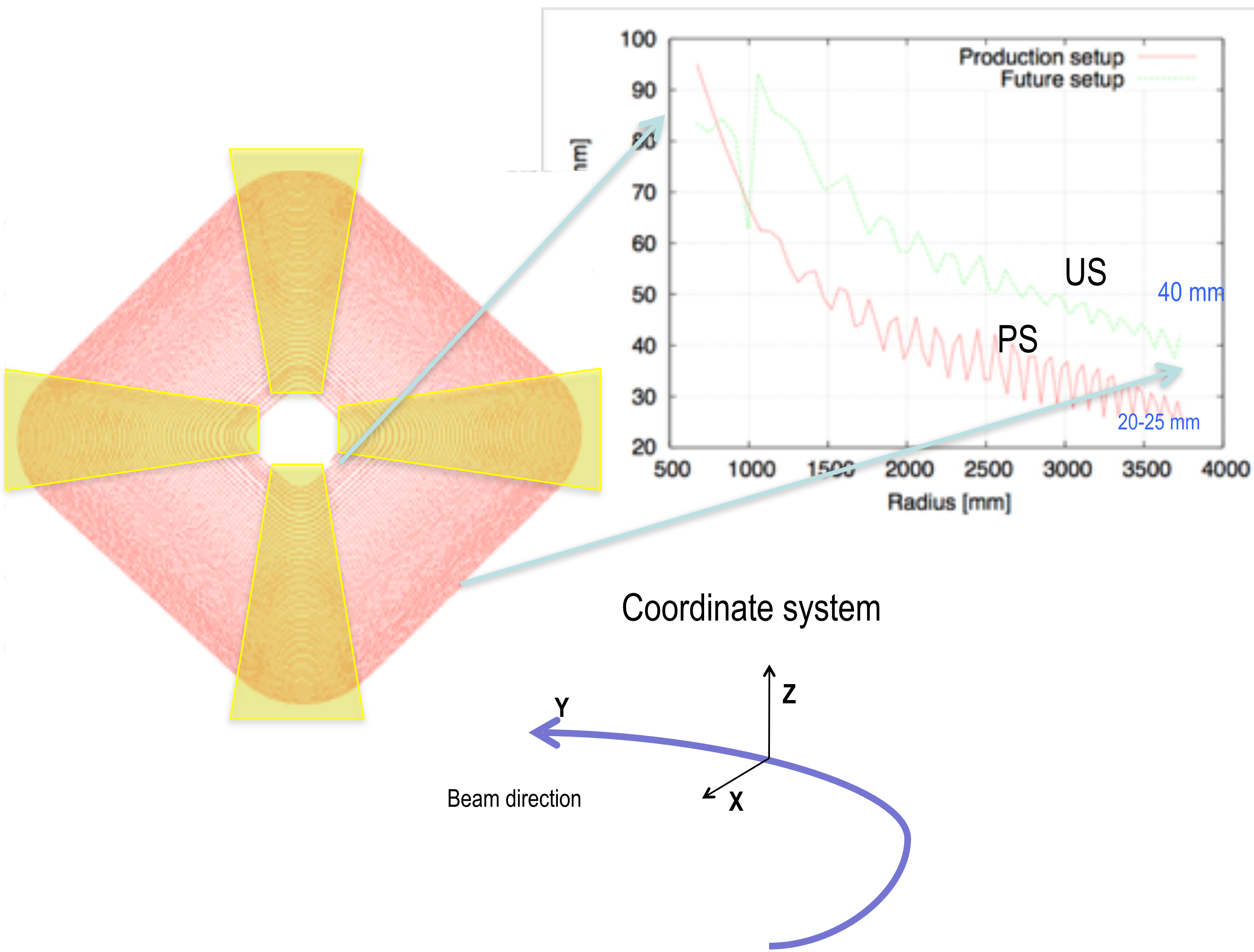




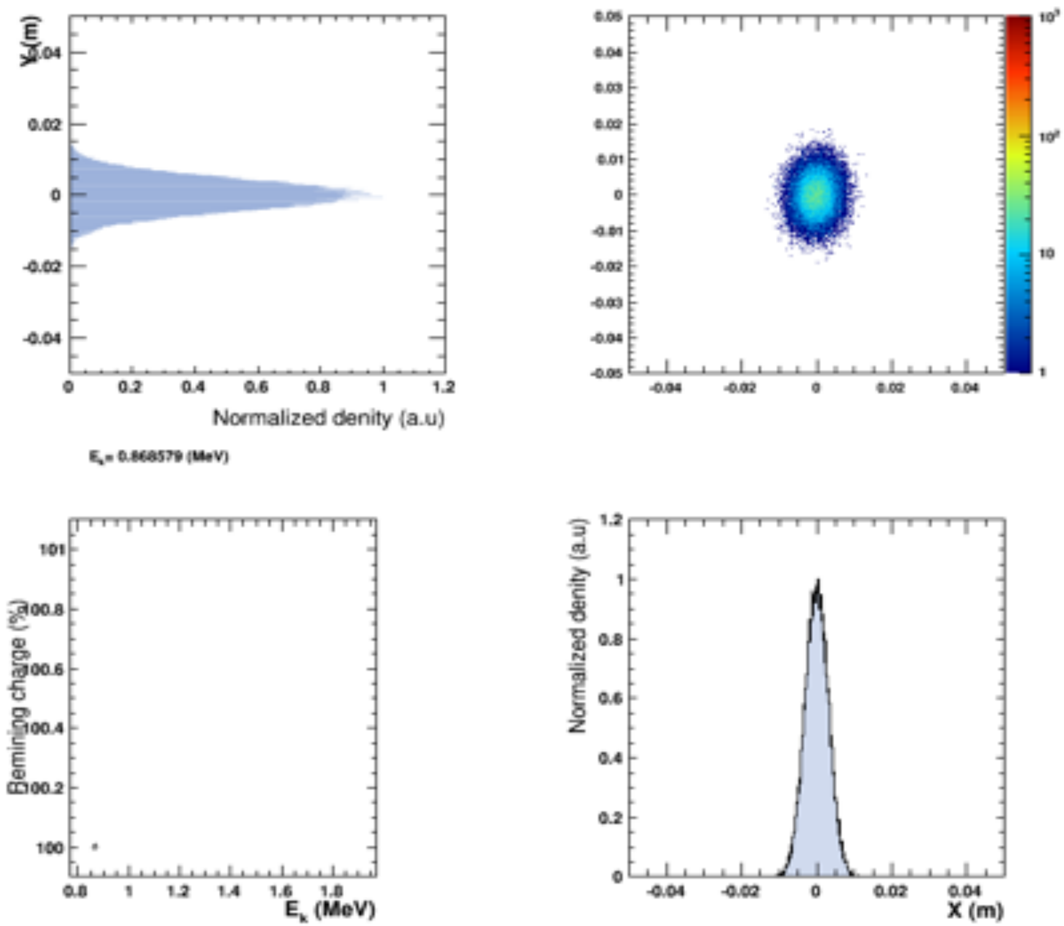
3 mA beam in 60 turns
The same central/extraction region

Configurations of Injector II



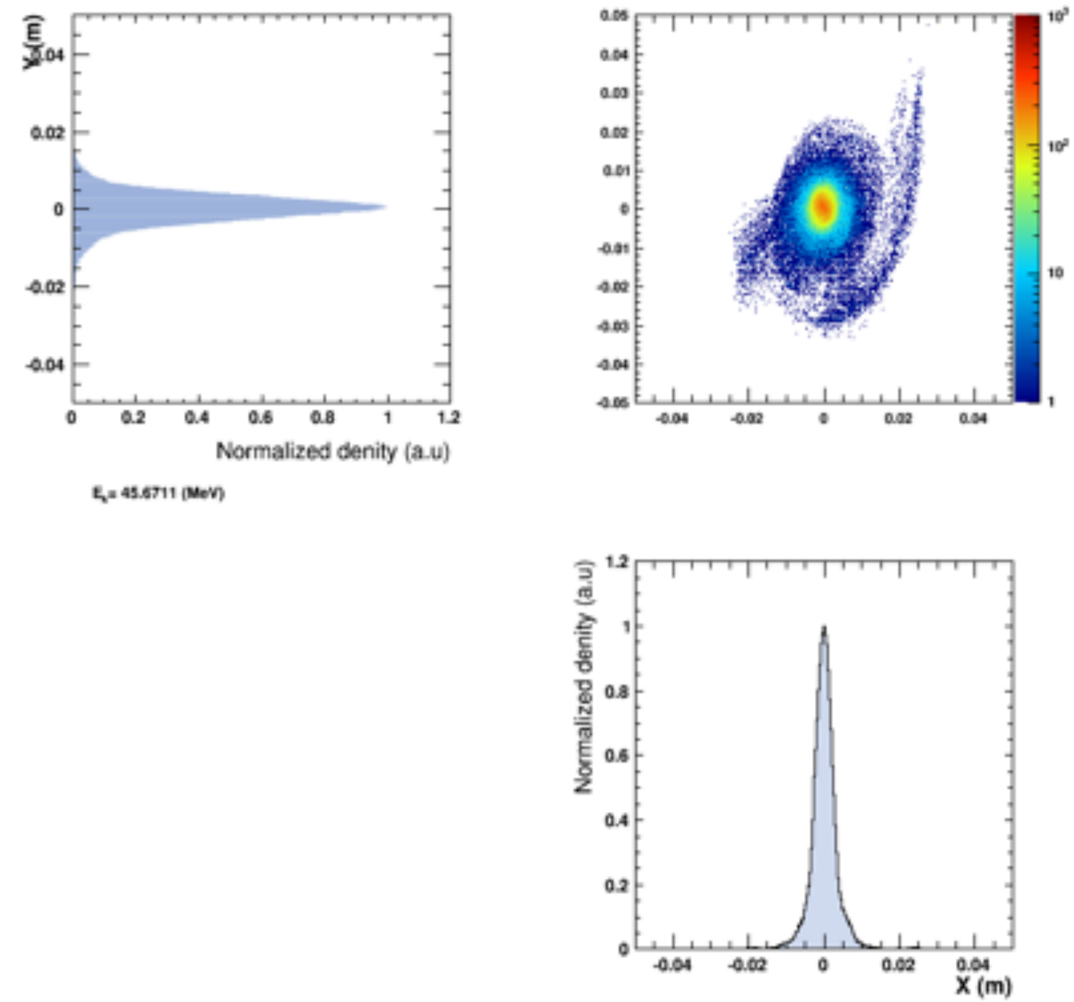
Production set-up with collimators

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

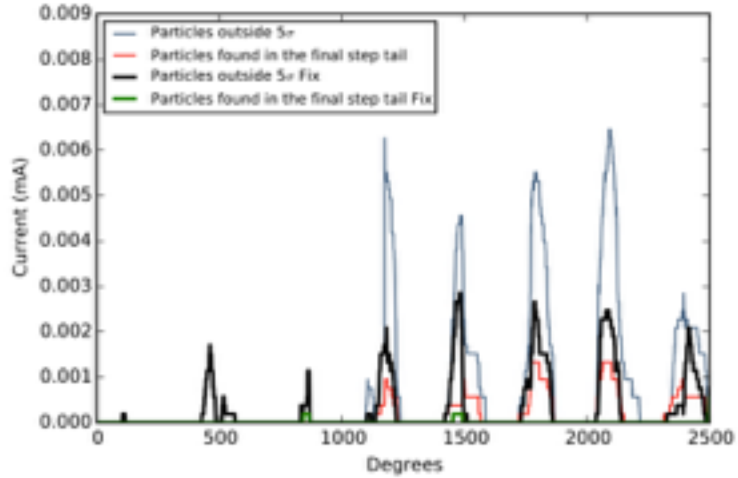


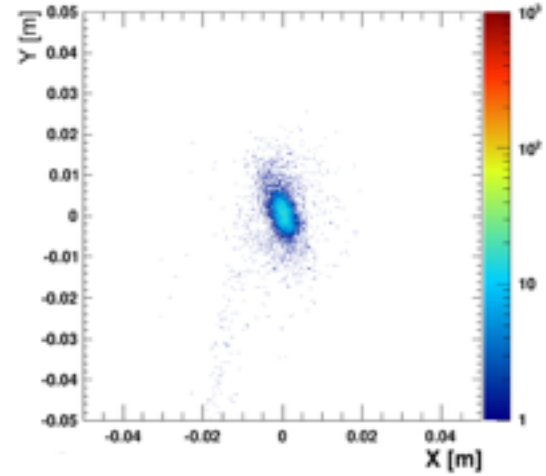
Space charge is not all that bad!

Last turn

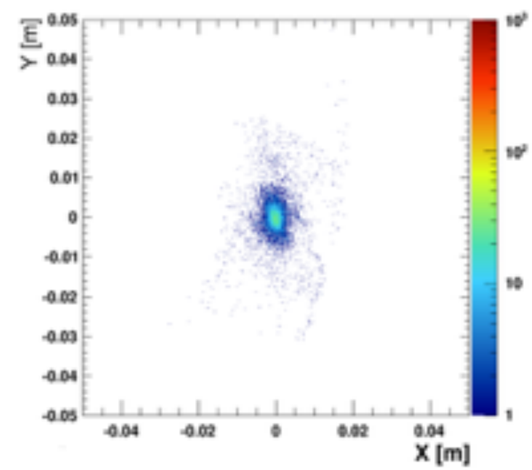


Halo and tail cleaning with KIP4 collimator





- ➢ 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

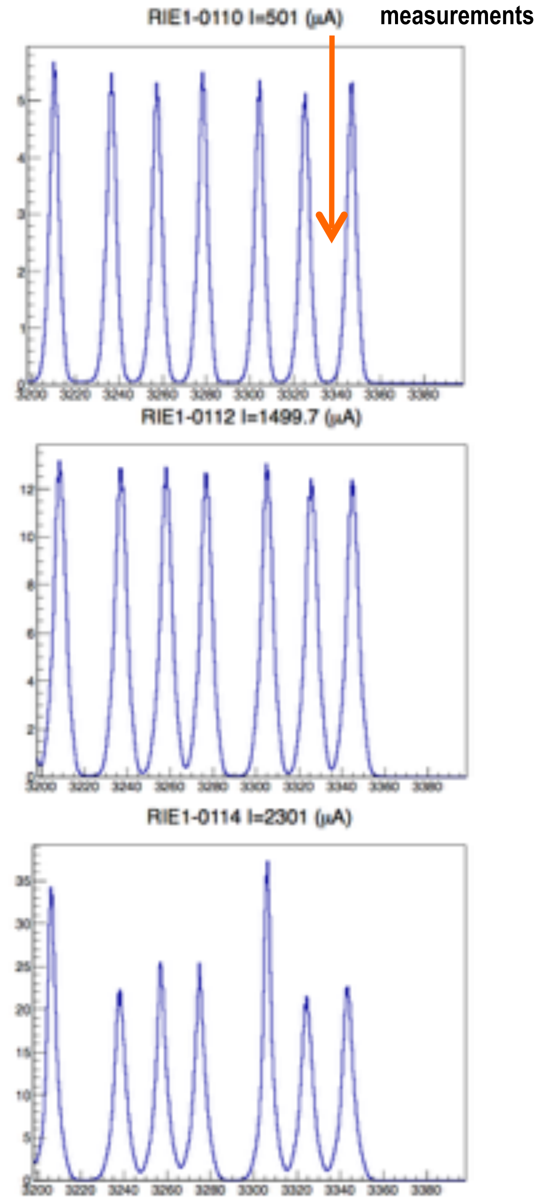


Measurements: radial profile

- 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

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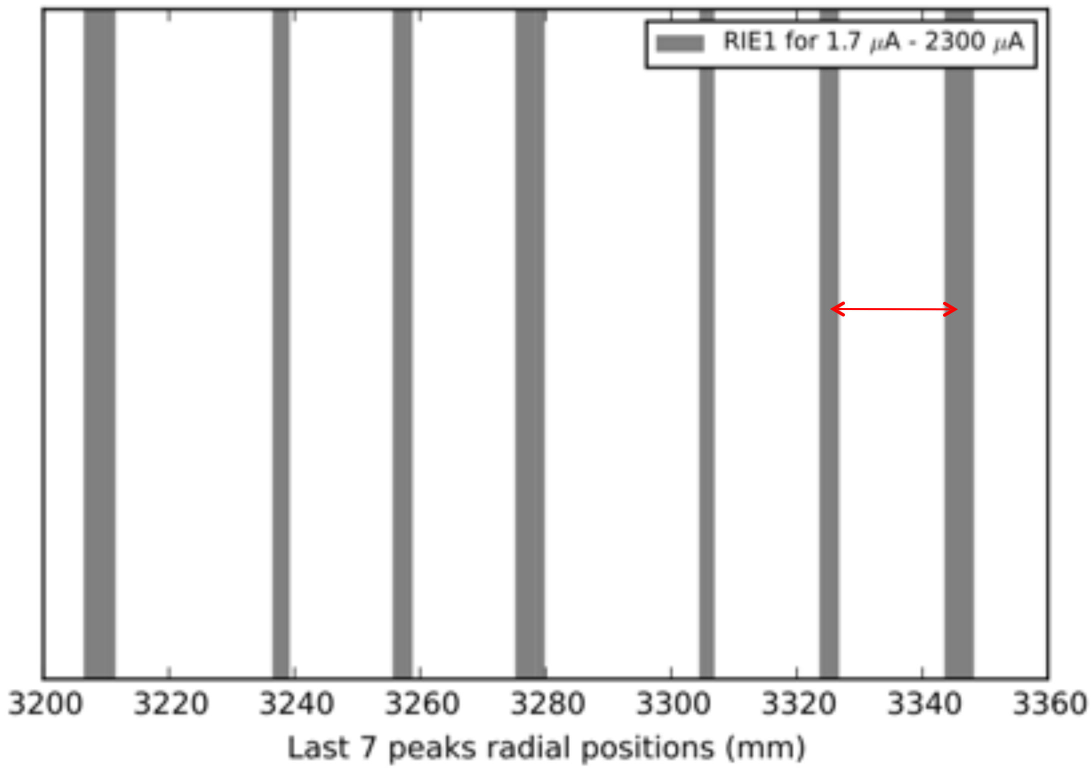
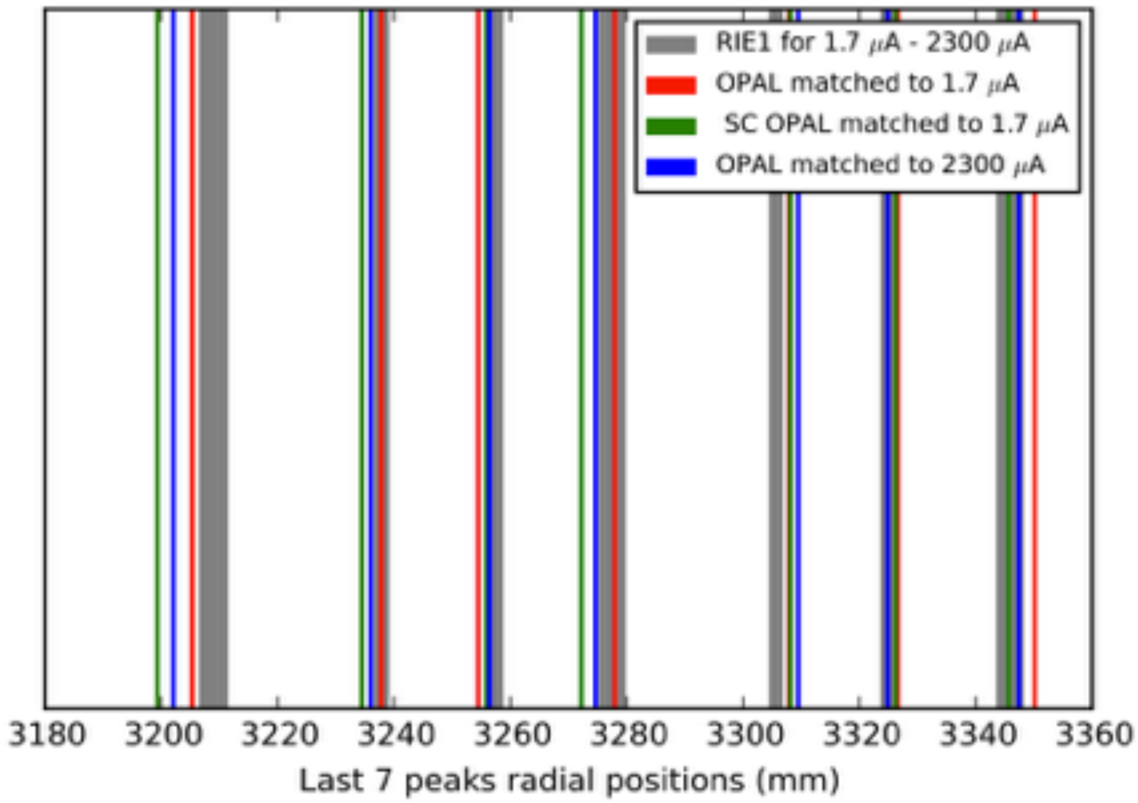
Injector II radial intensity peak **ranges**



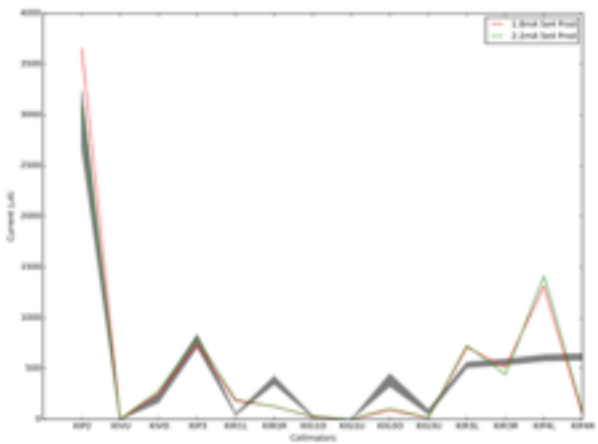
Radial peak positions

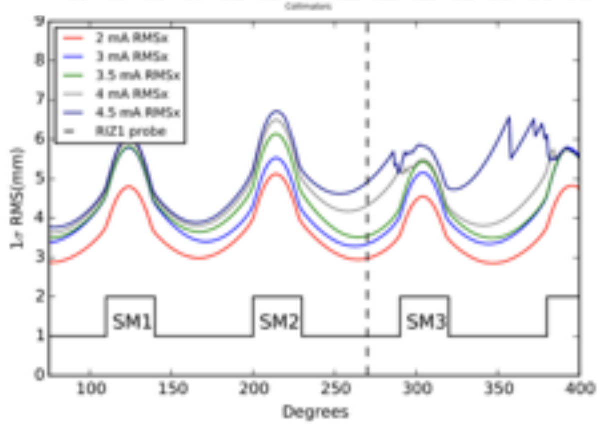
Run the same initial conditions with full space charge

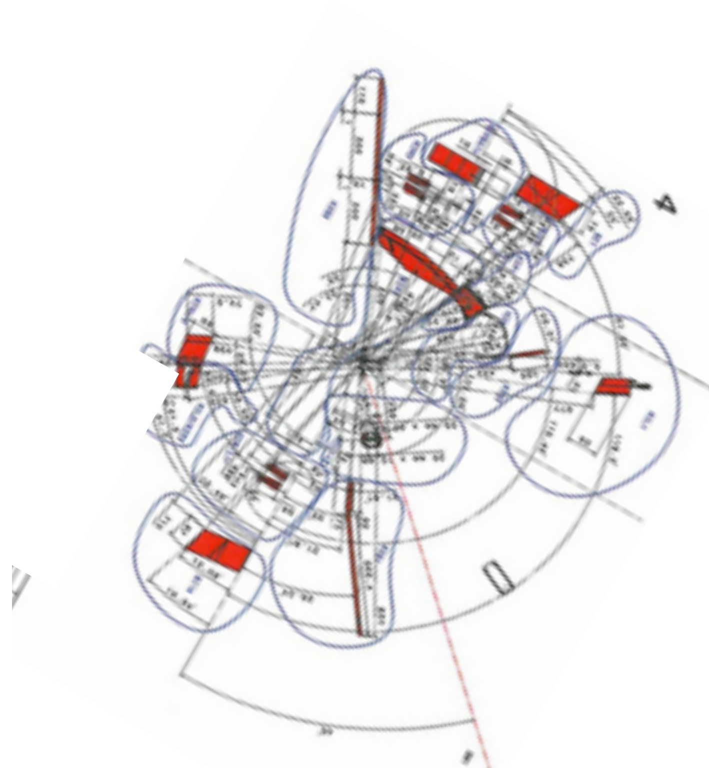


Validation

- 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





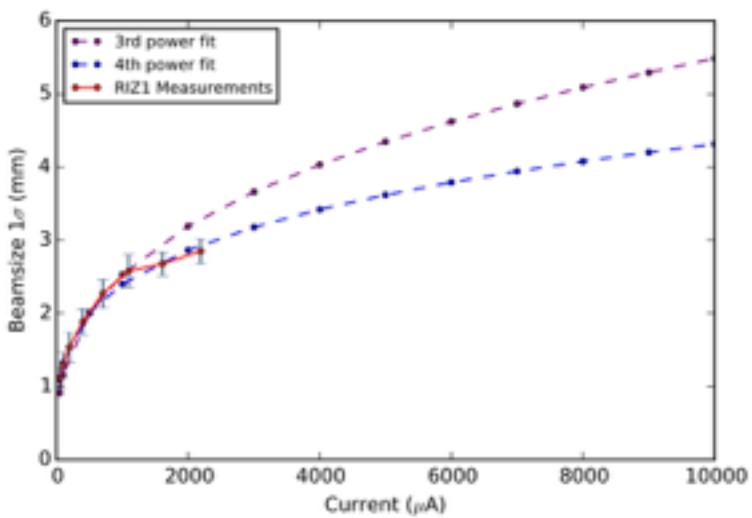


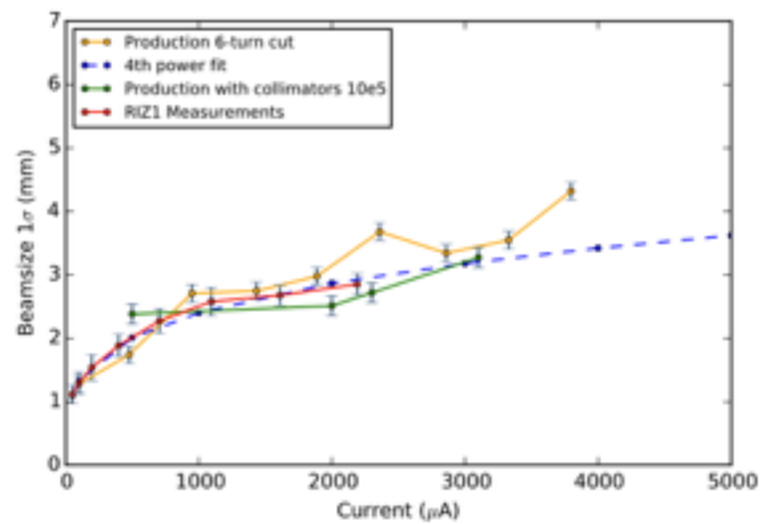
Central region collimators at energies between 0.87 and 2.5 MeV

Intensity limits of Injector II

➢ Theoretical limit says **approx 2 mA*** (we already know **2.7 mA** was extracted) → this strong transverse-longitudinal coupling combined with space charge sets higher limits

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





*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.

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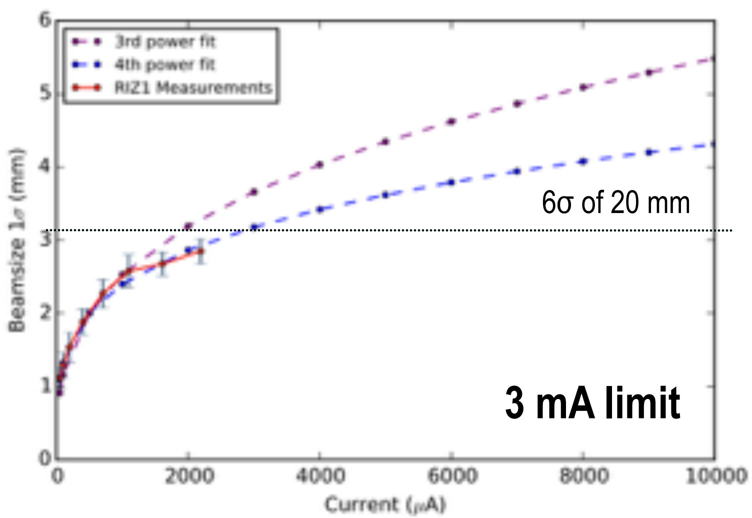
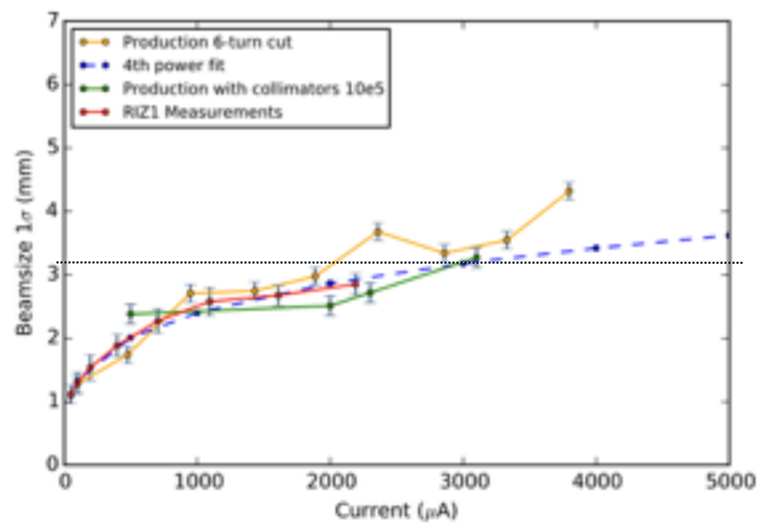
- Theoretical limit says **approx 2 mA*** (we already know **2.7 mA** was extracted) → this strong transverse-longitudinal coupling combined with space charge sets higher limits
- Following up on Joho`s scaling law** $\mathbf{I_{max}} \propto \mathbf{V^3}$ also for beamsize, with slightly better fit at power of 4, that is particularly good at higher intensities
- Our models/fits predict **new 3mA limit** with existing configuration
- After the upgrade even up to 5mA could be possible





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Summary

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NGAC DT

- ➢ Currents higher than 2 mA should be achievable
- ➢ Thanks to space charge and tuning of collimator positions
- ➢ New RF cavities will make it even higher

**I would like to express my sincere gratitude to
Prof Roger Barlow and Dr Andreas Adelmann
for their support, guidance and expertise during my PhD**

EPSRC
Engineering and Physical Sciences Research Council

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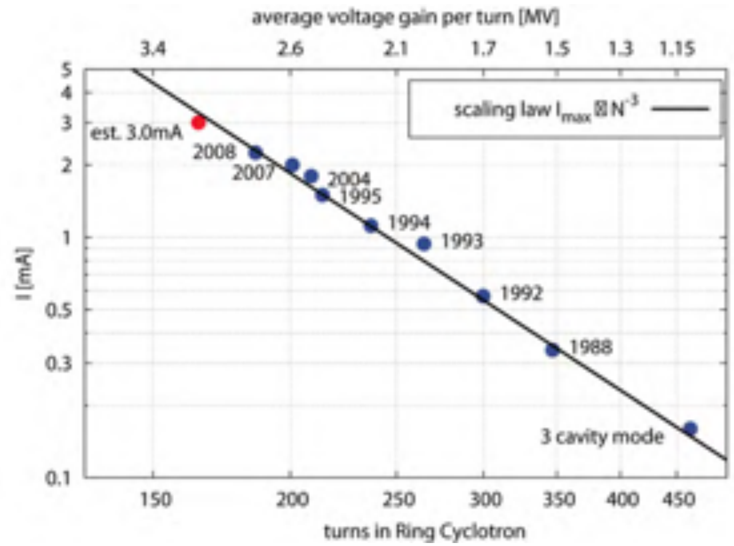
Joho‘s scaling law

- 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:

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

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



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