RECENT EXTRACTION DEVELOPMENTS AT MEDAUSTRON

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PRESENTATION OVERVIEW

MedAustron Overview and NCR Programme

COSE investigation results

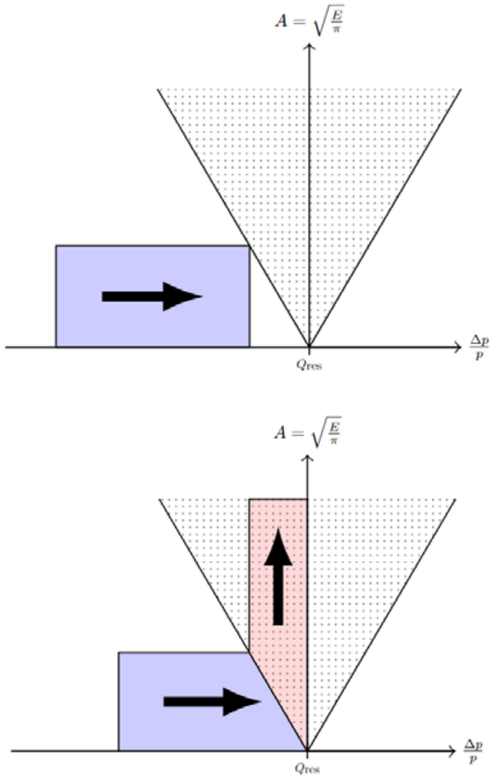
RF channelling of carbon ions

RFKO extraction development

MEDAUSTRON ACCELERATOR SPECIFICATIONS

- Based on the Proton-Ion Medical Machine Study (PIMMS) design and developed in close collaboration with CERN and CNAO
- 77 metre circumference
- Slow extraction based on third integer resonance using a Betatron core
- Present clinical extraction times of 10 & 4** seconds (0.1-30 seconds available for research)
- RF channelling used for beam ripple suppression**
- Future developments for performance improvement with patient safety in mind (medical device)

Particle type	Energy / range	Intensity (per spill)
Proton	62.4 – 252.7 MeV + 800 MeV* 3.3 – 38.6 cm + 2.35 m*	~10^{10}
Carbon ion	120 – 402.8 MeV/u 4 - 28 cm	~10^{8} **

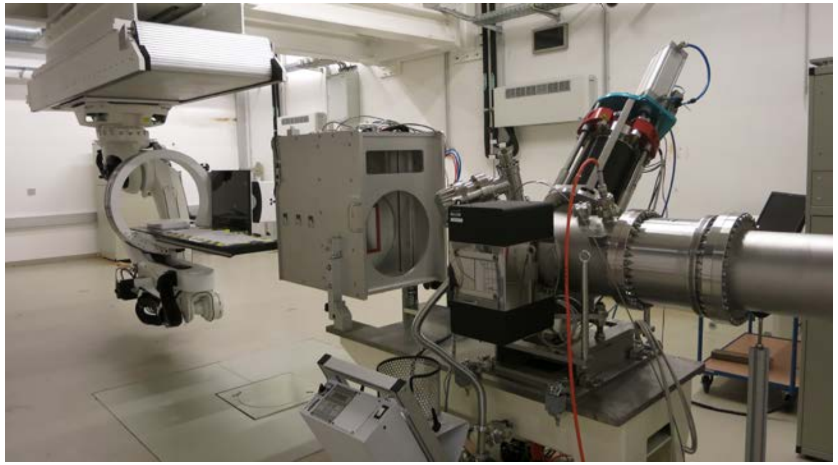


NON-CLINICAL RESEARCH (NCR) AT MEDAUSTRON

- **Research areas are divided into programs from P0-P7:**
  - P0 - Commissioning and Quality Assurance
  - P1 - Intrafraction Adaptive Radiation Therapy
  - P2 - Interfraction Adaptive Radiation Therapy
  - P3 - Imaging with Ion Beams
  - P4 - Magnetic Resonance Guided Particle Therapy
  - P5 - Energy Transfer Mechanisms and Applications in Physics and Biology
  - P6 - Pre-Clinical Animal Research
  - P7 - Accelerator physics

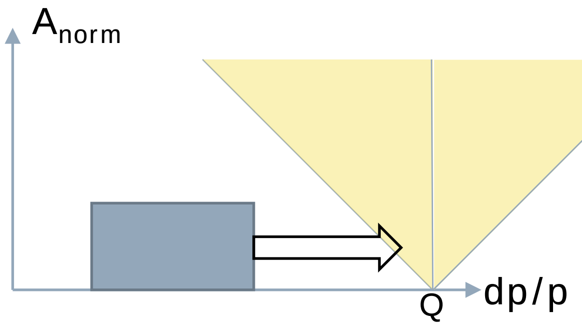
NCR research cooperation with the **Medical Universities of Vienna and Graz**, the **Technical University of Vienna** and the **Institute for High Energy Physics** (ÖAW) as well as the **University of Applied Sciences Wiener Neustadt** (FH WN)

Collaboration agreement “Development of Slow Extraction Techniques” between MedAustron and CERN

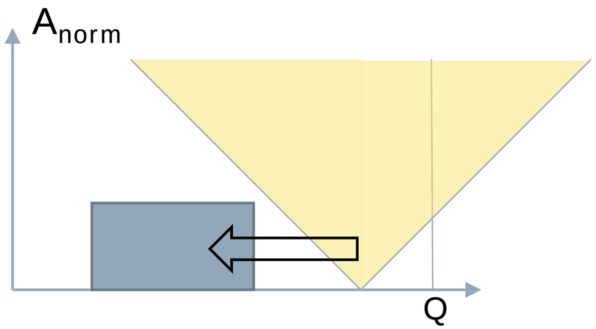


COSE INVESTIGATION

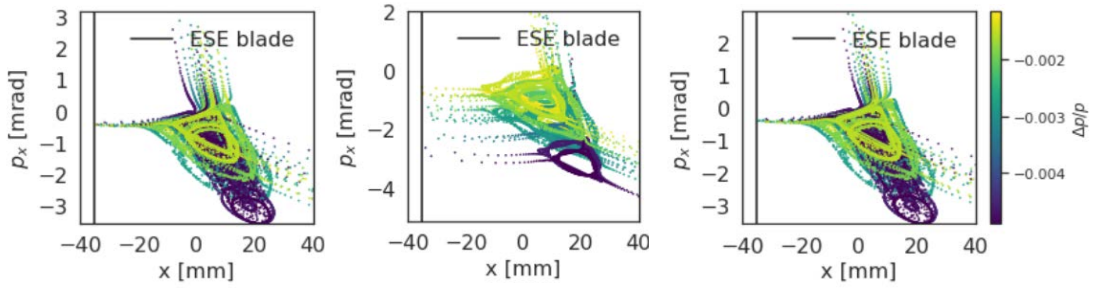
- COSE has been investigated as an alternative extraction method under the NCR P7 Accelerator Physics program
- COSE extraction mirrors the Betatron core extraction conditions
  - Hardt condition is met
  - Betatron core is inactivated (only magnet ramping)
- COSE has the added advantage that the same implementation can be utilised for a bunched multi energy extraction
- Implementation is via set point sequence (SSQ) curves in the control system to synchronously ramp the magnets
- The COSE extraction rate is set by the percentage of magnet ramping performed written as –X.X% ramping



Betatron core



COSE

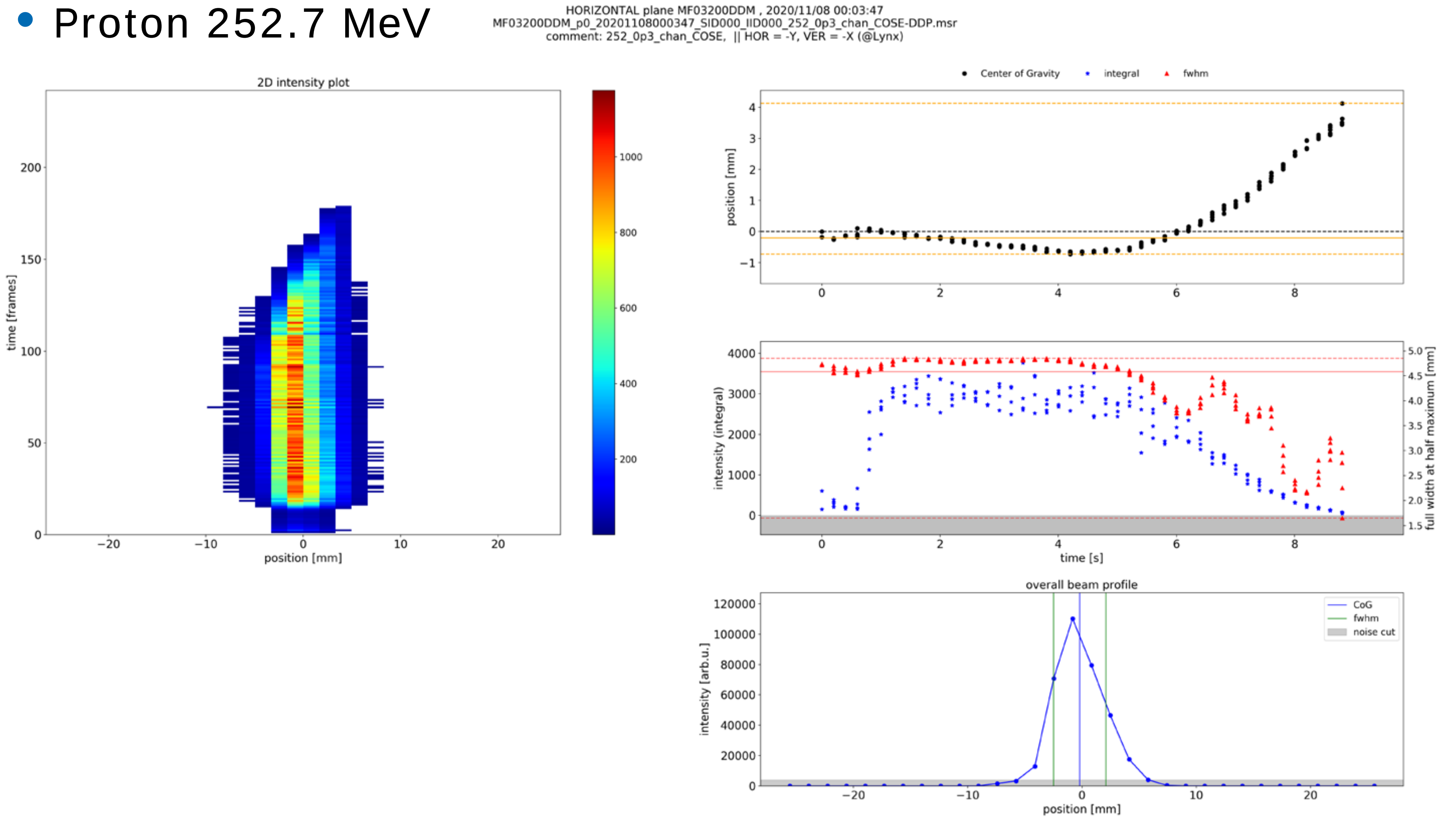


(a) Betatron core. (b) Q-sweep. (c) COSE.

P. Arrutia, Optimisation of Slow Extraction and Beam Delivery from Synchrotrons, Master Thesis, Royal Holloway, University of London, CERN-THESIS-2020-259, 2020.

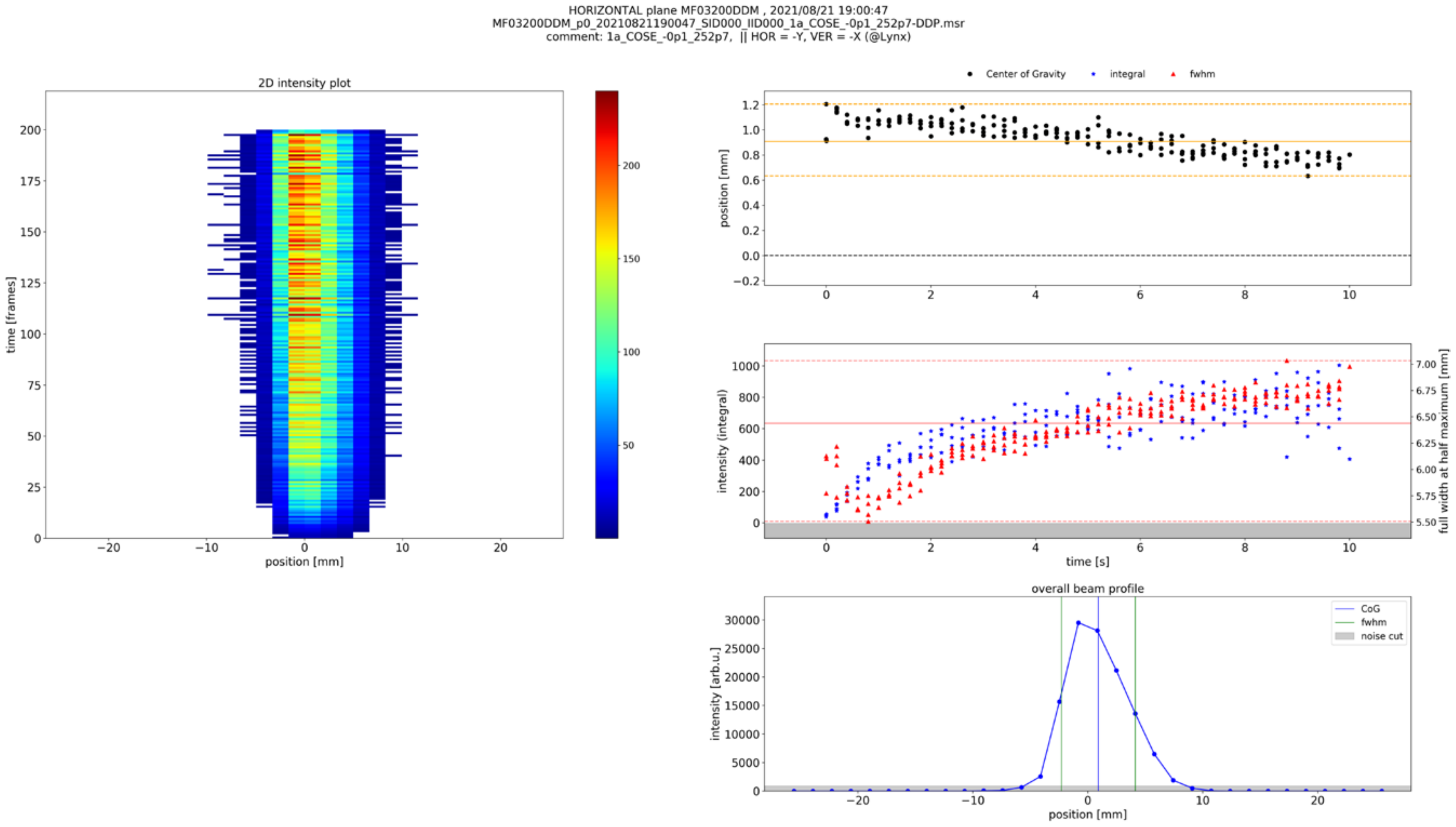
UNBUNCHED PROTON COSE EXTRACTION -0.3%

- Proton 252.7 MeV



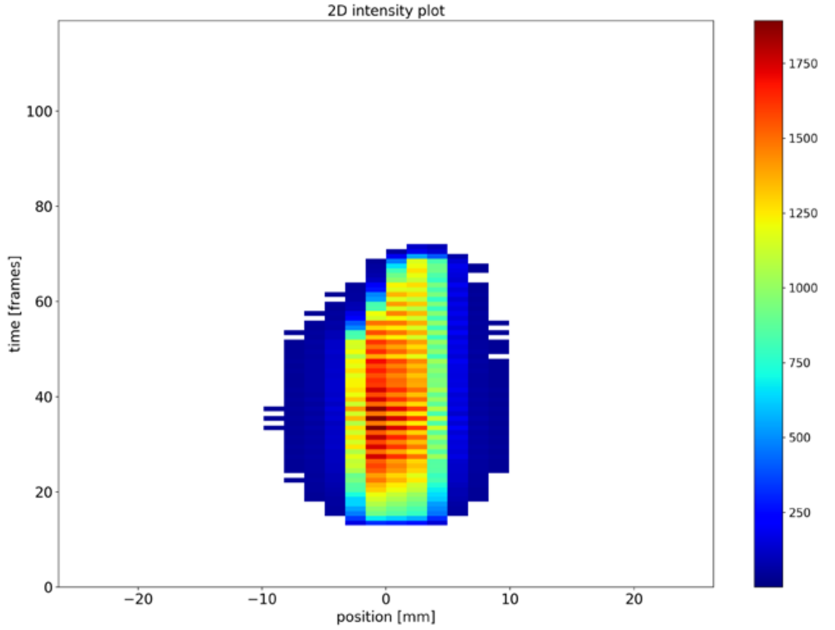
MedAustron Ion Therapy Center

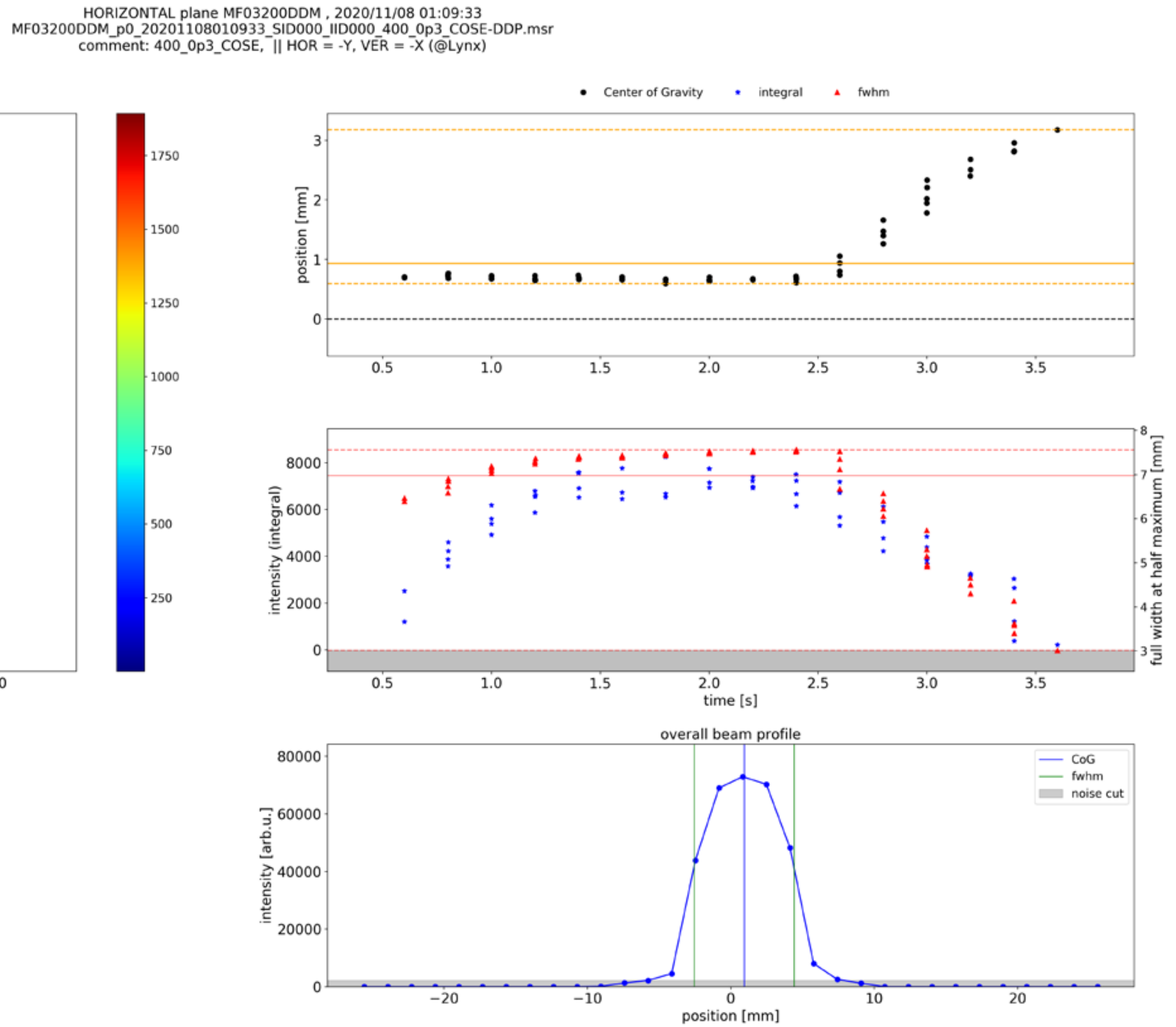
UNBUNCHED PROTON COSE EXTRACTION -0.1%



UNBUNCHED CARBON COSE EXTRACTON -0.3%

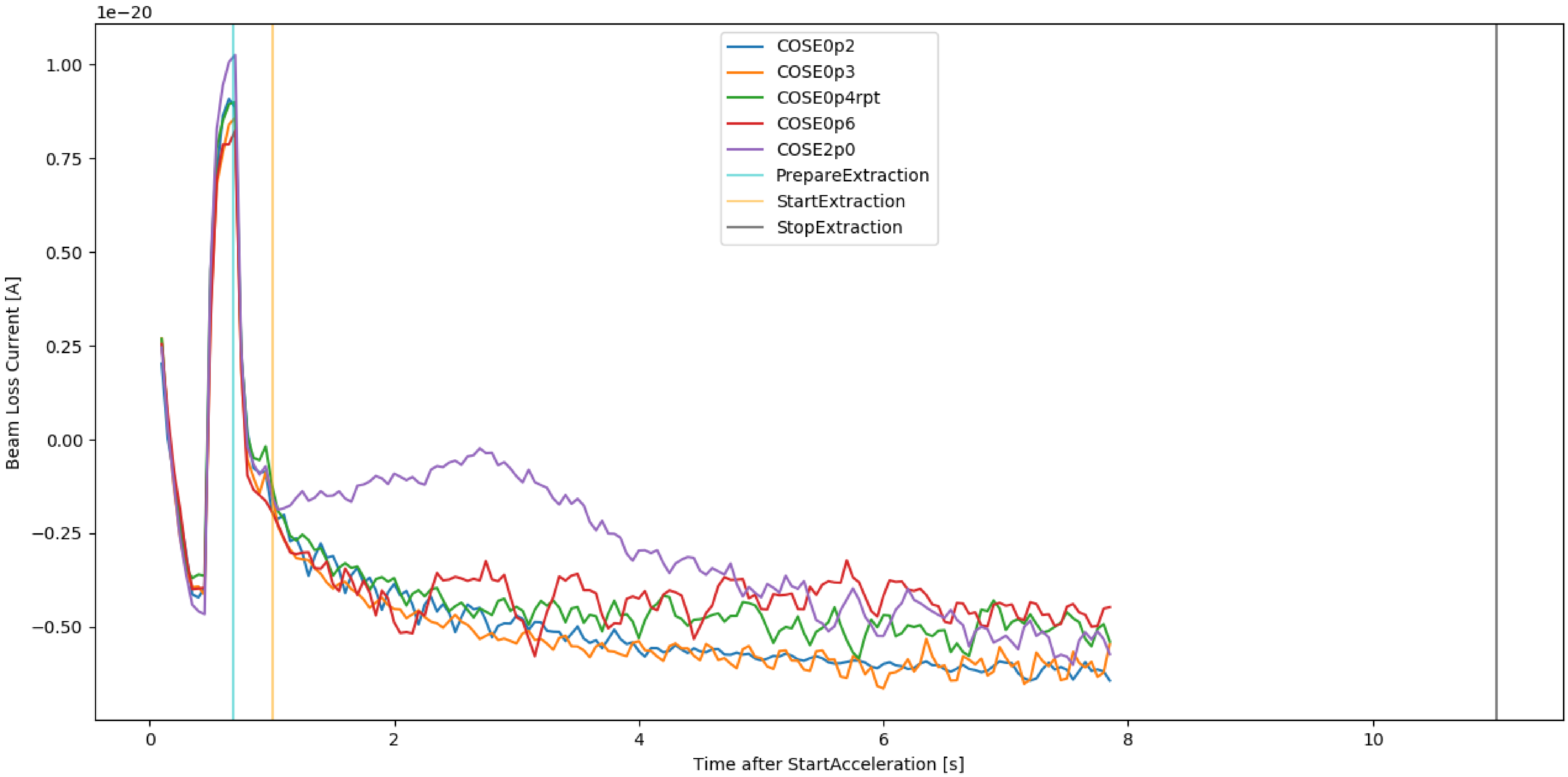
- Carbon 400.1 MeV/u





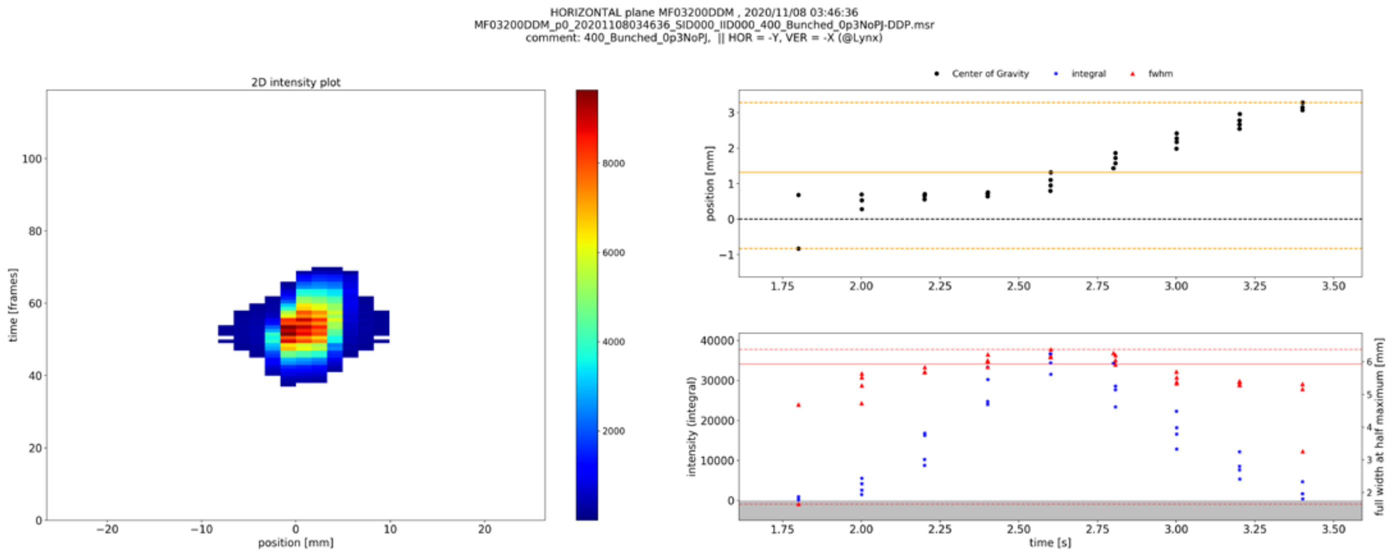
BEAM LOSSES MEASURED ON PIN DIODE

PIN diode located at split of the High Energy Beam Transfer line from the Synchrotron



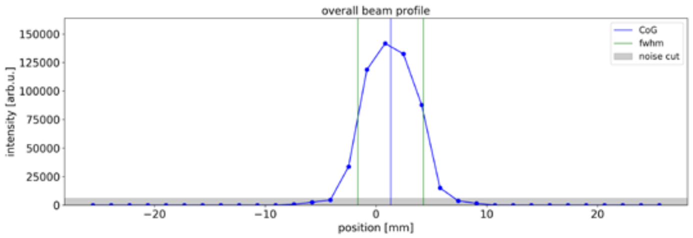
BUNCHED COSE

- Same settings as for the COSE presented earlier except:
  - Remove Phase Jump → smaller momentum spread
  - sRF remains turned on during extraction → beam stays bunched
  - Ramp the radial position from 20mm to zero to force the beam into extraction (synchronously with magnet ramping)



CChuman	400.1MeV C6+ | S2-IR2H | DEG100% | 90°
CChuman	no extractions | 6x6mm | var0ver0 | clinical
CC	7800236600120FA1
BS	2020110804453000-3
limits	ana: 0.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	n.a. | 1600 ms

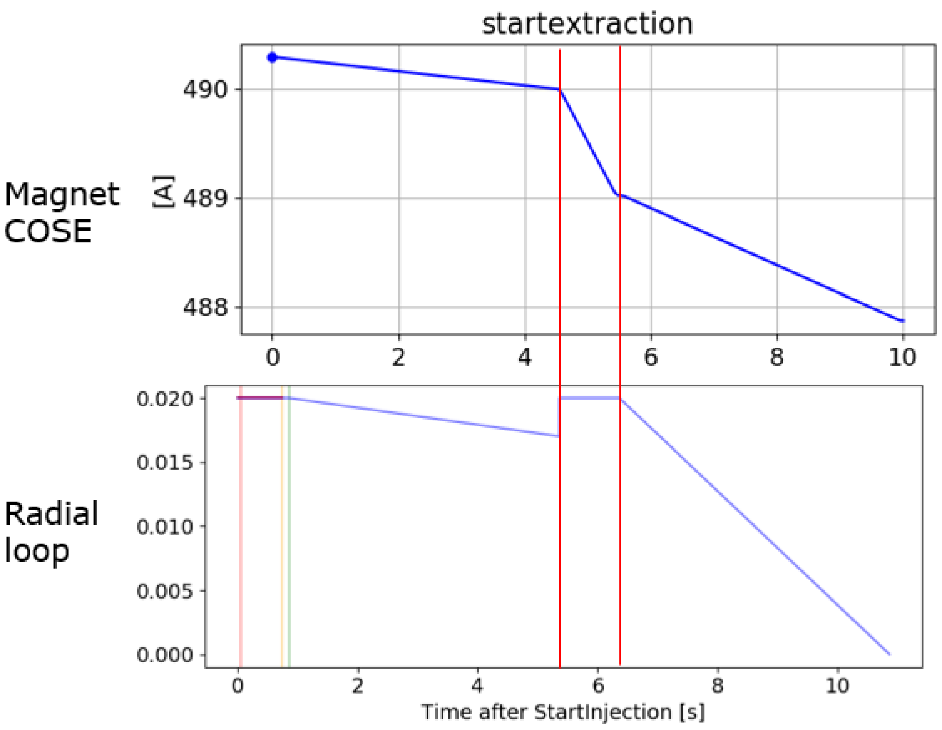
version	2.2.0
exp | fps	varying | 20 f/s
trigger	n.a. (DDS not sync.!)
SNR / BG-FID	279616559.0 [0]
intensity	0.5e6 arb.u.
CoGw	1.32 ± 0.1 mm [-0.8, 3.3]
FWHMw	5.93 ± 0.3 mm [1.6, 6.4]



- Bunched beam required for Multi-Energy Extraction(MEE) using COSE extraction
  - Energy control using the radial loop (for bunched beam bucket frequency control) combined with the magnet ramping

MULTI-ENERGY EXTRACTION COSE

- Same settings as for bunched COSE
- Effective energy change: +0.2% (0.5 MeV)

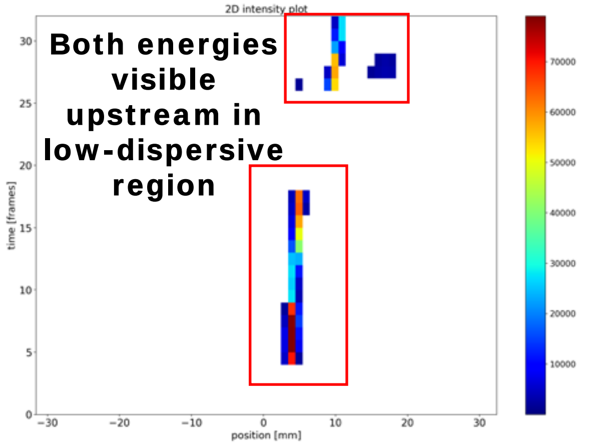


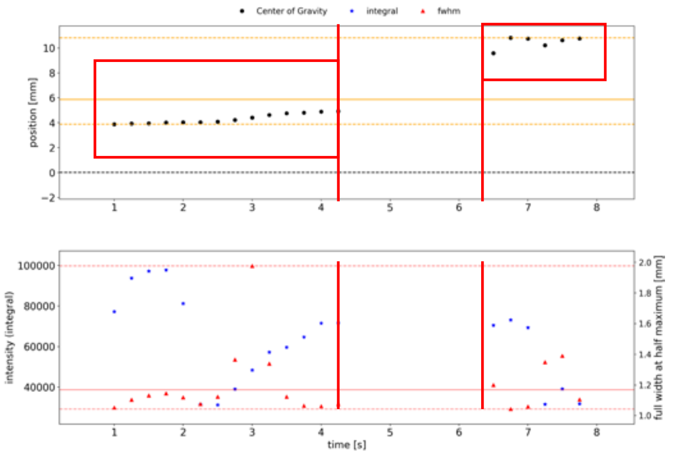
Time	Radial Loop	COSE	
0 – 4.5s	Ramp 20 → 15mm	Ramp -5/8500	Extraction EN 1
4.5s	Jump 15 → 20mm	-	-
4.5 – 5.5s	Constant at 20mm	Ramp -0.002	Acceleration to EN 2
5.5 – 10s	Ramp 20 → 0mm	Ramp -20/8500	Extraction EN 2

MEE COSE

- Energy step of 0.5 MeV proton, without HEBT scaling means that the 2nd energy scrapes in the high dispersive region of the beamline but is visible in the low dispersive region
- More than two energies attempted and focus of next COSE shifts

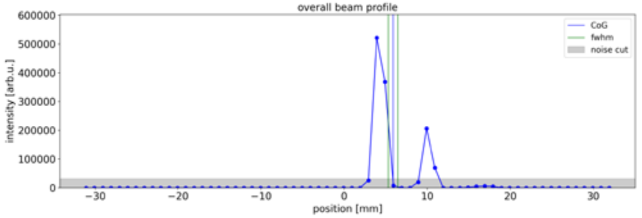
HORIZONTAL plane EX01001SFX , 2021/09/19 11:58:13
EX01001SFX_p0_20210919115813_SID000_IID000_2E_with_SFX.msr
comment: 2E_with_SFX

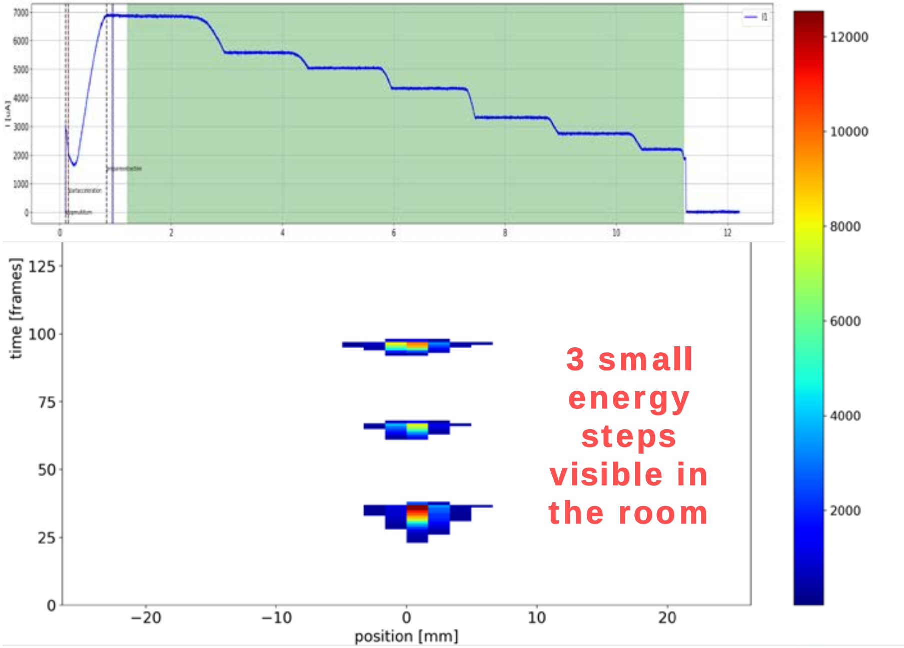


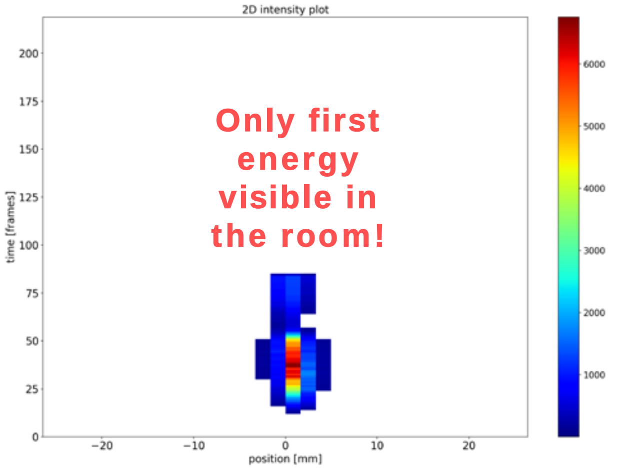


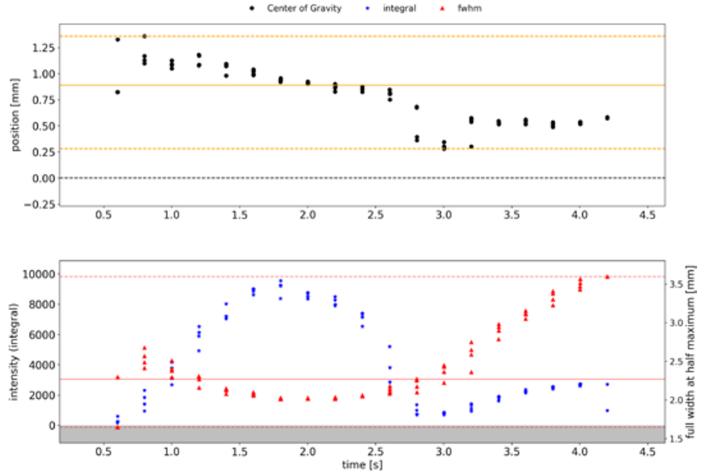
CChuman	252.7MeV H+ | S1-IR2H | DEG100% | GA 90°
CChuman	10s | 4x4mm | var0ver0 | clinical
CC	780023441A0909DF
BS	2021091913242500-21
limits	ana: 10.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	250 ms | 5000 ms

version	2.3.0
exp | fps	0.0ms | 4
trigger	StartExtraction
SNR / BG-FID	253.9 [0]
intensity	1.2e6 arb.u.
CoGw	5.87 ± 0.9 mm [3.9, 10.8]
FWHMw	1.17 ± 0.2 mm [1.0, 2.0]



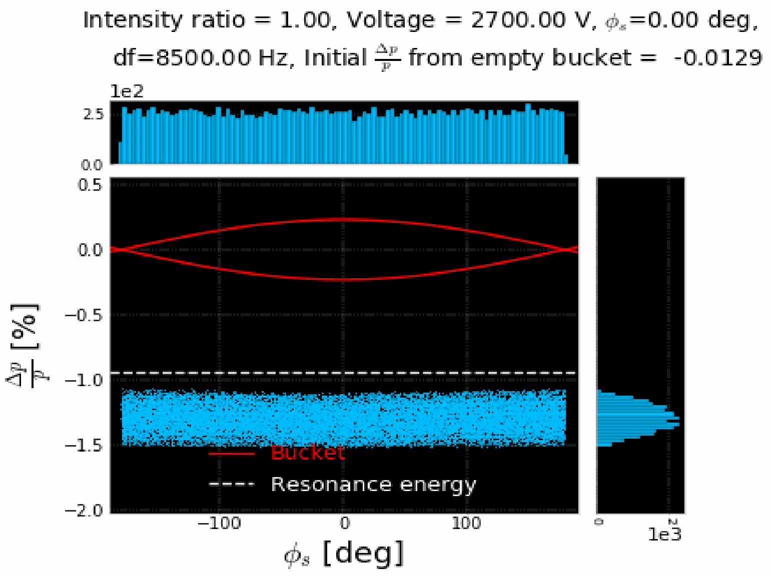


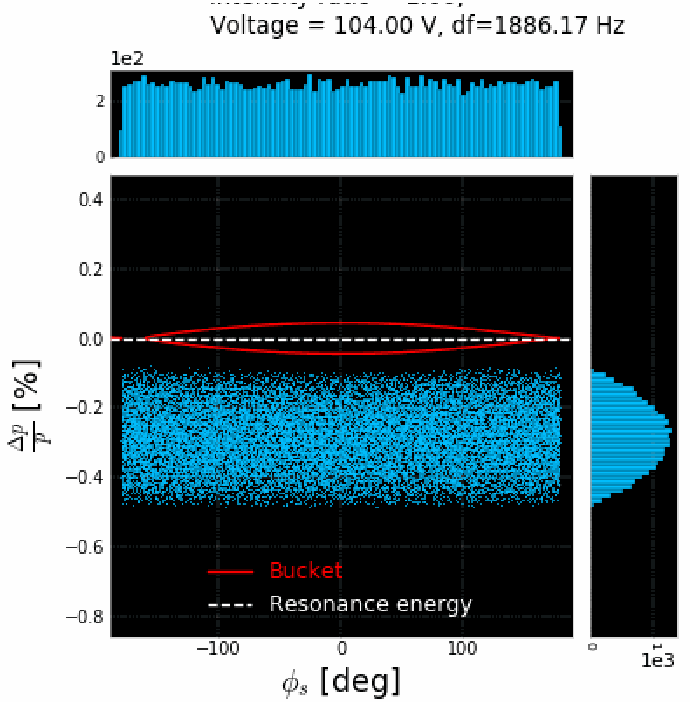




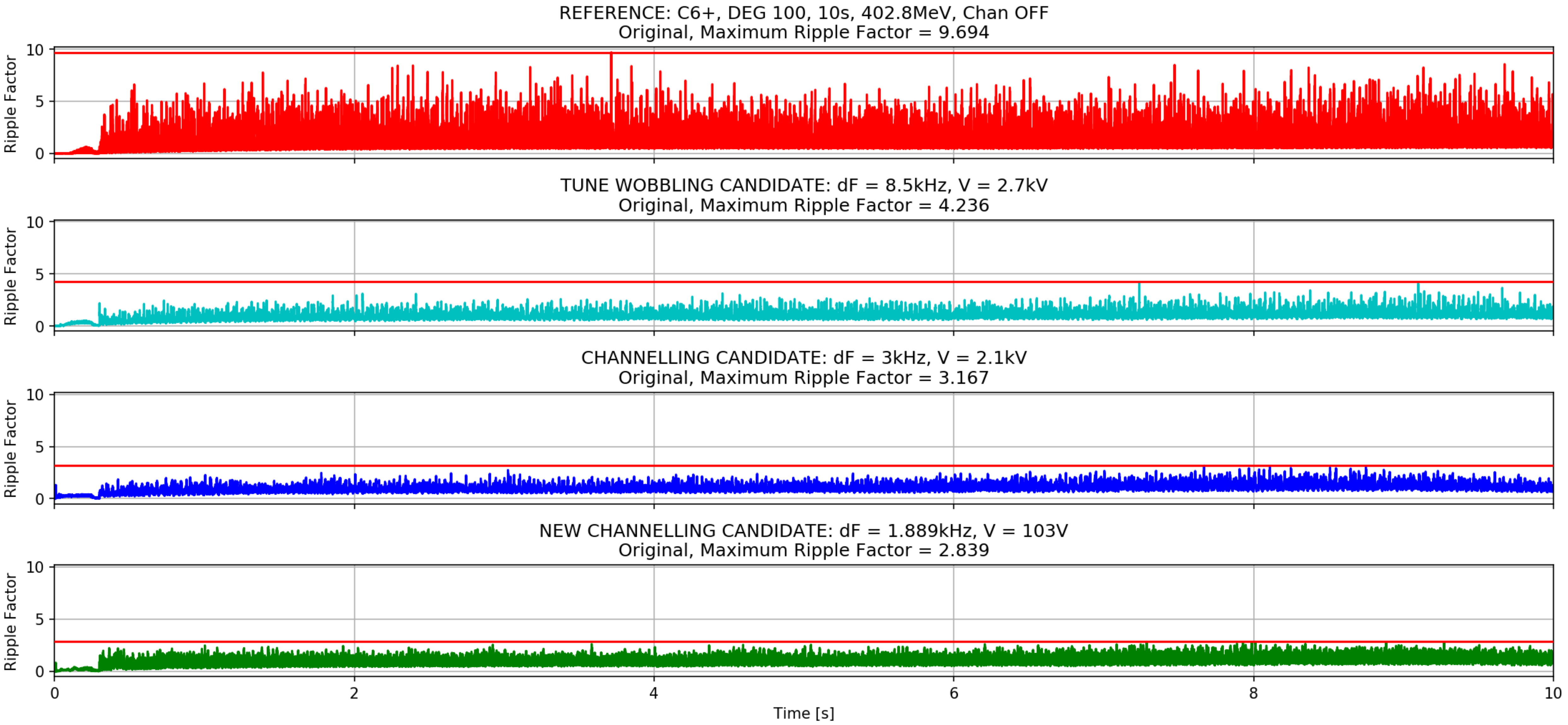
CARBON ION CHANNELLING

- Implementation of channelling for ripple reduction is currently being implemented for carbon ions as part of a performance improvement for carbons (PICar)
- Channelling was previously implemented for protons, however this was implemented more like the “tune wobble”, similar to as implemented at GSI, rather than channelling as outlined in the PIMMS design study
- The investigated options were simulated in BLonD and WinAgile before validation during the PICar feasibility study
- Measurements of the proposed settings matched the simulated results extremely well

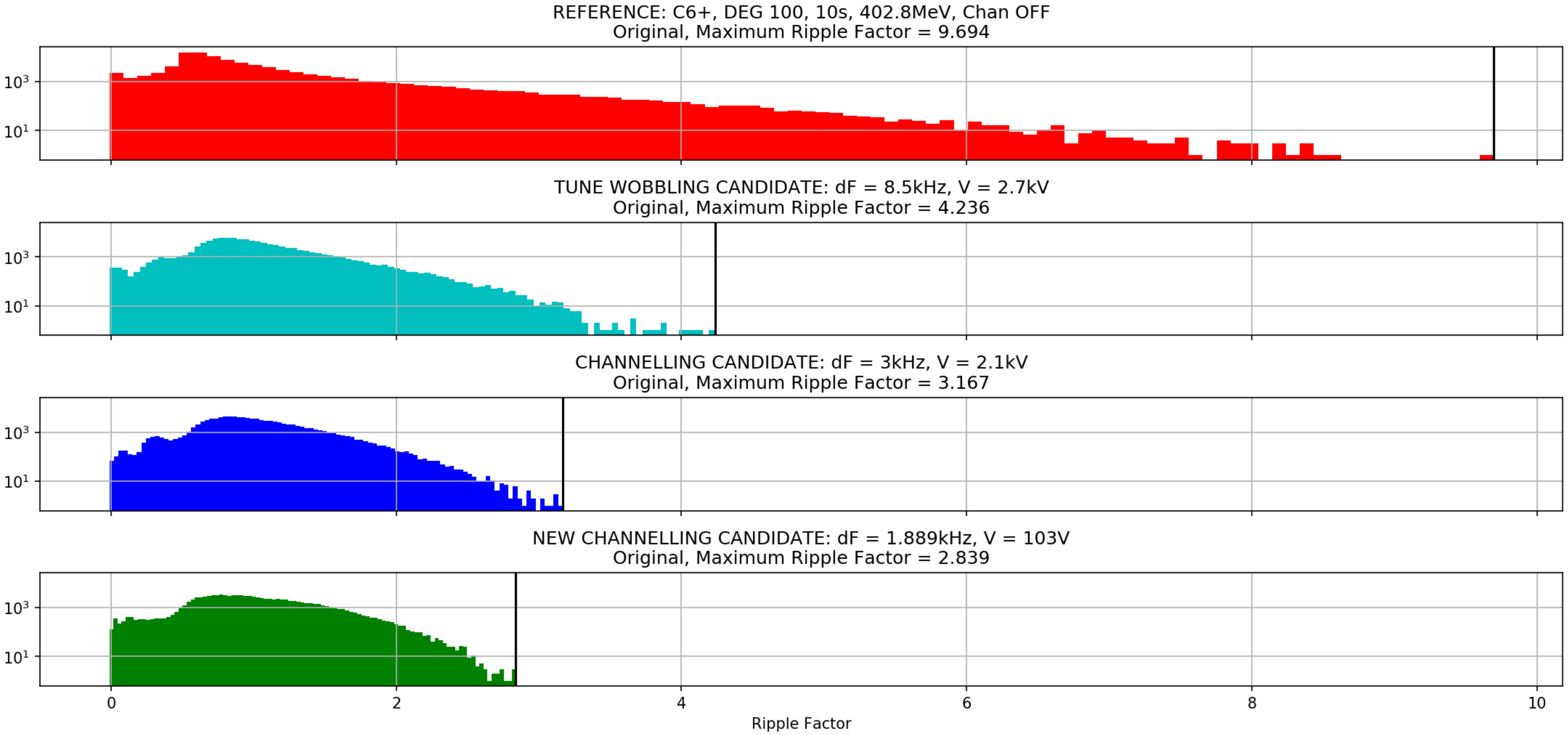




CARBON CHANNELLING RESULTS

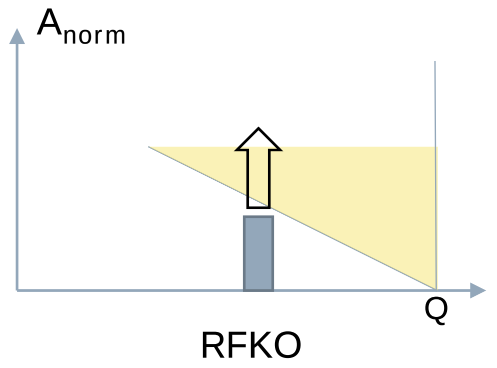


CARBON CHANNELLING RESULTS



RFKO DEVELOPMENT

- RFKO has been under recent development at MedAustron
    - RFKO is being focused on for a more efficient extraction (less chopping) with the possibility to implement multi-energy extraction and dynamic intensity control

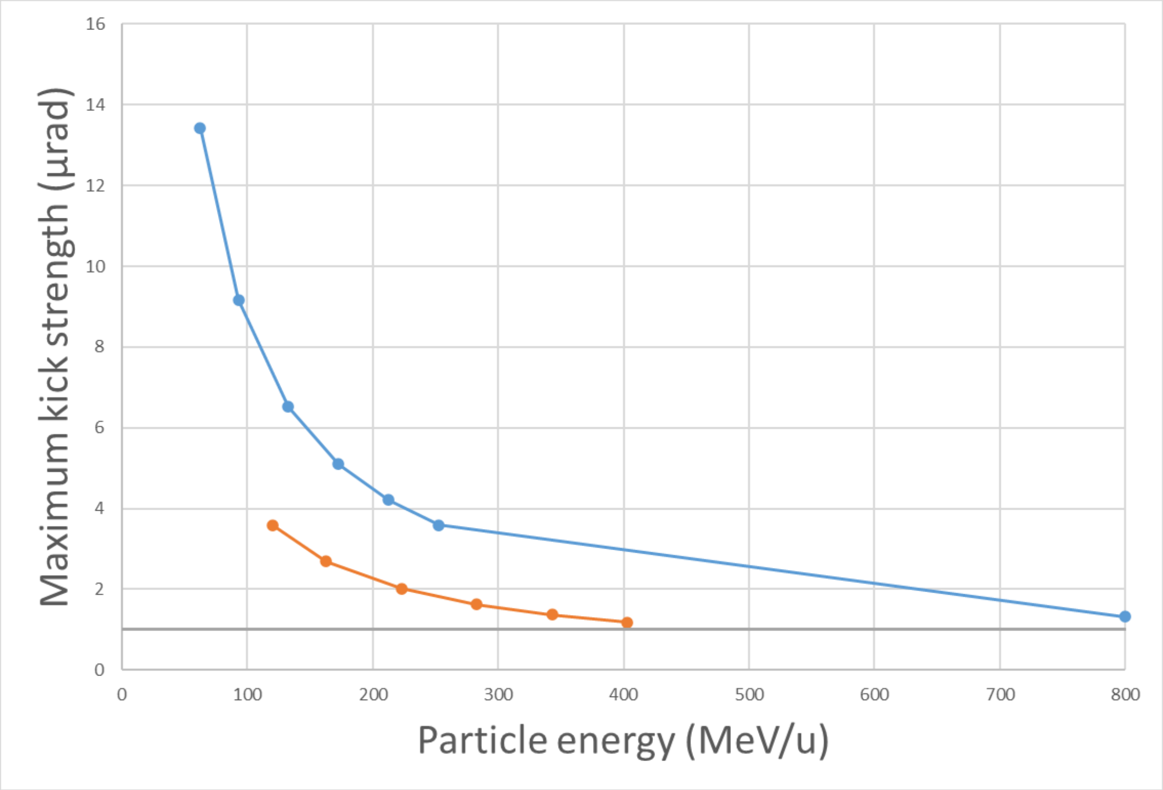


- The system design focus areas:
    - Signal generation (prototyping and production)
    - RF Amplification (1 kW)
    - Impedance and signal balancing (BalUn)
    - RF exciter

- The most sensitive components will be the RF kicker /exciter and the signal generation

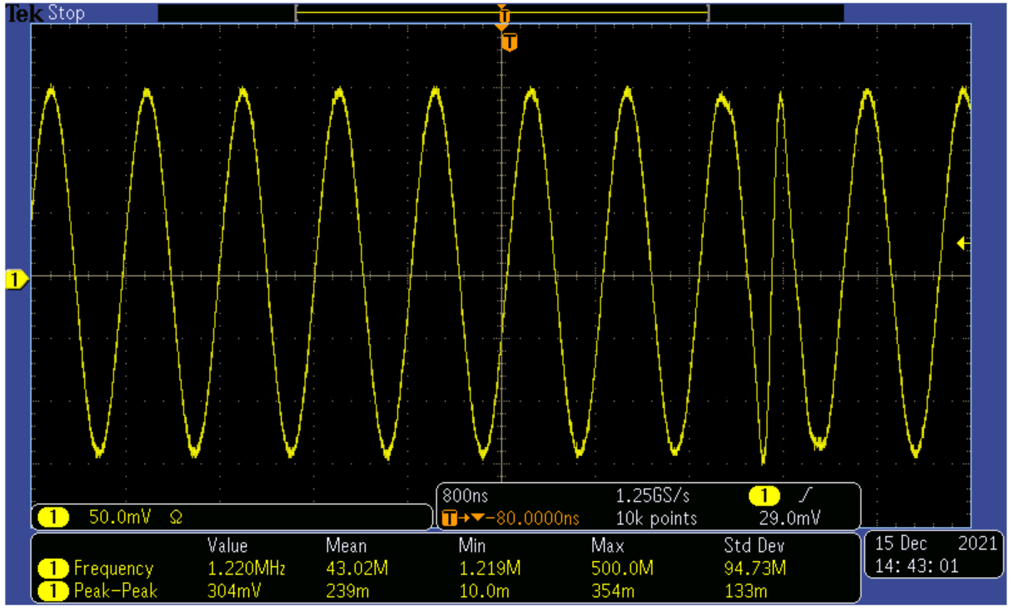
- Power amplifier maximum of 1 kW into a 50 Ohm load for a maximum peak-peak voltage of 632.5 V

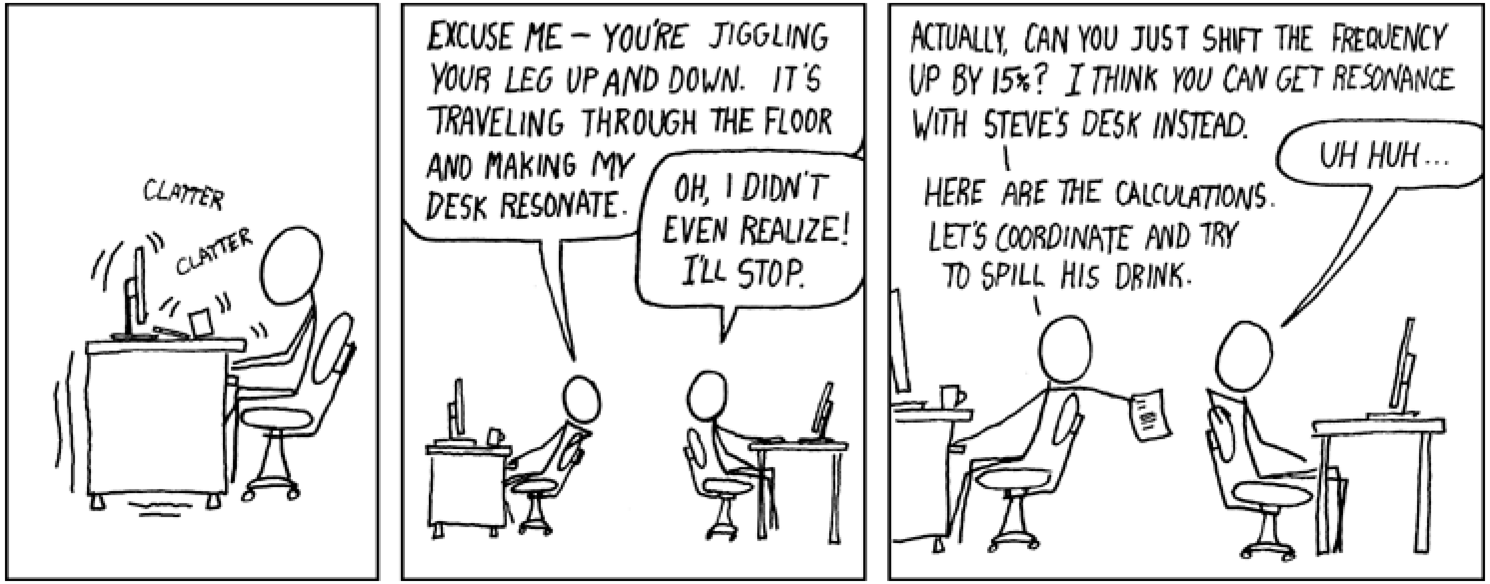
- Requirement to extract all particles in clinically relevant times = kick strength to be above 1 microradian



RFKO SIGNAL GENERATION

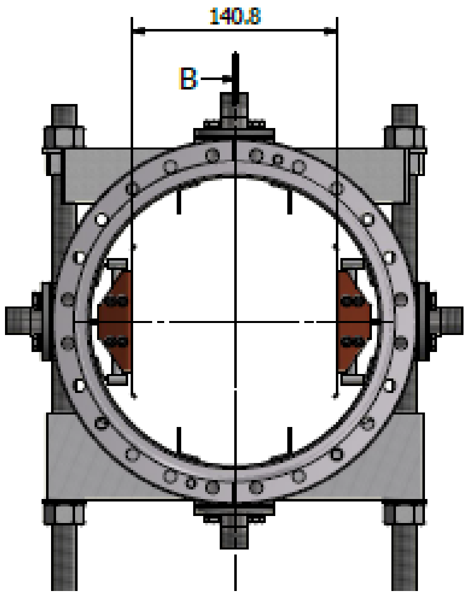
- Presently for signal generation prototyping for RFKO a software designed radio (SDR) is being used. Signal will be generated by the synchrotron LLRF in the final system.
  - Spreading of the signal is performed using frequency sweeping or random “noise” generation with phase shift keying to spread the fundamental frequency and excite the all of the beam
- Output of the generated signal is fed into a 1 kW amplifier to generate a maximum of 632 V signal on the exciter





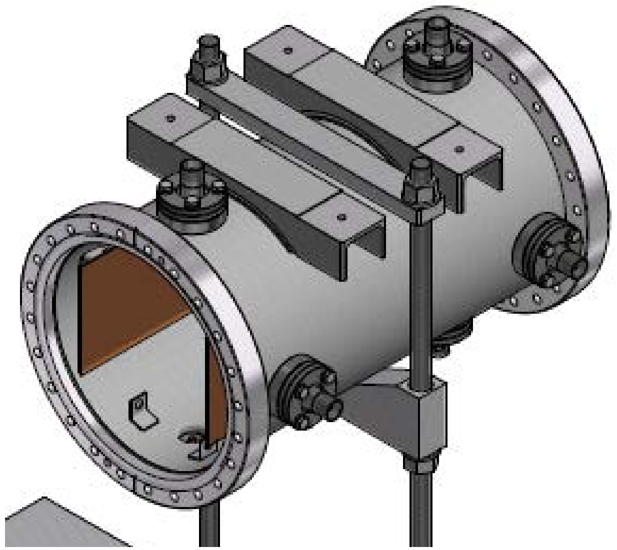
https://xkcd.com/228/

INITIAL CAD DESIGN FOR RF EXCITER



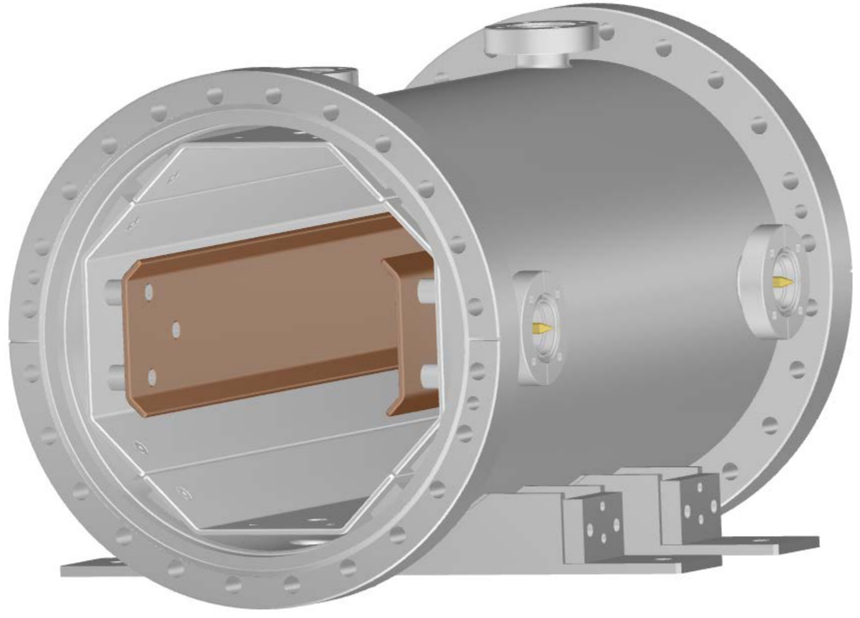
- The initial CAD design appeared suitable and met the requirements for analytical calculations (uniform E field of 4273.4 V/m), however validation of the design required electric field simulations

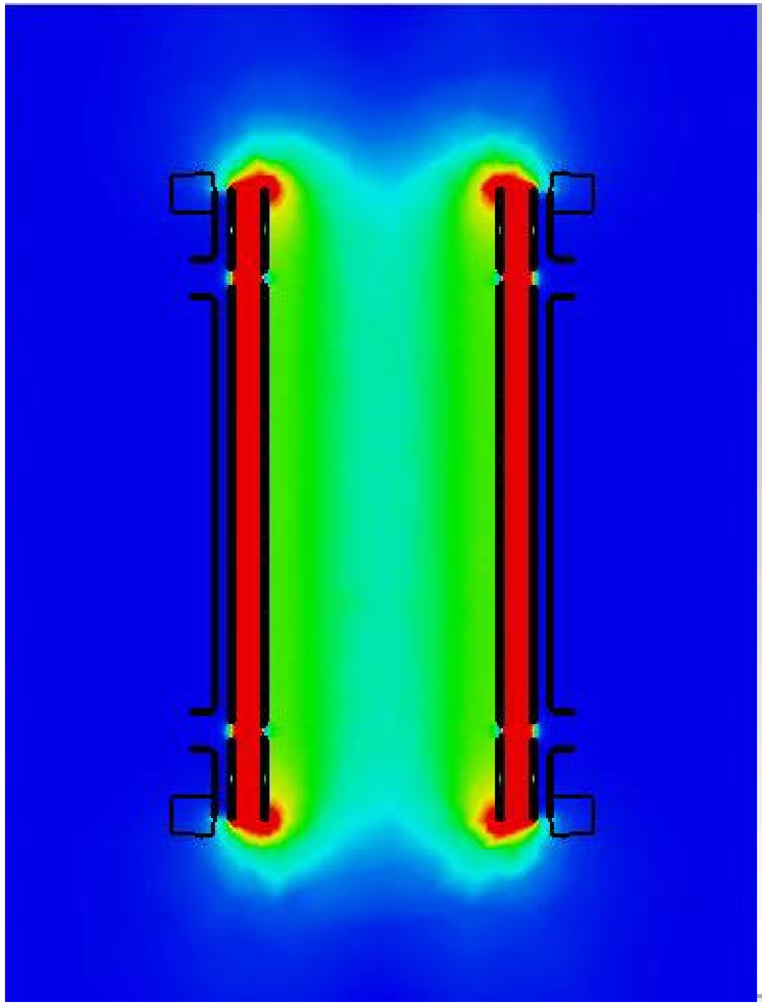
- Some optimisations from the E field simulations were required including:
  - Fine tuning was needed to minimise the high field regions at corners and edges of plates
  - Requirements on the balancing of the applied voltage between the plates (BalUn requirements)
  - Plate distance was optimised and an additional ground shielding plane was required

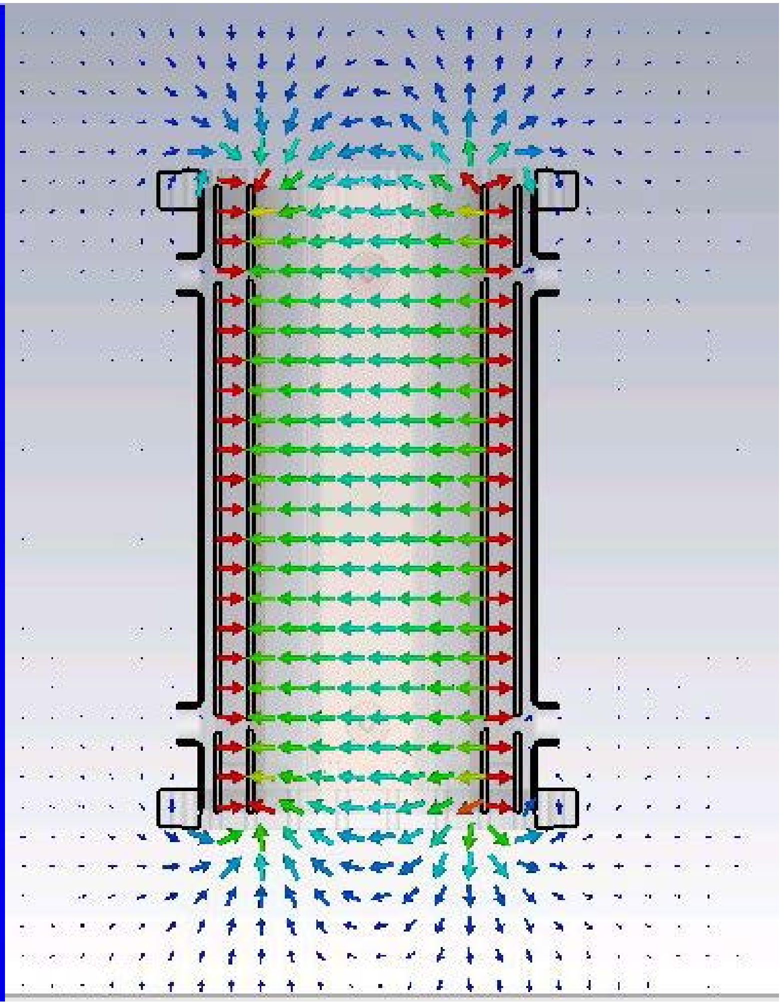


RF EXCITER E-FIELD SIMULATIONS

- The refined CAD design met the design requirements overcoming the identified issues
- Field along central axis matches well the analytically determined value
- Minor optimisation and room for future possible developments has been accommodated in the design



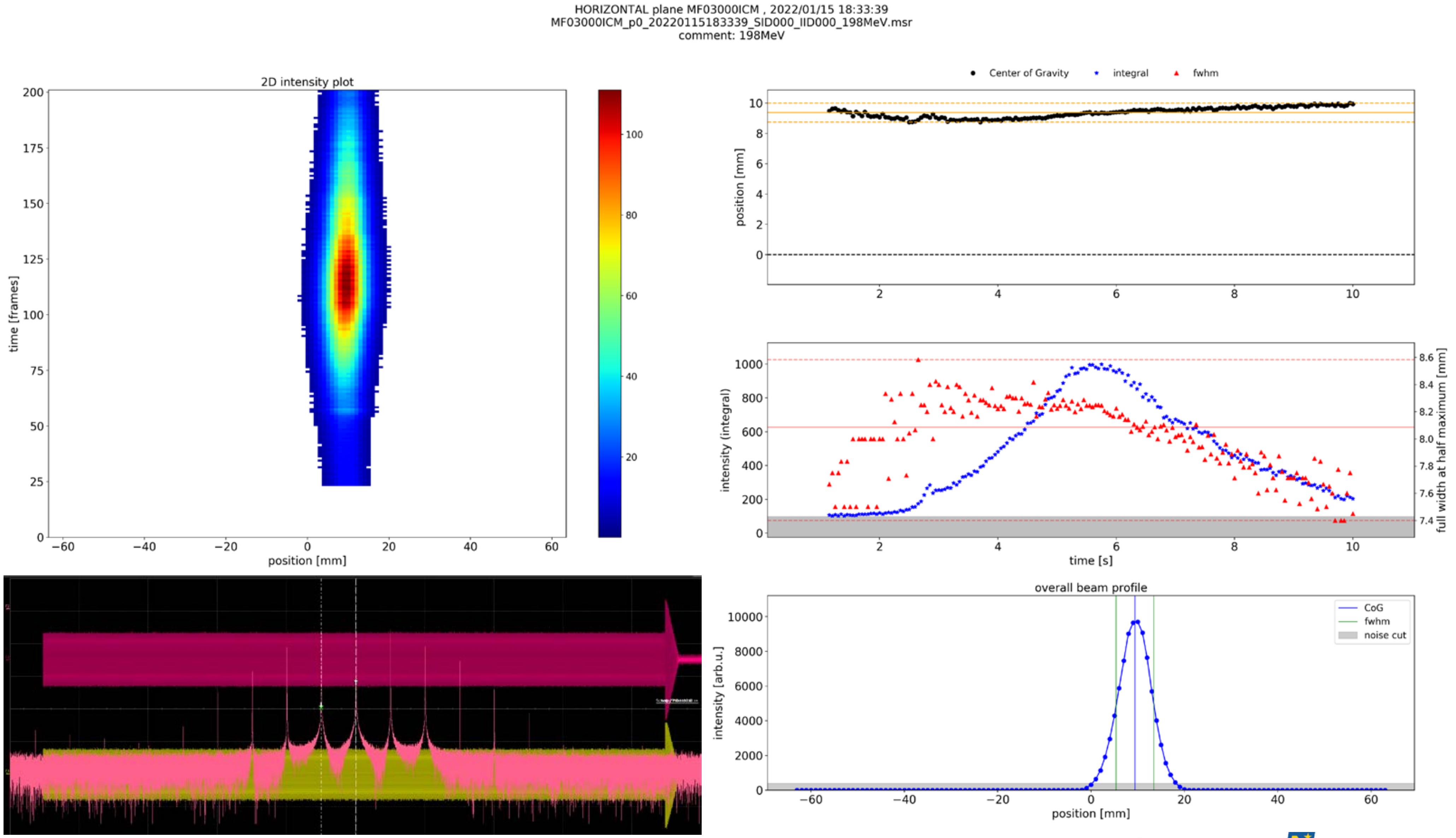




RFKO EXTRACTION OF 198 MEV PROTONS

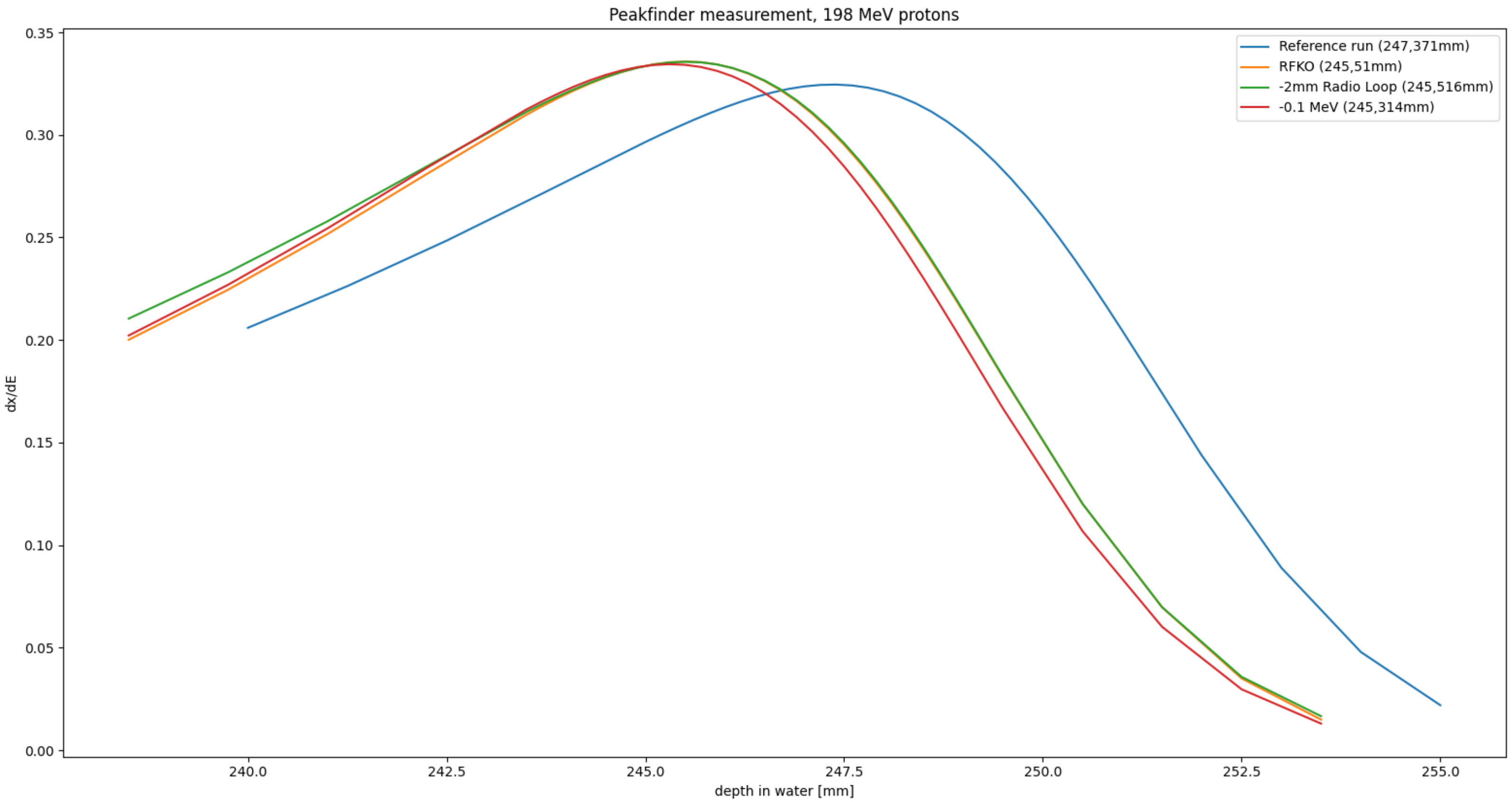
RFKO extraction rested at MedAustron using the LLRF to generate sidebands for excitation

Horizontal Schottky used for the excitation in lieu of a dedicated RFKO exciter



RFKO RANGE RESULTS

	PeakScan	Python fit	Mean
Reference	247,39	247,371	247,381
RFKO	245,5	245,51	245,505
-0.1 MeV	245,32	245,314	245,317



Courtesy of F. Feichtinger

SRIM(198.0 MeV) -> 251.8 mm
SRIM(197.9 MeV) -> 251.58 mm

- SRIM calculation takes no WET materials (I2M, DDS, window, etc.) in the beam path
- Reference of ~4.5 mm of WET for protons in the beamline at 198 MeV

Relative shift of the measured Betatron core range to RFKO range matches exactly the expected distance to the resonance

Error study for a 0.1 MeV energy offset could also be seen

FUTURE PLANS

- COSE Multi Energy extraction with more than 2 energies with varied extraction intensities (promising initial results)
  - Multiple sRF triggers can be used to optimise the MEE using COSE
- Implementation of improved beam loss monitors for use with investigations
  - Libera BLM with MHz frequency response
  - Complementary to existing PIN diode measurements
- Carbon ion channelling has been successfully tested and is currently being implemented
  - Investigation into optimisation and implementation of channelling for protons
  - Other ripple suppression techniques will also be investigated using measurements of beam position and intensity with high bandwidth (up to 10’s of MHz in collaboration with Cividec)
- RFKO development and implementation is ongoing with continued testing and refinement