SLOW EXTRACTION AT MEDAUSTRON

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MedAustron
Ionentherapiezentrum

OVERVIEW

1. MedAustron Overview
    a. Existing Slow Extraction
    b. P7 research stream
2. Low Frequency Ripple Studies
3. High Frequency Ripple Studies
4. Alternative Extraction Methods
    a. Tune Sweep
    b. COSE
    c. Bunched COSE
    d. Multi-Energy Extraction
5. Future Plans
    a. RFKO
    b. RF Noise
    c. Optimised Slow Extraction Methods

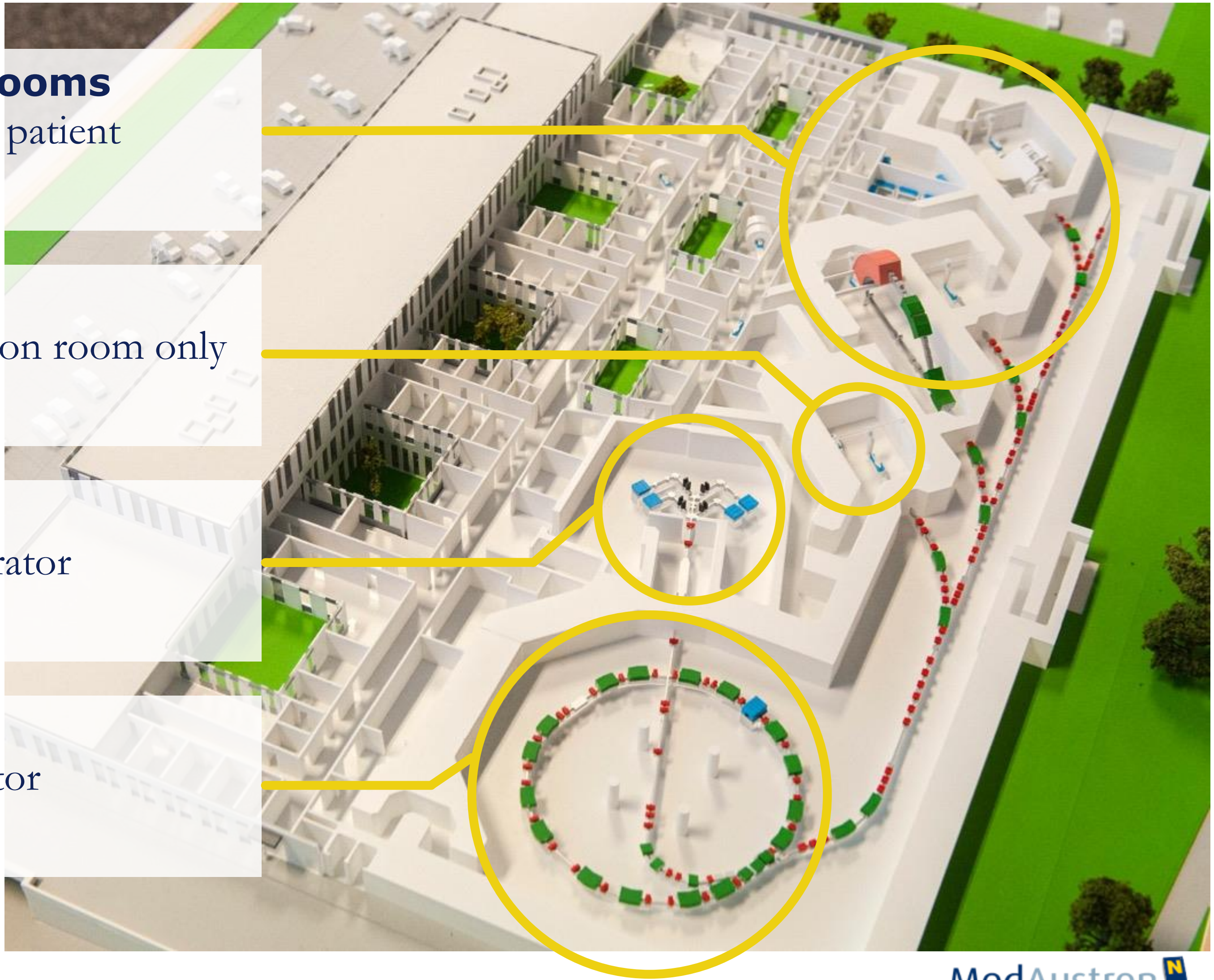
THE MEDAUSTRON FACILITY

Irradiation Rooms
Three rooms for patient treatment

Research
Separate irradiation room only for scientific use

Ion Sources
and linear accelerator

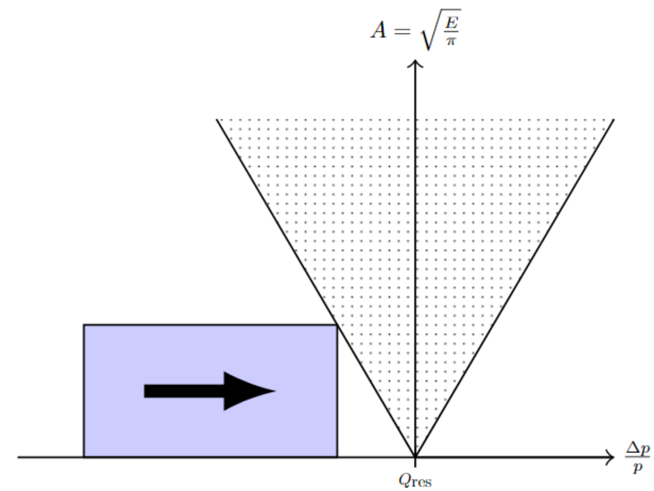
Synchrotron
Circular accelerator

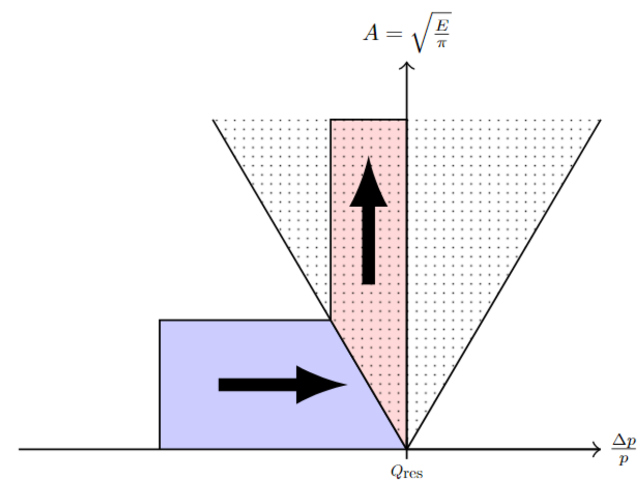


ACCELERATOR SPECIFICATIONS

- Based on the PIMMS design and developed in close collaboration with CERN and CNAO
- 77 metre circumference
- Extraction based on a third integer resonant slow extraction
- Existing extraction method is using a Betatron core to drive beam into unstable region with resonant sextupole to enlarge the stopband
- Clinical extraction times of 10 seconds (0.1-30 seconds available for research & development)
- RF channelling used for beam ripple suppression
- Future developments with patient safety is paramount

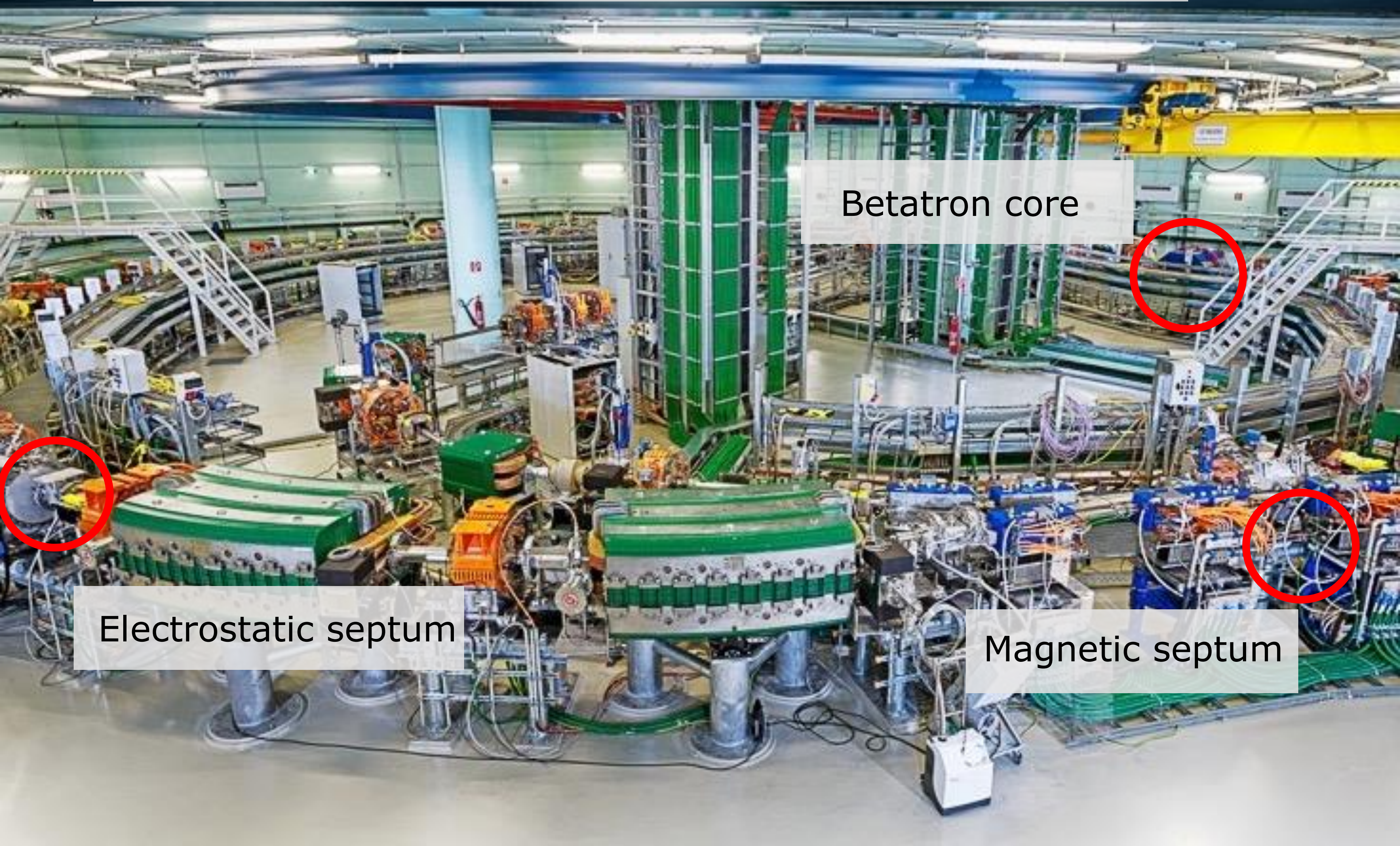
Particle type	Energy	Intensity (per spill)
Proton	62.4 – 252.7 MeV	$\sim 10^{10}$
Carbon ion	120 – 402.8 MeV/u	$\sim 10^{8}$






MEDAUSTRON SYNCHROTRON

MEDAUSTRON SYNCHROTRON



NON-CLINICAL RESEARCH (NCR)

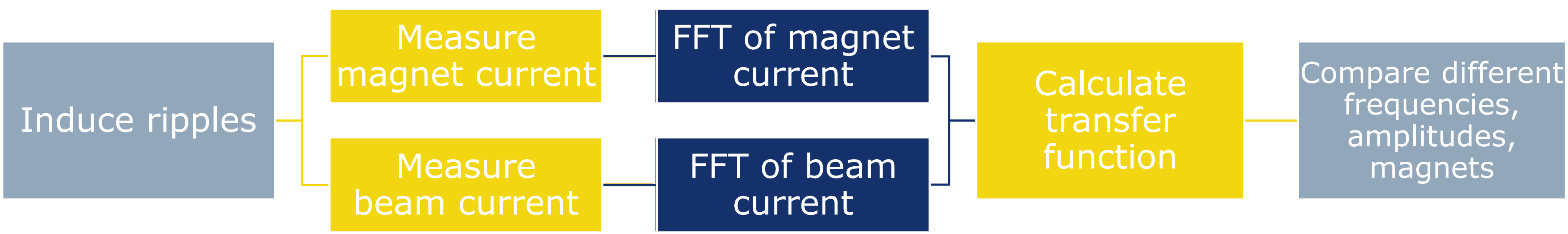
- **Research topics are divided into research priorities from P0-P7:**
  - P0 - Commissioning and Quality Assurance
  - P1 - Intrafraction Adaptive Radiation Therapy
  - P2 - Interfraction Adaptive Radiation Therapy
  - P3 - Imaging with Ion Beams
  - P4 - Magnetic Resonance Guided Particle Therapy
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

Collaboration agreement "Development of Slow Extraction Techniques" between MedAustron and CERN

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)

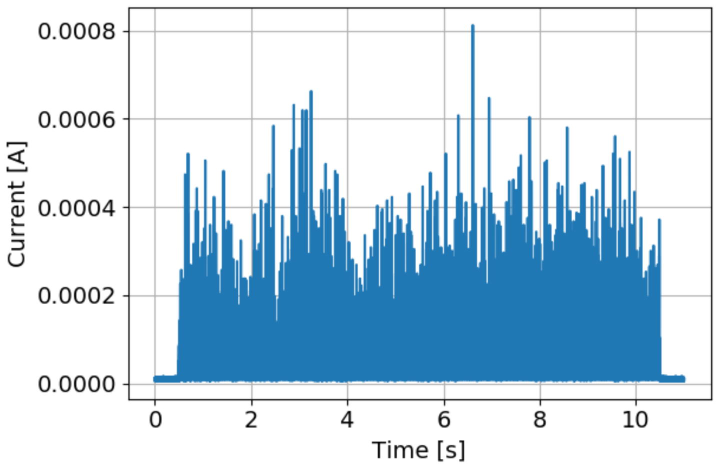
LOW FREQUENCY RIPPLE STUDIES

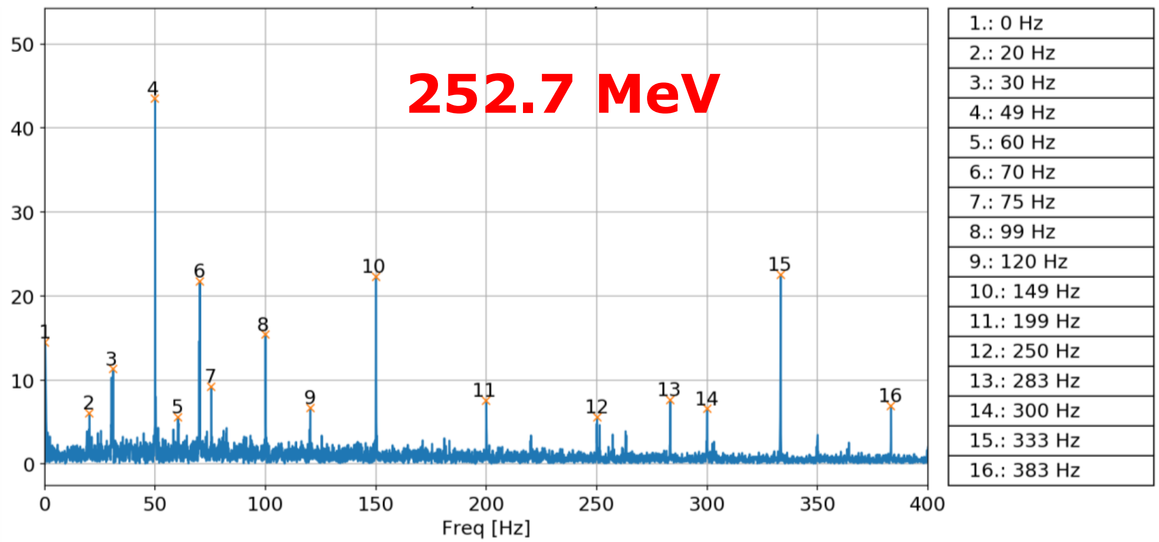
- Power supply ripple → tune fluctuations → separatrix area variation → beam spill ripple
- Low beam spill ripples mandatory for sufficient and time-effective treatment
- Measure the low frequency intrinsic ripples
- Induce ripples of known amplitude and frequency on each magnet family to determine the transfer function
- Measurements in isocentre of treatment room with a fast detector and amplifier from CIVIDEC (whole spill)
- Goal: Identify components with large contribution to beam spill ripples

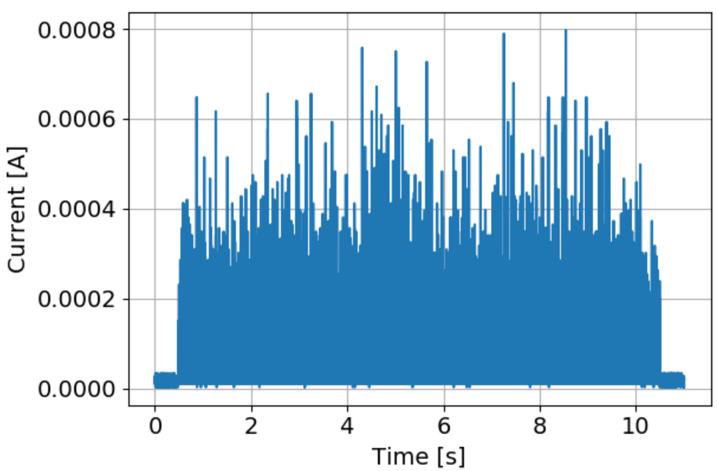


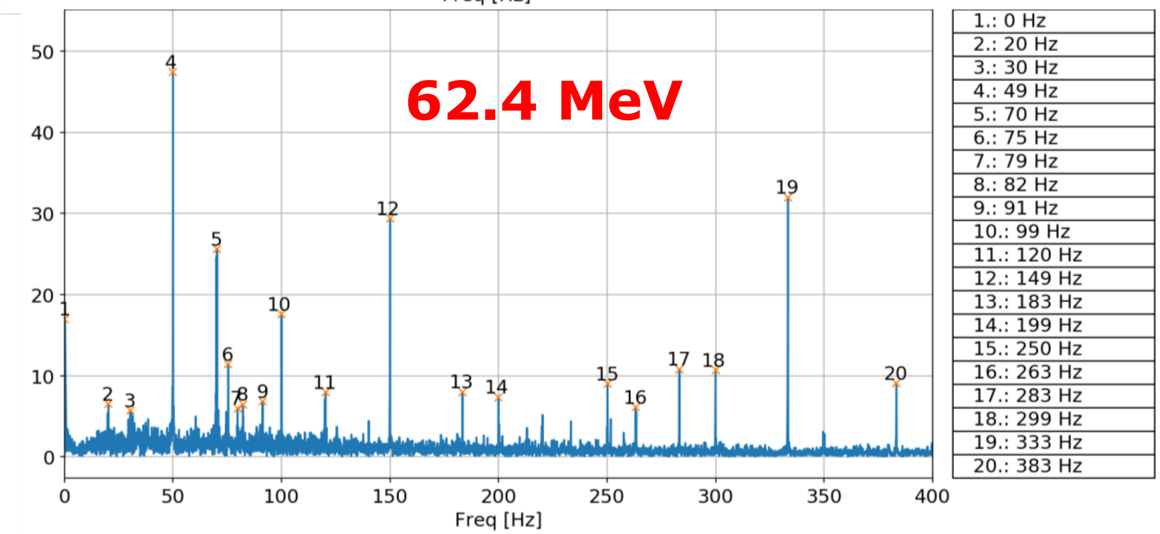
INTRINSIC RIPPLES

Standard medical beam settings
- Spill length: 10s
- RF-Channelling On

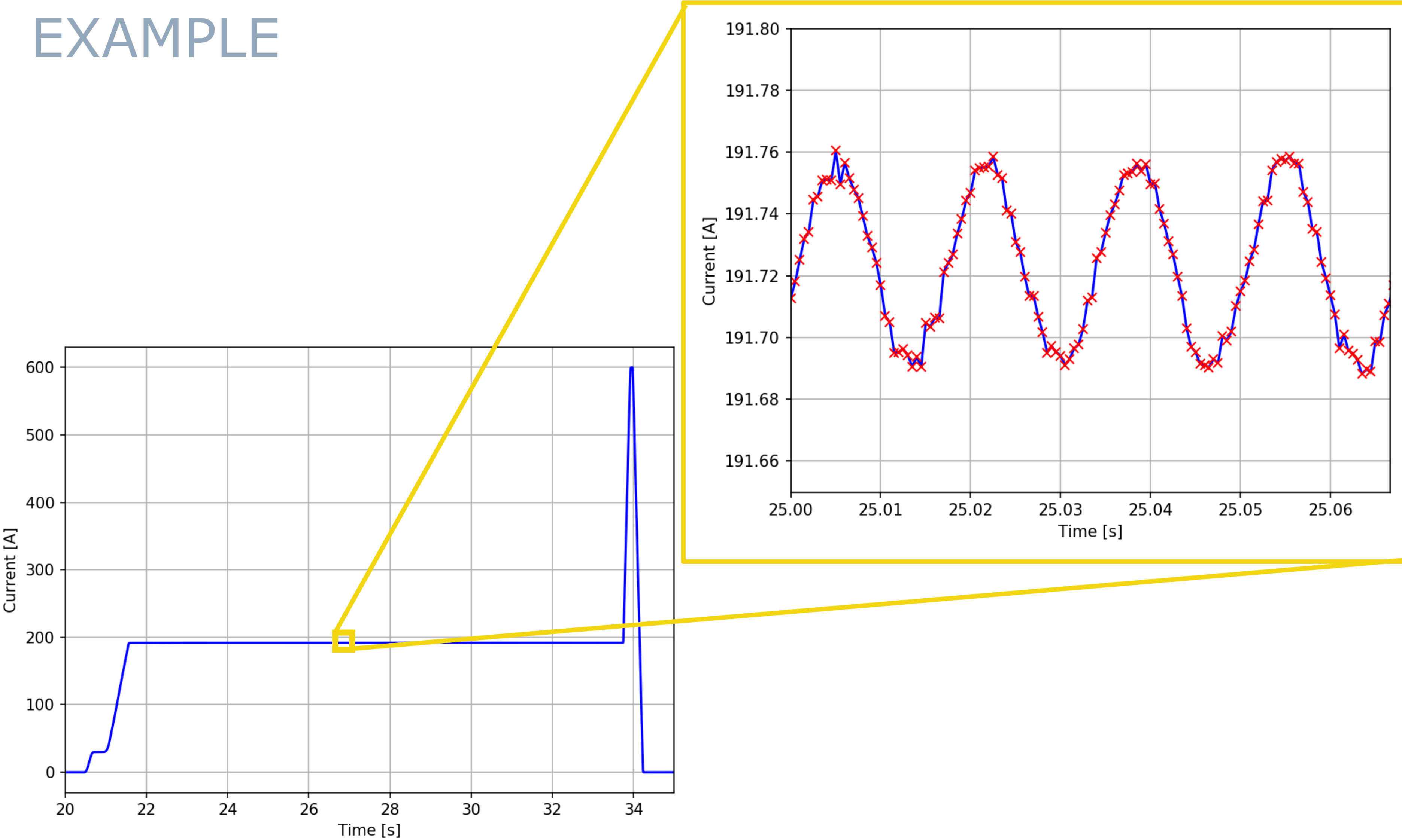








INDUCED RIPPLE EXAMPLE



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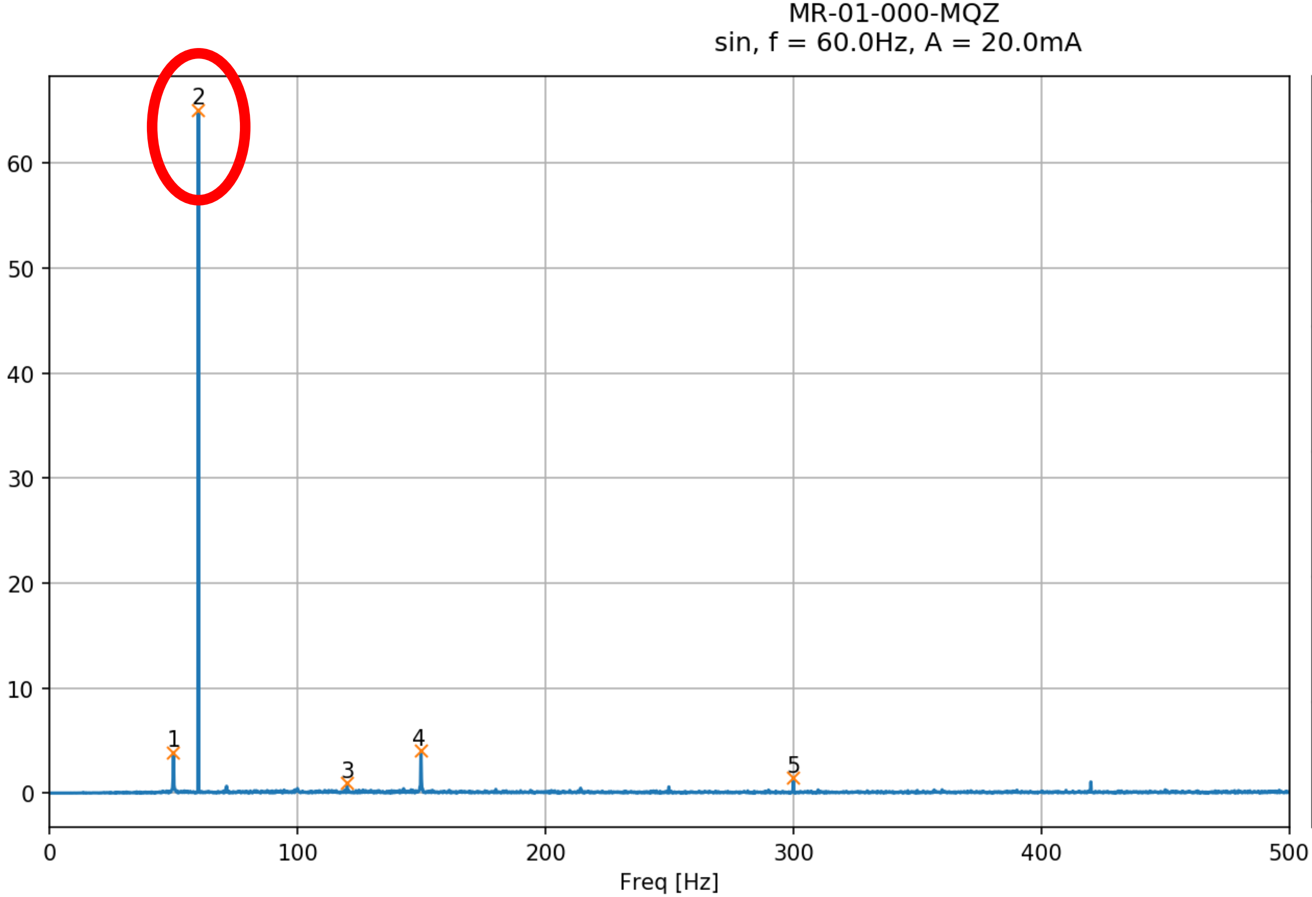
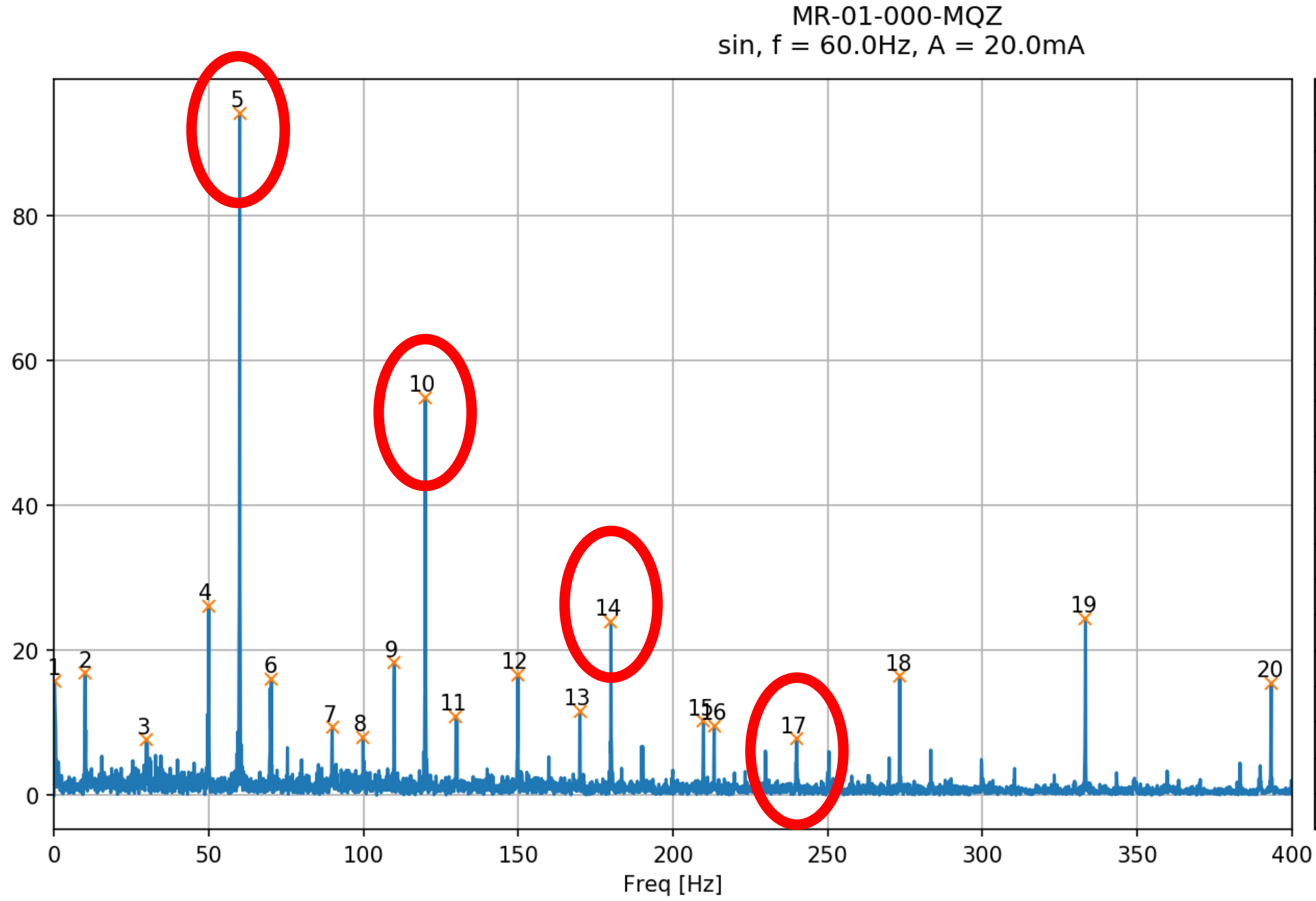
INDUCED RIPPLES – QUADRUPOLE: CURRENT MEASUREMENT



	Freq [Hz]	Amp	Phase
1	50	3.84	-0.7251
2	60	65.01	2.3489
3	120	0.9	-2.6778
4	150	3.99	-1.3351
5	300	1.38	2.9444

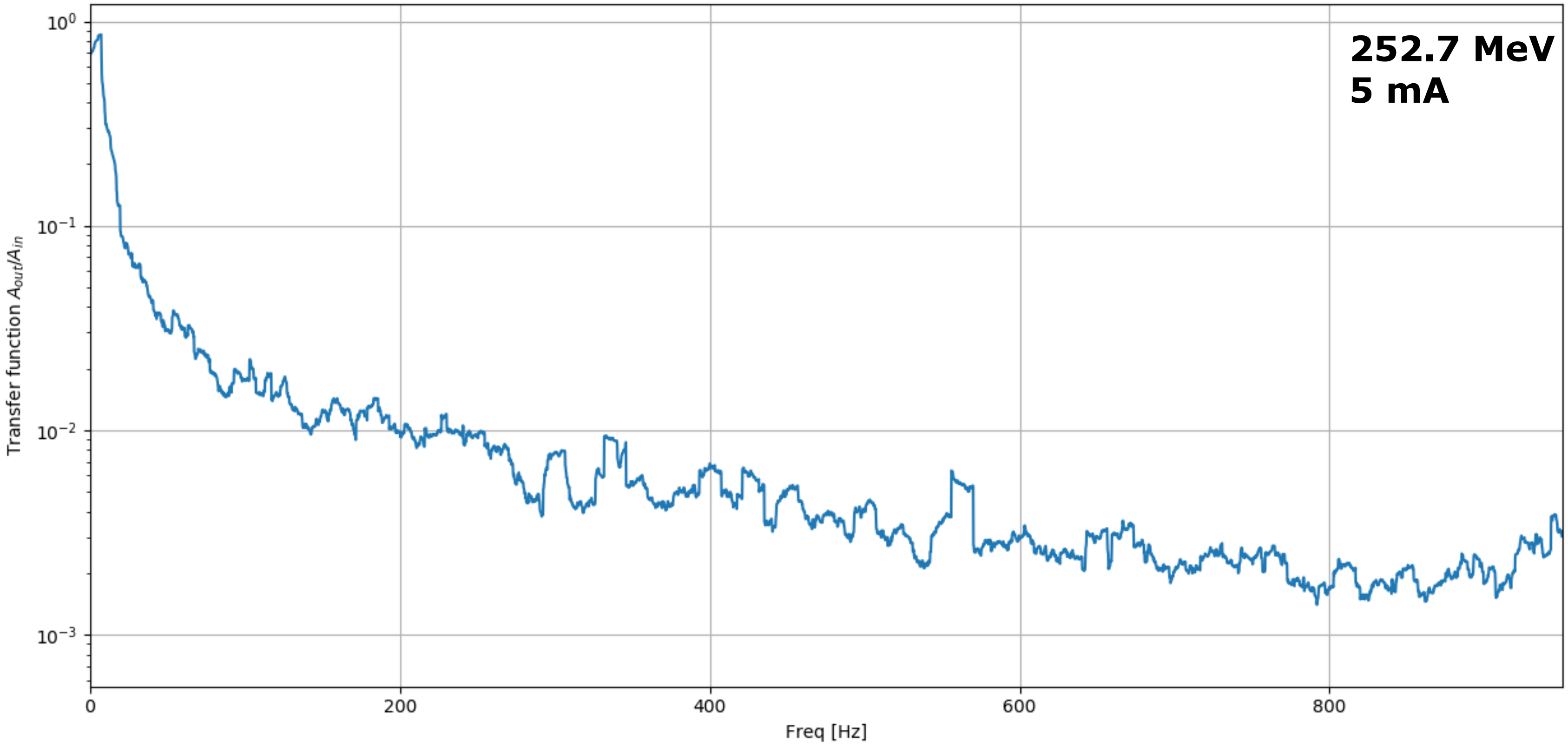
INDUCED RIPPLES – QUADRUPOLE: BEAM CURRENT AT ISOCENTRE



	Freq [Hz]	Amp	Phase
1	0	15.75	-2.8651
2	10	16.85	-1.4132
3	30	7.61	1.8948
4	50	26.15	-1.7162
5	60	94.14	-0.7302
6	70	16.07	2.3078
7	90	9.35	0.3579
8	100	7.95	0.1967
9	110	18.26	-2.244
10	120	54.88	-1.555
11	130	10.9	-0.418
12	150	16.63	-0.809
13	170	11.59	-2.9346
14	180	23.95	-2.3942
15	210	10.21	-1.5061
16	213	9.55	0.0421
17	240	7.79	3.1049
18	273	16.41	-0.8764
19	333	24.38	-1.8671
20	393	15.49	-2.5038

TRANSFER FUNCTION – QUADRUPOLE EXAMPLE

$$TF(f_0, A) = \frac{FFT_{beam}(f_0, A)}{FFT_{magnet}(f_0, A)}$$



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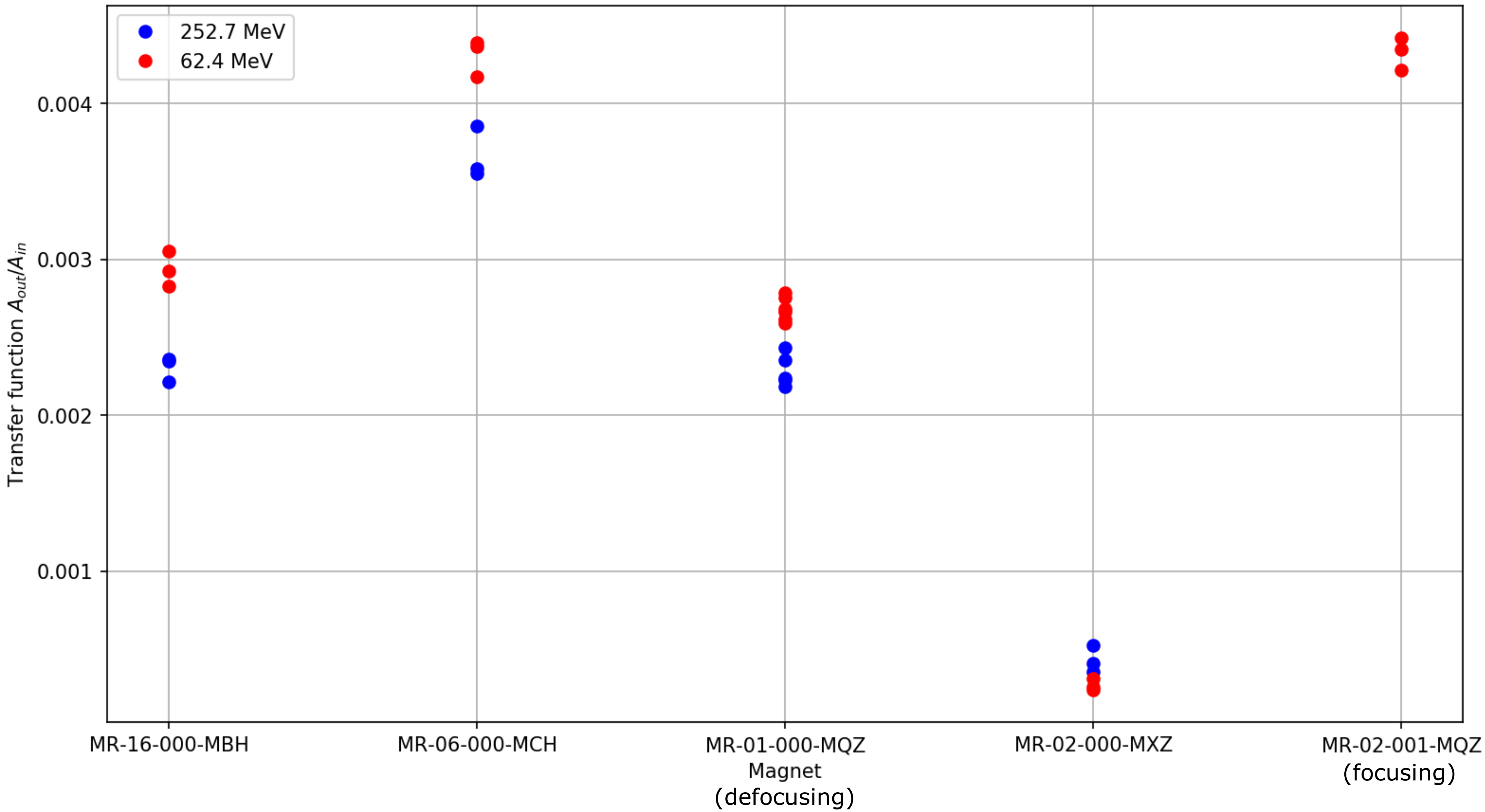
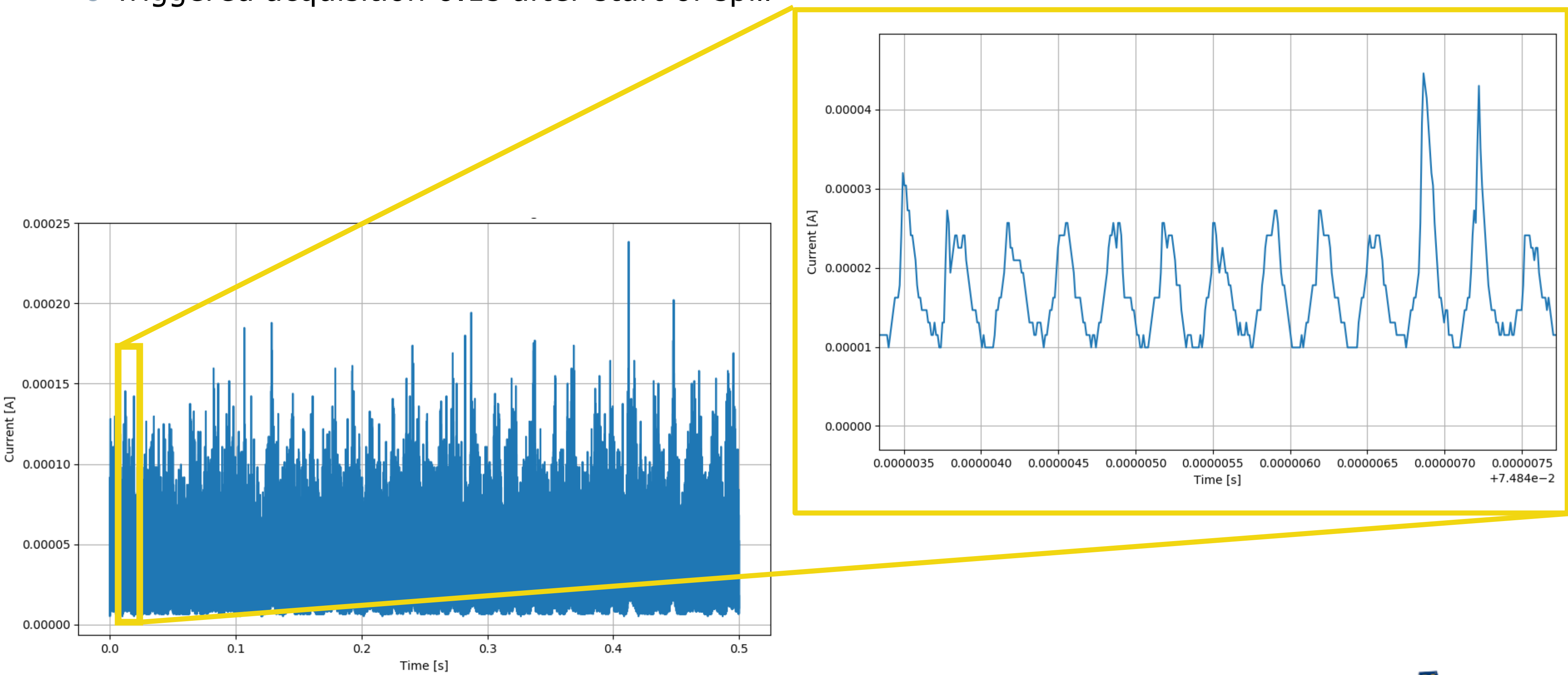
TRANSFER FUNCTION – ALL MAGNET FAMILIES



HIGH FREQUENCY RIPPLE STUDIES

- Measurement of the high frequency intrinsic ripples in isocentre of treatment room using a fast detector from CIVIDEC with a 100 MHz bandwidth response
  - 0.5 second measurement length limitation due to large number of samples
  - Triggered acquisition 0.1s after start of spill



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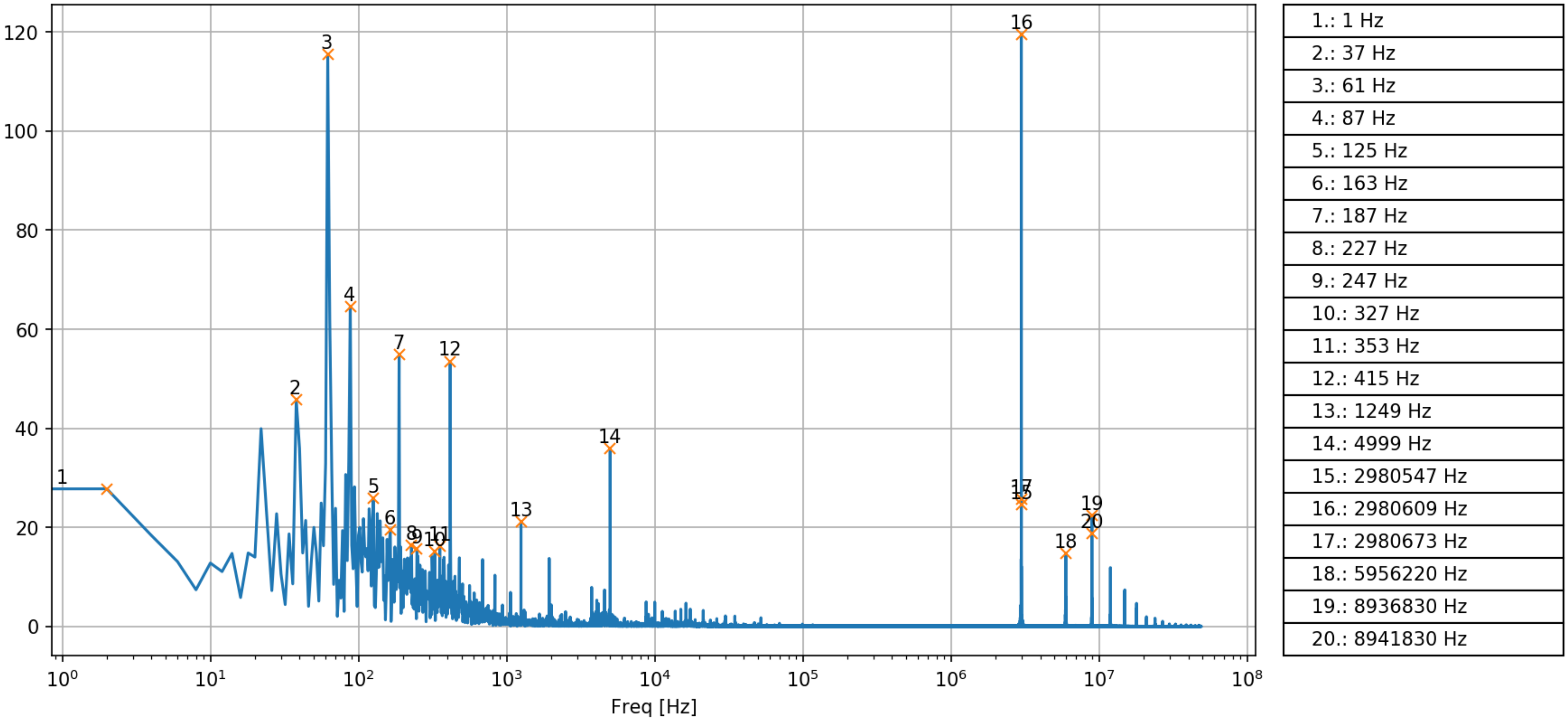
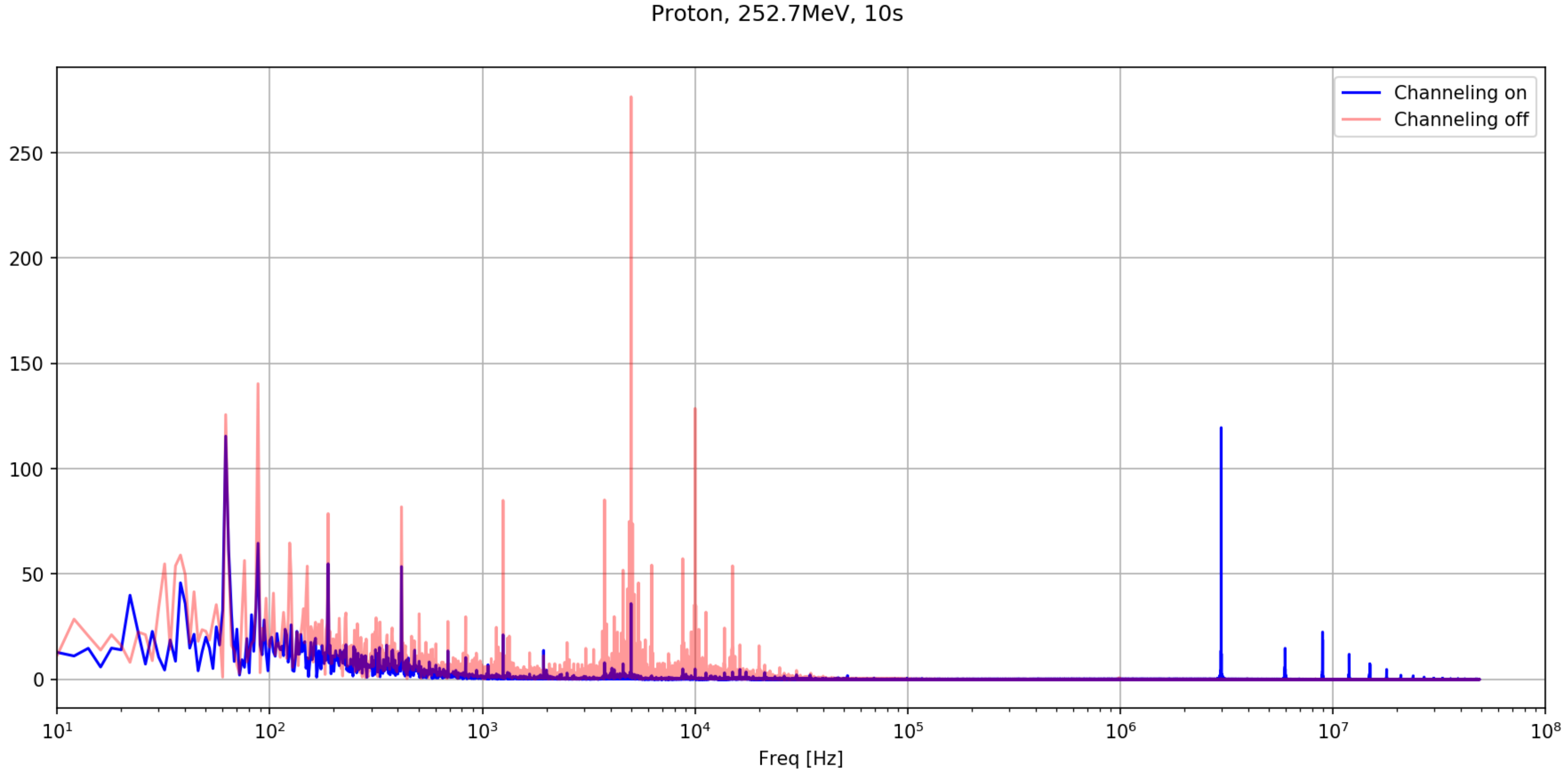
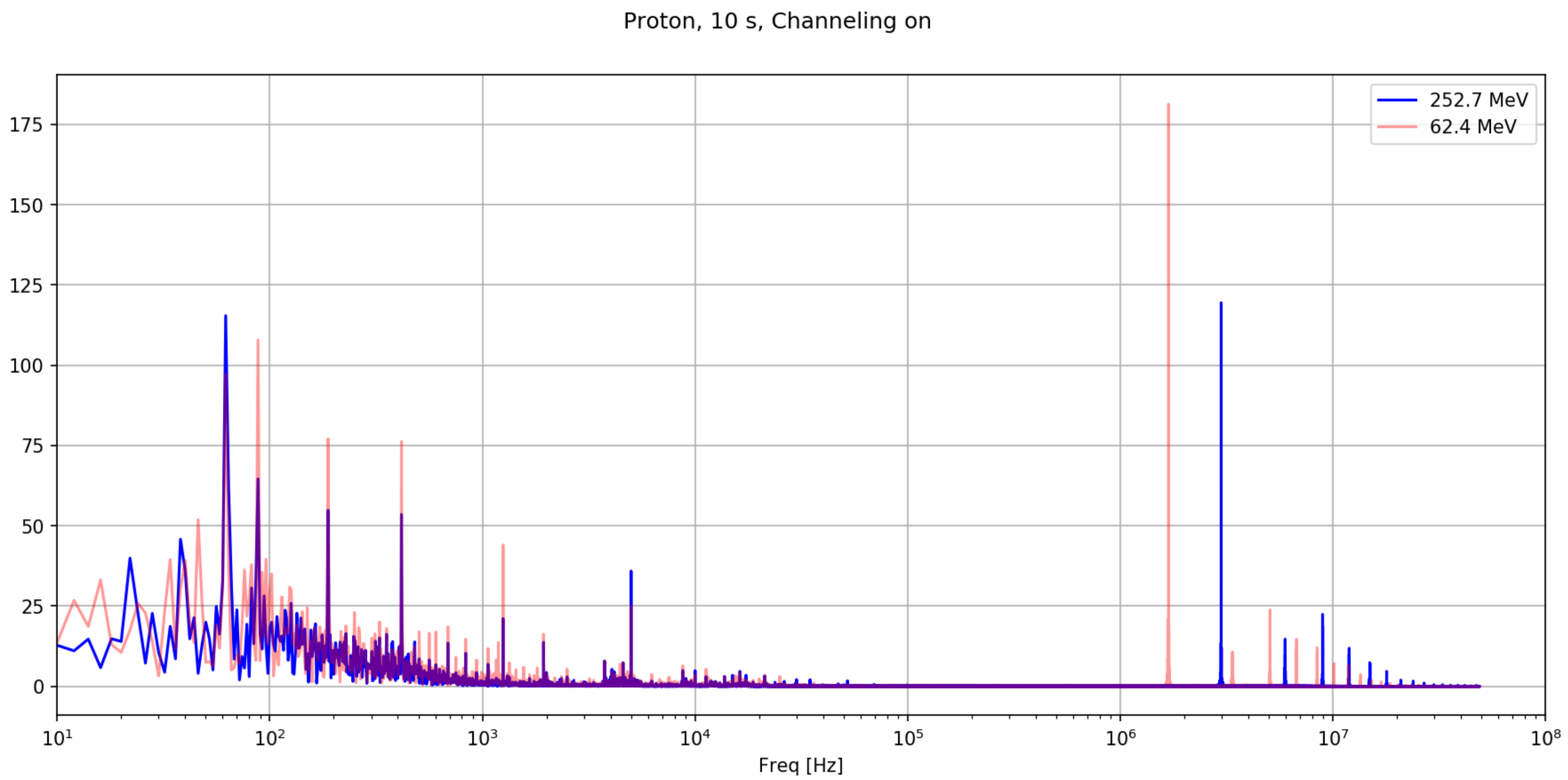
PROTON, 252.7 MeV, 10s, CHANNELLING ON



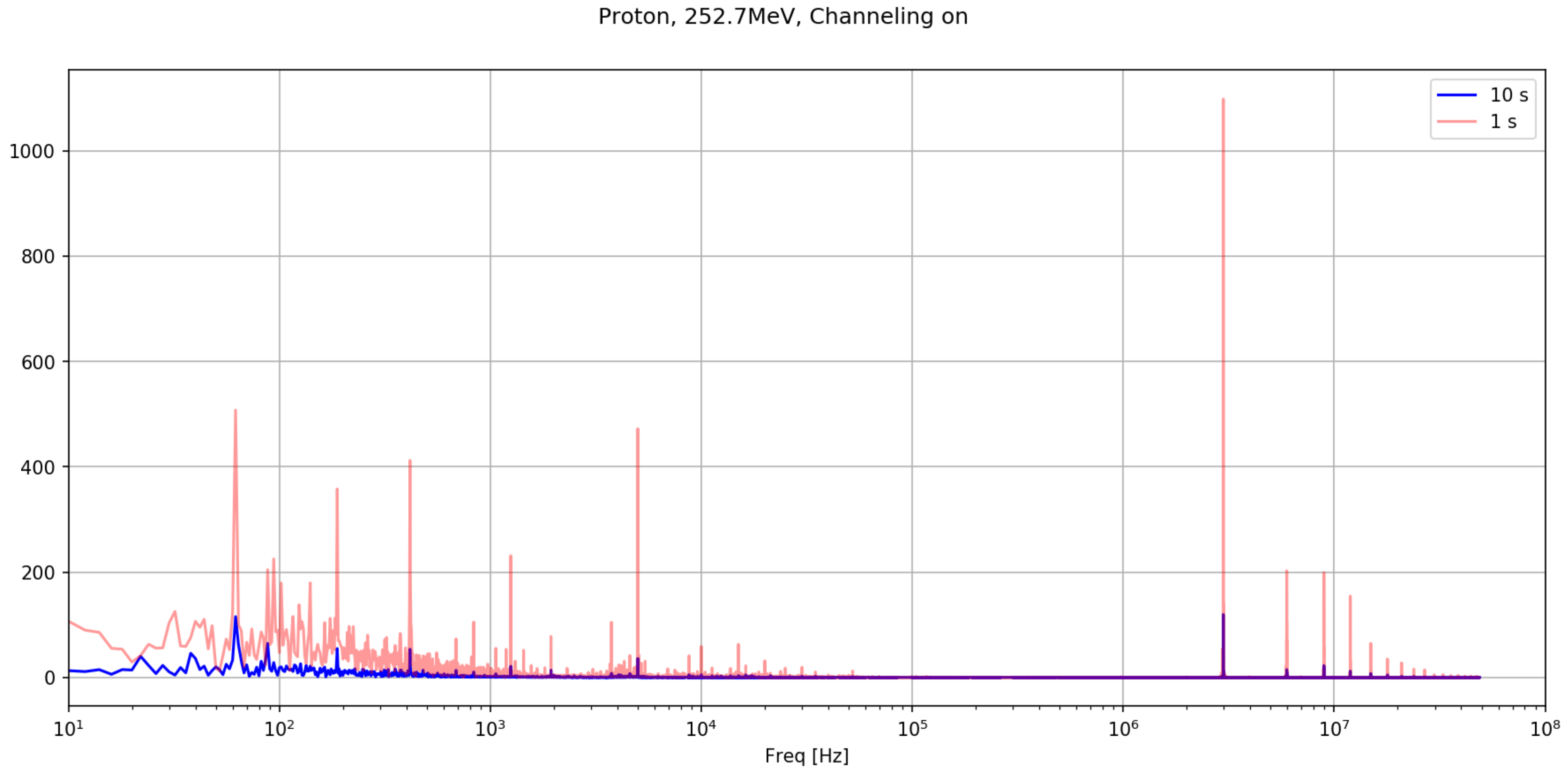
CHANNELLING ON vs. CHANNELLING OFF



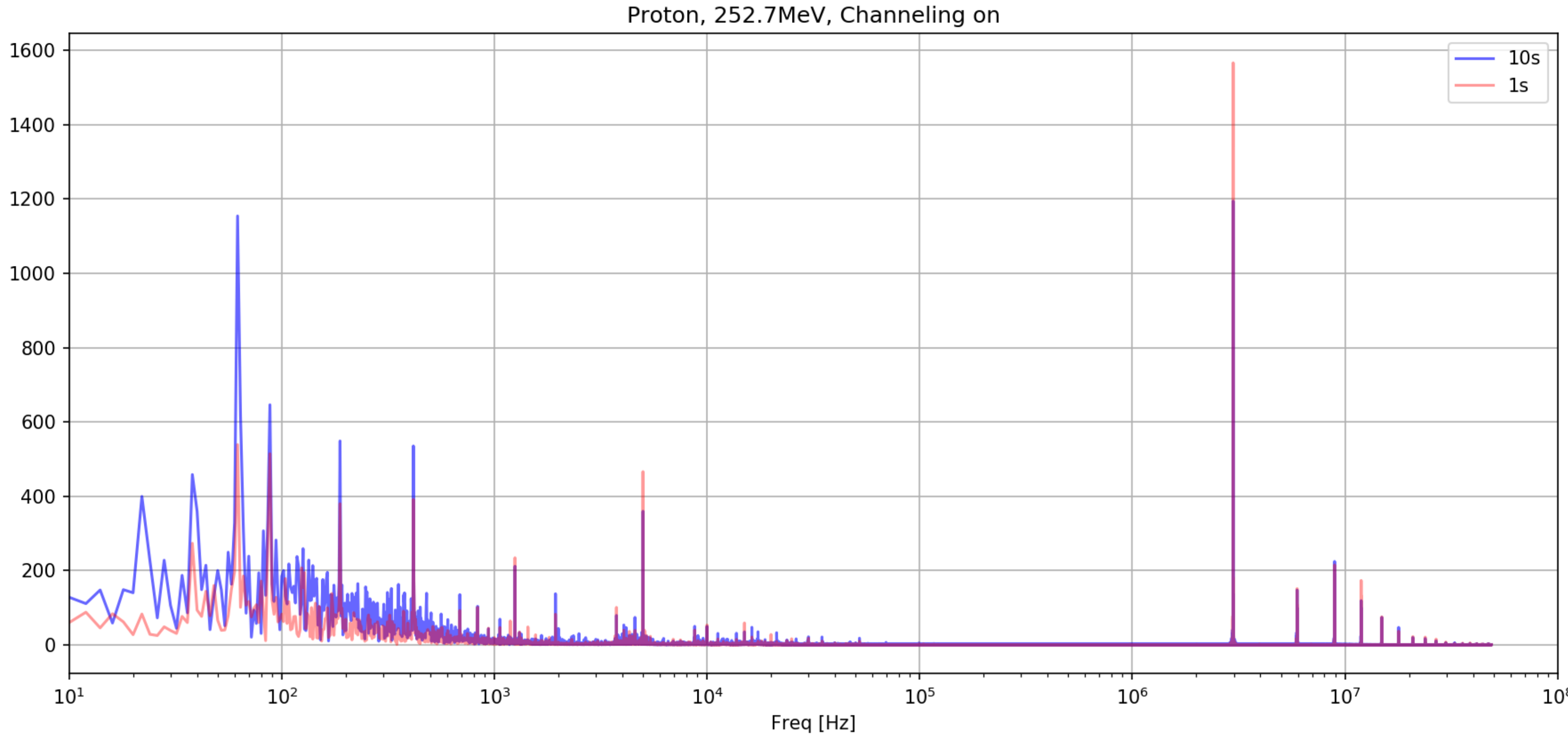
ENERGY: 252.7 MeV vs. 62.4 MeV



SPILL LENGTH: 1s vs. 10s



SPILL LENGTH: 1s vs. 10s NORMALIZED TO 1s



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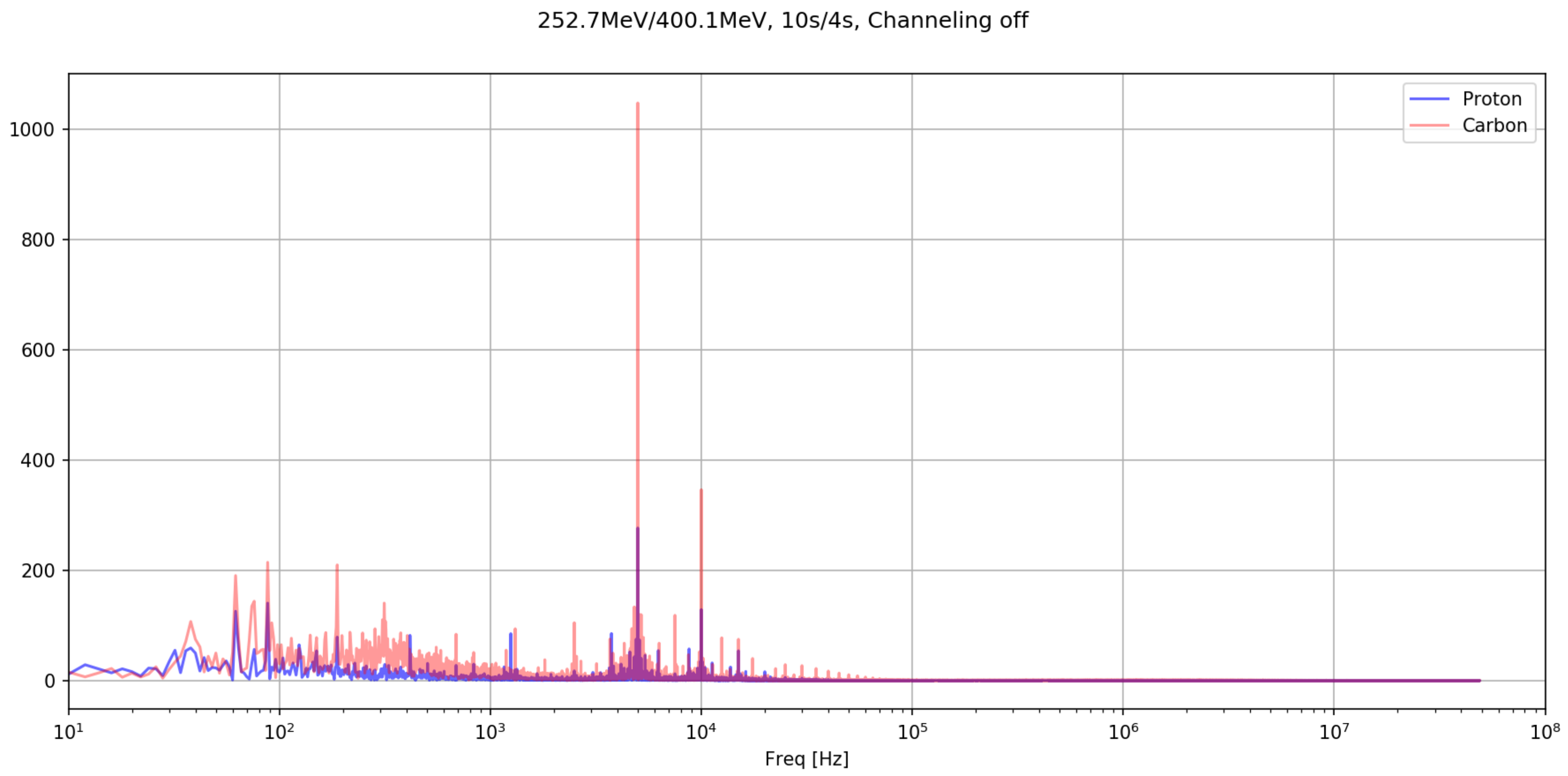
PARTICLE TYPE: PROTON vs. CARBON



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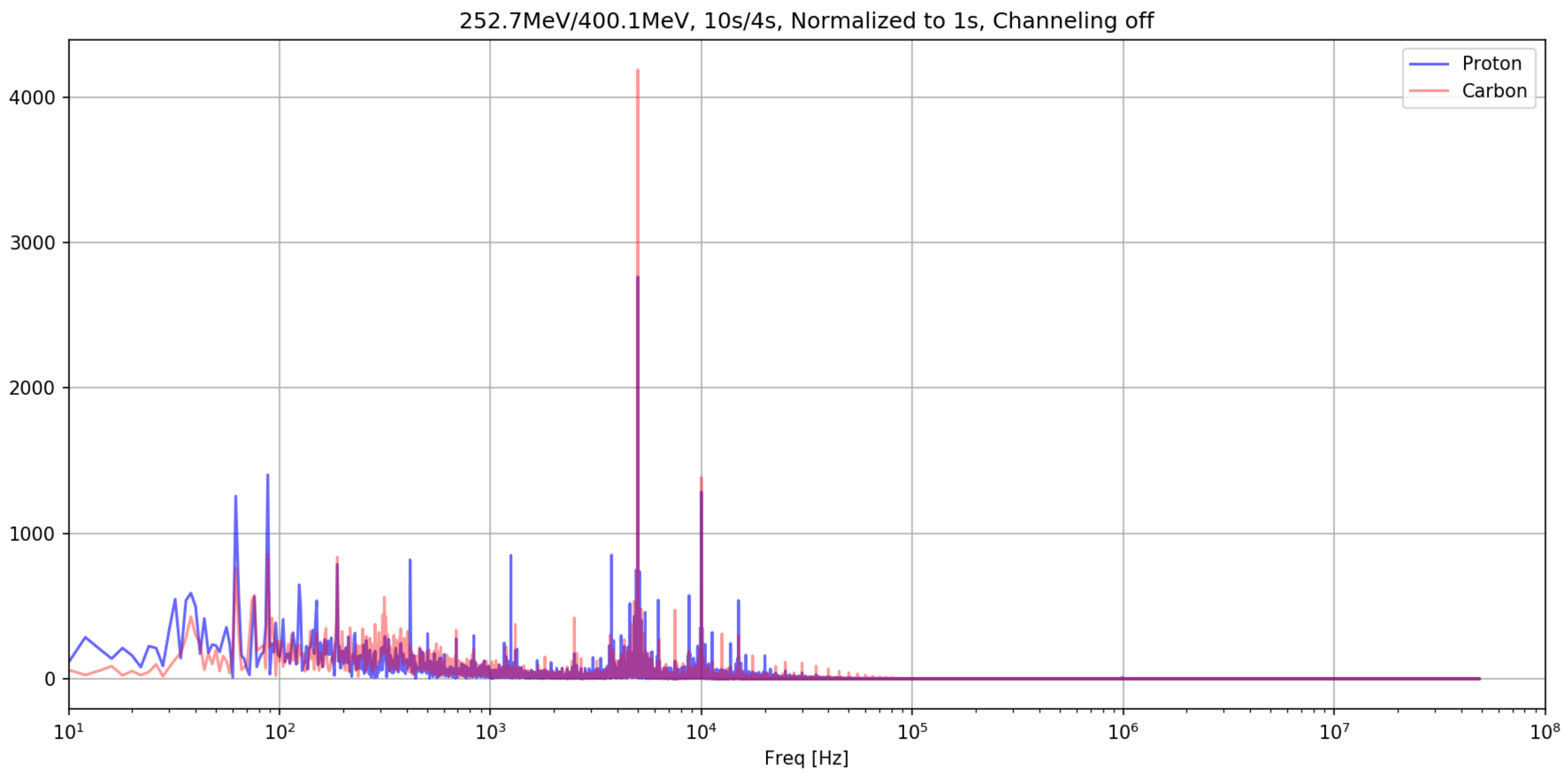
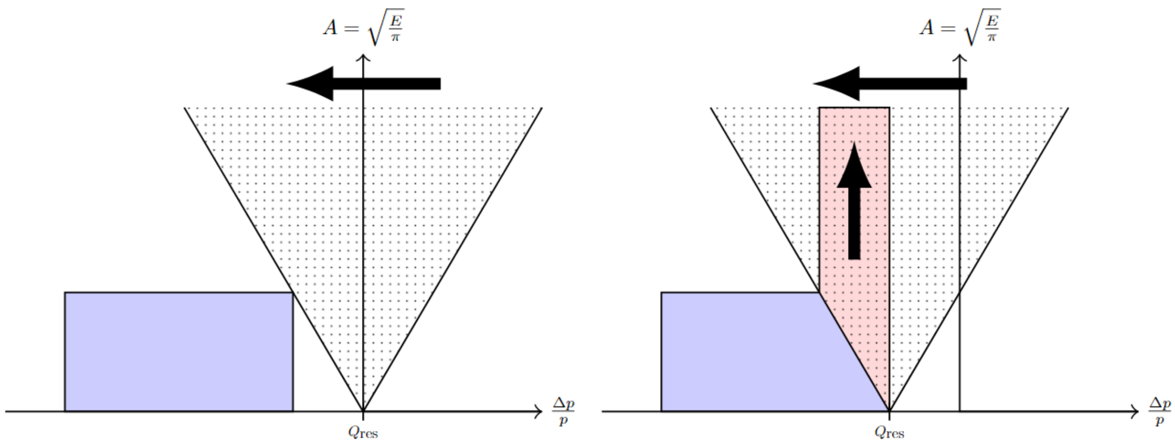
PARTICLE TYPE: PROTON vs. CARBON NORMALIZED TO 1s



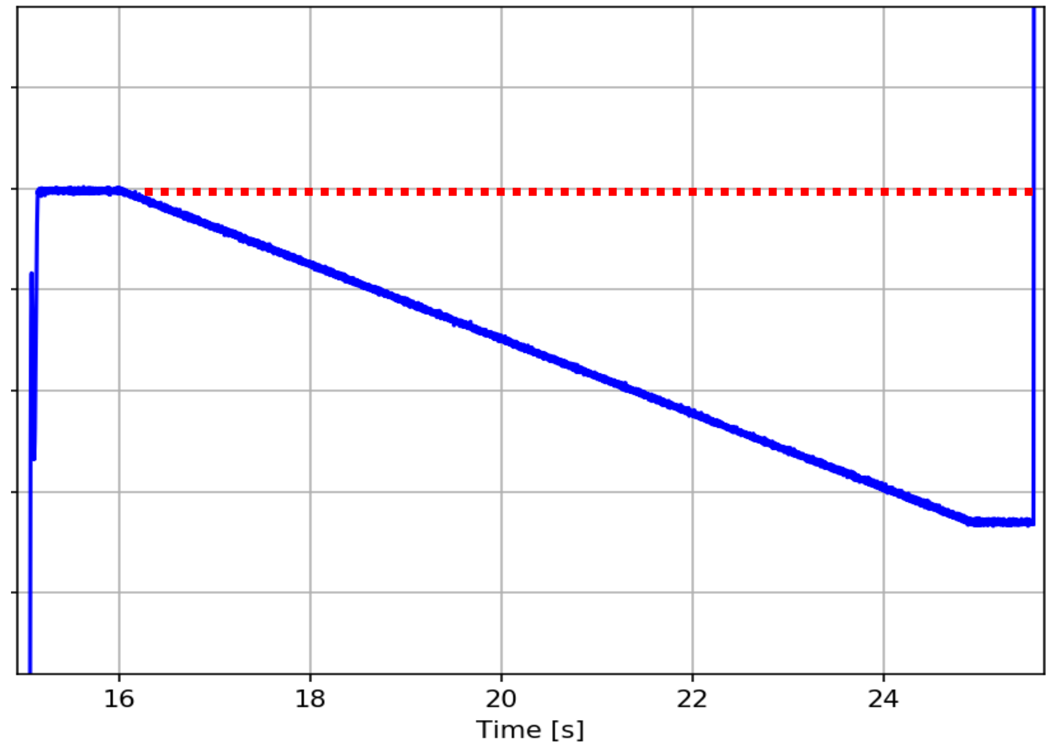
ALTERNATIVE EXTRACTION METHODS

- In addition to the Betatron core baseline extraction other extraction methods were tested including Tune Sweep and COSE
  - Initial testing of the alternative extraction methods were undertaken to determine optimised parameters offline for future testing
- **Tune Sweep**
  - Linear ramping of all Main Ring quadrupoles to adjust the tune for movement of the region of instability
- **Constant Optics Slow Extraction (COSE)**
  - Linear ramping of all magnets within the Main Ring
  - Optics of the Main Ring remain constant while tune is adjusted



TUNE SWEEP

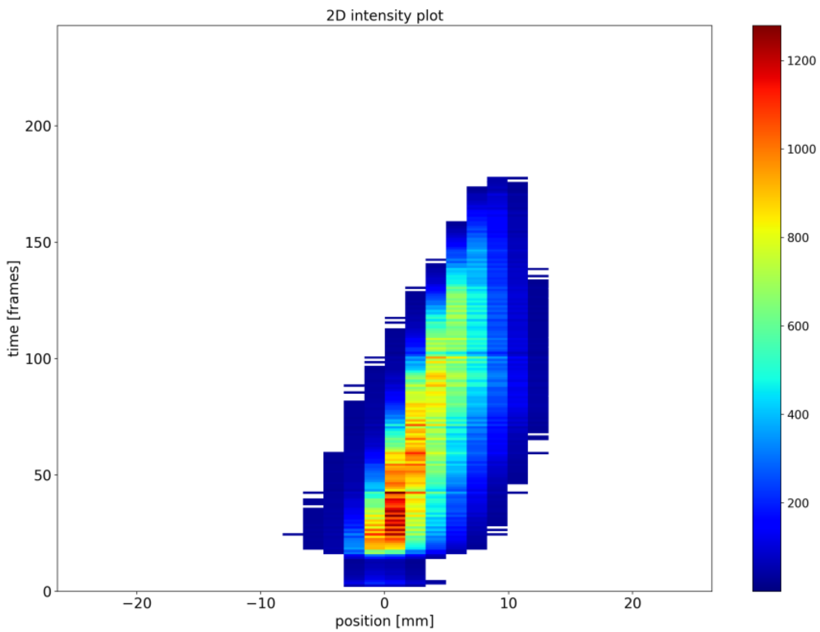
- Linear ramp used for all Main Ring quadrupoles to move the resonance into the waiting beam
- Investigation of different ramping slopes (-0.9%, -0.95%, -1%, -1.1%)
- Verified that Betatron Core was completely off and chopper was fully open
- For initial investigation only scaling of the Main Ring was undertaken without any scaling of the extraction line

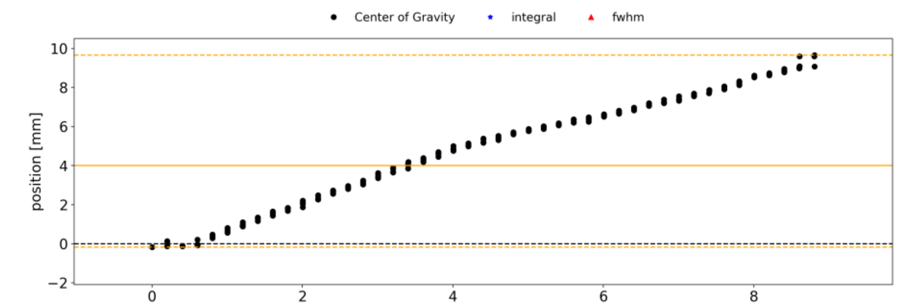


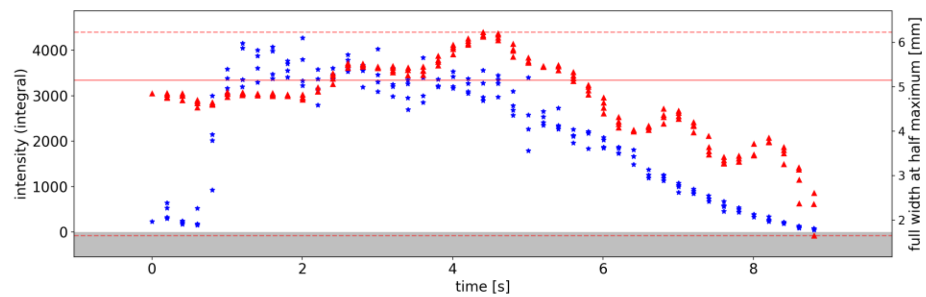
TUNE SWEEP -1%

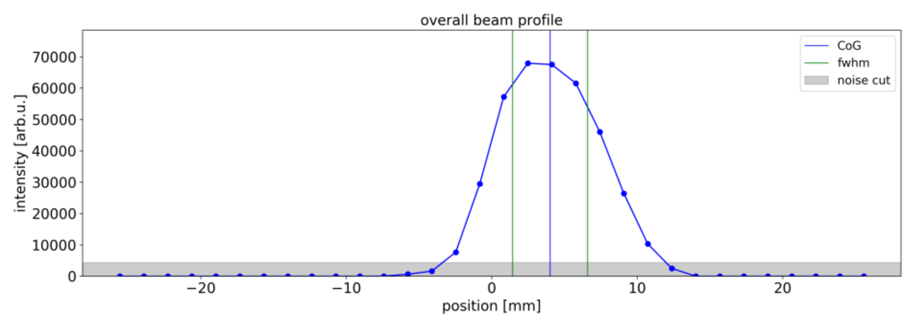
- Proton 252.7 MeV

HORIZONTAL plane H200000DDP , 2020/11/07 03:14:20
H200000DDP_p0_20201107031420_SID000_IID000_Q Sweep_1 perc_252 MeV-DDM.msr
comment: Q Sweep_1 perc_252 MeV, || HOR = -Y, VER = -X (@Lynx)









CChuman	252.7MeV H+ | S1-IR2H | DEG100% | 90°
CChuman	no extractions | 4x4mm | var0ver0 | clinical
CC	78002344000909DF
BS	2020110703522700-26
limits	ana: 0.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	n.a. | 8804 ms

version	2.2.0
exp | fps	varying | 19 f/s
trigger	n.a. (DDS not sync.!)
SNR / BG-FID	1132594.7 [0]
intensity	0.4e6 arb.u.
CoGw	4.01 ± 0.3 mm [-0.2, 9.7]
FWHMw	5.15 ± 0.3 mm [1.7, 6.2]

TUNE SWEEP -1%

- Proton 62.4 MeV

HORIZONTAL plane H200000DDP , 2020/11/07 03:11:01
H200000DDP_p0_20201107031101_SID000_IID000_Q Sweep_1 perc_62 MeV-DDM.msr
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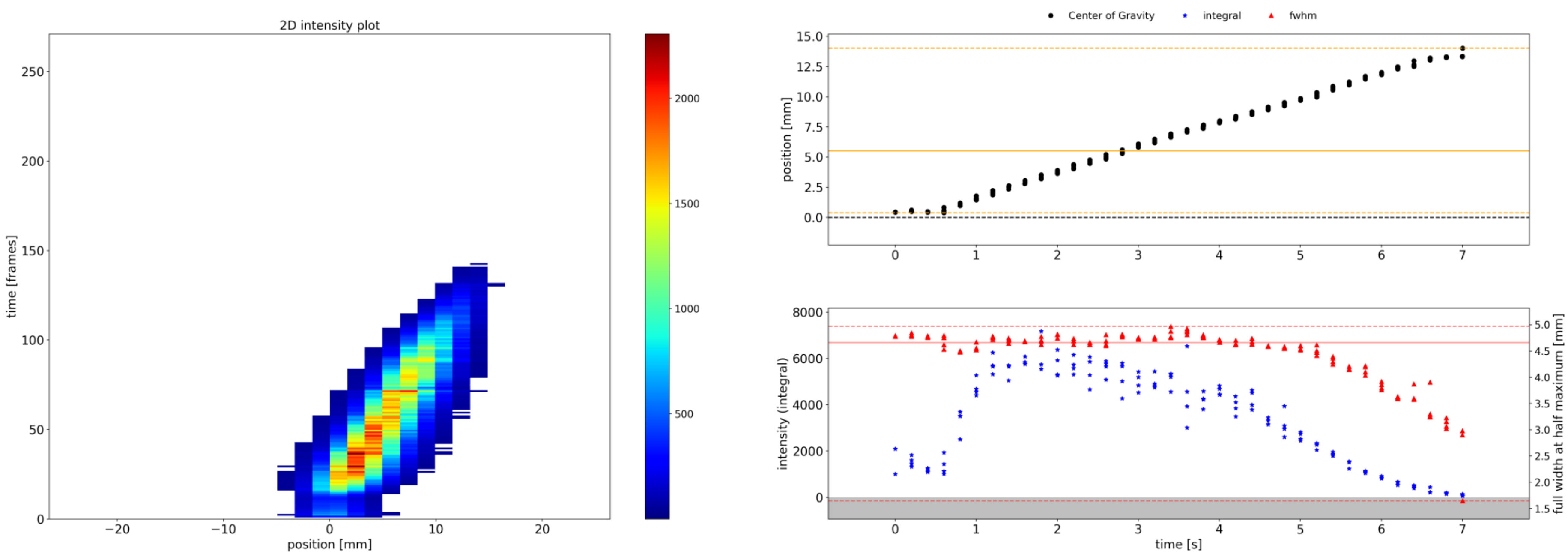
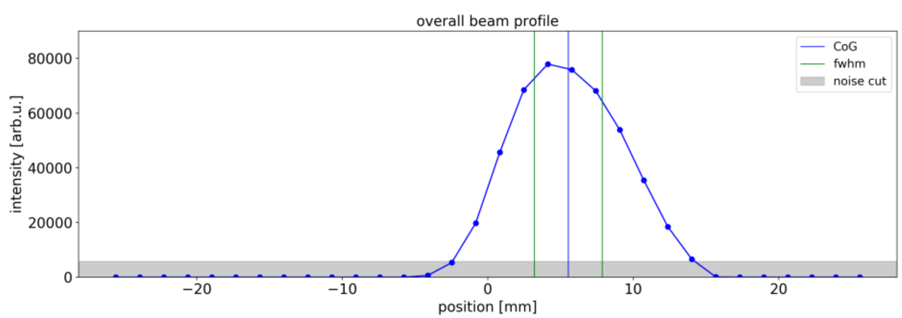


CChuman	62.4MeV H+ | S1-IR2H | DEG100% | 90°
CChuman	no extractions | 4x4mm | var0ver0 | clinical
CC	7800234400090270
BS	2020110703522700-22
limits	ana: 0.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	n.a. | 7001 ms

version	2.2.0
exp | fps	varying | 20 f/s
trigger	n.a. (DDS not sync.!)
SNR / BG-FID	2090394.2 [-1]
intensity	0.5e6 arb.u.
CoGw	5.53 ± 0.4 mm [0.4, 14.0]
FWHMw	4.66 ± 0.2 mm [1.6, 5.0]



TUNE SWEEP -1%

- Carbon 400.1 MeV/u

HORIZONTAL plane H200000DDP , 2020/11/07 03:53:55
H200000DDP_p0_20201107035355_SID000_IID000_Carbon_QSweep_1perc_120_MeV-DDM.msr
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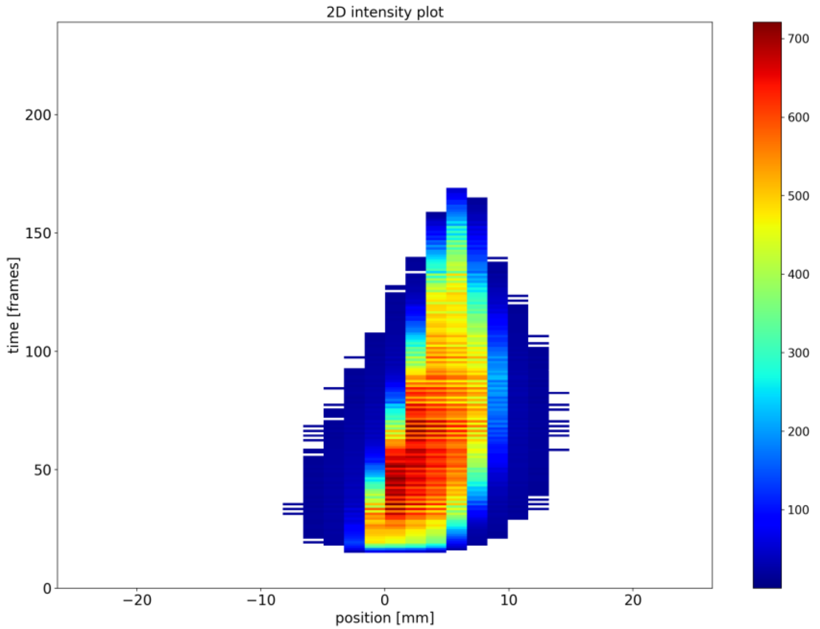
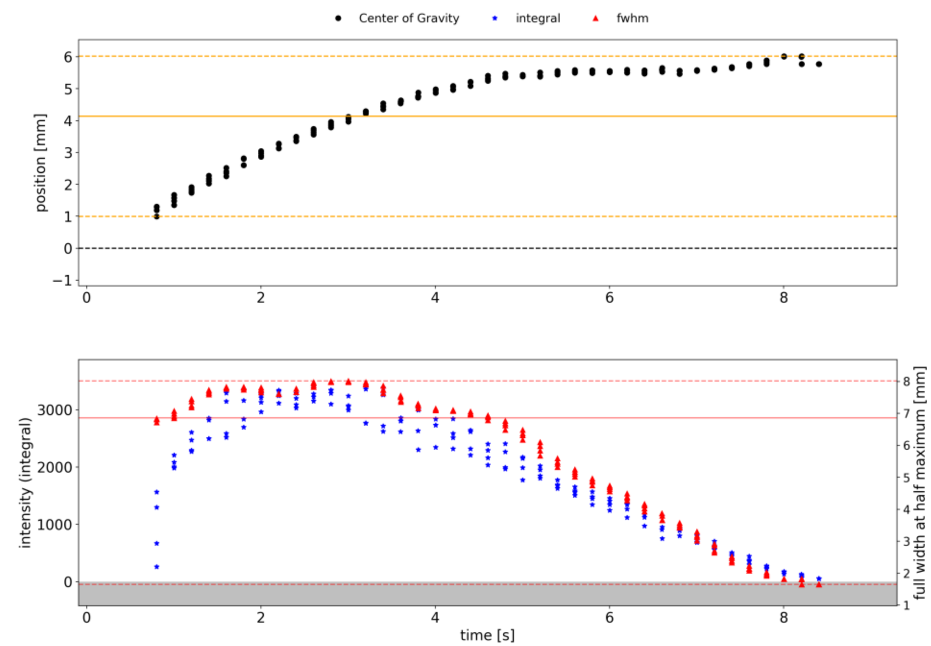
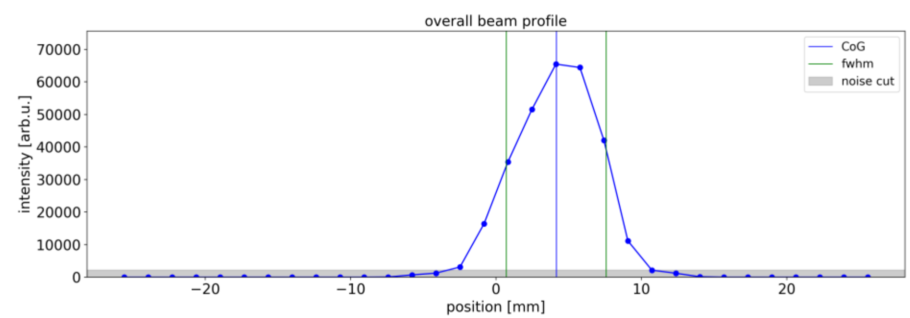




CChuman	400.1MeV C6+ | S2-IR2H | DEG100% | 90°
CChuman	no extractions | 6x6mm | var0ver0 | clinical
CC	7800236600120FA1
BS	2020110704472400-15
limits	ana: 0.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	n.a. | 7601 ms

version	2.2.0
exp | fps	varying | 20 f/s
trigger	n.a. (DDS not sync.!)
SNR / BG-FID	1893974.0 [0]
intensity	0.3e6 arb.u.
CoGw	4.14 ± 0.2 mm [1.0, 6.0]
FWHMw	6.86 ± 0.3 mm [1.6, 8.0]



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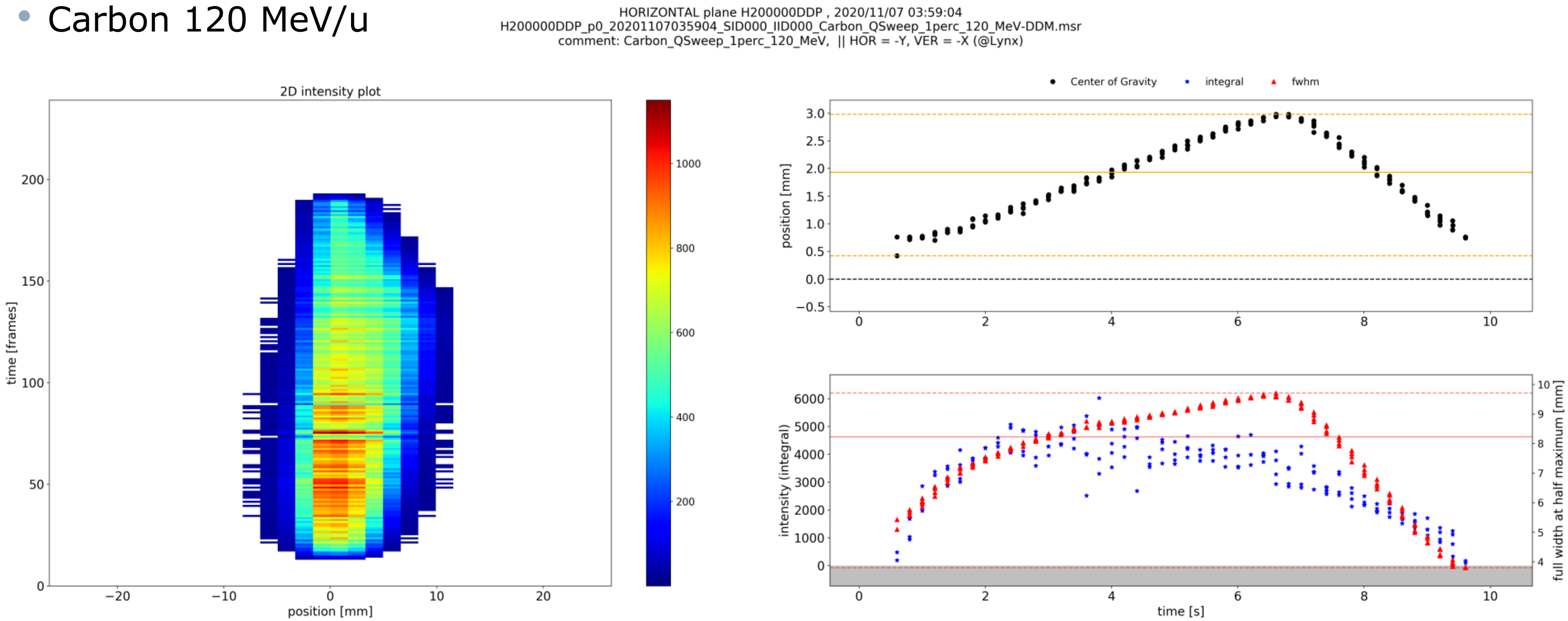
TUNE SWEEP -1%

- Carbon 120 MeV/u



CChuman	120.0MeV C6+ | S2-IR2H | DEG100% | 90°
CChuman	no extractions | 6x6mm | var0ver0 | clinical
CC	78002366001204B0
BS	2020110704472400-23
limits	ana: 0.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	n.a. | 9003 ms

version	2.2.0
exp | fps	varying | 19 f/s
trigger	n.a. (DDS not sync.!)
SNR / BG-FID	5392794.0 [-1]
intensity	0.6e6 arb.u.
CoGw	1.93 ± 0.1 mm [0.4, 3.0]
FWHMw	8.23 ± 0.4 mm [3.8, 9.7]

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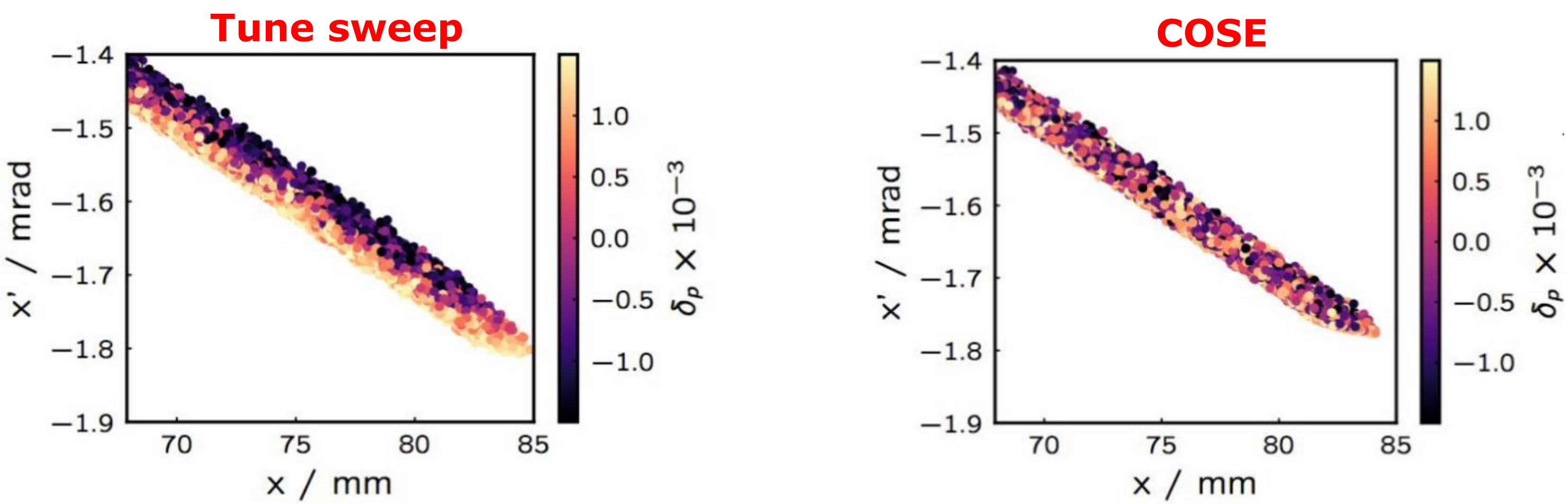
COSE (CONSTANT OPTICS SLOW EXTRACTION)

- Linear ramp of all magnets (dipoles, quadrupoles, sextupoles) to move the resonance to the waiting beam while keeping the MR optics constant
- Different ramping slopes (-0.1%, -0.25%, -0.3%, -0.35%)
- COSE has an advantage over Tune Sweep by ensuring that the optics are still fixed during the extraction process to minimise momentum sorting at the separatrix



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

V. Kain et al., Resonant slow extraction with constant optics for improved separatrix control at the extraction septum, Phys. Rev. Accel. Beams 22, 101001, 9 Oct. 2019.

COSE -0.3%

- Proton 252.7 MeV

HORIZONTAL plane MF03200DDM , 2020/11/08 00:03:47
MF03200DDM_p0_20201108000347_SID000_IID000_252_0p3_chan_COSE-DDP.msr
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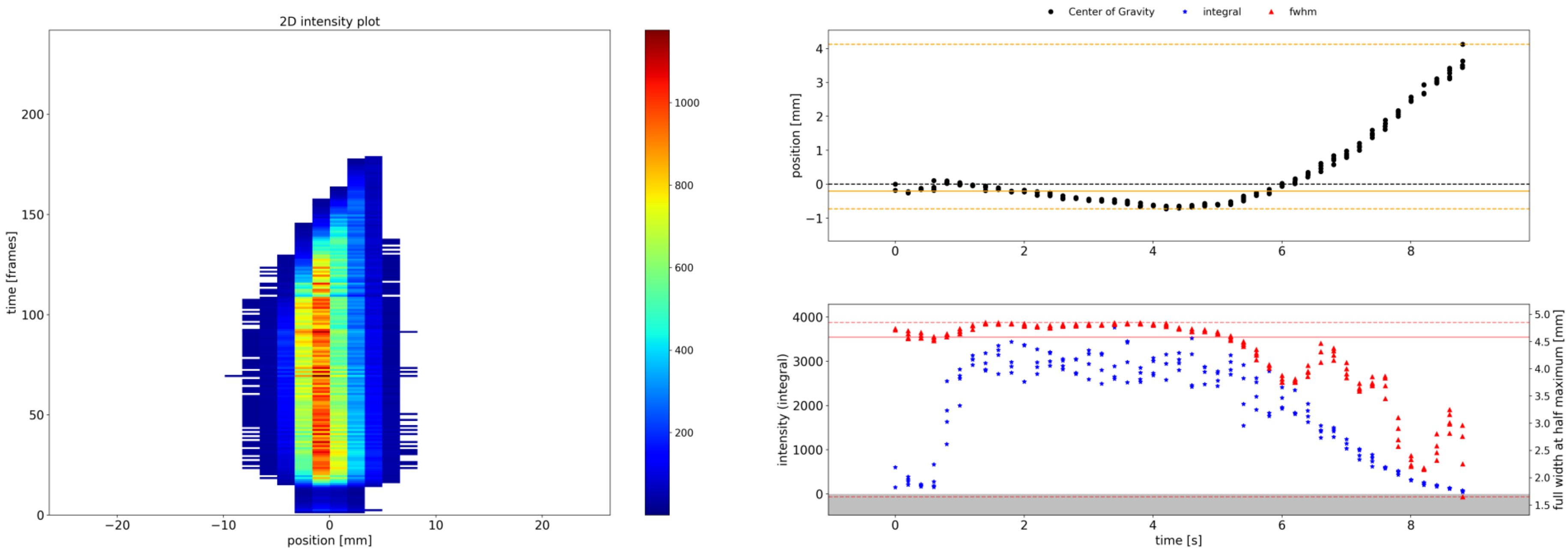

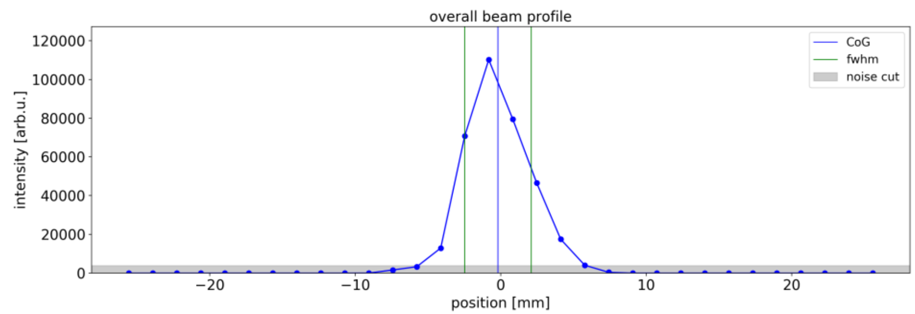

CChuman	252.7MeV H+ | S1-IR2H | DEG100% | 90°
CChuman	no extractions | 4x4mm | var0ver0 | clinical
CC	78002344000909DF
BS	2020110723424900-89
limits	ana: 0.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	n.a. | 8801 ms

version	2.2.0
exp | fps	varying | 20 f/s
trigger	n.a. (DDS not sync.!)
SNR / BG-FID	906666.0 [-1]
intensity	0.3e6 arb.u.
CoGw	-0.21 ± 0.1 mm [-0.7, 4.1]
FWHMw	4.58 ± 0.2 mm [1.6, 4.9]

COSE -0.3%

- Carbon 400.1 MeV/u

HORIZONTAL plane MF03200DDM , 2020/11/08 01:09:33
MF03200DDM_p0_20201108010933_SID000_IID000_400_0p3_COSE-DDP.msr
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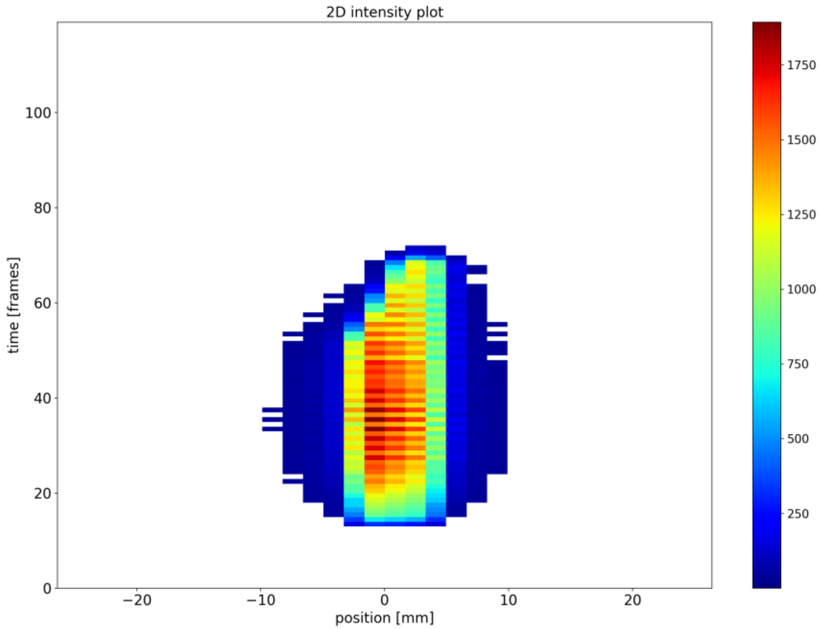

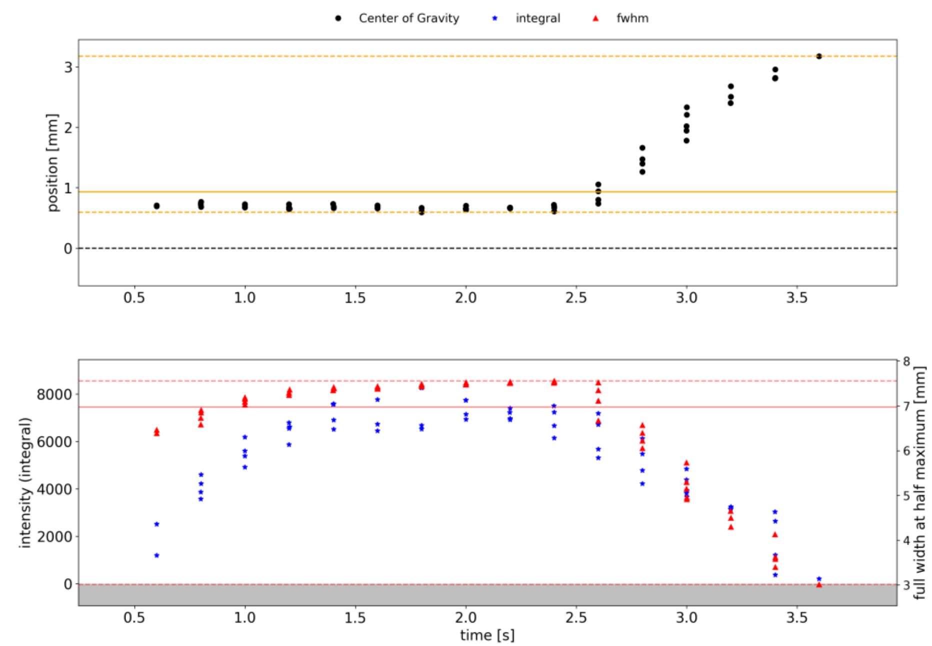

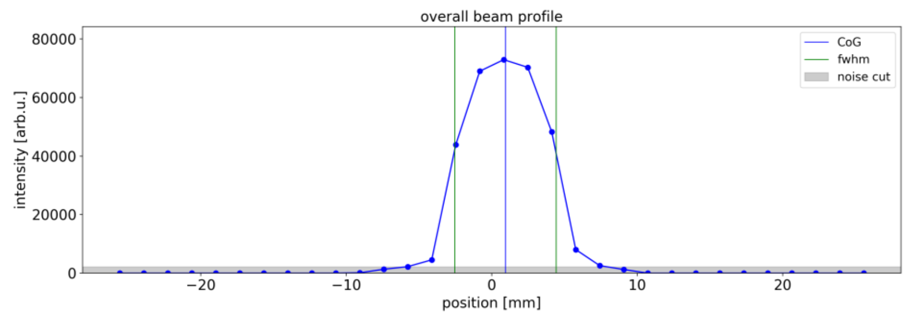

CChuman	400.1MeV C6+ | S2-IR2H | DEG100% | 90°
CChuman	no extractions | 6x6mm | var0ver0 | clinical
CC	7800236600120FA1
BS	2020110802063000-3
limits	ana: 0.0% | noise: 2.0%
IDs	IID: 0 | SID: 0
ts | dt	n.a. | 2999 ms

version	2.2.0
exp | fps	varying | 19 f/s
trigger	n.a. (DDS not sync.!)
SNR / BG-FID	6057633.0 [-1]
intensity	0.3e6 arb.u.
CoGw	0.93 ± 0.1 mm [0.6, 3.2]
FWHMw	6.98 ± 0.4 mm [3.0, 7.6]

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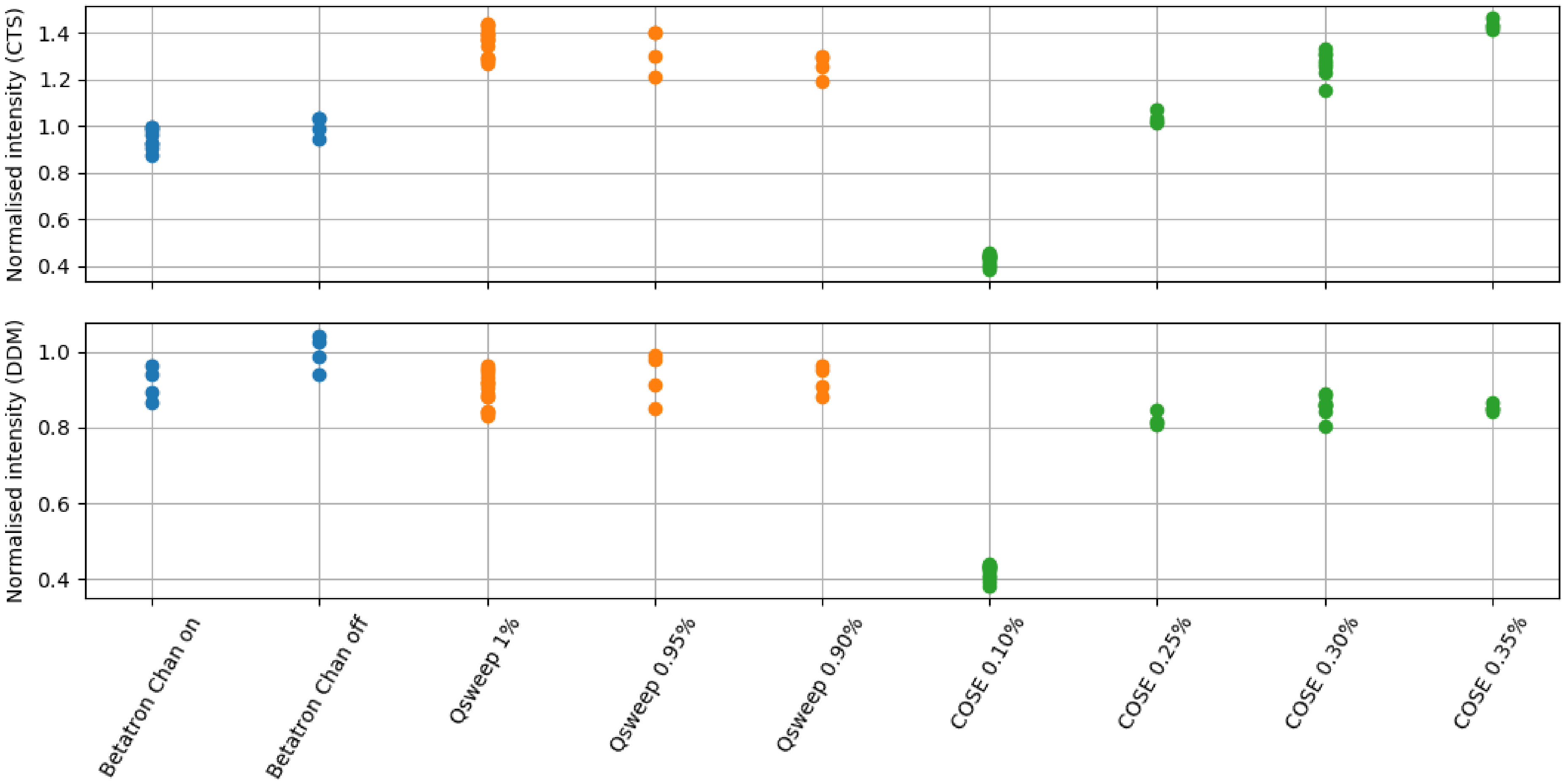
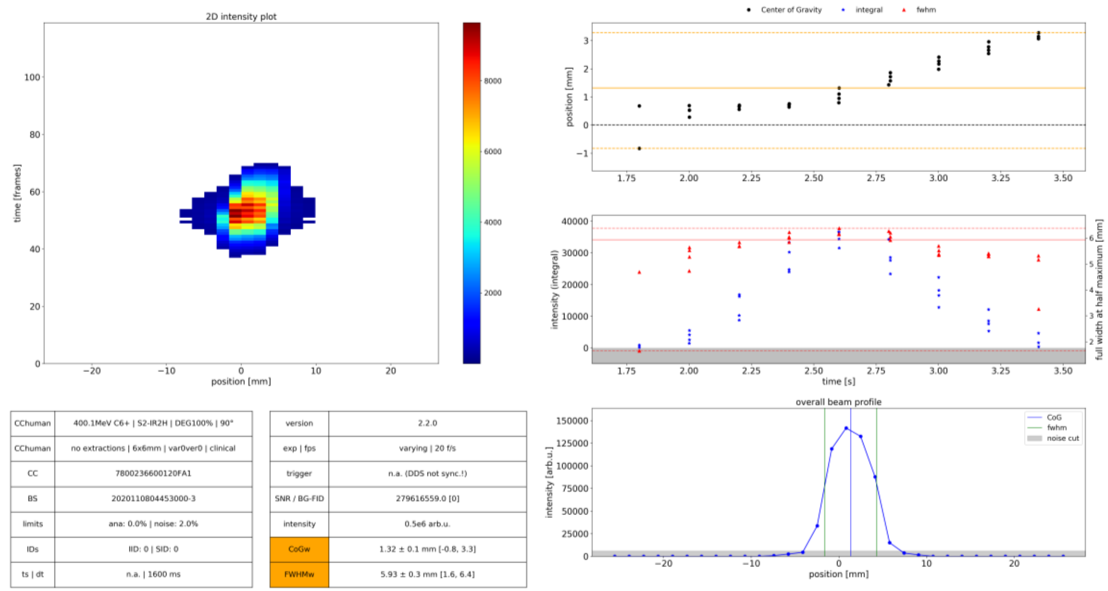
ALTERNATIVE EXTRACTION METHODS INTENSITY COMPARISON



BUNCHED COSE

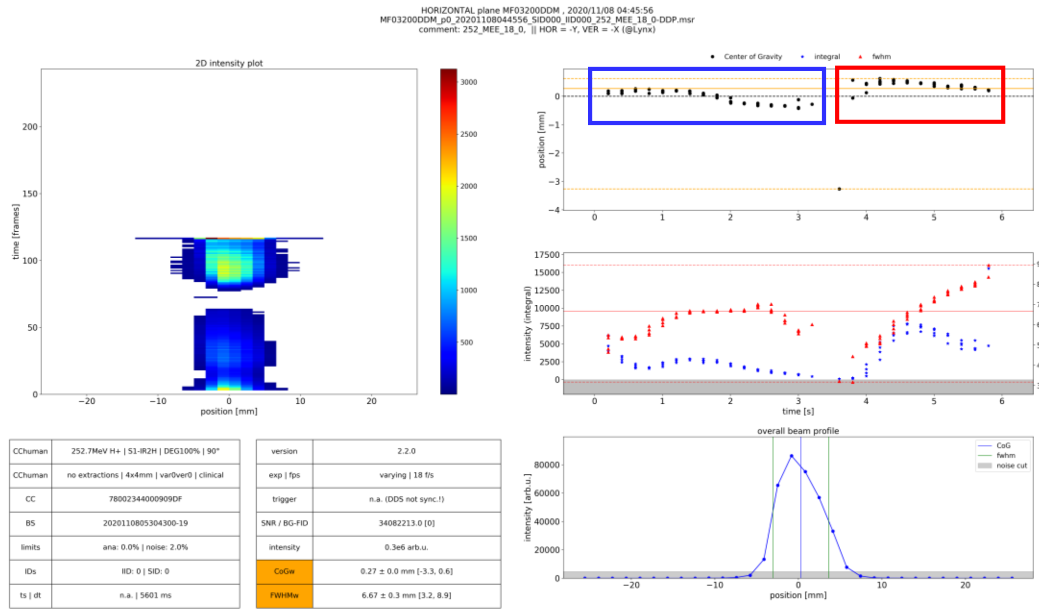
- Same settings as for the COSE presented earlier except:
  - Remove Phase Jump
  - sRF remains turned on during extraction
  - Ramp the radial position from 20mm to zero to force the beam into extraction (in synch with magnet ramping)
- Required for Multi-Energy Extraction using COSE extraction

- Successful test
  - Optimisation of ramping time and beam loss to be further investigated



MEE COSE

- Same settings as for bunched COSE
- Effective energy change: +0.02% (50 keV)
- Both energies reach the treatment room



Timing:	Radial loop:	Magnet current:
• 3s	• 20mm → 18mm (1st energy)	• COSE -0.15%
• 0.5s	• 20mm (Acceleration)	• Ramp +0.17%
• 3s	• 20mm → 0mm (2nd energy)	• COSE -0.15%

Average CoG for first energy	Average CoG for second energy
-0.017 mm	0.194 mm

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FUTURE PLANS

- Optimisation of COSE and Tune Sweep from existing data for optimised beam delivery investigations with the goal of identifying the best multi-energy extraction options

- Some initial RF Knockout test measurements have been taken in the past with RF Knockout and RF Noise driven extraction planned for future investigation shifts this year

- Optimisation of RF Knockout is a priority and we are currently undertaking RF Knockout implementation studies through both simulation and hardware implementation with a forward focus on realisation of this slow extraction method

- Further follow-up on the High and Low frequency ripple studies with ongoing investigation into how to further reduce the ripples using accumulated data

SUMMARY

- Improvement of Slow Extraction is focus of future developments at MedAustron
- Ongoing accelerator research into different slow extraction methods in collaboration with universities and research organisations
- Investigations to date have yielded significant slow extraction data
- Future focus on RF Knockout as the prime candidate extraction method for multi-energy extraction with dynamic intensity control
- We are very interested and open to any feedback and collaboration on slow extraction topics going forward

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+ All of the over 200 people working at MedAustron working together to improve the treatment available to particle therapy patients

ANY

Questions?

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