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Extraction Commissioning for Proton Clinical Beams at the MedAustron Particle Therapy Accelerator

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On behalf of the MedAustron Therapy Accelerator Division

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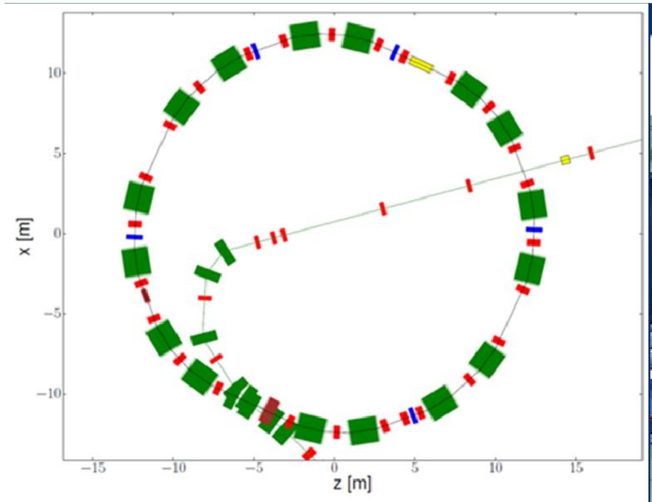
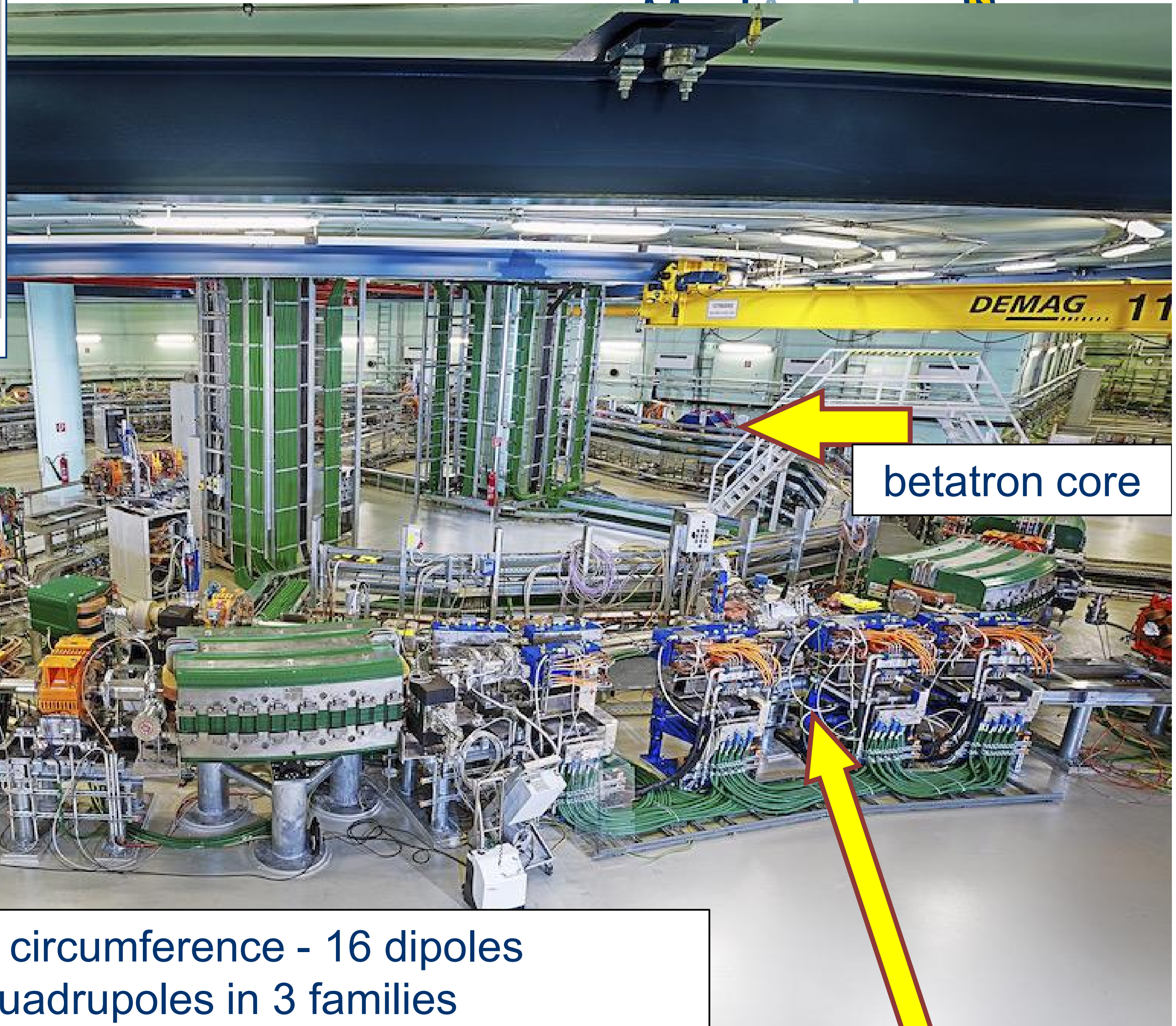
Based on Proton Ion Medical Machine Study (1990) and CNAO (Italy) designs, with important contribution of CERN (Switzerland) and PSI (Switzerland)





betatron core

- 77m circumference - 16 dipoles
- 24 quadrupoles in 3 families
- 5 sextupoles in 2 families + resonant
- off-mom.: inj. $-2.4\cdot10^{-3}$, extr. $-3.5\cdot10^{-3}$
- $\Delta p/p$: inj. $0.5\cdot10^{-3}$, extr. $4.0\cdot10^{-3}$

elec. extr. septum

mag. extr. septum

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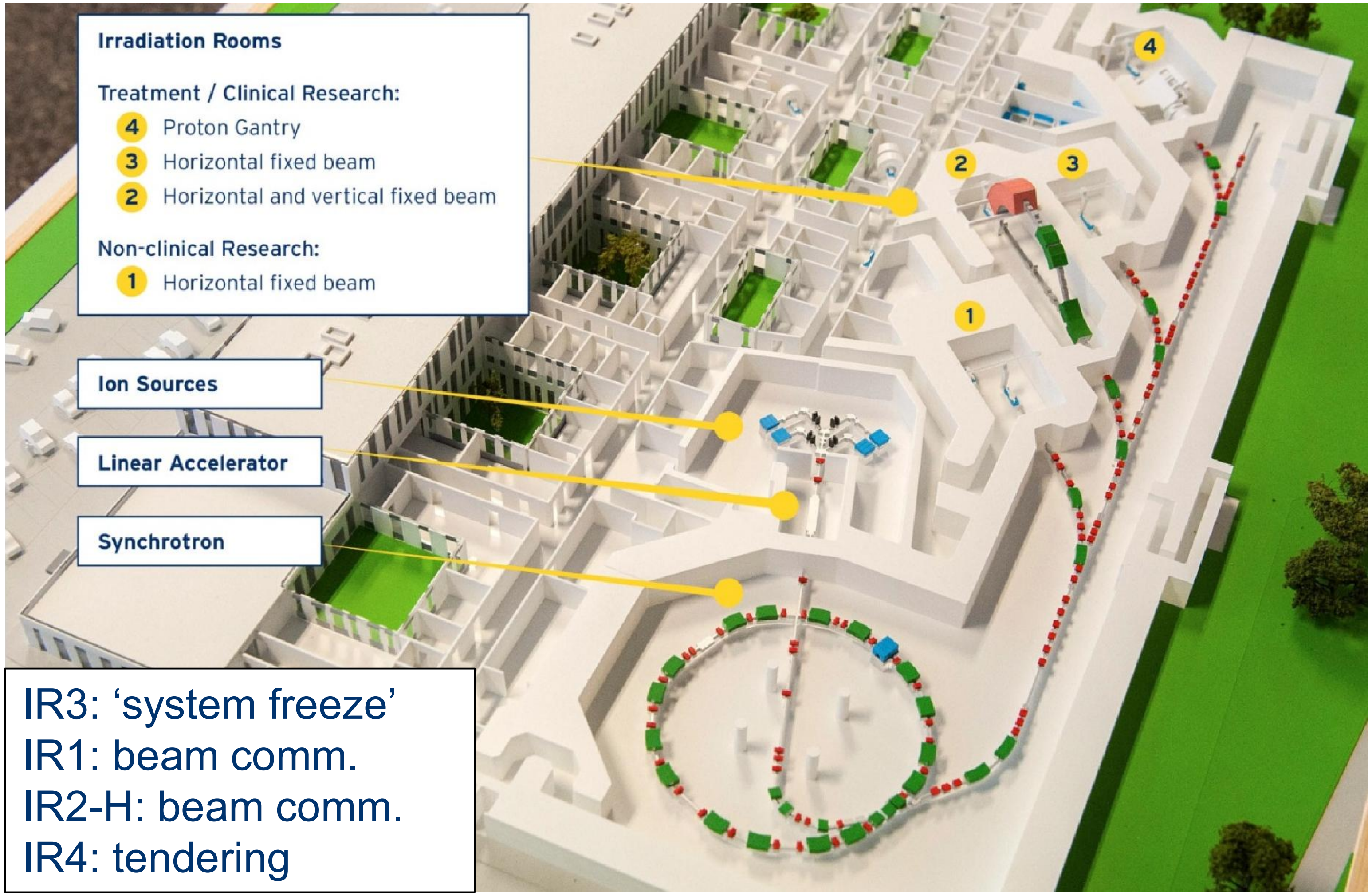

IR3: 'system freeze'
IR1: beam comm.
IR2-H: beam comm.
IR4: tendering

Based on Proton Ion Medical Machine Study (1990) and CNAO (Italy) designs, with important contribution of CERN (Switzerland) and PSI (Switzerland)

Proton Beam Parameters

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Intensity	**10^{10}** over **5 s** constant spills with **4 different intensity** levels
Transverse Position	0 ± 0.5 mm
Transverse Size	**Minimum Spot Size** in air (depends on scattering, defined as 4 mm FWHM in vacuum) **Round beam** with asymmetry < 10%
Penetration Depth	[30-380 mm] in **255 steps**, within ± 0.3 mm
Variation within spill	± 0.15 mm in range, ± 0.25 mm in position and ± 5 % in width

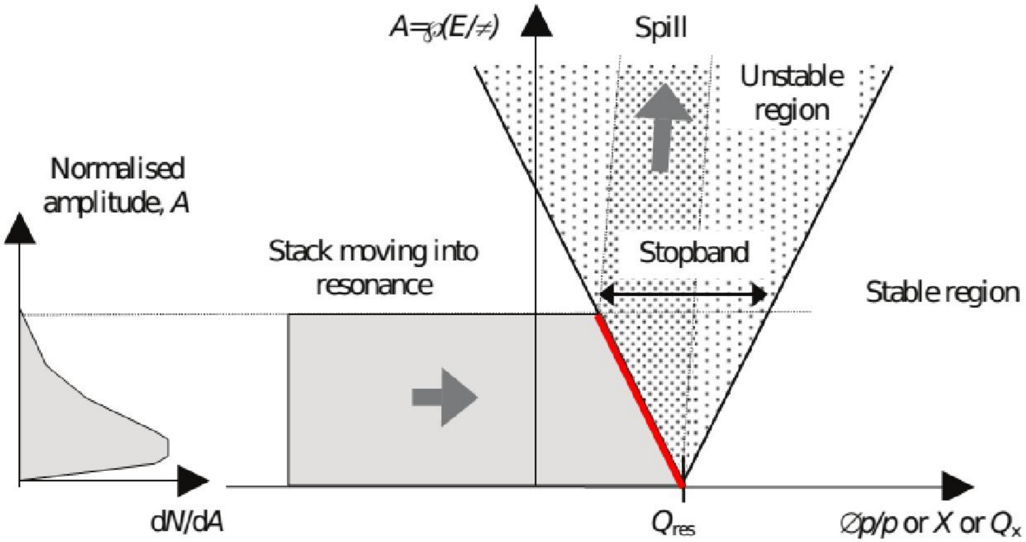
Multi-energy commissioning

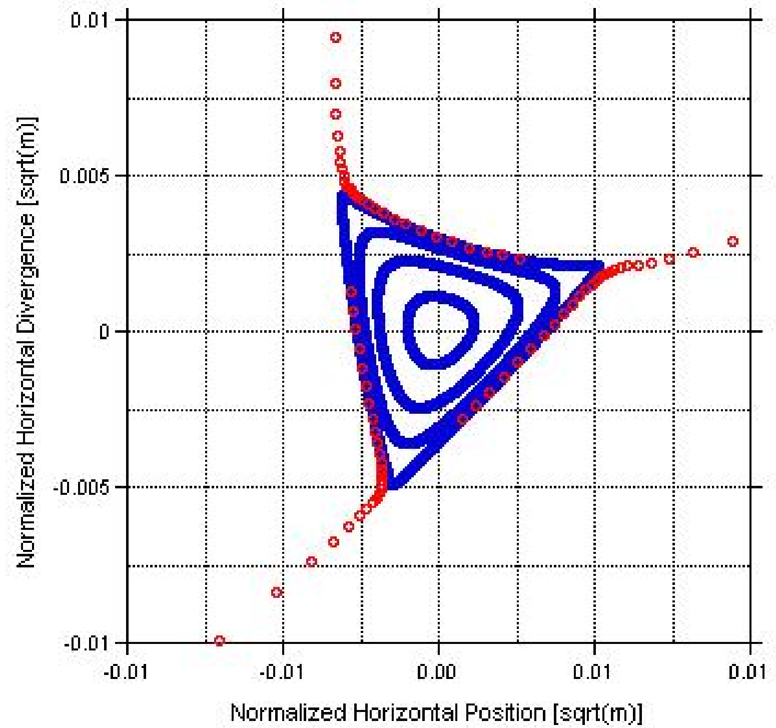
- Machine fine-tuning for 4 `main´ energies (62, 136, 198, 253 MeV)
- Interpolation of the main energies´ normalized parameters to obtain settings for remaining 251 energies

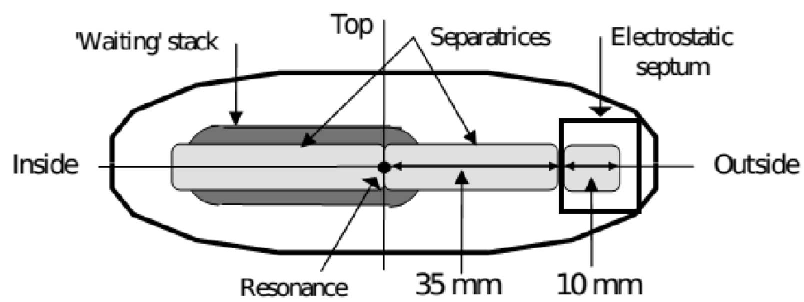
Slow Extraction

- Resonant sextupole enlarges the the horizontal third-integer resonance stopband

- Betatron core drives smoothly beam to instability (min 20 ms, clinical 1-10 s)







Dispersion and Orbit

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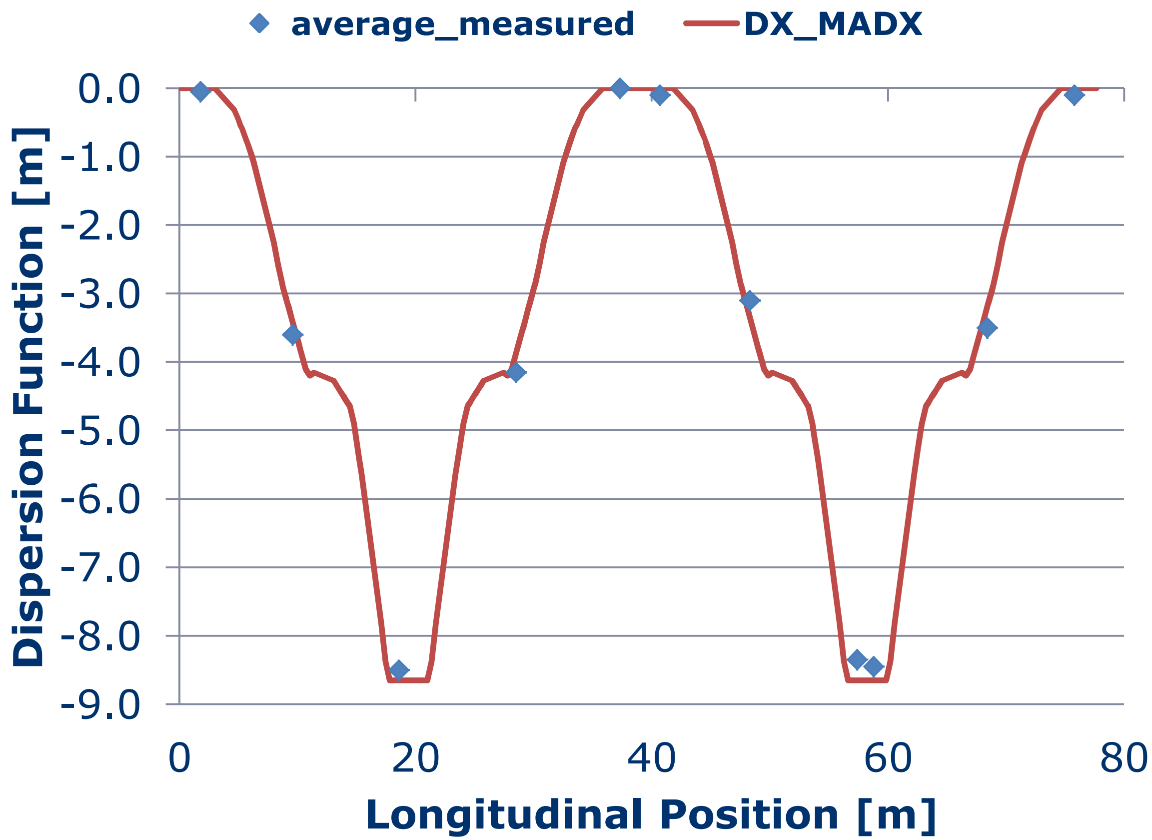
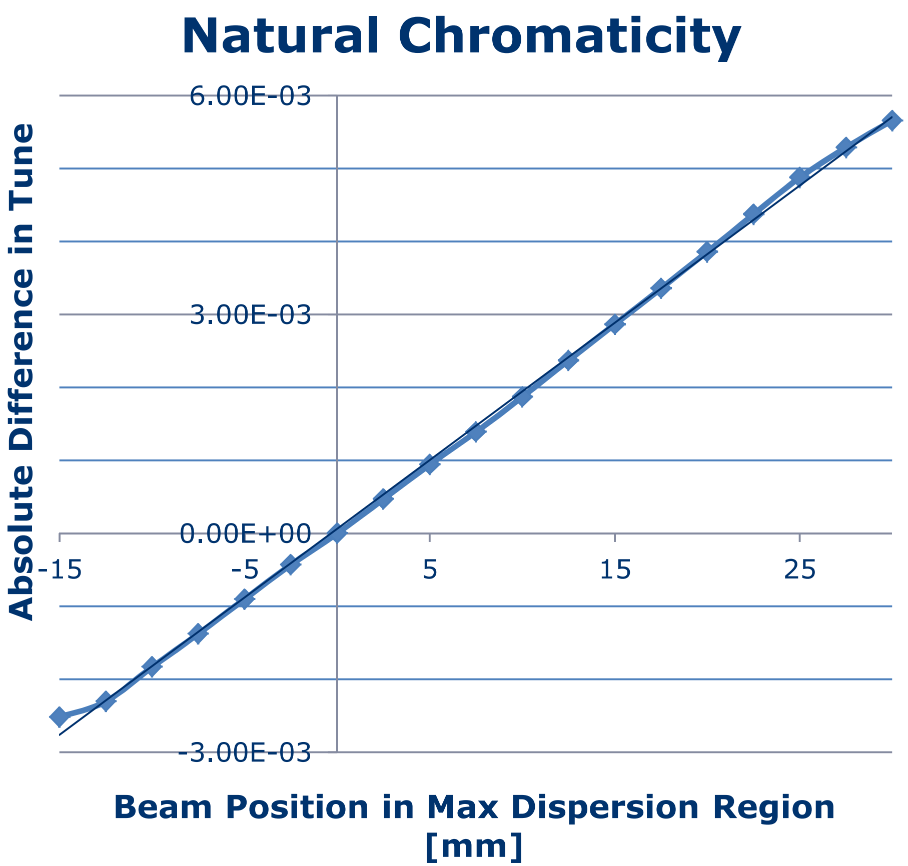


- closed-orbit error < 1 mm for both planes, with corrector strengths < 0.4 mrad
- good linear behaviour: same normalized strength for flatbottom and flattop (all energies)

Flattop optics

- Extraction optics adjustment (tunes and chromaticities) for 4 main energies

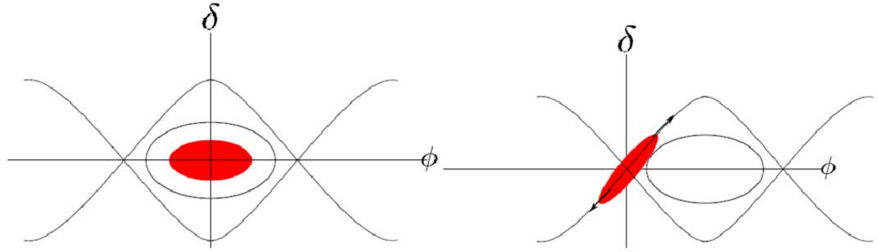
- Good linearity over good-field-region

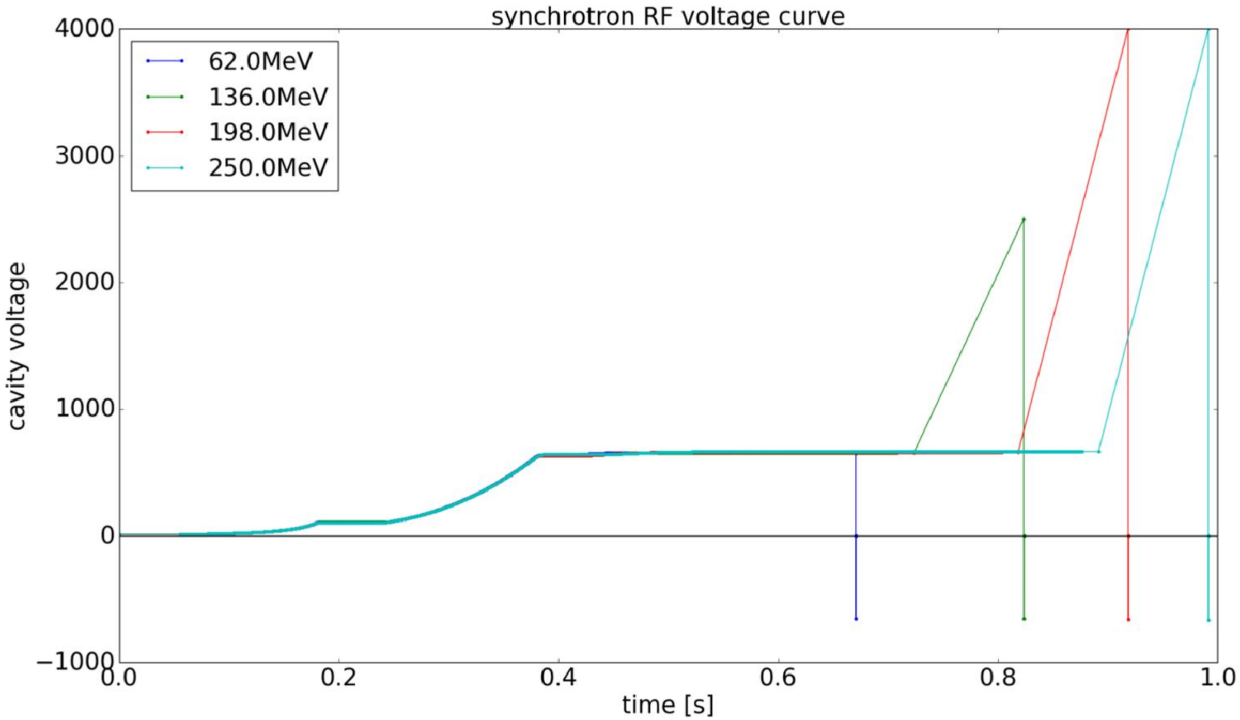


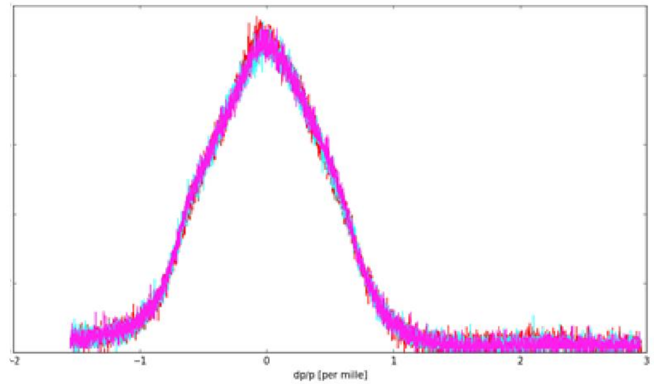
Design Parameter	Result over the 4 main energies
Q_H=1.667	1.667 ± 0.001
Q'_H = -4.0	-3.9 ± 0.2
Q_V=1.789	1.789± 0.004
Q'_V=-1.0	-1.2 ± 0.1

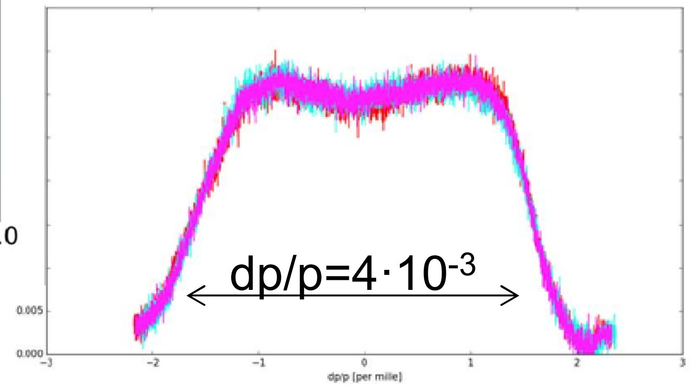
RF gymnastics for extraction

- RF phase jump via voltage inversior



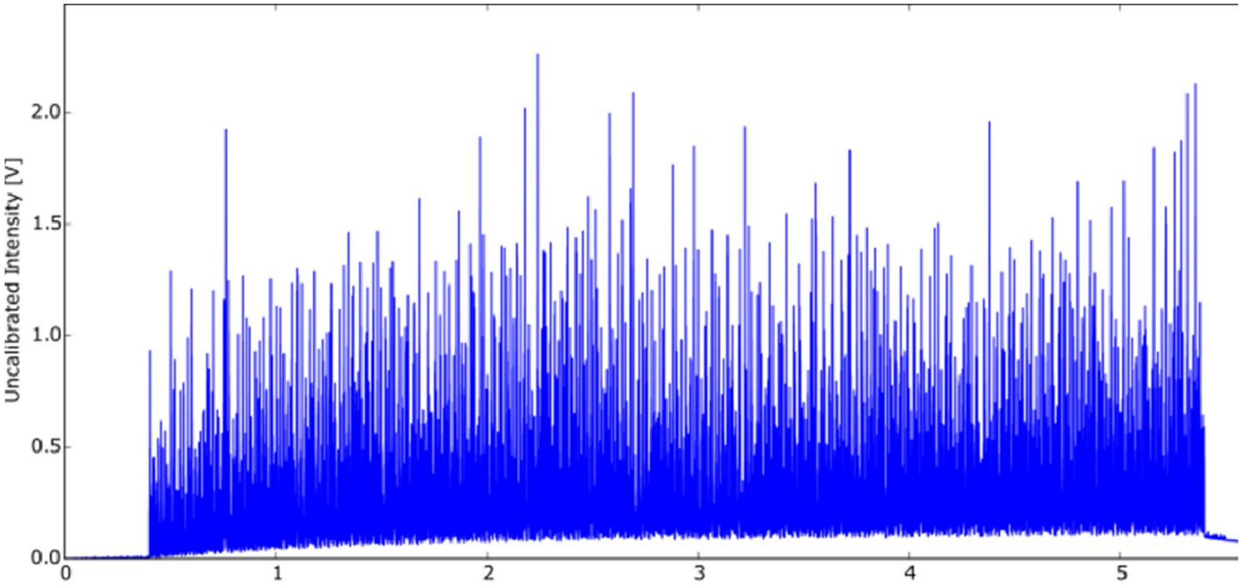


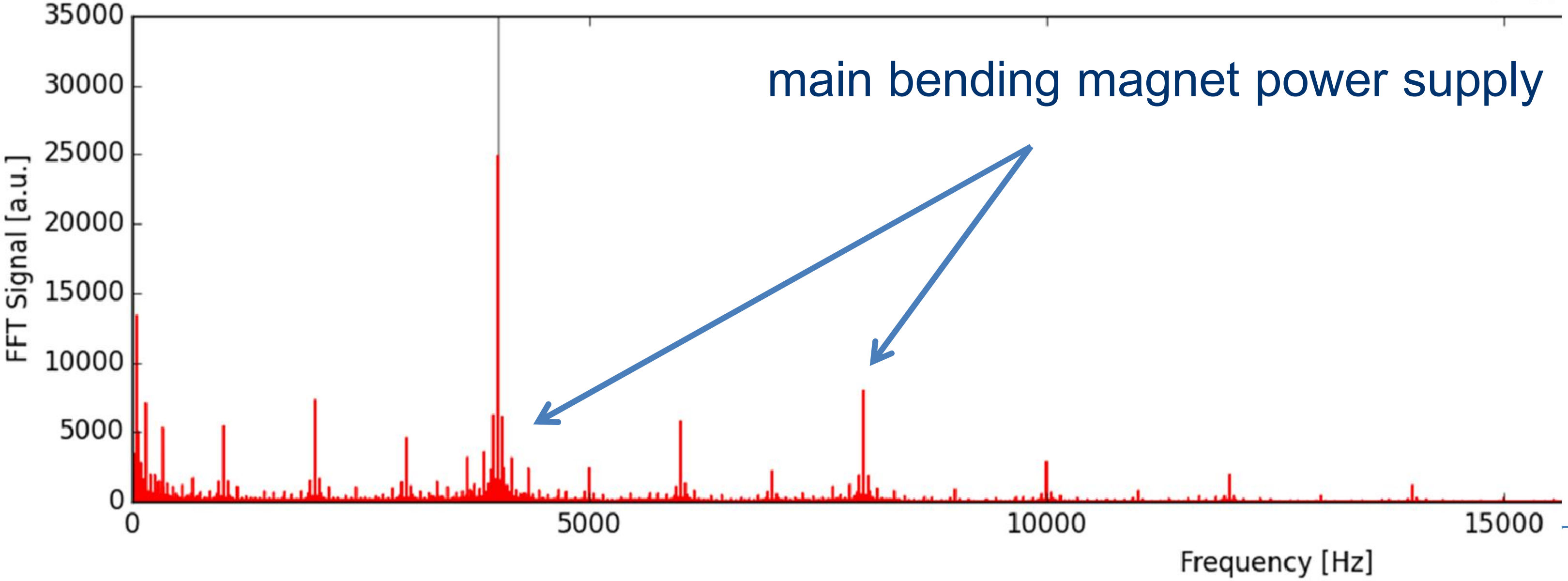




Ripples

- $I_{max}/I_{mean} \approx 3.5 \pm 1$
- 10 kHz, 5 ms voxel time

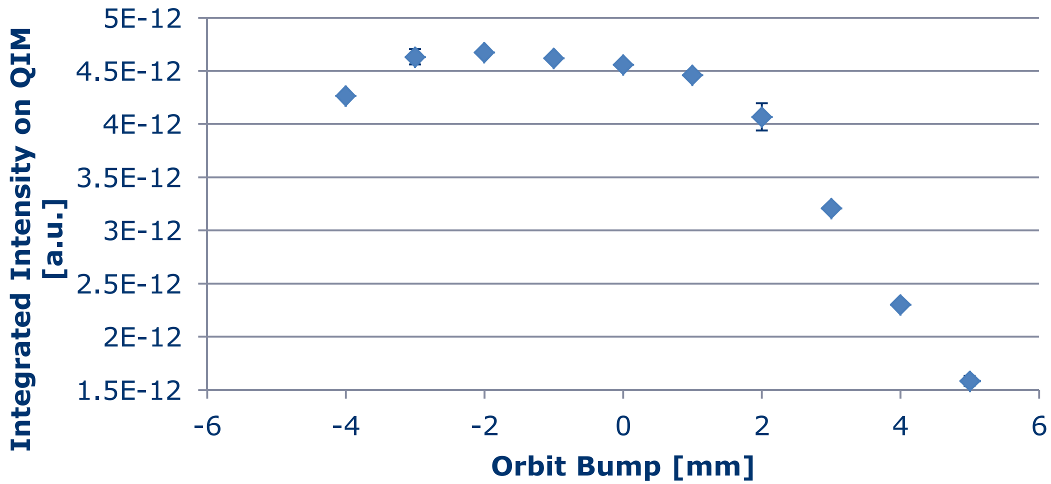




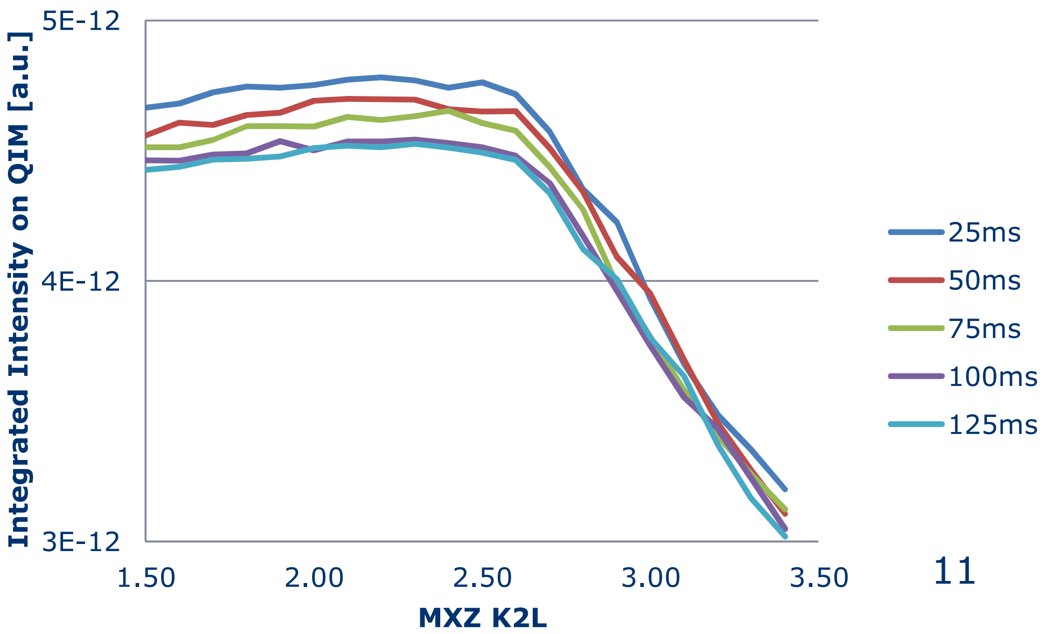
Intensity Optimization

- Orbit bump at ESE

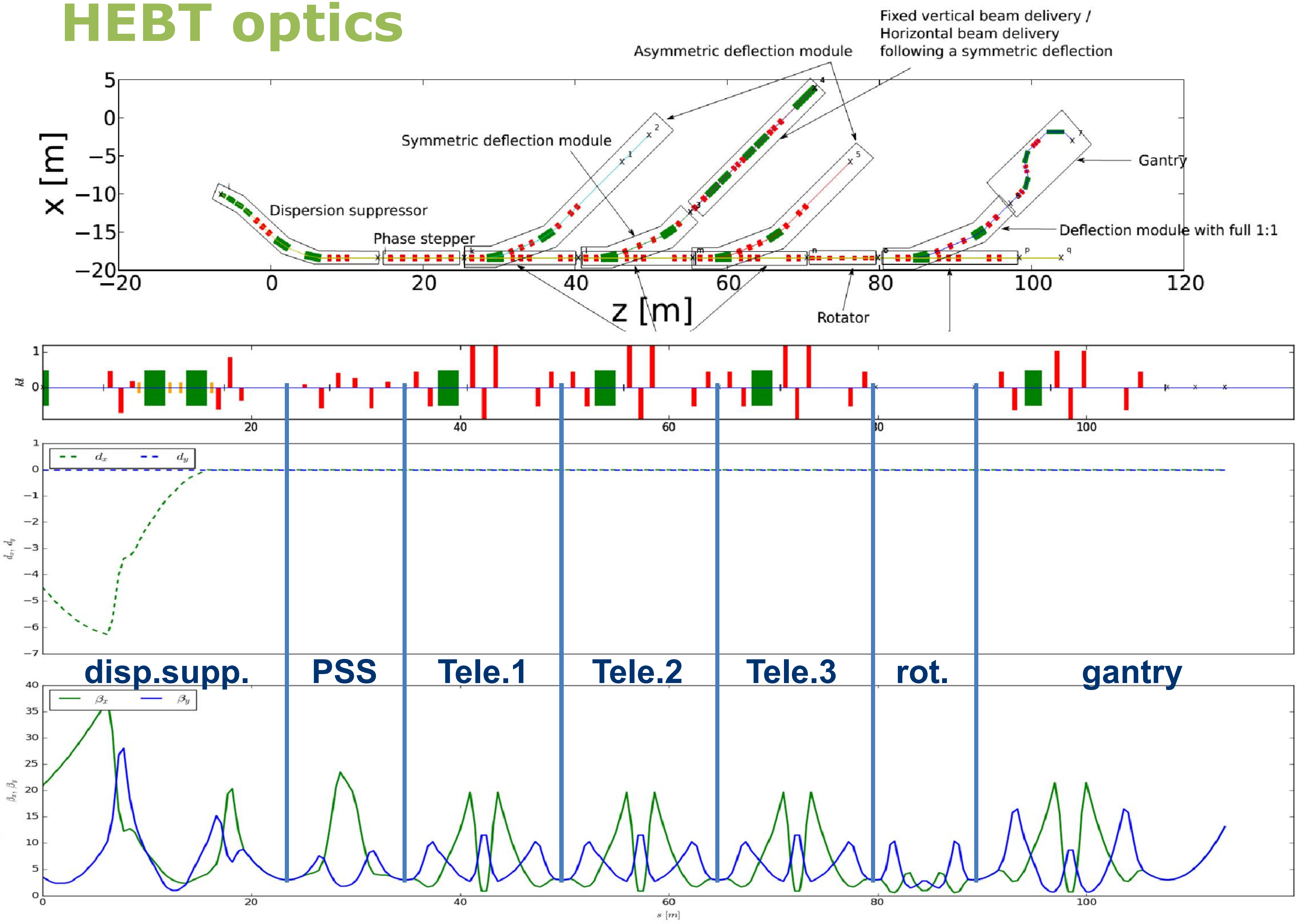
normalized extracted intensity



- Resonant sextupole strength



HEBT optics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Deflection module with full 1:1
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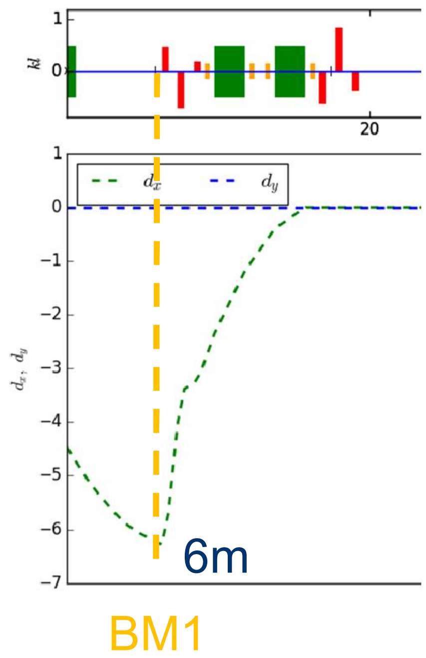
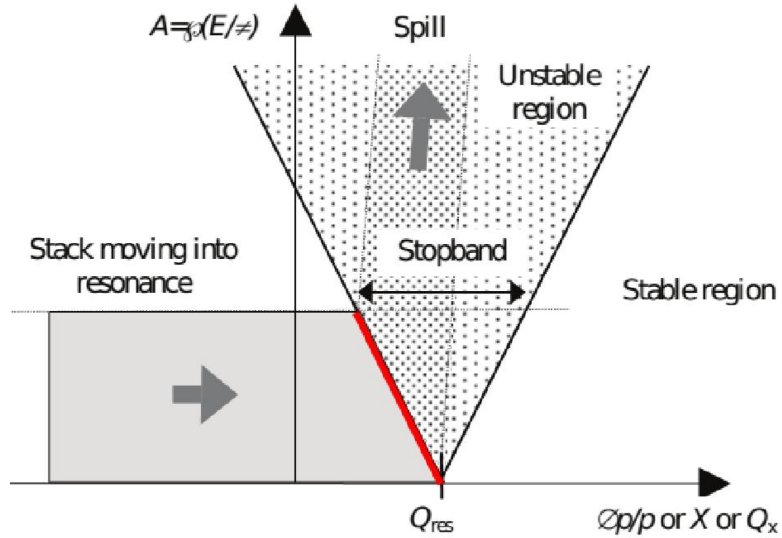
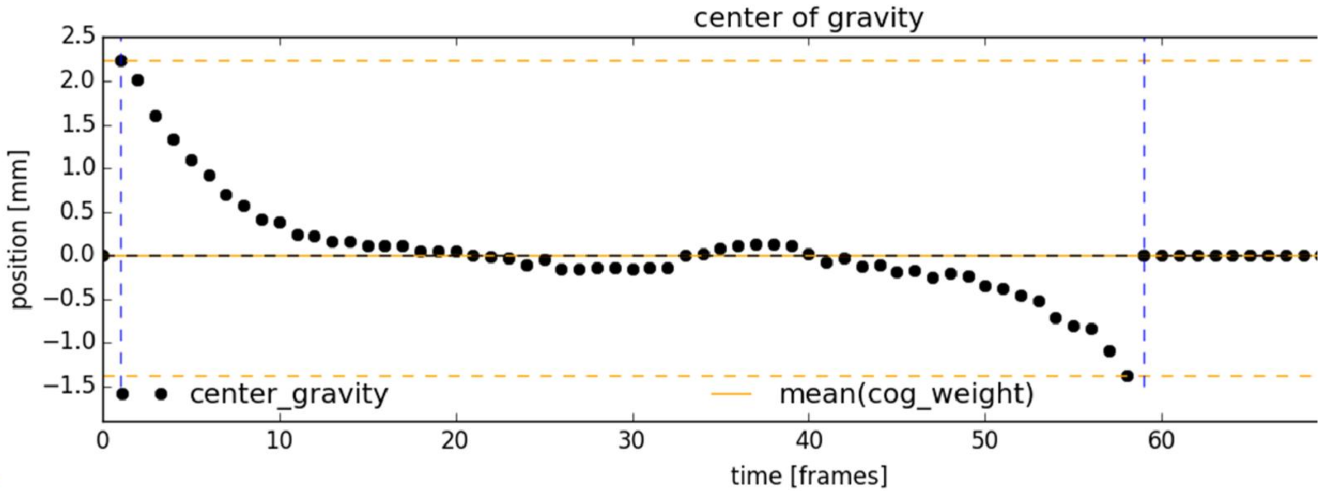
x [m]
z [m]
disp.supp.
PSS
Tele.1
Tele.2
Tele.3
rot.
gantry
s [m]

close dispersion – monitor @ dx≠0



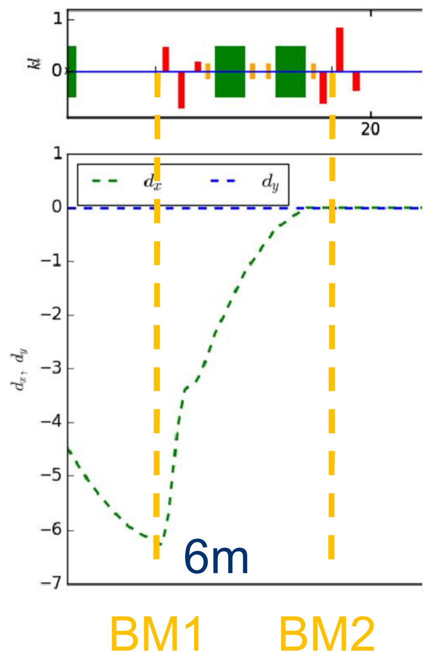


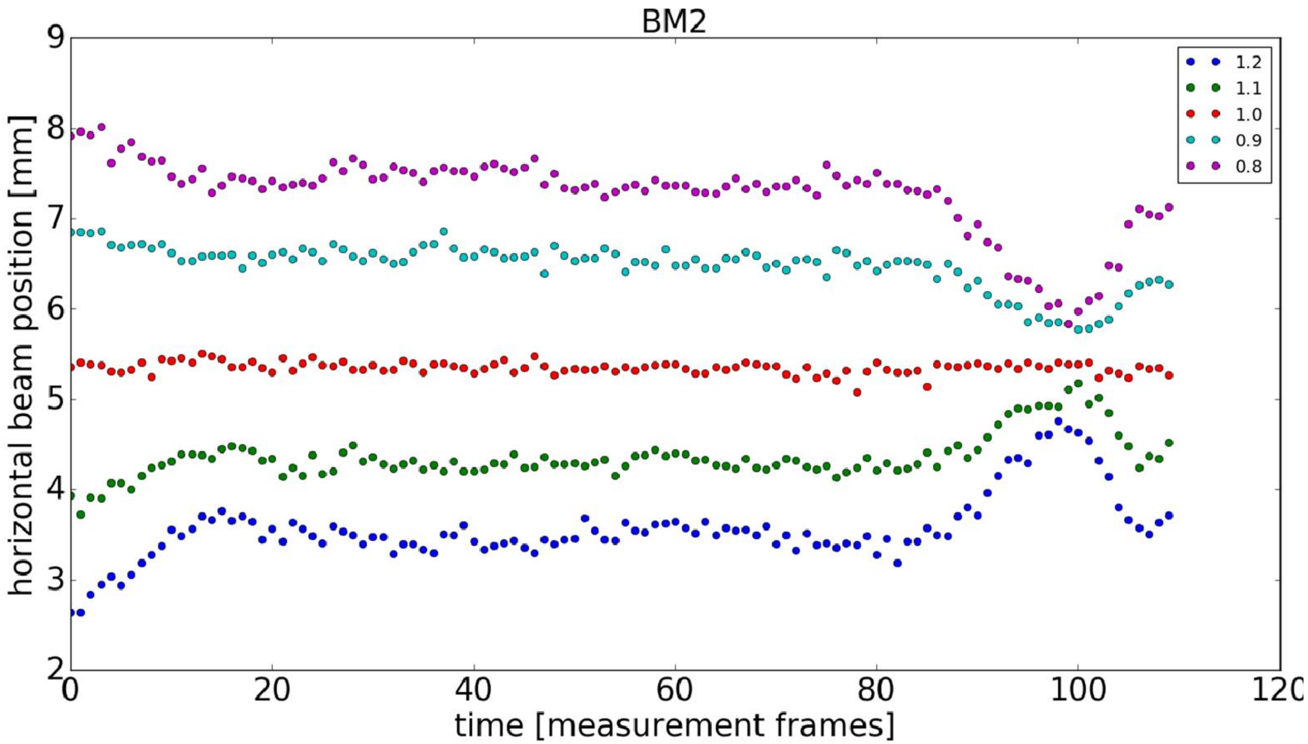


- beam position movement by shift of particle momentum

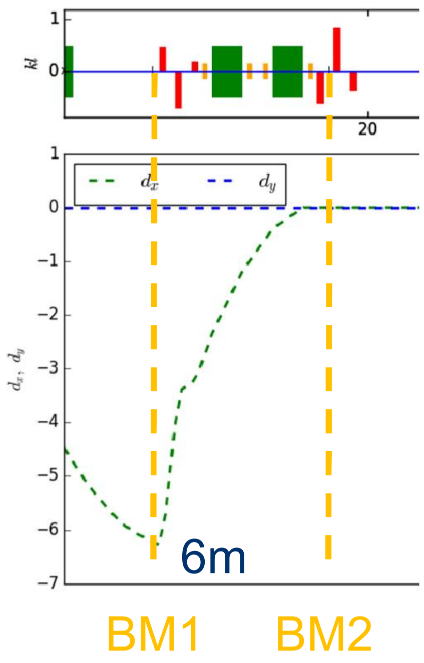
close dispersion – monitor @ dx=0

- no intraspill position changes expected when dx=0
- scaled K1L of quadrupole triplet ±20%





close dispersion – monitor @ dx=0



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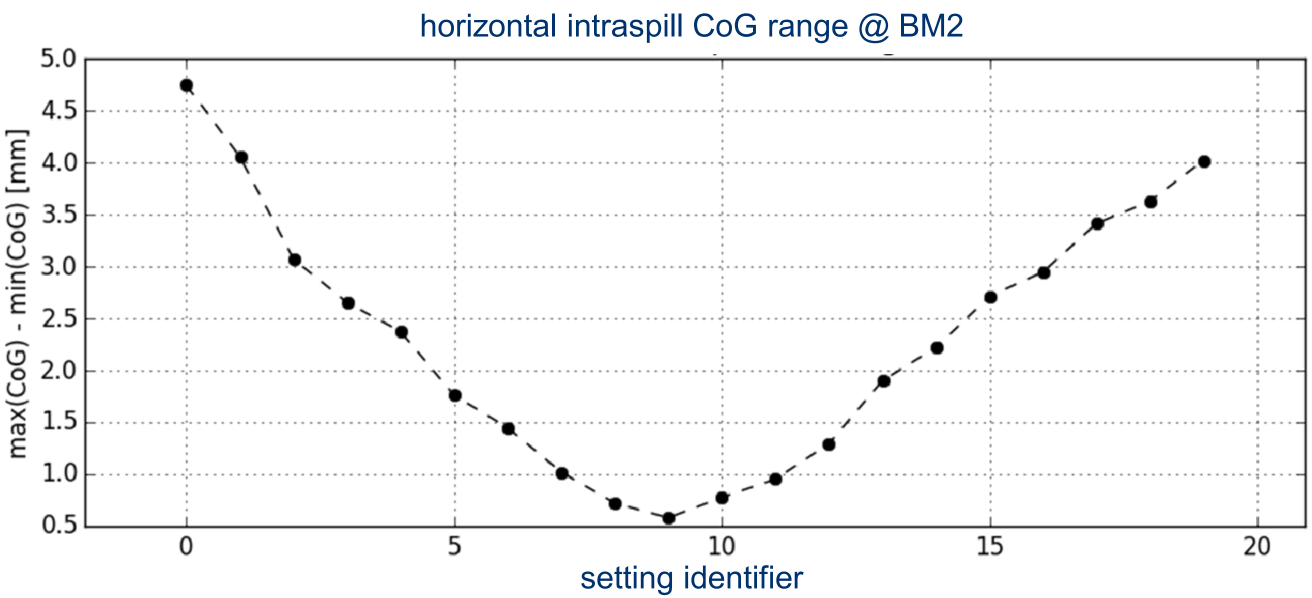
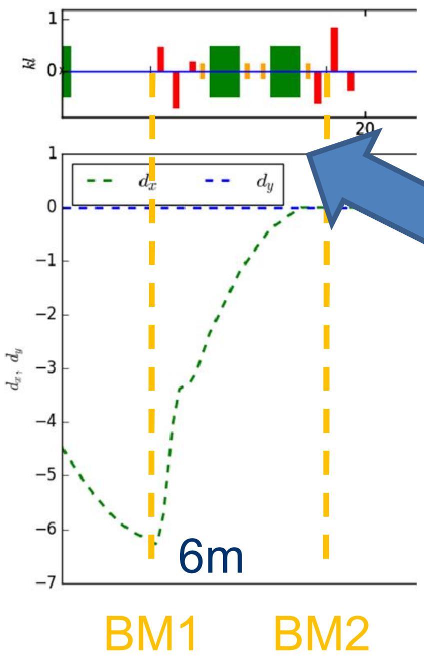
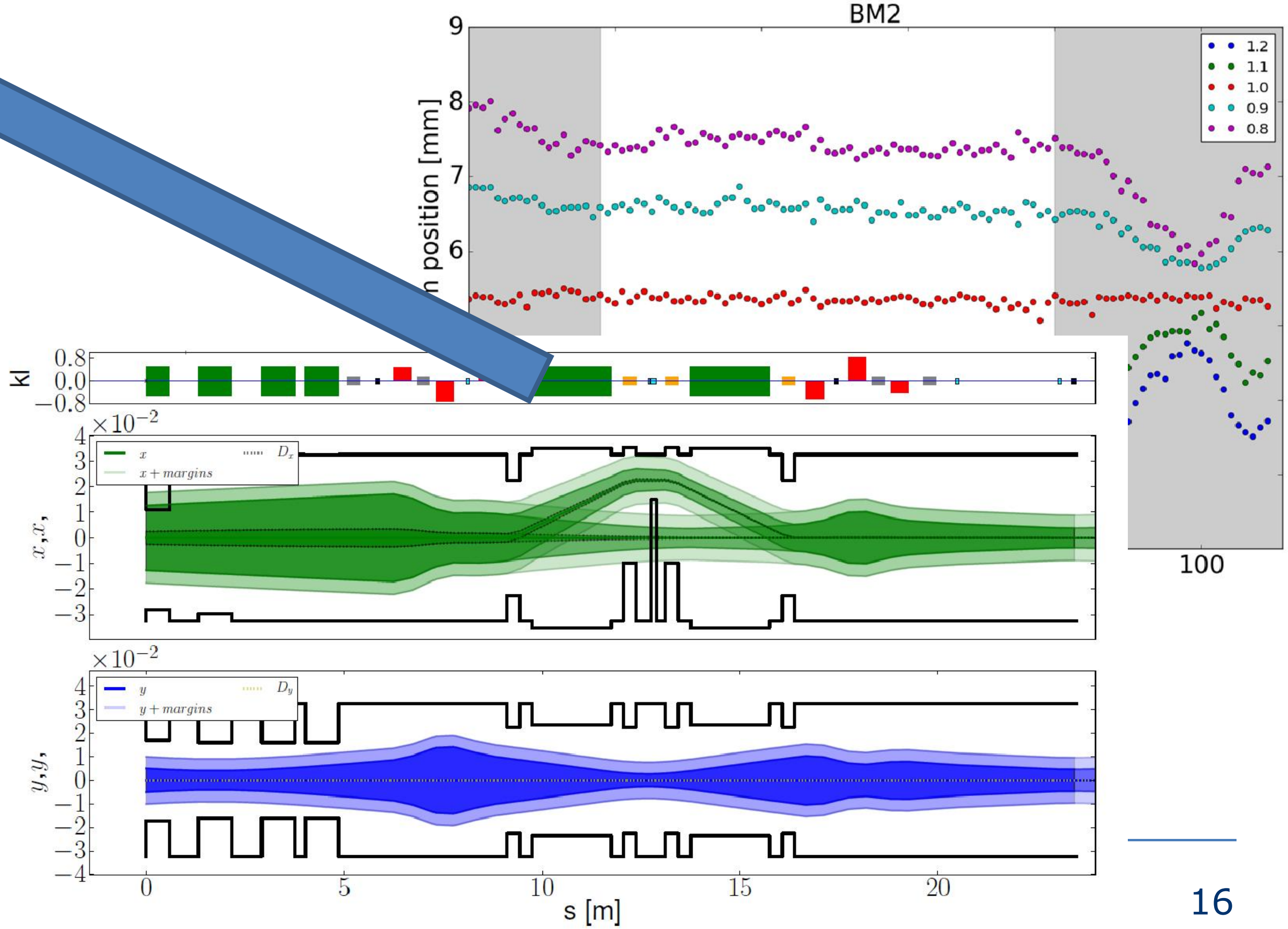


- closed dispersion at minimum beam position movement

close dispersion – chopping

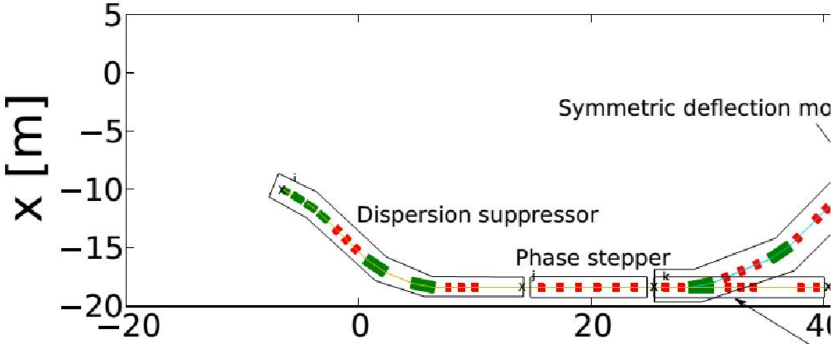


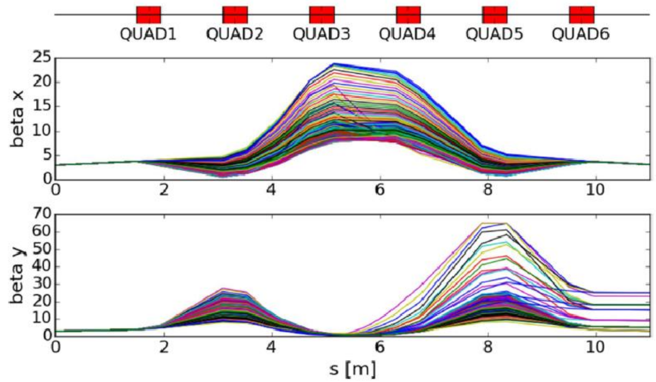
- chopping system cuts leading and trailing spill (<250us)

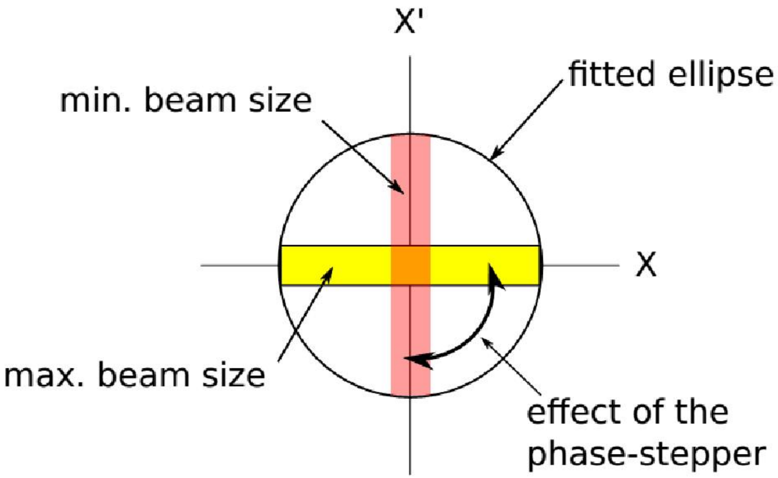


Spot Size Adjustment

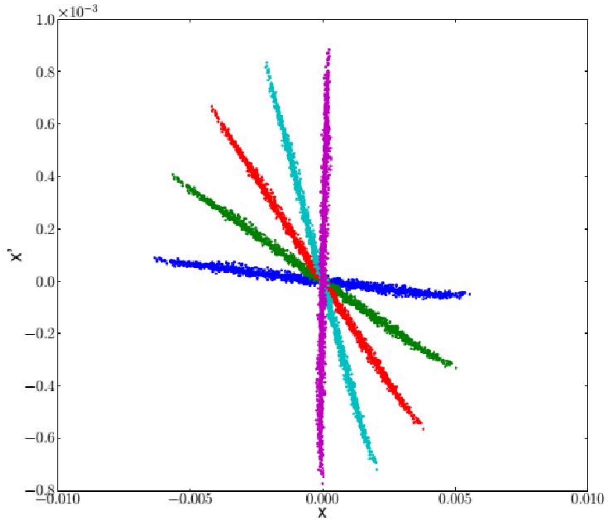
- horizontal phase space (bar-of-charge) rotation changes the projected beam size
- vertical beam size changed by variation of vertical beta function





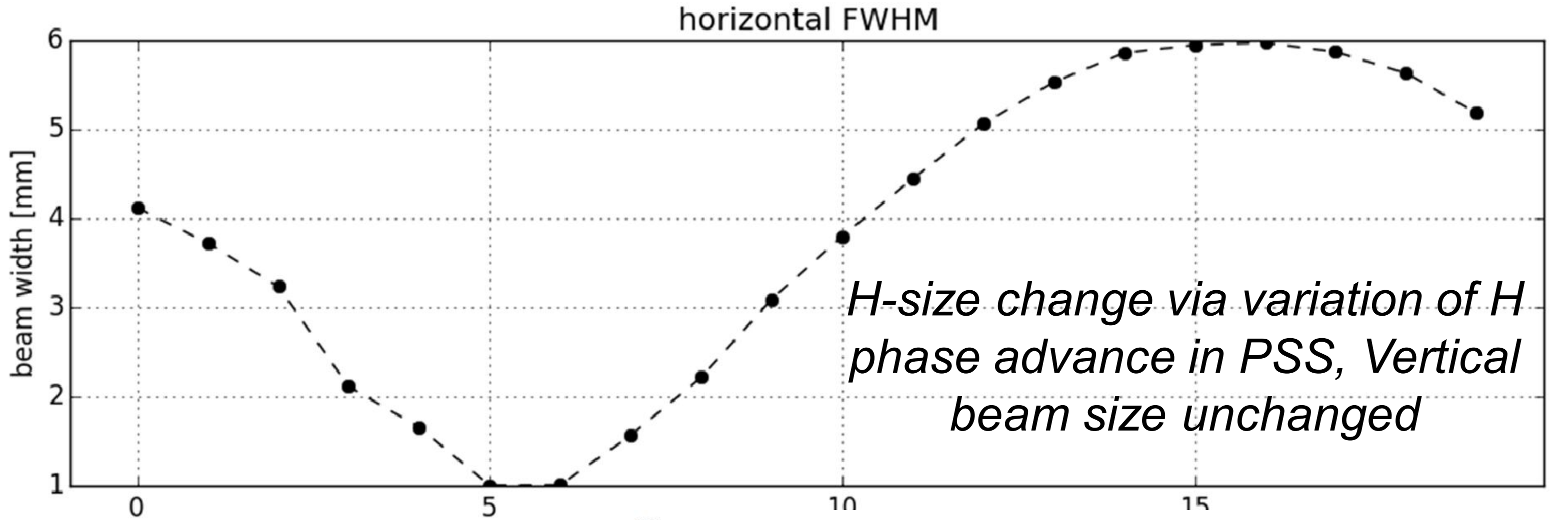


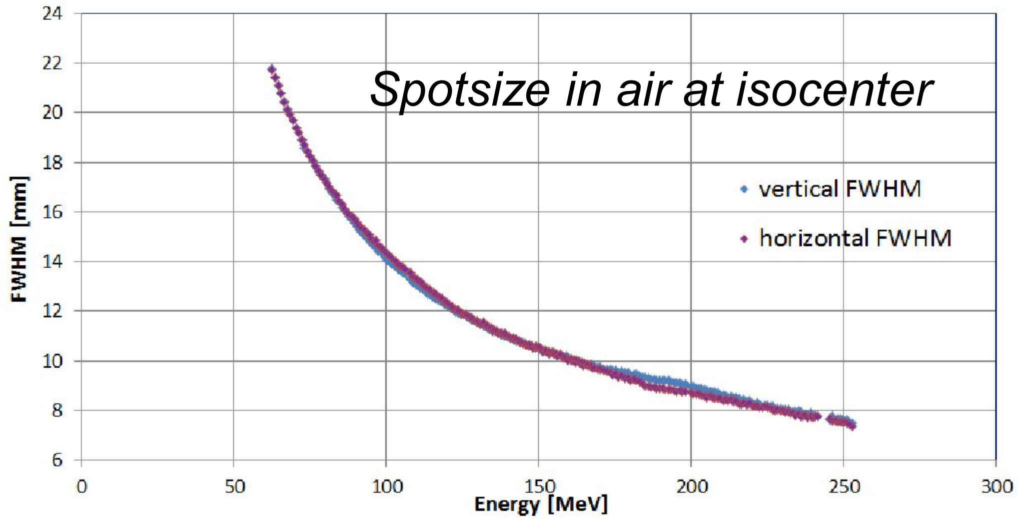
Normalized H phase space



Spot Size Adjustment

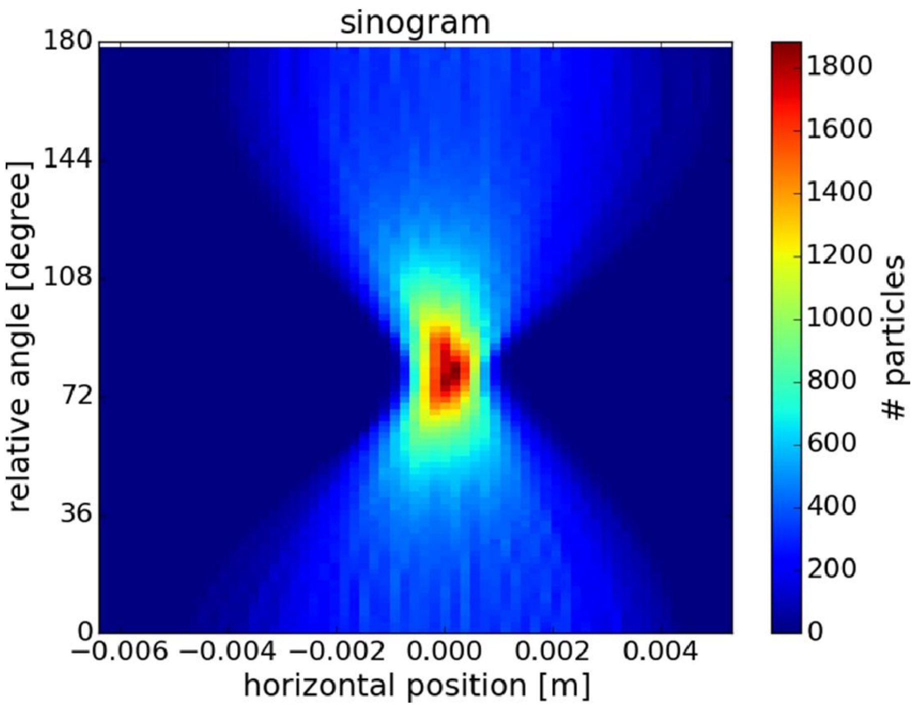
- Spot size adjustment via PSS and last quadrupole setting

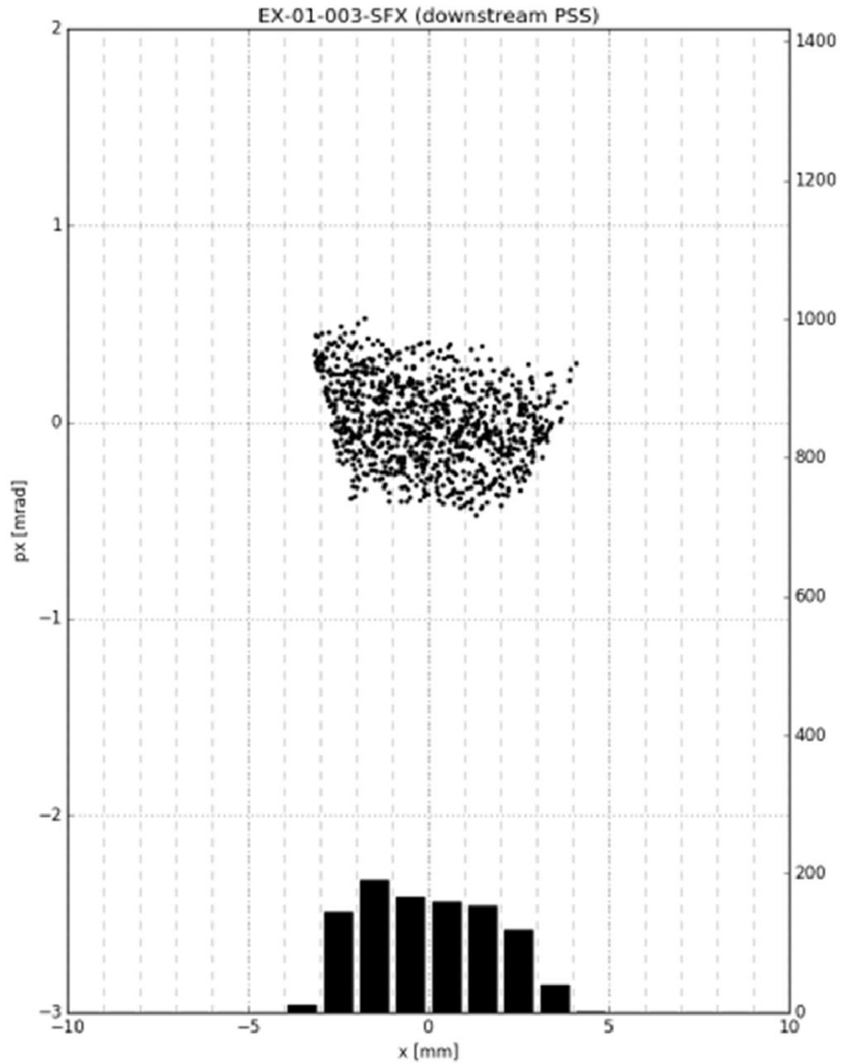




Tomoscope

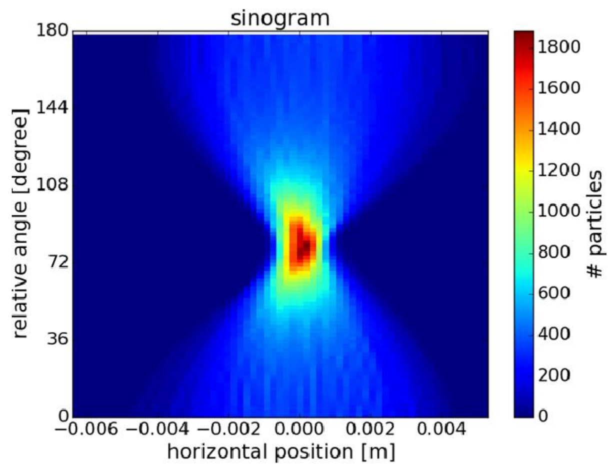
- vertical beam size is constant
- horizontal phase advance changed by 180° in 1°steps

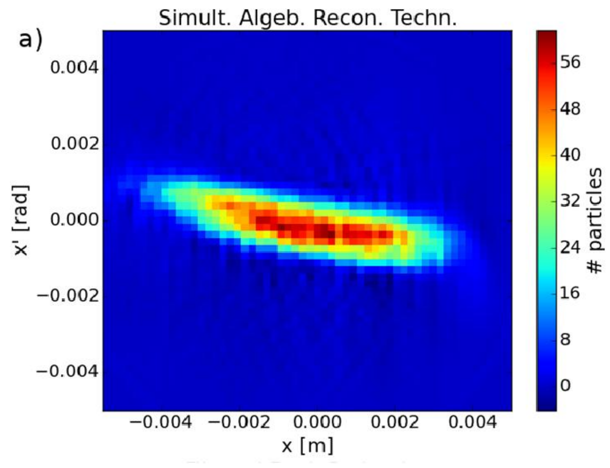




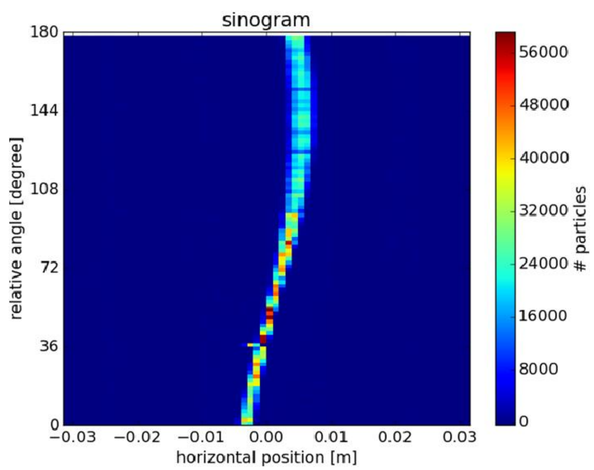
Tomoscope

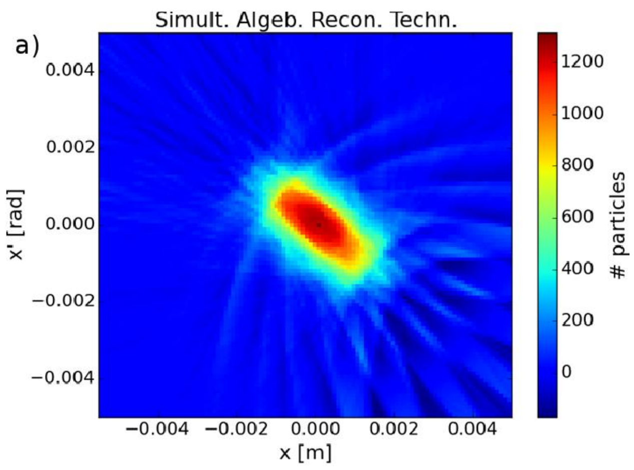
Simulated data



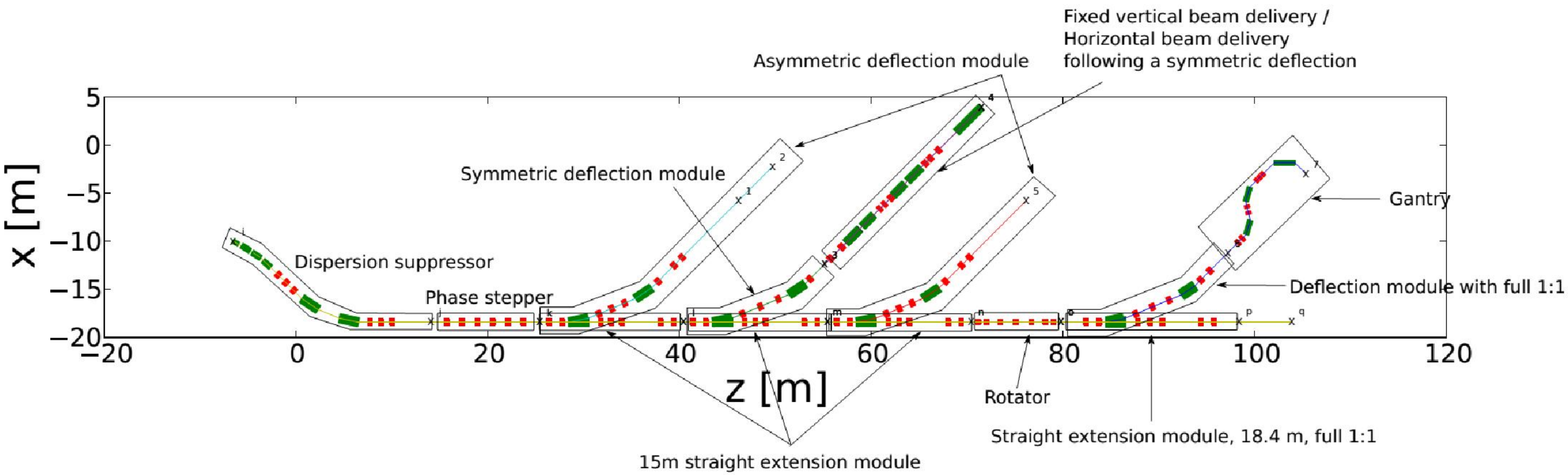


Measured data
(05/2015)

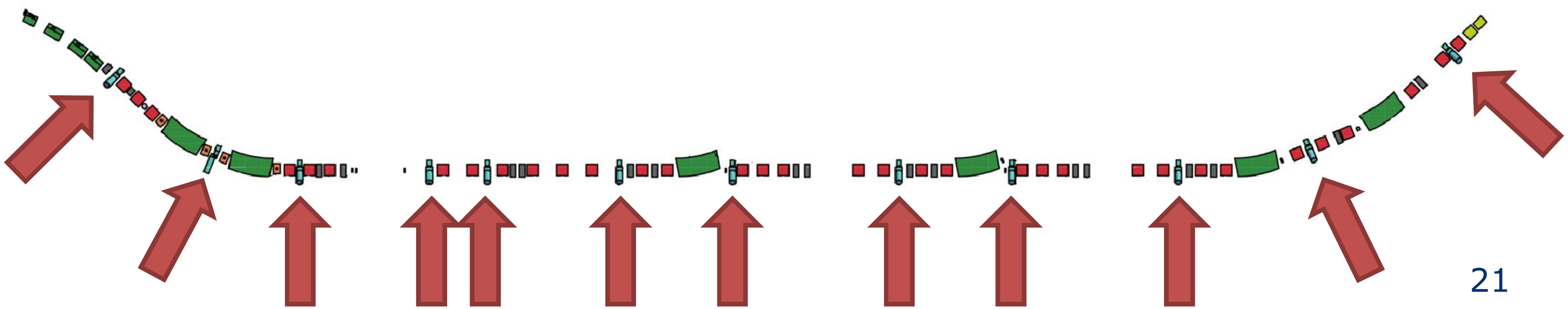




HEBT to IR3



Fixed vertical beam delivery /
Horizontal beam delivery
following a symmetric deflection
Asymmetric deflection module
Symmetric deflection module
Gantry
Dispersion suppressor
Phase stepper
Deflection module with full 1:1
Rotator
Straight extension module, 18.4 m, full 1:1
15m straight extension module
x [m]
z [m]



Lower intensities result in 3 times lower V emittance in HEBT

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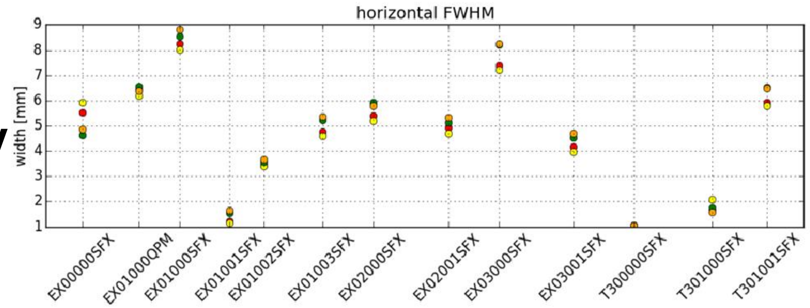
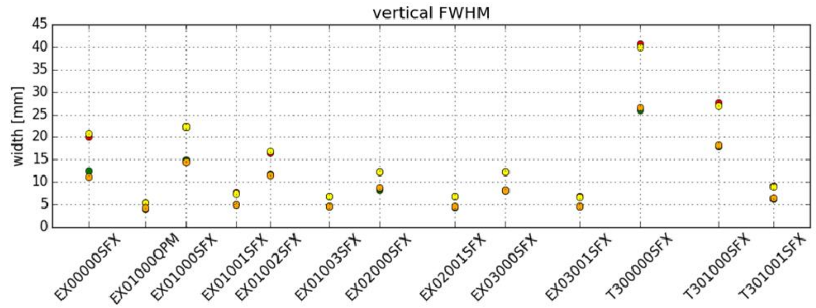
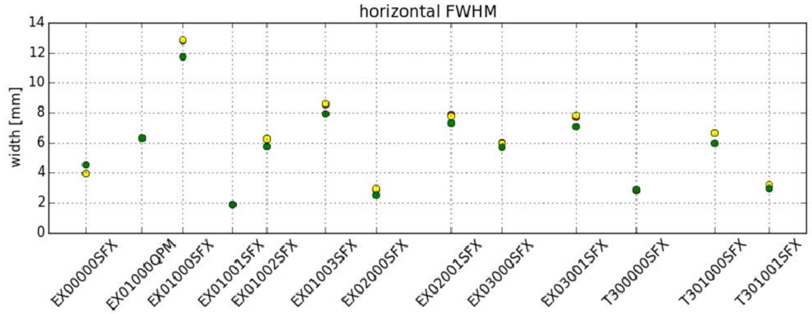
- Vertical FWHM in HEBT 40% lower for lower beam intensities (< 20% nominal I)

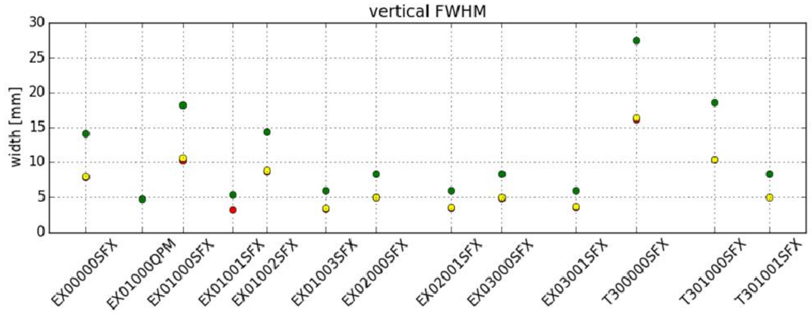
62 MeV

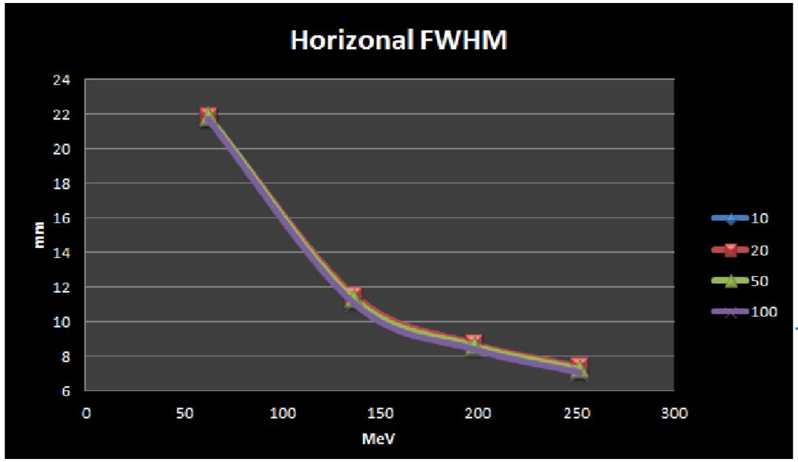


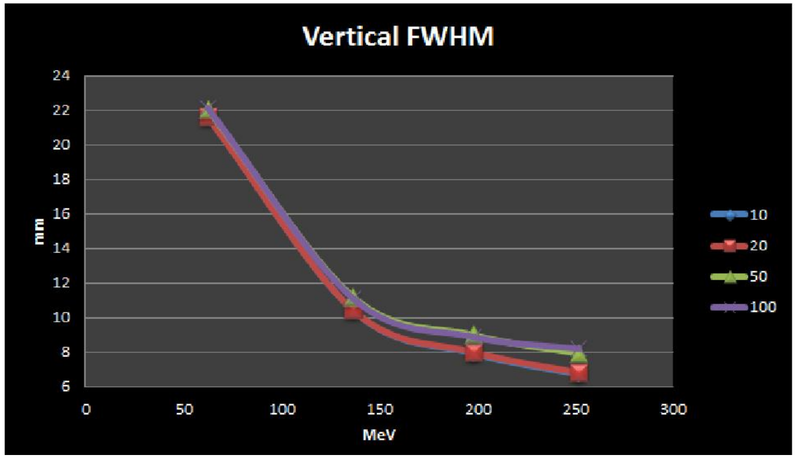


253 MeV









Intensity-dependent extracted beam properties

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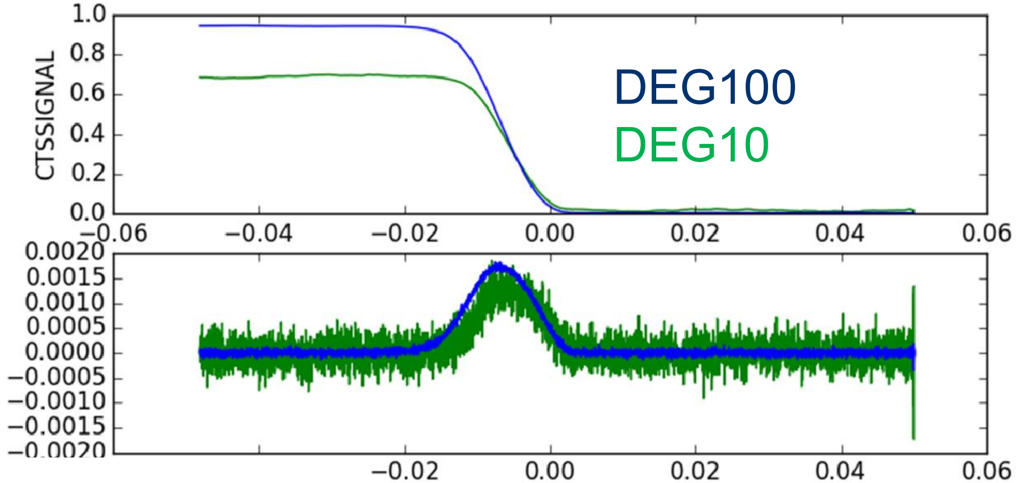
flat top in the synchrotron:

- Vertical emittance difference: < 20%

- Vertical tune before extraction $Q_v(I_{low})$-$Q_v(I_{high})$:

  60 MeV: < 0.3 %

  250 MeV: < 0.1 %



flat bottom in the synchrotron:

- Vertical tune before extraction $Q_v(I_{low})$-$Q_v(I_{high})$:

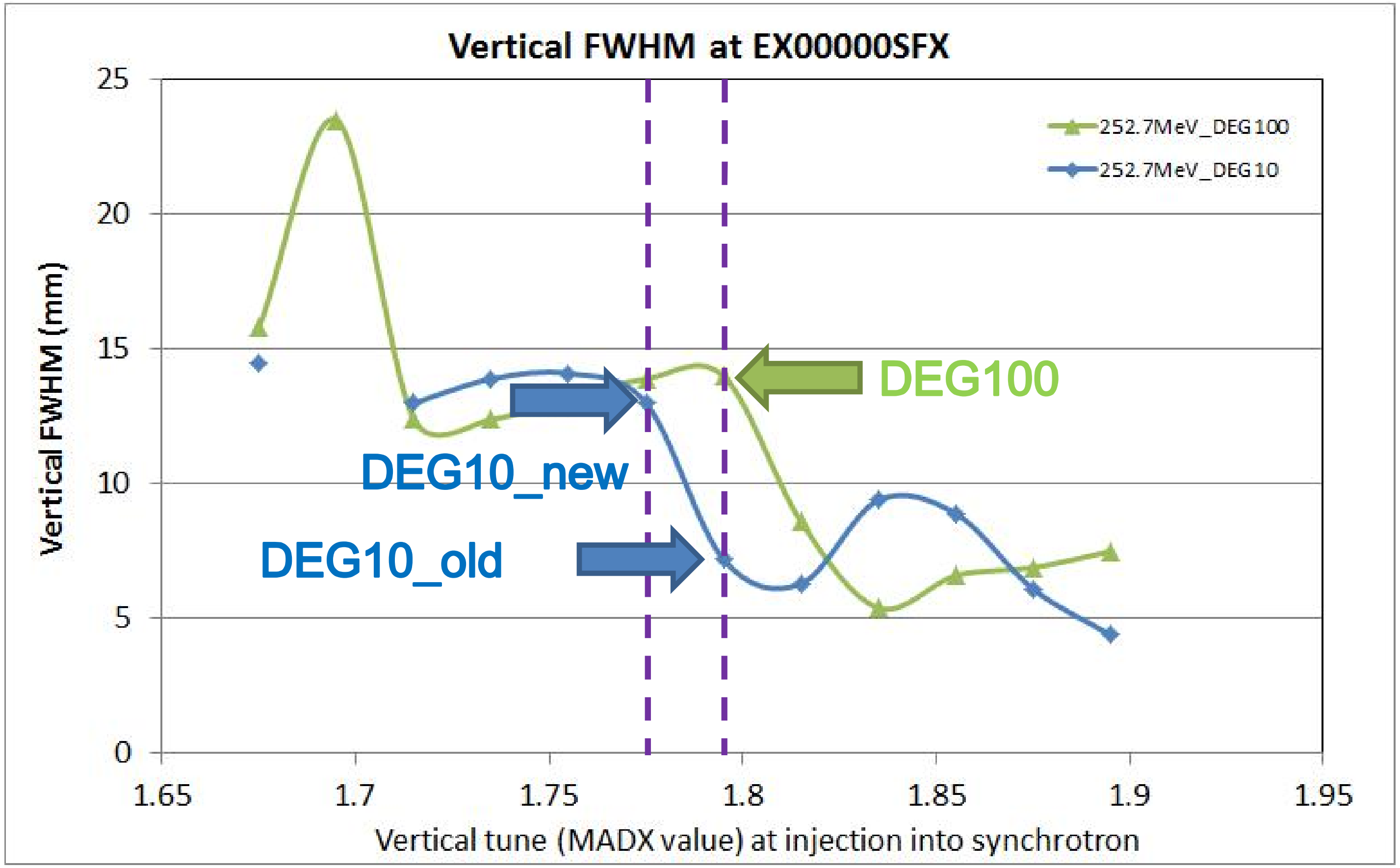
  7 MeV: < 0.7 %

- Tunes during acceleration (off-momentum, low I):

  $Q_v \approx 1.72 \rightarrow 1.79$

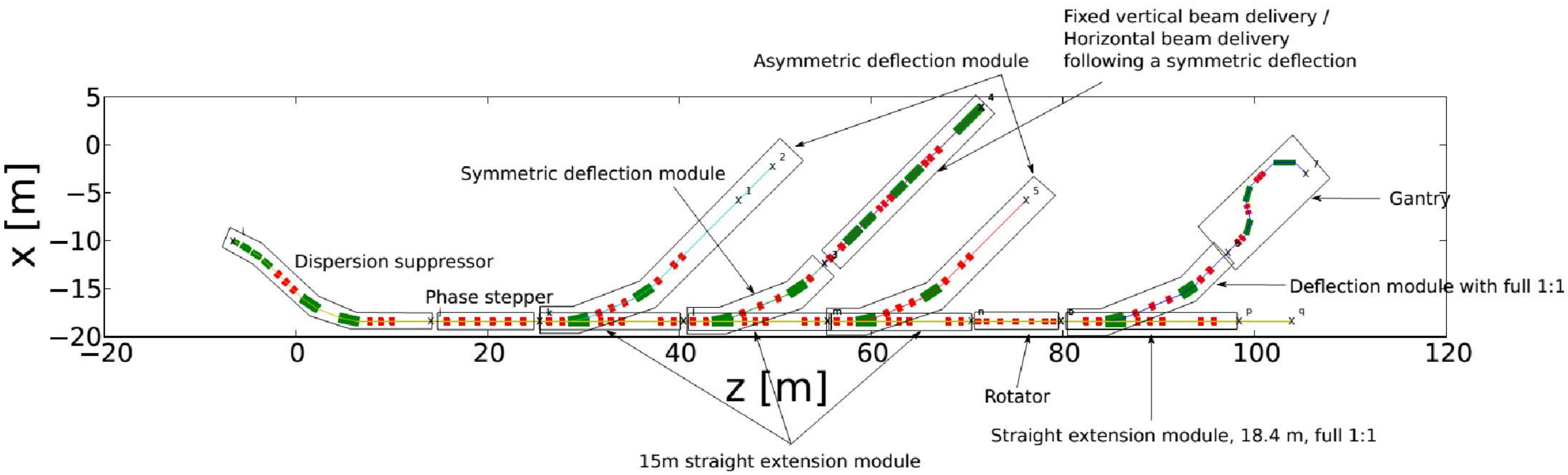
  $Q_h \approx 1.76 \rightarrow 1.68$

Spot size asymmetry



- Decrease of vertical injection tune by 0.03 for lower intensity settings allows to achieve < 4% spot size symmetry for all energies and all intensity levels

HEBT to IR3



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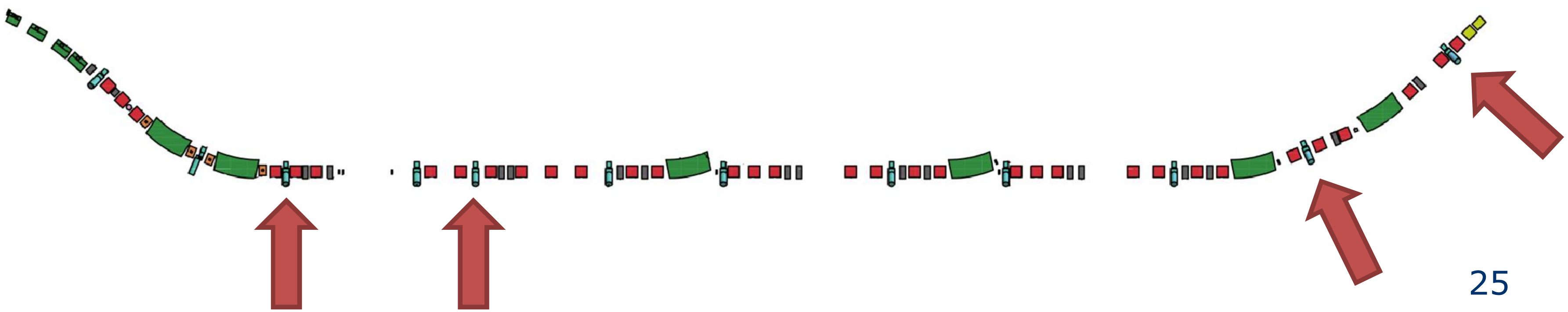
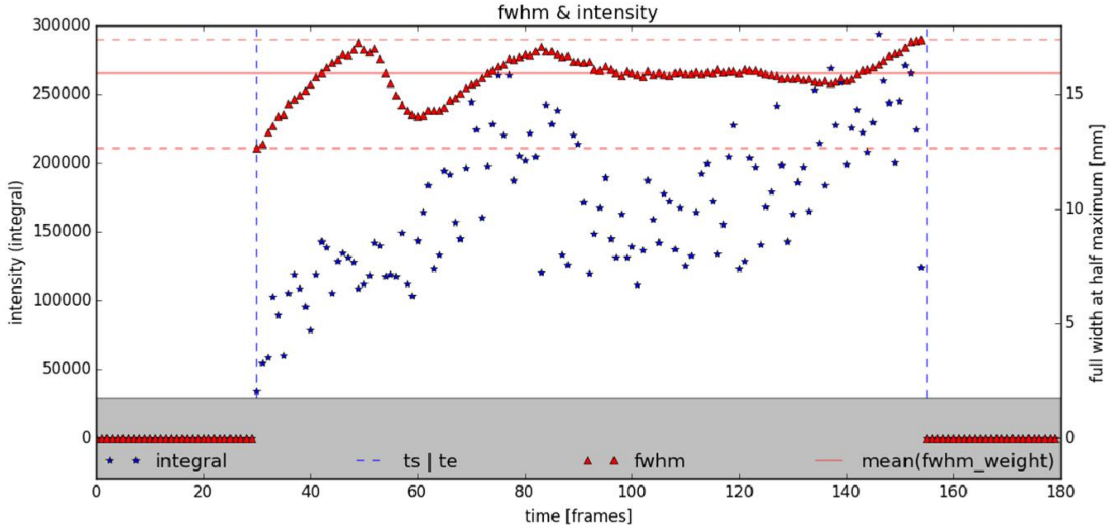
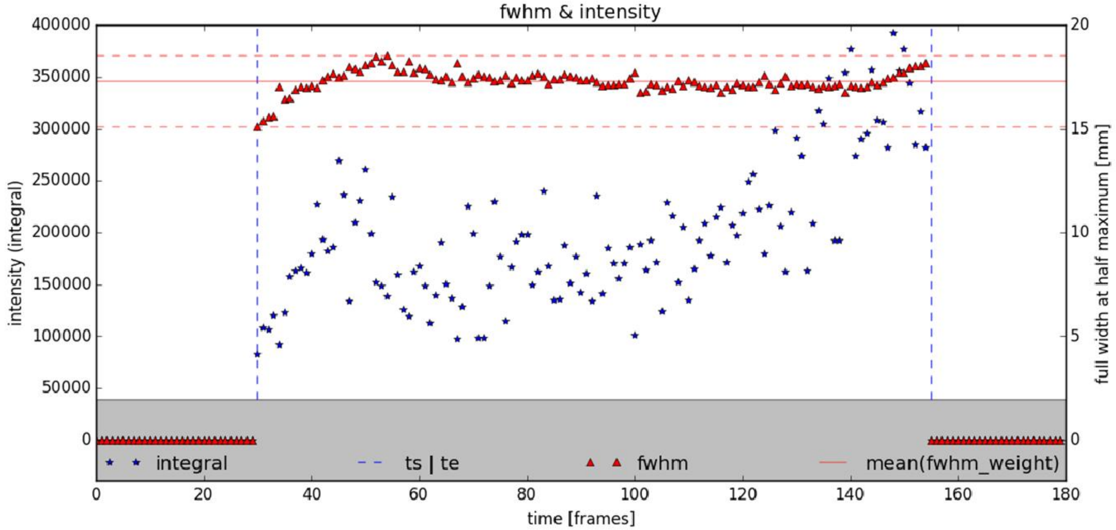


Intraspill width variation

FWHM horizontal
(↨ 4.7mm)



FWHM vertical
(↨ 3.4mm)



Width and position - variations within spill

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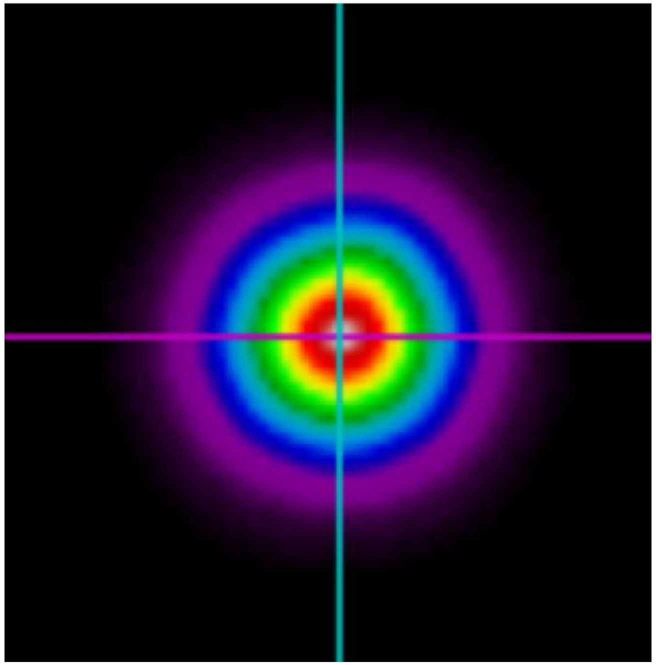
Oscillations in beam width

Energy [MeV]	T3-01-000-SFX		T3-01-001-SFX	
	H [mm]	V [mm]	H [mm]	V [mm]
62.4	1.6 (15 %)	0.4 (3 %)	0.9 (12 %)	0.6 (8 %)
136.8	0.9 (6 %)	0.6 (5 %)	0.7 (9 %)	0.3 (5 %)
179.2	0.9 (6 %)	0.7 (5 %)	0.6 (7 %)	0.4 (8 %)
252.7	1.1 (6 %)	0.5 (3 %)	0.5 (7 %)	0.2 (4 %)

Oscillations in beam position

Energy [MeV]	T3-01-000-SFX		T3-01-001-SFX	
	H [mm]	V [mm]	H [mm]	V [mm]
62.4	± 0.2	± 0.2	± 0.2	± 0.1
136.8	± 0.2	± 0.2	± 0.2	± 0.1
179.2	± 0.3	± 0.3	± 0.2	± 0.1
252.7	± 0.2	± 0.2	± 0.1	± 0.0

Beam in IR3



Accelerator Section	Transmission
Through LEBT, RFQ, Linac	45 %
Through MEBT	95 %
Through Synchrotron Injection	25 %
Through capture and acceleration	65 %
Through extraction and HEBT (max **1.8e10/spill**)	**80 %**

FAQ:

- Focus on proton activities to start clinical and non-clinical operation in 2016
- Carbon commissioning will start in 2017

Commissioning is a technical, scientific and human endeavor possible only with strong team spirit

Thanks to V. Lazarev (**Siemens**), M. Pullia, L. Falbo (**CNAO**), R. Rossmanith (KIT) and **CERN** for the crucial support