

PROTECT +
ENHANCE +
SAVE LIVES

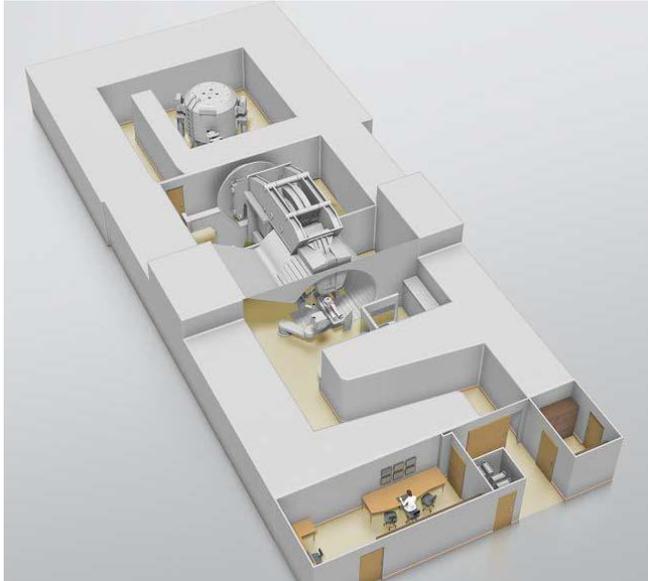


The **S2C2** : experiences from in-factory testing and on-site installations

Jarno Van de Walle
for the IBA S2C2 teams

- S2C2 and ProteusONE[®] : overview
- Beam alignment into the gantry
- Beam simulations in the gantry
- Beam energy

ProteusONE



- 2 sites clinical :
 - Centre Antoine Lacassagne (Nice, France)
 - Beaumont Hospital (Detroit, US)

- 3 sites on-going installation
 - Caen, France
 - Sapporo, Japan
 - Newport, UK

- 9 sites in the coming 2 years

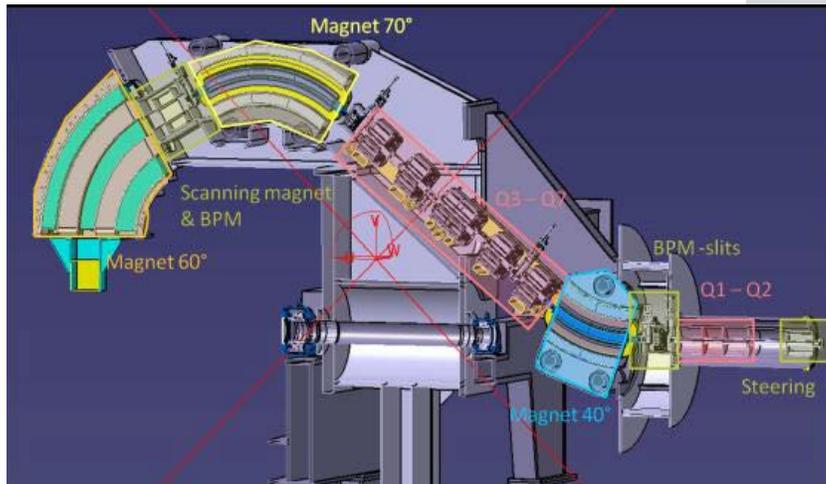
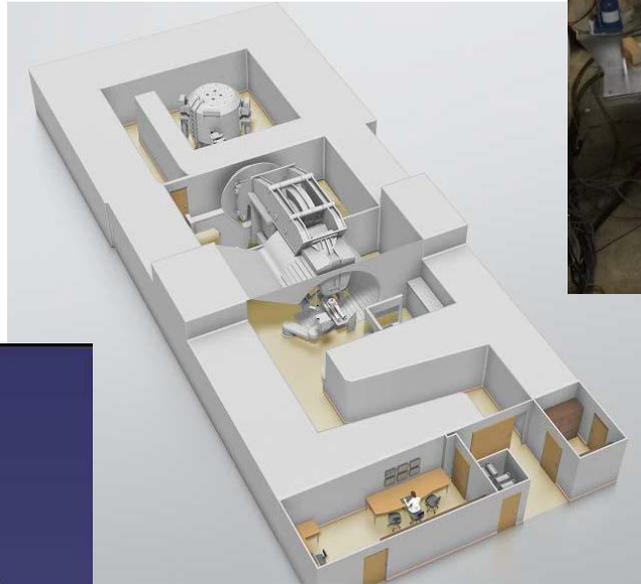
- Currently around 1 year from rigging to first patient
- To be reduced to 6 months ...
- Challenges :
 - Training of installation teams
 - Manufacturing capabilities
 - Clear, unambiguous installation procedures
 - S2C2 should be reproducible, well studied and understood

S2C2 and ProteusONE® : overview

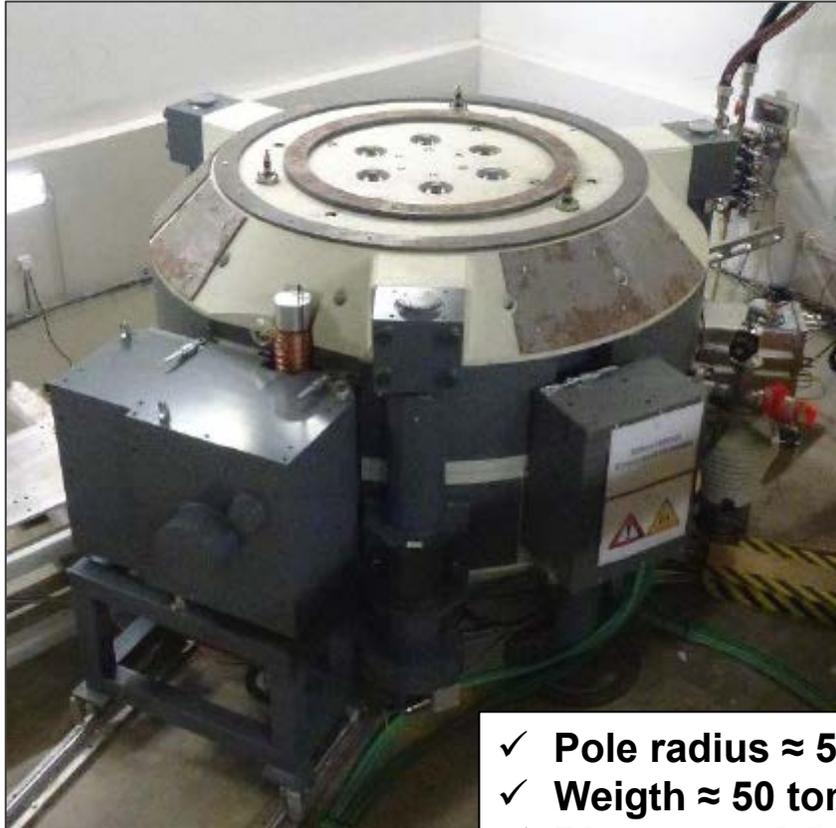


S2C2 and ProteusONE[®] : overview

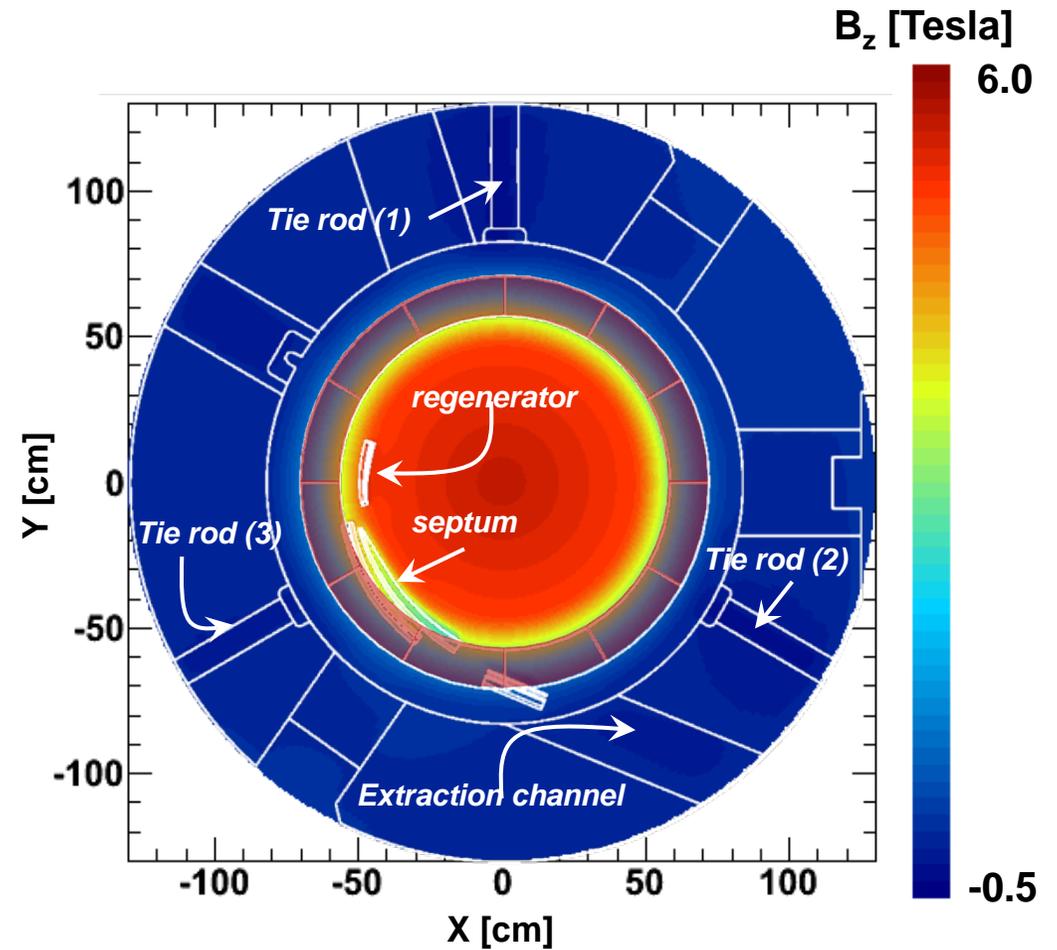
Proteus^{ONE}



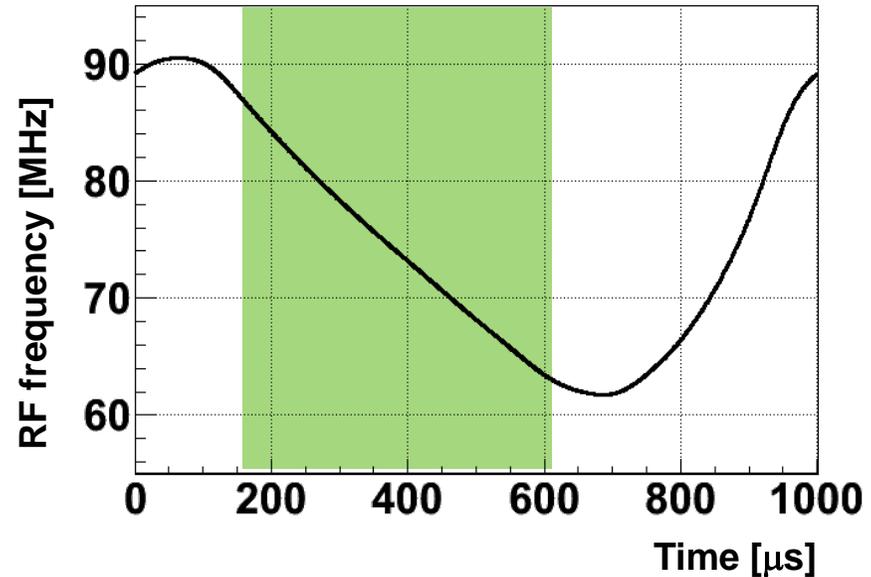
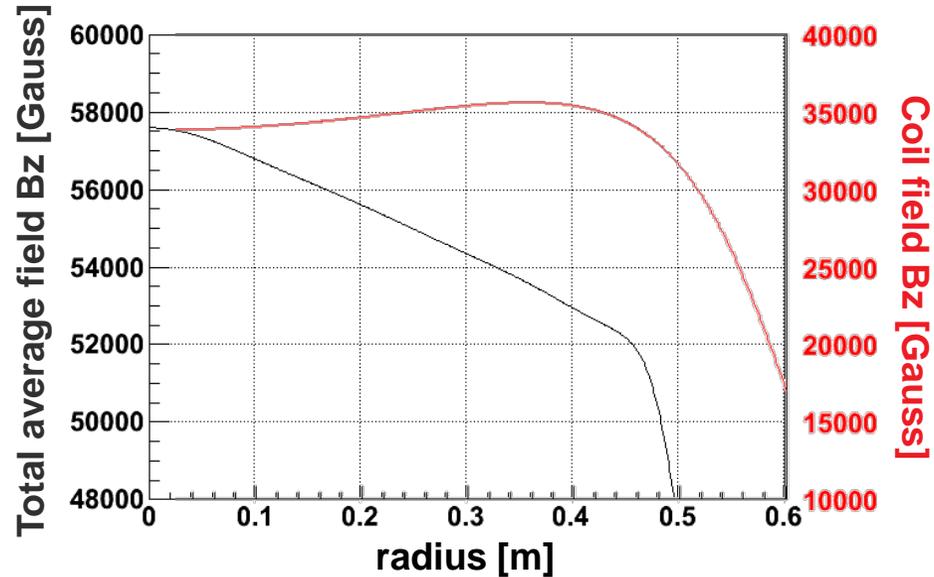
S2C2 : layout



- ✓ Pole radius ≈ 50 cm
- ✓ Weight ≈ 50 ton
- ✓ Diameter ≈ 2.5 m



S2C2 : main parameters

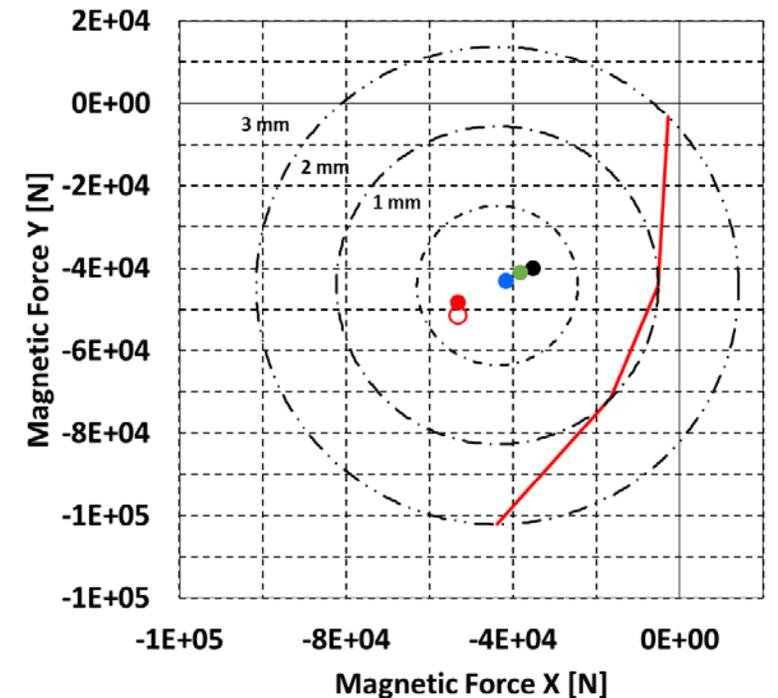
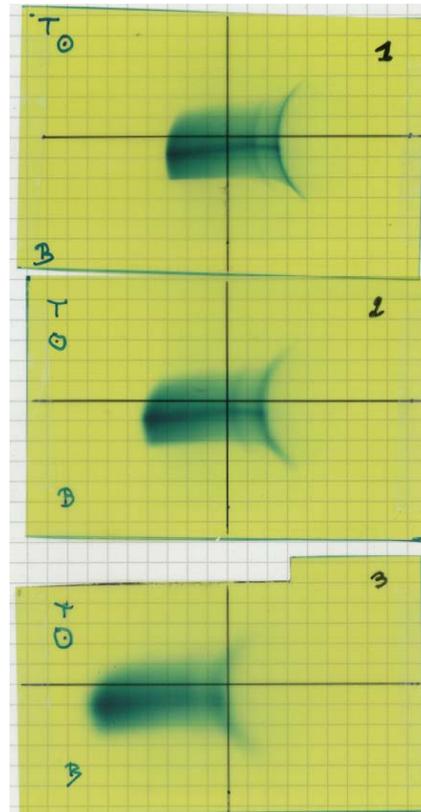
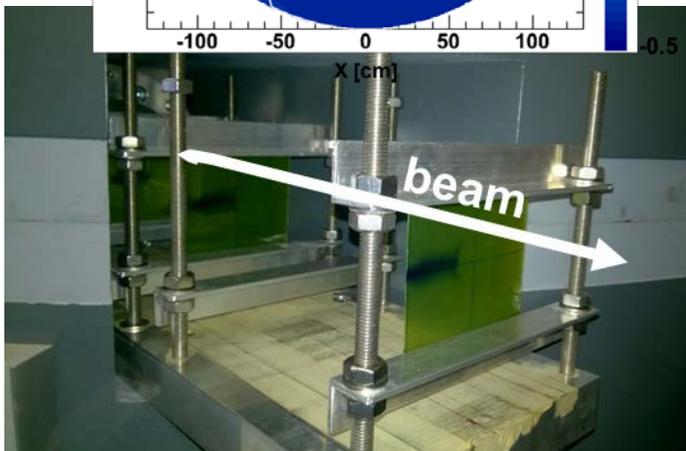
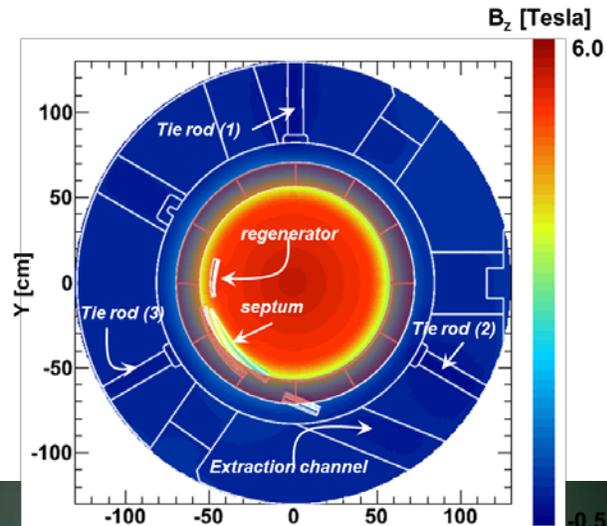


- ✓ Weak focusing ($n < 1$) – peak field = **6.1 T** (regenerator)
- ✓ Dee voltage : **7 → 10 kV**
- ✓ Frequency modulation (**90 → 60 MHz**) @ **1 kHz** ⇒ pulsed beam !
- ✓ Injection frequency **87 MHz**
- ✓ Extraction frequency **63 MHz**
- ✓ Acceleration time \approx **450 μs**
- ✓ Half-integer regenerative extraction (**$2\nu_r = 2$**)

■ Beam alignment into the gantry

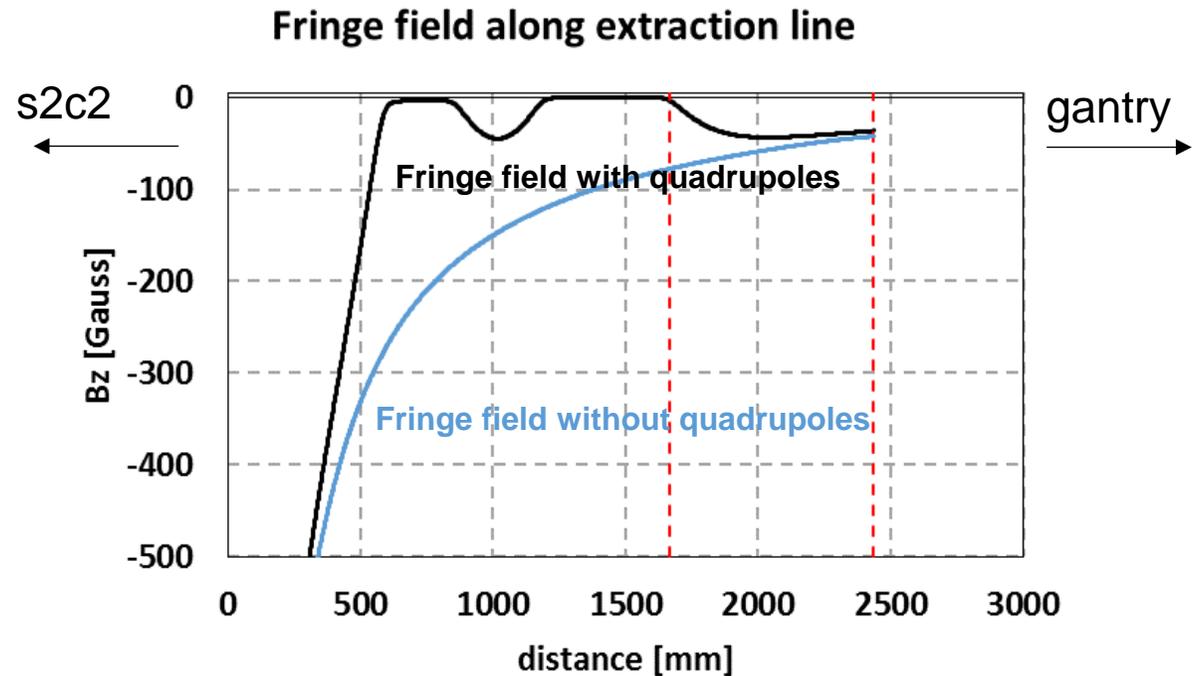
Horizontal alignment in extraction beam line

- ✓ Horizontal alignment of the beam : based on :
 - magnetic forces observed on the superconducting coil (tie rod forces)
 - reference trajectory in the return yoke and extraction channel (see gafchromics)



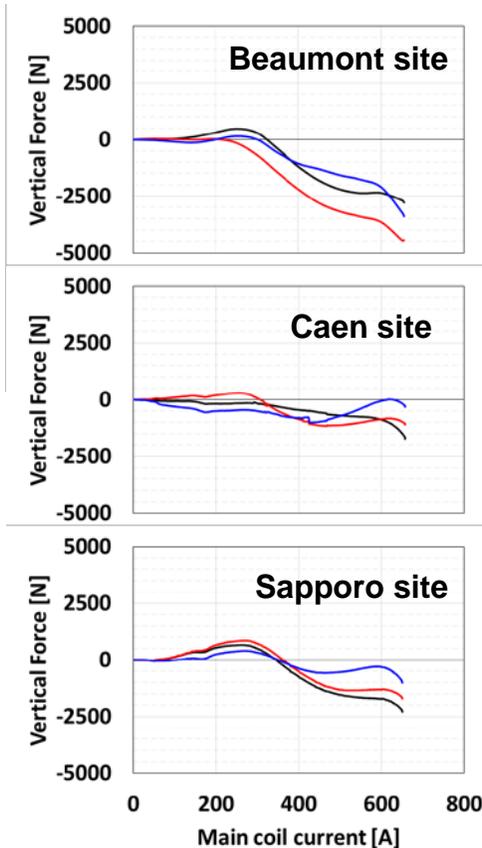
Horizontal alignment in extraction beam line

- ✓ Horizontal alignment of the beam : based on :
 - magnetic forces observed on the superconducting coil (tie rod forces)
 - reference trajectory in the return yoke and extraction channel (see gafchromics)
 - small deflection when entering the gantry due to small but non-negligible fringe field

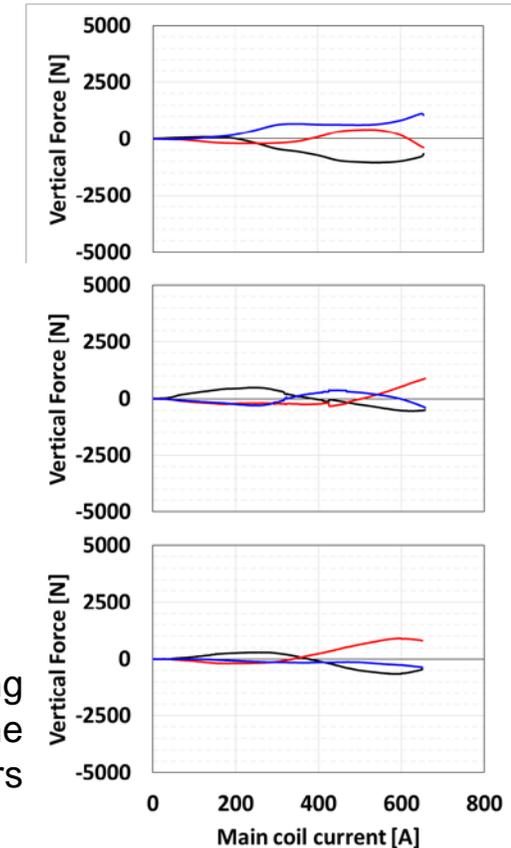


Vertical alignment in extraction beam line

- ✓ Several steps in vertical coil alignment :
 - Observation of vertical magnetic forces on the superconducting coil
 - Observation of beam inside the S2C2 near extraction
 - Observation of the vertical alignment at the exit of the S2C2
 - Observation of steering effects with quadrupoles in the extraction beam line



Vertical forces on the coil measured with three tie rod pairs

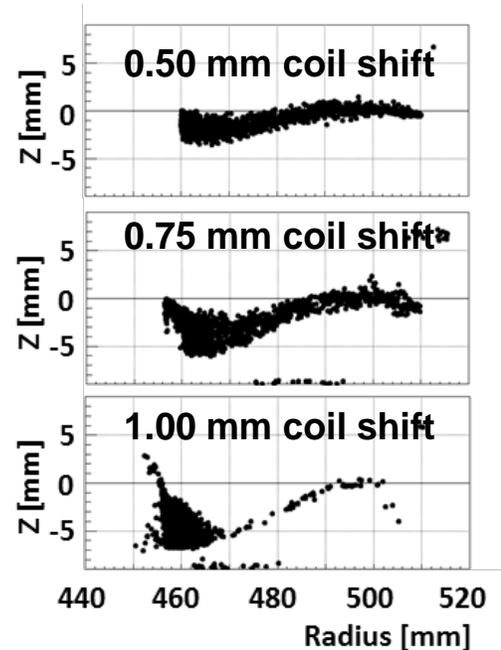
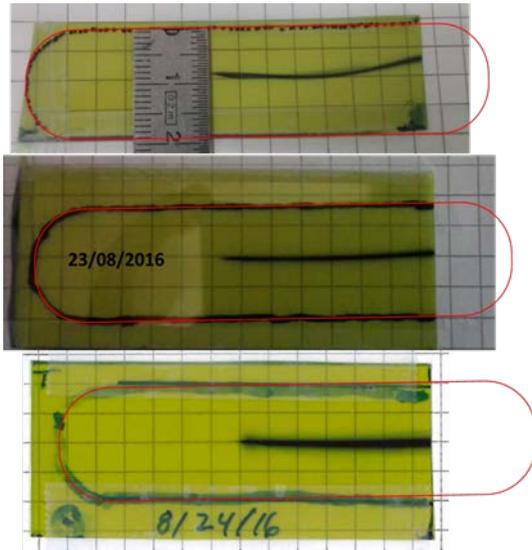


Torques on the coil measured along the axis connecting the center of the S2C2 to the vertical tie rod pairs

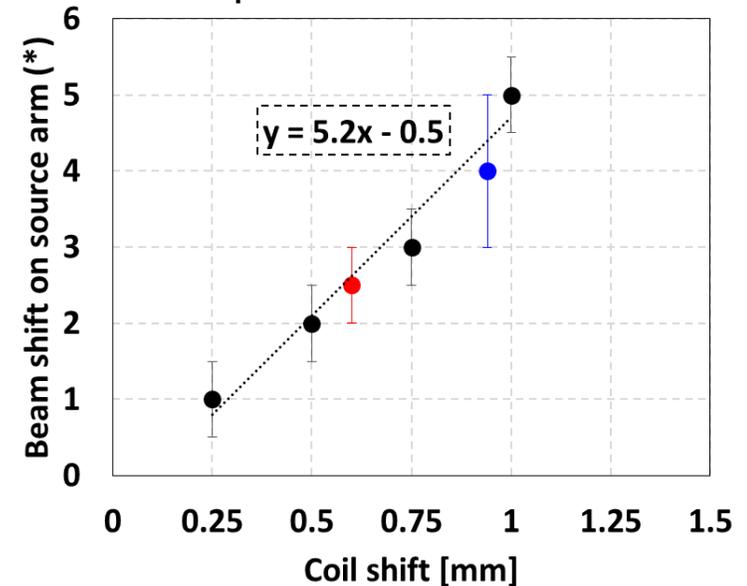
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Beaumont site data



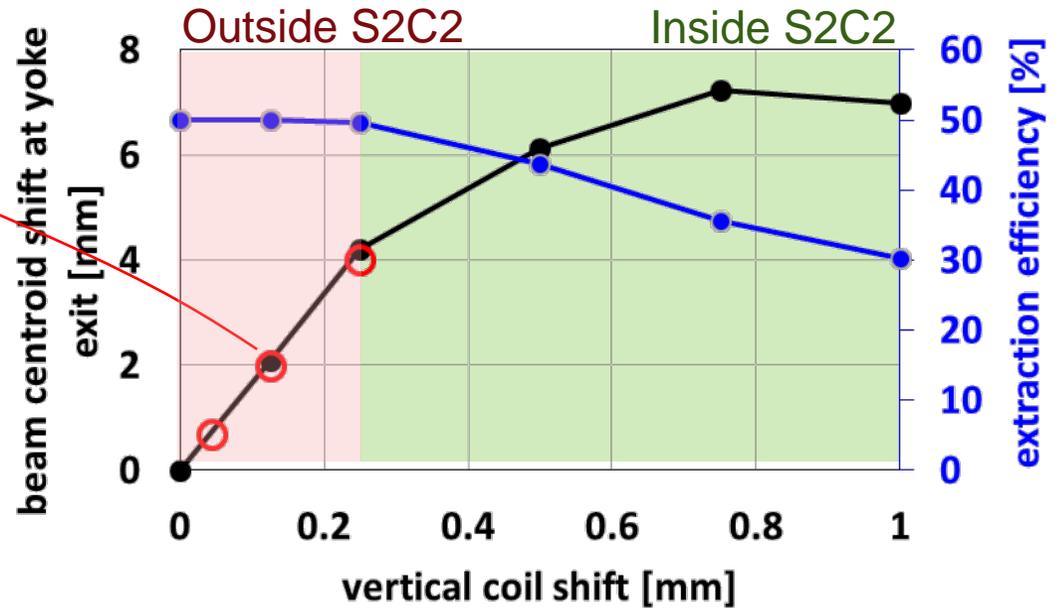
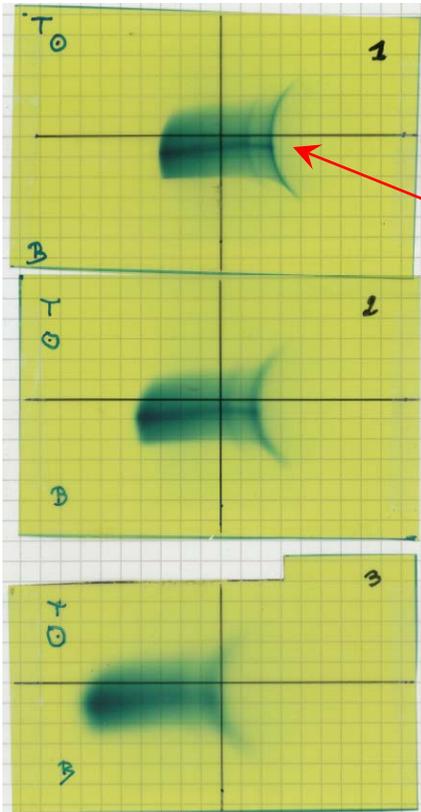
All experimental data



Below 0.25 mm coil displacement :
difficult to observe !

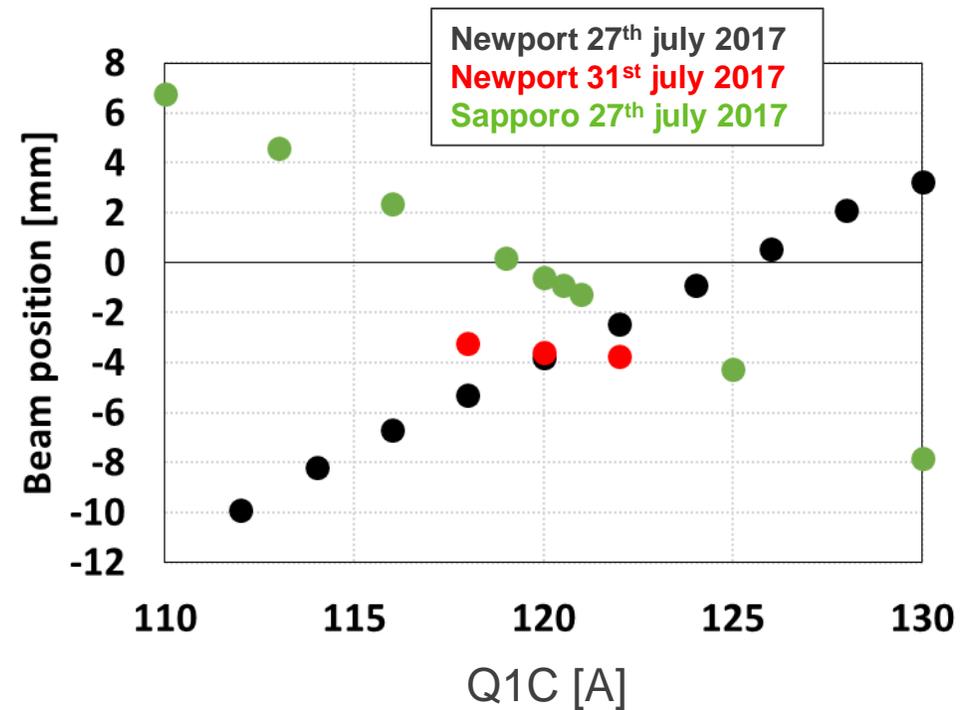
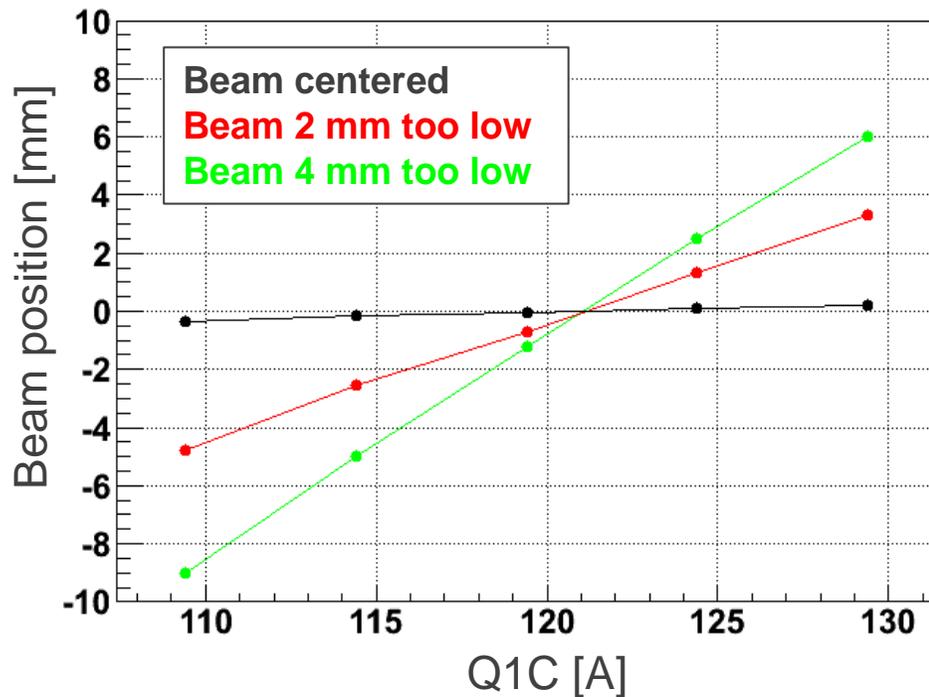
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Vertical alignment in extraction beam line

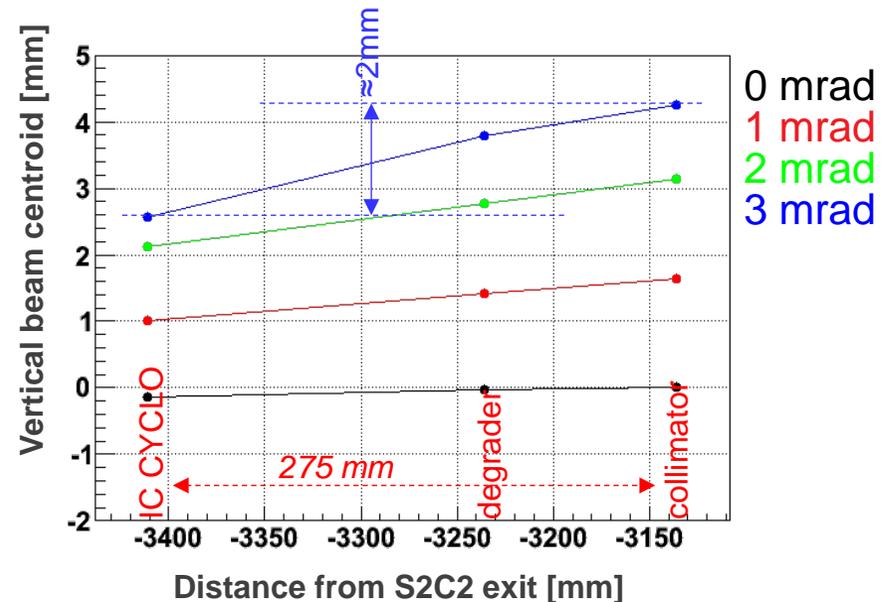
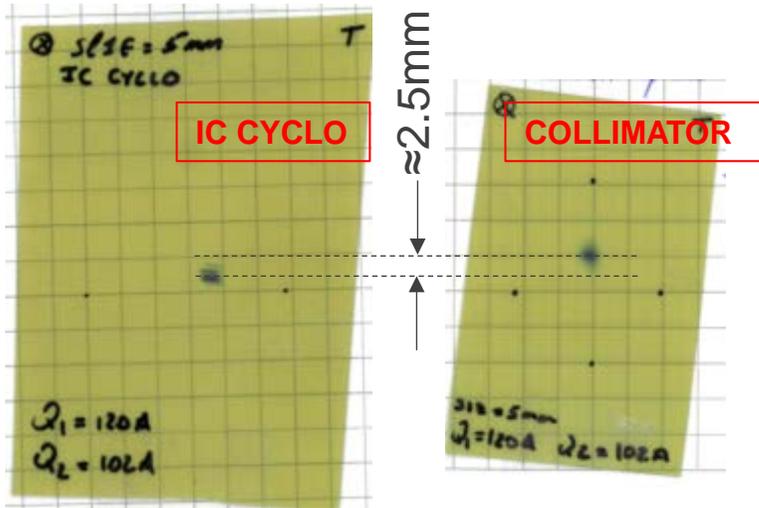
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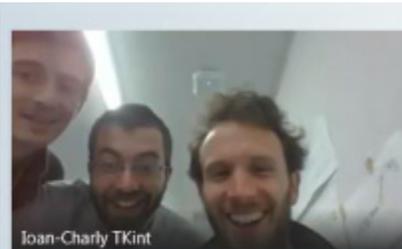
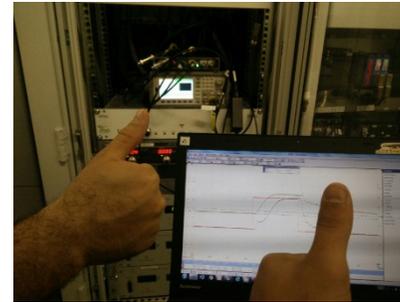
Vertical alignment in extraction beam line

- ✓ Several steps in vertical coil alignment :
 - Observation of vertical magnetic forces on the superconducting coil
 - Observation of beam inside the S2C2 near extraction
 - Observation of the vertical alignment at the exit of the S2C2
 - Observation of steering effects with quadrupoles in the extraction beam line
 - Observation of vertical beam angle

NEWPORT MEASUREMENT



S2C2 and ProteusONE[®] : overview



■ Beam simulations in the gantry

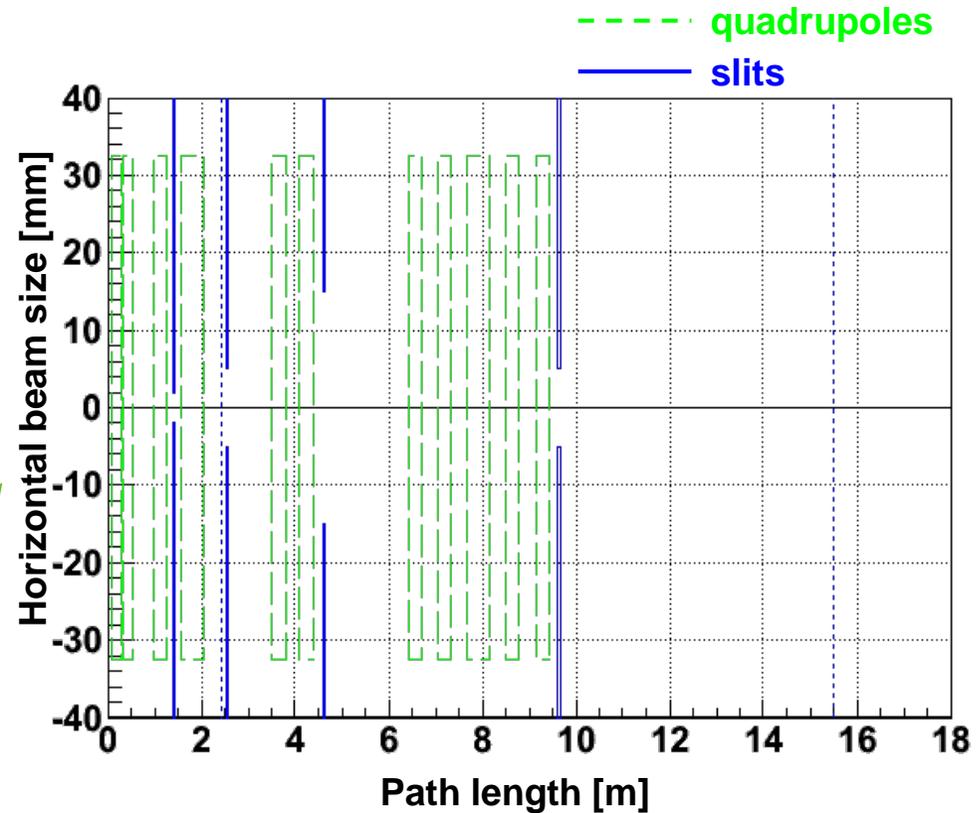
BEAM TRACKING FROM SOURCE TO ISOCENTER

- AOC : injection into the S2C2 up to 3 MeV
- 3 MeV to 225 MeV : “phase_motion” (energy, phase, vertical motion and orbit center motion)
- AOC from 225 MeV to extraction up to exit port
- TRANSPORT / MAD-X / transfer matrix formalism

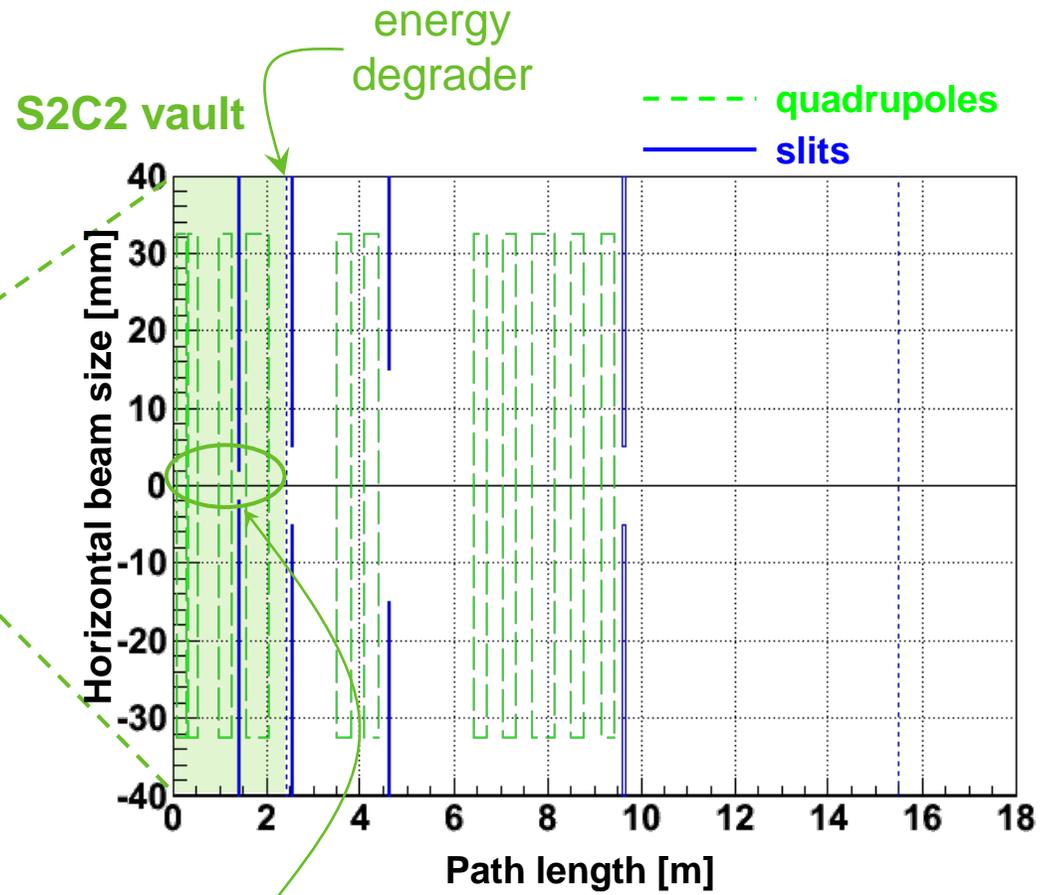
Beam tracking from S2C2 exit to isocenter

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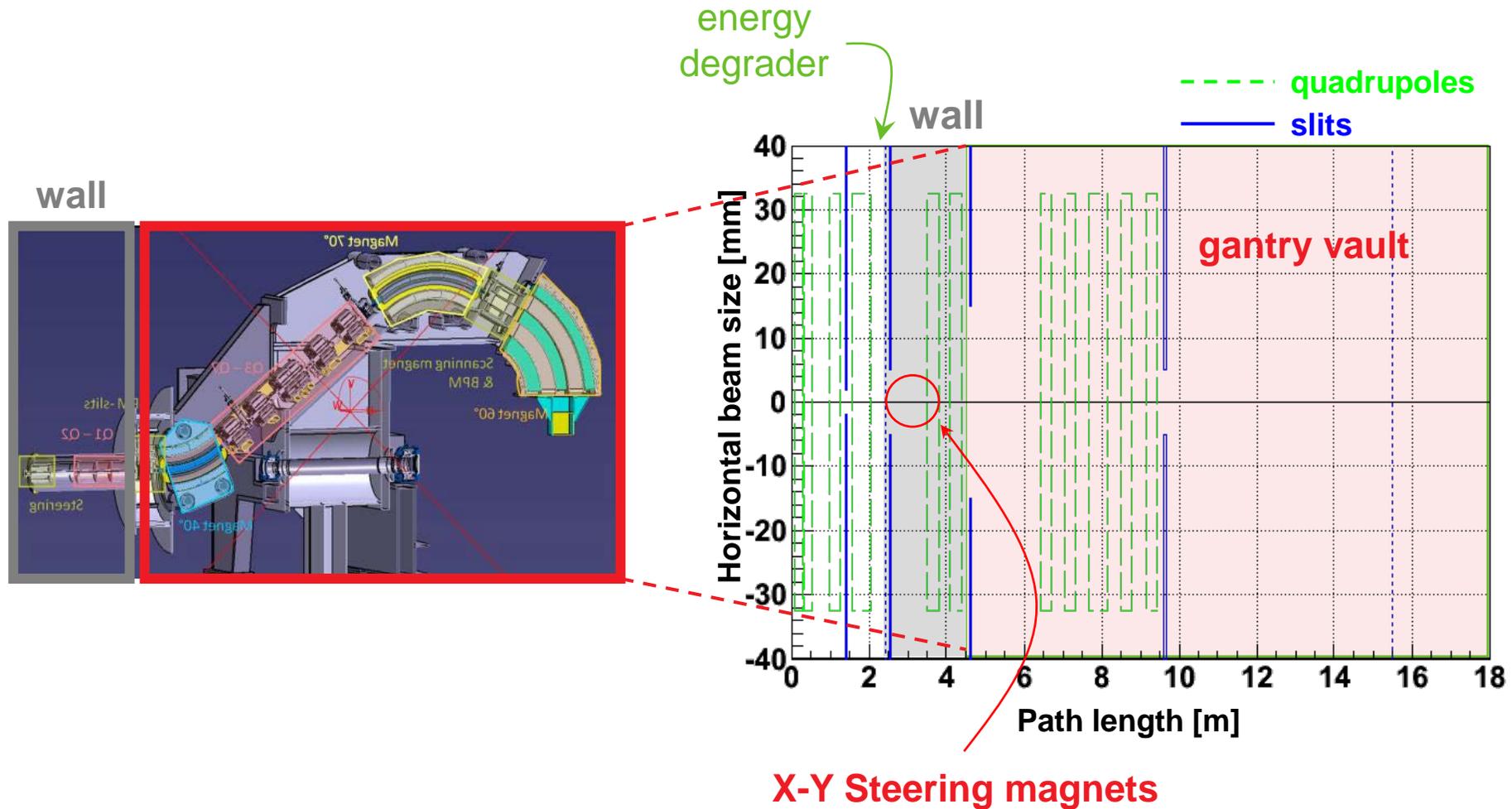


Beam tracking from S2C2 exit to isocenter

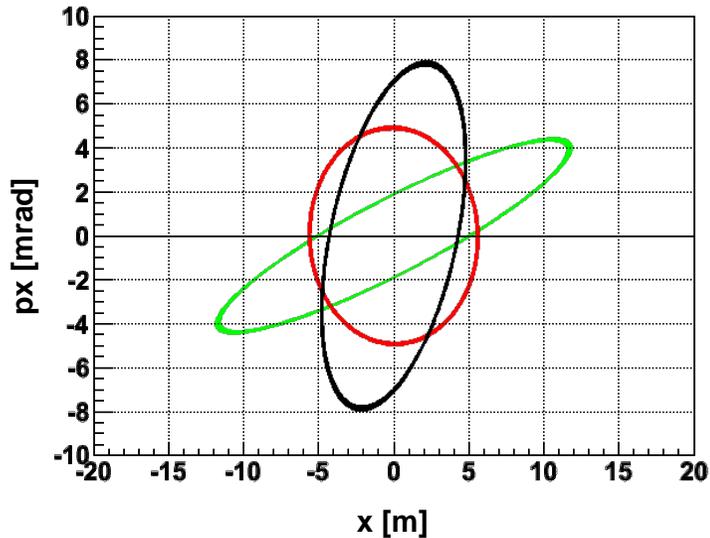


NO steering magnets

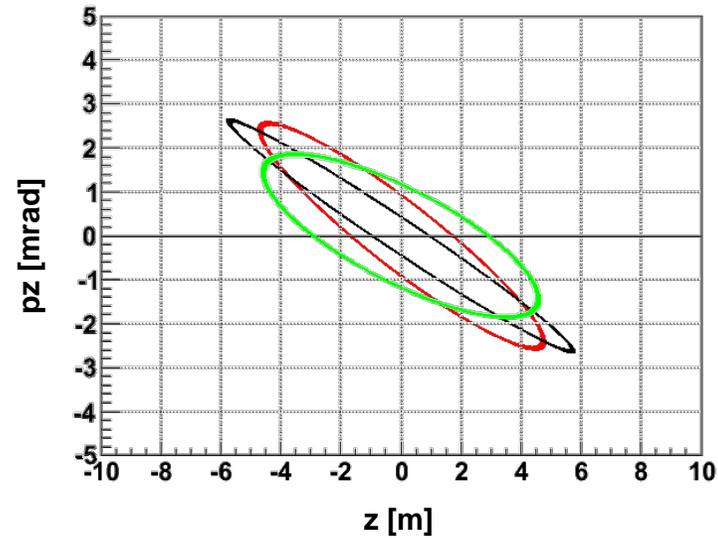
Beam tracking from S2C2 exit to isocenter



Beam tracking from S2C2 exit to isocenter



x	px	R12	eps
[mm]	[mrad]	[-]	[$\pi \cdot \text{mm} \cdot \text{mrad}$]
4.88	7.98	0.445	34.9
5.70	5.00	-0.016	28.5
11.90	4.46	0.902	22.9

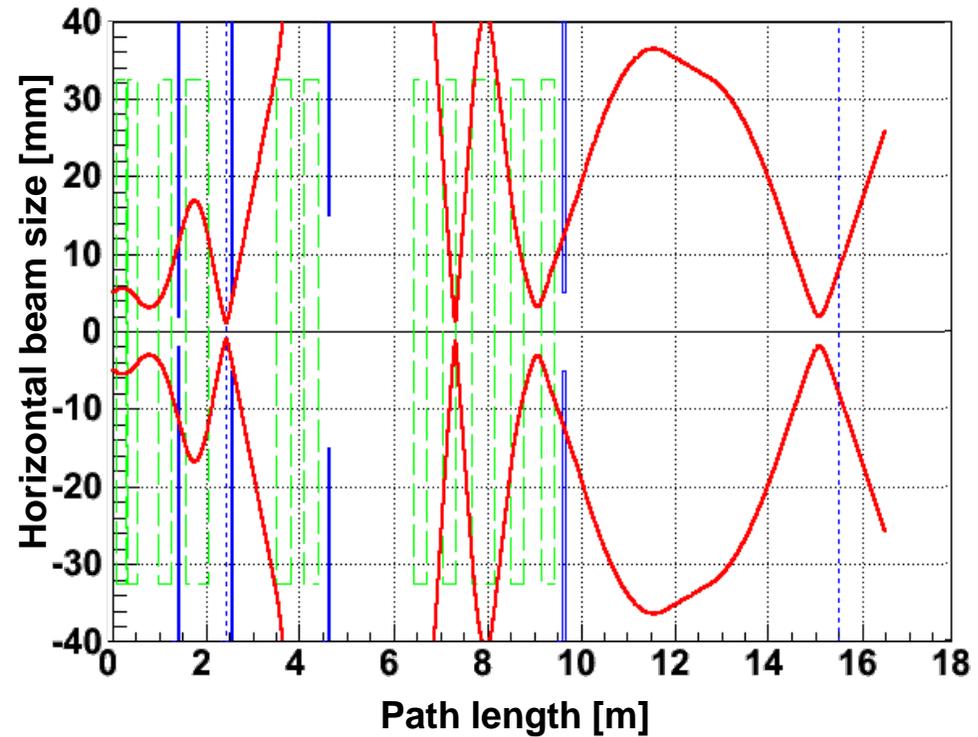


z	pz	R34	eps
[mm]	[mrad]	[-]	[$\pi \cdot \text{mm} \cdot \text{mrad}$]
5.82	2.67	-0.986	2.6
4.80	2.60	-0.933	4.5
4.66	1.89	-0.771	5.6

Fitted emittance to gantry beam sizes in Beaumont
 Measured emittance in Beaumont ("variquad")
 AOC emittance

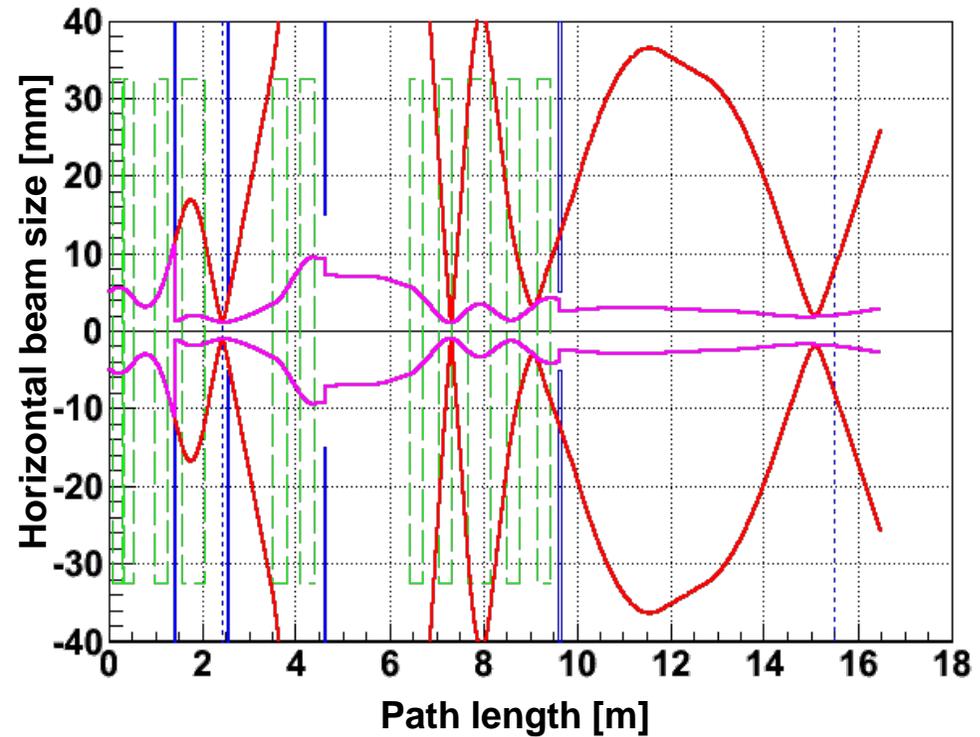
Beam tracking from S2C2 exit to isocenter

- Standard TRANSPORT code (not slits)

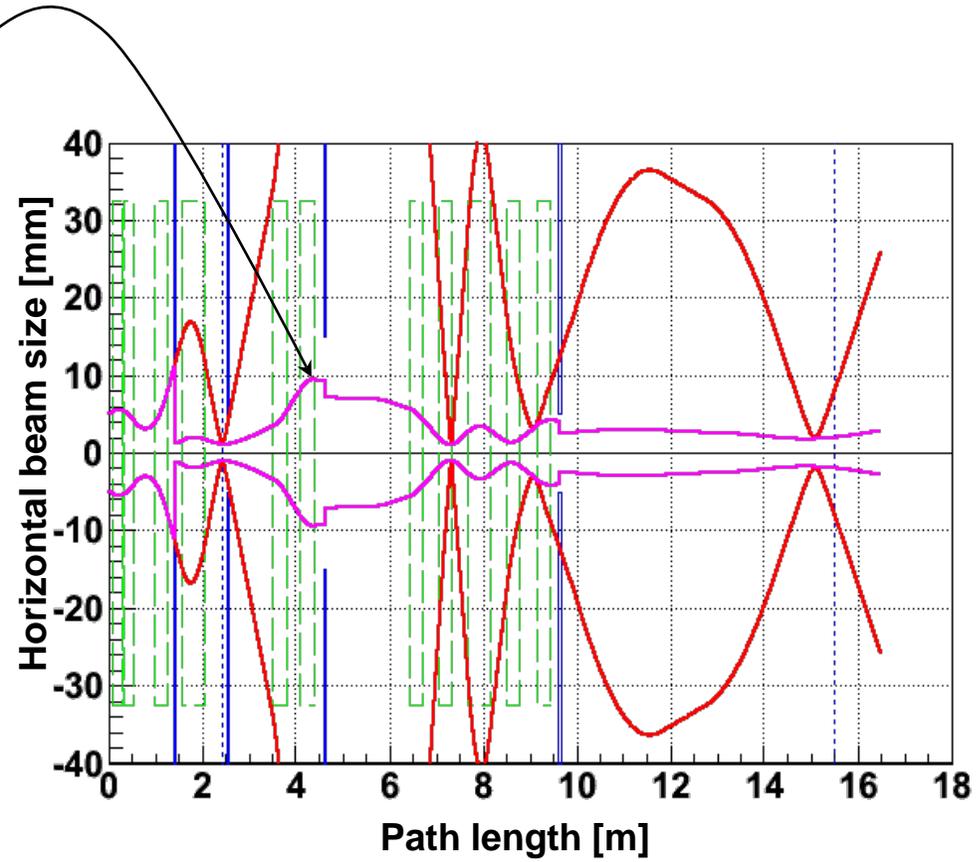
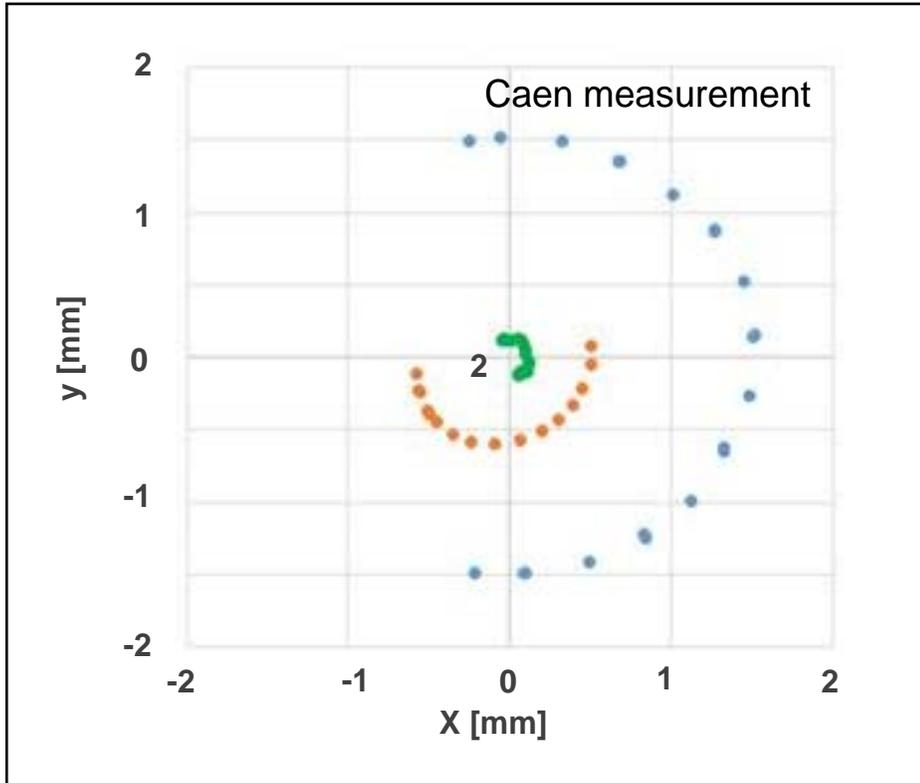


Beam tracking from S2C2 exit to isocenter

- Standard TRANSPORT code (not slits)
- TRANSPORT code with slits

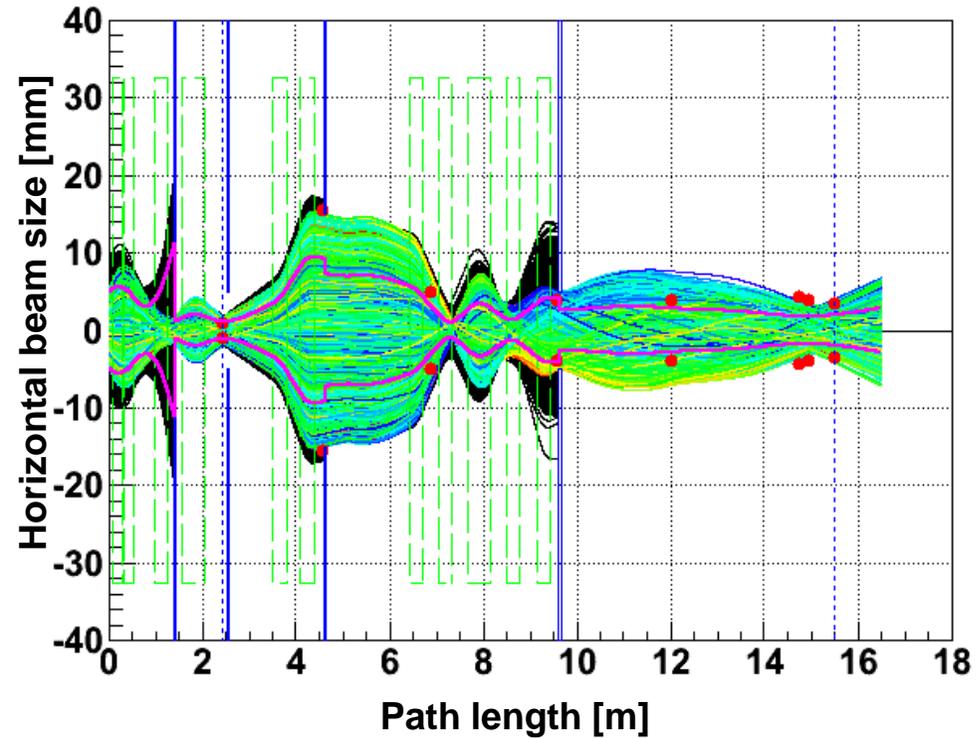


Beam tracking from S2C2 exit to isocenter

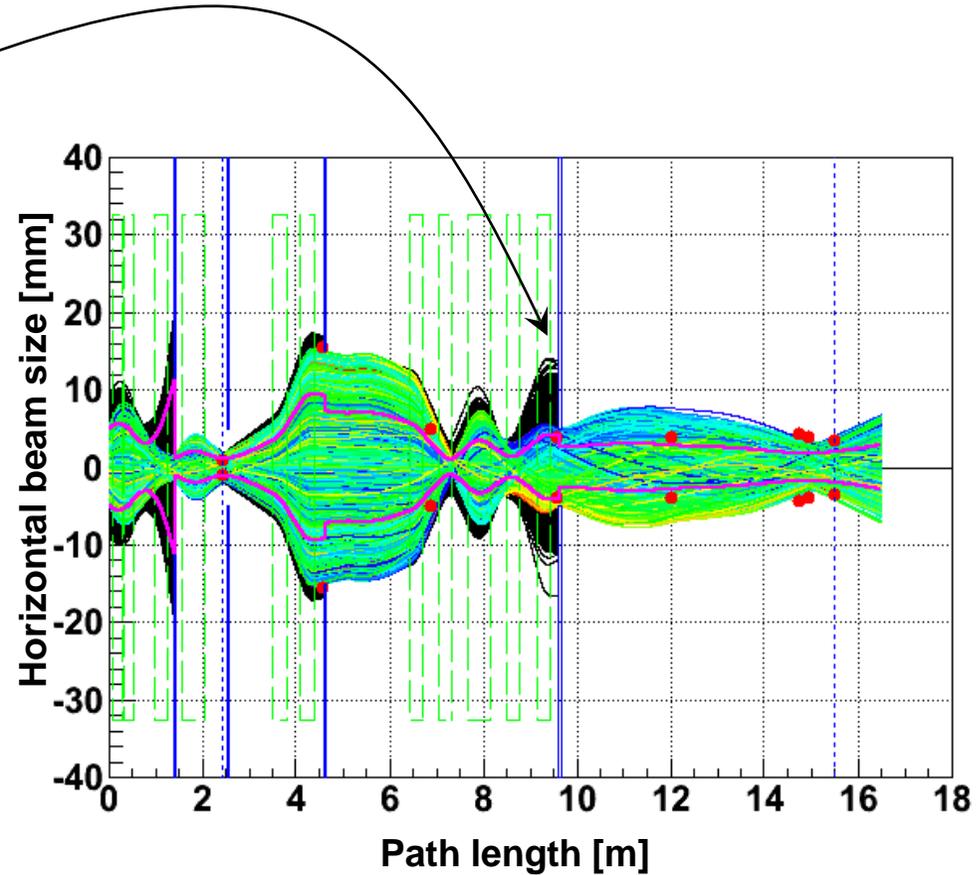
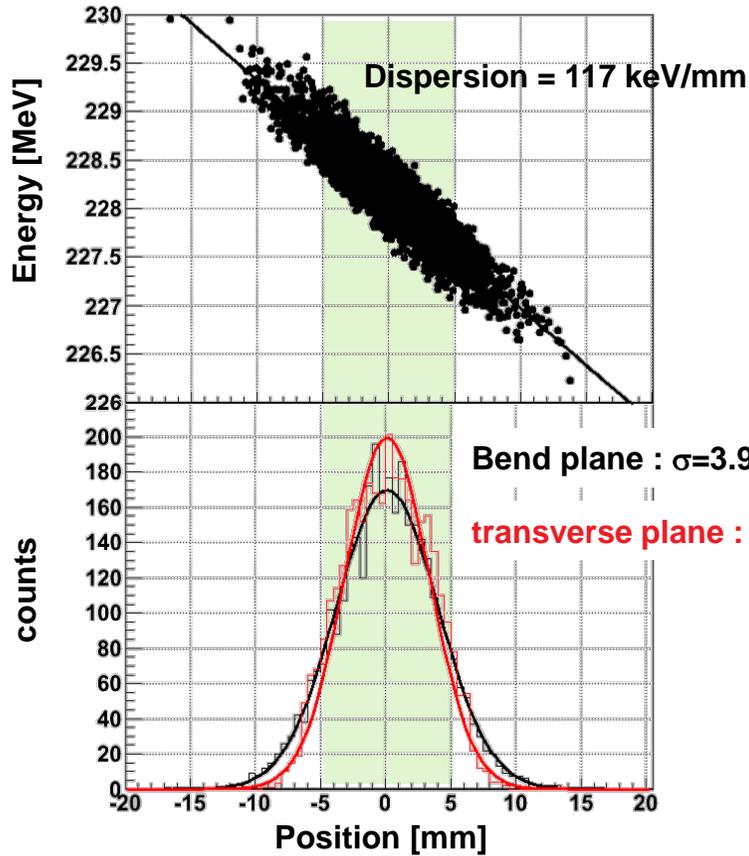


Beam tracking from S2C2 exit to isocenter

- Standard TRANSPORT code (not slits)
- TRANSPORT code with slits
- Proton tracking with matrix formalism

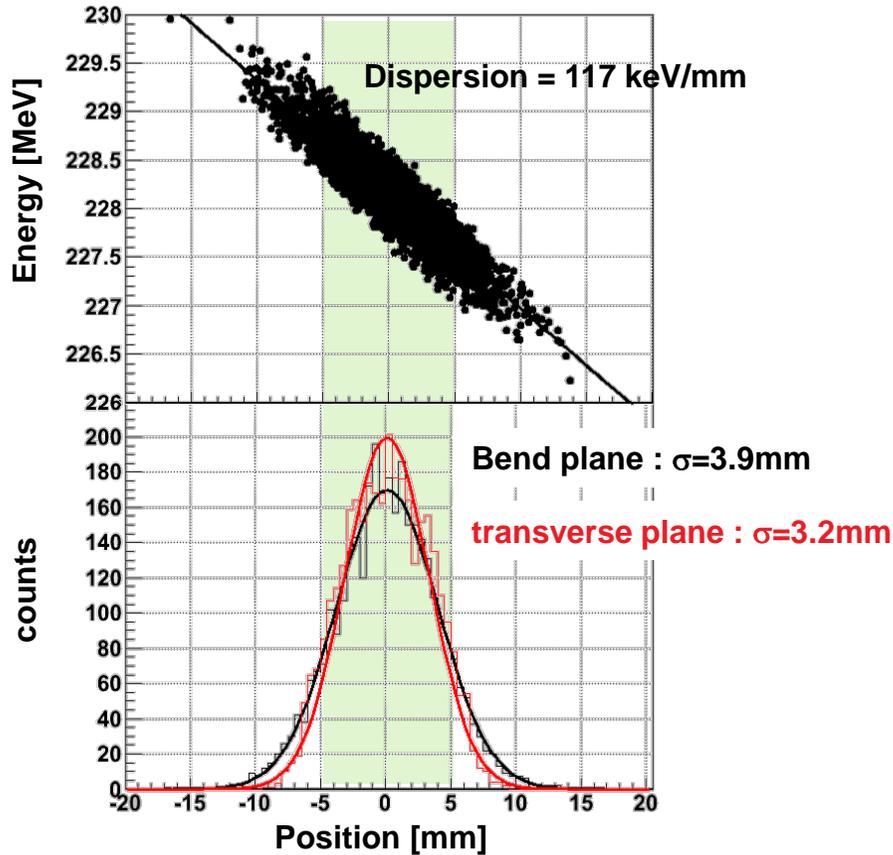


Beam tracking from S2C2 exit to isocenter

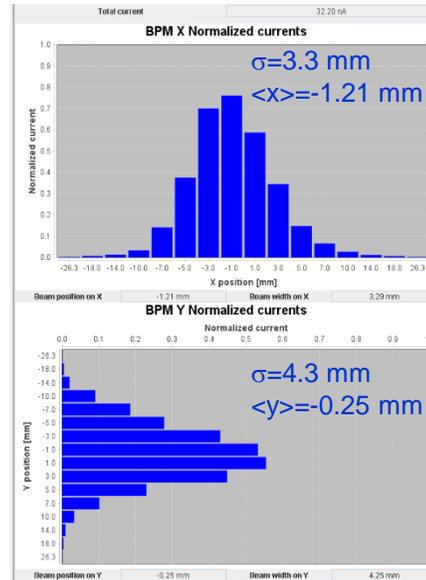


Simulation with initial energy spread from S2C2 = 500 keV

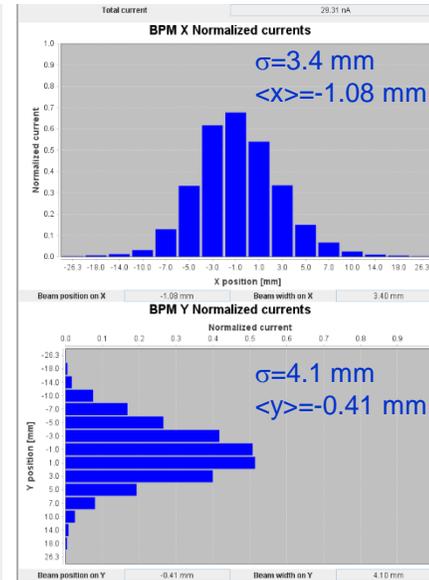
Beam simulations from source to isocenter



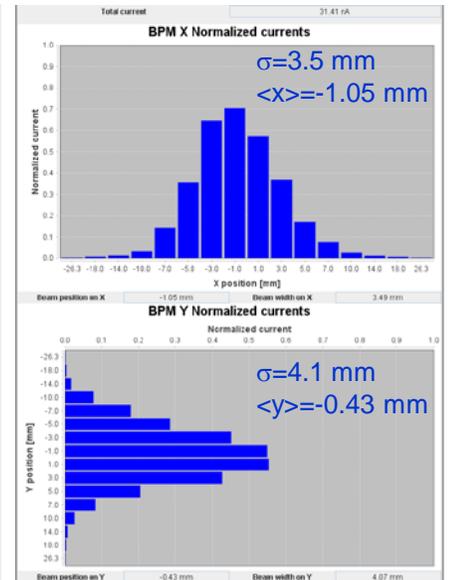
Vdee = 83%



Vdee = 90%



Vdee = 100%



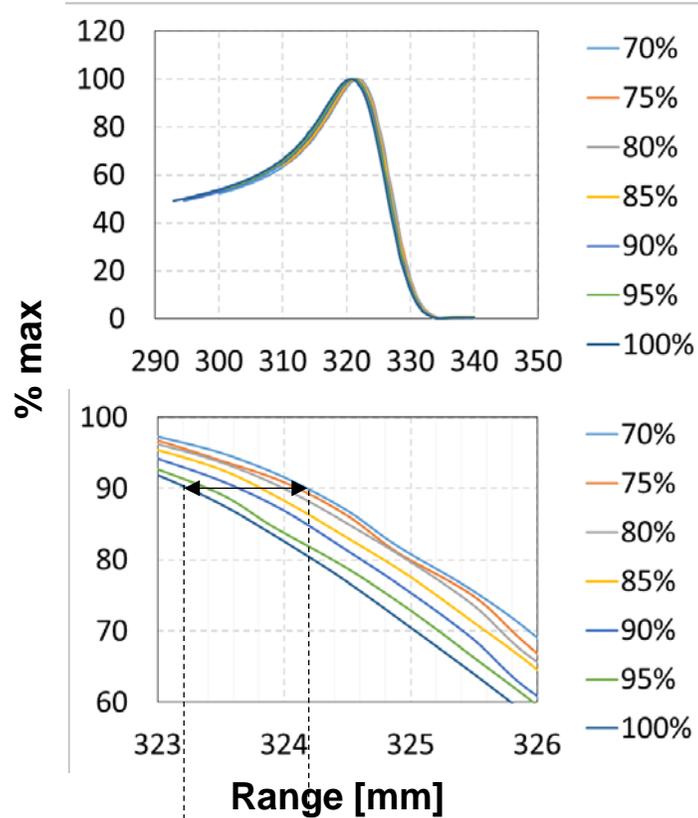
Beaumont measurement

Simulation with initial energy spread from S2C2 = 500 keV

■ Beam energy

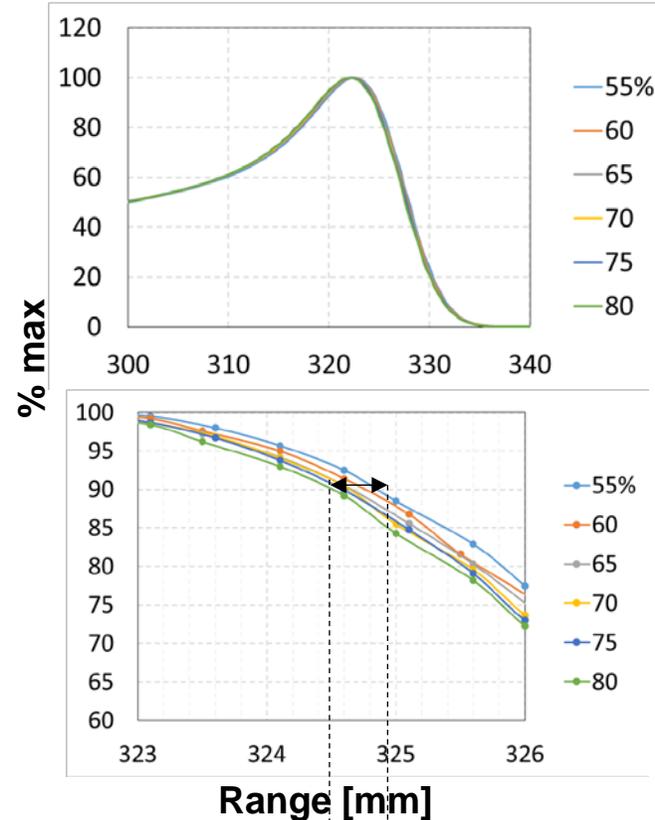
Beam energy from the S2C2

S2C2 Beaumont



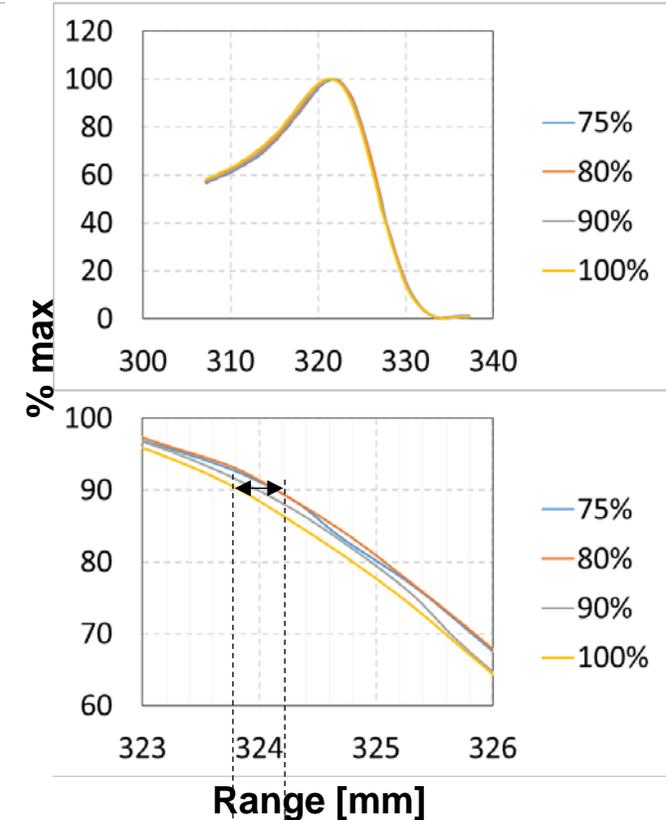
227.4 MeV – 227.8 MeV
 $\Delta E \approx 400$ keV

S2C2 Caen



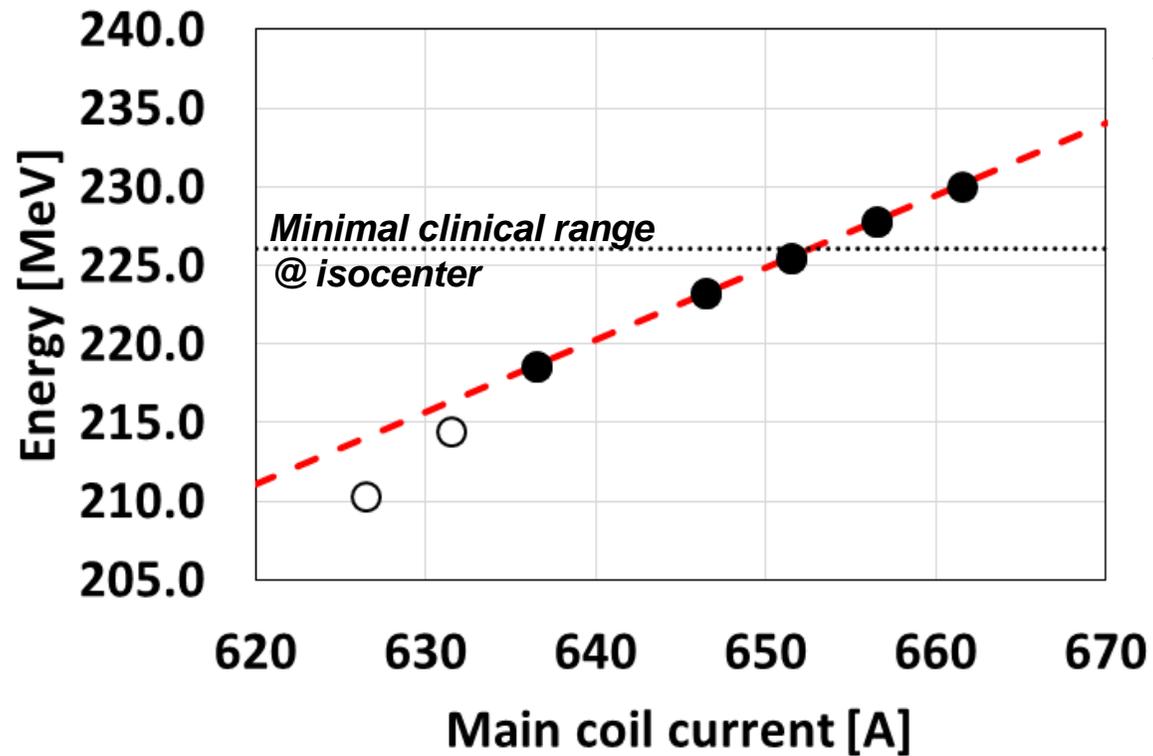
228.0 MeV – 228.1 MeV
 $\Delta E \approx 140$ keV

S2C2 Sapporo



227.7 MeV – 227.8 MeV
 $\Delta E \approx 140$ keV

Beam energy from the S2C2



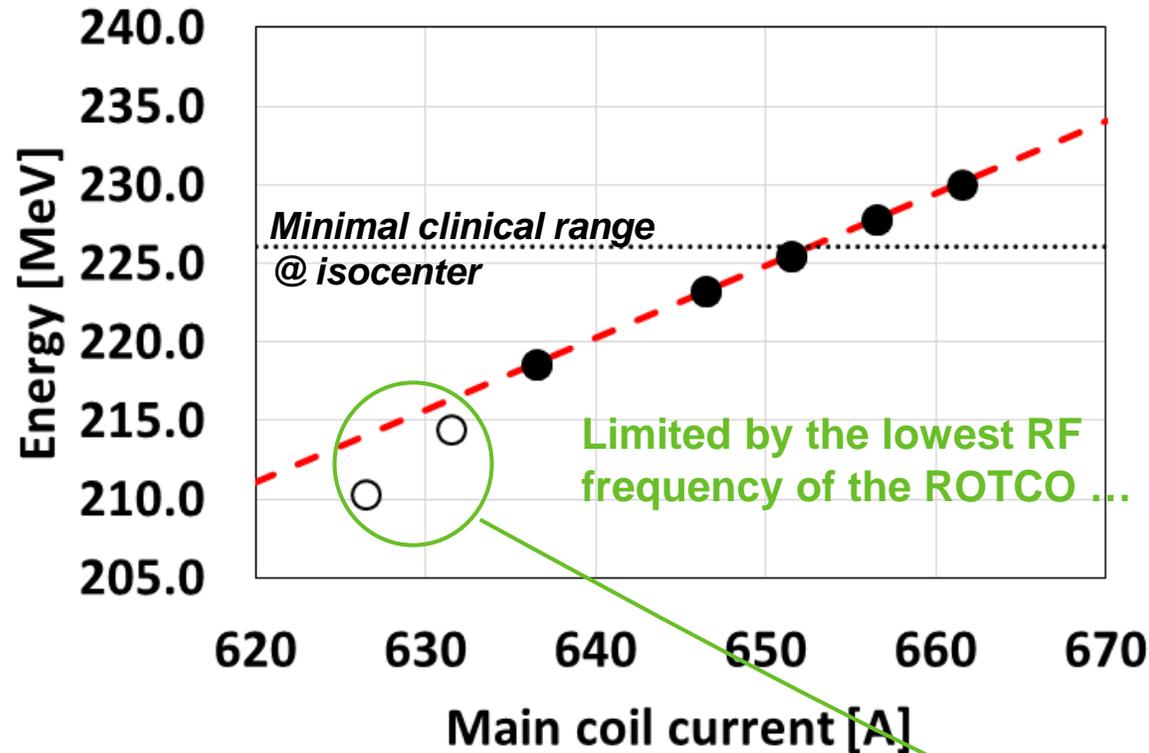
✓ Linearity of extracted beam energy versus coil current

= 460 keV/A

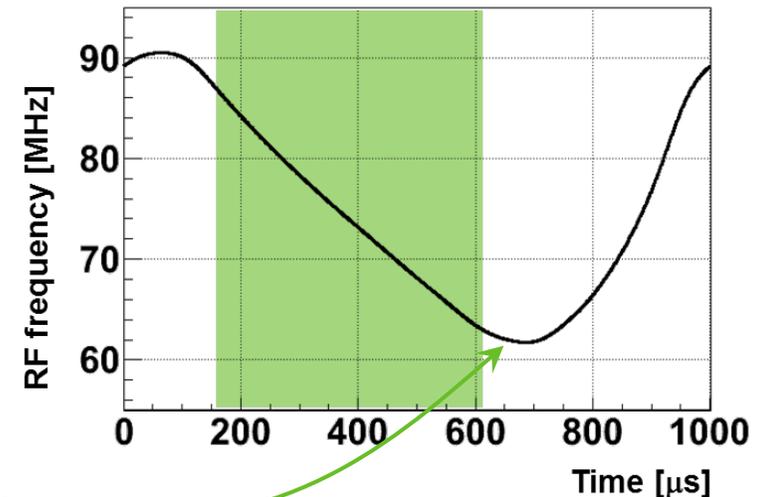
Beam energy from the S2C2

- ✓ Linearity of extracted beam energy versus coil current

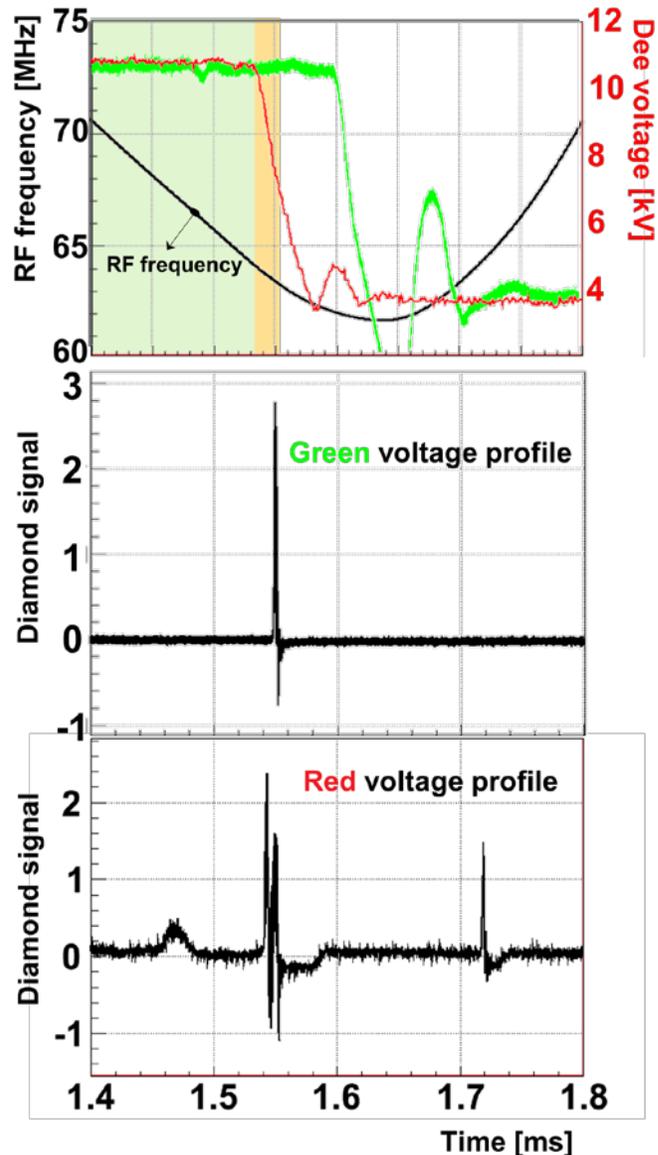
= 460 keV/A



- ✓ Much lower energies extracted :
 - Protons are not accelerated anymore near extraction radius
 - Protons can be extracted at lower energies due to “emittance blow-up”



What happened to “lost” protons again ...



What if ... We intentionally loose beam very close to extraction ?

We drop the dee voltage a few μs before extraction ...

Observation on 2nd RF period:

(1) protons coming out on the rising frequency flank

⇒ Explained from energy resonances (see previous)

$$f_{RF} = f_p$$

(2) protons coming out before the extraction frequency

⇒ Explained from emittance blow-up and orbit center instability when off-centering becomes too large.

$$f_{RF} = f_p \pm (v_r - 1) f_p$$

■ Conclusions

- ✓ Modeling the ProteusONE system from source to isocenter is very useful to link machine performance to measurements at different positions along the beam path.
- ✓ Steap learning curve from 5 on-site installations
- ✓ Coil and beam alignment are very well controlled and reproducible
- ✓ Energy spread and range stability in isocenter are linked with accurate source positioning
- ✓ Gantry optics is very valuable in deducing beam properties from the S2C2
- ✓ Future site installations need :
 - Efficient procedures
 - Well trained installation teams
 - Accurate and dedicated measuring methods
 - A careful follow-up to spot and analyze potential problems on the cyclotron side



Thank you

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