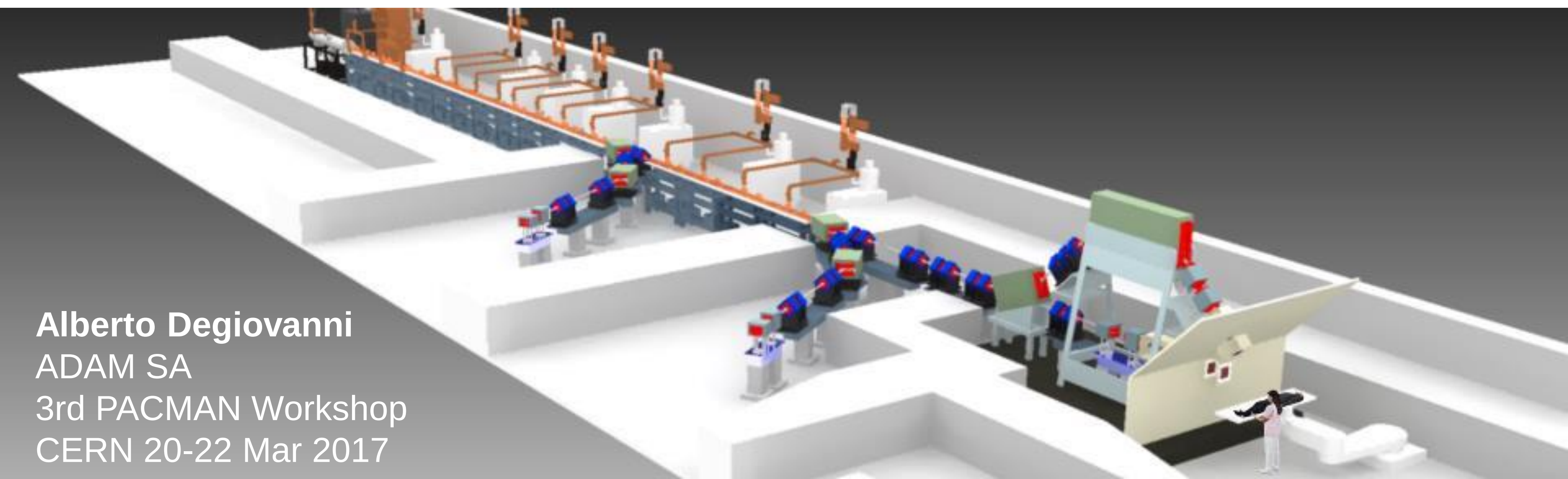
21st Mar 2017

Introduction to accelerators in the medical domain:
prerequisites and strategies for the alignment of magnets

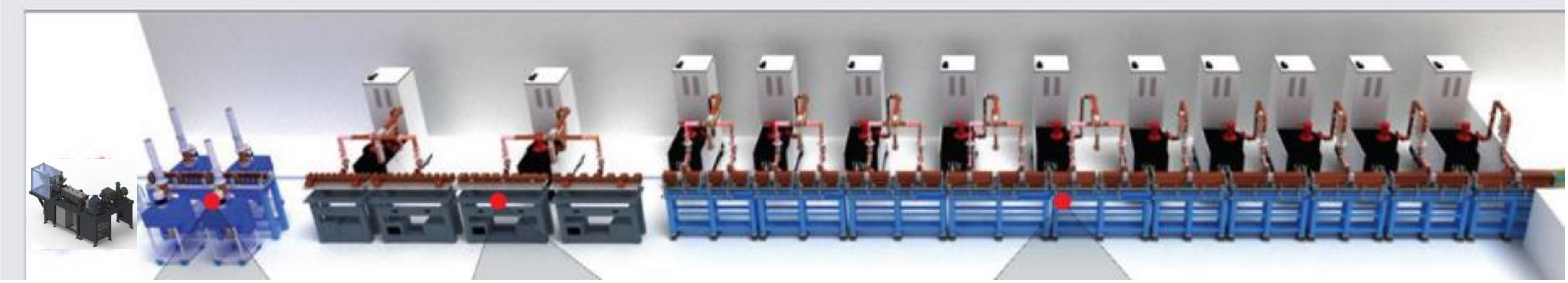


Alberto Degiovanni
ADAM SA

3rd PACMAN Workshop
CERN 20-22 Mar 2017

Outline of the talk

- **Introduction**
  - **Proton therapy**
  - **Accelerators for proton therapy**
- **Overview of the LIGHT system**
- **PMQ Characterization and alignment**
- **Conclusion**

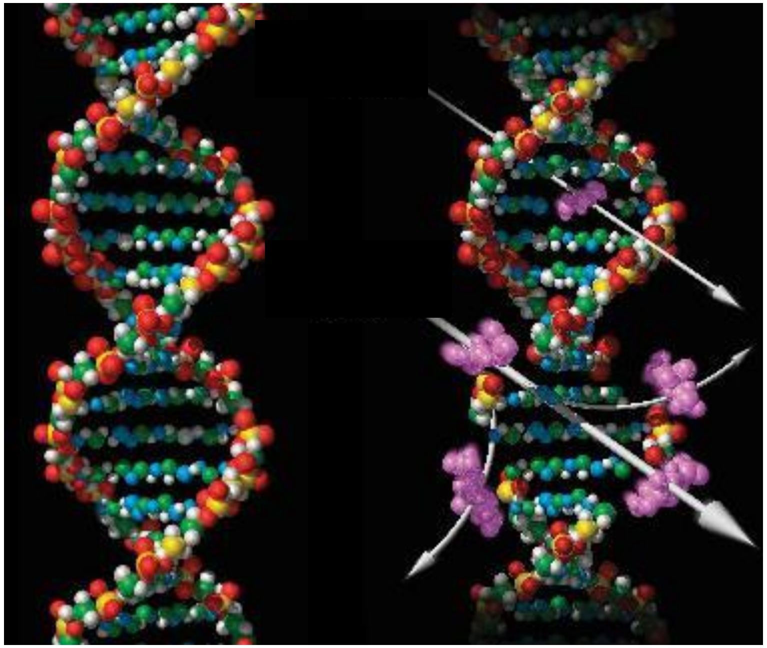


1. Introduction

Radiation therapy

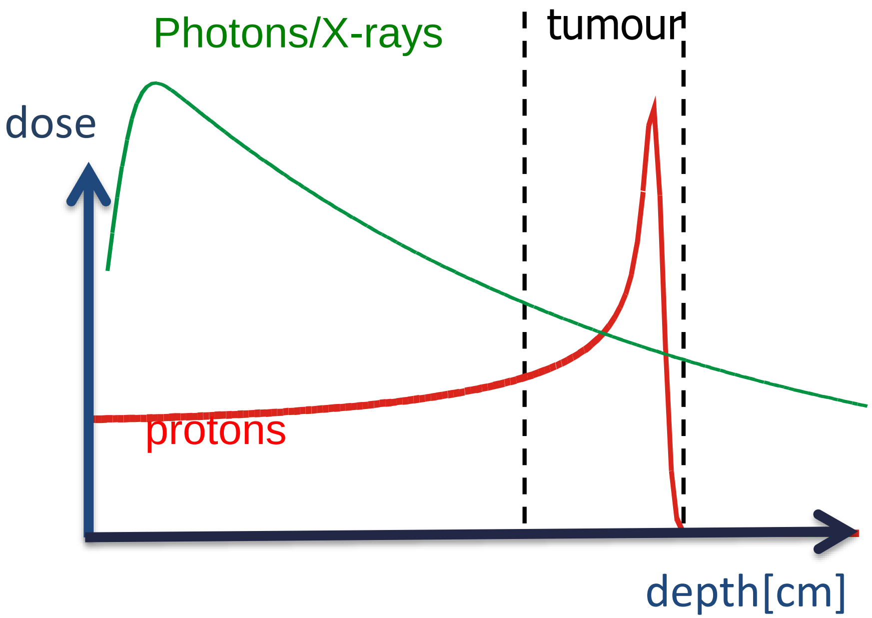
Radiotherapy methods

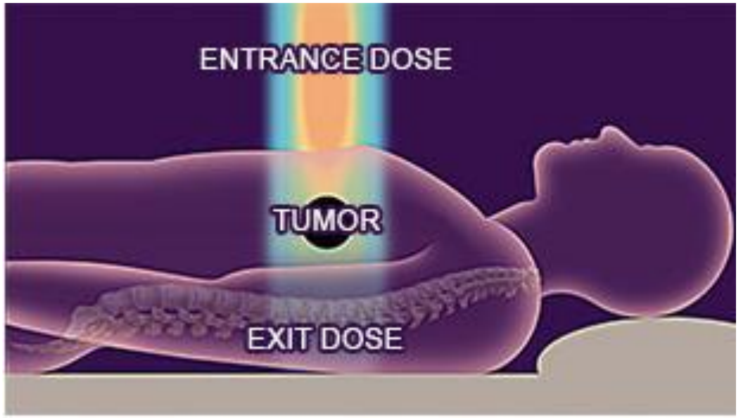
- X-rays/gamma rays/electron beams — Most current treatments
- Particle beams: E.g. protons — New treatments



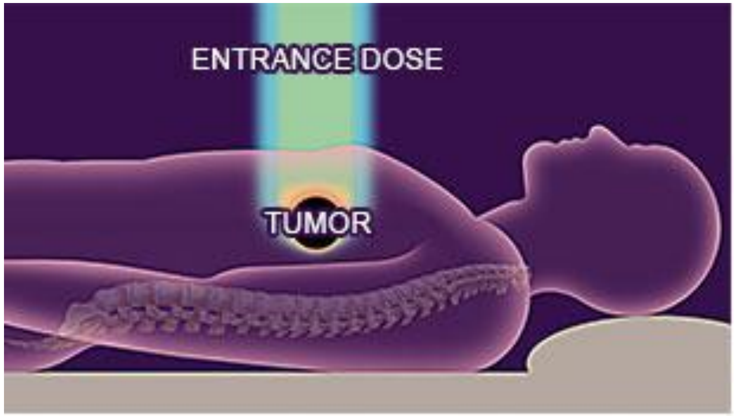
- Radiation can break the DNA of the cells they collide with
- Healthy cells get damaged too…
- **Advantage of protons (see next)**
  - Stop and loose dose in **well-localized** position
  - They are charged (can be steered with magnetic field)

Why use protons for radiotherapy?





CONVENTIONAL RADIATION THERAPY:
Deposits most energy before target



TARGETED PROTON THERAPY:
Deposits most energy on target

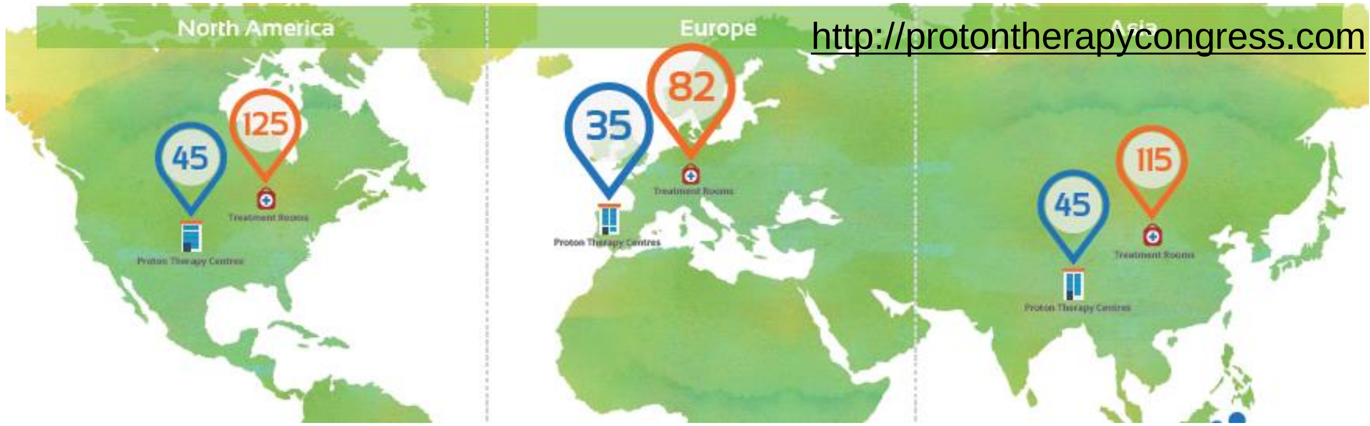
- Dose to close-by organs-at-risk is much lower with protons than with photons!

→ Better quality of life after treatment (less side-effects), and less chance for developing secondary cancer

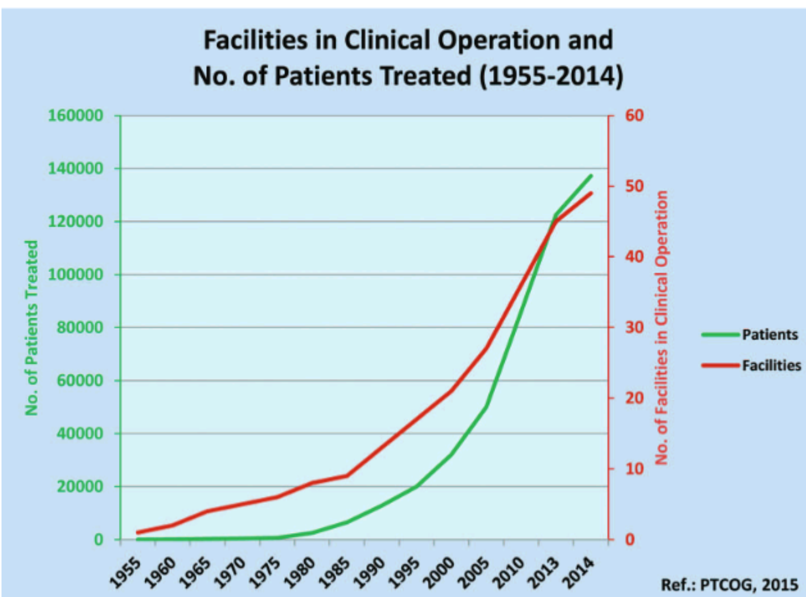
Hadrontherapy in the world

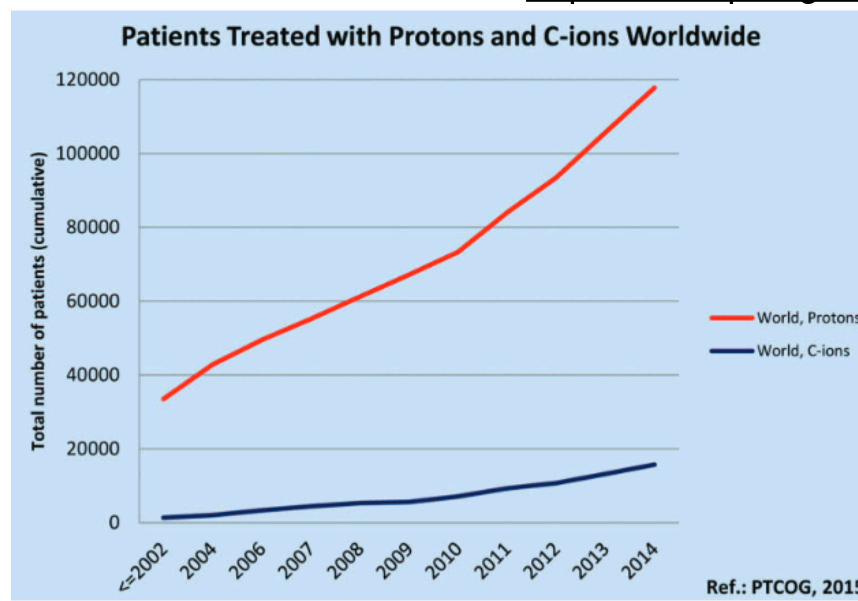
Treatment rooms in operation + planned for 2020

http://protontherapycongress.com



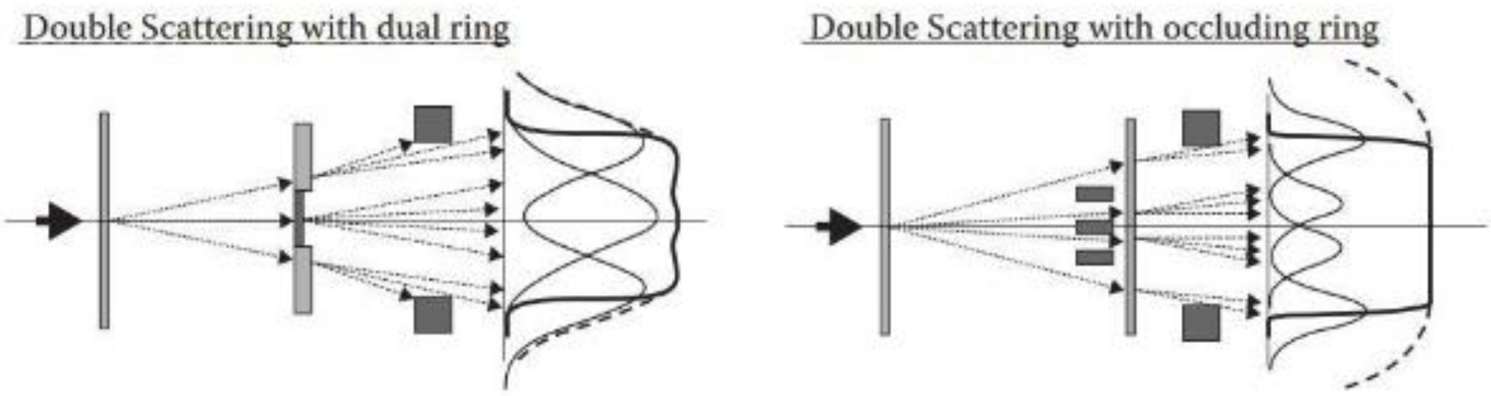
https://www.ptcog.ch





Dose delivery techniques

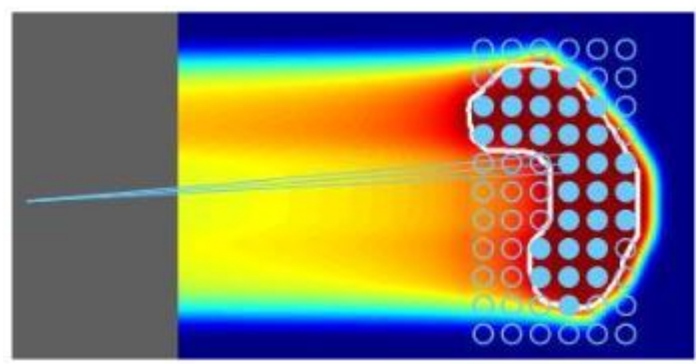
- Passive beam spreading or scattering technique



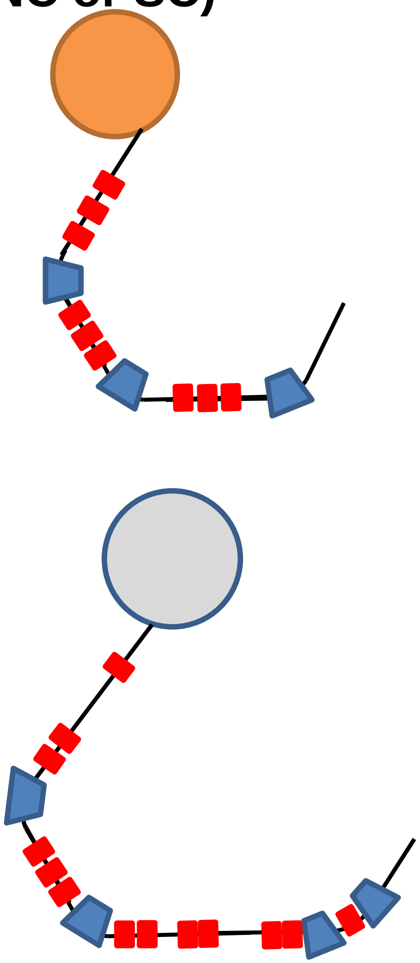
- Pencil beam scanning or 'spot' scanning

70-230 MeV

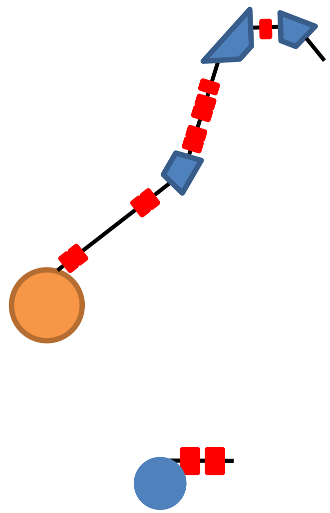
~1 nA



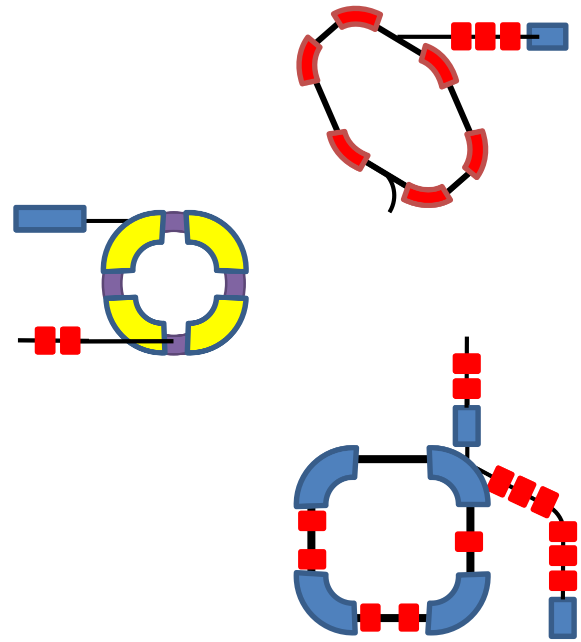
Isochronous cyclotrons (NC or SC)



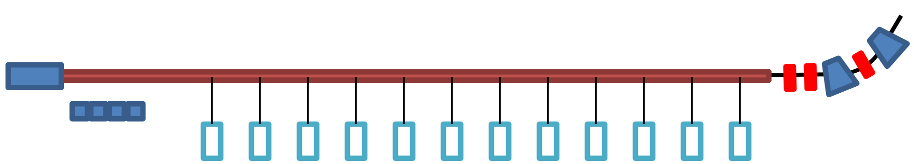
Synchro-cyclotrons

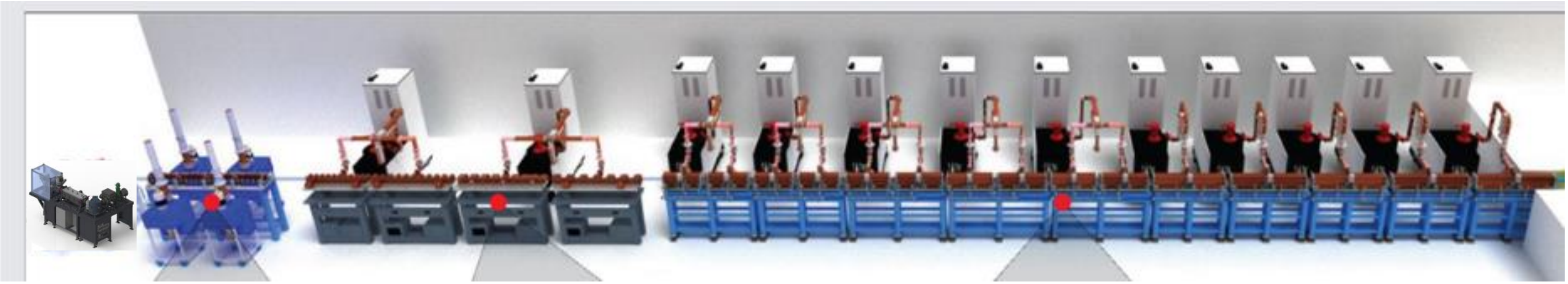


Synchrotrons (NC)



Linac (NC)





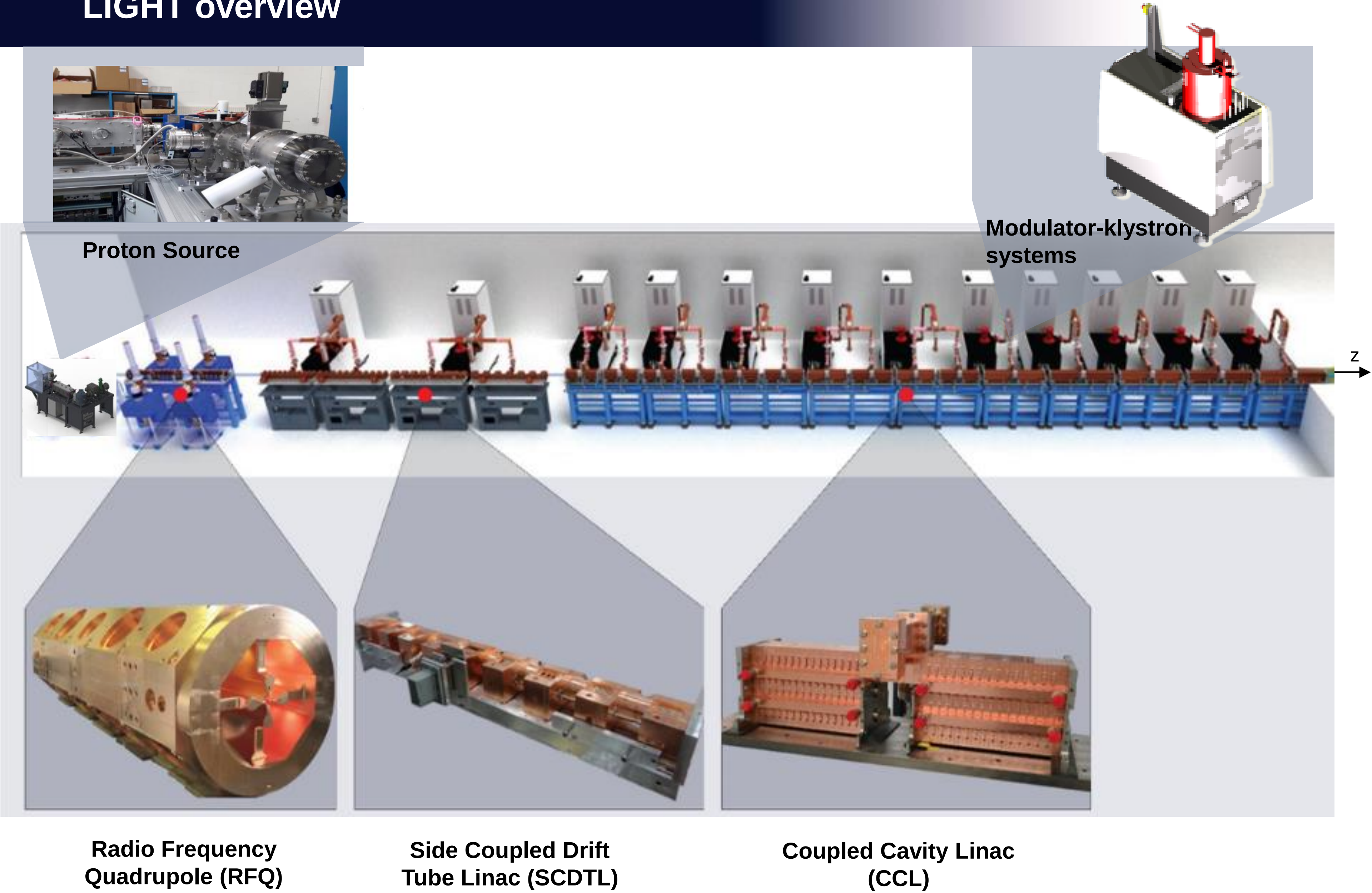
2. LIGHT
= Linac for Image Guided Hadron Therapy

LIGHT features for proton therapy

- Active energy modulation → no absorber and degrader
- Pulsed beam at 200 Hz → intensity and energy modulation in 5 ms
- Small beam emittance → small magnets aperture
- Small amount of losses → reduced shielding

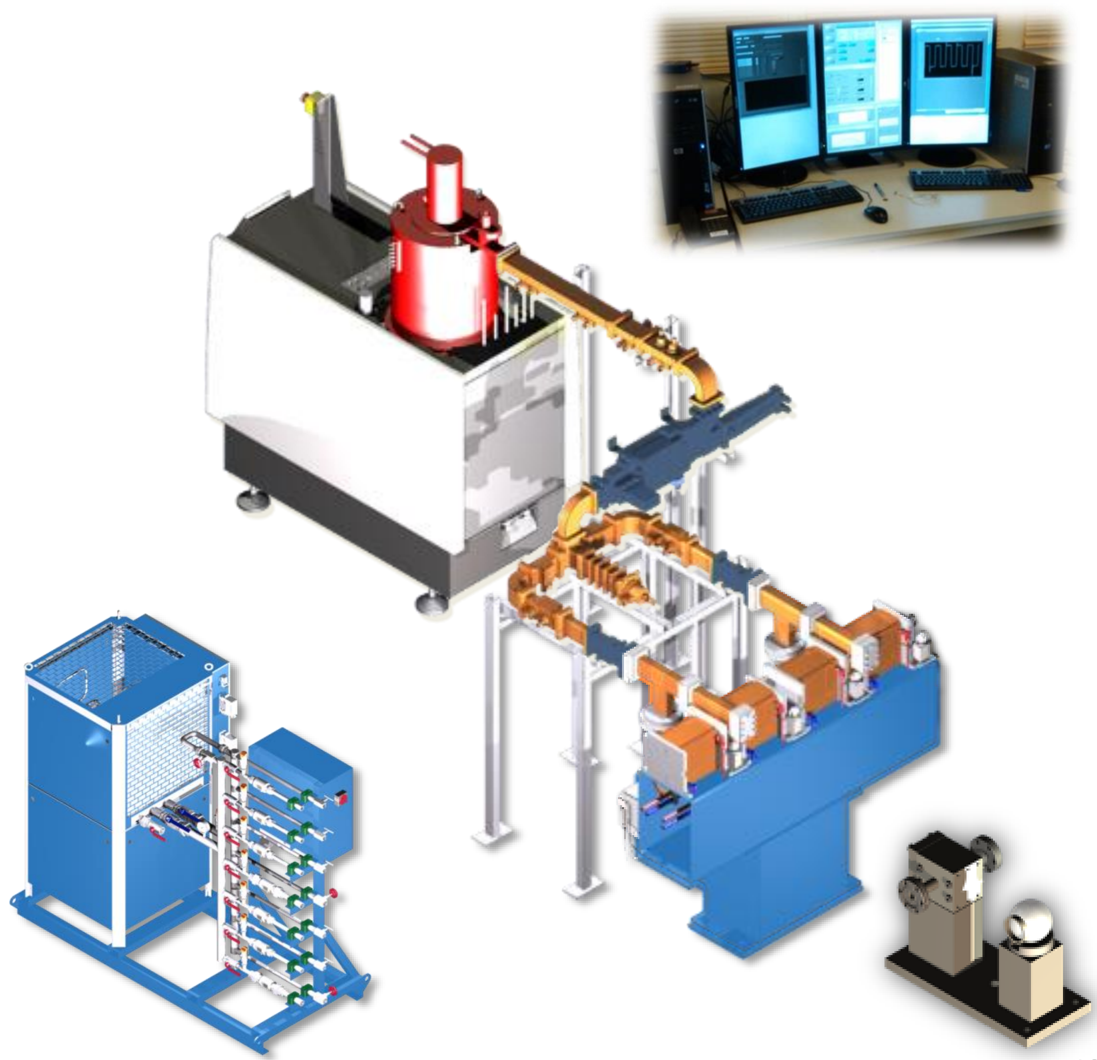
→ beam suited for 3D spot scanning

LIGHT overview



Unit Systems

1) Accelerating System
2) Control System
3) Cooling System
4) Focusing System
5) RF Network System
6) RF Power System
7) Support System
8) Vacuum System



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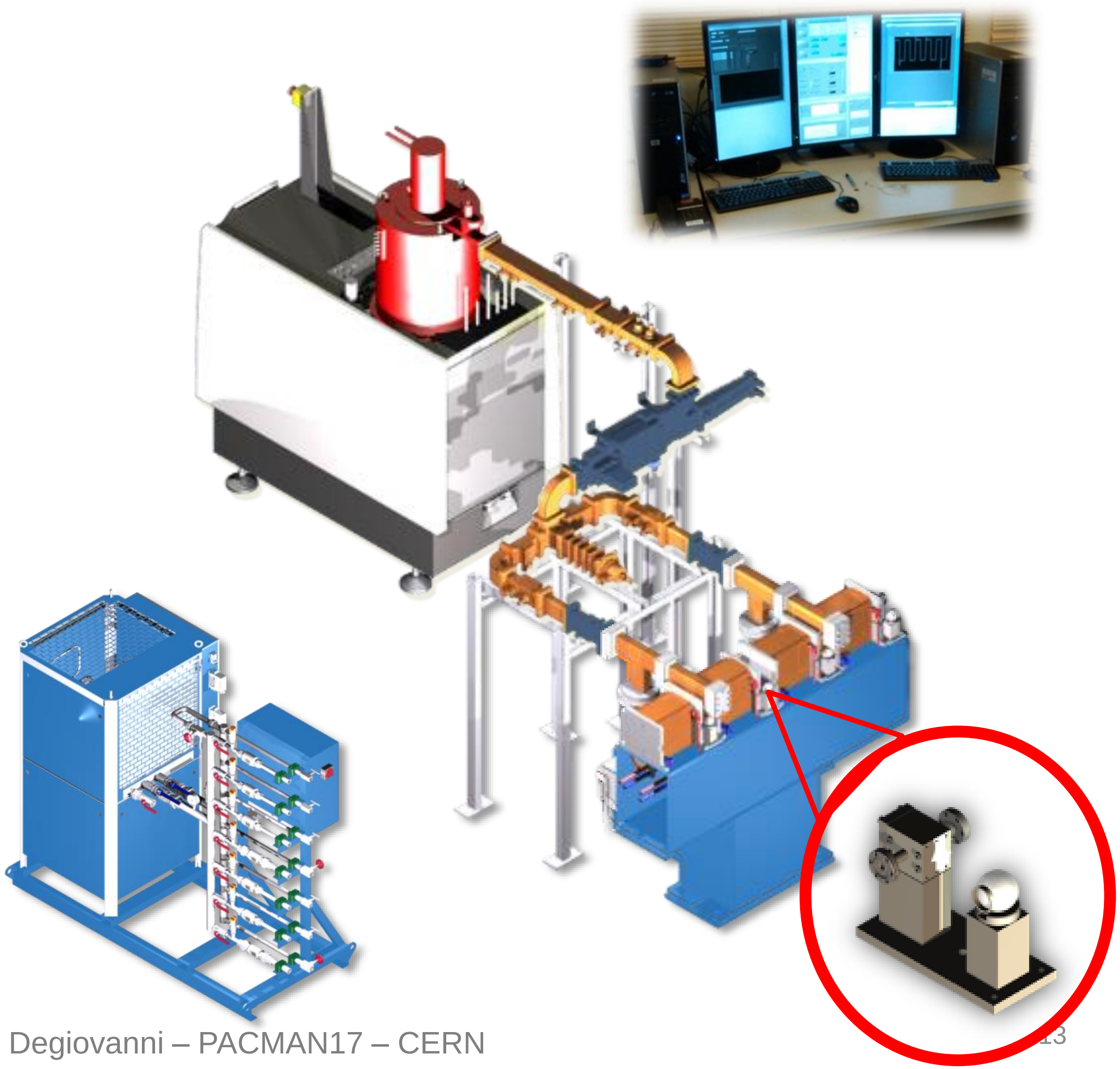
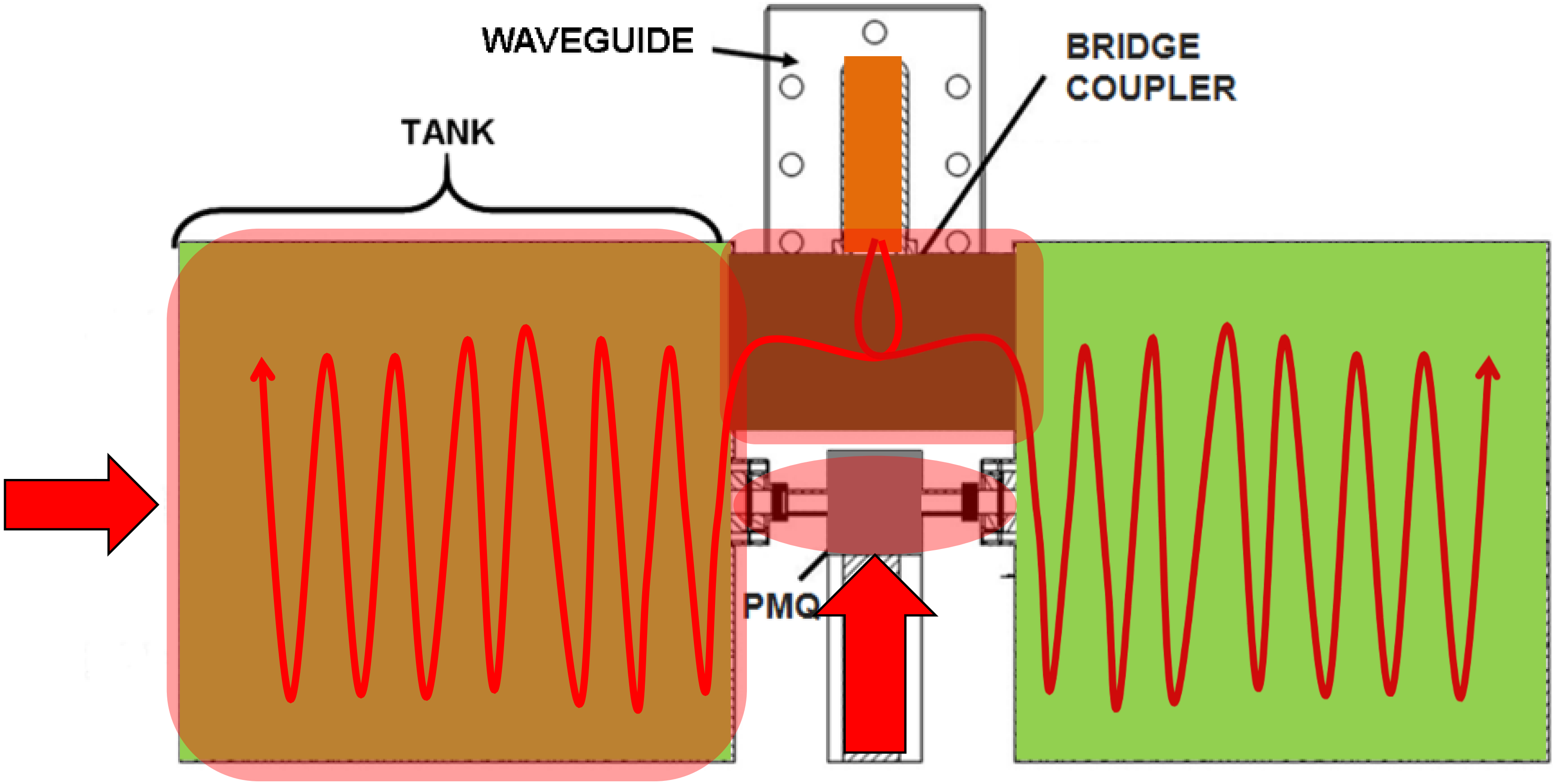
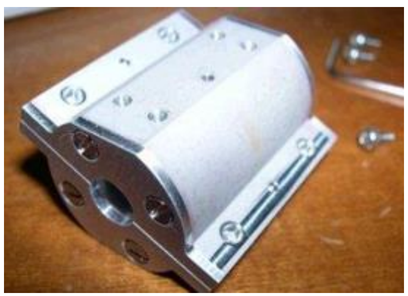


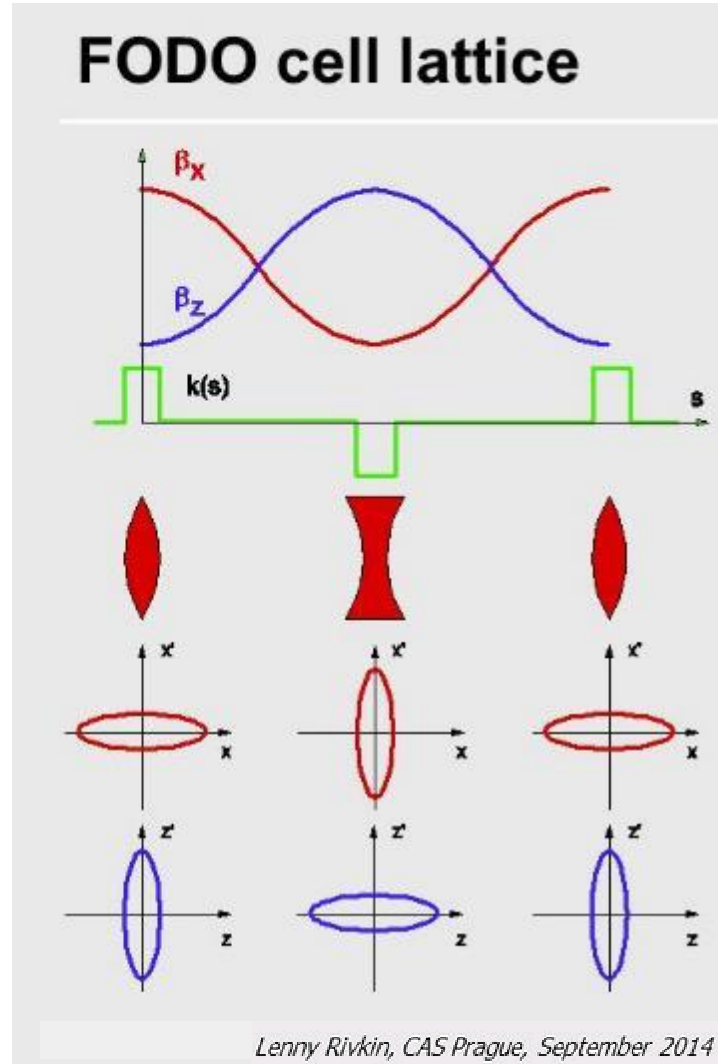

WAVEGUIDE
BRIDGE
COUPLER
TANK
PMQ

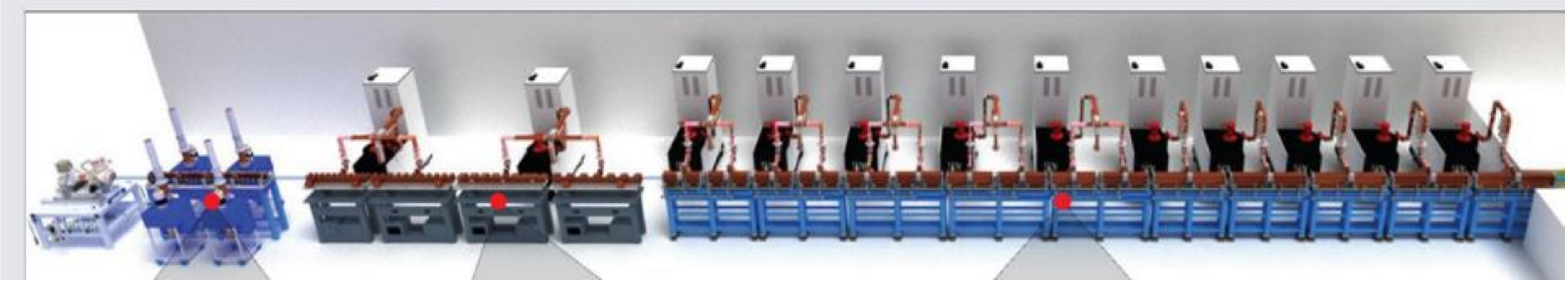
- A FODO lattice is used to keep the beam focused along the linac
- Small aperture Permanent Magnet Quadrupole (PMQ):



BJA Magnetics

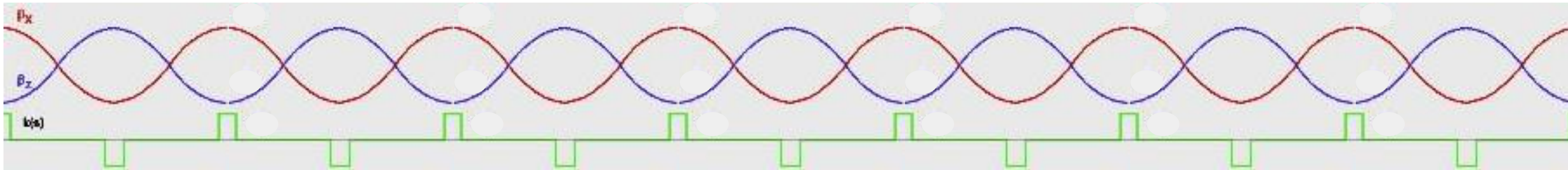
+ no power consumption !
+ strong gradient possible
+ reduced size and cost !
- Precision alignement needed !

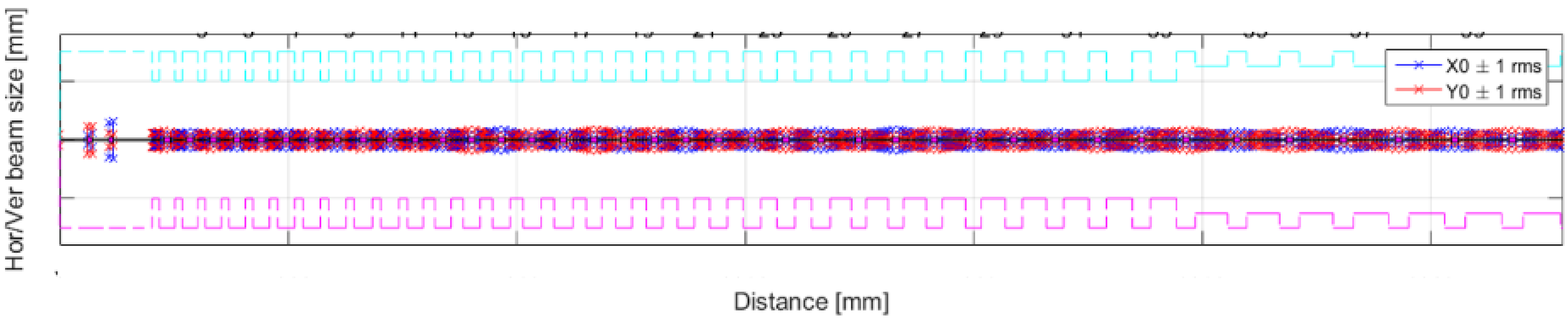


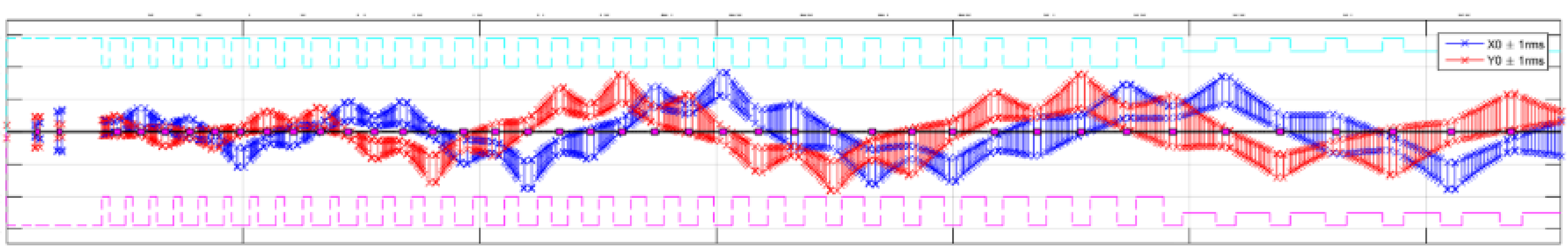


3. PMQ Characterization and alignment

Transverse beam optics







Analytical model for centroid displacement

- Quasi-periodic FODO lattice consisting of N thin quadrupoles
- Half cell length given by relative distance between successive PMQs

- Focal length of the ith PMQ in thin lens approximation: $F_i = p_i / qB_i' L_{PMQ,i}$

- Each PMQ is misaligned in the transverse plane by ξ_i $(1 \le i \le N)$.

- The centroid offset x_i at the centre of PMQ i (at first order) can be calculated as:

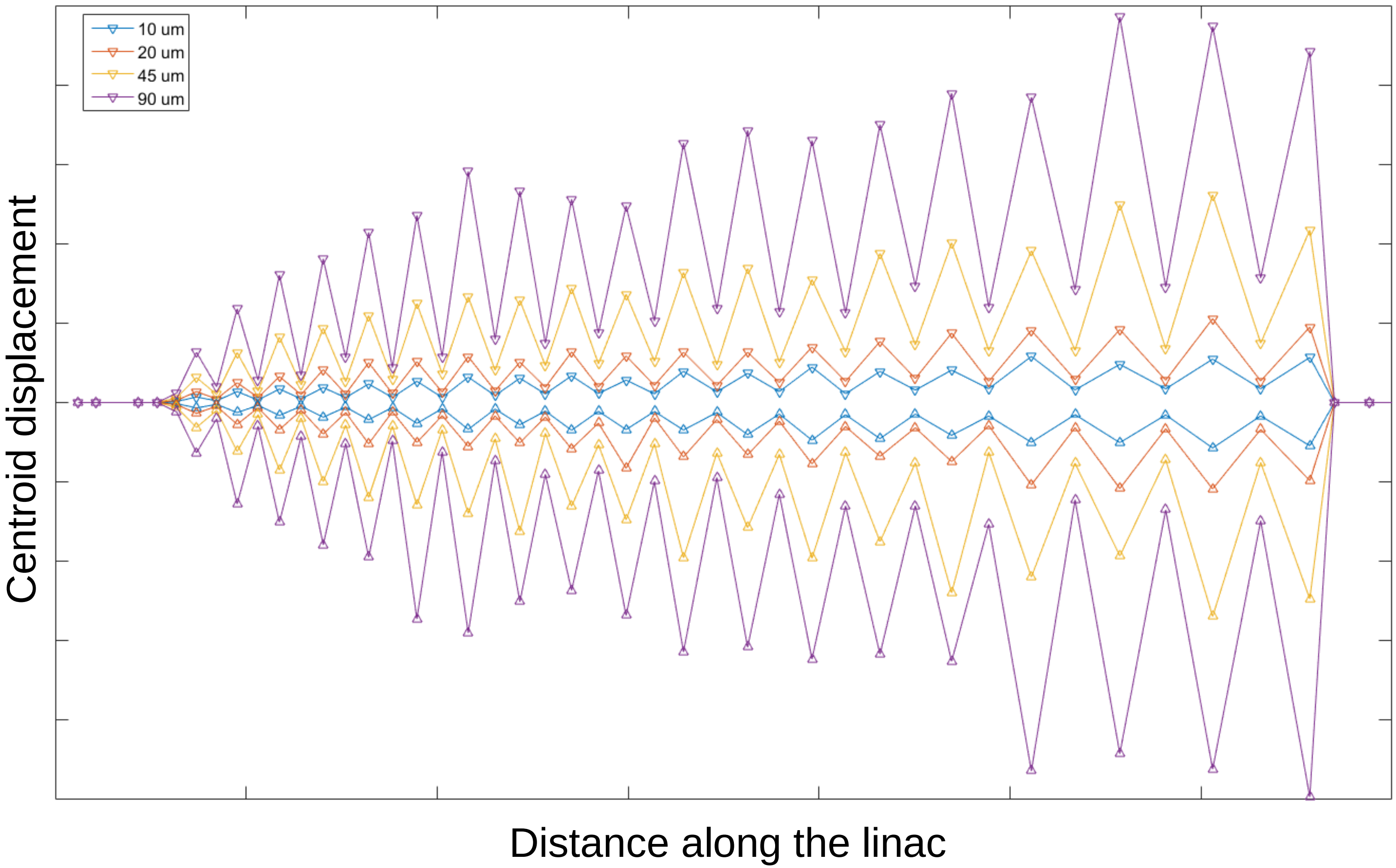
$$x_i = \sum_{k<i} R_{ik} \vartheta_k$$

- With $R_{ik} = \sqrt{\beta_i \beta_k} \sin(\varphi_i - \varphi_k)$ element (1,2) of the transfer matrix R

  $\vartheta_i = \pm \xi_i / F_i$ deflection angle resulting from offset of the ith PMQ

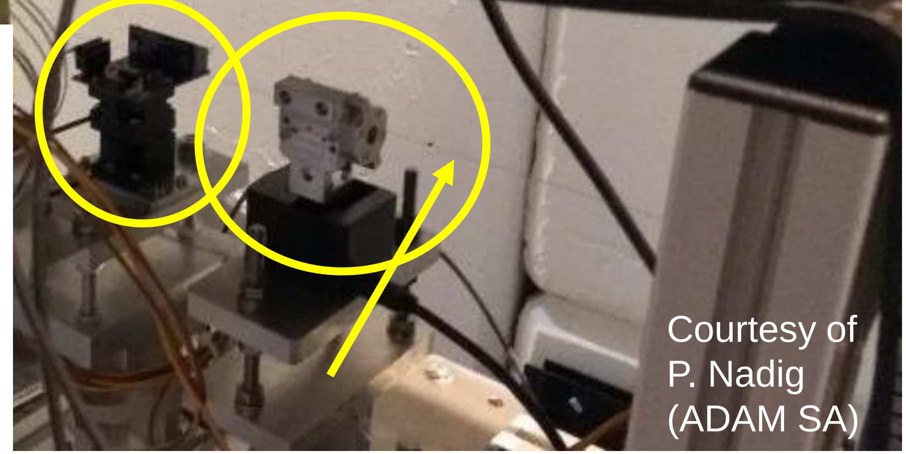
→ Stupakov, LINAC2000, MOE03, 269-271

Profile of X centroid offset vs Quad Displ tolerance

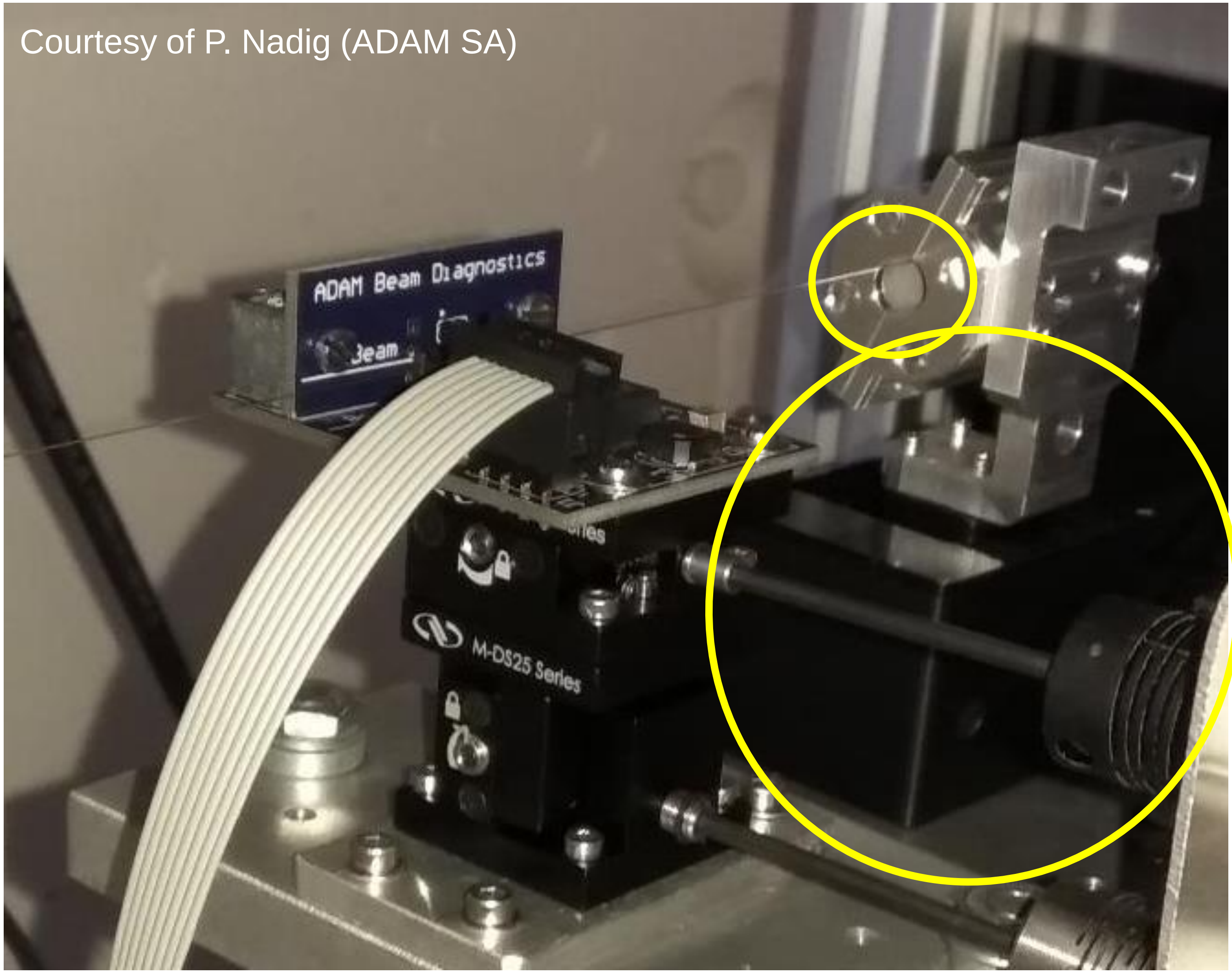


System overview

- Wire
- PMQ (movable)
- Optical sensor



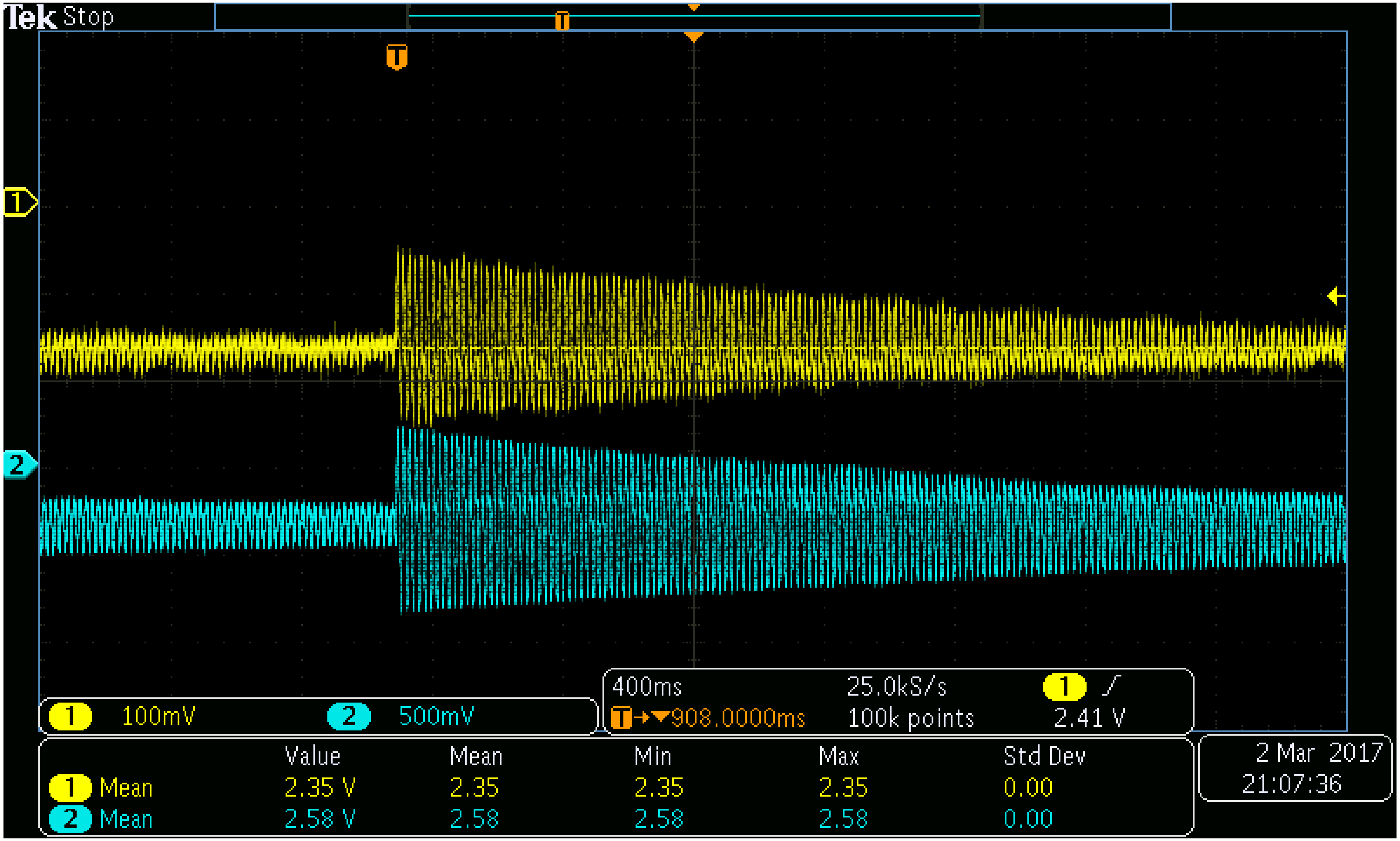
The PMQ



- > Vertical displacement
- < Horizontal displacement

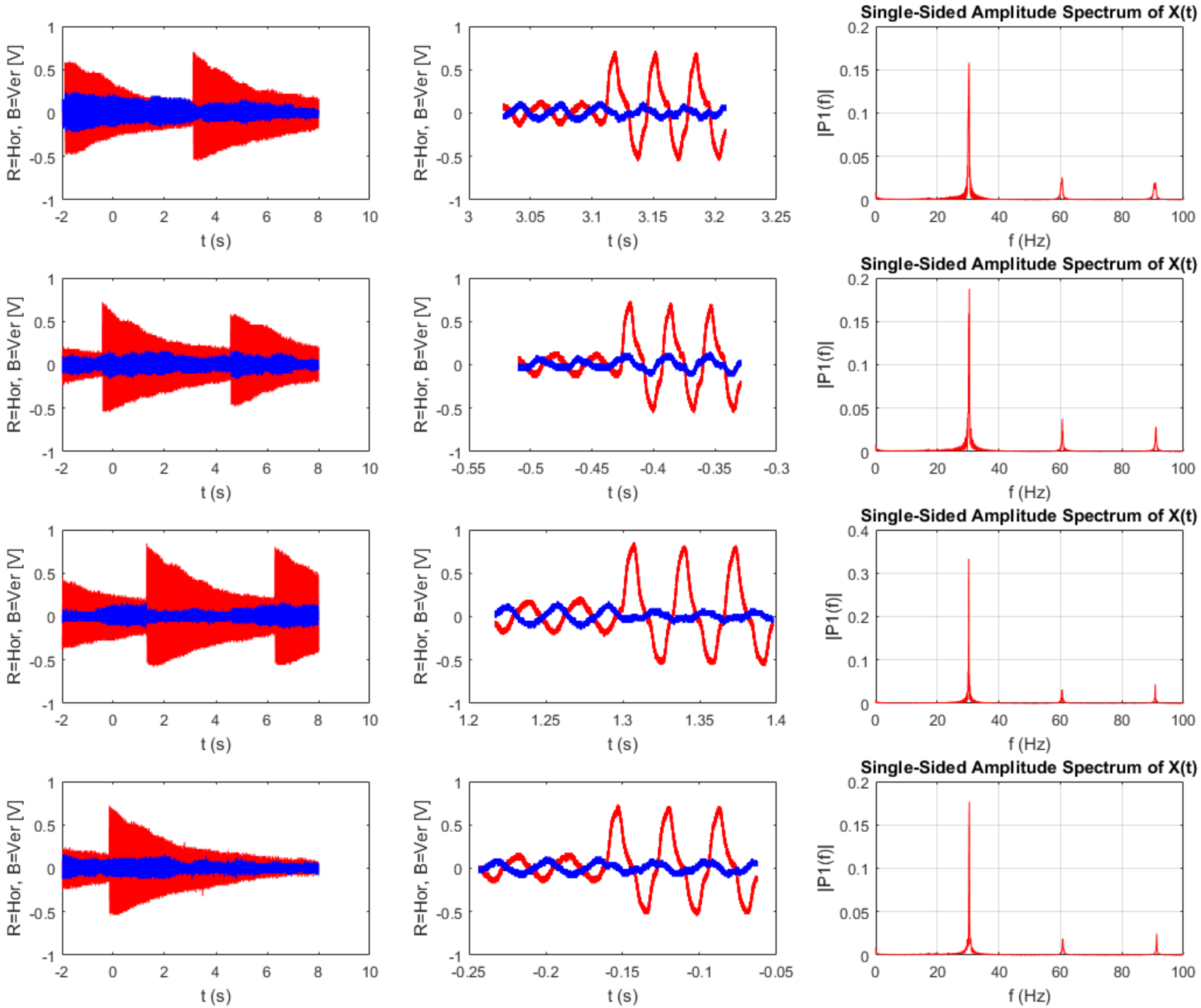
Wire is fixed
PMQ is movable!!

Pulsed wire

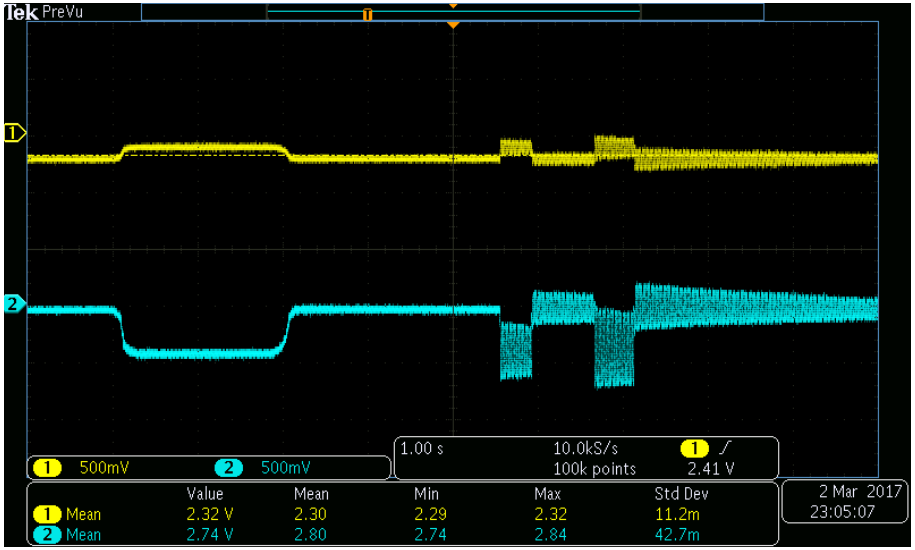


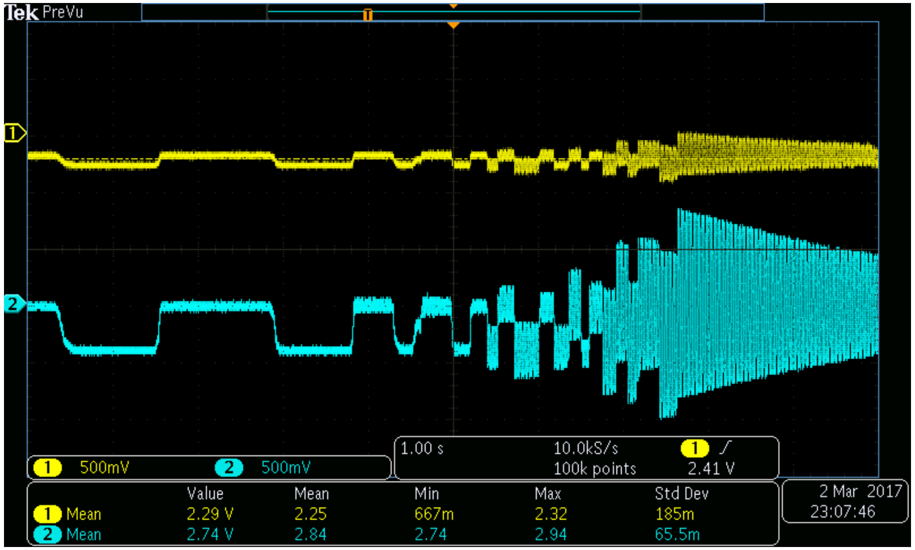
Tek Stop
100mV
500mV
400ms
25.0kS/s
908.0000ms
100k points
2.41 V
Value
Mean
Min
Max
Std Dev
Mean
2.35 V
2.35
2.35
2.35
0.00
Mean
2.58 V
2.58
2.58
2.58
0.00
2 Mar 2017
21:07:36

Photo-diode signals



Pulsing the wire

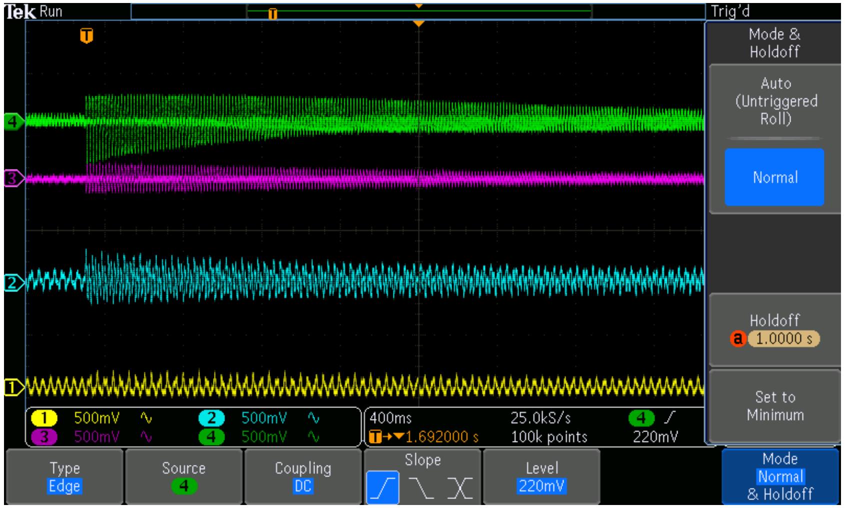


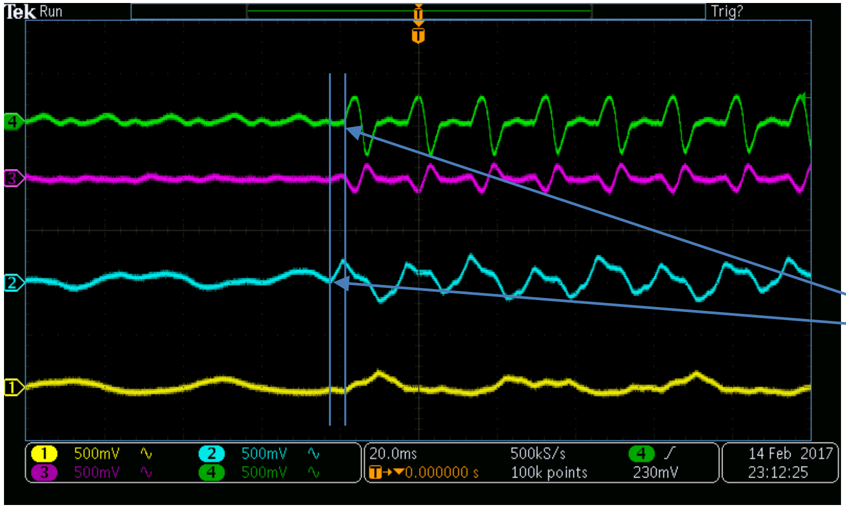


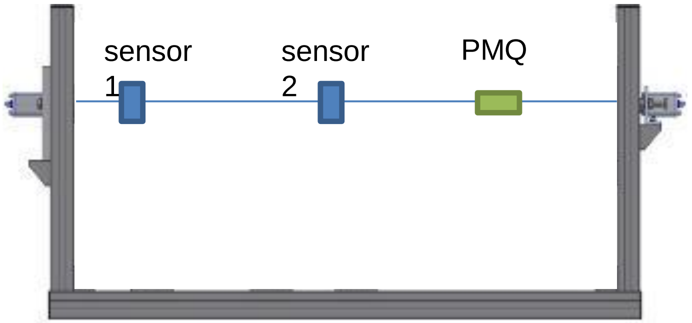
DC pulses of ~20 mA

Notice the difference in amplitude

Propagation speed between two sensors







Channel 1 (Y): sensor 2 H
Channel 2 (B): sensor 2 V
Channel 3 (P): sensor 1 H
Channel 4 (G): sensor 1 V

Difference in timing between sensor 2 and sensor 1 response ~ 4ms
Propagation speed ~ 100 mm/ms

Experience in ENEA-Frascati

C. Ronsivalle et al., TUPRO091, IPAC14

TUPRO091 Proceedings of IPAC2014, Dresden, Germany

SIMPLE CHARACTERIZATION METHOD OF SMALL HIGH GRADIENT PERMANENT MAGNET QUADRUPOLES

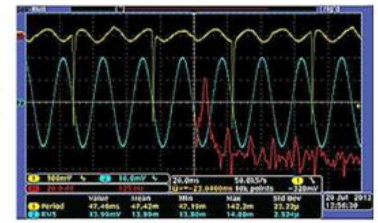
C. Ronsivalle, L. Picardi, M. Vadrucci, ENEA, Frascati, Italy
F. Ambrosini, La Sapienza University, Roma, Italy

2. MEASUREMENT OF THE HARMONIC FIELD IN THE PMQ APERTURE

MEASUREMENT SET-UP

- The PMQ is placed on a lathe where is put in rotation
- A 9- turns, 40 mm long and 1.4 mm wide coil is placed on the tool rest
- The PMQ is rotated and the induced voltage on the coil is measured and recorded
- 11 PMQs have been measured by usimg this quick and precise technique

Rrif=0



Rrif=1 mm

Harmonic content from $V = a_0 + \sum_{n=1}^{\infty} a_n \cos(nwt) + \sum_{n=1}^{\infty} b_n \sin(nwt)$

with n=1 (dipole),n=2 (quadrupole),n=3 (sextupole),n=4 (octupole)

Q-pole gradient rom $G = c_2 \cdot T / (N 4\pi L_{eff} d \cdot R_{rif})$

,with $c_2 = \sqrt{a_2^2 + b_2^2}$ T=period, Leff=3 cm, N=9 (number of coil turns),d=1.4 mm (coil width).

Displacement between the magnetic and geometrical axis of the quadrupole $\delta = 0.5 \cdot R_{rif} c_1 / c_2$

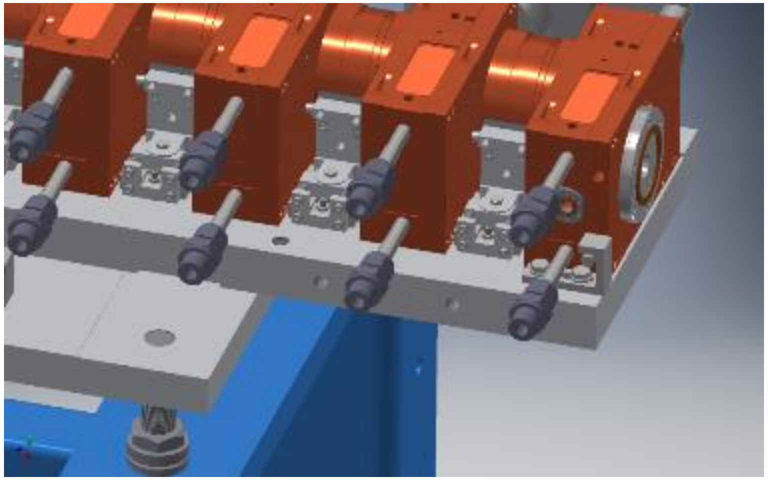
,with $c_1 = \sqrt{a_1^2 + b_1^2}$

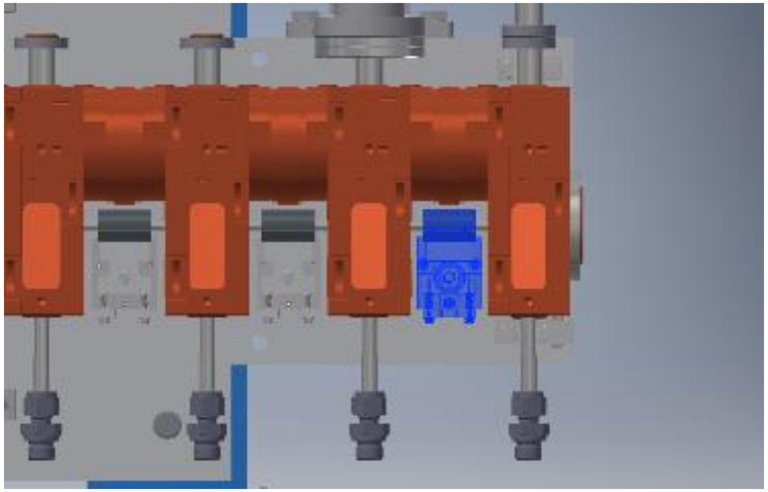
PMQ alignment strategy

- For each individual PMQ:
  - Characterize on test bench PMQ magnetic axis position
  - Based on support fiducialization pre-align PMQ on SCDTL support
  - Measure with stretched wire through accelerating module
  - Fine adjustment to minimize wire displacement

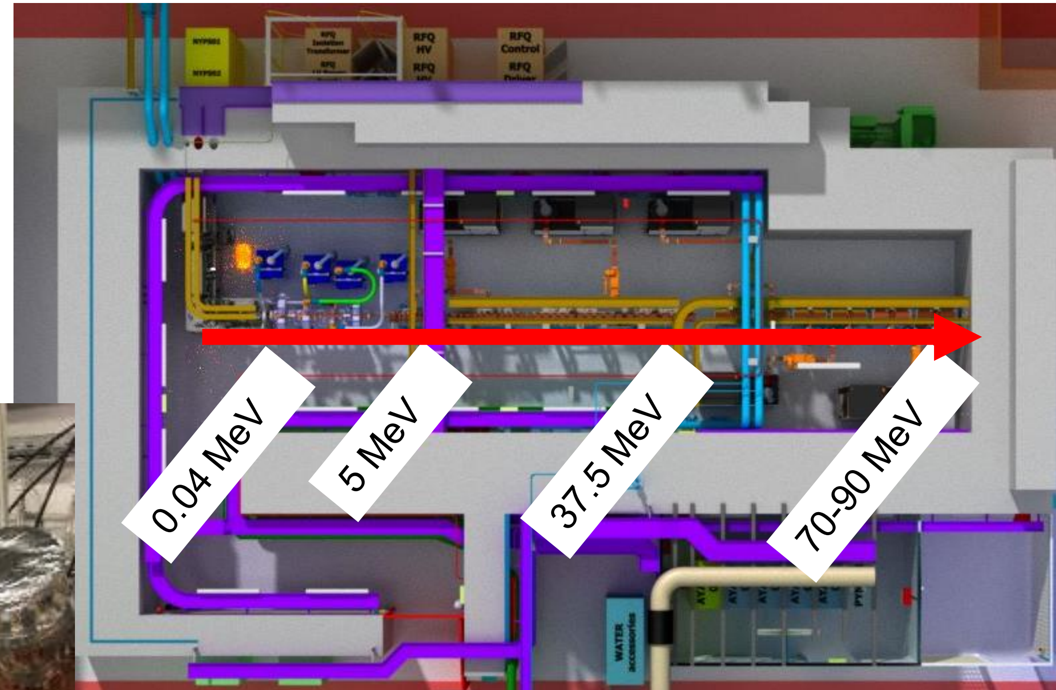
$$\Delta X_{wire} = \left(I \cdot \Delta t \cdot G \cdot L_e / (2\rho c)\right) \cdot \Delta X_{mag}$$

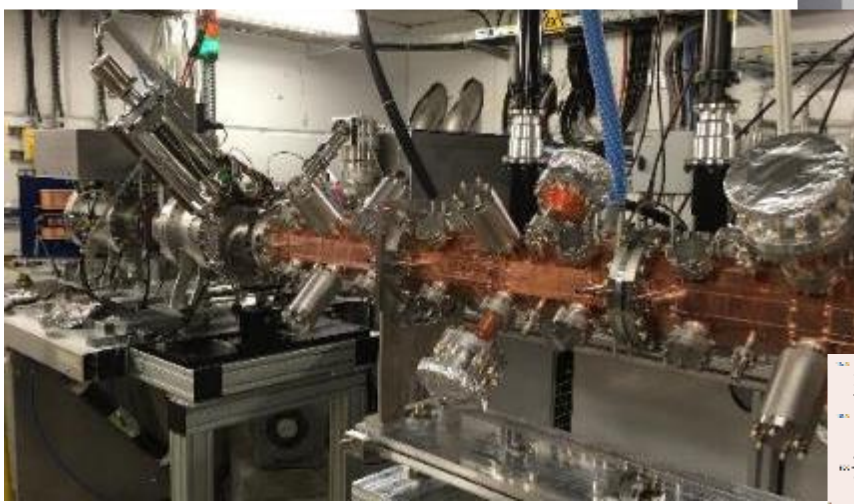
Fortgang et al., LINAC90, 426-428

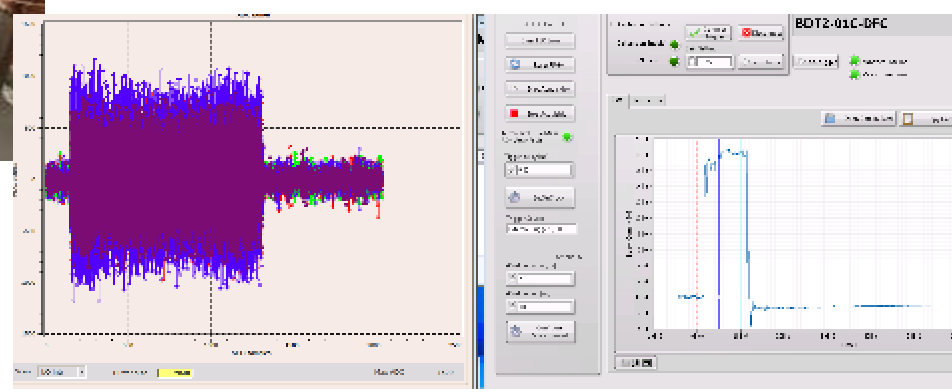




Commissioning of LIGHT @ CERN LHC-Point2







Conclusions

- An overview of the application of accelerator for proton therapy has been presented.
- A prototype of **LIGHT**, the first commercial 3 GHz linac for proton-therapy, is now under commissioning
- Magnetic measurements techniques and alignement strategies developed for research accelerators are applied to medical linacs
- LIGHT represents a good example of **technology and knowledge transfer** to industry and medical applications!

Acknowledgment

- We would like to acknowledge all CERN colleagues for their continuous and crucial support with this work.

Acknowledgment

THANK YOU FOR YOUR ATTENTION !