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FROM RESEARCH TO INDUSTRY

EXPERIMENTAL PLAN FOR STAGING EXPERIMENTS AT APOLLON/CILEX

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APOLLON/CILEX IN A FEW WORDS

- APOLLON is a French research infrastructure located near CEA Saclay.
  - Unique multi-PW laser in France 100% open.
  - Transnational access possible through ARIES project.

- 2 experimental rooms (short and long focal areas) for plasma acceleration: electrons and ions.
  - Acceleration of electrons in vacuum
  - Acceleration in the bubble regime with/without external injection.
  - Acceleration in (quasi-) linear regime with 1 or 2 stages.

APOLLON/CILEX PLANNING

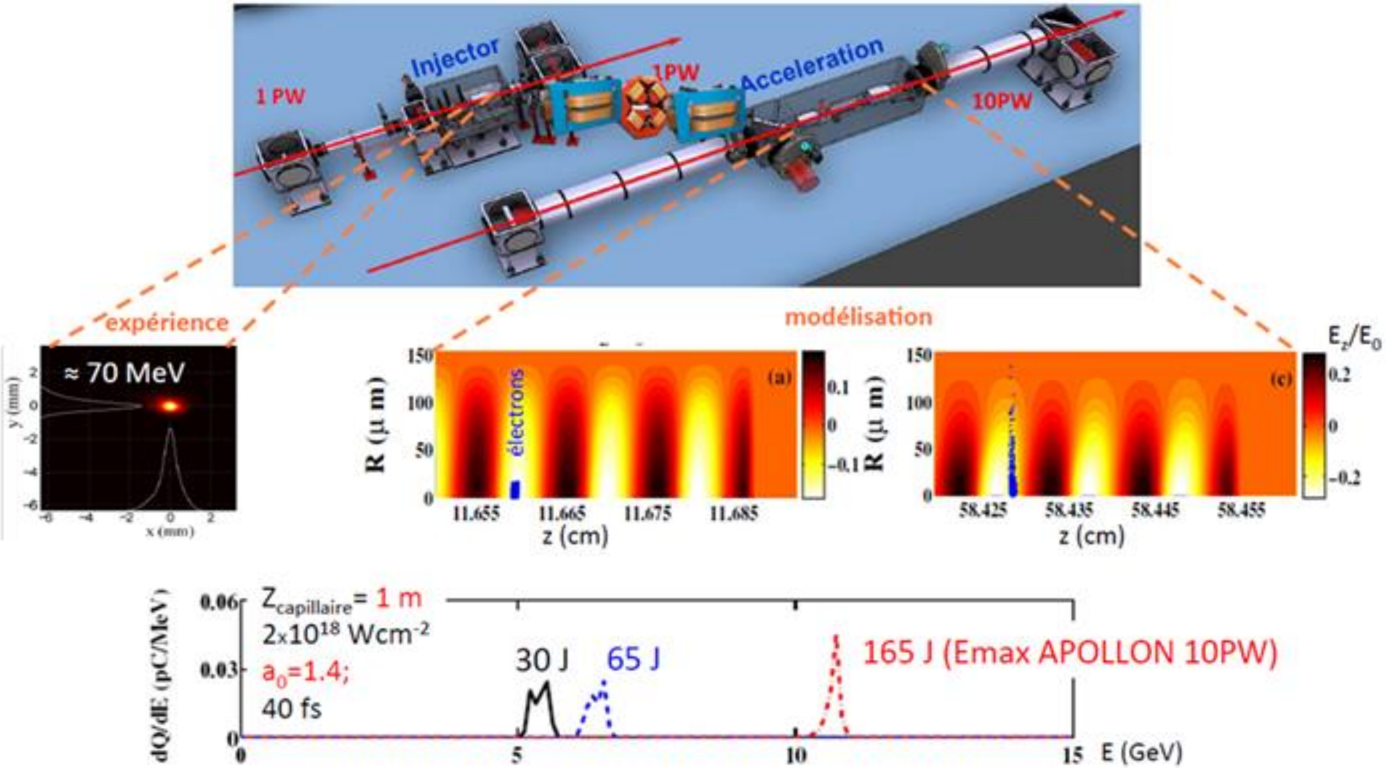
- Now:
  - Laser qualification in the short focal area
  - First experiment under mounting: electron acceleration.
- Spring 2019 :
  - 100J after amplification
  - First experiment in the long focal area
- Fall-Winter 2019:
  - Qualification experiments
  - « Users meeting »
  - Call for experiments at1 PW (September 2020 – September 2021)
- Early 2020:
  - Qualification of multi PW laser (7-8 PW)
- End 2020:
  - Call for experiments with a multi PW laser

MULTI-STAGE EXPERIMENTS AT APOLLON/CILEX

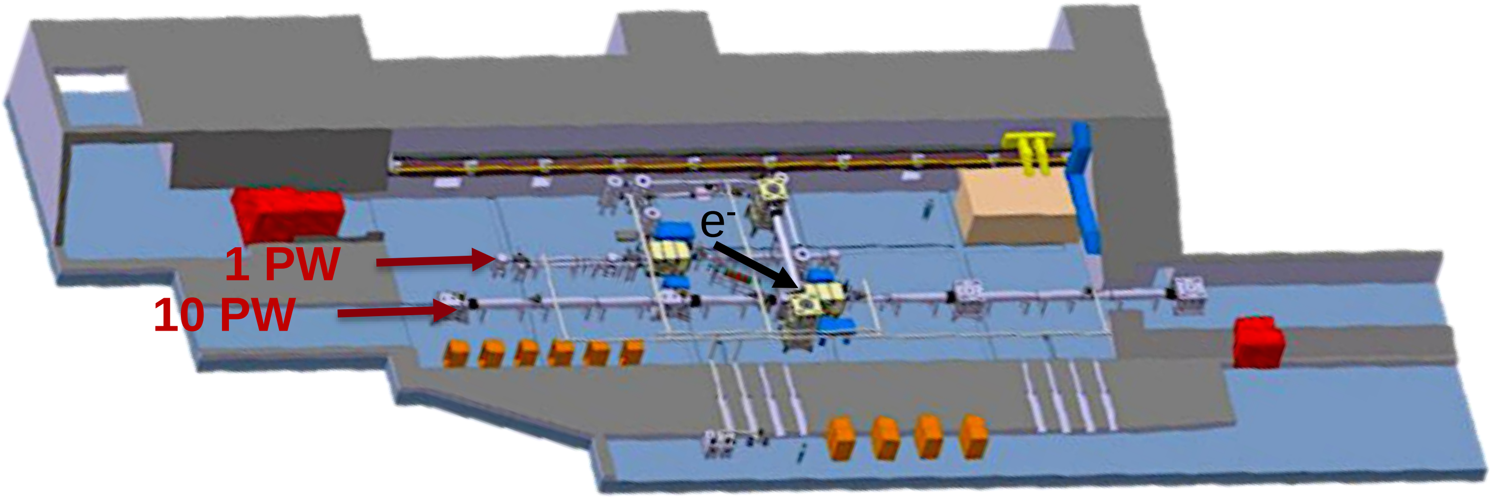
- Motivations for multi-stage experiments:
  - To demonstrate that an energy gain of ~10 GeV can be achieved for 10 pC beams after each plasma stage (length of ~1 m).
  - To check that such beams can be transported from one stage to another one.

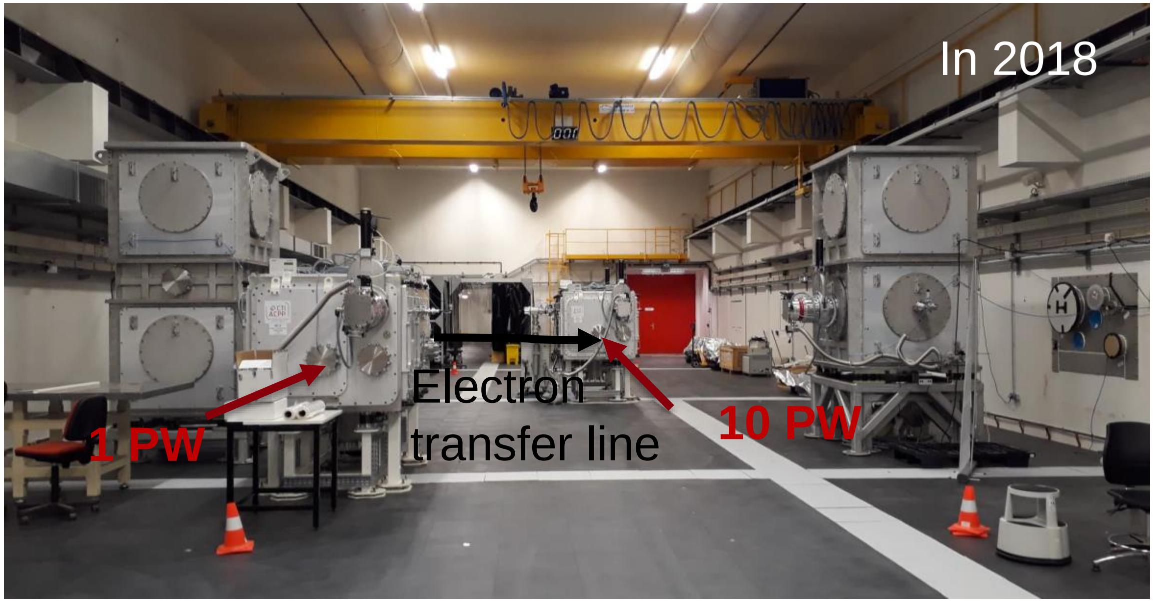
Paradkar et al., PoP, **20**, 8 (2013)
B. Cros, Nature, **530**, 165 (2016) ; S. Steinke et al, Nature, **530**, 190 (2016)

B. Cros, EAAC2013; T.L. Audet et al, NIMA, **829**, 304 (2016)
B. Cros et al, Proceedings IPAC 2017



VIEW OF THE EXPERIMENTAL AREA





BEAM LINE FEATURES

- Initial beam properties

Reference energy	300	MeV
Charge	10	pC
Normalized emittance	1	µm
$\beta_{x,y}$	1	mm
$\alpha_{x,y}$	0	-
RMS energy spread	1	%
RMS bunch length	5	fs
Peak current	1	kA
Repetition rate	**< 0.02**	**Hz**

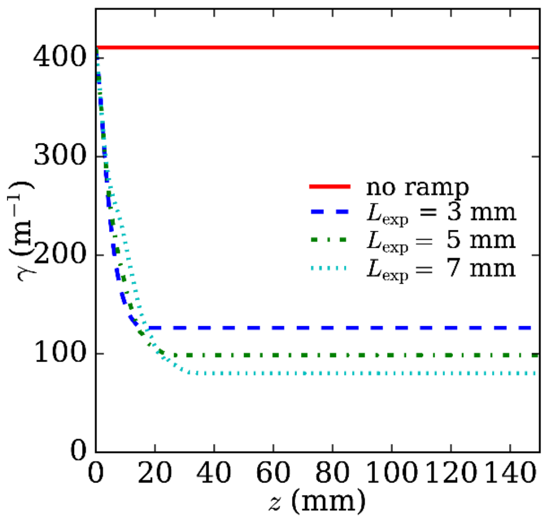
- Transfer line:
  - Dogleg to **enable experiments with 1 PW laser** without removing the line, to **protect second stage** from 1st laser, to enable energy selection, and **post-mortem diagnostics** for the laser.
  - Width: 3 meters
  - Length: 7.675 meters

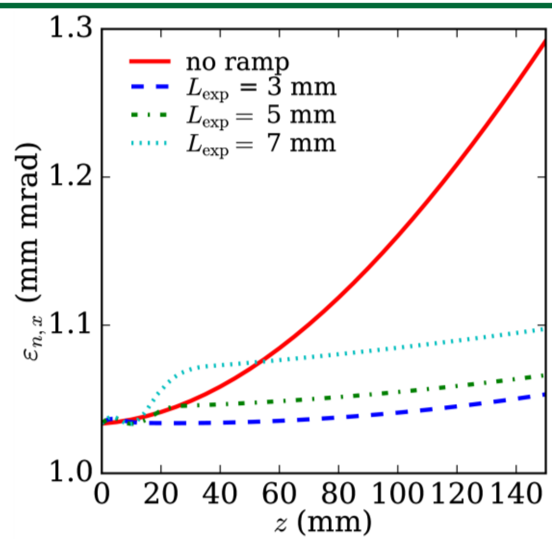
CHALLENGE #1: TO KEEP EMITTANCE

- **Plasma injector is to be optimized: energy spread and beam divergence**
  - Density ramp length (injection and acceleration stage) will be optimized.

Li et al., PRST-AB 22, 021304 (2019)

See « Simulations for EuPRAXIA accelerator design » by Phi NGHIEM, on Thursday





Density ramp

Beam tranfer line

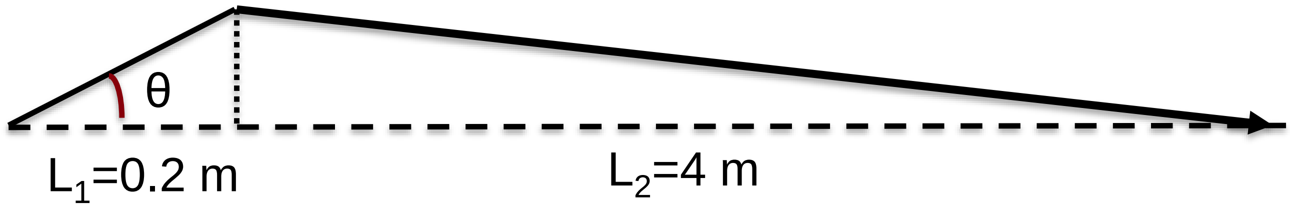
Plasma channel

$$\frac{\Delta\varepsilon_{x,y}^2}{\varepsilon_{x,y}^2} \approx 4T_{126}^2\gamma_{x,y}^2\sigma_\delta^2$$

No significant effect of space charge was seen (peak current of kA, probably because bunch is short only before 1st dipole)

CHALLENGE #2: TO KEEP SYNCHRONISM

- Different sources of dephasing between electrons:
  - Velocity difference: $\Delta L \approx \frac{l\,\delta^2}{\gamma^2}$ negligible at 300 MeV (<1 µm for δ=1% after 8 m)
  - Path length variation in one dipole: $\rho(\theta - \sin\theta)\delta$: 85 µm for~δ=1% and a dipole of 250 mm and an angle of 26° (used dipole for the line).
    - Not negligible at all.
    - **We need to correct the path length.**
  - Path length variation because of initial angle.



$\Delta L \approx \frac{\theta^2}{2} L_1 \left(1 + \frac{L_1}{L_2}\right) \approx 2\ \mu\mathrm{m}$ **for a divergence of 1 mrad**

- Not negligible for large divergences (several milliradians).
- Minimizing the beam divergence enables to solve this issue.

CHALLENGE #3: POINTING STABILITY

- Repetition rate: one shot every minute.
- We cannot use feedback systems: fluctuation from shot to shot cannot be corrected.
- Only static errors (like initial magnet misalignment) can be corrected.
- Beam line should minimize the sensitivity to pointing stability:
  - Use of an inverse mirror symmetry in the line.
  - $R_{12}=R_{34}=0$ to cancel position variation at the entrance of the second stage.

Simplification of the beam transfer matrix

Total matrix (R^M is the transfer matrix from the beginning to the middle):

$$R=\begin{pmatrix} 1+2R^M_{1,2}R^M_{2,1} & 2R^M_{1,2}R^M_{2,2} & 0 & 0 & 0 & 2R^M_{1,6}R^M_{2,2} \\ 2R^M_{1,1}R^M_{2,1} & 1+2R^M_{1,2}R^M_{2,1} & 0 & 0 & 0 & 2R^M_{1,6}R^M_{2,1} \\ 0 & 0 & 1+2R^M_{3,4}R^M_{4,3} & 2R^M_{3,4}R^M_{4,4} & 0 & 0 \\ 0 & 0 & 2R^M_{3,3}R^M_{4,3} & 1+2R^M_{3,4}R^M_{4,3} & 0 & 0 \\ 2R^M_{1,6}R^M_{2,1} & 2R^M_{1,6}R^M_{2,2} & 0 & 0 & 1 & 2\left(R^M_{1,6}R^M_{2,6}+R^M_{5,6}\right) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Hor. point-to-parallel and vertical point-to-point imaging at the middle $\left(R^M_{2,2}=R^M_{3,4}=0\right)$

Invariance of the path length and of the position at the middle with the energy $\left(R^M_{1,6}=R^M_{5,6}=0\right)$

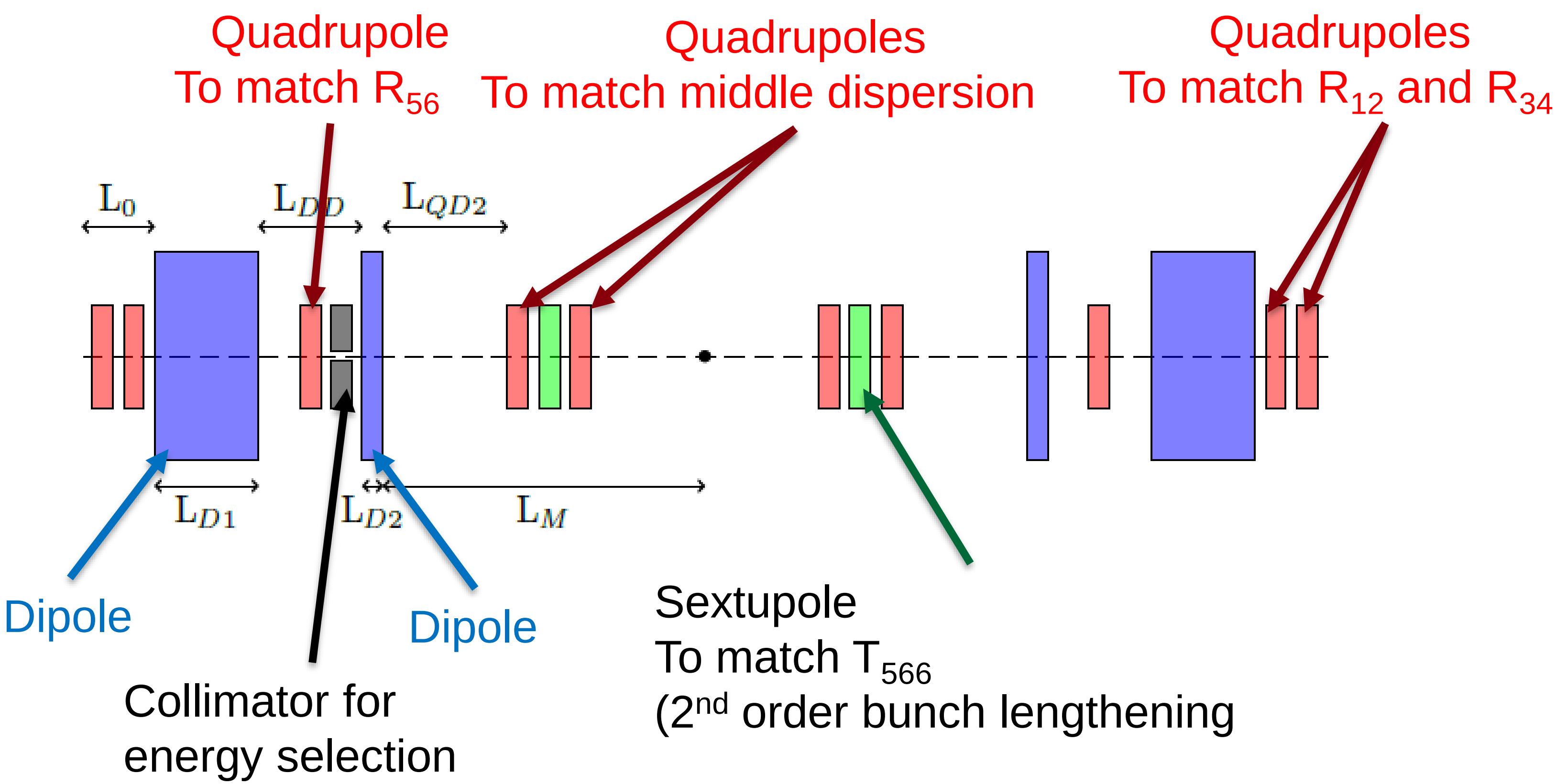
$$R=\begin{pmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 2R^M_{1,1}R^M_{2,1} & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 2R^M_{3,3}R^M_{4,3} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Other cancellations occur for second-order terms (not shown here).

Second order dispersion:

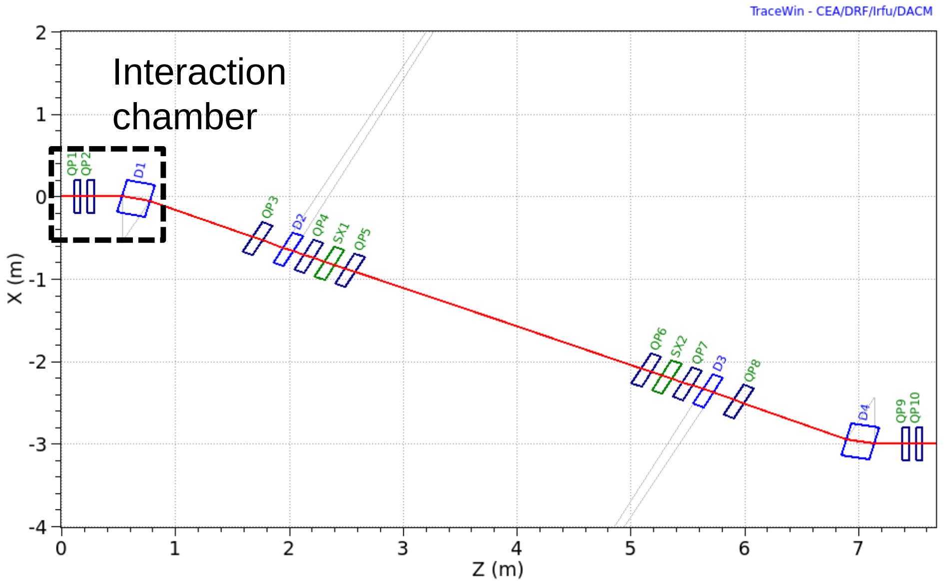
$T_{166}=0$

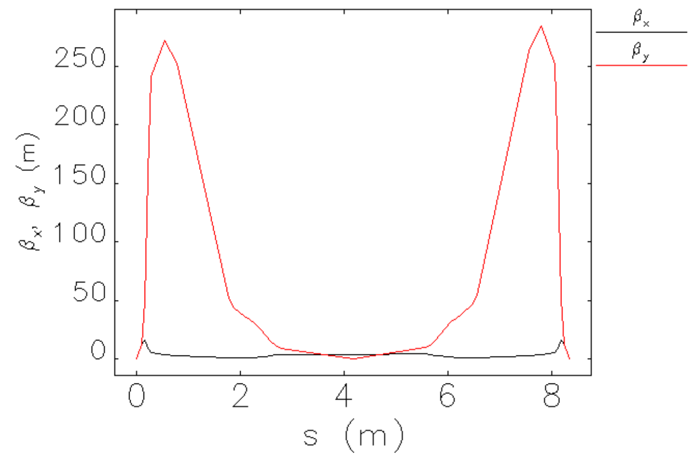
BEAM LINE

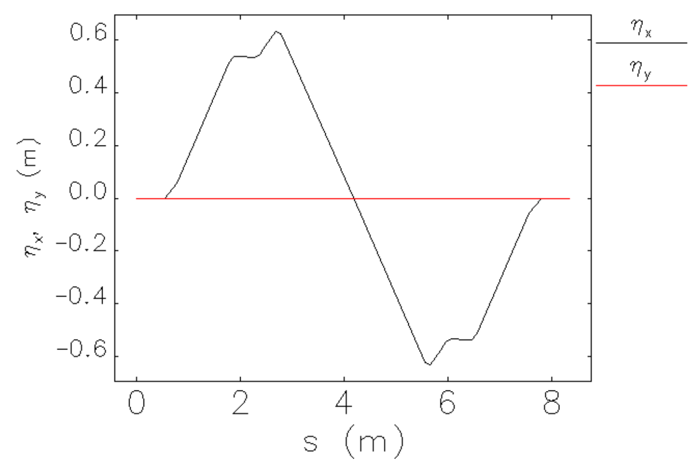


Dogleg similar to X-FEL compression line or ARES-SINBAD

BEAM LINE FEATURES

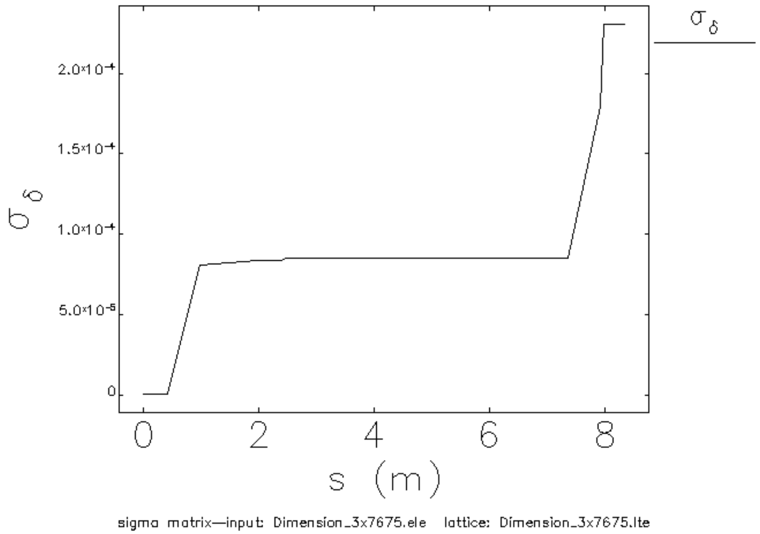


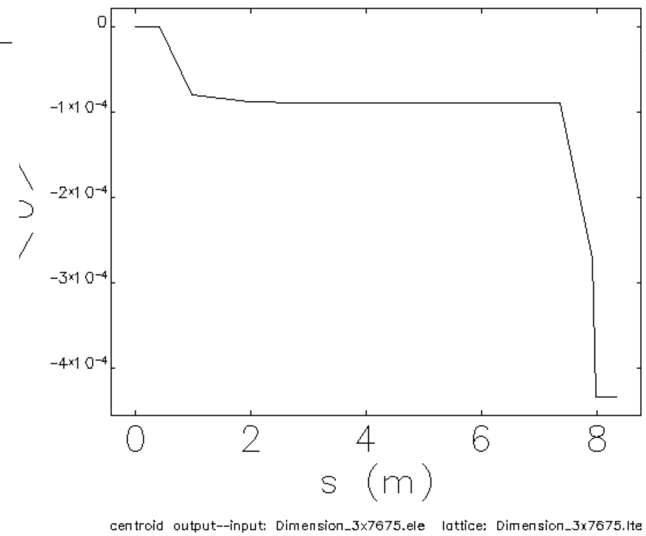


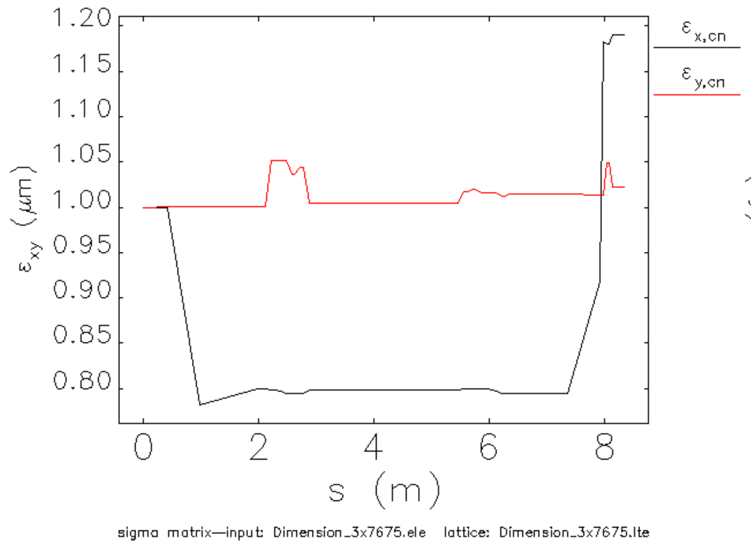


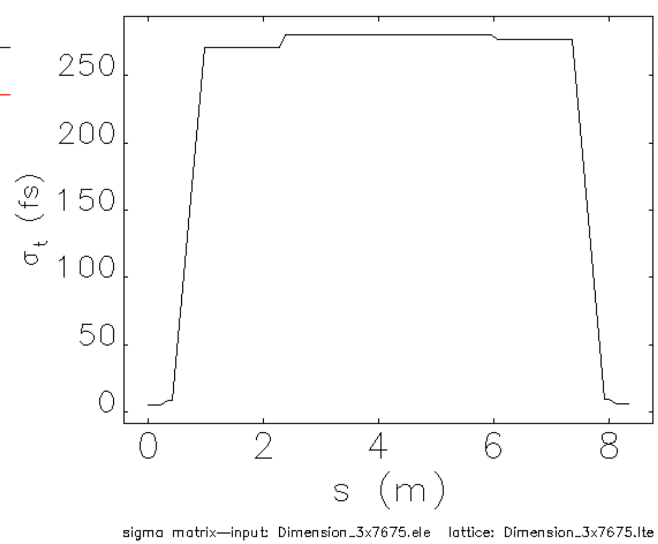
Magnet	Length	Max Strength
D1	250 mm	1,7 T/26°
D2	100 mm	0.15 T/1°
QP1	60 mm	206 T/m (PM)
QP2	60 mm	102 T/m (PM)
QP3/4/5	100 mm	15 T/m (EM)
SX1	100 mm	100 T/m^2 (EM)

CSR EFFECT









Calculation with initial momentum spread at zero and no shielding (most pessimistic case)

Momentum spread growth: 2.2 x 10^{-4}
Relative energy loss: 4.2 10^{-4}.

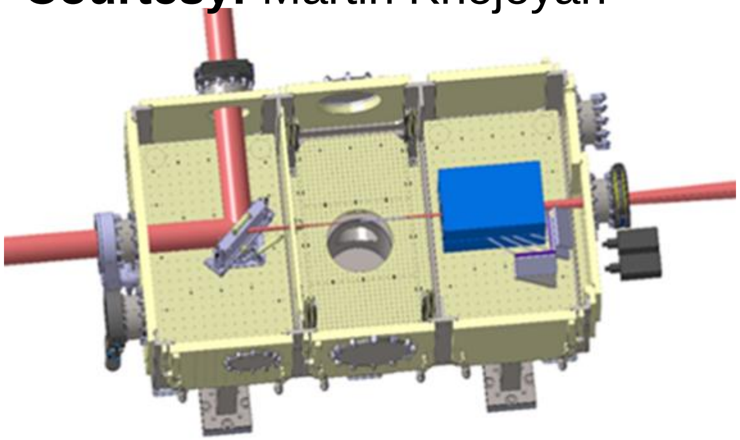
CSR effect should be negligible.

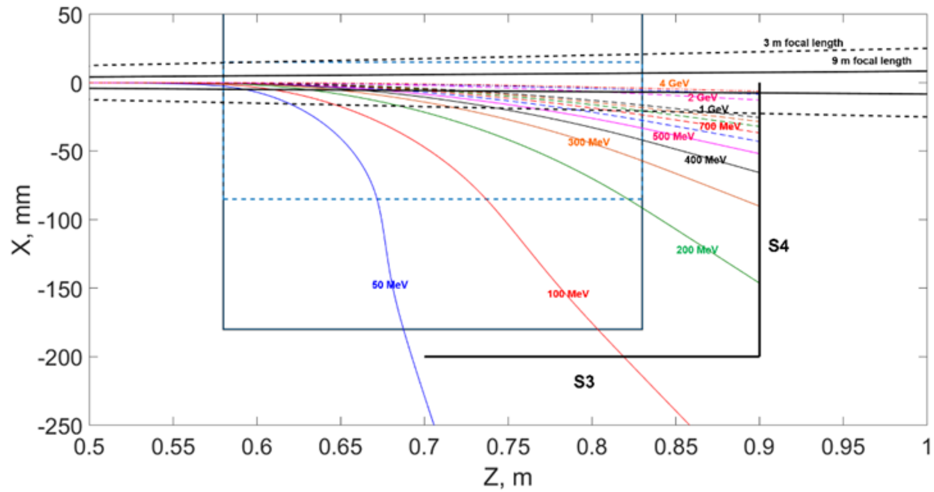
In agreement with first order formulae:

$$\gamma \gg (\rho/\sigma_s)^{1/3}$$

PERMANENT MAGNET DESIGN

Courtesy: Martin Khojoyan



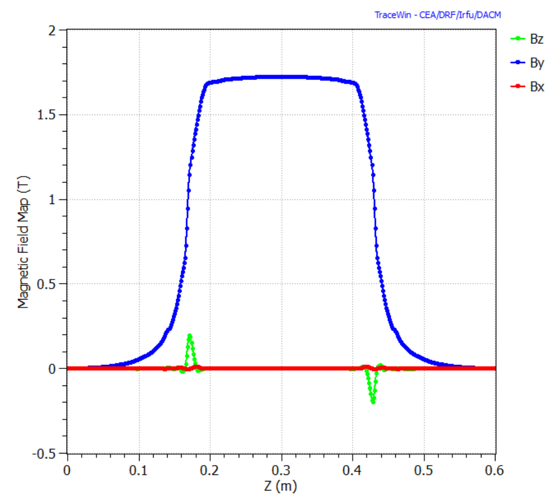


Permanent dipole has been designed (max. 1.7 T)

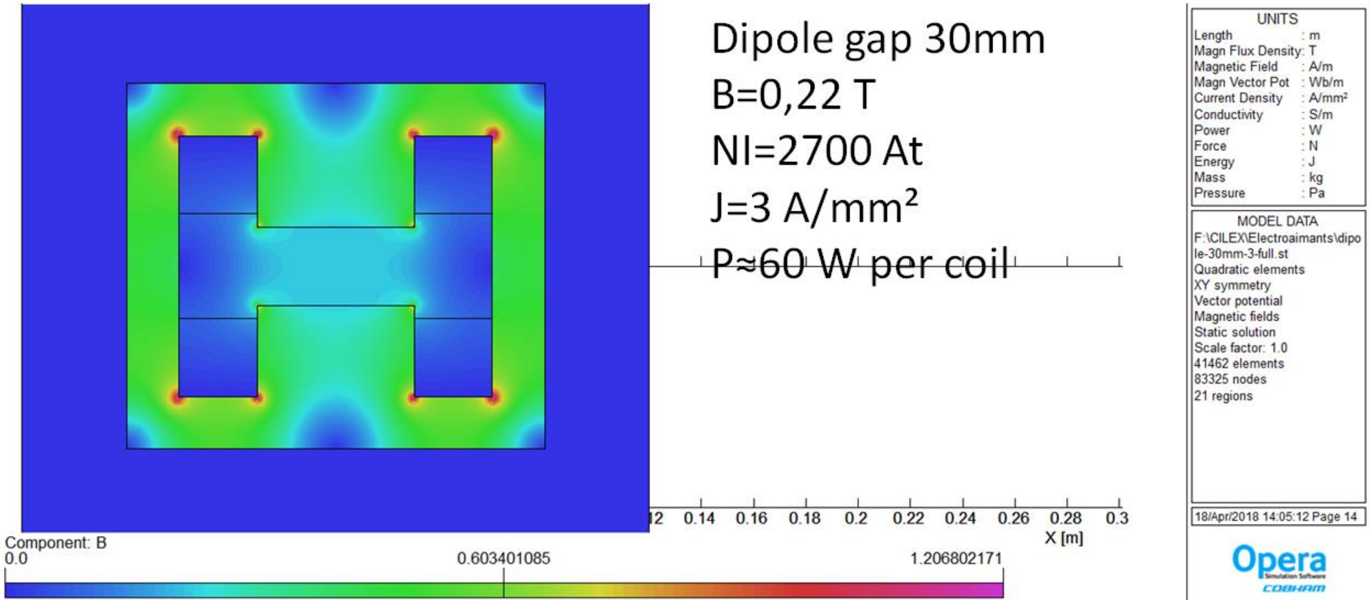
Under manufacture (should be delivered in May)

Initially used as an energy spectrometer (first phase of the project).

This dipole will be used as the first dipole of the transfer line (deflection angle of 26° for an energy of 300 MeV)

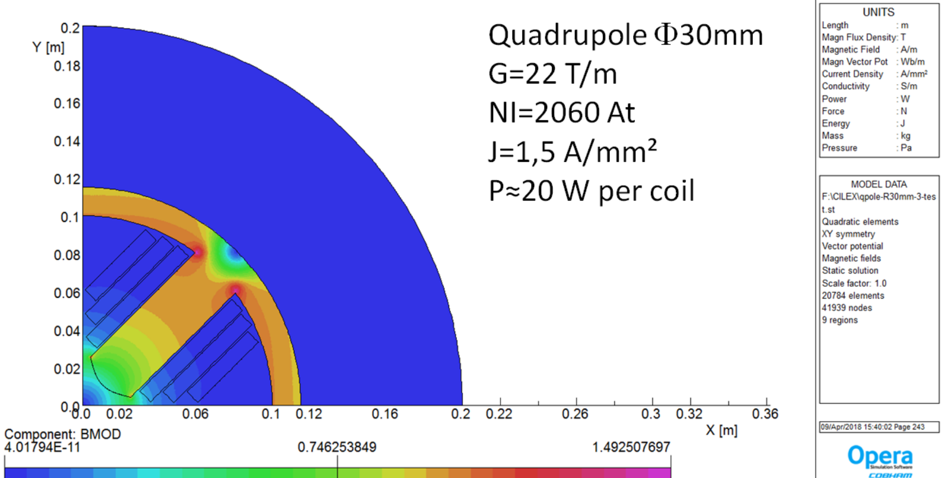


ELECTROMAGNETS

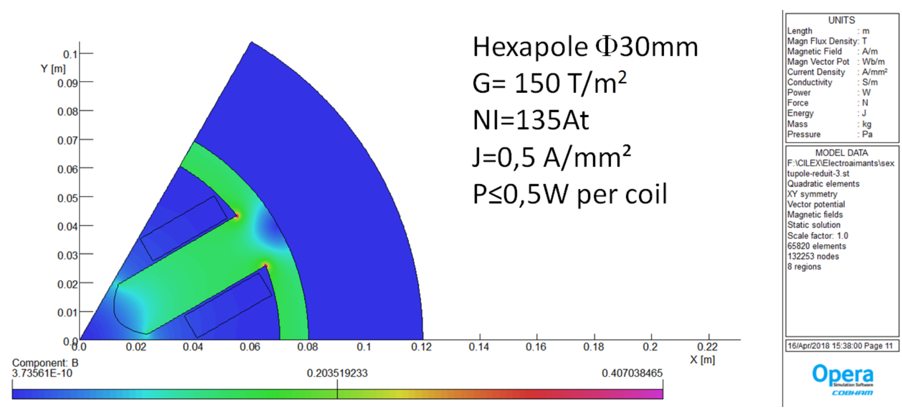


Dipole gap 30mm
B=0,22 T
NI=2700 At
J=3 A/mm²
P≈60 W per coil

Design of all electromagnets is done



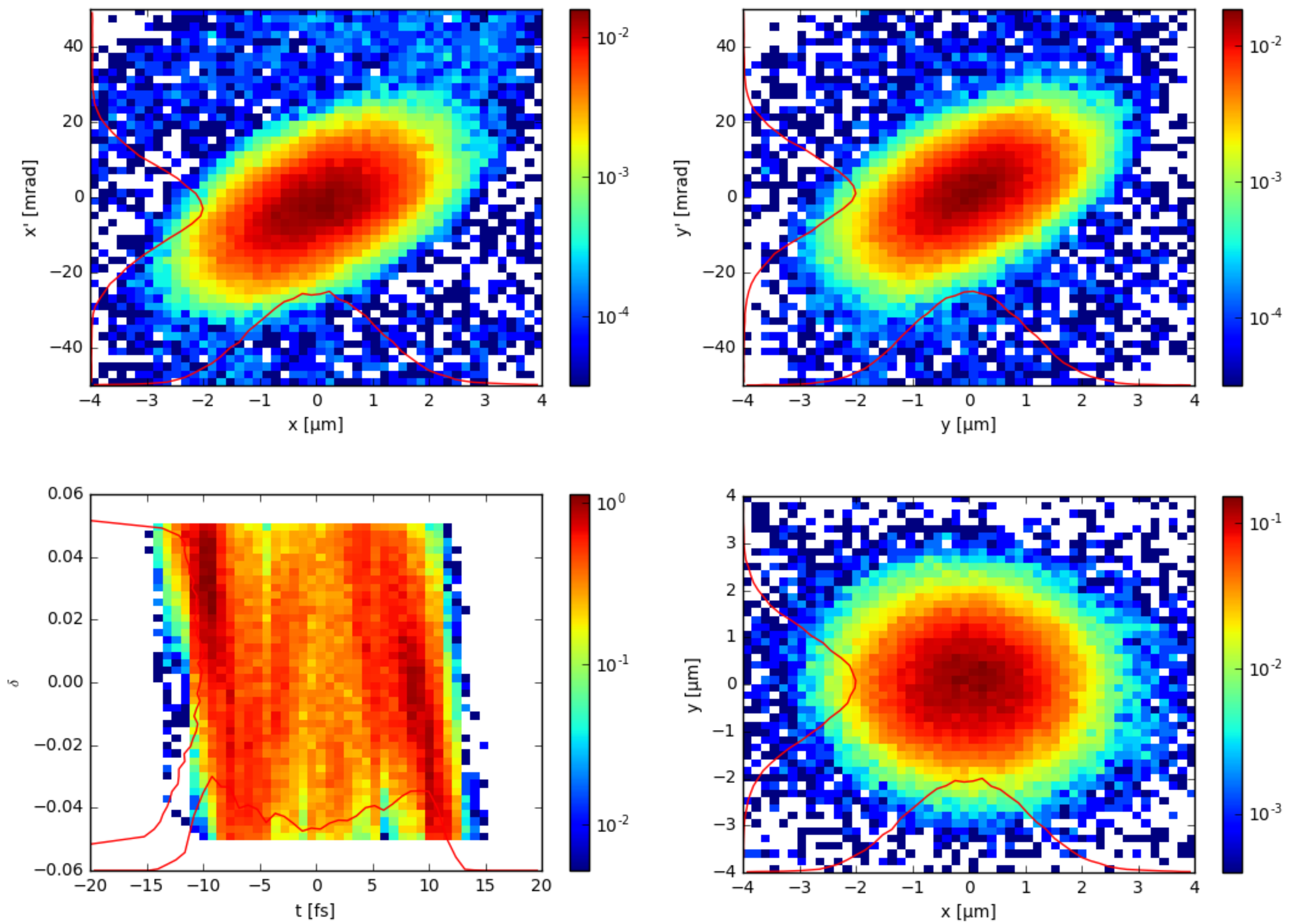
Quadrupole Φ30mm
G=22 T/m
NI=2060 At
J=1,5 A/mm²
P≈20 W per coil



Hexapole Φ30mm
G= 150 T/m²
NI=135At
J=0,5 A/mm²
P≤0,5W per coil

Courtesy: Olivier Delferrière

INITIAL DISTRIBUTION FROM SIMULATIONS



Normalized emittance: 7 µm

RMS Divergence: 17 mrad

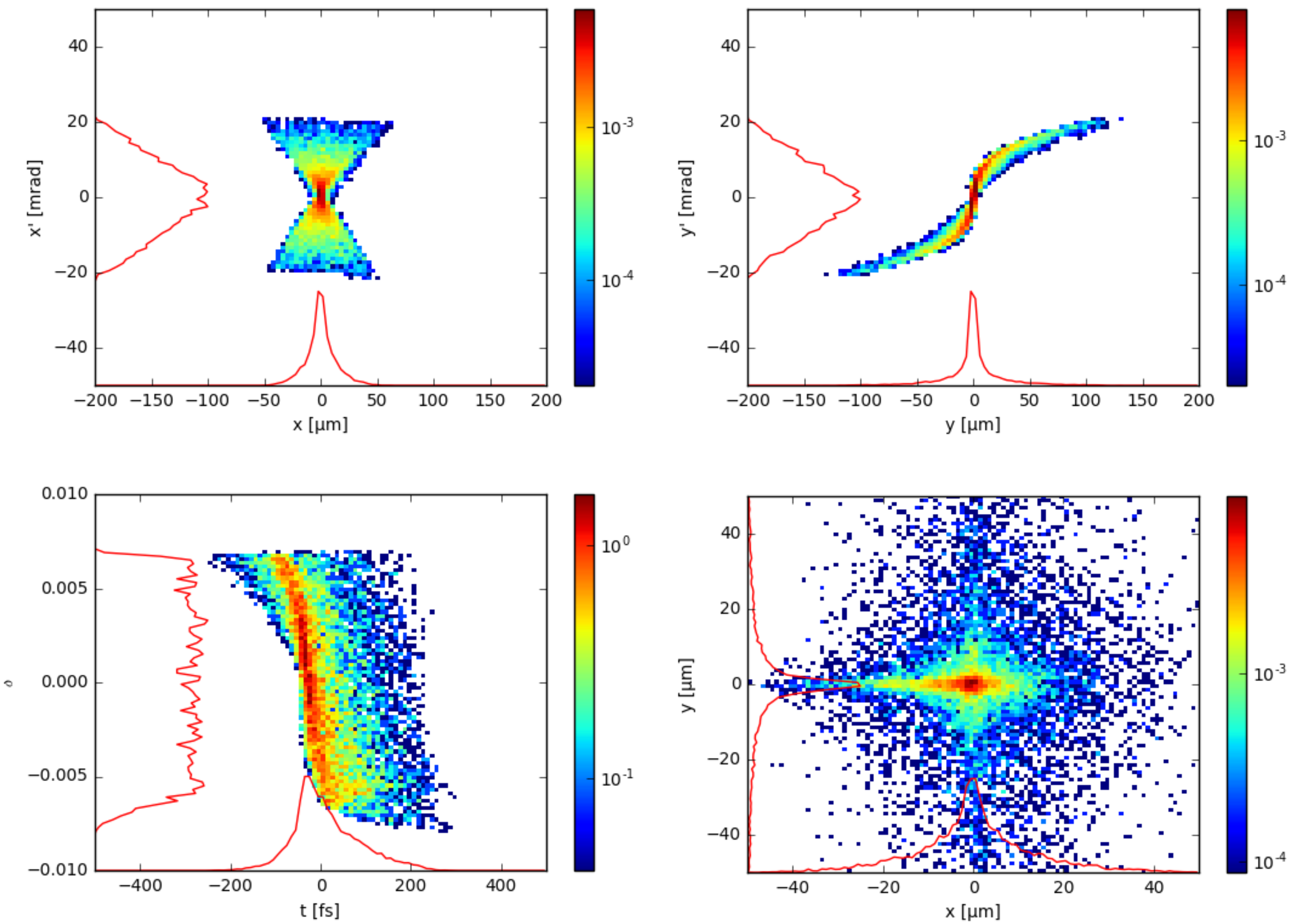
RMS energy spread: 15%

Still room for improvement.

Courtesy: Arnaud Beck

See Simulations of Staging Experiments at Apollon Francisco Massimo on Thursday

FINAL DISTRIBUTION



Cut in divergence at 20 mrad and in energy at 0.67% (with collimators)

Bunch lengthening just because of the large divergence.

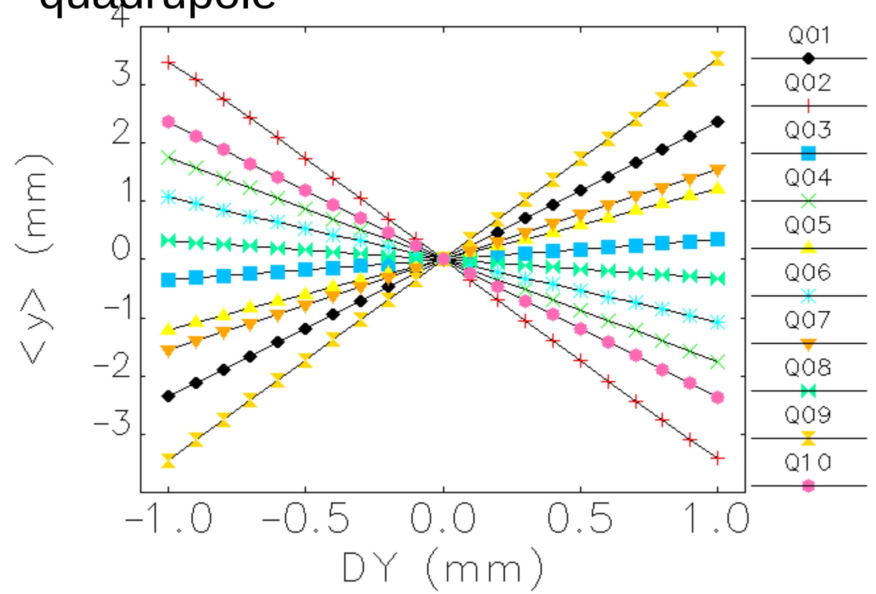
Courtesy: Arnaud Beck

See Simulations of Staging Experiments at Apollon Francisco Massimo on Thursday

SENSITIVITY TO LINE ERRORS

- First studies were performed to evaluate the misalignment and field errors (tracking studies).
- No feedback system is considered.
- Most critical issues are the transverse misalignment of the quadrupoles (**should be stabilized at a few µm)** and the tilt errors in the dipoles (**stabilization at a few 10s µrad**).

Example: variation of the final vertical beam center as a function of a vertical displacement of one quadrupole

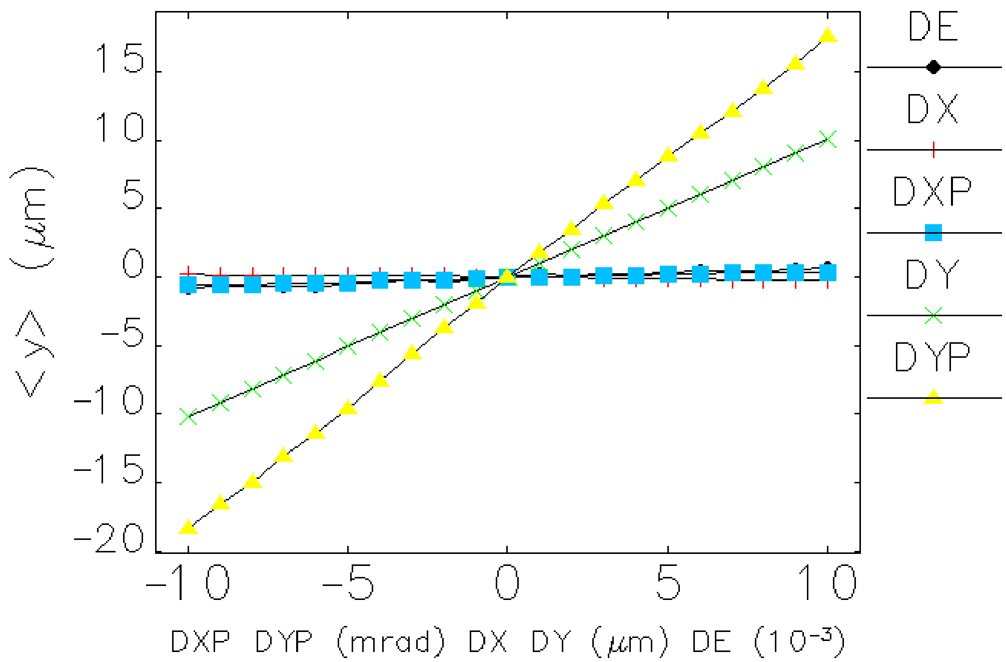


SENSITIVITY TO BEAM ERRORS

Despite cancelling first order terms (R_{34}), we see a linear dependence of beam centroid with pointing error.

$$\langle y \rangle = R_{34}DYP + T_{344}DYP^2 + U_{3444}DYP\left(\sigma_{y'}^2 + DYP^2\right) + o(3)$$

$R_{34}=0$
T_{344} = 0 (mirror symmetry)
U_{3444} = 13 m
$\sigma_{y'} \approx$ 10 mrad
The slope direcly comes from initial angular divergence and 3rd order terms



Solution: Reduce the initial beam divergence.

CONCLUSION

- Studies have been performed for a multistage experiment at CILEX/APOLLON.

- 2019-2020:
  - Measurement of the energy spectrum of the electron beam after the plasma injector (use of the permanent dipole, delivered soon).

- 2021:
  - Commissioning of the line (transport and characterization of the initial beam).
  - Part of the line is funded through ARIES project.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

  - Plasma injector should be optimized **to reduce energy spread but also beam divergence.**

THANK YOU FOR YOUR ATTENTION