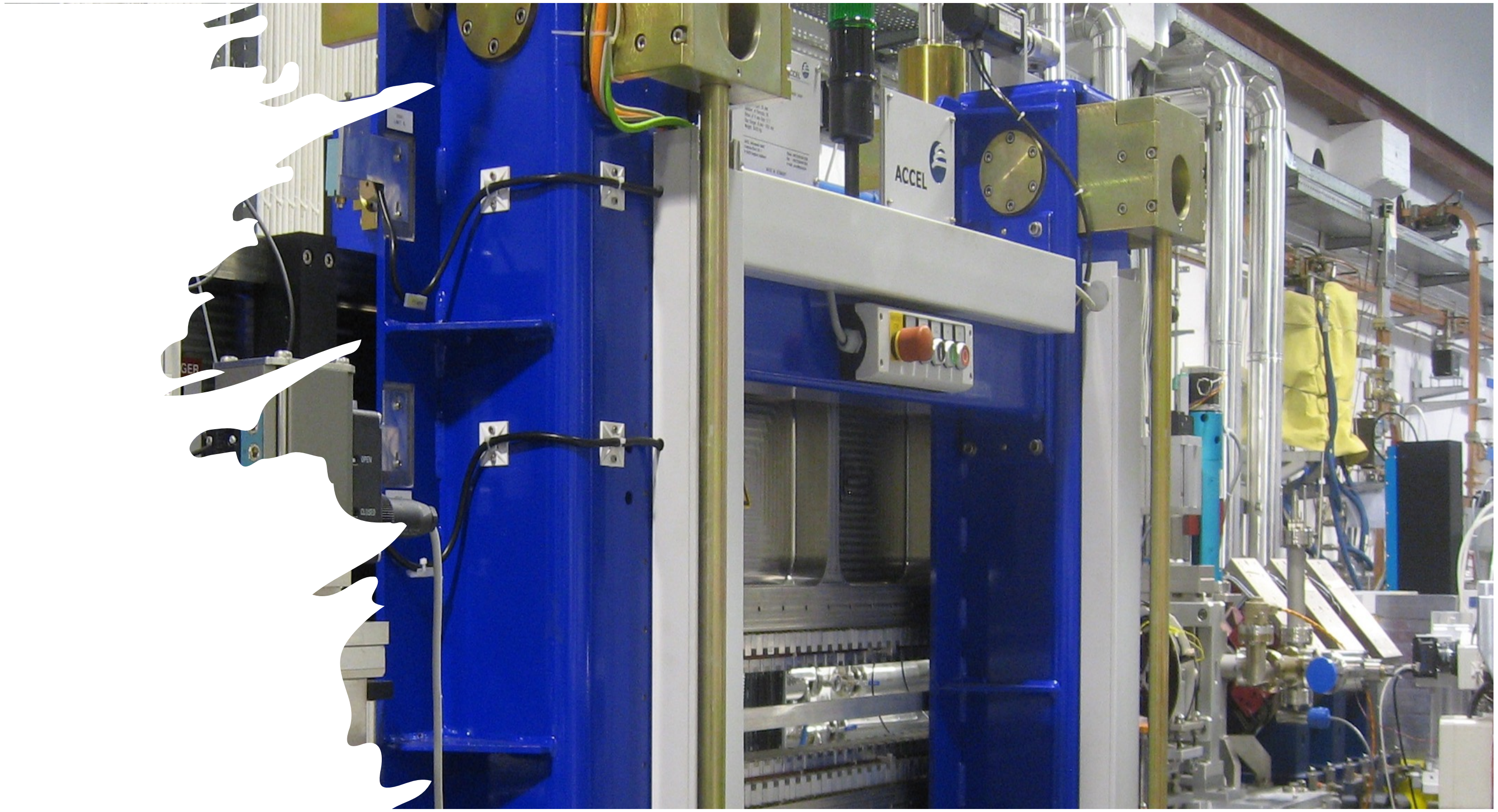
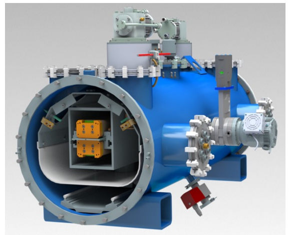


WA6 Report
FEL & Undulators

L. Giannessi (LNF), *on behalf of the WA6 collaboration team*

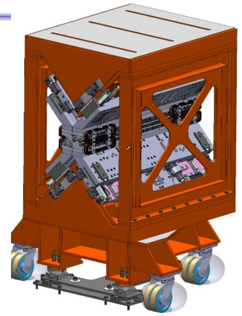
Cristian Boffo (FNAL), Mariano Carpanese (ENEA), Michele Castellano, Alessandro Cianchi (Un. TOV), Felice Dipace, Andrea Doria (ENEA), Mario Del Franco (LNF), Mario Galletti (LNF), Anna Giribono (LNF), Andrea Ghigo (LNF), Alina Iovine (LNF), Najmeh Mirian (DESY), Federico Nguyen (ENEA), Michele Opromolla (Un. Milan), Alberto Petralia (ENEA), Vittoria Petrillo (Un. Milan), Lucia Sabbatini (LNF), Andrea Selce (ENEA), Cristina Vaccarezza (LNF), Fabio Villa (LNF)

FEL Lines



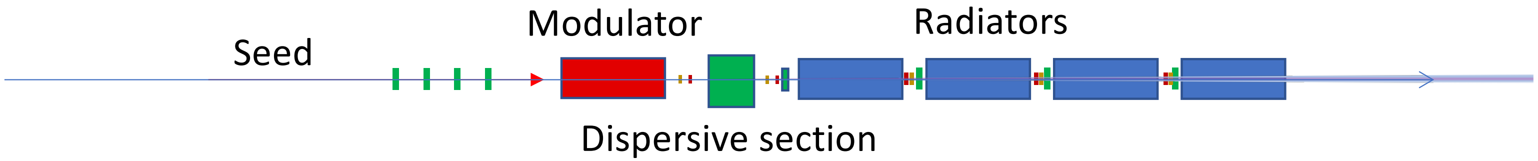
<u>Two FEL lines (ARIA) confirmed but not yet in the project budget:</u>

1) AQUA: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)

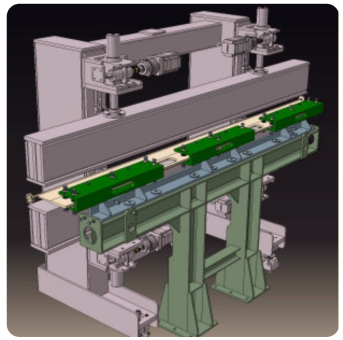


SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress

2) ARIA: VUV seeded HGHG FEL beamline for gas phase



FERMI FEL-1 Radiator



SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 430 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.

Notes from Committee report

"As understood now, the baseline design consists of the AQUA FEL line operating at a 100Hz repetition rate. ... Definition of the project baseline (including ARIA?) is also important to make sure the project baseline fits with the (a priori fixed) allocated budget of ~108 Me. The increasing material costs will likely have significant impact on the project cost and possibly timescale. "

Project baseline definition almost complete for the AQUA beamline. *The ARIA beamline requires specific funding, when eventually available the undulator specifications for ARIA are those of existing modules and do not need prototyping.*

"The AQUA and ARIA FELs seem to be proceeding along the correct trajectory. The use of tunable polarizations (linear, circular and maybe helical) need to be further explored. "

We present here an update of the work in progress

... further comments: investigate wake fields effects. -

Progress since previous meeting (June 6, 2022)

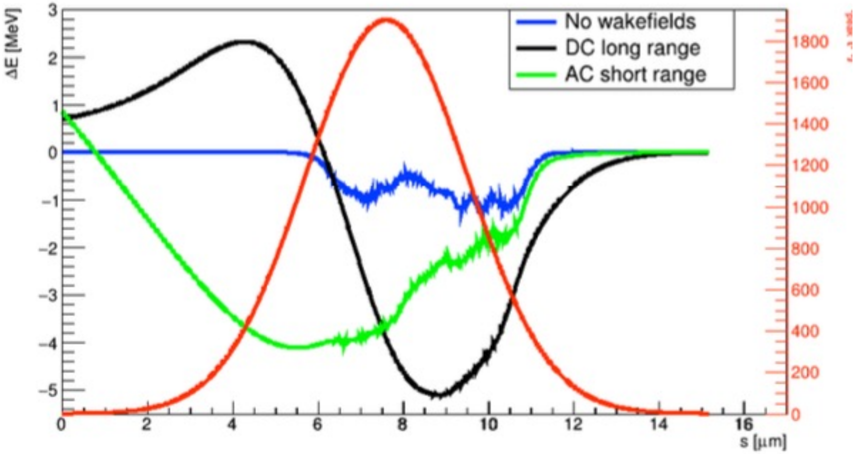
- **Simulations "in progress"**
  - First start-to-end simulation with improved peak current/beam quality – consistent beam & amplification simulated to undulator (C. Vaccarezza talk)
  - Analysis of wake fields and vacuum chamber design (aperture/impedance)

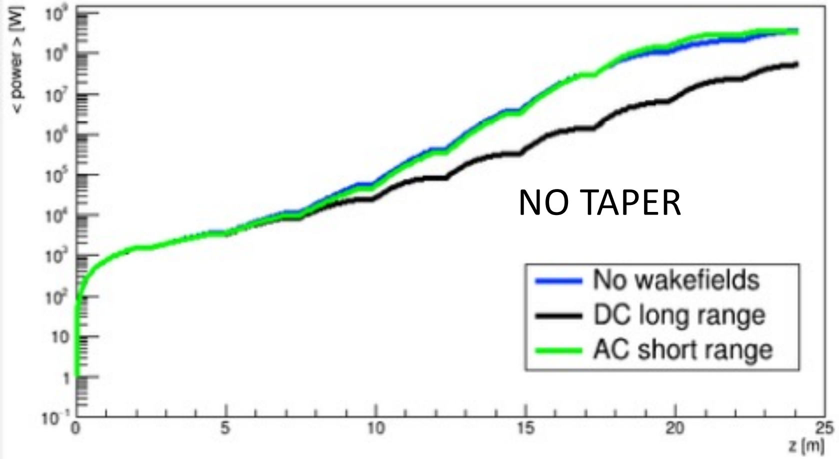
- **Undulator design**
  - Study of undulator terminations for field integrals minimization
  - Study of tolerances, impact of phase errors
  - Preliminary design (based on SABINA Undulator – KYMA)
  - Prototyping:
    - SABINA undulator under construction @ KYMA – first module assembly in progress
    - Status of SCU Undulator in construction at FNAL – final coil winding in progress

Analysis of wake fields and vacuum chamber design (Courtesy of Federico Nguyen, ENEA)

Wake fields analysis started; long range (Chao)/short range (K. Bane & G. Stupakov) models analyzed for the low charge, PWA acc. beam (30 pC) (high charge beam to be investigated).

- Vacuum pipe circular
- 2 mm radius
- resistive wall only





- Explored ideal beam only (gaussian current distribution)
- Undulator taper mitigates the energy detuning due to the wake, not yet considered
- Geometrical wakes to be investigated
- Transverse wakes & instabilities to be investigated

The transport of the high charge beam can be substantially more critical than the case shown here

Progress in undulator magnetic design (1) (Courtesy of Alberto Petralia, ENEA)

A larger aperture for the vacuum chamber requires a specific magnetic design, not equivalent to a "different gap"

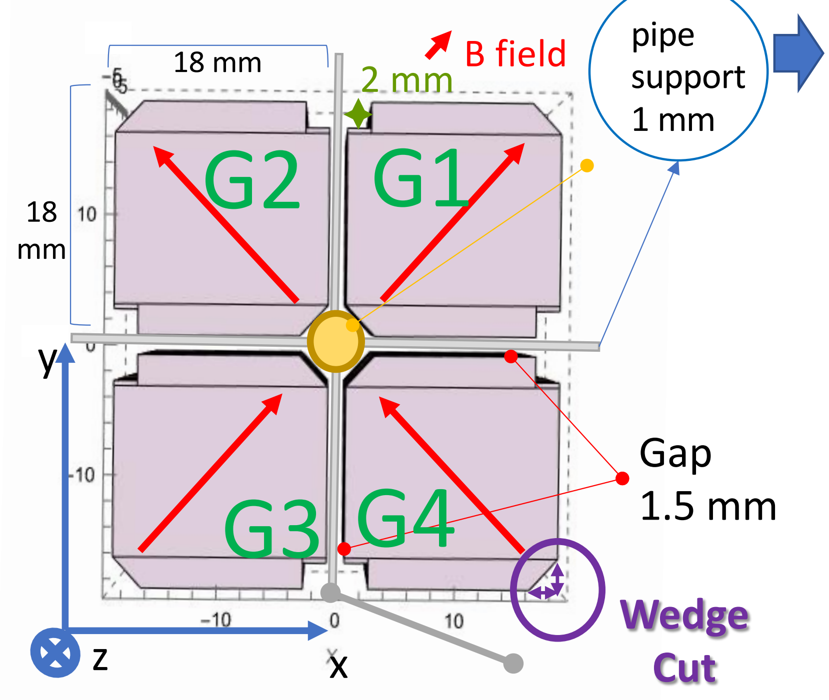
Modeling parameters

- Remanent field Br = 1.35 T
- Undulator period λu = 18 mm
- 4 blocks / period, NdFeB
- Block sizes (mm): 18x18x4.5
- Min. gap = 1.5 mm
- # of periods N = 110 (Lu=2m)

@ E=1 GeV

Pipe diameter	5 mm	6 mm	7 mm
Wedge cut (mm)	2.4	3.1	3.81
ϕ aperture (mm)	5.515	6.505	7.509
K max (in LP)	1.7	1.47	1.26
B max (T) (in LP)	1	0.87	0.75
K (RMS)	1.2	1.04	0.89
max λ (nm)	5.8	4.9	4.2
Negligible variation of the magnetic forces			

Transverse plane view



Vacuum chamber material/ construction/ support under study (A. Doria, ENEA)

Several options under study for vacuum chamber straightness:

1)stiff cross structure supported by blades (XFEL afterburner like)

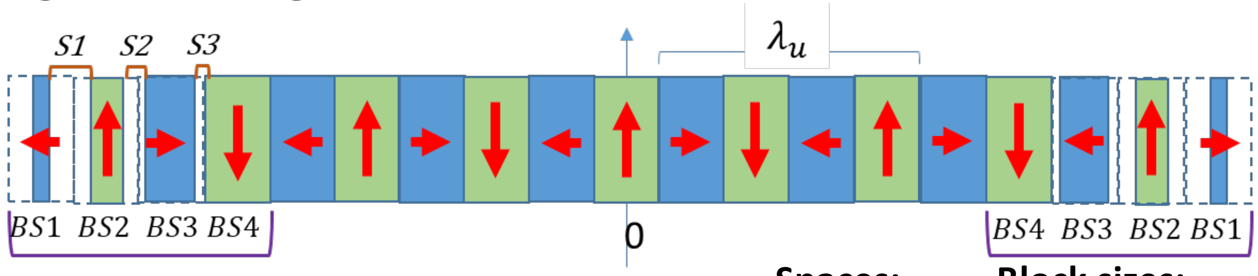
2) sail mast rigging like wires

3) mix of the two

Progress in undulator magnetic design (2) (Courtesy of Alberto Petralia, ENEA)

Choice of end magnets: minimizing field integrals

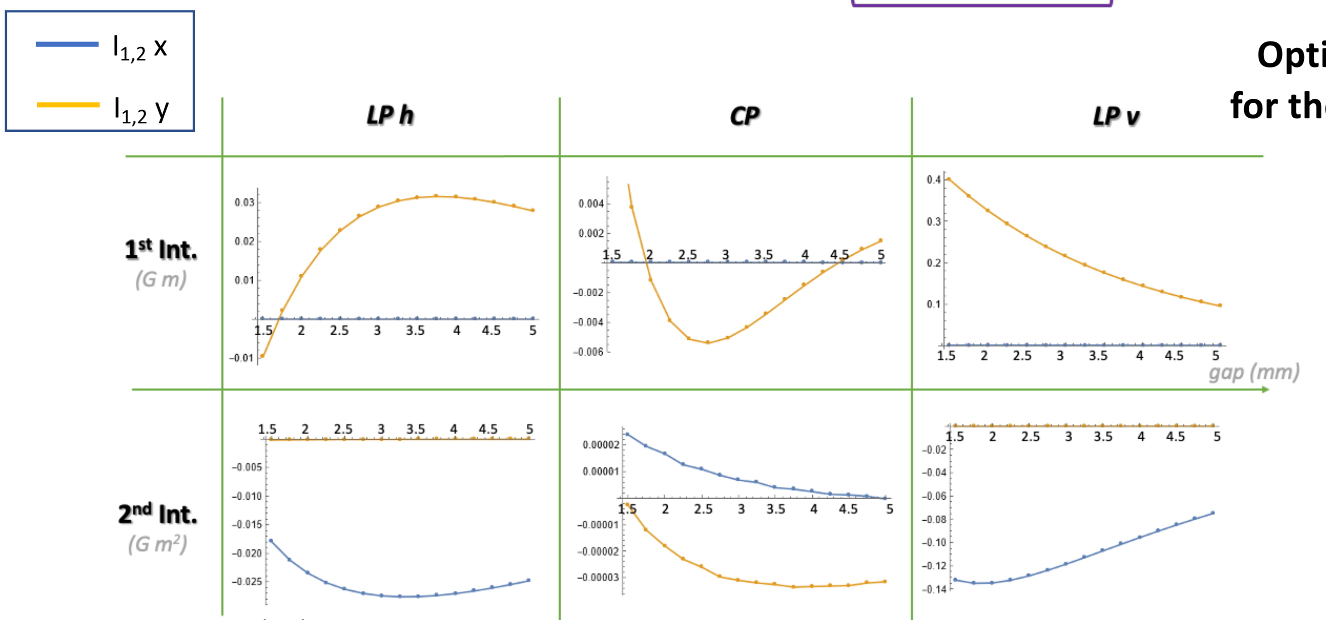
Field Integrals



- Block size realistic precision > 0.1 mm
- Further optimization **by shifting block positions** ∽0.1 mm

Optimized values for the end magnets: (mm)

Spaces:		Block sizes:
S1=0.1		BS1=1.1
S2=0.1	;	BS2=2.2
S3=0.1		BS3=2.4



	LP (h)	CP	LP (v)	units
Ix	0	0	0	G m
Iy	0.0119	-0.0095	0.4118	G m
IIx	0	-0.0179	-0.1322	G m^2
IIy	0	-0.0001	0	G m^2

Undulator Prototyping

- **SCU Undulator**
  - WIP at FNAL – Update from last meeting

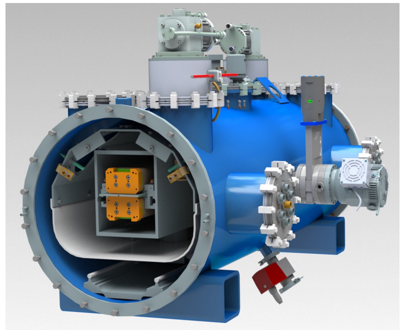
- **Apple X Undulator**

"In the framework of the SABINA project (IR-Thz FEL) development of (3) APPLE-X 1.3 m long modules. Mechanical design deformation & tolerance studies with the AQUA parameters TARGET – The undulator is a benchmark for a longer prototype that will be considered after the realization of these short modules."

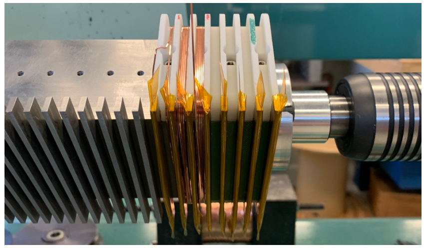
  - Progress on SABINA Undulator construction at *KYMA* (Delivery March 2023)
  - First AQUA Apple-X Sketch derived from SABINA Undulator (M. Del Franco)
  - Study of deformations on the SABINA Module (after 2Q 2023)

Timeline for SCU development at FERMILAB

(Courtesy of C. Boffo)

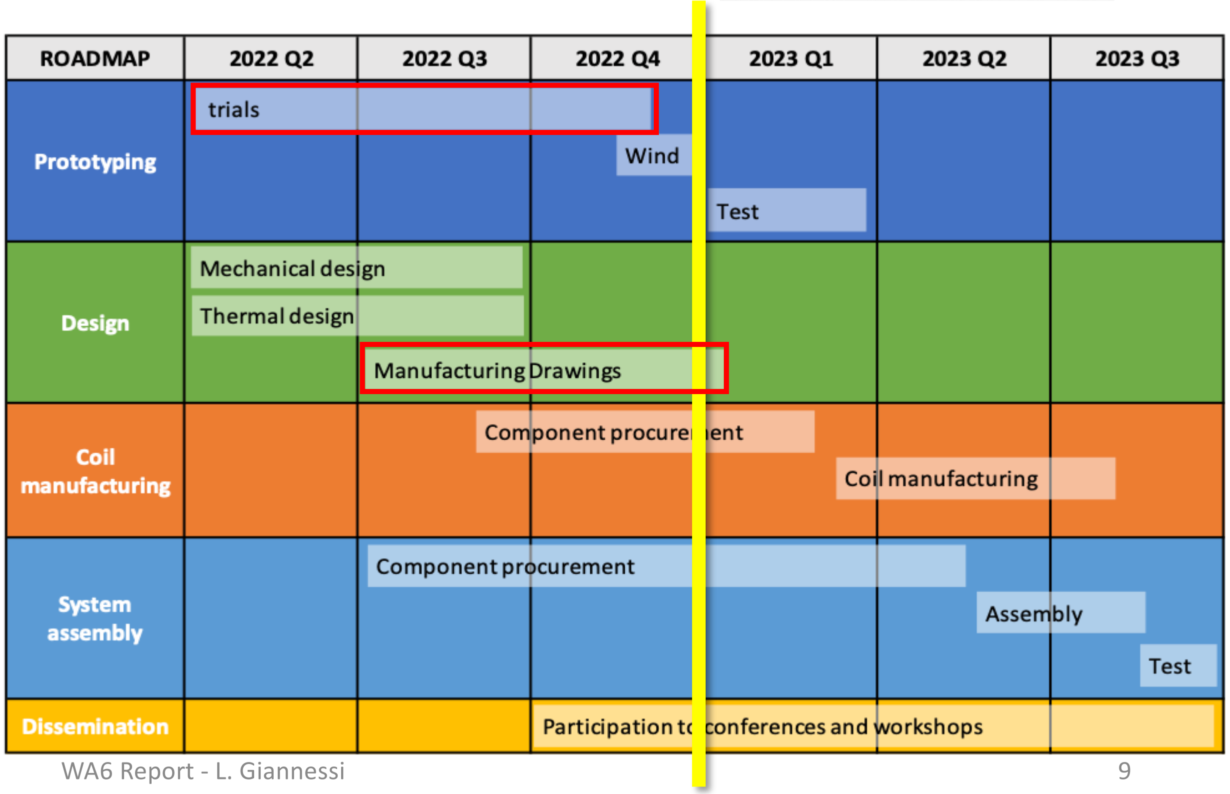


- Coil winding in progress (some delay in the prototyping / trials, now almost completed)



- Manufacturing drawings adapted to improved design
- Final deadline still unaffected:

Q3 2023 the prototype undulator should be completed – delivery in 2024

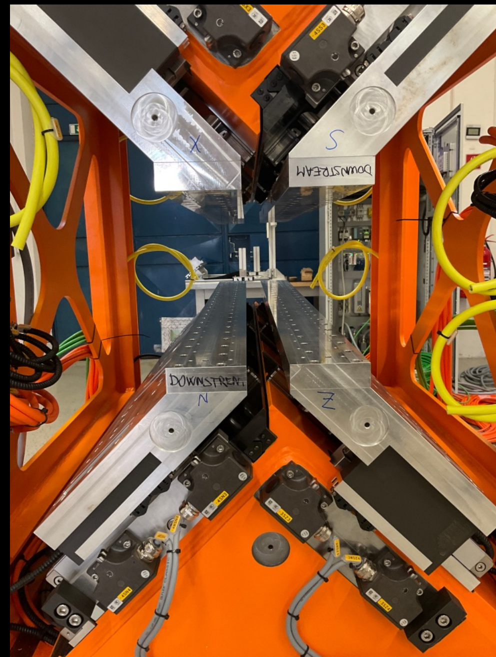


First SABINA module at *KYMA*, Sezana (SLO)

Last visit, Nov. 22, 2022

- Frames ready
- All components inhouse at *KYMA* (except for PLC controllers).
- First structure mechanical part assembled
- Tests of mechanical controls in progress (with a temporary PLC available at *KYMA*)

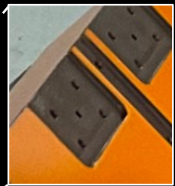
Next visit, Dec. 16, 2022



SABINA Undulator

Undulator frame

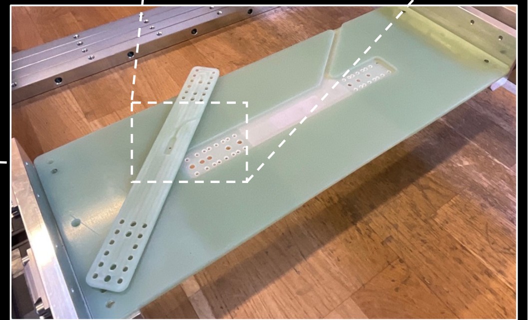
Vacuum/chamber blade fixed position



Holder for magnetic measurement board Vacuum/chamber

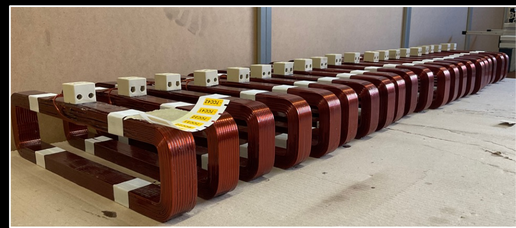
Undulator frame base

Magnetic measurement rails

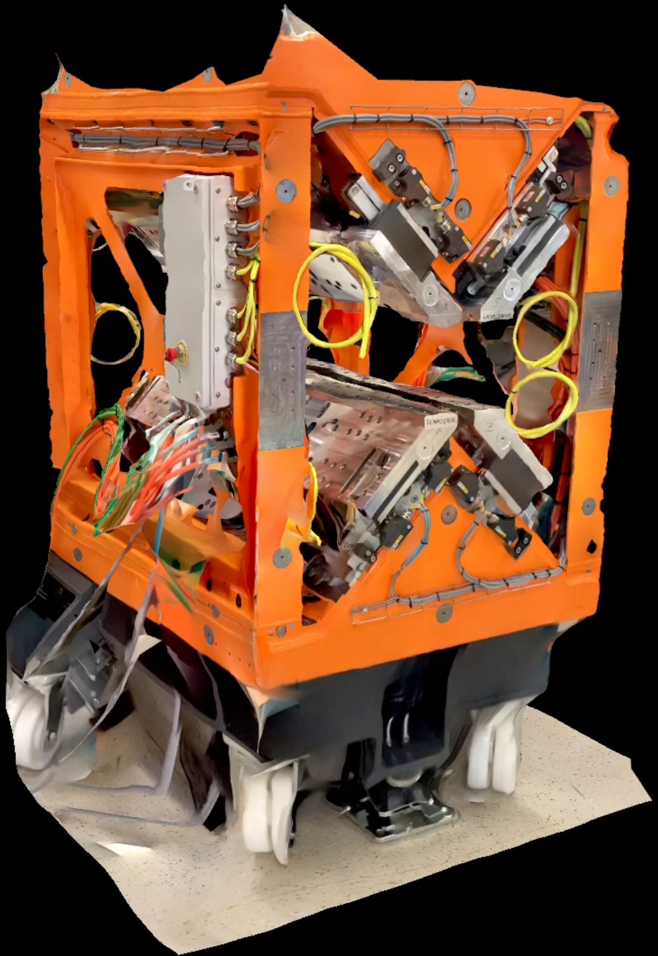


Hall probe holder

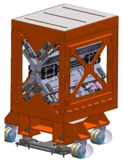
Correction coils



LIDAR 3D Scanner – Views of the SABINA Module



EUPRAXIA Undulator Mechanical Model (Courtesy of Mario Del Franco)

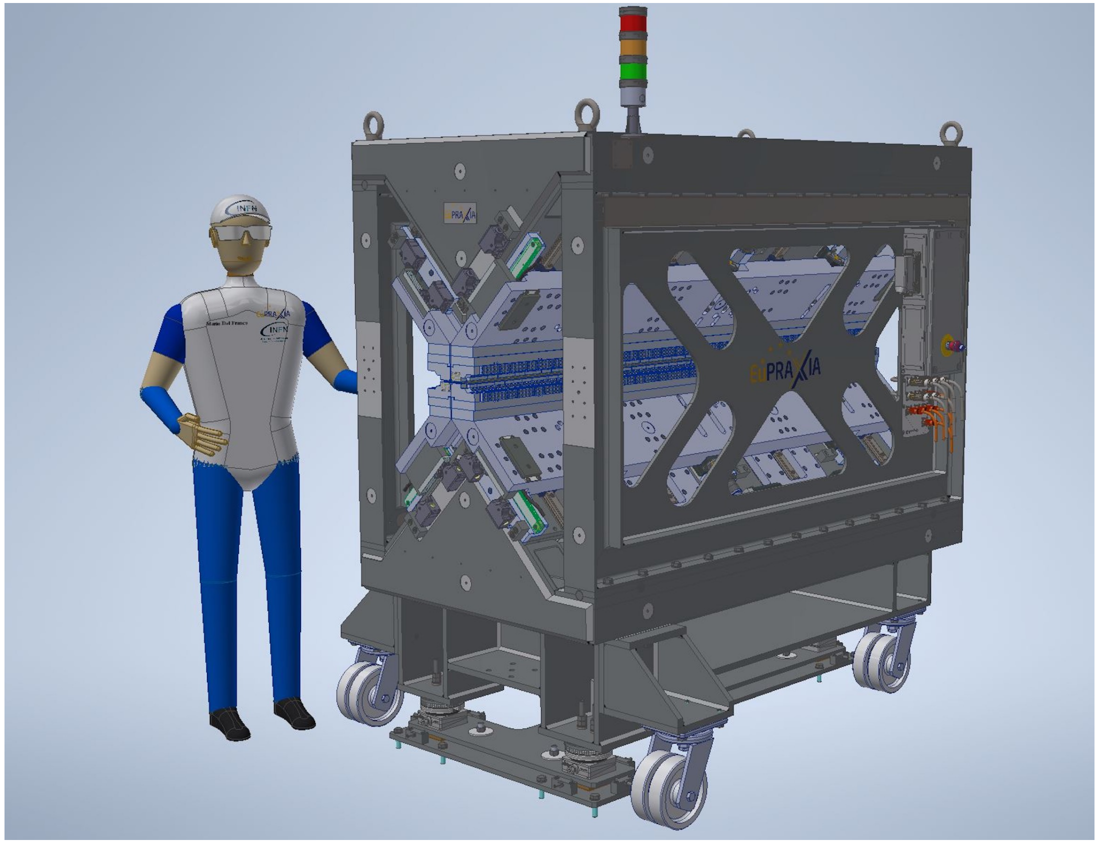
Derived from SABINA Undulator 

in construction at ***KYMA*** (APPLE-X 1.3 m long modules, period 5.5 cm – 10 mm aperture)

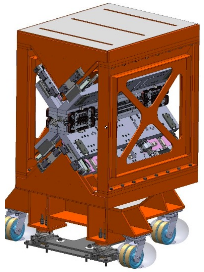
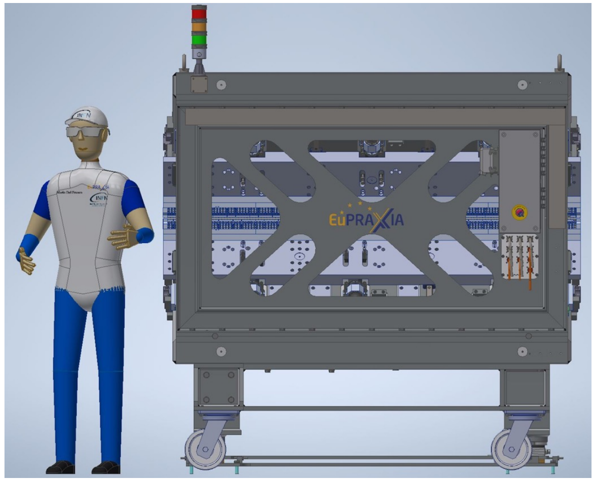
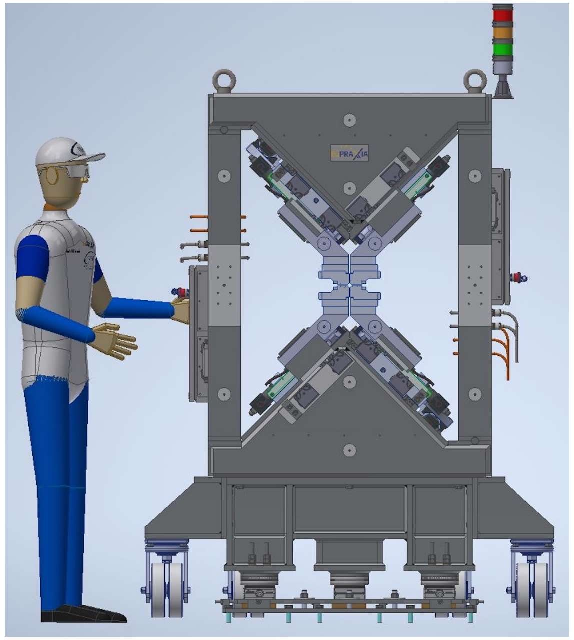
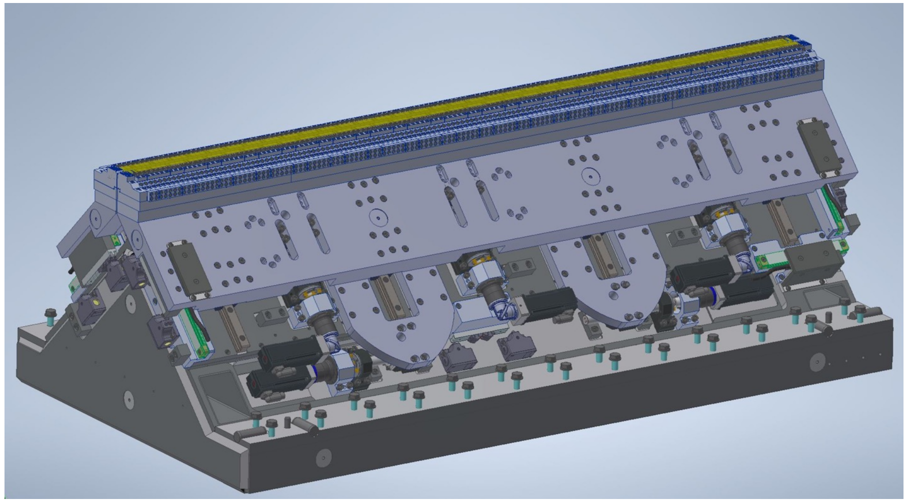
Length 2 m, 1.8 cm period,

Polarization circular left, circular right, linear horizontal, linear vertical.

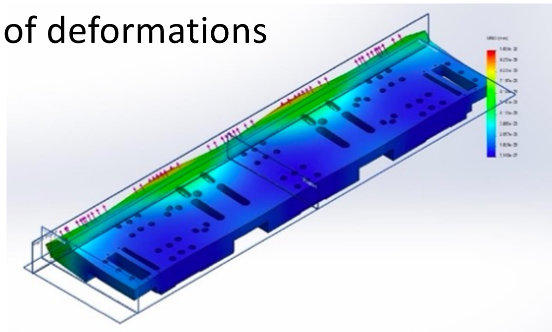
Symmetric field, in circular polarization same focusing strength on the two planes



Undulator Mechanical Model (Courtesy of Mario Del Franco)

SABINA undulator analysis
of deformations

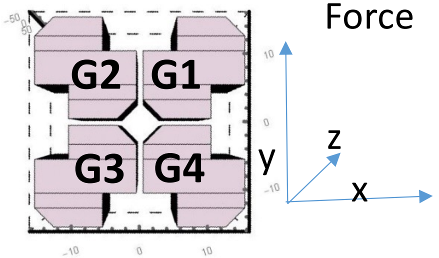


- Verify on the field the SABINA Undulator girder deformations (see next)
- Complete the AQUA mechanical design
- Carry on a similar analysis of deformations on the AQUA Undulator

Analysis of deformations

Magnetic forces on girders and effect on FEL gain: <u>work in progress.</u>

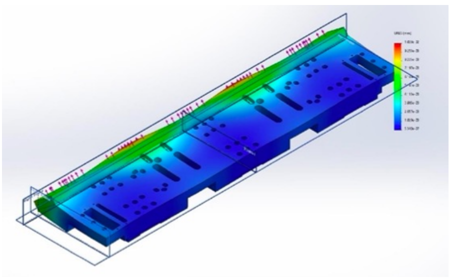
Force



Fx_{max} = ± 920 kg
Fy_{max} = ± 1200 kg
Fz_{max} = ± 160 kg

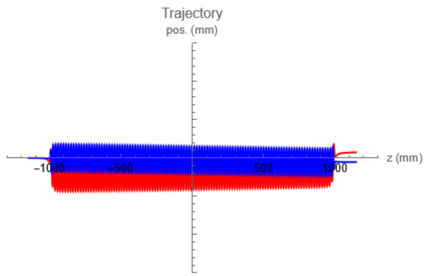
Alberto Petralia

Deformation



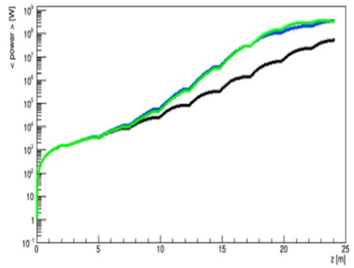
KYMA / Mario Del Franco

Field errors (integrals/phase)



Alberto Petralia

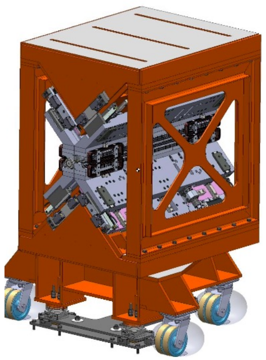
Effect on gain length



Federico Nguyen

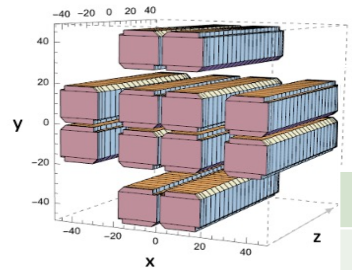
Mitigation:

(1) Stiffer structure



Mario Del Franco

(2) Compensation magnets



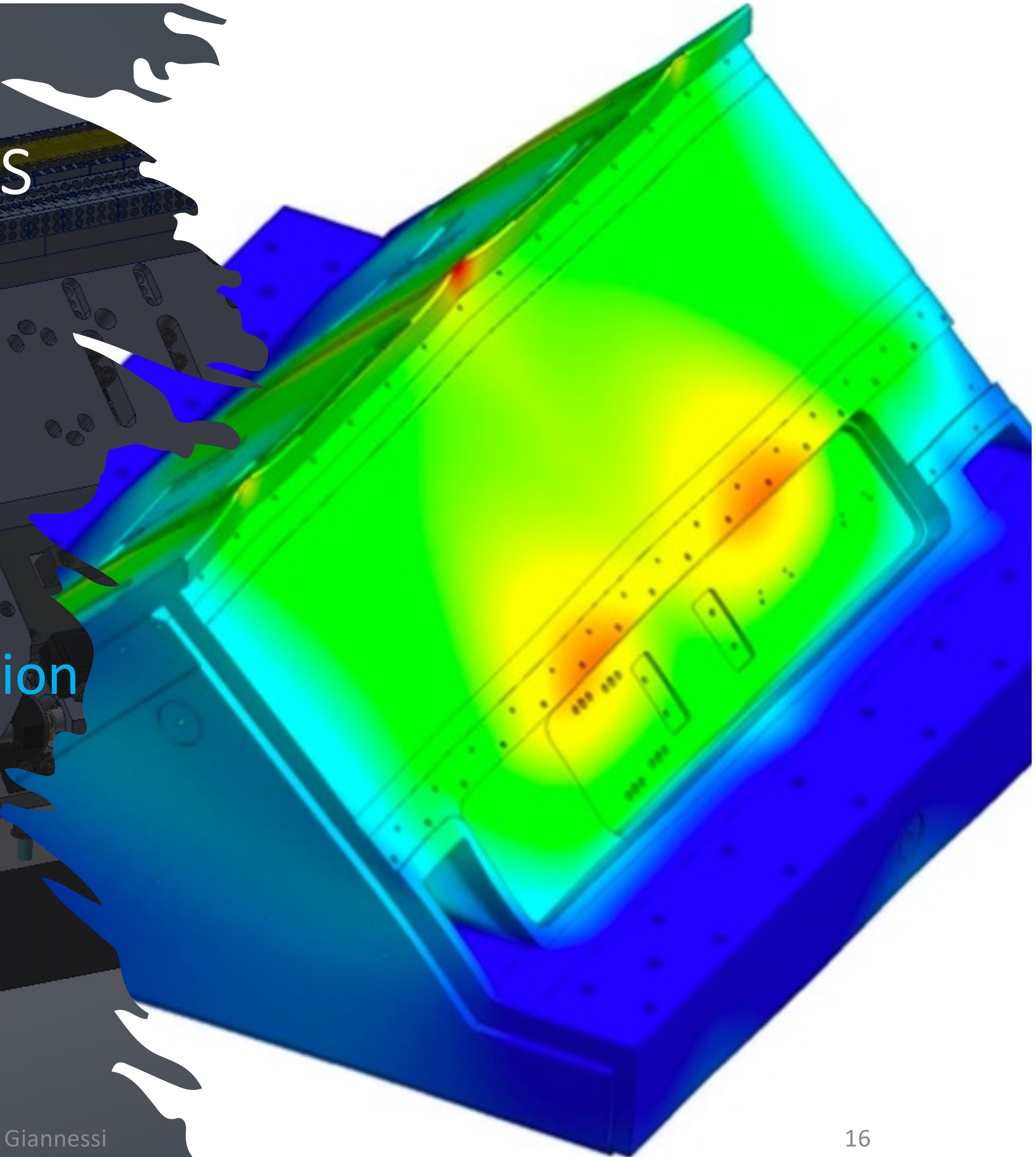
	No comp. mag. (Kg)	With comp. mag. (kg)
Fx	±920	±50
Fy	±1200	±155
Fz	±160	±30

Alberto Petralia

Measure of deformations

Collaboration with **H**olographyc **I**nterferometry & **F**ibre **O**ptic **S**ensors (HIFOS) Laboratory at ENEA

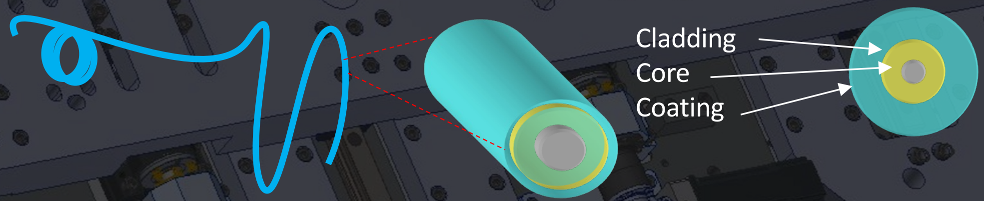
FBG Sensor: Optical fiber with diffraction grating along the fiber axis



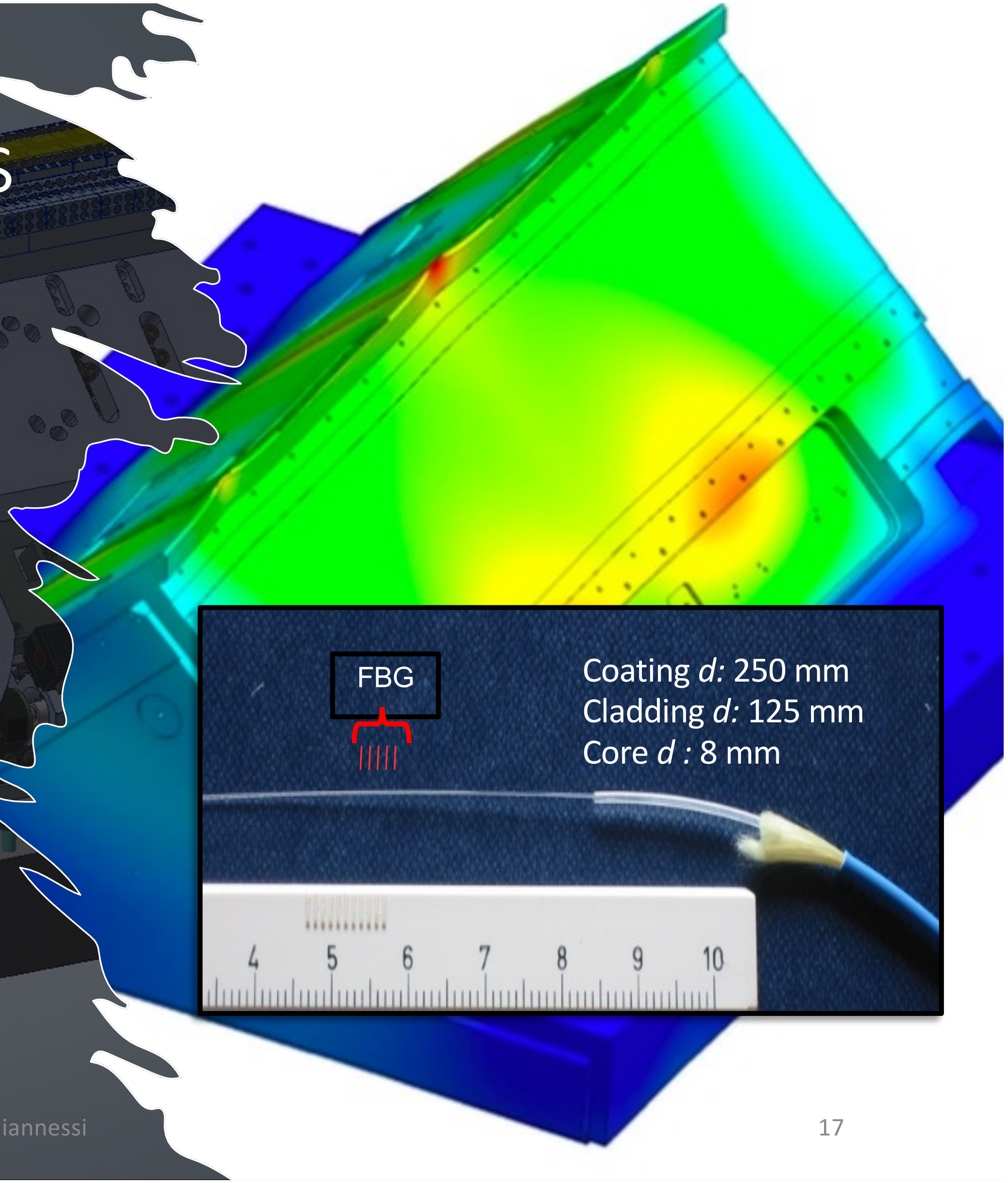
Measure of deformations

FBG Sensors *(Courtesy of M. Caponero ENEA)*

- The diffraction grating is produced by modifying the refraction index of the core of the fiber. Rough approximation: the refractive index has a sinusoidal modulation along the axis of the fibre.



- Sensor length 1-10 mm, temperature and strain sensing: 0.1K - $1/10^6$ relative elongation sensitivity
- Many sensors can stay chained along one fiber for quasi-distributed measurement
- Characterization of mechanical deformations
- Characterization of the local field to be explored, but
- … no sensitivity to e.m. fields (spectroscopic measurement)



STATUS

Steps to be completed:

1. AQUA Undulator magnetic design & specifications
2. FEL Layout definition
3. AQUA Beam optics analysis (undulator optics almost completed/spreader design in progress)
4. AQUA Base parameters simulation
5. Tolerance analysis
6. Start to end simulation
7. Definition of magnets specs
8. Final layout design

- done
- almost completed
- in progress
- yet to be done

CONCLUSION

- Beam dynamics **studies of combined RF+PWA accelerations** are showing a consistent progress towards high quality beams, **suited for FEL operation at the water window**
- The next step should include **analysis of wakes and a verification of the stability of the working point**: **sensitivity to jitters and errors.**
- **PRIORITY is given to PWA accelerated beam** – **pure RF X-band linac acceleration** provides **high charge operation:** larger number of photons/longer pulses – suitable for higher resolution spectroscopy – monochromatization/ ghost spectroscopy techniques. **Long-flat beam** (constant long. parameters) provides **narrow bandwidth seeded mode at ARIA line**.
- **The SCU undulator mechanical design is progressing**. Some delay in the definition of the final coil winding configuration are not affecting the completion deadline.
- **The APPLE-X undulator magnetic design is progressing**, we are closing the gap between mechanical deformations and their effect on FEL performance
- The Apple-X design is **taking advantage of the SABINA Undulator construction**. The synergy between the two developments is contributing to the both the mechanical design and the study of deformations of the EUPRAXIA Undulator.
- A strong contribution to the undulator design is provided by **FNAL (SCU undulator)** and **ENEA (AppleX undulator),** examples are study of, terminations, field integrals, deformations, forces mitigation, deformation measurements.