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The Synchrotron Radiation beamline as a pedagogical tool in engineering schools and universities

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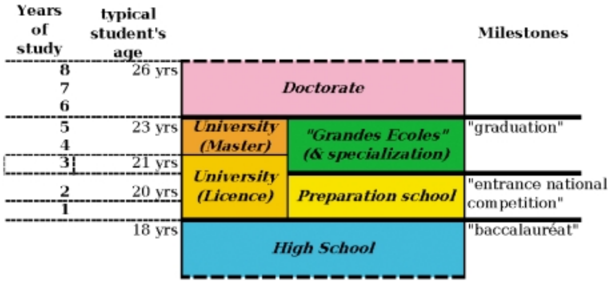
Abstract Abstract: As many superior education systems, French Grandes Ecoles have a need for a renewal of their pedagogy when teaching technical and scientific disciplines. The necessity of a multidisciplinary approach and a more efficient presentation of new collaborative tools (based on NICT) are among new key issues teachers are facing. We report an original pedagogical activity at Ecole Centrale Paris based on the multiple scientific aspects provided by the design of storage ring based synchrotron radiation beamlines. We intend to explain why this course has become a unique occasion for the student to discover how their basic knowledge in physics, heat transfer, mechanics, choice of materials and even social sciences can be put into practice. After five years, this course named ''integrated design of a synchrotron beamline'' has significantly increased the students' interest for basic and applied sciences. Results from a survey taken over the last four years are given.

1. INTRODUCTION: A Need for a Renewal of the Training of French Engineers

Traditionally, engineers educated in the French system are considered as talented persons, stemmed from a drastically selective system. Before they entered their specialization school (see table 1 and legend), they have systematically devoted two to three years to be trained in a ''preparation school'' to run competitive entrance exams so that they could be recruited by engineering schools on the basis of their skills in basic sciences (mostly mathematics and physics). Once they enter these engineering schools, they expect to be taught in a rather different way, so that they rapidly become efficient experts in their field (chemistry, electronics, aeronautics . . .).

A few schools, among which the Ecole Centrale Paris (ECP), have the ambition to give a wider spectrum to their teaching for a limited number of students selected among the best half thousand, each year. ECP strives towards training the future project managers, or engineers, who will be participating to the design or optimisation of a multiphysics system[1)]. The students graduating from ECP are hence expected to be aware of and understand the basics of each disciplines (mathematics, physics, thermal transfer, mechanics, materials, computer sciences, electronics, . . .), their concepts, standard approximations and solving strategies. They should be knowledgeable enough to argue with experts in each field and, in that respect, rely on a firm scientific and technical sole. This requirement for a large span of expertise involves a drastic change in the mentalities. Basic sciences, which were primarily considered for selection purposes, change their status. They ought to become the solid kernel from which other disciplines (such as thermal transfer, combus-

Table 1 Schematic French higher education system. The university path is widely open while the ''Grandes Ecole'' can only be accessed through a highly selective national entrance exam. These ''Grandes Ecoles'' provide France with most of the high level engineers, managers and entrepreneurs. They usually offer a general (common core) technical and scientific background and a strong specialization among different disciplines such as electricity, electronics, chemistry, civil engineering, aerospace, computer sciences, finance, . . .



tion, fluid mechanics, nano and life sciences, and other applied sciences) will develop. Such a transition in mentalities is often hard to carry out. In that respect, we believe that a multidisciplinary project based learning offers a greater opportunity of success.

2. Framework and pedagogical goals

As a recurrent request from potential employers, future engineers should be able to tackle a technically complex problem from a wide scientific perspective, fore backing on a confident knowledge of orders of magnitude. They are expected to have the ability to bring prospective from simple ''back of the envelop'' calculations. On the other hand, it would be inconceivable that they would not be familiar with today's appropriate information and communication techniques (ICT). They should master some standard numerical tools such as, of course a spreadsheet software (such as Excel), but also symbolic and numerical calculations codes (Mathematica, Mapple/ SciLab, Comsol, Python or equivalent) and Computer Aided Design programs (Catia, SolidWorks or AutoCad). Finally, the future engineer should feel at ease in a group, aware of the efficient behaviour conditions to carry out a successful team work. Today such a collaborative work must include the use of virtual environment and collaborative platforms using the internet technologies.

All these aspects are difficult to gather in a single activity and are frequently encountered separately in a standard engineer's curriculum. Since the sum of the parts is not the whole, Ecole Centrale Paris has been offering to a limited number of 4th year students (180, since year 2004) a so called ''active learning'' activity named ''Integrated Design of Synchrotron Beamline''[2)].

For a week, full time, the students are given the opportunity to see for themselves ''what it feels like to act as an engineer''. The purpose is to bring the students to an acute awareness of the richness of their curriculum, how their disciplines can be interconnected and their relationship to the ''real life''.

3. At the crossroad of an engineer training: The ''design of a synchrotron beamline'' activity

After four years of successful presentation to the students, the multidisciplinary training ''Integrated Design of a Synchrotron Beamline'', still appears as a rather unique teaching experiment[1)].

a. The synchrotron beamline seen as a pedagogical tool

To get started, no particular acquaintance with storage ring, accelerator or even synchrotron radiation (SR) physics is required. Students have to feel that, even with their modest knowledge in physics, they should be able to bring a significant, though partial, contribution to the design of a beamline.

The first morning of the week (**Table 2**), they are given two introductory talks (60 minutes each) explaining what SR is about, how it is generated, what it can be used for, what are the key elements of a beamline and what are the constraints an engineer is facing in that particular area.

Some emphasis is given to show what makes synchrotron radiation a particularly useful tool for imaging purposes in medicine of course (more powerful and versatile than the usual X-ray tube used for radiograms) or in biology, chemistry and materials science which are the most appropriate areas that appeal to students at this level.

Typically, a team is made of 21 students who will share the task to virtually build the beamline. They are splitted into four groups, each corresponding to one key component of the beamline. The extra student will act as the team leader. The task the students are then facing is the following: Given a set of 6 GeV electrons bunches at 200 mA current (standard parameters at the European Synchrotron Radiation Facility), each group is asked to design one of the following four parts of the ''synchrotron beamline'':

- The ''insertion device'' (ID). The global frame is provided as a numerical model under CATIA V5 software[3)]. Students should design the appropriate magnetic lattice for a given experiment (period, length, strength, magnets . . .) and propose a mechanical solution for precisely and securely driving the system. They should be able to explain the physics behind the SR emission process and what drives the spectrum characteristics. Students will acquire enough knowledge to motivate their choice between a wiggler and an undulator. Finally the spectrum is computed using the XOP software[4)]. It is this spectrum that will be used by the other groups downstream.
- The ''beam conditioning'' (BC). Students are expected to use their basic knowledge in crystallography, solid state physics and electromagnetism to explain how a perfect crystal (possibly with a focusing mirror) can be used to extract a particular set of wavelengths. By the end of the week, they are to provide a computer model of the monochromator with its driving system (with the requested precision). A well dimensioned cooling system must be included in the design.
- At the very end of the beamline, the ''sample environment'' (SE). Depending on the team, it can, for example, be a microscope using the X-rays if one is to conduct an element specific imaging of biological cells or, at another scale, a patient chair for performing a coronary angiography. This component of the beamline is often the one spe-

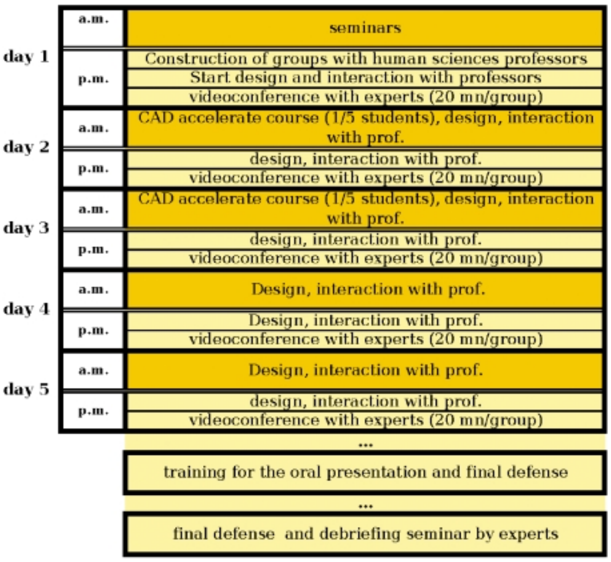
cifically designed for a particular experiment. It is thus at this level that the students are requested to calculate the photon beam specs such as the photon flux, the bandwidth(s) and the beam geometry. In the two above mentioned examples, these specs are very different. First, the angiography experiment requires high energy photons (30–40 KeV, contrast agent absorption edge) and fluorescence microscopy deals with valence electrons and necessitates low energy photons (around 6 KeV, in the case of chromium imaging). Second, for a real time imaging of a patient coronary angiography, the beam should have a typical transverse size of the order of 10–15 cm while element specific microscopy on biological cells need the x-rays beam to be focused down to a fraction of a micrometer.

- The ''front-end'' (FE). All students are to be aware of all the security issues involved in the design of a beamline. They are told that electrons and X-rays are strongly scattered or absorbed by the ambient air and therefore most of the beam path is confined in a secured succession of high vacuum pipes. The design of the beamline needs to include such a protection of the vacuum, insured by a system of valves separating the electrons in the storage ring from the synchrotron beamline. This is usually where the complex issue of heat load is first experienced by the students.

Even from such a partial description, the underlying complexity of each of these objects clearly appears to our students. Moreover, no object being completely isolated from the others, the mutual dependencies are conditioned, at least, by the amount of heat each component should evacuate. Moreover the students also quickly become aware of how the spectrum is modified through the propagation of the radiation in the beamline from one component to another.

Teams of 21 students per beamline, each divided into four subgroups (ID, BC, SE, FE) of five students plus one team leader. They are asked to design, scale and possibly optimize the above mentionned four key components in order to virtually build a technologically sound synchrotron beamline for a dedicated purpose. Since year 2005, two teams are assigned respectively an X-rays fluorescence microscopy and a high energy X-rays coronary angiography beamlines designs (respectively based on ESRF ID21 and ID17 beamlines).

Table 2 A typical ''Design week''. Note that students are asked to give intermediate deliverables every evening shortly after their interview with the experts. A final report (built up from their modified intermediate results) is posted on the collaborative workspace on the evening of day 5. Training for oral presentation is typically on week after day 5. The final defense and debriefing take place about 3 weeks later.



day 1	a.m.	seminars
	p.m.	Construction of groups with human sciences professors
		Start design and interaction with professors
		videoconference with experts (20 mn/group)
day 2	a.m.	CAD accelerate course (1/5 students), design, interaction with prof.
	p.m.	design, interaction with prof.
		videoconference with experts (20 mn/group)
day 3	a.m.	CAD accelerate course (1/5 students), design, interaction with prof.
	p.m.	design, interaction with prof.
		videoconference with experts (20 mn/group)
day 4	a.m.	Design, interaction with prof.
	p.m.	Design, interaction with prof.
		videoconference with experts (20 mn/group)
day 5	a.m.	Design, interaction with prof.
	p.m.	design, interaction with prof.
		videoconference with experts (20 mn/group)
		...
		training for the oral presentation and final defense
		...
		final defense and debriefing seminar by experts

b. Expected pedagogical outcomes

It can be argued that such a teaching is very much inspired from traditional ''project based training''. However, there are interesting points that bring a different dimension to this activity.

Firstly, the time structure is very short, it stands in a single week, full time. Very often projects are spread over a much longer period of time with few hours a week dedicated to the activity. Here, the schedule is so condensed that if the Monday, hardly any student know anything about synchrotron radiation and mechanical design, by the Friday, they all know the differences between a monochromator, a mirror and a filter, what power density is bearable for aluminium or tungsten, how one can play with mechanical properties and thermal conductivity of In-Ga and why a 3D CAD-model should be parameterized.

As the work progresses and the end of the day approaches (with the requirement to deliver the intermediate results), there is a rise in the stress of each group. This increasing tension generated by the necessity to satisfy daily deliverables, becomes a driving force of the learning process. The reason is that it encourages each member of the group to be more efficient and find his role in the design corresponding to his own area of expertise for the mutual benefits of the team as a whole. Students who are unfamiliar with group activities, in particular the necessity of sharing, learning from others, distributing evenly the workload, become aware of the role played by the team, in a matter of hours. They rapidly learn that the difficulty is not only brought by the isolated problems but by their interplay. The complexity is to account for every aspects of the problem so that the final design integrates explicit and implicit constraints. The specifications for each beamline, presented to the students the first day, are usually concentrated on a single sheet of paper, written in a style very different from the one encountered in academic problems. Here no exercise is given. It is a typical ill formulated, opened problem, close to those encountered in some Problem Based Learning approaches. It becomes immediately obvious that there is probably no unique ideal solution. The almost infinite number of degrees of freedom will appear progressively. Though many information are delivered, much more is hidden behind the simple words. One single value generates the necessity to understand some highly technical problems, implying a whole set of constraints and yielding a bibliographic search, a great deal of computations or a mere curve fitting.

Though ECP teachers in physics, thermal transfer, mechanics-CAD and materials choices are readily and immediately available upon request, they merely represent the academic side of the minimum necessary knowledge in basics sciences. In particular, none of them can reliably state on the viability of the global design of the beamline. So as to avoid unnecessary wandering in the design, and in order to be confronted to the reality, daily conception choices are to be validated by a remote submission to outside consultants. These consultants are experts in synchrotron beamline designs, working in one of the synchrotron facilities around the world (Grenoble and Saclay in France, Brookhaven in USA or Hyogo in Japan). Such remoteness amply justifies the resort of synchronous collaborative tools as explained in the section 5.

In that framework, the students are to imagine, design, calculate, scale but they are also facing the necessity to check the coherence of every values or pieces of drawings. As they become confronted with the advent of a tremendous flux of information, they thereby learn not to take for granted unexpected numerical values as well as the necessity to balance the ''reasonable doubt'' and faith in their co-workers.

4. A ''wide spectrum'' of interconnected disciplines

As mentioned earlier, in this course, we decided to rely on five major disciplines: physics, mechanics and mechanical design, materials science, heat transfer and human sciences. We here give a brief overview of what needs, difficulties and work is expected from the students in each of these topics.

a) Physics

In this particular project, the initial orders of magnitude are conditioned by the type of experiment to be performed on the sample. Hence, the study requires an accurate initial estimate of the desired X-Rays flux in a given bandwidth for a specific beam shape. These calculations involve a good understanding of the physical processes (absorption, fluorescence, scattering . . .) and will prove to be crucial for the work of the entire team. More often than not the values have to be refined during the week as the signal to noise ratio turns out to be shadowed by severe over heating issues. Students in different groups will encounter different aspects of physics related to their recent curriculum: of course electromagnetic spectrum from a relativistic particle but also Bragg law, index of refraction and plasma frequency, crystallography and structure factors computations. As an example for the latter, student build up a simple computer code using interpolation form of atomic scattering form factors. They can then choose the best type of crystal and miller indices for their monochromator. They will later use a more professionally oriented program such as XOP. All these difficult topics that where once taught to the students, with no connection to a clear necessity, now take a new importance and students who previously did not show any particular interest in physics become aware that such aspects can not be avoided. On this occasion, physics does become part of the standard engineer's toolbox.

b) Mechanics and mechanical design:

From a mechanical design perspective, the students are basically required to conduct a real preliminary plan. This is new and often has a destabilizing effect on them. In priority, they are to work on orders of magnitude allowing for the choice of technologies. They should therefore find the most appropriate model. Thereby, one breaks with the usual progress of a classical course in which the model and the underlying hypothesis are ordinarily provided to the students by the teacher at the beginning of the course.

The final goal is here to quickly converge towards an architecture scheme where the main components will be integrated into a 3D CAD model under CATIA V5.

Students will then be asked to justify their choices from a technical as well as a financial point of view. Assessment of the work is not based on the level of complexity of the models or theories but rather on the relevance of the studies that where conducted. One new aspect that is worth noting is the necessity for the students to progress iteratively in the conception work to bring their model to a viable result.

One should note that, usually, few students spontaneously recourse to the use of appropriate numerical tools to help them with such an iterative process: from the mere EXCEL spread sheet to more advanced programming tools such as MatLab or Python short programming. This course clearly emphasizes the necessity to recourse to that type of numerical tools when one deals with an actual exploratory study.

c) Science of materials

Diamond, steel, copper, indium, gallium, silicon, tungsten, aluminium, neodymium, boron, samarium, lead, . . . This list is only a sample of the wide variety of materials encountered by the students during their design of a synchrotron beamline. Much more than a simple catalogue of materials, the present active learning activity offers to the student the unique opportunity to address the question of the choice of materials inside a complete design process. Whereas traditional lectures and exercises sessions must introduce all the basic properties (crystallography, mechanical properties, elasticity, plasticity, defects, corrosion . . .), here the students are asked to use this basic knowledge in a practical case. The first challenge for the students is probably to point out the key material properties required by the various, and often extreme, working conditions. The first material selection is done using the performance indexes as proposed by Ashby5). This qualitative selection must then be refined in terms of quantitative values of the required material properties.

This quantitative step leads the student to face the physical limits of materials: e.g. finding a ductile material having a melting temperature of 10000K is rather difficult. . . . If they cannot change the design to reduce the imposed temperature, they will need a material having a high fusion temperature and a good thermal conductivity in order to cool it efficiently. This leads to an additional material property requirement! Mechanical and thermal calculations enable them to evaluate the various stresses and constraints their object will face. But such calculations can only be done using the correct material properties . . . the design process is thus iterative and strongly underlines the connections between theoretical subjects (thermal transfer, mechanical design, mechanics, joining processes, . . .).

At the end of the week, students have become familiar with the practical importance of the Young modulus, the melting temperature, the ultimate tensile strength, the density, the thermal conductivity, the thermal dilatation, the ductility, the magnetism. . . .

In addition to these intrinsic material properties, the student are also asked to check the compatibility of there choices: is gallium susceptible to embrittle copper by penetrating along its grain boundaries? Can the material chosen to support the insertion device magnets be also magnetic? Finally, once the material choice is almost made, the question of price and practical realization arises. What kind of forming and joining process can be used (foundry, machining, powder metallurgy, welding . . .) for the object that was designed? These essential questions lead the students to look for the actual industrial processes and possibly identify their various advantages and drawbacks.

d) Heat transfer

Thermal aspects of the ''problem'' are not given on the first day. The students know that they have some choices to do concerning the global design of the beamline, some dealing with the materials, others for the X-ray energies, but no direct question is asked that would drive them to some heat transfer modelling. They must discover by themselves that they will inevitably have to include efficient cooling devices in their design of the beamline.

Students use thermal properties to choose the best material for a given purpose, but they first must define very precisely this purpose on heat transfer criteria. For instance, the team in charge of the the front end fast shutter must compare materials according to thermal diffusivity in spite of thermal conductivity, because of transient heat transfer phenomena involved in the use of this device.

Calculating a convective heat transfer power is easy when the flow rates, the sizes of the tubes, the thermal properties, and so on, are already known. It can noticeably be more difficult to do some reverse engineering on the same problem. That means: design a system that will provide some given heat transfer exchange without any knowledge of the geometry and the sizes, the materials, the fluids, the inlet and outlet temperatures, even the type of heat transfer mode one can use between conduction, convection, radiation. . . . It becomes even more difficult when one must take into account some specifications as maximal flow rates (for non-vibration reason), maximal size (for reasons involving physical geometry of the experiment), economic limitations. . . .

This pedagogical activity is the first occasion for the students to encounter a non-linear computation as well as many necessary feedbacks and many unwanted dead end modellings. They must sometimes use Comsol [6] or equivalent finite elements numerical codes because of the failure of the ''blessed analytical'' one dimensional methods.

e) Human sciences for a better team work

The Human and Social Sciences Dept at Ecole Centrale Paris has a wide panel of activities. The main goal is to help the future engineers and managers to develop their knowledge of themselves and the outside world, especially that of companies. The department offers a teaching aiming at encouraging initiative and team spirit as well as a help for a careful choice of the students' first field of activity and work experience.

Within the framework of this ''synchrotron course'' and based on the principle that two roles are present in all group activity–a functional role and a behavioural role-, the Human and Social Sciences teachers have here two goals: firstly to develop students' teamwork abilities and secondly to improve their oral expression and communication skills with the overall aim of strengthening conceptualisation and the ability to put theory into practice. The ''subgroups'' for each beamline team are organized by means of the ''Belbin test''[7]. Given the personality types and needs of each team, this tool enables roles to be identified and allocated.

The cultural diversity of the students in this project (in 2007, 12 different nationalities were represented within the 42 students) should result in a rich and meaningful dialogue yet, at the same time, demonstrating the difficulties of group co-operation to achieve a complex technical end result.

By combining a theoretical background, the Belbin role model, group work functionality, communication and the principles of progress meetings as well as feedback and analysis of the key drivers to project success, participants understand and develop those lasting and transferable skills needed for the teamwork situations they will encounter in their future careers.

Each student is evaluated on his/her ability to become part of a group, to work in a team and his/her involvement in and contribution to the project as a whole.

5. A Numerical Environment for a better efficiency

Synchronous communication tools allow for a remote collaborative work. In this activity, students can consult the remote experts (France, USA, Japan) using a common whiteboard, sharing documents and applications. Though no student is particularly familiar with that type of professional videoconferencing, the tools are rapidly adopted, especially as the experts, who are better acquainted with their use, systematic resort to them during the daily 20 minutes interviews. Students indeed become aware of the power of ''a little sketch'', even a primitive one, to explain a structure or a principle diagram in the framework of a pilot study where the time saving can be crucial. **Fig. 1** shows such a modest drawing for a double bounce mirror, jointly ''elaborated'' on a shared whiteboard by the students and the expert during a critical analysis of a design choice.

It is essential to note that these collaborative tools have been rapidly adopted by all the participants

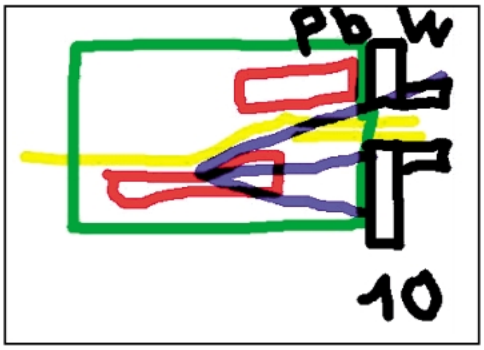
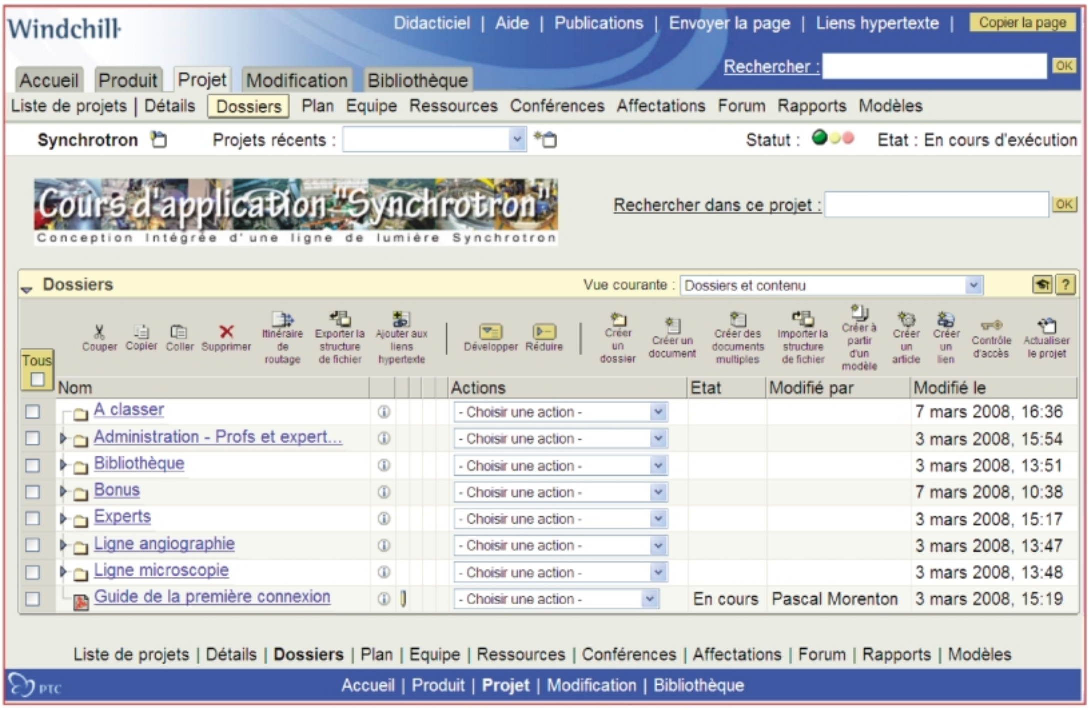


Fig. 1 A rough (preliminary) sketch (''hand drawing with the mouse'') of a harmonics rejecting mirror shared by the parties during the videoconference on a numerical whiteboard.



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☐	Bibliothèque	- Choisir une action -			3 mars 2008, 13:51
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☐	Ligne angiographie	- Choisir une action -			3 mars 2008, 13:47
☐	Ligne microscopie	- Choisir une action -			3 mars 2008, 13:48
☐	Guide de la première connexion	- Choisir une action -	En cours	Pascal Morenton	3 mars 2008, 15:19

Fig. 2 The Windchill collaborative workspace

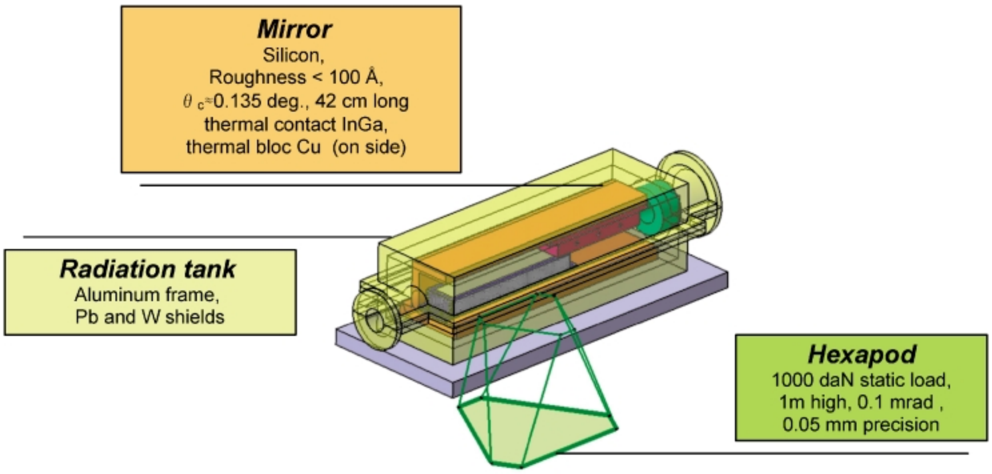

Fig. 3 CatiaV5 model for an harmonics rejection double mirror system and its hexapod elaborated by the students at the end of the 4 days work. Note that there is a huge difference with the initial hand-drawing (Fig. 1) shared with the experts on the internet video-conference whiteboard. All values and choice of materials were chosen by the students using knowledge from the courses of their curriculum. The hexapod part turned out to be too complicated to be designed by the students.

Table 3 Cumulative results of an anonymous opinion poll about the activity over the last 4 years (not all students answered the poll)

Anonymous Survey on 101 students for years 2005/2006/2007/2008	Definitely yes	Yes	No	Definitely no	No opinion
Think the course is useful to future engineers	73	28	0	0	0
The activity strengthened the interest in basic sciences of the students curriculum	40	37	13	0	1
Found the double approach ‘‘hard/soft sciences’’ important for a better pedagogical impact	42	39	13	2	3
Useful for better awareness of condition for successful team work	35	40	13	0	1
Found that collaborative work was essential to this project	42	46	7	1	2
Would advise other students to take this course	80	15	2	0	1

thanks to their easiness to implement. No particular sophisticated function is expected but emphasis is put on ergonomic aspects in implementation, installation and use.

After a careful benchmarking, we chose the solution provided by Webex in its ‘‘Application Service Provider’’ mode[8]. In this configuration, neither web server nor software is installed on the campus. We are mere web users of the services through the internet. One advantage of this approach is that firewalls are no longer an issue.

Asynchronous communication tools allow for managing the flux of documents between the students and the experts. As for the synchronous communication tools, we also chose an outside provider of collaborative workspace, Windchill[9]. Here also, the functionalities are limited, but the tools are easy to setup, through a friendly web navigator as displayed on **Fig. 2**.

The use of such a virtual workspace however brings additional constraints as compared with less structured and faster information dissemination means such as e-mail or FTP. It is thus vital, in the initial phase, to enforce its use notably for daily deliverables and questions postings to the experts. Quickly, the students discover the benefits of this tool and come to adopt it even for internal management of their documents.

Moreover, the students rapidly become aware of the necessity to go through many iterations of the design process before they can converge to a solution accounting for the numerous constraints implicit or explicitly in the specifications. Use of modelling, computation, analysis or simulation tools is strongly encouraged. **Fig. 3** shows a parameterized model for a harmonic rejection double mirror system obtained with CatiaV5. It allowed the students for evaluating different configurations by a mere change in geometrical, mechanical or physical parameters values.

6. CONCLUSION: the activity from a student perspective

This pedagogical activity brings numerous challenges to the students at the scientific and technical levels (degrees of freedoms, number of parameters in the design) as well as at the project team set up level (remote experts, multidisciplinary team coordination …). Let us emphasize the fact that the purpose of such an activity is not to actually build a synchrotron beamline! Our goal is pedagogical and the teachers team aims at bringing the students to an acute awareness of their scientific potential, the connection between the disciplines of the curriculum, the power of a well organized team work and the numerous possibilities of a collaborative numerical environment.

Table 3 reports the results from a survey conducted during 3 years among the students participating to the activity. The ''Integrated Design of synchrotron beamline'' activity proves to bring the students close to industrials issues that make vital the use of such scientific knowledge, tools and methodologies. By making the students actors of a project, derived from a real case, teachers thus show how and why they are to be used in the industry, especially in the case of multiphysics complex cases in the aim of which engineer-students at Ecole Centrale Paris are being trained.

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6) Comsol is a multiphysics simulator environment. More nformation at http://www.comsol.com/
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8) Webex is a videoconferencing solution. More at http://www.webex.com
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