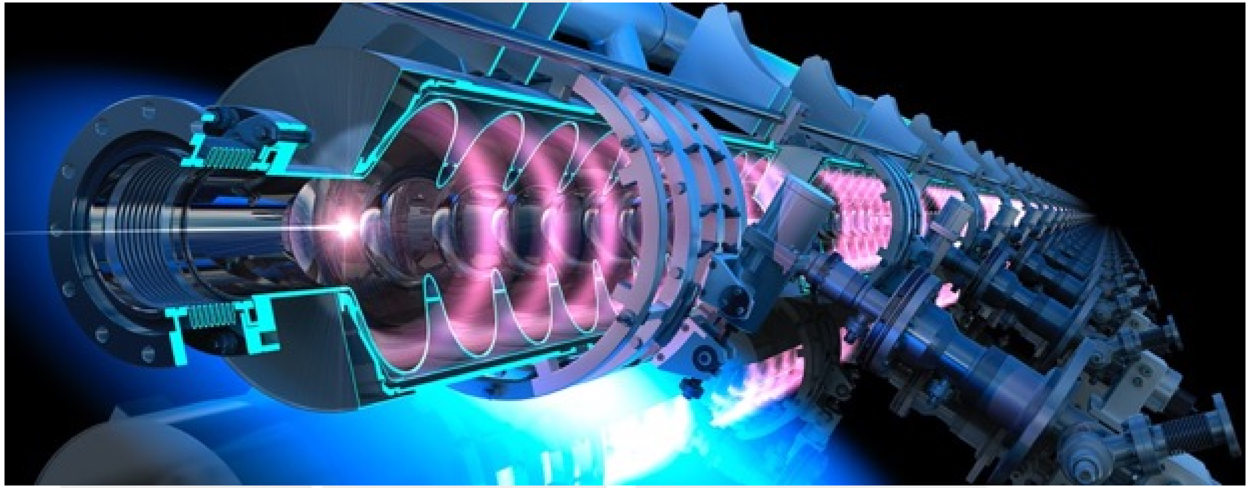
WISHEPP 2021

5th Winter School in HEP- Special Edition



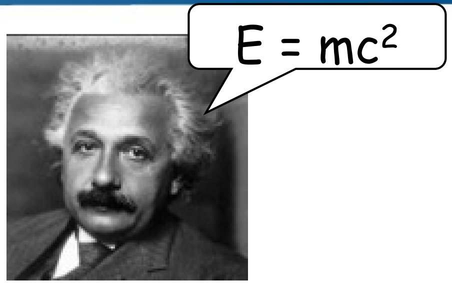
Accelerator Physics- Next challenges

Walid KAABI

Definition of particle accelerator

Accelerator is an instrument that generate, then ~~accelerate~~ particles

increase energy of



Accelerators could be distinguished by the following characteristics:

- Geometry: linear or circular
- Type of accelerated particles: Ions, Hadrons (protons), Leptons (electrons, muons)
- Used technology: Electrostatic, Normal conducting RF or Superconducting RF
- Operation mode: pulsed or continuous (CW)
- Range of beam parameters:
  - Energy : from some keV to some TeV
  - Current: from some pA to some kA
  - Luminosity (number of collisions/s): up to 10^{34} cm^{-2} s^{-1}

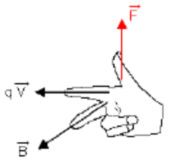
Acceleration of a charged particle

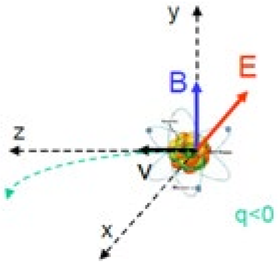
- Acceleration a of particle of mass m needs a force F : **F = m . a** (Newton low)

- Of the 4 fundamental forces, the **only one** we can control by **technological means** is the electromagnetic force

- from **Maxwell's 4 equations** describing electromagnetic fields (electric: E, magnetic: B), one obtains the Lorentz force which acts on a charge q evolving with speed v :

$$\boxed{\frac{d\vec{p}}{dt} = \vec{F} = q\left(\vec{E} + \vec{v} \wedge \vec{B}\right)}$$





- note: we can only accelerate **charged particles**

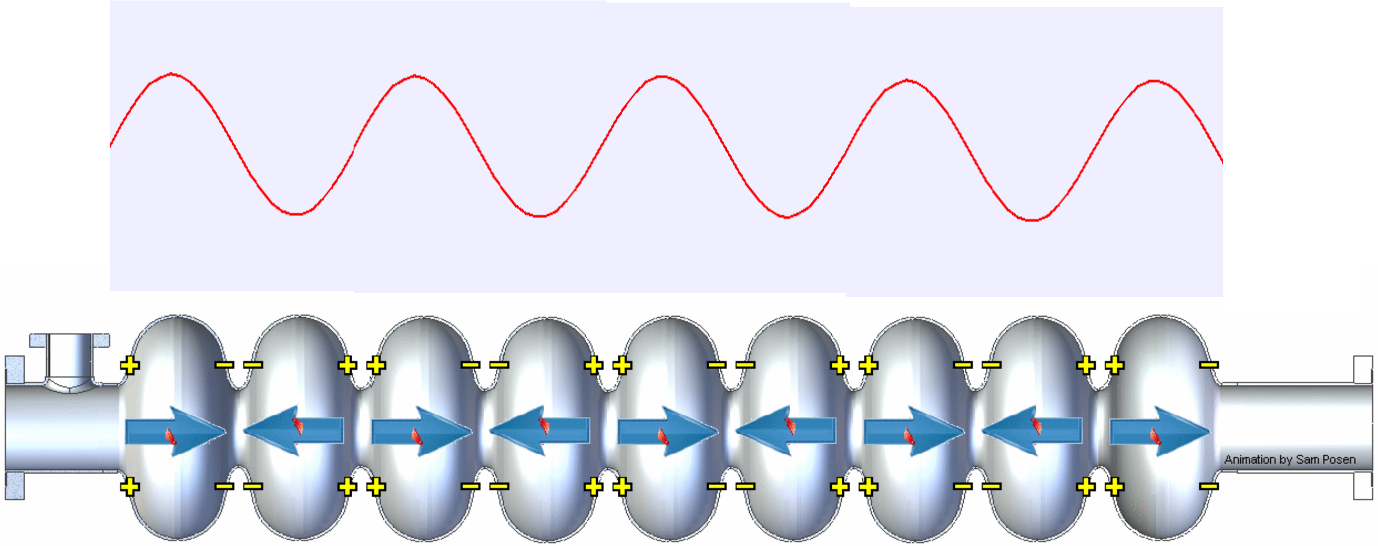
- Only the electrical field is useful for acceleration:
  - If $\vec{E} \perp \vec{v}$, no acceleration
  - If $\vec{E} /\!/ \vec{v}$, the acceleration is optimum

Thus, the energy gain ΔW of a charge q in an electric field generated by a potential V is: ΔW = q V

- typically used unit: electron volt [eV]

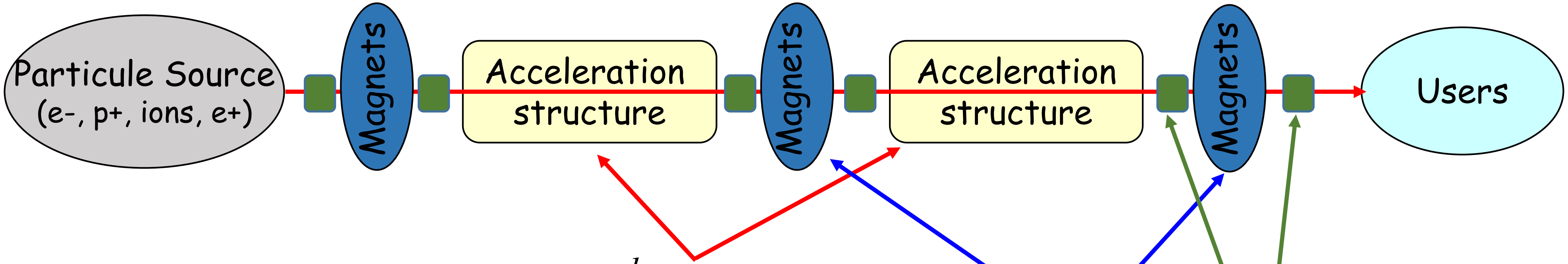
Particles acceleration in RF field

- An RF source (producing an electromagnetic wave characterized by its power and frequency) is used to generate an electric field in an area of a resonant metal structure.
- The particles that make up the beam must be located within bunches, and must be phased correctly with respect to the electric field in order to have an acceleration.



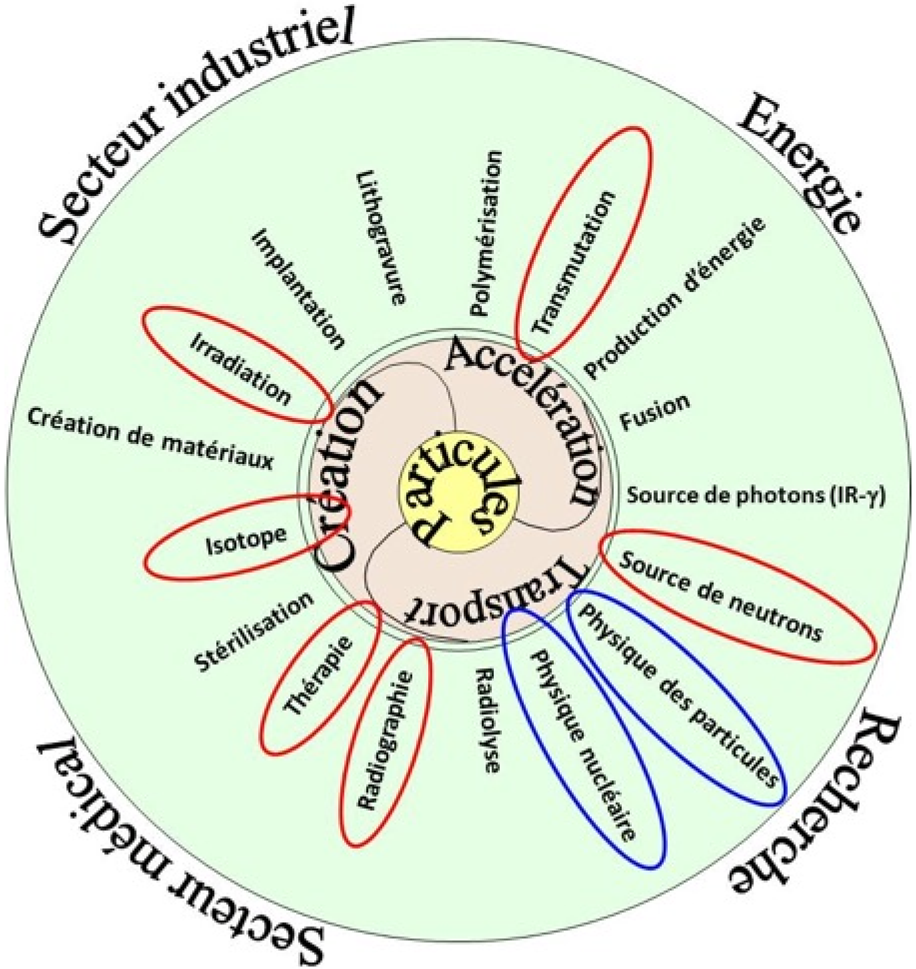
- To maintain acceleration throughout the particle path, this condition of synchronism must always be respected.

Scheme of a particle accelerator



- Electric field in RF structure (cavities) $\frac{dp_z}{dt} = q \cdot E_z$ for beam acceleration
- Magnetic field to deviate (dipole) or focalise (quadrupole) the beam $\vec{F} = q \cdot \vec{v} \wedge \vec{B}$
- Instruments to measure the beam properties: Beam diagnostics (energy, current, position, size, divergence, shape, emittance…
- Auxiliary systems: vacuum systems, electrical supplies, RF power sources, radioprotection, cryogenic plants, cooling systems, control & command…
- Users zone: could host complex experimental set-up like targets, spectrometers, detectors and even dispositive to create secondary particles (neutrons, photons, isotopes…)

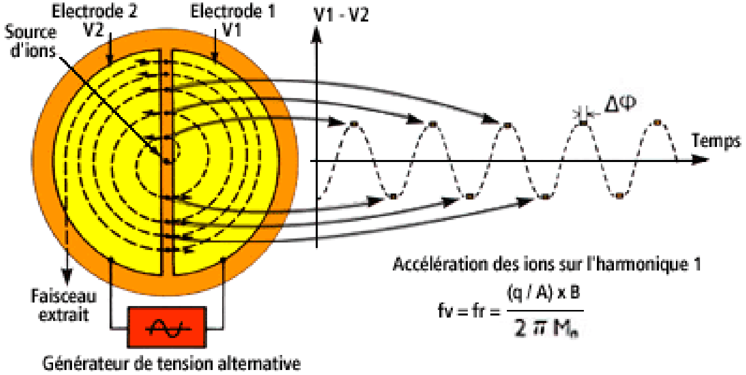
Accelerators users



Types of particle accelerator

- **Circular accelerators:** the beam passes several times through the same accelerating cavity

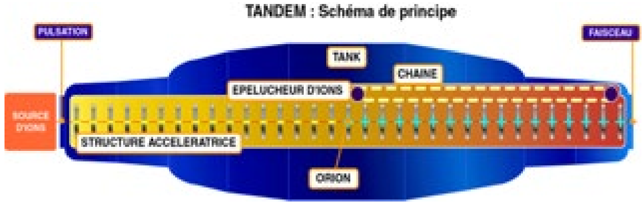
Cyclotrons:
B constant, trajectory radius increasing.



Synchrotrons:
B increasing, constant trajectory radius.

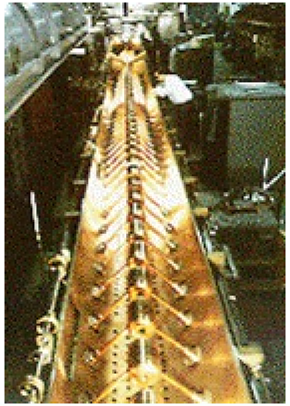
- **Linear accelerators:** the beam passes only once in each acceleration section

***Electrostatic accelerators*:**
Acceleration under a potential difference



Tandem d'IJCLab (15 MV)

RF Linac (LINear ACcelerator):
Acceleration under RF field in normal conductive (warm) or superconductive (cold) cavities.



Comparison of particle accelerator types

- In **electrostatic accelerators**, the energy gain is **limited by the maximum voltage that can be applied**, which is itself limited by electrical breakdowns.
- In **RF accelerators** (linacs, synchrotrons, cyclotrons) the final energy can exceed the maximum voltage because the **beam can be repeatedly subjected to this voltage**. The final energy is only limited by the budget ...
- **Synchrotrons** are **limited to moderate currents** because of the **beam instabilities** associated with the **repetitive cycle of the beam turn after turn**: the accelerating lattice is never perfect, and errors are accumulated in the conduct of the beam and until the beam is lost. In addition, **energy losses by synchrotron radiation** force an **increase in the radius of curvature** (size of the machine)
- **Cyclotrons** are not pulsed, but are **limited to moderate beam currents** because **beam focusing is weak** and **extraction difficult without losses**.
- **Linear accelerators** can deliver **very intense beams**, because it is possible to have very strong focusing to confine the beam, and they are not subject to the same instabilities as circular machines. The **economic criterion is the main limiting factor** of these machines.

Challenges for future particle accelerators

Particle physics and nuclear physics are the main driving forces of accelerator research and developments. The main pursued objectives are:

- Energy increase
- Intensity and/or luminosity increase
- Higher efficiency
- Higher reliability
- … and all of these coupled with cost reduction (either capital or operation cost)

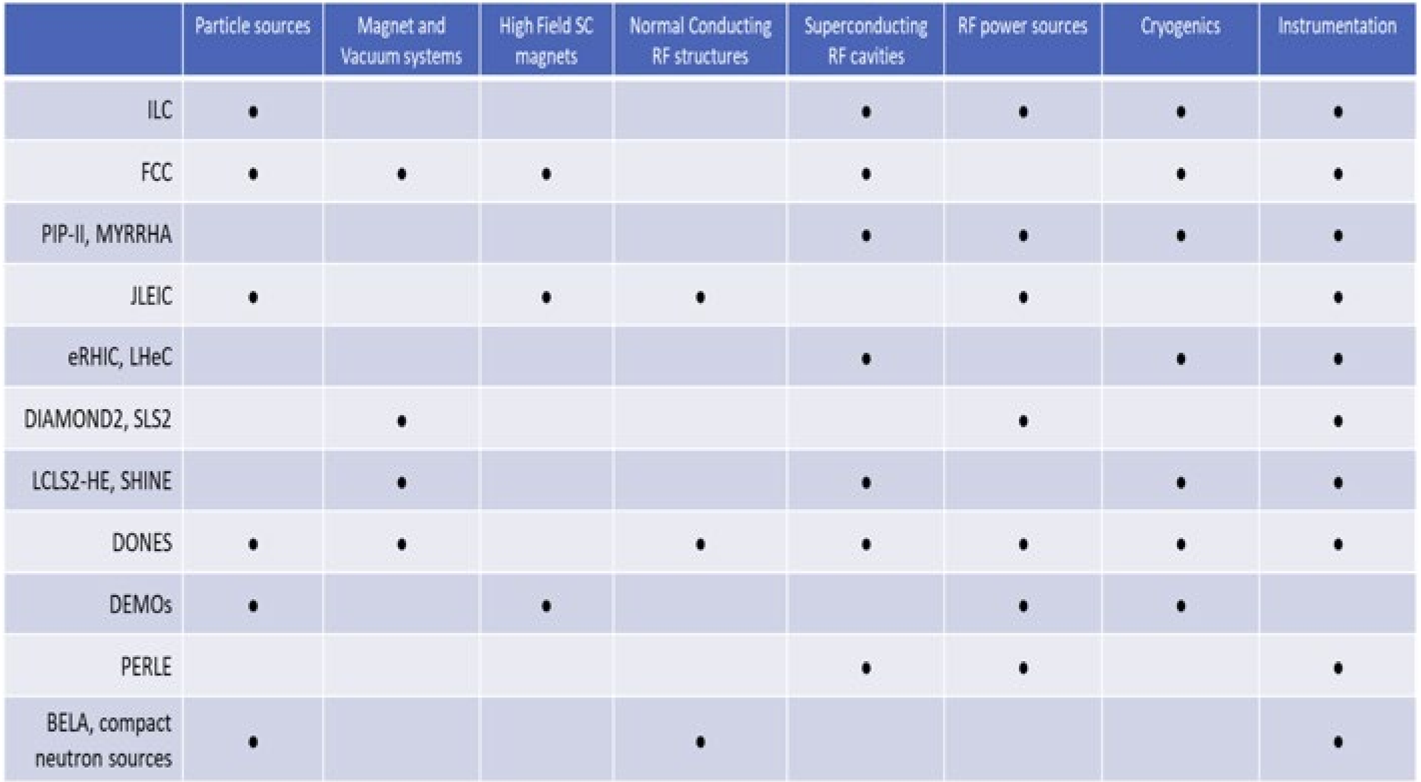
=> Challenges in accelerator science and technology are derived from all these objectives

- ➢ High accelerating gradients (Superconducting RF, laser-plasma acceleration)
- ➢ High fields magnets (superconducting magnets)
- ➢ High luminosity (advanced beam control and special devices such as crab cavities)
- ➢ High beam intensities (coupled to requirements on high reliability)
- ➢ Advanced beam dynamics computing to simulate sophisticated phenomenon

=> Upstream R&D to be conducted between 10-30 years before machine construction concerning novel accelerator concept or new material/process to accelerate particles

Challenges for future particle accelerators

The list of important Key* Technology Areas (KTAs) is regularly being updated at a EU level, most recently within the AMICI H2020 program (http://eu-amici.eu/)



	Particle sources	Magnet and Vacuum systems	High Field SC magnets	Normal Conducting RF structures	Superconducting RF cavities	RF power sources	Cryogenics	Instrumentation
ILC	●				●	●	●	●
FCC	●	●	●		●		●	●
PIP-II, MYRRHA					●	●	●	●
JLEIC	●		●	●		●		●
eRHIC, LHeC					●		●	●
DIAMOND2, SLS2		●				●		●
LCLS2-HE, SHINE		●			●		●	●
DONES	●	●		●	●	●	●	●
DEMOs	●		●			●	●	
PERLE					●	●		●
BELA, compact neutron sources	●			●				●

** Key = widely needed for future projects, AND presenting a high development potential for cost reduction*

Warm Vs. Cold technology

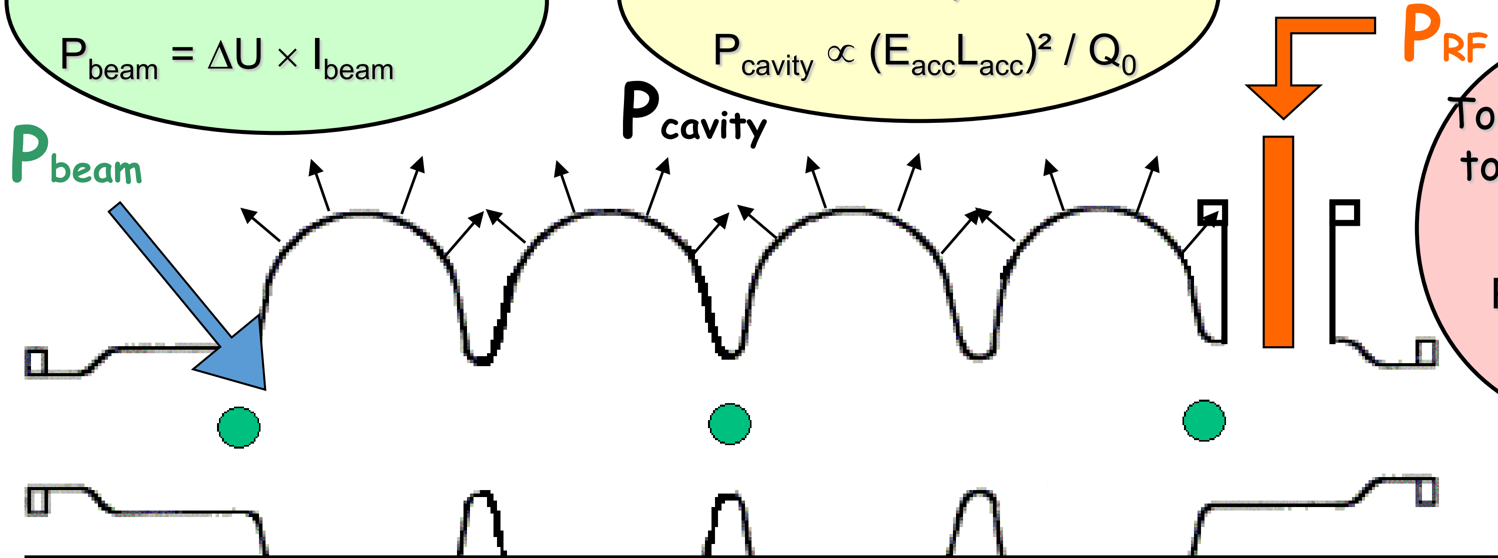
Q_0 : cavity « quality factor »

RF power transmitted to the beam

$P_{beam} = \Delta U \times I_{beam}$

Dissipated RF power on the cavity walls

$P_{cavity} \propto (E_{acc}L_{acc})^2 / Q_0$



Total RF power to give to the cavity

$P_{RF} = P_{beam} + P_{cavity}$

<u>Order of magnitude</u> *(700 MHz cavity - β = 0,65 - 5 cells- 10MV/m - φ=-30° - protons beam 10 mA)*

SC cavity ($Q_0 \sim 10^{10}$) : P_{beam} = 6 MeV × 10 mA = **60 kW**

$P_{cavity} \approx$ **16 W**

"Warm" cavity ($Q_0 \sim 3.10^4$) : P_{beam} = 60 kW also

$P_{cavity} \approx$ **5,5 MW !!!** ← *not possible in CW !*

Warm Vs. Cold technology

Superconductive cavities have excellent RF Yield: Nearly 100% of injected RF power is transmitted to the beam

- ✓ Operating costs saving compared to warm cavities solution, which dissipate a lot of power (10^5 times more)
- ✓ Possibility of accelerating continuous beams or beams with a high useful cycle (> 1%) while ensuring very high accelerating fields, which is not possible with warm cavities → Shorter accelerators.
- ✓ Possibilities to relax the constraints on the RF design of the cavity and to choose larger apertures for the beam tubes → less risk of activating structures = greater safety.
- ✓ Strong potential in terms of reliability and flexibility.

- ✓ the structures must be cooled with liquid helium→ need for a cryogenic cooling system with very low efficiency.
- ✓ Very complex cavity preparation process.

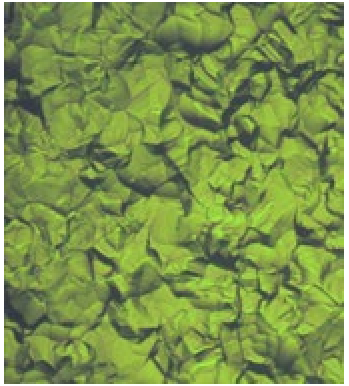
Superconductive cavity preparation


Ultrasonic cleaning


BCP etching


Ultra-pure water rinsing


Surface morphology prior to BCP etching


Surface morphology after 100 µm BCP etching


Cavity assembly in clean room


Power coupler preparation in clean room

Performances improvement of Superconductive cavity

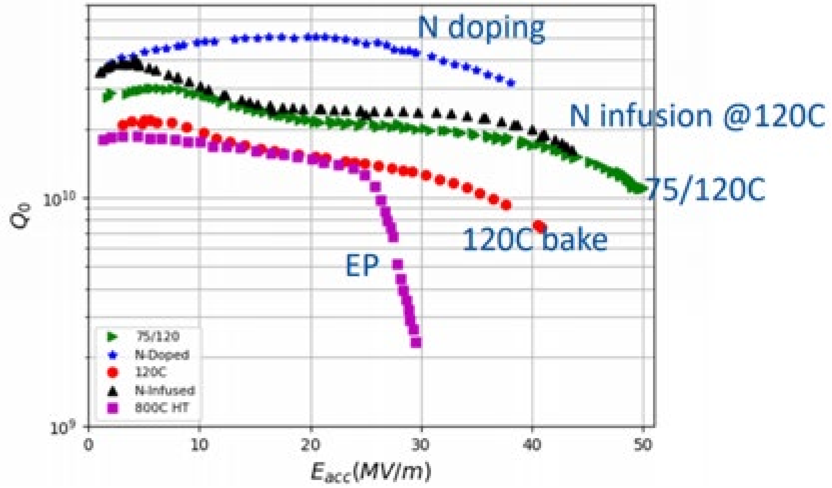
Acceleration using superconducting cavities is nowadays a technology of choice for either high current and/or high duty cycle accelerators

Special treatment on Niobium is helping: Electro-polishing, Heat treatments (baking, firing), Nitrogen doping or infusion, Slow cooling (magnetic hygiene)…

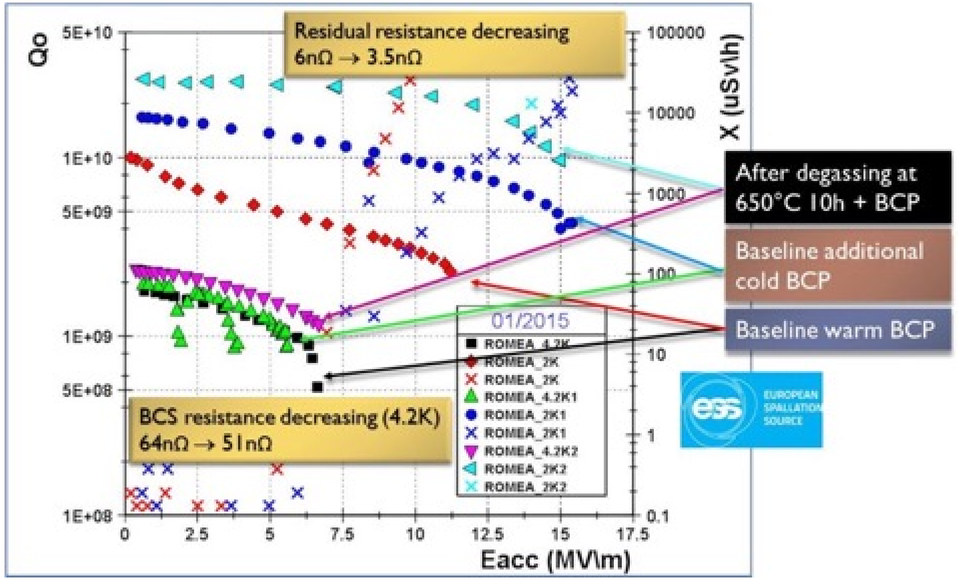
State of the art in high Q and high G (1.3 GHz, 2K)

Best Curves of 2019:

- **Q>3e10 @38 MV/m** with N doping, **> 5e10** at mid field
- Q >1e10 at **50 MV/m** (**B_{pk} ~ 220 mT**) with 'modified' low T bake



State of the art in high Q and high G (low beta cavities, 352 MHz, 2K)



Accelerator Physics Pole @ IJCLab

The main objectives of the Accelerator Physics Pole:

- Be a major actor on accelerator physics research in several key areas, selected for their strategic importance (potentiality for scientific and technological breakthrough) and our capacity to have an important and visible impact.
- Increase our capacity to build accelerators : a clear strategy to have important contributions to international projects, allowing us to take part in the definition of large equipment roadmaps and thus to facilitate the positioning of our research teams
- Contribute to an efficient use and development of our local accelerators and technological platforms: a key to keep accelerators expertise, training capabilities, and insure visibility and attractiveness

All Accelerator Research Activities are fully integrated in the IN2P3 accelerator R&D landscape

LPAC
Laser Plasma Acceleration & high-energy Colliders

SCPL
Superconducting RF Cavities & high-power Proton Linac

SRHI
Stable & Radioactive Heavy-Ions production & acceleration

IELS
Innovative Electron & Light Sources

Accelerator Physics Pole @ IJCLab

Structured around 3 scientific teams, 2 specialized groups and one technological platform

- **BIMP Team: Beam Instrumentation, Manipulation and Physics**
  Team leader: Luc Perrot; Assist: Angeles Faus-Golfe
- **MAVERICS Team: Materials for Accelerators, dynamic Vacuum and Innovative Research on Superconducting Cavities**
  Team Leader: Gaël Sattonnay
- **ALEA Team : Laser Acceleration and Applied science**
  Team Leader: Daniele Nutarelli ; Assist: Kevin Cassou
- **RF Service: Specialized service for RF science and technology**
  Team Leader: Guillaume Olry
- **Cryogenic Service: Specialized service for cryogenic science and technology**
  Team leader: Patxi Duthil
- **Vacuum and Surfaces Technological Platform**
  Team leader: Bruno Mercier

Accelerator Pole lead:
DSA : Sébastien Bousson
DSA Deputy : Walid Kaabi

Accelerator Physics Pole staff today:

- 88 persons
- 20 researchers (½ CNRS, ½ University)
- 52 IT (among which 31 research engineers)
- 15 Ph-D students
- 8 HDR

BIMP: Beam Instrumentation, Manipulation and Physics

Main research themes:

- Design of accelerators for nuclear physics (ALTO, GANIL) and high energy physics (ILC, CLIC, FCC) and their application (ThomX, MYRRHA)
- Beam dynamics simulations, beam control and monitoring
- Beam instrumentation
- Specific expertise (high intensity positron sources, nanobeams, collimation, machine learning for accelerator control)…

Equipe Physique, Instrumentation et Manipulation des Faisceaux

Effectifs totaux:	24	Ens. chercheurs:	0
		Chercheurs:	3
Permanents:	12	IR:	10
CDD:	2	IE:	1
Doctorants:	9	AI:	0
Apprentis:	0	T:	0

Main projects

- ThomX (Compton X-ray source)
- Next Particle Collider (NPC) – FCC – ILC – ATF2
- ALTO (RIB)
- MYRRHA (nuclear waste transmutation)
- GANIL: Spiral-2, DESIR
- PERLE: ERL demonstrator
- ARIES and I-FAST (accelerator R&D EU program)

ALEA (Acceleration Laser et Applications)

Main research themes:

- Gamma and X-ray source based on compton scattering
- Polarimetry (Beam diagnostic) based on Compton interaction
- Laser plasma amplification and interaction
- Laser plasma acceleration
- High power optical cavities
- Non linear optics

Equipe Accélération Laser et Applications

Effectifs totaux:	**21**	**Ens. chercheurs:**	**9**
		Chercheurs:	**2**
Permanents:	**14**	**IR:**	**4**
CDD:	**2**	**IE:**	**1**
Doctorants:	**4**	**AI:**	**0**
Apprentis:	**0**	**T:**	**0**
Emérites:	**1**		

Main projects

- ThomX (Compton X-ray source)
- Laser plasma acceleration (PALLAS)
- Minicav (high power cavity, industrial collaboration)
- LaseriX
- Polarimetry BELLE-II, SuperKEKb and ILC
- Gamma-Factory

MAVERICS

Equipe Matériaux, Vide et Surfaces

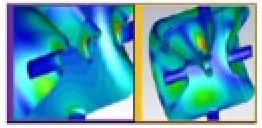
Effectifs totaux:	7	Ens. chercheurs:	1
		Chercheurs:	2
Permanents:	5	IR:	2
CDD:	0	IE:	0
Doctorants:	2	AI:	0
Apprentis:	0	T:	0

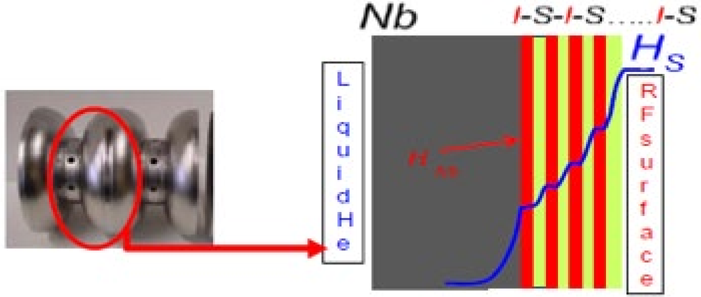
Main research themes:

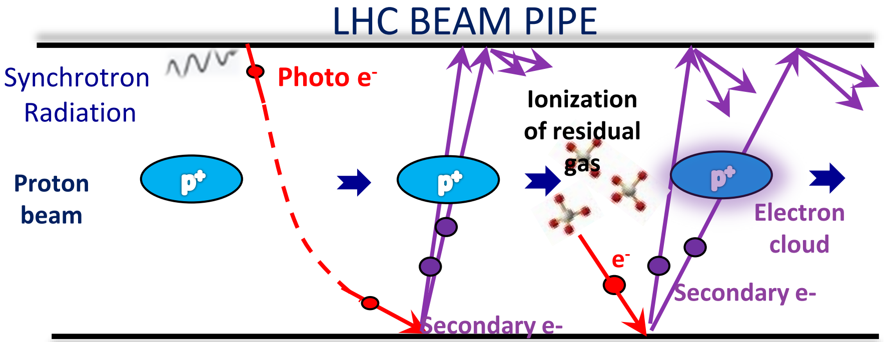
- New materials and surface treatment for SCRF cavities
  - Doping, infusion, thermal treatment
  - Alternative material to Niobium
  - Multilayers
- Dynamic vacuum
  - Stimulated desorption
  - Electron emission (SEY) from surfaces
  - Simulation : DYVACS code
- Multipacting
- Surface analysis

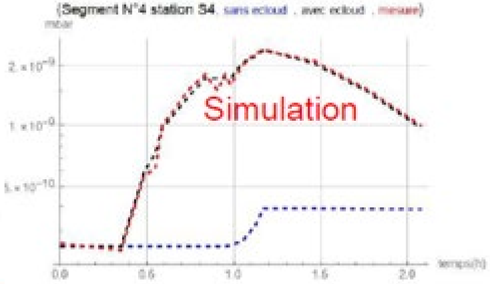
Main projects

- ESS
- MYRRHA
- PIP-II
- PERLE
- NPC : FCC – hh/ee
- Master project SRF









Plateforme Vide et Surface

Plateforme
Panama/vide/surface

Effectifs:	4	AI:	2
Permanents:	4	T:	2
CDD:	0		

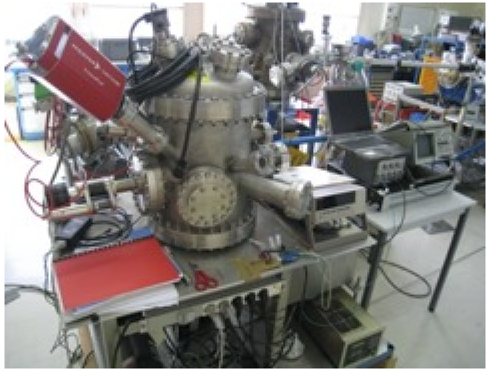
Main activities:

- Operate and develop surface analysis equipment related to MAVERICS activity (material and vacuum)
- Develop our expertise:
  - Materials for accelerators
  - Surface analysis
  - UHV
  - Simulation

Main projects

- ThomX
- NPC – FCC
- SRF Master project
- I3DMetal
- …


Setup for degazing rate measurement


Setup for desorption and SEY measurement


SIMS


Confocal microscope


RX Diffractometer

Service RF

Service RF

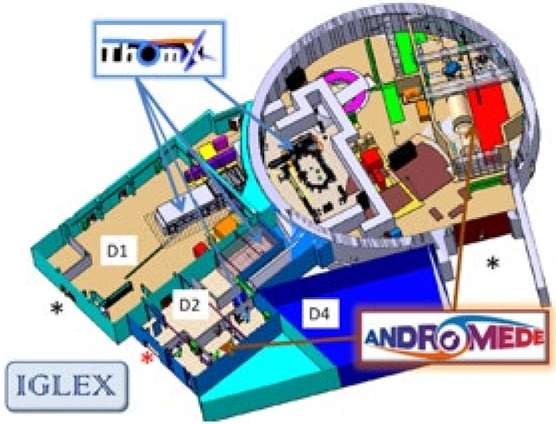
Effectifs totaux:	20	Ens. chercheurs:	0
		Chercheurs:	0
Permanents:	15	IR:	9
CDD:	4	IE:	2
Doctorants:	0	AI:	6
Apprentis:	1	T:	2

Main activities:

- Design, preparation and operation of RF accelerating structures (conventional or superconducting) as well as their related systems
    - Normal and Superconducting RF cavities
    - RF power sources
    - Low level RF systems
- Support for operations and maintenance of SupraTech RF systems
- Additional specialized expertise:
    - RF Photo-injector
    - RF systems for beam diagnostics (BPMs,…)
    - High voltage systems

Main projects

- ThomX
- ESS
- MYRRHA
- PIP-2
- PERLE
- SPIRAL-2



Service Cryogénie

Main activities:

Design and operation of cryogenic systems for accelerators and beyond

- Research axis:
    - Cryogenic instrumentation
    - Compact refrigeration without cryofluids
    - Heat transfer at cryogenic temperature
- Operational missions (within SupraTech)
    - Liquid Helium production
    - Operation, maintenance and development of cryogenic infrastructures
    - Cryogenic experiments
    - Cryogenic temperature sensors calibration
- Expertise:
    - Design of cryogenic systems (cryostat, cryomodules, cold box, cryo lines)
    - Numerical simulations of cryogenic systems

Service Cryogénie

Effectifs totaux:	**9**	**Ens. chercheurs:**	**0**
		Chercheurs:	**0**
Permanents:	**7**	**IR:**	**4**
CDD:	**2**	**IE:**	**3**
Doctorants:	**0**	**AI:**	**2**
Apprentis:	**0**	**T:**	**0**

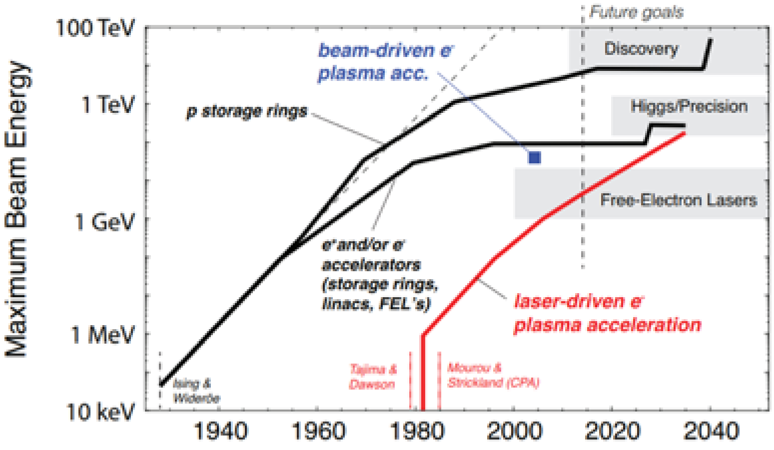
Main projects

- ESS
- MYRRHA
- PIP-2
- PERLE
- SPIRAL-2
- NGCryo
- MUGAST

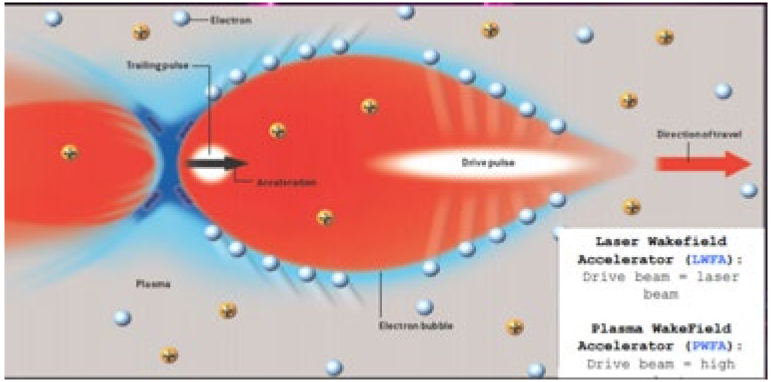
PALLAS Project @ IJCLab

Laser plasma acceleration uses high power laser (10ths of TW … PW) to accelerate electrons to high energy (100s of MeV to several GeVs).

- 8 GeV acceleration over a few cms demonstrated
- Several scheme are being studied (two stages laser plasma acceleration)
- An important effort being made in Europe within the Eupraxia program
- Many challenges (beam quality and control, advanced simulation tools…)



Courtesy to R. Assman



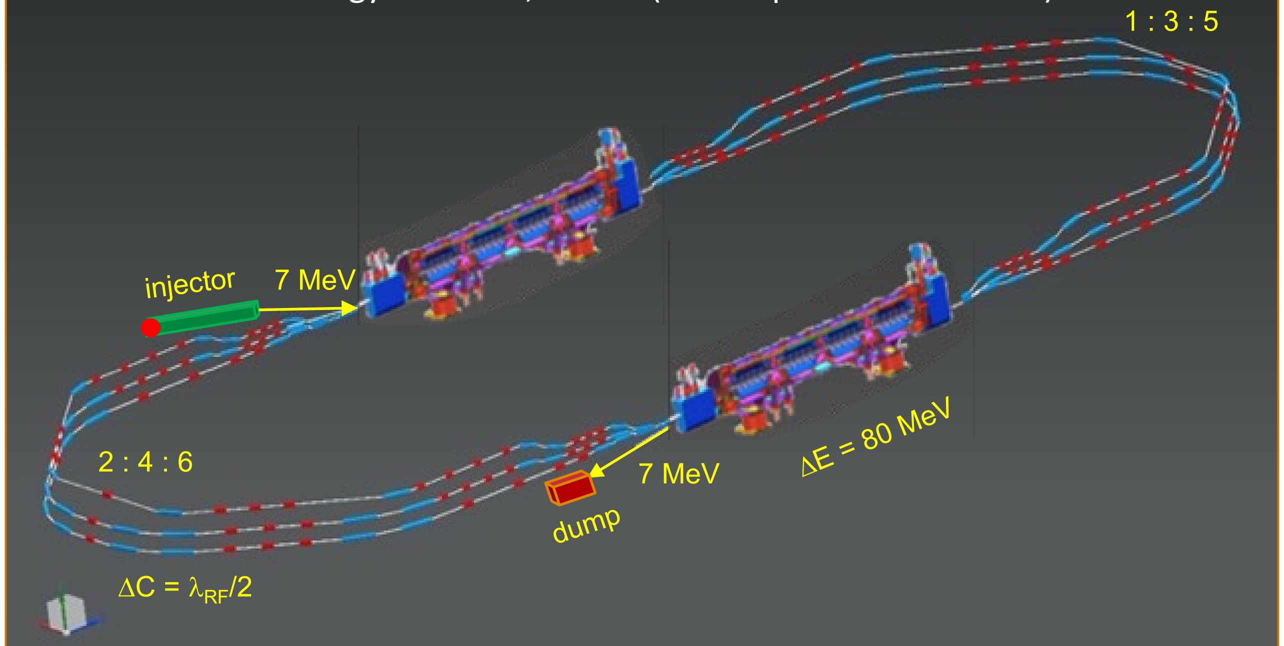
Courtesy to M. Ferrario

PERLE project @ IJCLab

PERLE @ Orsay is a demonstrator of an Energy Recovery Linac (ERL) facility

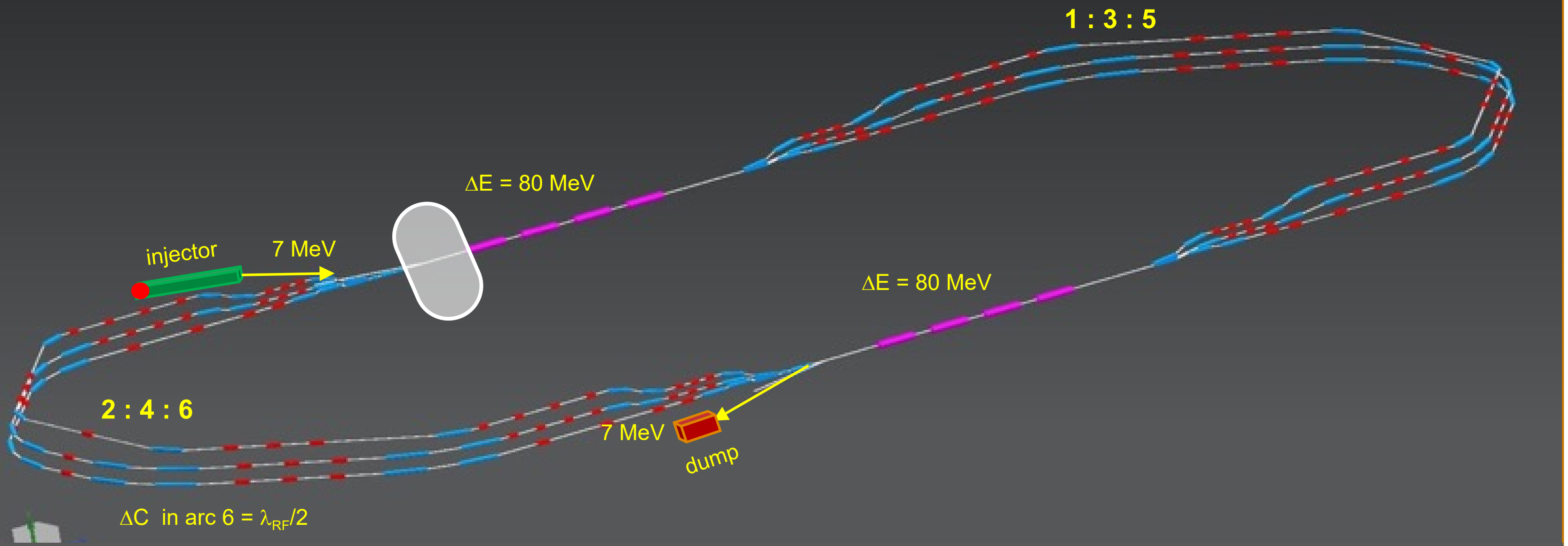
- A unique project of a ERL demonstrator, high current, with recirculation
- A collaboration is being set between CERN, JLab, Daresbury, Novosibirsk, Liverpool University, CNRS Orsay…

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV, 20 mA (Virtual power ~ 10MW!!!)



PERLE project @ IJCLab

Three passes ‘up’ to reach the maximum energy

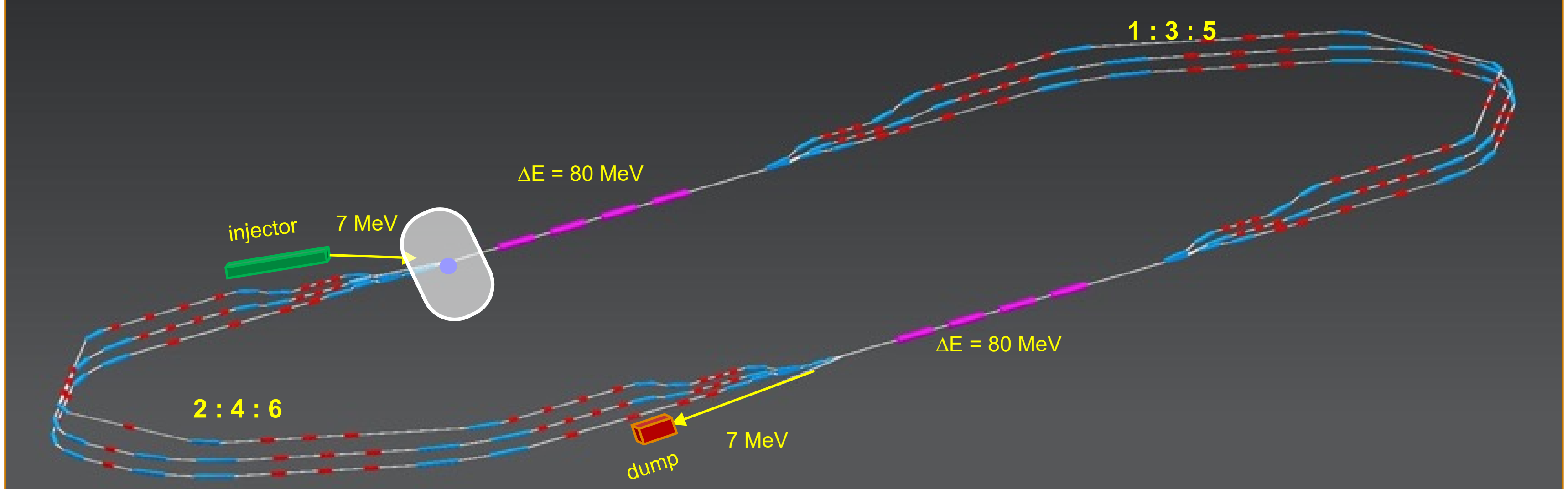


Electron beam at maximum energy could be used for:

- Elastic electron-proton scattering with polarised beam (Particle physics)
- Exploration of proton densities in exotic nuclei by electron scattering (Nuclear physics)
- Gamma ray production between 0.2 and 5 MeV (wide applications in Photo-nuclear physics),

PERLE project @ IJCLab

Three passes ‘down’ for energy recovery



Several benefits from this manipulation:

- The required RF power (and its capital cost and required electricity) is significantly reduced to that required to establish the cavity field and make up minor losses.
- The beam is constantly renewed: never reach equilibrium state --> provides flexibility to adapt beam properties for specific applications.
- The beam power that must be dissipated in the dump is reduced by a large factor.

Thank you for your attention!