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Review of Accelerators for ADS

caveat emptor

- Deliberately very basic, "common sense" physics considerations using partly material from a lectures series developed together with Carlo Pagani (INFN Milano) in 2002 and renewed for an IAEA school in 2007.
  (time constraints for discussing certain slides in detail!!)

Goal

- Reconsider the 2003 findings of OCDE NEA Report
  - **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice **for preliminary low power experiments**, where availability and reliability requirements are less stringent.
  - **CW linear accelerators must be chosen for demonstrators and full scale plants**, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.

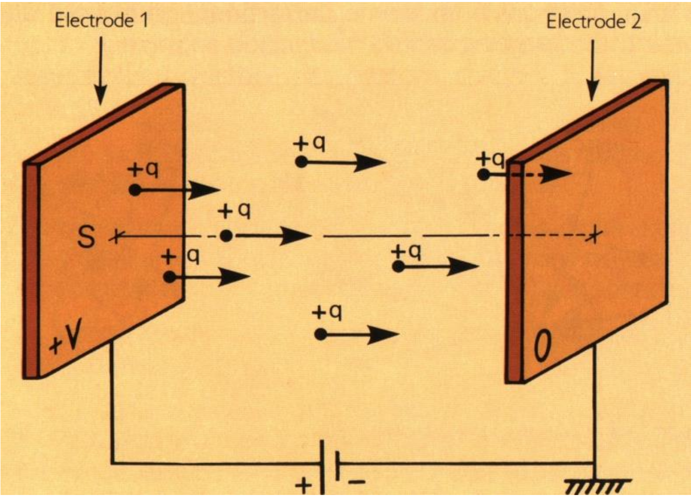
Accelerating Particles: some (very) basics

- acceleration a of particle of mass m needs a force F :

$$F = m \bullet a \qquad \text{(Newton)}$$

- 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 :

$$F = q\,(E + v \times B)$$



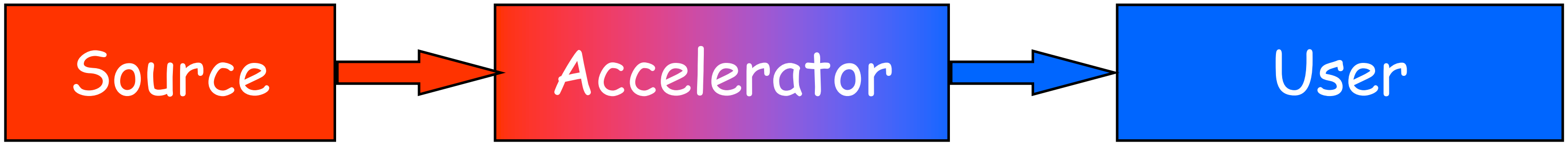
- note: we can only accelerate charged particles
- the energy gain W of a charge q in an electric field generated by a potential V is:

$$W = q\,V$$

- (typically used unit: electron volt [eV]]

Accelerating Particles (II)

schematic view



An accelerator has the following principal components

- a source of charged particles

  electrons, protons, heavy ions, special case: positrons & anti-protons

- accelerating elements

  electrostatic columns or radiofrequency cavities which provide the electric fields giving the energy to the particle (beam)

- beam guiding elements

  mainly magnetic, in order to maintain (focus) the beam on the wanted trajectory and to provide the orbit (closed for a synchrotron) in the case of a circular machine

- as most important ancillary systems vacuum and beam diagnostics

  high vacuum is needed to avoid perturbation of the beam by collisions with residual gas, and beam diagnostics assure the monitoring of the beam trajectories

- the user installation

  (often complex) experimental set-ups including targets, spectrometers, detectors
  special case: secondary beams produced by a nuclear reaction (e.g.: neutrons) or an electromagnetic process (e.g.: photons by Bremsstrahlung / Synchrotron Radiation)

The cathode ray tube:
a "complete accelerator at home"

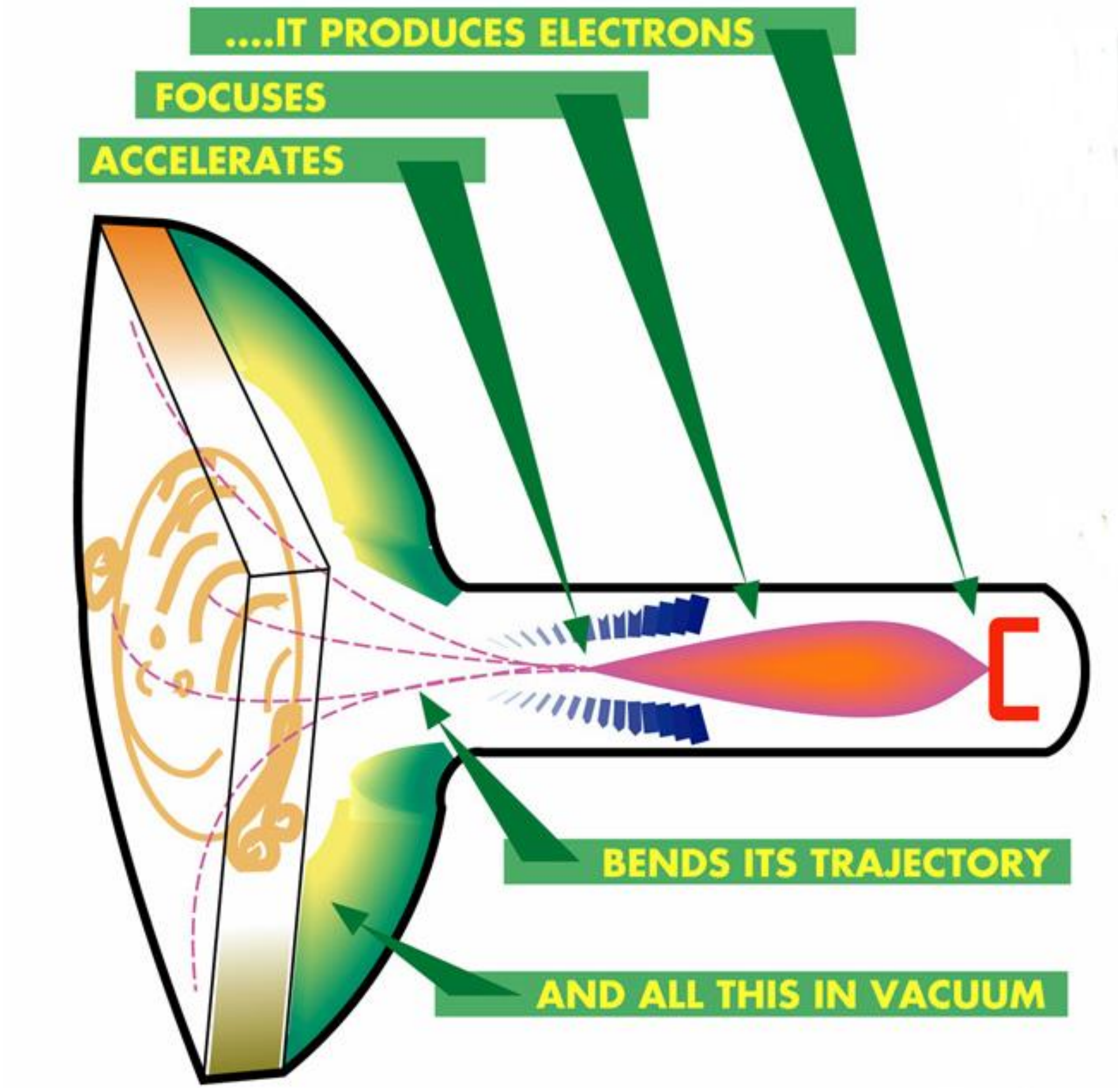


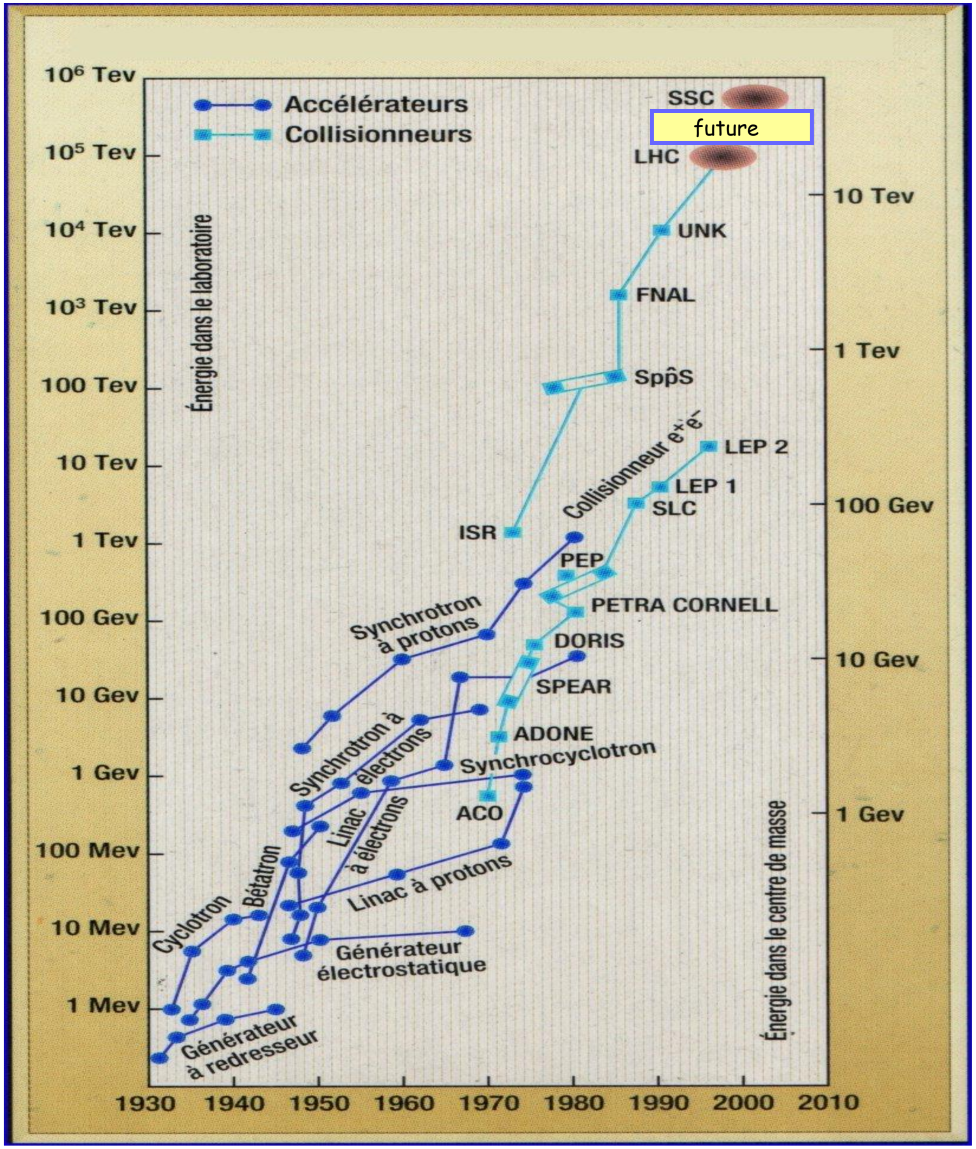
Figure from a CERN Website Mid-2000

Some milestones of the history of accelerators

• 20th century, first 25 years	Prehistory: fundamental discoveries made with "beams" from radioactive sources (Rutherford!) trigger the demand for higher energies
• from 1928 to 1932	Cockcroft&Walton develop a 700kV electrostatic accelerator based on a voltage multiplier, Van de Graaff uses a charge conveyor to reach 1.2MV.
• 1928	first Linac by Wideroe based on Ising's concept of resonant acceleration.
• 1929	Lawrence invents the cyclotron.
• 1944	MacMillan, Oliphant & Veksler develop the synchrotron
• 1946	Alvarez builts a proton linac with Alvarez structures (2π mode)
• 1950	Christofilos patents the concept of strong focusing
• 1951	Alvarez conceives the tandem
• 1954	Courant, Livingston and Snyder implant strong focusing at the Brook-haven Cosmotron Synchrotron (and learn with disappointment about Christrofilos's patent)
• 1956	Kerst stresses in a paper the concept of a collider, but physics with use-ful event-rates was much later (e.g. in the 80's with the Sp$\bar{p}$S)
• 1970	Kapchinski & Telyakov invent the radio-frequency quadrupole (RFQ).
• early 80's	superconducting magnets for cylotrons and synchrotrons considerably boost the performance (energy for size), in particular for colliders
• from mid 80's	Geller's ECR sources are implanted at many heavy ion accelerators and greatly improve reliability and energy range (they deliver high q)
• the last years	the development of superconducting accelerating cavities provides very high power conversion efficiency, and CW operation for high luminosity

The Livingston chart

- Around 1950, Livingston made a quite remarkable observation:
- Plotting the energy of an accelerator as a function of its year of construction, on a semi-log scale, the energy gain has a linear dependence.
- 50 years later, that still holds true.
- In other words, so far, builders of accelerators have managed exponential growth, every ten years, roughly a factor of 33 is won.
- Note that for a given "family" of accelerators, generally, saturation of maximum energy sets in after some time.



Specifications for different HPPA

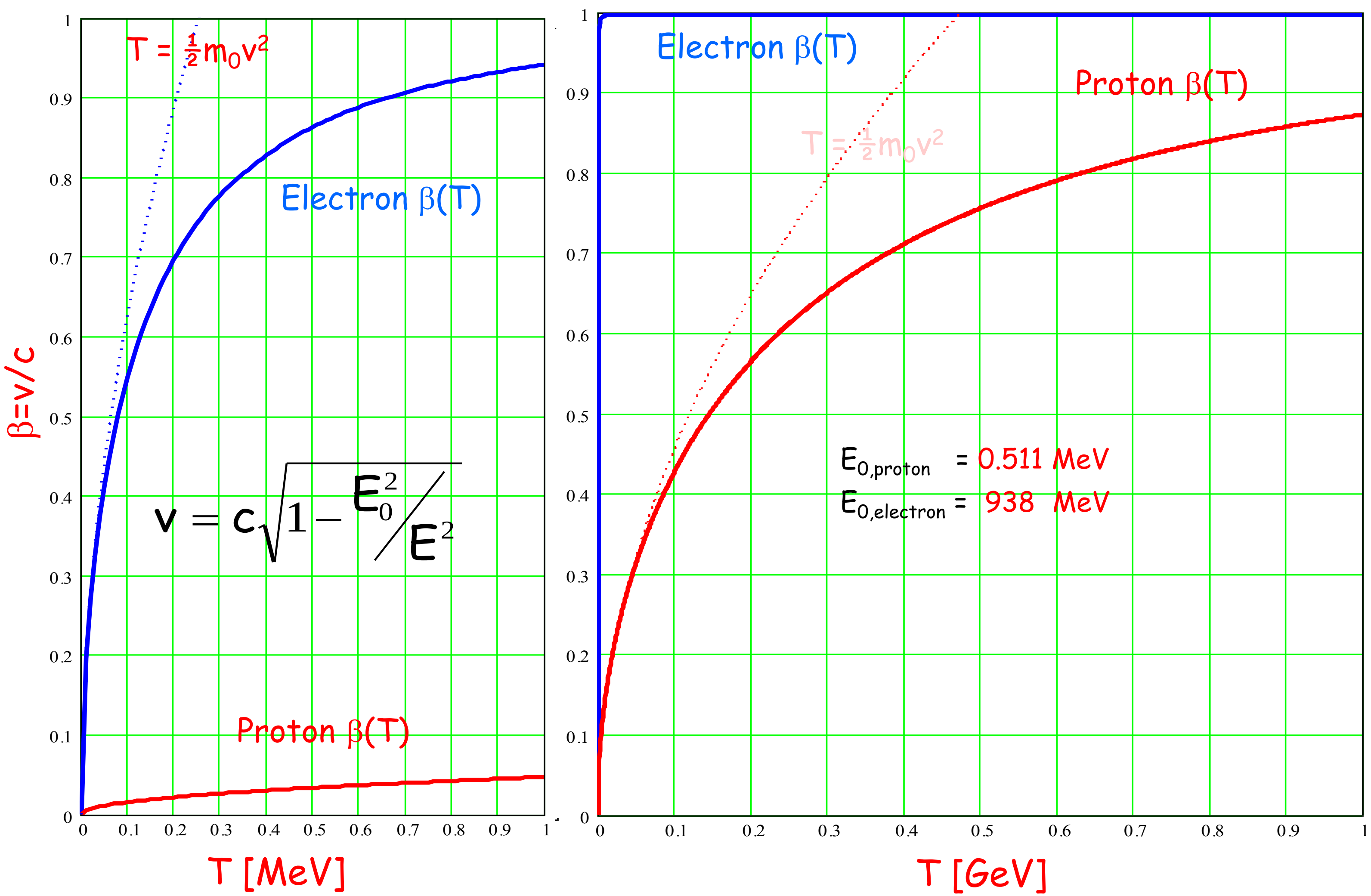
HPPA = High Power Proton Accelerator

>1

		Puissance [MW]	Énergie [GeV]
Faisceaux secondaires	Neutrinos, muons	4	2
Ions radioactifs	avec des protons avec des neutrons	.2 5	>.2 1
Irradiation des matériaux	par spallation par break-up ("IFMIF")	10 2 × 5.4	1 .04
Matière condensée	avec des neutrons	5	1.3
Transmutation	Démo 100 MW thermique Système industriel	5 10 à 20	.6 .8 à 1

≈ 1

Relativistic effects during acceleration



Basic Concepts: Fields

- Equation of motion and Lorentz force

$$\vec{F}_{Lorentz} = \frac{d\vec{p}}{dt} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{el} + \vec{F}_{mag}$$

  - Electric field can transfer energy to the particles

$$\Delta E = \Delta T = \int \vec{F}_{Lor} \bullet d\vec{s} = q \cdot \int \vec{E} \bullet \vec{v} \cdot dt$$

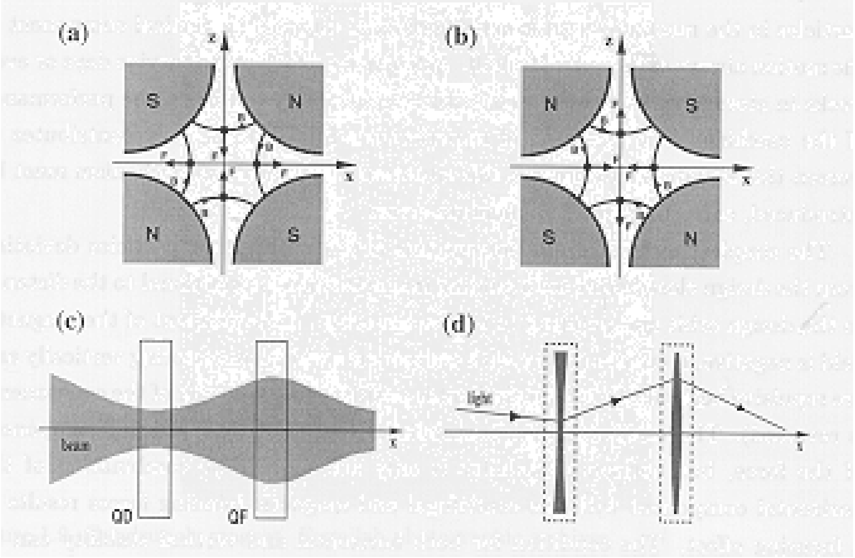
  - Magnetic field can guide the beam in a stable path

- All Particle Accelerators are based on these rules
  - The beam moves inside a vacuum chamber
  - Electromagnetic objects placed on the beam path perform the tasks
    - Magnets guide the beam on the chosen trajectory and produce focusing
    - Resonant RF cavities are used to apply the electric accelerating field
    - The few exceptions are: Betatron, RFQ and Electrostatic Accelerators

Transverse "Strong Focusing"

- Alternating gradient (AG) principle (1950's)
- A sequence of focusing-defocusing fields provides a stronger net focusing force.
- Quadrupoles focus horizontally, defocus vertically or vice versa. Forces are proportional to displacement from axis.
- A succession of opposed elements enable particles to follow stable trajectories, making small oscillations about the design orbit.

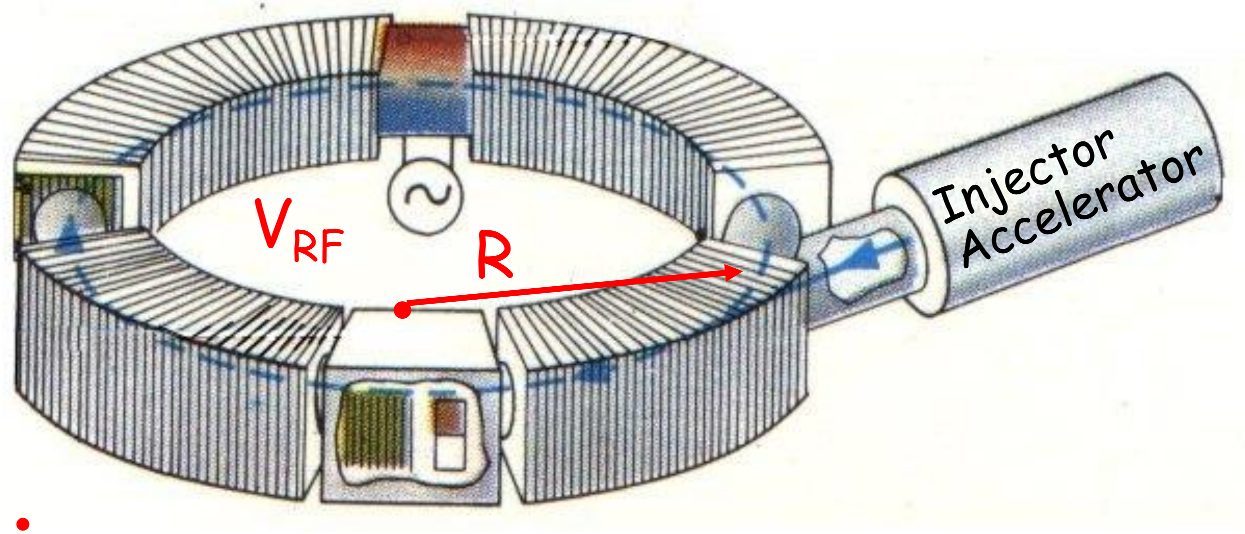
- Technological limits on magnets are high: iron saturation and dissipated power for high current
- Superconducting magnets are required for high field
- Solenoids are preferred at low energy, with high space charge forces: continuous focusing



Properties of Synchrotrons (I)

- the accelerating RF is applied to one (or more) cavities

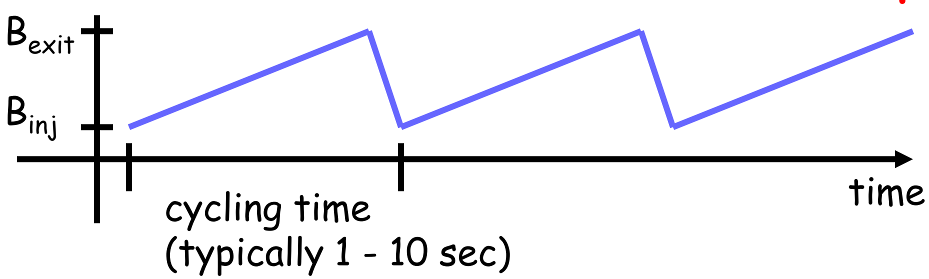
$V_{RF} = V_0 \sin \omega t$



- Synchrotron = "Ring"-Accelerator with radius R

- $\delta W = 2\pi\, \rho\, q\, \rho\, \dot{B}_m$

$$\Rightarrow \quad \delta W = 2\pi R^2 q\, \dot{B}_m$$



that means, that we have a constant energy gain per turn, which is equivalent to a linear increase, in time, of the average magnetic field B_m

- that means also, that this energy has to be provided by the accelerating radiofrequency cavities, hence $\delta W = q\, V_{RF} \sin \Phi_S$

Properties of Synchrotrons (II)

- synchrotrons accelerate up to the highest energies, determined by the bending fields (today, superconducting magnets approach B = 10T) and radius of the machine, recall $W\ [MeV] = 300\ Q\ B\ \rho\ [Tm]$, and it can be used as a collider
- a synchrotron is a pulsed machine, typical repetition rates are about 1 Hz
- the implantation of the principle of strong focusing in synchrotrons allows the acceleration of quite strong beams, in fact, up to about 10^{14} charges can be extracted, corresponding to internal beams circulating in the Ampère-regime.
- The low-duty factor, however, makes that the time averaged intensities are in the μA range, and therefore, a synchrotron is not considered for ADS

- the major components of a synchrotron (photo: MIMAS, SATURNE)
- the bending elements, magnetic dipoles
- the focusing elements, magnetic quadrupoles
- the accelerating elements, RF cavities

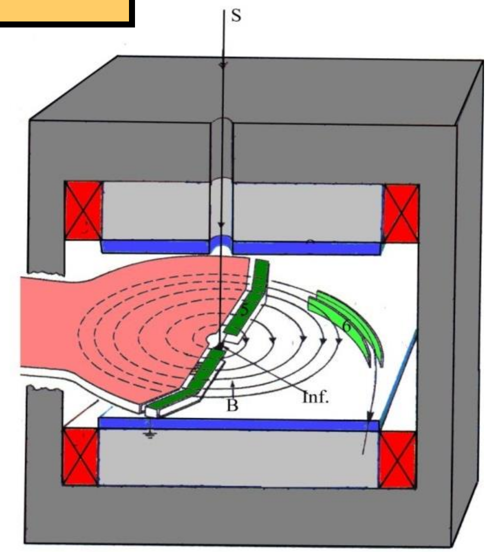
Properties of Cyclotrons (I)

- Cyclotrons ($\delta B_m = 0$) are intrinsically low-energy machines ($W_{kin} \ll W_{total}$), thus, from

$$2\,\delta W\,W = 2\,q\,c\,(\,q\,c\,B_m\,\rho\,)\,(\,r\,\delta B_m + B_m\,\delta\rho)$$

- one obtains

$$\delta W_{kin} / W_{kin} = 2\,\delta\rho/\rho$$



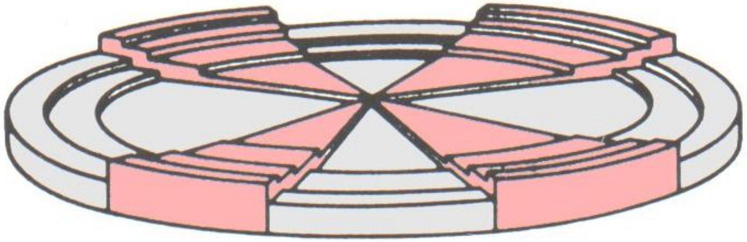
- which shows that the pitch of the spiral formed by the beam in the cyclotron is indeed small, just twice the ratio of the energy change
- a cyclotron typically has 1-4 accelerating cavities, with an energy gain of up to a few hundred keV
- thus the beam typically makes hundreds of turns in the accelerator, and the turn separation is rather small
- this actually means that we almost have a "closed turn" with $|p| \approx$ constant for the derivation of the equations, but it also hints that efficient extraction of the beam is a major challenge
- With $W_{kin} \ll W_{total}$ one also derives the formulas where the energy is in MeV, and A the mass-number of the accelerated particle, e.g. A=1 for the proton. The factor K is often used to describe a cyclotron's characteristics

$$W_{kin}/A = 48\,(B_m\,\rho)^2\,(Q/A)$$

or

$$W_{kin}/A = K\,(Q/A)^2$$

Properties of Cyclotrons (II)

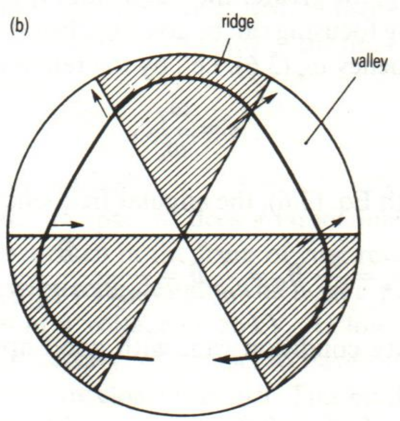


- the expression for the cyclotron frequency ν

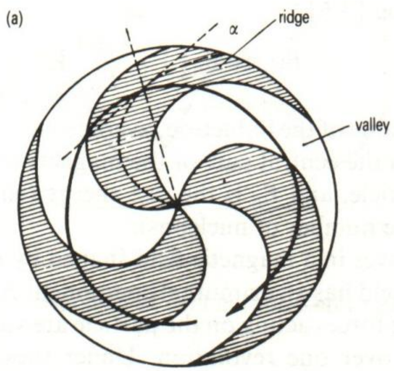
$$\nu = qB_m / 2\pi m_0$$

shows the link between mass, field and frequency,

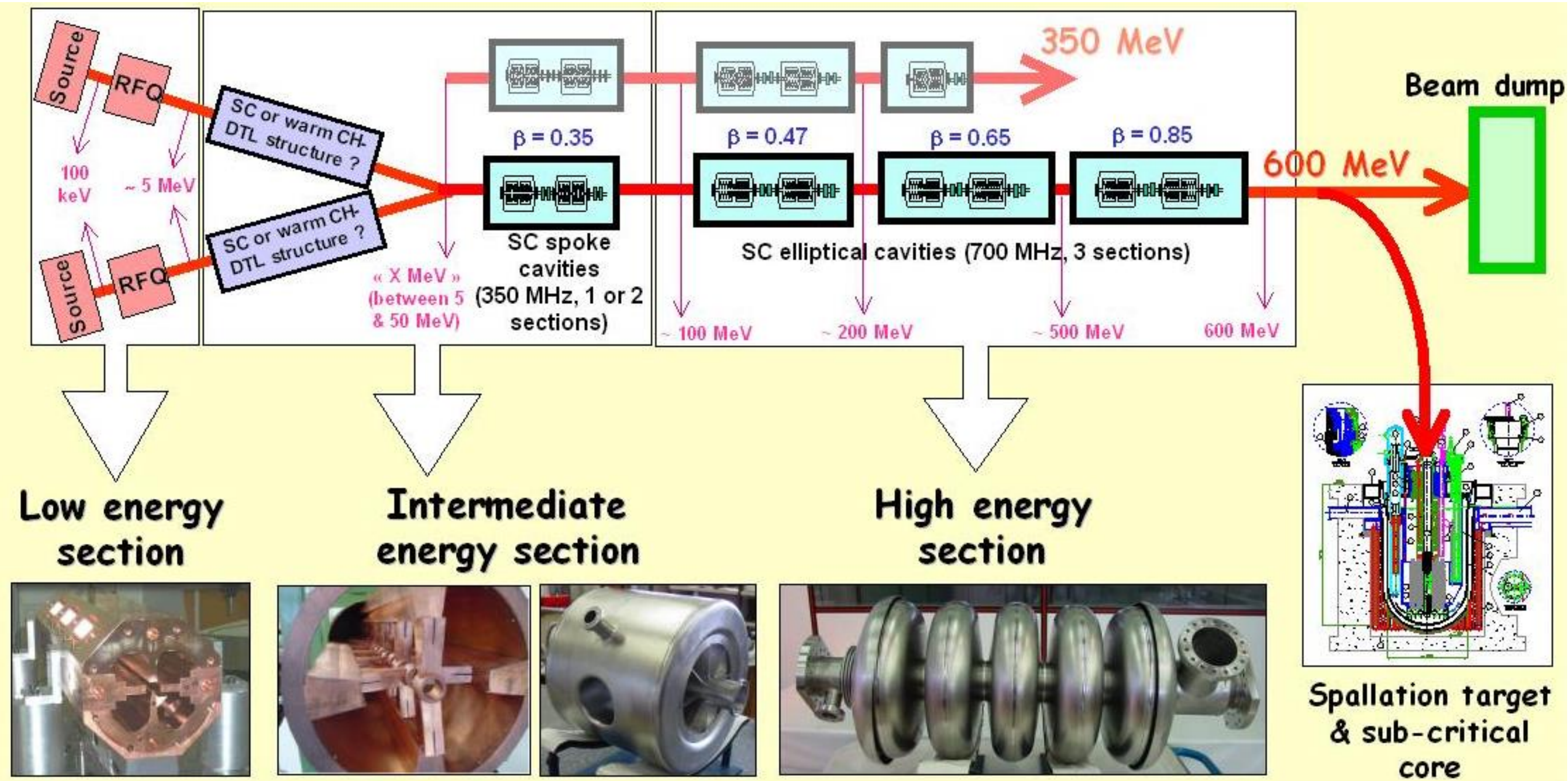
- but the formula, even more importantly, also suggests how to overcome the initial relativistic effects in a cyclotron (starting around 20 MeV for a proton): the relativistic mass increase with increasing $\beta = v/c$ of $m = \gamma \cdot m_0$, $\gamma = (1-\beta^2)^{-1/2}$ can be compensatedby correspondingly increasing the magnetic field in order to maintain the frequency ν constant, this can be done by shaping the poles (see figure) and adding "trim coils", such an accelerator is called an isochroneous cyclotron, varying ν, however, is technically challenging, and the corresponding accelerator, the synchrocyclotron, is necessarily a pulsed, weak current machine



- unfortunately, a cyclotron can not have any direct focusing elements inside and that for flight paths which exceed kilometers
- The way to overcome partially the absence of vertical focusing, is to use alternate gradient focusing, by passing in successively in sectors of strong and weak (or zero) fields.
  A radially decreasing field has also been shown to work, but of course this is in contradiction to the relativistic effect correction



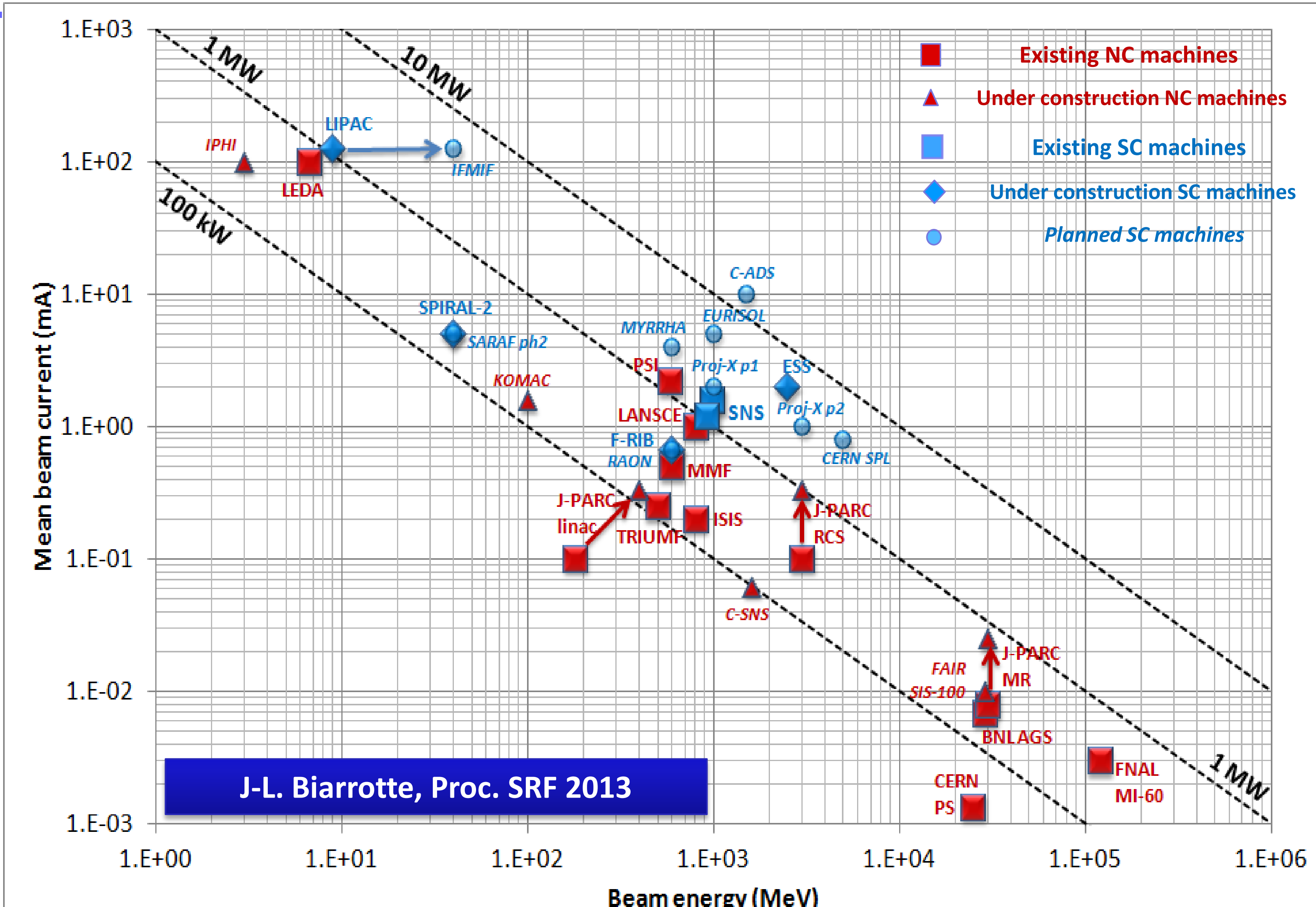
PDS-XADS Reference Accelerator Layout



Strong R&D & construction programs for LINACs underway worldwide for many applications

(Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)

Let us have a look at other accelerator projects



Why superconducting cavities?

Intrinsic advantage of cold cavities

Almost no losses on the cavity wall (thanks to superconductivity)

⇒ ~100% of the injected RF power goes to the beam : very high efficiency !!!

- Operating cost gain as compared to warm structures (which dissipate $\sim 10^5$ times higher)

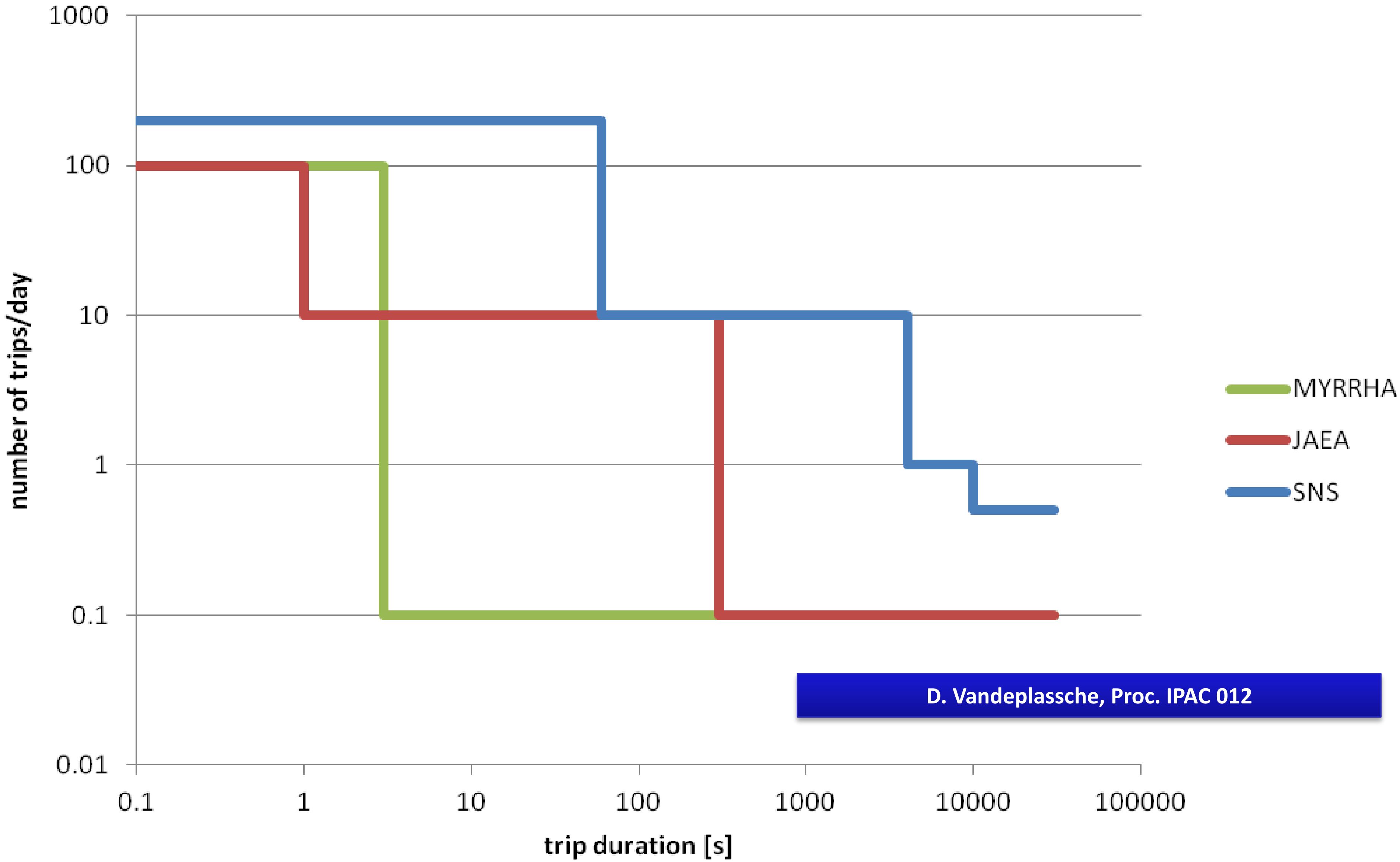
- Possibility to accelerate CW beams or beams with a high duty cycle (> 1 %) with high accelerating gradients (impossible with warm structures)

- Possibility to relax the constraints on the cavity RF design: choosing larger beam port aperture is possible ⇒ reduction of the activation hazard = security gain

- High potential for reliability and flexibility

- Main drawback : need to be operated at cryogenic temperature

Reliability



D. Vandeplassche, Proc. IPAC 012

The 3 principles for reliability improvement

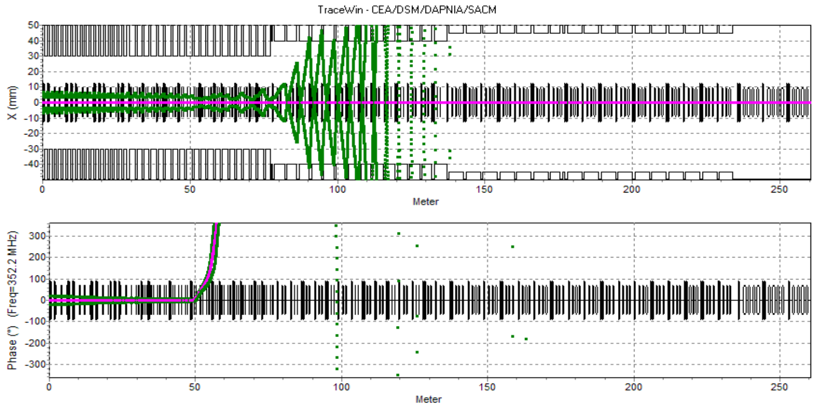
- Overdesign
  - basically only possible for linacs not running against
    - the limits of energy (relativistic effects)
    - The limits of intensity (weak focusing)

- Redundancy
  - basically only possible for linacs
    - because of their modularity
    - at the expense of efficiency (components used once)

- Fault tolerance
  - basically only possible for linacs
    - requires modularity
    - a very innovative concept

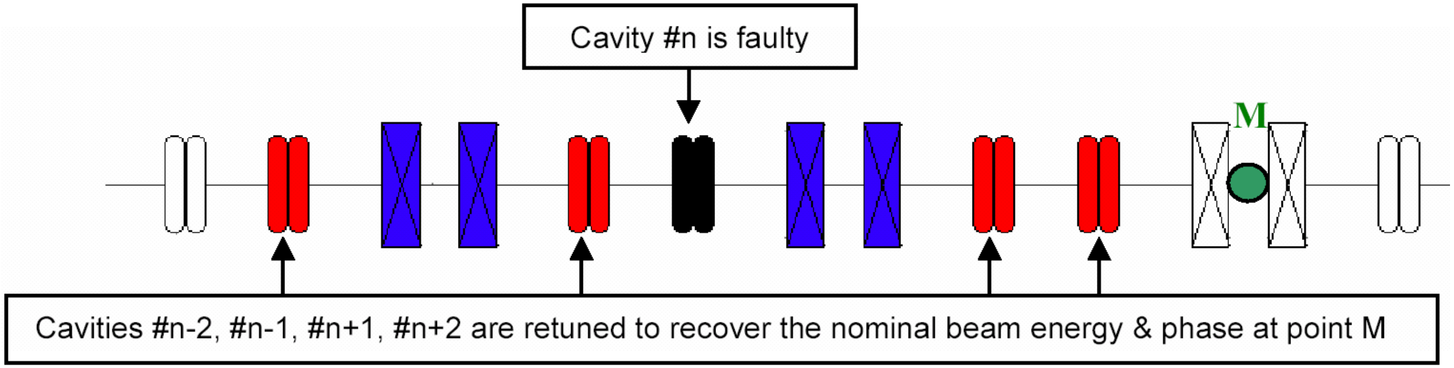
Fault Tolerance, a new concept uniquely applicable in a modular super conducting Linac

Fault tolerance in the independently phased SC sections is a crucial point because a few tens of RF systems failures are foreseen per year.



1. Consequences of the failure of a superconducting RF cavity
→An RF system failure induces phase slip (non relativistic beam)
→ If nothing is done, the beam is always LOST

2. Linac retuning after the failure of a RF cavity or of a quadrupole
→ Local compensation philosophy is used
→ In every case, the beam can be transported up to the high energy end without beam loss



Exotic hybride concepts?

- In contrast to cyclotrons, FFAG exhibit
  - strong focusing overcome the relativistic limitations
- In contrast to cyclotrons, FFAG
  - are pulsed machines, with intrinsically (much) lower intensity
- In contrast to cyclotrons and linac's, FFAG are
  - very complicated to build
  - No "real machine" existing since the 60 years after invention
- In contrast to linacs, FFAG exhibit
  - no potential for implementing the 3 basic principles of reliability improvement
- To my assessment,
  - FFAG are therefore unsuited for ADS

Conclusion: NEA was and still is right!

- **Main technical answers**
  - Superconducting linac
    - No limitation in energy & in intensity
    - Highly modular and upgradeable (industrial transmuter)
    - Excellent potential for reliability (fault-tolerance)
    - High efficiency (optimized operation cost)
  - Cyclotron
    - Attractive (construction) cost (?)
    - Required parameters at limits of feasibility ("dream machine")
    - Compact, but therefore not modular

- **In complete agreement with findings of the NEA report:**
  - **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice **for preliminary low power experiments**, where availability and reliability requirements are less stringent.
  - **CW linear accelerators must be chosen for demonstrators and full scale plants**, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.