Needs for High Intensity and High Brightness

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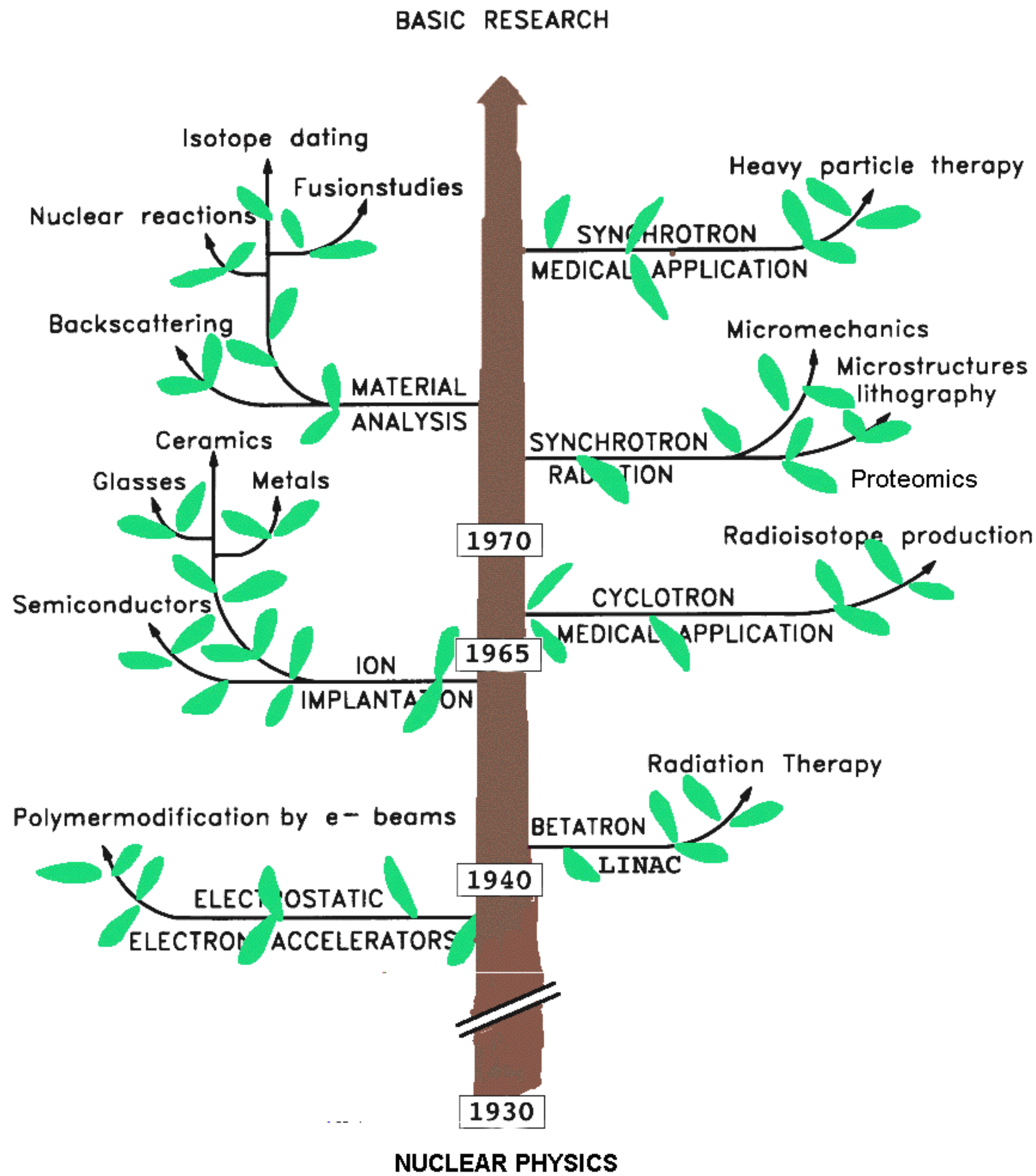
The Role of Accelerators in Physical and Life Sciences

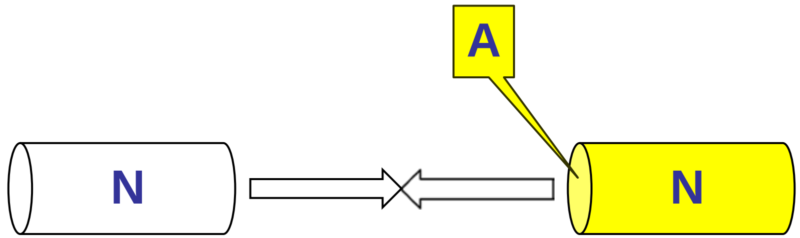
"It is an historical fact that scientific revolutions are more often driven by new tools than by new concepts"

Freeman Dyson



Particle colliders

Collider Luminosity, rate of interactions



Target density $\propto \frac{N}{A}$

High probability or the rate of collisions require high intensity and small beams

$$\mathcal{L} = f\,\frac{N^2}{A}\left[\frac{1}{cm^2 \cdot s}\right]$$

$$R = \frac{dn}{dt} = \mathcal{L} \cdot \sigma_{\text{int}}$$

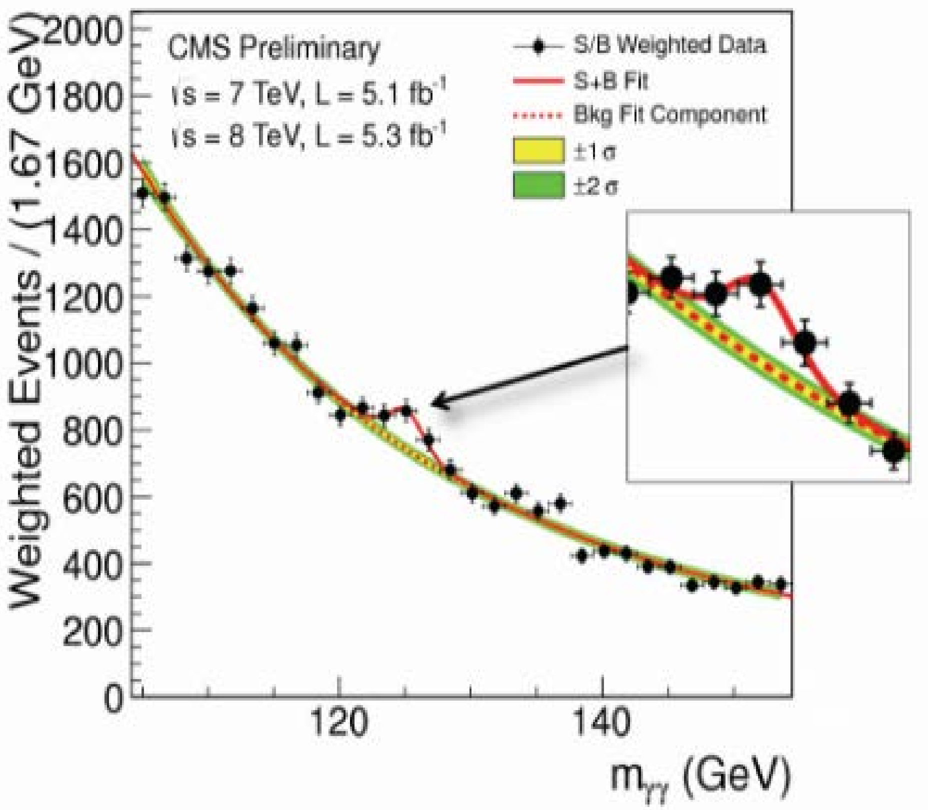
Need for high brightness hadron beams

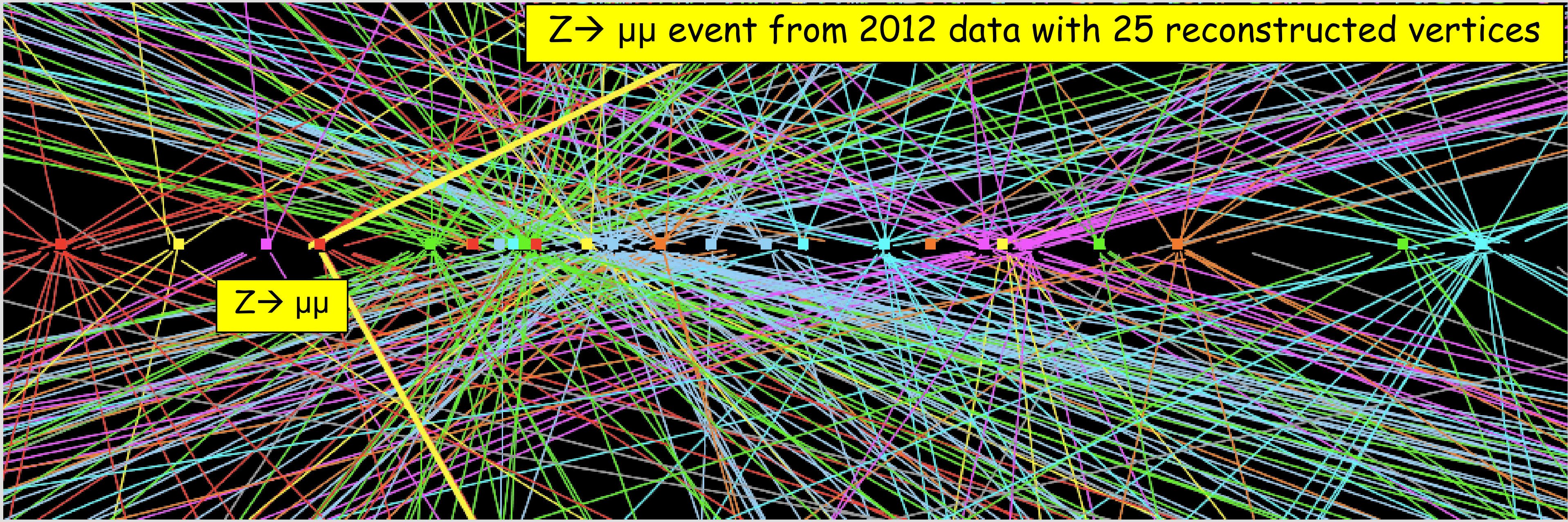
- ion sources
- preserving it through the acceleration cycle

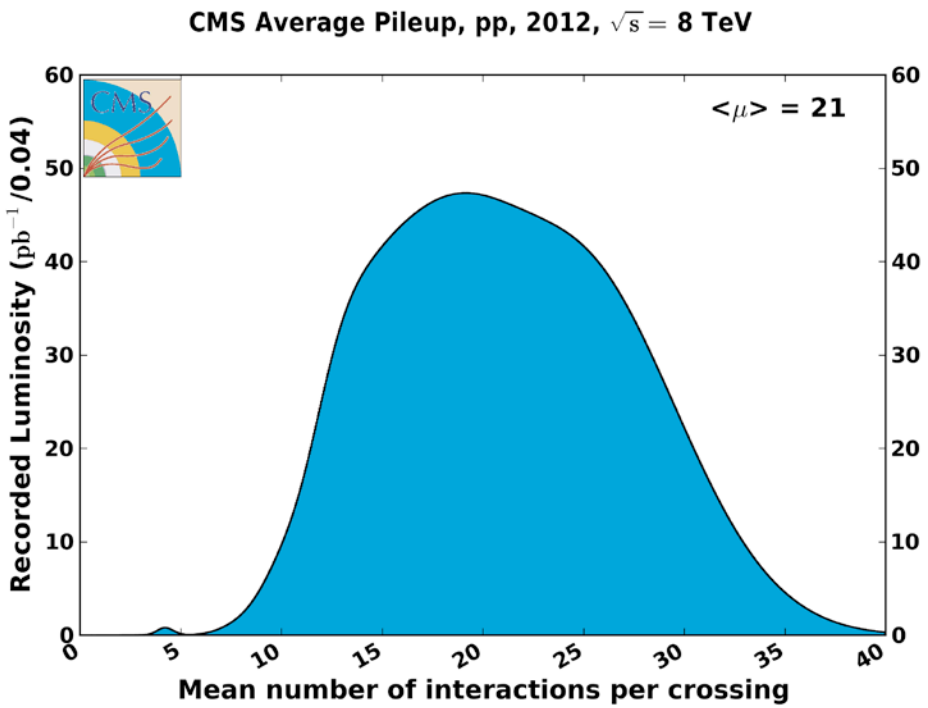
High energy colliders: luminosity challenge

High energy frontier exploration requires high luminosity at high energy (and thus high **intensity** and **beam power**)

- to overcome **Signal to Noise** in hadron colliders

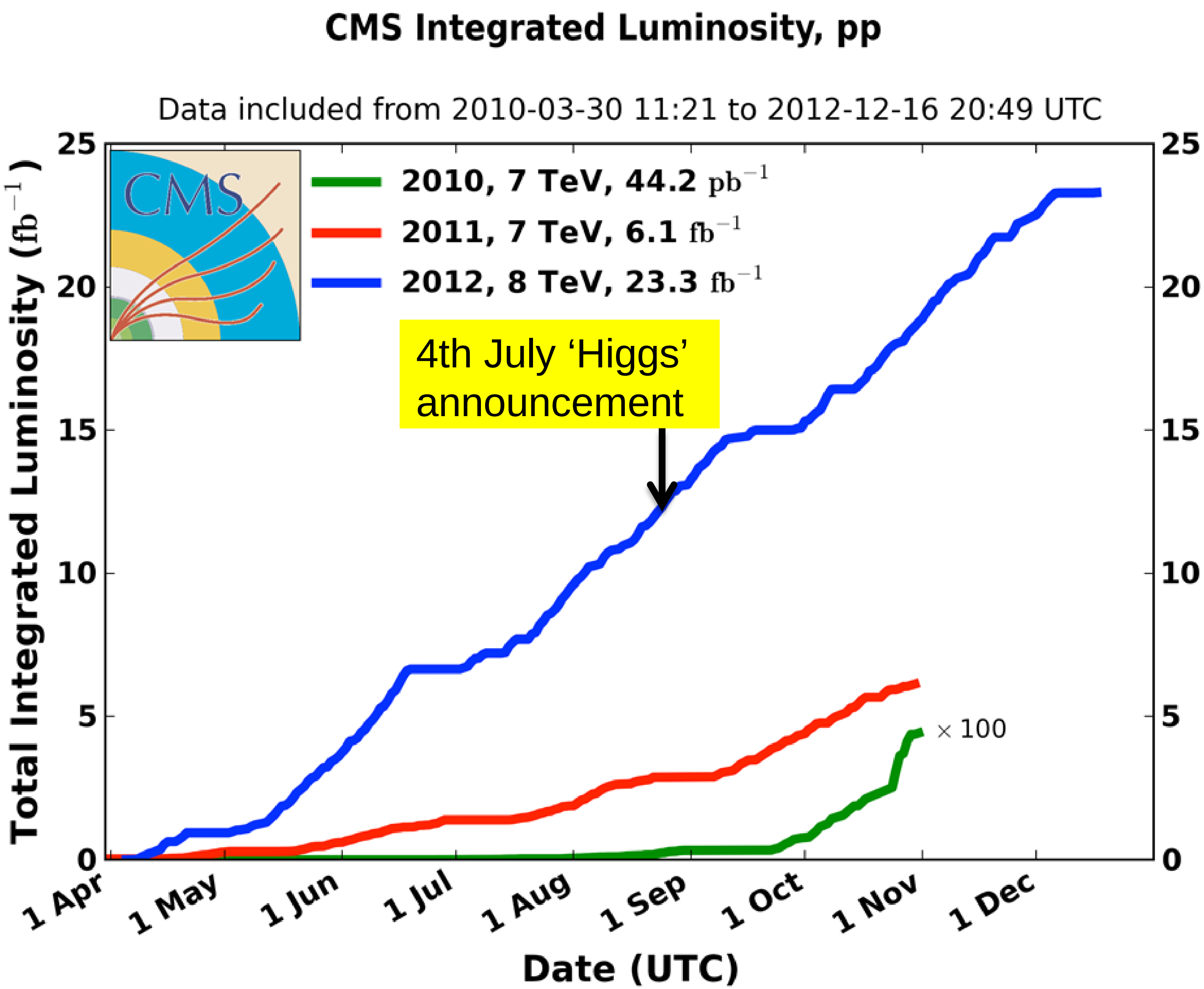






Lengthen the luminous region?

LHC INTEGRATED LUMINOSITY

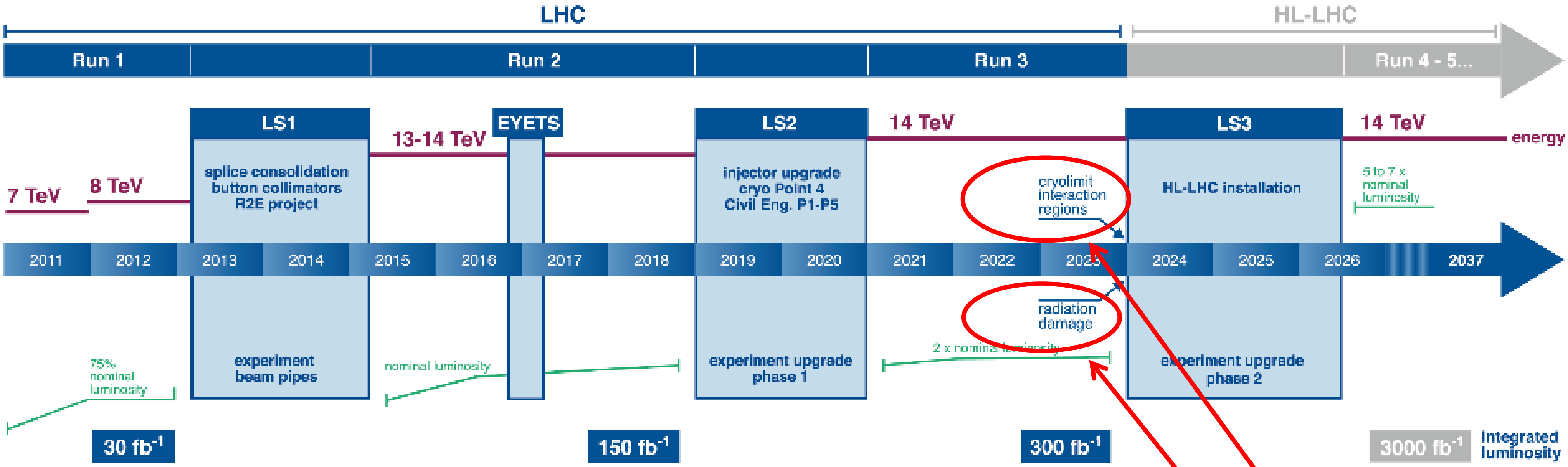


2012: 15 fb^{-1} at 8 TeV

2011: 5.6 fb^{-1} at 7 TeV

2010: 0.05 fb^{-1} at 7 TeV

LHC / HL-LHC Plan



$0.75\ 10^{34}\ cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

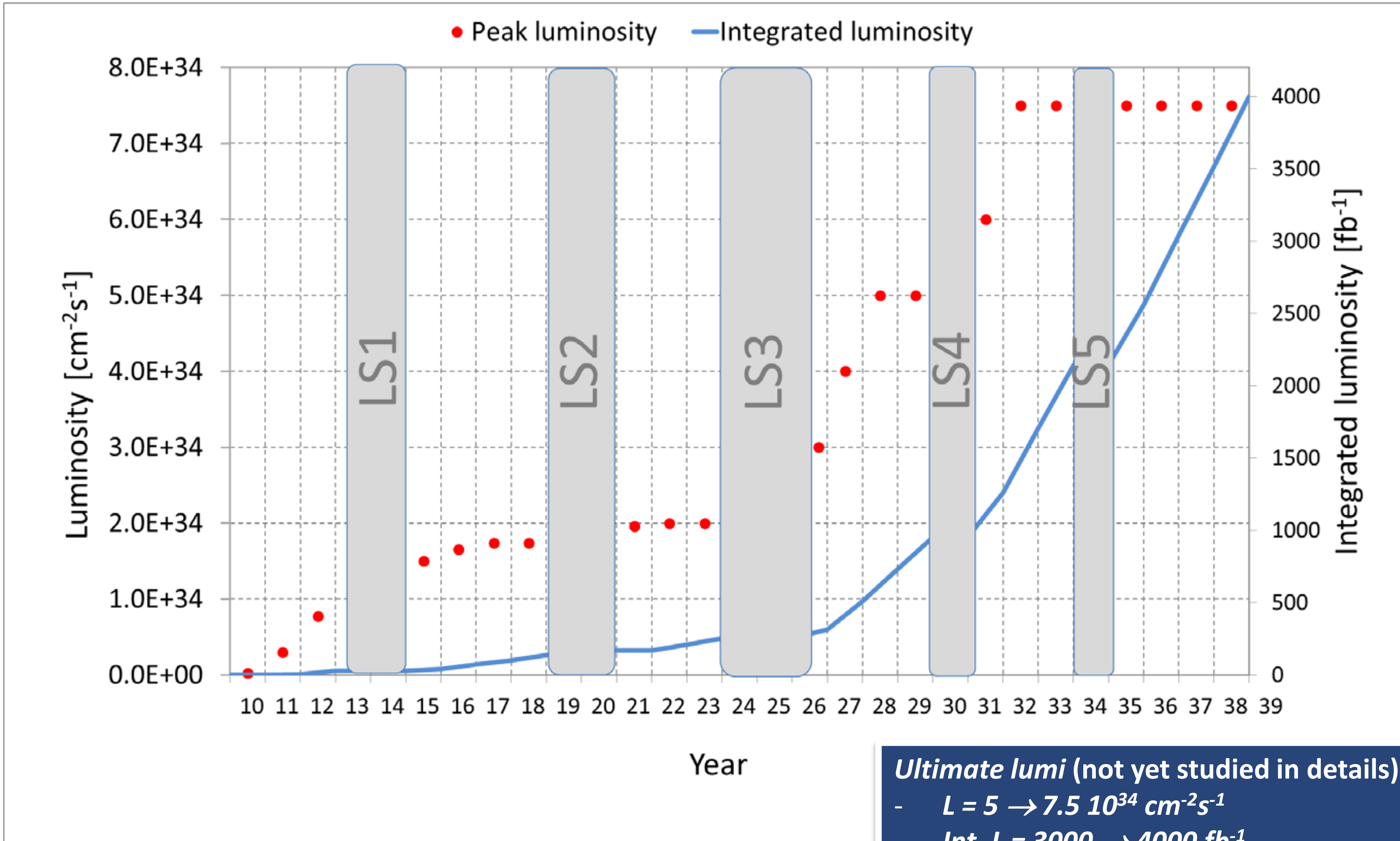
$1.5\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

$1.7\text{-}2.2\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

Technical limits to lumi increase (Machine & Experiments)

50 ⇒ 25 ns

HL-LHC ***ultimate*** *performance*



Ultimate lumi **(not yet studied in details)**

- ***$L = 5 \rightarrow 7.5\ 10^{34}\ cm^{-2}s^{-1}$***
- ***Int. $L = 3000 \rightarrow 4000\ fb^{-1}$***
- ***Pile up $\mu \sim 200$***

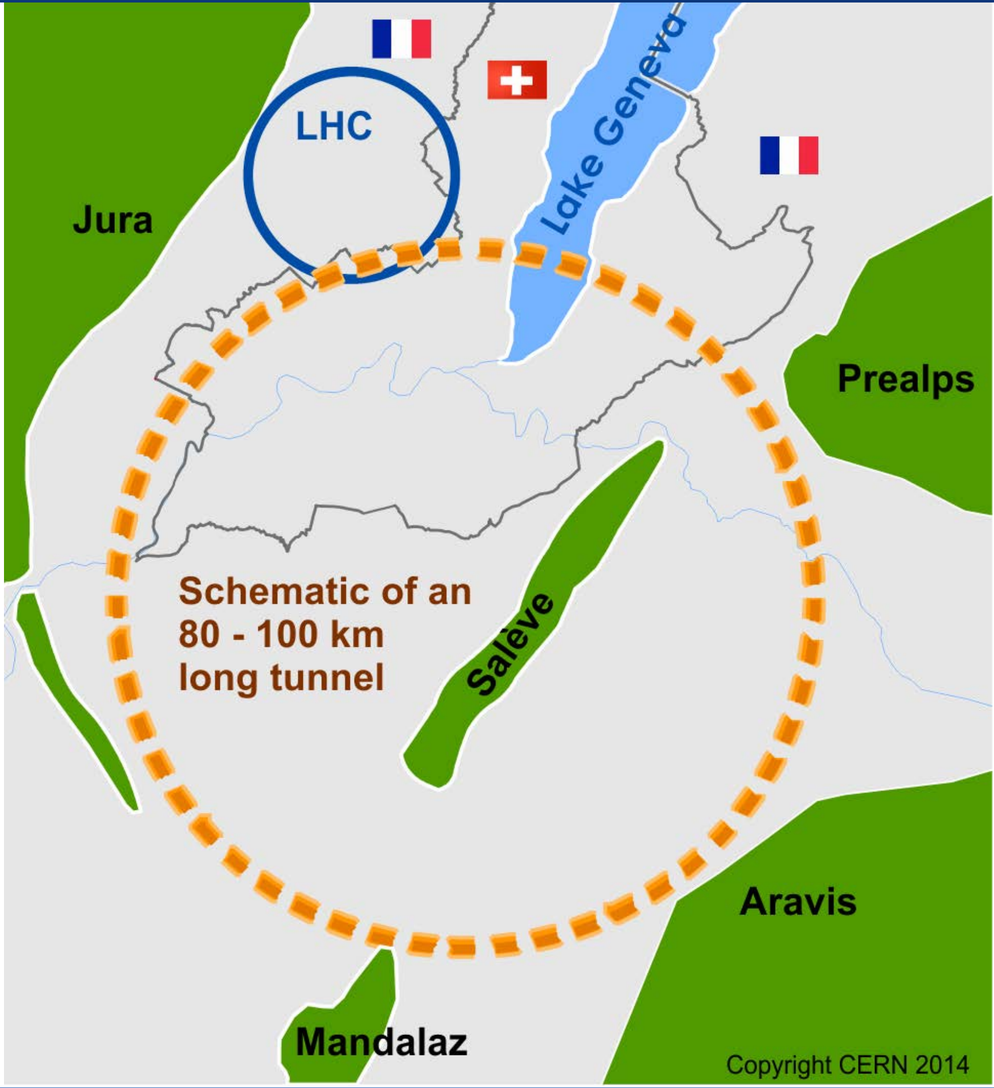
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (FCC-he) option**
- **HE-LHC** with FCC-hh technology



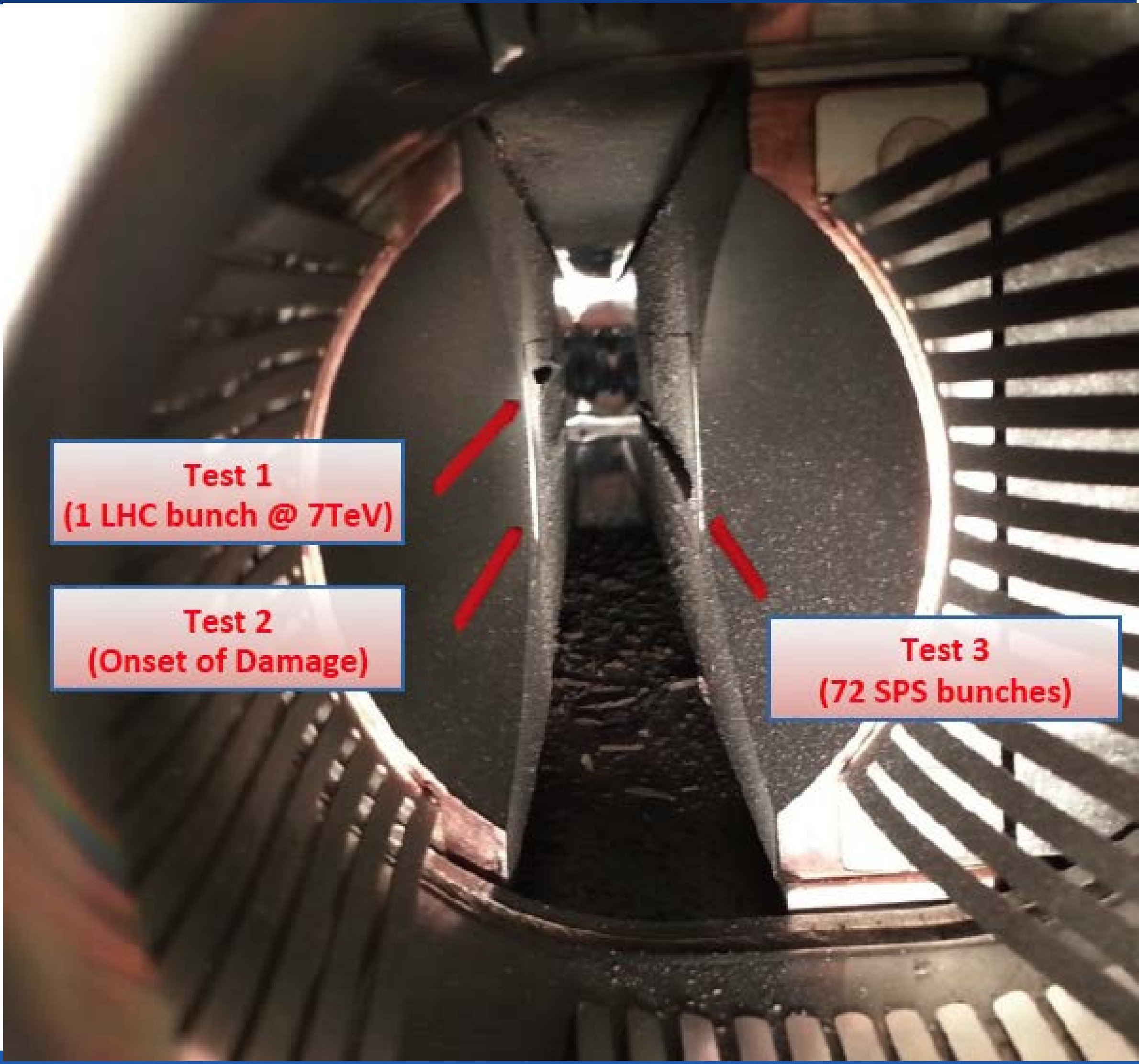
Hadron collider parameters

Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	25	12	1	5
events/bx	170	850 (170)	400	27	135
luminous region RMS [cm]	5.7	5.7			
normalised emittance [μm]	0.44	2.2		3.75	2.5
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchr. rad. [W/m/apert.]	30		58	0.2	0.35

Unprecedented beam power

- 8GJ stored energy / beam
  - Airbus A380 at 700km/h
  - 24 times larger than in LHC at 14TeV
  - Can melt 12t of copper
  - Or drill a 300m long hole
  - ⇒ **Machine protection**
  - ⇒ **Beam dumping**

- Any beam loss important
  - E.g. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background for the experiments
  - Activation of the machine
  - ⇒ **Collimation system**
  - ⇒ **Transfer and injection**



Lepton colliders

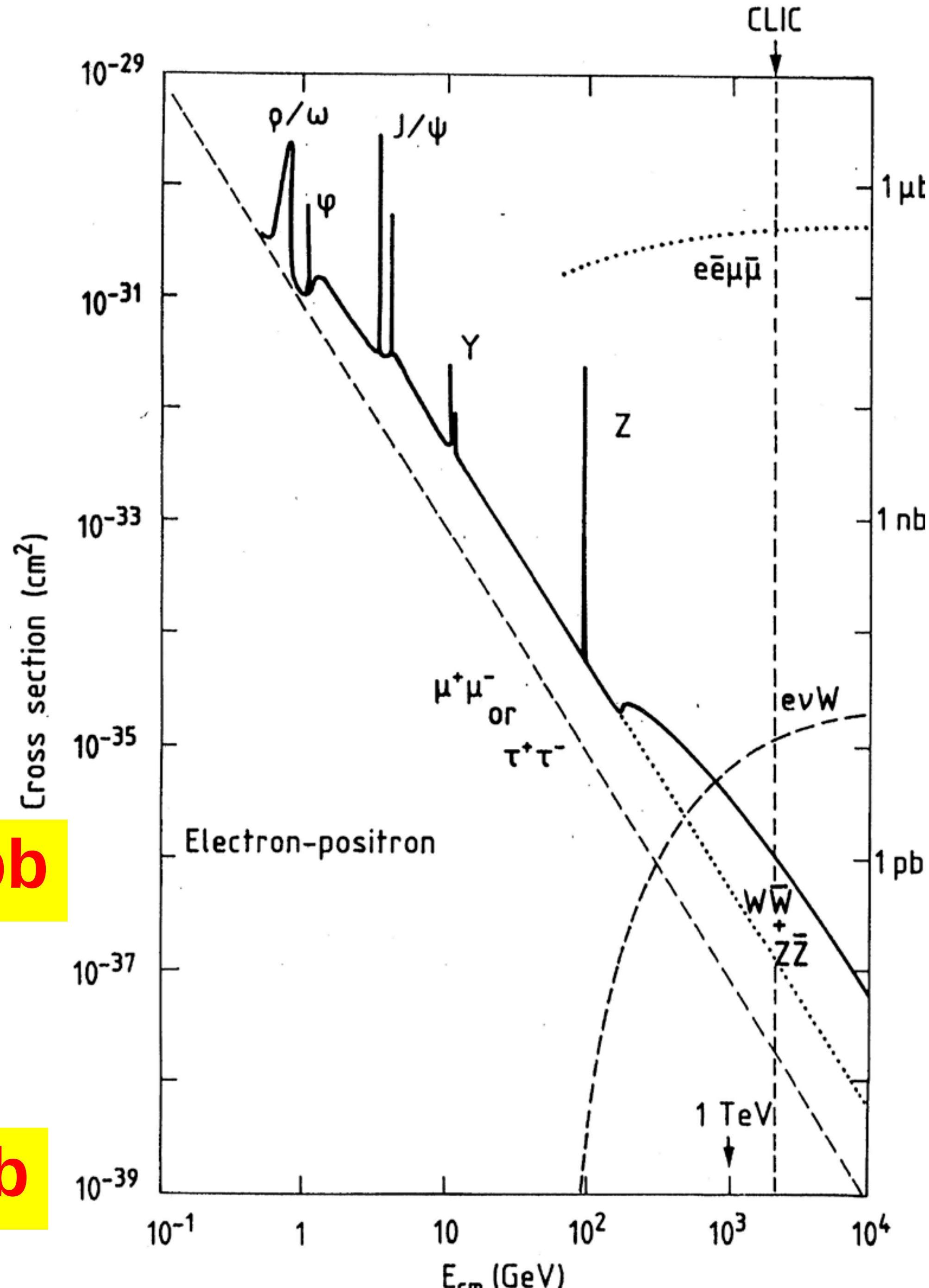
Point cross-section drops with $s = E^2_{cm}$

$$\sigma_{int} \propto \frac{1}{s}$$

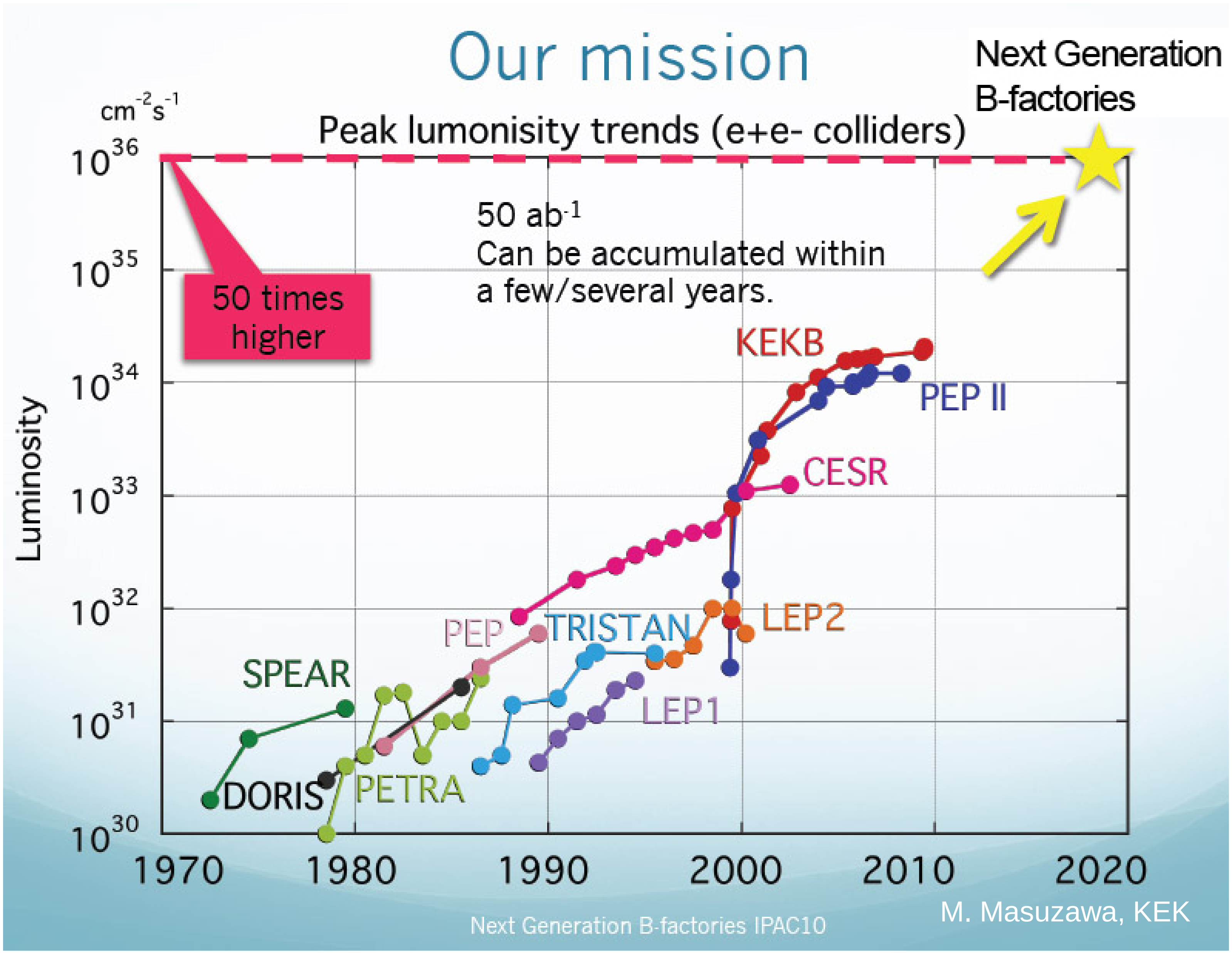
Unit: barn = 10^{-24} cm^2

1 pb

1 fb



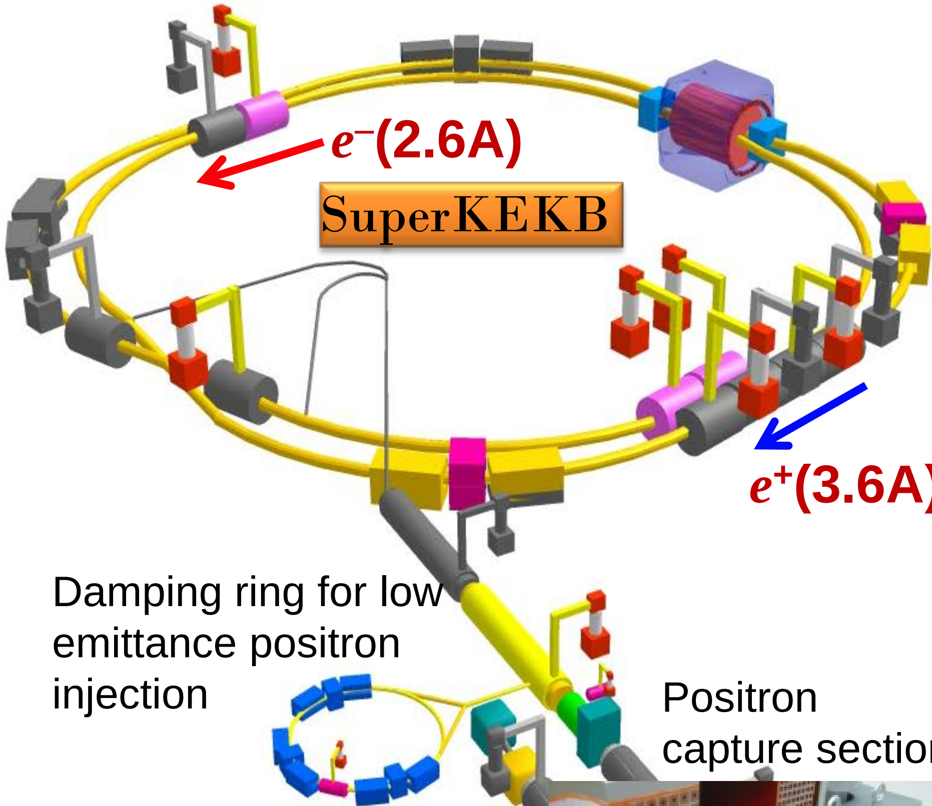
History of ring colliders luminosity



Next generation B-factory SuperKEKB

Low emittance lattice

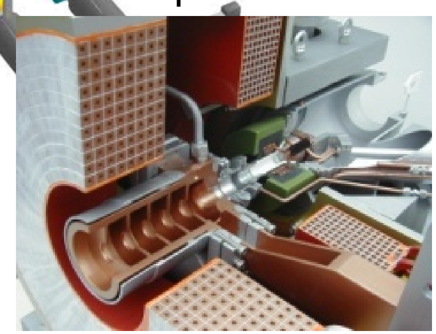
IR with β_y*=0.3mm
SC final focus system

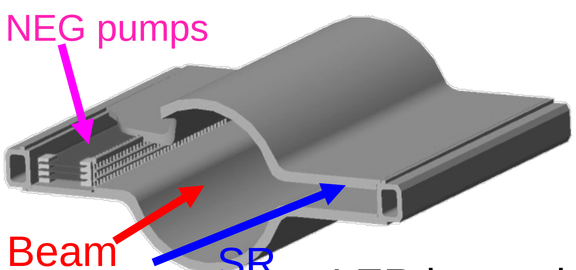


Add RF systems for higher beam current

Damping ring for low emittance positron injection

Positron capture section





LER beampipe to suppress photoelectron instability

Circular colliders: intensity challenges

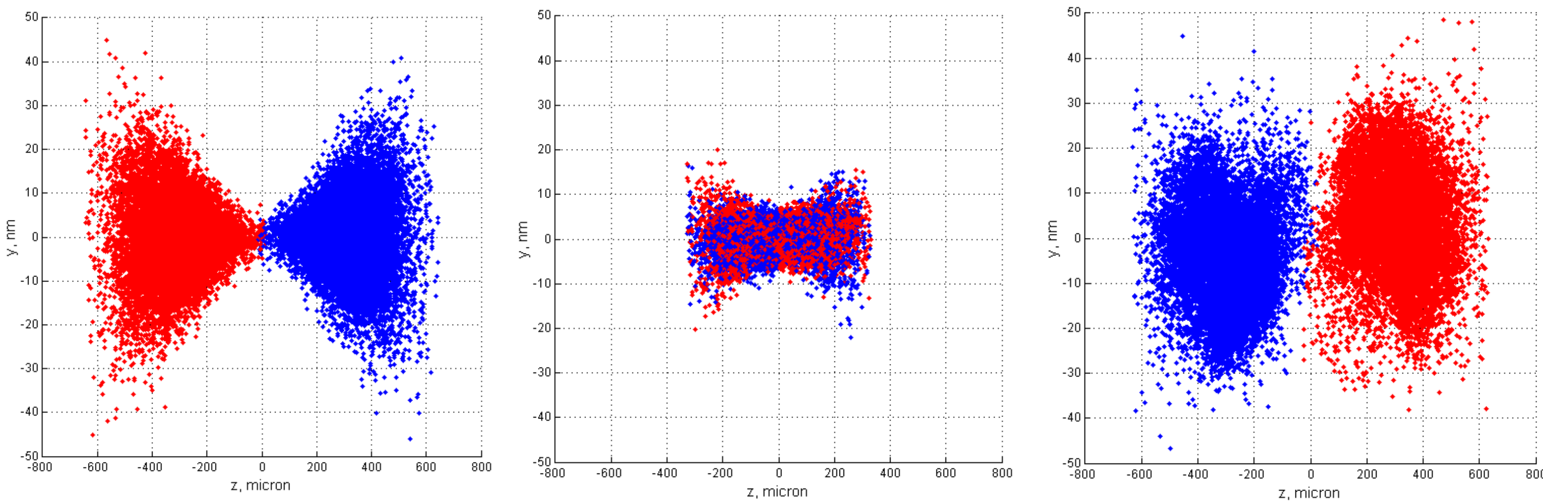
To achieve the design luminosity (examples):

- extreme stored beam power
- large number of bunches
- beam lifetime, including luminosity lifetime
- emittance preservation from source to collisions

Luminosity: linear colliders

H_D – beam-beam enhancement factor

$$\mathcal{L} = f \frac{N^2}{A} \cdot H_D$$



and in terms of beam power

$$P_b = E_{cm} \cdot f \cdot N$$

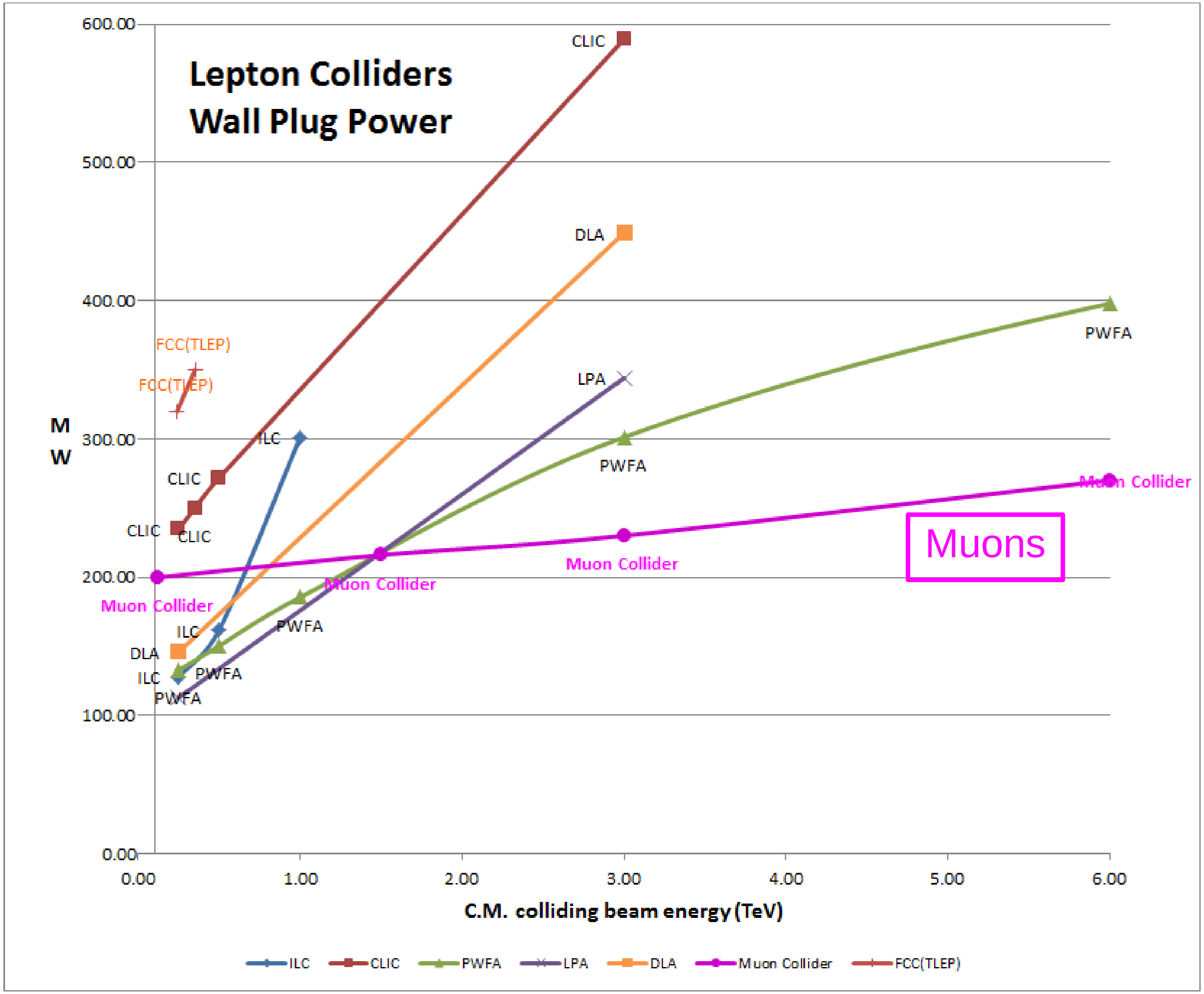
$$\mathcal{L} = \frac{P_b}{E_{cm}} \frac{N}{A} \cdot H_D$$

Beamstrahlung

Synchrotron radiation in the collective field of the bunch

- Center of mass collision energy is not well defined
- Backgrounds: direct synchrotron radiation
- Backgrounds: pair production from high energy photons

High energy: high wall plug power



Efficiency

Beam losses

J. P. Delahaye, CERN

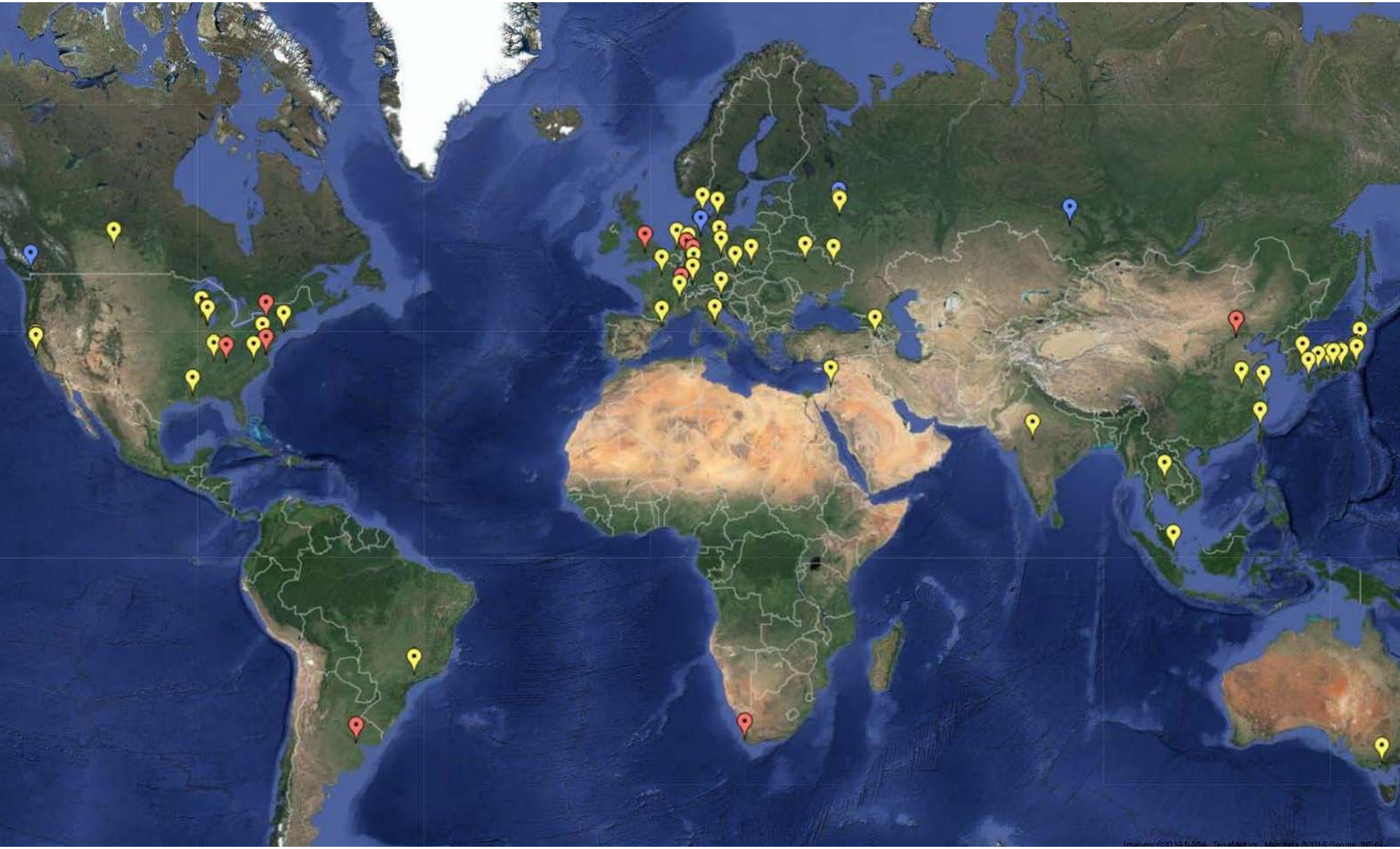
Linear colliders: intensity challenges

To achieve the design luminosity (examples):

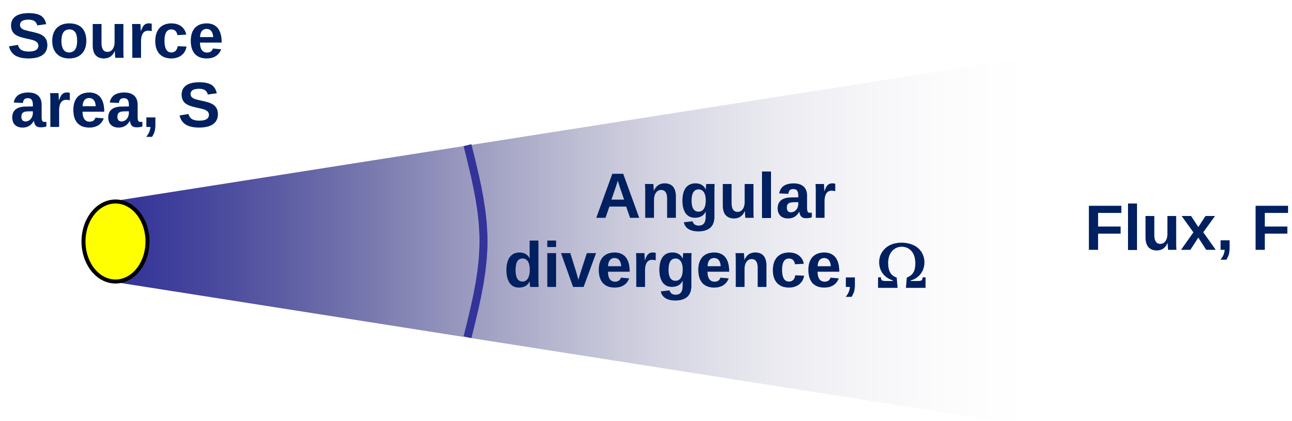
- extremely small (nm) beam sizes at IP
- good control of beamstrahlung and energy spread
- extremely small normalised emittance
- demanding damping rings
- emittance preservation from damping rings to IP

X-Ray sources

60‘000 SR users world-wide



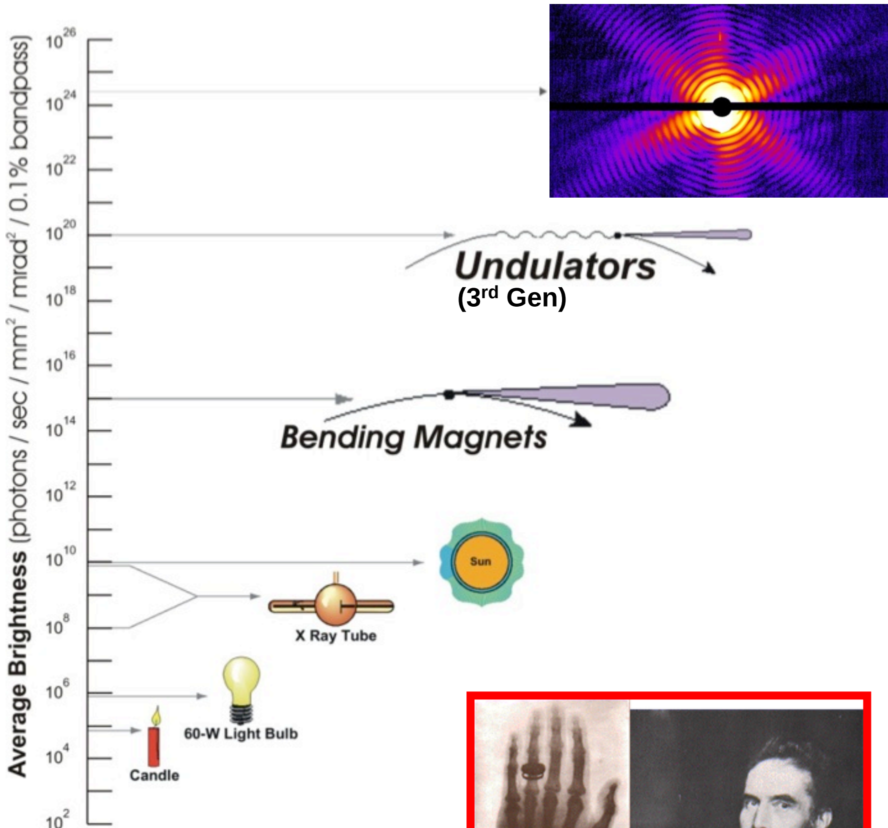
The "brightness" of a light source:



$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

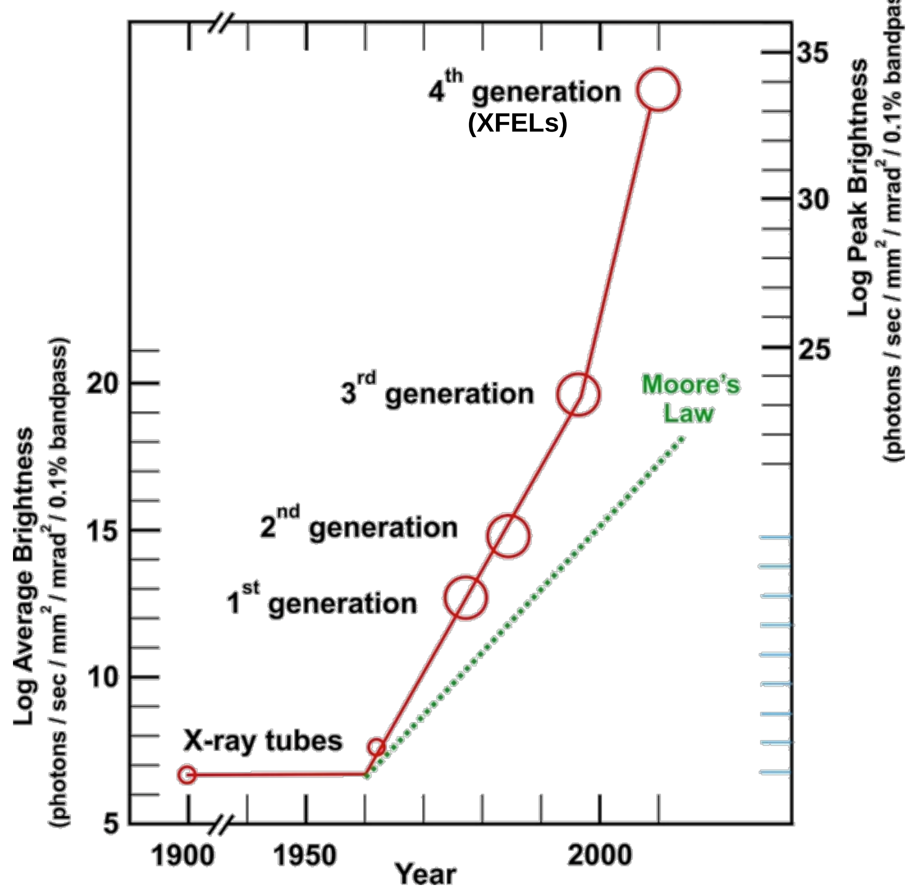
X-rays Brightness

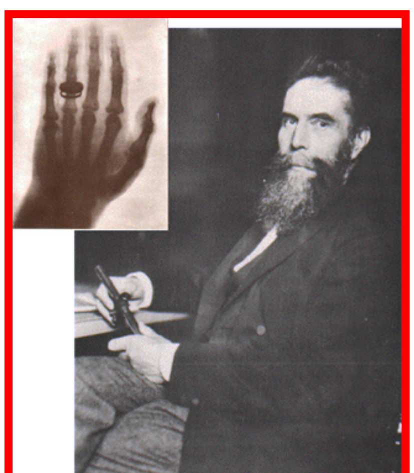
Average Brightness



XFELs

Peak Brightness





Bertha Roentgen's hand
(exposure: 20 min)

Particle beam emittance:

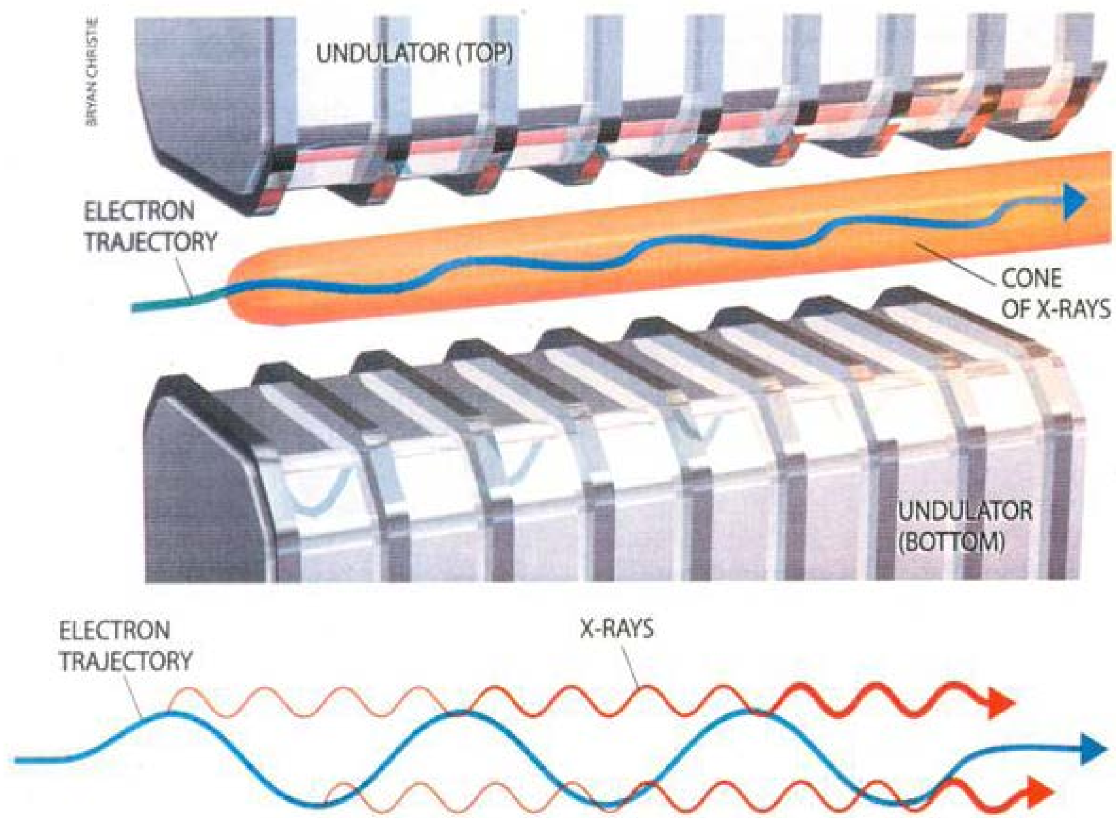
Emittance = S x Ω

Bright beams of particles: phase space density

Incoherent, spontaneous emission of light:

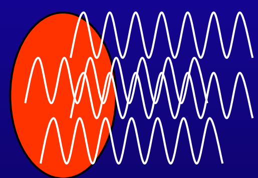
Large phase space

Coherent, stimulated emission of light



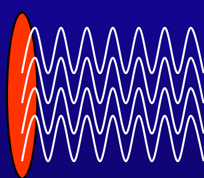
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto N$



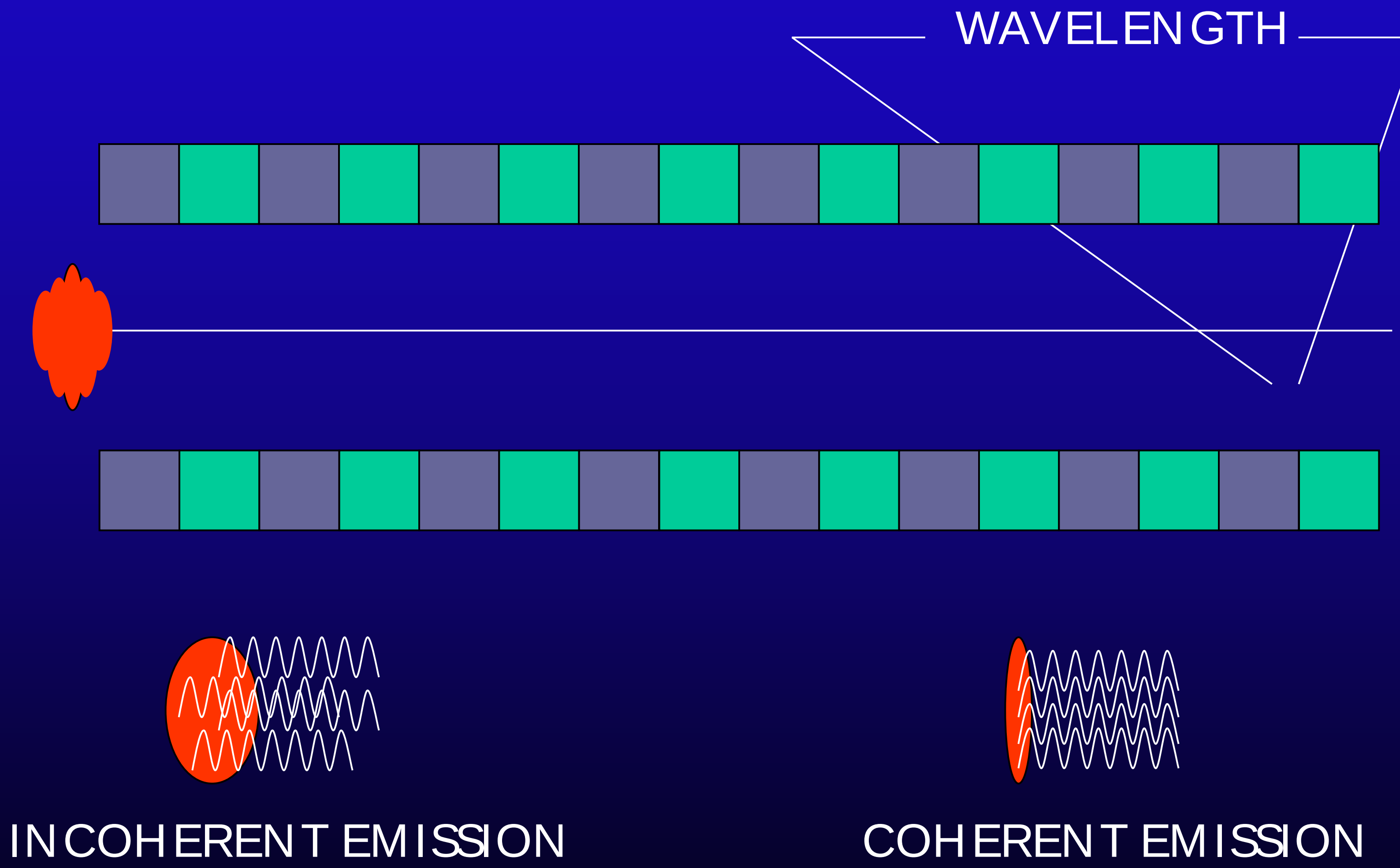
INCOHERENT EMISSION

Intensity $\propto N^2$



COHERENT EMISSION

MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE



The World of XFELs

PAL XFEL 2016

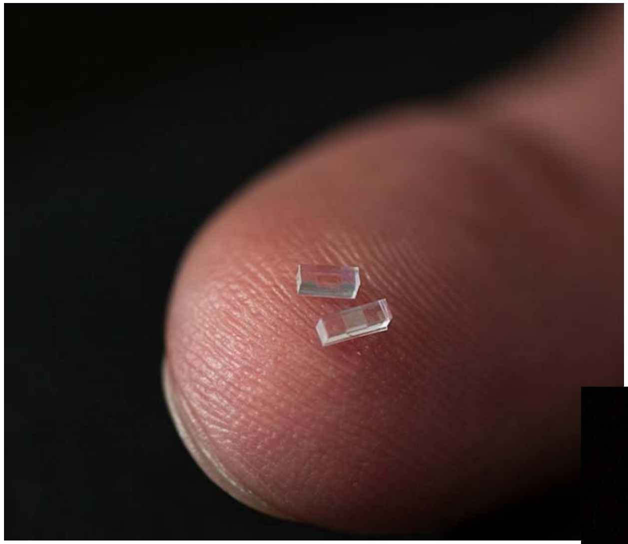
European XFEL
DESY, Hamburg 2017

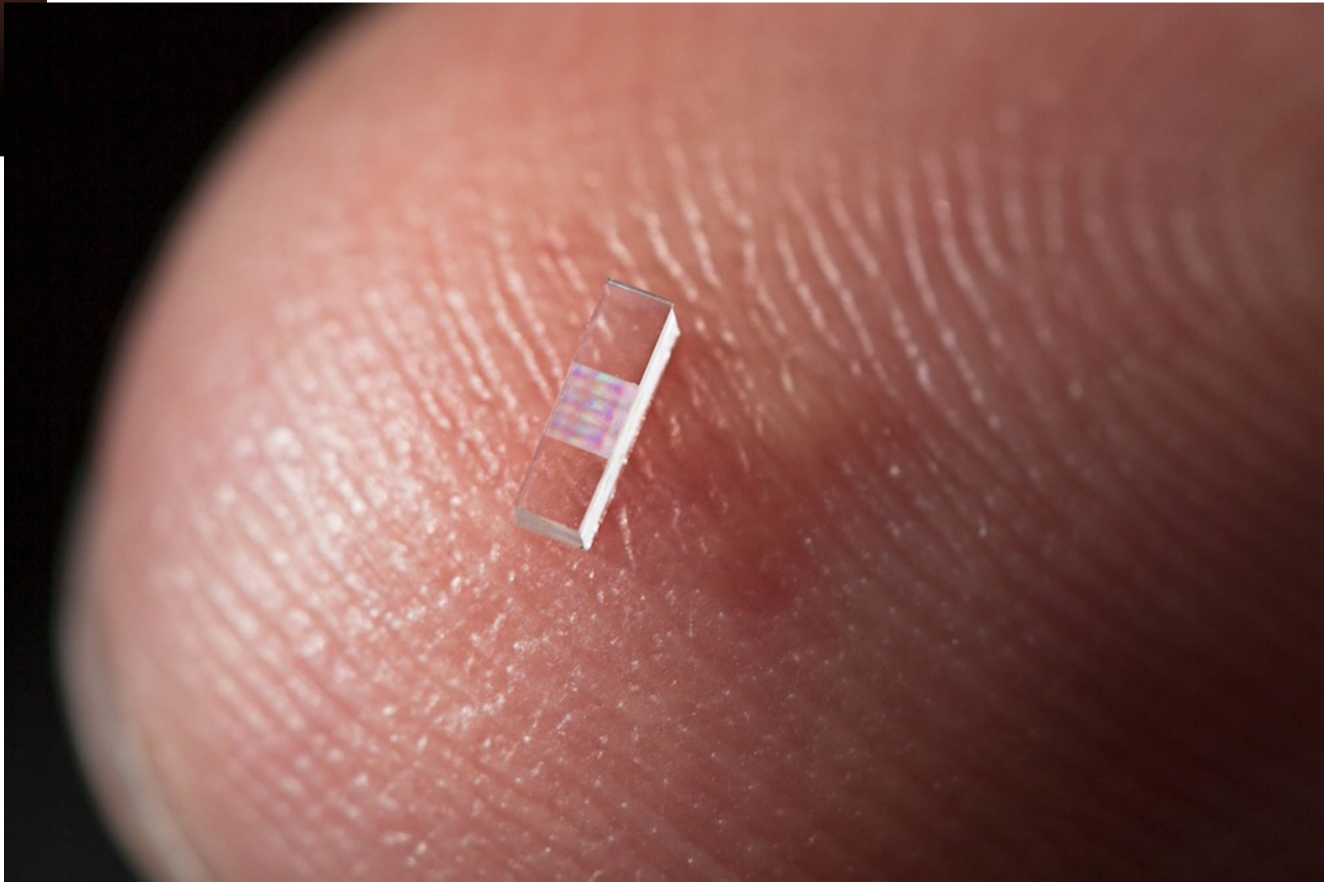
SACLA 2011
8.5 GeV, 60 Hz NC

LCLS I, II 2009, 2019

SwissFEL 2017

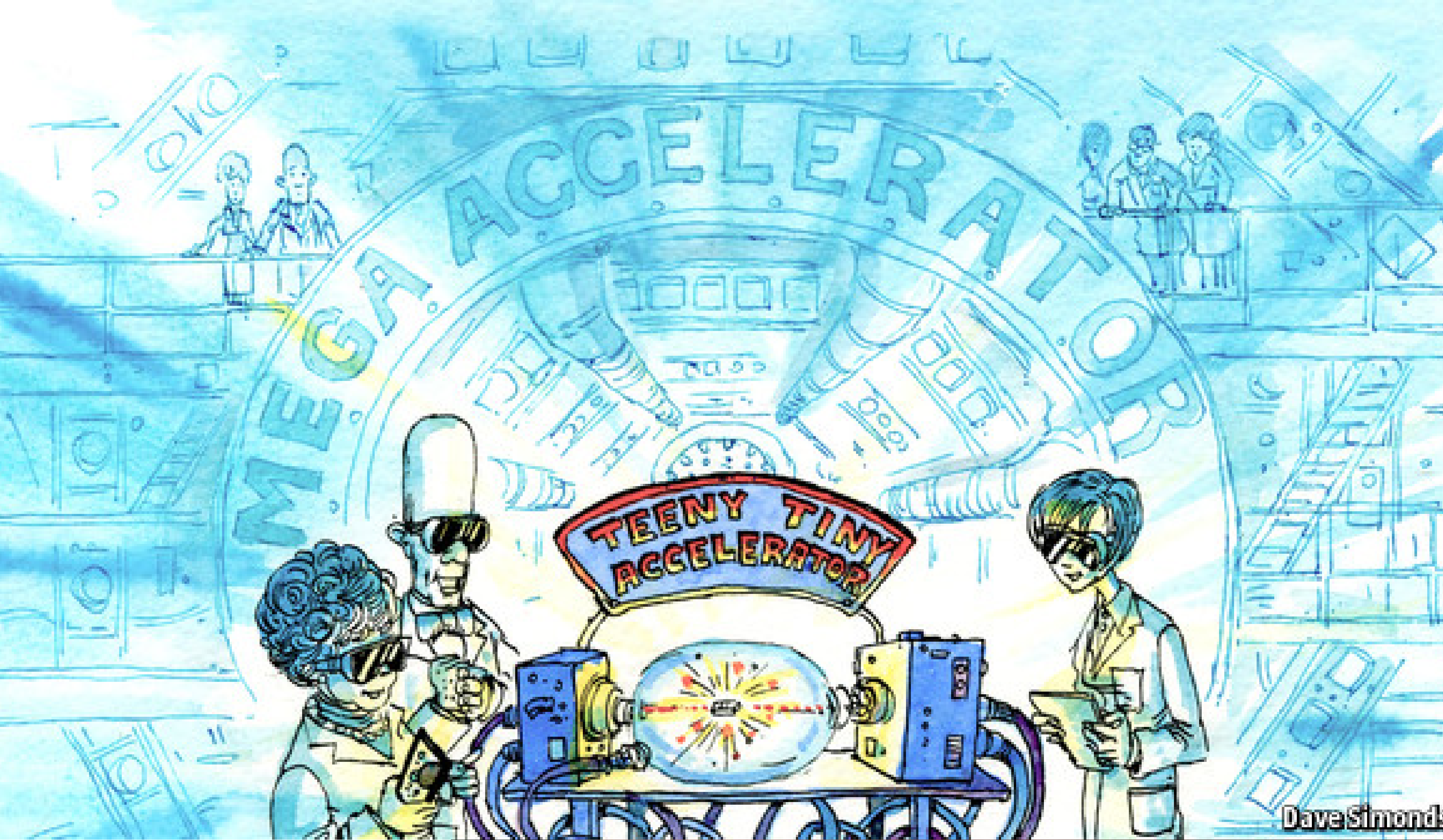
Accelerator on a chip



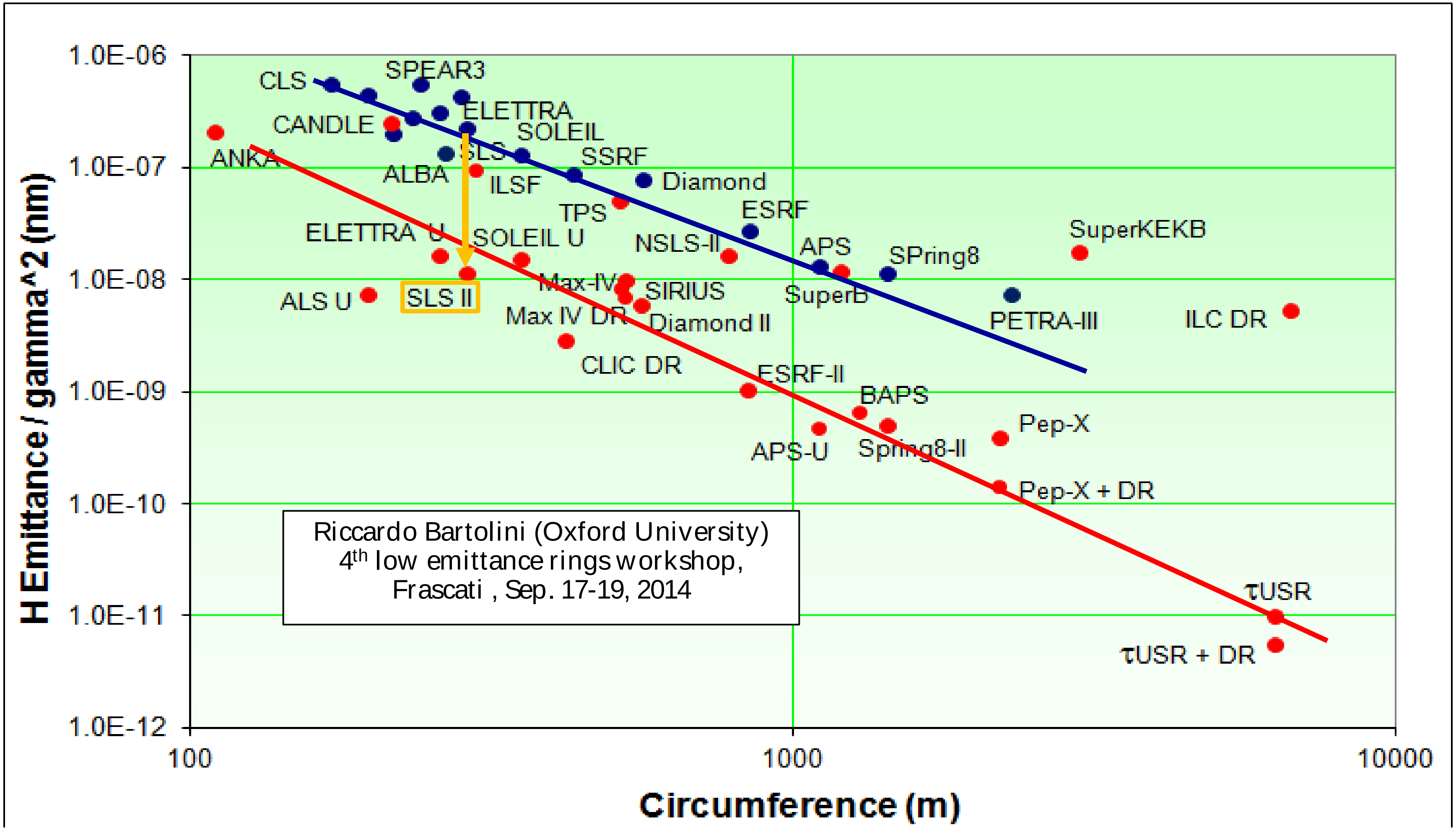


Accelerator on a chip

The Economist



The storage ring generational change

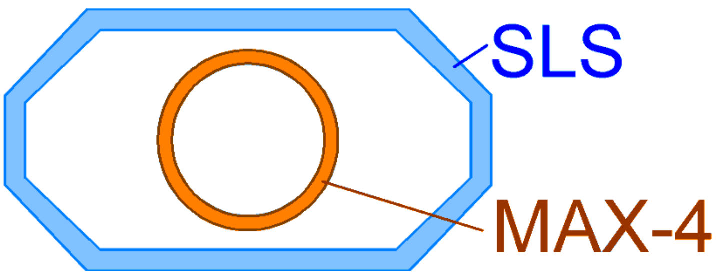


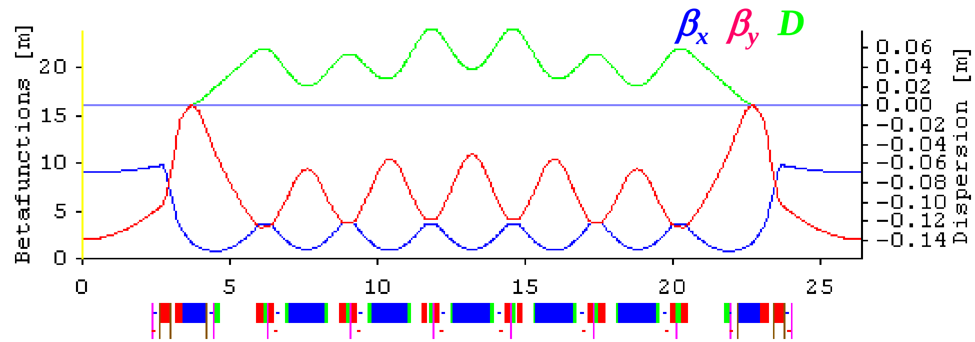
Storage rings in operation (•) and planned (•).
The old (—) and the new (—) generation.

A revolution in storage ring technology

Pioneer work: MAX IV (Lund, Sweden)

Aperture reduction ⟷ **Multi–Bend Achromat (MBA)**





Technological achievement:
NEG* coating of small vacuum chambers

- ⇨ Small magnet bore
- ⇨ High magnet gradient

- ⇨ short lattice cells
- ⇨ many lattice cells
- ⇨ low angle per bend

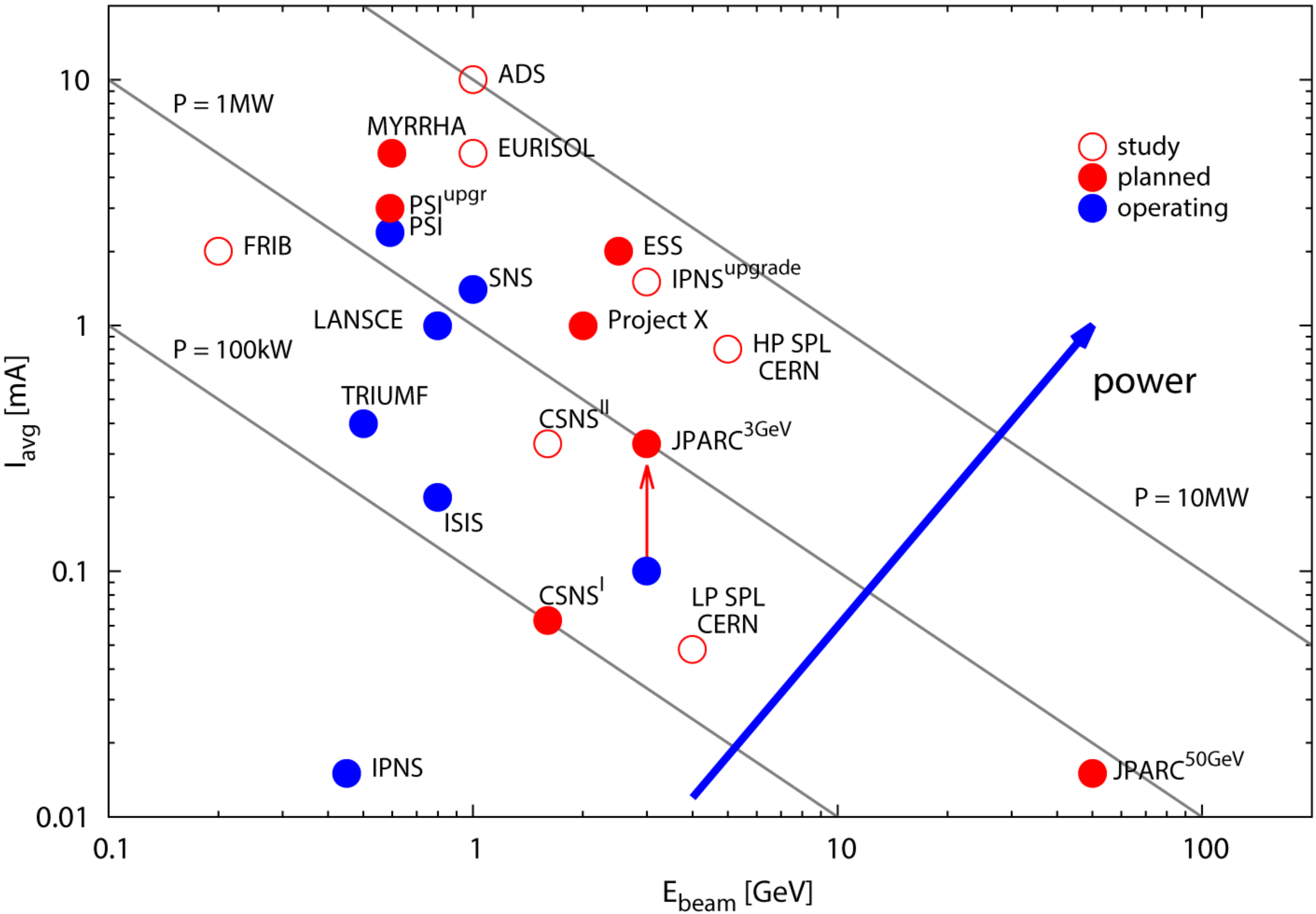
emittance $\varepsilon \propto (\text{energy})^2 \times (\text{bend angle})^3$

*Non Evaporable Getter

⇨ Emittance reduction from nm to 10...100 pm range

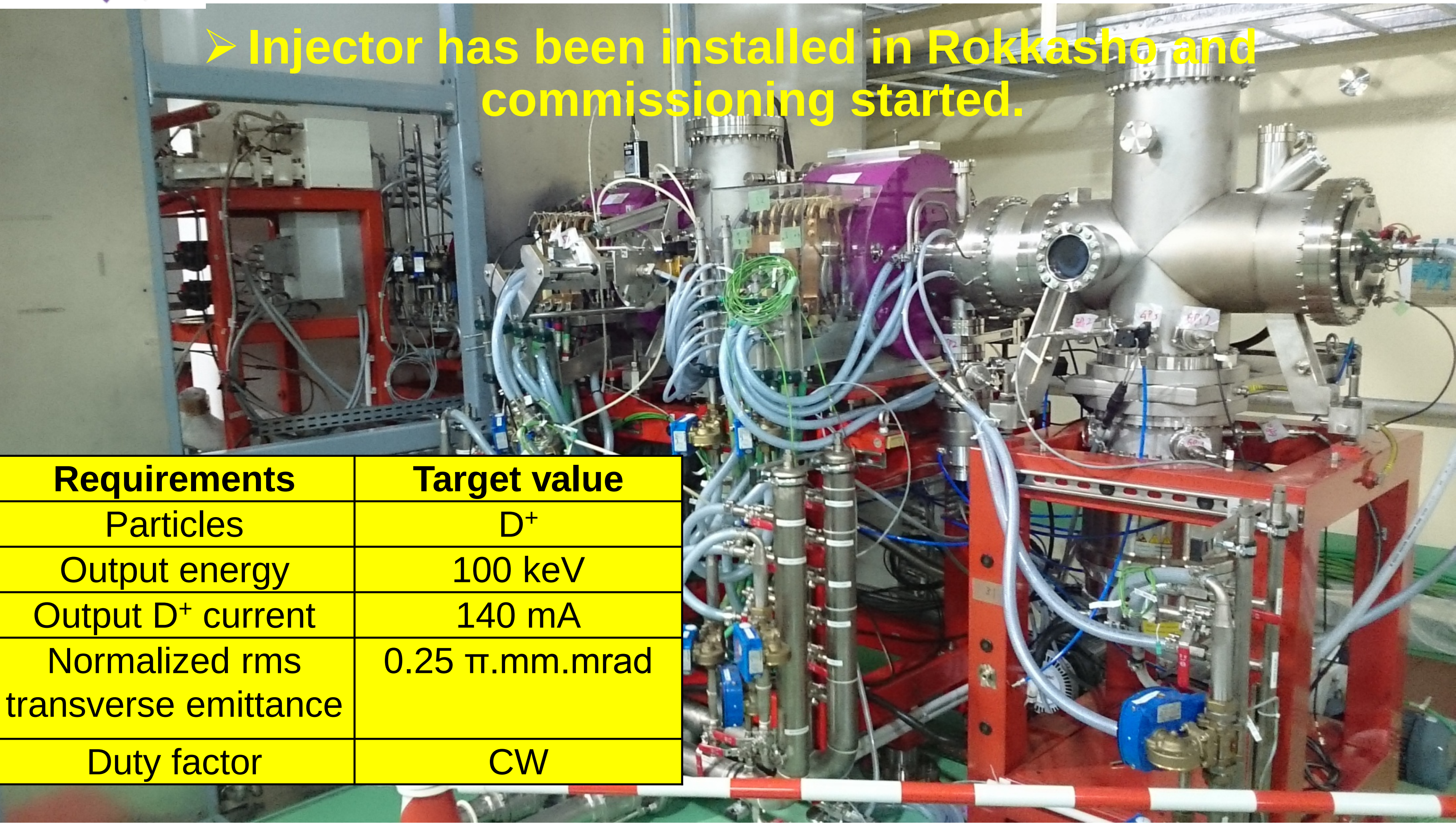
High intensity hadron beams

High intensity hadron facilities



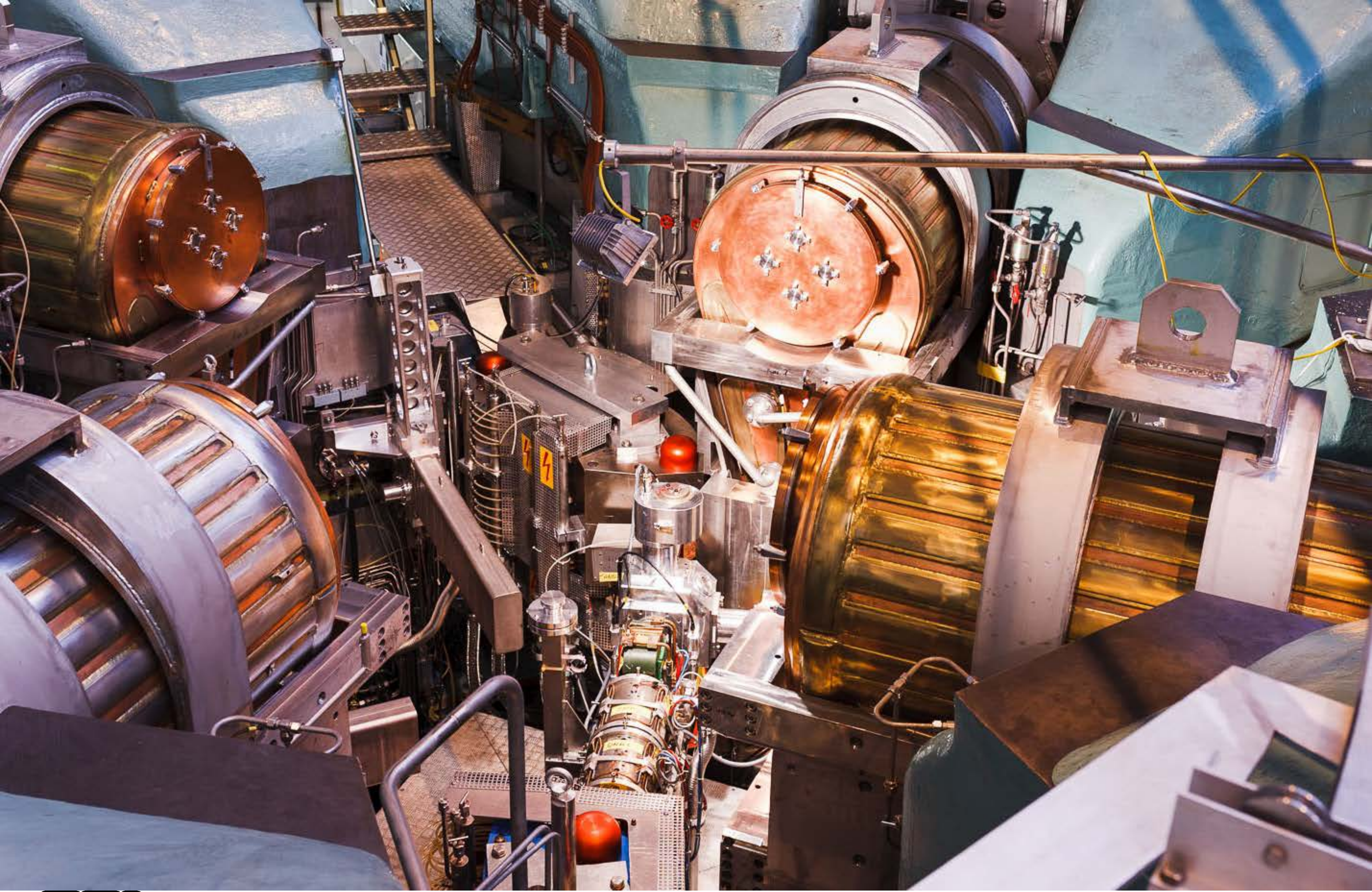
Ion source from Saclay: 140 mA

- **Injector has been installed in Rokkasho and commissioning started.**



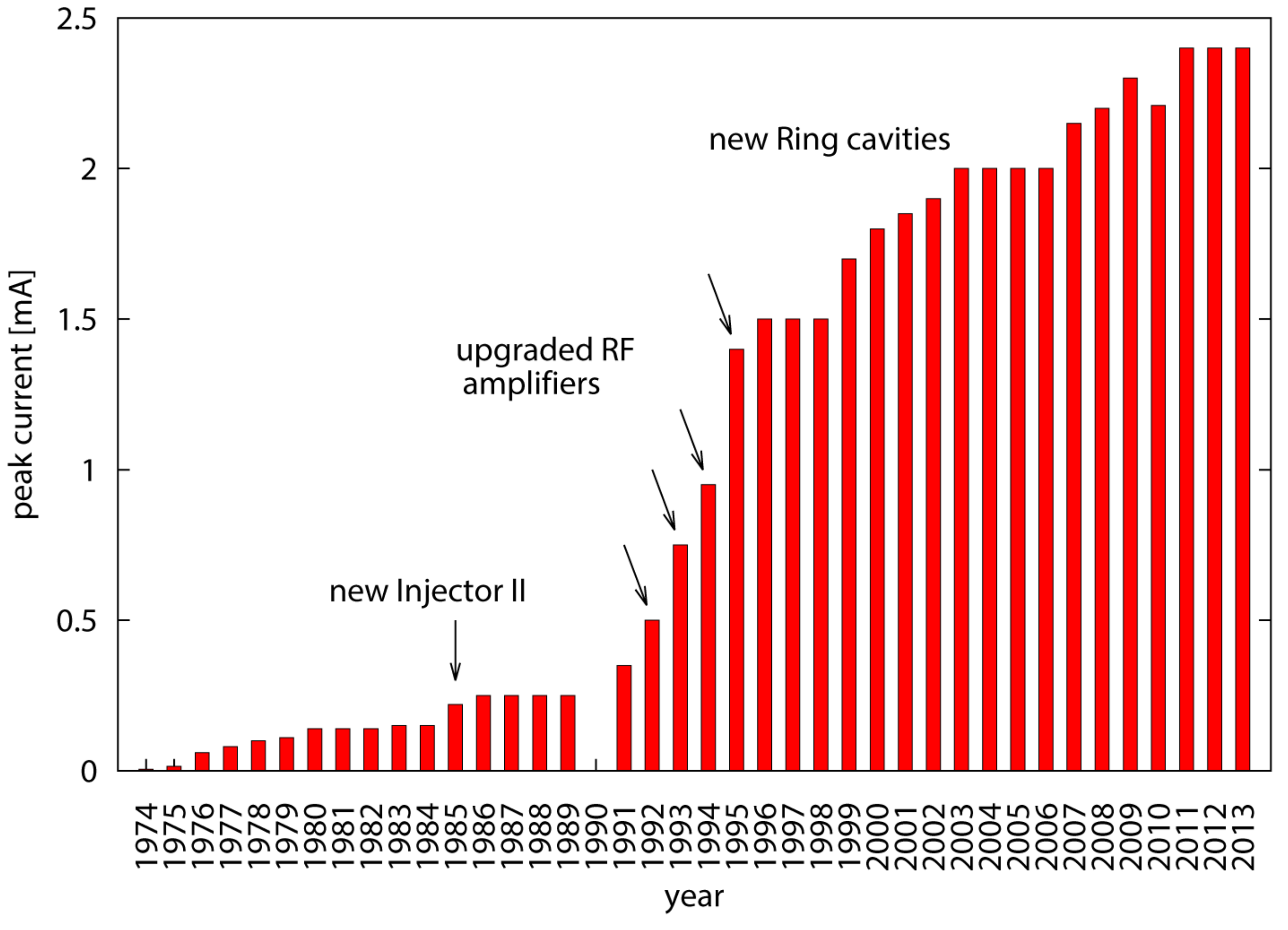
Requirements	Target value
Particles	D^+
Output energy	100 keV
Output D^+ current	140 mA
Normalized rms transverse emittance	0.25 π.mm.mrad
Duty factor	CW

Testing materials for ITER and future fusion reactors



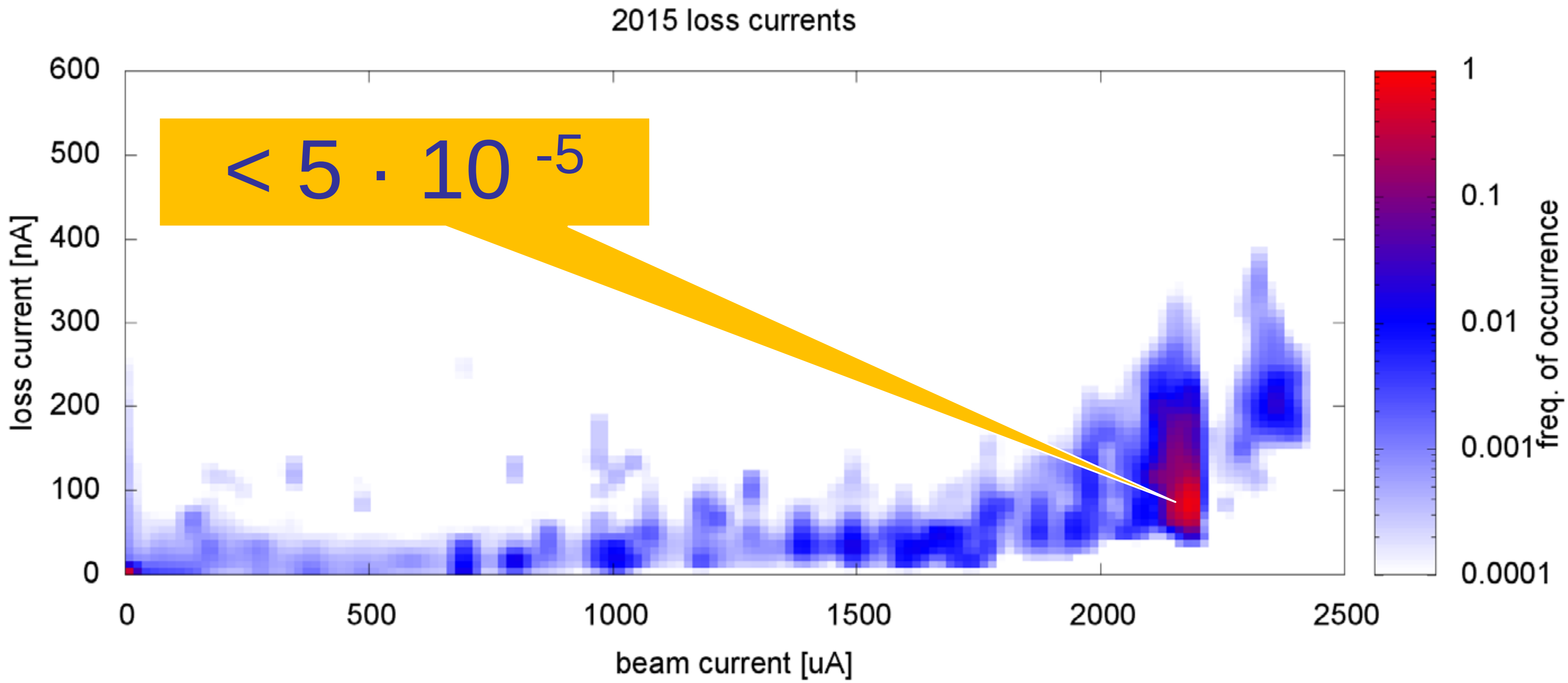
Proton beam with highest intensity: 1.4 MW

history of maximum beampower



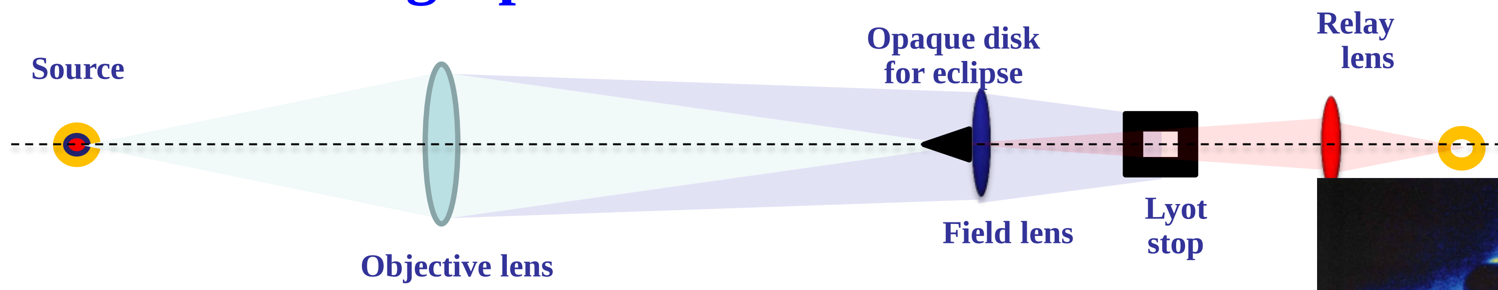
1974 planned: 100uA
today: 2.400uA
[routine: 2.200uA]

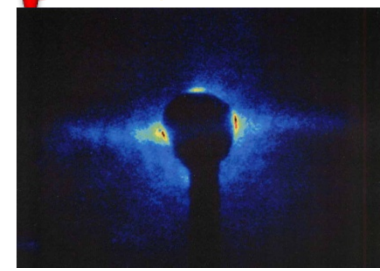
Intensity limit: beam losses



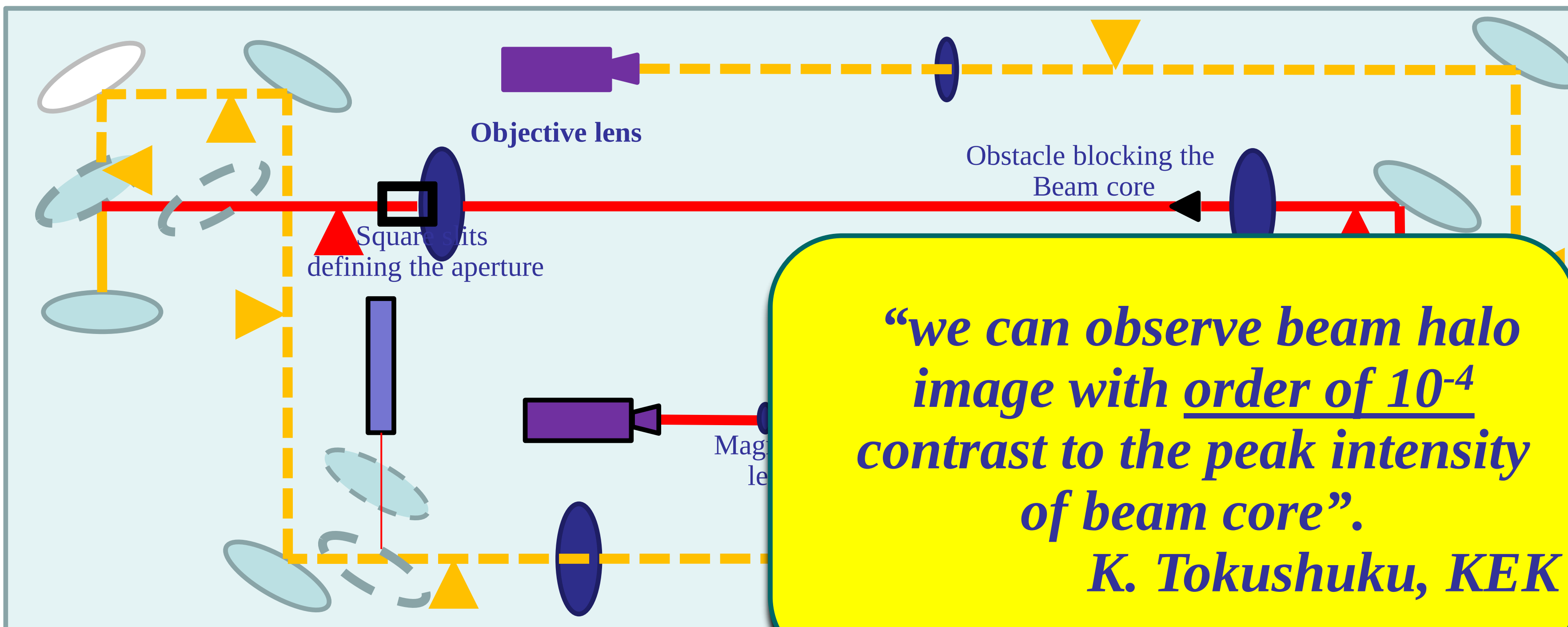
Beam halo monitoring

Coronagraph for beam halo measurement





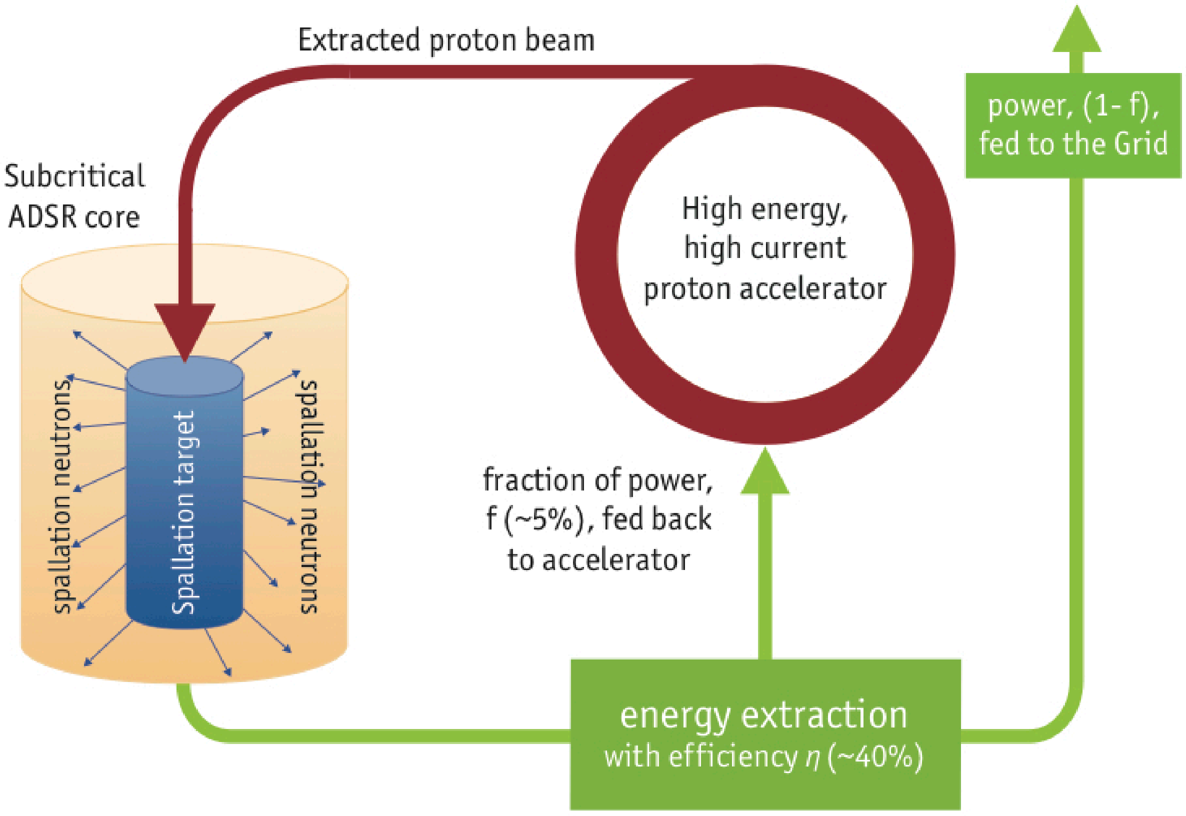
Setup of the coronagraph at B1



"we can observe beam halo image with order of 10^{-4} contrast to the peak intensity of beam core".
K. Tokushuku, KEK

ADS systems

Transmutation of nuclear waste isotopes or energy generation

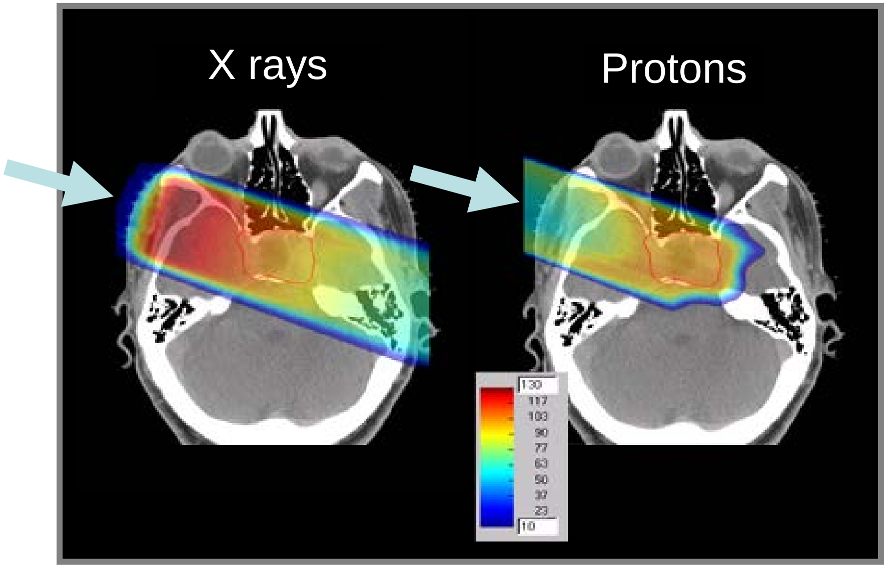


Thorium

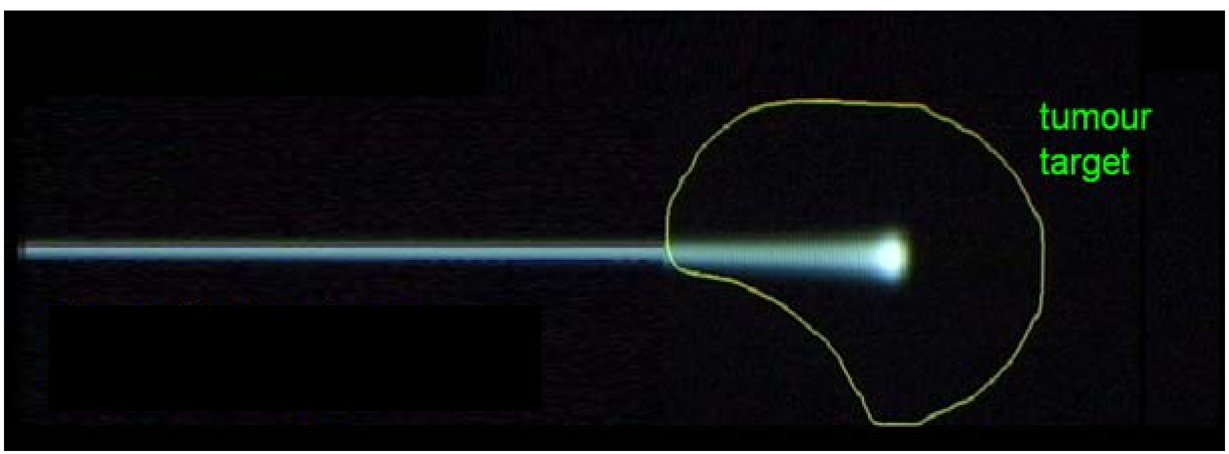
Major challenges for accelerator technology in terms of beam power (>10MW) and reliability

Medical applications

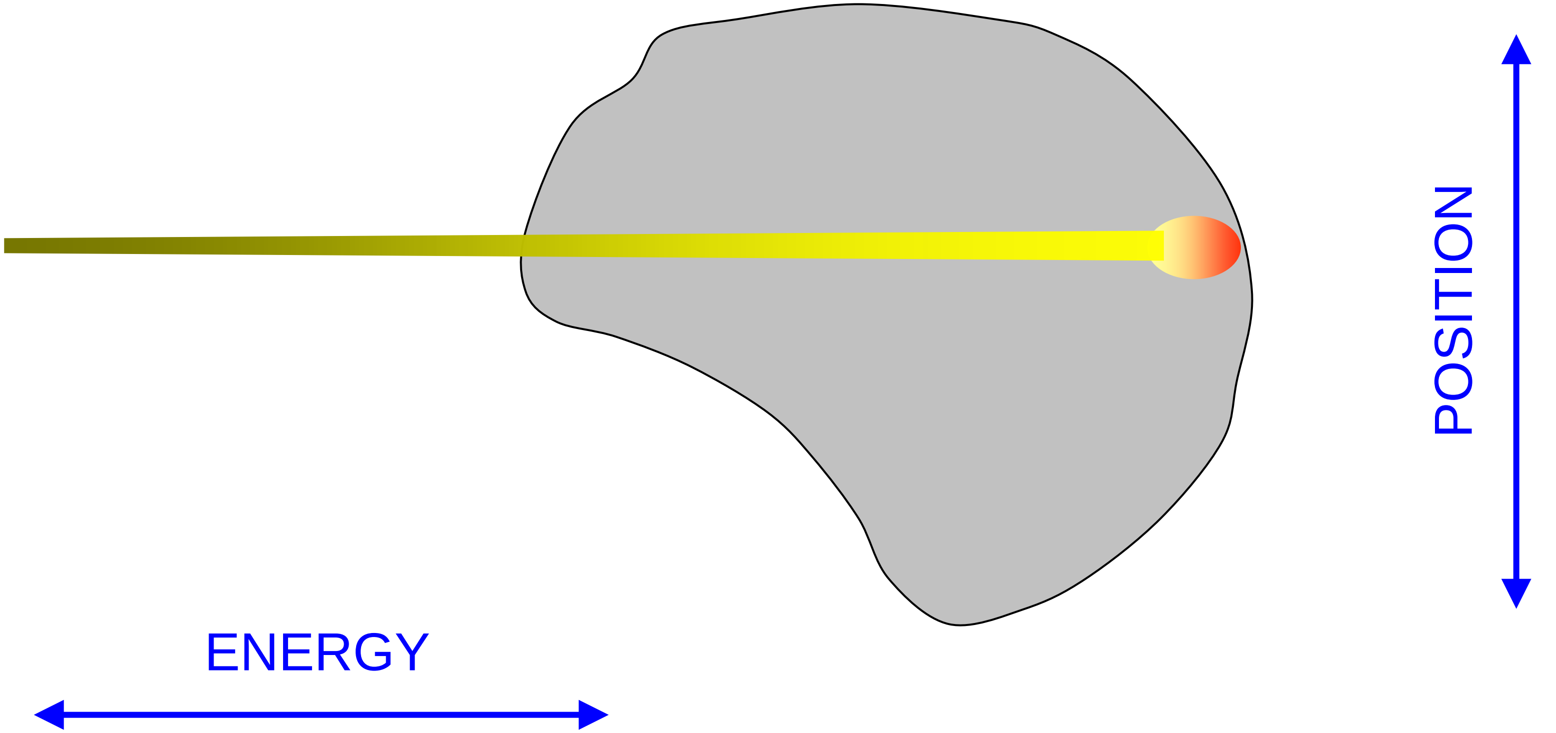
Medical applications: sharp particle knives



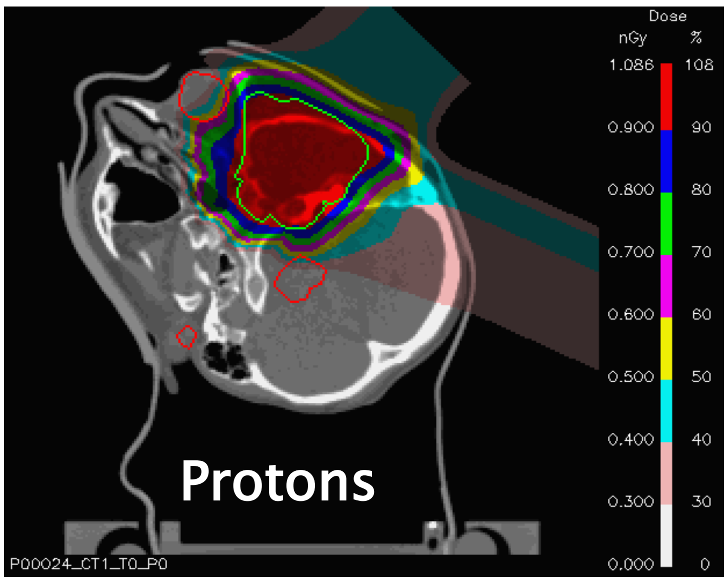
Bragg peak

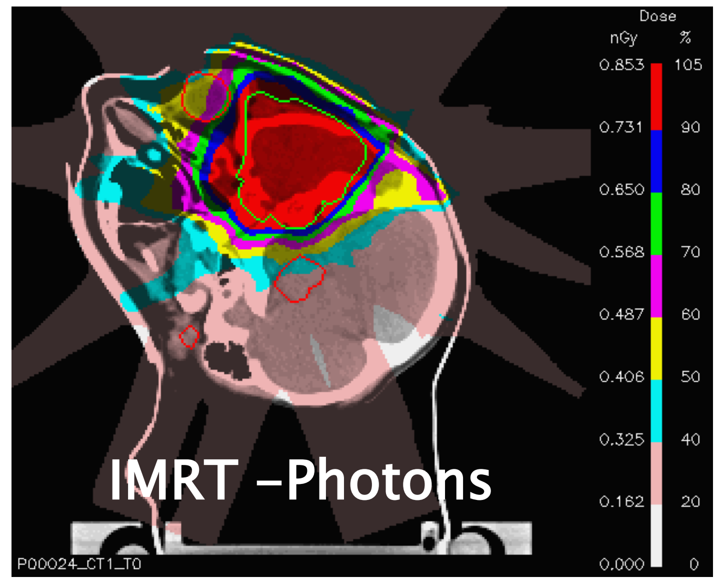


SPOT SCANNING



Aim of proton therapy: Dose concentrated in the tumor volume, low dose or no dose to healthy tissues





Intensity in a small phase space volume

Thank you for your attention

INTERNATIONAL
YEAR OF LIGHT
2015