Development and challenges in accelerators technologies

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Outline

- Particle Accelerators and their Perspectives: present, near- and long-term projects
- Accelerators in the world today and Main Applications
- Brief history of RF accelerators
- Main Accelerator types and techniques
  - RF linear accelerators: Normal, Super-Conducting and Dielectrics
  - Circular accelerators
  - Laser, Dielectric and Plasma Wakefield Acceleration→ EuPRAXIA@SPARC_LAB
- State-of-the-art and Challenge
- Conclusions and Future Developments

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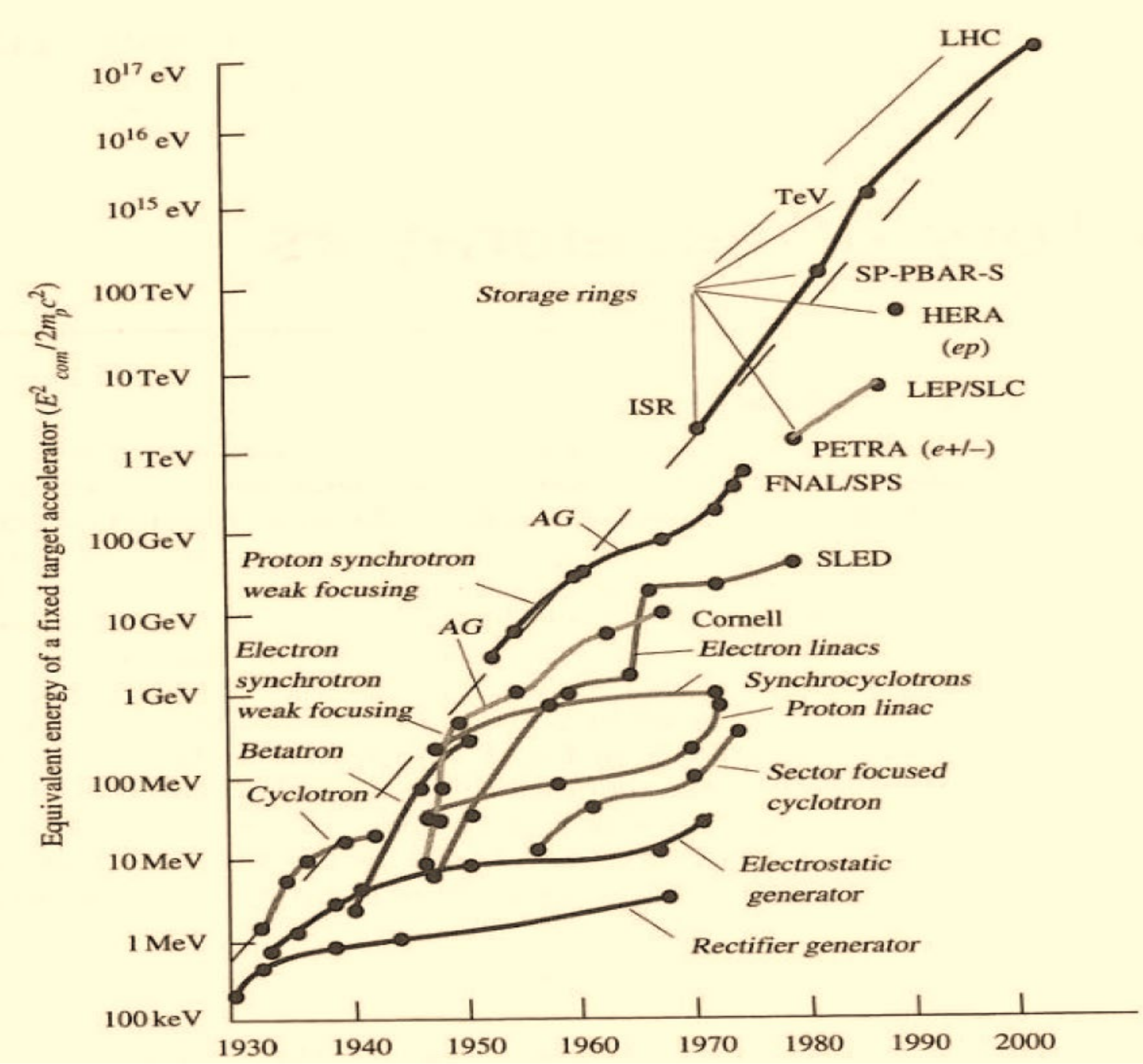
The Livingston Plot (up to early 2000’s)

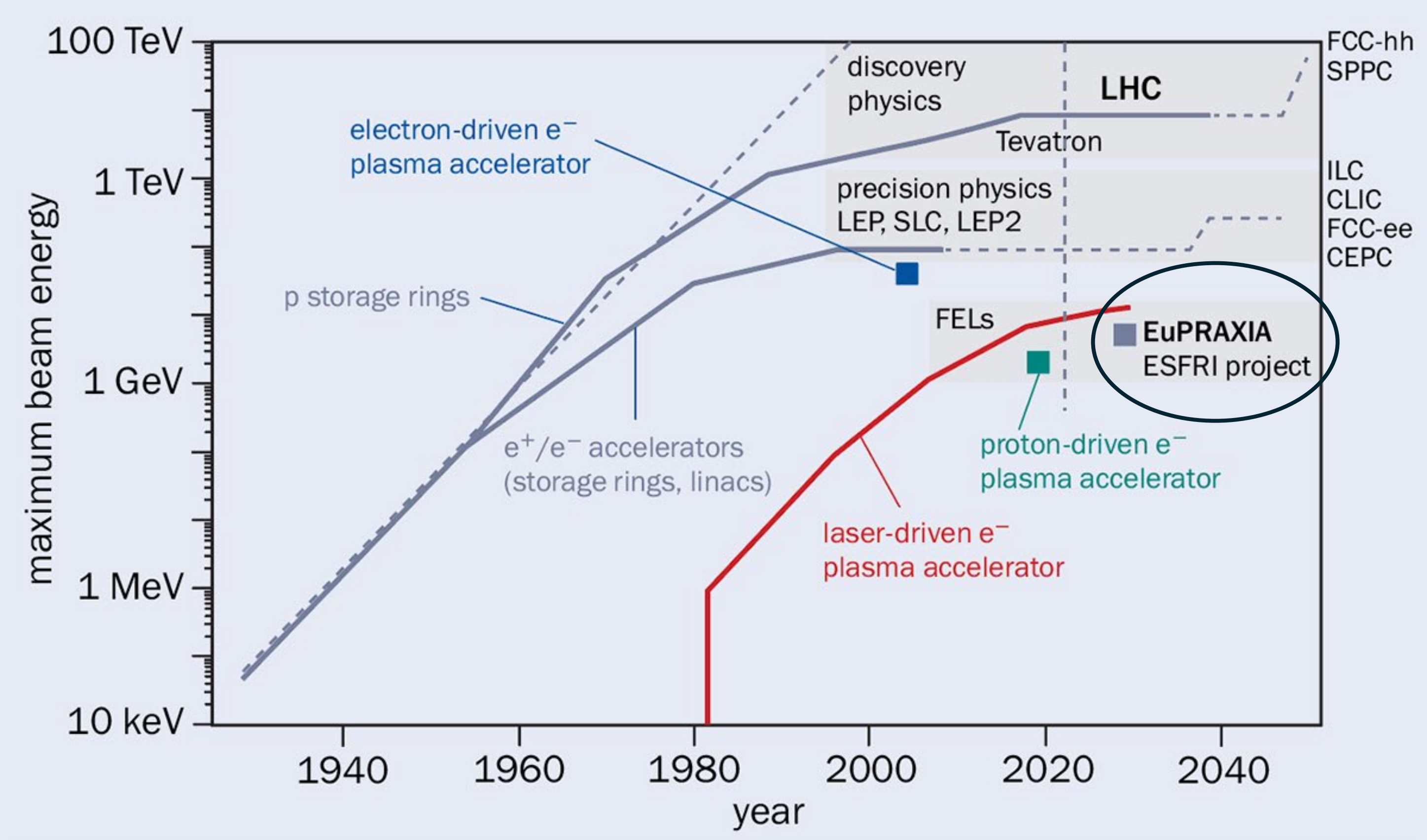
The goal of Particle Accelerators has been the same since 1930:
To transport charged particle beams in a “stable” fashion by utilizing magnetic fields and increasingly to boost their energy with electric fields.

- Each branch → New IDEA & New TECHNOLOGY;
- Accelerator evolution, like all exponential growths, cannot be sustainable over a long period



The Livingston Plot (near future)

The goal of Particle Accelerators has been the same since 1930:
To transport charged particle beams in a “stable” fashion by utilizing magnetic fields and increasingly to boost their energy with electric fields.



- Each branch → New IDEA & New TECHNOLOGY;
- Accelerator evolution, like all exponential growths, cannot be sustainable over a long period

- Projection with today established technology (likely **FLAT**)

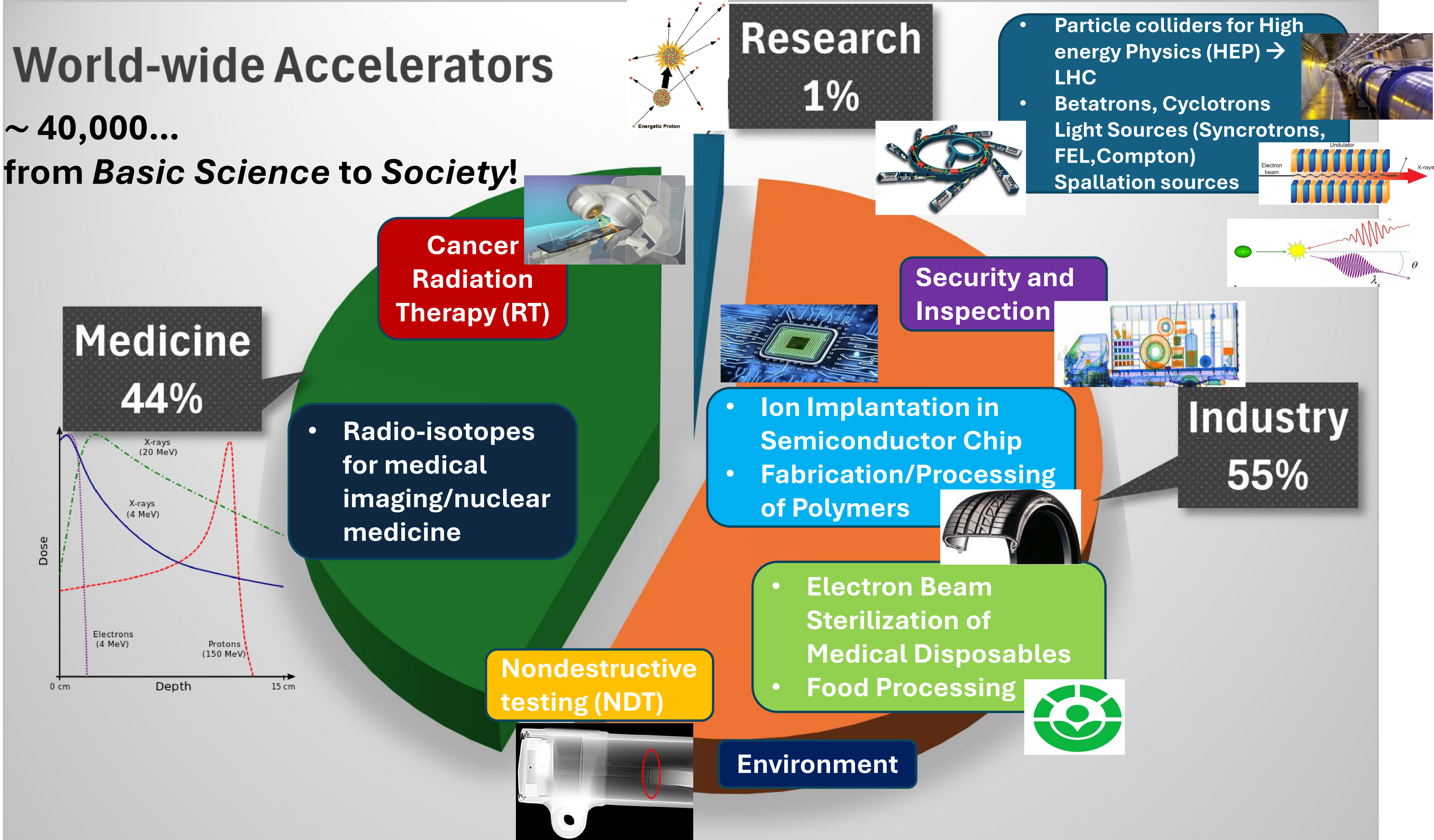
❖ **HOW to avoid this?**
Short answer, we know what to do.

Major R&D development efforts in:
RF accelerator technology (NC and SC) and Magnets
Dielectric and PLASMA → from «incremental» to «disruptive» innovation!!!

crucial

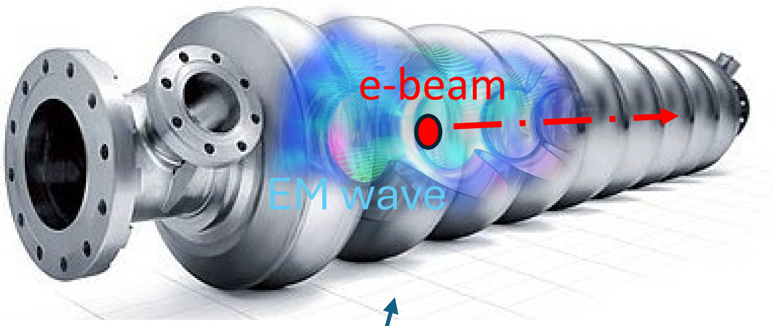
SUSTAINABLE TECHNOLOGY (Higher power efficiency, Reduction of the overall dimensions)

❖ **WHY do we (really) need it?**
Short answer, Yes. Most accelerators in the world work at relatively low energies…. But many planned high-energy machines worldwide.

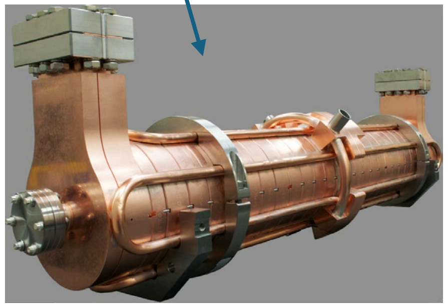

World-wide Accelerators
~ 40,000...
from Basic Science to Society!
Energetic Proton
Research
1%
• Particle colliders for High energy Physics (HEP) → LHC
• Betatrons, Cyclotrons
Light Sources (Syncrotrons, FEL,Compton)
Spallation sources
Undulator
Electron beam
X-rays
Cancer Radiation Therapy (RT)
Medicine
44%
• Radio-isotopes for medical imaging/nuclear medicine
X-rays (20 MeV)
X-rays (4 MeV)
Electrons (4 MeV)
Protons (150 MeV)
Dose
Depth
0 cm
15 cm
Security and Inspection
• Ion Implantation in Semiconductor Chip
• Fabrication/Processing of Polymers
Industry
55%
• Electron Beam Sterilization of Medical Disposables
• Food Processing
Nondestructive testing (NDT)
Environment

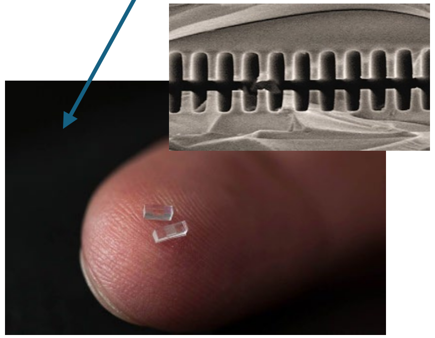
TYPES of particle Accelerators

1- Linear Accelerators (Linacs): Particles travel in a straight line through a series of accelerating cavities. Linacs are used as injectors to larger accelerators and as stand-alone when large beam intensities are required.

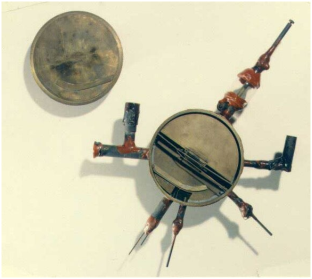


Metallic (Normal- or Super-conducting) and Dielectric Accelerators



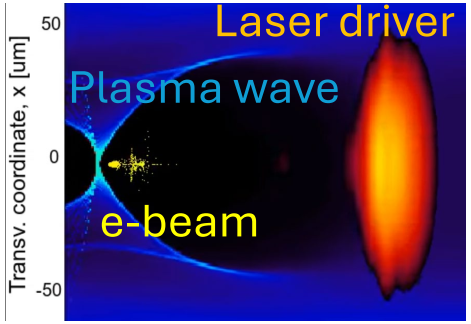


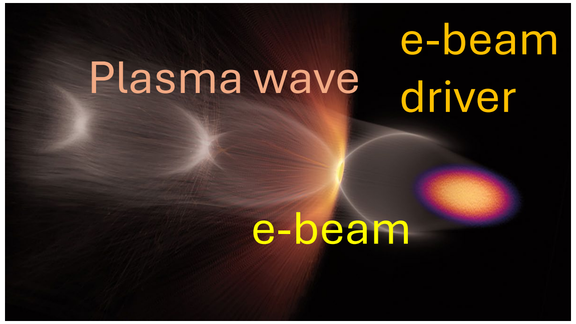
2- Circular Accelerators: Particles move in a circular path using magnetic fields, gaining energy with each pass (e.g., cyclotrons, synchrotrons).



The Lawrence and Livingston cyclotron (13 cm diameter and accelerated a proton beam to keV)

3- Laser/Dielectric/Plasma Wakefield Accelerators: Utilize waves in plasma or dielectrics to achieve compact, high-energy acceleration.





LORENTZ FORCE: ACCELERATION AND FOCUSING

The basic equation that describes the acceleration/bending/focusing processes is the **Lorentz Force**.
Particles are **accelerated through electric** fields and are **bended and focused through magnetic** fields.

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

$\vec{p} = momentum$

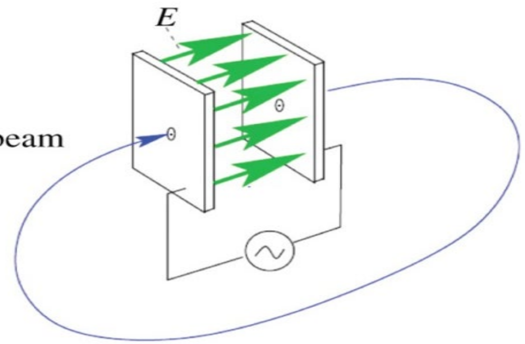
$m = mass$

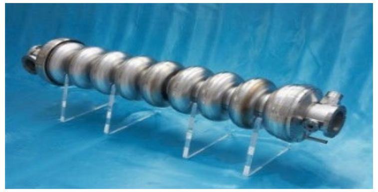
$\vec{v} = velocity$

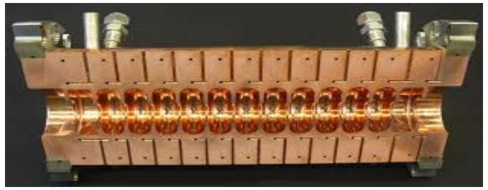
$q = charge$

ACCELERATION

To accelerate, we need a force in the direction of motion







Longitudinal Dynamics

Accelerating Gradient

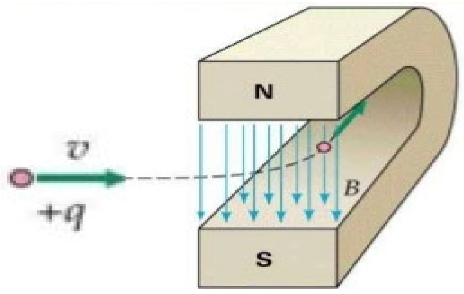
$$E_{acc}(V/m) = \frac{Energy\ Gain}{Length}$$

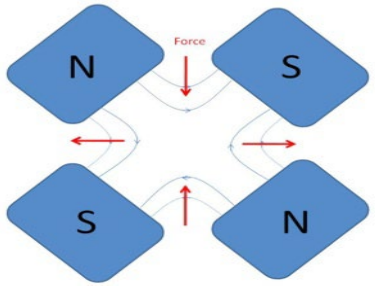
Main challenge

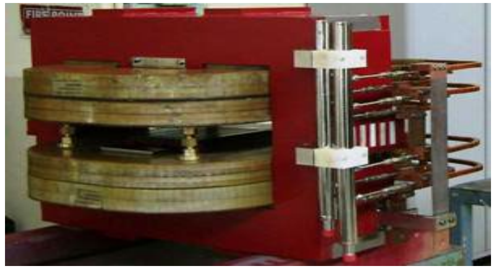
Higher E_{acc} for shorter machines

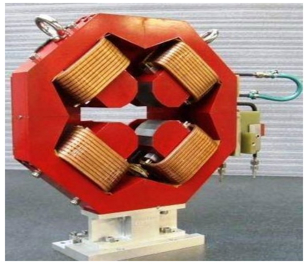
BENDING AND FOCUSING

2nd term always perpendicular to motion => no energy gain





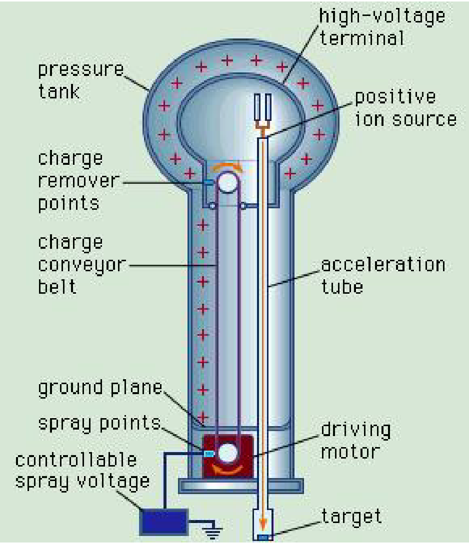


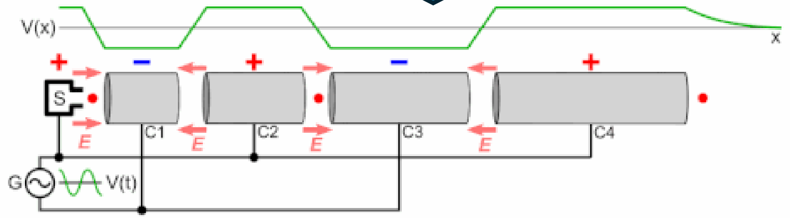


Transverse Dynamics

Brief history: from DC to RF Linear Accelerators

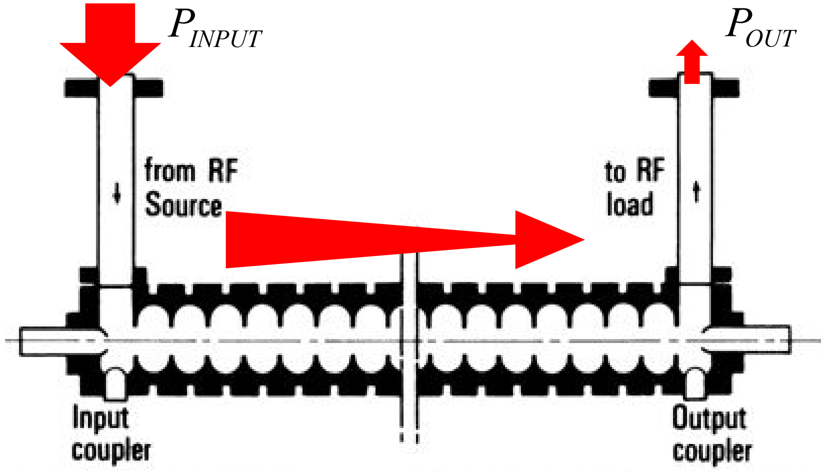
DC voltage as large as ~10 MV can be obtained (E~10 MeV). The main limit in the achievable voltage is the breakdown due to insulation problems.



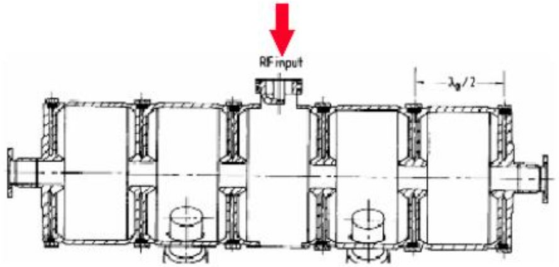


the particles are accelerated by the electric field in the gap between electrodes connected alternatively to the poles of an **AC generator**.

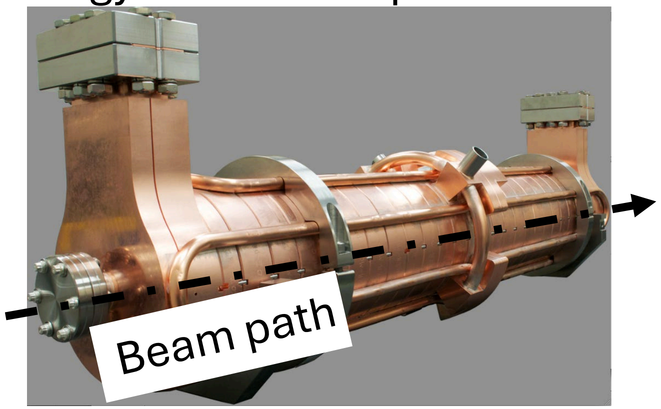
TW Linac



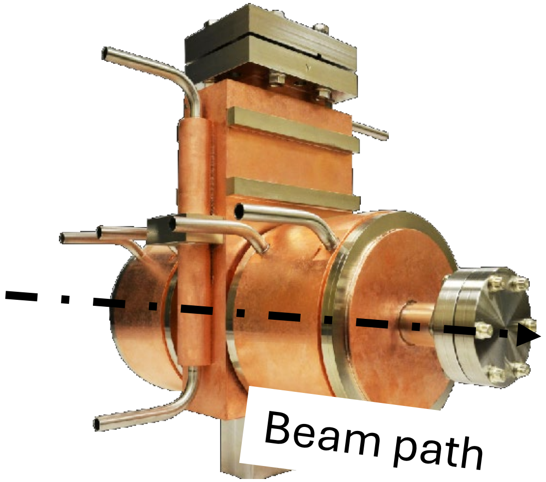
SW Linac



EM energy travels with particle beam



EM energy resonates inside cavi



Metallic LINEAR RF ACCELERATORS TECHNOLOGY: NORMAL vs SUPER-CONDUCTING

⇒The cavities (and the related LINAC technology) can be of different material:

- **copper** for **normal conducting (NC)** RF cavities;
- **Niobium** for **superconducting (SC)** RF cavities.

HOW to choose?	NC	SC
Accelerating Gradient	100 MV/m @ CLIC 60 MV/m @ EuPRAXIA@SPARC_LAB	30 MV/m @ ILC
RF Pulse Length	100's ns – few us	Up to ms
Power Dissipation	~ kW/m ($R_s = 10^{-3}\Omega$)	< 1W/m ($R_s = 10^{-9}\Omega$)
Duty cycle	≤ 0.1% (rep. rates 10-100 Hz)	> 1% up to 100% (CW)
RF-to-beam power Efficiency	30% - 60% (SLAC Linac, Compact industrial linacs) 20 - 40% (X-band high-gradient, e.g. CLIC)	60% - 80% (European XFEL, LCLS-II) ≥ 90% (medium-energy linacs)
Complexity	Lower capital cost	Higher capital cost
Operation Costs	Higher	Lower

Dissipated power into the cavity walls is related to the **surface resistance R_s** and currents

$$P_{diss} = \int_{cavity\ wall} \overbrace{\frac{1}{2} R_s H_{tan}^2}^{\text{power density}} \, dS$$

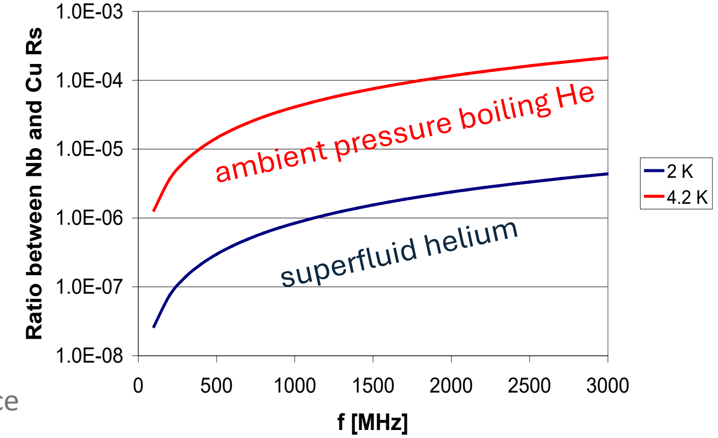
copper

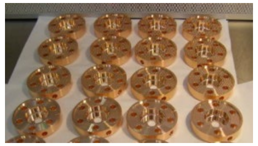
$$R_s[\mathrm{m\Omega}] = 7.8 f^{\frac{1}{2}}[\mathrm{GHz}]$$

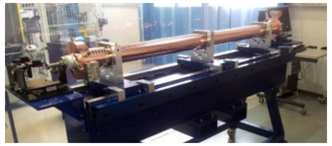
niobium

$$R_s[\mathrm{n\Omega}] = 9\times 10^4 \frac{f^2[\mathrm{GHz}]}{T[\mathrm{K}]} \exp\left(-\frac{17.664}{T[\mathrm{K}]}\right)$$

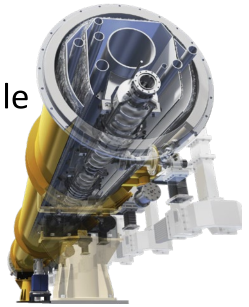
Between copper and Niobium there is a factor 10^5-10^6

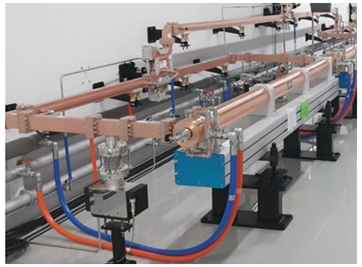






cryomodule

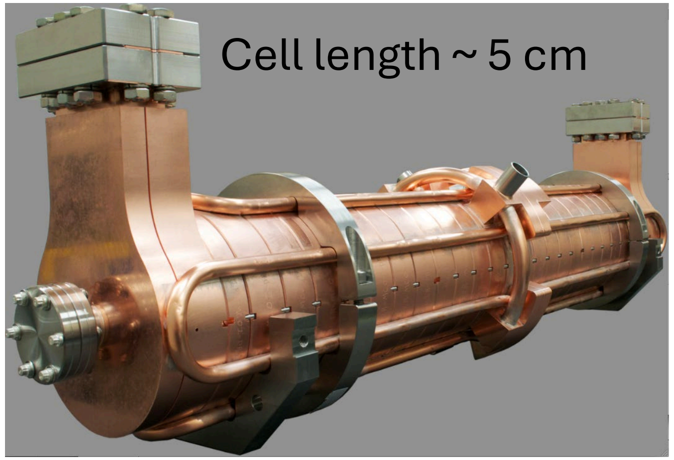




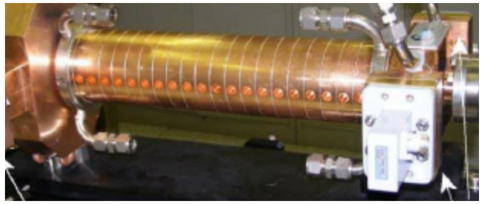
Normal conducting RF structures

State-of-the-art

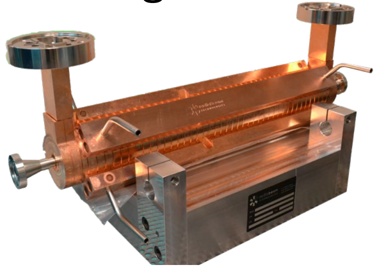
Warm Cavities	Accelerating Gradient	Repetition Rate
S-Band (3 GHz)	15 - 30 MV/m	50-300 Hz
C-Band (5-6 GHz)	> 50 MV/m	< 100 Hz
X –Band (11-12 GHz)	> 100 MV/m	< 100 Hz

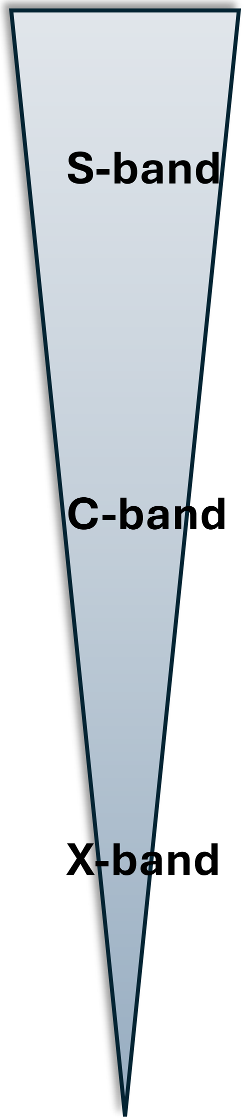


Cell length ~ 2.5 cm



Cell length ~ 1 cm





Need to be affordable: cost-effective production/manufacturing

R&D on NC LINACS @INFN-LFN

- **EuPRAXIA@SPARC_LAB**
- **ASTERIX** experiment. Funded by INFN CSN5.
- **MICRON** experiment. Funded by INFN CSN5.
- Previously funded experiment by INFN CSN5: DiElectric and METallic Radiofrequency Accelerator (**DEMETRA**) 2015-2018

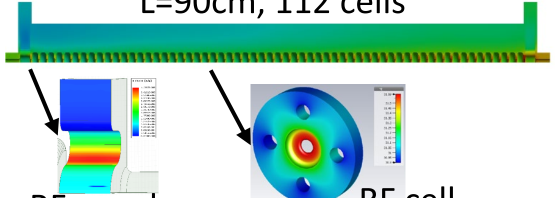
Applications

- Research on RF Breakdown Rate and RF Breakdown Physics;
- Electron beam longitudinal phase-space manipulation in FELs (EuPRAXIA@INFN-LNF, CompactLight FEL, UC-XEL@UCLA)
- Multi-frequency accelerators (S. Tantawi, SLAC)
- Development of single and multi-frequency high-power RF klystrons

Start-to-end fabrication flow-chart: EuPRAXIA@SPARC_LAB structure

RF and thermo-mechanical design

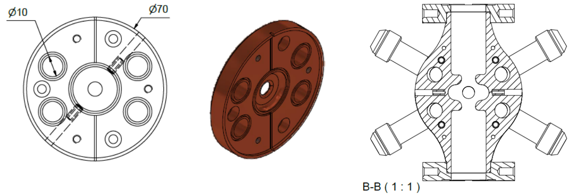
L=90cm, 112 cells



RF coupler

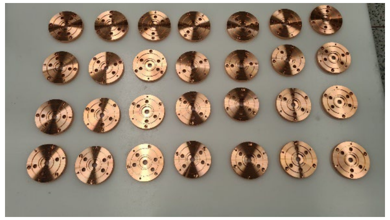
RF cell

Engineering

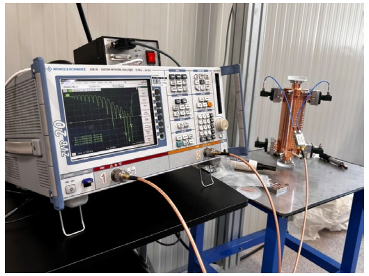


High-precision Machining

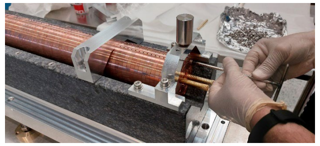
Quality control



Low RF power characterization



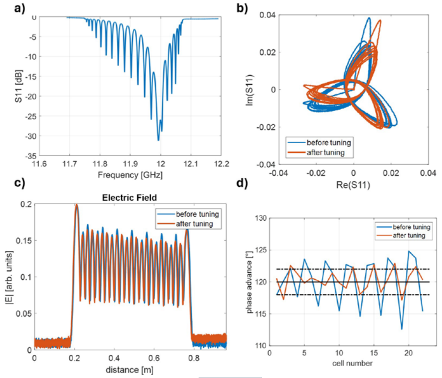
Assembly and Brazing



L=90cm

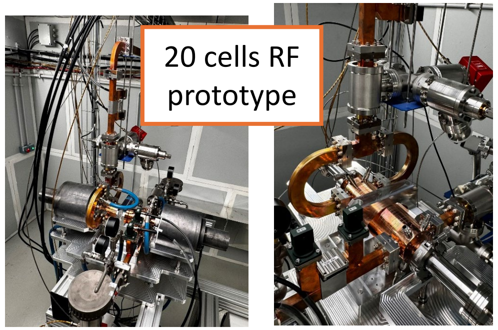
Leak check

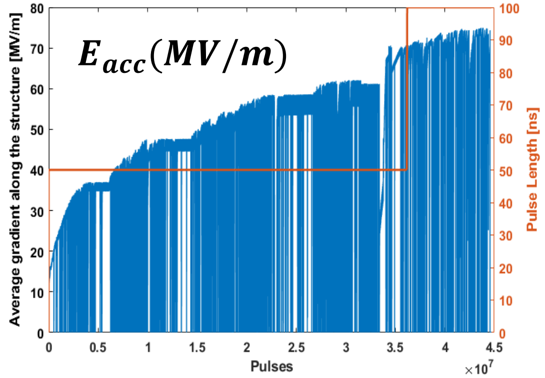
RF tuning



Bake-out and outgassing

High RF power conditioning





Main Operational Limitation: RF Breakdown phenomenon

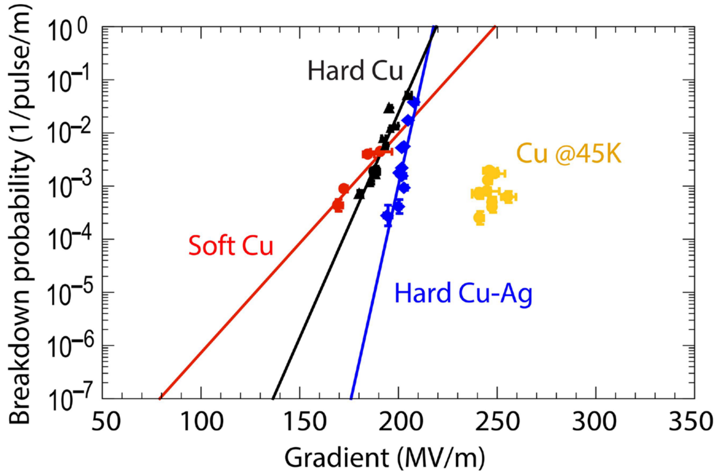
High accelerating gradient is needed for future accelerators: higher energies in **smaller footprint**!

The main limitation for a high-gradient structure is **RF breakdown phenomenon** →

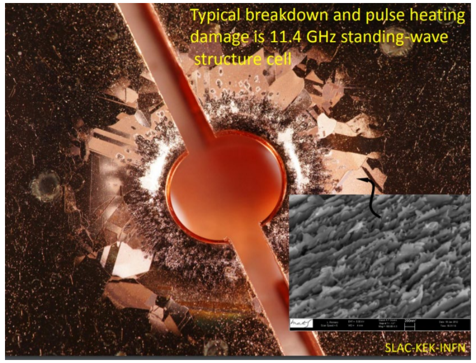
- Vacuum activity
- Visible light
- X-rays

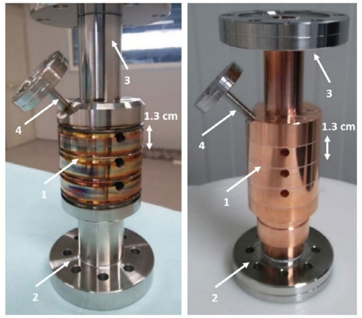
RF breakdown arcs take place in the vacuum volume of the accelerating structures with a certain statistical probability that reduces the performance of the accelerator

- disturb the trajectory of the beam and its emittance
- luminosity loss
- possibly beam loss.



Breakdowns in high-gradient linacs can interrupt accelerator operation, leading to downtime.





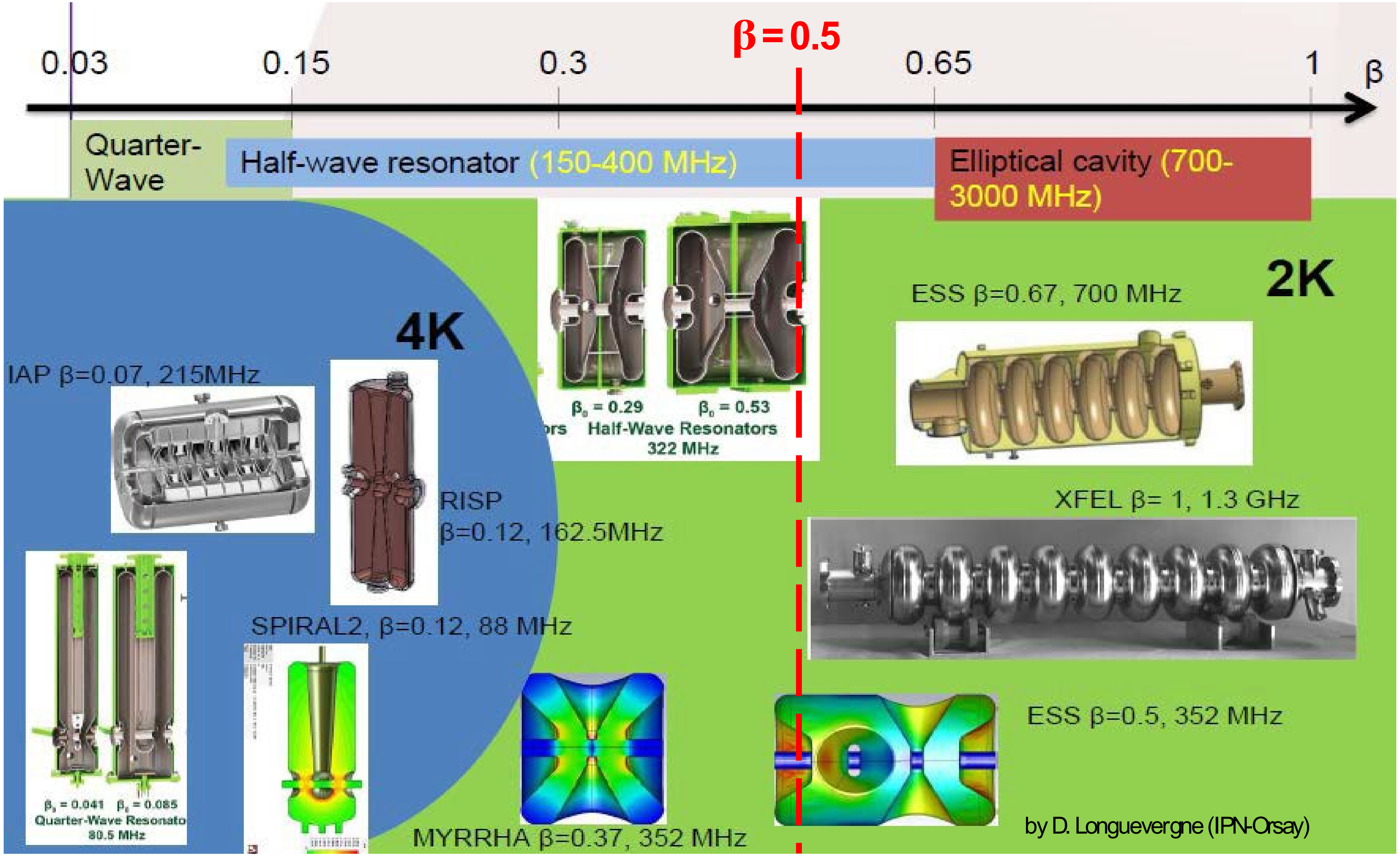
Hard Cu and hard CuAg have better performance then soft heat-treated copper.

→ **Hard CuAg had record performance for room temperature structures.**

← **New joining techniques: welding.**

Dolgashev VA, Faillace L, Spataro B, Tantawi S, Bonifazi R. High-gradient rf tests of welded X-band accelerating cavities. Physical Review Accelerators and Beams. 2021 Aug 10;24(8):081002.

SRF Resonators Families: $\beta < 0.50$ & $\beta > 0.50$

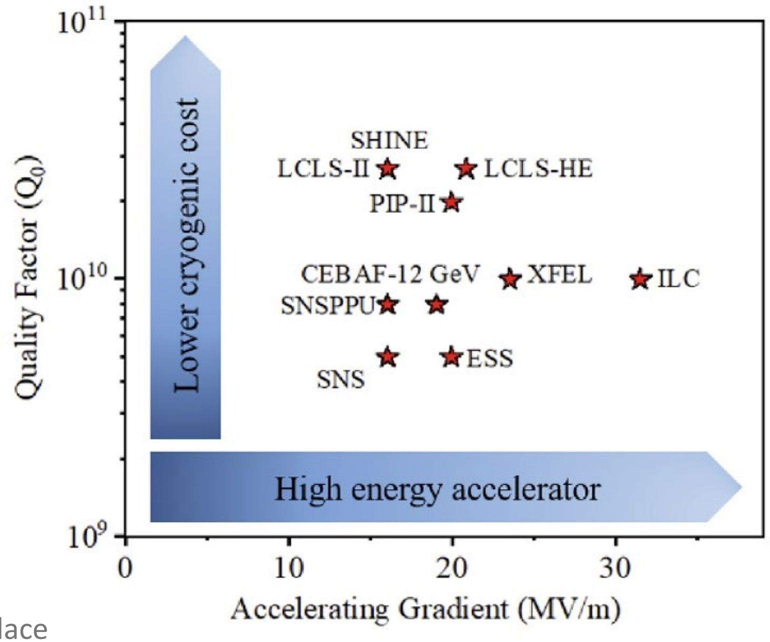


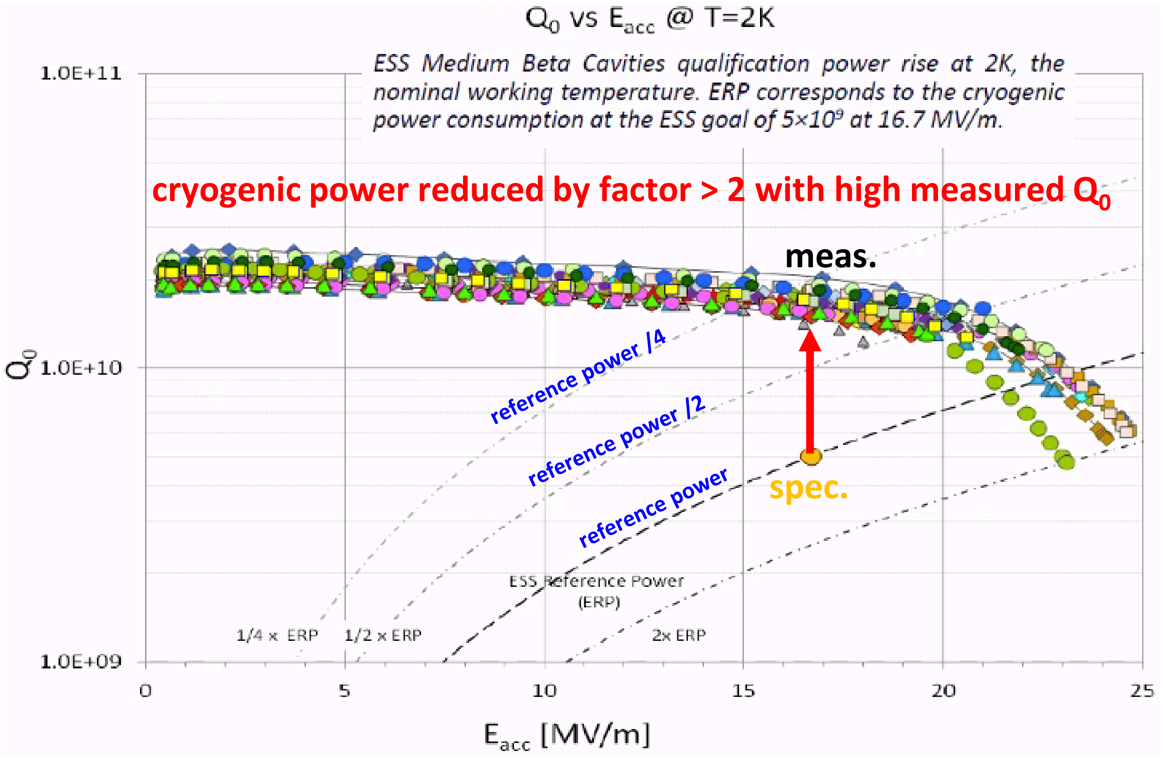
Courtesy of L. Monaco, D. Sertore, C. Pagani

Towards future large and sustainable machines

- For future accelerators, it is important to:
  - **Increase E_{acc}**:
    - Target energy reached with less cavity
    - Reduce machine length
  - **Increase Q_0**: Quality factor
    - Reduce power consumption
    - Minimize cryogenic power → sustainability

$$P_{diss} = \frac{(\boldsymbol{E_{acc}}L)^2}{\left(\frac{R}{Q}\right)\boldsymbol{Q_0}}$$





Courtesy of L. Monaco, D. Sertore, C. Pagani

Bulk Niobium performance increase

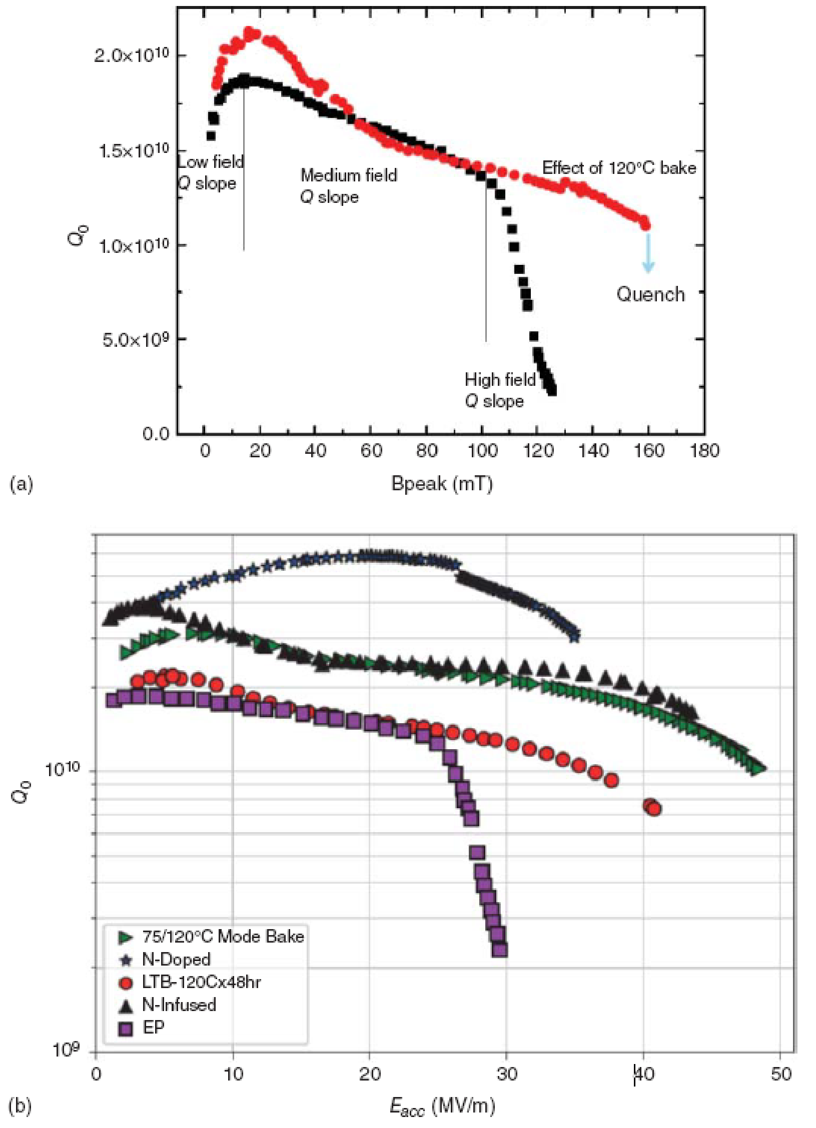
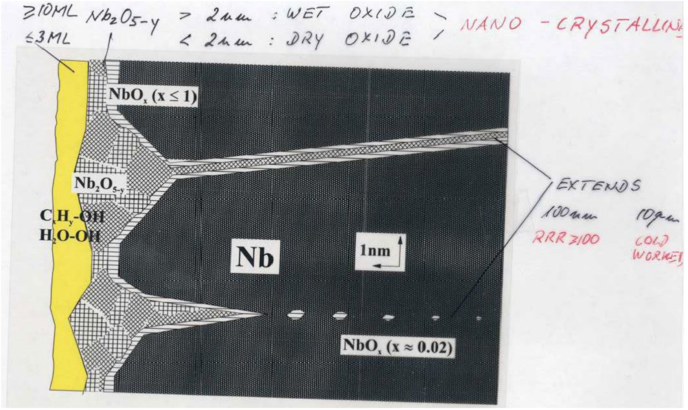


Figure 2.6 (a) Low field, medium field, and high field Q-slopes observed after standard treatment of EP. 120 C bake removes the HFQS, leaving an extended region of MFQS [42] Courtesy of A. Grassellino, Fermilab. (b) Q_0 versus E_{acc} at 2 K of 1.3 GHz Nb SRF cavities treated at FNAL with state-of-the-art surface treatments, such as nitrogen-doping, two-step baking, and nitrogen infusion, compared to standard treatments of EP or EP followed by 120 C baking [12] Courtesy of D. Bafia, Fermilab.

To go beyond the standard power rise, a **carefull processing of the inner surface** of the cavity is mandatory.

Specific processes are necessary to cure Q slope at different accelerating field:

- *Low T baking. 120 °C*
- *Two–step baking (75 °C + 120 °C)*
- *N infusion at 120 °C*
- *Mid T baking: 300 °C*
- *N doping*



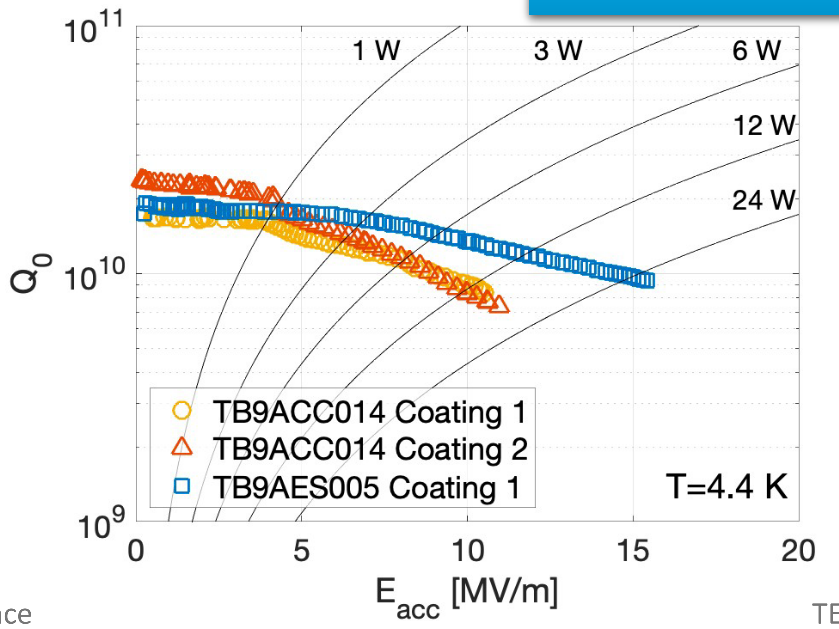
J. Halbritter, Proc. SRF'01, Tsukuba, Japan, p. 292

Courtesy of L. Monaco, D. Sertore, C. Pagani

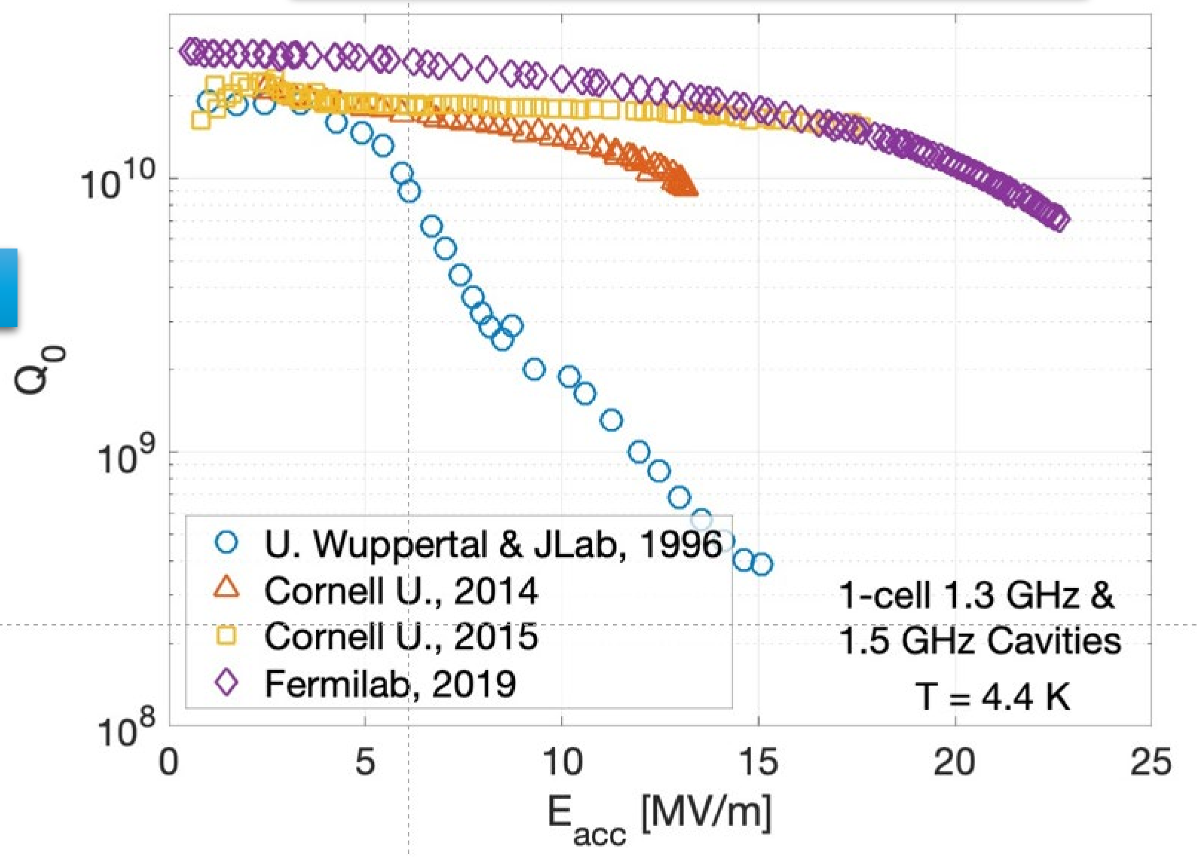
Nb3Sn for operation at higher temperature

- Vapor diffusion of Nb_3Sn (T_c ~ 18 K hence small R_s) on Nb substrate
  - Small R_s opens the possibility of using cryocooler, recently demonstrated
- Similarities with Nb_3Sn in magnet wire but
  - Strict control of impurities
  - Can achieve very clean grain boundaries
  - Relative smooth surface finishing to avoid field enhancement

9-cell coated cavities



Single Cell Evolution over the years



Courtesy of L. Monaco, D. Sertore, C. Pagani

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DLA Motivations

High <u>accelerating</u> gradients enable compact/miniaturized particle accelerators

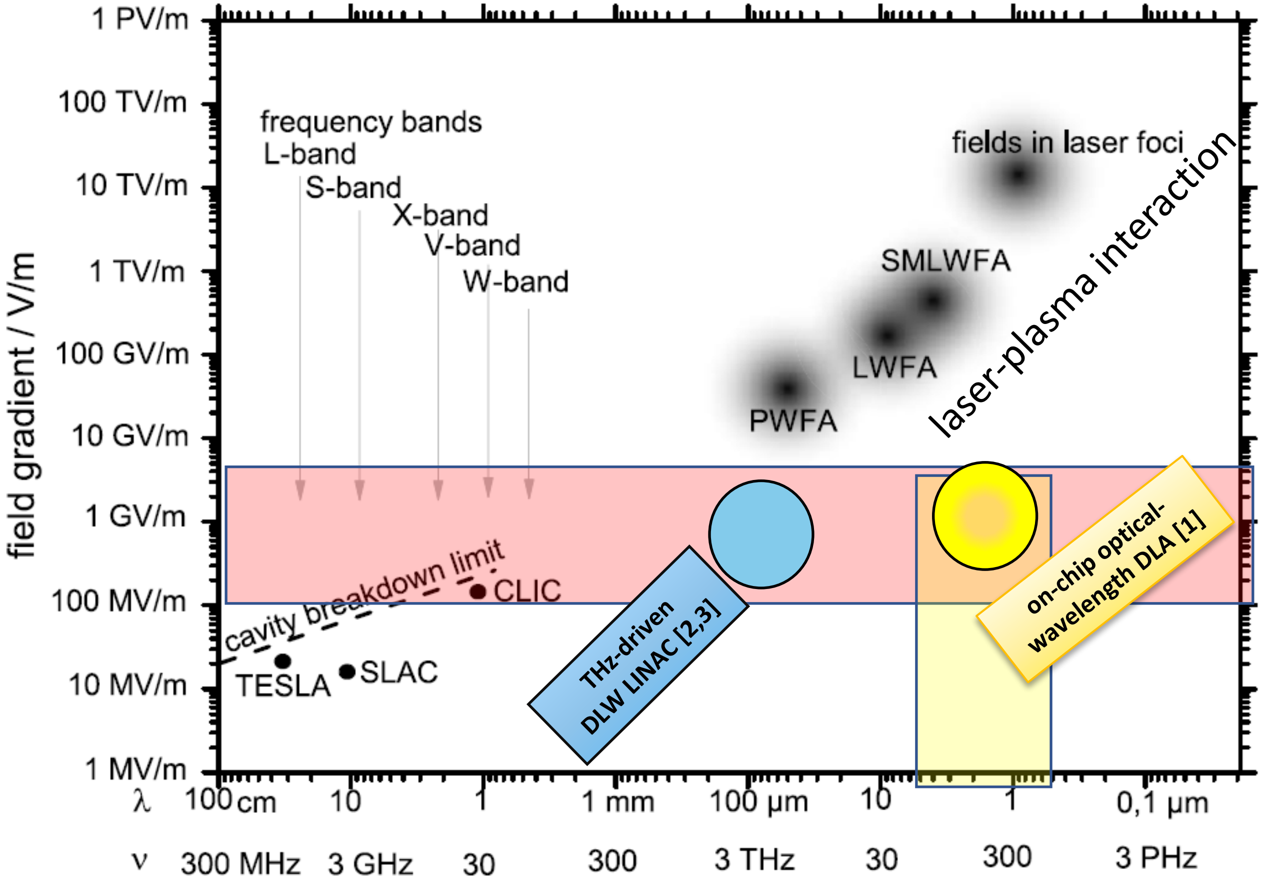
TARGET

Accelerating Gradient: <u>~ 500 MV/m - 2 GV/m</u>

Main advantages of DLA:
<u>larger damage threshold of dielectrics</u> in near infrared with respect to metals;

<u>Dielectric Laser Accelerator (DLA) structures operating at optical</u> wavelengths (~ 1- 5 μm)

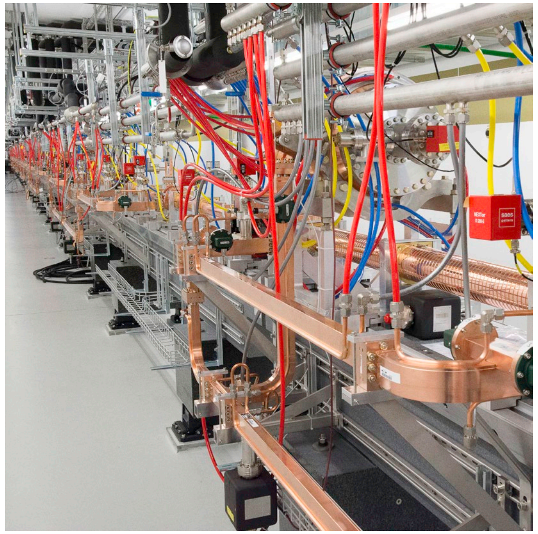
schematic overview of the accelerating gradient for different types of accelerators

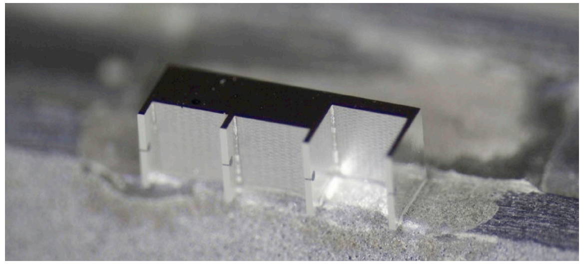


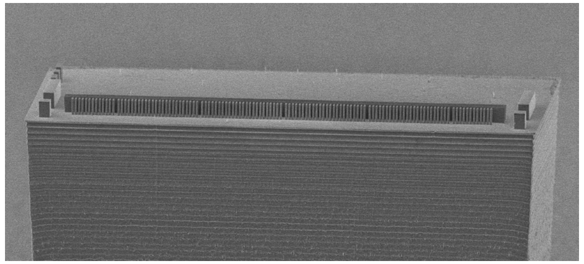
[1] R. Joel England et al., Rev. Mod. Phys. 86, 1337-2014
[2] E. Nanni, et al., Nat Commun 6, 8486 (2015).
[3] F. Lemery, et al.” Commun Phys 3, 150 (2020).

Courtesy of G. Torrisi

From Radio Frequencies to Infrared Light

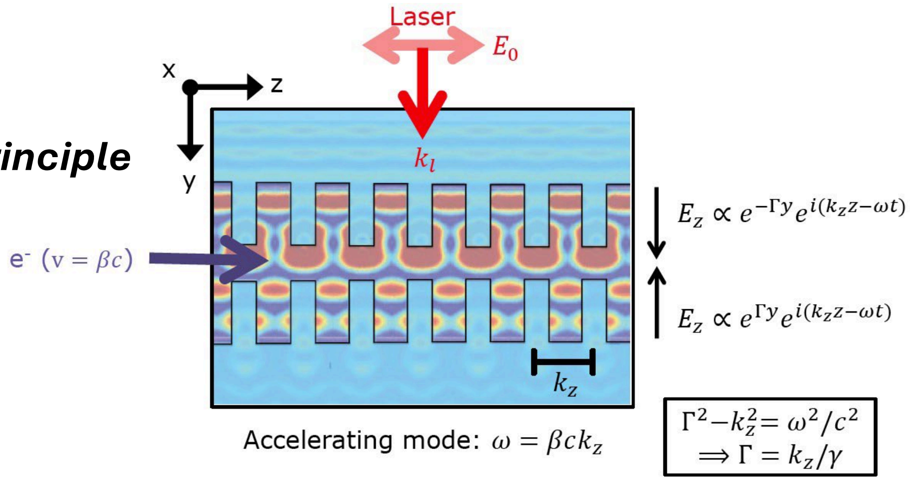






[Rasmus Ischebeck, **Structure-based accelerators (e.g. ACHIP) and advanced radiation generation schemes,** talk *@the 2022 EuroNNAc Italy 18- 24 September 2022] [https://agenda.infn.it/event/28376/contributions/178676/*

DLA Operating Principle



- **Simple idea: Use scale-invariance of Maxwell equations and shrink down size of particle accelerators by 4 orders of magnitude.**
- **Replace RF power (cm-wavelength) with laser (um-wavelength)**
- **Material properties are frequency dependent -> dielectrics**
- **Beam dynamics challenges**

DLA typical parameters

Parameter	RF	DLA
Power Source	Klystron	laser
Wavelength	2-10 cm	1-10 μm
Bunch Length	1-5ps	10-100 as
Bunch Charge	0.1- 4 nC	1-10 fC
Norm. Emittance	0.1-1 μm rad	1-10 nm rad
Rep Rate	1-1000 Hz	100 MHz
Material	Metal	Dielectric
Unloaded Gradient	**10-50 MV/m**	**1-10 GV/m**

Courtesy of G. Torrisi

DLA leverages advances in two major areas:

solid state lasers + semiconductor fabrication

Not high peak power lasers!

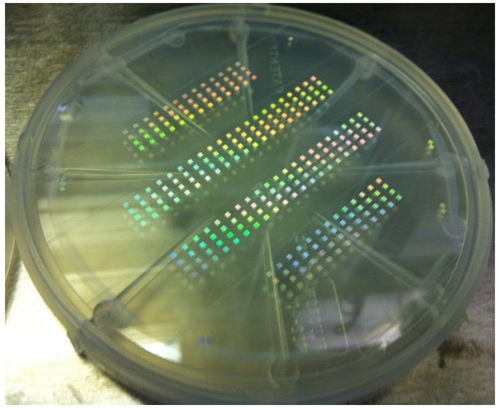
Parameter	DLA Value
Wavelength	2 μm
Pulse Duration	100 fs
Pulse Energy	μJ – mJ
Laser Power	100 W
Rep Rate	100 MHz – KHz
Laser Efficiency	30%
Cost/laser	$200k

Solid-state laser

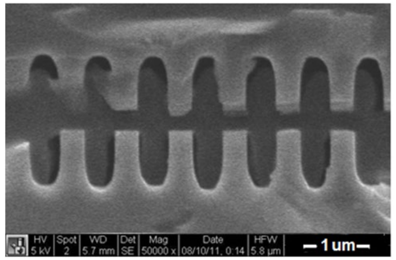
Available now "off the shelf"

[Pietro Musumeci, **Accelerator on a chip program overview** invited talk @ *EuroNNAc* La Biodola Bay, Isola d'Elba, Italy 18- 24 September 2022] https://agenda.infn.it/event/28376/contributions/179636/

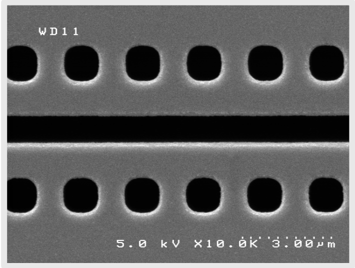
Fabricated using techniques of the integrated circuit industry.



SEM images of DLA prototypes



fused silica

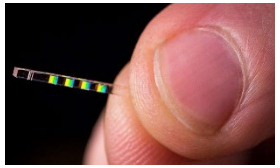


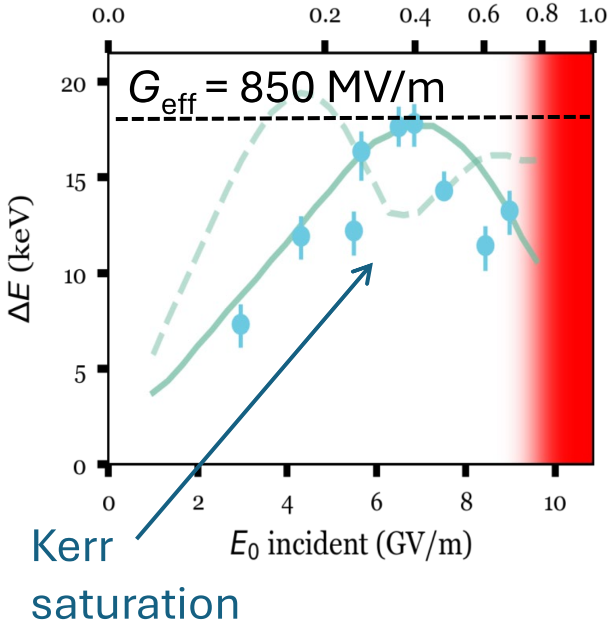
silicon

Courtesy of G. Torrisi

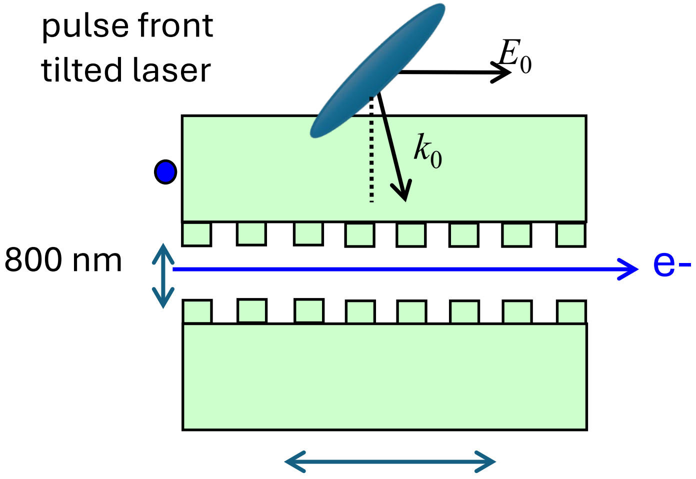
Experiments with relativistic beams have demonstrated record gradients and energy gain

SLAC/UCLA: 0.85 GeV/m*

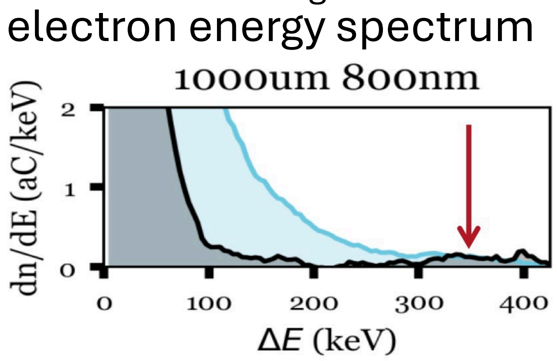




SLAC/UCLA: 0.3 MeV energy gain**



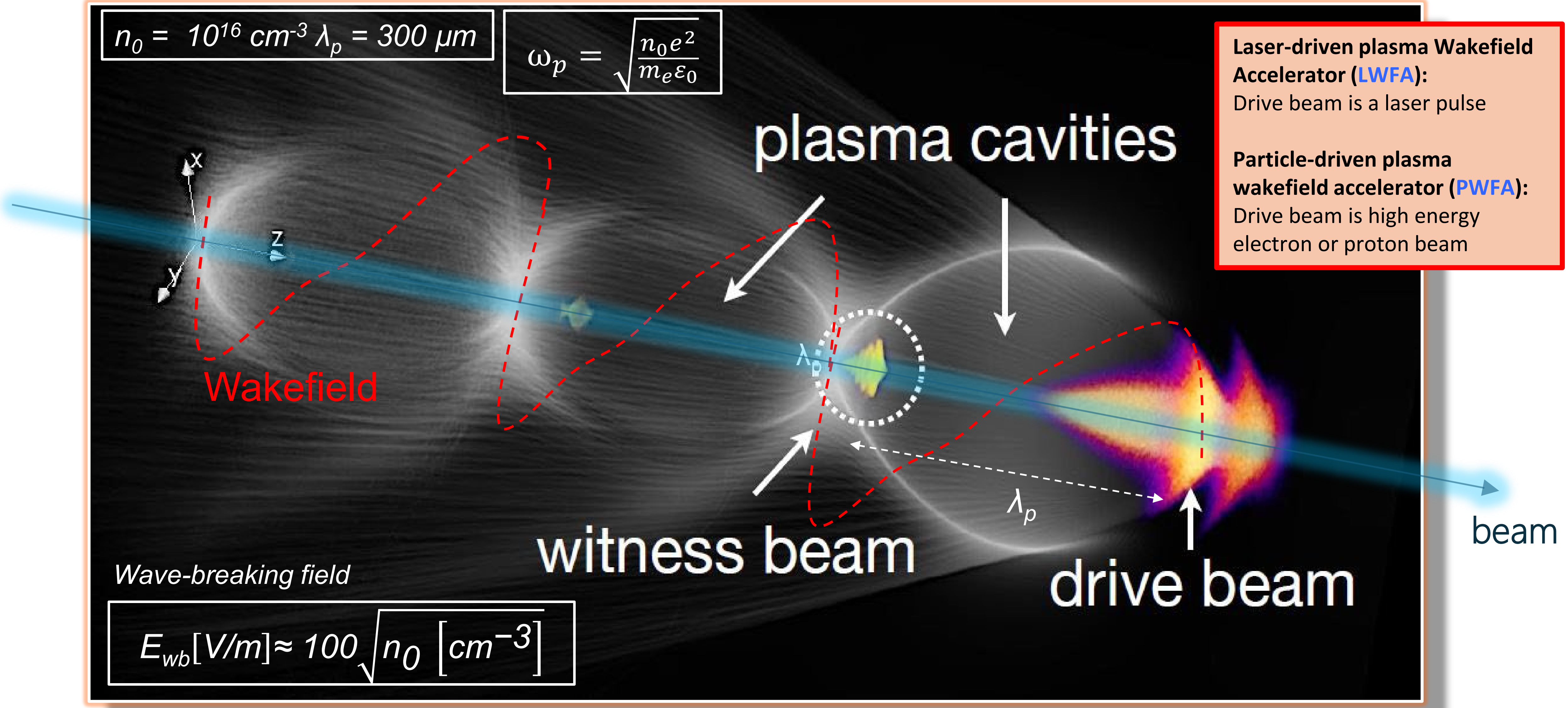
Interaction length > 500 um



* D. Cesar et al, Communications Physics 1(4), 1-7 (2018)
** D. Cesar et al, Optics Express 26 (22), 29216 (2018)

Courtesy of G. Torrisi

Principle of plasma acceleration



Laser-driven plasma Wakefield Accelerator (LWFA):
Drive beam is a laser pulse

Particle-driven plasma wakefield accelerator (PWFA):
Drive beam is high energy electron or proton beam

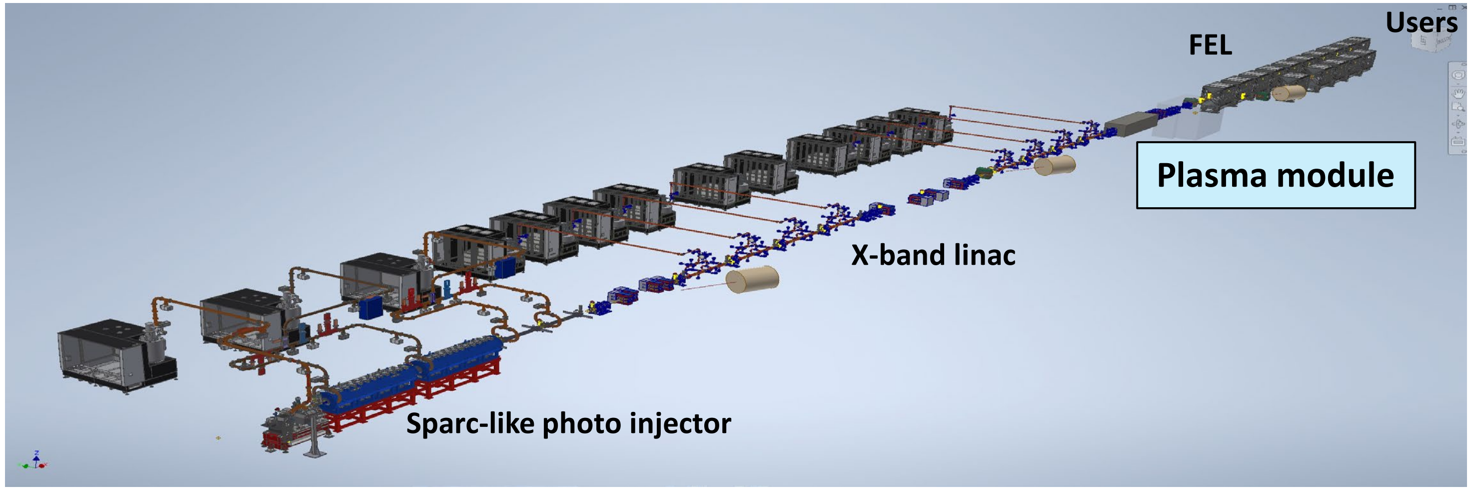
Courtesy of A. Biagioni

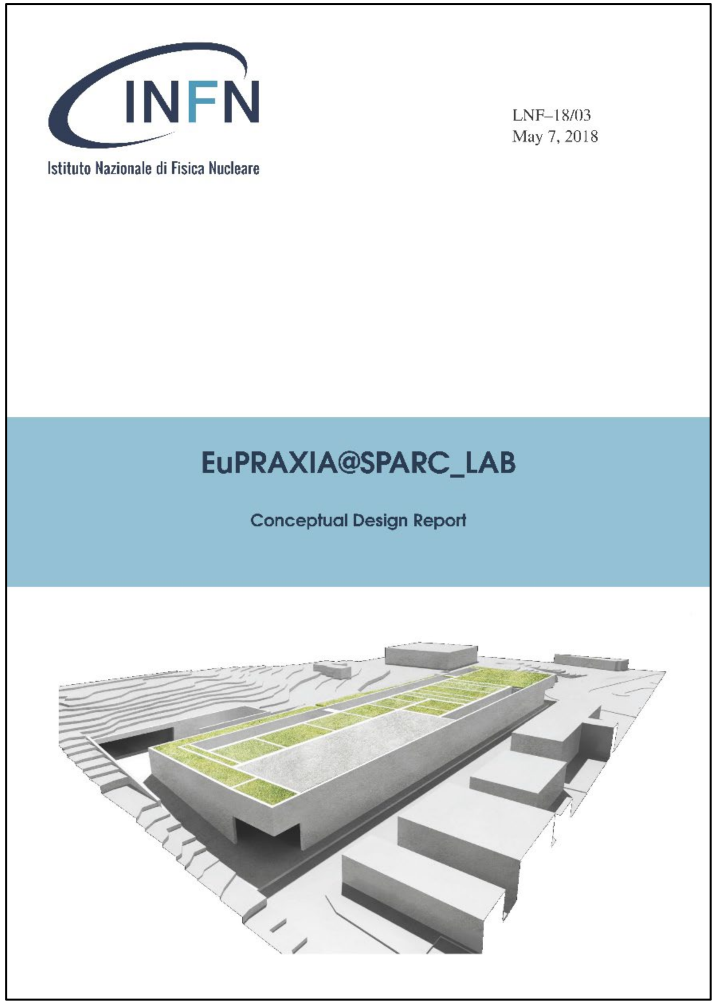
EuPRAXIA@SPARC_LAB (1 – 5 GeV)

- Distributed RI
- **2 FEL Construction Sites**
- Several Excellence Centers

Particle-driven wakefield acceleration

EuPRAXIA at LNF-INFN (Site 1)




INFN
Istituto Nazionale di Fisica Nucleare
LNF–18/03
May 7, 2018
EuPRAXIA@SPARC_LAB
Conceptual Design Report

Courtesy of A. Biagioni

Plasma accelerating module

TABLE I. EuPRAXIA SPARC_LAB parameters extracted from Ref[3] and last update[2]

Goal parameters

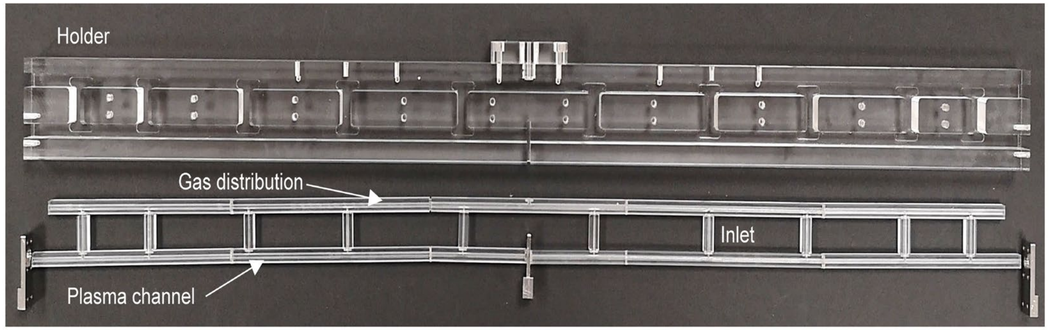
Device	Parameter	Value	Unit
Plasma Accelerator Stage	Energy Gain	0.5	GeV
	Length	> 50	cm
	Density	10^{15} - 10^{17}	cm^{-3}
	Repetition Rate	10-100	Hz
Active Plasma Lens	Strength	1-5	kT
	Length	2-4	cm
	Density	$1 - 10 \times 10^{17}$	cm^{-3}
	Repetition Rate	10-100	Hz

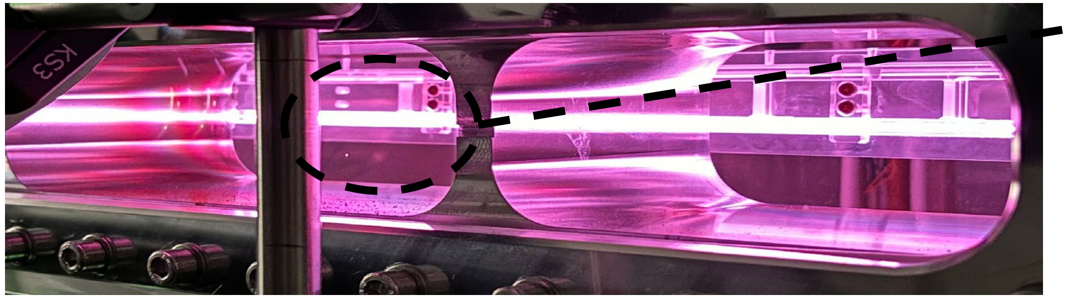
100-400 Hz

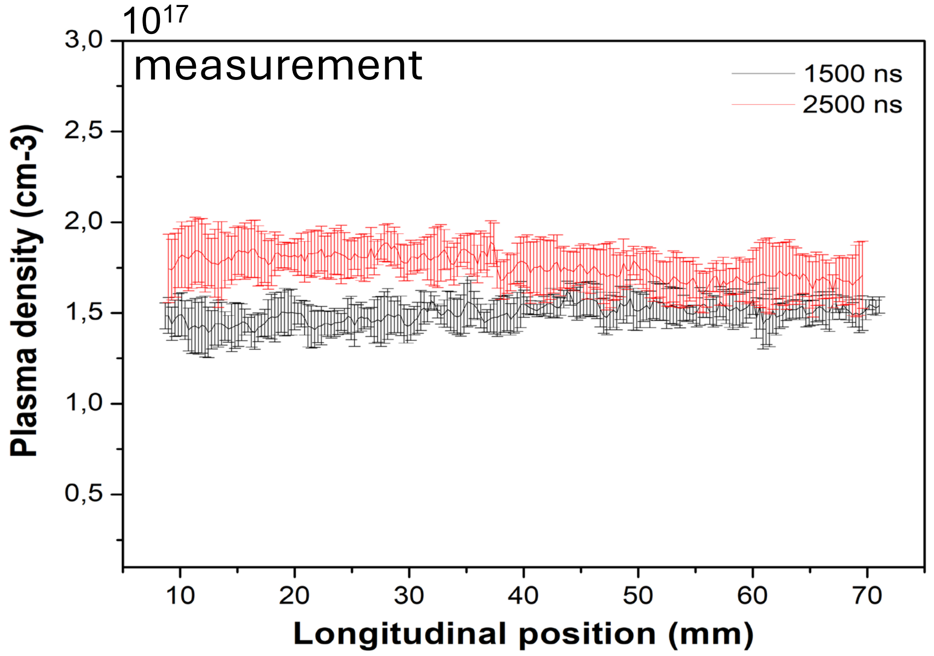
Nominal values

1.1 GeV (1 GV/m 60cm capillary - density 10^{16} cm-3)

- Fabrication by machining
- 10 increasing diameter
- Density range 10^{16} -10^{17} cm^{-3}
- 13 kV with 500 A
- **100 Hz rep Rate (nominal value)**







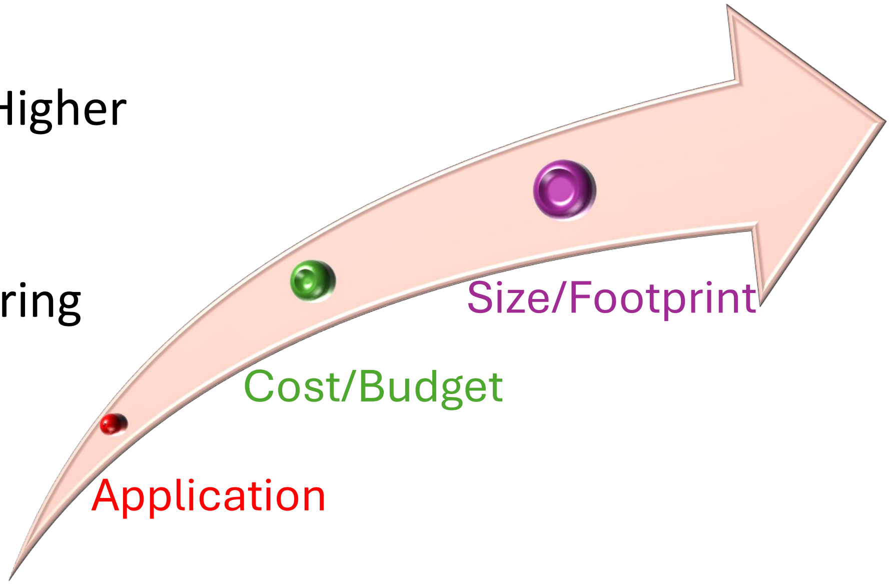
Courtesy of A. Biagioni

CONCLUSIONS AND FUTURE WORK

- Review of main Technologies for Particle Accelerators:
  - RF acceleration (normal-, super-conducting and dielectrics)
  - Wakefield acceleration.

- Main Challenges for all accelerators: Higher Accelerating Gradient and Higher Quality Factor → more compact and sustainable machines.

- Future developments: New materials, new geometries, new manufacturing processes, etc.



What is the acceleator of the future?

- It all depends on the required application, available budget and footprint.

Acknowledgements

- INFN-Laboratori di Frascati: A. Gallo, D. Alesini, A. Biagioni, TEX (TEst stand for X-band, F. Cardelli, S. Pioli) group; INFN-Milano: L. Monaco, D. Sertore, C. Pagani, D. Giove; INFN-Labratori del Sud: G.Torrisi for their comments and slides.