I.FAST Work Package 5

Strategies and Milestones for Accelerator Research and Technologies (SMART)

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Participating Institutes:
INFN, CERN, CEA, CNRS, KIT, PSI, United Kingdom Research and Innovation, GSI,
Bergoz Instrumentation, Barthel HF-Technik GmbH, HIT Heidelberg + JGU Mainz

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WP5 – SMART !

INFN

CERN

cea

cnrs

KIT
Karlsruher Institut für Technologie

PAUL SCHERRER INSTITUT
PSI

UKRI
UK Research
and Innovation

GSI

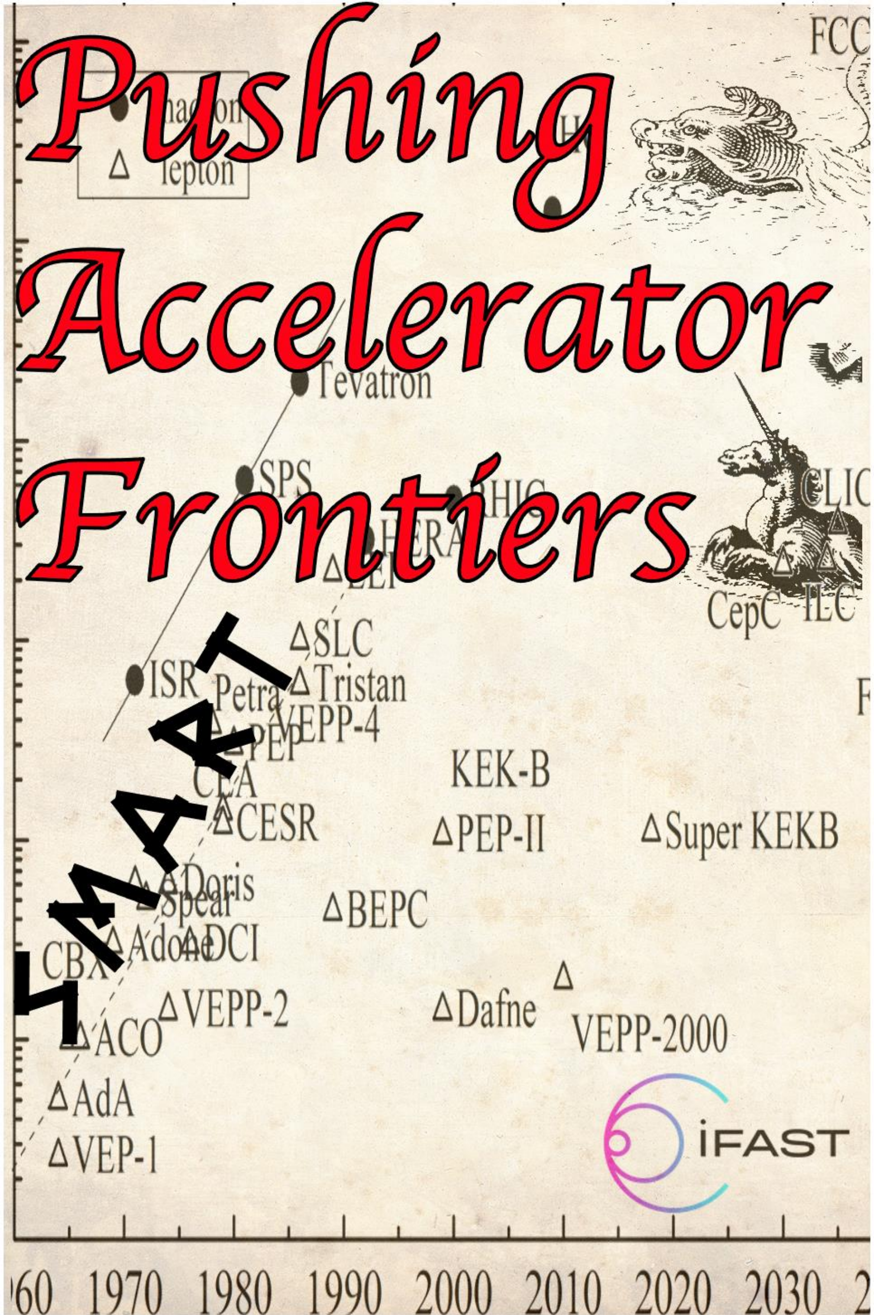
bergoz
INSTRUMENTATION

HIT
Heidelberger Ionenstrahl-Therapiezentrum

JG|U
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

the three SMART pillars

Task 5.1 MUon colliders STrategy network (MUST)
Coord.: Nadia Pastrone (INFN)
<u>INFN</u>, CERN, CEA, CNRS, KIT, PSI, UKRI
Support the effort to design a muon collider and to project and plan the required R&D.
Consolidate the community devoted to developing an international future facility.
Prepare the platform to disseminate the information



Task 5.3 Improvement of Resonant slow EXtraction spill quality (REX)
Coord.: Peter Forck (GSI)
<u>GSI</u>, BI, BT, CERN, HIT
Mitigate intensity fluctuations of slowly extracted beam from synchrotrons by means of detailed parameter simulations, related experimental verifications, and active beam control
Produce a prototype of improved hardware for power supply control to achieve a current stability in the range of $\Delta I / I < 10^{-6}$.
Design and produce a high-performance RF-amplifier with versatile control for knock-out extraction.

Task 5.2 Pushing Accelerator Frontiers (PAF)

- **Main tools: topical workshops and dedicated prospective studies**

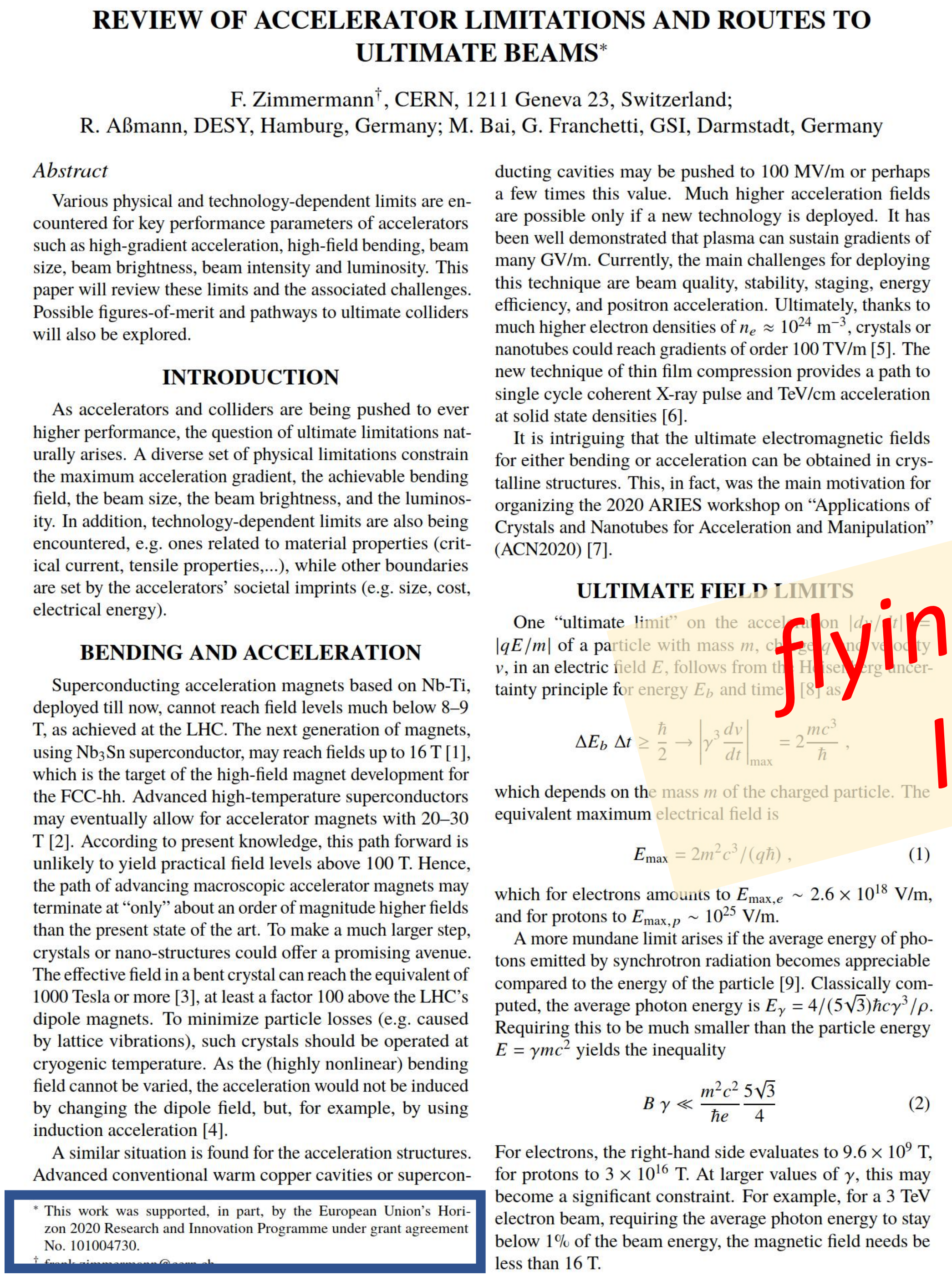
- **Overriding goal:** survey **frontiers of classical accelerators and develop long-term strategies** for boosting the performance of **future facilities** and for **overcoming limitations**

- **Thrust 1:** networking on **novel intense positron sources**, providing a **"condensation point" for the worldwide positron-source community**
  (**CNRS – Iryna Chaikovska**)
  - different methods of e^+ production, both classical techniques & especially novel/exotic ones

- **Thrust 2: survey extreme beams and ultimate limits**, and examine **approaches to overcome the present limits on beam brightness** (**CERN – Frank Zimmermann, GSI – Giuliano Franchetti**)
  - **space-charge compensation or cooling, crystalline beams,..**
  - review the ultimate limits on **high-gradient acceleration, high-field bending, beam size, beam density, and luminosity**

- IPAC'21 paper!

flying start at IPAC’21



REVIEW OF ACCELERATOR LIMITATIONS AND ROUTES TO ULTIMATE BEAMS*

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Abstract

Various physical and technology-dependent limits are encountered for key performance parameters of accelerators such as high-gradient acceleration, high-field bending, beam size, beam brightness, beam intensity and luminosity. This paper will review these limits and the associated challenges. Possible figures-of-merit and pathways to ultimate colliders will also be explored.

INTRODUCTION

As accelerators and colliders are being pushed to ever higher performance, the question of ultimate limitations naturally arises. A diverse set of physical limitations constrain the maximum acceleration gradient, the achievable bending field, the beam size, the beam brightness, and the luminosity. In addition, technology-dependent limits are also being encountered, e.g. ones related to material properties (critical current, tensile properties,...), while other boundaries are set by the accelerators’ societal imprints (e.g. size, cost, electrical energy).

BENDING AND ACCELERATION

Superconducting acceleration magnets based on Nb-Ti, deployed till now, cannot reach field levels much below 8–9 T, as achieved at the LHC. The next generation of magnets, using Nb_3Sn superconductor, may reach fields up to 16 T [1], which is the target of the high-field magnet development for the FCC-hh. Advanced high-temperature superconductors may eventually allow for accelerator magnets with 20–30 T [2]. According to present knowledge, this path forward is unlikely to yield practical field levels above 100 T. Hence, the path of advancing macroscopic accelerator magnets may terminate at “only” about an order of magnitude higher fields than the present state of the art. To make a much larger step, crystals or nano-structures could offer a promising avenue. The effective field in a bent crystal can reach the equivalent of 1000 Tesla or more [3], at least a factor 100 above the LHC’s dipole magnets. To minimize particle losses (e.g. caused by lattice vibrations), such crystals should be operated at cryogenic temperature. As the (highly nonlinear) bending field cannot be varied, the acceleration would not be induced by changing the dipole field, but, for example, by using induction acceleration [4].

A similar situation is found for the acceleration structures. Advanced conventional warm copper cavities or superconducting cavities may be pushed to 100 MV/m or perhaps a few times this value. Much higher acceleration fields are possible only if a new technology is deployed. It has been well demonstrated that plasma can sustain gradients of many GV/m. Currently, the main challenges for deploying this technique are beam quality, stability, staging, energy efficiency, and positron acceleration. Ultimately, thanks to much higher electron densities of $n_e \approx 10^{24}$ m^{-3}, crystals or nanotubes could reach gradients of order 100 TV/m [5]. The new technique of thin film compression provides a path to single cycle coherent X-ray pulse and TeV/cm acceleration at solid state densities [6].

It is intriguing that the ultimate electromagnetic fields for either bending or acceleration can be obtained in crystalline structures. This, in fact, was the main motivation for organizing the 2020 ARIES workshop on “Applications of Crystals and Nanotubes for Acceleration and Manipulation” (ACN2020) [7].

ULTIMATE FIELD LIMITS

One “ultimate limit” on the acceleration $|dv/dt| = |qE/m|$ of a particle with mass m, charge q and velocity v, in an electric field E, follows from the Heisenberg uncertainty principle for energy E_b and time [8] as

$$\Delta E_b \, \Delta t \geq \frac{\hbar}{2} \rightarrow \left|\gamma^3 \frac{dv}{dt}\right|_{\max} = 2\frac{mc^3}{\hbar} ,$$

which depends on the mass m of the charged particle. The equivalent maximum electrical field is

$$E_{\max} = 2m^2c^3/(q\hbar) , \qquad (1)$$

which for electrons amounts to $E_{\max,e} \sim 2.6 \times 10^{18}$ V/m, and for protons to $E_{\max,p} \sim 10^{25}$ V/m.

A more mundane limit arises if the average energy of photons emitted by synchrotron radiation becomes appreciable compared to the energy of the particle [9]. Classically computed, the average photon energy is $E_\gamma = 4/(5\sqrt{3})\hbar c\gamma^3/\rho$. Requiring this to be much smaller than the particle energy $E = \gamma mc^2$ yields the inequality

$$B\,\gamma \ll \frac{m^2c^2}{\hbar e}\,\frac{5\sqrt{3}}{4} \qquad (2)$$

For electrons, the right-hand side evaluates to 9.6×10^9 T, for protons to 3×10^{16} T. At larger values of γ, this may become a significant constraint. For example, for a 3 TeV electron beam, requiring the average photon energy to stay below 1% of the beam energy, the magnetic field needs be less than 16 T.

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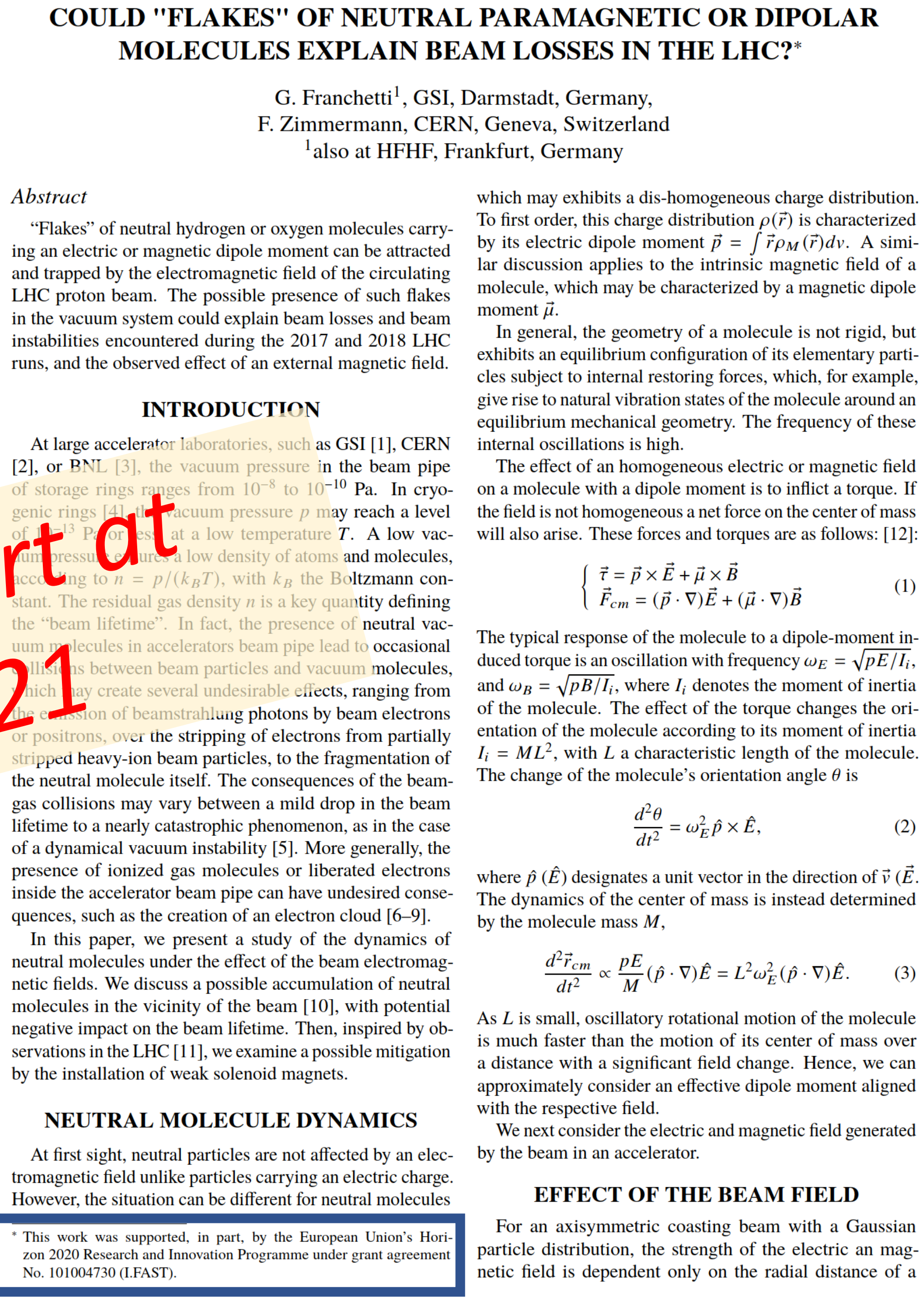

COULD "FLAKES" OF NEUTRAL PARAMAGNETIC OR DIPOLAR MOLECULES EXPLAIN BEAM LOSSES IN THE LHC?*

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Abstract

“Flakes” of neutral hydrogen or oxygen molecules carrying an electric or magnetic dipole moment can be attracted and trapped by the electromagnetic field of the circulating LHC proton beam. The possible presence of such flakes in the vacuum system could explain beam losses and beam instabilities encountered during the 2017 and 2018 LHC runs, and the observed effect of an external magnetic field.

INTRODUCTION

At large accelerator laboratories, such as GSI [1], CERN [2], or BNL [3], the vacuum pressure in the beam pipe of storage rings ranges from 10^{-8} to 10^{-10} Pa. In cryogenic rings [4], the vacuum pressure p may reach a level of 10^{-13} Pa or less at a low temperature T. A low vacuum pressure ensures a low density of atoms and molecules, according to $n = p/(k_B T)$, with k_B the Boltzmann constant. The residual gas density n is a key quantity defining the “beam lifetime”. In fact, the presence of neutral vacuum molecules in accelerators beam pipe lead to occasional collisions between beam particles and vacuum molecules, which may create several undesirable effects, ranging from the emission of beamstrahlung photons by beam electrons or positrons, over the stripping of electrons from partially stripped heavy-ion beam particles, to the fragmentation of the neutral molecule itself. The consequences of the beam-gas collisions may vary between a mild drop in the beam lifetime to a nearly catastrophic phenomenon, as in the case of a dynamical vacuum instability [5]. More generally, the presence of ionized gas molecules or liberated electrons inside the accelerator beam pipe can have undesired consequences, such as the creation of an electron cloud [6–9].

In this paper, we present a study of the dynamics of neutral molecules under the effect of the beam electromagnetic fields. We discuss a possible accumulation of neutral molecules in the vicinity of the beam [10], with potential negative impact on the beam lifetime. Then, inspired by observations in the LHC [11], we examine a possible mitigation by the installation of weak solenoid magnets.

NEUTRAL MOLECULE DYNAMICS

At first sight, neutral particles are not affected by an electromagnetic field unlike particles carrying an electric charge. However, the situation can be different for neutral molecules which may exhibits a dis-homogeneous charge distribution. To first order, this charge distribution $\rho(\vec r)$ is characterized by its electric dipole moment $\vec p = \int \vec r \rho_M(\vec r) dv$. A similar discussion applies to the intrinsic magnetic field of a molecule, which may be characterized by a magnetic dipole moment $\vec\mu$.

In general, the geometry of a molecule is not rigid, but exhibits an equilibrium configuration of its elementary particles subject to internal restoring forces, which, for example, give rise to natural vibration states of the molecule around an equilibrium mechanical geometry. The frequency of these internal oscillations is high.

The effect of an homogeneous electric or magnetic field on a molecule with a dipole moment is to inflict a torque. If the field is not homogeneous a net force on the center of mass will also arise. These forces and torques are as follows: [12]:

$$\begin{cases} \vec\tau = \vec p \times \vec E + \vec\mu \times \vec B \\ \vec F_{cm} = (\vec p \cdot \nabla)\vec E + (\vec\mu \cdot \nabla)\vec B \end{cases} \qquad (1)$$

The typical response of the molecule to a dipole-moment induced torque is an oscillation with frequency $\omega_E = \sqrt{pE/I_i}$, and $\omega_B = \sqrt{pB/I_i}$, where I_i denotes the moment of inertia of the molecule. The effect of the torque changes the orientation of the molecule according to its moment of inertia $I_i = ML^2$, with L a characteristic length of the molecule. The change of the molecule’s orientation angle θ is

$$\frac{d^2\theta}{dt^2} = \omega_E^2 \hat p \times \hat E, \qquad (2)$$

where $\hat p$ $(\hat E)$ designates a unit vector in the direction of $\vec v$ $(\vec E)$. The dynamics of the center of mass is instead determined by the molecule mass M,

$$\frac{d^2\vec r_{cm}}{dt^2} \propto \frac{pE}{M}(\hat p \cdot \nabla)\hat E = L^2\omega_E^2(\hat p \cdot \nabla)\hat E. \qquad (3)$$

As L is small, oscillatory rotational motion of the molecule is much faster than the motion of its center of mass over a distance with a significant field change. Hence, we can approximately consider an effective dipole moment aligned with the respective field.

We next consider the electric and magnetic field generated by the beam in an accelerator.

EFFECT OF THE BEAM FIELD

For an axisymmetric coasting beam with a Gaussian particle distribution, the strength of the electric an magnetic field is dependent only on the radial distance of a

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* This work was supported, in part, by the European Union’s Horizon 2020 Research and Innovation Programme under grant agreement No. 101004730 (I.FAST).

Task 5.2 Pushing Accelerator Frontiers (PAF) – cont'd

- **Thrust 3:** **artificial intelligence for accelerators,** exploring applications of **machine learning, deep learning, advanced optimization algorithms and neural networks**, for accelerator control and design (**PSI – Rasmus Ischebeck**)

- **Thrust 4:** **accelerators for "dark sector"& precision physics**

  (**CERN – Christian Carli, GSI – Bernd Lorentz**)

  - accelerator/beam requirements for dark-sector searches in fixed-target experiments
  - investigating current precision frontier accelerator developments, such as EDM ring designs

Task 5.2 Pushing Accelerator Frontiers (PAF) – cont'd

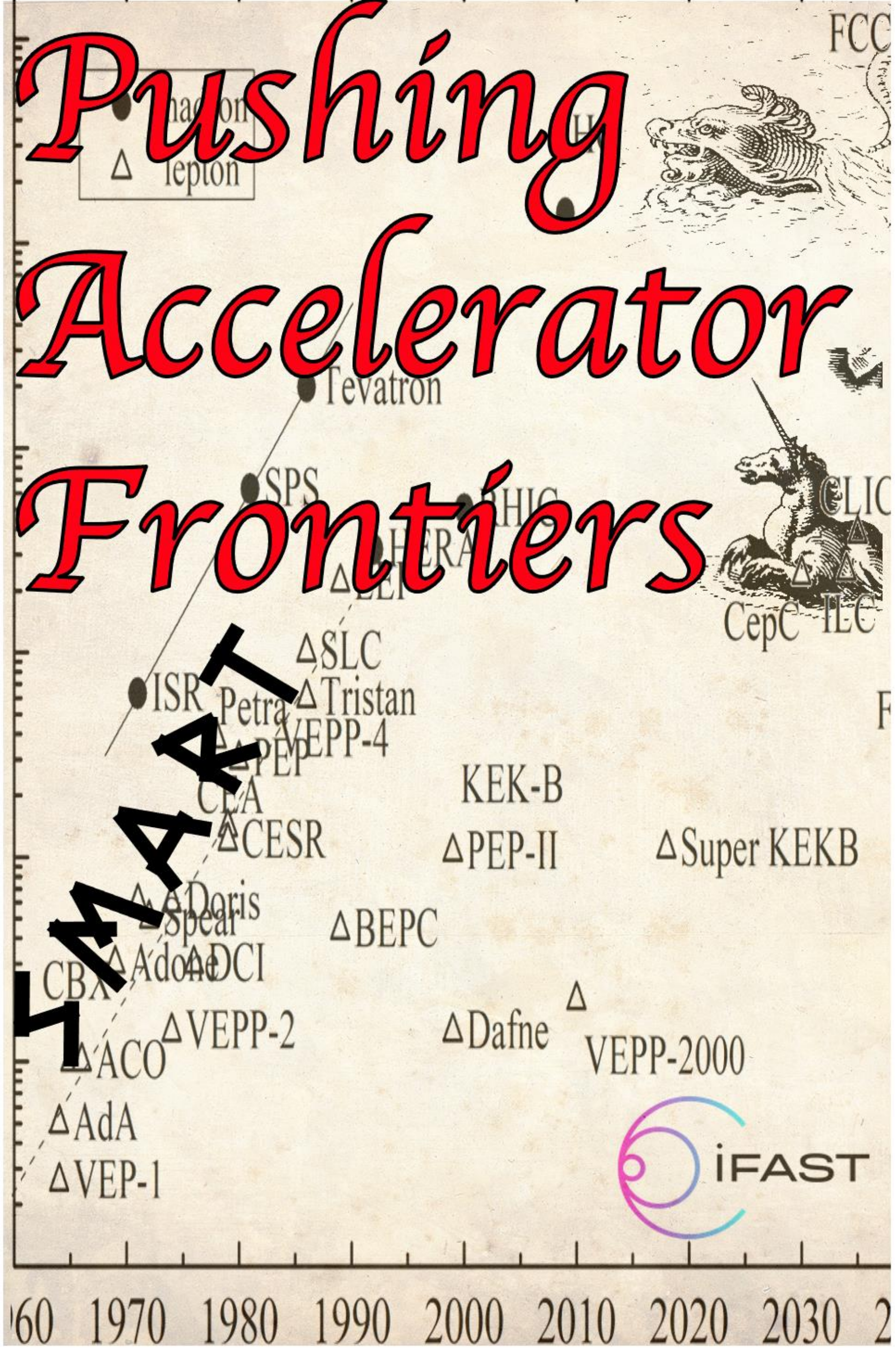
Thrust 5: **green accelerators, sustainable accelerator concepts, e.g. energy recovery, energy efficiency, and possibly particle (e.g. positron) recycling** (**CERN, GSI, CNRS, PSI, + JGU – Florian Hug**)

WP5 - **Task 5.2 PAF synergies:**
with Task 5.1 MUST: positron sources, ultimate limits, and particle recycling ..
with the Task 5.3 REX: dark sector fixed-target experiments and machine learning …

→ PAF will develop a coherent landscape for future accelerators and issue targeted R&D recommendations

WP5 deliverables

D5.1: International collaboration plans towards a multi-TeV muon collider **Report on established collaboration and results disseminated by the action [MUST]**	**M46**
D5.2: Roadmap for future accelerators Strategy for intense positron sources; R&D plan towards ultimate beams; State of the art and possible directions for crystalline beams; Strategy and requirements for EDM ring or other precision experiments; Roadmap for accelerator AI; State of the art and future roadmap for green accelerators [PAF]	M42
D5.3: Ripple mitigation for slow extraction beam quality improvement Simulation results for improvements including their experimental verifications, and design considerations of the accelerator control with related hardware. [REX]	M46



… we are already

on the way ….