Summary of ARIES Workshop
“Applications of Crystals and Nanotubes for Acceleration and Manipulation – ACN2020”

L. Bandiera (INFN Ferrara), F. Blanc (EPFL), A. Bonatto (U Manchester and CI), I. Chaikovska (IJCLab), S. Dabagov (INFN Frascati), A. Fomin (KIPT and CERN), V. Guidi (INFN Ferrara), R. Ischebeck (PSI), A.V. Korol (MBN Research Center), A. Mazzolari (INFN Ferrara), D. Mirarchi (CERN), A.E. Nanni (SLAC), N. Pastrone (INFN Torino), A. Perera (Liverpool U), T. Pieloni (EPFL), Q. Qin (IHEP Beijing), S. Redaelli (CERN), J. Resta Lopez (Liverpool U), L. Rivkin (PSI), R. Rossi (CERN), A. Sahai (U Colorado Denver), W. Scandale (CERN/INFN), M. Seidel (PSI), V. Shiltsev (FNAL), Y. Shin (NIU/FNAL), A.V. Solov’yov (MBN Research Center), M. Tomut (U Siegen), G. Xia (U Manchester and CI), F. Velotti (CERN), M. Zanetti (INFN Padua), F. Zimmermann (CERN)

edited by the ACN2020 workshop organisers
T. Pieloni (EPFL), M. Zanetti (INFN Padua), F. Zimmermann (CERN)
and the ACN2020 program advisors
G. Franchetti (GSI), R. Ischebeck (PSI), V. Shiltsev (FNAL), T. Tajima (UCI)

Beam acceleration or guidance in crystals or nanostructures hold the promises of ultra-high accelerating gradients or continuous focusing and extremely strong bending, respectively. These features render crystals and nanotubes highly attractive for future high-energy physics colliders. The ARIES workshop on Application of Crystals and Nanotubes for Beam Acceleration or Manipulation, **ACN2020**, reviewed the progress of these concepts over the past years and discussed the path towards proof-of-principle demonstrations and promising applications. The workshop also promoted discussions between teams working on pertinent technologies and the beam physics community, in order to develop a roadmap of future steps and possible experiments. This summary includes some general information, workshop statistics, photographs, and highlights from the individual presentations provided by the workshop participants.

This workshop took place at the EPFL in Lausanne on 10 and 11 March 2020, while countries and laboratories were shutting down to combat the Covid-19 crisis. The workshop counted: **10 Live attendees:** Fred Blanc (EPFL), Rasmus Ischebeck (PSI), Aravinda Perera (U Liverpool), Tatiana Pieloni (EPFL), Aakash Sahai (U Colorado Denver), Mike Seidel (EPFL & PSI), Youngmin Shin (formerly NIU/FNAL), Andrey Solov’yov (MBN), Francesco Velotti (CERN), Frank Zimmermann (CERN); with a person-to-person seating distance larger than 2 to 3 m; **19 Remote attendees:** Laura Bandiera (INFN Ferrara), Alexandre Bonatto (U Manchester), Iryna Chaikovska (IJCLab), Sultan Dabagov (INFN Frascati), Alex Fomin (KIPT & CERN), Andrea Mazzolari (INFN Ferrara), Emilio Nanni (SLAC & MIT), Nadia Pastrone (INFN Torino), Qing Qin (IHEP), Stefano Redaelli (CERN), Javier Resta Lopez (U. Liverpool), Daniele Mirarchi (CERN), Lenny Rivkin

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(PSI & EPFL), Roberto Rossi (CERN), Walter Scandale (CERN, INFN, IN2P3), Marilena Tomut (U Siegen), Marco Zanetti (INFN Padova), Vladimir Shiltsev (FNAL); and **1 Poster:** Aravinda Perera (U. Liverpool).

The 29 participants (see Figs. 1, 2 and 3) mainly came from European countries, though with a noticeable participation from the U.S. and China. Shown below is a breakdown of the participants by country and institute of origin.

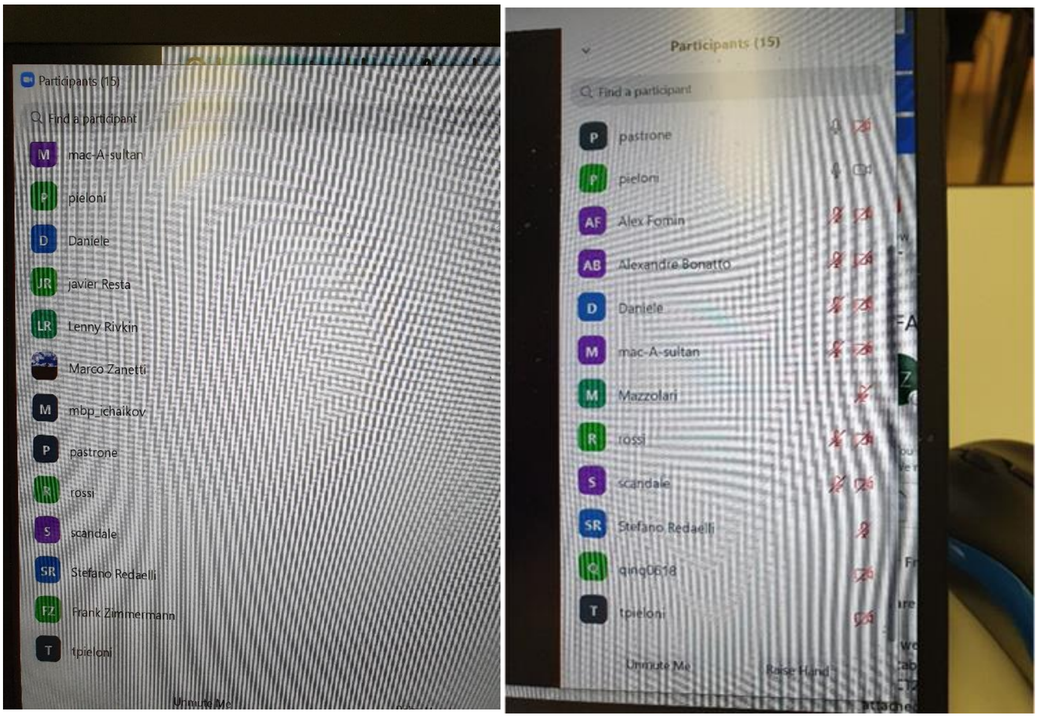
- China: 1 (IHEP)
- France: 1 (IJCLab)
- Germany: 2 (MBN, U Siegen)
- Italy: 5 (INFN Ferrara, INFN Frascati, INFN Padua, INFN Torino)
- Switzerland: 5 (EPFL, PSI)
- UK: 3 (U Liverpool, U Manchester)
- Ukraine: 1 (KIPT)
- CERN: 6
- USA: 5 (NIU, FNAL, U Colorado Denver, MIT/SLAC, UC Irvine)

The workshop was composed of the following sessions/blocks:

1. Channeling Overview, Nanotube and Fibre Acceleration, Dielectric Structures , chaired by Frank Zimmermann (CERN)
2. Crystalline Undulators, Channeling and Volume Reflection at the LHC, SPS and PS, Crystal Shadowing, Beam Steering and Nanomodulation, chaired by Mike Seidel (EPFL & PSI)
3. Carbon-Nanotube Arrays, Crystal-Assisted Positron Production, hollow Plasma Channels, chaired by Tatiana Pieloni (EPFL)

The details of the program as well as a collection of all talks are available on the indico web site: https://indico.cern.ch/event/867535/ . Figure 4 shows the workshop poster.

Fig. 1: Live participants outside of the UNIL Amphipol in front of the Lake Geneva, from left to right: Aravinda Perera, Tatiana Pieloni, Andrei Solov'yov, Rasmus Ischebeck, Frank Zimmermann, Youngmin Shin, Mike Seidel, Aakash Sahai, Fred Blanc, Francesco Velotti.



Participants (15)

Find a participant

mac-A-sultan
pieloni
Daniele
javier Resta
Lenny Rivkin
Marco Zanetti
mbp_ichaikov
pastrone
rossi
scandale
Stefano Redaelli
Frank Zimmermann
tpieloni

Unmute Me

Participants (15)

Find a participant

pastrone
pieloni
Alex Fomin
Alexandre Bonatto
Daniele
mac-A-sultan
Mazzolari
rossi
scandale
Stefano Redaelli
qing0618
tpieloni

Unmute Me
Raise Hand

Fig. 2: Remote participants on the EPFL Zoom video system.

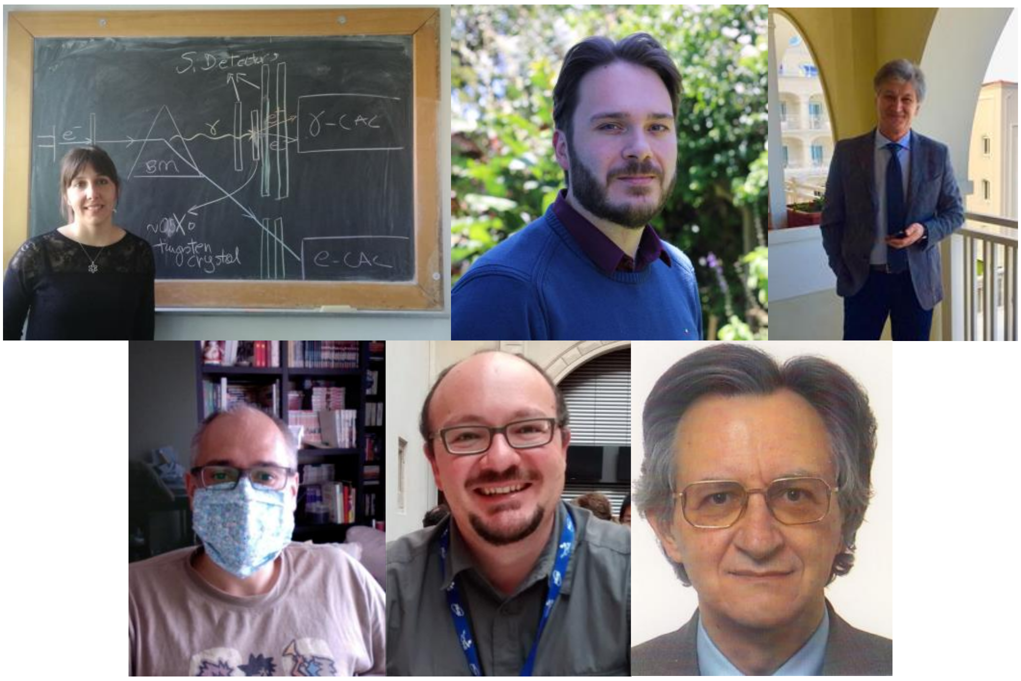


Fig. 3: Photos of some remote participants: Laura Bandiera, Alexandre Bonatto, Sultan Dabagov, Stefano Redaelli, Javier Resta Lopez, Walter Scandale

EPFL
École polytechnique fédérale de Lausanne

ACN 2020

ARIES

ARIES Workshop on
Applications of **C**rystals and **N**anotubes
for beam acceleration and manipulation

Dates:10–11 March 2020
Venue: École Polytechnique Fédérale de Lausanne (CH)

Invited Speakers

- Dr Armen Apyan (AANSL)
- Dr Sultan Dabagov (INFN LNF)
- Dr Rasmus Ischebeck (PSI)
- Dr Max Kellermeier (DESY)
- Dr Emilio Nanni (SLAC & MIT)
- Dr Stefano Redaelli (CERN)
- Dr Javier Resta Lopez (U. Liverpool)
- Dr Aakash Sahai (U. Colorado at Denver)
- Dr Walter Scandale (IN2P3 & CERN)
- Dr Youngmin Shin (formerly NIU/FNAL)
- Prof Andrey V. Solov'yov (MBN Frankfurt)
- Dr Marilena Tomut (U Münster)

…

Co-Chairs
Dr Tatiana Pieloni (EPFL)
Prof Marco Zanetti (INFN-University of Padova)
Dr Frank Zimmermann (CERN)

Program Advisors
Dr Giuliano Franchetti (GSI)
Dr Rasmus Ischebeck (PSI)
Dr Vladimir Shiltsev (FNAL)
Prof. Toshiki Tajima (UC Irvine)
https://indico.cern.ch/e/ACN-ARIES2020

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Fig. 4: ACN2020 poster

A few selected highlights

- Crystals are already widely used for assisting proton-beam collimation, local reduction of beam losses, positron production, dedicated particle physics experiments, but not yet for acceleration (S. Redaelli, F. Velotti, R. Rossi et al.).
- Carbon nanotube (CNT) or fiber-like nanostructured tube accelerators could be a steppingstone to crystal acceleration, and have multiple applications themselves (Y. Shin, A. Sahai).
- Proof-of-principle experiments for CNT or fiber-like tube acceleration have been proposed and are being further developed (Y. Shin, A. Sahai, A. Perera, J. Resta Lopez).
- Shadowing extraction septum by crystal array exploited numerical optimizers and machine learning to automatize the shadowing set up; loss reduction target is a factor 4 for the SPS slow extraction in future operation (F. Velotti, R. Rossi).
- Benefit of crystal collimation was demonstrated through several tests during the LHC Run 2 (2015-2018). Crystal collimation is now part of the HL-LHC baseline. Bent crystals are also considered for a fixed-target physics program at the LHC (S. Redaelli).

- EU projects CRYSBEAM and SELDOM support EDM/MDM measurements of baryons at the LHC using crystals (A. Mazzolari); successful UA9 experiments with double channeling and target upstream of the second crystal (R. Rossi).
- Diffracting relativistic electrons in a single-crystal silicon, combined with emittance exchange, can modulate the electron beam current on the nm scale.
- Compact X-ray sources could be based on super-radiant emission from an electron beam with a longitudinal modulation on the nm scale from transverse grating and emittance exchange (E. Nanni) and/or on crystalline undulators (A. Solov'yov).
- Crystal-based Light Sources offers a low-cost alternative to conventional Light Sources and have enormous number of possible applications in basic sciences, technology and medicine. Extremely high brilliance in the photon energy range of 0.1 to 10 MeV could be reached with crystalline undulators (A. Solov'yov).
- Hybrid scheme based on channelling radiation emitted in a crystal presently is the preferred concept for intense positron sources (I. Chaikovska). The use of crystalline undulators could be an interesting alternative (I. Chaikovska, A. Solov'yov).
- The radiation emitted by sub-GeV electrons via planar channeling and volume reflection (VR) in a 30 μm-thick bent Si crystal peaks in the few-MeV range. Crystal channeling and volume-reflection radiation could be used for an intense photon or gamma-ray source and for positron production (L. Bandiera).
- The most advanced manufacturing techniques of crystals suitable for operation at ultra-high energy and ultra-high intensity particle accelerators have been developed in Ferrara (A. Mazzolari).
- Wake fields in CNTs, CNT arrays or fiber-like nanostructured tubes are being computed in 2D and 3D PIC simulations with various approximations (Y. Shin, A. Sahai, A. Perera, J. Resta Lopez, A. Bonatto, G. Xia).
- Relative importance of channeling versus plasma response may need to be considered (S. Dabagov).
- Parameter scans for CNT predict effective plasma density for arrays (A. Bonatto). Future experiments with CNTs and CNT arrays need to be prepared (A. Perera, Y. Shin, J. Resta Lopez).
- Hollow channel history using a purely electromagnetic mode was detailed (including PoP 1995 and PRL 1998 work by Chiou, Katsouleas, and Decker, and Dielectric Wakefield Accelerators); in his PRAB paper 2017 Aakash Sahai showed that the crunch-in regime electrostatic mode acceleration can reach the wavebreaking limit (which had not been seen in earlier works); need to identify the optimum hollow channel or fiber-like tube parameters (A. Sahai).
- Laser damage of dielectric accelerating structures are being studied along with beam stability. Near term applications of dielectric structures include generation of radiation, electron diffraction [6], and beam shaping (R. Ischebeck).

Highlights of individual contributions

1. Channelling: Highlights, Lessons, Directions

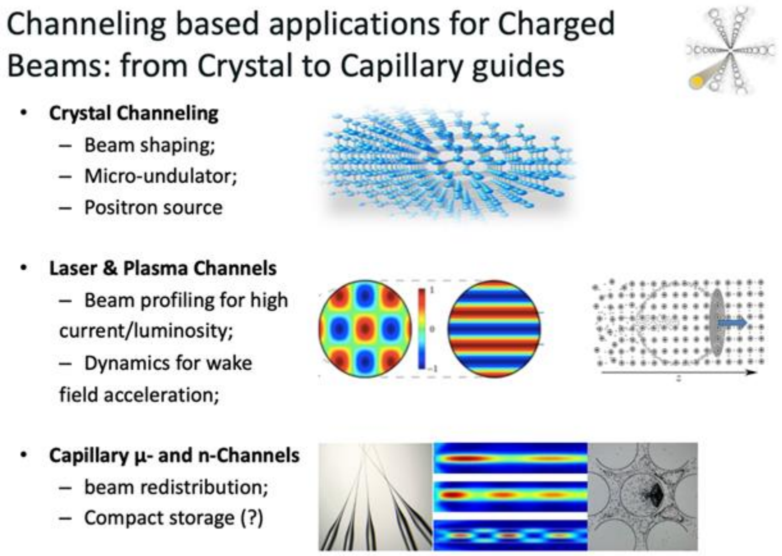
Sultan Dabagov, INFN-LNF

1) Take-home messages

Channelling is a **phenomenon well-known in the physics world** mostly related to the propagation of the beams of charged particles in aligned crystals. Since the beginning of 1970s, the phenomenon of channelling of **high-energy leptons** (electrons/positrons of several MeV up to hundreds of GeV energies) and **hadrons** (protons/ions of tens GeV up to several TeV energies) has been applied at various famous world research centers, within different national/international projects, and utilized to **shape the beams** as well as to **produce high power x-ray and gamma radiation sources**.

Recent studies have revealed the feasibility of applying the **channelling phenomenology for describing various other mechanisms of interactions** of both charged and neutral particle beams in solids, plasmas and electromagnetic fields, covering diverse research areas, ranging from **crystal/laser/plasma-based undulators and collimators** to **capillary-based x-ray and neutron optical elements** (Figs. 5 and 6).

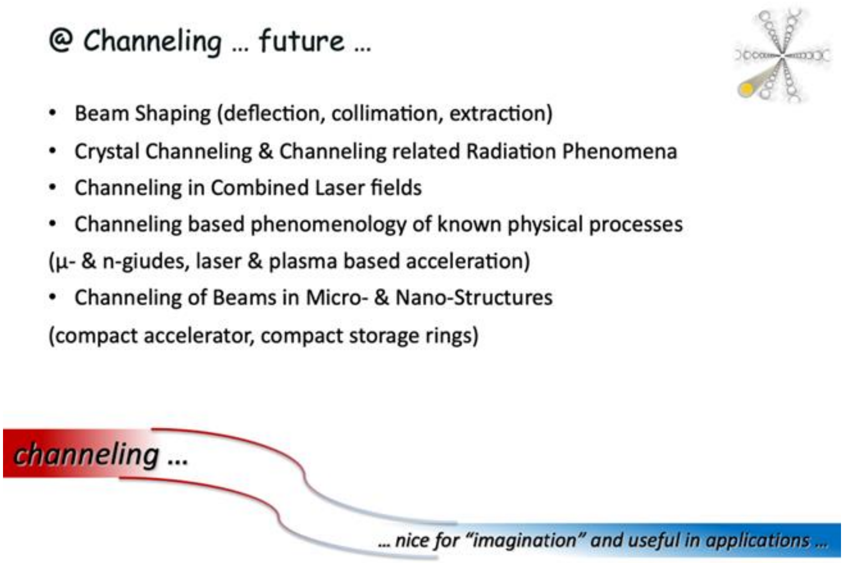
2) A few highlights pictures



Channeling based applications for Charged Beams: from Crystal to Capillary guides

- **Crystal Channeling**
  - Beam shaping;
  - Micro-undulator;
  - Positron source
- **Laser & Plasma Channels**
  - Beam profiling for high current/luminosity;
  - Dynamics for wake field acceleration;
- **Capillary μ- and n-Channels**
  - beam redistribution;
  - Compact storage (?)

Fig. 5: Slide on channelling-based applications.



@ Channeling … future …

- Beam Shaping (deflection, collimation, extraction)
- Crystal Channeling & Channeling related Radiation Phenomena
- Channeling in Combined Laser fields
- Channeling based phenomenology of known physical processes

(μ- & n-giudes, laser & plasma based acceleration)

- Channeling of Beams in Micro- & Nano-Structures

(compact accelerator, compact storage rings)

channeling …

… nice for "imagination" and useful in applications …

Fig. 6: Slide on future applications of channelling.

3) Review papers related to this presentation (for general basic principles)

[1] S.B. Dabagov, and Yu.P. Gladkikh, Advanced Channeling Technologies for X-ray Applications (invited review), *Radiation Physics & Chemistry* **154** (2019) 3-16.

[2] S.B. Dabagov, Advanced Channeling Technologies in Plasma and Laser Fields (invited review), *European Physical Journal Web Conferences* **167** (2018) 01002.

[3] S.B. Dabagov, and N.K. Zhevago, "On radiation by relativistic electrons and positrons channeled in crystals" (invited review), *La Rivista del Nuovo Cimento* **31** (9) (2008) 491-529.

[4] S.B. Dabagov, "Channeling of Neutral Particles in Micro- and Nanocapillaries" (Reviews of Topical Problems), *Physics Uspekhi* **46** (10) (2003) 1053-1075.

4) Proceedings of Channeling meetings (for complete activity list):

[5] S.B. Dabagov, Ed., "Channeling 2018", Proc. of the 8th International Conference "Charged and Neutral Particles Channeling Phenomena" (Ischia (Napoli), September 23-28, 2018), *Physical Review: Accelerators and Beams* (2019) - in processing.

[6] S.B. Dabagov, Ed., "Channeling 2016", Proc. of the 7th International Conference "Charged and Neutral Particles Channeling Phenomena" (Sirmione-Desenzano del Garda, September 25-30, 2016), *Nuclear Instruments and Methods in Physics Research* **B 402** (2017) 392 pp.

[7] S.B. Dabagov, Ed., "Channeling 2014", Proc. of the 6th International Conference "Charged and Neutral Particles Channeling Phenomena" (Capri, October 5-10, 2014), *Nuclear Instruments and Methods in Physics Research* **B 355** (2015) 402 pp.

[8] S.B. Dabagov, Ed., “Channeling 2012”, Proc. of the 5th International Conference "Charged and Neutral Particles Channeling Phenomena" (Alghero, September 23-28, 2012), *Nuclear Instruments and Methods in Physics Research* **B 309** (2013) 280 pp.

[9] S.B. Dabagov, L. Palumbo, and V. Guidi, Eds., “Channeling 2010”, Proc. of the 4th International Conference "Charged and Neutral Particles Channeling Phenomena" (Ferrara, October 3-8, 2010), *Nuovo Cimento* **C 34** (4) (2011) 560 pp.

[10] S.B. Dabagov, and L. Palumbo, Eds., Charged and Neutral Particles Channeling Phenomena - “Channeling 2008”, Proc. of the 51st Workshop of the INFN Eloisatron Project, World Scientific, (2010) 823 pp.

[11] S.B. Dabagov, Ed., “Channeling 2006”, Proc. of the International Conference on Charged and Neutral Particles Channeling Phenomena (Frascati, July 3-7, 2006), *Proc. of SPIE* **6634** (2007).

[12] S.B. Dabagov, Ed., “Channeling 2004”, Proc. of the International Conference on Charged and Neutral Particles Channeling Phenomena (Frascati, November 2-6, 2004), *Proc. of SPIE* **5974** (2005) 506 pp.

2. CNT Accelerator - Path Toward TeV/m Acceleration: Dynamics of Plasmon-Assisted Acceleration in CNTs

Young-Min Shin, formerly NIU and FNAL

1) Key result(s) achieved

- First ever PIC-simulation/theoretical analysis of plasma acceleration with a **solid-level plasma density**
- **First ever PIC-simulation/theoretical analysis of ”CNT-acceleration”** (effective CNT-model)
- Introduction of theoretical models for **nanotube arrays** with beam-driven and laser-driven acceleration
- Pioneering theoretical and numerical analyses of **optical properties of multi-wall CNT** for the case of laser-driven acceleration
- Conceived **CNT-plasmon driven acceleration concept** and proved the concept with theoretical calculations and PIC simulations
- Outlined **experimental layout for proof-of-concept (POC) test** based on direct energy shift measurements
- Pioneering full-scale end-to-end simulation modeling of POC-experiment beamline (gun to target)

- First implementation of **POC test at Fermilab FAST beamline** with commissioning of test equipment and beam diagnosis tools, followed by the **demonstration of bunch density modulation with a slit-mask along a chicane**
- Successful **fabrication of CNT-target with AAO-membrane**
- Laid out a **tabletop pump-probe electron diffraction test** to measure an energy-gain from a CNT target with theoretical analysis of diffraction patterns.

2) Next steps and outlook

- Find a facility and secure experimental resources and financial support to continue and **complete the POC-Test with the goal to demonstrate an energy-gain from a CNT-target**.
- Coherent, Multilateral, and Multidisciplinary Collaborations

3) A few highlights pictures

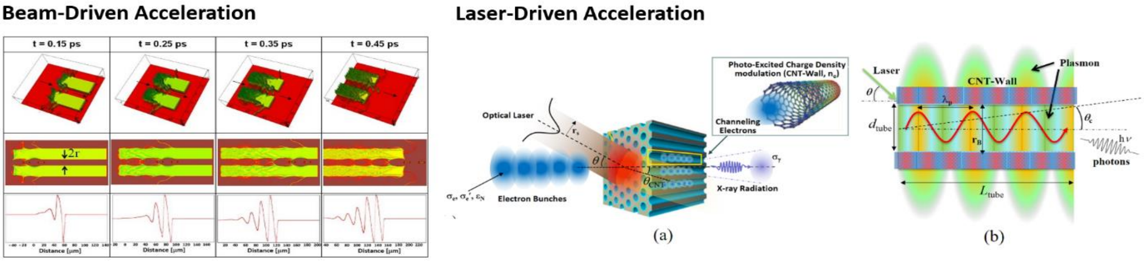
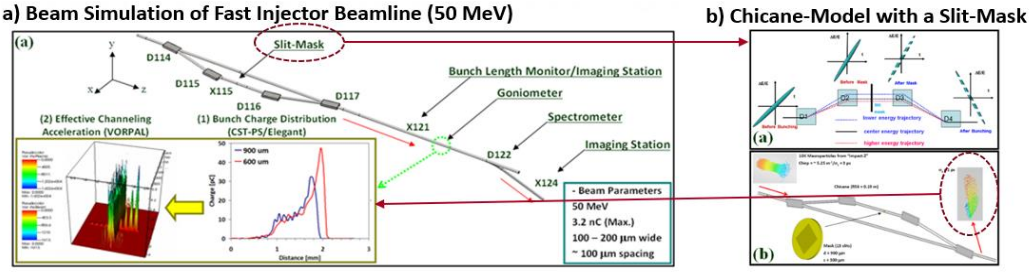


Fig. 7: Time-tagged snapshots of beam-driven acceleration in an effective carbon nanotube (CNT) from PIC-model (left) and schematic illustration of laser-driven acceleration in CNTs (right).



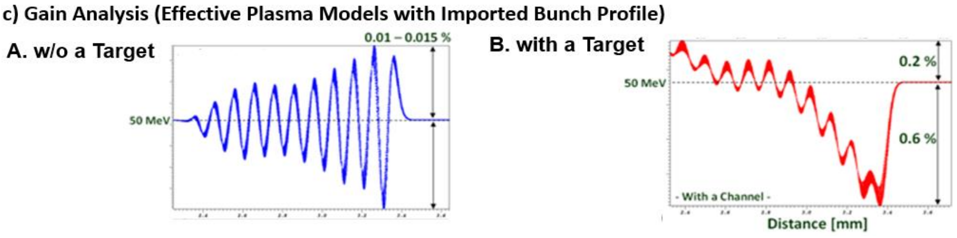


Fig. 8: Layout (end-to-end beamline model with a self-driven CNT acceleration model) of Fermilab POC experiment (top) and simulated energy distributions of a modulated bunch (bottom-left) without and (bottom-right) with a CNT-target.

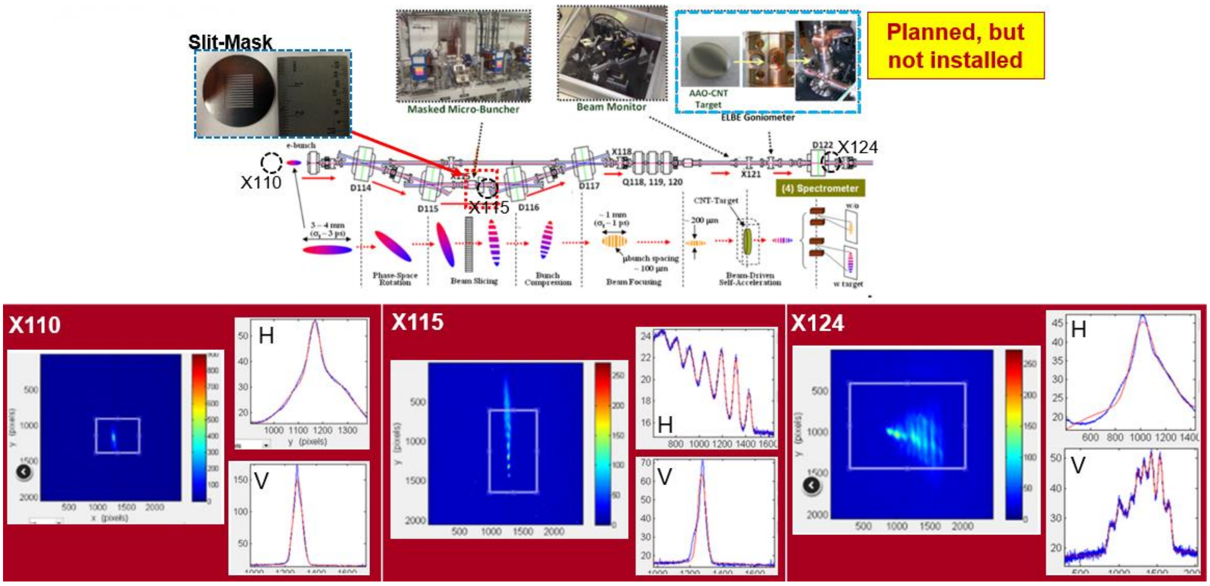


Fig. 9: Experimental setup with the installed test equipment (top) at Fermilab FAST injector beamline and 1st beam-test images of the POC experiment only with a slit-mask beam-modulator installed at the chicane (bottom).

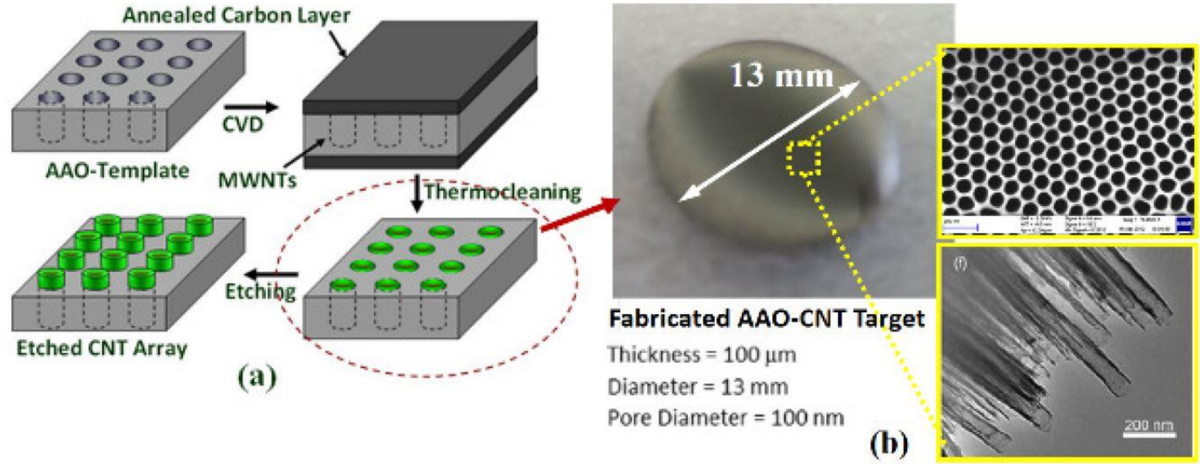


Fig. 10: (a) Flowchart of AAO-CNT fabrication process (b) fabricated AAO-CNT target (inset: SEM images of AAO-membrane and AAO-CNT array after chemical cleaning"

4) Take-home messages

Future energy frontier HEP needs a ground-breaking idea**. CNT-acceleration can be a stepping-stone toward the development of TeV/m** with crystal acceleration technology. The CNT-acceleration is conceptually sound and feasible, but it has not been experimentally demonstrated yet – Unfortunately, the first effort to implement the POC-Test in Fermilab ended up being unsuccessful. The takeaway from this experience is that the HEP Community (at least US-HEP) is still conservative and they are not ready for a paradigm shift. However, on the other hand, we will need to continuously explore practical ways to resolve the challenging open issues of the CNT-acceleration concept for a practical application to HEP acceleration machines.

5) Relevant references

[1] Young-Min Shin, "Carbon nanotube accelerator – Path toward TeV/m acceleration: Theory, experiment, and challenges, IJMPA 34 (34), 1943005 (2019)

[2] Y. M. Shin, and M. Figora, "Quasi-relativistic ultrashort electron beam source for electron diffractions and spectroscopies", RSI 88, 103302 (2017)

[3] Young-Min Shin, "Optically Controlled Coherent X-Ray Radiations from Photo-Excited Nanotubes", NIM-B 407, 276 (2017)

[4] Young-Min Shin, "Plasmon-Driven Acceleration in a Photo-Excited Nanotube", POP 24, 023115 (2017)

[5] Xiaomei Zhang, Toshiki Tajima, Deano Farinella, Youngmin Shin, Gerard Mourou, Jonathan Wheeler, Peter Taborek, Pisin Chen, Baifei Shen (2016). "X-ray Wakefield Acceleration and Betatron Radiation in Nanotubes", PRST-AB 19(10), 101004-1 ~ 101004 (2016).

[6] X. Zhu, D. R. Broemmelsiek, Young-Min Shin, "Theoretical and numerical analyses of a slit-masked chicane for modulated bunch generation", JINST 10, P10042 (2015).

[7] Young-Min Shin, Lumpkin, A. H., Thurman-Keup, R., "TeV/m Nano-Accelerator: Channeling Acceleration Research at Fermilab - Advanced Superconducting Test Accelerator (ASTA) Facility", NIM-B 355, 94 (2015).

[8] Young-Min Shin, "Beam-driven acceleration in ultra-dense media", APL 105 (11), 114106 (2014)

[9] Young-Min Shin, Dean A. Still, and Vladimir Shiltsev, "X-ray driven channeling acceleration in crystals and carbon nanotubes", POP 20 (12), 123106 (2013)

3. Fiber Accelerator: TV/m Crunch-in Wakefields

Aakash Sahai, University of Colorado Denver

Collaborators: Toshiki Tajima (UC Irvine), Vladimir Shiltsev (Fermilab), Peter Taborek (UCI), Gérard Mourou (Paris)

1) Key results

- This work introduces and lays the theoretical framework for a **novel nonlinear surface crunch-in mode [Sahai 2017, 2015] in a fiber-like nanostructured tube with vacuum-like core**. Using this collective solid-state mode framework built on existing technological capabilities our collaboration seeks **proof-of-principle demonstration of unprecedented TeVm^{-1} acceleration gradients using crystals**.

It is demonstrated that a **fiber-like nanostructured tube is better suited** for such an effort as compared to bulk solid crystals or CNTs.

- These fields are **many orders of magnitude higher** than both the time-tested radio-frequency accelerators as well as the gaseous plasma wakefield acceleration techniques [Tajima 1979]. Naturally, a realizable crystal accelerator promises to not only open new horizons for particle colliders [Shiltsev 2012, 2019] but possibly also non-collider paradigms [Ellis 2008] towards Planck-scale physics.
- But there have been **major challenges** to its realizability: (i) **lack of intense attosecond bunches** to excite collective modes in bulk solids; (ii) drawbacks of **direct irradiation of bulk solids**.
- The **novel solid-state nonlinear surface or "crunch-in" mode** is introduced here to overcome the key challenges. Advances in attosecond compression and nanofabrication technology allow an **intense bunch propagating in vacuum-like core of nanostructured tubes of hundreds of nanometer radius and effective wall densities, $n_t \cong 10^{22\text{-}24}$ cm^{-3} to strongly drive the tube wall electrons to crunch-in into the core.**

- The **many TVm^{-1} focusing wakefields of the crunch-in mode in the tube walls** makes a high energy particle beam **even more strongly focused causing hundreds of nanometer envelope modulations.** The self-focusing and nano-modulation effect results in more than an **order of magnitude increase in the peak beam density**. This significant increase in the peak beam density **results in even higher accelerating fields.**

- In this work it is demonstrated using **3D PIC and 3D analytical modeling** that **near solid submicron multi-GeV electron bunch can effectively excite TVm^{-1} longitudinal crunch-in wakefields in nanostructures, such as a fiber-like tube of 200nm core diameter**.

- Our **3D analytical model which is based on kinetic theory** not only demonstrates the existence condition of the crunch-in mode by avoiding blow-out but also provides an analytical estimate of both the focusing and the acceleration fields and matches well with the 3D PIC simulations. It also demonstrates that the **existence condition** and the **crunch-in field amplitudes** depend upon the beam and tube parameters such as beam density and dimensions as well as tube density and tube wall thickness etc.
- Even with currently available electron bunches (being commissioned at FACET-II or FLASHForward facilities) and nanofabrication technologies, the resulting accelerating fields can reach unprecedentedly high levels to allow the demonstration of **O(GeV) energy gain in mm long tubes**. Besides the unmatched rapid particle acceleration, induced nano-modulation also **opens up controlled O(100MeV) radiation production**.

2) Future outlook and plans

- The **3D PIC simulations** supported by **3D analytical results** provide a strong tool to understand and model the tube wakefields sustained by a **quasi-neutral relativistic electron gas in ionic lattice** driven by a charged particle beam or an intense x-ray pulse. However, further understanding of ionization, long-term behavior of the tube wakefields, and many related effects need to be modeled.

- While it is quite evident from our theoretical framework that neither bulk crystal nor CNTs are suited for tube wakefield, there is need to fabricate a nanostructured tube with hundreds of nanometer internal diameter and tunable wall thickness.

- Exploration of the pathways for experimental proof-of-principle implementation of the model using facilities such as FACET-II or LCLS-II etc.

3) Take-home message

A nano wakefield accelerator which uses the **nonlinear surface crunch-in regime** driven as wakefields by a sub-micron high density charged particle beam in nanostructured tubes promises opening a wide range of novel pathways which include: **"TeV on a chip"** as well as a **"gamma-ray FEL on a chip".**

4) Highlight picture

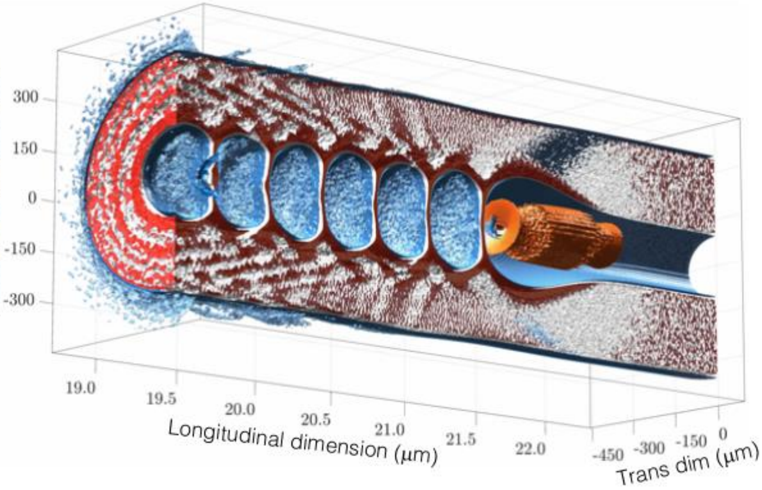


Fig. 11: 3D PIC simulation of near solid electron beam-driven crunch-in wakefield in a nanostructured tube of 200nm core diameter (unlike a CNT).

5) Relevant references

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4. Numerical investigation of beam-driven wakefields in hollow plasma channels modelled with carbon ions

A. Bonatto[1,2], G. Xia[1,2] | [1]University of Manchester, UK, [2]Cockcroft Institute, UK

1) Abstract and overview

Hollow plasma channels can be modelled as shells of heavy ions, populated by **pre-ionised electrons**. Although this model does not consider the crystalline structure of a solid, hence neglecting the properties emerging from such structure, it is adopted here as a **simplistic approximation of a carbon nanotube** (CNT). This approach allows for the investigation of beam-driven wakefields **using conventional particle-in-cell (PIC) codes**. In this work, simulation results for single hollow-plasma-channels show how such wakefields are affected by **the hollow plasma radius** and **wall thickness**. Moreover, **simulation results for CNT arrays** are also presented. Under some conditions, an effective density might enable the use of analytical results from the linear theory, developed for uniform plasmas, to describe the wakefields excited in these CNT arrays. Finally, preliminary results for laser X-ray driven wakefields, with ~TV/cm amplitudes, are presented.

2) Key results

- Existing results [1,2] for CNT beam-driven wakefields, previously simulated using a 2D cartesian geometry, were revisited with FBPIC [3], using a 2D axisymmetric geometry. The wakefield amplitudes obtained from 2D axisymmetric simulations match with analytical estimates from linear theory, while in the linear regime.
- Parameter scans performed for the CNT internal radius r_{in}, and wall thickness w, show the existence of optimal dimensions / aspect ratios to achieve higher amplitude wakefields (see Figs. 12 (a) and 12 (b), respectively).

- By using a set of concentric hollow plasma channels, a CNT array was built in a 2D axisymmetric geometry (Figs. 13 (a) and 13 (b)). Under some conditions, an effective density might enable the use of analytical results from the linear theory, developed for uniform plasmas, to describe the wakefields excited in these CNT arrays.
- The maximum wakefield amplitudes E_z^{max}, obtained from PIC simulations, are compared to values analytically obtained. It is shown (Fig. 13 (c)) that the agreement is good if the effective density n_{eff} is adopted.
- Initial simulations for laser x-ray driven wakefields show agreement with previous results [4].

3) Next steps and outlook

Although limited, the adopted model (an electron gas neutralised by a shell of carbon ions), might be useful under some conditions [4] to investigate CNT wakefields by using conventional particle-in-cell (PIC) codes, properly reproducing the wakefield amplitudes expected from analytical results. The continuation of this work consists of the following steps:

- Improve the validity of the model by constraining the transverse motion of plasma electrons within the CNT wall and its vicinities.
- Perform simulations adopting CNT dimensions and driver parameters compatible with facilities that could potentially be used to perform these experiments.
- Regarding laser x-ray driven wakefields in CNTs, we are particularly interested in performing a **parameter scan based on European X-FEL parameters**.
- Further investigate the validity of the effective density approach to describe **wakefields in CNT arrays**.

4) Highlight pictures

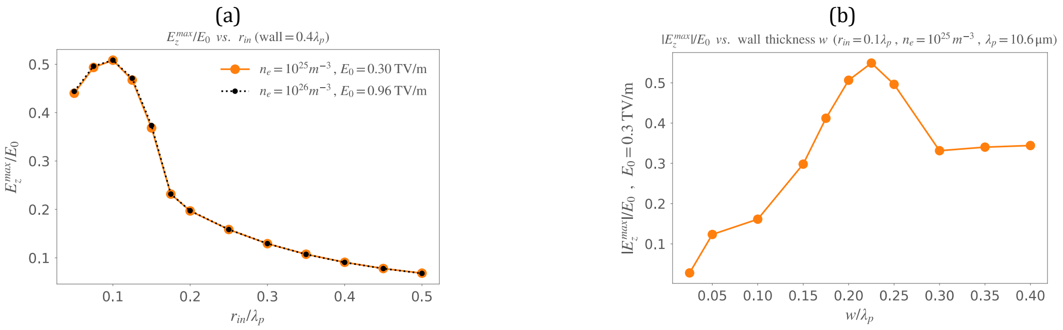

Fig. 12: Simulated CNT wakefields as a function of internal radius r_{in}, (a) and wall thickness w (b)

(a) (b) (c)

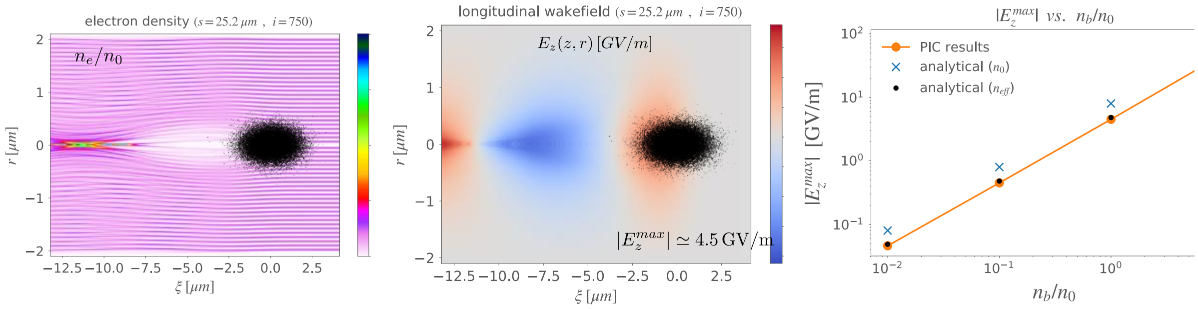

Fig. 13: Simulated electron density (a) and longitudinal wakefield in 2D CNT array modelled as hollow plasma channel (b) and comparison with analytical estimate based on an effective density (c).

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5. Studies of ultra-high gradient acceleration in carbon nanotube arrays

Aravinda Perera and Javier Resta-Lopez, Liverpool University

1) Summary:

Charged particle acceleration using **solid-state nanostructures** has attracted attention in recent years as a method of achieving ultra-high acceleration gradients of up to 1 TV/m [1-4]. The **use of carbon nanotubes (CNT) has the potential to overcome limitations found in natural crystals, such as the channeling aperture and thermo-mechanical robustness.**

This contribution presents recent preliminary PIC simulation results on beam-driven wakefield acceleration in CNT arrays. As a first approximation, we have considered a **2D multi-hollow plasma, alternating hollow channels and plasma walls (2D Fermi gas)** with density $n_e > 10^{25}\ \mathrm{m}^{-3}$. The system is excited by a driving electron bunch. For instance, assuming a short electron bunch with energy 200 MeV crossing an array of CNT with 20 nm channel radius and 40 nm plasma wall thickness, longitudinal accelerating gradients of up to 40 GV/m can be generated (Fig. 14).

2) Highlight picture

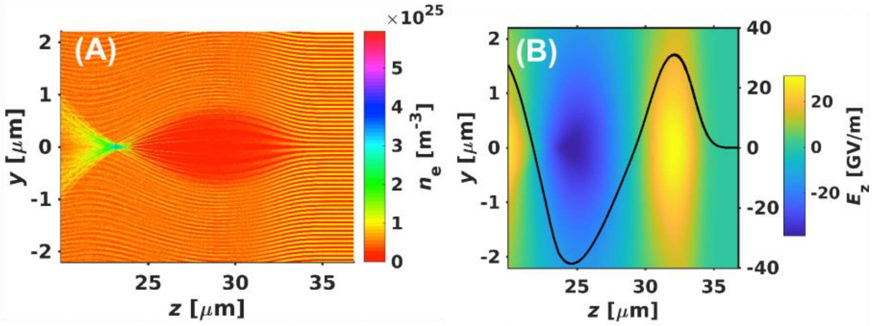

Fig. 14: (A) Plasma electron density perturbation and (B) longitudinal electric field at the propagation distance z=20 μm in the case of a strong (non-linear) driver for beam density $n_b=n_e$.

3) Next steps

- Full comprehensive study of the underlying mechanism to induce electric wakefields by both beam-driven and laser-driven excitation to be used for acceleration of charged particles.
- **Optimization studies of wall-thickness, nanotube radius, crystalline geometry and array properties.**
- Detailed experimental plan towards a **first proof-of-concept demonstration of CNT based wakefield acceleration in available test beam facilities, such as CLARA (Daresbury), CLEAR (CERN) or FLASHForward (DESY).**

4) References:

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6. Crystal-based intensive gamma-ray light sources

Andrei V. Korol and Andrey V. Solov'yov, MBN Research Center, Altenhöferallee 3, 60438 Frankfurt am Main, Germany

1) Key messages

We discuss design and practical realization of **novel gamma-ray Crystal-based Light Sources (CLS)** that can be constructed through exposure of oriented crystals (linear, bent, periodically bent) to beams of ultra relativistic charged particles. CLSs can generate radiation in the photon energy range where the technologies based on the charged particles' motion in the fields of permanent magnets become inefficient or incapable. In an exemplary case study, we estimate **intensity and brilliance of radiation emitted in a Crystalline Undulator (CU)** [1, 2] LS by available positron beams.

Figure 15 left presents peak intensities of the first (solid lines) and third (dashed lines) harmonics of CU Radiation (CUR) calculated for different positron beams. **Intensity of CUR in the photon energy range 1–10 MeV**, which is inaccessible to conventional synchrotrons, undulators and XFELs, **greatly exceeds that of laser-Compton scattering LSs (open circles)** and can be **higher than predicted in the Gamma Factory proposal to CERN** (marked with the horizontal dash-dotted line) [3].

Even more powerful radiation can be emitted by a pre-bunched beam due to the effect of 'superradiance' [5] as illustrated by Fig. 15 right. Thick curves correspond to superradiant CUR. In the photon energy range 0.1–10 MeV the brilliance of superradiant CUR by orders of magnitudes exceeds that of the spontaneous CUR emitted by random beams. Remarkable feature is that the **superradiant CUR brilliance** can not only be much higher than the spontaneous emission from the TESLA magnetic undulator, but also be **comparable to the values achievable at the XFEL facilities, which operate in much lower photon energy range.**

Though we expect that, as a rule, the highest brilliance can be reached in CU-based LSs an analysis similar to the one presented can be carried out for other types of CLS based on linear and bent crystals. CLSs provide a **low-cost alternative to conventional LSs and have enormous number of possible applications in basic sciences, technology and medicine**. CLSs could be used **for disposing of nuclear waste, as a tool for nuclear medicine, providing new imaging techniques, enhancing production of rare isotopes, initiating photo-induced nuclear reactions, non-destructive imaging of complex molecular systems** with the resolution allowing detection of the positions of the nuclei and γ-ray material diagnostics. Another possible application for the radiation emitted by electron beams (beam energy in the tens of GeV range) in CU-based LSs is **production of intensive positron beams** which are of a great current interest [6].

Support by the European Commission through the N-LIGHT Project within the H2020-MSCA-RISE-2019 call (GA 872196) and by Deutsche Forschungsgemeinschaft (Project No. 413220201) is acknowledged.

2) Highlight picture

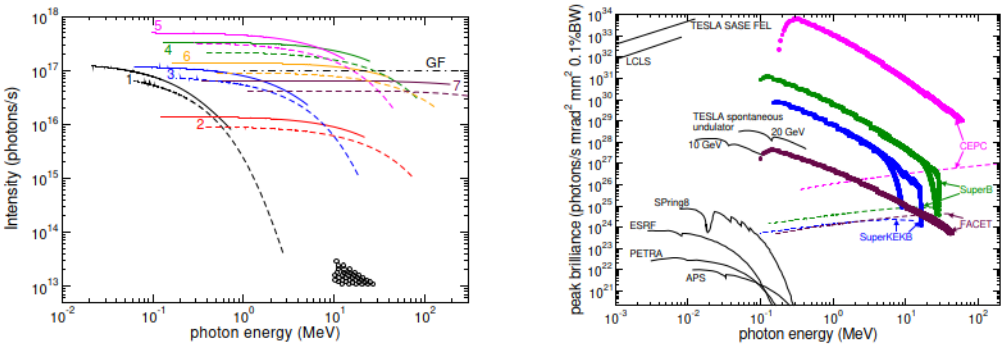

Fig. 15: Left. Peak intensity (number of photons per second) of diamond (110)-based CUs calculated for positron beams at different facilities: 1 - DAΦNE, 2 - VEPP4M, 3 - BEPC-II, 4 - SuperB, 5 - SuperKEK, 6- FACET-II, 7 - CEPC. Solid and dashed lines correspond to the emission in the first and third harmonics, respectively. Open circles indicate the data on the laser-Compton backscattering [4]. Horizontal dash-dotted line marks the intensity indicated in the Gamma Factory (GF) proposal for CERN [3]. Right. Peak brilliance of superradiant CUR (thick solid curves) and spontaneous CUR (dashed lines) calculated for the SuperKEKB, SuperB, FACET-II and CEPC positron beams versus modern synchrotrons, undulators and XFELs.

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7. Channelling and Volume Reflection in Bent Crystal

Walter Scandale, Spokesperson of UA9 Collaboration, CERN and INFN

1) Key results

Volume reflection and channeling are coherent interactions of particles entering a bent crystal at small angle with respect to the crystal planes. Concurrent incoherent effects are the so-called **de-channelling and volume capture process** and the **multiple Coulomb scattering** when the entering angle is far from being parallel to the crystal planes.

These processes where intensively investigated by the **UA9 collaboration, using primary and secondary beams produced in the North Area of the CERN-SPS**. The UA9 detector is schematically shown in Fig. 16 and a typical result in Fig. 17.

Bent crystals for applications in particle accelerators were optimized and tested. The main goal was to optimize the deflection efficiency whilst keeping the bending angle in a range of interest for implementing **crystal assisted collimation or extraction of the circulating particles.**

The publication summarizing the key results of the UA9 collaboration is [1].

2) Relevant reference

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3) Highlight pictures

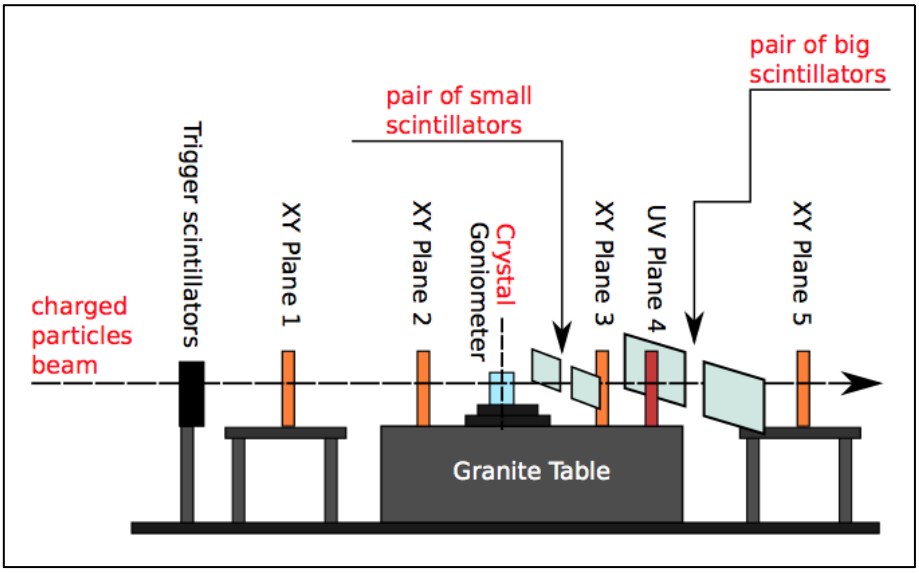

Fig. 16: Experimental layout in the SPS North-Area H8 beam line.

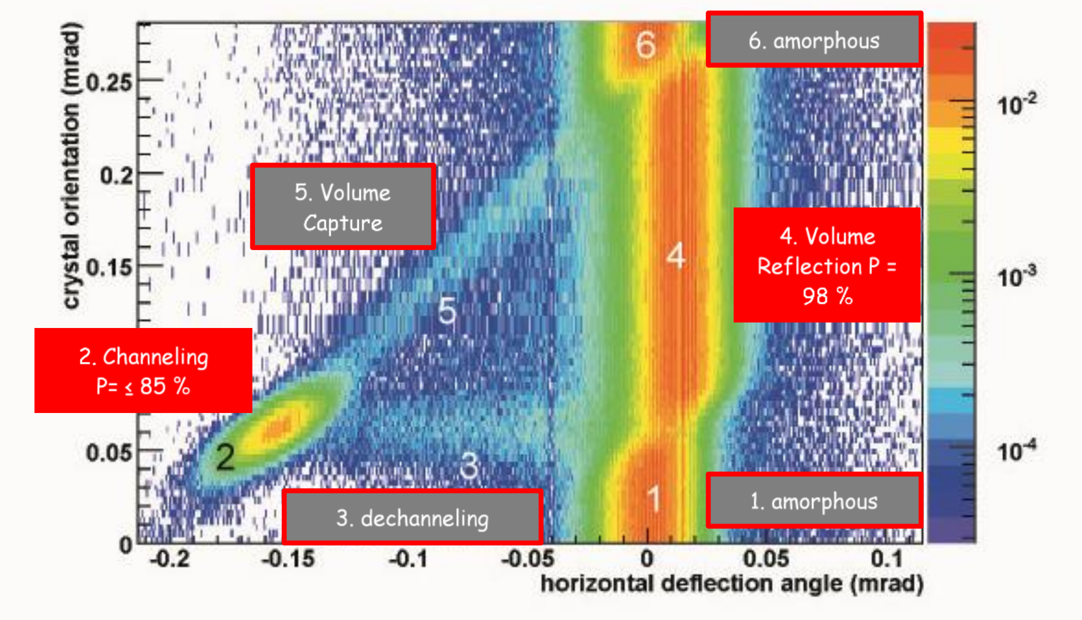

Fig. 17: Typical results of UA9 experiment in the SPS North Area.

8. Crystal-assisted collimation tests at the CERN SPS - UA9 experiment report

Roberto Rossi, CERN, on behalf of the UA9 Collaboration

1) Introduction

Crystal Channelling was discovered at the beginning of the XX century and its applications to high energy physics developed in the following years [1, 2]. Particles with a transverse momentum lower than the potential well generated by two crystalline planes are trapped in the channel, while they travel in/through the crystal [3]. A critical angle for which particles can be channeled or not, can be defined as a function of the material and of the particle energy. In channelling, the particles travel in a relatively empty space; thus, a lower rate of nuclear interactions is observed with respect to amorphous material. The fundamental idea was to bend the crystals in order to deflect coherently charged particles for beam manipulation purposes [4, 5].
The UA9 collaboration was created to study the feasibility of **a crystal collimation setup for circular machine, in particular for LHC**. The crystal collimation scheme is based on a crystal as a primary stage collimator which is able to deflect coherently the beam particles onto a single absorber. Since 2010, UA9 has studied this particular collimation scheme performing feasibility study in the SPS [6], where an experimental layout was installed and maintained up to present day.

2) Summary of Results for Crystal Collimation

The SPS experimental layout was used to asses crystal collimation performances with both protons and heavy ion beams for the first time [7, 8]. A **general reduction of losses**

was observed along the machine when crystal is oriented in channelling with respect to its amorphous orientation. In particular, the **reduction of losses was noted in the high dispersion area immediately downstream the crystal collimation setup** [9].

Other studies have been carried out during recent years in order to investigate in detail some features of the crystal collimation setup of LHC. A **comparison between absorber in tungsten (W) and carbon (C),** both available to intercept the channeled halo, was performed. This was a useful study for the LHC crystal collimation setup, given that the collimators available in that machine are based on carbon or tungsten. The experiment in SPS showed that the **carbon collimator is not suitable to properly absorb the channeled halo with both proton and ion beams**, neither at the SPS reduced energy and beam intensity with respect to LHC. For this reason, it was concluded **that for the LHC system a combination of both carbon and tungsten collimators is needed to absorb the channeled halo.**

Other observations about the effect of an upstream collimator close to the aperture of a primary crystal, were performed. The results showed that even a few σ difference behind the crystal aperture produces a degradation of the loss reduction in channeling orientation [10].

3) Future Crystal application in Circular Accelerators

During the last 5 years, UA9 has further used the SPS layout appropriately modified in order to test different schemes of beam manipulation with crystals.

Crystals can be used to extract or to assist the extraction from a circular machine. For future fix target program at CERN SPS, the extraction flux required is 4 times the actual year performance. For safety reasons, it is required to reduce by the same factor the losses in the extraction region. Crystals are proposed to be used to achieve the goal in different schemes: **shadowing of the electrostatic septum in resonant slow extraction**, **and in non-resonant extraction** with a crystal as a halo deflector toward the extraction line. The first scheme was tested in 2018 **where a crystal was used to shadow the electrostatic septum wires, showing a good reduction of losses** [11–13]. The latter is a well-known scheme [14] that was tested at SPS in 2016 [15]. The main characteristics of this layout are:

- **Non-local**: UA9 Goniometers (LSS5) and Fixed Target Extraction Line are opposite in the SPS ring.
- **Stochastic:** particle diffusion from the beam core was enhanced by means of the Transverse Adiabatic Damper (ADT, random transverse kicks).

For both schemes, studies are ongoing to optimize the layout (goniometers position, etc.) and the crystal properties for future experiment.

Another particular layout was proposed to measure some **properties of very short living particles in the framework of future collider physics** [16, 17]. Given the high equivalent magnetic field experienced by a particle travelling in a bent crystal, one can **measure the spin precession of short living particles**. To do so, in a circular machine one should separate the halo from the circulating beam in order to deflect it onto a production target. Downstream of the target, a second crystal has to be used to channel the short living particles produced, and make their spin precess. This **double crystal**

layout was prepared in 2016 and tested for the first time in 2017. The double channeled halo was successfully observed in both 2017 and 2018 [18]. The layout was upgraded in 2018 with a small tungsten target in front of the second crystal. At the end of the same year, **double channelling with a target upstream of the second crystal** was additionally observed.

4) Conclusions and Outline

In recent years, crystals have been increasingly used for different activities in hadron beam manipulation [1–3]. Bent Crystal Channelling is now considered a reliable technology for various applications in circular accelerators [4, 5]. In the UA9 framework, crystals are applied and tested with extracted beam in the SPS North Area (H8 line), in the SPS and LHC. The experimental layout in the SPS [7] has been used for crystal collimation feasibility study in Run 1 [8–10], and as test-bench in Run 2. Many results were published and applied to the LHC crystal collimation setup. In the future, the SPS crystal layout could still be used as a test-bench for the LHC collimation. It was proved that an upstream obstacle close to the crystal transverse aperture affects the channelling performance of the crystal collimation system [11]. Furthermore, it was demonstrated that a graphite collimator is not suitable to absorb the channelling halo, even in the SPS with reduced energy and beam intensity. A dedicated channeled halo absorber is needed for operational use. Crystals were additionally applied for support for beam extraction to the SPS North Area. A crystal was employed as deflector of dangerous particles during slow resonant extraction [12–14], and to deflect particles into the extraction line in a non-resonant mode [16]. A feasibility study for a double crystal channelling scheme was carried out opportunely. The double crystal channelling in a circular machine was demonstrated in the SPS [19], with and without a target upstream the second crystal. The two above referred applications are very important for future fixed target program at CERN. Optimisation studies for both extraction and double channelling are evolving, and the UA9 layout will be accordingly updated for test and experiments during the CERN LHC Run 3.

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9. Crystal shadowing for loss reduction

F.M. Velotti, L.S. Esposito, M. Fraser, B. Goddard, V. Kain, W. Scandale, CERN

1) Main results achieved

- A methodology to **reduce slow extraction losses via silicon bent crystals** has been developed: **crystal electrostatic septum (ES) shadowing**.
- First the method was proposed and tested in simulations. Then a crystal has been installed in the CERN-SPS following the proposed local scheme.
- Simulations had predicted a loss reduction by about a factor of 2, in channelling, with the local shadowing scheme. The effect was then measured in the SPS, and an **actual loss reduction of 44% was found when in channelling mode, close to the prediction**.
- Exploiting the measurements from the crystal shadowing, it was possible to estimate the electrostatic septum effective width to ~500 ??m. This value was then actually measured on the hardware.
- Beam tests have demonstrated operational stability in both channelling and volume reflection regime (here, with 20% loss reduction). **The plan is to restart in 2021 with the crystal to reduce slow extraction losses in standard operation**.
- A **non-local version of the shadowing concept has also been proposed**, exploiting the machine non-linearities. Simulation suggest that here it is **possible to achieve a factor 4 loss reduction**, using a single crystal in channelling.
- Replacing the crystal with a **Multi VR array of 5 crystals**, the loss reduction for the non-local case can be pushed by a factor 10, thanks to the high efficiency and stability of VR.
- A full hardware specification has been provided and **activities are ongoing to produce and install such a MVRA in the SPS LSS4 in 2022.**

2) A few highlights pictures

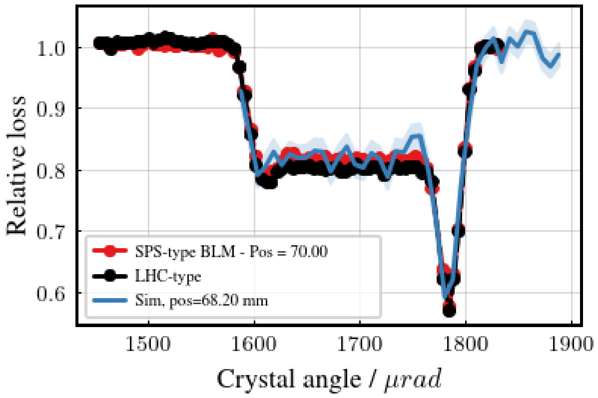

Fig. 18: Measured (black and red) and simulated (blue) angular scan in the SPS for local shadowing.

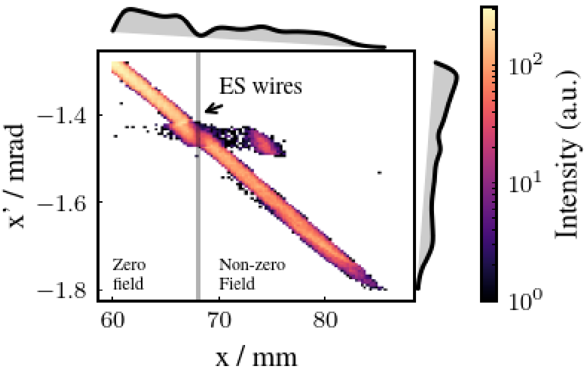

Fig. 19: Simulated phase-space at the ES for non-local shadowing using a single crystal in channelling.

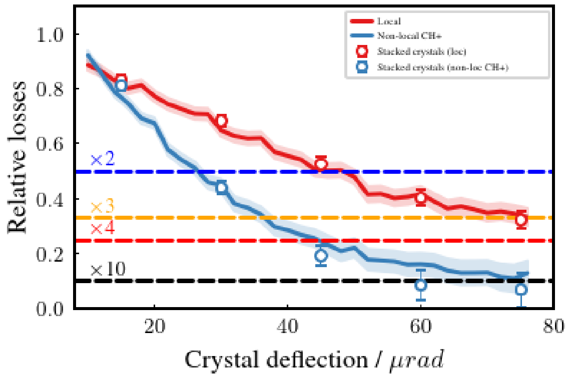

Fig. 20: Simulations of relative loss reduction as a function of number of crystals in VR. For a MVRA made of 5 crystals, a loss reduction of factor 10 can be achieved

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10. Application of crystals for beam collimation at the Large Hadron Collider

Stefano Redaelli, CERN

1) Key messages

- This contribution presented the status of the R&D on crystal collimation of high-energy hadron beams for applications for the Large Hadron Collider (LHC) and its High-Luminosity upgrade project (HL-LHC). **The benefit of crystal collimation was demonstrated through several tests during the LHC Run 2 (2015-2018) that uses a crystal collimation test stand installed in the LHC betatron cleaning insertion (IR7)**. The system consists of 4 bent crystals, one per beam and per plane (horizontal and vertical), which enables complete collimation tests.
- Overall, the experimental results are very promising. Channeling with bent crystal was demonstrated for proton and ion beam at the unprecedented beam energy of 6.5 Z TeV and a solid demonstration of the benefits that this technique can bring for ion beam cleaning, was demonstrated. It was shown that gains up to a factor 7 for collimation cleaning can be achieved compared to the present system. Following these promising results**, crystal collimation has been made part of the HL-LHC upgrade baseline.**
- In addition to beam tests, **crystals were also used operationally for the first time in a special LHC physics run at 450 GeV,** demonstrating a significant suppression of background for the forward physics experiment TOTEM.
- Studies for future applications include the **prospect to use bent crystals for a fixed-target physics program at the LHC**: a crystal might be used to separate the halo from the high-intensity beam and send it to a target upstream of an LHC experiment. This promising study is being pursued as a part of the Physics Beyond Colliders program at CERN.

2) Relevant link

(1) HL-LHC Crystal Collimation Day https://indico.cern.ch/event/752062>

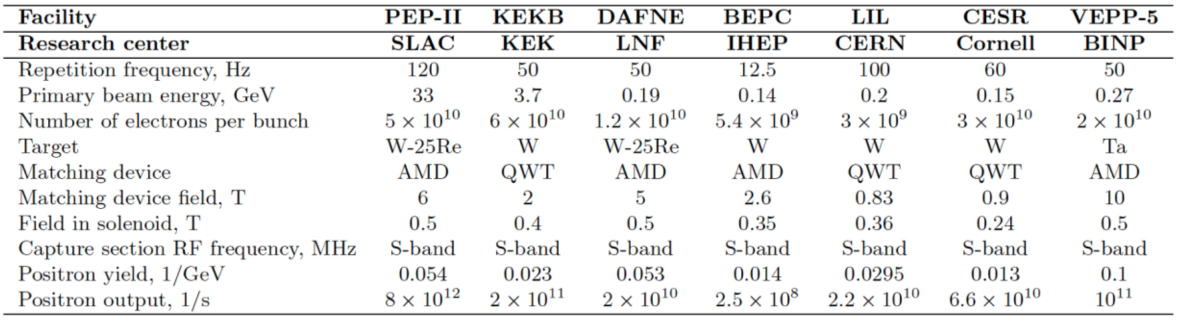
11. **Crystal-assisted positron source**

Iryna Chaikovska, IJCLab

1) Key messages

Positron sources are a key element of past, present and future colliders. This is essentially due to the very high beam intensity and low emittance required to achieve a high luminosity (e.g. ILC, CLIC, SuperKEKB, FCC-ee). In such a way, increasing interest in high-intensity and low-emittance positron beams for electron-positron colliders gave rise to different approaches.
In this framework, recent investigations led to the concept of a hybrid scheme based on a relatively new kind of positron source using the intense photon production by high energy (some GeV) electrons channeled along a crystal axis (i.e. channelling radiation). Thus, electrons propagating in the crystal at glancing angles to the axes are channeled and emit a large number of soft photons due to the collective action of a large number of nuclei [1]. Several experiments at CERN and KEK, including a proof-of-principle experiment in Orsay, have been performed to study the performance of the **hybrid target** [2-4].

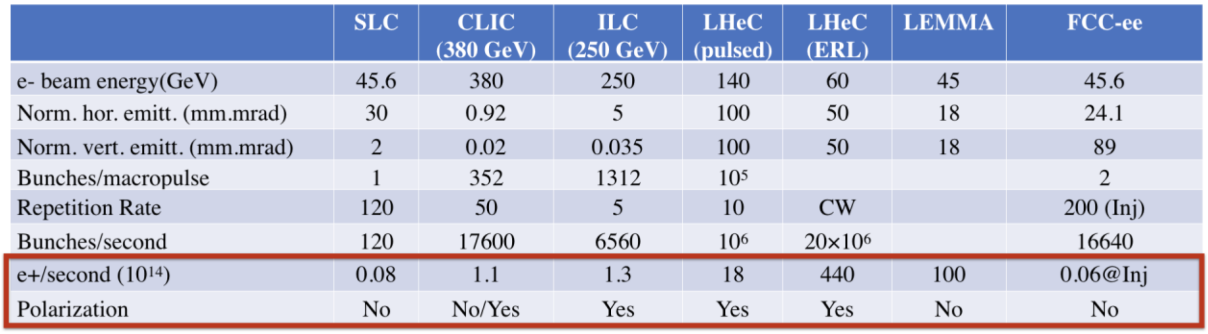
Table 1 summarizes the main parameters for the positron sources of some past and present colliders. Almost all these sources were integrated in the injector complex of circular lepton colliders. Thus, performances achieved in bunch population are of the order of few 1e10 e+/bunch and in average current lower than 1 μA except for the PEPII/SLC case ~1 μA [5]. The positron source of the SLC used the conventional target, where the positrons were obtained with a 33 GeV incident electron beam on a $6X_0$ thick tungsten target. At present, the positron production rate obtained at the SLC is still considered the world record for the existing accelerators (about 1 Ne^+/Ne^- extracted from the DR [6]).



Facility	**PEP-II**	**KEKB**	**DAFNE**	**BEPC**	**LIL**	**CESR**	**VEPP-5**
Research center	**SLAC**	**KEK**	**LNF**	**IHEP**	**CERN**	**Cornell**	**BINP**
Repetition frequency, Hz	120	50	50	12.5	100	60	50
Primary beam energy, GeV	33	3.7	0.19	0.14	0.2	0.15	0.27
Number of electrons per bunch	5×10^{10}	6×10^{10}	1.2×10^{10}	5.4×10^{9}	3×10^{9}	3×10^{10}	2×10^{10}
Target	W-25Re	W	W-25Re	W	W	W	Ta
Matching device	AMD	QWT	AMD	AMD	QWT	QWT	AMD
Matching device field, T	6	2	5	2.6	0.83	0.9	10
Field in solenoid, T	0.5	0.4	0.5	0.35	0.36	0.24	0.5
Capture section RF frequency, MHz	S-band	S-band	S-band	S-band	S-band	S-band	S-band
Positron yield, 1/GeV	0.054	0.023	0.053	0.014	0.0295	0.013	0.1
Positron output, 1/s	8×10^{12}	2×10^{11}	2×10^{10}	2.5×10^{8}	2.2×10^{10}	6.6×10^{10}	10^{11}

Table 1: Positron source parameters [5].

On the other hand, the intensity required for the positron source at the future colliders like CLIC, ILC or LHeC (see Table 2) is a few orders of magnitude higher than that delivered by any existing facility. The hybrid scheme for positron production is a very **promising solution offering lower values of the power deposited in the target-converter and Peak Energy Deposition Density**.



	SLC	CLIC (380 GeV)	ILC (250 GeV)	LHeC (pulsed)	LHeC (ERL)	LEMMA	FCC-ee
e- beam energy(GeV)	45.6	380	250	140	60	45	45.6
Norm. hor. emitt. (mm.mrad)	30	0.92	5	100	50	18	24.1
Norm. vert. emitt. (mm.mrad)	2	0.02	0.035	100	50	18	89
Bunches/macropulse	1	352	1312	10^5			2
Repetition Rate	120	50	5	10	CW		200 (Inj)
Bunches/second	120	17600	6560	10^6	20×10^6		16640
e+/second (10^{14})	0.08	1.1	1.3	18	440	100	0.06@Inj
Polarization	No	No/Yes	Yes	Yes	Yes	No	No

Table 2: Future collider project challenges.

In such a way, the required beam intensities and emittances are imposing a true technological challenge for the positron source design (target design, cooling systems, capture optics, power dissipated on the structures, remote handling/target removal engineering design, etc.). Further investigations, technological R&D and experimental tests are mandatory to ensure adequate performance and reliability of this source.

2) Outlook

Several of this workshop's contributions have a synergy with the field of positron production, bringing new ideas for possible schemes.

- **Investigate other sources of photons (e.g. crystalline undulators, etc.)** to be used for positron production in collaboration with the experts in the field. In this context, several novel solutions for positron sources are also planned to be explored in the future ARIES Innovation Pilot (I.FAST) project.

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12. Channelling radiation and related phenomena in straight and bent crystals as a tool for intense e.m. radiation generation

Laura Bandiera, INFN Sezione di Ferrara

1) Key messages

Enhancement of electromagnetic radiation emitted by charged particles in crystals have been known since the 60s and used for the generation of **linearly polarized γ-beams through coherent bremsstrahlung.**

Here, we report on a series of **experiments carried out at the MAinzer MIkrotron (MAMI)** with the aim of investigating the electromagnetic radiation generated by 855 MeV electrons in thin bent crystals. Such study allows one to investigate the influence of the crystalline curvature on the radiation emitted by **sub-GeV electrons in a bent crystal** and the possible application of this kind of radiation. Firstly, the deflecting power [1] and the **radiation emitted [2] by electrons via planar channeling and volume reflection (VR) in a 30 µm-thick bent Si crystal** has been investigated. The **spectral intensity was much more intense than for an equivalent amorphous material, and peaked in the MeV range** (see Fig. 21). Differently from a straight crystal, also for an incidence angle larger than the Lindhard angle, the spectral intensity remains nearly as high as for channeling. This is due to VR for which the intensity remains high at a large incidence angle over the whole angular acceptance, equal to the bending angle of the crystal.

In a second series of experimental tests, we investigated the **steering and radiation emission capability of planar channeling and VR vs. the curvature radius** for 15 um-thick Si and Ge crystals [3]. **For silicon, the channeling efficiency exceeds 35%, a record for negatively charged particles** (see Fig. 22). The experimental results have been well reproduced by Monte Carlo simulations based on the Baier Katkov quasi-classical method [4,5] (see Fig. 21).

The presented experimental and simulation results are relevant for crystal-based beam steering/extraction from sub-GeV/GeV electron accelerators, as well as for innovative **intense X- and gamma-radiation sources** based on bent and periodically bent crystals, i.e. crystalline undulators. Furthermore, the developed code [4,5] can be adapted to study the possibility to exploit **channeling radiation in high-Z straight crystals for the realization of a positron source for future colliders**.

2) A few highlights pictures

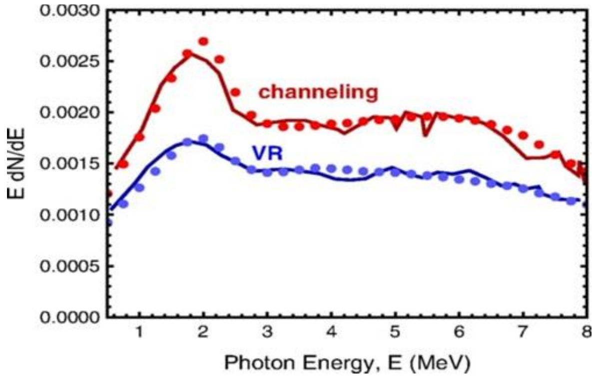

Fig. 21: Channelling and VR radiation emitted by 855 MeV electrons in a 30 µm bent Si crystal (lines experiment [23], dots simulations [5]).

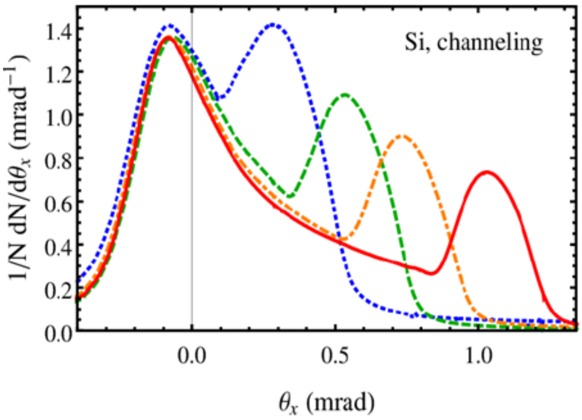

Fig. 22: Deflected 855 MeV e- via channelling in a bent Si crystal 15 um thick, bent at different radii [3].

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13. Silicon crystals for steering of high-intensity particle beams at ultra-high energy accelerators

A. Mazzolari, INFN Sezione di Ferrara, Via Saragat 1, 44122 Ferrara, Italy

1) Key messages

In a crystal, atoms occupy well defined positions in the crystal lattice, resulting in a target with a regular atom structure made of planes and axes of atoms. Exploiting this property, coherent scattering of electromagnetic radiation of particle beams by a crystal occurs, as they are reciprocally properly oriented.

Various experimental campaigns related to the studies of interactions between charged particle beams and crystals took place in the ’80 in Russian laboratories, and were followed by further experiments at worldwide particle accelerators such as Tevatron [1], the Relativistic Heavy Ion Collider [2], the Super Proton Synchrotron[3, 4], and Large Hadron Collider at CERN [5]. Experimental results and simulation models show that crystals might play a relevant role for the development of new generations of high-energy and high-intensity particle accelerators, and might disclose innovative possibilities at existing ones.

We report the **most advanced manufacturing techniques of crystals suitable for operations at ultra-high energy and ultra-high intensity particle accelerators**, showing as an example of potential application the collimation of the particle beam circulating in the Large Hadron Collider at CERN in the frame of the High Luminosity Large Hadron Collider project [6, 7].

2) References

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14. Nanomodulated electron beams via electron diffraction and possible use in accelerators

Emilio A. Nanni, SLAC

1) Key messages

We presented a powerful method for the **generation of relativistic electron beams with current modulation on the nanometer scale** [1]. The current modulation is produced by **diffracting relativistic electrons in single crystal silicon which has been patterned to have a periodic variation in longitudinal thickness**. The thickness is tuned to create regions where the electron beam is either strongly diffracted into a single Bragg peak or through either multiple or no scattering the electron beam is transmitted at its incident angle. This transverse density modulation is selected as either a bright or dark field image and transported by accelerating the diffracted beam and imaging the crystal structure, then **transferring the image into the temporal dimension via emittance exchange**. The modulation period can be tuned by adjusting electron optics after diffraction [2]. This tunable longitudinal modulation can have a coherent nanometer-scale period**, enabling production of coherent x-rays from a source based**

on inverse Compton scattering at low-energy or with undulator radiation at high energy. Electron beam simulations from cathode emission through diffraction, acceleration and image formation with variable magnification indicate that the beams structure can be preserved and manipulated to tune wavelength. Early experimental results demonstrating high contrast modulation [3,4,5] have motivated ongoing efforts to develop an accelerator facility to test these concepts [6].

2) A few highlight pictures

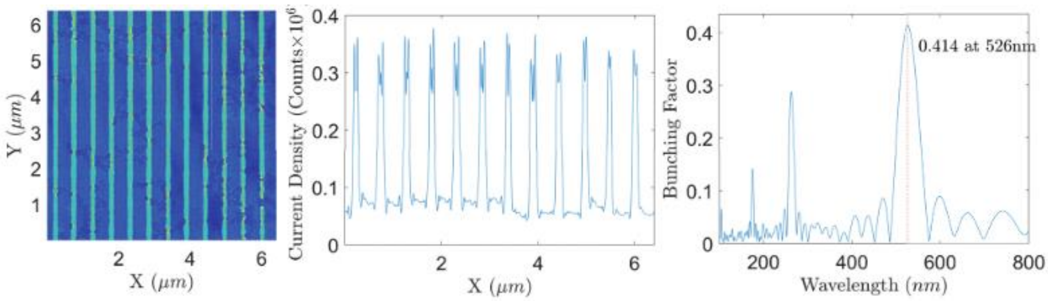

Fig. 23: (left) Transmission electron micrograph bright-field image of Si grating, with (middle) current density and (right) bunching factor [5].

3) References

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15. ACHIP - First measurements toward laser driven acceleration inside dielectric structures at the SwissFEL

Rasmus Ischebeck, PSI

1) Key messages

The Accelerator-on-a-Chip International Program (ACHIP) is an international collaboration, with the goal to pursue research on **laser-driven particle acceleration in dielectric structures**, and to develop paths towards applications of this technology. Recent achievements with non-relativistic electrons include the **first experiments with an on-chip structure designed using a photonic inverse-design approach** [1], as well as the net acceleration of non-relativistic electrons [2-3]. The achievable accelerating gradient is limited by the damage threshold of the structures. The **study of laser-induced damage** is presented in [4]. Energy gain is only one aspect of particle accelerators. Of equal importance for a practical application is the **transverse and longitudinal stability** of the accelerated bunches. Simulations of electron beam dynamics at low energies suggest a method to achieve focusing of the electron beam along several thousand accelerator periods [5].

While initial work performed in the ACHIP collaboration was basic accelerator research, we have recently started evaluating possible **near-term applications of dielectric structures in the generation and shaping of electron beams**. These include the **generation of radiation, electron diffraction [6], and shaping of beams from conventional accelerators** [6]. Applications with a longer horizon, such as accelerators for a linear collider at the energy frontier, are evaluated by the Advanced Linear Collider Study Group ALEGRO [8].

2) References

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3) A highlight picture

Fig. 24: Inside view of the ACHIP experimental chamber in SwissFEL. Permanent magnet quadrupoles are used to focus the electron beam, and the accelerating structure can be mounted on a hexapod.

Further reading

Int. J. Mod. Phys. A has published a series of articles (about 18) on the subject of crystal and CNT acceleration, starting with **Int. J. Mod. Phys. A34, 1943001** (2019). Rolling the last number 01 (in 1943001) to other numbers, e.g., between 01 to 18, the other articles appear.
Recently, an entire book was published on this subject: **Beam Acceleration in Crystals and Nanostructures**, Eds. S. Chattopadhay, G. Mourou, V. Shiltsev, T. Tajima (World Scientific, Singapore, 2020).

Workshop photo snapshots

Fig. 25: Y. Shin (left) and A. Sahai (right) presenting intriguing results on CNT/fibre accelerators.

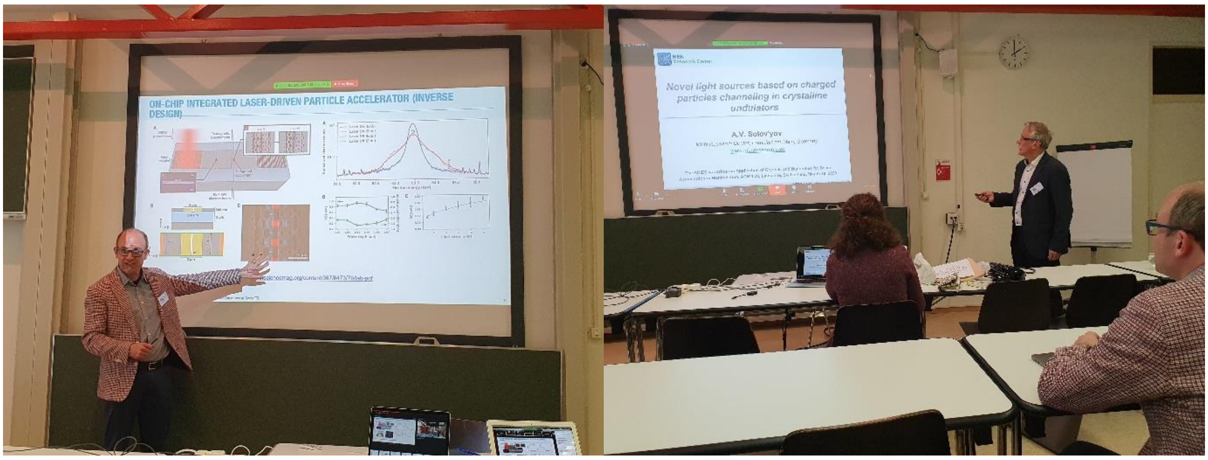

Fig. 26: R. Ischebeck (left) and A. Solov'yov (right) discussing details of dielectric acceleration structures and the next generation of compact crystal-based light sources.

Fig. 27: A. Solov'yov (left) and F. Velotti (right) highlighting advances on crystalline undulators and crystal shadowing.

Fig. 28: A. Perera, in collaboration with J. Resta Lopez, discussing simulations and experimental plans for CNT acceleration (left) and presenting his poster to T. Pieloni (right).