Crystals as Medical accelerator Extraction Devices – The CrysMED project

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Overview

The CrysMED project focuses on to studying the **application of bent crystal in medical accelerators**

Proposal:

- Prove channeling with ion beams in the range of hundreds of MeV/u
- Conceptual design of an extraction layout assisted by bent crystal for medical synchrotron

Outlook

- Motivations
- The CrysMED project
- Experimental layout
- Final outcome
- Project details
- Conclusions

Motivations

Medical synchrotron and beam in the CNAO facility

- The CNAO facility [28-30]
  - One of the six hadrontherapy centers in the world to use both proton and carbon ions for patient treatments
  - The synchrotron is designed to accelerate up to 400 MeV/u for $^{12}C^{6+}$ ions and up to 250 MeV for protons [28-30]

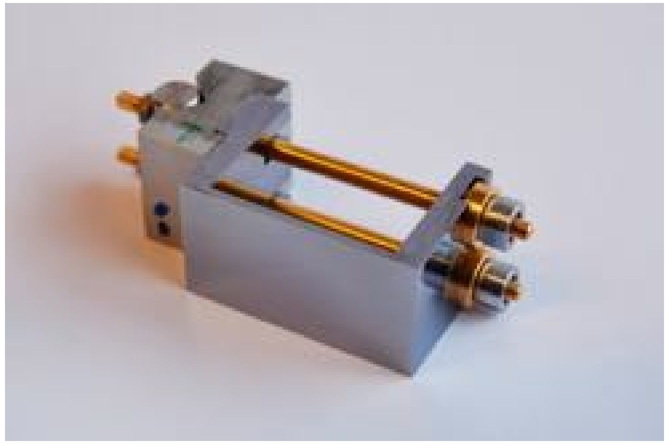
- The beam is delivered [31] to the treatment room using slow resonant extraction
  - Driven 3rd order resonance (sextupoles)
  - Betatron core to drive beam into unstable region
  - Electrostatic septum needed to separate the extracted beam
  - Extraction over times of the order of 1 second
  - Extraction efficiency of ≈ 50 %

Crystals for beam manipulation

- Crystals could improve the extraction in medical synchrotron
  - No longer required: extraction sextupoles, electrostatic septum and betatron core ⇛ simplified machine layout and optics
    - Cost and space reduction ⇛ cheaper accelerator design and more reliable operation
  - Extracted beam tunability ⇛ extracted beam is gaussian in both transverse planes
    - Reducing emittance and asymmetry

- Crystal assisted extraction is proved or proposed in several HEP accelerators [20-24]
  - Medical accelerators beam energies are lower and the rings are much more compact
  - Requires crystals with large bending (O(mrad))

- A dedicated experiment is needed to assess the crystal channeling and give inputs for the development of a possible extraction layout
  - Crystals are available and have been tested at higher energy
    - Allow the investigation of a less know channeling regime
    - Scaling factor for channeling efficiency with these beam energies

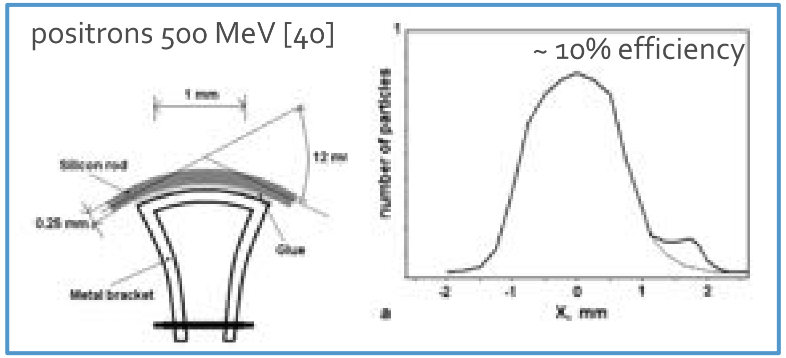


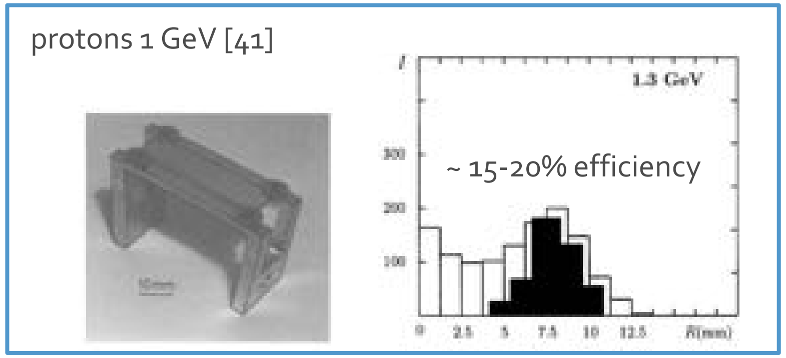
The CrysMED project

The CrysMED project

Objectives:

- ❑ channeling of low energy ion beams
- ❑ channeling efficiency assessment





- No dedicated observations with ions at this energy range
  - Previous low energy experiments with both positrons (500 MeV [40]) and protons (1 GeV [41])
- An efficiency level of a few tens % is suitable for extraction
  - Multi-pass effects [35,36,24,20] would improve the channeling efficiency in the ring
- Benchmark for crystal channeling simulation [33, 34]

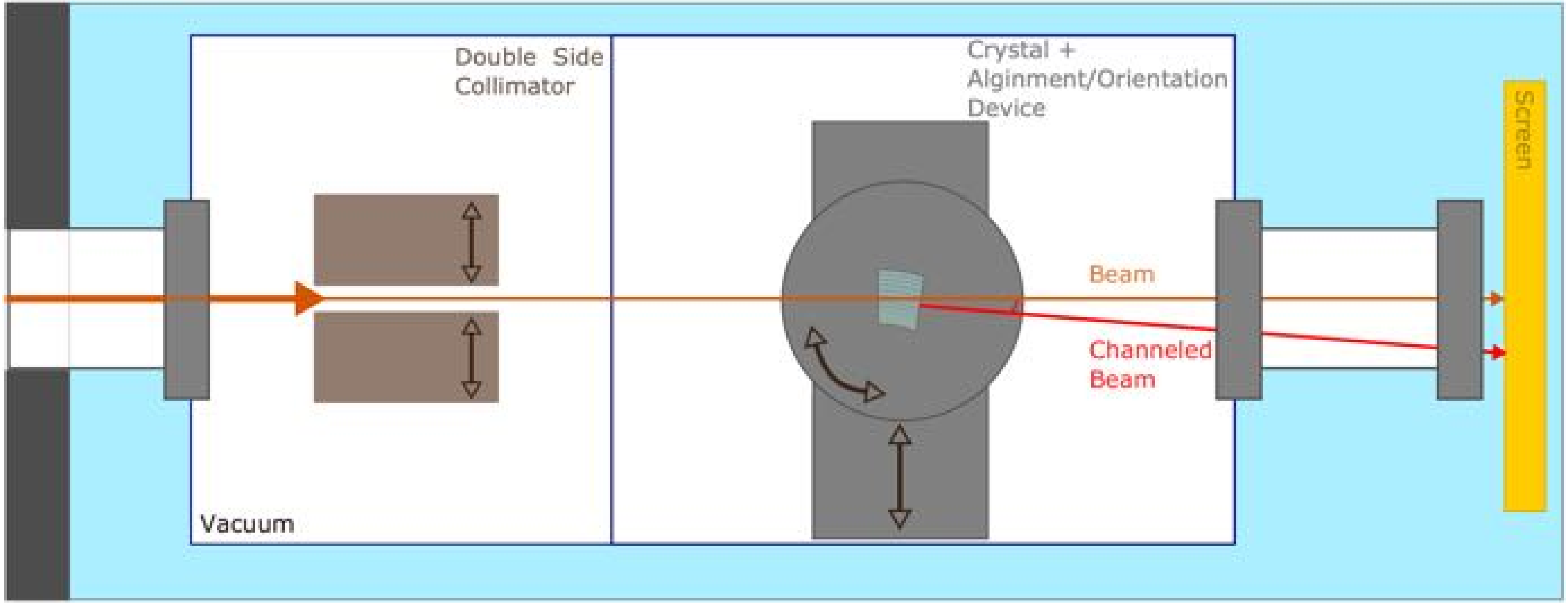
Outcome:

- ❑ development of a new conceptual design for a hadrontherapy synchrotron extraction assisted by bent crystals

Experimental layout

The CrysMED project experimental layout

A compact layout for differential measurement of crystal efficiency will be employed



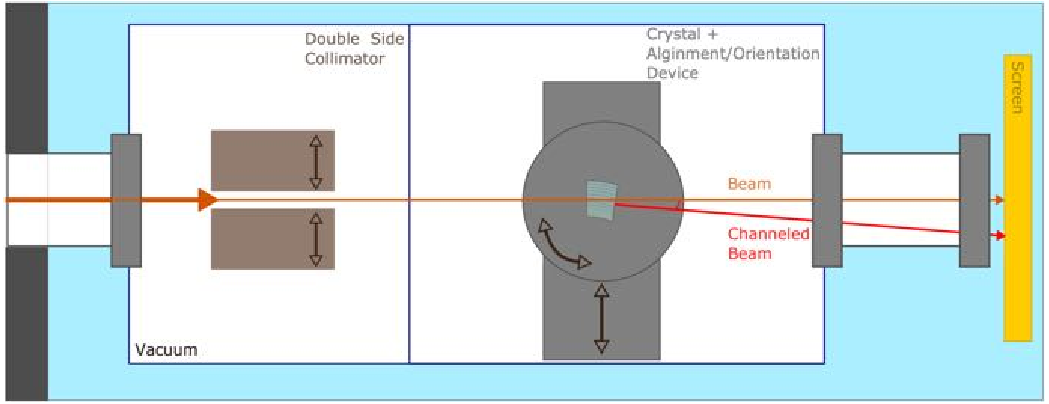
CNAO has offered the access to the experimental room and logistic and technical support

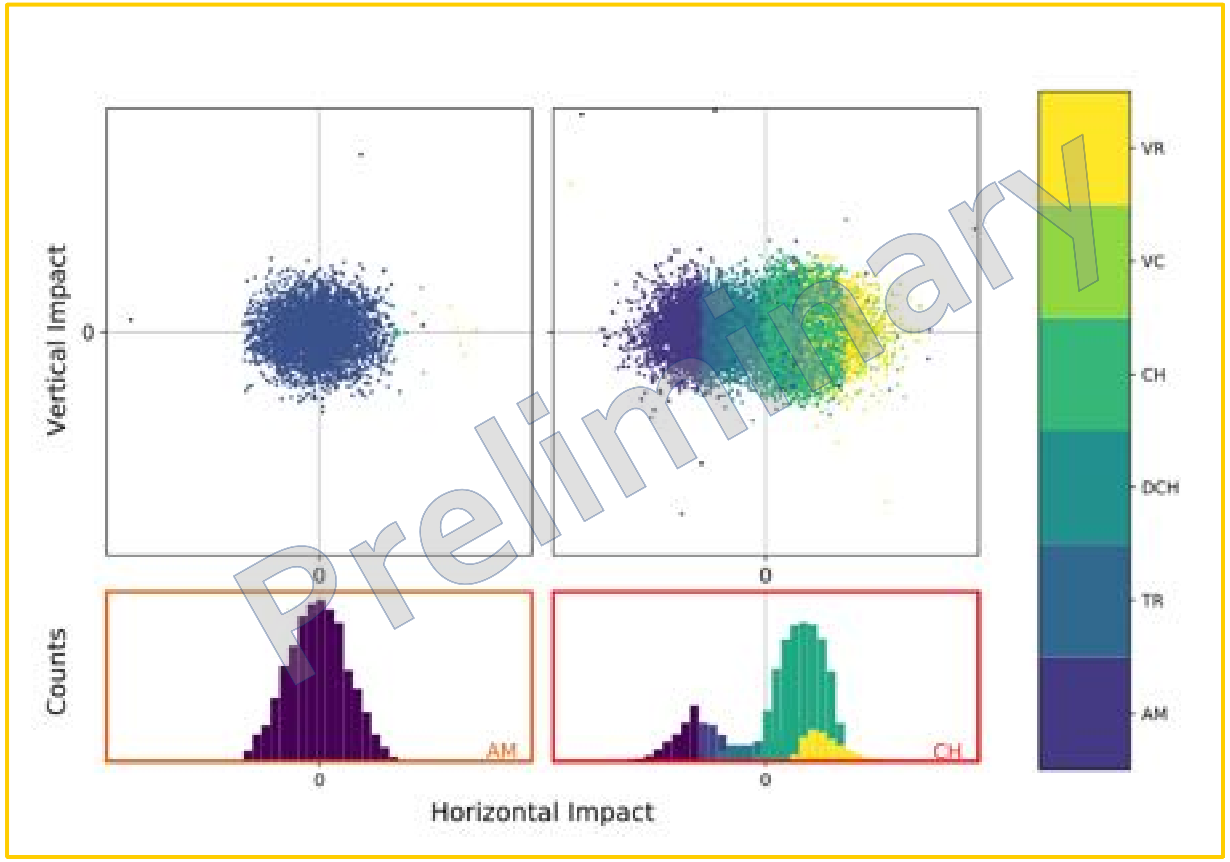
A complete tracker is not considered suitable ⇛ low angular resolution

- Material budget not negligible with this beam species and energy
- Short space available

The measurements

- The goal: Observe the channeling and evaluate its efficiency by means of differential measurement
  - The distribution downstream of crystals will be sampled orienting it both in channeling and in amorphous



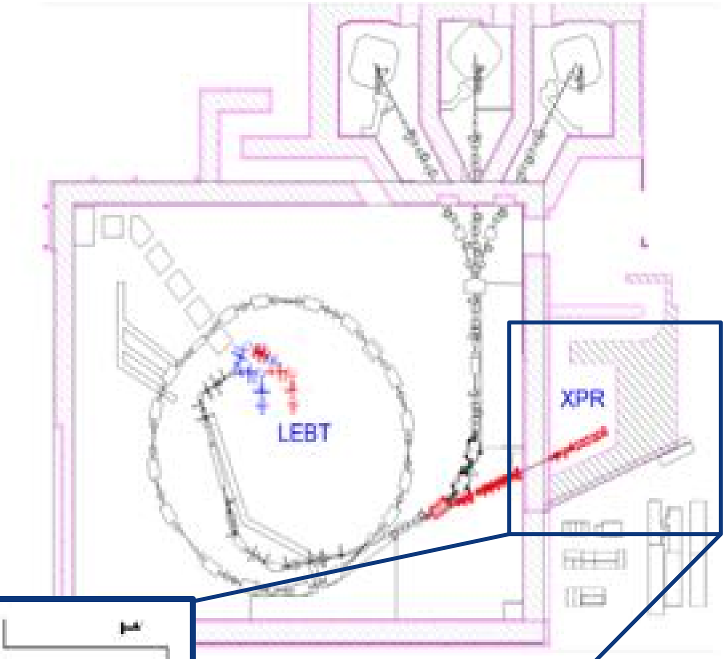


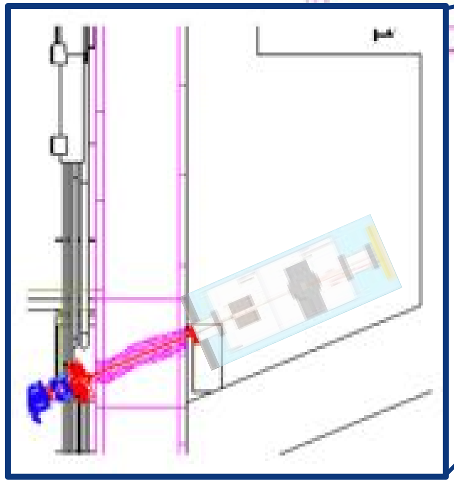
The CNAO Experimental Room (XPR)

- The CNAO XPR [32] offers multiple possible configurations with a maximum space of 5 m
  - This is when scanning magnets are removed
  - Beam intensity for C 2.8e8 p/s, tunable in the range 10^6-10^8 p/spill
  - The delivered beam covers a spot of ~1 cm^2 with a divergence of about 1 mrad

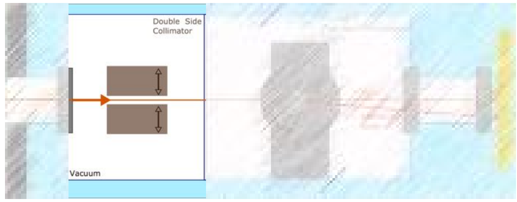
- To conform the impact distribution a collimator is proposed to shape the beam
  - Matching the crystal dimension [~1 mm]
  - Reducing the divergence within the critical angle range [200-300 μrad]

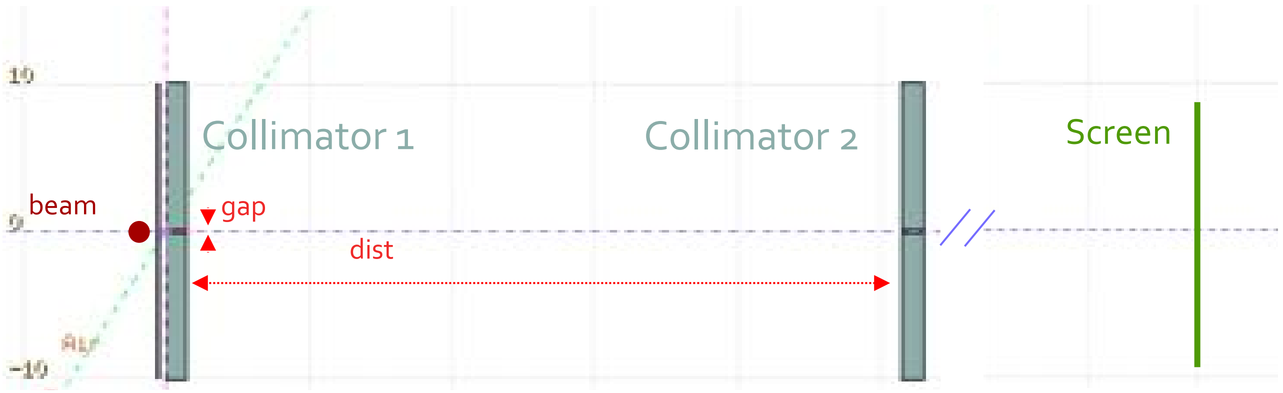
Beam Species	Energy	Critical Angle
$^{12}C^{6+}$	400 MeV/u	223.6 μrad
$^{12}C^{6+}$	150 MeV/u	365.1 μrad
p	250 MeV	400.0 μrad





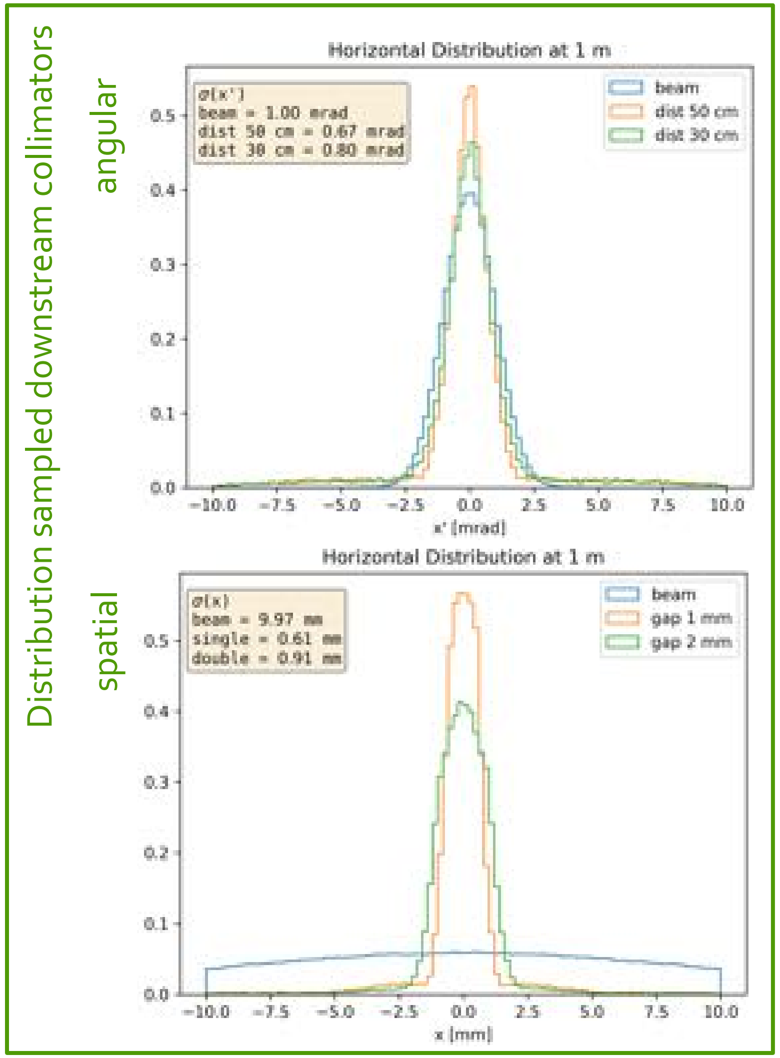
Beam shaping simulations – preliminary studies



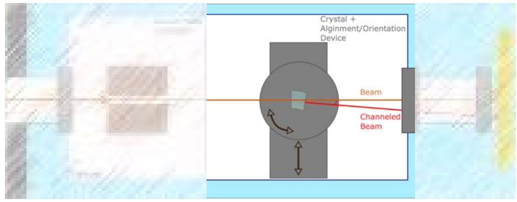


- Preliminary simulations of the best collimator layout
  - Beam divergence ⇛ two set of jaws at a distance (> 50cm)
  - Beam spot ⇛ small gap (~1mm)
  - Secondary products pollution ⇛ materials + short length + vacuum tank

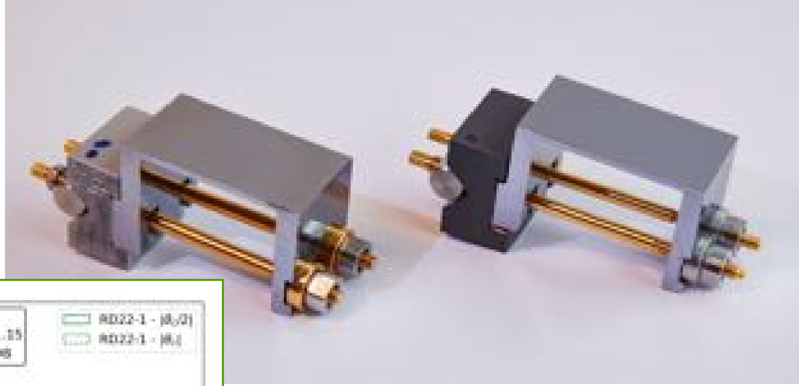
- These studies will generate insights to finalize the design of the collimator

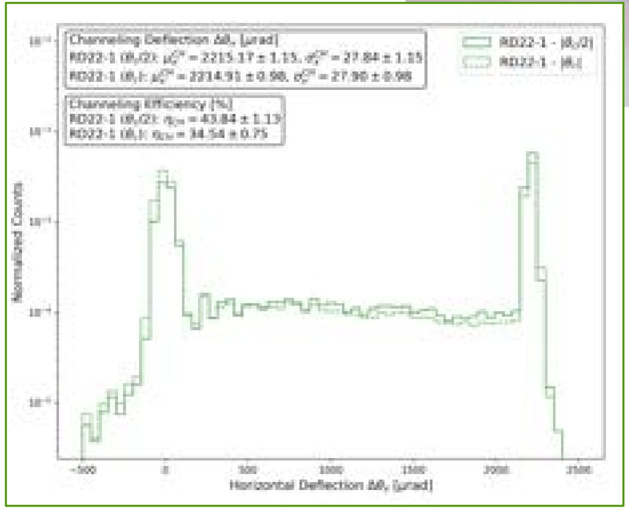


The crystal/goniometer assembly



- Crystals are in-kind contribution from the UA9 collaboration
  - 25 or 40 mm length along the beam
  - 1-2 mrad adjustable bending angle [12]





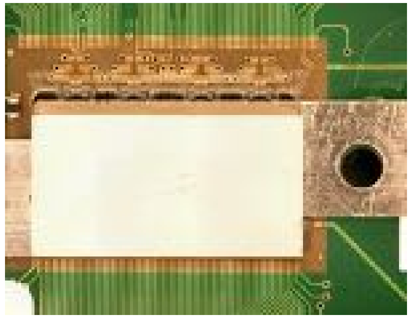
- Goniometer to align the crystal to be purchased externally
  - Two-stage goniometer
    - Vacuum compatible (10^{-9} hPa)
    - Linear stage [0.1 μm rep.]
    - Rotational stages [20 μrad rep.]
  - Hexapod
    - More compact
    - Better angular resolution [2 μrad rep.]
    - Vacuum compatible (10^{-6} hPa)
    - More expansive (controller)

N.B. After decommissioning, adapting the vacuum system will allow reusing the goniometer for other experimental usages.

The detector

A high granularity detector is required

- Pixel sensor with ITkPix front-end (ATLAS) is the baseline solution, in-kind contribution from the INFN Milano
  - Larger active area (20x20 mm²)
    - Possible to have a quad sensor (39x40 mm²)
  - Smaller pixel pitch (50x50 μm²)
    - Also available with 25x100 μm² pixels
  - High rate capability 10^9 hit/cm²/s
  - Will also push the development of the sensor for applications other than HEP



- TimePix3 as a backup plan
  - Smaller active area (14x14 mm²)
  - Larger pixel pitch (55x55 μm²)
  - Off-the-shelf – ready to use for online alignments, beam parameter checks, etc.
  - Possible to acquire MediPix4 sensor trough MEDIPIX4 INFN

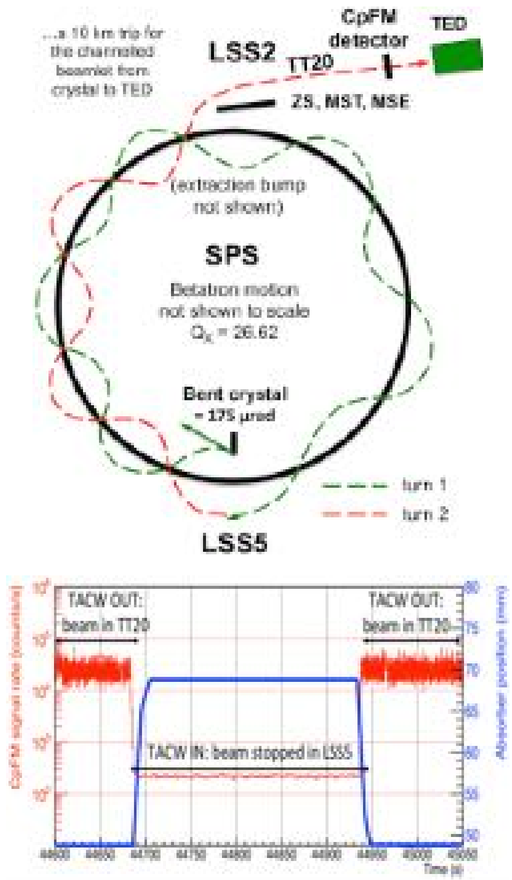
The outcome

The outcome

Once the project concludes on the crystal efficiency with low energy ions, it will be possible to design a crystal assisted extraction scheme

- Two schemes are pre-selected and will be studied in details
  1. In the slow extraction scheme, the crystal is used to deflect particles over the wire of the electrostatic septum (used in IHEP Protvino [21] – p @ 70 GeV)
  2. Direct extraction of the beam deflected by a bent crystal (studied in CERN SPS [23] – p @ 400 GeV)
- The latter scheme is of particular interest
  - The beam is driven on the crystal with a transverse RF exciter or with dipole magnet
  - It is possible to <u>synchronize the beam extraction with external signals</u> such as the breathing of an irradiated patient

Non-resonant extraction in CERN SPS [23]



Project details

Synergies and Impacts

Synergies:

- UA9 Collaboration – interested in the new developments for crystal-particle interaction at low energy
  - Crystals in-kind contribution
- CNAO – interested in project results and development of conceptual design
  - Granted access to the experimental room and logistic and technical support
- MedAustron (project observer) – interested in results for future applications at their facility
- CERN – NIMMS (Next Ion Medical Machine Study) could as well profit of the project outcome
- INFN – with the testing and development of detector technologies with low energy beams
  - The project will rely on in-kind contribution and technical support from the INFN Milano for ITkPix and the DAQ system
  - MEDIPIX4 INFN has been consulted and expressed interest in the proposal
- CSN5 – SHERPA project have expressed interest for the potential synergies

Impacts:

- Design of hadrontherapy machines – Crystal assisted extraction will make the design of new hadrontherapy synchrotrons more compact, less expensive and therefore more feasible
- New regime for crystal applications – Project outcomes (proved channeling) can lead to the development of other applications such as the beam delivery up to the patient treatment room
- Significance at the EU level – The project core topics in adaptive particle therapy are highly relevant for the new 2021-2027 Horizon Europe program
- Interdisciplinary research for medical application
- Detector development
- Advanced computation and modelling
- Scientific publications
- Technology transfer
- Possible patents in different fields

Project team

Three groups together: INFN Milano, INFN Roma I, and CNAO

With significant experience in

- ✓ Accelerator physics
- ✓ Crystal channeling
- ✓ Beam instrumentation and detectors
- ✓ Beam-matter interaction
- ✓ Simulations (interaction/tracking)
- ✓ Project management

Participant name	Unit	Role	Age	Sex	FTE
Roberto Rossi	Milano	Project Leader	33	M	1.0
Attilio Andreazza	Milano	Unit Research Lead	54	M	0.2
Saverio D'Auria	Milano	Staff Researcher	56	M	0.2
Marco Pullia	CNAO	Unit Research Lead	58	M	0.1
Alessio Mereghetti	CNAO	Lab Staff Researcher	38	M	0.1
Alessandro Variola	Roma	Unit Research Lead	55	M	0.5
Walter Scandale (Associate)	Roma	Senior Researcher	76	M	0.4
Matteo Bauce	Roma	Associate Researcher	35	M	0.1
Francesco Collamati	Roma	Associate Researcher	34	M	0.2
Paolo Valente	Roma	Staff Researcher	52	M	0.2
Young Researcher*	Milano	(Under)Graduate Student	~28		0.6
Averages & Percentages			49.1	0 %	
Total					3.0

*Record not included in the averages and total.

N.B. Three CNAO researchers expressed interest in joining the team, and they'll be included once the project starts

Work Packages, Milestones/Deliverable and Timeline

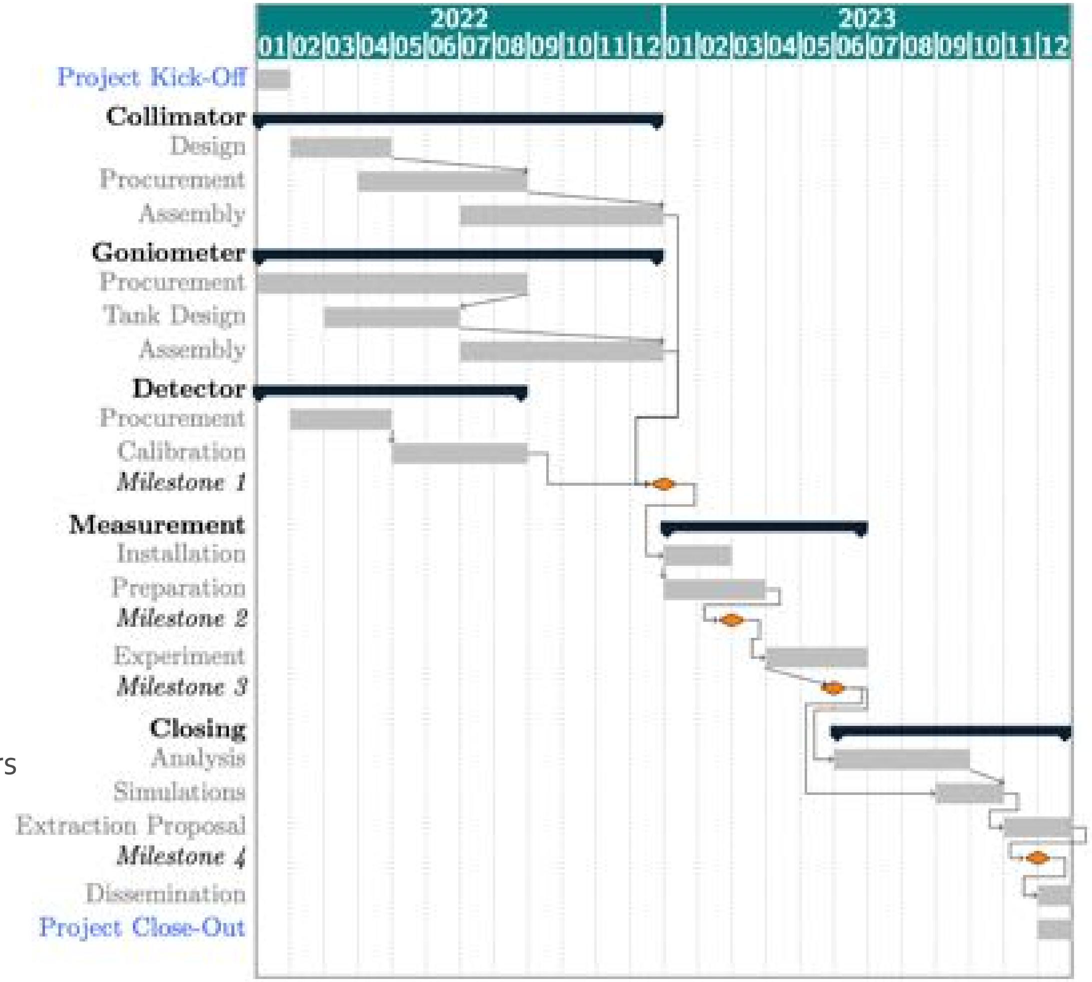
Management – the proponent and the leaders of the participant in each participants institution

Work Packages

- **Collimator** - Design (Proponent, INFN Roma), material procurement (Proponent) and assembly and test (CNAO, Proponent) of the collimator and its vacuum tank.
- **Goniometer** - Procurement (Proponent) of the positioning devices; integration in the vacuum system and test (CNAO, Proponent).
- **Detectors** - Procurement of the silicon pixel detector and related equipment; calibration and preparation of the detectors (Proponent, INFN Milano).
- **Experiment** - Installation of the layout and preparatory commissioning; final execution of the test (Proponent, CNAO, INFN Milano, INFN Roma).
- **Closing** - Data analysis and input for simulation of crystal assisted extraction (Proponent, CNAO, INFN Roma); dissemination of knowledge (Proponent).

Milestones ⇛ Deliverable

1. Production of all the equipment (Collimator, Goniometer and Detectors)
   ⇛ Report on each device
2. Preliminary tests for the silicon pixel and the collimator to assess beam parameters
   ⇛ Report on test and inputs for benchmark simulations
3. Measurement of channeling
   ⇛ Report on measurement results and inputs for extraction scheme design
4. Proposal for a crystal assisted extraction scheme in medical synchrotron



Costs and Risk analyses

- Proposed budget is based on
  - Comparison with projects using similar technologies
  - Market research
- Continuous cost baseline check from project start to end

	Origin	Cost (k€) Year 1	Year 2	Total
Equipment		70	35	105
Goniometer	Outsource	35	–	35
Collimator	Outsource / CNAO	10	–	10
TimePix	Outsource / MEDIPIX4	–	10	10
Vacuum Tanks	Outsource / CNAO	25	25	50
Consumables	Various	2	10	12
Services	Various	1	2	3
Travel	Various	1	20	21
Overheads	Various	1	4	5
Total		75	71	146

- Preliminary risk analysis took into consideration both scientific and managerial aspects
  - For each risk – probability, impact and approach [37]

An example:

Unavailability of or delay with equipment or assembly Should the delivery of part of the assembly or of the fundamental equipment be extended beyond what is originally planned due to unanticipated circumstances, the impact of the COVID-19 pandemic on manufacturing, or the time overruns beyond the agreed delivery date, this could impact negatively on the project by shifting its timeline considerably.

Risk: Moderate - Probability: Low - Impact: High

Approach: Mitigate/Avoid - Excellent procurement management will be required first and foremost on the project coordinator's side. He will be the focal point with suppliers and will negotiate with them on a timeline which ensures on-time delivery in the respect of the schedule baseline.

N.B. The sponsor and the team will have access to regularly updated documentation

- Transparency
- Lessons learnt

Conclusions

Conclusions

- Feasibility
  - Clear and achievable objectives agreed through extensive consultations between the proponent and the interested stakeholders
  - Relying on a mix of R&D and off-the-shelf technologies that ensures both interest and reliability
- Expertise
  - Involved groups and participants with the best expertise in their own fields
- Synergies
  - Medical applications – the project will drive innovation for the application of crystal in medical accelerators
  - Detector development – the project will expand the use of the pixel detector beyond HEP
  - Advanced computation – the measurement will be used as benchmark for channeling simulations in this energy regime
- Scientific publications / Knowledge Dissemination
  - New knowledge will be generated and shared
- Innovation / Technology transfer
  - A scheme based on bent crystals with or without resonant extraction will make the design of new hadrontherapy synchrotrons more compact, less expensive, more efficient and therefore more feasible
  - The evidence of channeling will pave the way for low energy ion/hadron beams manipulation. Possible development of other applications like beam delivery up to the patient treatment room
  - Will rely on devices and last generation scientific instrumentation developed both in-house by INFN and purchased externally (Italian and international private industry)
- Inheritance
  - The devices developed for the project (the collimator and the goniometer) will remain available for future activities

Recap

Objectives:

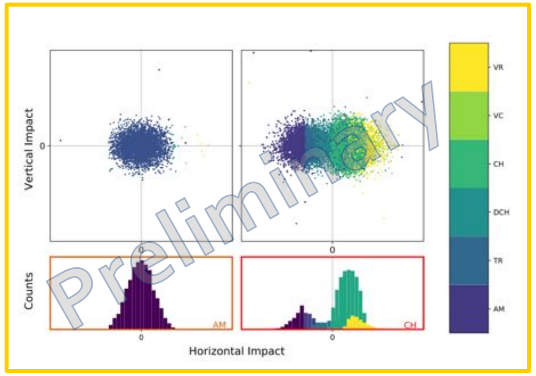
- channeling of low energy ion beams
- channeling efficiency assessment

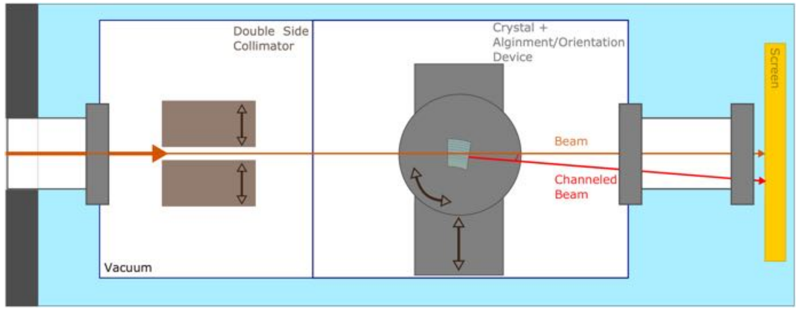
- The observation of channeling would be a premier with this beams species and energies

Outcome:

- development of a new design for a hadrontherapy synchrotron extraction assisted by bent crystals

- Of interest for the whole particle therapy community





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