CERN

Technologies Summary

Andrzej SIEMKO, CERN

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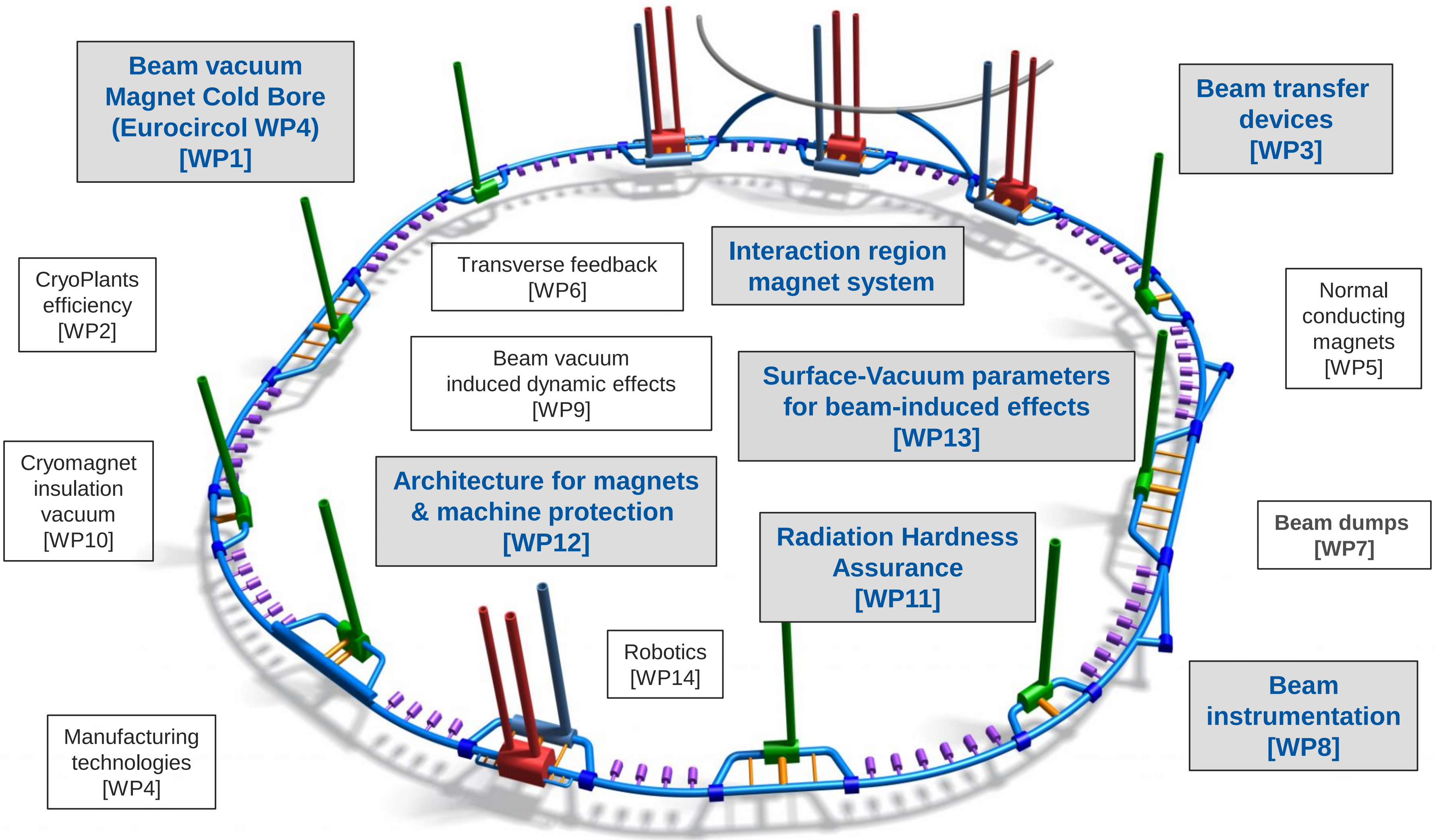
ALBA[1], BINP[2], CEA[3], CERN[4], CNR SPIN[5], GSI[6], INFN[7], ICMAB-CSIC[8], IHEP[9], NRC “Kurchatov institute”[10], STFC[11], U. of Technology and Economics Budapest[12], U. of Calabria[13], U. of Loughborough[14], Riga Technical University[15], North-western University[16], Wigner Institute[17], MIT[18].

Special thanks to José Miguel Jimenez for leading the FCC special technology R&D effort until the end of last year.

Outlook

- Scope of the FCC special accelerator technologies
- Main aims of the initial phase of R&D
- Collaborations to address the R&D opportunities
- Some selected highlights from the initial phase of the FCC R&D
- Outlook for the second phase of R&D activities

Scope of FCC Special Accelerator Technologies



Aims of the initial phase of R&D

- Study the special technologies at conceptual aspects required for the FCC accelerators and identify the possible design and performance limitations.
- Establish collaborations in order to address the R&D challenges.
- Provide feasible solutions for the FCC CDR.
- Identify opportunities for technological breakthroughs.

Collaborations to address the R&D opportunities

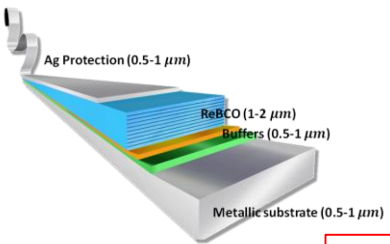
Collaborations were clearly the key to success of the initial phase of the FCC R&D program

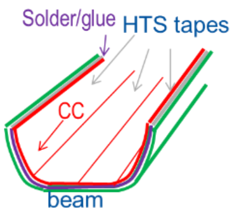
Some selected highlights from the initial phase of R&D

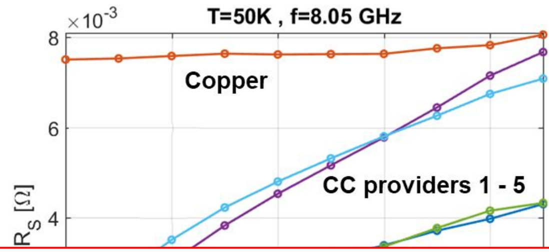
- Beam vacuum systems
- Injection and extraction systems
- Beam related machine protection
- Special IR magnets
- Beam instrumentation system
- Radiation environment assessment

Beam vacuum systems:

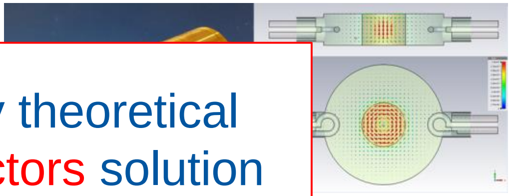
HTS coated conductors for FCC-hh beam screen impedance reduction





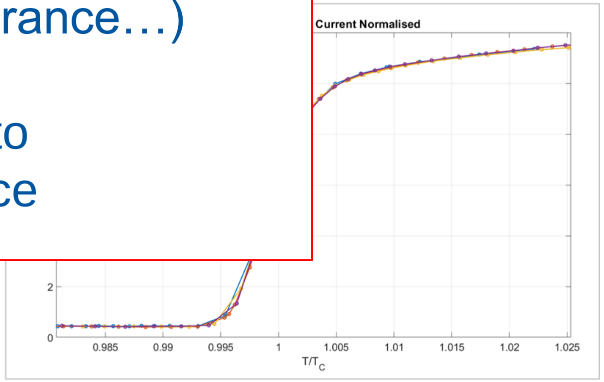


3x improvement at 8 GHz compared to copper, expected 20x improvement at 1 GHz ($f^{3/2}$)



All experiments on samples, supported by theoretical modelling, indicate that the Coated Conductors solution attains FCC-hh performance goals (impedance reduction in high magnetic field) and accelerator compatibility (e-cloud, SR radiation tolerance…)

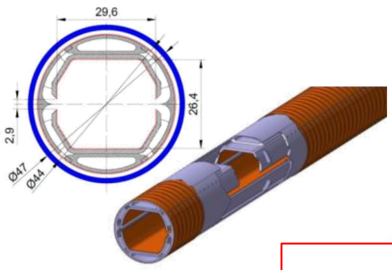
Ready to undertake scaling-up to real-scale proof-of-concept device



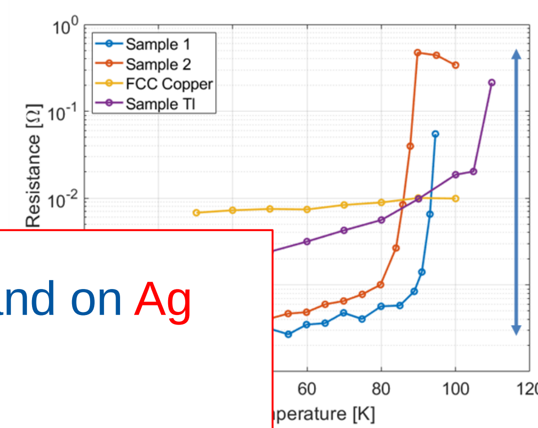
Courtesy of A. Saba, P. Krkotic, A. Romanov, S. Calatroni, R. Kersevan

Beam vacuum systems:

HTS Tl-1223 coatings for FCC-hh beam screen impedance reduction



First RF test shows Tc ~110 K and better than copper surface resistance (no applied B field)



Coating of Tl-HTS demonstrated on $SrTiO_3$ and on Ag textured substrates, Tc > 110 K.

Road paved for experimental assessment in RF at high magnetic field, optimization and scaling to larger sizes.

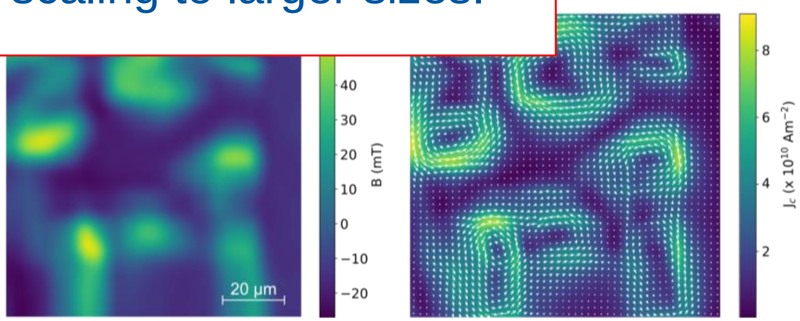
SPIN

ATOMINSTITUT

TU WIEN TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology

USTEM

Hall microprobe scans at 5 K on Tl-HTS coated on Ag indicate large critical currents



Beam vacuum systems:

- **Proposal for further development 2020-2022**

- Next goal: **build a proof-of-concept model beam screen** incorporating the lessons learned
- Similar consortium, well balanced in background and opportunities; capabilities, knowledge and well-trained people thanks to the first project.
- Further develop soldering technology, mechanical testing, ancillaries and all needed DC & RF test equipment
- In-depth study and **assessment of persistent currents effects** and mitigations

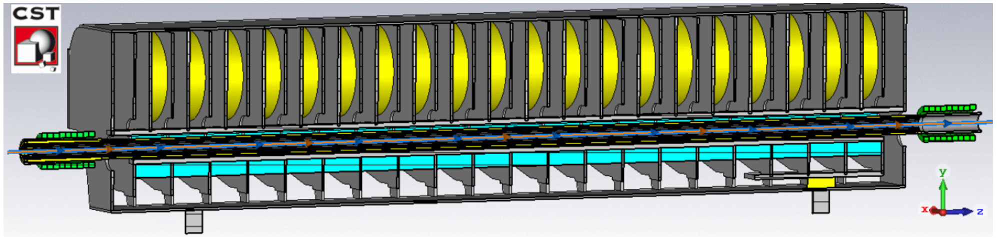
- Next goal: **optimization of Tl-1223 coating on Ag substrate**.
- Profit from established unique collaboration, and the tight links between the participating institutes.
- RF testing to assess **surface resistance at high magnetic field**
- Explore scalability, also through other precursor deposition techniques (ink-jet, etc.)

Courtesy of A. Saba, P. Krkotic, A. Romanov, S. Calatroni, R. Kersevan

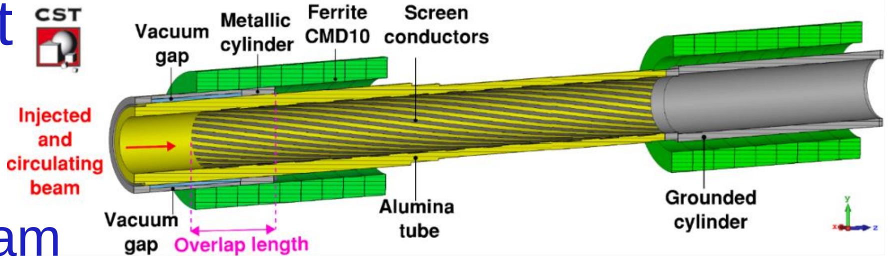
Injection and extraction systems:

New Spiral Beam Screen Design for the FCC-hh Injection Kicker Magnets

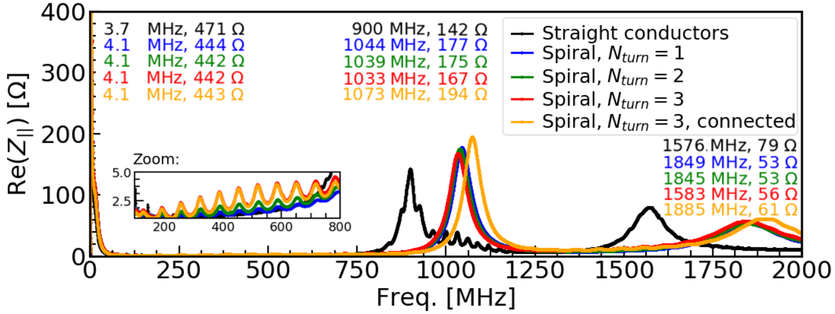
- Development of Injection Kicker Magnet



- Development of new concept of a **spiral beam screen**



- Main features of the new spiral beam screen design
  - ✓ **improved high voltage performance**
  - ✓ **low longitudinal impedance**
  - ✓ **flexibility in terms of different design options**
  - ✓ **possibility to tune transverse resonant modes**
  - ✓ **no quadrupolar component**
  - ✓ **good field homogeneity** (Opera simulations)
  - ✓ **fast field rise and fall times** (Pspice simulations)



- Spiral beam screen, with possible tweaks is the **only solution to fit into FCC transverse impedance budget**
- no heating issues expected for the FCC-hh injection kickers

Courtesy of A. Chmielinska and T. Kramer

Injection and extraction systems:
New Spiral Beam Screen Design for the FCC-hh Injection Kicker Magnets

- Proposal for further development

- **Proof of concept on a model of spiral beam screen**
  - **Field rise-time measurements**
  - **Sensitivity of influence of small errors in induced voltage** upon field rise time
  - **High-voltage tests**
  - **Analysis of "tuning" of frequency**
  - **Impedance measurements:**
    - **Concept of "switch" to connect all screen conductors to the beam pipe**, once injection is complete ⇨ verify low beam coupling impedance[1].
    - **Concept of "tuning**" of frequency of transverse impedance resonances
    - **Possibly in a test facility, e.g. CLEAR**

- **Prototyping,** test and measurement of an FCC injection kicker magnet with **spiral beam screen**.

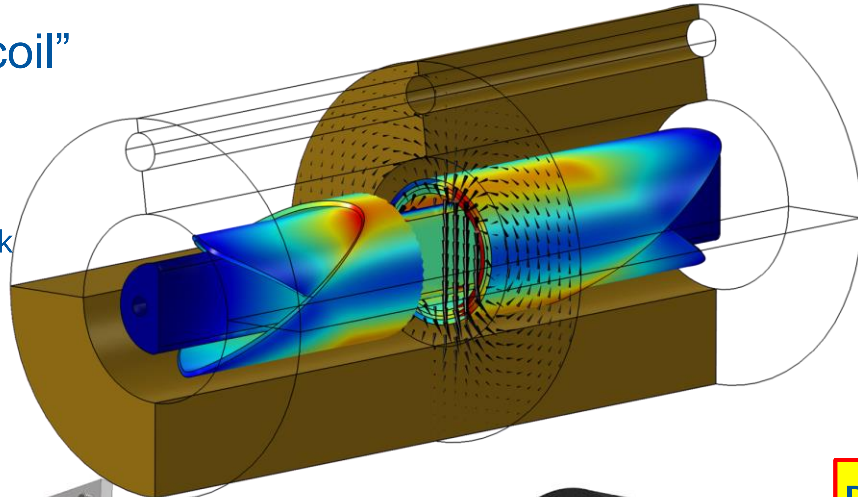
Prototype alumina tube with spiral screen conductors

Courtesy of Agnieszka Chmielinska

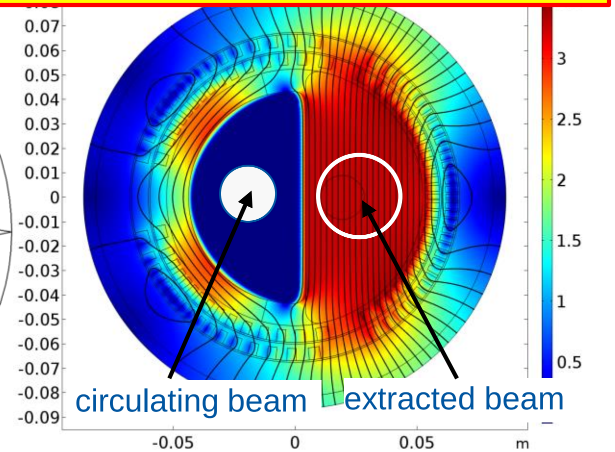
Injection and extraction systems:

<u>Development of novel FCC SuShi septum magnet: current achievements</u>

Simplified "block coil" simulation
- design coils,
- estimate B_{peak}
- L=142 mH

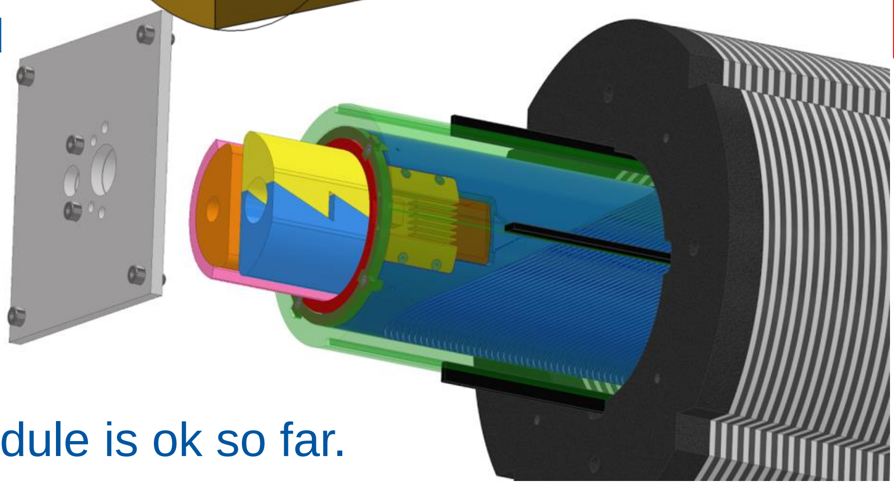


Field quality: well within +/- 1.5%

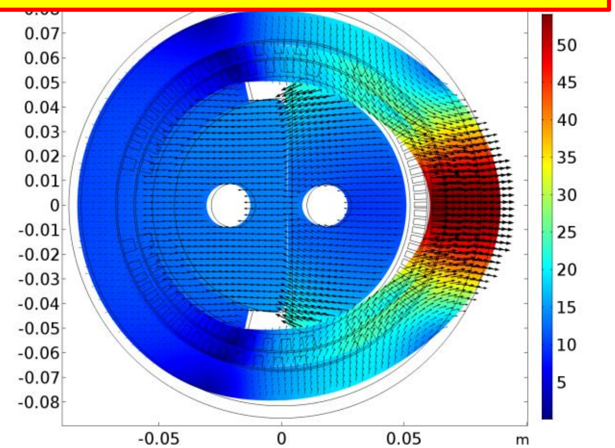


CAD design well advanced

profiting from Hi-lumi CCT corrector design



Displacements within acceptable 50 μm



Project schedule is ok so far.

Courtesy of D. Barna and M. Novak

Injection and extraction systems:

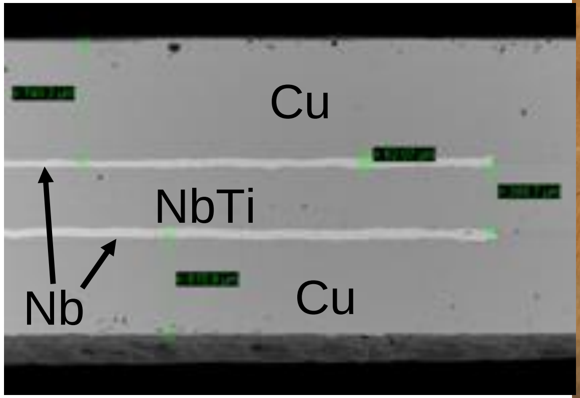
Development of novel FCC SuShi septum magnet: current achievements

- Proposal for further development

1. NbTi/Cu multilayer sheet manufacturing R&D (Wigner RCP, Univ. Miskolc)
   - Part of project description, without details & coverage
   - Need CERN support (consultation with material experts & political)
   - Grant request submitted

2. MgB2
   - Develop large bulk shields (one piece or joining)
   - Improve stability against flux jumps
     - Doping
     - Preparation under vacuum

3. Construction of magnet demonstrator prototype expected to start next year



First single-sequence Cu-Nb-NbTi-Nb-Cu sheet rolled @ Miskolc Univ.

Courtesy of D. Barna and M. Novak

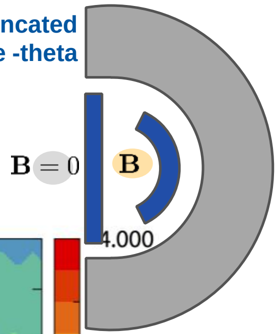
Injection and extraction systems:

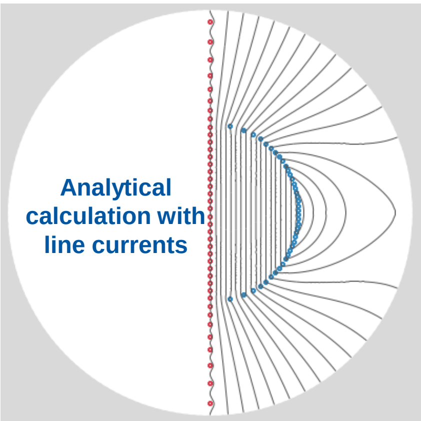
Development of novel GSI/FCC s.c. truncated cosine-theta septum magnet

- **current achievements**
  - ✓ truncated cosine-theta concept developed
  - ✓ theoretical studies
  - ✓ know-how of 2D electromagnetic design
  - ✓ 2D optimisation with software (Roxie)
    - ✓ 4 T septum, NbTi cable, 30 mm septum thickness

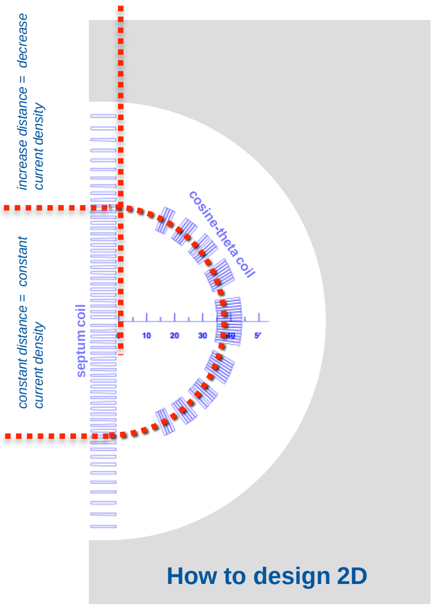
FCC-hh extraction scheme

Concept of truncated cosine -theta



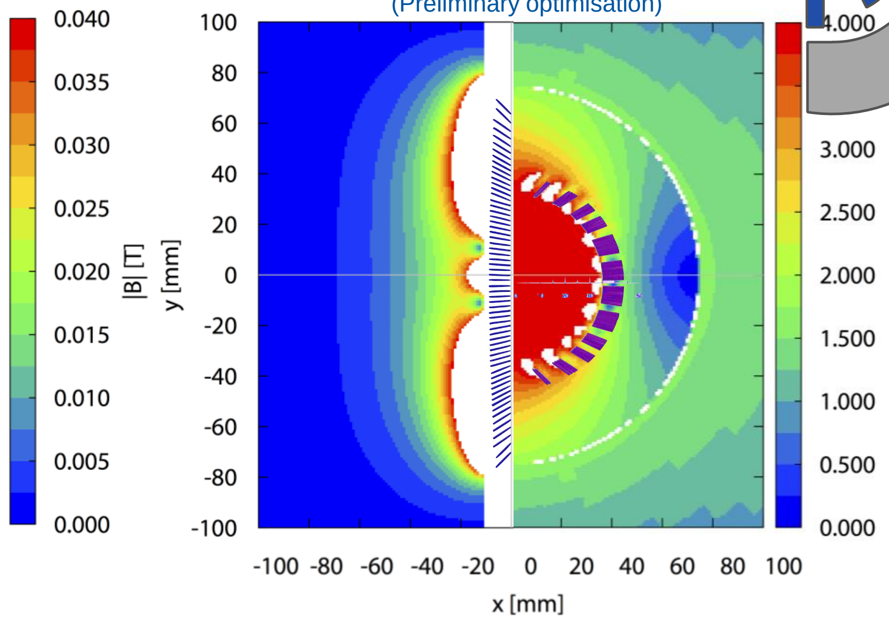


Analytical calculation with line currents

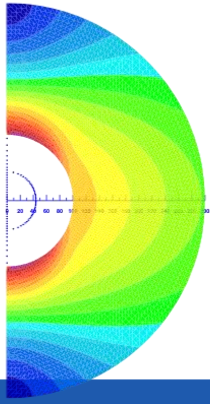


How to design 2D

Stray field / Main field
(Preliminary optimisation)



Roxie calculation with line currents



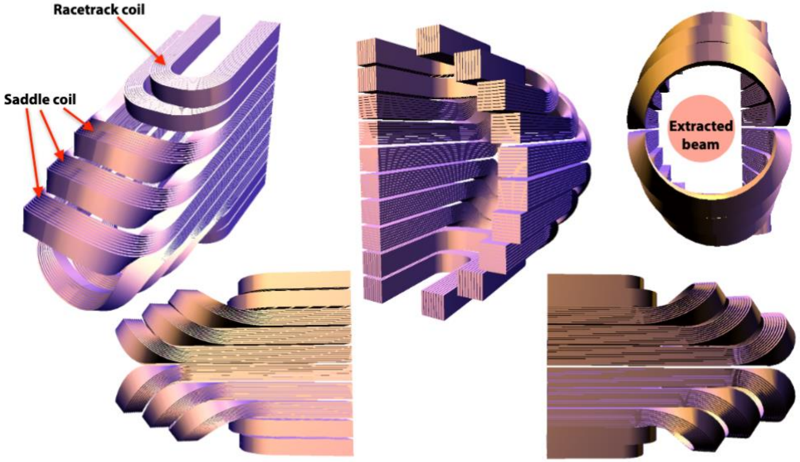
Courtesy of K. Sugita and E. Fischer

Injection and extraction systems:

Development of novel GSI/FCC s.c. truncated cosine-theta septum magnet

- **recent achievements**
  - ✓ preliminary mechanical analysis
  - ✓ several coil end designs are proposed

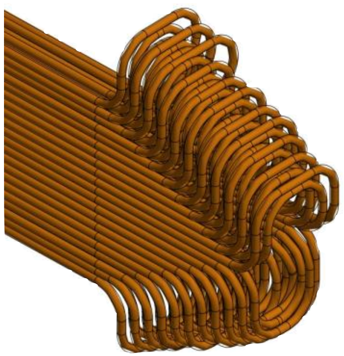
Flat Rutherford cable
Block coil design



- **Proposal for further development**

- mechanical and cryogenic design studies
  - iteration of electromagnetic design and engineering design
- prototyping
- collaborations
  - CERN-GSI collaboration meeting will be held on 2nd July.
  - Discussion, suggestion, collaboration proposal are very welcome.

Surface winding
(for medical accelerator)



Nuclotron cable
(for fast ramped, high heat load magnet)

Courtesy of K. Sugita and E. Fischer

Beam-related Machine Protection Studies:

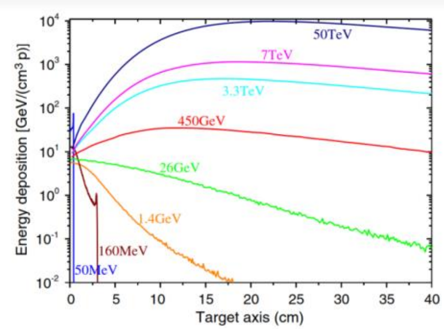
FCC-hh beam impact and damage studies of superconducting materials

- Challenge for FCC-hh: stored beam energy is ~20 times higher than at LHC (> 8 GJ per beam), while energy density is ~150 times higher (> 100 GJ/mm^2).
- Beam-impact studies are essential to ensure a reliable and efficient machine protection:
  - Beam-induced degradation of s.c. strands measured (HiRadMat) at rt and at cold (4.5 K).
  - Inside the cold environment, plastic deformation of Nb_3Sn strands observed for local heating above 550 K, while Nb-Ti showed no visible damage up to 1100 K. I_c measurements ongoing.
- Relevant beam-related failures include:
  - Fast failures: UFOs, failures of magnets with short time constant and at large beta function, …
  - Ultrafast failures: extraction failures, missing beam-beam kick, crab cavities failures, quench heater firing on the circulating beam, …

HiRadMat

N.A. Tahir, F. Burkart et al.

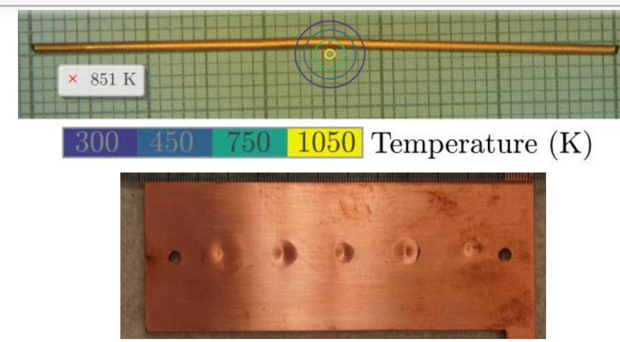
First experimental proof of the hydrodynamic tunnelling effect



Y. Nie et al.

Simulated energy deposition per impacting proton on a copper target for σ = 0.2 mm.

HiRadMat



A. Will et al.

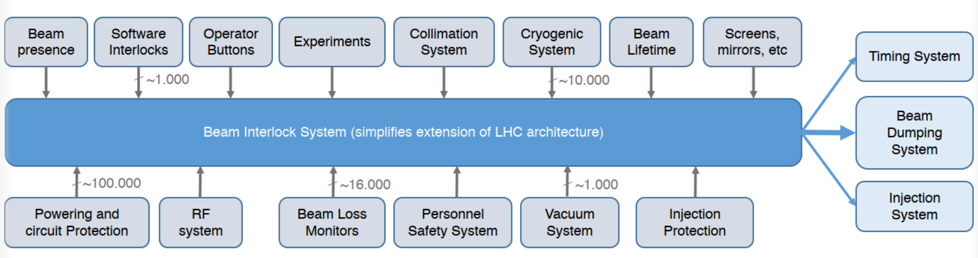
Deformation of Nb_3Sn strand after impact of 440 GeV proton beam (top) and impact marks on Cu sample holder (bottom).

Courtesy of Christoph Wiesner

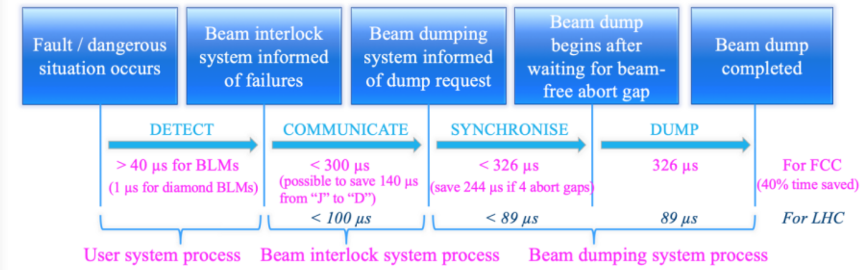
Beam-related Machine Protection Studies:

FCC-hh machine Protection System (MPS)

- The MPS for FCC-hh will be based on the successful strategy adopted for LHC. It's main requirements are: reliability, availability and fast reaction time.
- An estimated >100 000 elements will have to be connected to the Beam Interlock System.
- Challenging trade-off between machine protection and high availability required → option of using voting logic on redundant interlock channels (e.g. 2oo3).
- Compared to LHC, improvements in several key areas are needed:
  - Reduced MPS reaction time.
  - Improved control of the time constants for the magnetic field decay.
  - Efficient control and/or monitoring of the transverse beam profile.



Architecture and client systems of the Beam Interlock System (BIS).



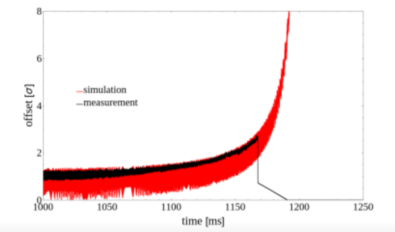
Reaction time of the MPS from fault detection to beam dump.

Courtesy of Christoph Wiesner

Beam-related Machine Protection Studies:

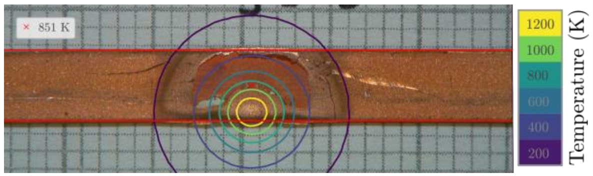
- **Proposal for further R&D work**
- **Beam-related failures**
  - Study of new fast and ultra-fast beam-related failure scenarios and their mitigation measures.
- **Next-generation interlock systems**
  - Study of new technologies for the beam and related machine interlock systems and inclusion of new failure scenarios.
- **Beam impact and damage studies**
  - Study the damage limits of superconducting materials, including sample coils.
  - Investigation of hydrodynamic-tunnelling effects in accelerator materials.
  - Study the feasibility and limitations of new materials and mechanisms for beam-intercepting devices.
- **Develop and test radiation-tolerant cold bypass diodes**
- **Availability**
  - Investigate novel architectures for reliability and availability critical systems; develop advanced simulation tools and failure prediction models via machine learning.

Measured and simulated beam orbit offset during Crab Cavity ramp at the CERN SPS



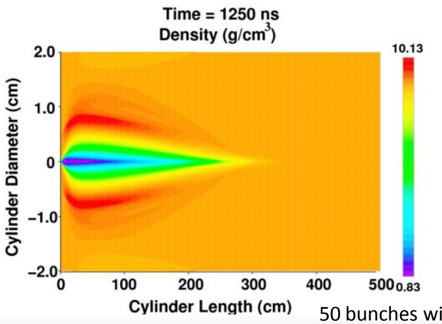
B. Lindstrom et al.

Damaged YBCO tape due to a 440 GeV proton beam impact.



A. Will et al.

Hydrodynamic tunneling effect for a 40 TeV proton beam impacting on a copper target.



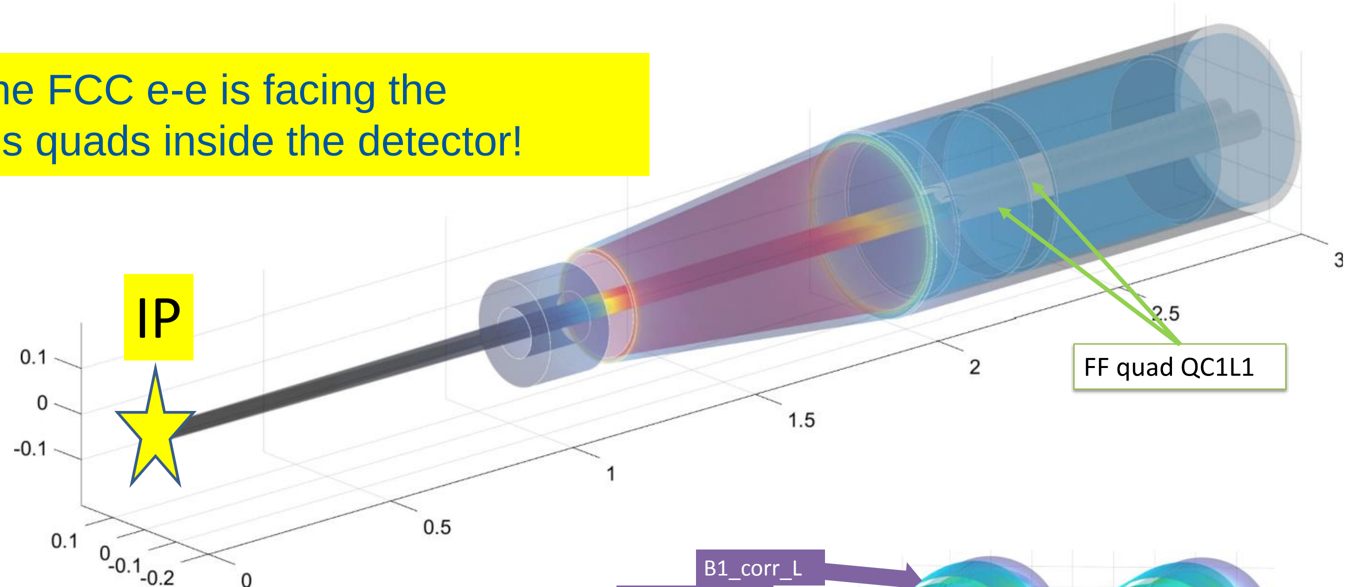
50 bunches with 1e11 p+

N.A. Tahir et al.

Special IR magnets:

FCC-ee Final Focus and corrector CCT superconducting magnets

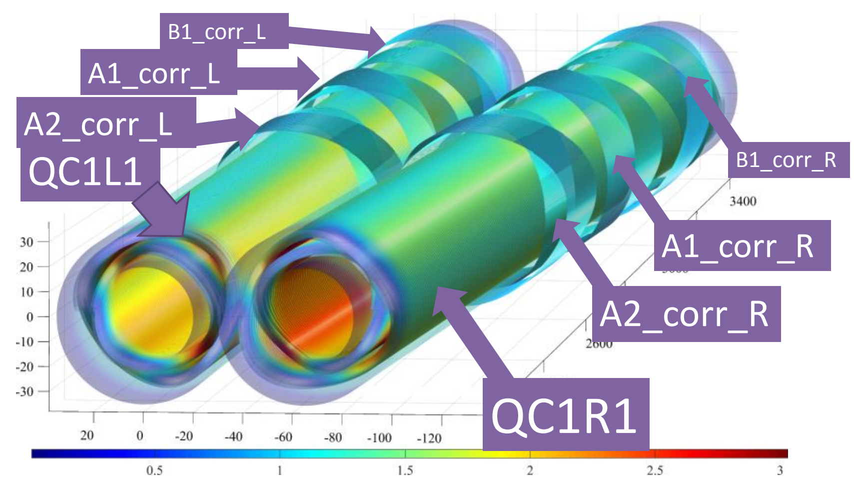
Unlike linear colliders the FCC e-e is facing the challenge of Final Focus quads inside the detector!



The stringent requirements of the final focus quadrupoles are satisfied by using a canted-cosine theta design with iron-free coils and field quality of better than 0.1 units for all multipoles.

Dipole and skew quadrupole correctors can be incorporated without increasing the length of the magnetic system.

A full magnetic analysis has been performed, including a misalignment analysis.

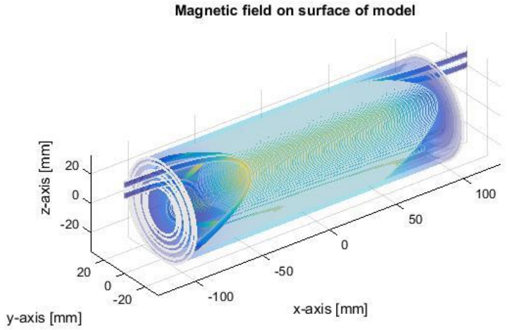


Special IR magnets:

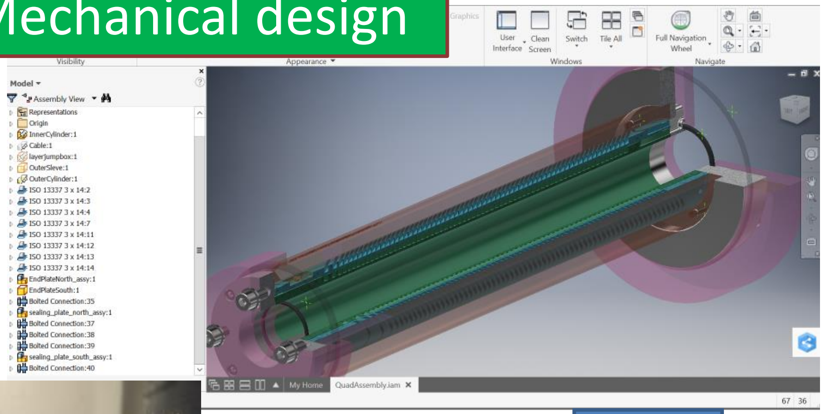
FCC-ee Final Focus prototype CCT superconducting magnets

- **Recent achievements**

Magnetic design

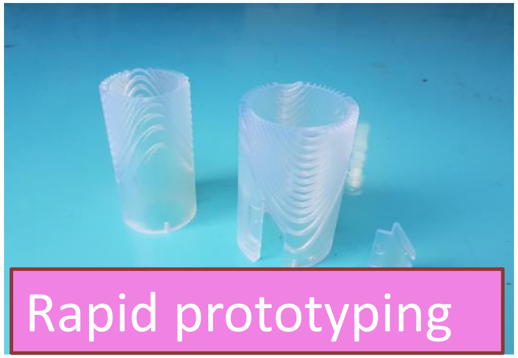


Mechanical design



Winding

Manufacturing



Rapid prototyping

Courtesy of Mike Koratzinos

Special IR magnets:

FCC-ee Final Focus and corrector CCT superconducting magnets

- **Proposal for further R&D work**

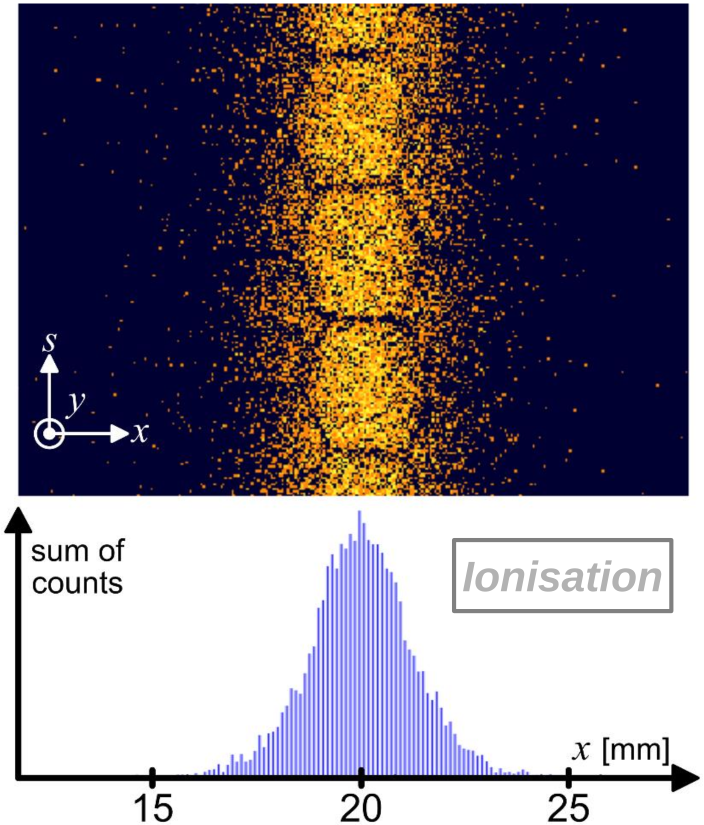
- Currently on prototype no. 1; need to test it and possibly build prototype 2 with lessons learned (both single aperture)
- The wish for the next prototype is to use HTS tape instead of NbTi. The price of the conductor has gone down in recent years (in the case of our prototype the price of the HTS tape according to the quote we have today would be O(10kCHF)
- A twin aperture prototype is next
- The very strong crabbing sextupoles of FCC-ee are next. Very compact (30cm length) and max. field at the conductor of 11T. HTS tape is a must for these sextupoles
- Prototype octupoles and decapoles which most probably will be needed for good performance at FCC-ee

Courtesy of Mike Koratzinos

Beam instrumentation system:

R&D on ionisation profile monitors for FCC-hh and FCC-ee

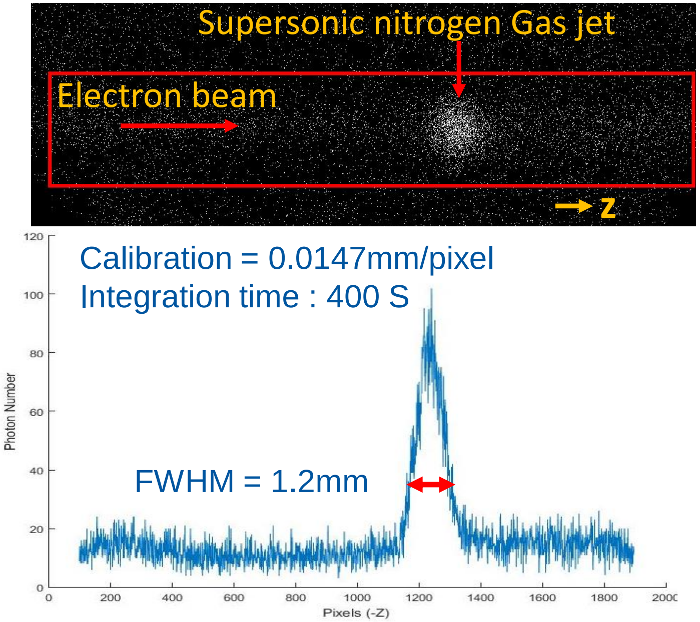
- **Recent achievements**



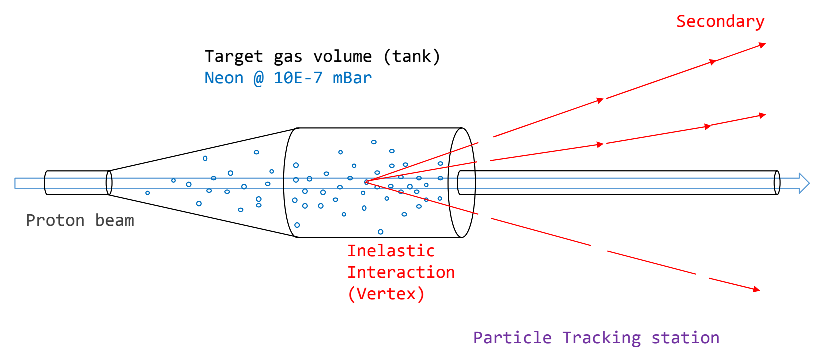
Ionisation profile monitoring on the PS

Image of ionised Neon gas.

Beam induced fluorescence *currently under development as diagnostic for hollow electron lenses*



Beam Gas Vertex *demonstrator*

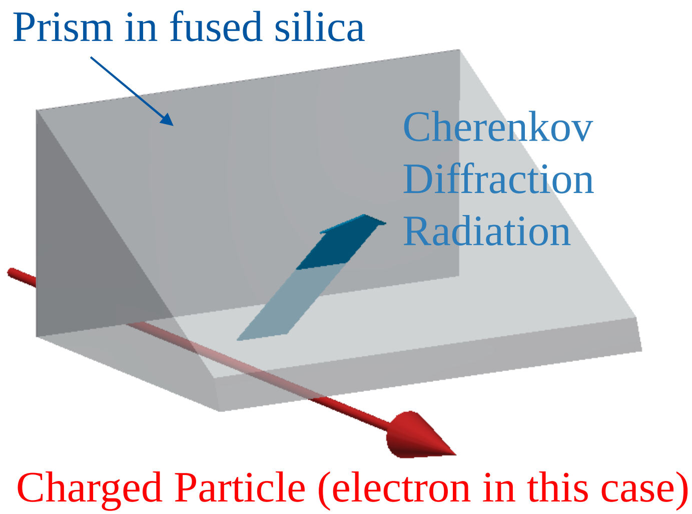


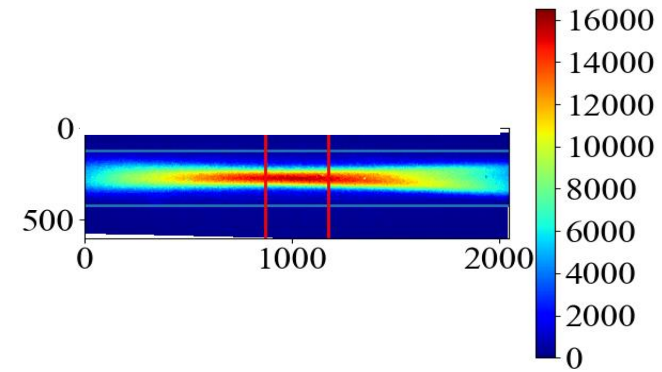
Courtesy of T. Marriott-Dodington and T. Lefevre

Beam instrumentation system:

Direct beam imaging using Cherenkov diffraction radiation

Example of direct beam imaging Using Cherenkov Diffraction radiation as measured at ATF2/KEK



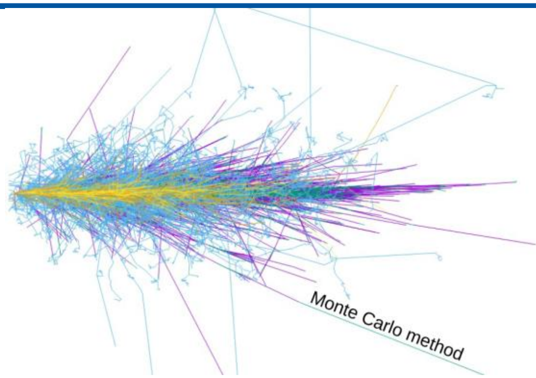


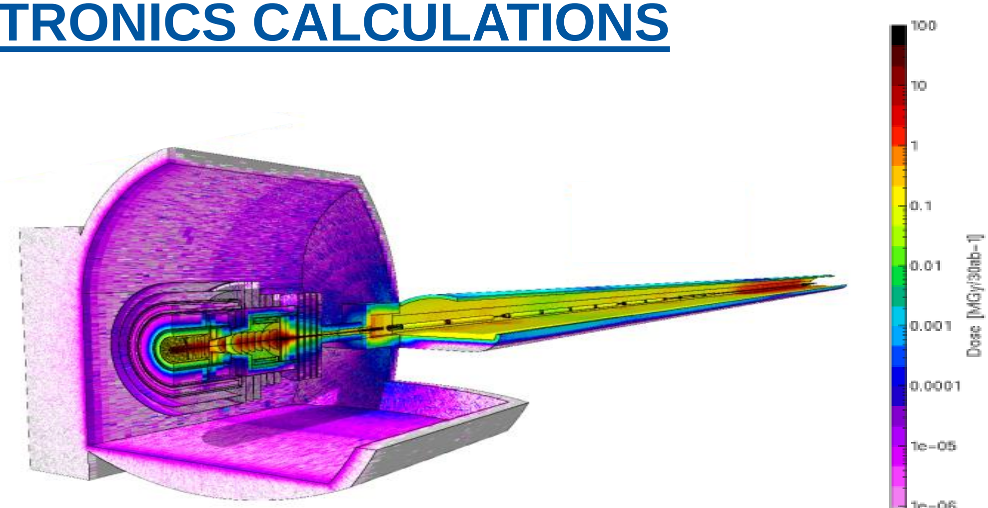
- **Proposal for further R&D work**
  - Radiation environment in FCC is considerably worse than in LHC and will require R&D on radiation hard electronic design
  - R&D on focused gas jets as an alternative to wire scanners for calibration
  - R&D on beam gas vertex detector to provide an online beam monitoring from injection to top energy
  - R&D on synchrotron light monitors using X-ray imaging techniques (i.e. pinhole cameras) or interferometry in the visible range
  - R&D on direct imaging using Cherenkov Diffraction Radiation

Courtesy of T. Marriott-Dodington and T. Lefevre

Radiation environment assessment:

Status of RADIATION TO ELECTRONICS CALCULATIONS





- **Proposal for further R&D work**
  - Radiation environment in the FCC e-e needs to be calculated in more details as radiation levels are relatively high and severely impacting on electronics
  - Limitations of existing simulation tools:
    - Managing big geometries and scaling to the FCC (ee or hh)
    - Need of co-simulation framework

Status of simulations

➢ FCC-hh arc [1]	refreshed
➢ FCC-hh Experimental IR (detector and machine) [2]	available
➢ FCC-hh betatron cleaning insertion [3]	
➢ FCC-ee arc [4]	to be updated
➢ FCC-hh extraction region [3]	to be calculated
➢ HE-LHC betatron cleaning insertion [3]	
➢ HE-LHC arc [1]	to be modelled
➢ HE-LHC Experimental IR [2]	

Courtesy of F. Cerutti and S. Gilardoni

Some personal remarks and outlook for the next phase of R&D

- We are at a transitory period for the FCC R&D programme.
- Decisions that are expected to be taken early next year will certainly impact on the scope and priorities of the future R&D activities related to the special accelerator technologies.
- Established collaborations ought to be preserved in order to complete the ongoing and prepare the future activities.
- Proposals for further development are already defined for the majority of R&D projects (bottom-up approach).
- Identified opportunities for technological breakthroughs are in principle project-independent and should continue.

Conclusions

- **Very successful collaborative R&D effort,** involving dozens of universities, scientific institutions and industrial partners.
- All required contributions to the **FCC CDR** have been provided.
- Several important challenges were spotted, but **no major showstopper** has been identified.
- Several promising **technology breakthroughs** were preliminarily explored.
- Looking forward for the next phase !!!

Thank you for your attention.

CERN