From QCD to Hadrons and Nuclei

Advanced Subatomic Physics Course (V)

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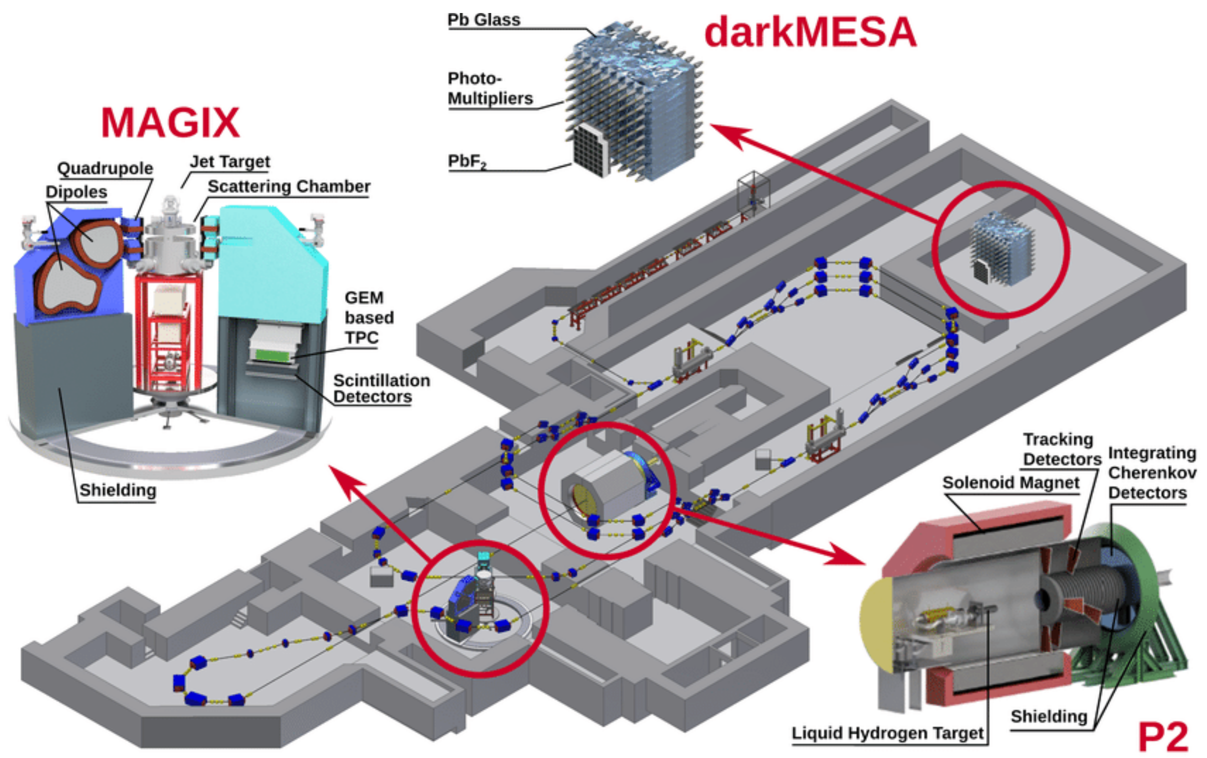
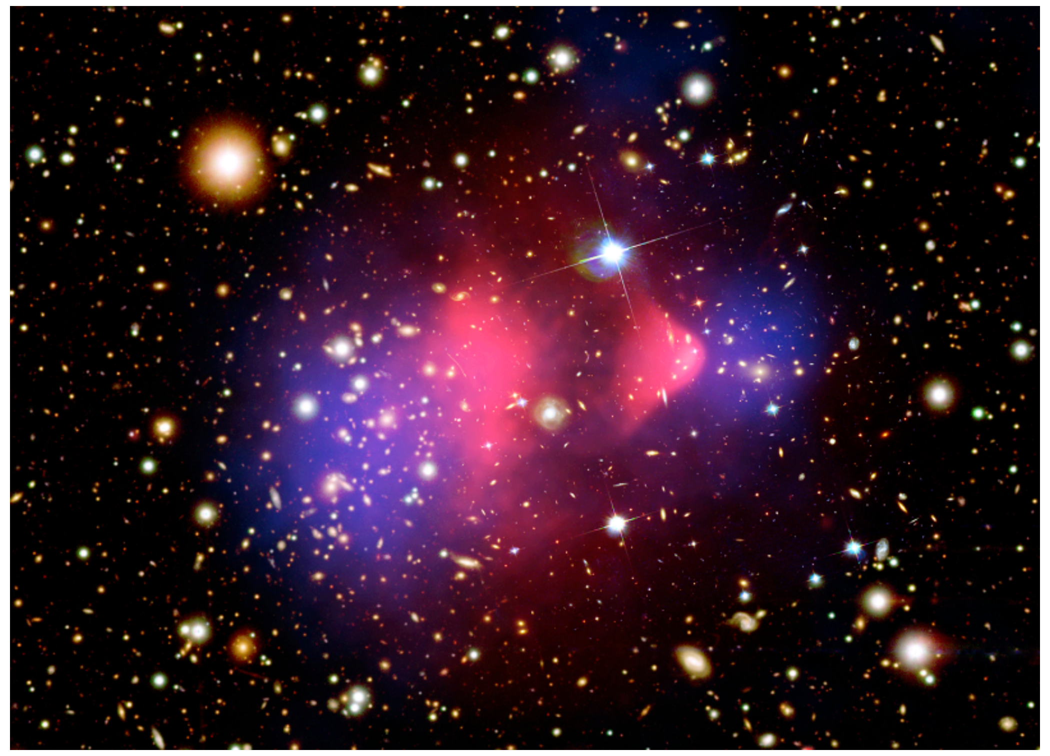
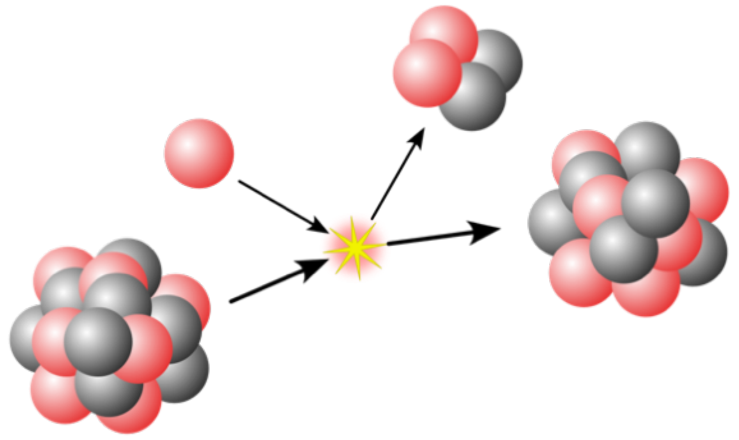
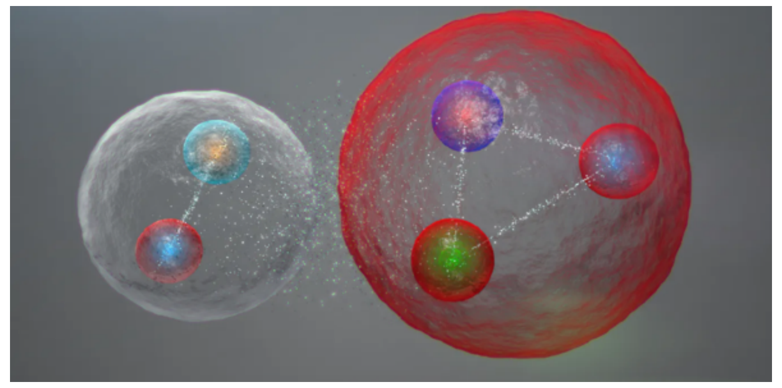








Sommersemester 2022

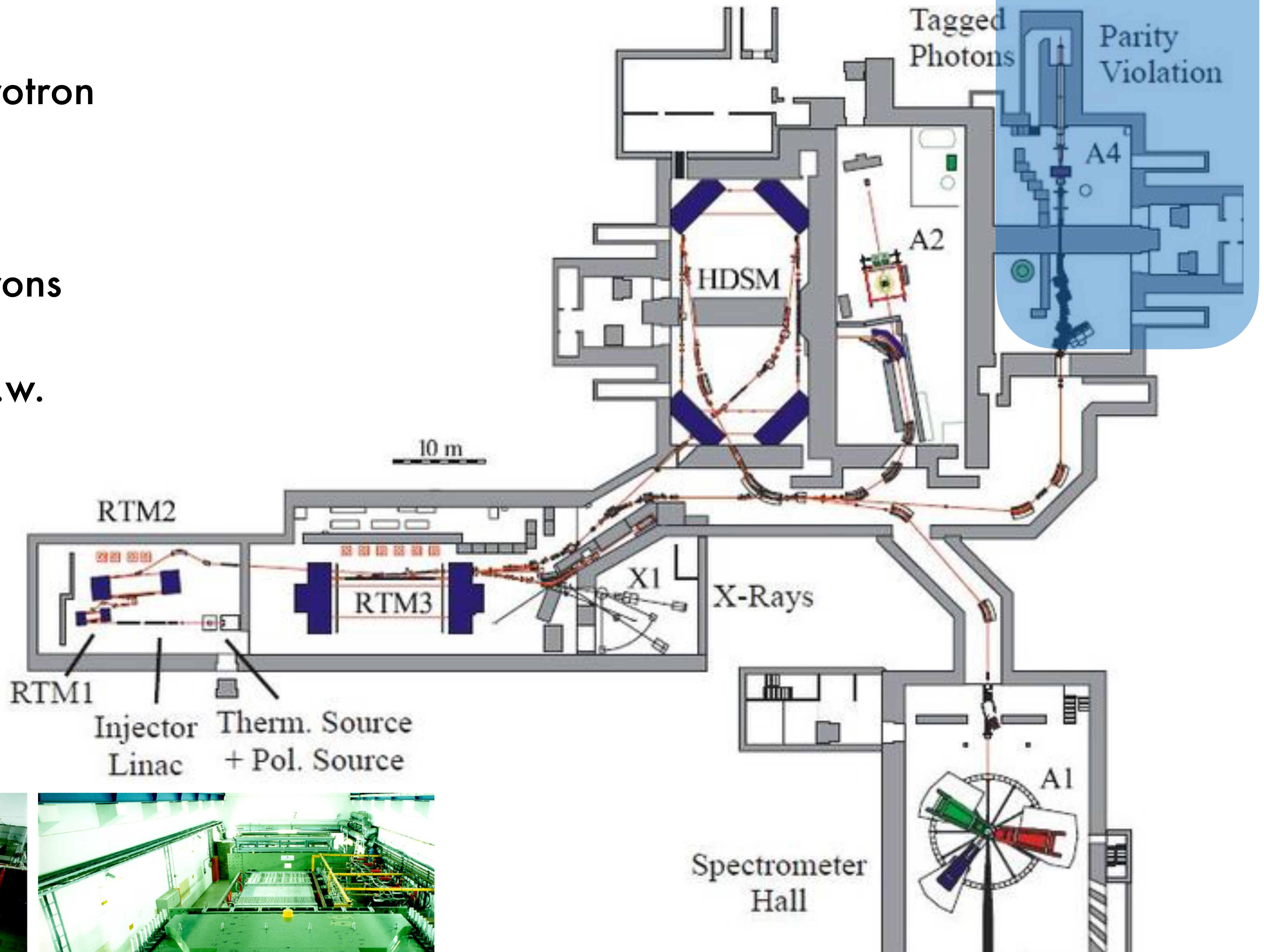
Syllabus

1. Introduction to strong interactions in the perturbative and non-perturbative regimes.
2. Hadrons and Nuclei
3. Electron and neutrino scattering experiments on hadrons and nuclei: form factors, elastic and inelastic scattering, resonances, deep inelastic physics.
4. **Experimental methods and facilities with focus on MAMI and MESA at JGU Mainz.**
5. Dark Matter
6. Search for dark matter with "intensity frontier" experiments, in particular, electron scattering experiments.
7. Search for dark matter with “direct detection” experiments with focus on argon.
8. Nuclear astrophysics and nuclear reactions of astrophysical relevance (in the Big Bang and stars).
9. Experiments for measuring astrophysical reactions with accelerators.
10. Discussion of a relevant published scientific paper on one of the topics discussed during the course.

The MAMI and MESA Facilities

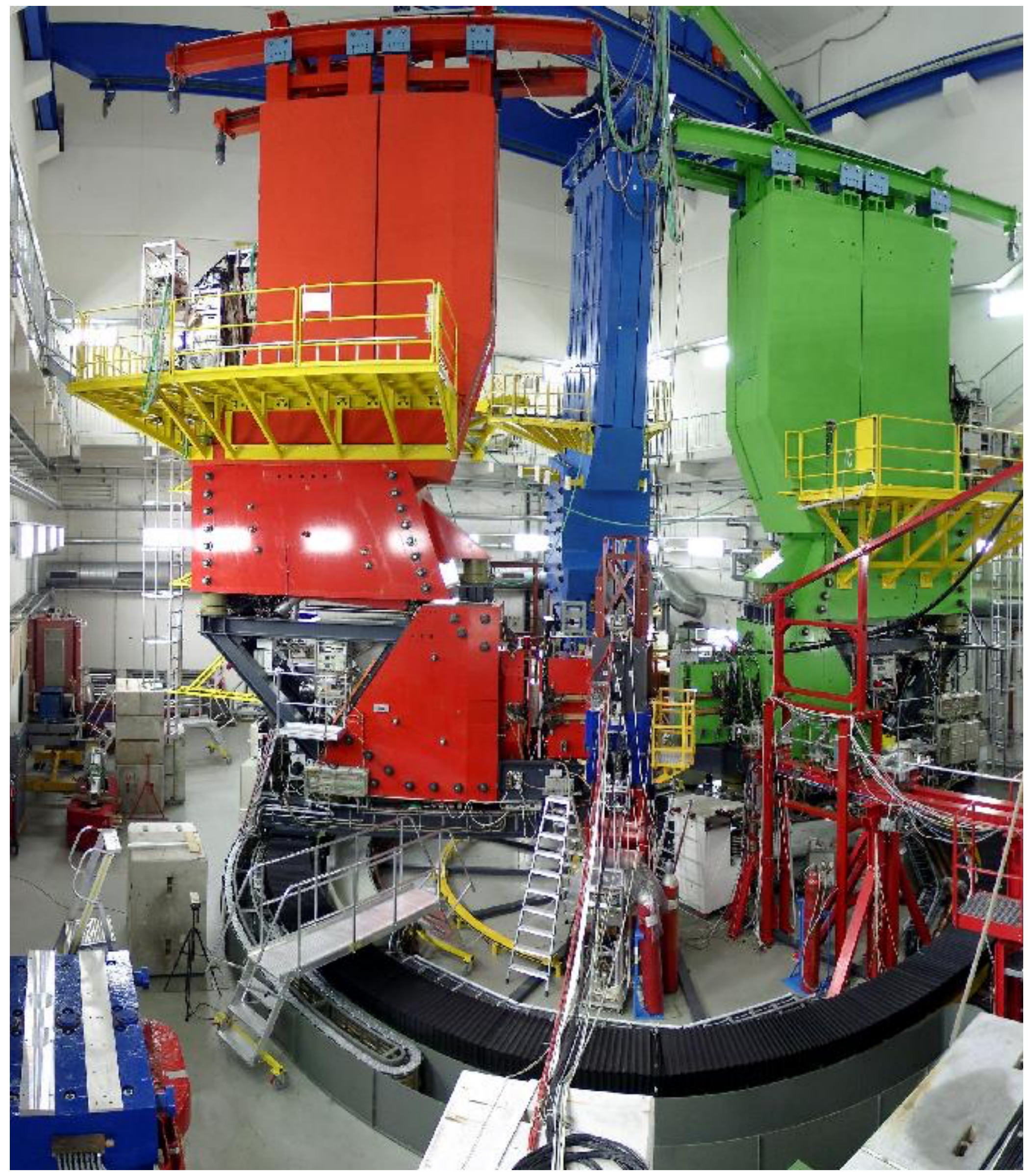
MAMI-C (since 2007)
Harmonic Double-sided Microtron
E= 1.5 GeV

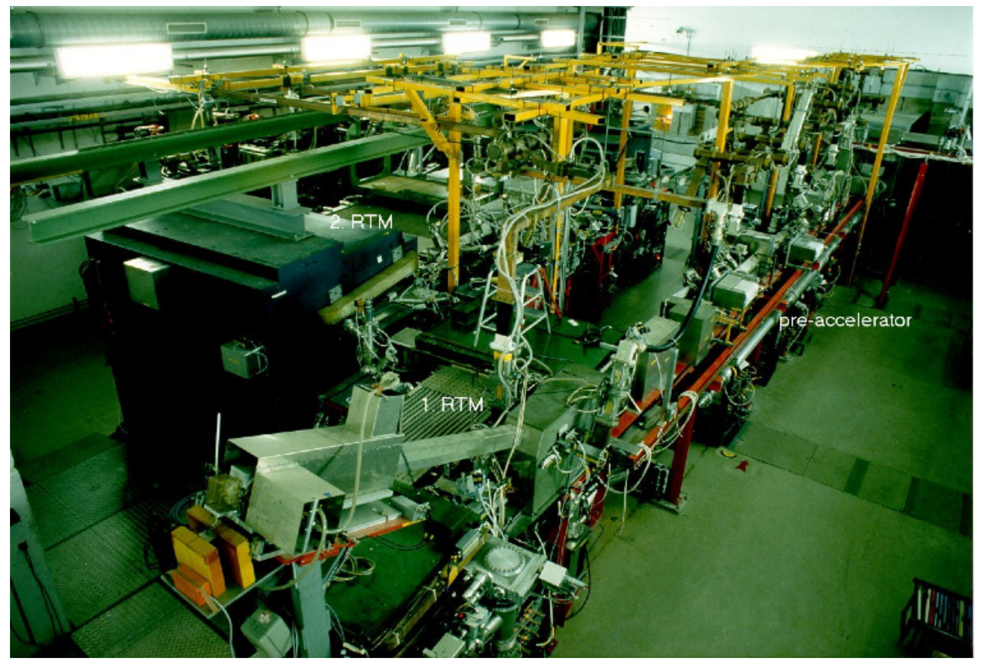
MAMI-B
3 cascaded Racetrak Microtrons
E=180-883 MeV
Max beam current 100 uA c.w.

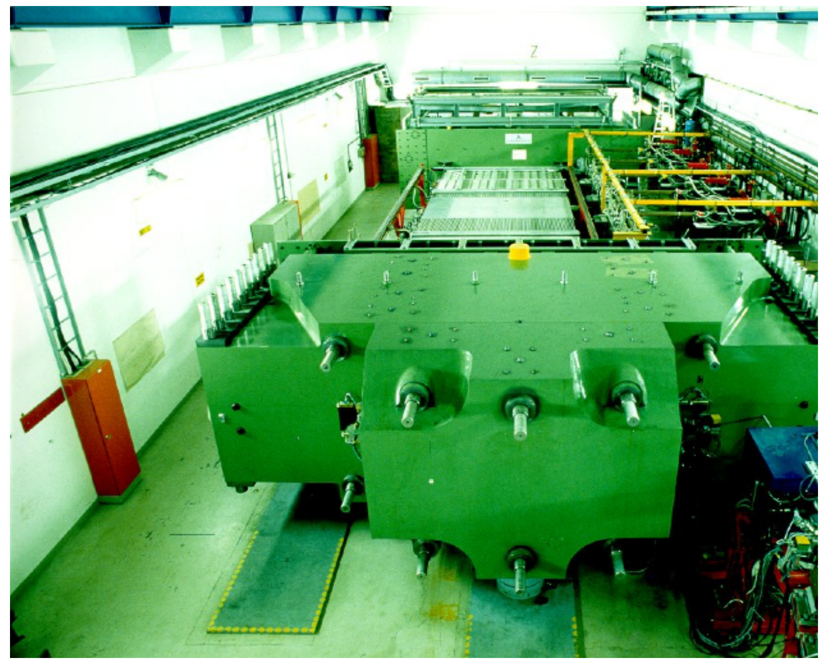


MESA

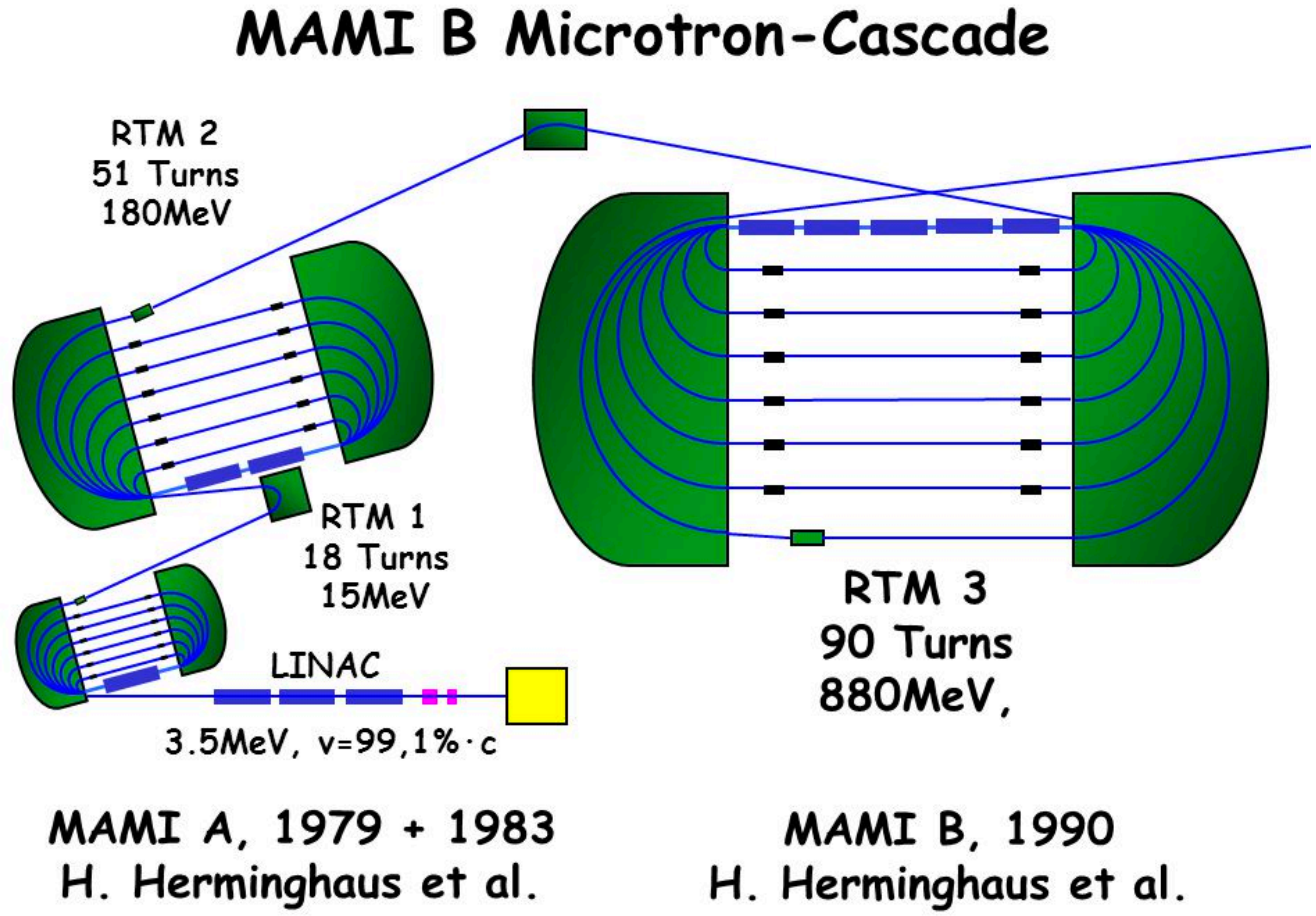
A1 Collaboration
3-spectrometer setup
Experiments with electrons

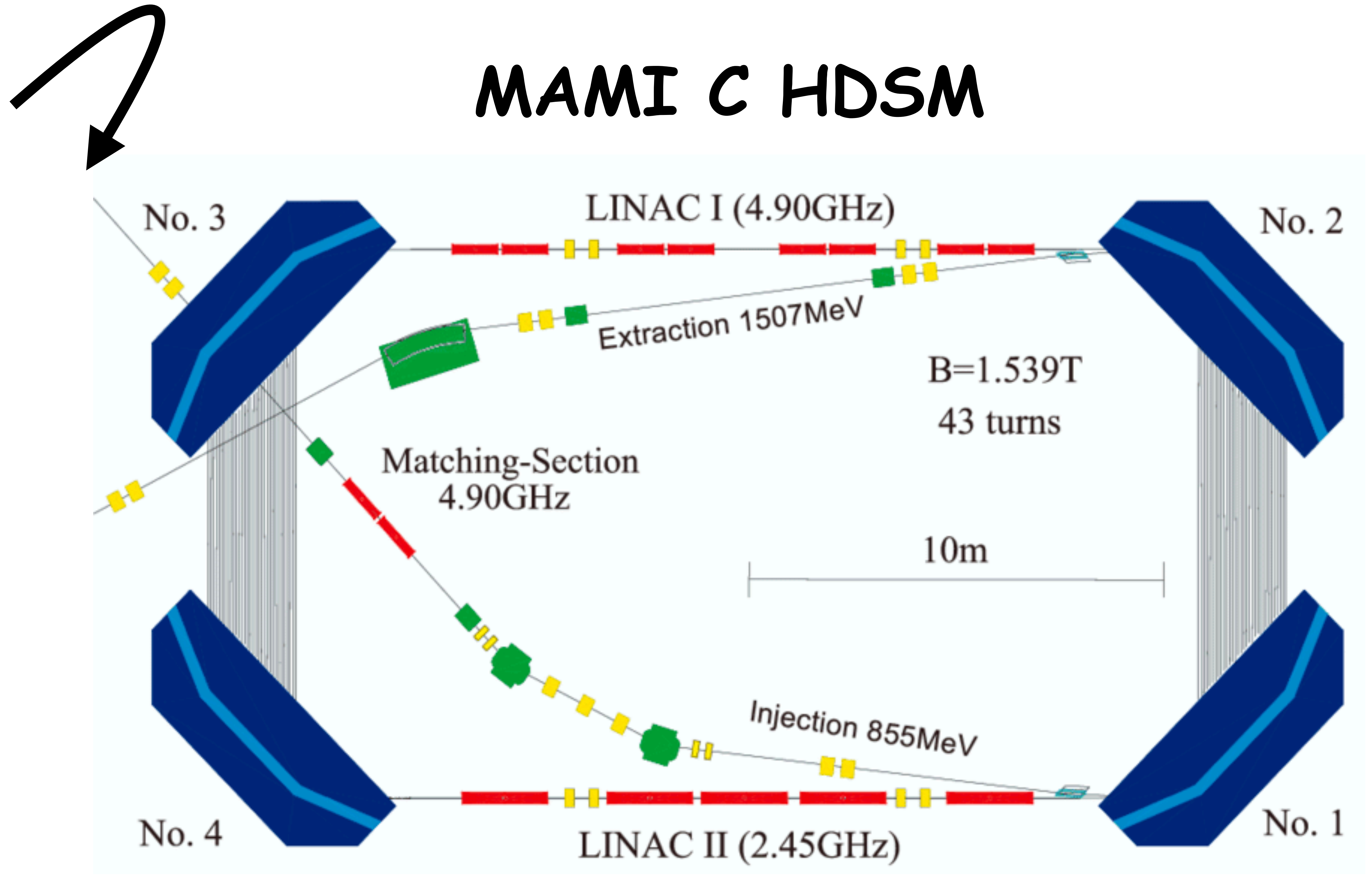




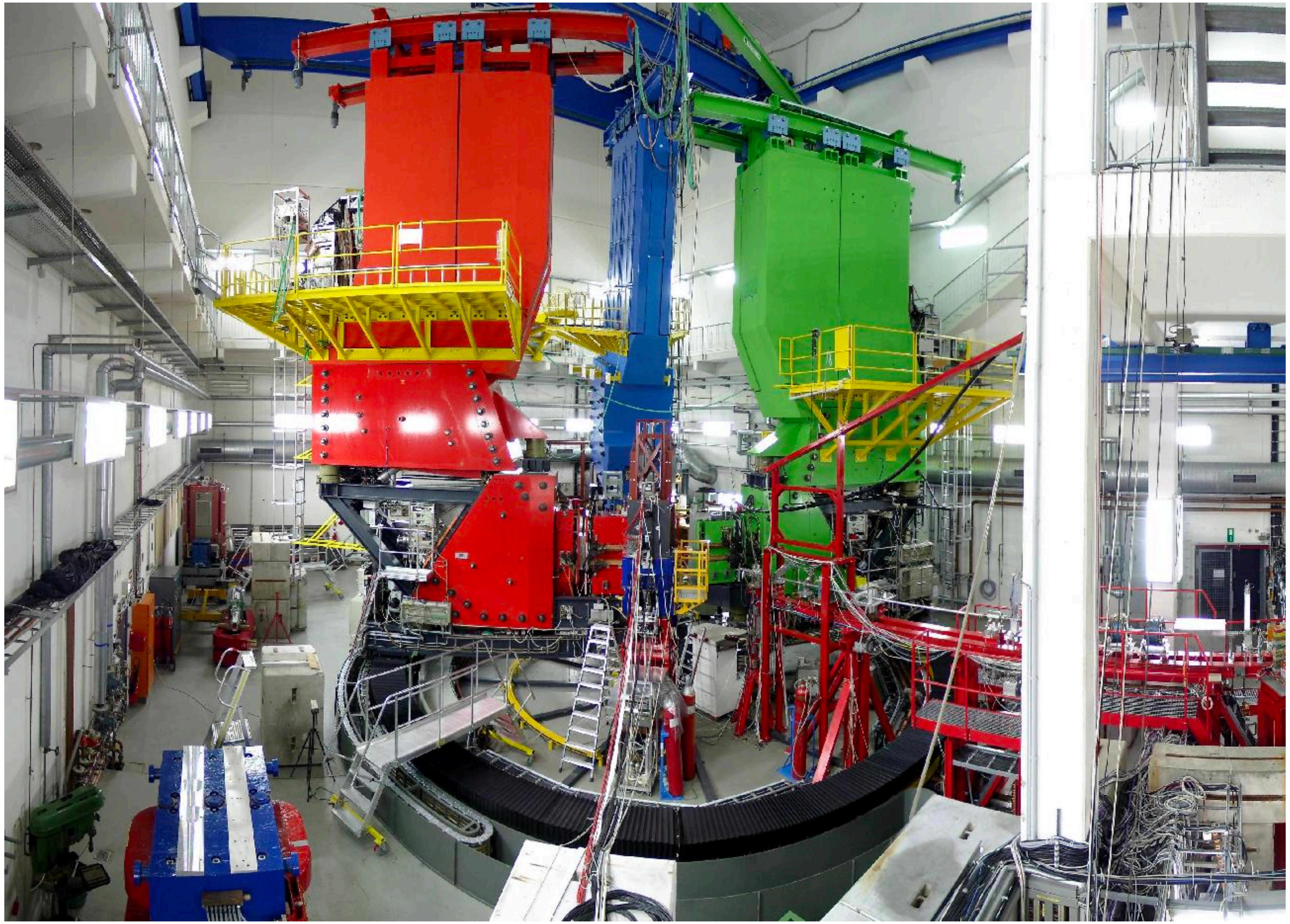


The MAMI Accelerator complex



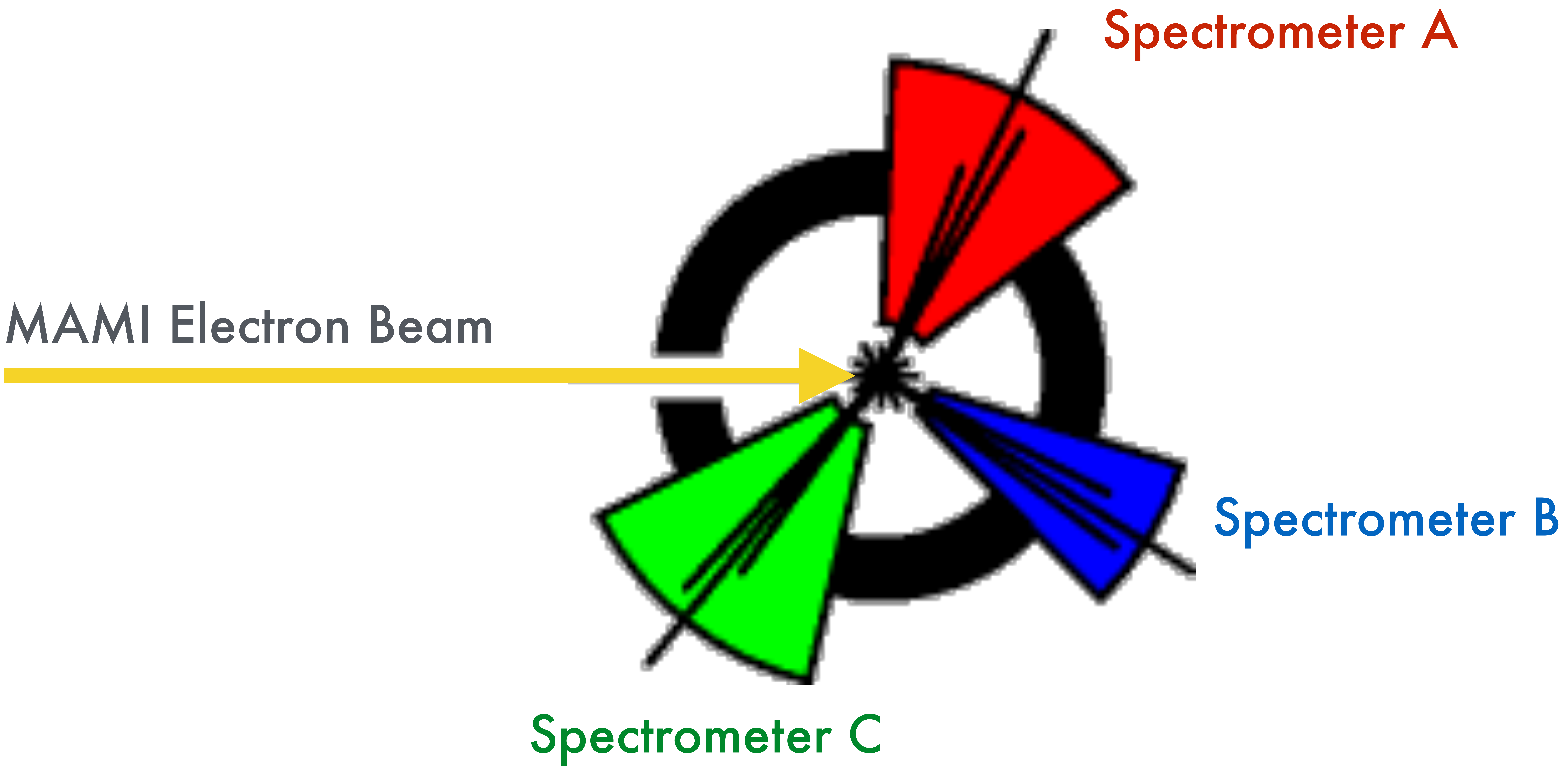


A1 Collaboration Setup

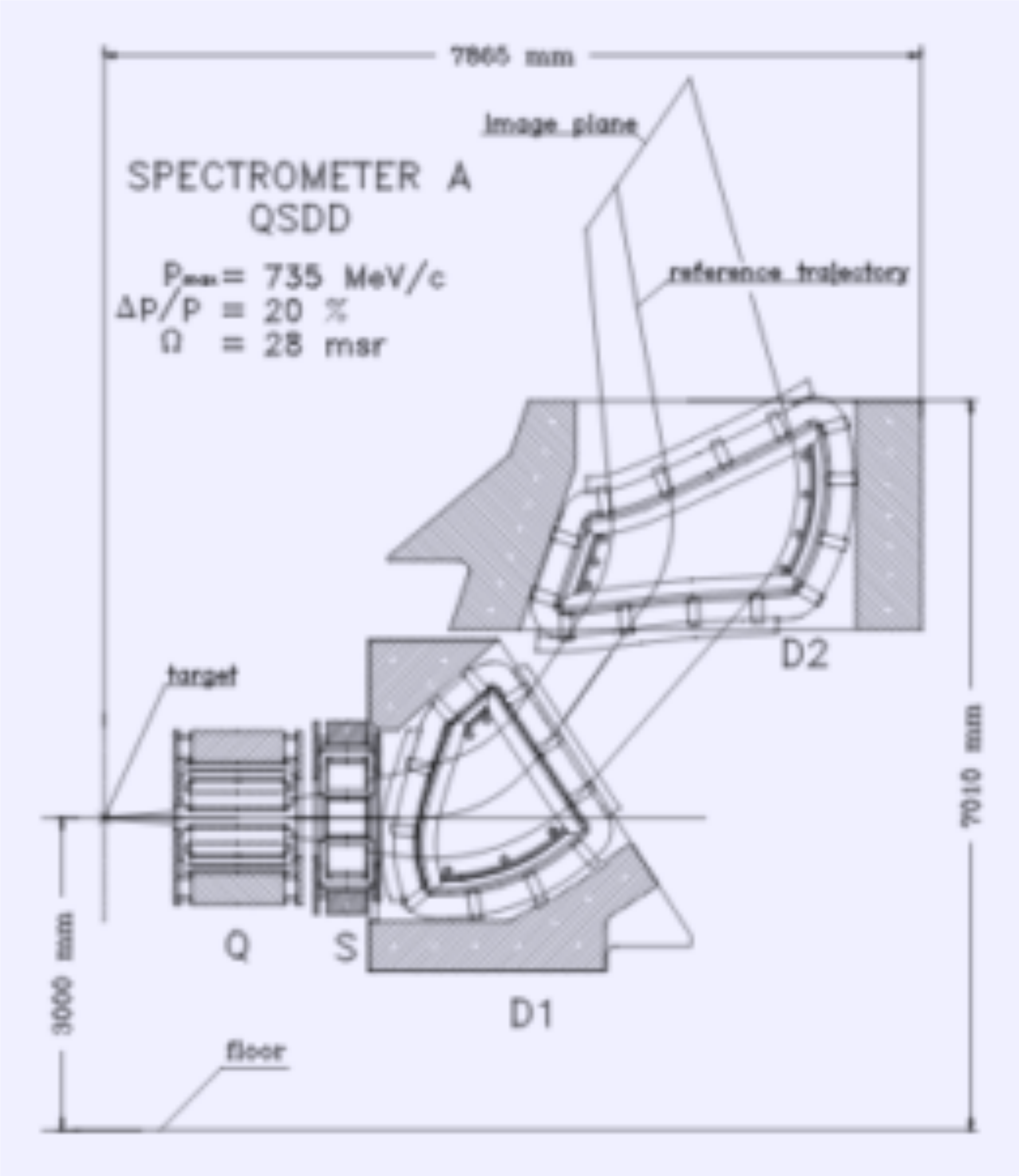


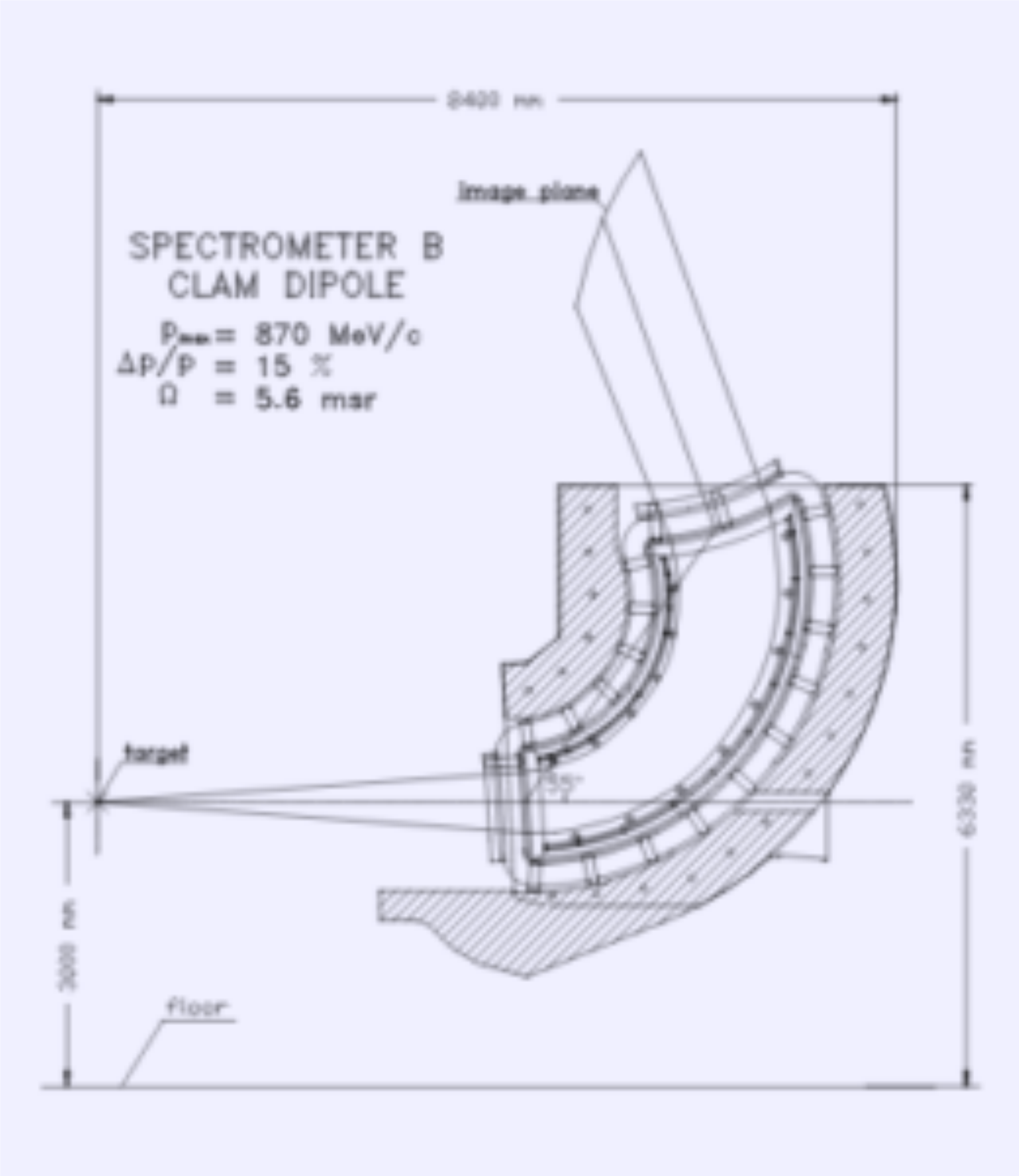
12 m

A1 Collaboration Setup



Spectrometer Design





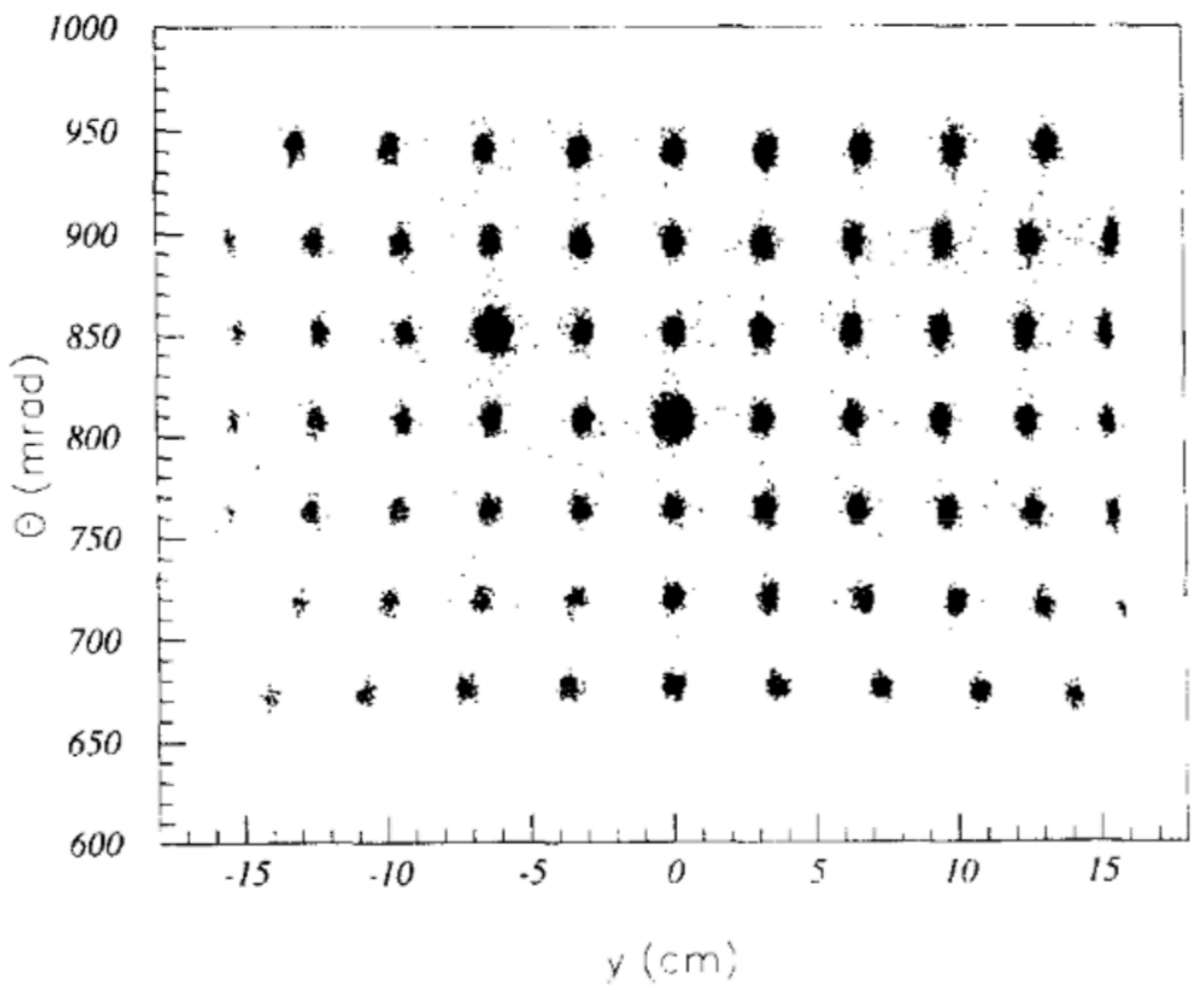
Spectrometer Magnetic Optics

Basic equation of motion of charged particles in EM fields: $F = q(E + v \times B)$

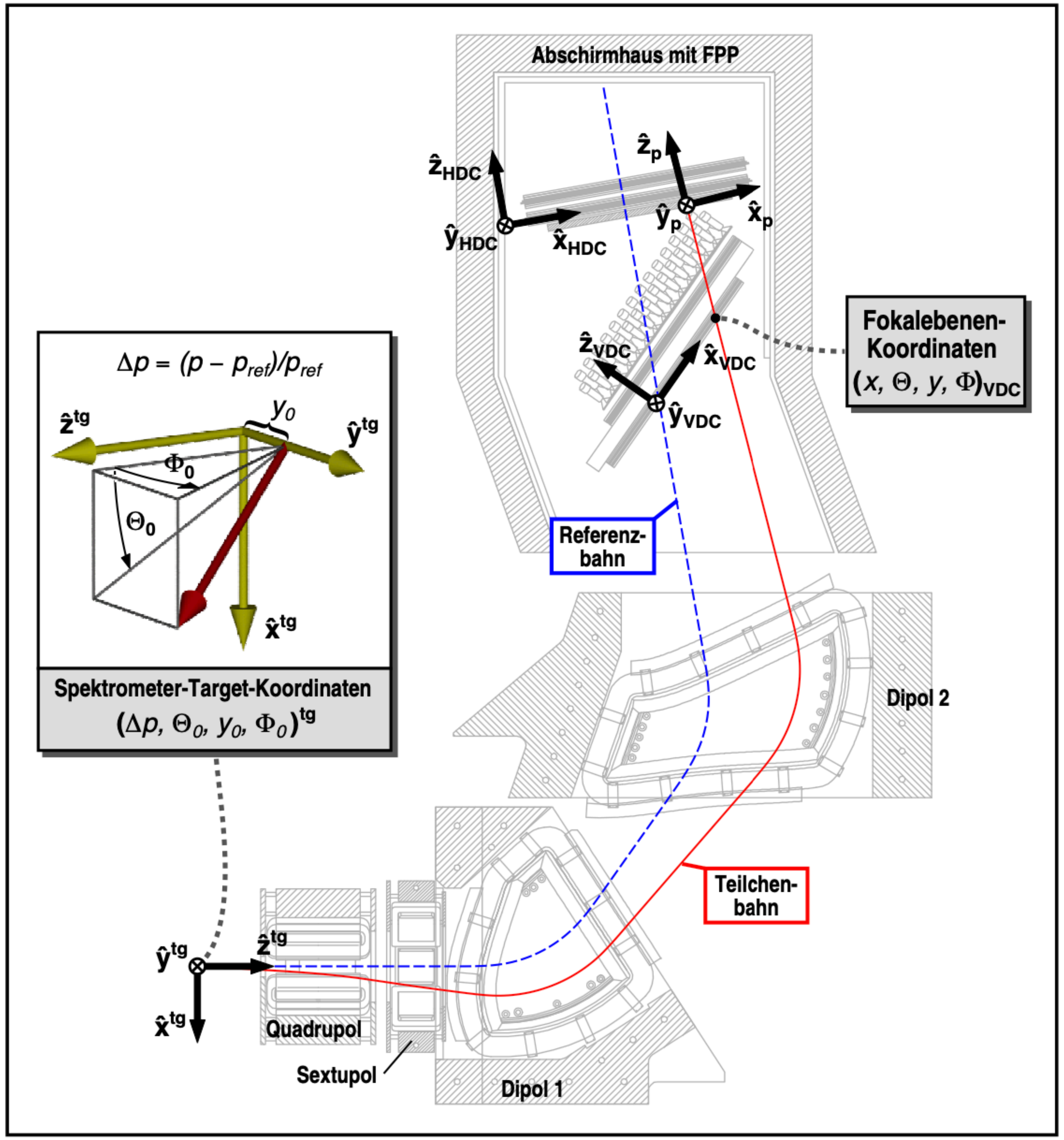
Transfer Matrix formalism

$$Q_0 = \sum_{ijkl} \langle Q_0 | x^i \Theta^j y^k \Phi^l \rangle \, (x - x_{ref})^i (\Theta - \Theta_{ref})^j (y - y_{ref})^k (\Phi - \Phi_{ref})^l$$

Coefficients calculable in principle from equartions of motion.
Practically determined with “experimental ray-tracing”.
Order 5 to 9 are used.



Spectrometer Magnetic Optics

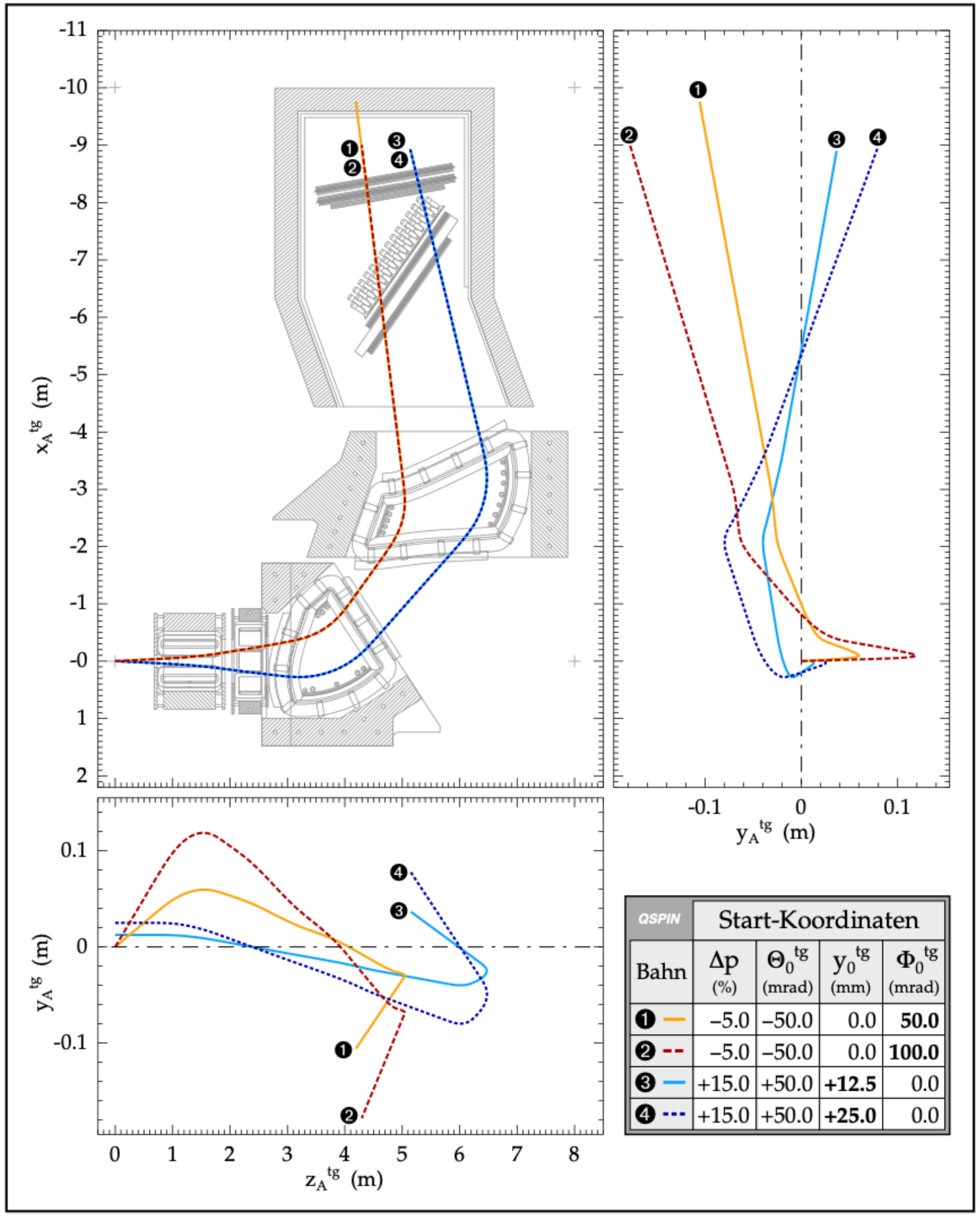


Point-to-point focussing in dispersive plane:

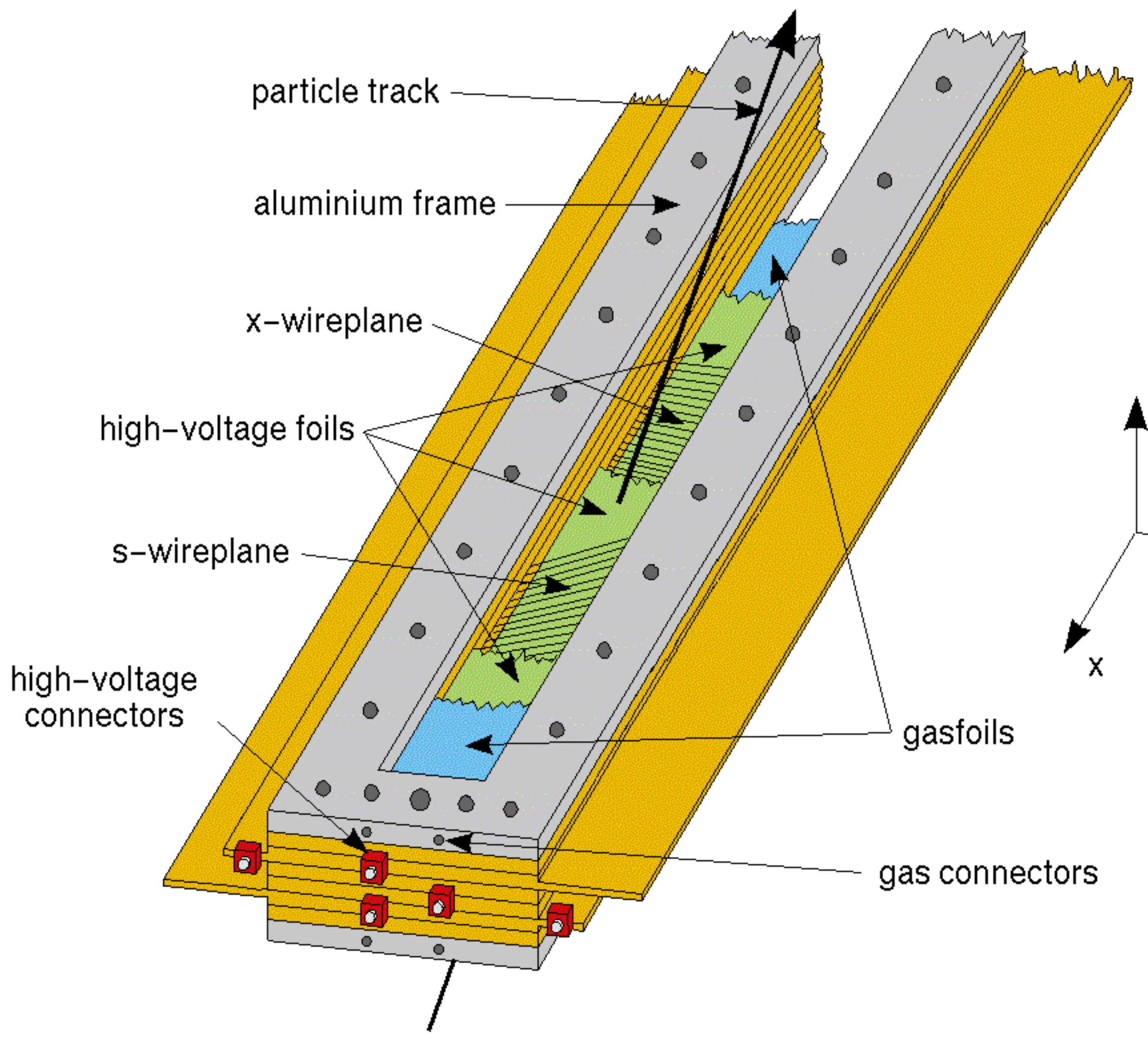
$$(x|\theta) = 0$$

Parallel-to-point focussing in non-dispersive plane:

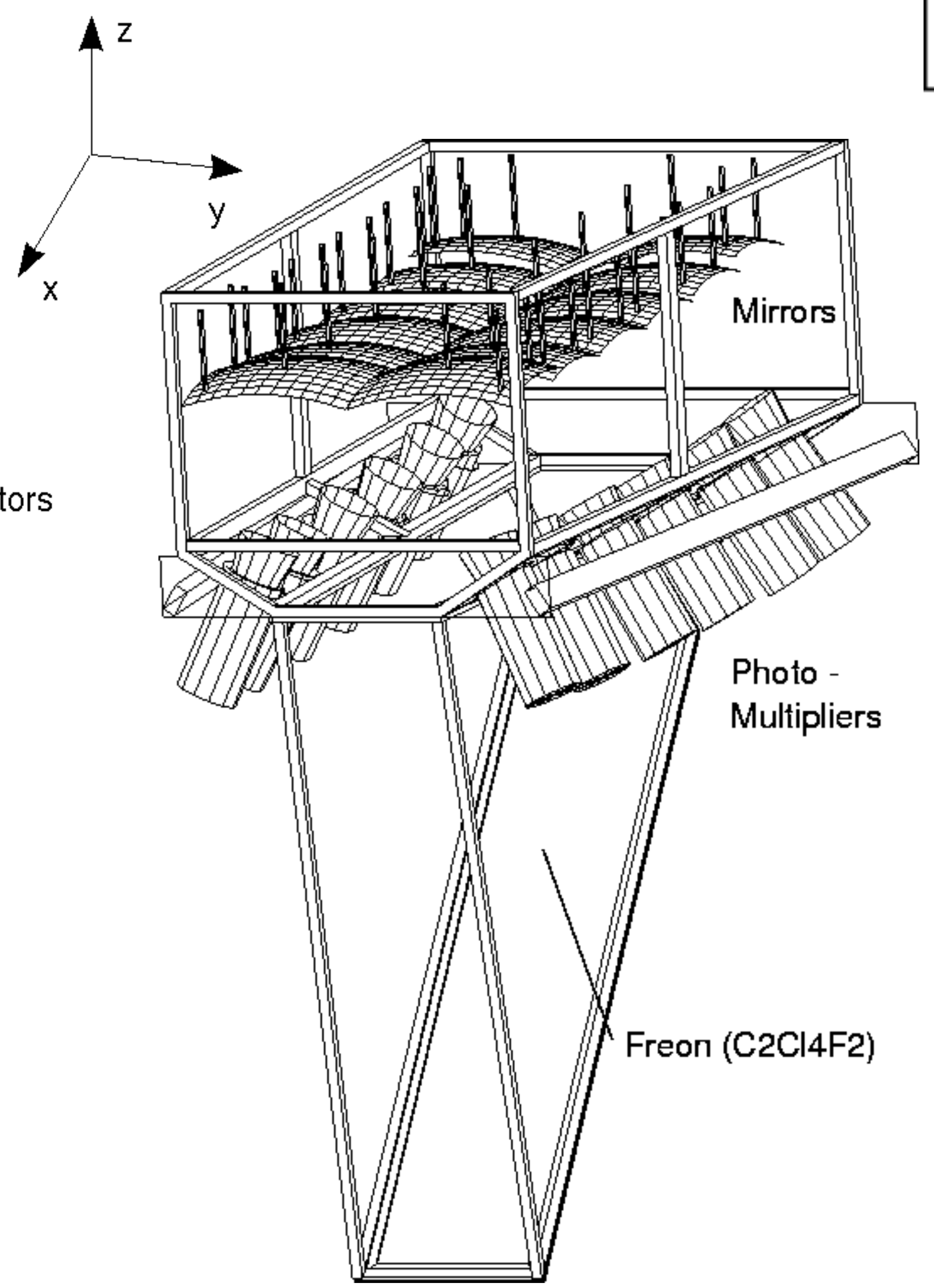
$$(y|y) = 0$$



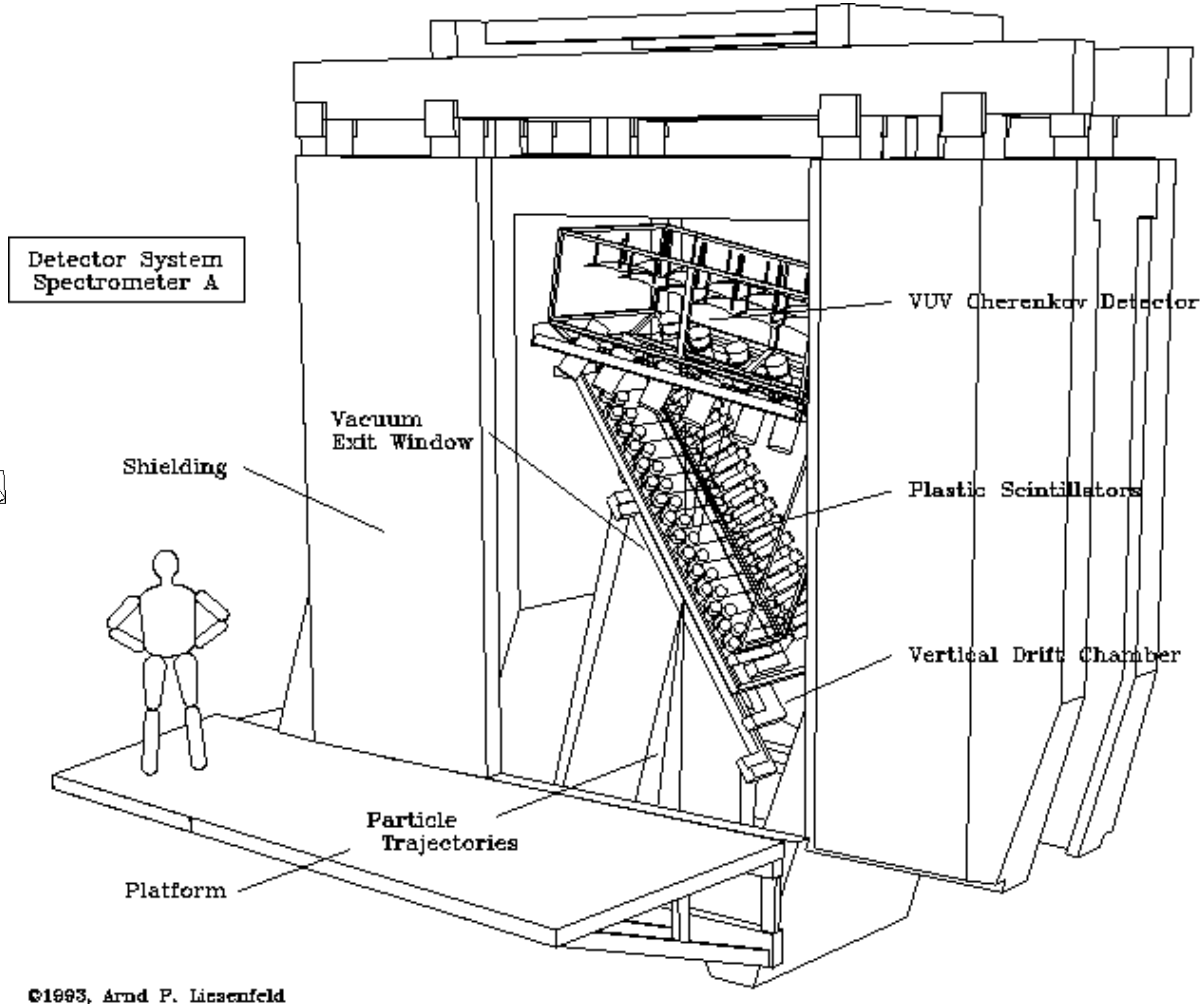
Detectors



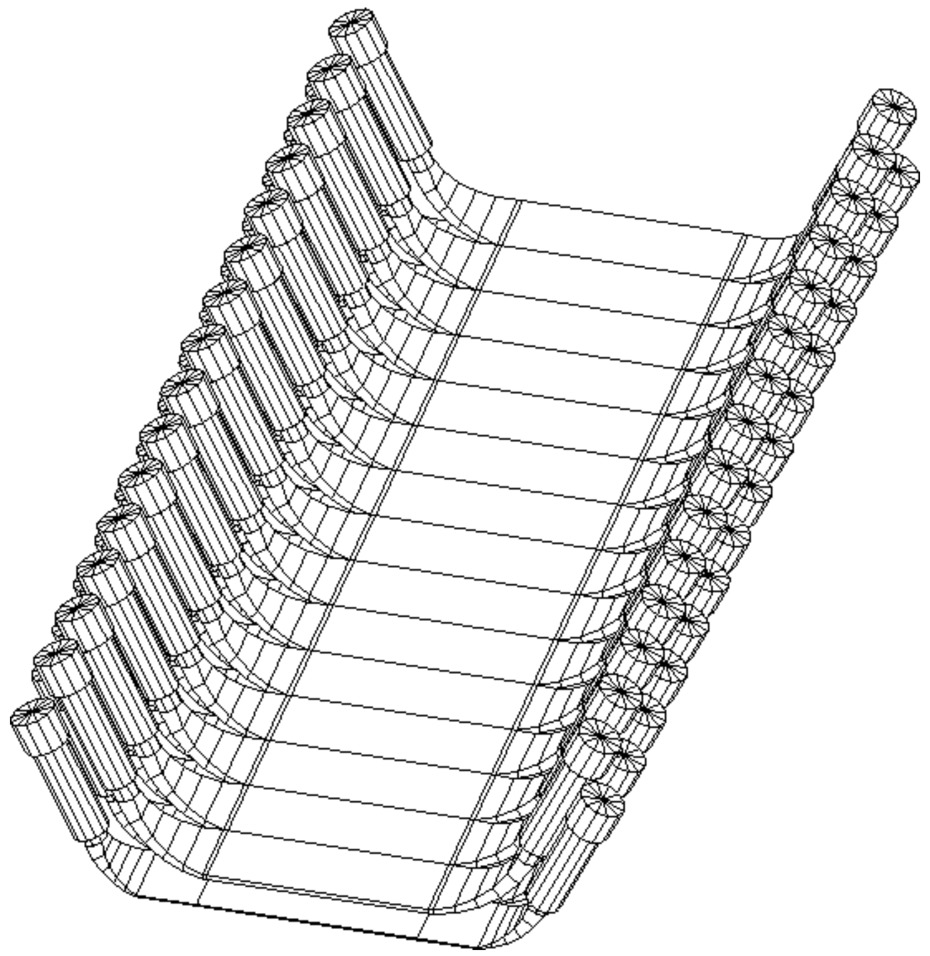
particle track
aluminium frame
x–wireplane
high–voltage foils
s–wireplane
high–voltage connectors
gasfoils
gas connectors



z
y
x
Mirrors
Photo - Multipliers
Freon (C2Cl4F2)



Detector System Spectrometer A
VUV Cherenkov Detector
Vacuum Exit Window
Shielding
Plastic Scintillators
Vertical Drift Chamber
Particle Trajectories
Platform
©1993, Arnd P. Liesenfeld



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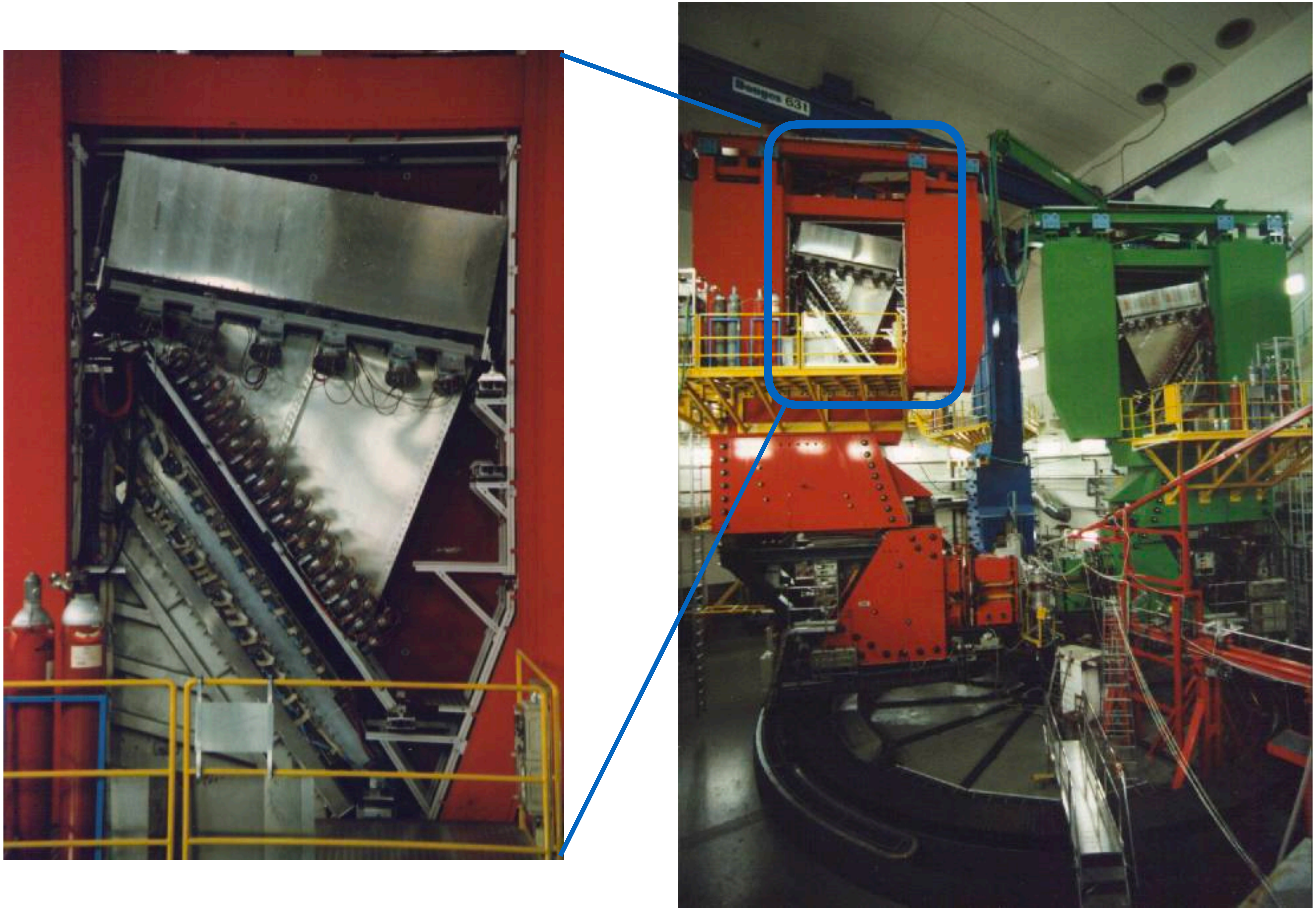
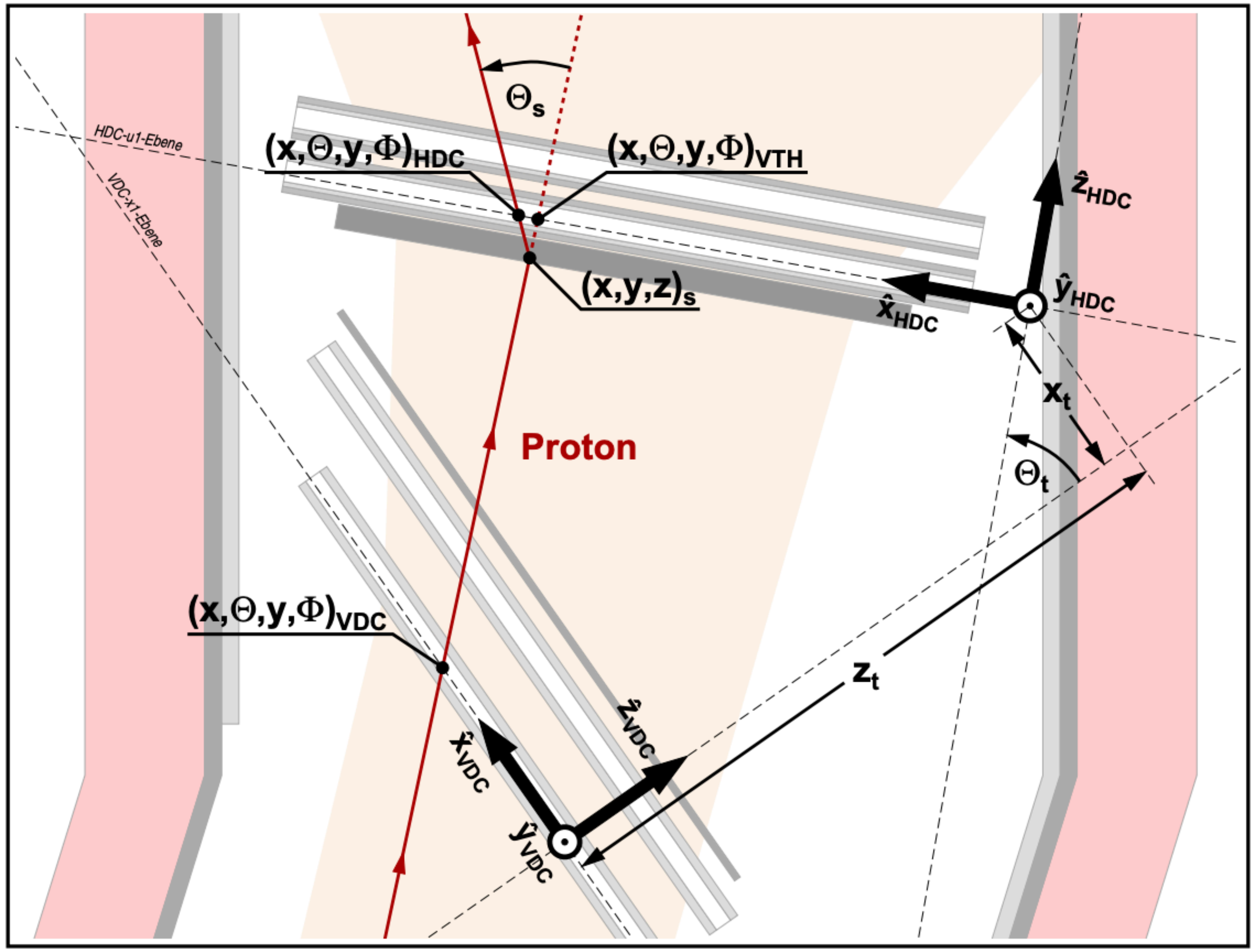
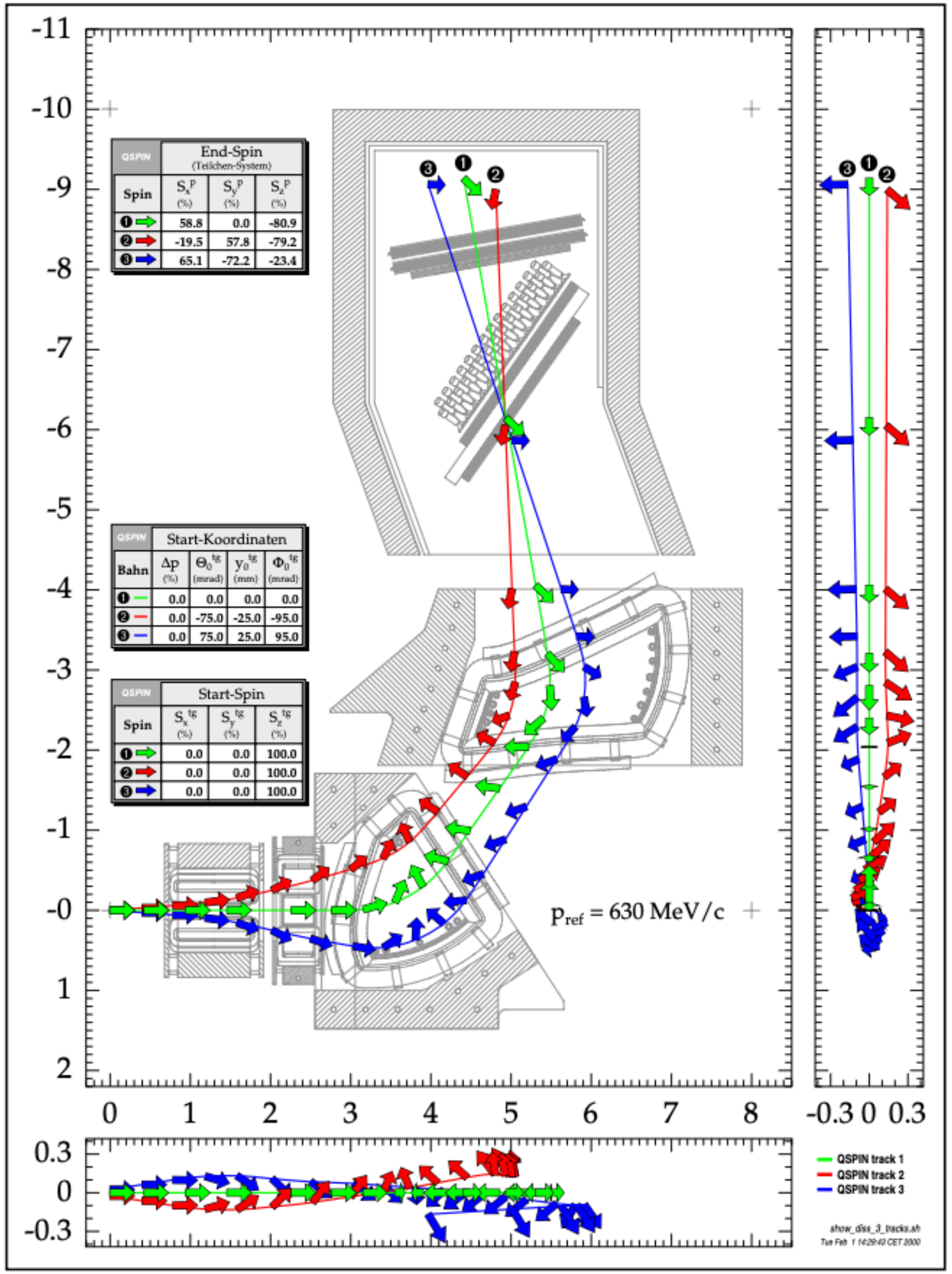


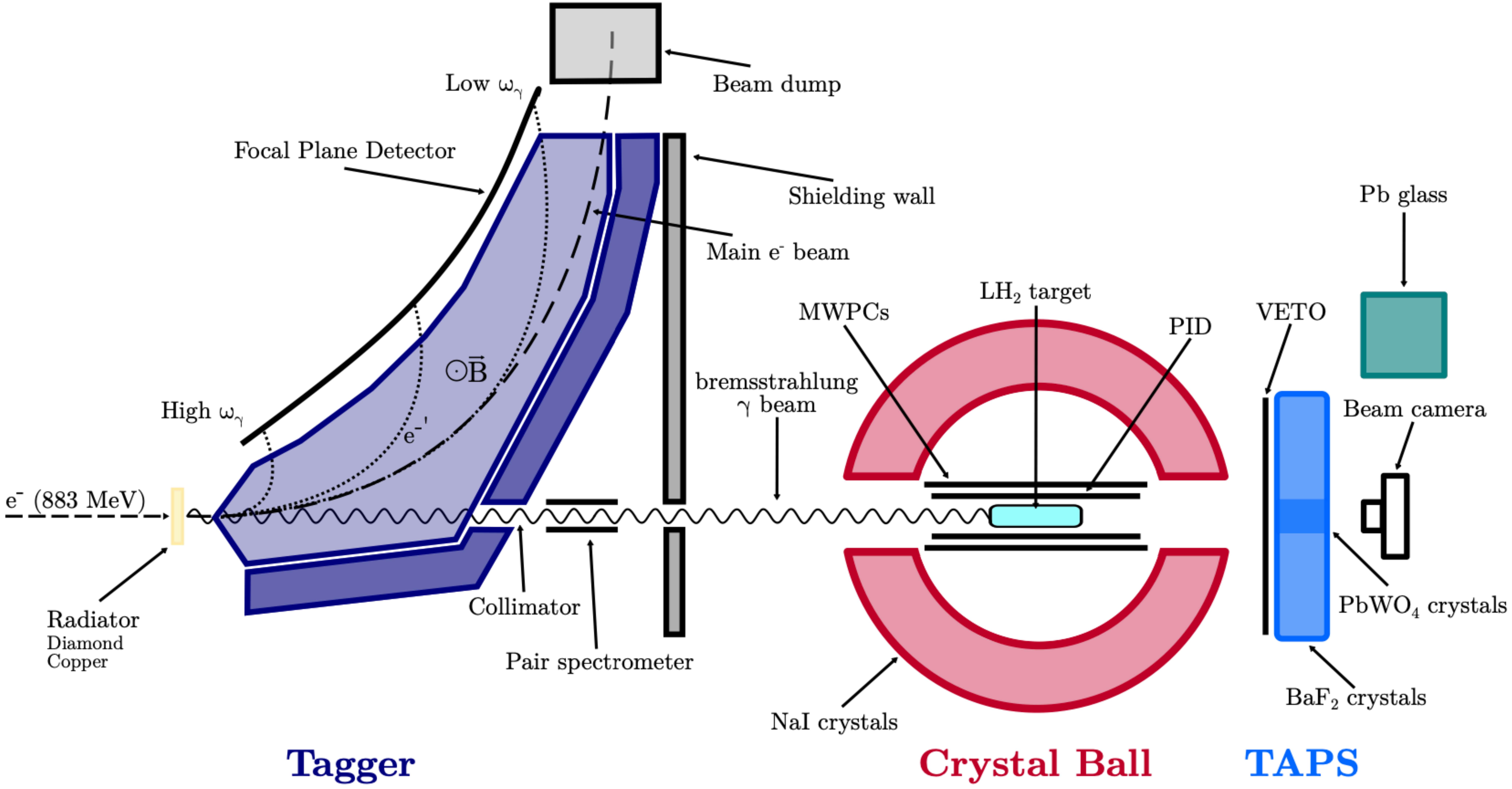
Focal Plane Polarimeter



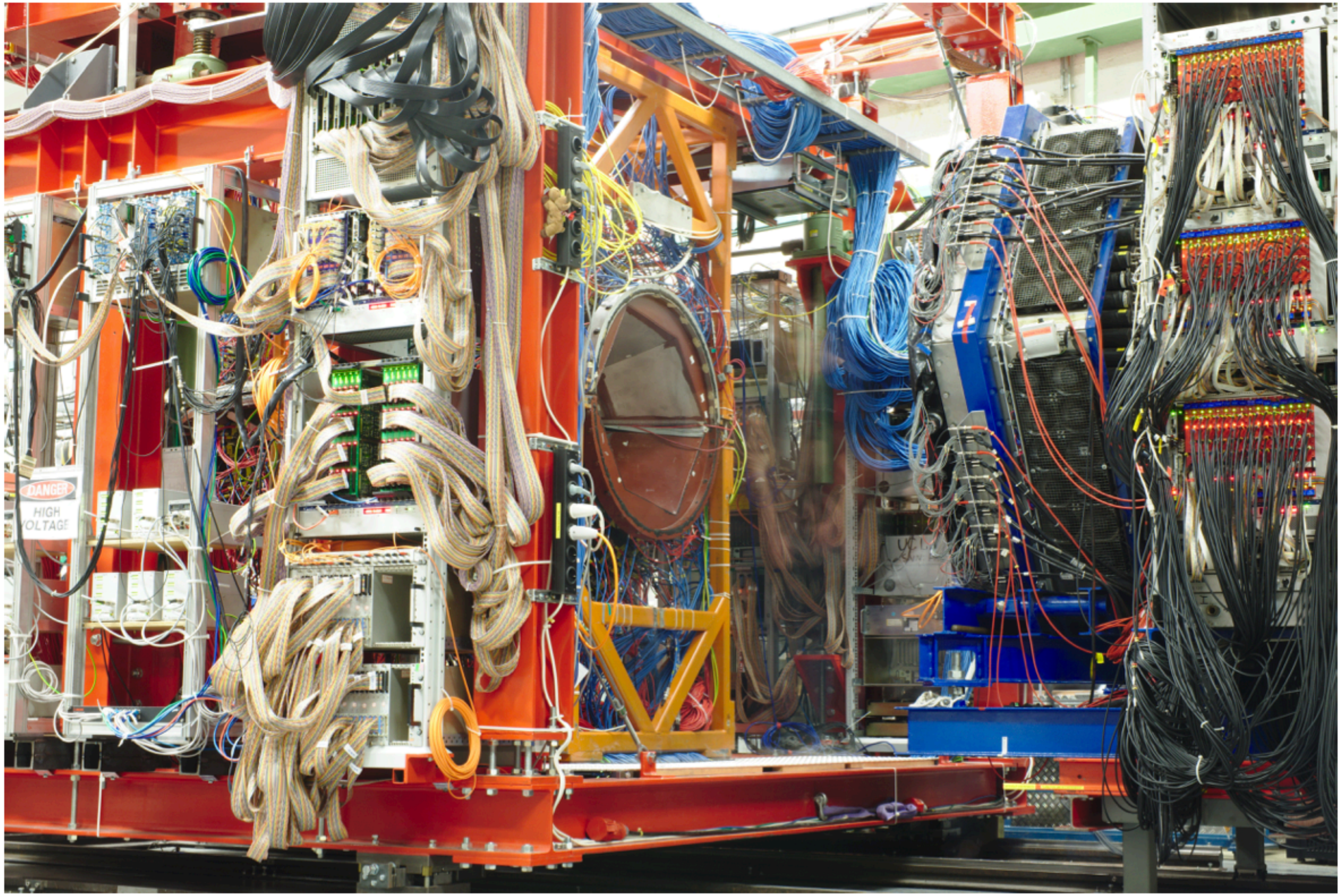


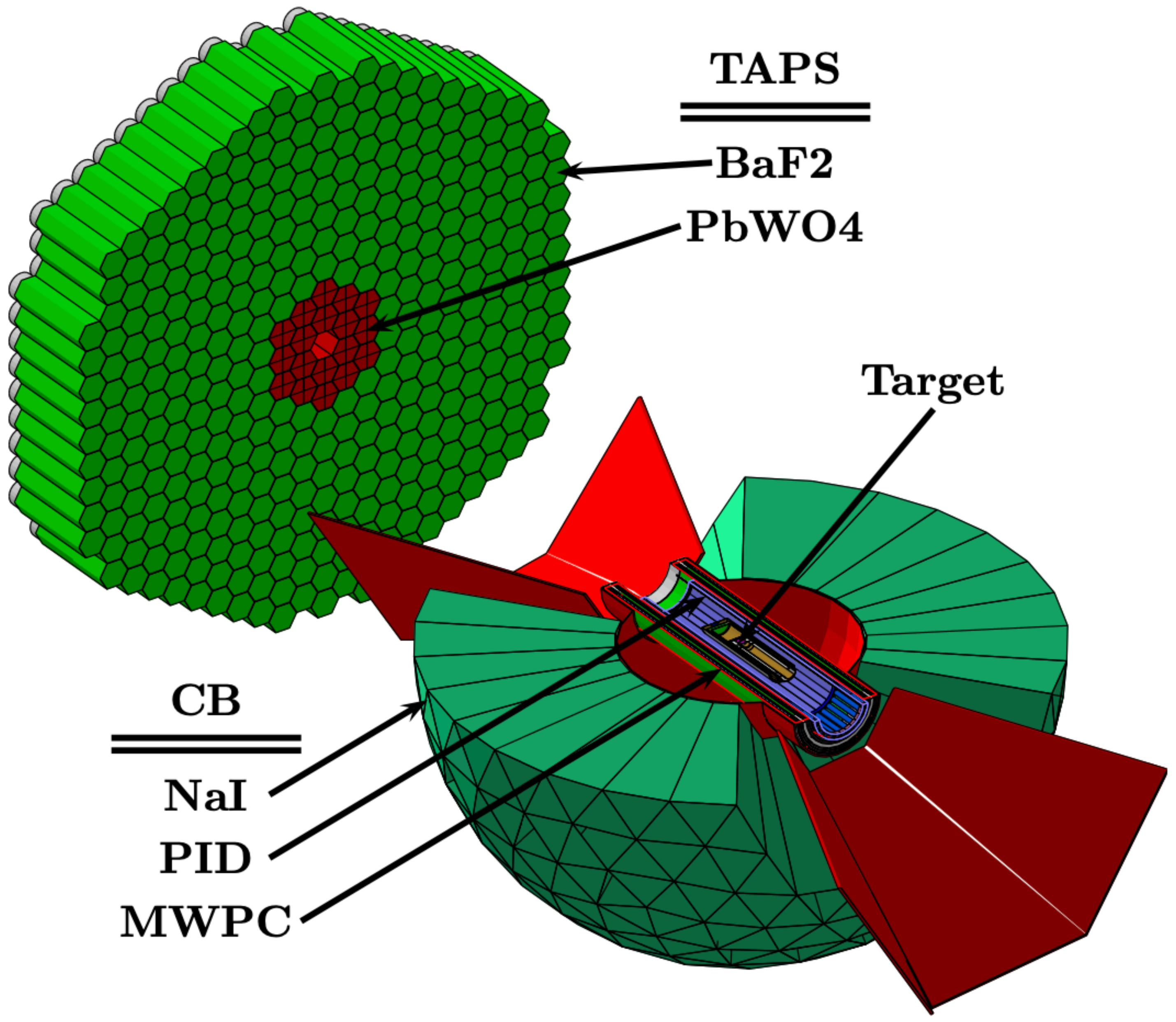
$$\begin{pmatrix} P_x \\ P_y \end{pmatrix}^{\mathrm{p}} = \begin{pmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \end{pmatrix} \cdot \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}^{\mathrm{tg}}$$

A2 Collaboration Setup



A2 Collaboration Setup





Bremsstrahlung

Radiation from (de)accelerated electrons

$$\theta \lesssim \frac{1}{E}$$

Energy-momentum conservation

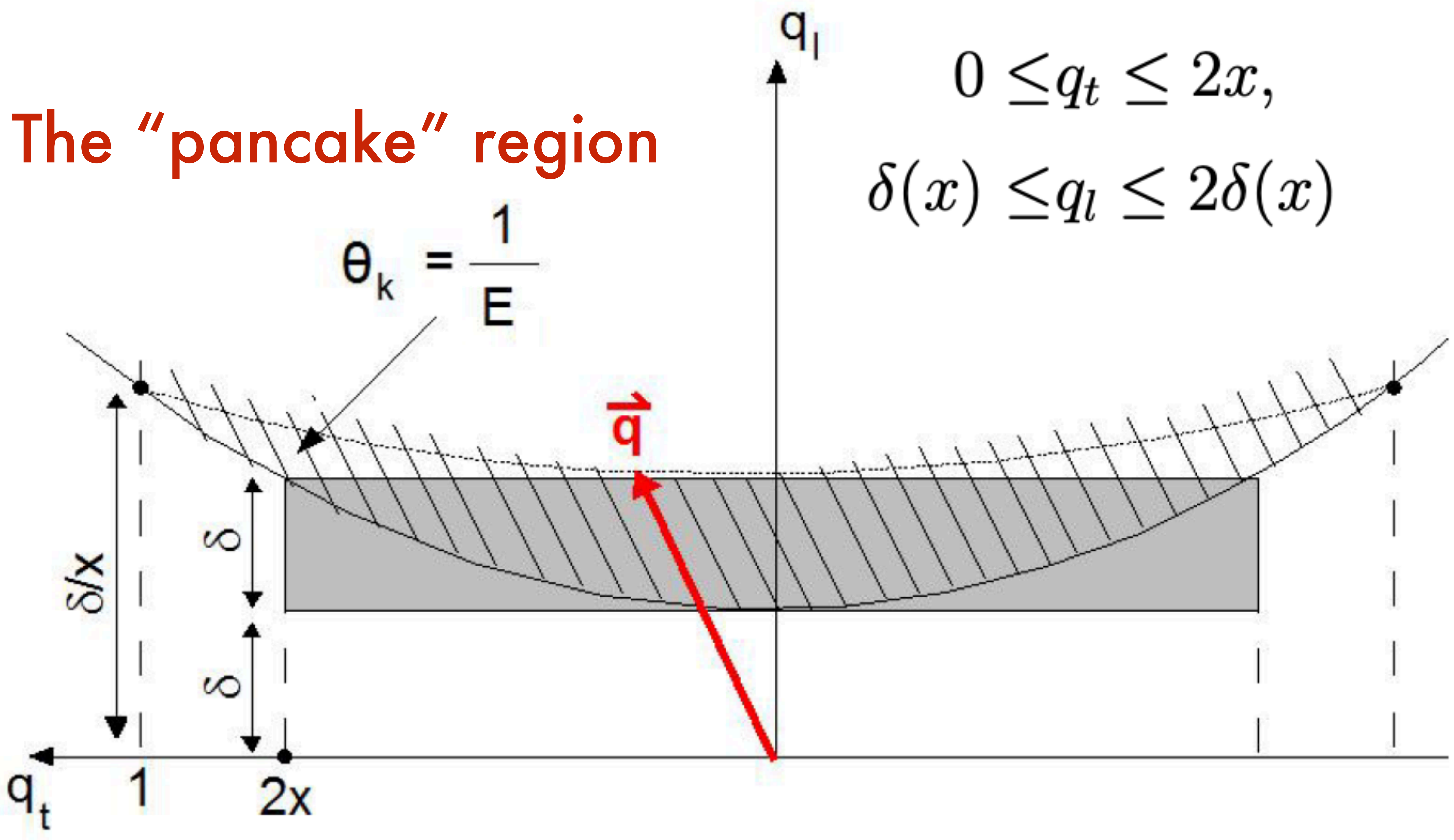
$$E = E' + k + T,$$
$$\vec{p} = \vec{p'} + \vec{k} + \vec{q}.$$

Nucleus recoil energy (about zero)

$$T = \frac{|\vec{q}|^2}{2M}$$

The "pancake" region

$$0 \leq q_t \leq 2x,$$
$$\delta(x) \leq q_l \leq 2\delta(x)$$



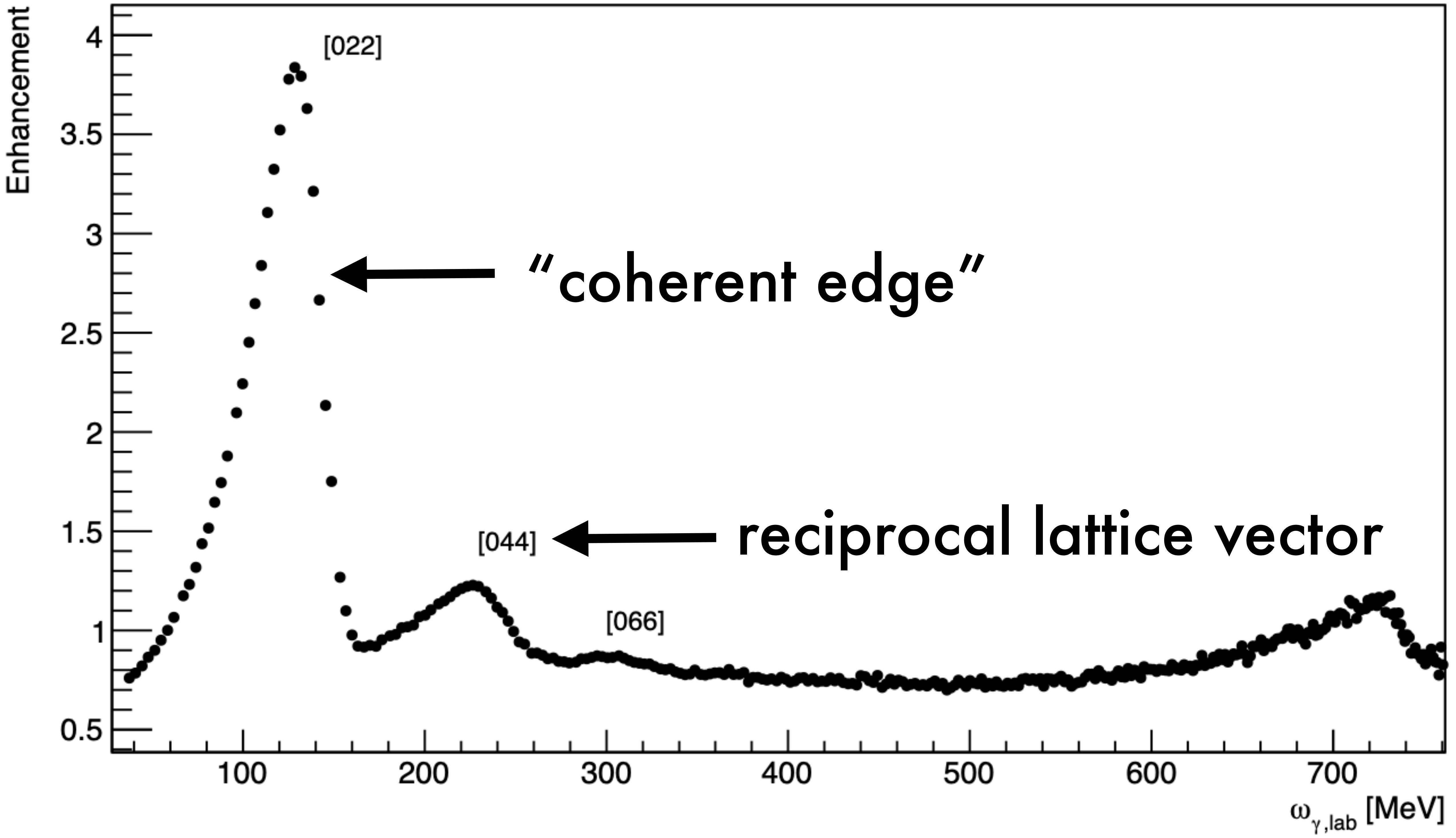
Fractional Energy $x = \frac{k}{E}$

Minimum longitudinal momentum $\delta(x) = \frac{x}{2E(1-x)}$

Polarised Bremsstrahlung (Linear Polarisation)

Incoherent bremsstrahlung: the electron beam impinges on an amorphous radiator, for example a thin metal foil. The electrons interact with the electric field of the nuclei and each point of the “pancake" region can be the end point of the recoil vector q. The cross-section for incoherent bremsstrahlung the Bethe-Heitler cross section, with dependence ~1/E.

Coherent bremsstrahlung: An electron beam impinging upon a thin crystal will produce both incoherent and coherent radiation. In the coherent case, the electron interacts with the whole crystal (not with a single nucleus). The bremsstrahlung cross-section is thus enhanced at discrete values of q causing broad peaks superimposed on the incoherent spectrum.



Polarised Bremsstrahlung (Linear Polarisation)

Enhancement: $R = \frac{\sigma^{crystal}}{\sigma^{incoh}}$ $\longrightarrow$ $\sigma^{crystal} = \sigma^{coh} + \sigma^{incoh}$

$\downarrow$

$$\sigma^{coh} = \sigma^{\parallel} + \sigma^{\perp}$$

Degree of polarization: $P = \frac{\sigma^{\perp} - \sigma^{\parallel}}{\sigma^{crystal}} = \left(1 - \frac{1}{R}\right) \frac{\sigma^{\perp} - \sigma^{\parallel}}{\sigma^{coh}}$

Parallel and orthogonal directions are defined with respect to the plane identified by the incoming electron and the lowest reciprocal crystal lattice vector.

$$\vec{a}^* = 2\pi \frac{(\vec{b} \times \vec{c})}{(\vec{a} \times \vec{b}) \cdot \vec{c}}$$

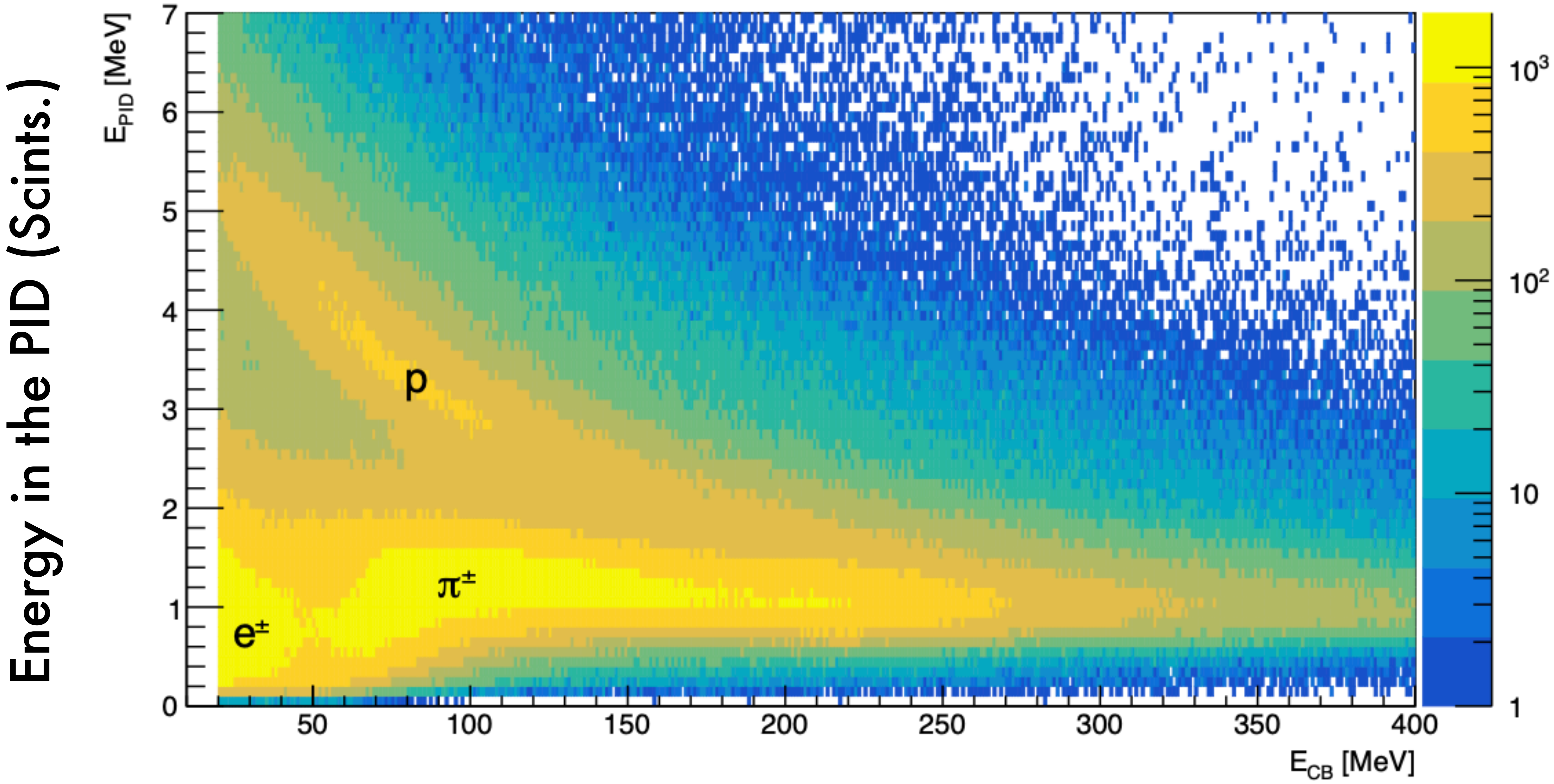
$$\vec{b}^* = 2\pi \frac{(\vec{c} \times \vec{a})}{(\vec{a} \times \vec{b}) \cdot \vec{c}}$$

$$\vec{c}^* = 2\pi \frac{(\vec{a} \times \vec{b})}{(\vec{a} \times \vec{b}) \cdot \vec{c}}$$

Circular polarisation is achieved with polarised beam and non-crystalline radiator.

Crystall Ball (NaI)

Density [g/cm3]	3.67
Melting point [K]	924
Thermal expansion coefficient [C-1]	47.7 x 10-6
Cleavage plane	<100>
Hardness (Mho)	2
Hygroscopic	Yes
Wavelength of emission max. [nm]	415
Refractive index @ emission max	1.85
Primary decay time [ns]	250
Light yield [photons/keVγ	38
Temperature coefficient of light yield	0.3%C-1



Energy in the Crystal Ball
(almost total E measurement)

Bethe-Bloch Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$