PRIOR

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HEPM-2010

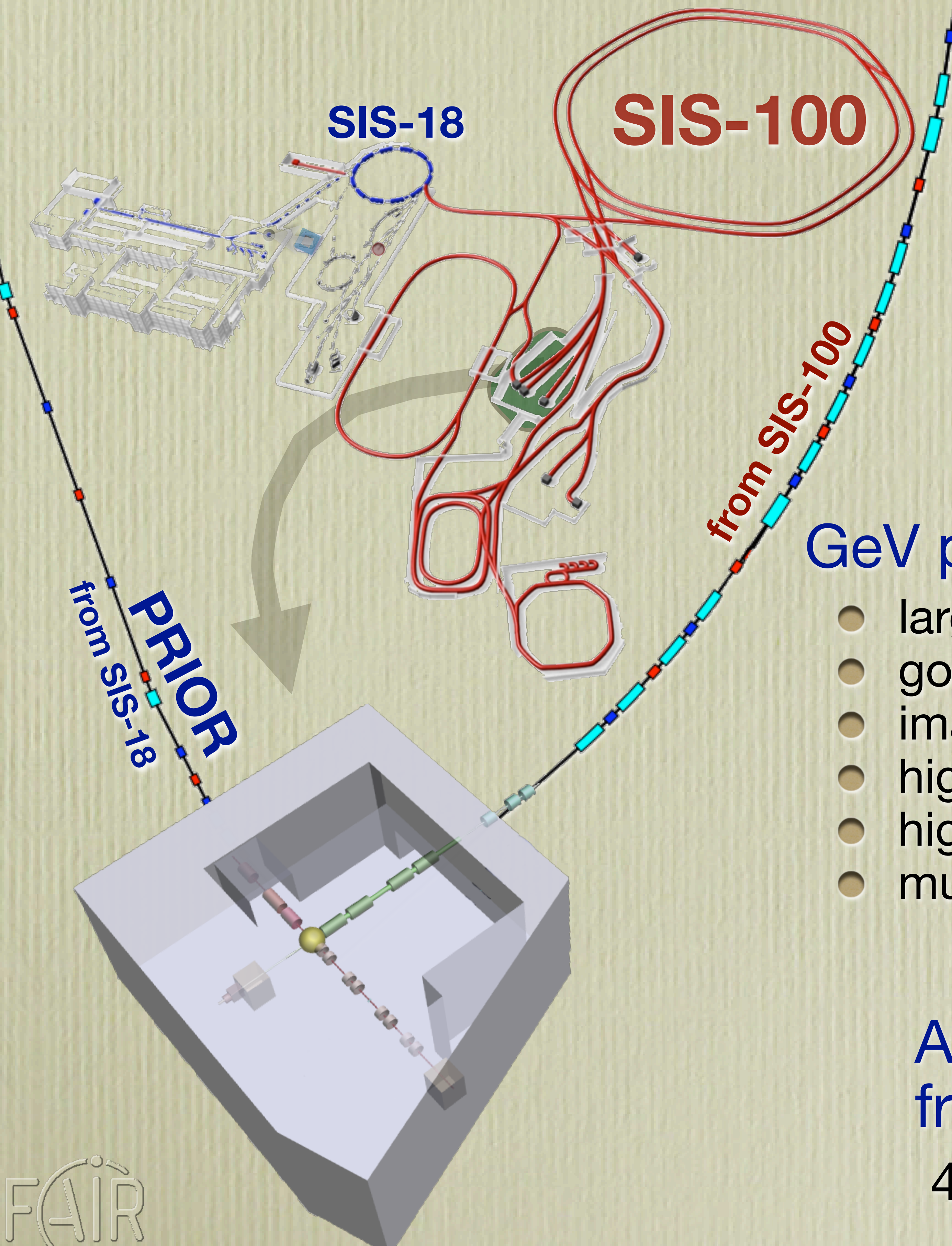
Proton Microscope for FAIR

HELMHOLTZ ASSOCIATION

112 | JOINT RESEARCH GROUP

Los Alamos NATIONAL LABORATORY

High Energy Proton Microscopy at FAIR



Challenging requirements for density measurements in dynamic HEDP experiments:

- up to ~20 g/cm^2 (Fe, Pb, Au, etc.)
- ≤10 μm spatial resolution
- 10 ns time resolution (multi-frame)
- sub-percent density resolution

GeV protons:

- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnets
- high spatial resolution (microscopy)
- high density resolution and dynamic range
- multi-frame capability for fast dynamic events

At FAIR: a dedicated beam line from SIS-18 for radiography

4.5 GeV, $5 \cdot 10^{12}$ protons

PRIOR project will accomplish two main tasks:

- FAIR proton radiography system which a core FAIR installation will be designed, constructed and commissioned in full-scale dynamic experiments with 4.5 GeV proton beam

- prior to FAIR using the same SIS-18 proton beam, a worldwide unique radiographic facility may become operational at GSI that would provide a capability for unparalleled high-precision experiments with great discovery potential at the leading edges of plasma physics, high energy density physics, biophysics, and materials research

Technical specifications and resolution scalings

Spatial resolution scalings with proton energy:

- object scattering

$$\sigma_o \propto \frac{\ell_t^{\frac{3}{2}}}{p}$$

- chromatic aberrations

$$\sigma_c \propto \frac{\ell_t^{\frac{1}{2}}}{p^{\frac{3}{2}}}$$

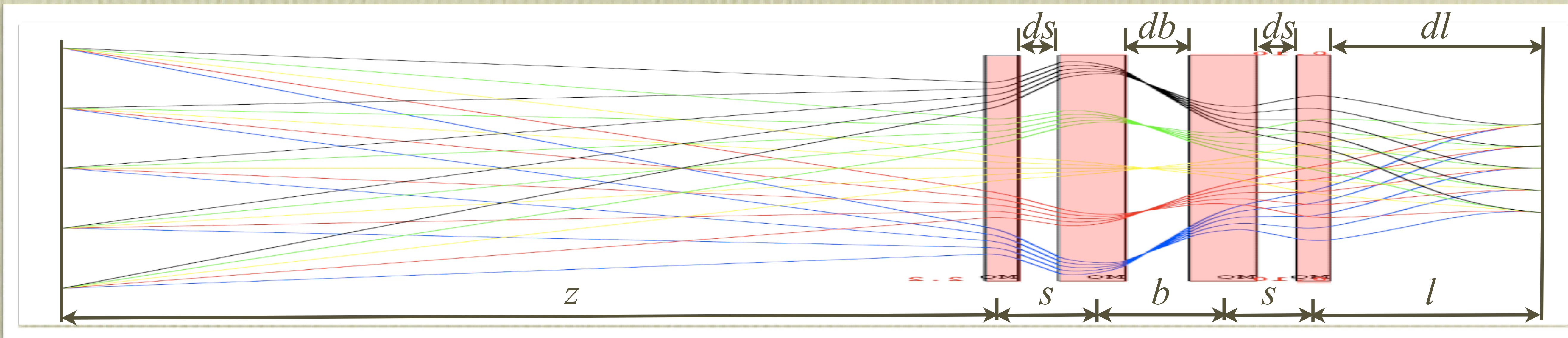
- detector blur

$$\sigma_d \propto \frac{\ell_s \ell_t^{\frac{1}{2}}}{p}$$

PRIOR technical specifications (for FAIR experiments):

- proton energy: 4.5 GeV
- spatial resolution: ≤10 μm
- temporal resolution: 10 – 20 ns
- multi-framing capability: 1 – 4 frames within 1 μs
- target characteristics: up to 20 g/cm^2
- areal density reconstruction: sub-percent level
- field of view: 10 – 15 mm
- stand-off distance: 1 – 1.5 m
- proton illumination spot size: 3 – 15 mm
- total length after object plane: less than 15 m
- using permanent magnets or/and existing electromagnets

Magnetic lens design: thin lens approximation



$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-1}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{k}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-k}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -m & 0 \\ M_{21} & \frac{-1}{m} \end{pmatrix}$$

Total length: $x = z + 2 \cdot s + b + l$

Quad focal length: $$f = \sqrt{\frac{k^2ms^2}{km - m + k - 1} - \frac{k^2s^2}{km - m + k - 1} + \frac{2k^2lms}{km - m + k - 1} - \frac{2klms}{km - m + k - 1}}$$

Last Quad to detector: $$z = \frac{(km - k)\, s + (k - 1)\, lm}{k - 1}$$

Distance 2nd to 3rd Quad: $$b = \frac{(km - k)\, s^2 + (2k - 2)\, lms}{(k^2 - k)\, ms + (k^2 - 2k + 1)\, lm}$$

Chromatic length - complicated function of lens spaces:

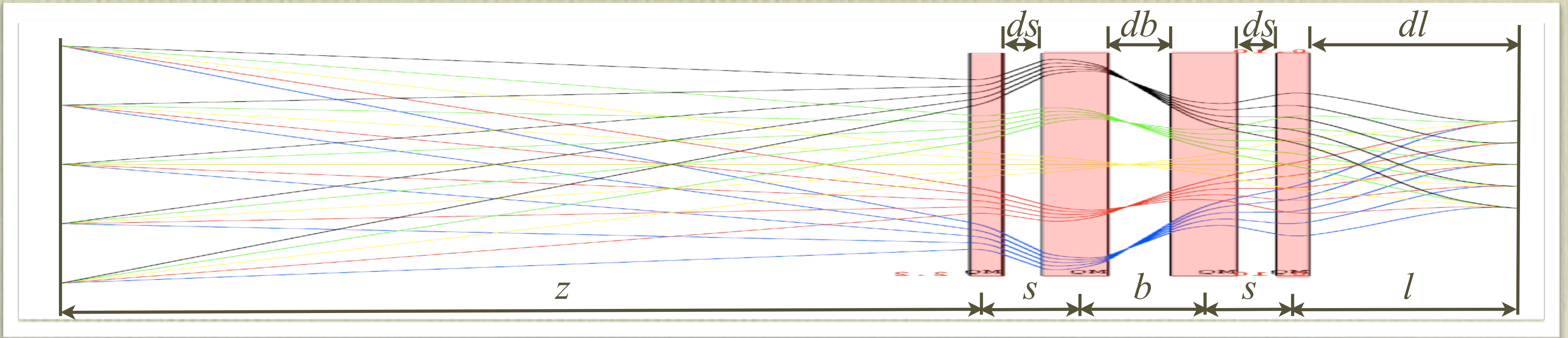
$$M_{126} = \frac{-4bk^2ls^2z}{f^4} + \frac{3bk^2s^2z}{f^3} + \frac{4lsz}{f^2} + \frac{2bk^2sz}{f^2} - \frac{2sz}{f} + \frac{2bk^2lz}{f^2} - \frac{4bklz}{f^2} + \frac{2blz}{f^2} + \frac{bkz}{f} - \frac{bz}{f} - \frac{3bk^2ls^2}{f^3} + \frac{2bk^2s^2}{f^2} + \frac{2bk^2ls}{f^2} + \frac{2ls}{f} - \frac{bkl}{f} + \frac{bl}{f}$$

$$M_{346} = \frac{-4bk^2ls^2z}{f^4} - \frac{3bk^2s^2z}{f^3} + \frac{4lsz}{f^2} + \frac{2bk^2sz}{f^2} + \frac{2sz}{f} + \frac{2bk^2lz}{f^2} - \frac{4bklz}{f^2} + \frac{2blz}{f^2} - \frac{bkz}{f} + \frac{bz}{f} + \frac{3bk^2ls^2}{f^3} + \frac{2bk^2s^2}{f^2} + \frac{2bk^2ls}{f^2} - \frac{2ls}{f} + \frac{bkl}{f} - \frac{bl}{f}$$

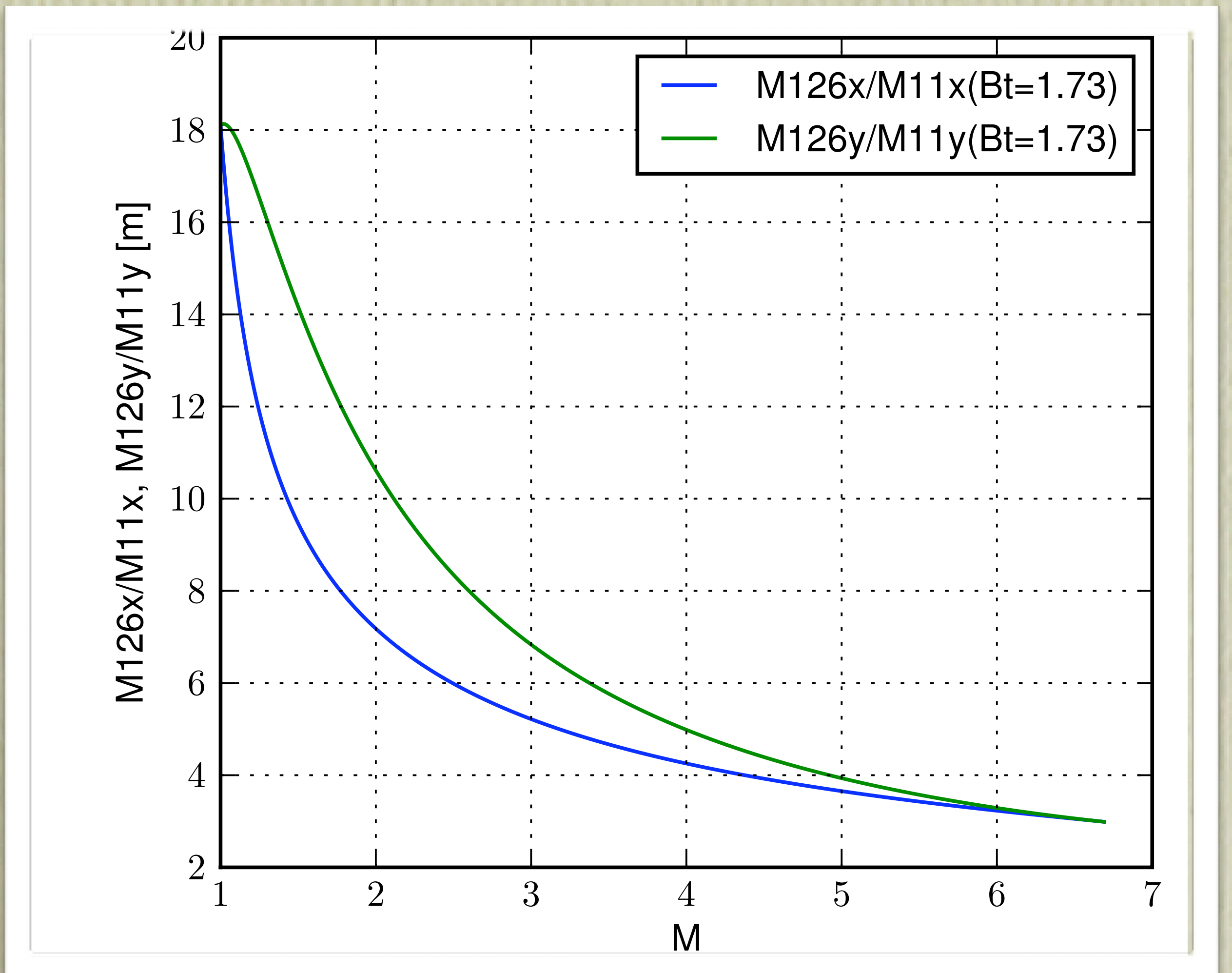
Chromatic blur:
(characterize spatial resolution)

$$x_0 - \frac{x_i}{M_{11}} = \frac{M_{126}\theta_A\delta}{M_{11}};\, y_0 - \frac{y_i}{M_{33}} = \frac{M_{346}\theta_A\delta}{M_{33}}$$ - for properly matched beam

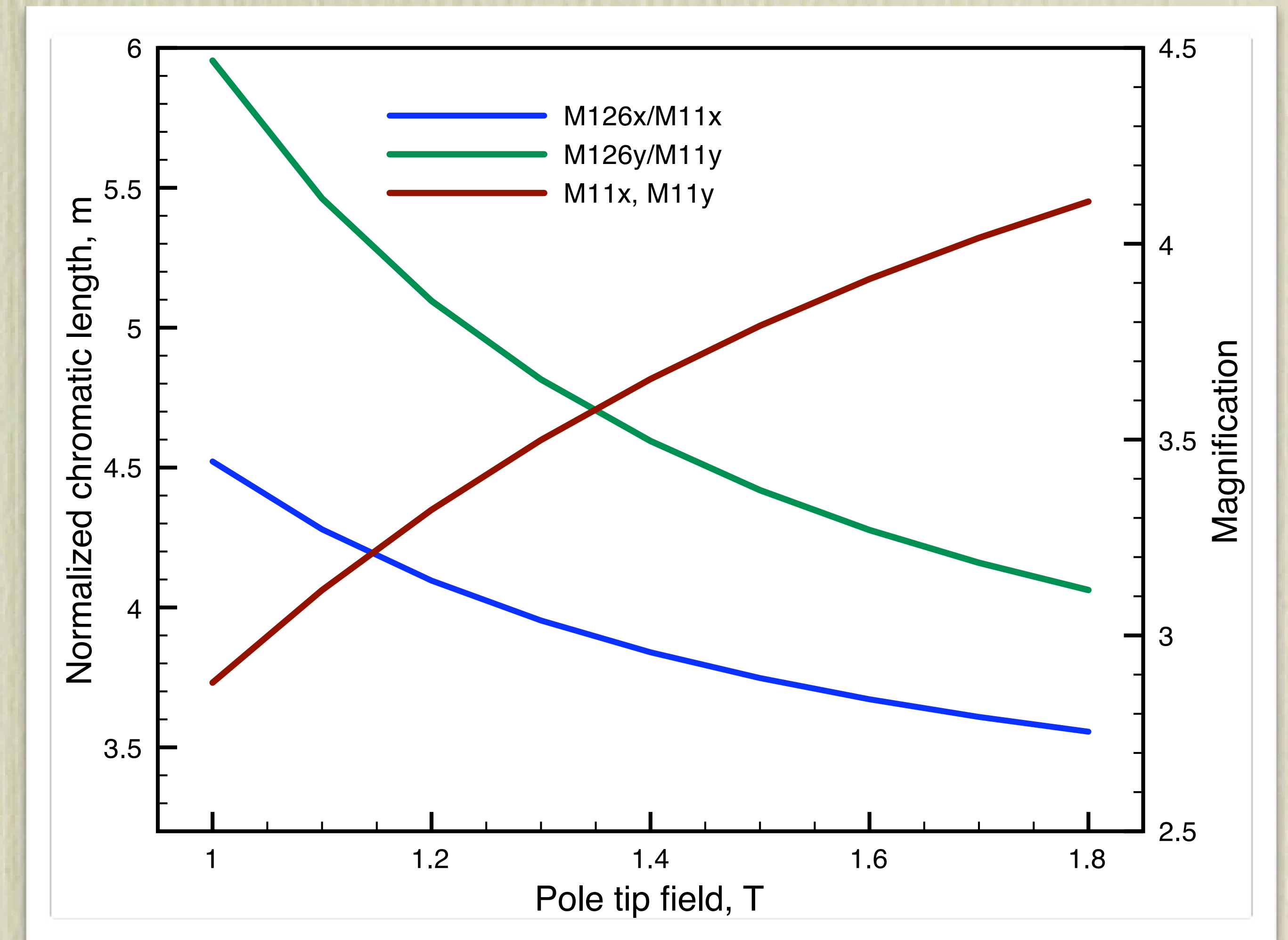
Magnetic lens design: thin lens approximation



Normalized chromatic length vs magnification (Fixed total length x=10 m and pole tip field B_t=1.73 T)



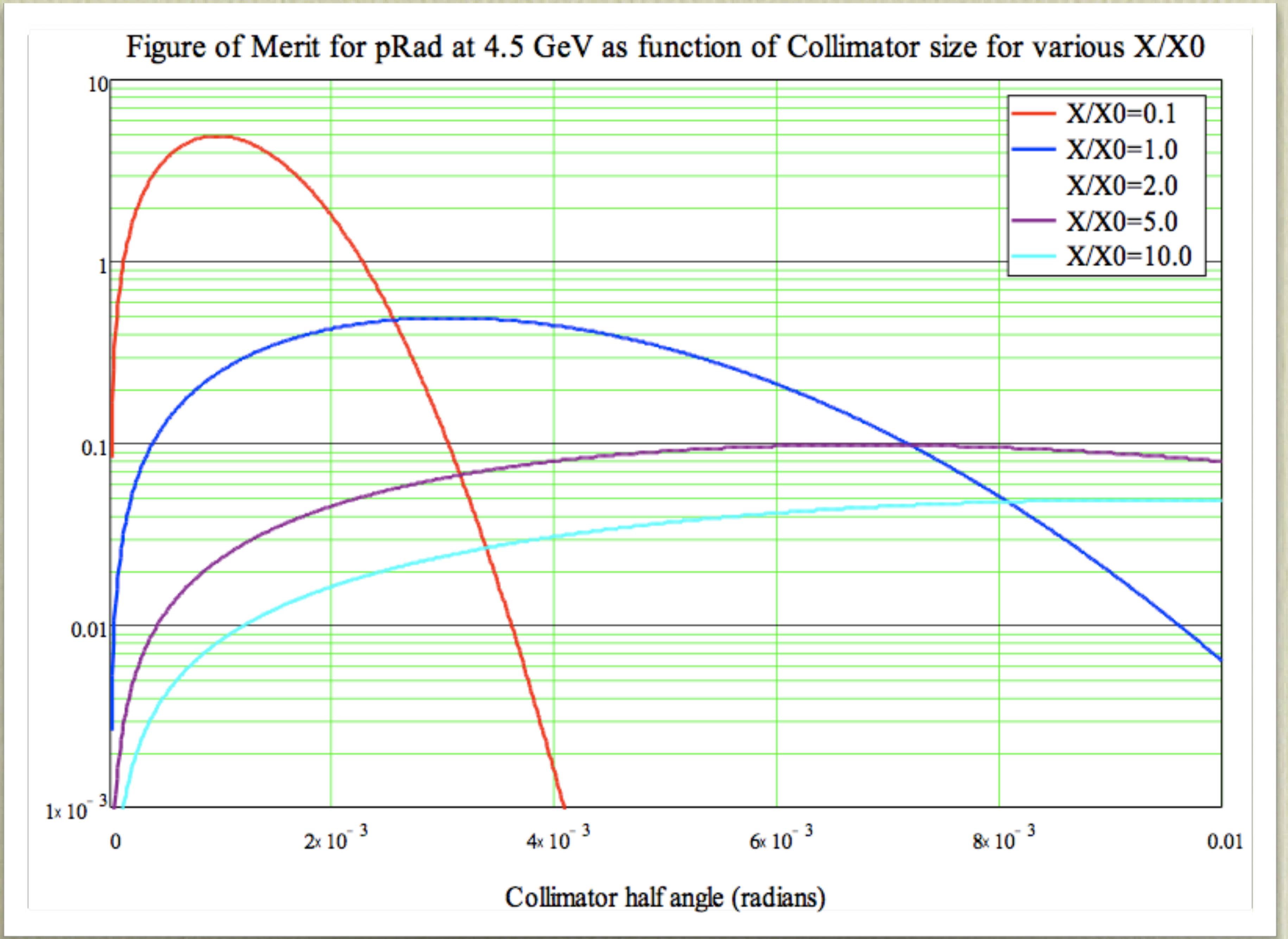
Normalized chromatic length and magnification vs pole tip field B_t (Fixed total length x=10 m)



Density reconstruction figure of merit

$$\Delta\rho \propto \sqrt{T(\ell,\theta_c)} \cdot \frac{1}{T(\ell,\theta_c)} \frac{\partial T(\ell,\theta_c)}{\partial \ell}, \quad \ell = X/X_0$$

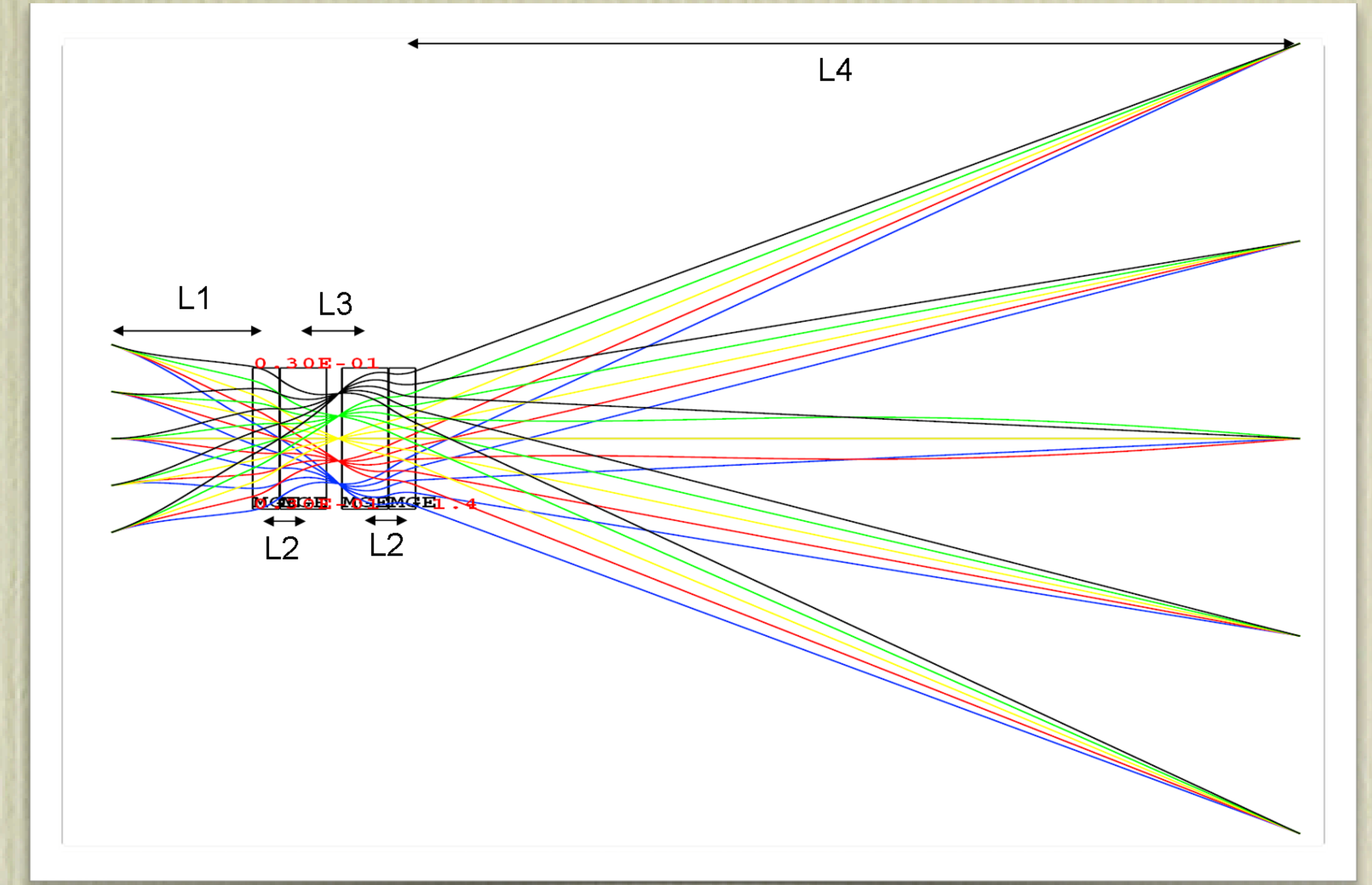
$$\Delta x \propto C_x \cdot \theta_c \cdot \delta E(\ell)$$



- anti-collimator can also be used to enhance accuracy for thin objects

PRIOR magnetic lens design – 15 mm PMQ aperture

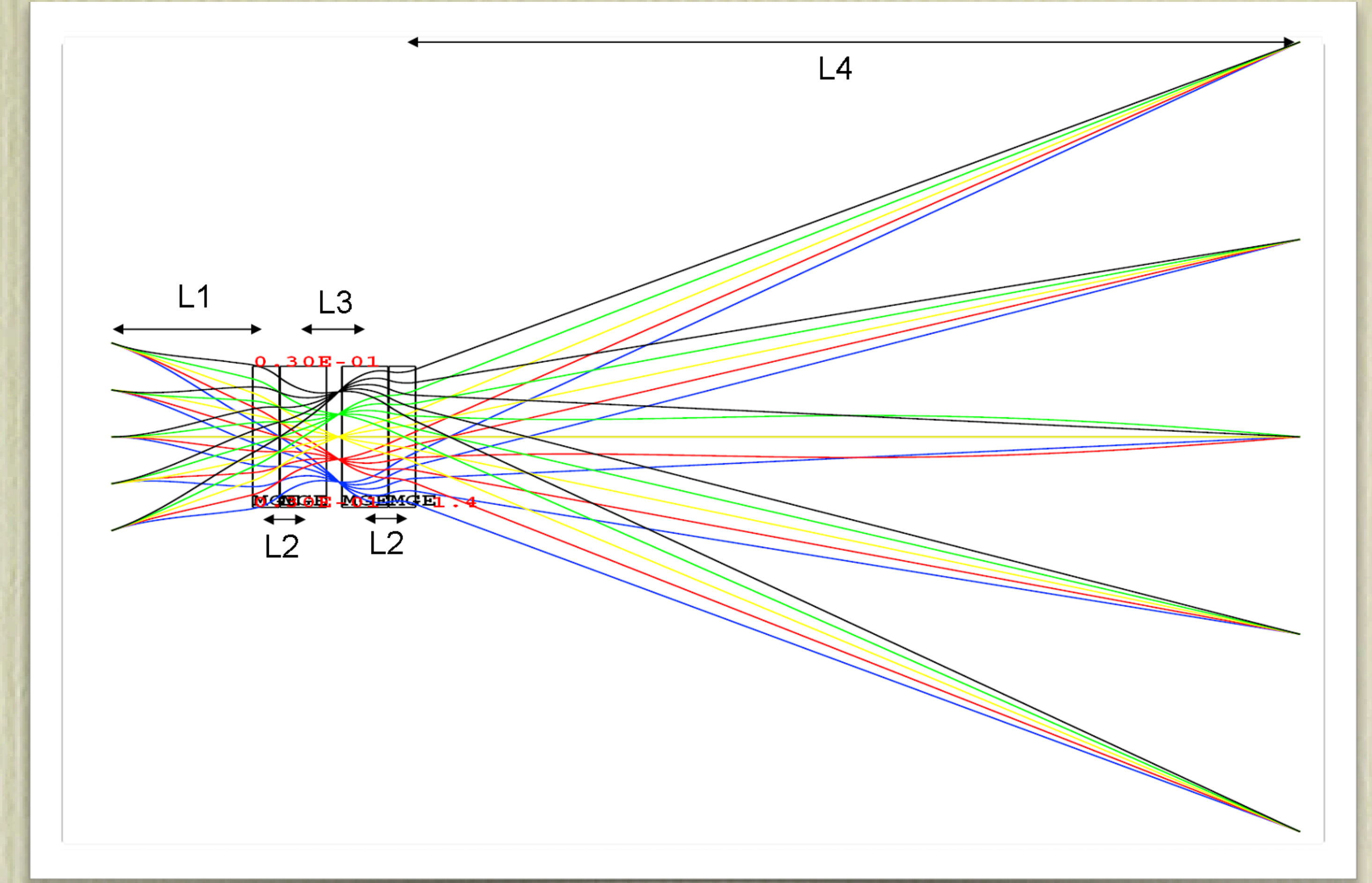
Parameter	Value
Proton energy	4.5 GeV
PMQ inner aperture, $2 \cdot R_i$	15 mm
PMQ outer aperture, $2 \cdot R_o$	79 mm
REPM remanent field	1.16 T
Field gradient	238 T/m
"Short" quadrupole length	110 mm
"Long" quadrupole length	220 mm
L_1 (object to first quad)	1.0 m
L_2 (first to second)	0.202 m
L_3 (second to third)	0.346 m
L_4 (last to image)	8.25 m
Total length	10.000 m



Parameter	Value
Magnification	6.12
Spatial resolution	6 – 7 μm
Horizontal chromatic length, C_x	2.74 m
Vertical chromatic length, C_y	2.40 m
Angular acceptance	5 mrad
Horizontal matching correlation, M_x	-0.42 mrad/mm
Vertical matching correlation, M_y	-0.53 mrad/mm

PRIOR magnetic lens design – 30 mm PMQ aperture

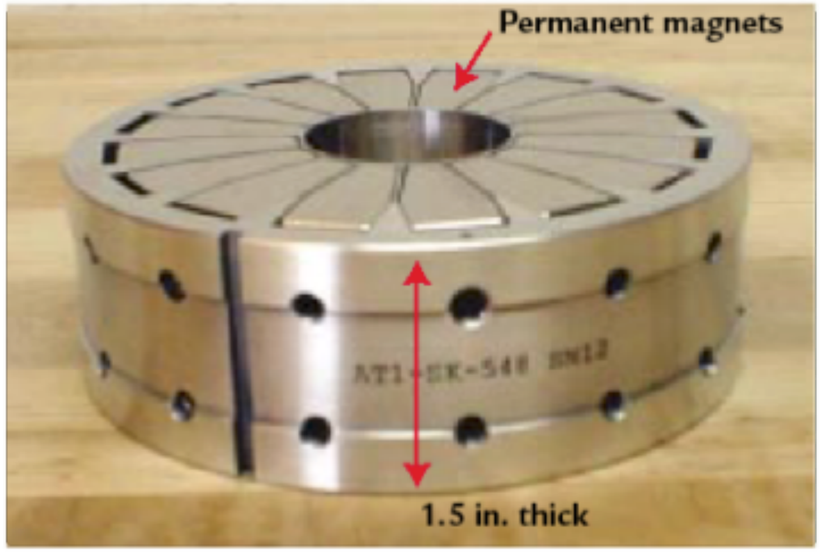
Parameter	Value
Proton energy	4.5 GeV
PMQ inner aperture, $2 \cdot R_i$	30 mm
PMQ outer aperture, $2 \cdot R_o$	100 mm
REPM remanent field	1.16 T
Field gradient	115 T/m
"Short" quadrupole length	165 mm
"Long" quadrupole length	330 mm
L_1 (object to first quad)	1.3 m
L_2 (first to second)	0.307 m
L_3 (second to third)	0.515 m
L_4 (last to image)	7.576 m
Total length	10.000 m



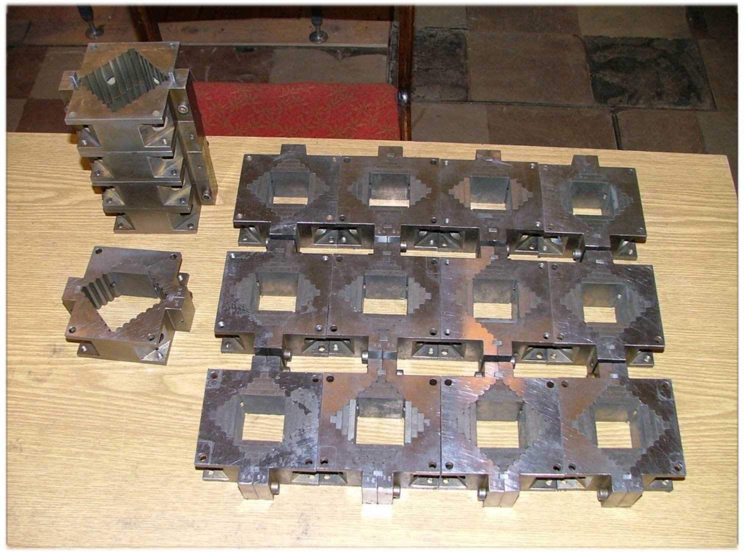
Parameter	Value
Magnification	4.1
Spatial resolution	8 – 10 μm
Horizontal chromatic length, C_x	3.99 m
Vertical chromatic length, C_y	3.41 m
Angular acceptance	5 mrad
Horizontal matching correlation, M_x	-0.45 mrad/mm
Vertical matching correlation, M_y	-0.55 mrad/mm

Permanent Magnetic Quadrupoles (PMQ)

High-gradient (Halbach) split-pole (LANL)



Quasi-Sheet Multipole (ITEP)



ITEP microscope

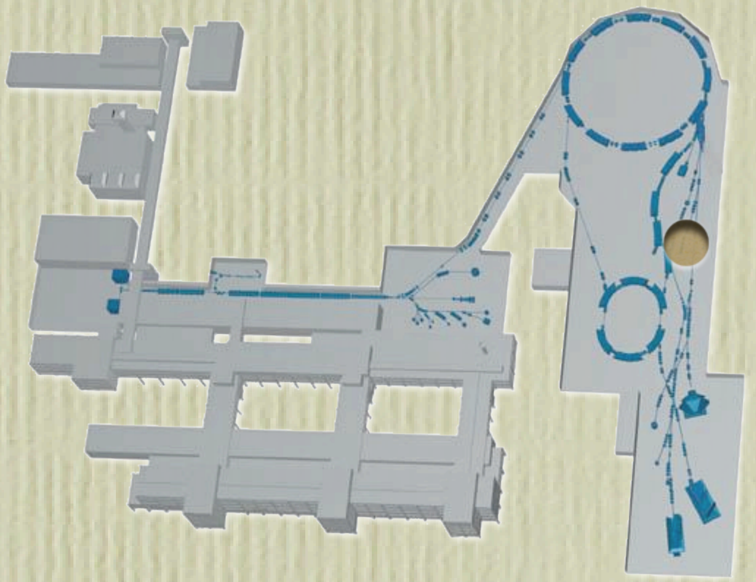
PMQ parameter	Value
Inner aperture, $2 \cdot R_i$	15 mm
Outer dimensions, $2 \cdot Ro$ x L	79 x 100 mm
Internal ring magnetization	1.16 T
External ring magnetization	1.19 T
Pole tip field	1.7 T
Field non-linearity	< 0.75 %
Field gradient	238 T/m
Integrated field	23.8 T

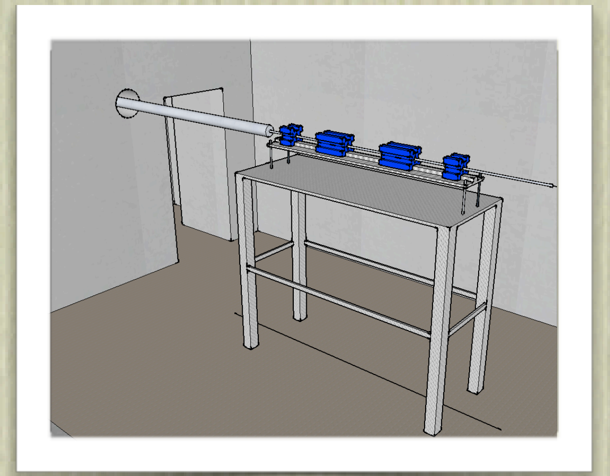
- field gradients up to 240 T/m
- 0.75% or better field linearity
- design and measured PMQ parameters agrees to measurement accuracy
- REPM: Sm-Co vs Nd-Fe-B
- off-line measurements of the PRIOR 16-sector high gradient split-pole PMQ prototypes have been already started at ITEP

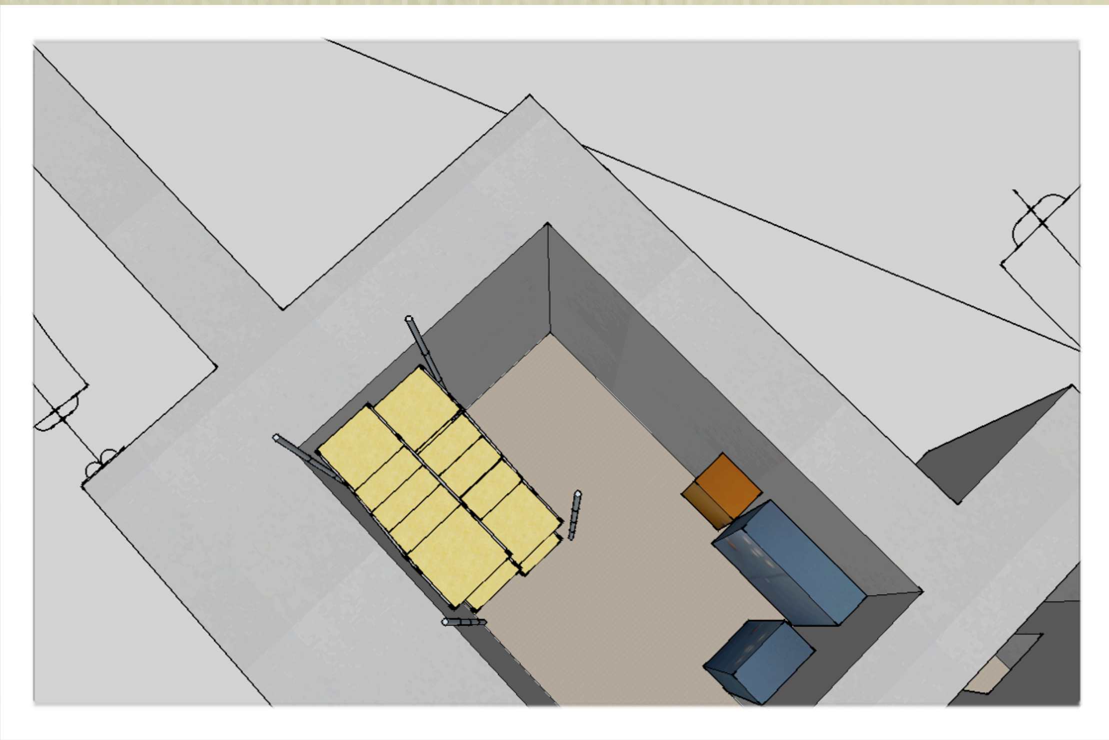
PRIOR setup features

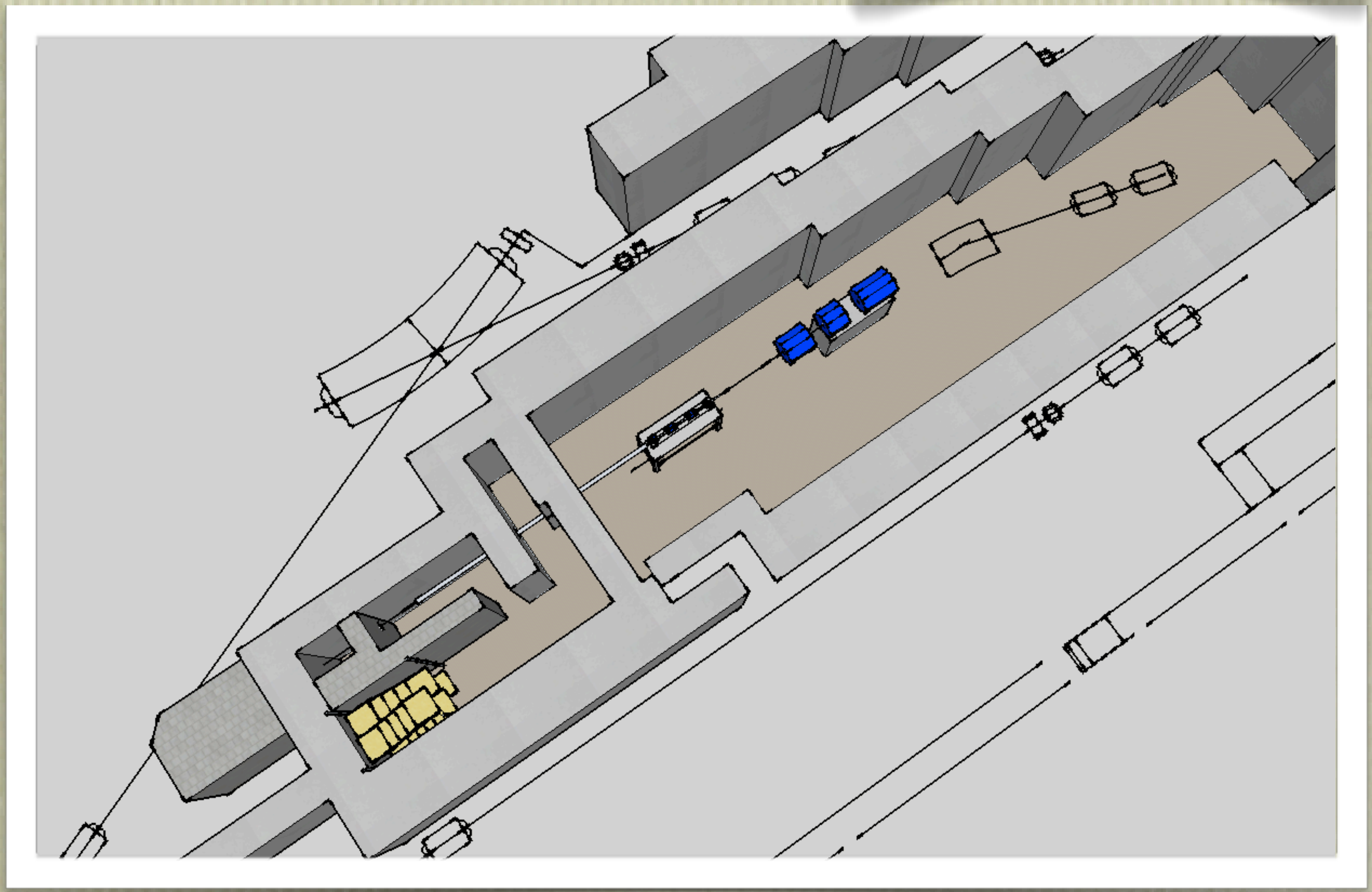
- flexible design: can be optimized for a particular experiment:
  - proton energy can be reduced
  - standoff can be changed
  - magnification can be increased
- SIS-18 electron cooler: both transverse (⇒ density resolution) and longitudinal (⇒ spatial resolution) emittances of the beam can be reduced by an order of magnitude or more

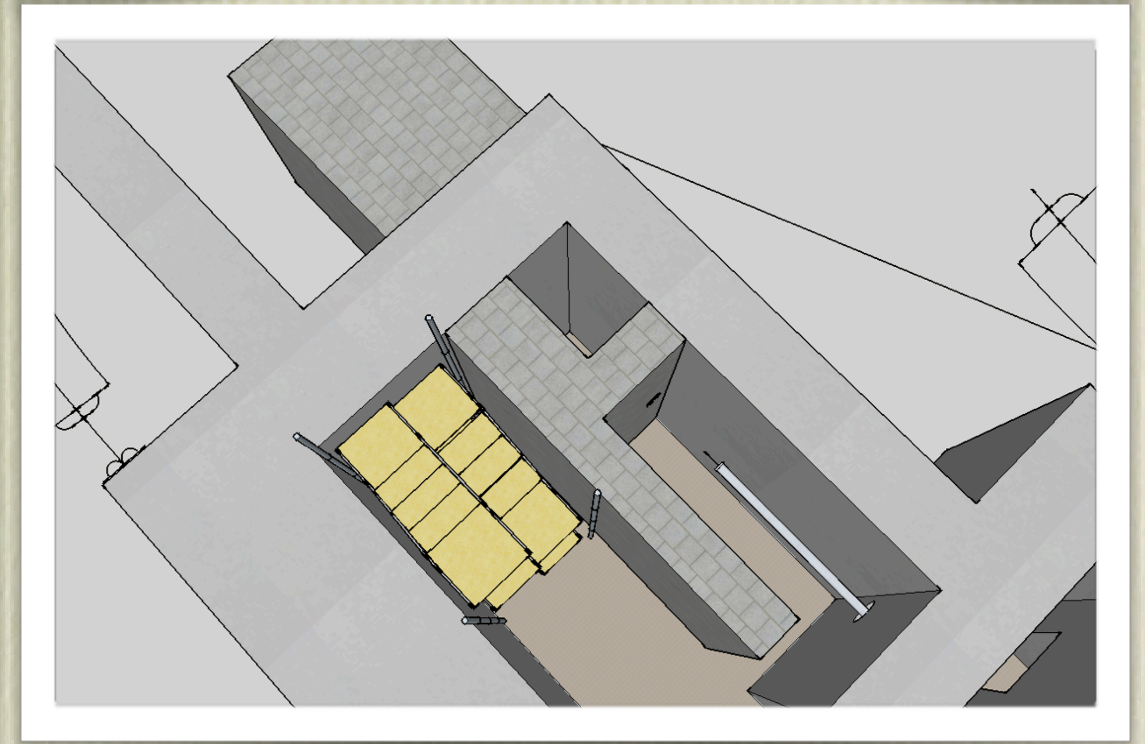
Fielding at GSI – a minor reconstruction of the HHT cave





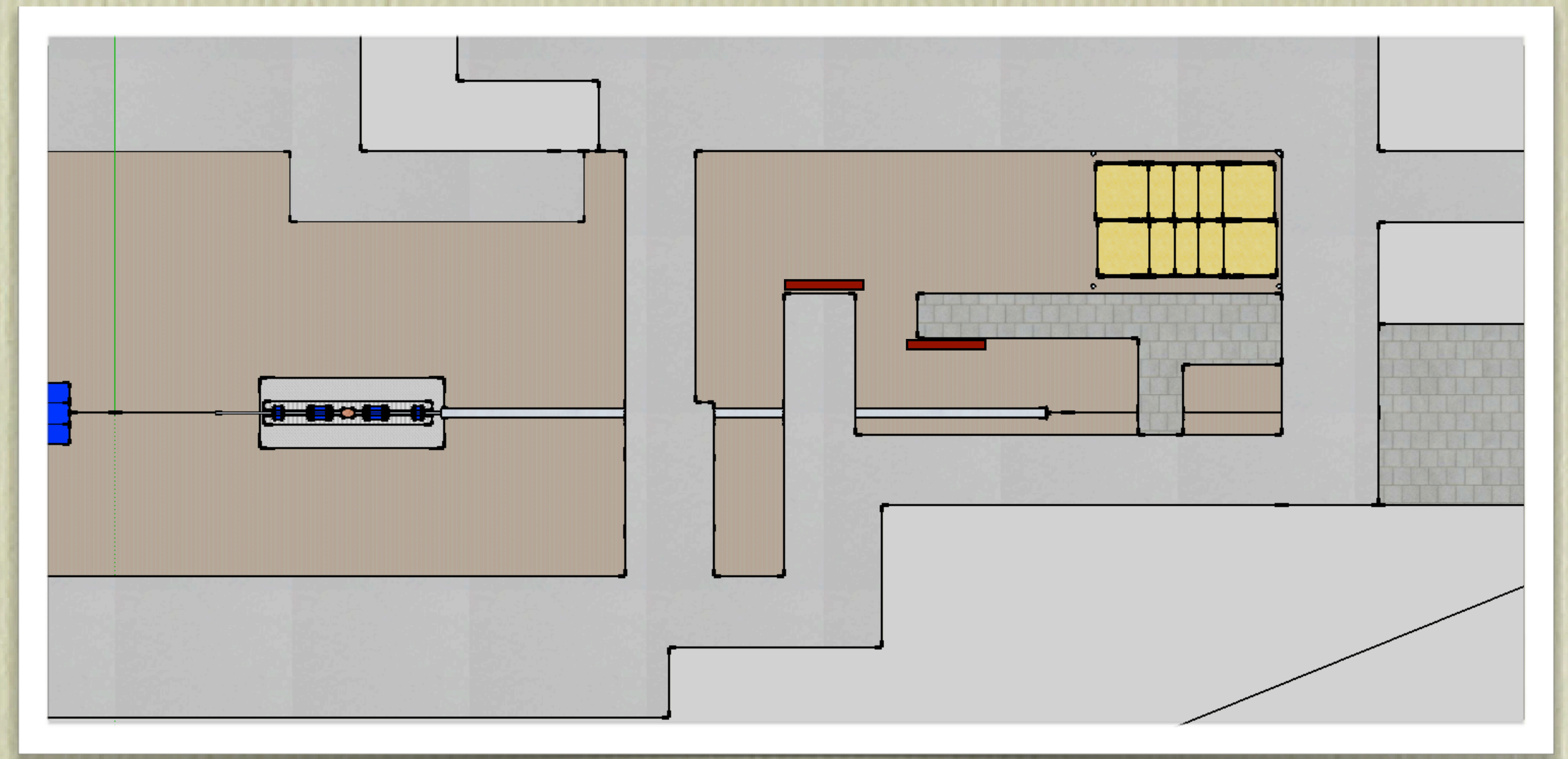


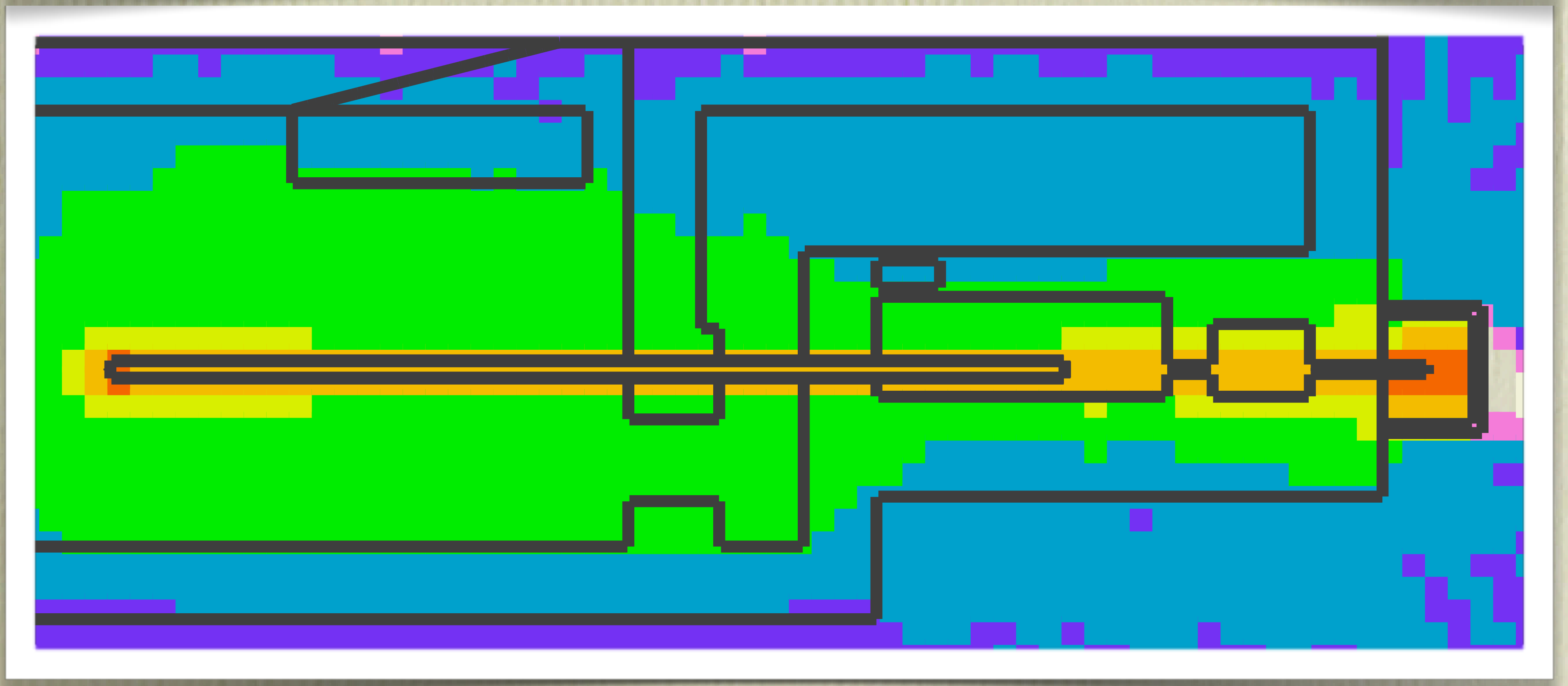




- a compact system but long drift is needed for the microscope

Radiation safety – preliminary simulations





- 4.5 GeV protons
- $5 \cdot 10^{10}$ / pulse, 10^7 / s
- beam dump: 150 cm Fe, 350 cm concrete
- < 0.5 μSv/h

PRIOR cost estimates

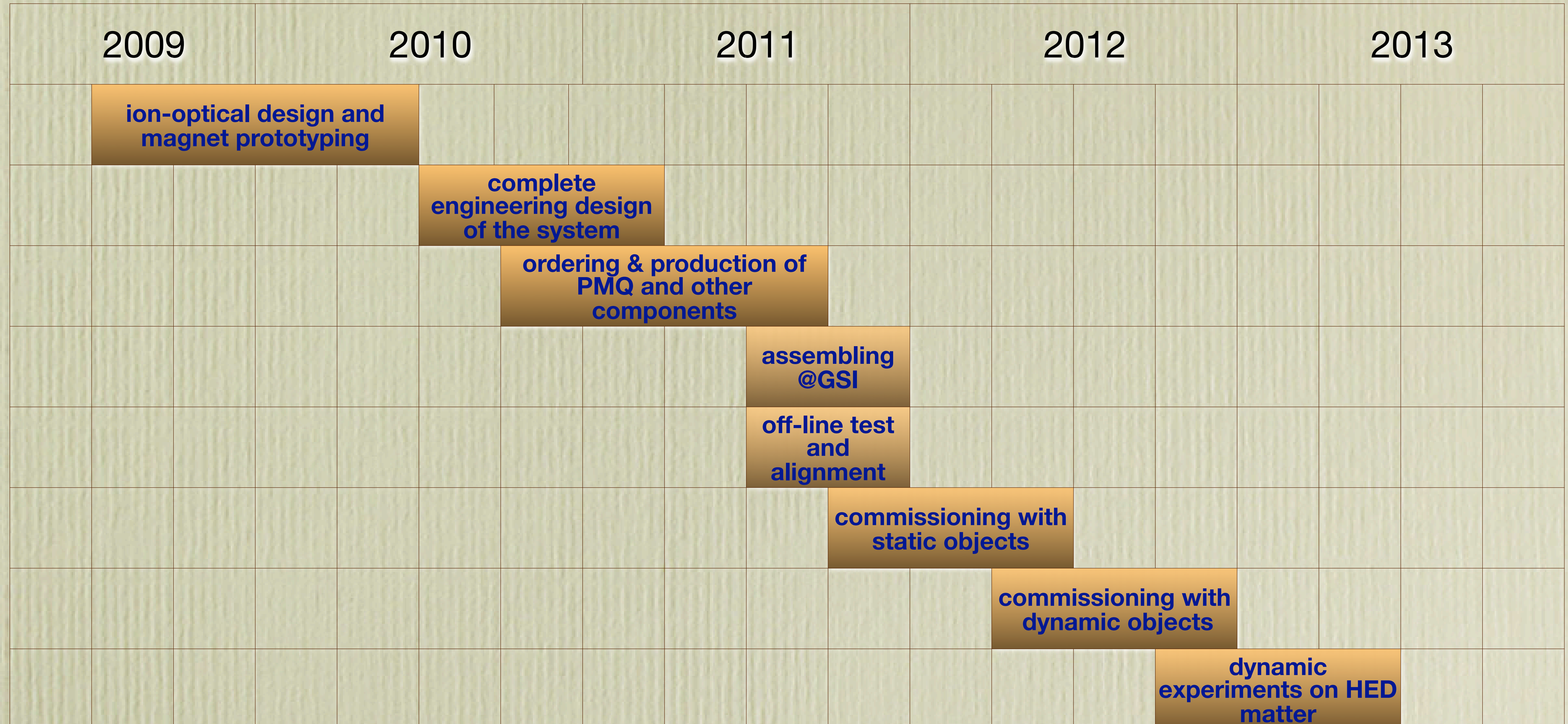
Setup costs (design, production, installation):

Item	**Cost, k€**
PMQ	40 – 80
Mechanics, motion, alignment	50
Detectors (LSO, optics)	30
Stand, vacuum, mounting	20
Total:	***140 – 180***

Infrastructure costs (preparing the area):

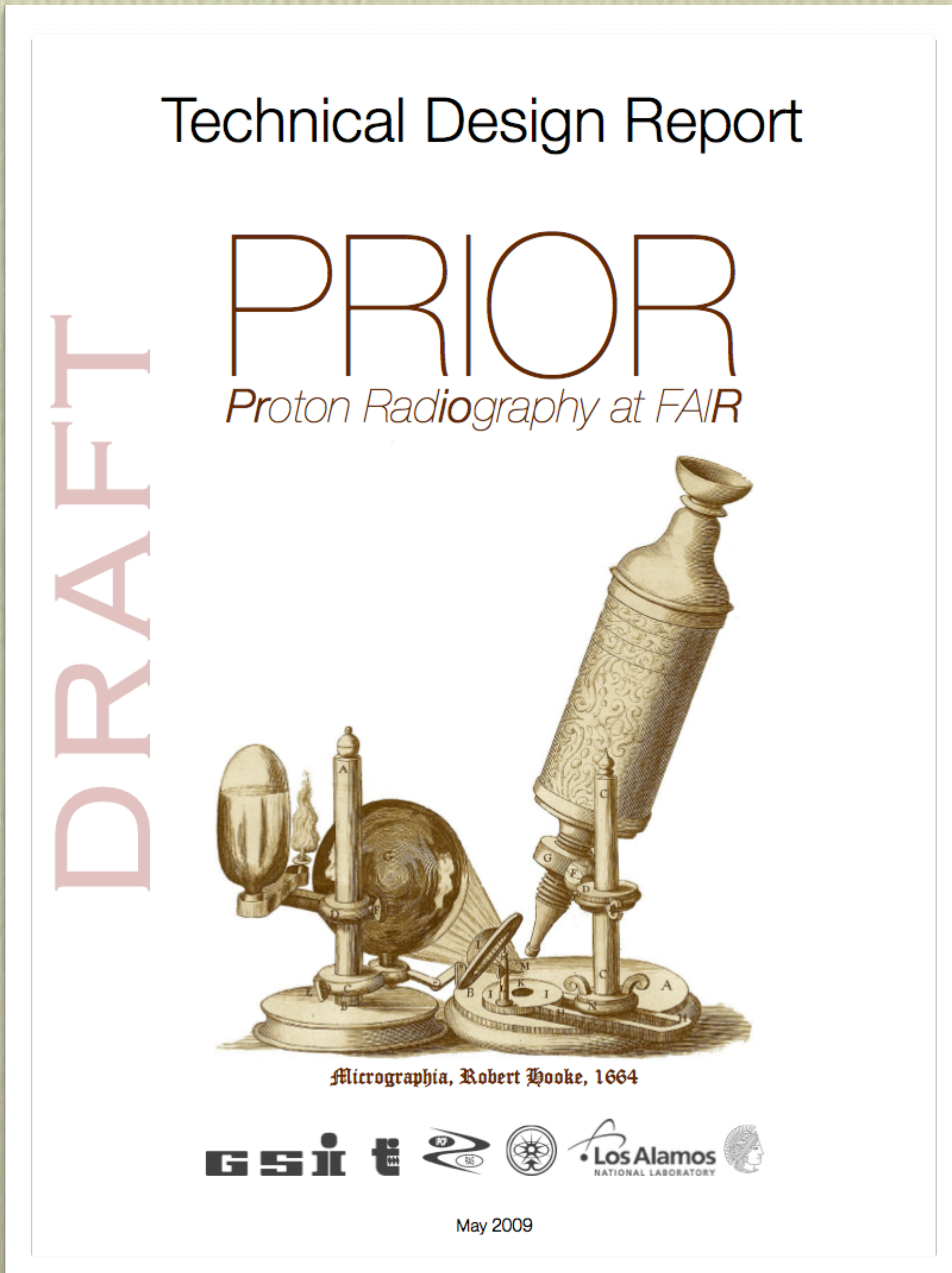
Item	**Cost, k€**
HHT area reconstruction (concrete wall / roof, beam dump)	30
Moving three electric / safety distributor boxes from HHT	100 (?)

Time schedule and milestones for PRIOR project



- 1st HEPM workshop at GSI — Q3 2009
- 2nd HEPM workshop at IPCP — Q3 2010
- ordering production of main components — Q4 2010
- submitting first beam time applications — Q2 2011
- assembling and off-line measurements — Q4 2011
- commissioning with static objects — Q1 2012
- commissioning with dynamic objects — Q3 2012

Summary and outlook


Technical Design Report

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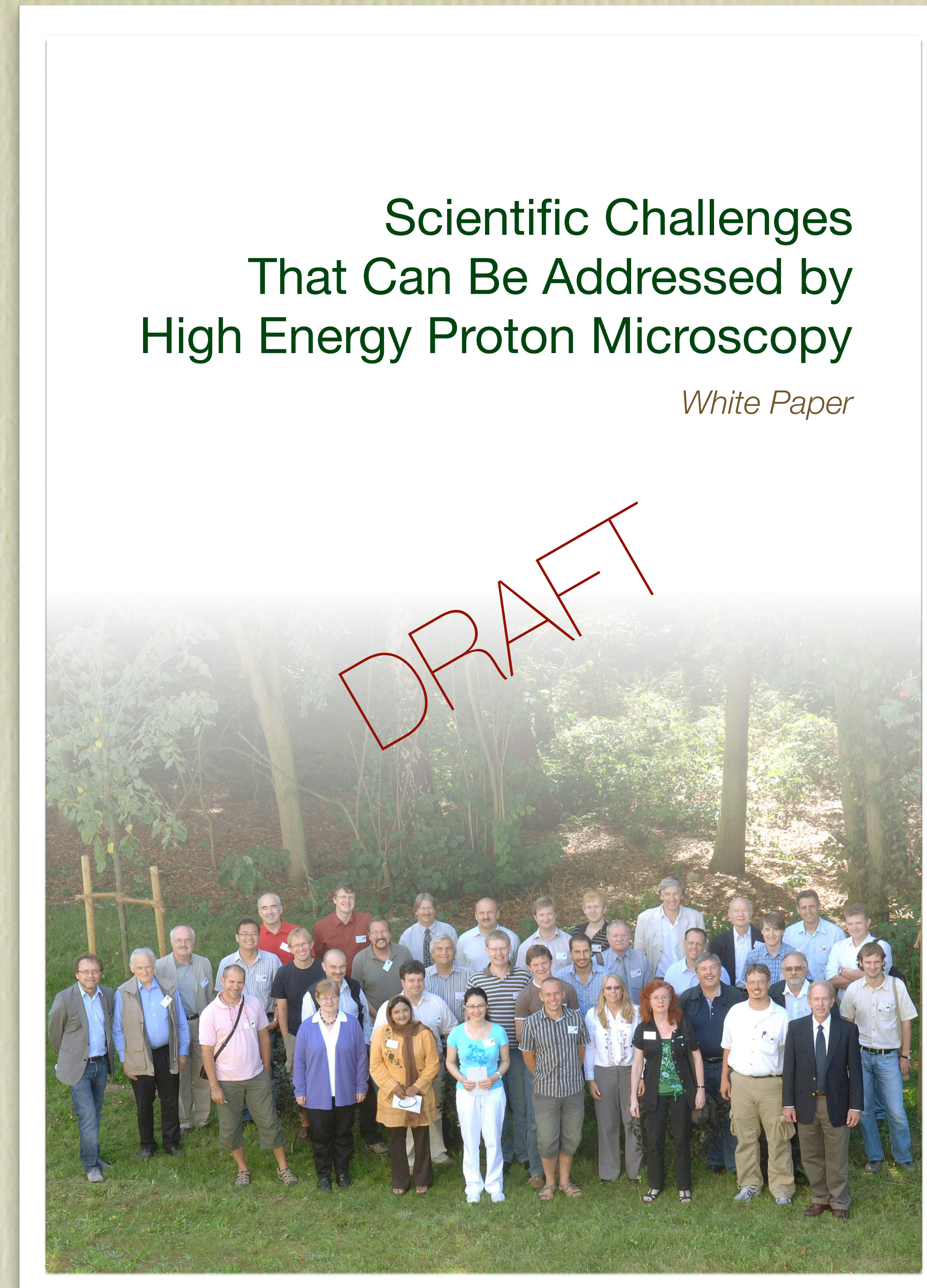
PRIOR

Proton Radiography at FAIR

Micrographia, Robert Hooke, 1664

Los Alamos
NATIONAL LABORATORY

May 2009


Scientific Challenges
That Can Be Addressed by
High Energy Proton Microscopy

White Paper

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