GRK-Seminar: Mass and Symmetries after the Discovery of the Higgs Particle at the LHC

Measuring

the Electric Dipole Moment of Protons

May 22nd, 2019

Achim Stahl – RWTH Aachen University – JARA-FAME

In the beginning …

created matter and antimatter
in equal amounts

tested in the lab

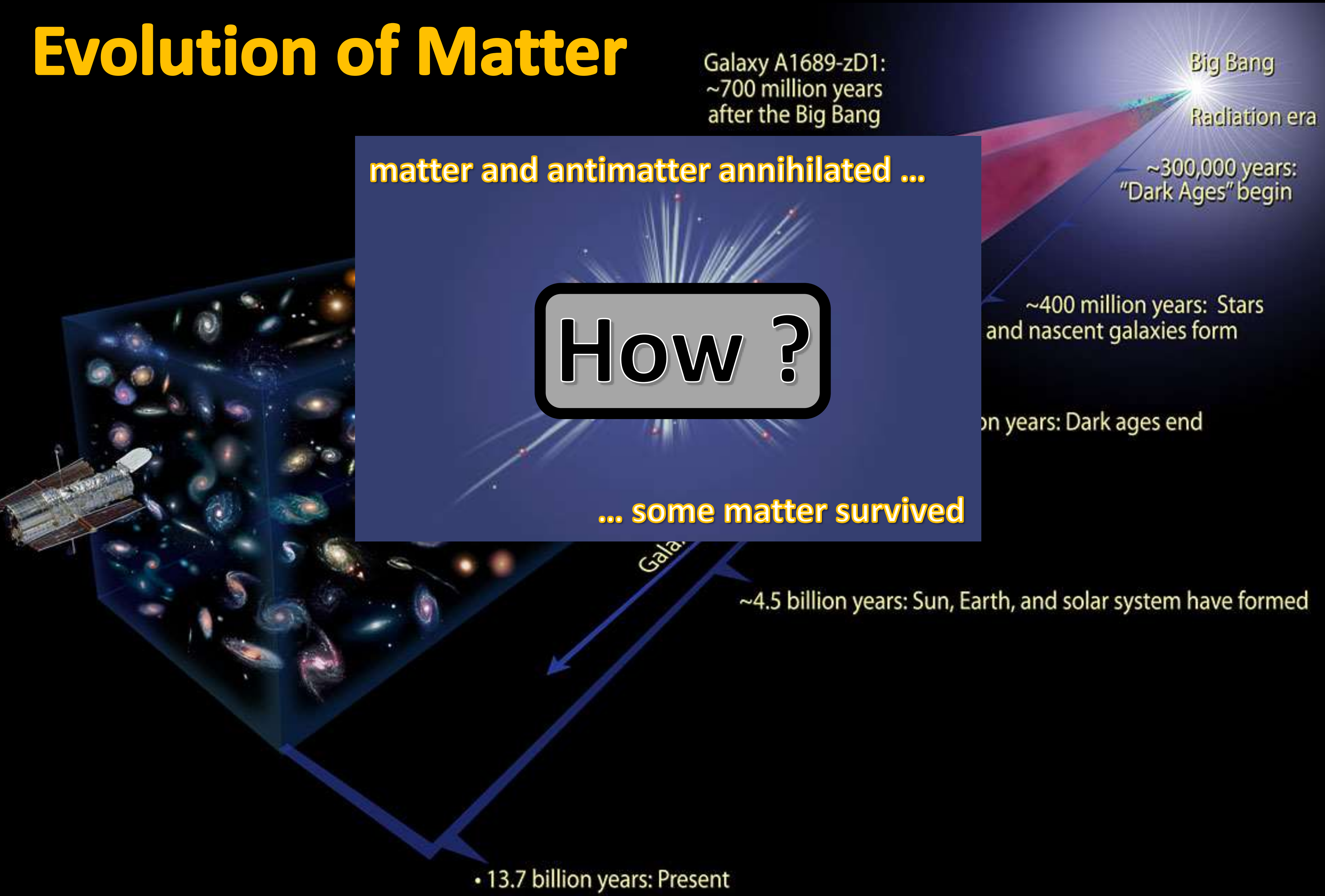
„a million times"

… the Big Bang

Today …

… we only find matter

Evolution of Matter



Today …

Baryon to Photon Ratio:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 5 \cdot 10^{-10}$$

$$n_\gamma \approx 0.4/mm^3$$

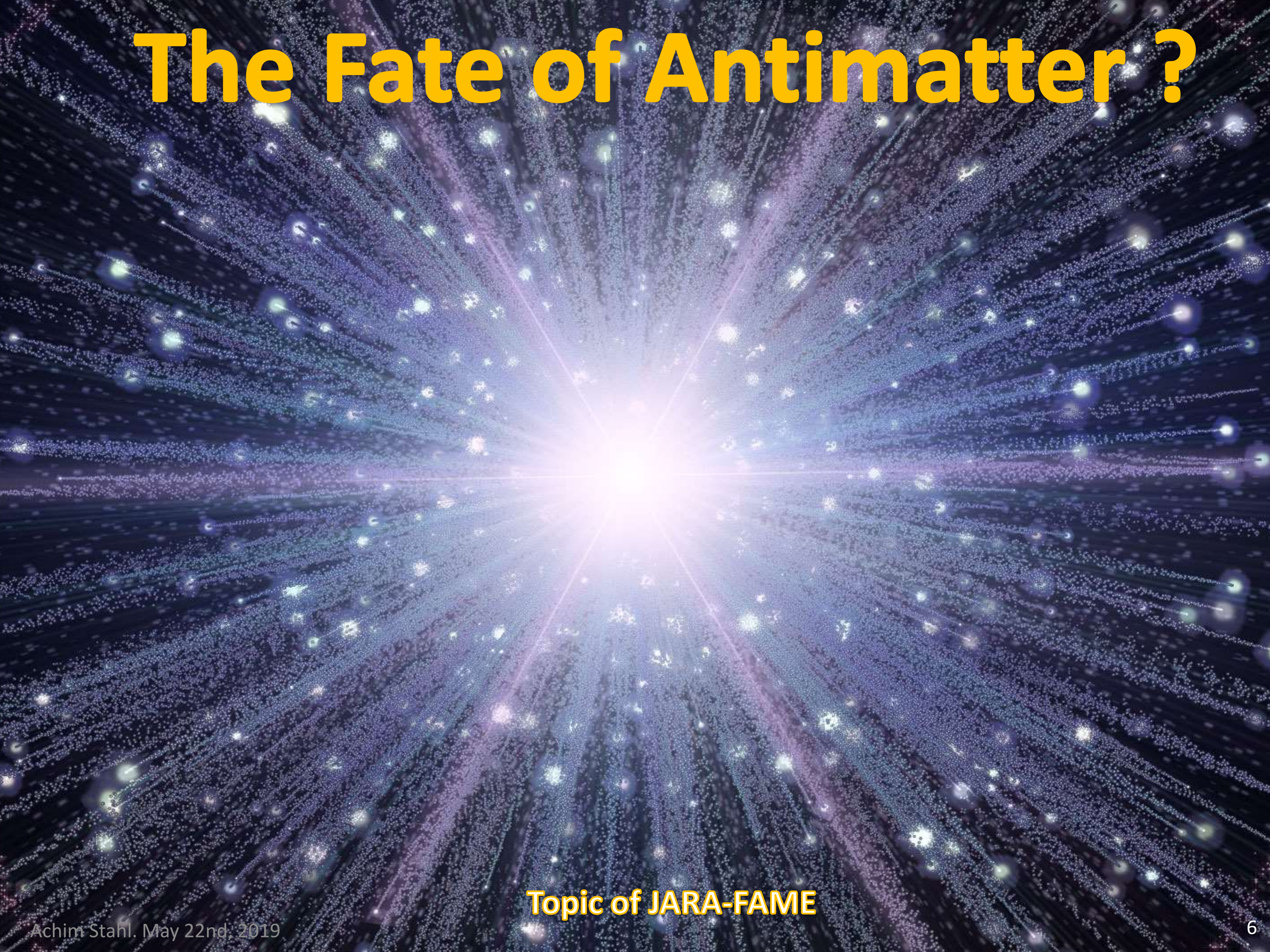
$$n_B \approx 0.2/m^3$$

$$n_{\bar{B}} \approx 0$$

Standard Model fails by many orders of magnitude

… we only find matter

The Fate of Antimatter ?



Topic of JARA-FAME

Content

- The Fate of antimatter – Introduction
- EDM: Experimental Method
- Electrostatic Storage Rings
- Experimental Strategy and Goals

annihilated

a tiny fraction of matter survived

(approx. 1 particle in 10^9)


our universe

THE SAKHAROV CONDITIONS

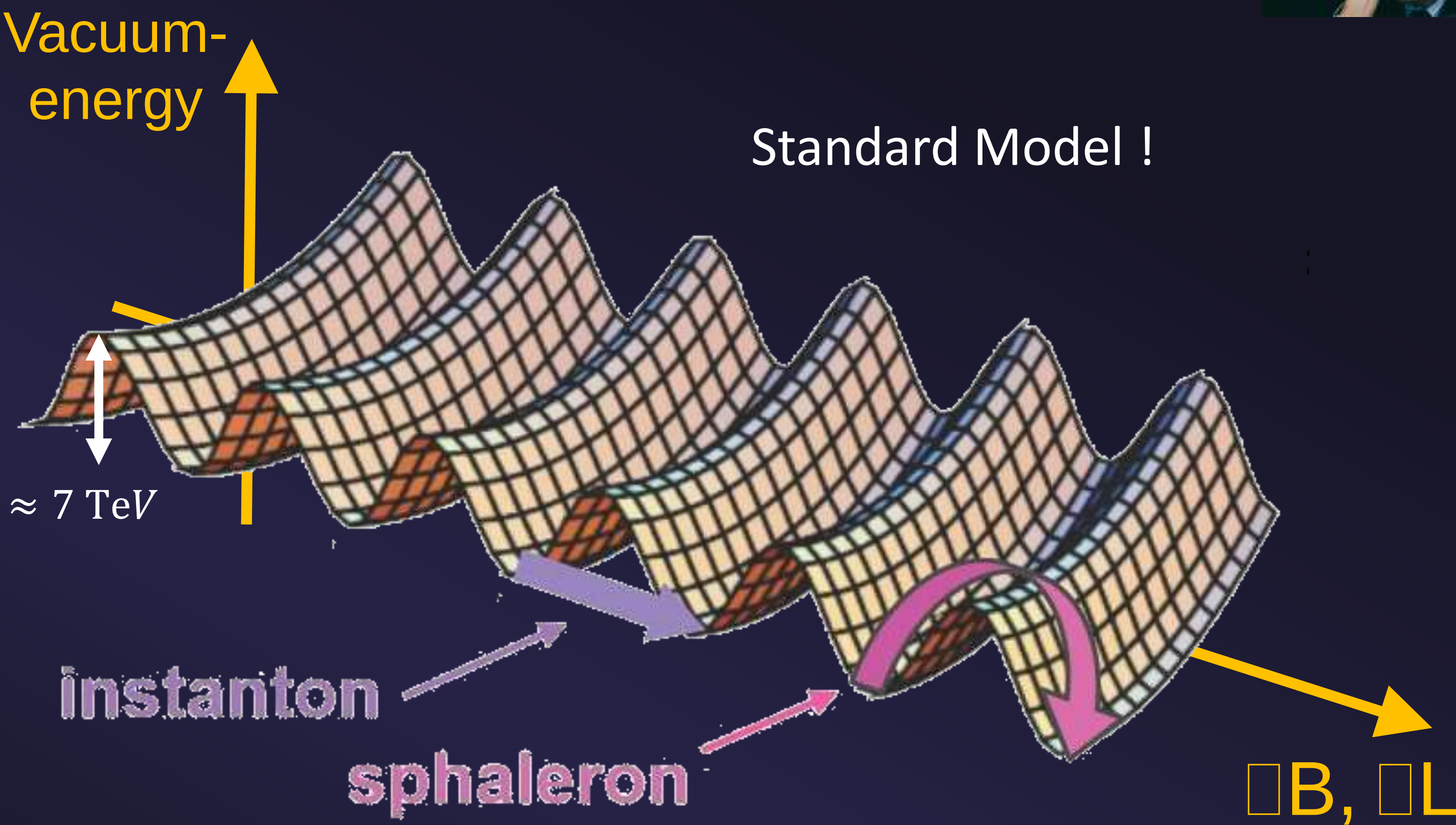
1. Baryon-Number Violation
2. CP-Violation
3. Thermal Non-Equilibrium

A.D. Sakharov, „*Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe*”, Journal of Exp. and Theo. Physics Letters 5 (1967) 24 – 27.

Necessary condition for any model

BARYON-NUMBER VIOLATION

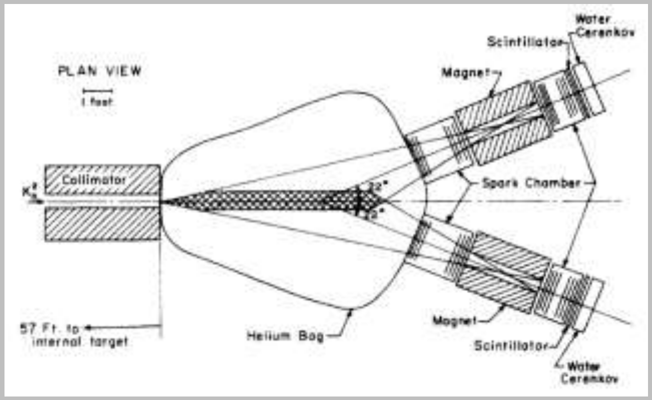
Standard Model !



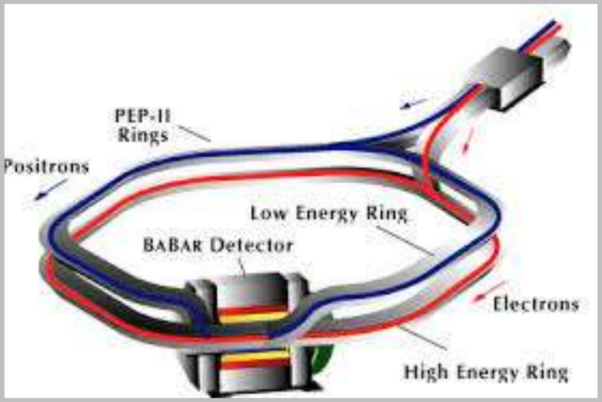
Electroweak phase transition: $T \approx 100\ \mathrm{GeV}$

CP-VIOLATION

Standard Model !



K^0-System



B-System

But: $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$ too small !

NON-EQUILIBRIUM

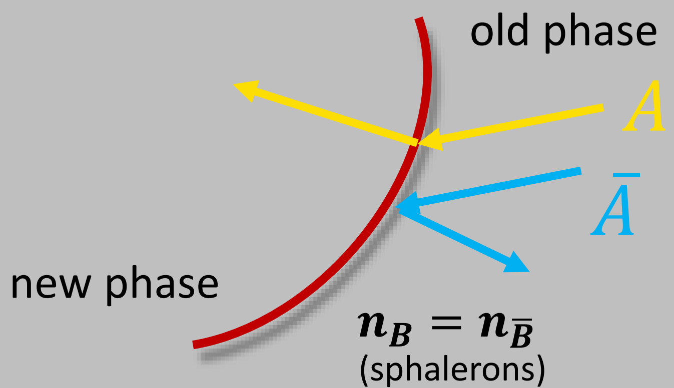
In equilibrium:

$$\bar{A} \Leftrightarrow B$$

antimatter ⇔ matter

CPT ensures equal rates

Out-of equilibrium:



Matter excess created in the walls between the phases

NON-EQUILIBRIUM

THE SAKHAROV CONDITIONS

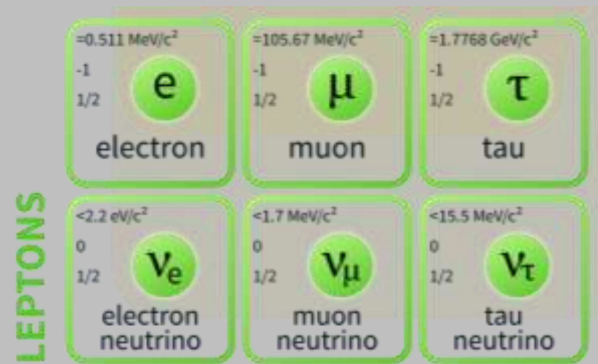
1. Baryon-Number Violation **theoretical ideas**
2. CP-Violation **not enough !**
3. Thermal Non-Equilibrium **several solutions**

A.D. Sakharov, „*Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe*”, Journal of Exp. and Theo. Physics Letters 5 (1967) 24 – 27.

More CP-violation needed !

LEPTO- AND BARYOGENESIS

Leptogenesis



Process started with leptons

Baryogenesis

Process started with baryons

here ?

here ?

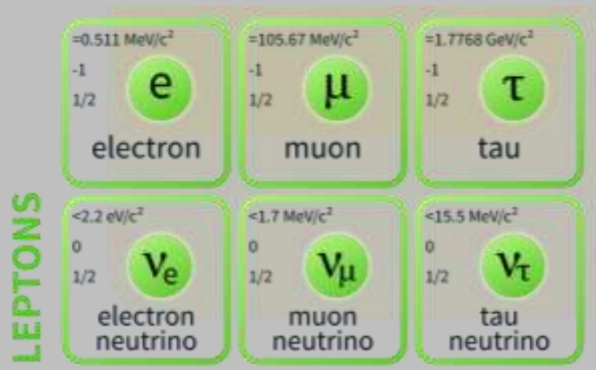
hint for leptogenesis

hint for baryogenesis

More CP-violation needed

LEPTO- AND BARYOGENESIS

Leptogenesis



Process started with leptons

Baryogenesis

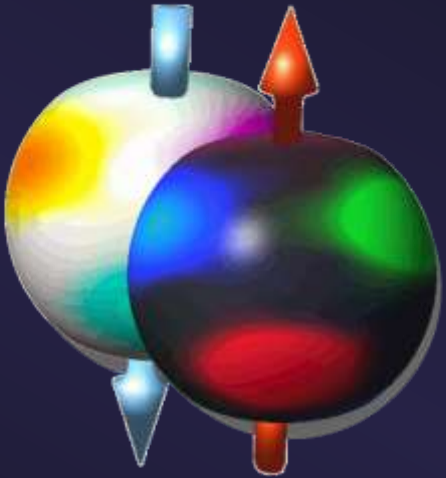
Process started with baryons

Experimental search for new sources of CP-violation

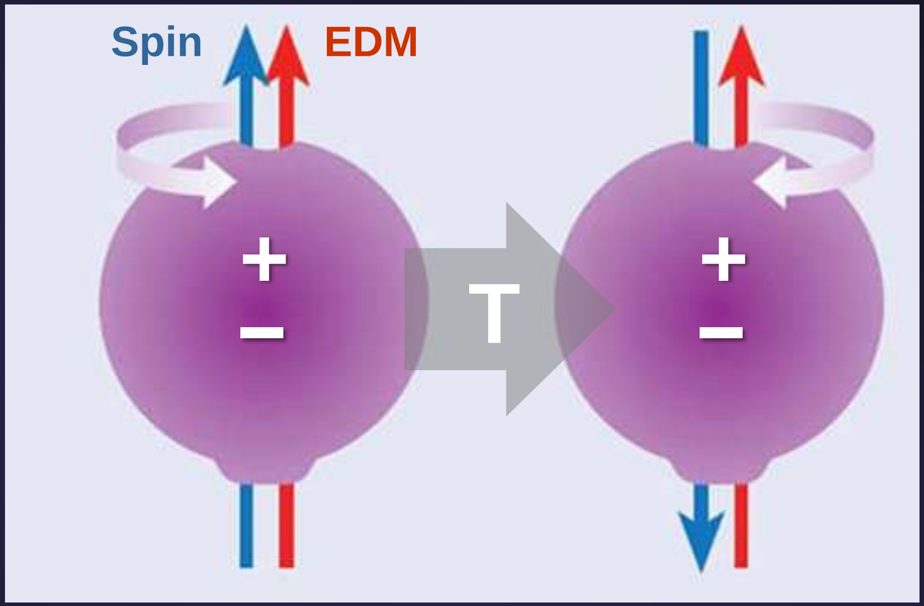
Neutrino-Oscillations

Electric
Dipole Moments

Electric Dipole Moment



ELECTRIC DIPOLE MOMENT



Spin: $\vec{S}$

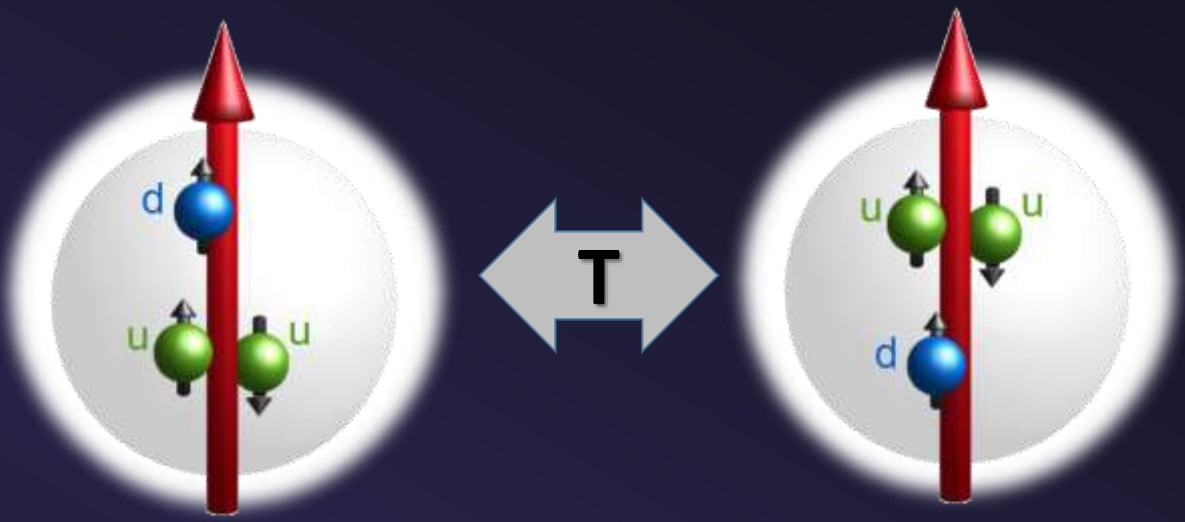
EDM: $\vec{d}$

EDM violates T

CPT → violates CP

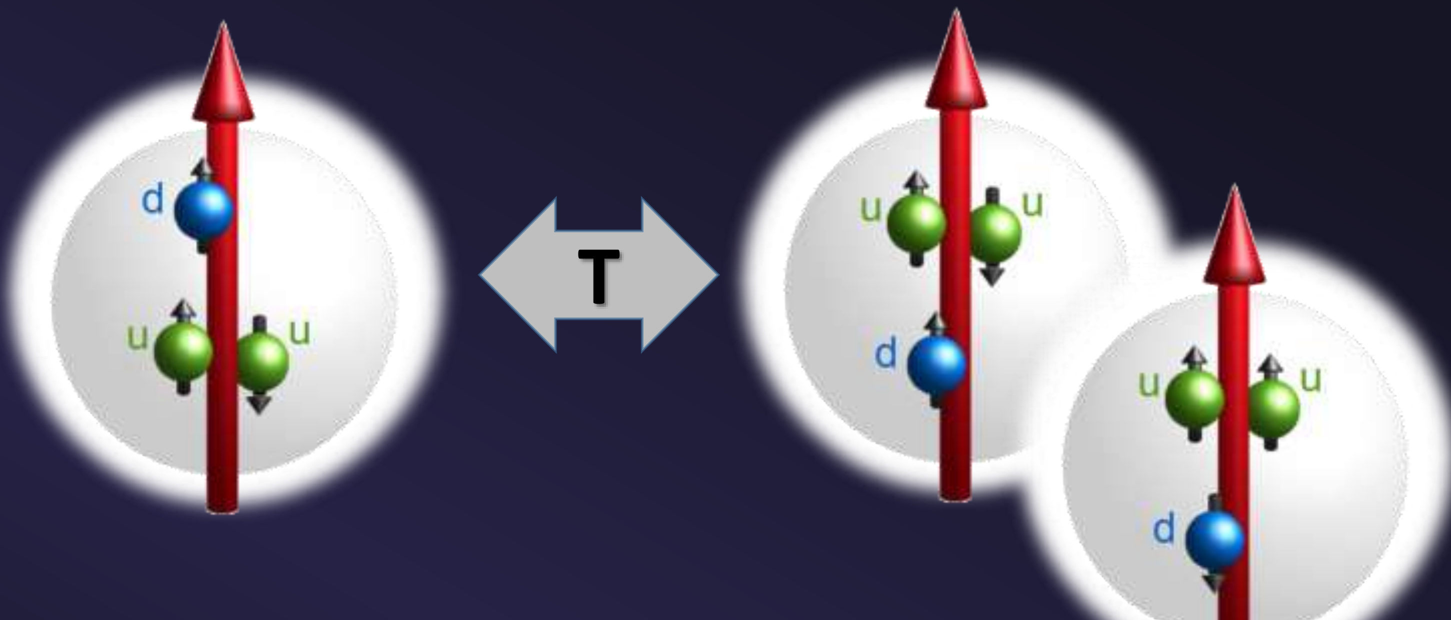
$$\langle \vec{S} \cdot \vec{d} \rangle \overset{T}{\Leftrightarrow} -\langle \vec{S} \cdot \vec{d} \rangle$$

EDM and QCD



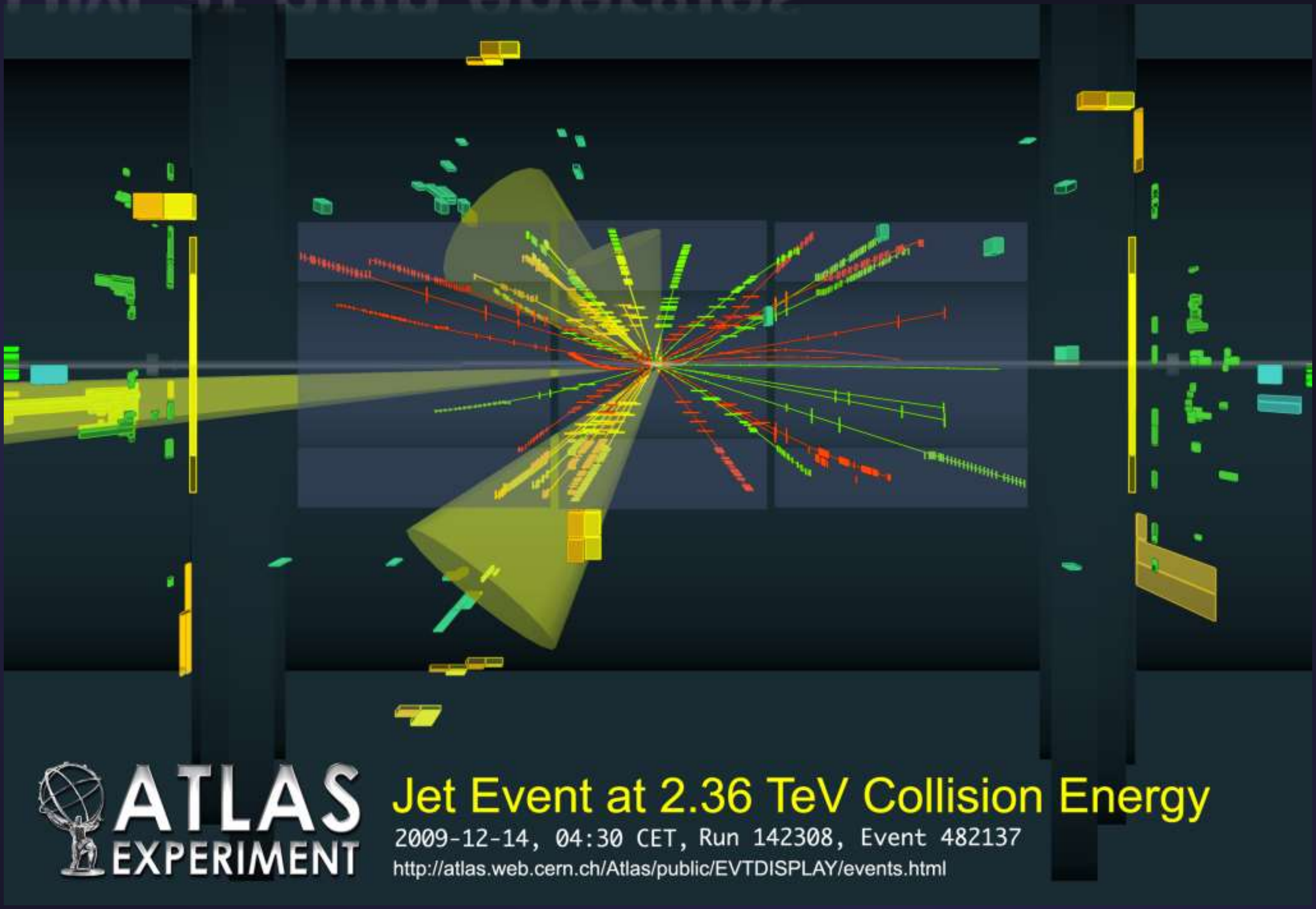
T-Violation in QCD: Prefer one over the other

EDM and QCD



T-Violation in QCD: Prefer one over the other

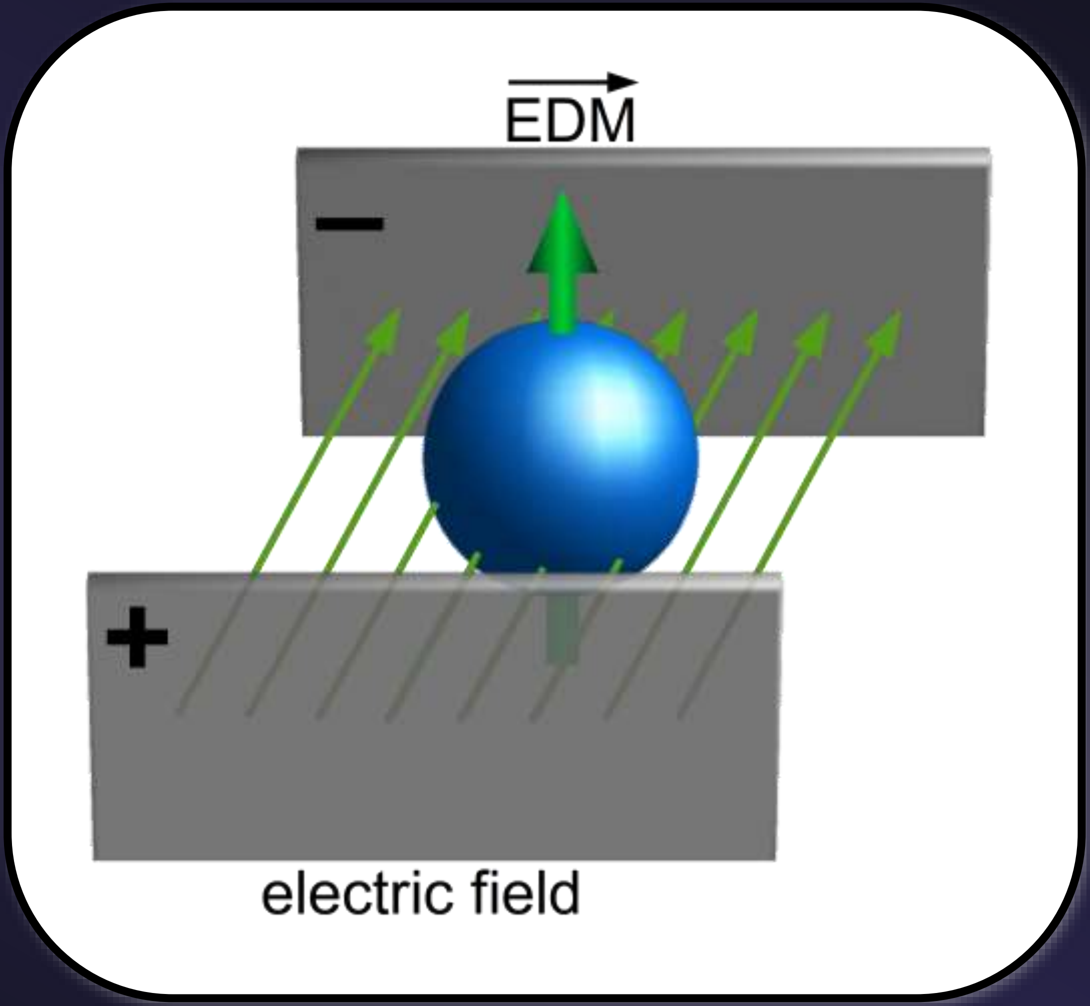
EDM at high energies



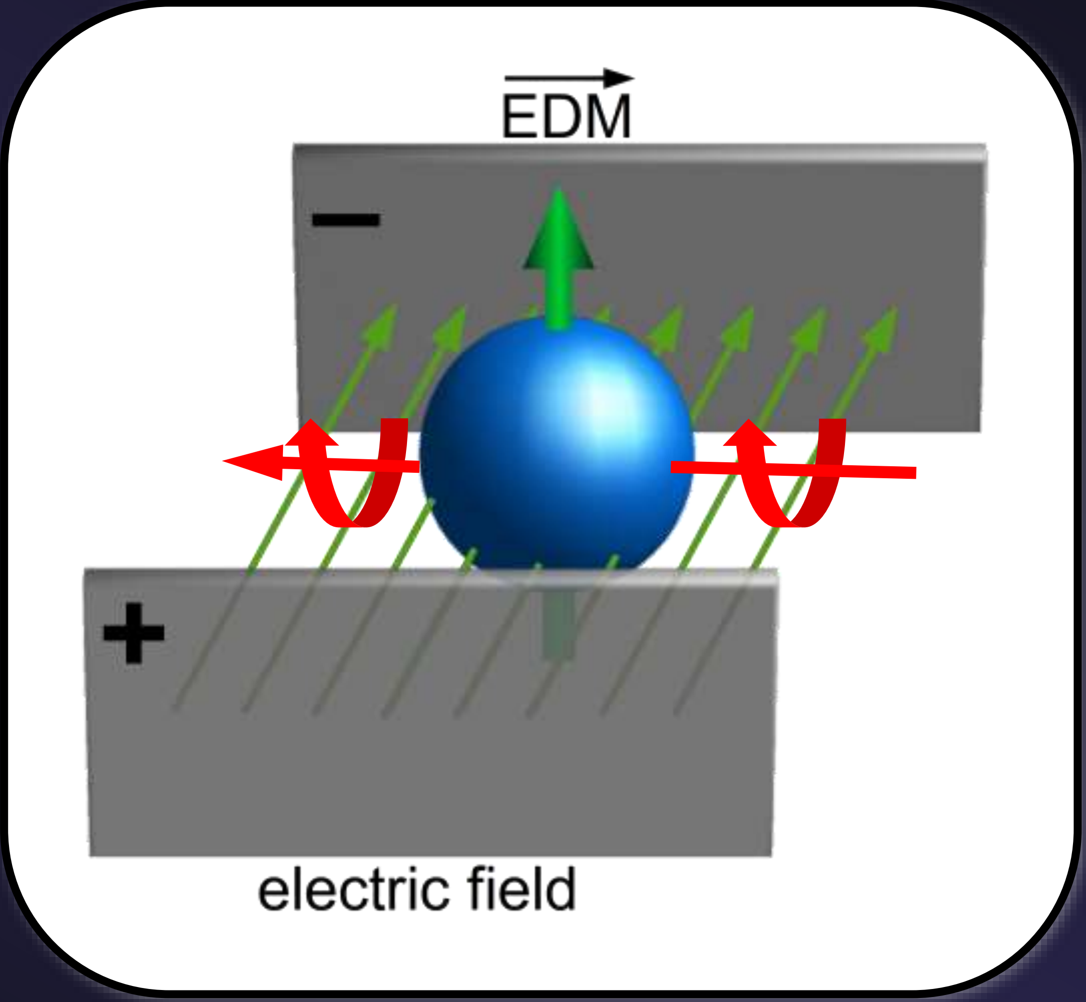
EDM at high energies

Experimental Method

DIPOLES in a FIELD

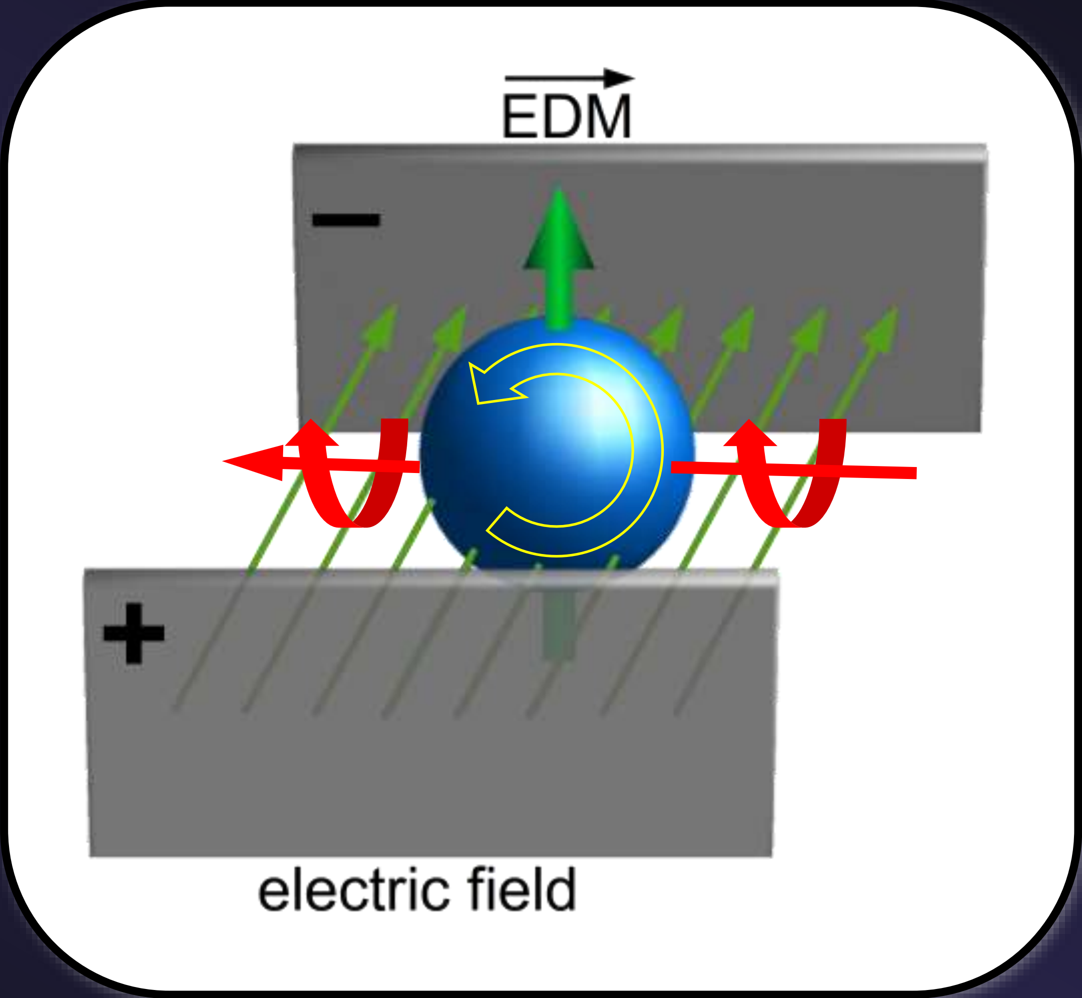


DIPOLES in a FIELD



- Field exerts a torque on the spin

DIPOLES in a FIELD

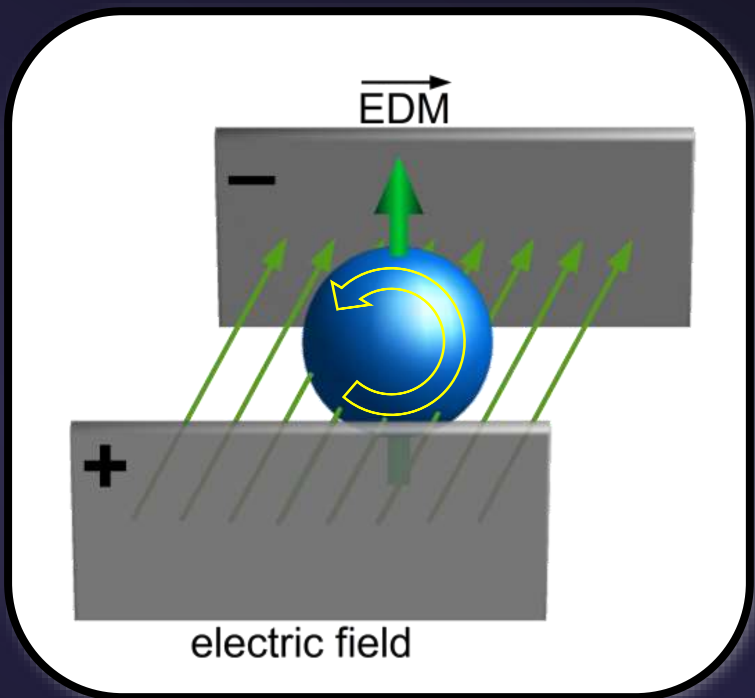


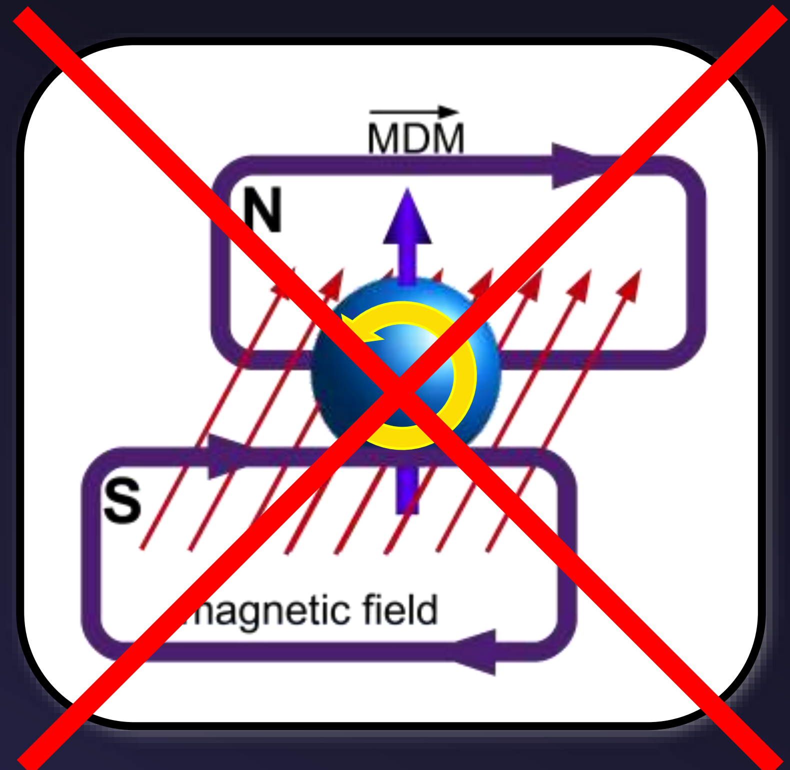
- Field exerts a torque on the spin
- Spin precesses around the field direction

SPIN PRECESSION

DIPOLES in a FIELD

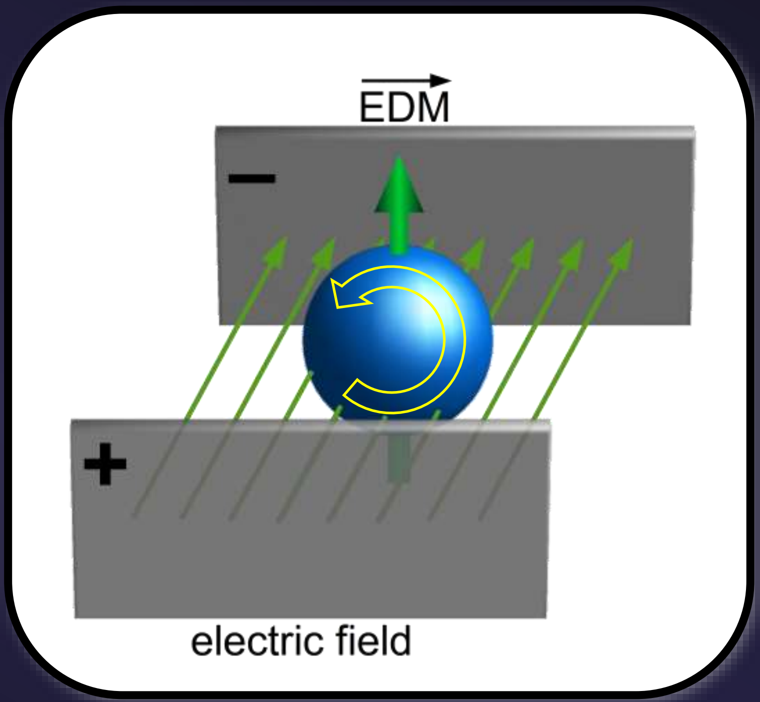
eliminate magnetic fields

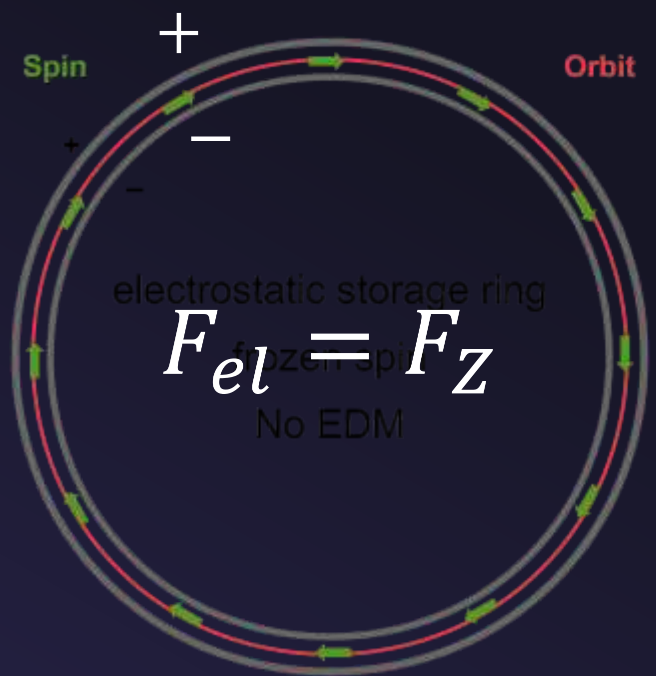




Problem: Magnetic effect much larger !

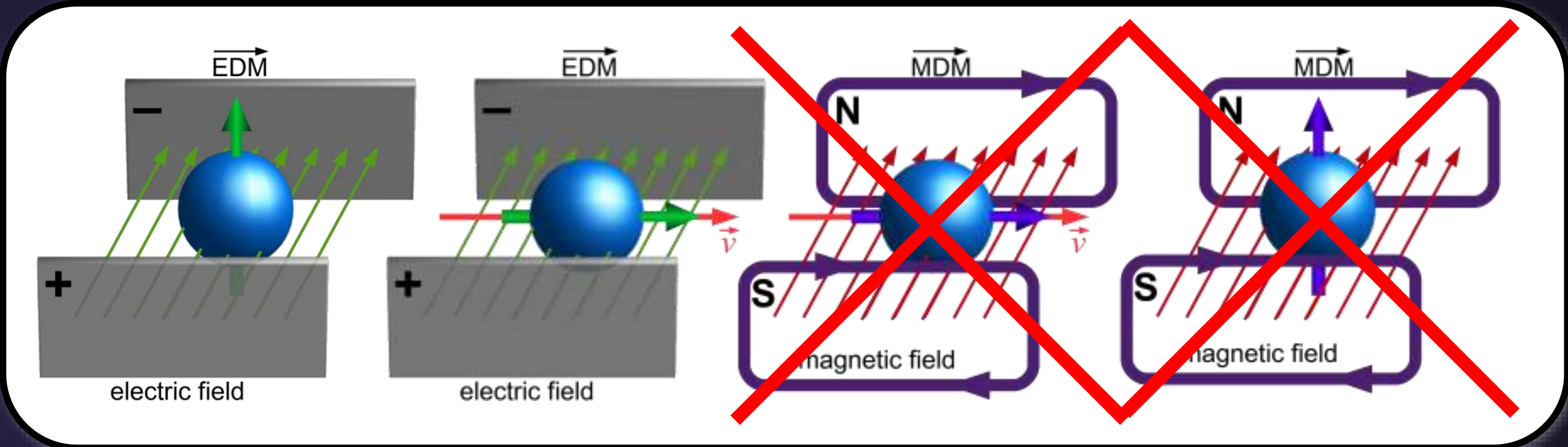
PROTONS in a FIELD





$$F_{el} = F_Z$$

EXPERIMENTAL METHOD



Thomas BMT-Equation:

negligible

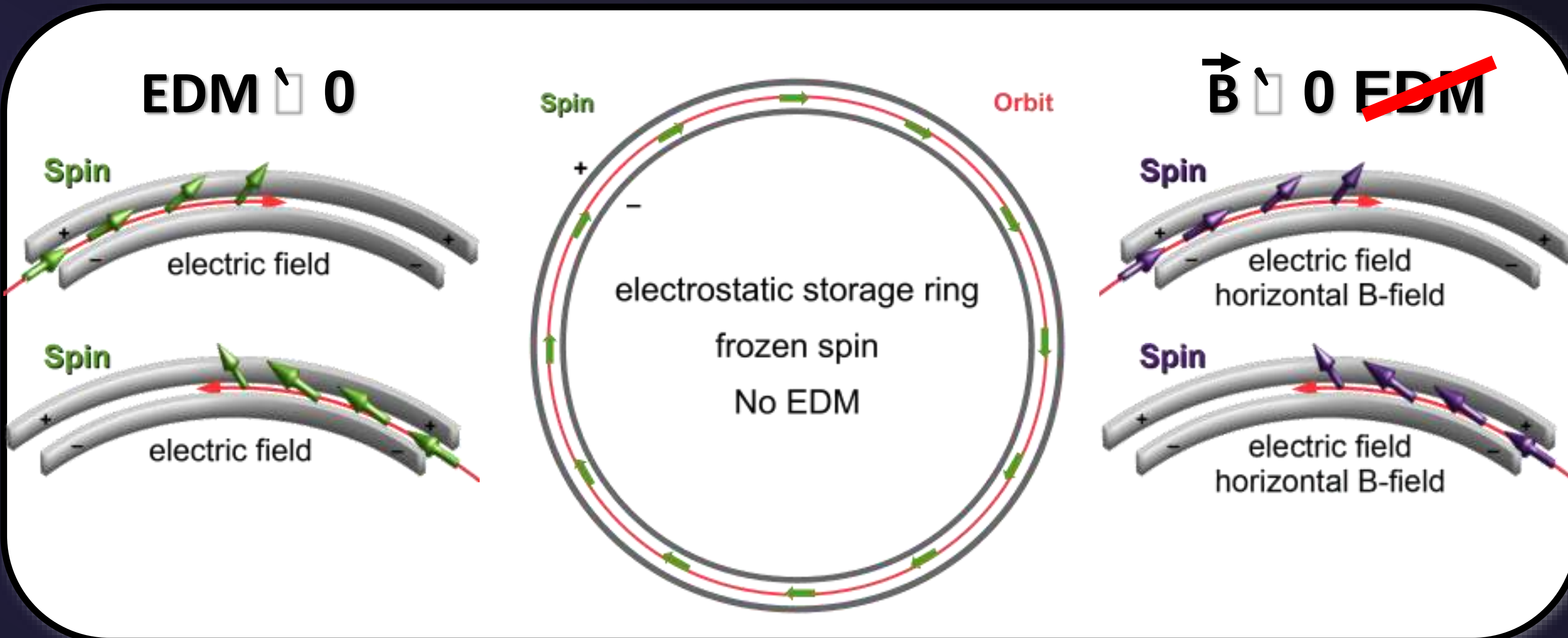
$$\vec{\omega} = \frac{e}{m_p}\left[a\vec{B} + \left(\frac{\gamma^2}{1-\gamma} - a_p\right)\vec{\beta}\times\frac{\vec{E}}{c} + \frac{d}{2}\left(\vec{\beta}\times\vec{B}\right) + \frac{d}{2}\frac{\vec{E}}{c}\right] \qquad a_P = \frac{g_P - 2}{2}$$

If zero: magic momentum
frozen spin

For protons: 700.7 MeV/c

DIPOLES in a FIELD

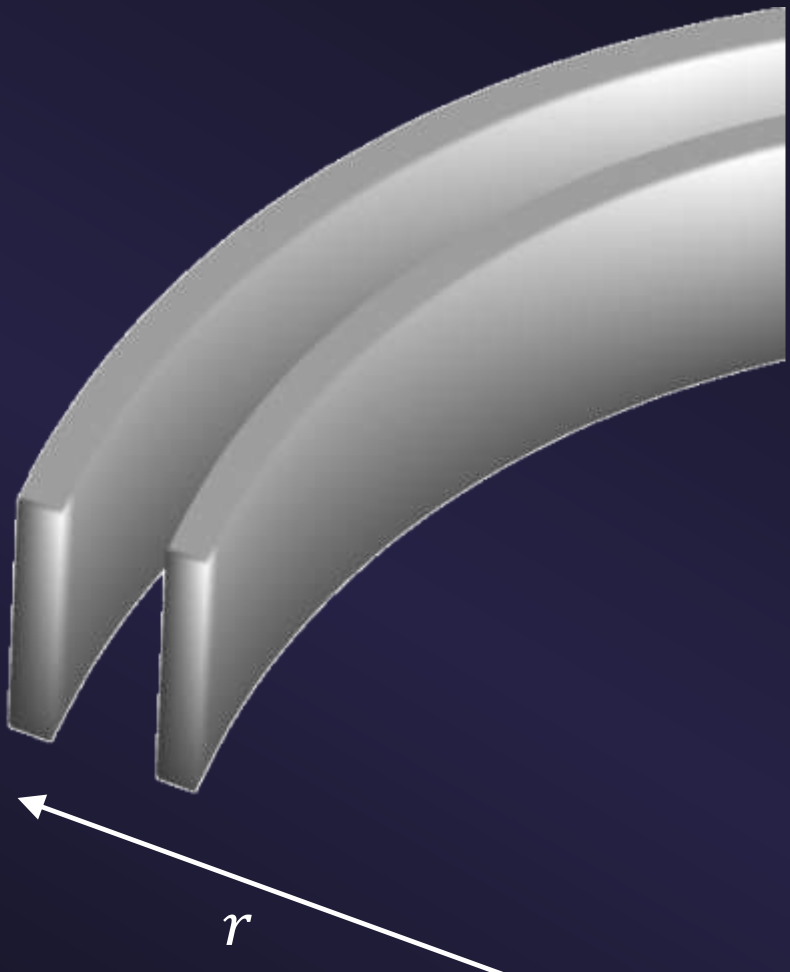
Beam-separation through B-field



Counter-rotating beams: Identifies false signal from B-field

Electrostatic Ring

ELECTROSTATIC DIPOLE



Perfect Dipole:

$$\vec{E} = E_0 \, \hat{e}_r$$
$$\varphi(r) = \varphi_0 \, (r - r_0)$$

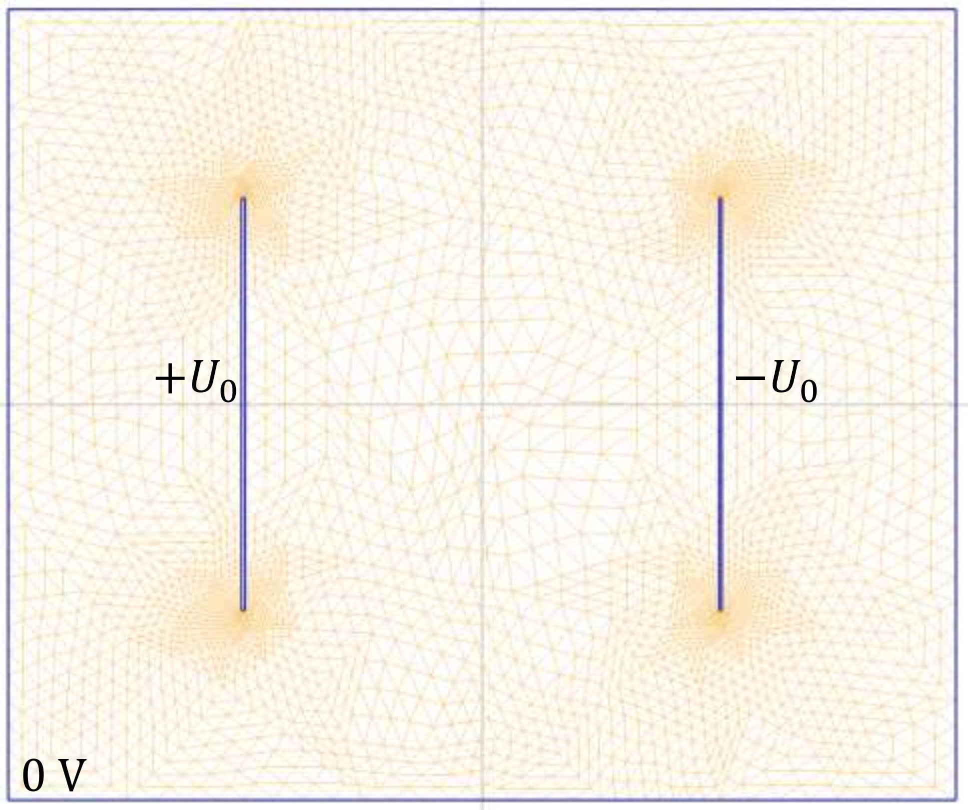
Nominal field: 10 MV/m

(+/- 200 kV over 4 cm)

ELECTROSTATIC DIPOLE

AGROS 2D

Finite Element Analysis



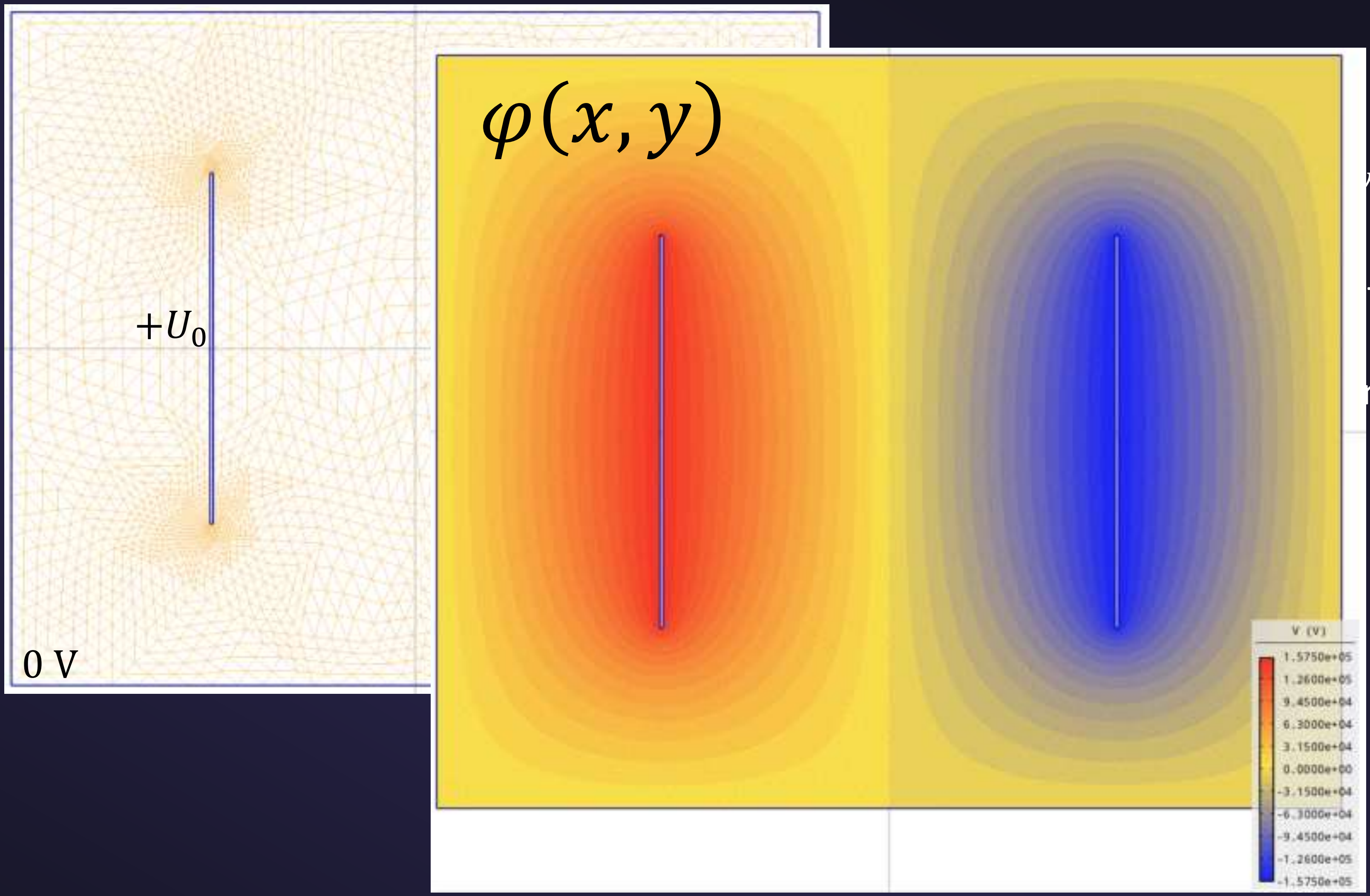
Poisson's equation: $\Delta\varphi(x, y) = \frac{\rho}{\varepsilon_0}$

Plates: metallic surfaces with const. potential (boundary condition)

ELECTROSTATIC DIPOLE

AGROS 2D

Finite Element Analysis



$) = \frac{\rho}{\varepsilon_0}$

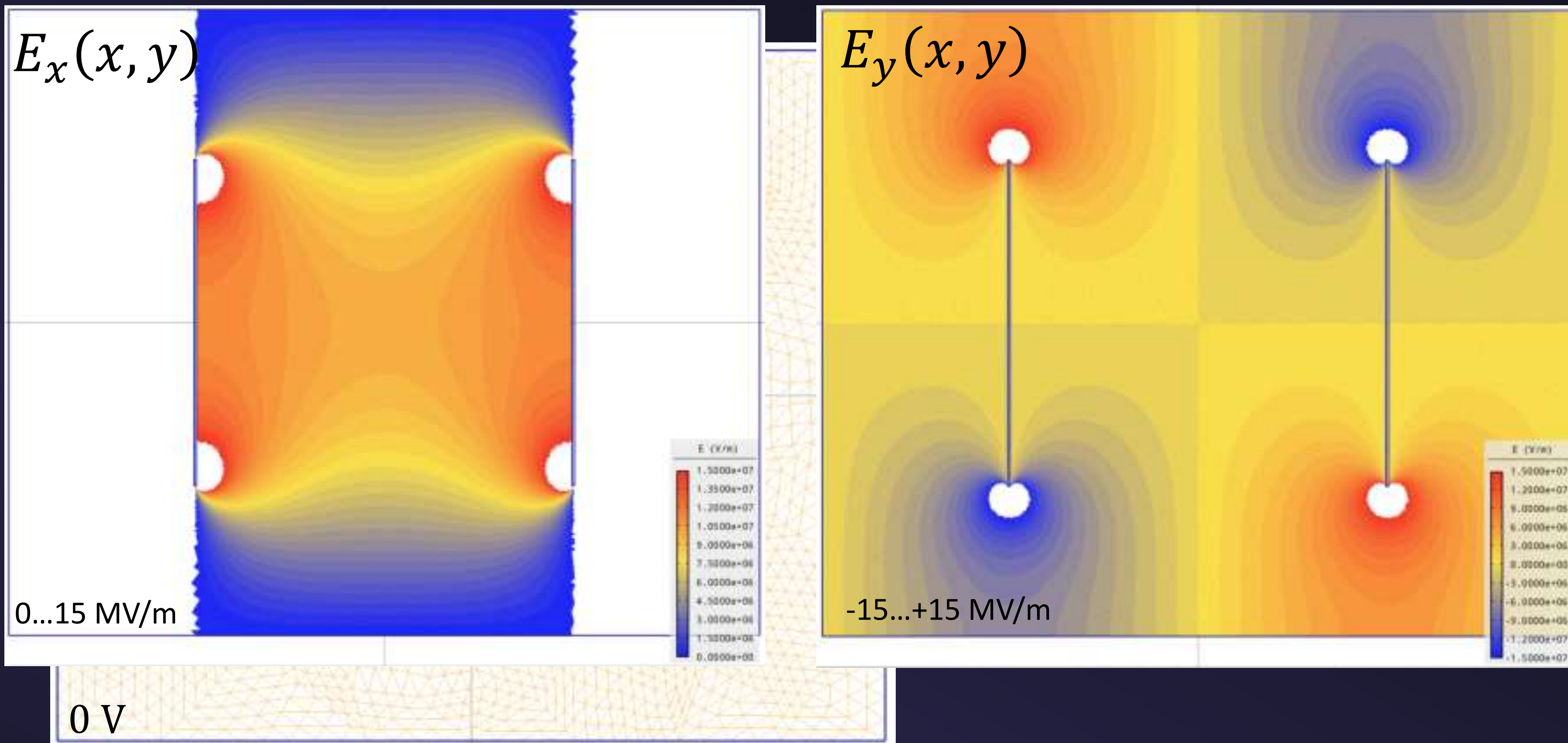
th

n)

ELECTROSTATIC DIPOLE

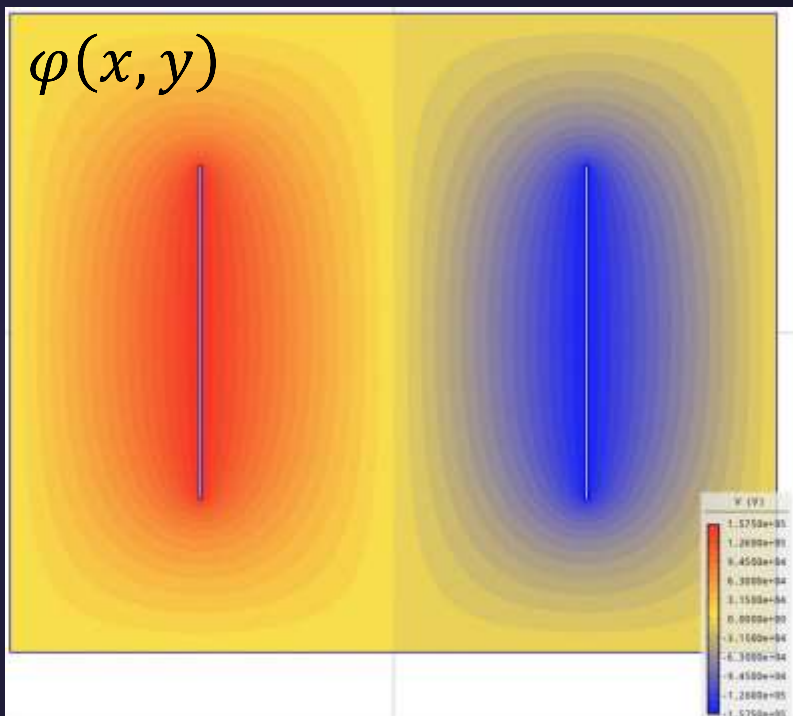
AGROS 2D

Finite Element Analysis

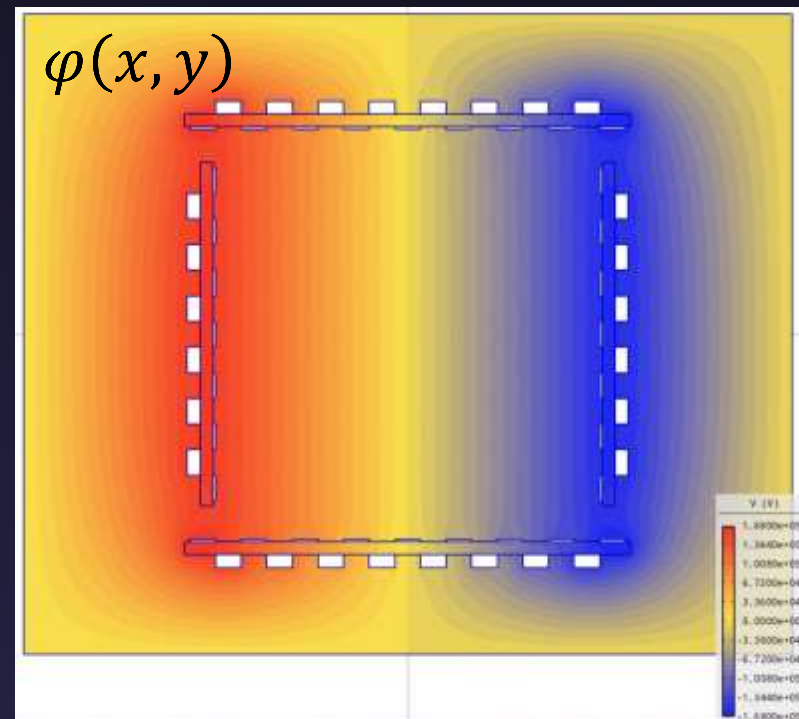


$$\vec{E} = -\vec{\nabla}\varphi$$

ELECTROSTATIC DIPOLE

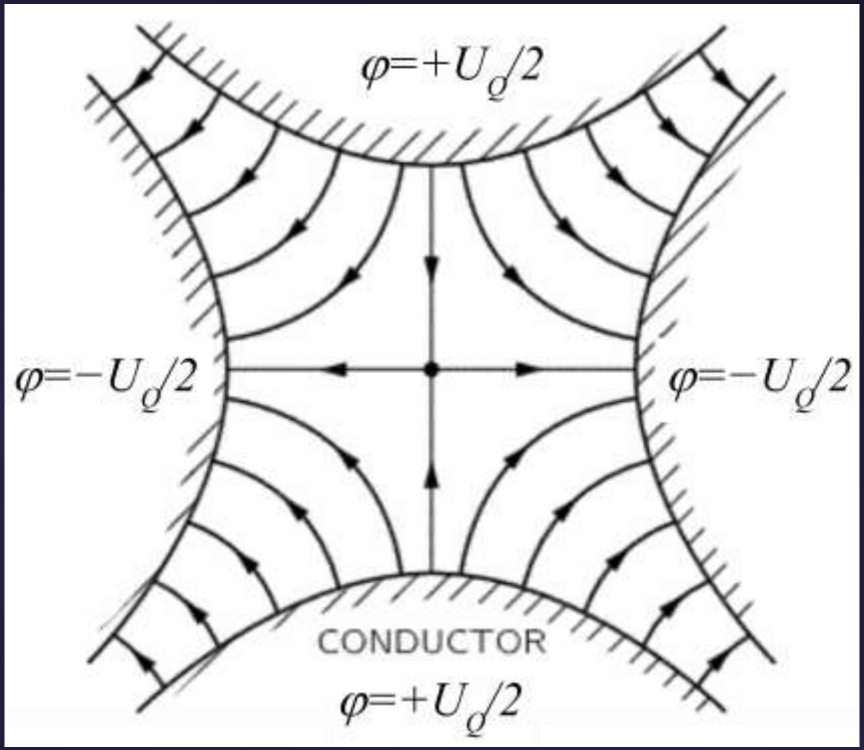


Simple Capacitor



Field Cage

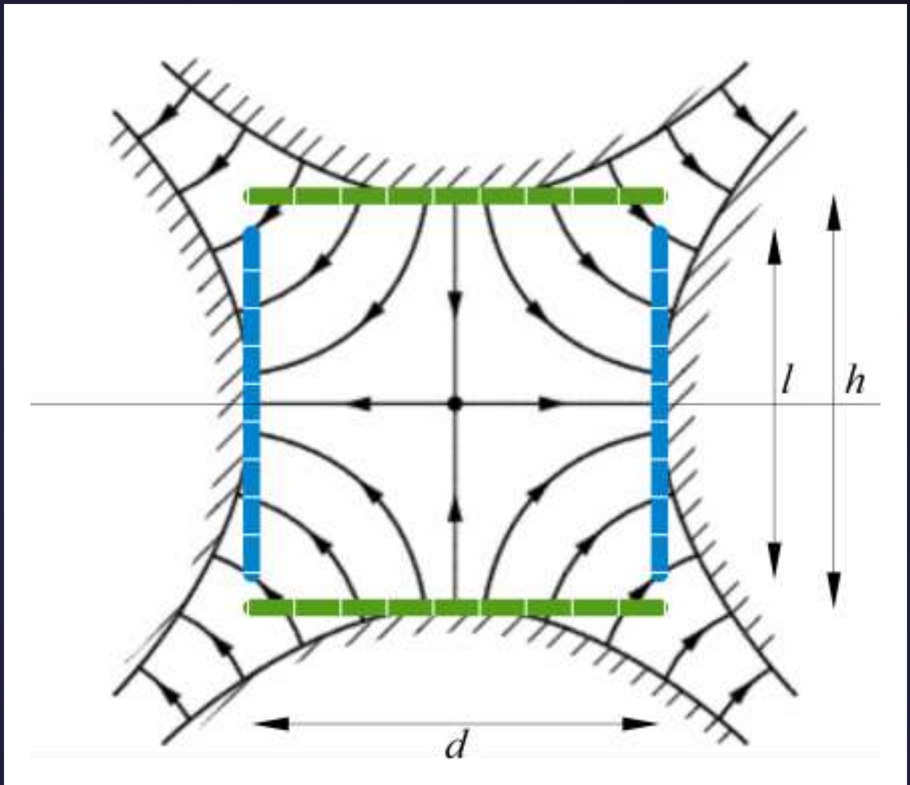
THE QUADRUPOLE FIELD



$$\varphi_Q(\vec{r}) = 2U_Q \frac{x^2 - y^2}{d^2}$$

$$\vec{E}_Q(\vec{r}) = \frac{4U_Q}{d^2}(-x, y, 0)$$

THE QUADRUPOLE FIELD



Electric field fixed by potential:

$$\vec{E} = -\vec{\nabla}\varphi(\vec{r})$$

Potential can be fixed by metal strips

$$\varphi(\vec{r}_i) = U_i$$

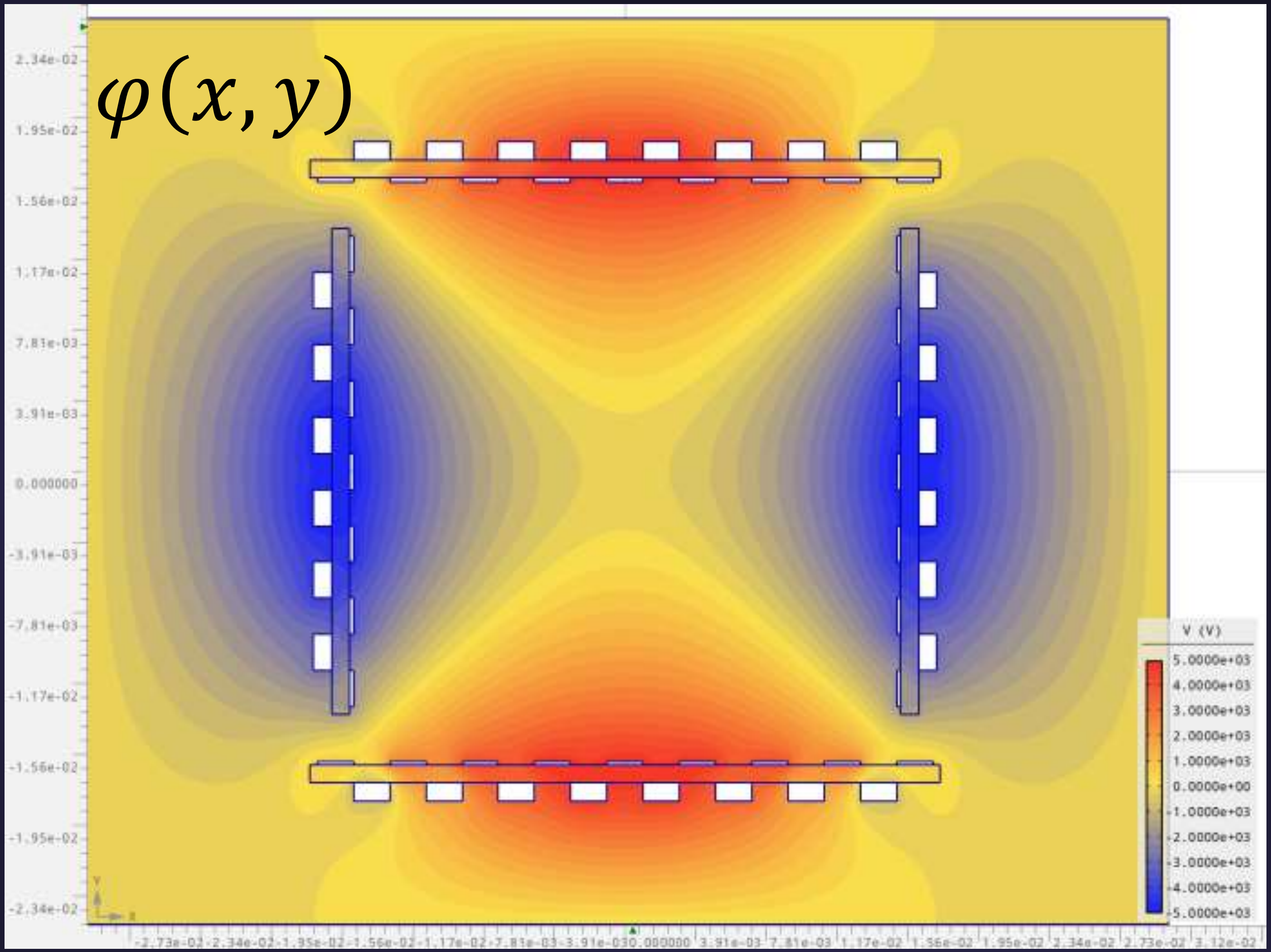
Advantage:

- Arbitrary shape of field cage

Disadvantage:

- Need many different voltages
- Finite granularity of field strips

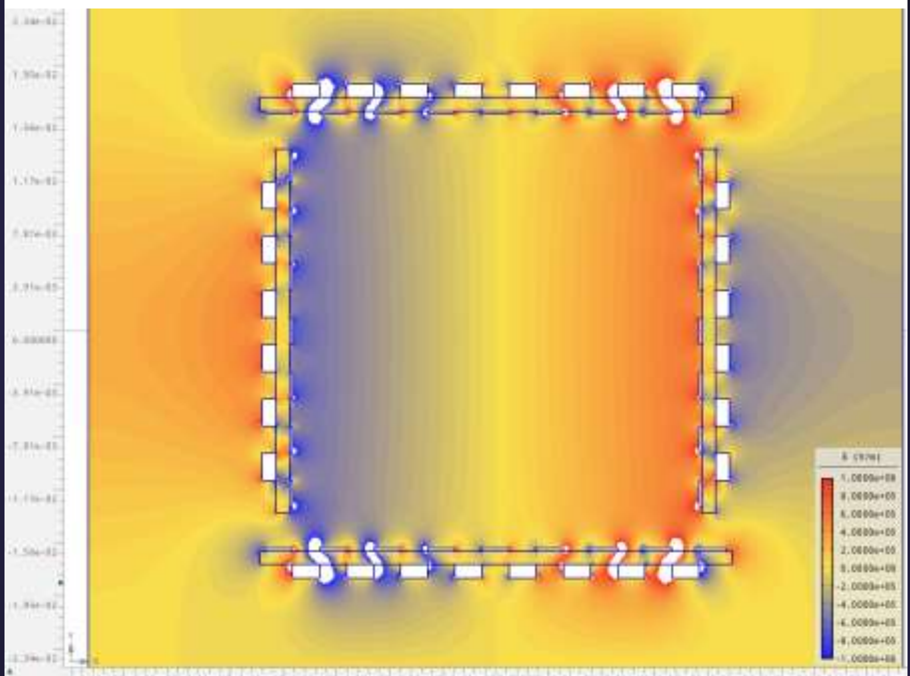
QUADRUPOLE


$\varphi(x,y)$
V (V)
5.0000e+03
4.0000e+03
3.0000e+03
2.0000e+03
1.0000e+03
0.0000e+00
-1.0000e+03
-2.0000e+03
-3.0000e+03
-4.0000e+03
-5.0000e+03

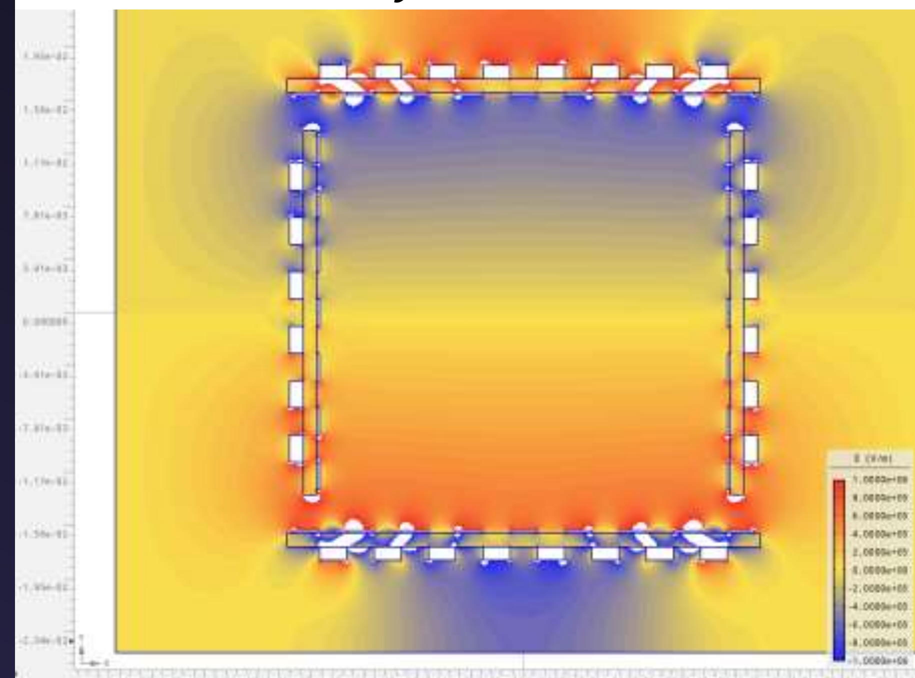
QUADRUPOLE

AGROS 2D

$E_x(x,y)$

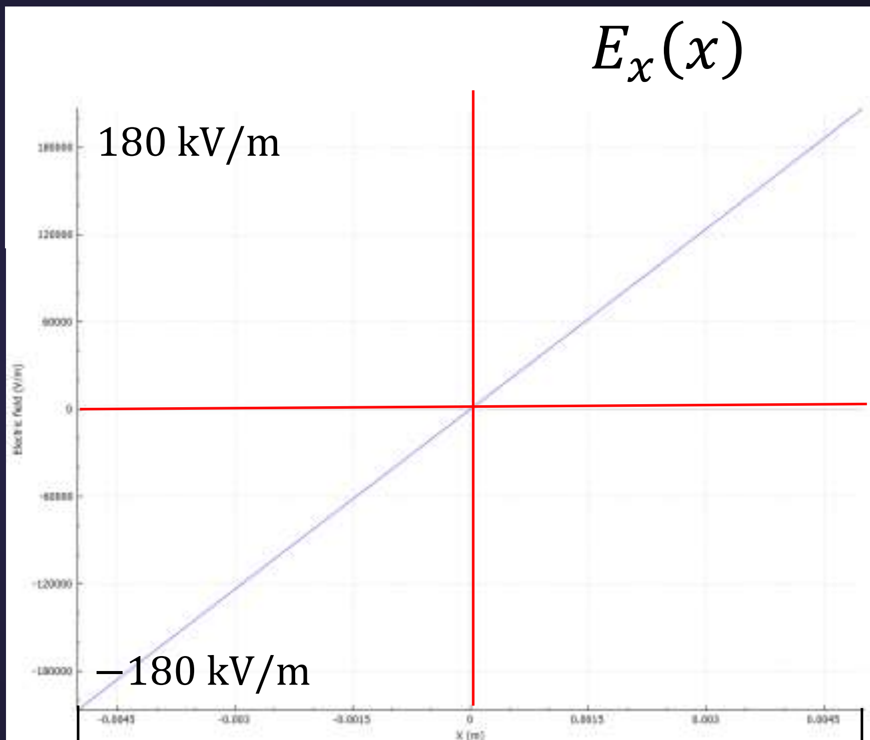


$E_y(x,y)$

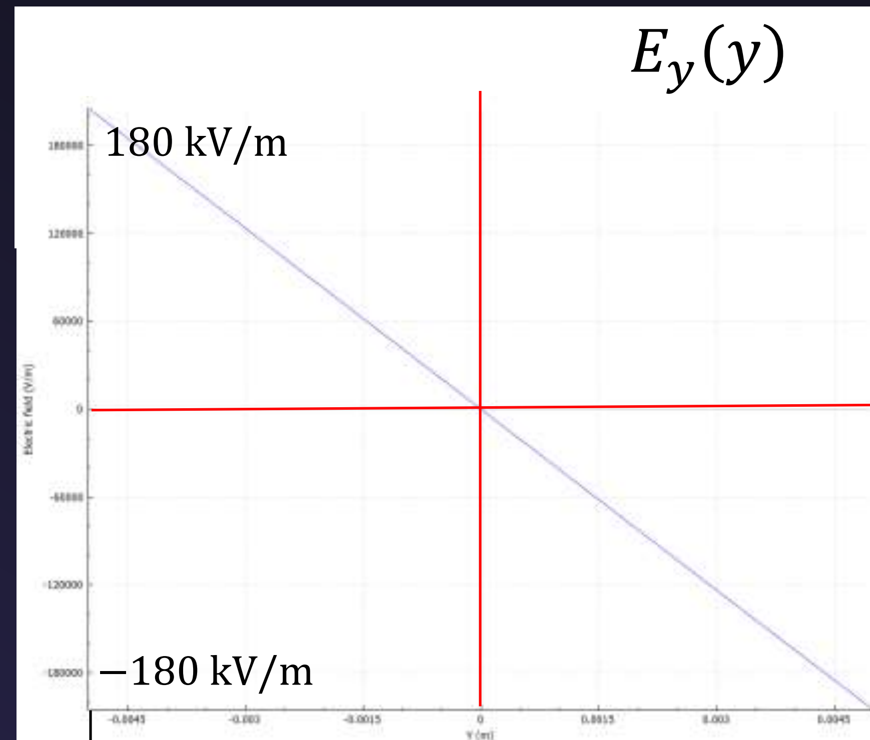


QUADRUPOLE

AGROS 2D



−5 mm 5 mm



−5 mm 5 mm

COMBINED FUNCTION

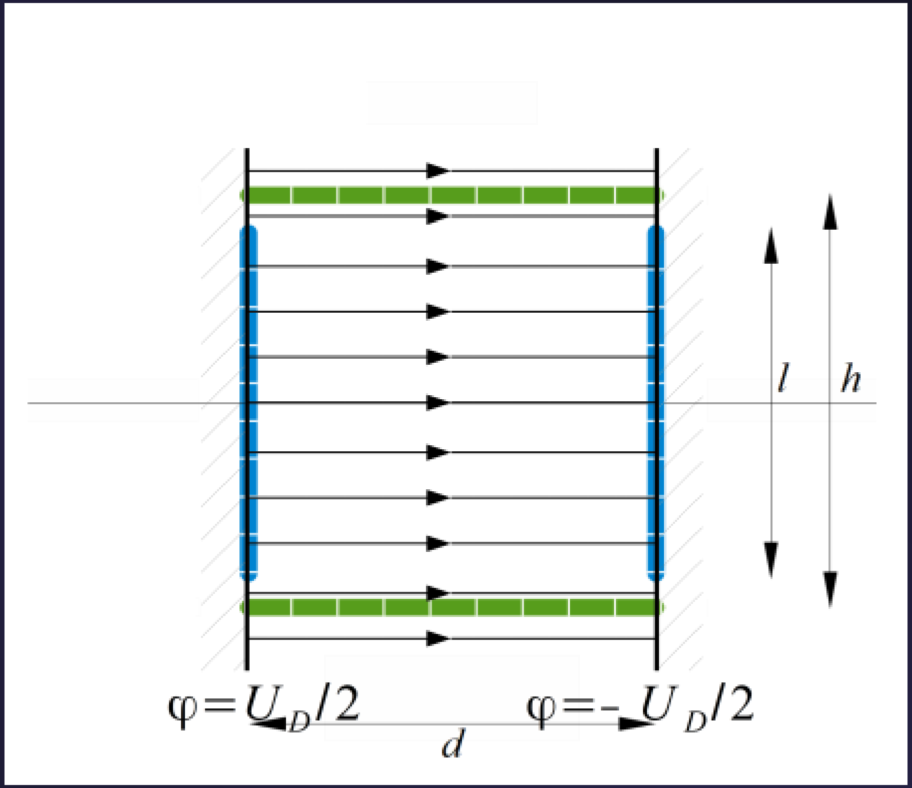
Poisson's equation is linear: $\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$

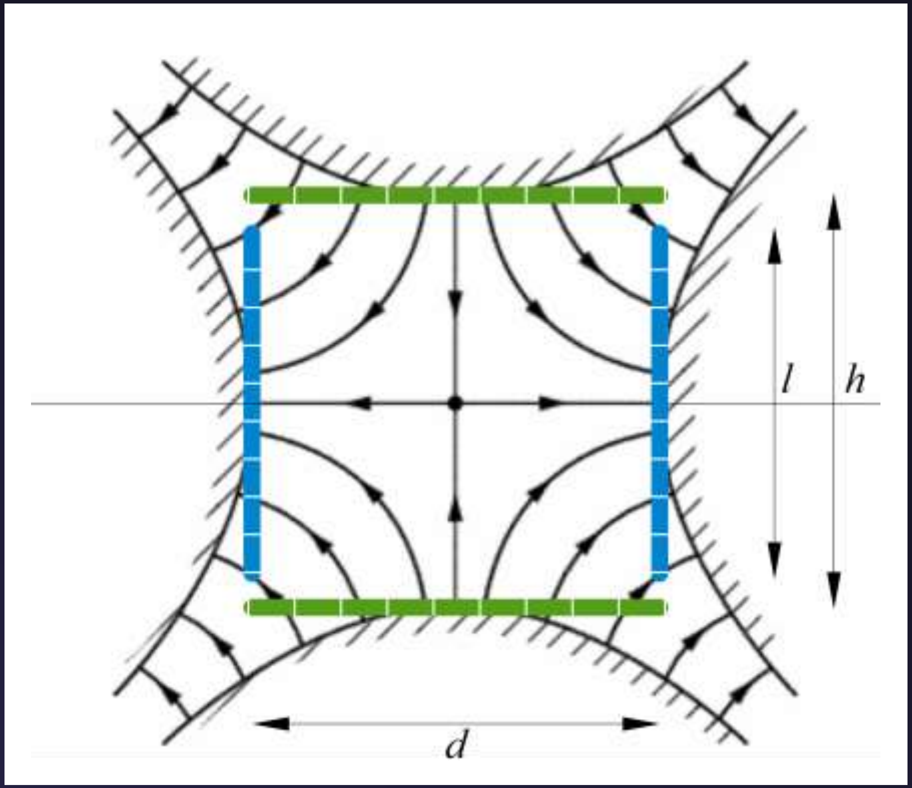
→ potential and electric fields super-impose

Combined Function: $\vec{E}_{c.f.} = \vec{E}_{\mathrm{Dipole}} + \vec{E}_{\mathrm{Quadrupole}} + \cdots$

→ strips: $U_{strip} = U_{Dipole} + U_{Quadrupole}$+…

COMBINED FUNCTION



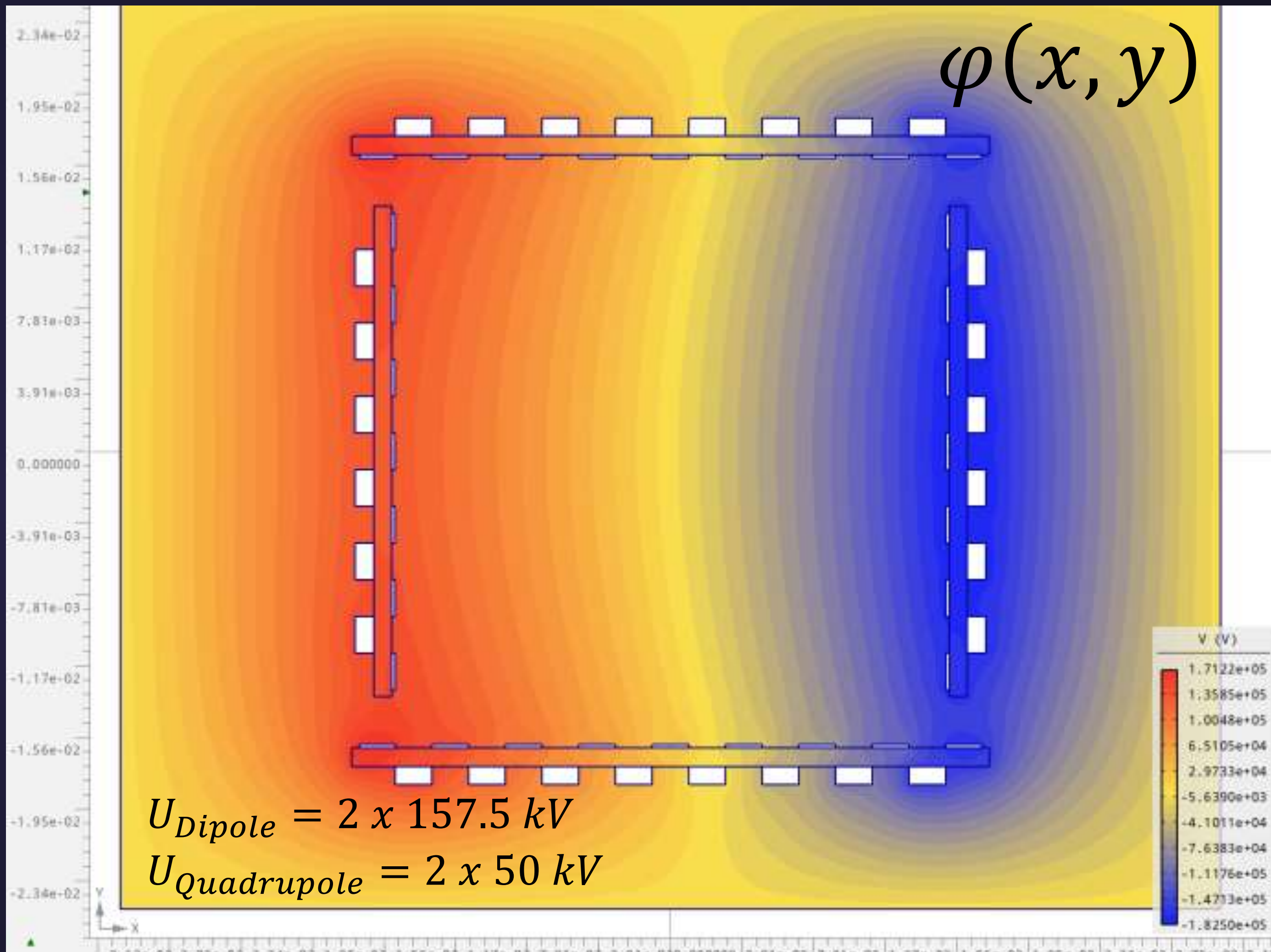


Combined Function: $\vec{E}_{c.f.} = \vec{E}_{\text{Dipole}} + \vec{E}_{\text{Quadrupole}} + \cdots$

→ strips: $U_{strip} = U_{Dipole} + U_{Quadrupole} + \ldots$

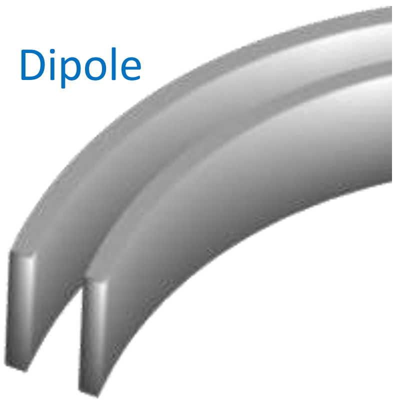
COMBINED FUNCTION

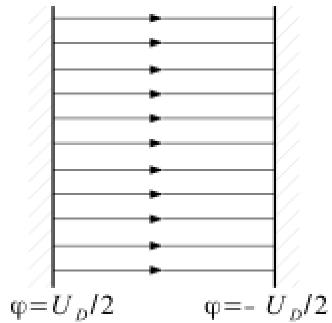
AGROS 2D

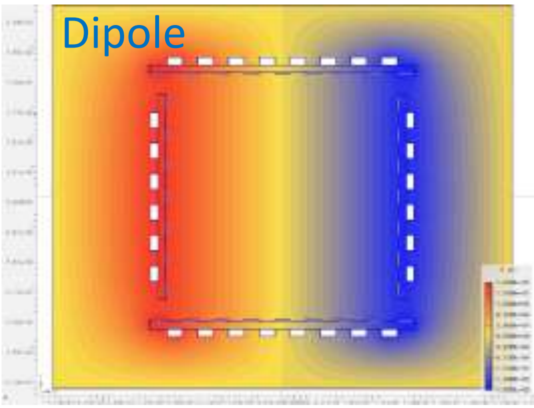


BEAM OPTICS

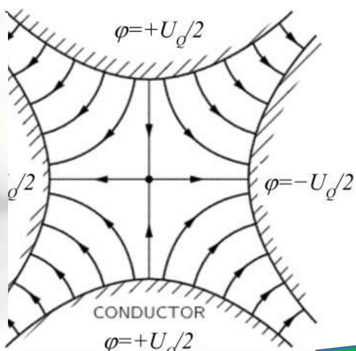
Dipole

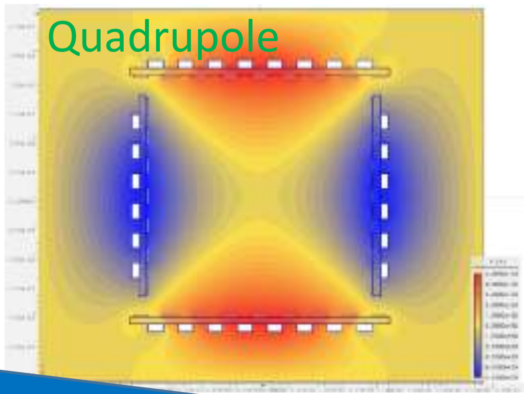






Quadrupole

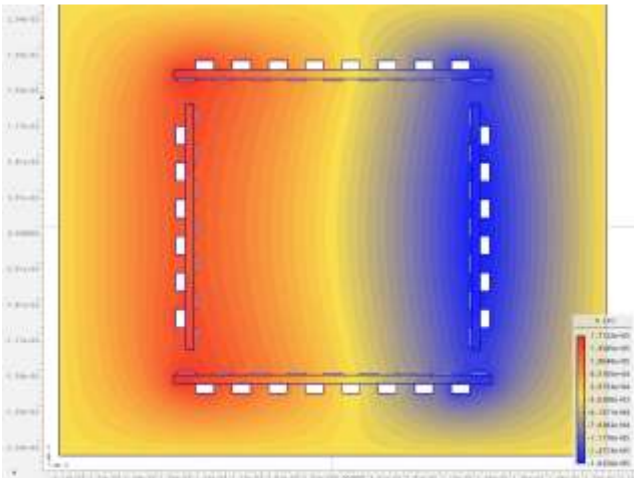


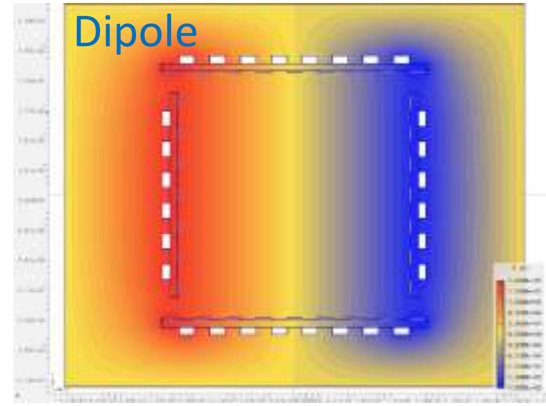


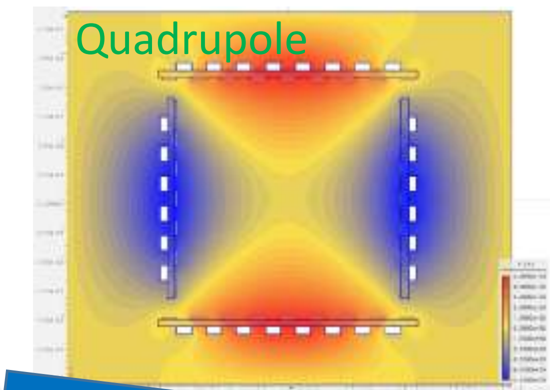
fringe fields !

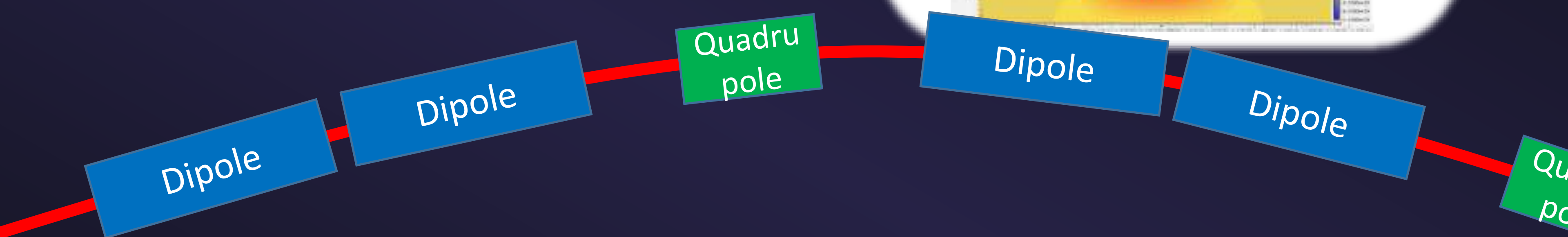
BEAM OPTICS

Combined Function



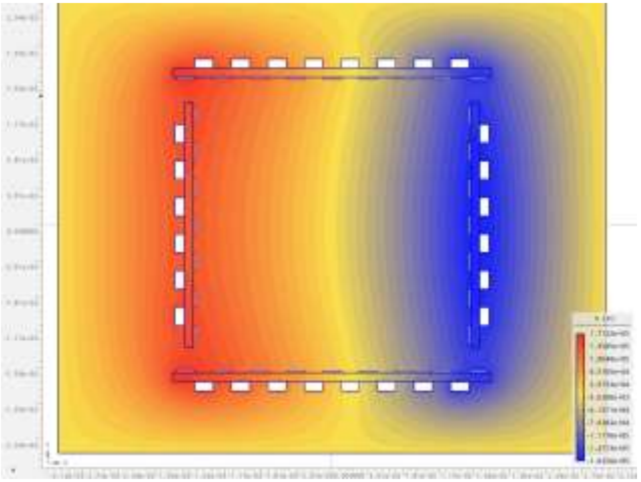


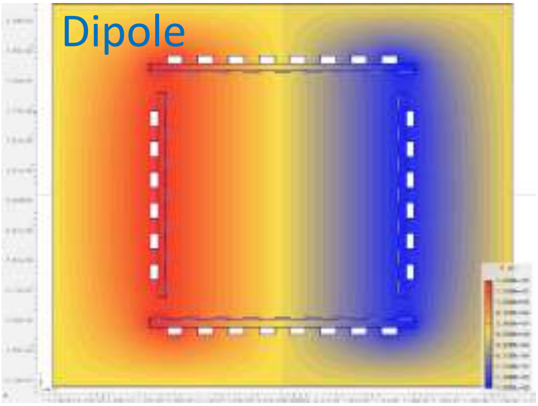


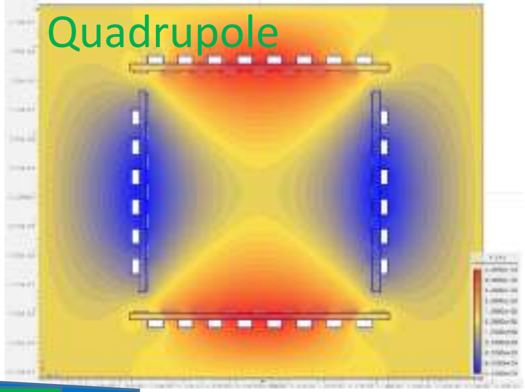


BEAM OPTICS

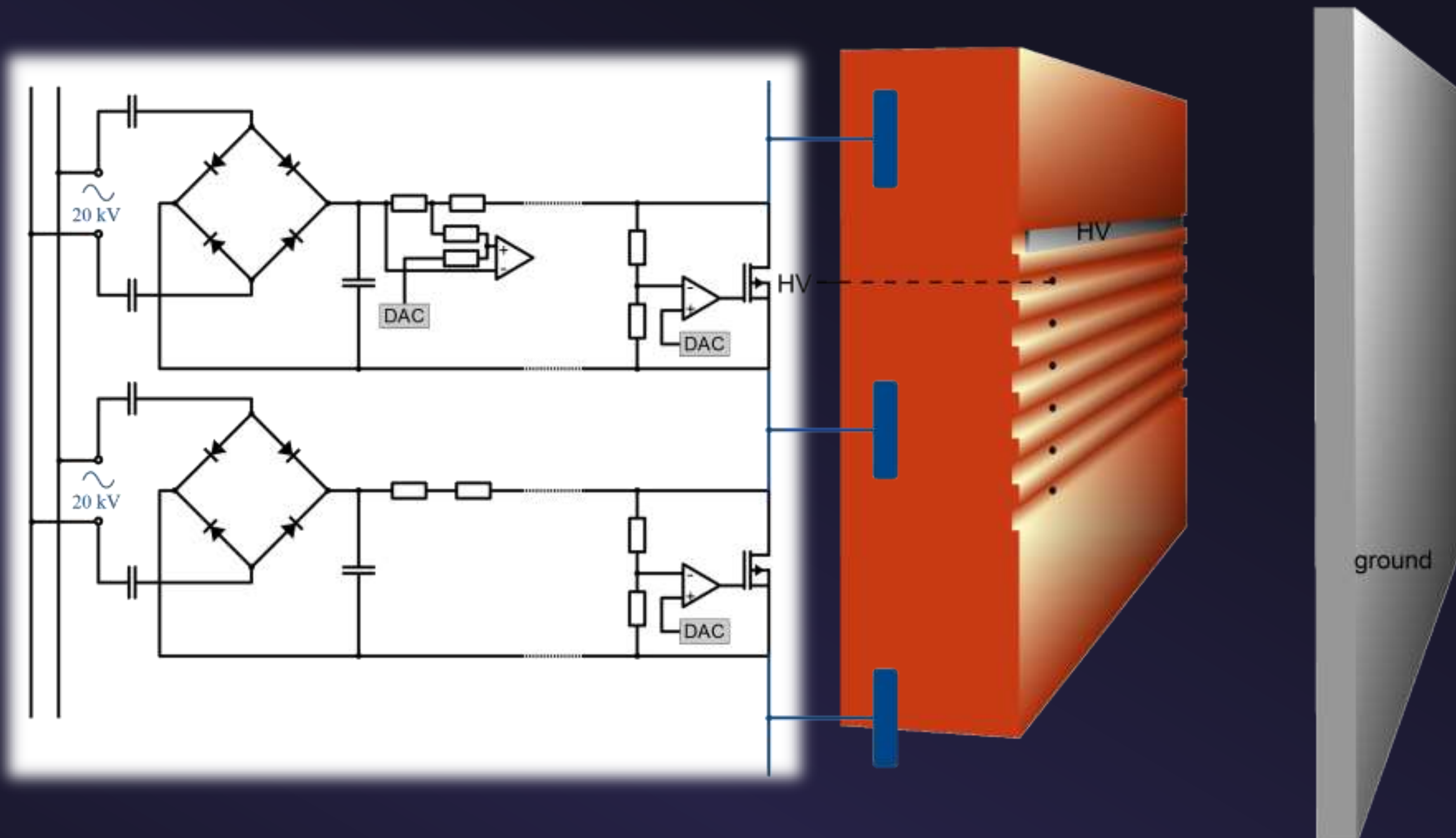
Combined Function



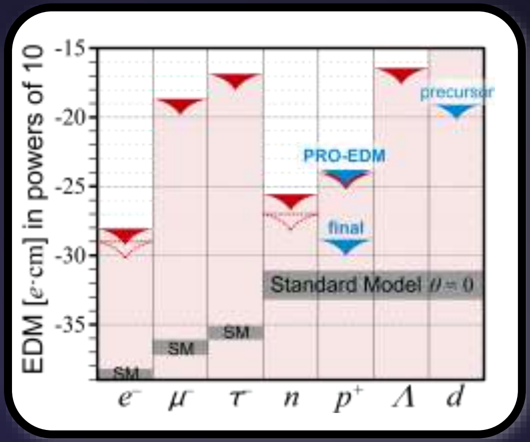




PROTOTYPE



Strategy and Goals



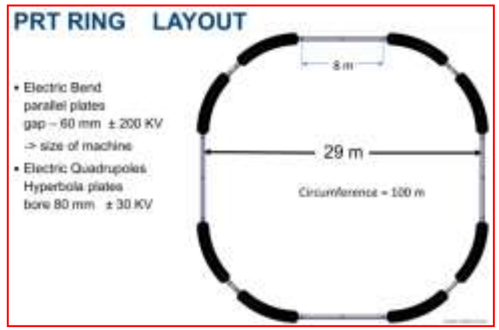
EXPERIMENTAL STRATEGY: 3 STEPS

Precursor @ COSY
Forschungszentrum Jülich

Ongoing

- Magnetic storage ring
- Limited E-field in RF Wien filter

Prototype Ring
Forschungszentrum Jülich



Could start soon

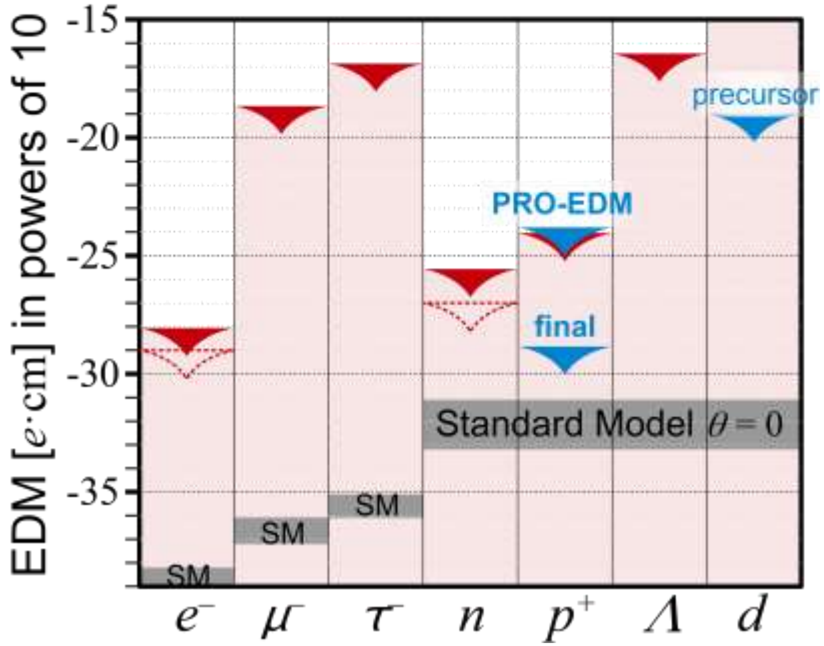
- Electrostatic storage ring
- $p \approx 35\ \mathrm{MeV/c}$ (non-magic)
- Counterrotating beams
  or
  frozen spin

Magic Ring
Open Site

Final step

- Electrostatic storage ring
- Magic momentum
- Counterrotating beams **and** frozen spin

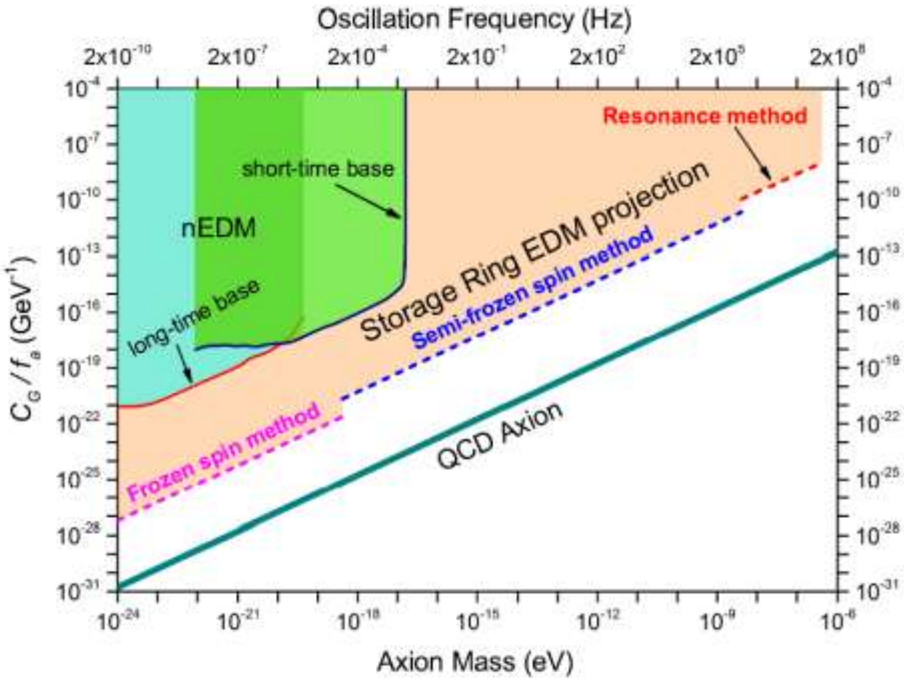
SCIENTIFIC GOALS



Scientific Motivation

- Fate of Antimatter
- θ-puzzle of QCD
  $-\theta \frac{n_f g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \quad \theta < 10^{-10}$?
- Dark Matter:
  Oscillation EDMs from axion fields

SCIENTIFIC GOALS



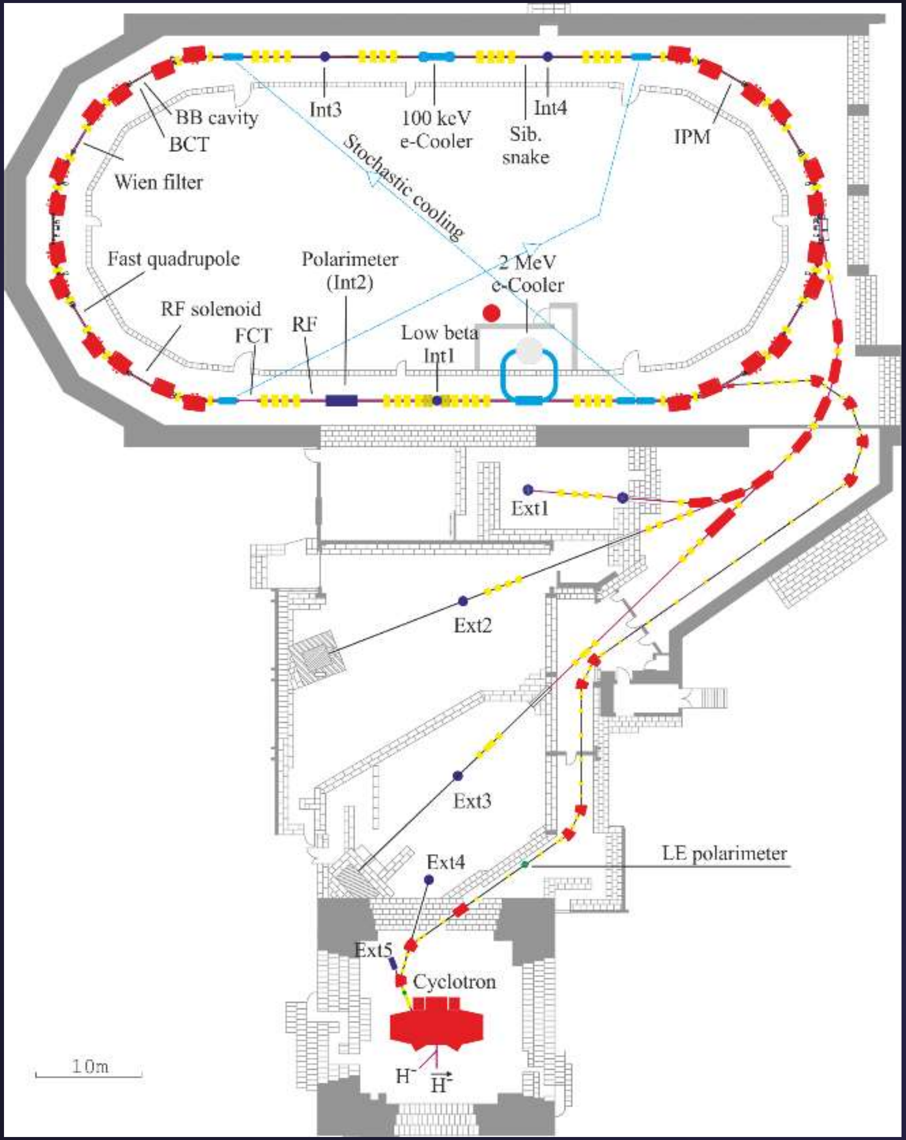
Scientific Motivation

- Fate of Antimatter
- θ-puzzle of QCD
  $-\theta \frac{n_f g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \quad \theta < 10^{-10}$?
- Dark Matter:
  Oscillation EDMs from axion fields

Precursor @ COSY

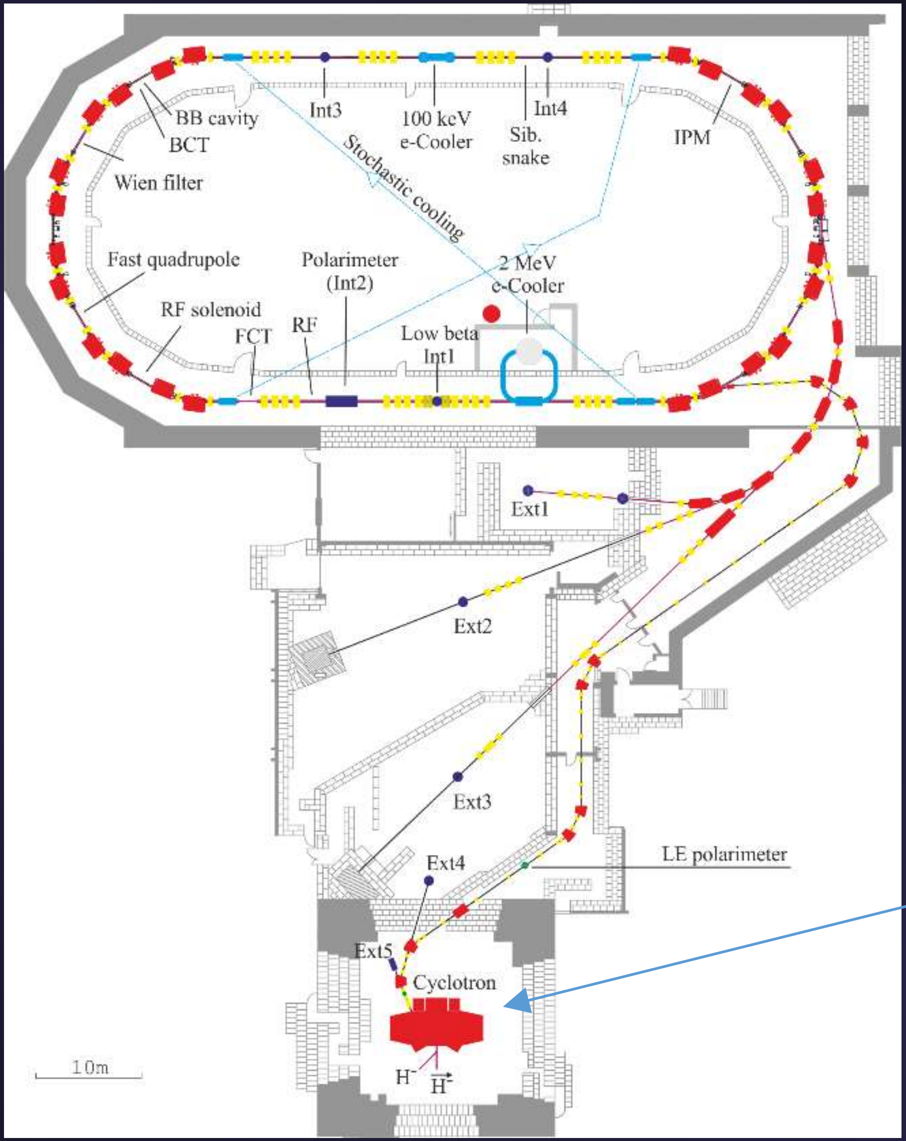
COSY

COOLER SYNCHROTRON



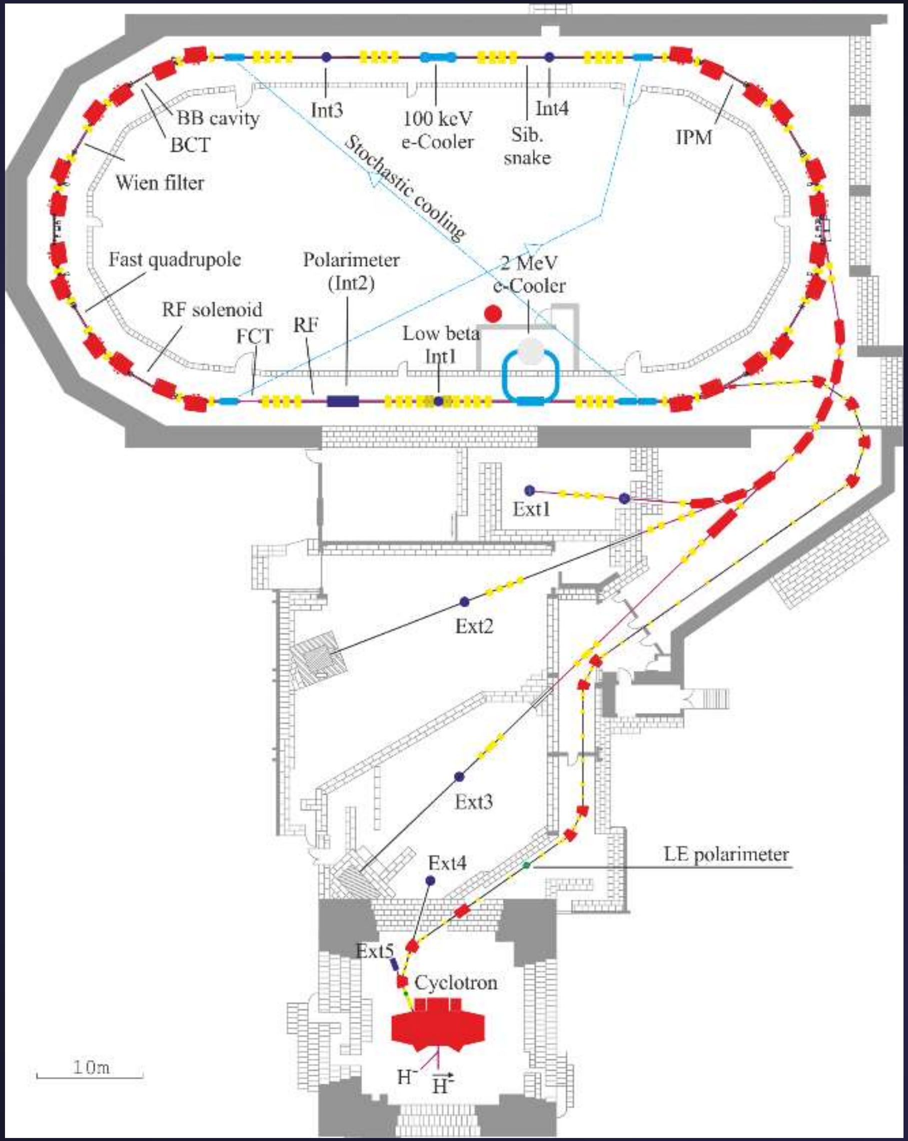
COoler SYnchrotron (COSY) at Forschungszentrum Jülich (Germany)

COOLER SYNCHROTRON



- Cyclotron as injector
- 45 MeV H⁻, 76 MeV D⁻ via stripping injection
- ~10^{11} protons/deuterons per injection
- Polarized (p,d) beams up to 3.7 GeV/c

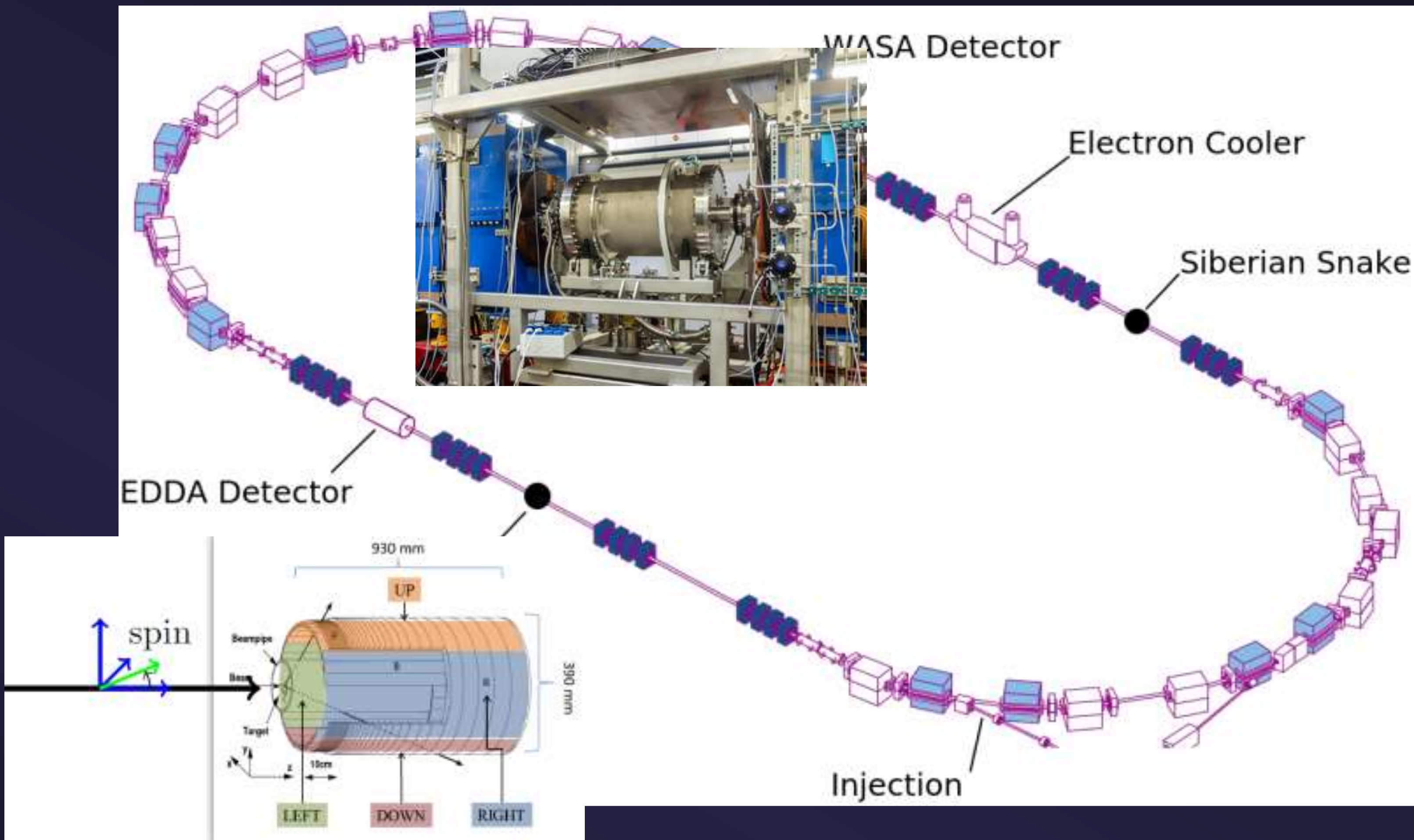
COOLER SYNCHROTRON



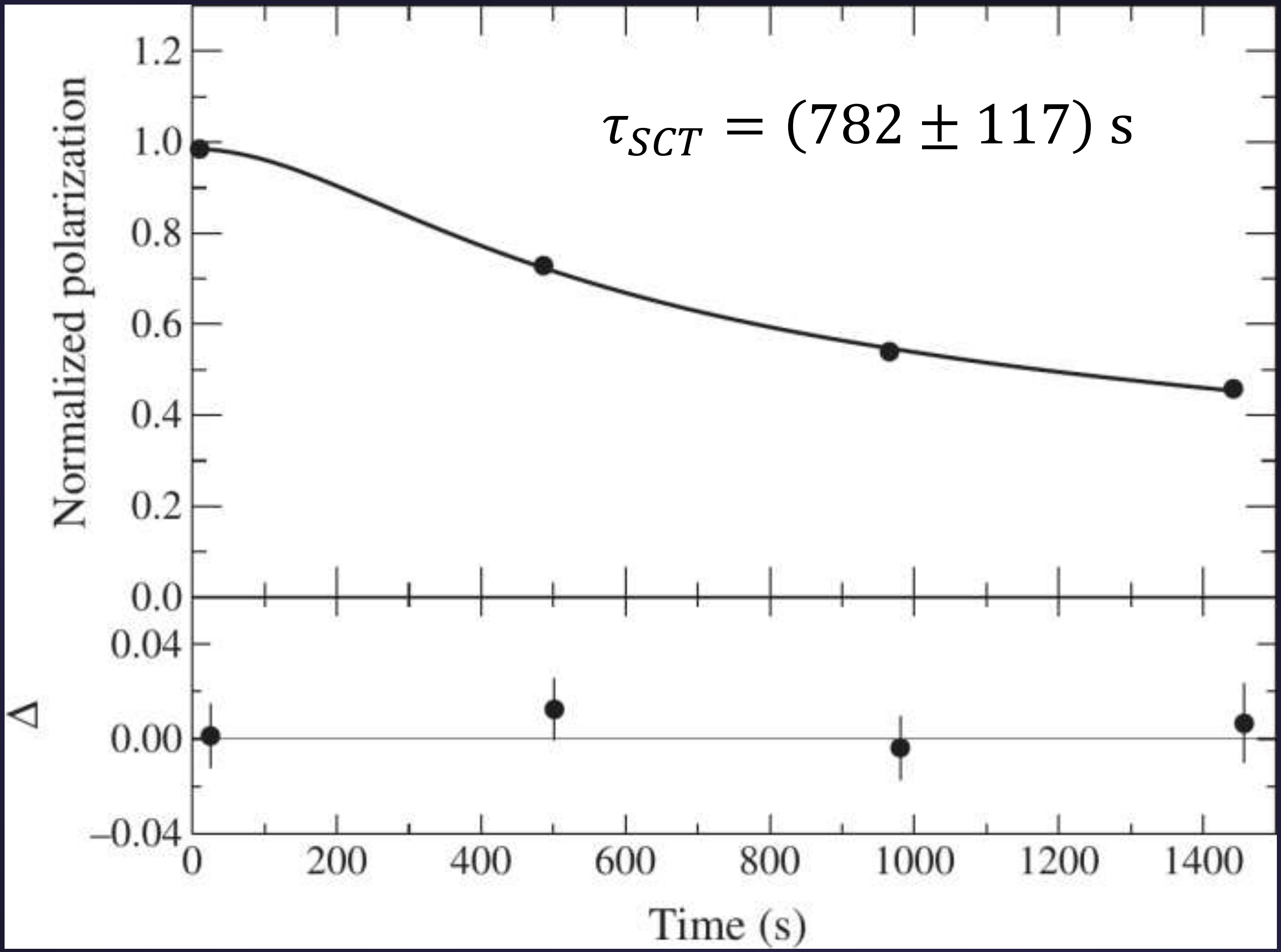
- 100 keV and 2 MeV electron cooler
- Stochastic cooling
- RF spin manipulation
- Internal and external target places at COSY and injector cyclotron

→ **Worldwide unique facility for spin physics**

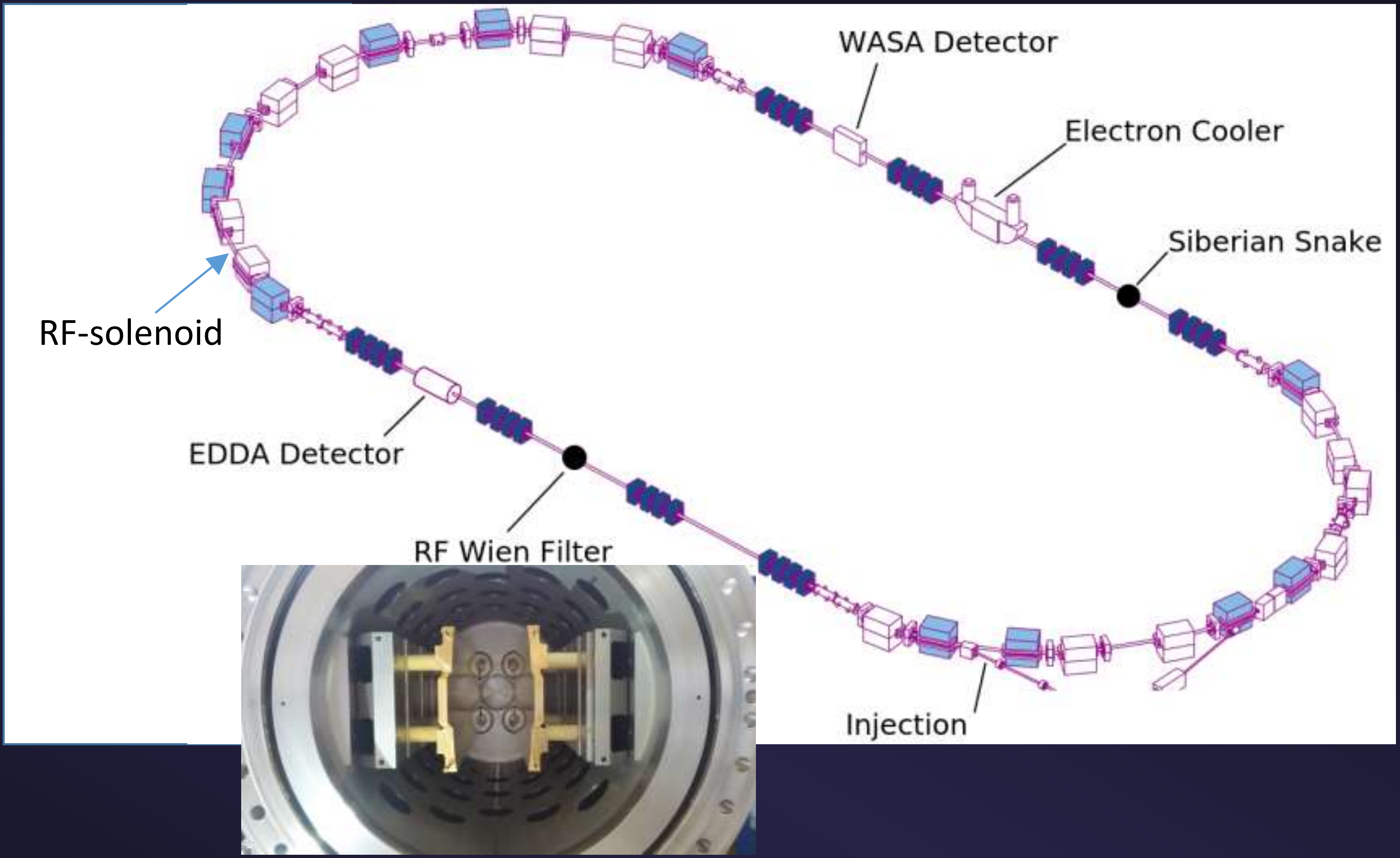
PRECURSOR EXPERIMENT



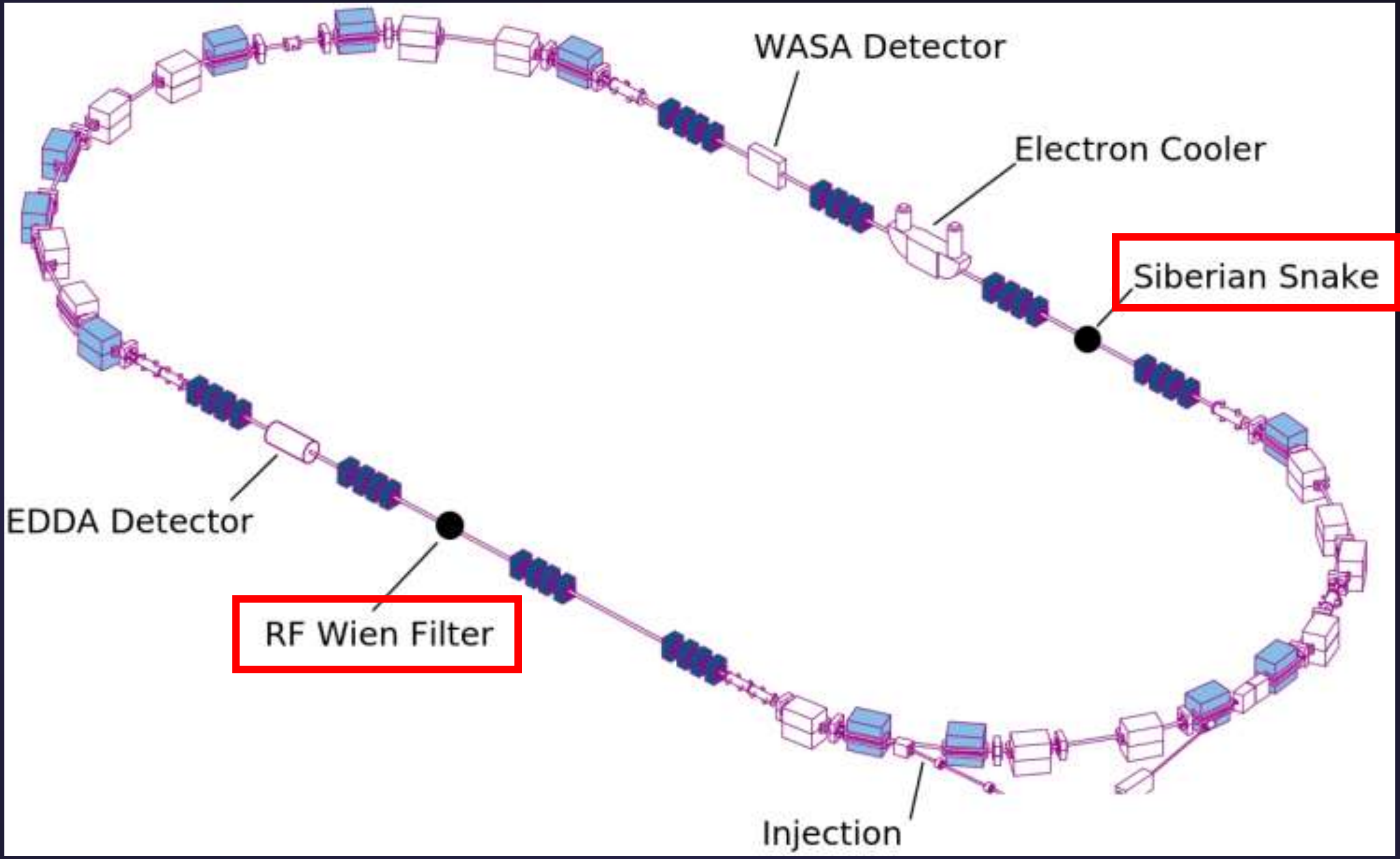
SPIN COHERENCE TIME



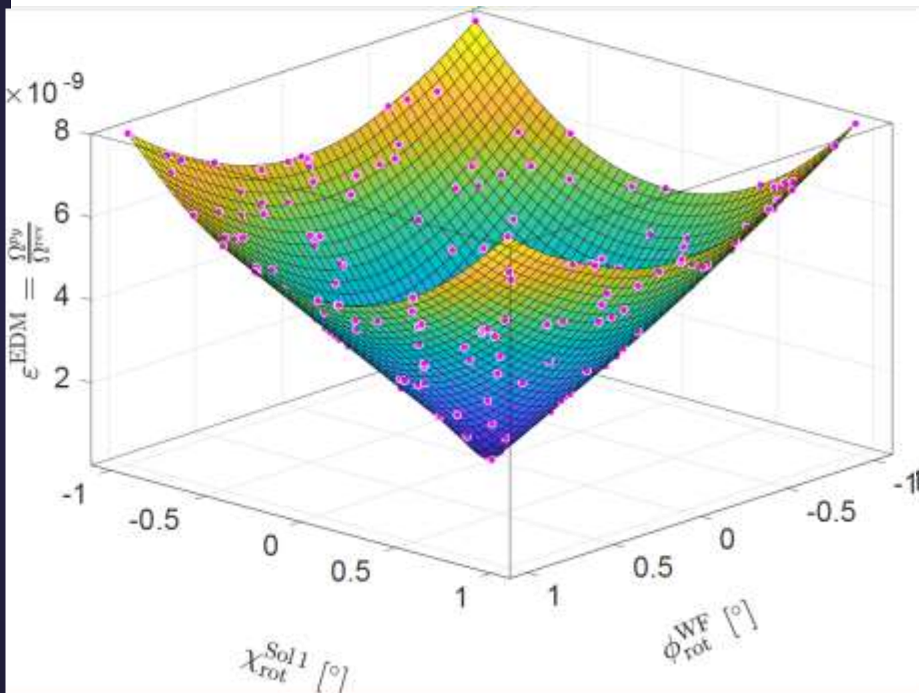
ELECTRIC FIELD IN COSY



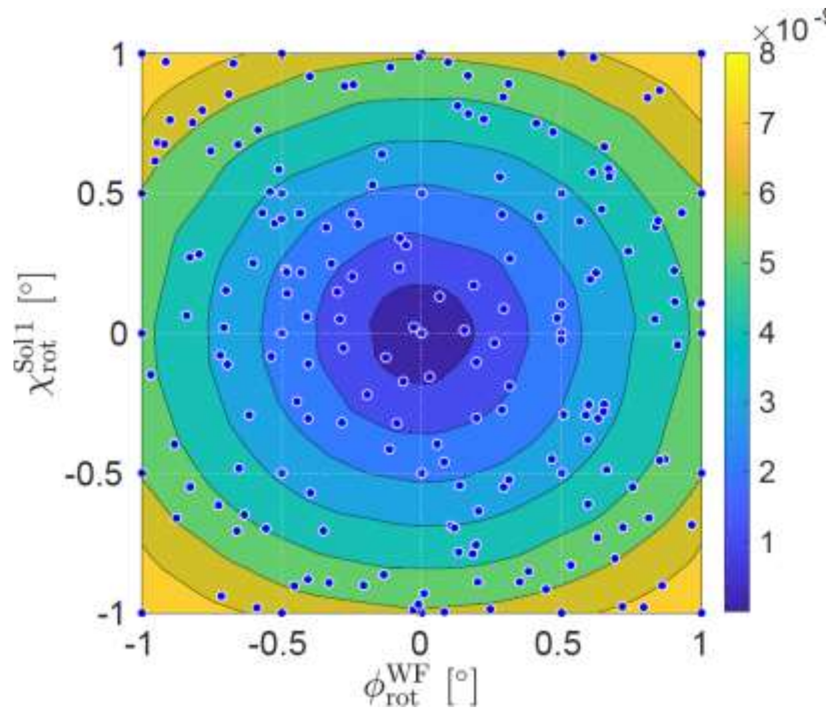
PRECURSOR EXPERIMENT



PRECURSOR: SIMULATION

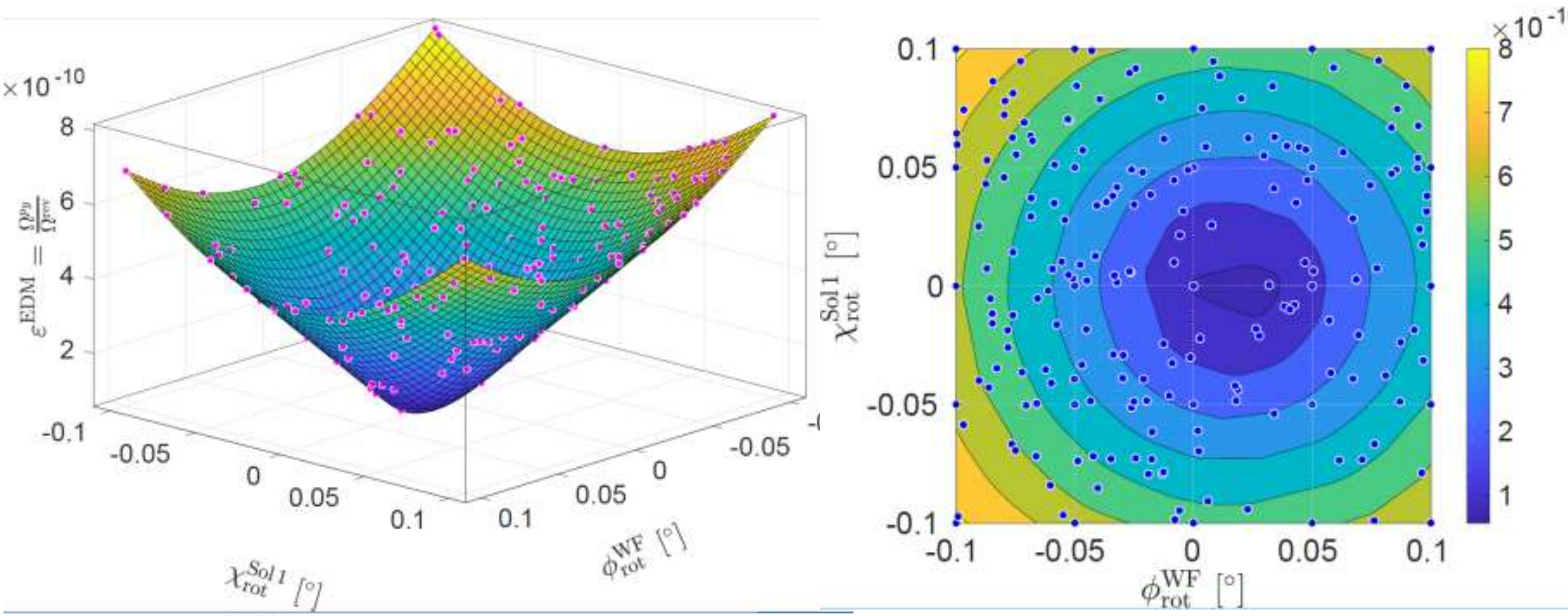


(a) ε^{EDM} for $d = 10^{-20}\,\text{e cm}$.



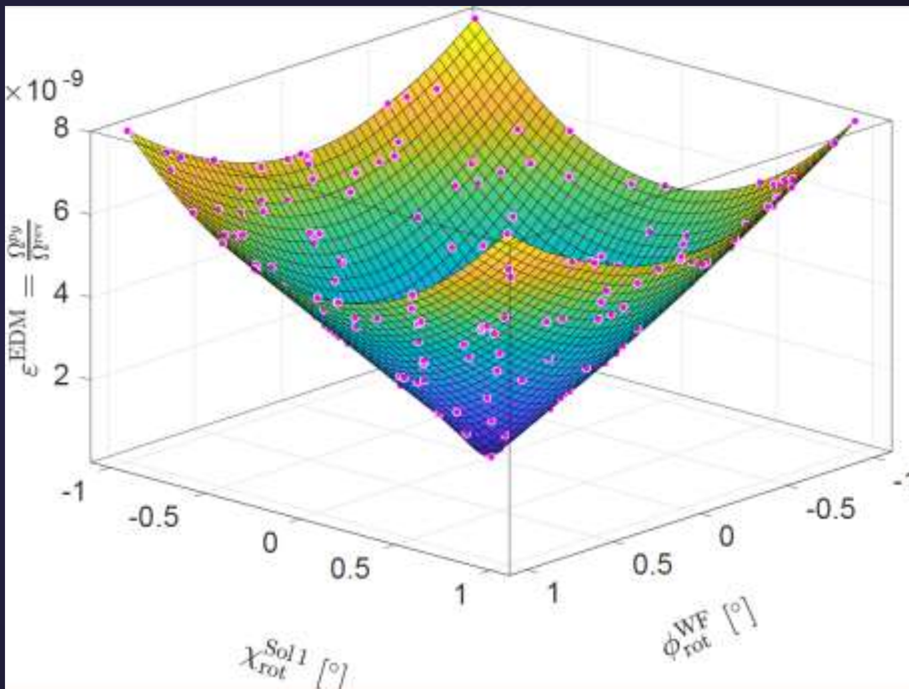
(b) Contour plot of (a).

PRECURSOR: SIMULATION

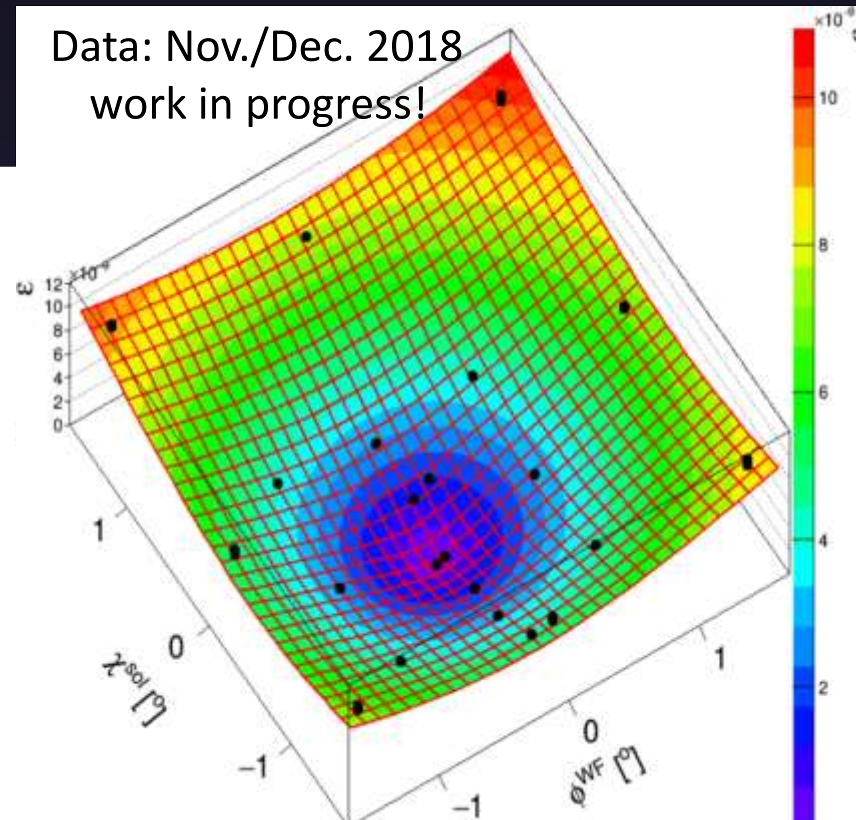


(c) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-18}$ e cm. (d) Contour plot of (c).

PRECURSOR: RESULT



(e) Simulated $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-20}$ e cm.

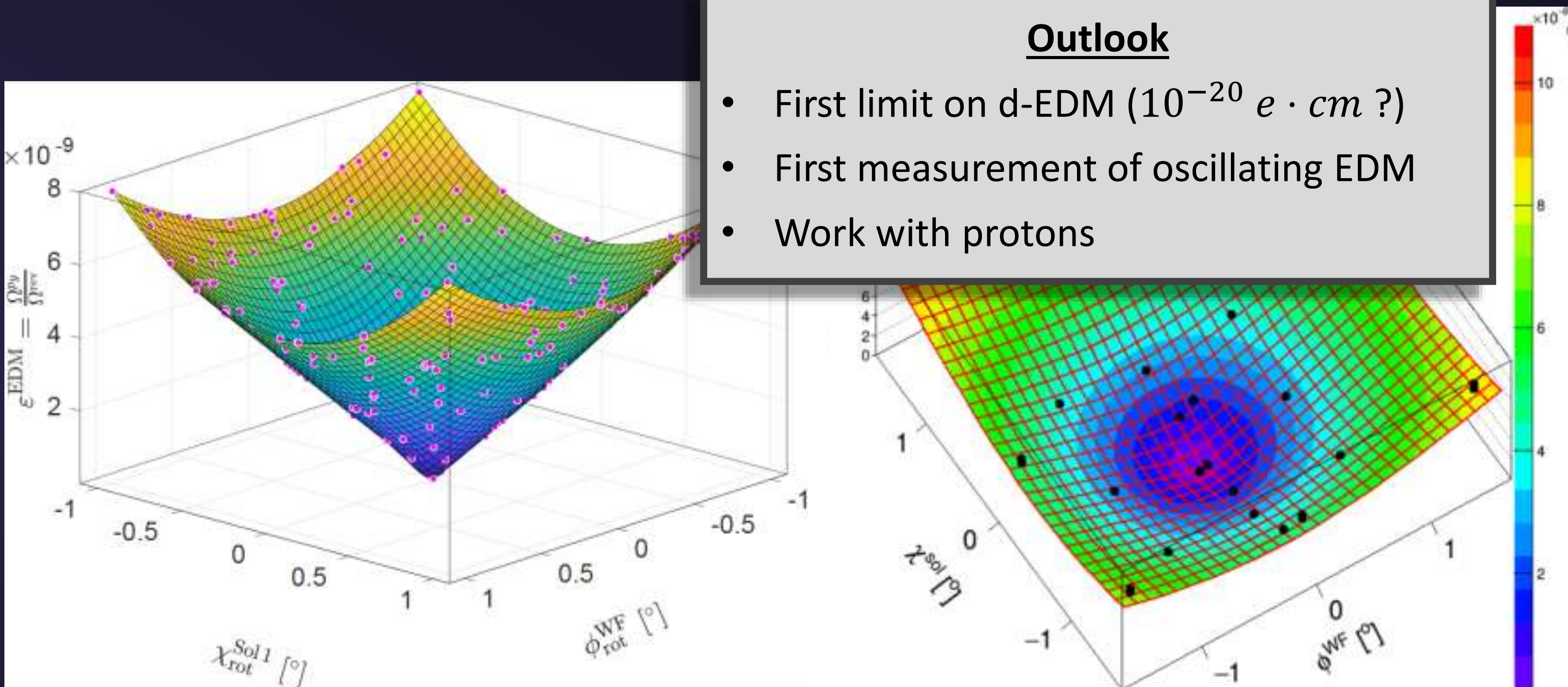


(f) First 9 + 9 + 14 data points on 3 maps (≈ 2 weeks)

PRECURSOR: PLANS

Outlook

- First limit on d-EDM ($10^{-20}\ e \cdot cm$?)
- First measurement of oscillating EDM
- Work with protons



(e) Simulated $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-20}$ e cm.

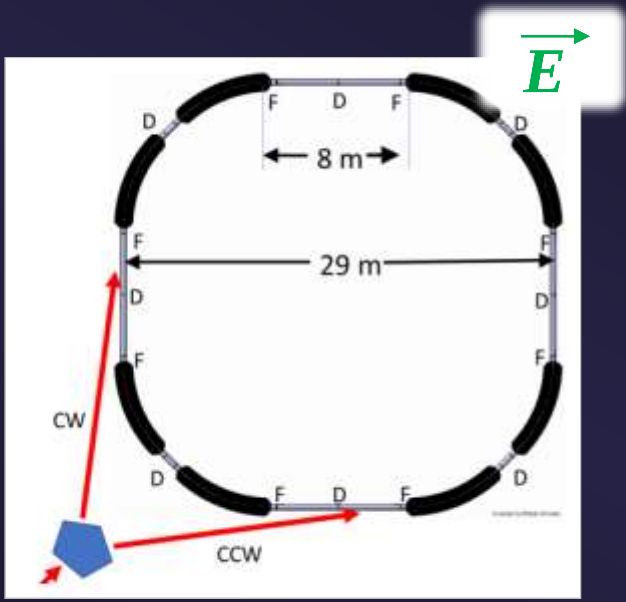
(f) First 9 + 9 + 14 data points on 3 maps (≈ 2 weeks)

ProEDM

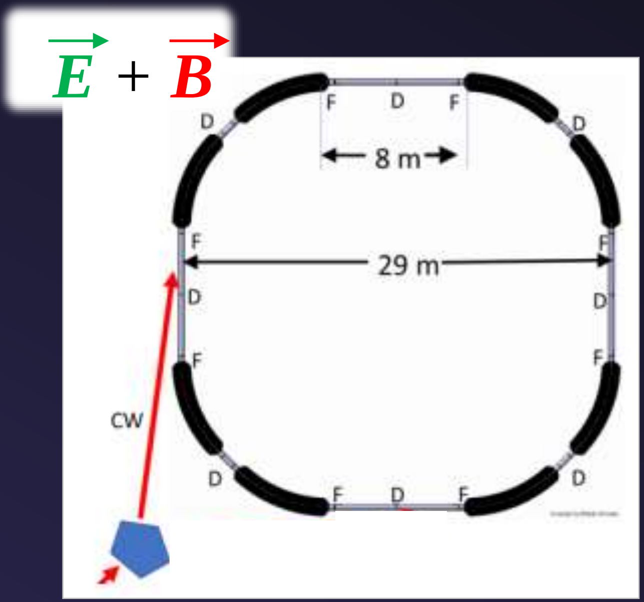
PROTO-EDM RING

- Small ring (~ 100 m circumference)
- All-electric ring
- Counter-rotating beams
- ~~Frozen spin~~
- ~~Measurement of p-EDM~~

- Small ring (~ 100 m circumference)
- ~~All~~-electric ring
- ~~Counter-rotating beams~~
- Frozen spin
- Measurement of p-EDM

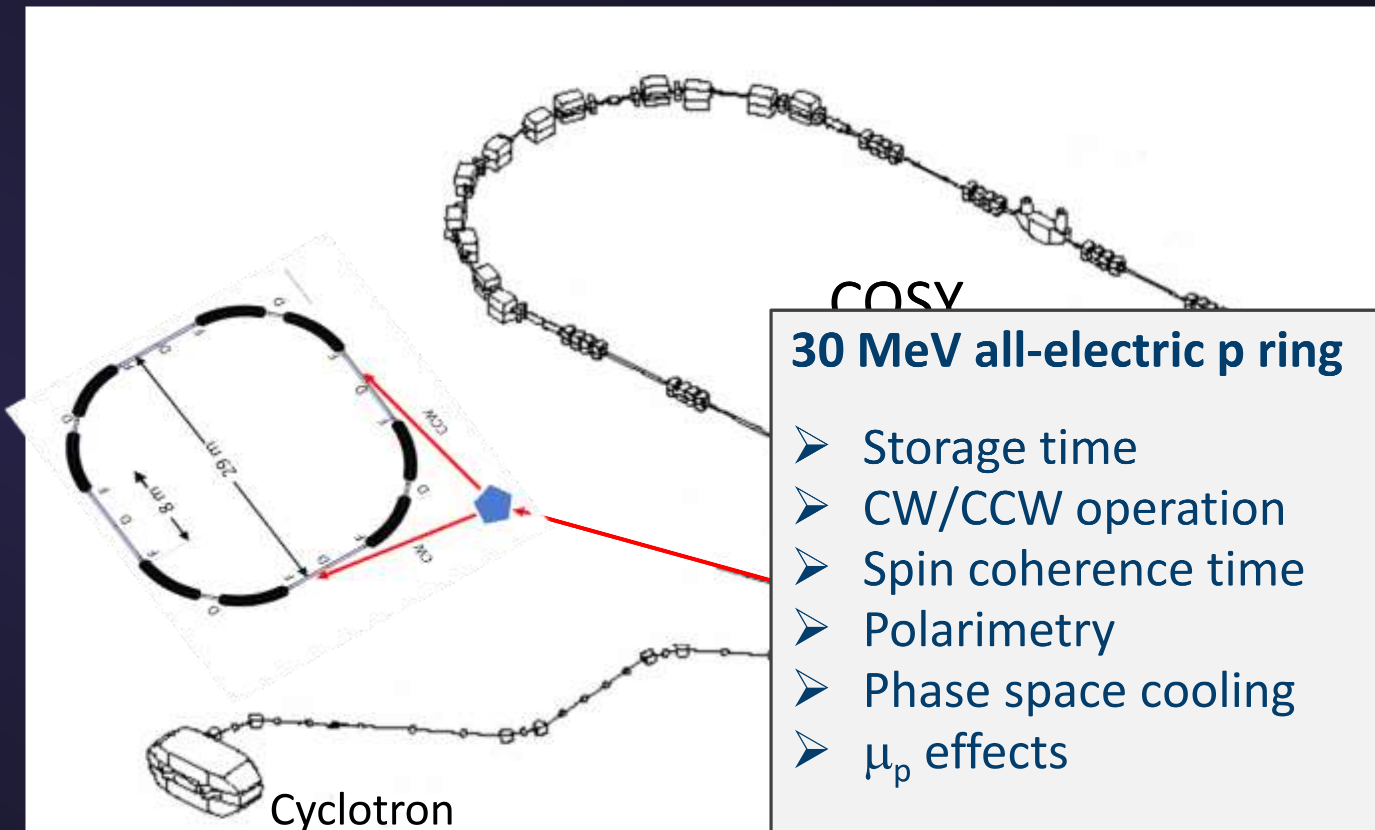


$E_{kin} = 30$ MeV



$E_{kin} = 45$ MeV

PROTO-EDM RING



30 MeV all-electric p ring

- Storage time
- CW/CCW operation
- Spin coherence time
- Polarimetry
- Phase space cooling
- μ_p effects

Option: **add B-field, 45 MeV**

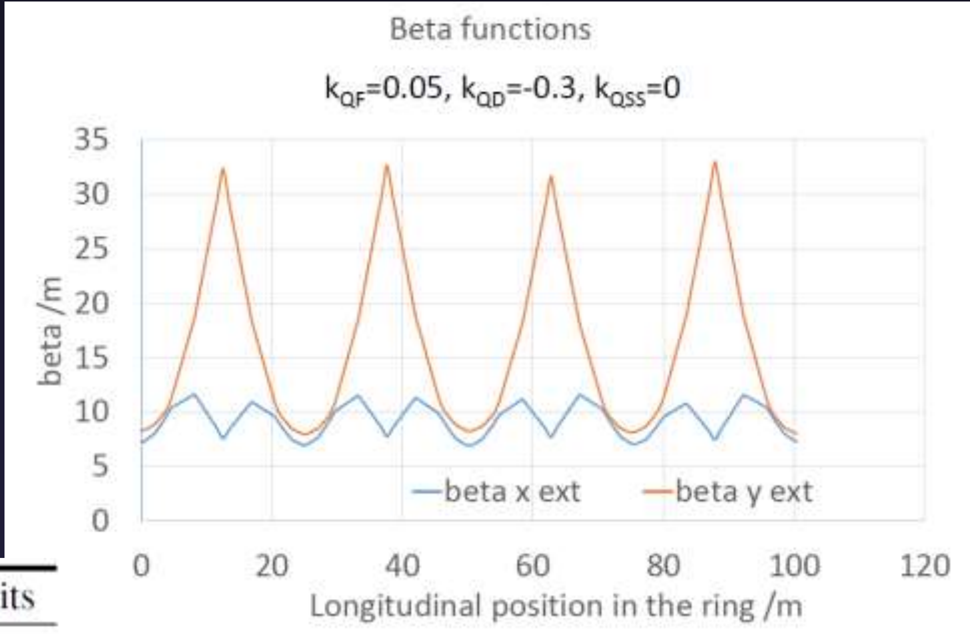
- **pEDM** measurement

PROTO-EDM RING

CPEDM

Table 1: Basic beam parameters.

	E only	$E \times B$	unit
kinetic energy	30	45	MeV
$\beta = v/c$	0.247	0.299	
momentum	239	294	MeV/c
magnetic rigidity $B\rho$	0.798	0.981	T·m
electric rigidity $E\rho$	59.071	87.941	MV
γ (kinetic)	1.032	1.048	
emittance $\varepsilon_x = \varepsilon_y$	1.0	1.0	mm·mrad
acceptance $a_x = a_y$	1.0	10.0	mm·mrad

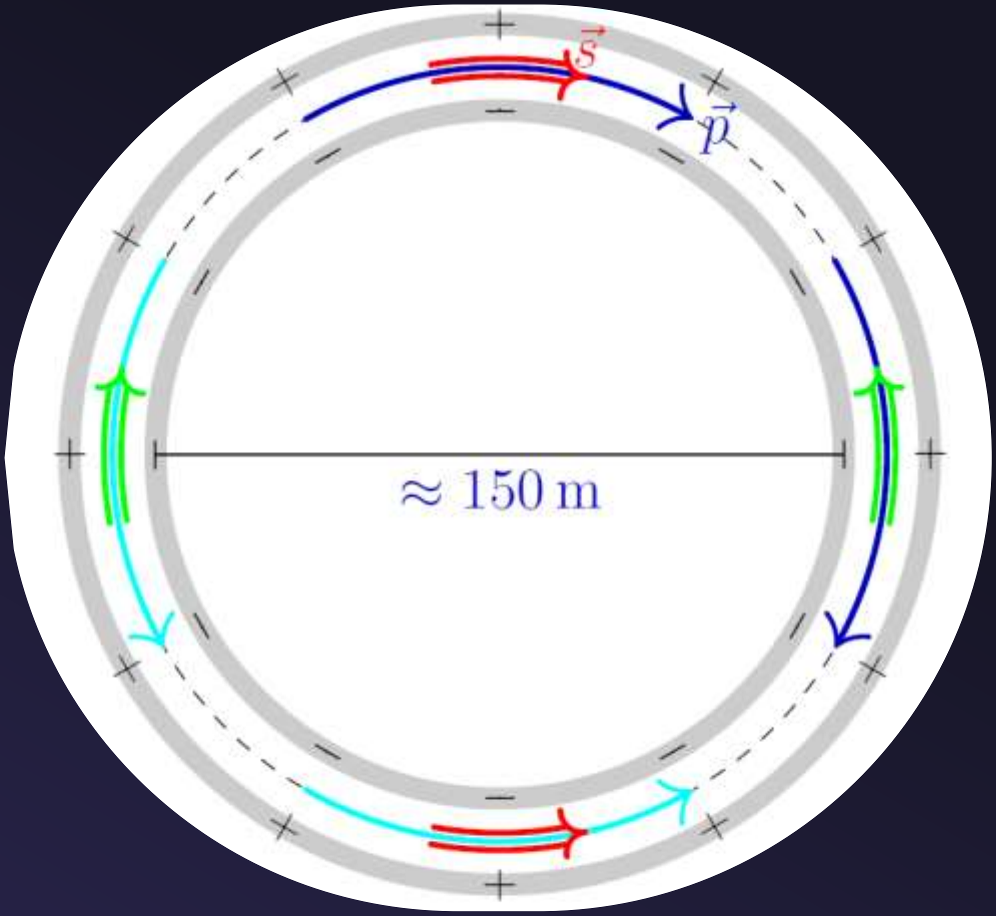


		units
# B-E deflectors	8	
# arc D quads	4	
# arc F quads	8	
# straigh quads	4	
quad length	0.400	m
straight length	8.000	m
bending radius	8.861	m
electric plate length	6.959	m
arc length (45°)	15.718	m
circumference total	100.473	m

Magic Ring

THE MAGIC RING

- Magic momentum:
  $p = 701\ \mathrm{MeV}/c \quad E_{kin} = 233\ \mathrm{MeV}$
- All-electric
- Counter-rotating beams
- Frozen spin
- Measurement of p-EDM (static and oscillating)



- Design in progress (systematic limitations!)
- Many new ideas
- Site-open studies
- Ultimate sensitivity !

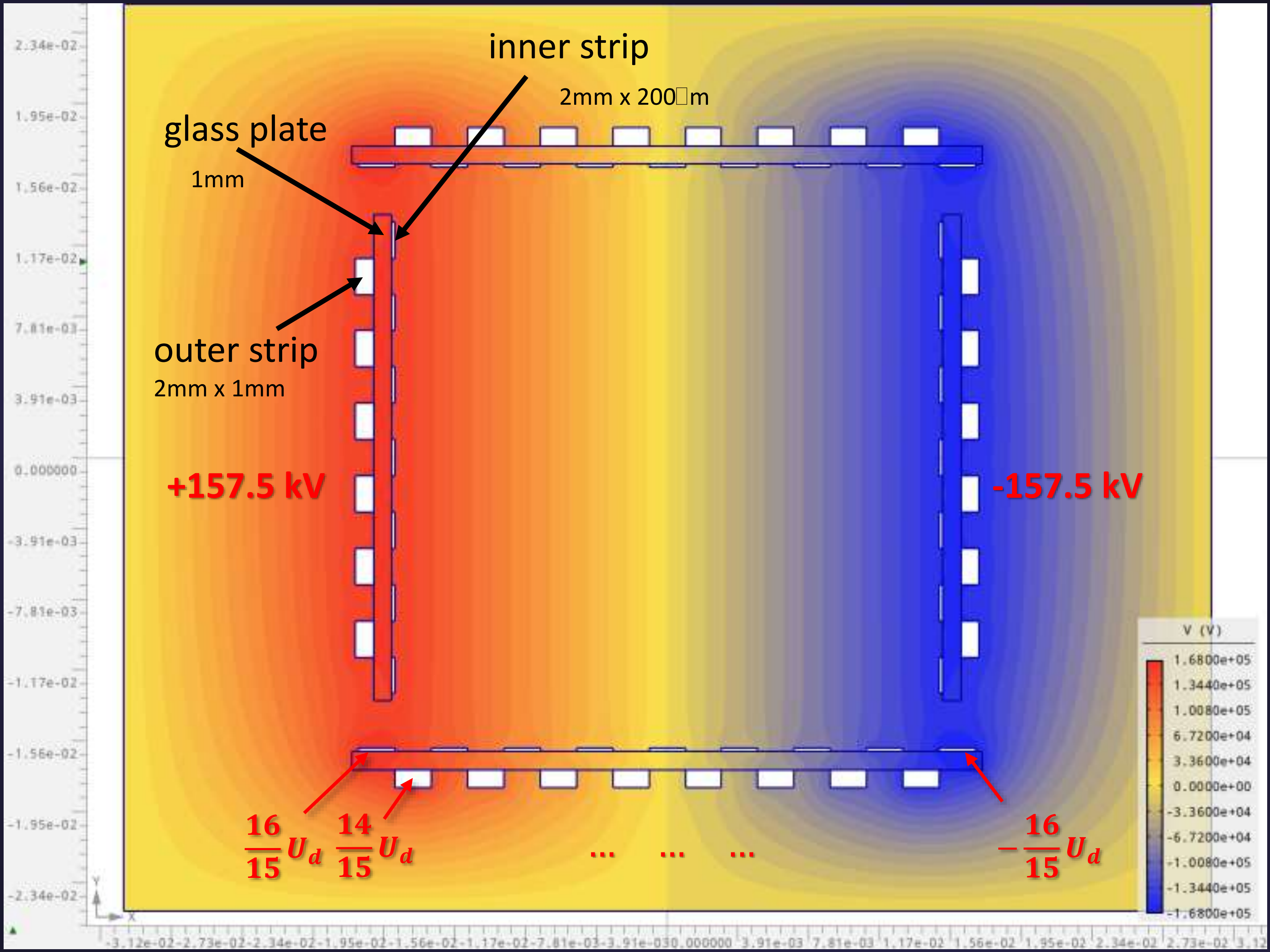
Conclusions

- **EDM: Window to CP-Violation**
- **Proton: longterm improvents**
- **Interesting experimental challenges**

New collaborators welcome

Backup

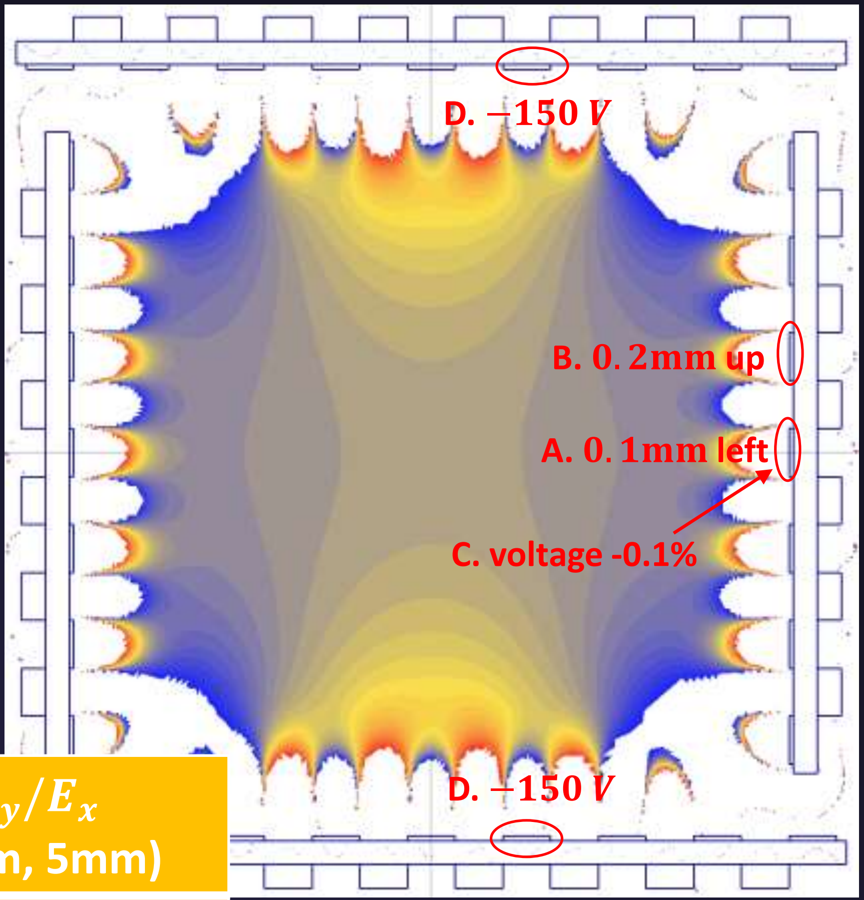
AGROS: DIPOLE



AGROS: DIPOLE

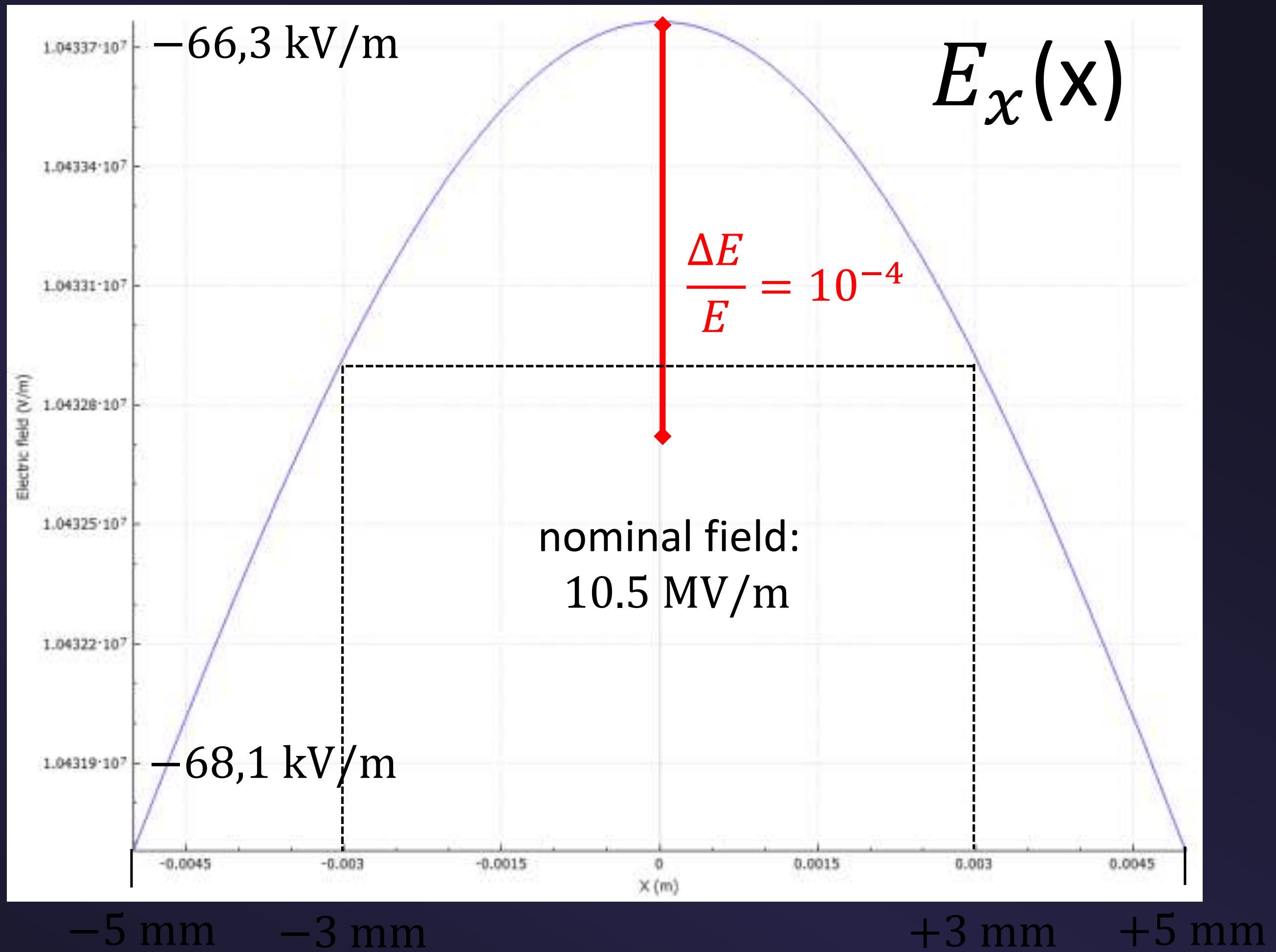
Impact of imperfections on the field

Mechanical percision: better than 0.1 mm
Voltages better than 10^{-3}



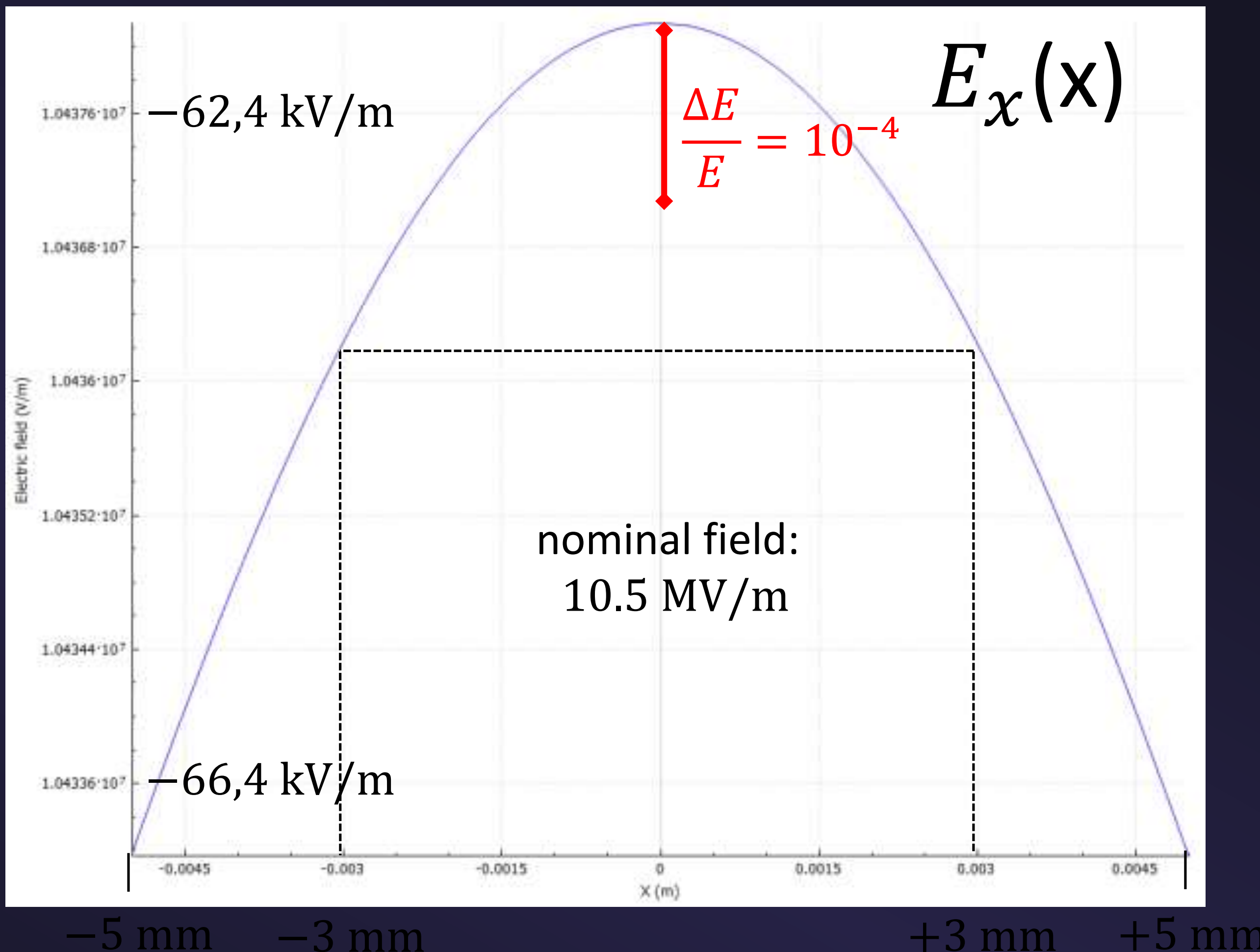
	$\Delta E_x / E_x(0,0)$	$\Delta E_x(5mm)/E_x$	E_y/E_x (5mm, 5mm)
nom	0.000 %	-0.024 %	-5500 V/m
A	0.058 %	-0.045 %	-7000 V/m
B	0.001 %	-0.022 %	+ 6500 V/m
C	-0.045%	-0.028 %	-5700 V/m
D	0.003 %	-0.020 %	+6800 V/m

AGROS: DIPOLE



$y = 0$ mm

AGROS: DIPOLE



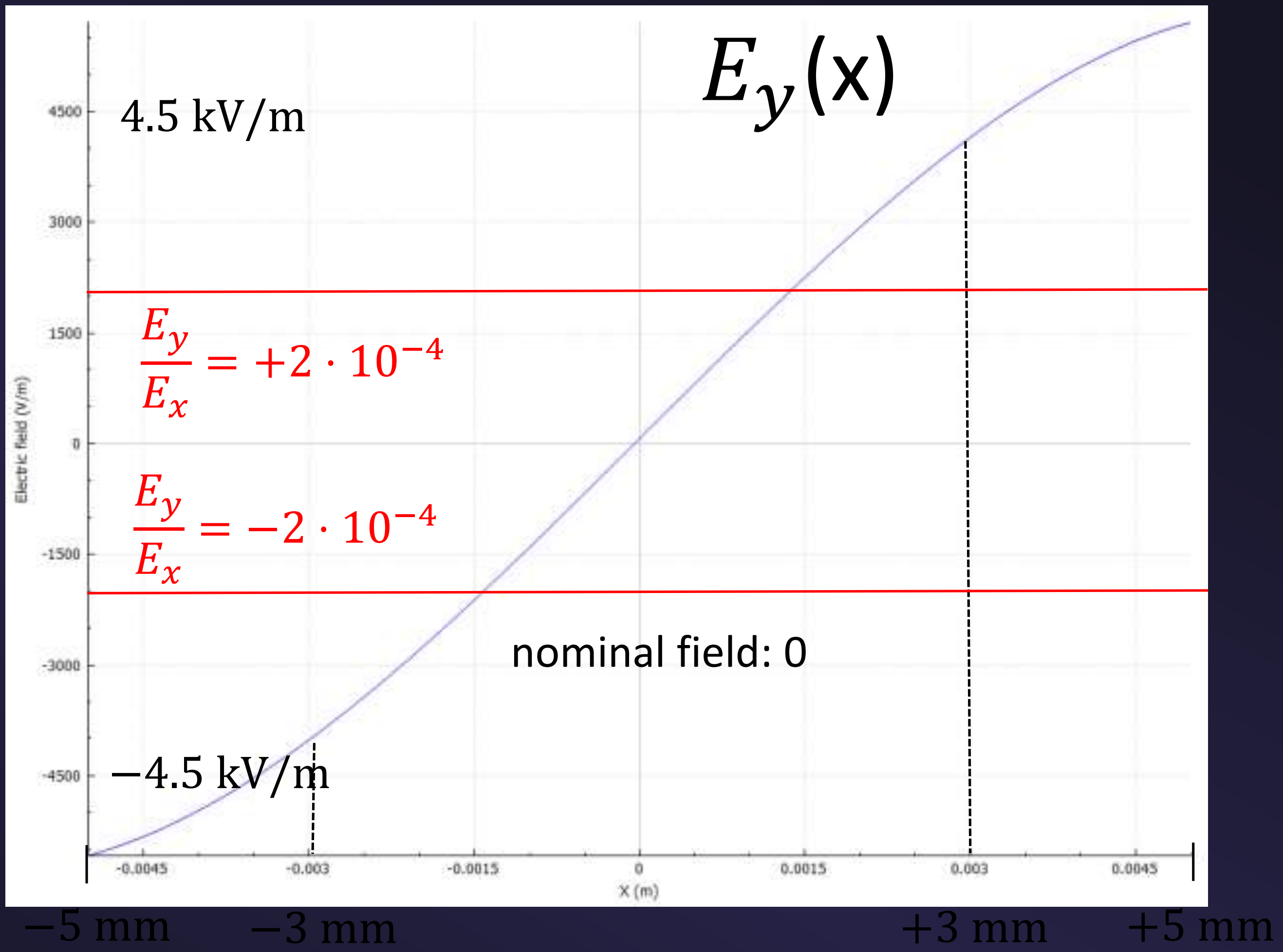
$E_x(x = 0)$

$y = 0$ mm $\quad -66.3$ kV/m

$y = 5$ mm $\quad -62.0$ kV/m

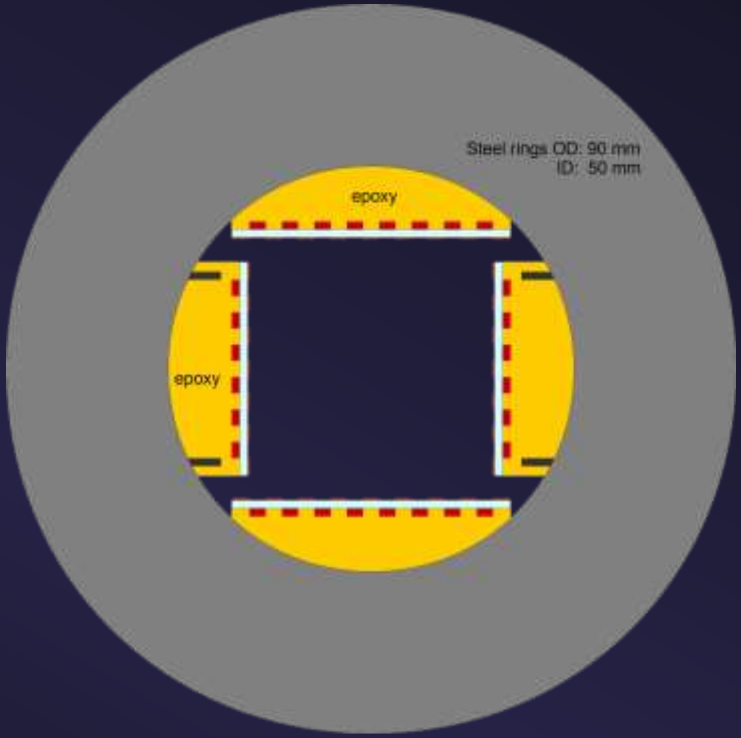
$y = 5$ mm

AGROS: DIPOLE



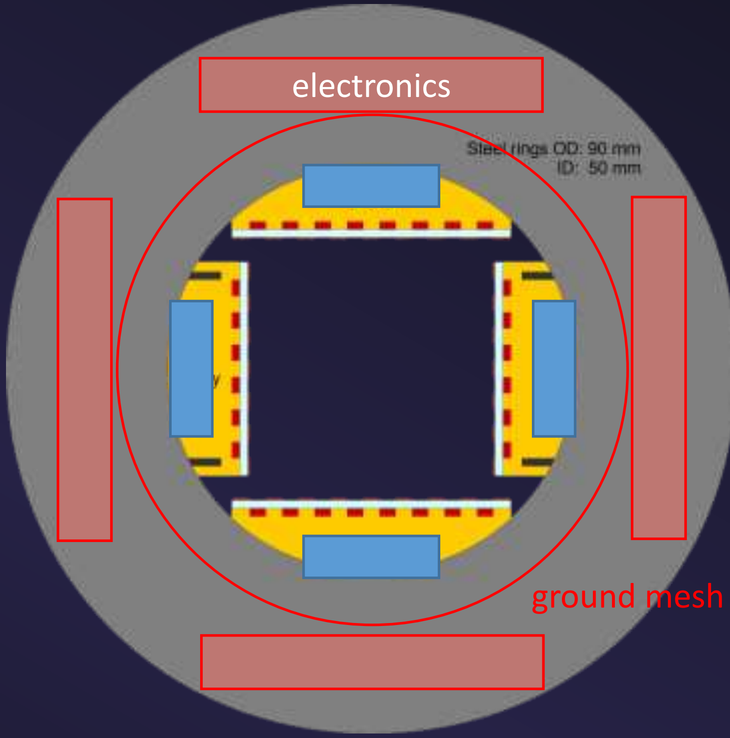
$y = 5$ mm

1ST IDEA ON MECHANICS

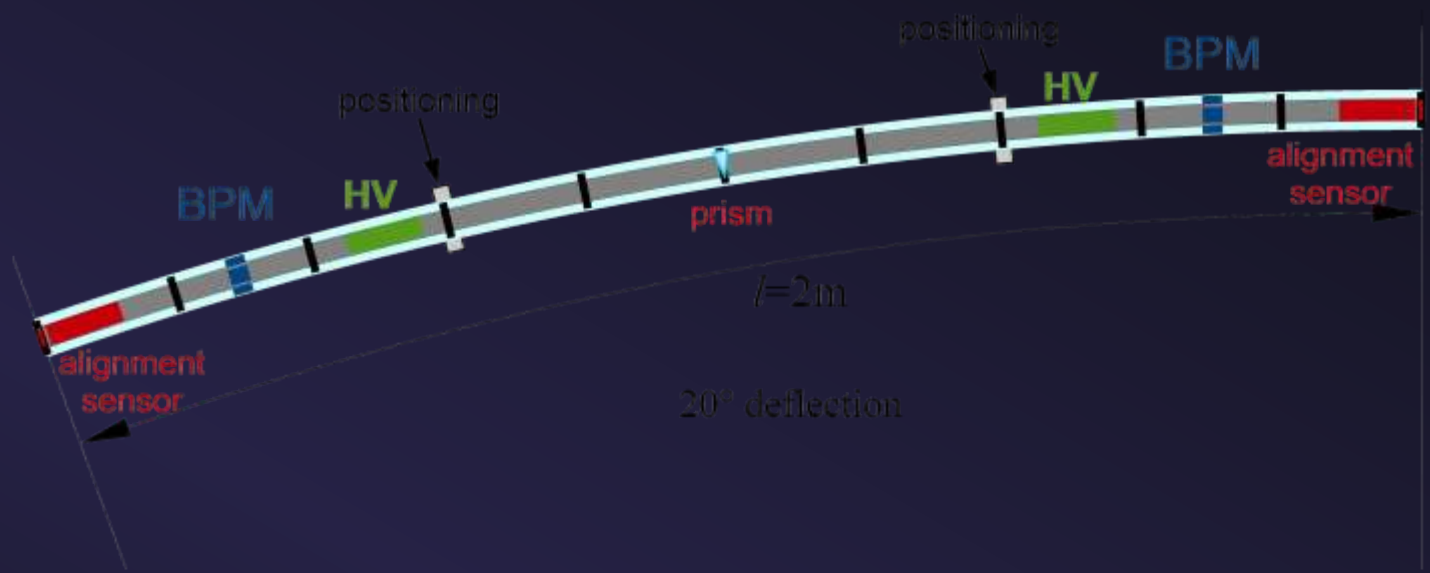


Steel disks every 10 cm (?)
electrodes glued into stiff plates
might need stiffeners inside plates

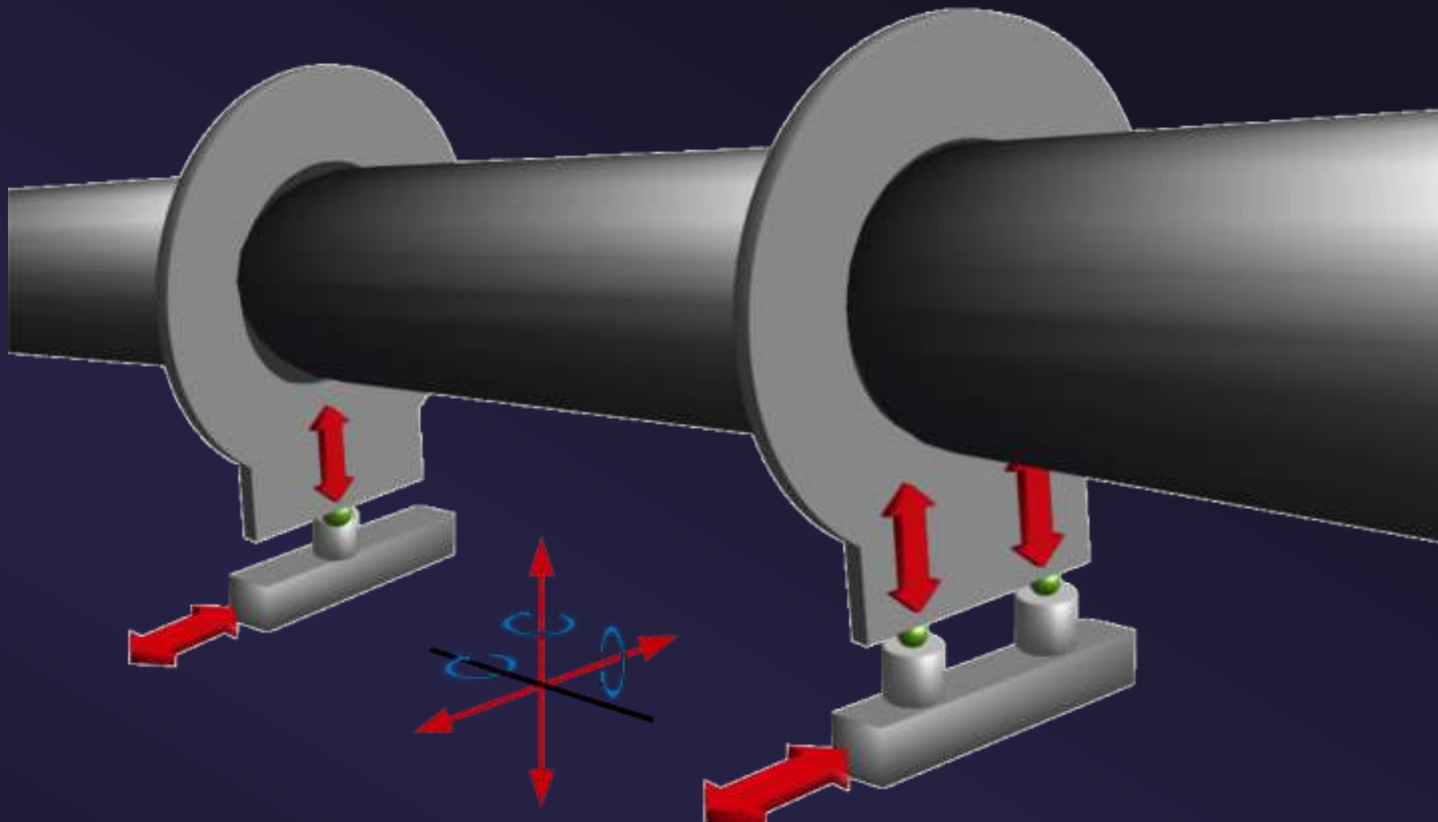
BEAM POSITION MONITORS



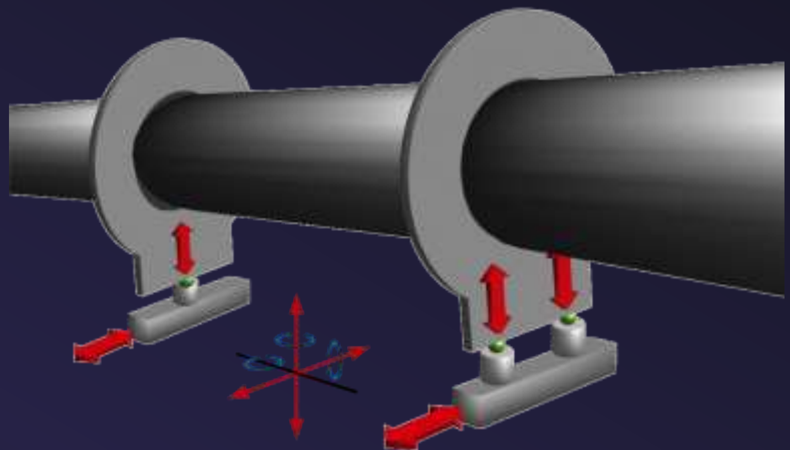
DEFLECTORS


positioning
positioning
BPM
HV
BPM
HV
prism
alignment sensor
alignment sensor
l=2m
20° deflection

MECHANICAL POSITIONING

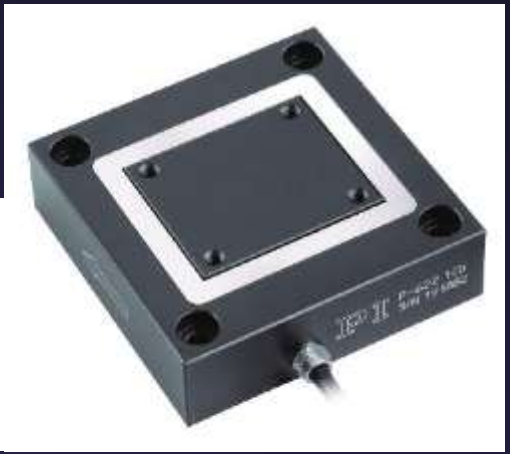


MECHANICAL POSITIONING



Piezo-Actuators ?

- Travel ranges 50 to 1800 µm
- Resolution to 0.1 nm
- Linearity error 0.02 %
- Direct metrology with capacitive sensors
- X, XY, Z, XYZ versions



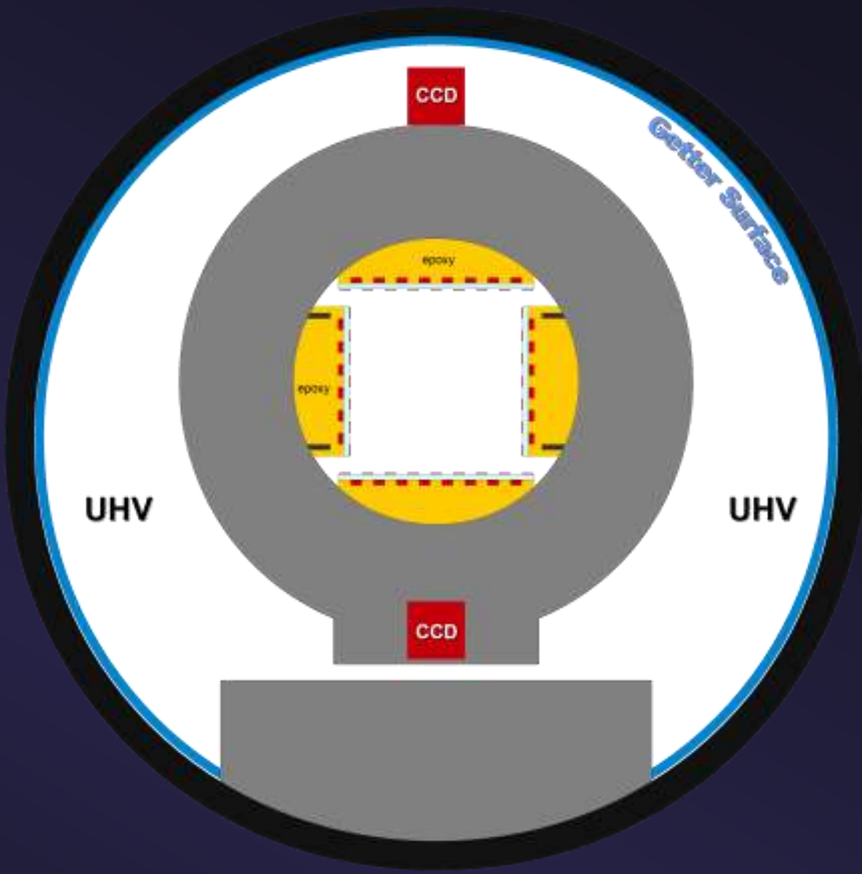
LASER ALIGNMENT

2 systems: above & below deflector

Laser alignment system used for example in CMS (Stefan Schael)

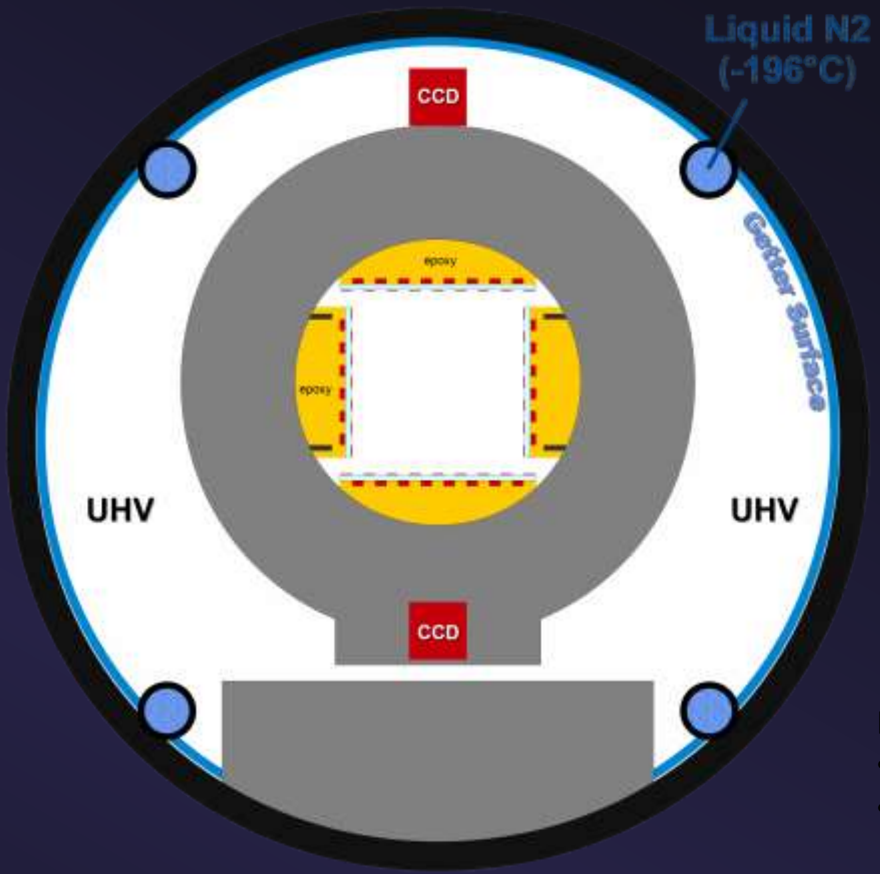
- IR-Laser (amplitude modulated)
- Si-strip detectors detect beam
- Metal layers removed for transmission of IR-beam

VACUUM SYSTEM



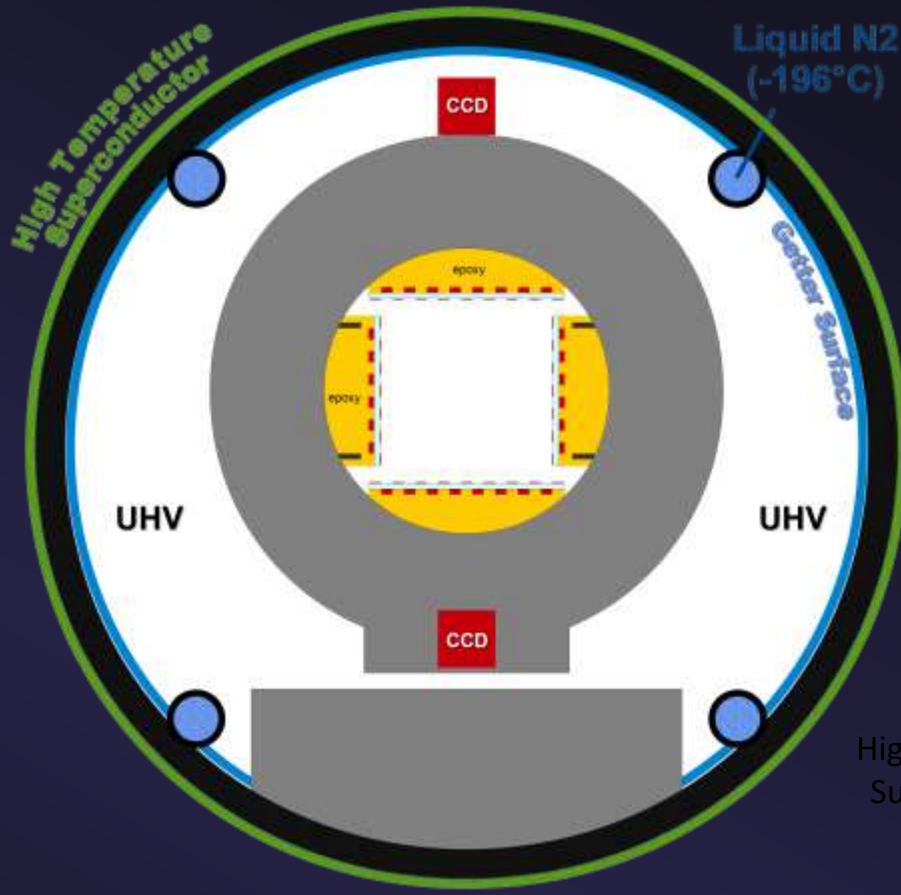
Beam pipe
- Steel pipe
- ID 15 cm

VACUUM SYSTEM



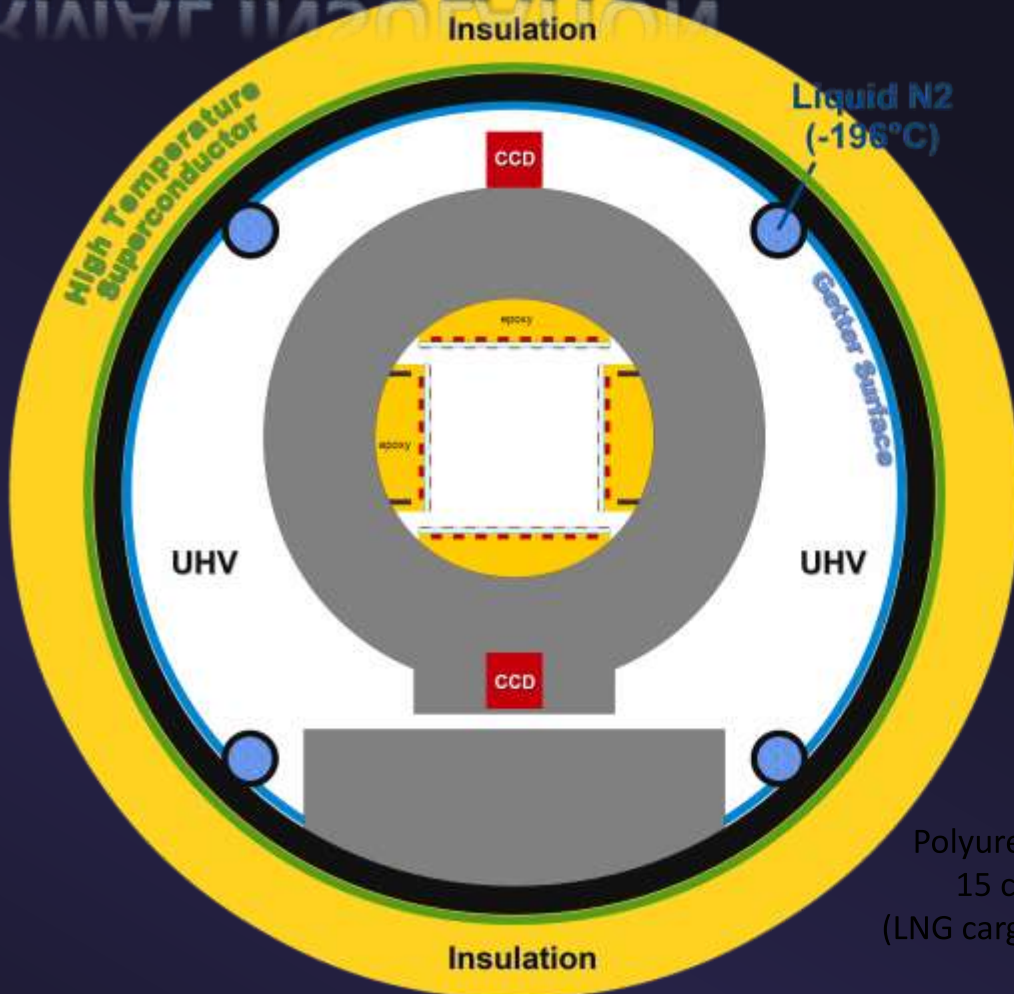
Beam pipe
- Steel pipe
- ID 15 cm

MAGNETIC SHIELDING



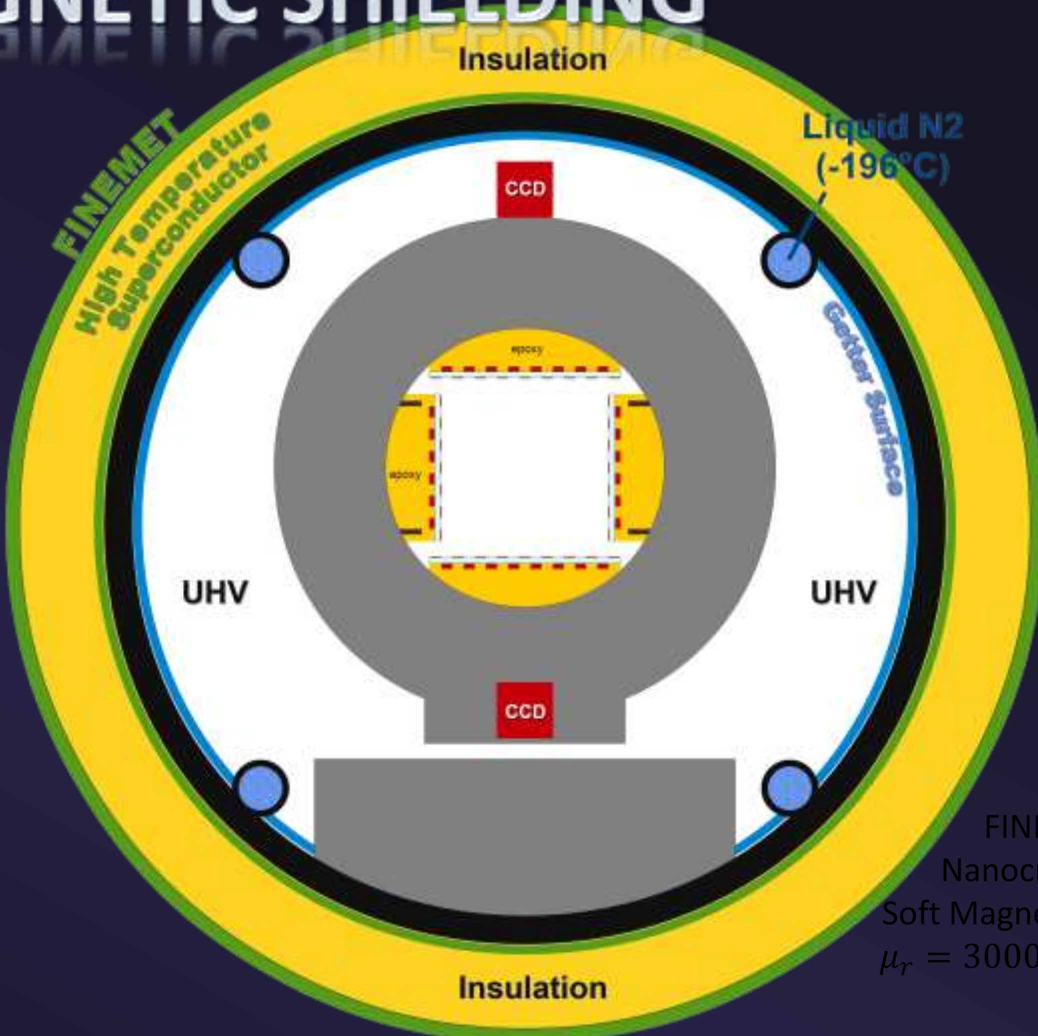
High Temperature Superconductor

THERMAL INSULATION



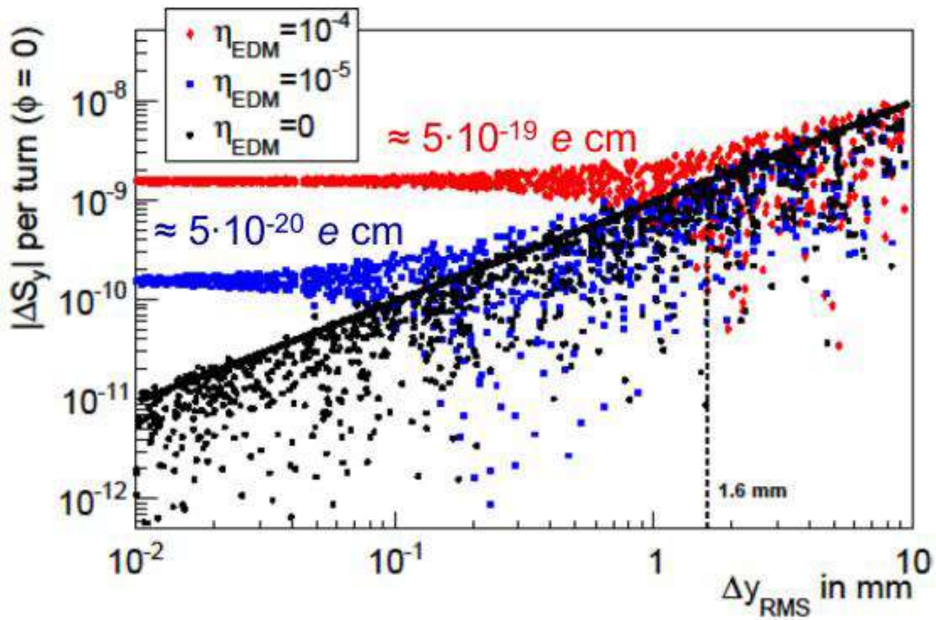
Polyurethane foam
15 cm shown
(LNG cargo uses 25 cm)

MAGNETIC SHIELDING



FINEMET
Nanocrystaline
Soft Magnetic Material
$\mu_r = 30000 \ldots 100000$

Systematics



Absolute average change of the vertical spin component ΔS_y per turn for different Δy_{RMS} and an initial Wien filter phase 0°. Wien filter magnetic field 10^{-4} mT (0.8 m length) and