

# A Electron-Nucleon-Collider at the HESR of the FAIR Facility

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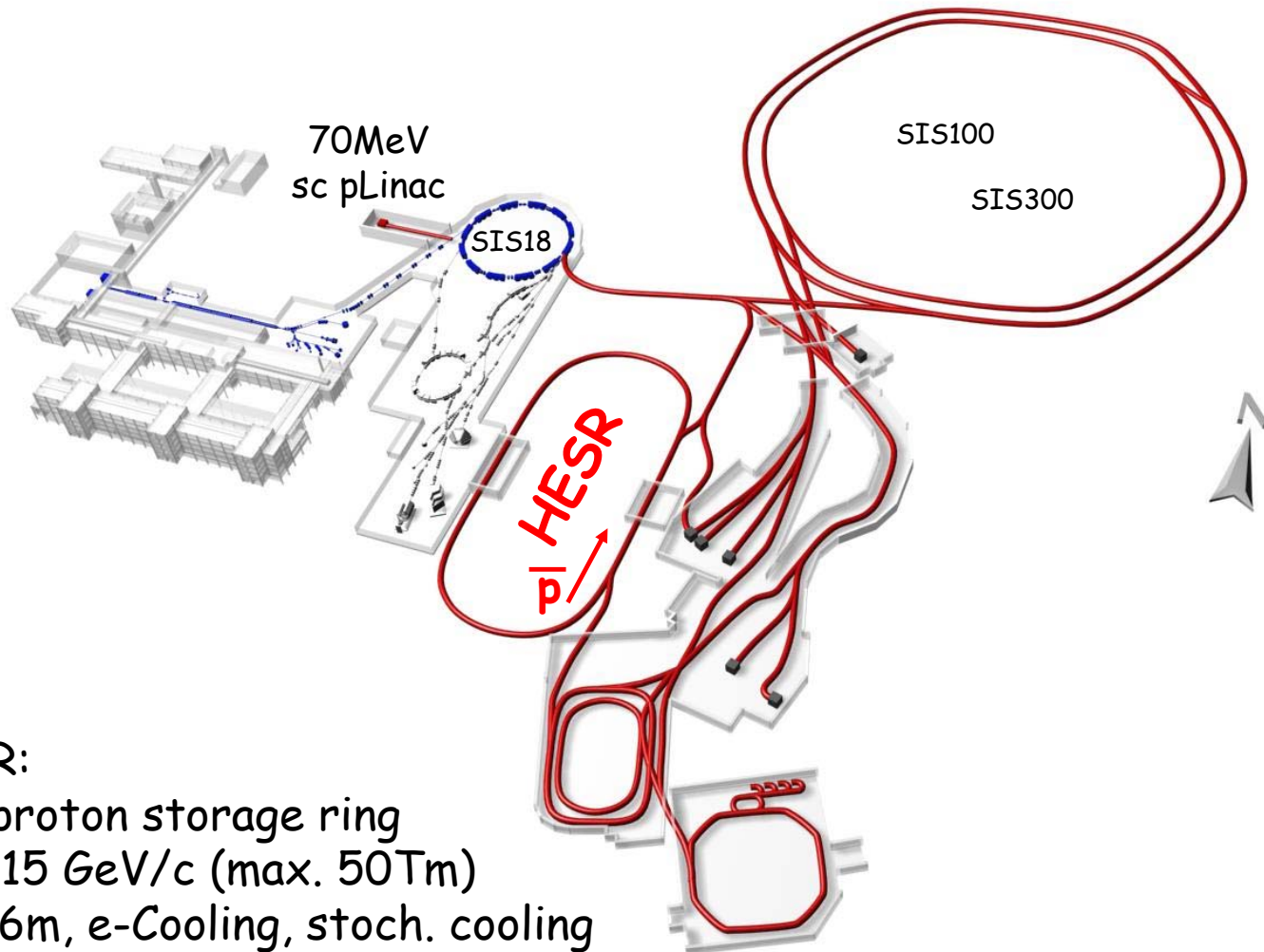
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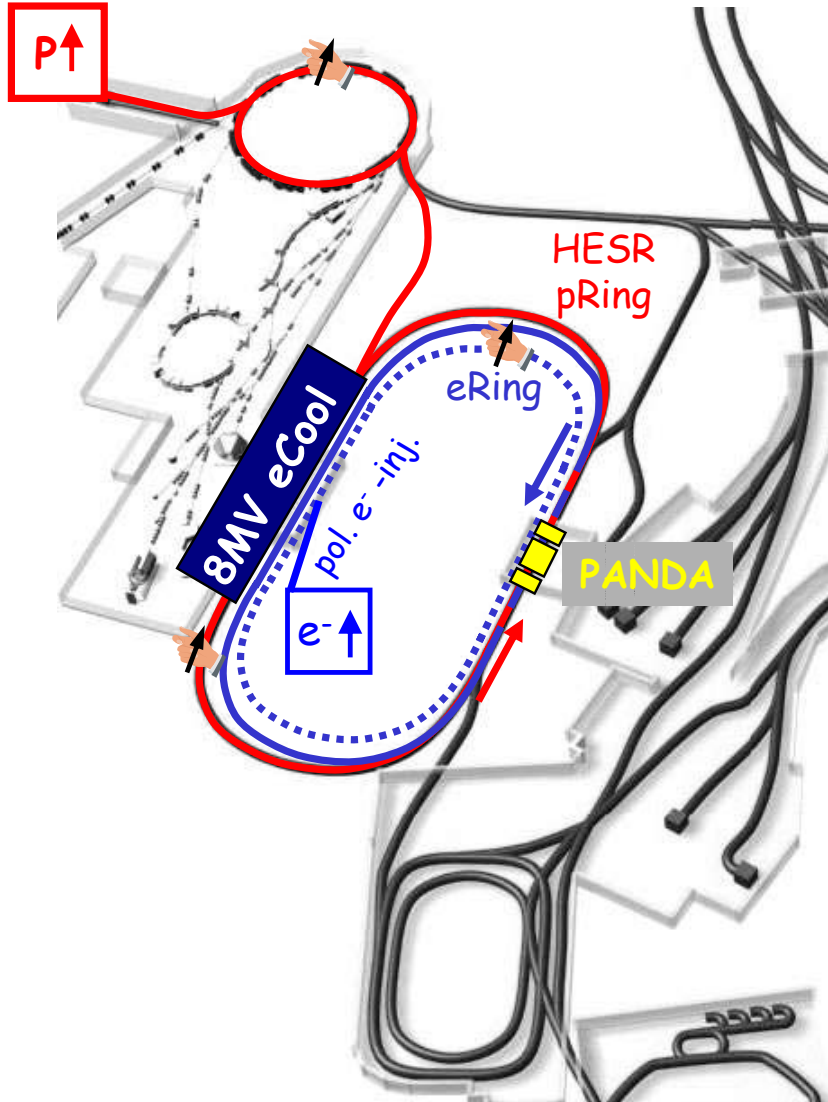
- A “simple” idea:  
electron - nucleon collisions using the HESR
- First baseline parameter set for e-p collisions at  $s=180\text{GeV}^2$  (3GeV  $e^-$  on 15GeV p)
- Some comments on the necessary ingredients
- What’s about e-d ?
- How to increase the luminosity ?
- Conclusion

# A "simple" idea: ENC@FAIR (i)



HESR:  
anti proton storage ring  
1.5 - 15 GeV/c (max. 50Tm)  
L=576m, e-Cooling, stoch. cooling  
PANDA fixed target experiment

# A "simple" idea: ENC@FAIR (ii)



## nuclear physicists wish list

$$L=10^{33} \text{ 1/cm}^2\text{s}$$

$$s > 100\text{GeV}$$

(3GeV  $e^- \leftrightarrow 15\text{GeV } p$ )

polarised  $e^- / e^+$  (?) (> 80%)



polarised  $p / d$  (> 80%)  
(longitudinal and transversal)

time sharing operation  
with PANDA should possible

using the PANDA detector,  
including the forward spectrometer

## First baseline parameter set e-p (i)



In August 2008 a accelerator working group was established:

Kurt Aulenbacher, A.J, MAMI / Mainz

W. Hillert, ELSA / Bonn

A. Lehrach, COSY, HESR / FZ-Jülich

Th. Weis, DELTA / Dortmund

mandate by nuclear physicist of  
Bonn, Mainz

**luminosity of an e-p collider, round beams, same radius**

$$L = f_{\text{coll}} \cdot \frac{n_p \cdot n_e}{2 \cdot \pi \cdot (r_e^2 + r_p^2)} = f_{\text{coll}} \cdot \frac{n_p \cdot n_e}{4 \cdot \pi \cdot \varepsilon_p \cdot \beta_{\text{IP}}}$$

$f_{\text{coll}}$ : collision-frequency,  $n_{e,p}$ : particles / bunch,  $r_{\text{IP}}$ : beam radius at IP  
(round beams, same radius)

**1) beam radius at IP, limited by proton beam:**

$$r_{\text{IP}} = \sqrt{\varepsilon_p \cdot \beta_{\text{IP}}} = \sqrt{\frac{\varepsilon_p^{\text{norm}} \cdot \beta_{\text{IP}}}{\beta_p \cdot \gamma_p}}$$

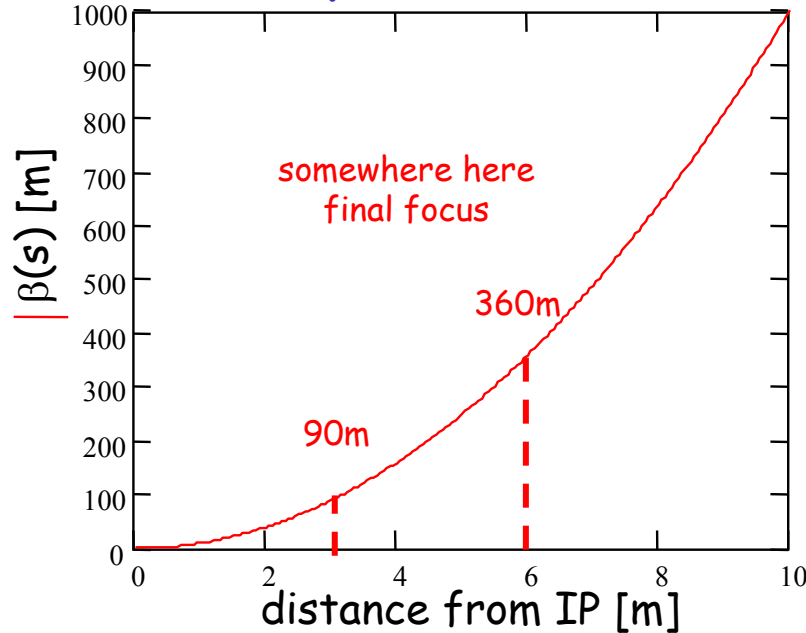
**Goal:**

- minimise  $\beta_{\text{IP}}$
- maximise  $\gamma_p$  or reduce  $\varepsilon_p$  by **cooling**

# First baseline parameter set e-p (ii)

$$\beta_{IP} = 0.1 \text{ m}$$

$$\beta(s) = \beta_{IP} + \frac{s^2}{\beta_{IP}}$$



$\beta_{IP} = 0.1 \text{ m}$ , implies (due to hour glass effect)  $l_b = 0.1 \text{ m}$

$$\varepsilon_p = 1.3 \cdot 10^{-7} \text{ m rad} \quad (\varepsilon_p^{\text{norm}} = 2 \cdot 10^{-6} \text{ m rad})$$

$$\rightarrow r_{IP} = 0.114 \text{ mm}$$

beta-Cool calculations done by Andreas Lehrach (FZJ) shows that these values could be reached and maybe somewhat increased (by 20 - 30%).

cooler-parameter: 8.2MV, 1 - 3 A, B=0.2T (magnetised cooling),  $T^T=1\text{eV}$ ,  $T^L=0.5\text{meV}$   
 $B_r/B < 10^{-5}$ , 24m effective cooler length

# First baseline parameter set e-p (iii)

## 2) parameter of the proton beam

$$L = f_{\text{coll}} \cdot \frac{n_p \cdot n_e}{4 \cdot \pi \cdot r_{\text{IP}}^2}$$

$$f_{\text{coll}} \cdot n_p = f_{\text{HESR}} \cdot h_p \cdot n_p = f_{\text{HESR}} \cdot N_p$$

$h_p$ : number of bunches in HESR,  $N_p$ : total protons in the HESR

$f_{\text{HESR}}$ : revolution frequency in HESR

519.455kHz@ $\gamma_p=16$  / 516.391kHz@ $\gamma_p=8$  / 450.743kHz@ $\gamma_p=2$

What defines  $h_p \cdot n_p$ :

a) space charge (Laslett) tune shift:

$$\Delta Q_{\text{sc}} = \frac{e}{8\pi^2 \cdot \epsilon_0 \cdot m_p} \cdot \frac{B \cdot h_p \cdot n_p}{\beta_p \cdot \gamma_p^2 \cdot \epsilon_p^{\text{norm}}} = L_p / l_p \cdot n_p$$

B: bunching-factor =  $\lambda_{\text{rf}} / l_p$  (rf wave-length / bunch-length),  $L_p$ : circumference

$\beta_{\text{IP}} = 0.1\text{m}$  implies  $l_p = 0.1\text{m}$  (hour glass reduction 76%)

$L_p/l_p = 576\text{m}/0.1\text{m} = 5760$  and  $\Delta Q = 0.1 \rightarrow n_p < 3.6 \cdot 10^{10}$  (p / bunch)

beam-beam parameter  $e^-$  ( $\xi^e < 0.05$  typ.):  $\xi^e = \frac{r_{0,e}}{4\pi} \cdot \frac{n_p}{\gamma_e} \cdot \frac{\beta_e}{r_p^2} = 0.011$  ✓

## First baseline parameter set e-p (iv)

b) choice of  $h_p$  determined by

- collisions frequency
- distance of parasitic collisions from IP (beam separation)
- technical realisation of the rf-systems of HESR (bunch formation process)

$$f_{\text{coll}} = h_p \cdot f_{p,\text{rev}}$$

$f_{\text{coll}}$ : collision-frequency,  $h_p$ : harmonic number,  $f_{p,\text{rev}}$ : revolution freq. protons

$$h_p = 100 \rightarrow f_{\text{coll}} = 51.95 \text{ MHz}$$

$N_p = 3.6 \cdot 10^{12}$  protons in 100 0.1m long bunches in HESR !

$\lambda_{\text{coll}} = 5.76 \text{ m}$  (bunch spacing HESR)  $\rightarrow$  parasitic collision at 2.88m from IP  
(bunch separation)

### 3) electrons per bunch

(bunch length, **emittance (?)** and bunch structure poses no problem and will be adopted to the requirements defined by the pRing)

Number of electrons is limited due to single bunch effects in eRing  
(multi bunch instabilities must be counteracted by feedback systems)

$$I_{b,e}^{\text{thres}} = \sqrt{2\pi} \cdot \frac{\alpha \cdot E[\text{eV}] \cdot \sigma_E / E}{\langle \beta_{\perp} \cdot Z_{\text{BBR}} \rangle} \quad \text{und} \quad Z_{\text{BBR}}(\omega) = \frac{L_e}{\pi \cdot r_{\text{kammer}}^2} \cdot \frac{Z(\omega)}{n}$$

$$I_{b,e}^{\text{thres}} \sim \frac{E}{L_e} \Rightarrow n_e \sim E$$



## First baseline parameter set e-p (v)



Comparing the single bunch currents reached in machines like ELETTRA, DELTA, DAΦNE one can estimate the following scaling for  $n_e$ :

$$n_e = 7.5 \cdot 10^{10} E[\text{GeV}] \rightarrow n_e = 2.3 \cdot 10^{11} \text{ e / bunch}$$

beam-beam parameter  $p$ : ( $\xi^p < 0.01$  typ.)  $\xi^p = \frac{r_{0,p}}{4\pi} \cdot \frac{n_e}{\gamma_p} \cdot \frac{\beta_p}{r_e^2} = 0.013$  ✓

Take in mind synchrotron radiation power:

$$P_{\text{SR}} [\text{kW}] = 88.2 \cdot \frac{E_e^4 [\text{GeV}^4]}{R_e [\text{m}]} \cdot I_e [\text{A}] = 88.2 \cdot \frac{E_e^4 [\text{GeV}^4]}{R_e [\text{m}]} \cdot e [\text{C}] \cdot f_{\text{coll}} [\text{Hz}] \cdot n_e$$

At 3GeV a eRing with radii  $R = 30\text{m}$  (same as HESR) results at  $P_{\text{SR}} = 456\text{kW}$  !  
( sr-power/meter  $\sim 1.3\text{kW/m}$  )

e.g. in a machine with a footprint like COSY with  $R=8\text{m}$   $\rightarrow P_{\text{SR}} = 1.7\text{MW}$   
( sr-power / meter  $\sim 15\text{kW/m}$  !! )

# First baseline parameter set e-p (vi)



	HESR / 15GeV p	eRing / 3GeV
L [circumference, m]	576	577.126
R [bending radius, m]	30	30
$\varepsilon^{\text{norm}} / \varepsilon^{\text{geo}}$ [mm mrad]	2 / 0.13	2 / 0.13
$\beta_{\text{IP}}$ [m]	0.1	0.1
$r_{\text{IP}}$ [mm]	0.114	0.114
l [bunch length, m]	> 0.1	< 0.1
n [particle / bunch $10^{10}$ ]	3.6	23
$I_b$ [bunch current, mA]	3	19.1
h [bunches / ring]	100	100
I [total current, A]	0.3	1.91
$P_{\text{SR}}$ [sr-Power, kW]		455.8
$f_{\text{coll}}$ [collision freq., MHz]	51.946	51.946
$\lambda_{\text{coll}}$ [bunch distance, m]	5.76	5.7713
$\Delta Q_{\text{sc}}$	0.1	
$\xi$ [beam beam parameter]	0.013	0.011
Luminosität (inc. 76% hour glass red.)	<b><math>2.0 \cdot 10^{32} \text{ 1/cm}^2\text{s}</math></b>	
P [polarisation, %]	>70%	>80%

## Some comments to the necessary ingredients (i)



1) To get the desired proton beam of 100 bunches with

$$l_b=0.1\text{m}, n_p=3.6\cdot 10^{10}, \varepsilon_p=1.3\cdot 10^{-7}\text{mrad}, P_p > 80\% @ 15\text{GeV}/c$$

into the HESR needs:

- a polarised p source at the new 70MeV sc proton linac
  - spin manipulation in the SIS18 (tune jump quads, ac dipole)
  - proton transfer line + injection counter clockwise to the HESR
  - spin manipulation in the HESR (full snake in back straight)
  - accumulation of > 50 SIS18 shots at injection in the HESR (at least no space charge problem  $\Delta Q \sim 0.009$ , but complicated process with bunching - bunch to bucket transfer - bunch merging)
  - complicated rf-gymnastic at 15GeV/c in the HESR  
adiabatic bunching in  $h=100$  under strong electron cooling  
→ without eCool necessary cavity voltage would exceeds MV !
  - a powerful 8MeV, 1 - 3 A magnetised electron cooler (4.5MeV is designed within the HESR consortium, upgrade to 8MeV will be studied. At present even 4.5MeV eCool is not in FAIR phase A)
- already included in the PAX proposal

## Some comments to the necessary ingredients (ii)

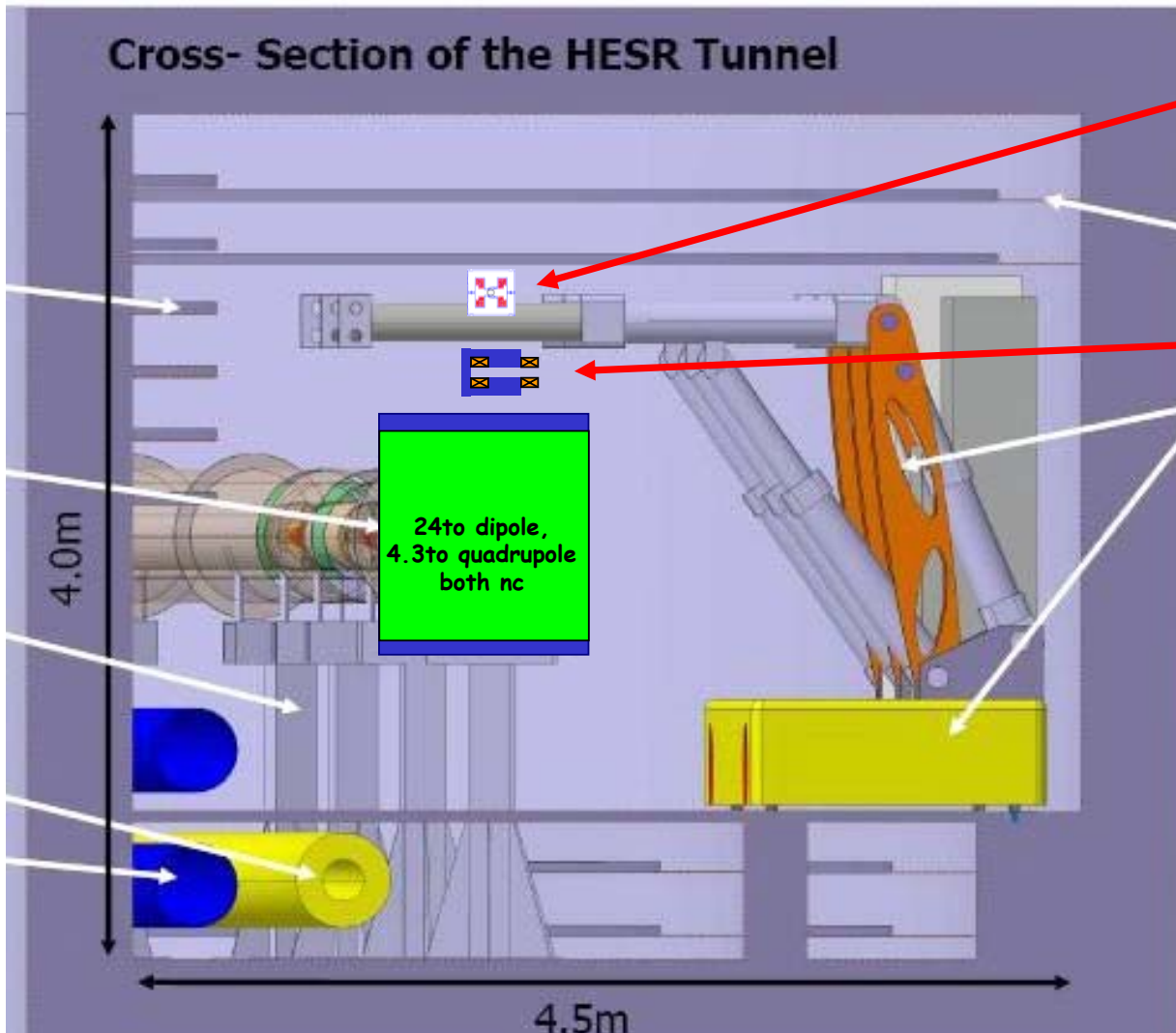


### 2) Design of the eRing:

- polarised  $e^-$  source, linac and full energy injector synchrotron; could be very compact (cross section), also installed inside the HESR tunnel
- simple scheme for eRing with one snake in back straight for preservation of polarisation and free spin angle at detector seems not to be feasible  
 $\tau_{\text{depol}} < 20\text{min}$  (following first estimations of D. Barber / DESY)
  - spin in arcs needs to be vertical
  - spin manipulators before and behind IP mandatory (space problem ?)
- single bunch currents of 19mA and total currents of 1.9A needs to be handled by optimised impedance budget and multi-bunch feedback
- SR power of 500kW needs to be handled (and maybe more)
- flexible adjustment of the beam emittances  
e.g. usually  $\varepsilon_{\text{vert}} \ll \varepsilon_{\text{hori}}$  (flat beam), here we suppose to equalised the emittances by adjustment of the coupling via skew-quads.  
Will that be possible without disturbing spin motion ?  
Most likely answer: No !
  - increase of vertical beta-function in eRing
  - increase of electrons vertical beam beam tune shift

## Some comments to the necessary ingredients (iii)

3) Apparently it is a good idea to built the eRing inside the HESR tunnel !



Full-Energy-Booster dipole a la SLS:  
ca. 0.2m×0.2m and  
ca. 0.7to for 4m length

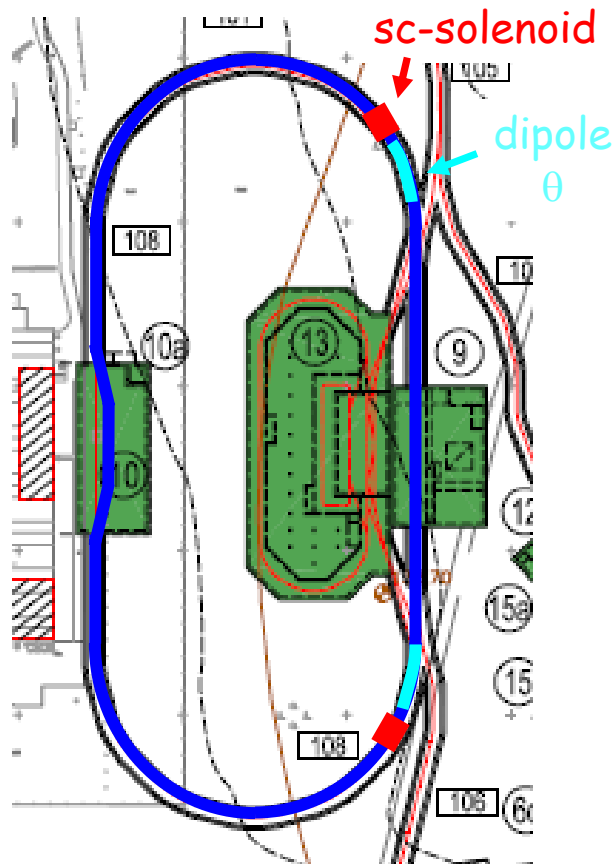
eRing dipole:  
ca. 0.4m×0.25m and  
1.6to for 4m length

But don't forget:

- cavities
- spin-manipulation
- injection/extraction
- feedback
- ...

## Some comments to the necessary ingredients (iv)

### 4) Spin manipulation for eRing in HESR tunnel (first draft)



- electron spin must be vertical in arcs
- sc solenoid to turn spin from vertical to in-plane, directing inside or outside
- last bending in horizontal plane turns spin to longitudinal direction forward/backward

conditions to be fulfilled due to spin dynamics requirements:

$$\gamma \cdot a = n + \frac{1}{2} \quad (a=0.0011596)$$

and

$$\Delta\phi_{\text{spin}} = \gamma \cdot a \cdot \theta \quad (\Delta\phi_{\text{spin}}=90^\circ)$$

in our case:

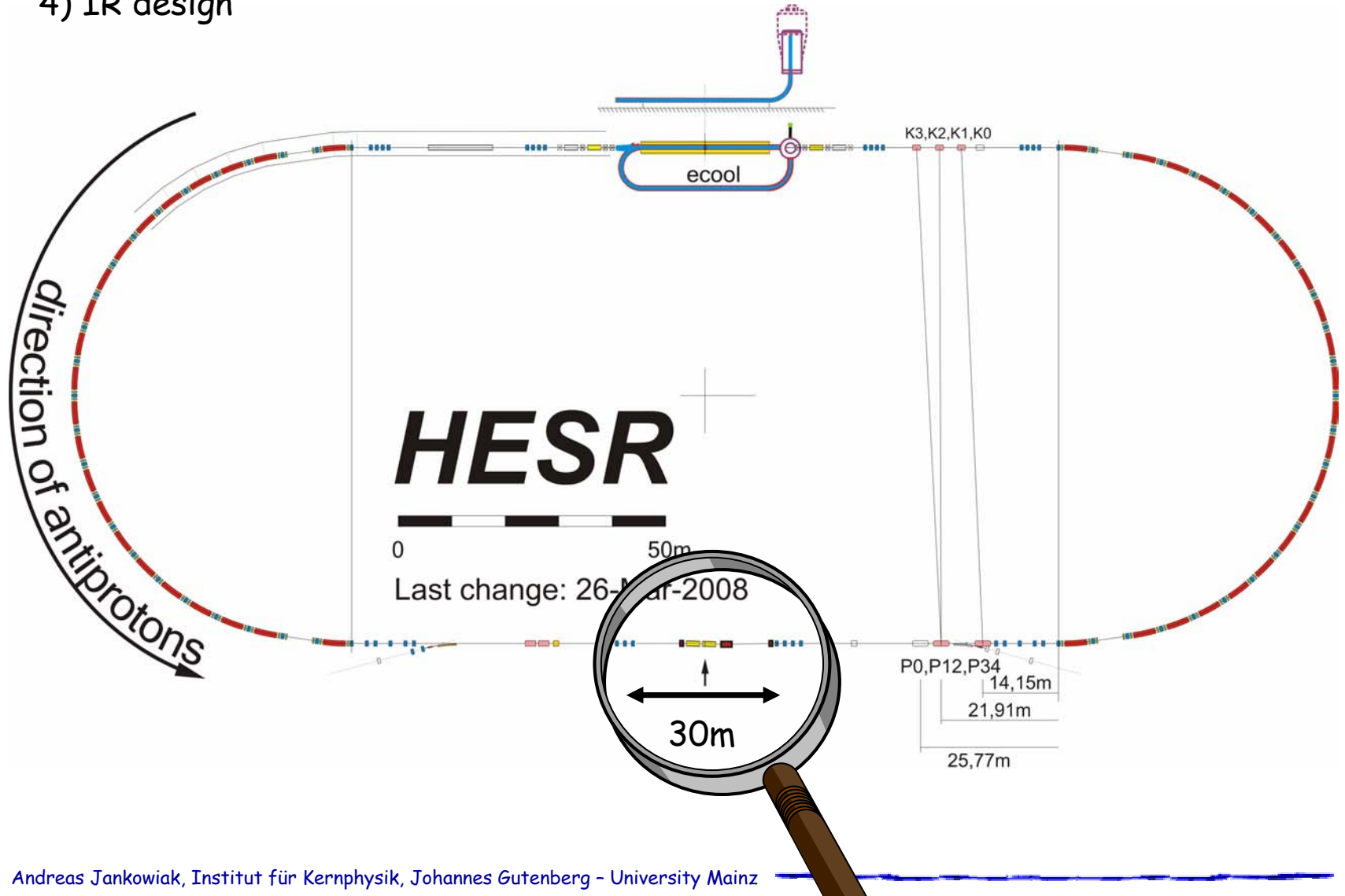
1)  $\gamma=6467 \rightarrow E=3.305\text{GeV}$ ,  $\theta=12.00^\circ$  (+47% SR)

2)  $\gamma=5605 \rightarrow E=2.864\text{GeV}$ ,  $\theta=13.85^\circ$  (-17% SR)

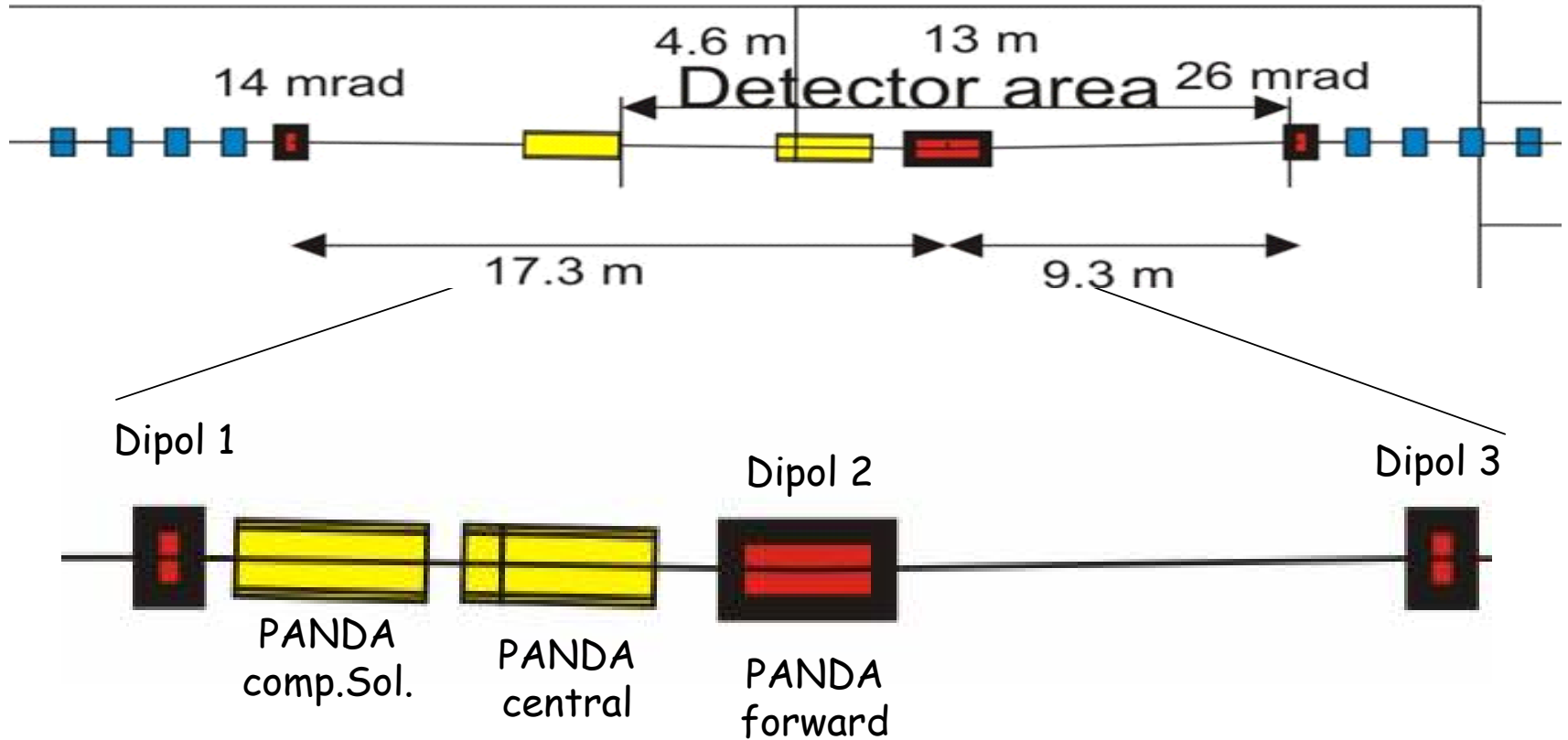
each arc consists of 15(13)  $12.00^\circ(13.85^\circ)$  achromatic bending systems. The last/first used for spin manipulation !

# Some comments to the necessary ingredients (v)

## 4) IR design



# Some comments to the necessary ingredients (vi)



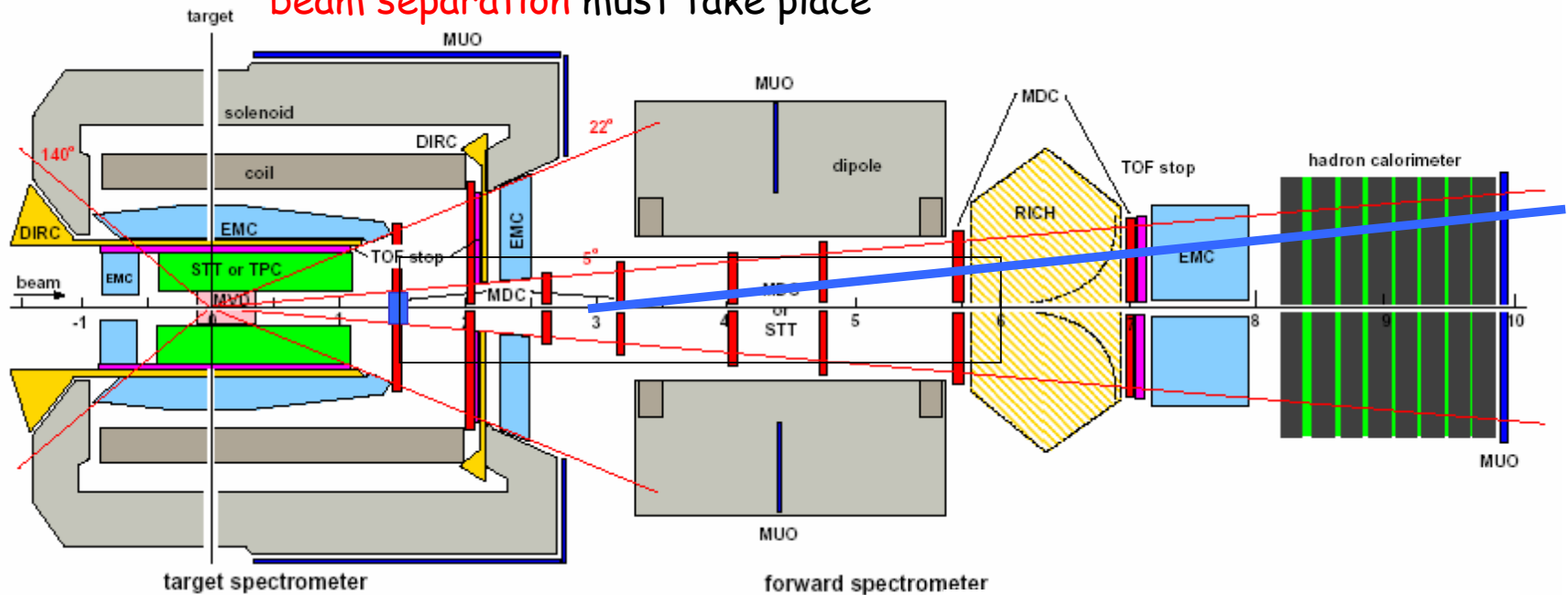
3 dipole-bump,  
detector is not on a straight of the HESR



# Some comments to the necessary ingredients (vii)

side view of PANDA

area where the **final-focus and beam separation** must take place



met Christoph Montag / BNL at  
EIC collaboration meeting in Berkeley  
→ very first IR design till 03/2009

additional

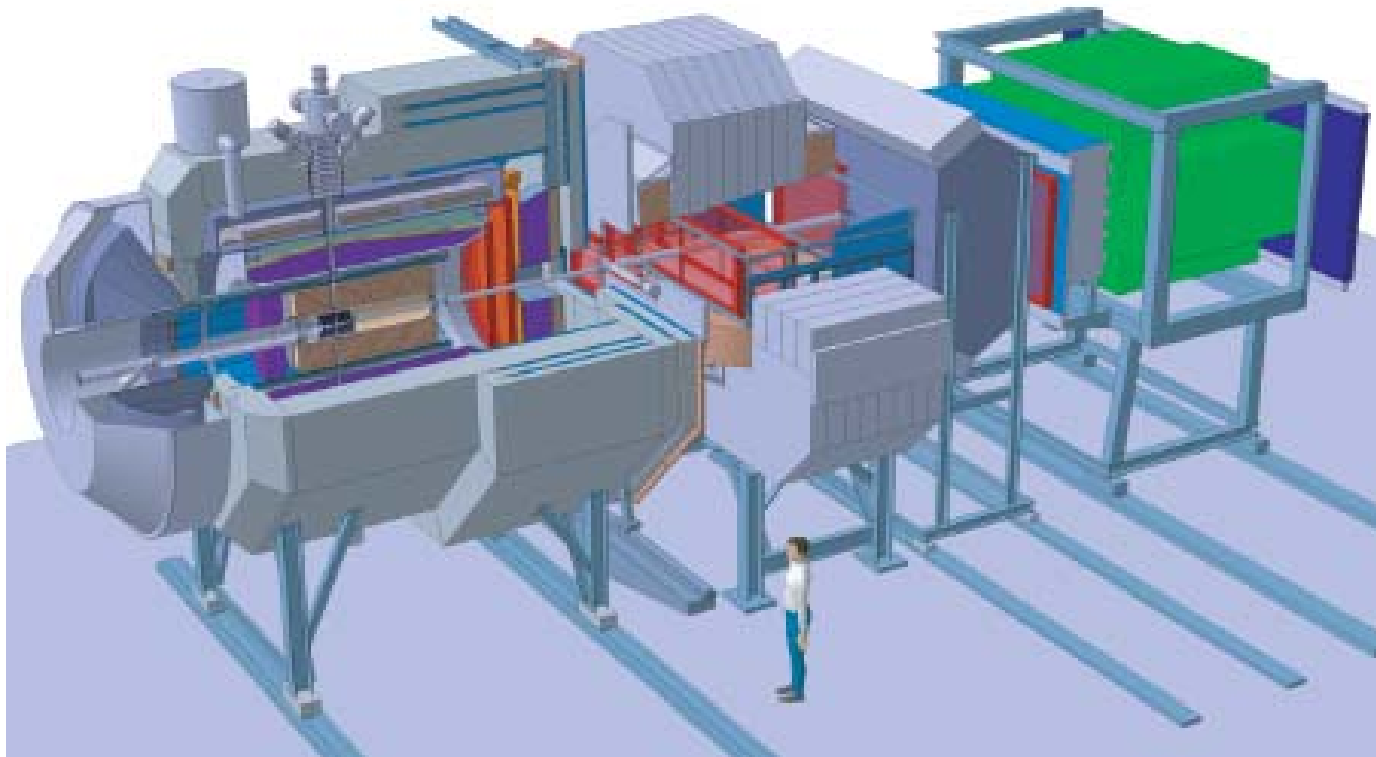
- compensation solenoid eRing
- quadrupoles for matching
- multipole-corrections
- spin-manipulation (e,p)

## Some comments to the necessary ingredients (viii)



How to rearrange this setup for colliding beam physics ?

n.b. also the  $e^-$  requires a forward detector under small angles



# What's about e-d (i)

scaling for cooling times:

$$\tau_{\text{cool}} \sim \frac{A_i}{Z_i^2} \cdot \gamma_i^5 \cdot \beta_i^4$$

scaling for IBS growth rate:

$$\tau_{\text{IBS}} \sim \frac{A_i^2}{Z_i^4} \cdot \gamma_i^4 \cdot \beta_i^3 \cdot \frac{\varepsilon_{i,h} \cdot \varepsilon_{i,v} \cdot \Delta p/p}{n_i}$$

comparison proton - deuterium at  $p=15\text{GeV}/c$ :

**Proton**

$$m_p = 938.27\text{MeV}$$

$$A=1, Z=1$$

$$\gamma=16.02, \beta=0.9980$$

**Deuterium**

$$m_d = 1875.61\text{MeV}$$

$$A=2, Z=1$$

$$\gamma=8.06, \beta=0.9922$$

therefore

$$\frac{\tau_{\text{cool},p}}{\tau_{\text{cool},d}} = 15.88 \quad \text{and} \quad \frac{\tau_{\text{IBS},p}}{\tau_{\text{IBS},d}} = 3.97$$

- cooling time of deuterium is 16 times shorter than for protons
  - IBS growth rate is 4 times higher than for protons
    - cooling for deuterium is more efficient
- one can expect at least the same performance as for protons

## What's about e-d (ii)

Colliding polarised deuterium ( $\gamma_d=8$ , instead of  $\gamma_p=16$ ) with polarised  $e^-$

- needs a polarised d source at the UNILAC
- needs other rf-frequencies and adaptation of eRing length ( $\beta_p=0.998$  compared to  $\beta_d=0.9922$ )
- needs only a 4MV cooler (and the relation between cooling times and IBS growing times is a factor of 4 better than for protons with the same impulse)
- the space charge tune shift for the HESR at collision is still the limit for the particle number and worse due to smaller  $\gamma_d$

$$\rightarrow n_d = \frac{1}{4} n_p$$

Therefore one gets for the luminosity:

$$L_d = 1 \cdot 10^{32} \text{ 1 / cm}^2\text{s (per d)}$$

beam beam parameter of d ( $\xi^d < 0.01$  typ.):

$$\xi^d = \frac{r_{0,d}}{4\pi} \cdot \frac{n_e}{\gamma_d} \cdot \frac{1}{\varepsilon_d} = 0.0139 \quad \checkmark$$

# What's about e-d (iii)



	HESR / 15GeV d	eRing / 3GeV
L [circumference, m]	576	580.486 (+3.36m)
R [bending radius, m]	30	30
$\varepsilon^{\text{norm}} / \varepsilon^{\text{geo}}$ [mm mrad]	2 / 0.13	1 / 0.13
$\beta_{\text{IP}}$ [m]	0.1	0.1
$r_{\text{IP}}$ [mm]	0.114	0.114
l [bunch length, m]	> 0.1	< 0.1
n [particle / bunch $10^{10}$ ]	0.916	23
$I_b$ [bunch current, mA]	0.76	19.1
h [bunches / ring]	100	100
I [total current, A]	0.076	1.91
$P_{\text{SR}}$ [sr-Power, kW]		455.8
$f_{\text{coll}}$ [collision freq., MHz]	51.645	51.645
$\lambda_{\text{coll}}$ [bunch distance, m]	5.76	5.8049
$\Delta Q_{\text{sc}}$	0.1	
$\xi$ [beam beam parameter]	0.0139	0.0028
Luminosität (inc. 76% hour glass red.)	<b><math>1.0 \cdot 10^{32} \text{ 1/cm}^2\text{s}</math></b>	
P [polarisation, %]	>70% ????	>80%

# How to increase the luminosity

$$L = f_{\text{coll}} \cdot \frac{n_p \cdot n_e}{4 \cdot \pi \cdot (\varepsilon_p \cdot \beta_{\text{IP}})}$$

$$\xi_e = \frac{r_{0,e}}{4\pi} \cdot \frac{n_p}{\gamma_e} \cdot \frac{\beta_{e,\text{IP}}}{r_p^2} \quad \Delta Q_{\text{sc}} = \frac{e}{8\pi^2 \cdot \varepsilon_0 \cdot m_p} \cdot \frac{L_p / l_p \cdot n_p}{\beta_p^2 \cdot \gamma_p^3 \cdot \varepsilon_p} \quad \xi_p = \frac{r_{0,p}}{4\pi} \cdot \frac{n_e}{\gamma_p} \cdot \frac{\beta_{p,\text{IP}}}{r_e^2}$$

$$n_e = 7.5 \cdot 10^{10} \cdot E[\text{GeV}]$$

$$P_{\text{SR}} = 88.2 \cdot \frac{E_e^4}{R_e} \cdot e \cdot f_{\text{coll}} \cdot n_e$$

$\Delta Q_{\text{sc}} < 0.1$  fixes  $n_p$ ,  
 $E_e = 3\text{GeV}$  fixes  $n_e$   
 $L$ ,  $\Delta Q_{\text{sc}}$  and  $\xi^{e,p}$  proportional to  $1/\varepsilon_p$   
 (no way out ?)

Increasing  $f_{\text{coll}}$  (more bunches in HESR and also eRing), but:  
 Realisation ?  $P_{\text{SR}}$  increases !  $\Delta Q_{\text{sc}}$  in HESR@2GeV increases !  
 Multi bunch instabilities in eRing and HESR with increasing current !

# How to increase the luminosity

$$L = f_{\text{coll}} \cdot \frac{n_p \cdot n_e}{4 \cdot \pi \cdot (\epsilon_p \cdot \beta_{\text{IP}})}$$

$\xi^e =$  
**advanced schemes like:**

- smaller beta-function at IP and compensation of the hour glass effect by travelling focus system
- higher collision frequency under crab crossing
 $= \frac{r_{0,p}}{4\pi} \cdot \frac{n_e}{\gamma_p} \cdot \frac{\beta_{p,IP}}{r_e^2} = \frac{P_{\text{SR}}}{R_e} \cdot e \cdot f_{\text{coll}} \cdot n_e$

$\Delta Q_{\text{sc}} < 0.1$  fixes  $n_p$ ,  
 $E_e = 3\text{GeV}$  fixes  $n_e$   
 $L, \Delta Q_{\text{sc}}$  and  $\xi^{e,p}$  proportional to  $1/\epsilon_p$   
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Increasing  $f_{\text{coll}}$  (more bunches in HESR and also eRing), but:  
 Realisation ?  $P_{\text{SR}}$  increases !  $\Delta Q_{\text{sc}}$  in HESR@2GeV increases !  
 Multi bunch instabilities in eRing and HESR with increasing current !

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## Conclusion



- ENC is very interesting option for FAIR
- Accelerator working group is established (Mainz, Bonn, Dortmund, FZJ, ...)
- Main topics to deal with
  - space requirements for eRing
  - spin and beam dynamics in eRing (Bonn / Verbundforschungsantrag, Dortmund, D. Barber / DESY)
  - beam dynamics in HESR  
bunch formation process under eCool (Mainz / Verbundforschungsantrag, FZJ)
  - IR design with PANDA and spin rotators (Chr. Montag / BNL, Mainz)
  - eCool at 8MV and ampere currents
  - concepts for increase of luminosity