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

Andreas Jankowiak
Institut für Kernphysik
Johannes Gutenberg – Universität Mainz

Accelerator Working Group:
K. Aulenbacher, A.J., W. Hillert, A. Lehrach, Th. Weis

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LBNL Berkeley
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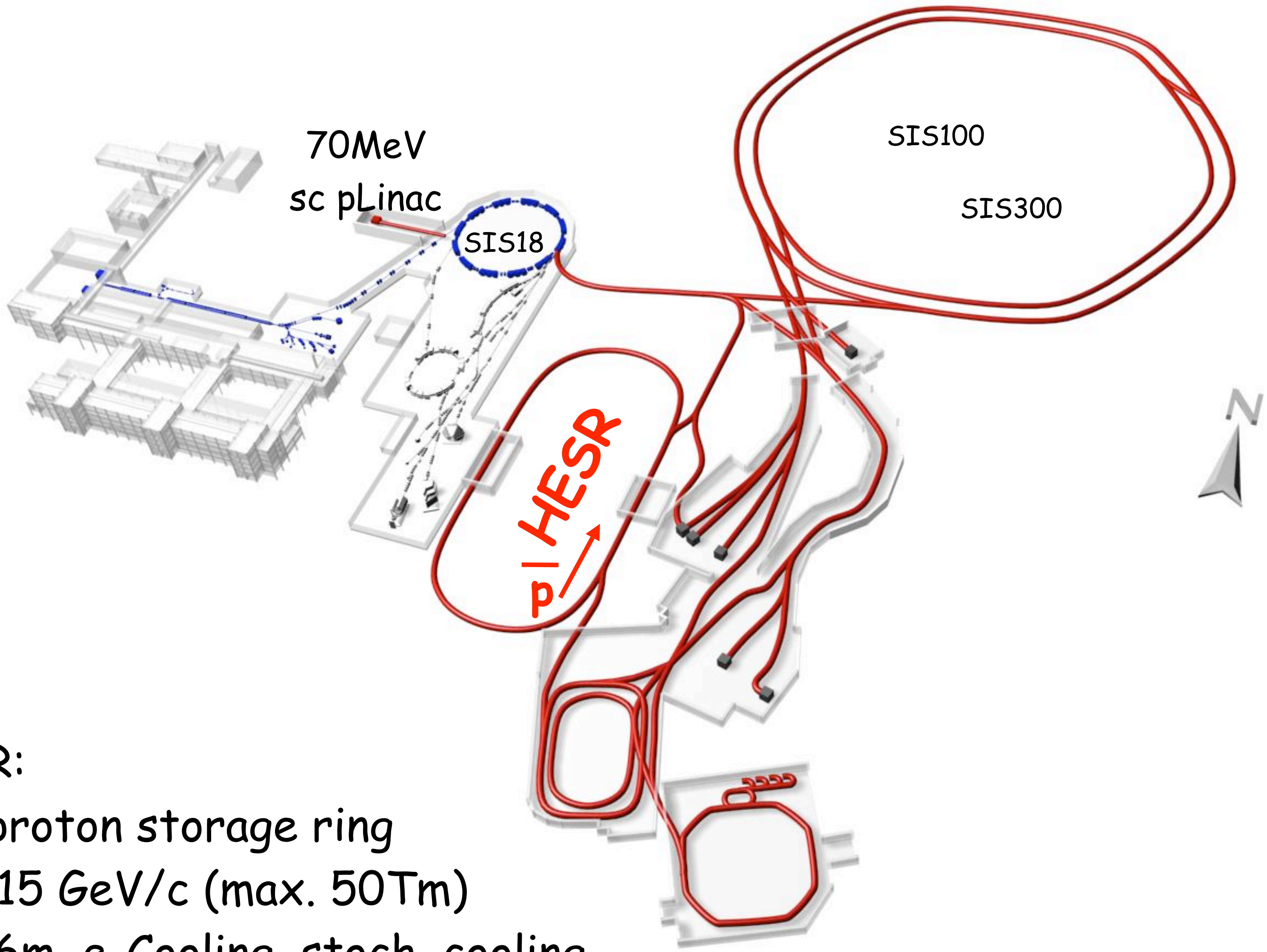
The menu

- A “simple” idea:
  electron – nucleon collisions using the HESR
- First baseline parameter set for e-p collisions at $s=180\mathrm{GeV}^2$ (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:

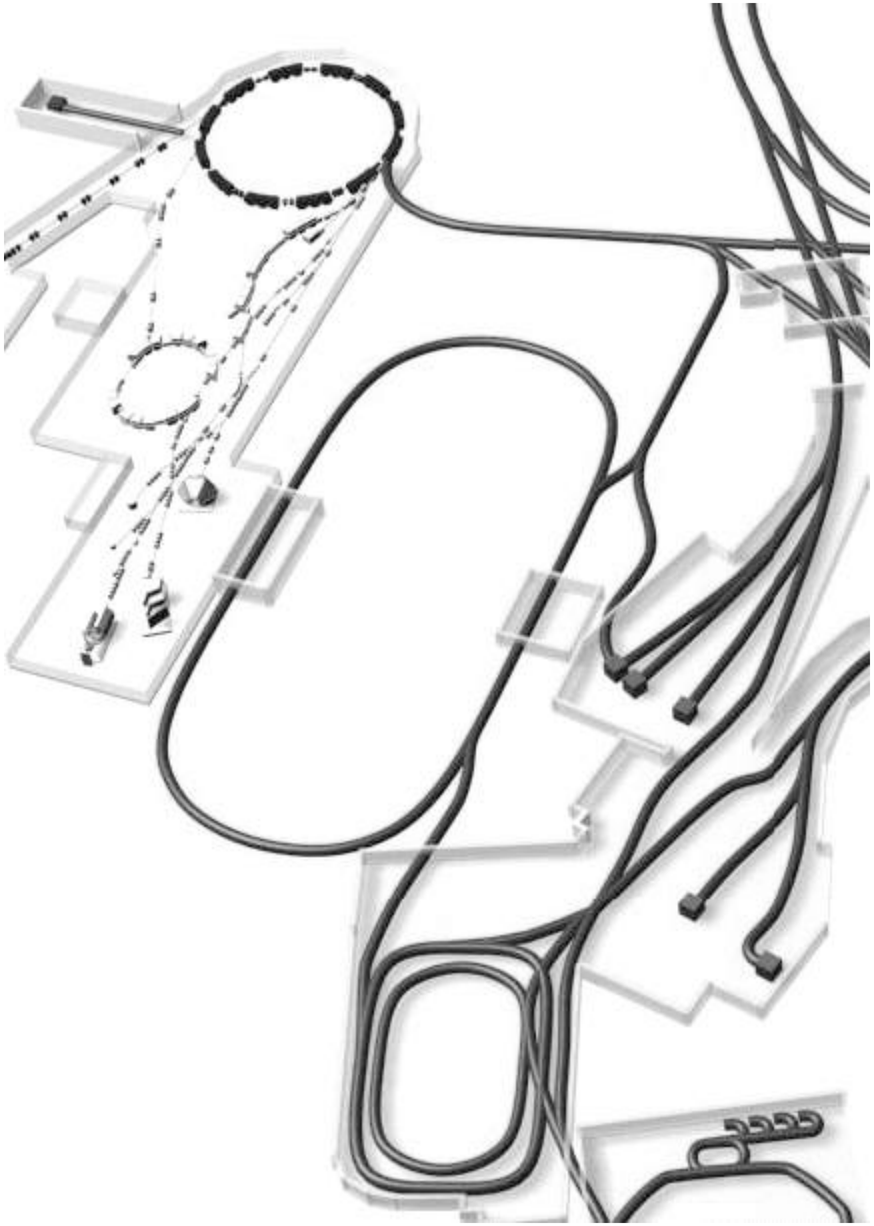
anti proton storage ring

1.5 – 15 GeV/c (max. 50Tm)

L=576m, e-Cooling, stoch. cooling

PANDA fixed target experiment

A “simple” idea: ENC@FAIR (ii)



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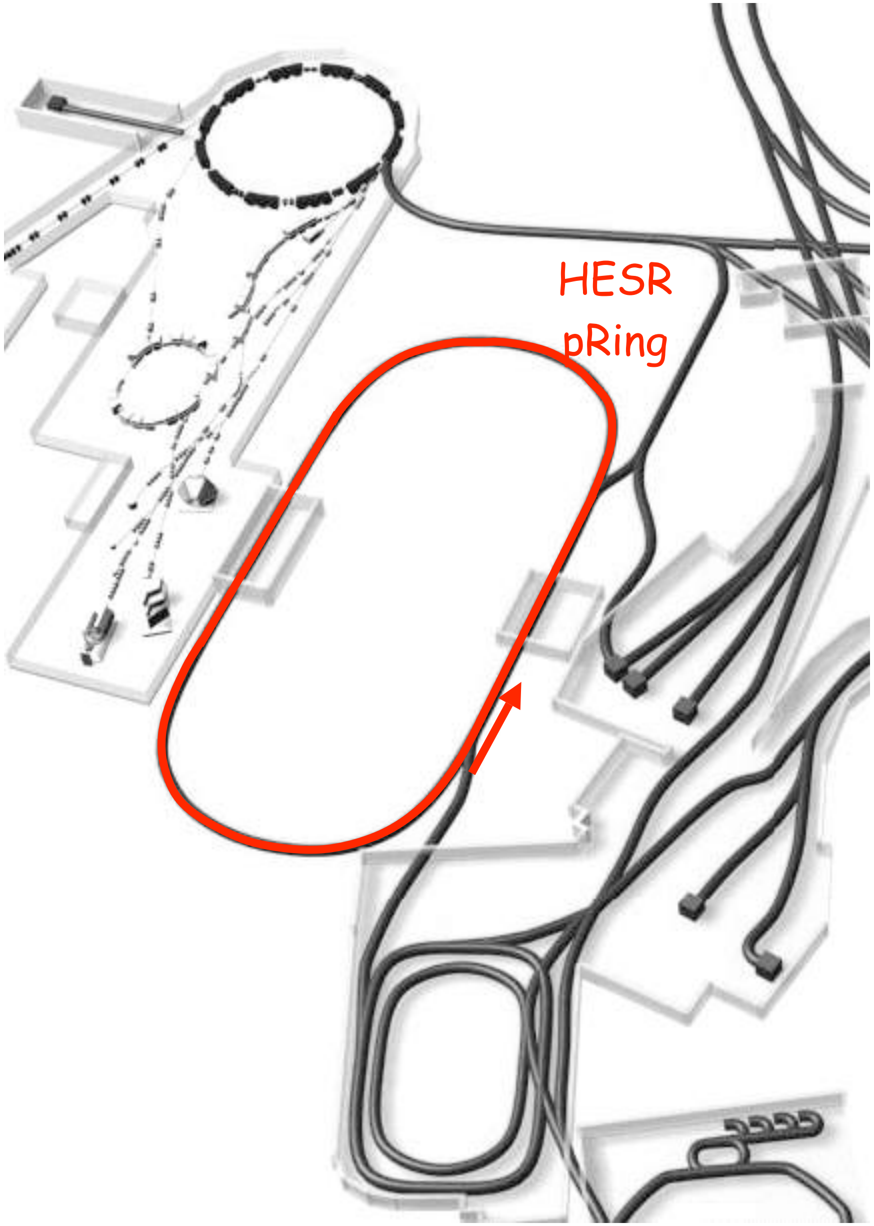

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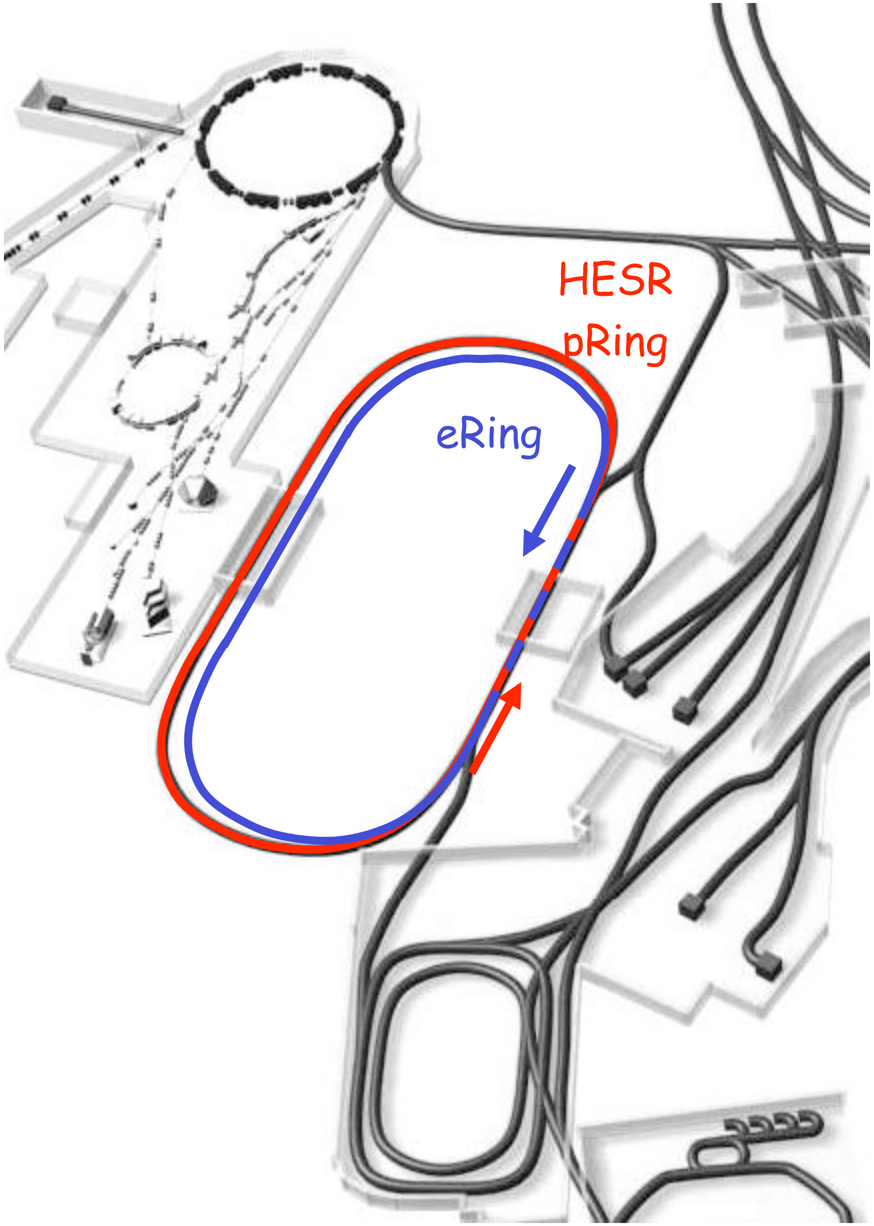

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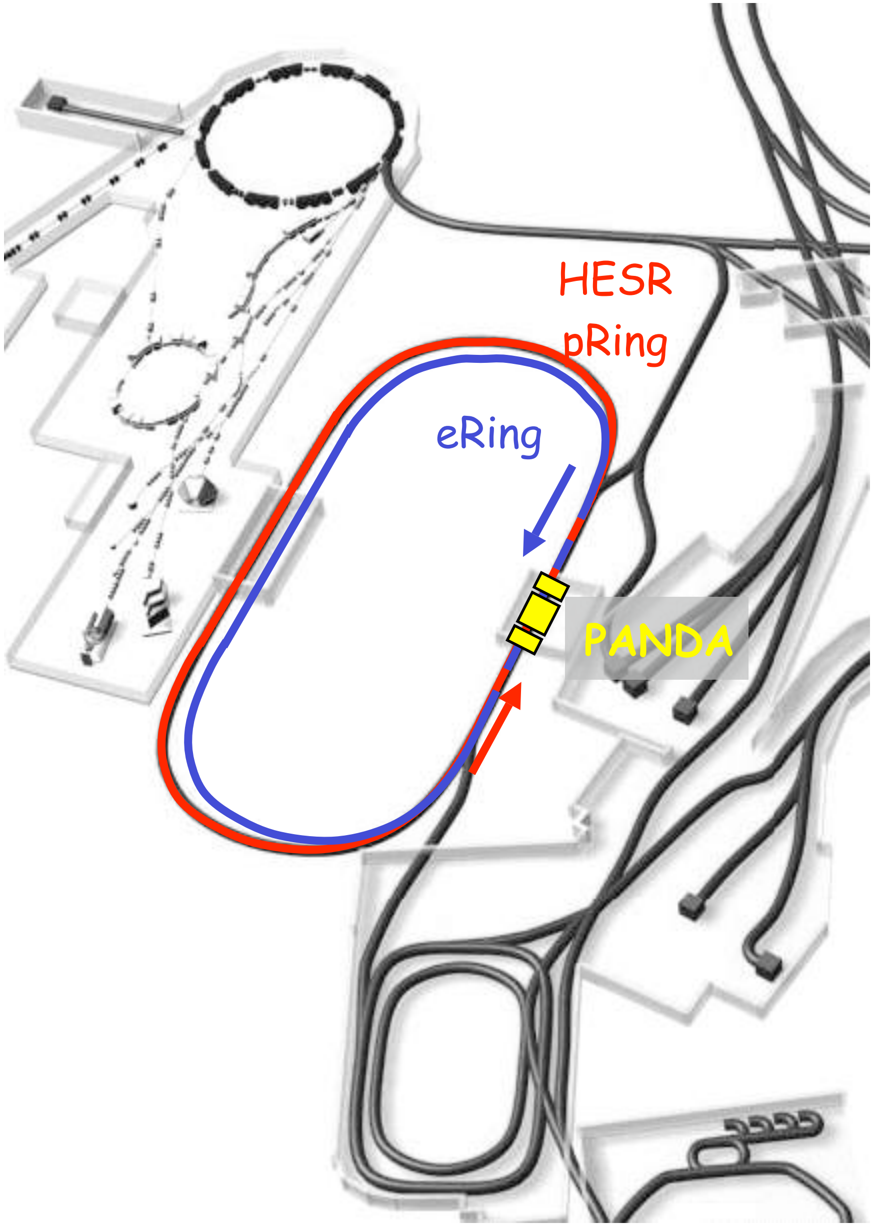

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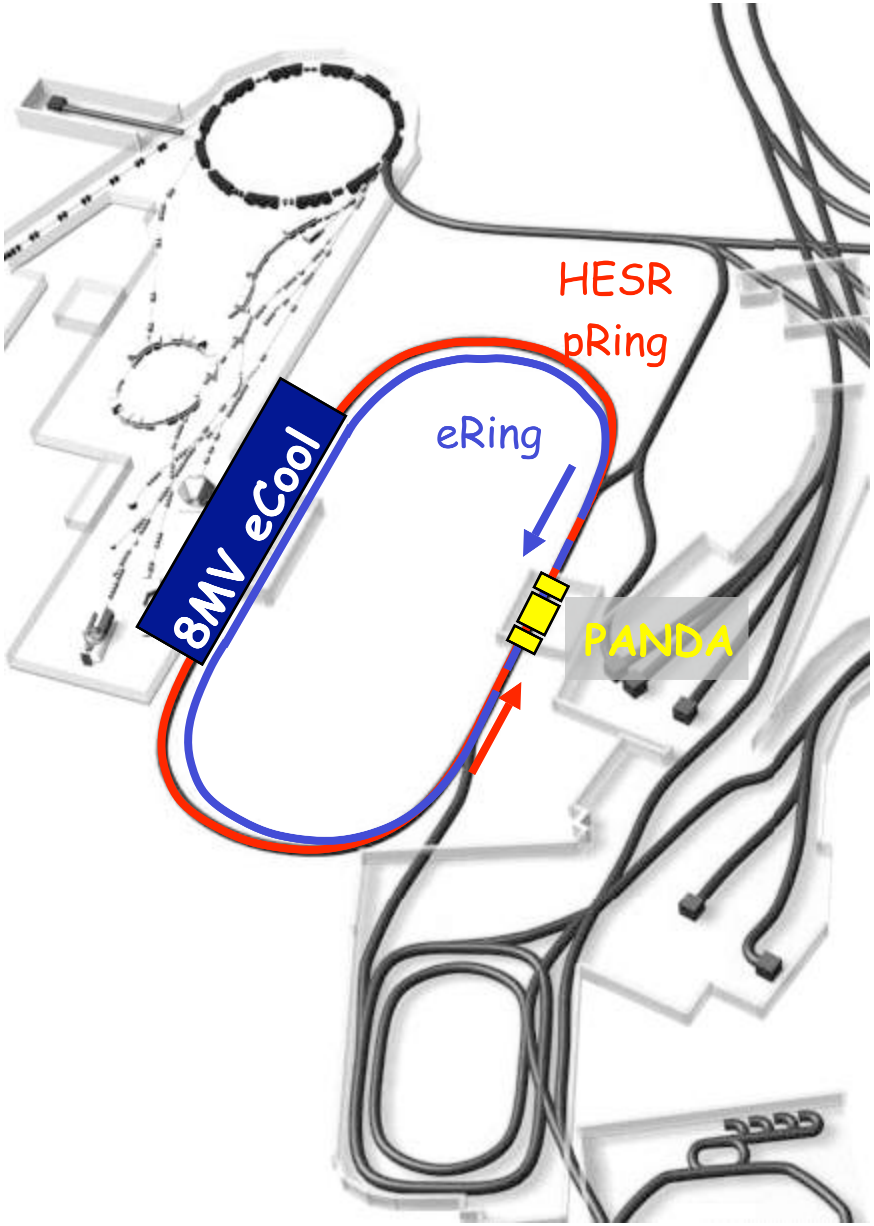

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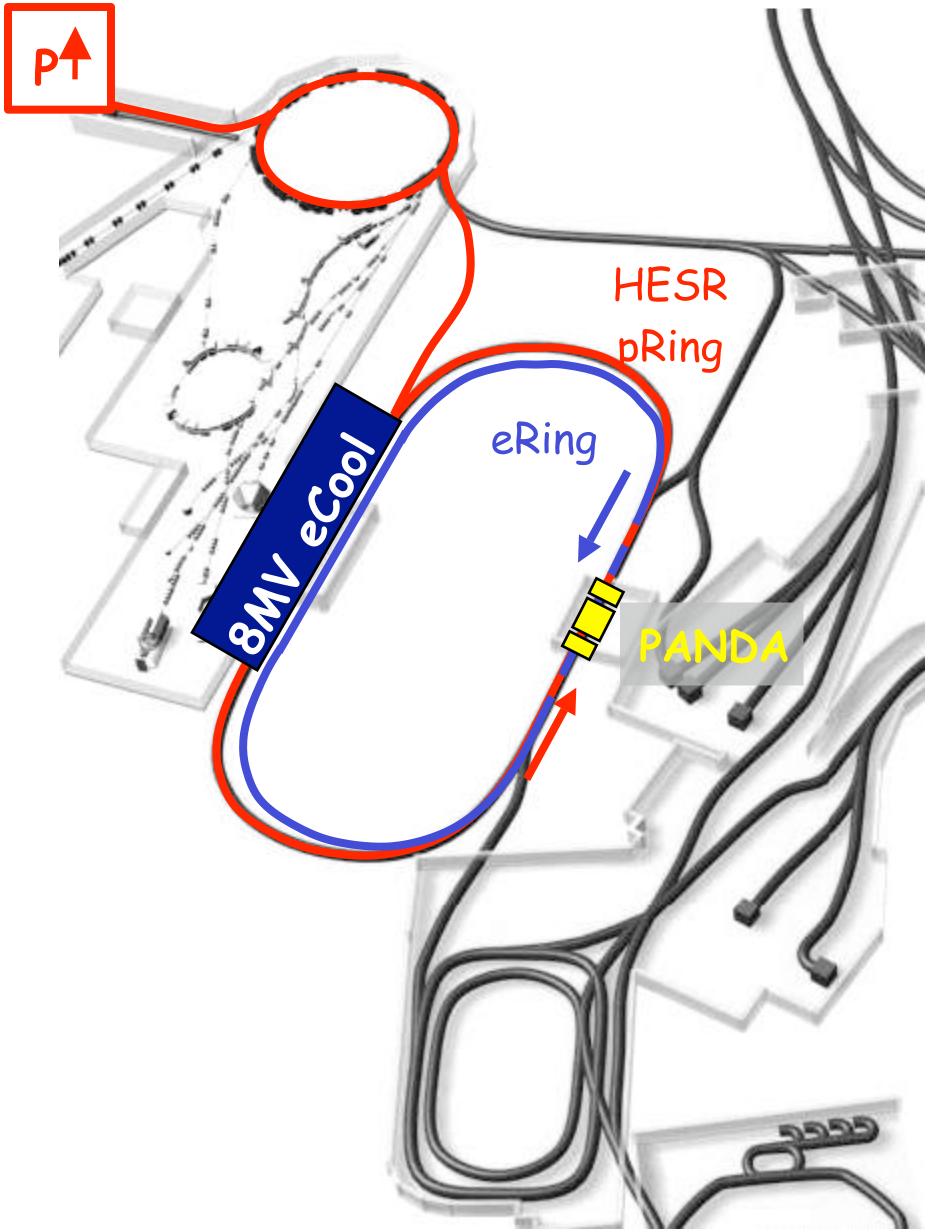

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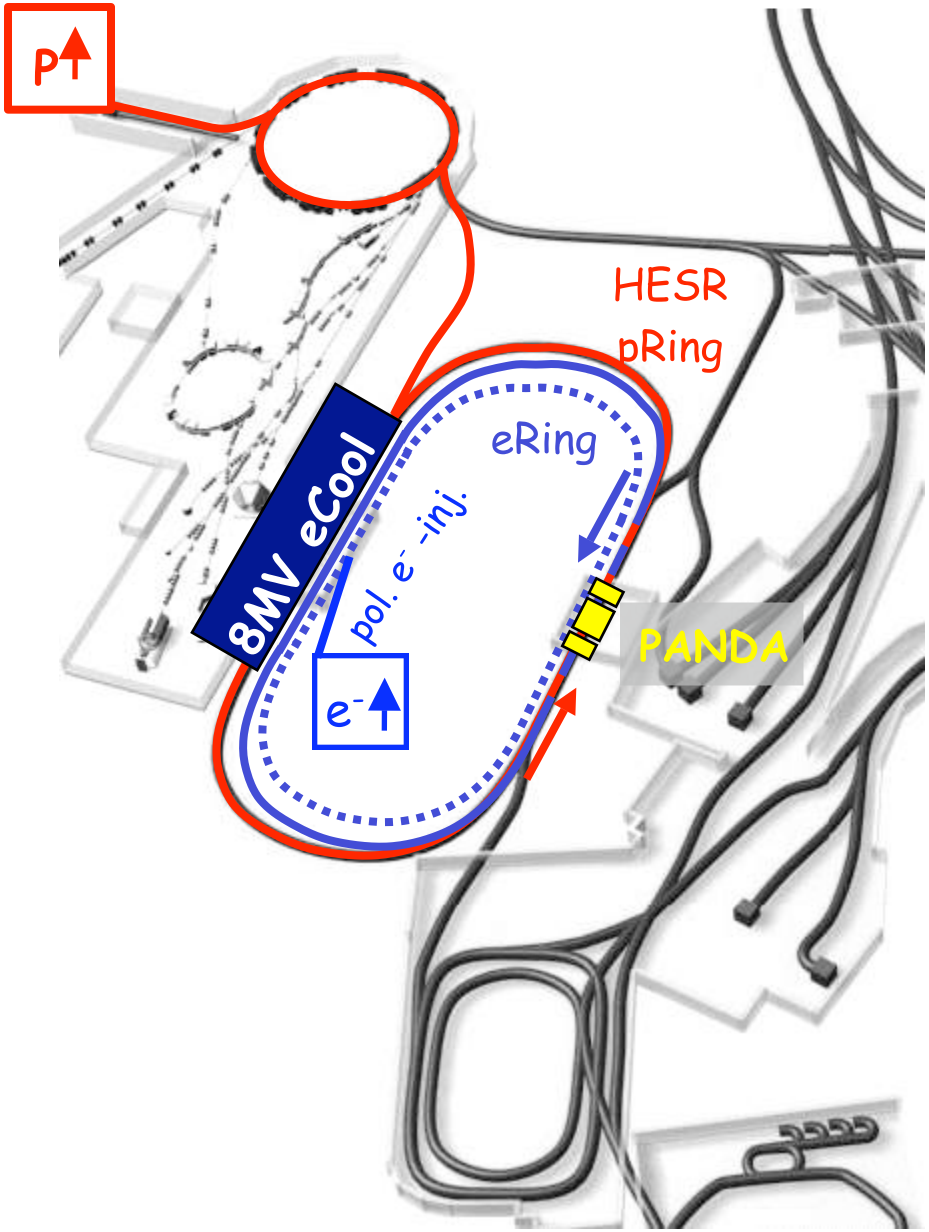

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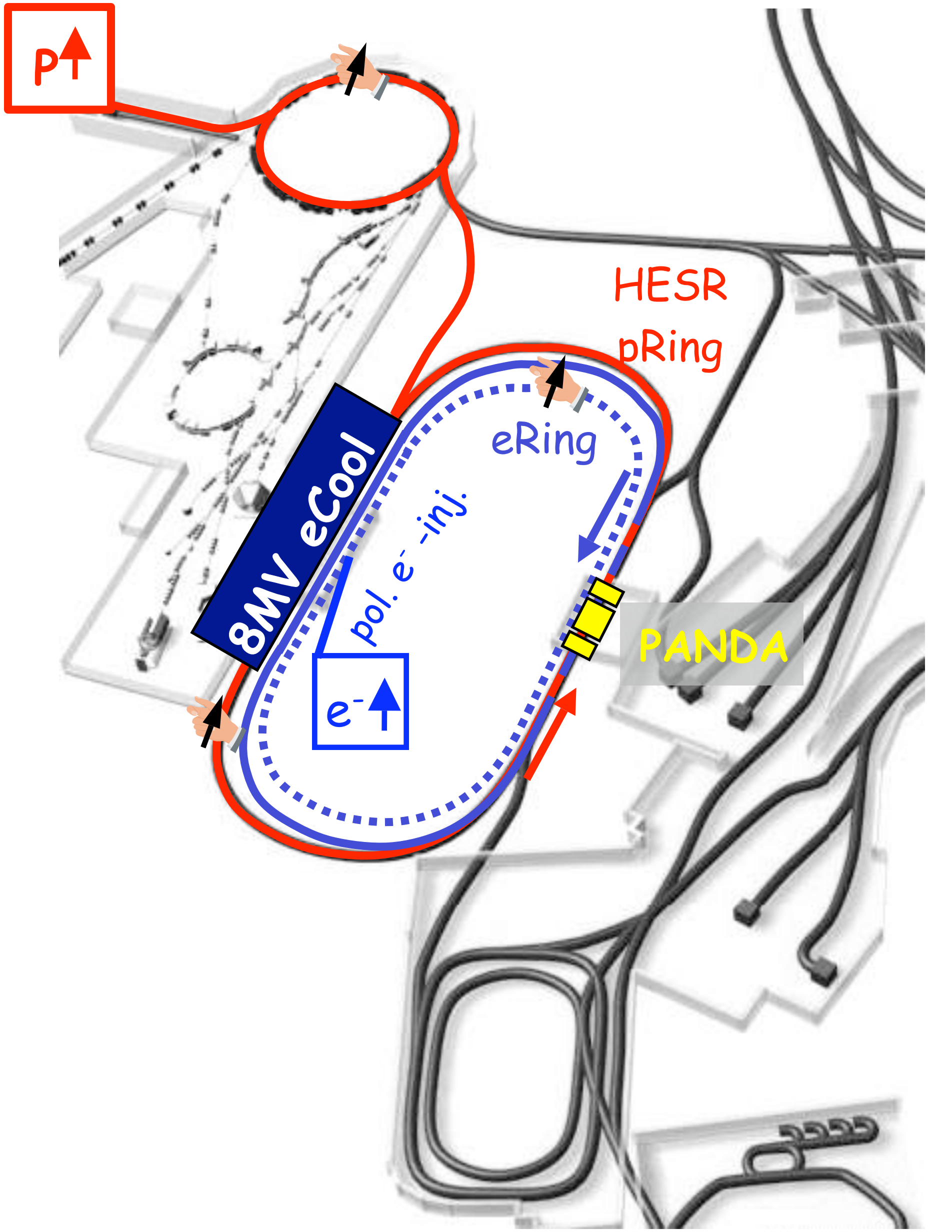

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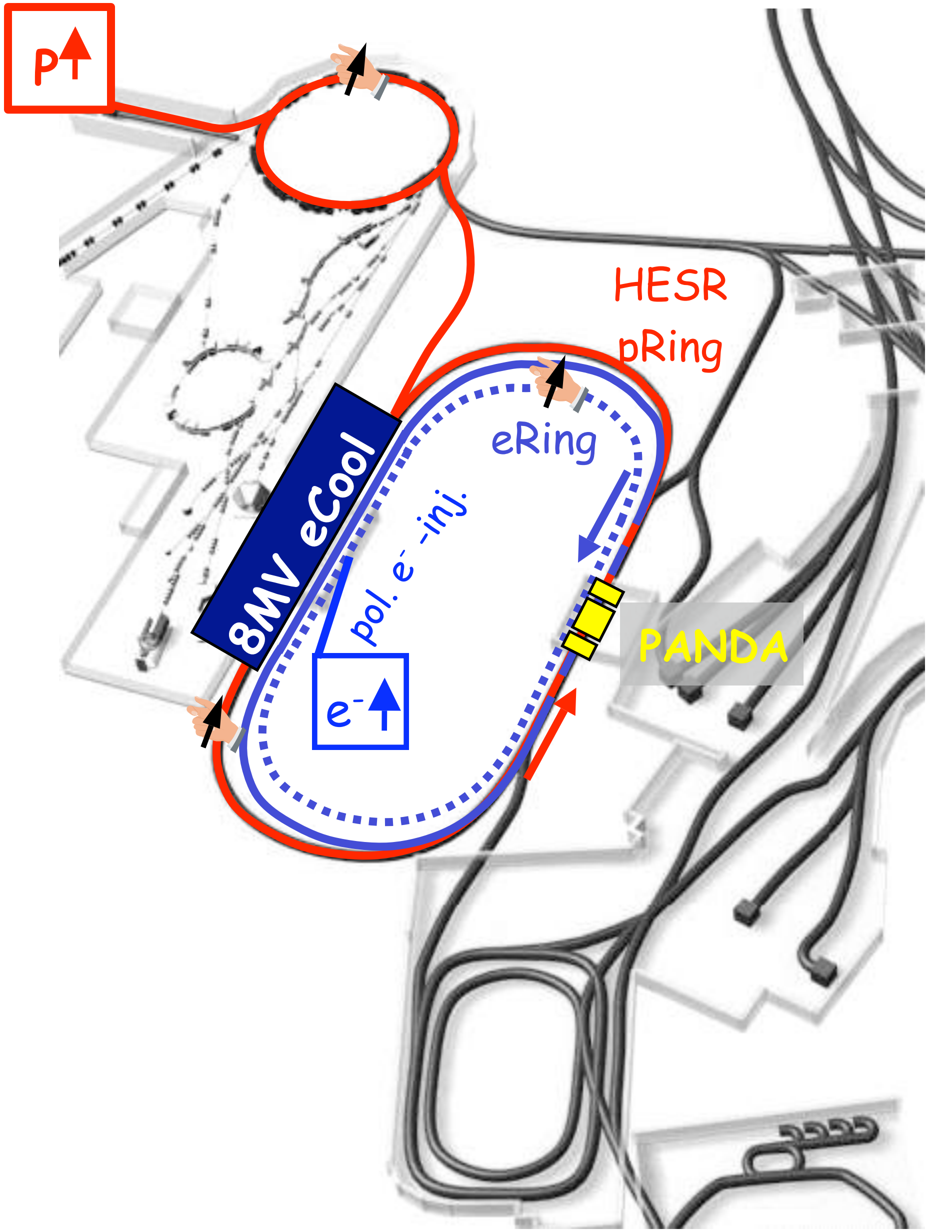

nuclear physicists wish list

(soon it will be Christmas)

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

s > 100GeV

(3GeV e^- ↔ 15GeV p)

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

⟷

polarised p / d (> 80%)

(longitudinal and transversal)

½ a / ½ a time sharing operation with PANDA should possible

using the PANDA detector,

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, FZ-Jülich
Th. Weis, DELTA / Dortmund

mandate by nuclear physicist of
Bonn, Mainz (Dietrich von Harrach), Jülich, ...

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

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

f_{coll}: collision-frequency, $n_{e,p}$: particles / bunch, r_{IP}: beam radius at IP
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1) beam radius at IP, limited by proton beam:

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

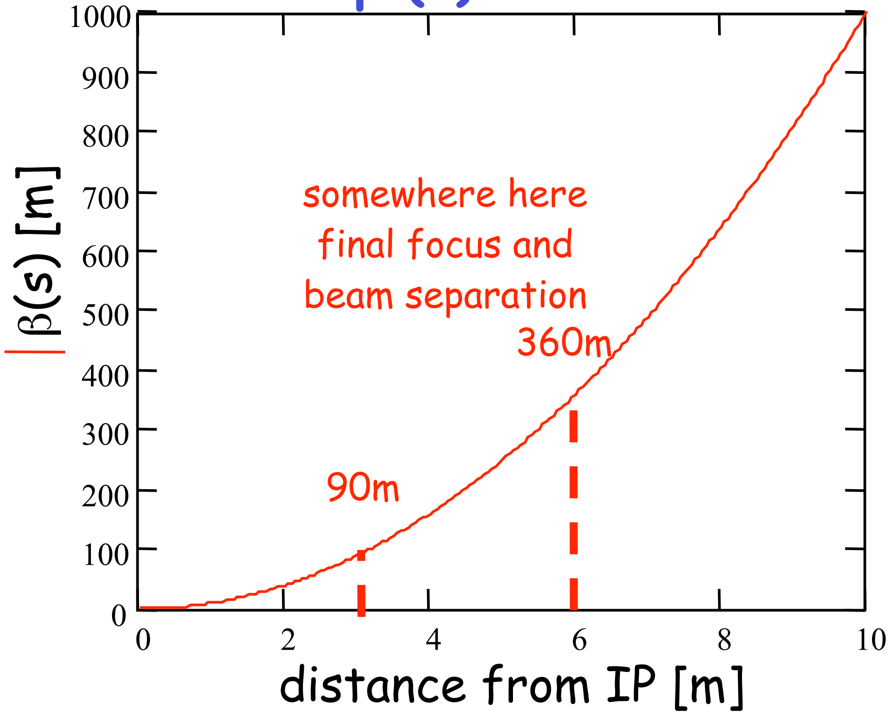
Goal:

- minimise β_{IP}
- maximise γ_p or reduce ε_p by **cooling**

First baseline parameter set e-p (ii)

β_{IP}=0.1m

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



somewhere here
final focus and
beam separation

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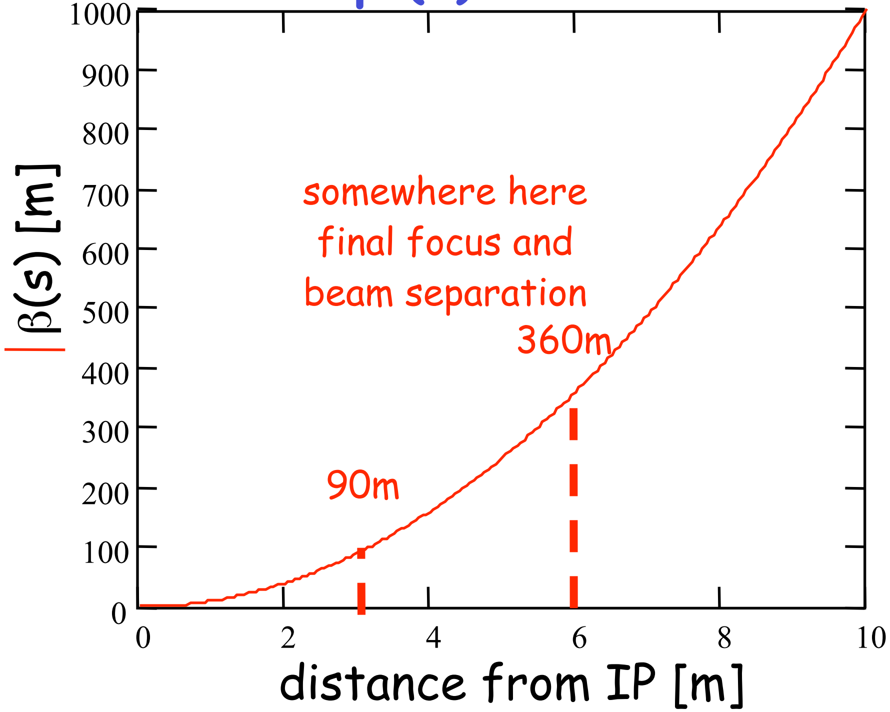

somewhere here
final focus and
beam separation

360m

90m

β_{IP} = 0.1m, implies (due to hour glass effect) l_b=0.1m

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

→ r_{IP} = 0.114mm

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=1eV, T^L=0.5meV

$B_r/B < 10^{-5}$, 24m effective cooler length

First baseline parameter set e-p (iii)

2) parameter of the proton beam

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

$$f_{coll} \times n_p = f_{HESR} \times h_p \times n_p = f_{HESR} \times N_p$$

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

f_{HESR}: revolution frequency in HESR

519.455kHz@γ_p=16 / 516.391kHz@γ_p=8 / 450.743kHz@γ_p=2

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What defines $h_p \cdot n_p$:

a) space charge (Laslett) tune shift:

$$\Delta Q_{sc} = \frac{e}{8\pi^2 \times \varepsilon_0 \times m_p} \times \frac{\boxed{B \times h_p \times n_p}}{\beta_p \times \gamma_p^2 \times \varepsilon_p^{norm}} \quad = L_p / l_p \cdot n_p$$

B: bunching-factor = λ_{rf} / l_p (rf wave-length / bunch-length), L_p: circumference

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$= L_p / l_p \cdot n_p$

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β_{IP} = 0.1m implies l_p = 0.1m (hour glass reduction 76%)

L_p/l_p=576m/0.1m=5760 and ΔQ=0.1 → $n_p < 3.6 \cdot 10^{10}$ (p / bunch)

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

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)

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

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h_p=100 → f_{coll}=51.95MHz

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

λ_{coll} = 5.76m (bunch spacing HESR) → parasitic collision at 2.88m from IP (bunch separation)

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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)

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

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

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:

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

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Take in mind synchrotron radiation power:

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

At 3GeV a eRing with radii **$R = 30$m** (same as HESR) results at **$P_{SR} = 456$kW** !

(sr-power/meter ~ 1.3kW/m)

e.g. in a machine with a footprint like COSY with R=8m → P_{SR} = 1.7MW

(sr-power / meter ~ 15kW/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
ε^{norm} / ε^{geo} [mm mrad]	2 / 0.13	2 / 0.13
β_{IP} [m]	0.1	0.1
r_{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_{SR} [sr-Power, kW]		455.8
f_{coll} [collision freq., MHz]	51.946	51.946
λ_{coll} [bunch distance, m]	5.76	5.7713
ΔQ_{sc}	0.1	
ξ [beam beam parameter]	0.013	0.011
Luminosität	2.0 10^{32} 1/cm^2s	

Some comments to the necessary ingredients (i)

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

l_b=0.1m, n_p=3.6·10^{10}, ε_p=1.3·10^{-7}mrad, P_p > 80% @ 15GeV/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 ΔQ~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

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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
- easy scheme for eRing with one snake in back straight for preservation of polarisation and free spin angle at detector seems not to be feasible

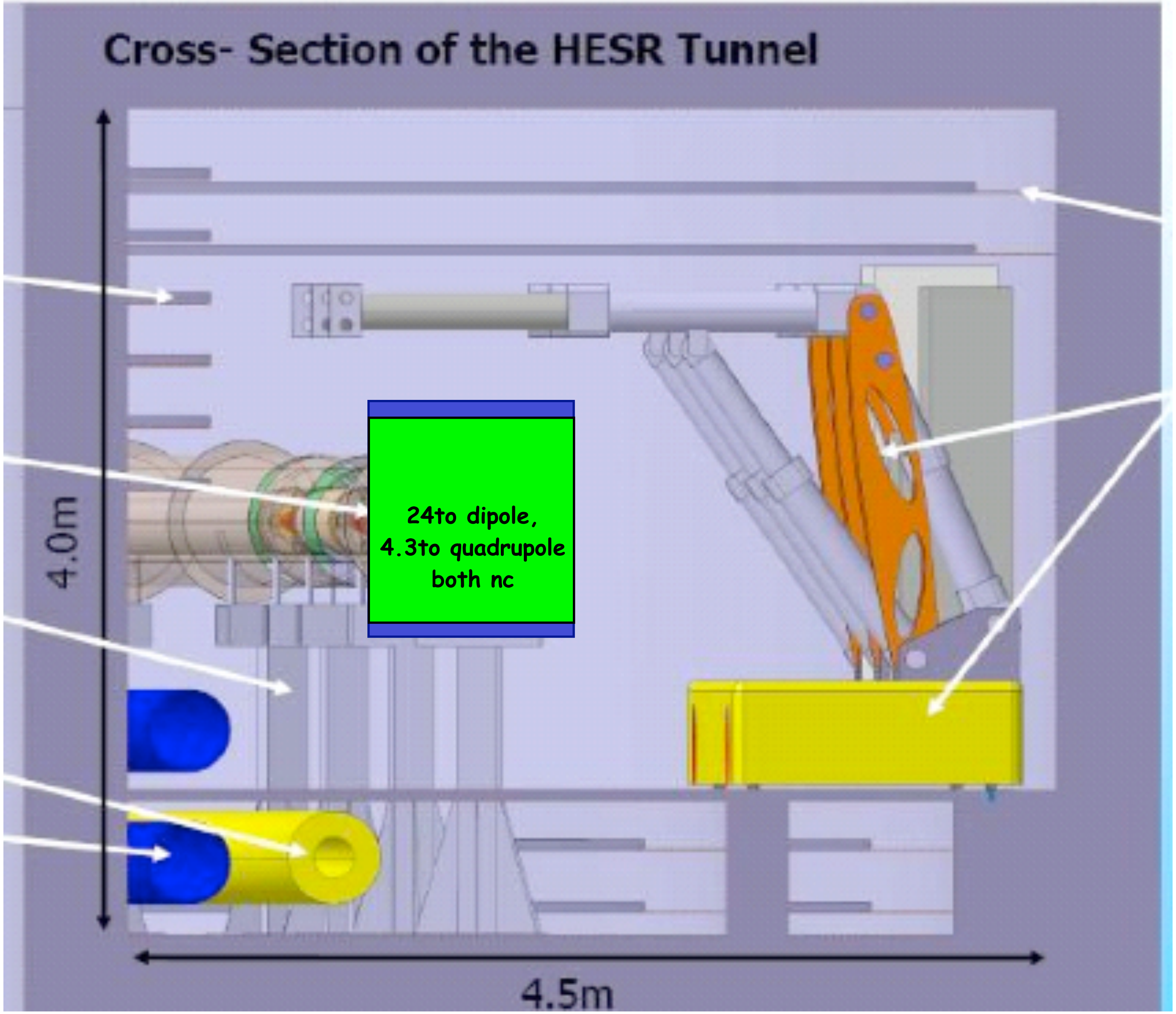
  τ_{depol} < 20min (following first estimations of D. Barber / DESY)

  → 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 $\varepsilon_{vert} \ll \varepsilon_{hori}$ (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 !

Some comments to the necessary ingredients (iii)

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



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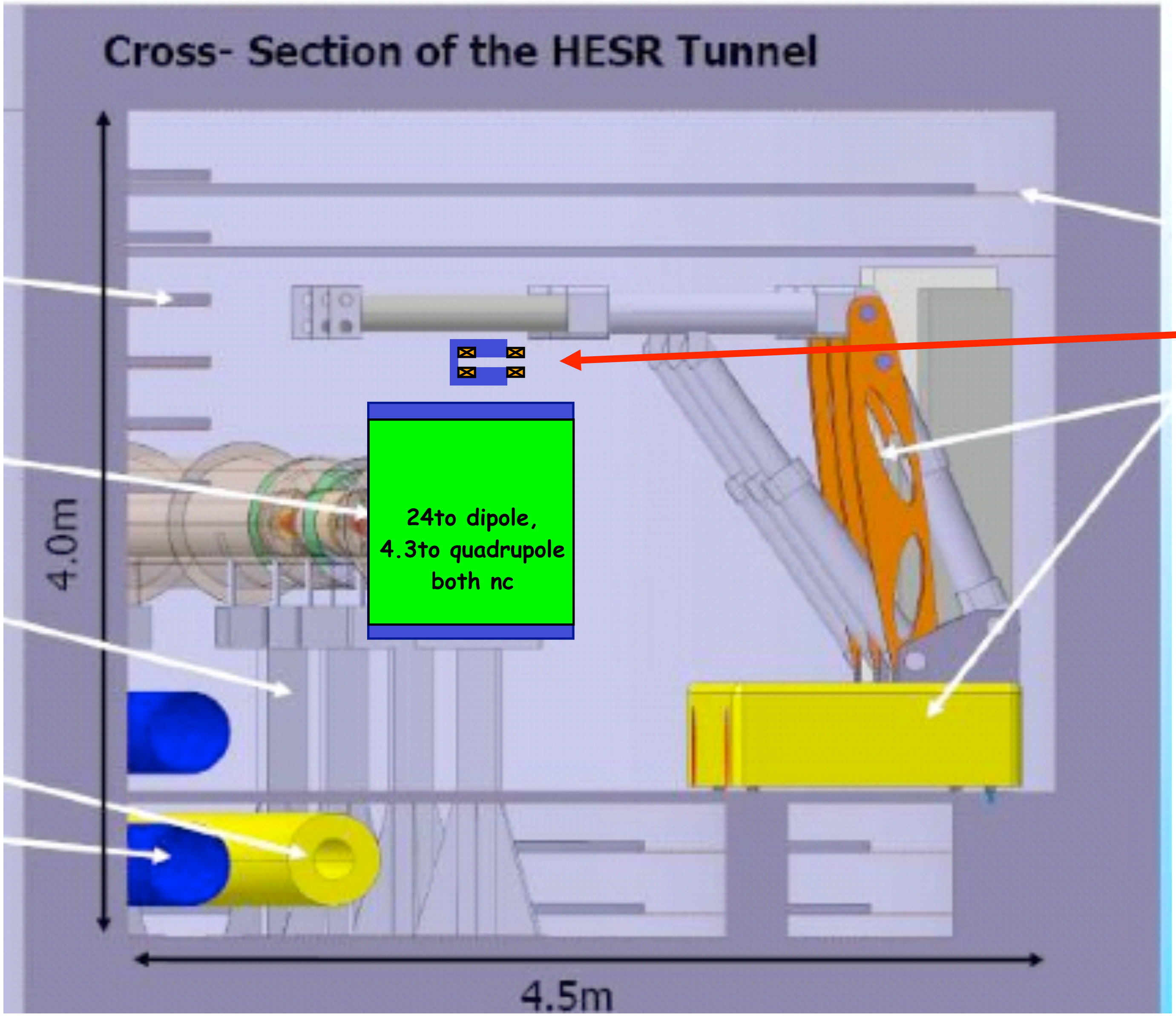

eRing dipole:
ca. 0.4m×0.25m and
1.6to for 4m length

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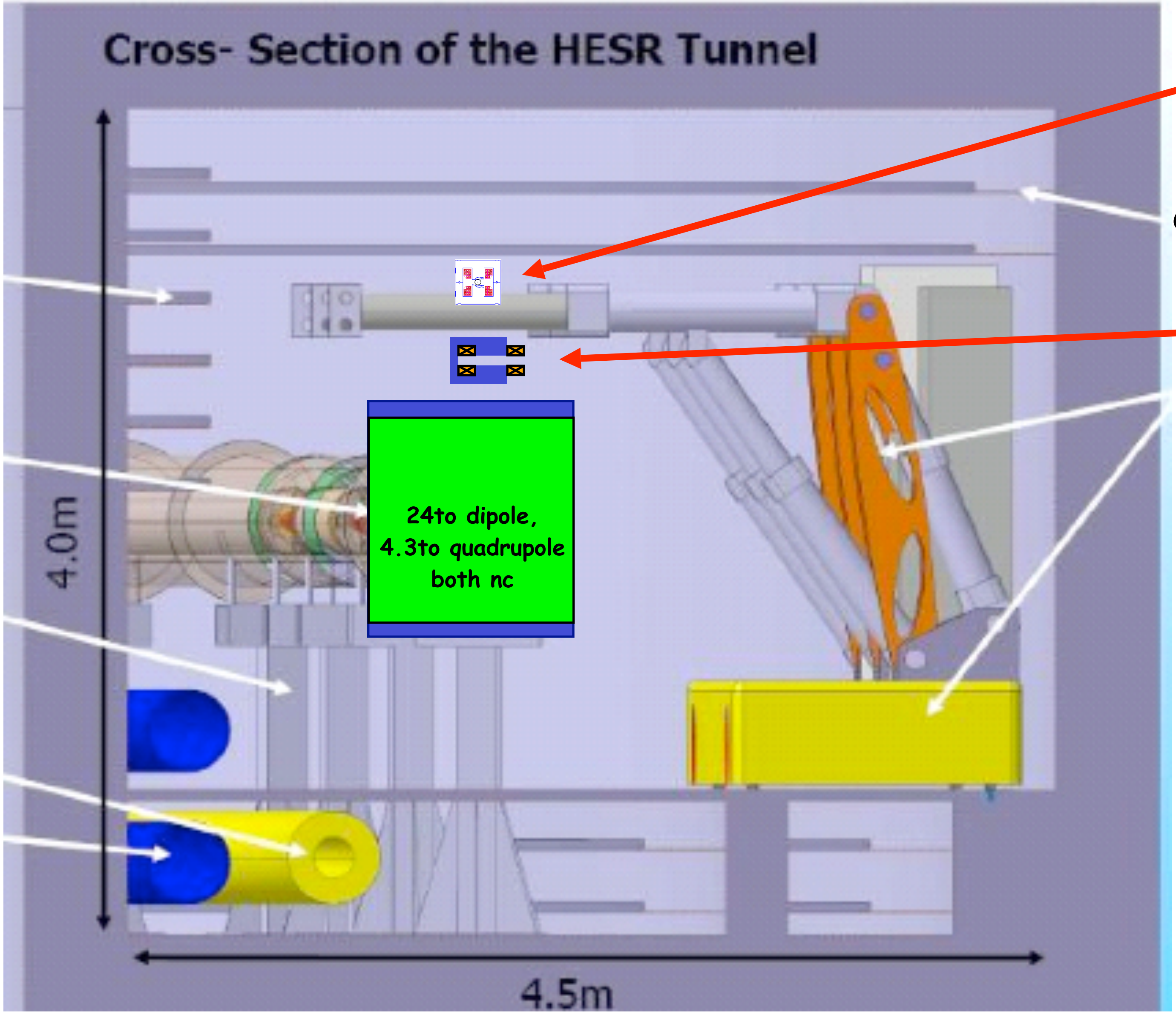

Full-Energy-Booster dipole a la SLS:
ca. 0.2m×0.2m and
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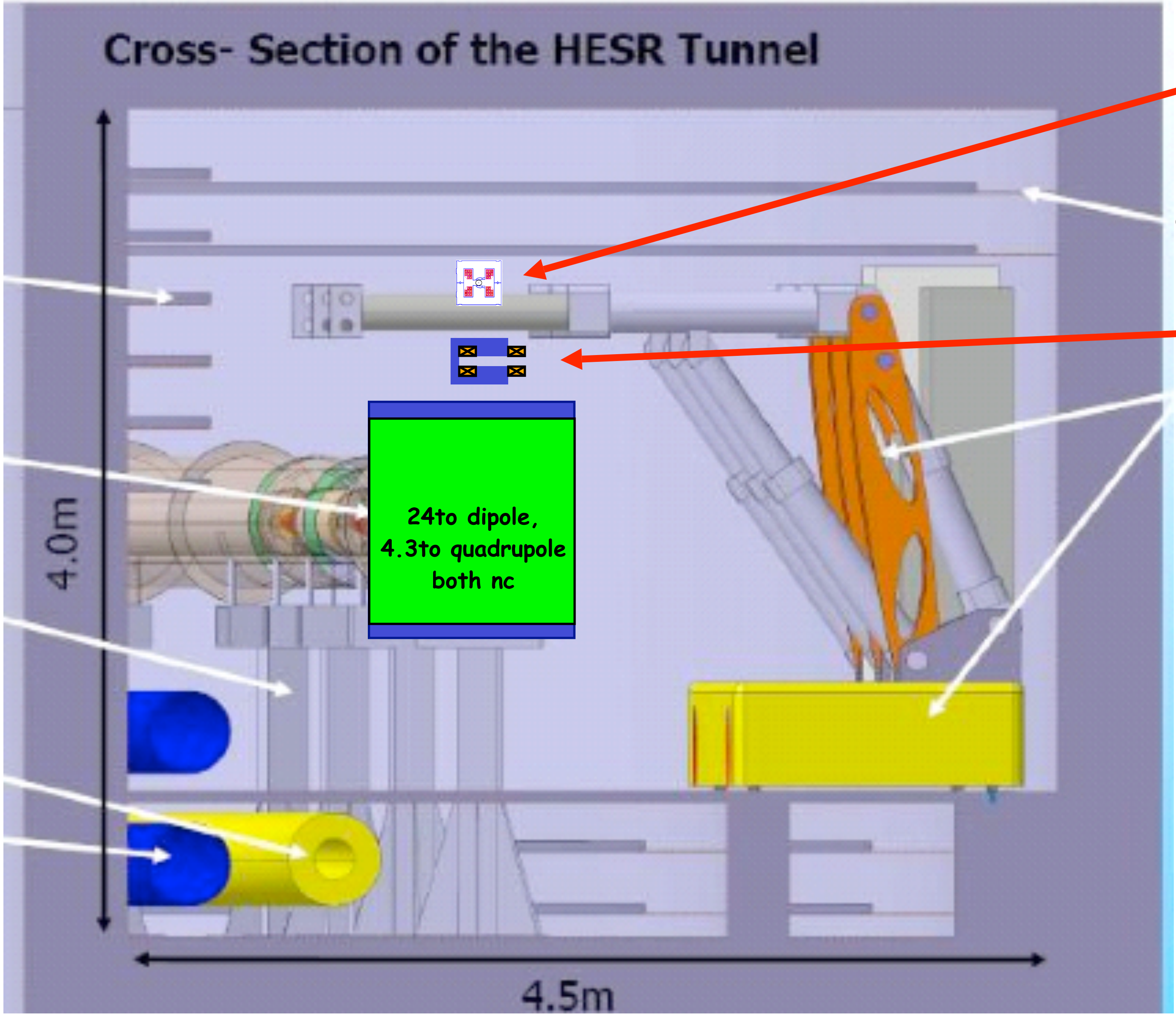

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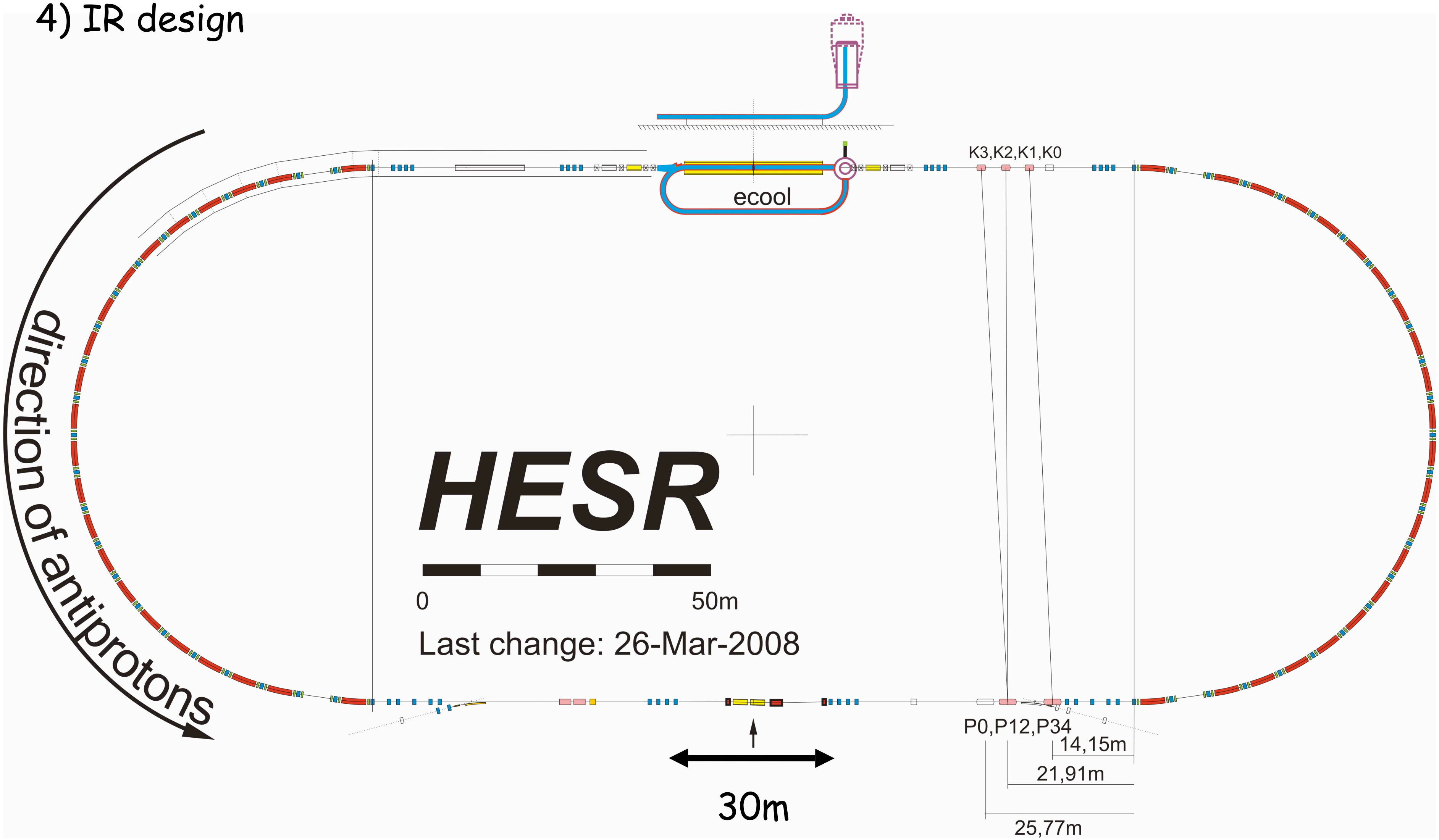
But don't forget:

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

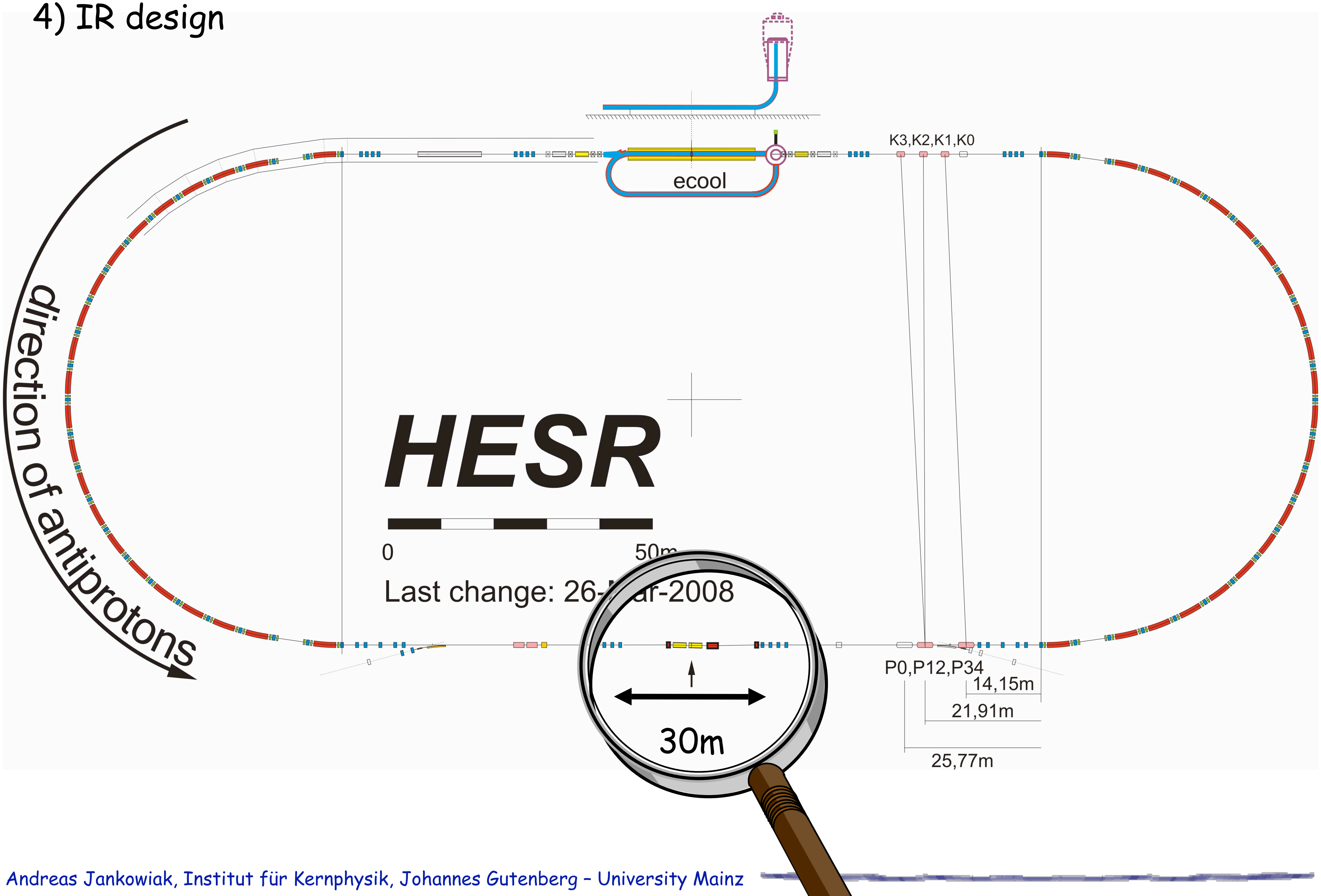
Some comments to the necessary ingredients (iv)

4) IR design



Some comments to the necessary ingredients (iv)

4) IR design



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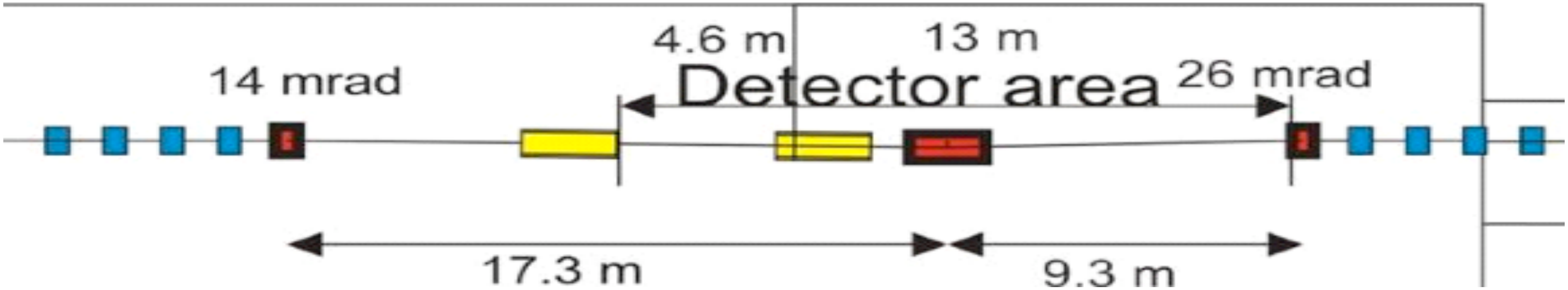

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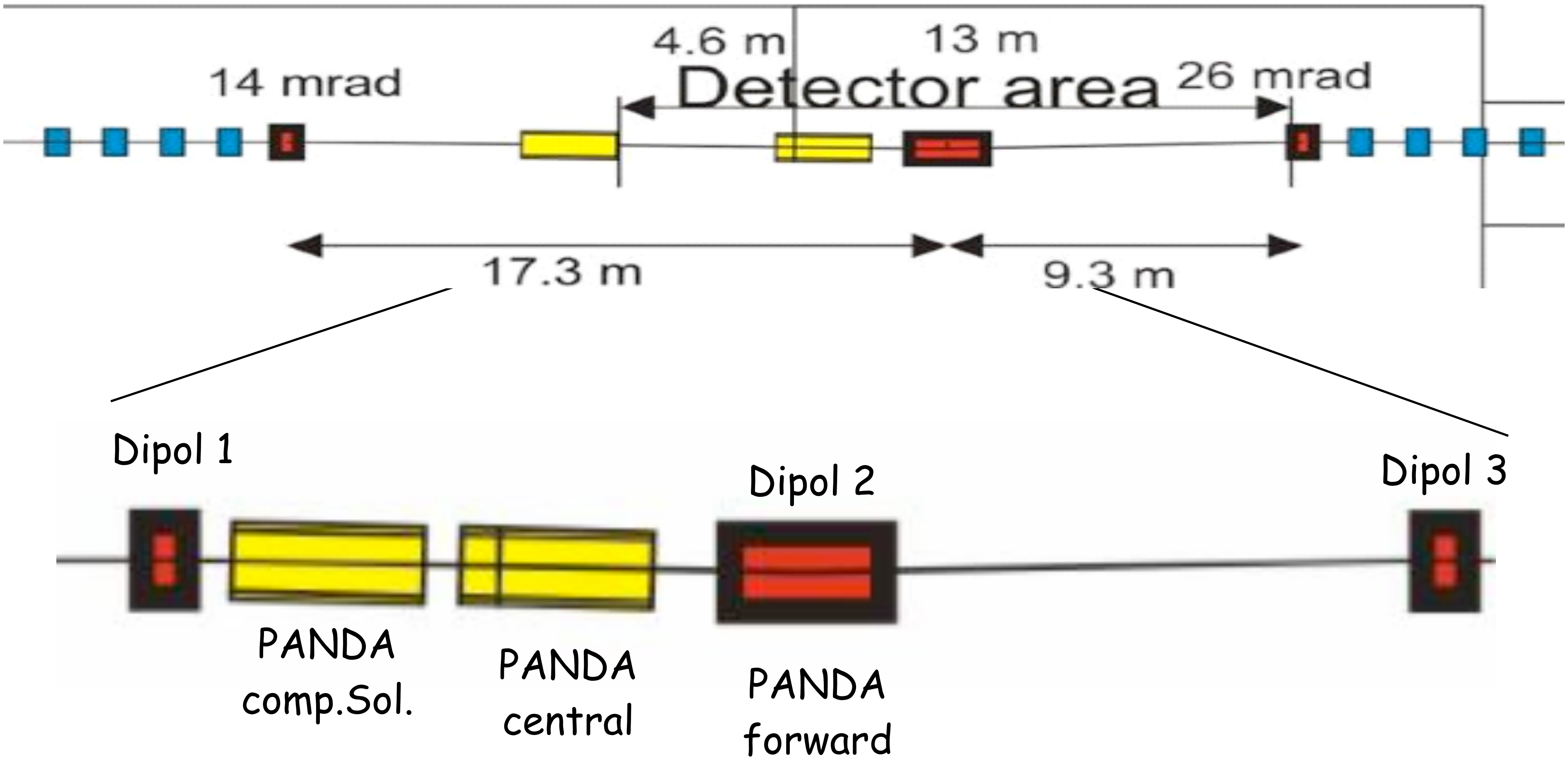
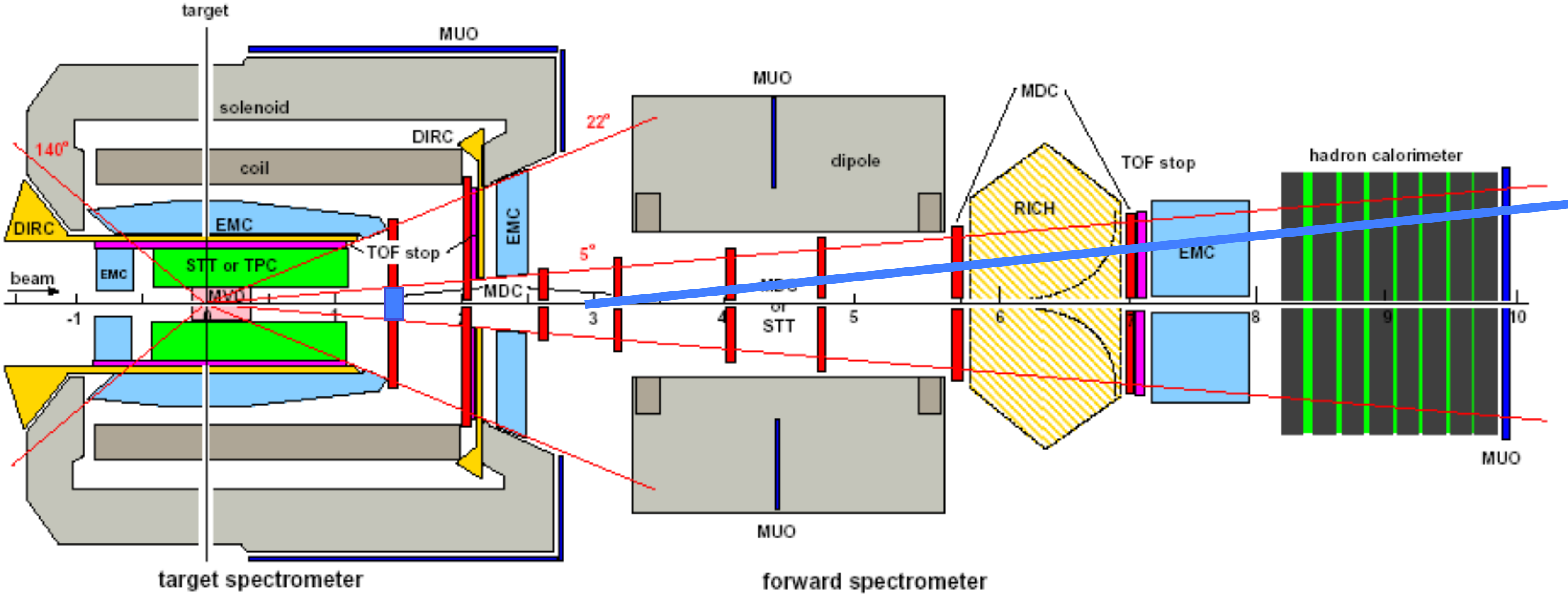


3 dipole-bump,
detector is not on a straight of the HESR

Some comments to the necessary ingredients (vi)

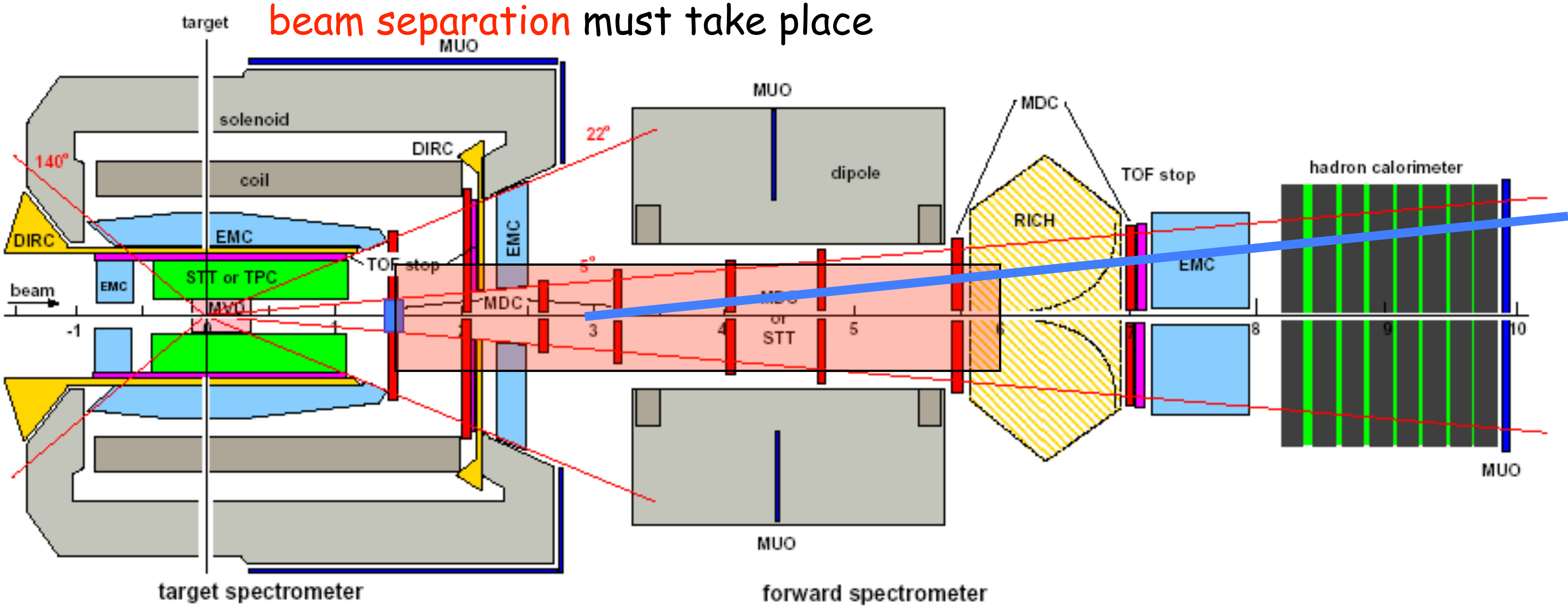
side view of PANDA



Some comments to the necessary ingredients (vi)

side view of PANDA

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



Some comments to the necessary ingredients (vi)

side view of PANDA

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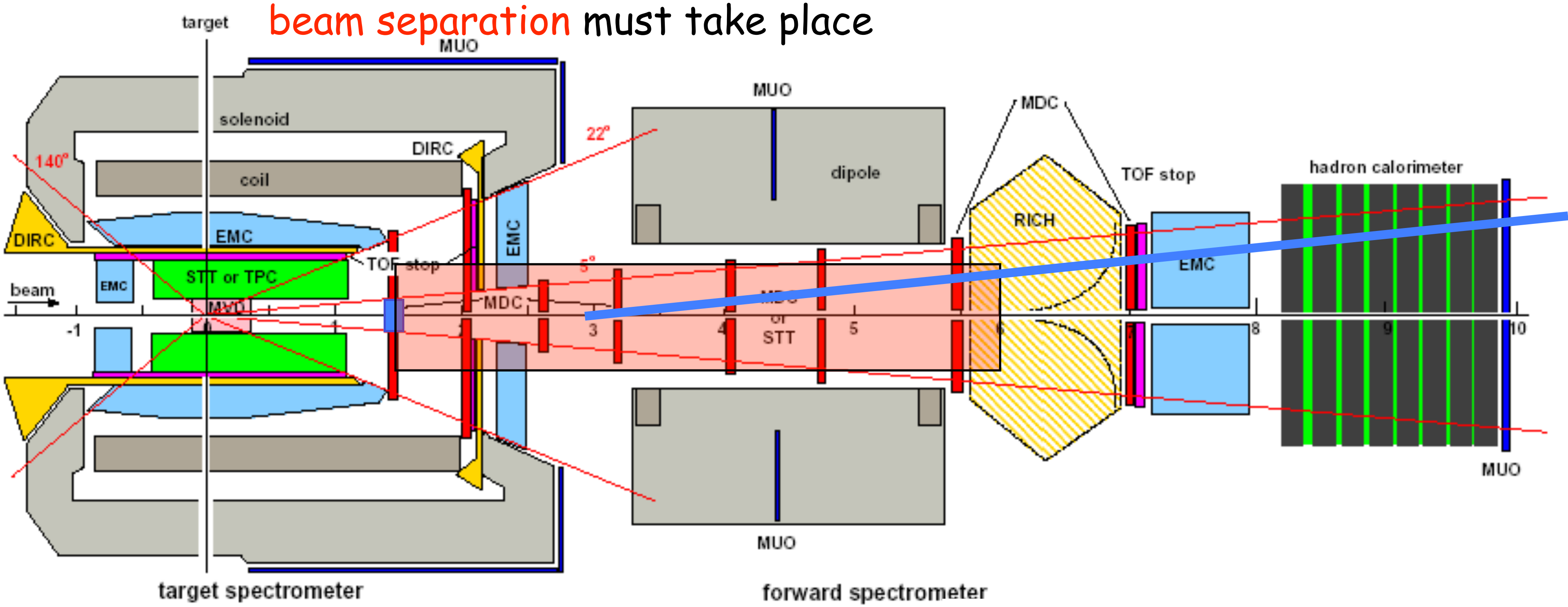


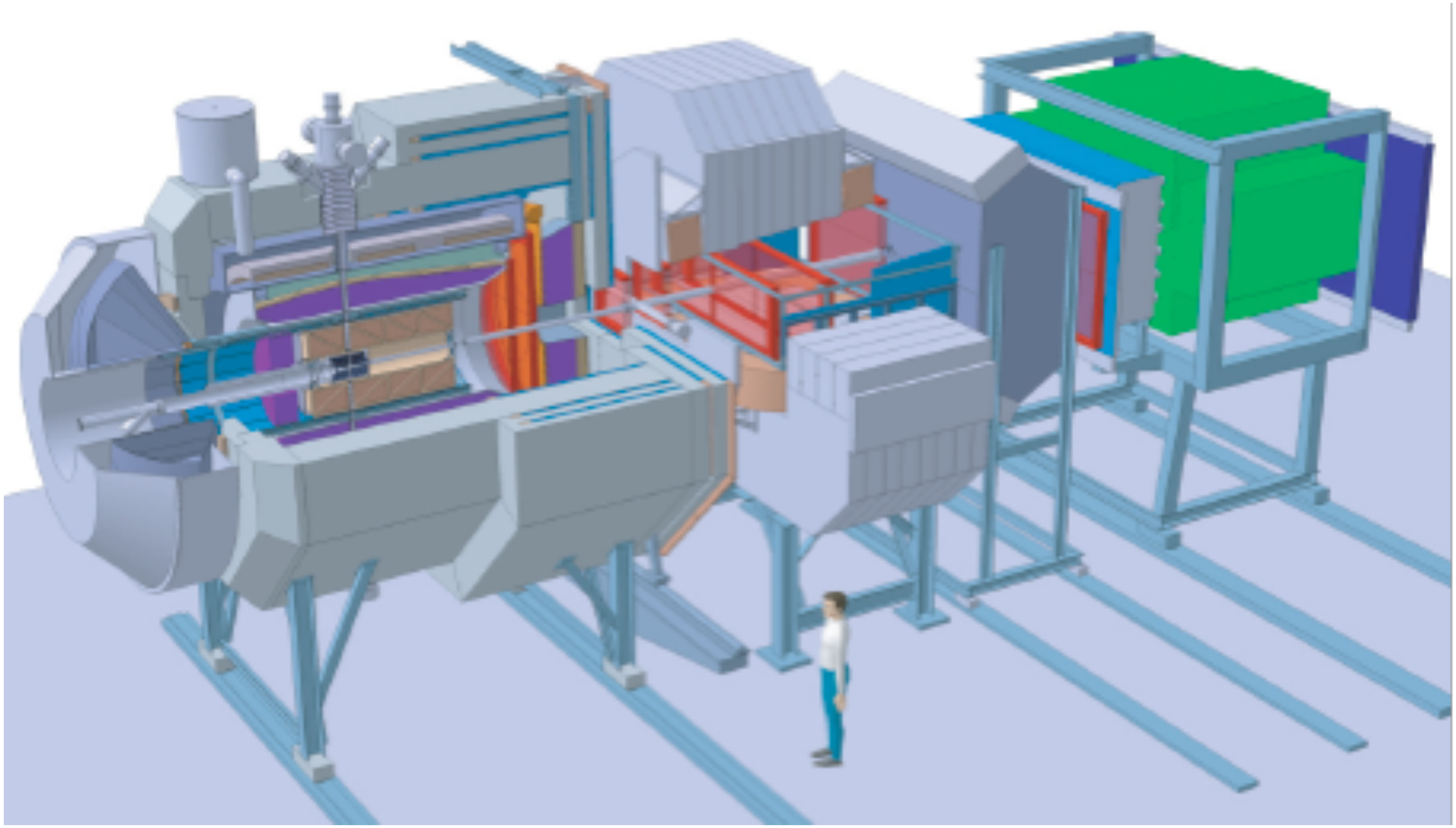
additional

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

Some comments to the necessary ingredients (vii)

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:

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

scaling for IBS growth rate:

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

comparison proton – deuterium at p=15GeV/c:

Proton	**Deuterium**
m_p=938.27MeV	m_d=1875.61MeV
A=1, Z=1	A=2, Z=1
γ=16.02, β=0.9980	γ=8.06, β=0.9922

therefore

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

- 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 (γ_d=8, instead of γ_p=16) with polarised e^-

- needs a polarised d source at the UNILAC
- needs other rf-frequencies and adaptation of eRing length (β_p=0.998 compared to β_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 γ_d

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

Therefore one gets for the luminosity:

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

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beam beam parameter of d (ξ^d < 0.01 typ.): $\xi^d = \frac{r_{0,d}}{4\pi}\times\frac{n_e}{\gamma_d}\times\frac{1}{\varepsilon_d} = 0.0139$ ☑

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
ε^{norm} / ε^{geo} [mm mrad]	2 / 0.13	1 / 0.13
β_{IP} [m]	0.1	0.1
r_{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_{SR} [sr-Power, kW]		455.8
f_{coll} [collision freq., MHz]	51.645	51.645
λ_{coll} [bunch distance, m]	5.76	5.8049
ΔQ_{sc}	0.1	
ξ [beam beam parameter]	0.0139	0.0028
Luminosität	$1.0 \cdot 10^{32}$ 1/cm²s	

How to increase the luminosity

How to increase the luminosity

$$L = f_{coll} \times \frac{n_p \times n_e}{4 \times \pi \times \left(\varepsilon_p \times \beta_{IP}\right)}$$

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

$$n_e = 7.5 \times 10^{10} \times E[\mathrm{GeV}] \qquad P_{SR} = 88.2 \times \frac{E_e^4}{R_e} \times e \times f_{coll} \times n_e$$

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

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Increasing f_{coll} (more bunches in HESR and also eRing), but:

Realisation ? P_{SR} increases ! ΔQ_{sc} in HESR@2GeV increases !

Multi bunch instabilities in eRing and HESR with increasing current !

How to increase the luminosity

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

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

$$\xi^e = \quad \ldots \quad = \frac{r_{0,p}}{4\pi} \times \frac{n_e}{\gamma_p} \times \frac{\beta_{p,IP}}{r_e^2}$$

$$\times f_{coll} \times n_e$$

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Conclusion

- ENC is very interesting option for HESR
- 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, Dortmund, D. Barber / DESY)
  - beam dynamics in HESR bunch formation process under eCool (Mainz, FZJ)
  - IR design with PANDA and spin rotators (Chr. Montag / BNL, Mainz)
  - eCool at 8MV and ampere currents